GEOCHRONOLOGY IN THE EAST KIMBERLEY AREA
OF WESTERN AUSTRALIA

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for the degree of

DOCTOR OF PHILOSOPHY

by
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STATEMENT

The material contained in this thesis is based on experimental work completed within the period 20th November, 1964 to 20th November, 1967.

All data and the resultant interpretations are the responsibility of the author except in those instances where due acknowledgement is made.

V. M. BOFINGER
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INTRODUCTION

The Kimberley Region of Western Australia is an area of predominantly Precambrian rock with minor basins of Palaeozoic and younger sediments situated some 2,200 miles north-west of Perth; it has as its eastern boundary the Northern Territory-Western Australia border.

In 1962 combined field parties of the West Australian Geological Survey and the Bureau of Mineral Resources began a programme of intensive regional mapping of the area. This author participated in the mapping programme during 1963 and returned to the area in 1964 and 1965 to collect samples specifically for radiometric dating.

The East Kimberley area contains Precambrian elements which range from greater than 2,700 m.y. to approximately 600 m.y. in age. These include metamorphic and igneous basement complexes, extensive basic and acidic volcanics, and successions of relatively unaltered sediments; major diastrophic events have effected many of the rocks and large unconformities separate most individual units. Information which is fundamental to the field geologist is

1) what period of time is represented by the rocks presently exposed, and

2) what stratigraphic correlations of Precambrian rocks can be supported or suggested by radiometric means.
Geochronology in the East Kimberley area, as submitted in this thesis, is particularly addressed towards supplying this information. Intrusive and extrusive igneous rocks have been dated to provide a framework in time for the various sedimentary units and their unconformities. Research has been undertaken to assess the meaning of isochrons constructed for total rock shale samples in an attempt to employ the sediments directly to assess limits to their depositional periods. This work has been carried out in conjunction with, and as an addition to, the geological mapping. It has served to elucidate problems of field geology and also to indicate the most productive approach for definite information in future work.

It has proved convenient to present this material in the following manner. An outline of the geology of the area, based on information derived from the mapping programme, is first presented as a basis for the new information. This is followed by the major section of the thesis in which the geochronological data for each unit is presented and its significance discussed; a summary of this information is given in conclusion. An attempt has been made to present the information for each stratigraphic unit as a self-contained segment so that continual reference to other sections is avoided as far as possible. This approach has led to a certain amount of repetition but the usefulness
of the thesis as a general reference to the geochronology
of the area is considered to be increased.

Appendix A contains details of the research undertaken
into the Rb-Sr dating of shales of known ages and the
resultant methods of interpretation. The information is a
major contribution to the use of argillaceous material as an
instrument in geochronology and to the understanding and
interpretation of the results. The conclusions of this section
contribute to the validity of the assessments of data from
shales made in the main portion of the thesis.

Appendix B contains a discussion of the Rb-Sr method of
age determination, statistical assessment of the results, and
information on the mass spectrometry and collection and
preparation of samples.

Descriptions of the samples collected from the East
Kimberley area and used in this work are listed in Appendix C.

In Appendix D are tables listing the mineralogical
compositions of shales from the East Kimberley area as
obtained by X-ray diffraction. Some discussion is given
concerning the methods employed and the significance of the
results.

Appendix E consists of tables listing the A.N.U. (G.A.)
sample number, B.M.R. equivalent (based on 4 mile sheet areas),
and location of each of the samples. A further set of
tables serve as a sample number cross-reference and the
samples are listed under the major 1:250,000 sheet areas from which collections were made.

Acknowledgements

Throughout the last three years my supervisor on this project has been Dr W. Compston to whom I am deeply indebted. He first suggested that this project be undertaken and submitted for a Higher Degree and during the course of the work provided valuable help and encouragement. I would also express my gratitude to Mr M.J. Vernon for constant assistance with the chemical preparation and to Messrs. R. Rudowski, Z. Wasik, and H. Berry for assistance with the separation of minerals and the preparation of total rock samples. Preliminary X-ray fluorescence analyses were made by M.J. Rhodes of the B.M.R.. Drs A. Turek and P.A. Arriens provided the computer programmes for many of the calculations. A.W. Webb carried out the K-Ar analyses listed in this thesis.
OUTLINE OF GEOLOGY

The geology of the East Kimberley area has been recorded by Dow, Gemuts, Plumb, and Dunnet (1964), Roberts, Halligan, and Gemuts (1965), and Gellatly, Derrick, and Plumb (1966). A compilation of all information is now being prepared by Dow and Gemuts.

The geology is dominated by the Halls Creek Mobile Zone, a narrow belt of intensely deformed metamorphic and igneous rocks partly covered by strongly faulted sedimentary rocks. The name Lamboo Complex was used by Matheson and Guppy (1949), and later defined by Guppy et al. (1958), to describe these metamorphic and igneous rocks.

The Halls Creek Fault on the east and the Greenvale Fault on the west form the margins of the Mobile Zone. These faults are of great magnitude and are linked by a series of anastomising faults all with throws comparable to that of the boundary faults. These major faults are of great antiquity and have complex histories of movement. Some have been active since the Devonian, but the majority of movement took place during the older Precambrian deformations and the movement since has been on a steadily decreasing scale.

The Halls Creek Mobile Zone is flanked by stable areas - the Kimberley Block on the west and the Sturt
Block on the east. The younger Precambrian rocks on these blocks are little deformed except near fault areas. Faulting and broad folding distinguish the rocks of these blocks from the older Precambrian material of the Mobile Zone where strong folding and faulting are both of regional significance and metamorphism of a high grade is apparent. Intermittent movement along faults is reflected in the sedimentation which has taken place throughout the area and the resultant unconformities provide the basis for subdivision of the stratigraphic column.

The establishment of relationships between stratigraphic units older than the latest Precambrian has only been possible through the use of isotopic age determinations. While lithologic correlations have been attempted there has been no real evidence to support these assumed relationships and some, based on field evidence alone, have been shown to be in error by about 1,000 m.y.
OLDER * PRECAMBRIAN STRATIGRAPHY

HALLS CREEK GROUP

The oldest exposed rocks are those of the Halls Creek Group consisting of dominantly geosynclinal sediments with lesser amounts of basic and acidic volcanics which have been tightly folded and regionally metamorphosed. They are intruded by granite and overlain unconformably by younger Precambrian rocks. Despite the structural complexity, the Group is generally little altered in the central part of the outcrop area, but is metamorphosed (low to high greenschist facies) in the southern section. Metamorphism is more marked and of a higher grade near granitic intrusions and along large faults.

The oldest unit is the Ding Dong Downs Formation, a poorly exposed, strongly faulted and folded unit consisting of epidotized basalt and dolerite, quartz-muscovite and quartz-biotite schist, albitized porphyritic rhyolite, and some "phyllite" and "slate". Granoblastic textures, recrystallization of minerals, impressed foliation, and retrogressive metamorphism give evidence of the alteration suffered by the rocks of this unit.

The base of the unit is not exposed but it unconformably underlies rocks of the Saunders Creek
Formation which consists of indurated quartz sandstone, quartz conglomerate and feldspathic sandstone. In the type section the Formation is 600 feet thick but thins rapidly to between 50 and 100 feet at its eastern and western limits. The unit is conformably overlain by the Biscay Formation.

Rocks of the Biscay Formation have been metamorphosed to the low greenschist facies and consist mainly of basic volcanics and intrusives, acid and intermediate igneous rocks, muscovite and biotite schists and calc-silicates. The predominant rock types are basalt and dolerite, the least altered of which show very few primary features and evidence of recrystallization and replacement. The rocks are tightly folded and highly sheared: the thickness of the Formation is not known.

The Olympio Formation overlies, apparently conformably, the Biscay Formation, and consists of greywacke, feldspathic greywacke, and arkose, interbedded with siltstone and shale. Minor pebble conglomerate and rare limestone occur in the basal portions of the formation. The shale and siltstone are generally laminated or thinly bedded and the greywacke massive; relative amounts of greywacke and siltstone vary considerably.
All rocks show alteration. The fine-grained beds are impressed with an axial plane cleavage, and a marked lineation parallel to steeply dipping fold axes is obvious in some areas of outcrop. Regional metamorphism to low greenschist facies is shown by the coarser-grained rocks.

Incomplete sections indicate that at least 10,000 feet of sediment are exposed but the Formation is certainly much thicker.

Arkose and feldspathic sandstone cropping out as fault blocks have been included in the Halls Creek Group although contacts with all other units are faulted and poorly exposed. This unit, the Moola Bulla Formation appears to be about 12,000 feet thick. Slate is interbedded with the arenaceous rocks in some parts of the sequence but is not common.

WHITEWATER VOLCANICS

The name is applied to a relatively thick (1500-2000 feet) sequence of predominantly rhyolitic volcanic rock resting with strong angular unconformity on the Halls Creek Group. The main area of exposure is west of the Greenvale Fault but the unit also crops out in the northern section of the Halls Creek Mobile Zone about the Carr Boyd Ranges.

The Volcanics consist of both igneous and sedimentary material of which the former is the more abundant. The
6.
sedimentary section consists of volcanic conglomerate, agglomerate, arenites, and minor chert and siltstones situated 600 to 800 feet stratigraphically below the top of the Volcanics, and varying in thickness from 0 to 800 feet. This rapid lateral variation is a function of the relief of the erosion surface on which the sediments were laid down. A slight erosional unconformity exists between the sediments and basal volcanics; the upper volcanics are conformable.

The igneous rocks consist of red, green, and black rhyolite lavas, minor rhyolite agglomerate, and welded tuff. The lavas are porphyritic and consist of phenocrysts of euhedral to subhedral quartz, euhedral twinned and zoned plagioclase randomly orientated in a fine-grained groundmass of ragged feldspar, quartz, chlorite, and devitrified glass. The plagioclase is in the albite-oligoclase range of composition, invariably sericitized and embayed, and commonly replaced by granular epidote. Potash feldspar is generally present as aggregates of feldspar and quartz in the coarser rocks of the lower half of the sequence where chlorite commonly pseudomorphs amphibole and rarely pyroxene.

Intrusive acid porphyry (the Castlereagh Hill Porphyry in the central region and the "Watery River Porphyry" in the southwest area) is present in the lower
portions of the Volcanics. It is similar in composition and fabric to rocks of the Volcanics and there are considerable quantities of this porphyry which cannot be distinguished from the Volcanics. There is strong evidence to suggest that the Porphyry and the Volcanics are both co-magmatic and coeval.

Flow banding in the upper section of the Volcanics is marked and there is no doubt that these are true lava flows. However, in the lower section flow banding is rare and sedimentary inclusions may be seen and this portion appears more likely to be a high level intrusive.

REVOLVER CREEK FORMATION

This name is given to a sequence of sandstones, siltstones, and basic volcanics which overlie the Whitewater Volcanics with erosional unconformity and rocks of the Halls Creek Group with marked angular unconformity; an angular unconformity separates the Formation from the overlying Carr Boyd Group.

Exposures of the Formation are restricted, to areas within the Carr Boyd Ranges and in the reference area (lat. 16°43'S, long. 128°20'E) it attains a total thickness of 4,000 feet. The volcanics (basalts) are highly altered, the ferromagnesian minerals being completely altered to chlorite, and the feldspar to albite with the release of calcite.
Strong folding with the development of low-grade metamorphic rocks occurred before the deposition of the Carr Boyd Group. The deposition of the Formation post-dates the intense regional folding and metamorphism of the Halls Creek Group.

"YOUNGER" PRECAMBRIAN STRATIGRAPHY

The "younger" Precambrian rocks have been defined by Dow et al. (1964), as "those rocks which unconformably overlie the Lamboo Complex. They overlie the Halls Creek Group with marked angular unconformity." (p.27). The base of the younger Precambrian sequence is taken at the base of the Carr Boyd Group or the base of the Speewah Group. On the eastern side of the Mobile Zone the base of the Red Rock Beds satisfies the requirements.

The rocks are generally undeformed, apart from faulting and broad folding, except near major faults which contrasts with the general deformation and metamorphism of the "older" Precambrian rocks. They consist essentially of interbedded arenites and lutites with minor carbonate and volcanic rocks; basic intrusions also occur.

Dow et al. (1964) state (p.27): "Three distinct successions are exposed in different areas within the Region. They are separated by major faults and little
overlap is present between them. The successions are apparently of different ages but correlations are doubtful. Unconformities are common throughout." These three successions are the Carr Boyd Group (Halls Creek Mobile Zone), the Western Succession (Kimberley Block), and the Eastern Succession (Sturt Block).

CARR BOYD GROUP

The majority of the rocks of this Group are exposed in the northern section of the Halls Creek Mobile Zone; only minor outcrops occur east of the Halls Creek Fault. The Group has a maximum thickness of 30,000 feet and consists of six units, these being:

Pincombe Formation - top
Stonewall Sandstone
Glenhill Formation
Lissadell Formation
Golden Gate Siltstone
Hensman Sandstone - bottom

Regional unconformities occur at the base of all units except the Golden Gate Siltstone. The deposition of the Group took place in a tectonically active area; the activity of the Halls Creek Fault was responsible for many of the observed unconformable relationships. Marked features are transgressive deposition, depositional thinning, cyclic sedimentation, and the local erosion of the upper sections of units prior to the deposition of the following sediments.

The succession consists of a series of alternating sandstones and siltstones or shales. The normal
sedimentary cycle has an unconformity at the base followed by a thick sequence of sandstone which grades into siltstone or shale. After another unconformity the cycle is repeated. Dow et al. (1964) have observed that an overall gradation in the lithology of the lutites occurs through the succession as a whole. The silts of the older formations are poorly sorted and contain abundant mica and chlorite. The silts near the top of the succession are highly siliceous, well sorted, and contain very minor micaceous material.

Erosion has deeply dissected the main area of outcrop and the topmost beds have been removed. Generally the Group is unconformably overlain by Palaeozoic sediments, but to the east of the Halls Creek Fault the minor outcrops are unconformably overlain by much younger Precambrian sediments (Duerdin Group) and a sandstone of unknown age.

WESTERN SUCCESSION

The Western Succession includes those rocks contained in the Kimberley Basin, a large structural basin covering the whole of the Kimberley Plateau area and bounded in the east and west by north-north-east and north-west trending older Precambrian rocks of the Halls Creek Mobile Zone. For the purpose of this thesis the upper limit of the Succession is taken to be the base of the Precambrian glacial sequence.
The Succession consists mainly of quartz sandstone with minor siltstone, shale, feldspatic sandstone, volcanics and carbonate rocks, the sediments in the lower part generally reflecting deposition in a more unstable tectonic environment than those in the upper part where the Succession is dominated by thick sequences of quartz sandstone.

In the Ord River Region, east of long. 127°30'E, Dow et al. (1964) recognise three distinct Groups. The following stratigraphic table is given by Dow et al. (pp. 46-47).

| Bastion Group          | Cockburn Sandstone          |
|                       | Wyndham Shale               |
|                       | Mendena Formation           |
|                       | Pentecost Sandstone         |
|                       | Elgee Silstone              |
| Kimberley Group       | Warton Sandstone            |
|                       | Carson Volcanics            |
|                       | King Leopold Sandstone      |
| Speewah Group         | Luman Silstone              |
|                       | Lansdowne Arkose            |
|                       | Valentine Siltstone         |
|                       | Tunganary Formation         |
|                       | O'Donnell Formation         |

An erosional unconformity occurs at the base of the O'Donnell Formation and local major angular unconformities exist at the base of the Tunganary Formation and Valentine Siltstone. Local unconformities also occur at the base of the Kimberley Group.

To the south west between long. 126°00' and 127°30', Roberts, Halligan, and Gemuts (1965) recognise further
units. The Speewah and Kimberley Groups are common to both areas but the Bastion Group has been correlated with the Crowhurst Group, and two further units are recognised overlying this Group. Roberts et al. (Table 15) give the following succession.

| Glidden Group          | Maddox Formation |
|                       | Forman Sandstone |
|                       | Matheson Formation |
|                       | Harms Sandstone  |
|                       | Colombo Sandstone |
| Crowhurst Group       | Hibberson Dolomite |
|                       | Collett Sandstone |
|                       | Liga Shale       |
|                       | Hilfordy Formation |

Kimberley Group

Speewah Group

Unconformities exist between the Crowhurst Group and Colombo Sandstone, and between the Colombo Sandstone and the Glidden Group.

Both the Crowhurst and Bastion Groups conformably overlie the Kimberley Group, and the bases of both Groups mark similar lithological changes, and it is thought that the basal boundaries may be isochronous. The correlation which has been made between the Crowhurst and Bastion Groups appears to be well substantiated.

Within the Ord River Region the Succession has been measured at 19,000 feet, while about 16,000 feet is given for the exposures to the west.
Samples of material thought to be suitable for age determination were collected from various units within the Succession over a wide geographical area. Glauconite was extracted from beds within the O'Donnell Formation and the Pentecost Sandstone where localized development of this mineral had taken place. Massive rhyolitic ashstone within the Valentine Siltstone, and massive saussuritized and chloritized basalt within the Carson Volcanics are the only stratigraphically positioned igneous rocks within the Kimberley Basin. Suites of shale samples were collected from the Wyndham Shale, Liga Shale, and Matheson and Maddox Formations. Mica, thought to be authigenic, was extracted from near the base of the Warton Sandstone unit.

All silty and shaley rocks within the region are markedly affected by cleavage, jointing, and relatively deep weathering; minor faulting is very common. Weathering, although not as obvious, is quite apparent within the sandstone beds. The collection of samples suitable for age determination from such outcrops has proved a problem.

EASTERN SUCCESSION

East of the Halls Creek Fault, younger Precambrian rocks crop out as a narrow discontinuous belt between the older Precambrian basement and the upturned edge of
the overlying Cambrian rocks. For the purpose of this discussion, the top of the Succession will be taken as occurring below the base of the glacial sequence, similar to the definition already given for the Western Succession.

The most complete sequence is exposed in the Osmond Range, a complexly faulted anticline, and in the Albert Edward Range. For the most part the rocks are considered to be unmetamorphosed, predominantly well-sorted, shallow-water sediments resting with strong angular unconformity on the Halls Creek Group.

Dow et al. (1964, p.68) list the succession as

<table>
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<th>Name</th>
<th>Approx.</th>
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<td>Wade Creek Sandstone</td>
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<td>520</td>
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<td>Mt. John Shale Member</td>
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<td>1750</td>
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<td>Bungle Bungle Dolomite</td>
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<td>4500</td>
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<td>Mt. Parker Sandstone</td>
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<td>500-1000</td>
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<td>Red Rock Beds</td>
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<td>11000</td>
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<td>Halls Creek Group</td>
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Unconformities separate all units except the Helicopter Siltstone and Wade Creek Sandstone, and each unconformity represents the erosion of more than 4000 feet of sediment.

No equivalents of these rocks are recognized in the Western Succession; Dow et al. (1964, p.68) suggest that the rocks of the two successions "may be of different ages or they may have been deposited contemporaneously in different environments." Roberts, Halligan, and Gemuts (1965, Table 15), based on work of Dow and Gemuts
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**PLATE 1**: Correlation chart of the "Younger" Precambrian units.
(in prep.), have correlated the Wade Creek Sandstone and Helicopter Siltstone with the Glidden Group and make a partial correlation of the Colombo Sandstone with the Bungle Bungle Dolomite and Mt. Parker Sandstone (Plate 1).

The Mt. John Shale Member of the Wade Creek Sandstone yields the only suitable samples for age determinations within the Eastern Succession.

**PRECAMBRIAN GLACIAL AND POST-GLACIAL ROCKS**

Two periods of glaciation, each followed by marine sedimentation, occurred during the late Precambrian in the East Kimberley Region. These deposits are the oldest that can be confidently correlated from the Sturt Block across the Halls Creek Mobile Zone onto the Kimberley Block. Thicknesses of the units vary considerably and deposition of interglacial and post-glacial rocks has not necessarily been synchronous throughout the whole area, but the periods of glaciation themselves can be equated.

East of the Halls Creek Fault, Dow et al. (1964) recognized glacial rocks unconformably overlying the Helicopter Silstone and referred these to the Duerdin Group (Dow and Gemuts, in prep.). The Group consists of rare outcrops of basal tillite overlain by up to 200 feet of quartz sandstone (Fargoo Tillite).
Overlying this unit (unconformably in the type locality) is the **Moonlight Valley Tillite** consisting of up to 450 feet of tillite capped by 6 to 12 feet of laminated thin-bedded dolomite, also of possible glacial origin (varves?). Conformably overlying this latter unit is the **Ranford Formation** of quartz sandstone and siltstone with a prominent interbedded shale member (**Johnny Cake Shale Member**).

Unconformably overlying the Duerdin Group is the **Albert Edward Group** consisting of quartz sandstone, siltstone, dolomite, and shale. From this Group two units, the **Elvire Formation** and the **Timperley Shale**, have been used for age determination. Antrim Plateau Basalt of Cambrian age unconformably overlies this Group.

Glacial rocks also occur in the south-west section of the area. These have been called the **Kuniandi Group** by Roberts et al. (1965) and are correlated with the Duerdin Group. The Group contains four rock units of which the basal one is the **Landrigan Tillite**; the conformably overlying **Stein Formation** also contains material of glacial origin.

The Group is unconformably overlain by the **Louisa Downs Group** which is the stratigraphic equivalent of the Albert Edward Group. Shale, sub-greywacke, and siltstone form the major portion of the Group but minor amounts of tillite and associated carbonate-bearing rocks occur at
The most important unit for the purposes of age determination is the McAlly Shale which comprises some 5000 feet of the total 13000 feet of the Group; the Shale is the equivalent of the Timperley Shale of the Albert Edward Group.

To the west of the area Gellatly, Derrick, and Plumb have described a glacial succession now defined as the Mt. House Group. The basal unit, the Walsh Tillite, was first correlated with the tillite in the Ord River Region by Harms (1959). He further correlated the Ranford Formation of the Duerdin Group with the Mt. House Beds of Guppy et al. (1958). These beds have now been redefined and the Throssell Shale of the Mt. House Group is regarded as the direct equivalent of the Ranford Formation.

**LAMBOO COMPLEX**

The term Lamboo Complex was defined by Guppy (1958) and used by later workers to include all the basic and acidic plutonic rocks, high-grade metamorphics and greisses cropping out in the East Kimberley Region. With few exceptions the rocks of the Complex are confined to the Halls Creek Mobile Zone; outcrops exposed outside this zone invariably occur close to the boundary faults.
METAMORPHIC ZONES
in the
ORD RIVER REGION
(After Dow et al., 1964)

LATE INTRUSIVES
GNEISSIC GRANITE
ZONE A { Greenschist facies
ZONE B
ZONE C Almandine-amphibolite facies
ZONE D { Almandine-amphibolite to granulite facies
ZONE E

PLATE 2.
Intrusive rocks constitute about two-thirds of the outcrop; contact relationships between the intrusives are usually obscured.

The oldest rocks are the Tickalara Metamorphics which are considered to be (e.g. Dow et al. 1964) the more highly metamorphosed equivalents of the Halls Creek Group. The metamorphic grade varies from moderate greenschist facies in the south to granulite facies in the north and a variety of rocks are present. Mica schist, paragneiss, orthogneiss, calc-silicate rocks, amphibolite, and basic granulite are recognised, the boundaries between each being generally gradational. Dow et al. recognise five metamorphic zones within the Ord River Region (Plate 2).

Closely associated with the higher grade metamorphics is the Mabel Downs Granite, a large lenticular body of gneissic granite paralleling the Halls Creek Fault. A relatively small outcrop of equivalent material to the east of the Fault has been called the McHale Granodiorite. The contacts are normally concordant with the metasediments and often transitional. Slight discordancy has been reported in two places; a wide marble band is truncated by the main body of granite on the eastern margin and marble xenoliths are present in the granite. To the south amphibolites are intruded and incorporated in the granite (Dow et al. 1964, p.97).
The problem regarding the genesis of these "gneissic granites" is not solved by field observations or petrographic study. The transitional nature of the contacts between paragneiss and gneissic granite, the generally contaminated nature of the mineralogical composition (sillimanite and to a lesser extent garnet are normal constituents) and the generally concordant contact relationships lend support to the suggestion that these gneissic granites could have been formed by melting of the paragneiss of the Tickalara Metamorphics (Dow et al.). On the other hand, the observed structure, composition, and relationships could be equally well explained in terms of a "normal" granitic magma incorporating sedimentary material during emplacement in a tectonically active zone undergoing metamorphism. In either case, the crystallization of the material now forming the gneissic granites has taken place after the emplacement of the parental material of the Tickalara Metamorphics.

Ultrabasic and basic rocks of the Alice Downs Ultrabasics and McIntosh Gabbro respectively are the oldest known rocks within the Complex of undoubted igneous plutonic intrusive origin. The ultrabasics usually occur as flat elliptical differentiated sill-like bodies showing rhythmic layering in some sections, but also occur as small lenticular bodies along the margins.
of, and as xenoliths within, the McIntosh Gabbro. The ultrabasics (and basic differentiates) have been almost completely serpentinized and now consist of relict serpentinized olivine set in a tremolite-chlorite matrix, or decussate serpentine pseudomorphs after olivine and pyroxene, with chromite and magnetite.

Basic rocks of the McIntosh Gabbro make up a high proportion of the Lamboo Complex and are considered to be comagmatic and coeval with the ultrabasic rocks. The largest of the intrusions are again elliptical sheet-like bodies which are commonly folded into broad synclines. Remnants of such bodies, and also less regular forms, form the majority of the basic intrusives. Rock types represented include gabbro, troctolite, norite, metagabbro, and amphibolite (Dow et al. 1964) which may show rhythmic layering (Roberts et al. 1965). Most have been altered by regional metamorphism, shearing, or later granitic intrusions, the alteration usually taking the form of saussuritization and uralitization. They have been intruded by both the Mabel Downs and the younger Bow River granites.

Dow et al. have suggested that these exposed basic bodies represent the upper differentiates of the ultrabasic sills; in one large exposure grading, from ultrabasic rocks at the base to leucogabbro at the top, can be seen.
The **Bow River Granite**, a coarse-grained and porphyritic granite, is by far the most extensive of the intrusives in the Complex and crops out as large masses of batholithic proportions and also as small irregular intrusions. The **Sophie Downs Granite** east of the Halls Creek Fault also belongs to this group of rocks. The texture of the granites ranges from even-grained to porphyritic, and the mineralogy is normally anhedral microcline and granular quartz (which form large phenocrysts in the porphyritic types), clusters of biotite, subsidiary andesine and albite, and accessory muscovite, magnetite, zircon, apatite, and tourmaline. Variants of this general composition include biotite-rich phases, hornblende granite (?granodiorite), and muscovite granite dykes. Contact relationships with intruded metasediments may be faulted, stoped, or migmatitic. Primary foliation is apparent in localized areas; tectonic foliation and shearing parallel to major faults with the possible development of mylonites is also localized. In general, the rocks are little altered and virtually unmetamorphosed; they apparently post-date the metamorphism which formed the Tickalara Metamorphics and with which the emplacement of the Mabel Downs Granite was associated.

The **Castlereagh Hill Porphyry**, a quartz-feldspar porphyry, crops out east of the Greenvale Fault about
lat. 17°00'S and extends northwards through the Complex. It is bounded by the Bow River Granite or one of the many faults and is intrusive into the basal sections of the Whitewater Volcanics. As previously mentioned, this porphyry and the lower portions of the Volcanics are indistinguishable and considered to be comagmatic and virtually coeval. Outcrops of porphyry occurring further to the north-east in the Mobile Zone have been equated with the Castlereagh Hill Porphyry.

The age relationships of these porphyries to other intrusives are confused. Field evidence gives conflicting results, assuming the identification of all porphyries as belonging to the same intrusion is valid. In the McPhee Creek and O'Donnell Brook areas the porphyry is reported to be intruded by "porphyritic granite". In the exposures in the far north-east of the area the porphyry is also reported to be intruded by a coarse-grained, even-grained phase of the "porphyritic granite". However, in the area about Greenvale Homestead, Castlereagh Hill Porphyry has chilled margins where contacts with the Bow River Granite are exposed. In this latter area there is no doubt that the Porphyry post-dates the granite intrusion.

**Late stage dykes** ranging in composition from dolerite to aplite and pegmatite intrude the Lamboo
Complex and Halls Creek Group. The dolerite dykes post-date the intrusion of the Bow River Granite and nearly all trend in a north-westerly direction at a marked angle to the regional trend of the area. Rhyolite dykes intrude the Bow River Granite and a large mass of rhyolite is intrusive into the McIntosh Gabbro near Armanda Creek. Aplite dykes intrude the Tickalara Metamorphics north of Mabel Downs Homestead, and east of Turkey Creek, pegmatite dykes show similar relationships. The latter outcrops are associated with the Mabel Downs Granite and are assumed to pre-date the Bow River Granite intrusion. Dykes of rhyolitic and dacitic material intrude the Halls Creek Group about the area of the Sophie Downs Granite; not all dykes are necessarily associated with the intrusion of this mass. Similar relationships exist in the far south of the area about the McLintock and Cummins ranges. Within this latter area a tin-niobium bearing pegmatite intrudes the Halls Creek Group and is exposed paralleling the regional trend. This pegmatite shows no apparent relationships with any other known intrusive and its genesis remains a mystery. The Sophie Downs Granite was once thought to be the parental rock, but this now seems unlikely. The pegmatite has proved to be very important in the age determination of the area.
"YOUNGER" INTRUSIVES

Younger Precambrian sedimentary rocks, as well as rocks of the Lamboo Complex, has been intruded by basic igneous rocks of doleritic composition.

Amygdaloidal dolerite and basalt associated with the Red Rock Beds of the Eastern Succession have been called the Fish Hole Dolerite (Dow et al. 1964). They are highly epidotized and occur as sills intruding the Red Rock Beds or as lava flows, and are older than the Mt. Parker Sandstone.

Dolerite dykes and sills are known intruding the Whitewater Volcanics and O'Donnell Formation. In one area a sill estimated to be 5000 feet thick intrudes the upper part of the Formation. The dolerite is uralitized, saussuritized, and commonly sheared. It is lightologically similar to the Fish Hole Dolerite and occupies a similar stratigraphic position.

The most extensive of the basic intrusions is the Hart Dolerite, consisting of large sills intruding younger Precambrian rocks of the Western Succession. It is most extensive in the Speewah Group where a sill 6000 feet thick occurs. Large blocks of sedimentary rocks, some over a mile square and several hundred feet thick, have been rafted and completely enclosed by the dolerite.

Minor feeder dykes and sills intrude rocks of the Kimberley Group up to the level of the Carson Volcanics.
in the Ord River Region (Dow et al., 1964) and are reported intruding the Elgee Silstone and Pentecost Sandstone in the Lansdowne area (Gellatly, Derrick, and Plumb, 1966). The dolerite is tholeitic in composition and rock types range from dolerite and quartz dolerite to coarse-grained gabbro and diorite, and in some areas granophyre (rich in quartz with potash feldspar and quartz forming myrmekitic intergrowths) forms the upper contact to the sills.

Dow et al. (1964, p.105) state that "petrologically the Hart Dolerite, Carson Volcanics, and Antrim Plateau Volcanics all belong to a similar petrogenetic suite.... Petrology is of no value in determining their age." Later these authors state that in the Ord River Region the Hart Dolerite is unconformably overlain by Antrim Plateau Volcanics, and that since they faithfully show the structure of the rocks they intrude it is unlikely that they are much younger than the country rocks. They further suggest that their association with the Carson Volcanics suggests a likely age relationship. They conclude that the large sill intruding the Speewah Group is a composite body and the Hart Dolerite represents an appreciable time span. "The Hart Dolerite in the East Kimberleys therefore is probably similar in age to the Kimberley Group." (p.105).
STRUCTURE

Diastrophic events are responsible for most of the alteration seen in samples of rocks from the East Kimberley area. Weathering, while being quite marked over much of the region, has only contributed a minor amount to this alteration. Metamorphism, *sensu stricto*, is the end result of the majority of the alteration seen in the older Precambrian rocks, particularly those of the Lamboo Complex.

Within the younger Precambrian formations, alteration is normally regarded as slight, but where macro-evidence of alteration does exist it can be related to folding and faulting within the area. Within most outcrops of sedimentary rock various combinations of cleavage are obvious; in the fine-grained beds, pencil shale is common. An understanding of the structural history of the rocks is therefore important in the assessment of the results of age determinations.

Two periods of folding can still be recognized within the Halls Creek Mobile Zone. The first was a period of isoclinal folding producing axial plane cleavage, and the second resulted in strain-slip cleavage. Both events probably occurred before the deposition of the younger Precambrian sediments. Intrusion and metamorphism has obliterated much of the structure, particularly in the northern section where ptygmatig or isoclinal folding, and deformation by plastic flow, has occurred.
Rocks of the Halls Creek Group have been tightly folded into anticlinoriums. Beds now dip from 60° to 90° and overturning is common. Metamorphism in the greenschist facies has occurred throughout much of the Group, and axial-plane and strain-slip cleavage is widespread.

The younger Precambrian rocks are gently dipping to sub-horizontal in outcrops away from the Mobile Zone. Folding becomes more intense near the Zone but this is mainly a secondary effect of the faulting.

About the Halls Creek Fault there exists a shear zone about \( \frac{1}{4} \) mile wide. The fault dips steeply and the total displacement may be distributed over several faults in a zone up to 4 miles wide. The minimum vertical throw is 9000 feet but may be up to 30,000 feet, with a probable horizontal displacement of up to 16 miles. The Carr Boyd and Revolver Creek Faults have movements comparable to those on the Halls Creek Fault, and in the fault wedges developed between these major faults the intensity of folding and shearing is markedly increased. Movement has been intermittent: for instance older Precambrian rocks have been strongly affected by the Revolver Creek Fault but the movement dies out within the Lissadell Formation.

To the south a fault wedge between the Revolver Creek and Carr Boyd Faults has subsided at least 6000 feet since the deposition of the Glenhill Formation.
On the western side of the Mobile Zone there is a similar fault system. The major fault is the Greenvale in which drag folds indicate a high angle reverse movement with a vertical throw of 5000 feet. Movement along splay faults and the other major faults of the system (the Dunham and Ivanhoe Faults) indicates a possible horizontal component of 20,000 feet. The movements have resulted in the intense shearing of exposures of rocks older than the Speewah Group. As with the Halls Creek Fault system, intermittent movement is again seen and the Dunham and Ivanhoe Faults show evidence of strong post-Devonian movement.

On the Sturt Block the younger Precambrian is intensely faulted and the beds are dipping vertically near the marginal zone. Most faulting post-dates the deposition of the Red Rock Beds but lessens in intensity after the deposition of the Mt. Parker Sandstone, although the Duerdin Group has been downthrown by at least 2000 feet by movement on the Halls Creek Fault. Cambrian rocks away from the Halls Creek Fault have also been affected and reflect post-Cambrian movement along basement faults.

Sediments on the west of the Kimberley Block are mostly flat lying to gently domed with dips up to 30°; these increase towards the east and the margin of the
Mobile Zone with most of the deformation located within 20 miles of the Zone. The structure is controlled by splay faults from the Greenvale system, having small vertical movement but up to 20,000 feet of horizontal movement. Drag within these fault wedges is slight, shearing is minor, and the rocks have yielded by fracture along narrow zones.

The relatively undisturbed flat-lying sediments on both Blocks have not been subject to any large scale movement but still show evidence of strain-slip, axial-plane, and fracture cleavage, of which the latter is the most prominent.
HALLS CREEK GROUP

(1) Ding Dong Downs Formation

The Formation is described as consisting of epidotized basalt and dolerite, quartz-muscovite and quartz-biotite schist, albitized porphyritic rhyolite, and some phyllite and slate. Dow et al. (1964) state: "We know little about the Formation because it is poorly exposed and is strongly faulted and folded." (p.13). The basic rocks have been included in the sequence but the authors suggest that they could well be intrusive and may even correlate with the younger Fish Hole Dolerite.

One example of rhyolite (5057) is available for age determination. In outcrop the rock shows little disturbance, is well jointed, spheroidally weathered, and apparently relatively fresh. Its relationship to the surrounding sediments is not known and it may be intrusive or extrusive.

Thin section examination shows that the sample consists of anhedral quartz, microperthite, and plagioclase, with interstitial chlorite and clear mica. All grains exhibit corroded margins with the development of sericitic mica. Chloritized biotite occurs as small individual flakes, and clinopyroxene,
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**TABLE 1**

**DING DONG DOWNS FORMATION**
altered to tremolite in part, occurs throughout as a primary constituent. The rock has not suffered regional metamorphism but hydrothermal alteration is present.

Analytical data for 5057 is given in Table 1.

The age is dependent on the initial $\text{Sr}^{87}/\text{Sr}^{86}$ value used and the maximum apparent age is 2050 m.y. at an assumed initial $\text{Sr}^{87}/\text{Sr}^{86}$ value of 0.70. At an initial $\text{Sr}^{87}/\text{Sr}^{86}$ value of 0.705 the age is 2005 m.y., and at 0.71 it is 1962 m.y.

Discussion

The known stratigraphy of the area and age determination data from younger intrusive material (see later the Mabel Downs Granite) leads one to conclude that the maximum apparent age of the rhyolite is of the right order of time for an estimate of the age of the Ding Dong Downs Formation. However, as an estimate it falls far short of the actual time of emplacement of the Formation (see later the information given by G.A. 5106).

If the rhyolite is intrusive then this assumption of minimum age fits in with the known geology, but the intrusion itself has to be regarded as a discrete event with no recognized relationship to any other intrusive or "parent" event. However, the apparent age shows it could be related to an initial metamorphic event affecting the Tickalara Metamorphics or to the time of emplacement of the Cummins Range granite (see later).
If on the other hand the rhyolite is an integral part of the Formation, then the assumption of minimal age is dependent on the rock sample having been an open chemical system at some time in its history. Evidence of hydrothermal alteration is given by the petrography and the degree of alteration is considered to be sufficient to allow movement and partial loss or gain of elements. The apparent age of 1962 m.y. at an initial $\text{Sr}^{87}/\text{Sr}^{86}$ value of 0.71 is precisely the age of emplacement of the Mabel Downs Granite and formation of the Tickalara Metamorphics (see later) and it is possible that this event was the source of the hydrothermal solutions.

The degree of dynamothermal alteration indicated by the sediments is not reflected in the rhyolite. Therefore it seems more probable that the rhyolite is actually intrusive and that the maximum apparent age of the sample is a measure of its time of emplacement.

(2) **Biscay Formation**

The Biscay Formation consists mainly of basic volcanics and intrusives, with lesser acid and intermediate igneous rocks, schists, and calc-silicates. Two samples of material mapped as part of the Formation have been collected for age determination studies.

Sample 5055 is from a dyke-like body of fine-grained sodic rhyolite consisting of quartz, microperthite,
albite, sodic amphibole, altered "muscovite" or "biotite", and secondary carbonate. In outcrop the rock is well jointed, shows flow structure (in thin section this is shown by the alignment of sodic amphibole crystals), and is aligned parallel to the regional trend of the area.

Sample 5058 is a medium to fine-grained dyke-like alkali microgranite which, in outcrop, appears fresh, porphyritic, and amygdaloidal in parts and consists essentially of quartz, microperthite, albite, ragged biotite, muscovite, and secondary carbonate. The muscovite normally occurs in very small flakes around feldspar and has most probably formed from their breakdown.

Fluorite in more than accessory amounts is common to both rocks and the rocks are most probably comagmatic.

Alteration is not marked; the feldspars are relatively clear and the quartz shows no undue strain. However, pneumatolytic alteration (greisenization) seems probable. Alteration in the basic rocks of the Formation is much more marked: plagioclase has been saussuritized with further alteration to sericite, and kaolin, and the ferromagnesian minerals have been uralitized with even further alteration to biotite in some instances; recrystallization is marked and complete obliteration of primary features common.
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5058 ACID VOLCANICS INTRUDING BISCAY FORMATION

FIGURE 1

ACID VOLCANICS INTRUDING BISCAY FORMATION

FIGURE 1.
Some doubt exists as to whether these two samples of acidic material represent post-Formation intrusives or extrusive rocks which are part of the stratigraphic succession. The general strike of 5058 transgresses the regional trend of the sediments by a few degrees, and the discrepancy in the metamorphic response of the basic and acidic rocks suggests that these samples could well be from post-deformation intrusives. The sediments of the Biscay Formation are vertical to steeply dipping with obvious evidence of strike faulting and for any intrusion the line of least resistance would be parallel to the bedding of the intruded sediments. Such a situation would account for the apparent conformity of the units and any subsequent error in interpretation.

Analytical data for samples 5055 and 5058 are given in Table 2 and plotted on an isochron diagram in fig. 1. The maximum age given by the samples is 1537 m.y. (initial Sr$^{87}$/Sr$^{86}$ of 0.70) based on the data of 5058. For 5055 the maximum age is 1490 m.y. At an assumed initial Sr$^{87}$/Sr$^{86}$ value of 0.71, the apparent ages of 5058 and 5055 are reduced to 1508 and 1424 respectively.

Discussion

The maximum apparent age of 1537 m.y. can only be regarded as a minimum estimate for the age of the Biscay Formation since units stratigraphically younger than the
Formation have reliable ages of greater value.

The meaning of the 1537 m.y. and 1490 m.y. values is not known but a few interpretations are possible.

1) The rocks are actual stratigraphic units within the Formation and have reacted to varying degrees to an event or series of events whereby they became complete or partial open chemical systems. In the event of the rocks having become complete open chemical systems the apparent ages are the maximum value for the time since the rocks became closed chemical systems, i.e., since the last major event. If the samples have only been partial open chemical systems the results represent a mean value of response of each sample to a series of events and in terms of geological time become meaningless. However, the discrepancy between the high degree of alteration shown by the basic rocks and the relatively unaltered nature of the acidic rocks does not support the initial suggestion that the latter are actually primary units of the Formation.

2) The samples are actually later intrusives and the apparent ages represent the maximum values for the times of intrusion of separate bodies.

3) Assuming that the two samples are intrusive, comagmatic, and coeval then the data for 5058 represents the maximum age of intrusion and that for 5055 reflects
the response to alteration of this particular sample. Petrographic evidence supports this insofar as 5055 shows a much higher degree of alteration (particularly in the mica) than 5058.

4) Both samples are from comagmatic, coeval intrusions and show variable response to one or more events. The apparent ages therefore are minimum estimates for the time of emplacement of the bodies.

(3) **Olympio Formation**

Six samples from two sampling sites, have been collected from rocks of the Olympio Formation. Samples 5102 were selected from exposures previously described by one geologist as the least altered fine-grained examples of the Formation in the whole area. They consist of black shale from beds which are, in parts, very silty and interbedded with phyllitic rocks. The outcrops in the immediate vicinity are mainly schists and phyllites dipping steeply at about 80°. Cleavage is prominent.

Samples from such unsatisfactory sites would normally be regarded as unsuitable for age determination, but it was hoped that these may have remained closed chemical systems and that some idea of the absolute age of the Formation could be gained.

Samples 5232 came from the steeply dipping plane of one of the many faults splaying out from the Halls Creek
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<thead>
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<th>G.A. SAMPLE NO.</th>
<th>RB - PPM</th>
<th>SR - PPM</th>
<th>R87/SR86</th>
<th>SR87/SR86</th>
<th>CALC.</th>
<th>MEAS.</th>
</tr>
</thead>
<tbody>
<tr>
<td>5102A TOTAL ROCK</td>
<td>351.3</td>
<td>25.6</td>
<td>40.146</td>
<td>1.3812</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5102B TOTAL ROCK</td>
<td>367.3</td>
<td>29.5</td>
<td>35.781</td>
<td>1.4038</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5102C TOTAL ROCK</td>
<td>441.4</td>
<td>35.6</td>
<td>35.659</td>
<td>1.3448</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5232A TOTAL ROCK</td>
<td>138.7</td>
<td>62.0</td>
<td>6.432</td>
<td>0.8822</td>
<td>0.8803</td>
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<tr>
<td>5232B TOTAL ROCK</td>
<td>380.7</td>
<td>36.9</td>
<td>29.677</td>
<td>1.4292</td>
<td>1.4264</td>
<td></td>
</tr>
<tr>
<td>5232C TOTAL ROCK</td>
<td>429.5</td>
<td>32.7</td>
<td>37.761</td>
<td>1.6310</td>
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<td></td>
</tr>
</tbody>
</table>
FIGURE 2
Fault and cross-cutting the general strike of the beds of the Halls Creek Group. The samples are fine-grained, flaggy, "shales". Slickensliding parallel to the bedding is marked and mica is prominent along the slip planes. The samples were expected to reflect the age of at least one of the periods of faulting within the area.

The analytical data for the six total rock samples is given in Table 3 and plotted in fig. 2. An alignment of data points is shown by samples 5232, but samples 5102 are scattered. An apparent age of 1705 m.y. is indicated by the samples from the fault plane, with an initial Sr$^{87}/$Sr$^{86}$ ratio of 0.7250, calculations being based on the data for the most enriched sample 5232C. For samples 5102, an age of 1400 m.y. (assuming an initial Sr$^{87}/$Sr$^{86}$ of 0.70) is calculated from the data for 5102B, which is the maximum value given by any of the three samples. An isochron defined by 5102A and C has an apparent age of 581 m.y. with an initial Sr$^{87}/$Sr$^{86}$ ratio of 1.0557.

Discussion

The maximum indicated age of the samples is 1705 m.y. The Halls Creek Group has been intruded by igneous rocks which have apparent ages much greater than that given by these samples from the Olympio Formation. The 1705 m.y. value must therefore be regarded as unrealistically too young for the age of deposition of the Formation.
However, the reasonably good fit of the three 5232 samples suggests that homogenization (in terms of the Sr$^{87}$/Sr$^{86}$) has taken place at some time and that the rocks themselves have remained closed chemical systems since this event. The mineralogical composition of the samples supports, to some degree, this concept of an homogenizing event insofar as the total rocks contain "excessive" amounts of muscovite when compared to other shales.

Stratigraphic control shows that this period of homogenization does not coincide with deposition or diagenesis, but the energy associated with faulting could account for the observed relationships. Since these samples have been collected from a fault plane it is reasonable to assume that the age of 1705 m.y. reflects the time of one period of faulting within the Halls Creek Group.

The maximum value of 1400 m.y. shown by the 5102 samples is obviously too young, but no conclusive statement can be made as to its meaning. The area has undergone quite marked dynamothermal metamorphism and strong faults are present in the vicinity of the sample sites. It is known that movement along most of the faults in the Kimberley Region was sporadic and it is possible that each sample reflects varying degrees of response to one or more of these movements. This being the case,
the 580 m.y. alignment of samples 5102 A and C could reflect a Cambrian event such as the extrusion of the Antrim Plateau Volcanics.

However, the scatter of 5102 data points can be explained equally well in terms of surface leaching. The sampling sites lie in the bank of a creek and the surrounding area shows evidence of deep surface weathering. Leaching of Sr$^{87}$ or addition of Rb, or a combination of both processes would give the observed scatter. Of these two processes, the leaching of Sr$^{87}$ seems the most likely.

LAMBOO COMPLEX

McIntosh Gabbro

Basic rocks constitute a large proportion of the Lamboo Complex and are extensively developed throughout the Halls Creek Mobile Zone. The majority are small irregular bodies or remnants of larger bodies. The larger intrusions are sheet-like, roughly circular or elliptical, commonly folded in broad synclines, and often show layering. The McIntosh Gabbro is representative of the latter group.

Most of the bodies have been altered by regional metamorphism, shearing, or later granite intrusives. Feldspars are normally saussuritized, and the pyroxene uralitized; secondary biotite is often developed.

Within the Gabbro, only one small area of exposure has remained "unaltered". Some saussuritization of the
<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>5221</td>
<td>PYROXENE</td>
<td>0.085</td>
<td>0.1654</td>
<td>38.4</td>
<td>1729</td>
<td></td>
</tr>
<tr>
<td>5222</td>
<td>PYROXENE</td>
<td>0.165</td>
<td>0.1659</td>
<td>4.3</td>
<td>1732</td>
<td></td>
</tr>
<tr>
<td>5222</td>
<td>PYROXENE</td>
<td>0.164</td>
<td>0.1659</td>
<td>4.3</td>
<td>1732</td>
<td></td>
</tr>
</tbody>
</table>
feldspar has occurred, but there is no petrographic evidence of change in the pyroxene.

Two samples (5221 and 5222) have been collected from this "unaltered" area and pyroxene separated. K-Ar age determinations were made on these two samples by A.W. Webb after the methods outlined by McDougall (1964, 1966). The analytical data are listed in Table 4.

The apparent ages are 1729 m.y. and 1732 m.y. for pyroxenes 5221 and 5222 respectively. There is little doubt that both samples define a single event.

Discussion

The McIntosh Gabbro is intruded by gneissic granite and rhyolite-microgranite, the respective ages of which are 1961 m.y. and 1813 m.y. (see later). The ages of both intrusives greatly exceed the indicated age of the Gabbro.

In any comparison of Rb-Sr and K-Ar age determination results, there is the problem of choice of half-lives of the radioactive isotopes. The values used in the K-Ar determinations are those presently accepted, and there is little likelihood of any significant change being made. According to Smith (1964) any revision of the value of the constants would probably reduce the apparent ages of samples, although this reduction is likely to be less than the limits of error introduced by other factors.

Two possible values are presently accepted for $\lambda_{\text{Rb}^87}$; these are $1.47 \times 10^{-11}$ yr$^{-1}$ (Flynn & Glendenin, 1959) and
$1.39 \times 10^{-11} \text{yr}^{-1}$. The latter has been used in all calculations throughout this work and a six percent reduction in the apparent ages of all units dated by the Rb-Sr method would be permissible.

Using $\lambda_{\text{Rb}}^{87} = 1.47 \times 10^{-11} \text{yr}^{-1}$, the age of the gneissic granite is reduced to 1854 m.y. and that of the rhyolite-microgranite to 1713 m.y. The age of the latter intrusive is now reduced to a value below that of the Gabbro. However, the anomalous relationship between the Gabbro and gneissic granite is still retained, and variations in the assumed value of $\lambda_{\text{Rb}}^{87}$ will not clarify the situation.

The K-Ar value of 1730 m.y. must be regarded as a minimum estimate of the time of emplacement of the McIntosh Gabbro. Because it is a value which is reproducible by two separate and distinct samples, the probability that it is the result of random leakage of radiogenic Ar is remote. It would appear that the reproducibility was caused by the response of these samples to an event occurring 1730 m.y. ago, causing loss of radiogenic Ar from the pyroxenes, after which the minerals remained closed chemical systems.

Gneissic Granites and Tickalara Metamorphics

The oldest rocks of the Lamboo Complex are the Tickalara Metamorphics which range in metamorphic grade from moderate greenschist facies in the south of the
area to granulite facies in the north. Closely associated with the higher grade metamorphics is the Mabel Downs Granite, a large lenticular body of gneissic granite whose contacts are normally concordant with the Metamorphics. Relatively small outcrops of equivalent material to the east of the Halls Creek Fault have been termed the McHale Granodiorite.

The granite is markedly gneissic and inhomogeneous in composition (Gemuts, 1965). Discordancy of contact is apparent in a few places, and there is no doubt that the granite body has been developed from a mobile magma; the gneissosity was impressed during crystallization. It is envisaged that emplacement took place during a tectonically active period and as such the granite would be regarded as syntectonic.

Migmatites are strongly developed in the Tickalara Metamorphics adjacent to the granite and the contact between granite and metamorphics is often transitional. The general impression, based on field observations, is that the migmatites have formed in situ during metamorphism and represent the concentration of lower melting point material sweated out from an inhomogeneous mixture of various sedimentary and basic igneous rocks. If the above hypothesis is valid then the gneissic granite could represent the end-stage in the concentration
mechanism, i.e., the granite could have formed as the end product of an anatexitic process.

Dow et al. (1964) recognize five metamorphic zones within the Kimberley Region, the highest grade adjoining the Mabel Downs Granite with decrease in metamorphic grade outward from the granite. A remarkable similarity exists between this occurrence of granite and metamorphics and that described by Joplin (1942, 1943) from the Cooma area of N.S.W. For this latter area Joplin (1947) showed that the chemical evidence suggested the possible derivation of the Cooma Granite from the mixing of psammo-pelitic sediments in the area with an aplitic magma phase. A dominantly sedimentary origin for the granite was supported by the later work of Vallance (1960). Stacey, Joplin and Lindsay (1960) considered that the lit-par-lit type veins of the migmatite zone surrounding the Cooma Granite could be the result of segregation of low melting-point fractions into bands which gave the impression of multiple intrusion. Joplin (1962) further considered that although much differential melting of sedimentary rocks had occurred, some granitic material had been added to a partially melted and mobilized sedimentary sequence. However, she submitted that this granitic material could be differentially derived from the melting of sediments at a lower level in the sequence.
Isotopic studies carried out by Pidgeon and Compston (1965) showed that even though the relatively unmetamorphosed sediments in the Cooma area retained an age which was significantly greater than that of either the granite or the high-grade metamorphics, the relative Sr\(^{87}/Sr^{86}\) values of all units was compatible with the production of the granite by anatexis of the sediments.

The same detailed characteristics which may be compared and found similar in both the Cooma and Kimberley areas led to the initial assumption that there was a very close genetic relationship between the gneissic granite and the high-grade metamorphics of the Kimberley Region.

Collection was made of samples representative of both the granite proper and the metamorphic rocks. A total of nineteen total rocks and seventeen minerals have been analysed. Of these total rock samples, eight are from the high-grade metamorphics, Zones D and E of Dow et al. (1964) which are the sillimanite-almandine subfacies transitional to the hornblende-granulite subfacies of Fyfe et al. (1958). Seven samples are representative of the gneissic granite proper, and a further four samples are from "transitional areas", rocks which cannot be considered to belong undeniably to either the gneissic granite or the metamorphics. They are representative of the transitional contacts which exist
between the two main rock divisions.

With the exception of one sample, 5097, all have been collected from the central section of the map area. Sample 5097 is a granite aplite which occurs as a narrow dyke in the south-east (Mt. Ramsay 4-mile sheet area) of the region. It is bounded by amphibolite on two sides and incorporated in foliated coarse-grained granite (Bow River Granite) at one extremity. The other extremity of the dyke is obscured. Initially it was not known whether this granite aplite was part of the Tickalara Metamorphics or a differentiate of the Bow River Granite. The present work indicates that the rock is most logically part of the metamorphics. Mineralogically it conforms to the composition of the initial anatectic melt of Winkler and Platen (1961) and is further evidence for the derivation of the migmatites by anatexis.

Eighteen of the total rock and four mineral (K-feldspar) samples are considered in this discussion. The remaining total rock (McHale Granite) and thirteen mineral (biotite) samples can be excluded for the time being on the grounds that they have been obvious open chemical systems with respect to Rb and Sr, and their significance will be discussed elsewhere.

Analytical data for the twenty two "acceptable" samples are listed in Table 5 and plotted on an isochron diagram in fig. 3.
<table>
<thead>
<tr>
<th>G.A. SAMPLE NO.</th>
<th>RB PPM</th>
<th>SR PPM</th>
<th>Rb87/Sr86</th>
<th>Sr87/Sr86</th>
<th>Sr87/Sr86</th>
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<td>957 TOTAL ROCK</td>
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<td>575.0</td>
<td>0.220</td>
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<td>291.1</td>
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<td>959 TOTAL ROCK</td>
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<tr>
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<tr>
<td>970 K-FELSPAR</td>
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<td>975 TOTAL ROCK</td>
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<td>975 K-FELSPAR</td>
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<td>215.4</td>
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<td>1098 TOTAL ROCK</td>
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<td>1099 TOTAL ROCK</td>
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<td>1100 TOTAL ROCK</td>
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<td>374.3</td>
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<td>G.A. SAMPLE NO.</td>
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<td>SR PPM</td>
<td>RBB7/SR86</td>
<td>SR87/SR86</td>
<td>SR87/SR86</td>
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<tr>
<td>1101 K-FELSPAR</td>
<td>206.8</td>
<td>629.5</td>
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<td>1367 K-FELSPAR</td>
<td>257.8</td>
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<td>129.4</td>
<td>140.0</td>
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</tr>
<tr>
<td>5097 TOTAL ROCK</td>
<td>125.2</td>
<td>152.5</td>
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<td>0.7655</td>
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</tr>
<tr>
<td>5150 TOTAL ROCK</td>
<td>53.6</td>
<td>595.9</td>
<td>0.259</td>
<td>0.7097</td>
<td>0.7060</td>
</tr>
</tbody>
</table>
FIGURE 3.
GNEISSIC GRANITES and METASEDIMENTS

FIGURE 4.
Discussion

Regression of the analytical data for the eighteen total rock and four mineral samples from the Mabel Downs Granite, McHale Granite, and Tickalara Metamorphics results in a Model IV isochron (MSWD = 12.47) having an apparent age of 1963 ± 46 m.y. with an initial $\text{Sr}^{87}/\text{Sr}^{86}$ of 0.7017 ± 0.0016. The residual variance is greater than experimental error, and combined variation in the initial $\text{Sr}^{87}/\text{Sr}^{86}$ and movement of Rb and/or Sr is suggested.

The residual variance may be significantly reduced by the deletion of data for samples 1102 and 5150 total rocks, and 970, 1101, and 1367 K-feldspars from the regression. Regression of the remaining seventeen samples results in an isochron with MSWD = 1.22. The apparent age is 1950 ± 24 m.y. with initial $\text{Sr}^{87}/\text{Sr}^{86}$ of 0.7013 ± 0.0006. All error can be regarded as experimental since, for fifteen degrees of freedom, a MSWD of 1.22 is not significant at the 95% confidence level.

The residual variance may be further reduced to a value which is unequivocally within experimental error by further exclusion of the data for samples 958, 976, and 1099 total rocks. The regression based on the fourteen remaining samples has a Model I solution (MSWD = 0.50) having an apparent age of 1961 ± 27 m.y. with an initial $\text{Sr}^{87}/\text{Sr}^{86}$ of 0.7010 ± 0.0006. These results (fig. 4) are not
significantly different to those obtained for twenty two samples.

The Diff/SE values for samples 958, 976, and 1099 are much higher than those of the other fourteen samples but statistically there is no completely valid reason for their exclusion from the regression. However, as will be seen later, two of these samples more precisely fit another isochron and their exclusion can therefore be justified on "geological grounds". Inclusion of the one remaining sample results in an isochron whose error is greater than experimental. All three samples are therefore excluded as a unit.

The preferred isochron has the apparent age of \(1961 \pm 27\) m.y. with an initial \(\frac{\text{Sr}^{87}}{\text{Sr}^{86}}\) of \(0.7010 \pm 0.0006\) - fig. 4. This isochron is defined by samples from both the gneissic granites and the metamorphic rocks and is independent of rock type.

This isochron establishes the close relationship existing between the gneissic granites and the high-grade metamorphics, and confirms the validity of the original working hypothesis. It shows that the two units are coeval and have an identical initial \(\frac{\text{Sr}^{87}}{\text{Sr}^{86}}\) value.

The significant Model I solution to the regression discounts the possibility of a rearrangement of elemental and/or isotopic material later than 1961 m.y. This age
therefore represents the last major event of sufficient intensity and extent to cause total rocks over a wide areal distribution to become open chemical systems. Later events are known to have effected certain minerals within rocks, and in localized areas, the total rock themselves, but none of these later events have had such a widespread effect as this dated metamorphism. The age of this major metamorphism is reproduced in the gneissic granites, and 1961 m.y. is therefore regarded as a minimum estimate of the time of emplacement of these bodies.

The initial Sr$^{87}$/Sr$^{86}$ value is quite low and lies well below the upper limit for mantle-type strontium. It suggests that the gneissic granites, and necessarily the high-grade metamorphics, could have been derived from the upper mantle. While this is possible for the granites it is theoretically and practically impossible for the original sediments of the metamorphics without some intermediate step.

The low initial Sr$^{87}$/Sr$^{86}$ value of the metamorphics could only come about in two ways; either the sedimentary portion was derived from mantle-type material whose age was not significantly greater than the apparent age of the metamorphics, or during metamorphism the rocks became open chemical systems with complete loss of radiogenic Sr$^{87}$. 
The metamorphics have been formed from an intimate mixture of igneous and sedimentary rocks of unknown age. Assuming that the Sr$^{87}$/Sr$^{86}$ of the igneous rocks had a value close to that of primordial strontium at the time of metamorphism, then to maintain this low value during homogenization the sediments would also have to have a very low Sr$^{87}$/Sr$^{86}$. This is necessary to satisfy both the initial Sr$^{87}$/Sr$^{86}$ of 0.7010 defined by the isochron and estimates of the amounts of original sedimentary material. The amount of original sediment exceeds that of igneous material.

A lower limit to the value of the initial Sr$^{87}$/Sr$^{86}$ for sedimentary rocks from a marine environment is usually taken as that of sea-water strontium, generally considered to be about 0.709 for present day waters (e.g., Hamilton, 1966; Peterman and Tourtelot, 1966), although there is no completely valid reason for this assumption. There is some evidence to suggest that this value may be a little lower for the Lower Palaeozoic waters (Bottino and Fullagar, 1966; Petermann and Tourtelot, 1966; Whitney and Hurley, 1964) and for Precambrian sediments (Peterman, 1966), but no report has been made previously of unmetamorphosed sediments with initial Sr$^{87}$/Sr$^{86}$ values approaching 0.701. However, an estimate of 0.701 for the mean initial Sr$^{87}$/Sr$^{86}$ has been made
by Peterman (1966) for the Superior province in northern Minnesota and adjacent Ontario. This province is similar to that under discussion here, consisting of mafic, granitic, and metasedimentary rocks.

Consideration of the probable minimum limits to the initial $^{87}\text{Sr}/^{86}\text{Sr}$ of sediments and the apparent proportions of igneous to sedimentary rock in the area suggests that the indicated initial $^{87}\text{Sr}/^{86}\text{Sr}$ for the metamorphics is not a primary feature. If this is so, then the most realistic model which will explain this low initial $^{87}\text{Sr}/^{86}\text{Sr}$ is complete expulsion of radiogenic $^{87}\text{Sr}$, with reversion to a primordial value, during metamorphism.

According to the initial $^{87}\text{Sr}/^{86}\text{Sr}$ value the granite could have formed as the end product of the metamorphism of the Tickalara beds and represent the ultimate in a migmatization process. A similar conclusion was arrived at for the origin of the Cooma Granite by Pidgeon and Compston (1965).

**Genesis of the "Gneissic" Granites**

As has been stated earlier, the migmatites of the area appear to have formed in situ from the surrounding rocks after the manner suggested by Eskola (1933) and others. This theory is favoured in preference to others involving large-scale metasomatism, movement of
migmatizing fluids, intrusion of granitic magma, etc., with a granitic magma body as the source. This preference is based on the following:

1) The metamorphism is of "regional" rather than "contact" type (Dow et al., 1964) and has occurred at relatively high levels in the crust (Lambert and Heier, in press).

2) The metamorphic grade increases towards the gneissic granite body with consequent increase in the amount of migmatic material; sharp contacts are maintained between acidic and basic metamorphics until bordering the granite when the rocks become almost entirely migmatite and differences become obliterated.

3) Migmatites have formed in areas far removed from the gneissic granite where no connection with a granitic body is apparent. Even relatively close to the gneissic granite, the migmatites appear to be discrete.

4) In areas isolated from the granite, but where it is apparent that the grade of metamorphism has been locally increased, the initial stages of migmatite formation may be seen as narrow (1-2 mm.) discrete areas of quartz-feldspar concentration in the host rock (granulite). In such cases the migmatite may appear as a series of indiscriminately orientated whorls scattered across the face of the exposure.
In the light of such observations it is rather easy to envisage the gneissic granite as having formed by the concentration of remobilized material in an area of greatest mobility - the core of the metamorphism. As such it would represent the ultimate in the anatexis of the surrounding rocks and the area of highest temperature or water vapour pressure during metamorphism. Gemuts (1965) has independently arrived at a similar conclusion for the origin of the Mabel Downs Granite, although he suggests partial fusion as a necessary part of the mechanism.

Partial differentiation is not necessarily a part of such a series of events. If partial differentiation has been a mechanism in the formation of the gneissic granites, then, in some way or other, the Rb depletion of the granite relative to the acid migmatites must be explained. The analytical tables and the isochron diagram figures show that the gneissic granites have a much lower Rb/Sr and lower abundance of Rb compared to the acid migmatites. In fact the abundances are more comparable with those of the basic granulites. If the granites formed by differentiation from the metamorphics then enhancement in the more volatile elements such as Rb and K would be expected. Lambert and Heier (in press) have indicated that the K/Rb ratios
of the metamorphics are normal, and that a normal value is also given for the one gneissic granite analysed. This latter suggests that depletion in K as well as Rb has occurred.

Furthermore, if partial differentiation is the mechanism by which the granite was formed, large amounts of basic differentiate proportional to the volume of granitic material should be present. While basic rocks are abundant throughout the region, all these bodies are considered to be older than the age of granite formation, although some doubt exists in certain instances.

However, it is not essential that differentiation should take place. It has already been suggested by Dow et al. (1964) that the Tickalara Metamorphics are the metamorphosed equivalents of the Halls Creek Group. This latter Group consists dominantly of greywacke, arkose, siltstone, and shale, with subordinate rhyolite, basalt, pebble conglomerate and carbonate rocks - typically a geosynclinal rock suite. Complete melting of such a suite would result in a "granitic" magma whose actual composition would depend on the Na<sub>2</sub>O/K<sub>2</sub>O of the initial melt (Winkler and von Platen, 1961) but could not approach the composition of the basic igneous rocks (Wyllie and Tuttle, 1961).

Winkler and von Platen (1961) experimented with the anatetic melting of greywacke and found that they could
the weighted mean of acidic and basic contribution to the anatetic melt.

Further support for a hypothesis of melting is that sillimanite is often a mineral constituent of the granite, with the possibility of cordierite and garnet. The composition of the granitic body varies from granite to tonalite, a feature which while often present in granitic bodies of undoubted magmatic origin, could in this instance reflect areal variations in an original parent material.

While the author favours a hypothesis involving complete melting of the original Tickalara beds, it is possible that the present relationships occurred through a combination of various mechanisms: metamorphism and complete loss of radiogenic Sr$^{87}$ in the more affected areas, anatexis in the zones of high-grade metamorphism, and concentration of certain fractions in the core of the metamorphic area where mixing with a granitic magma having a primordial Sr$^{87}$/Sr$^{86}$ value took place. This series of events is similar to that envisaged by Joplin (1962) for the Cooma area of N.S.W.

**Tickalara Metamorphics**

In the previous section certain total rock samples were deleted from one of the regressions on the grounds that they fitted another isochron with greater precision. These, and other samples, come from the area of high-grade
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</table>
FIGURE 5
metamorphics and are considered, on field location, to belong to the Tickalara Metamorphics. Petrologically some of the total rocks are identical to those of the gneissic granite, so the classification is based entirely on field location.

A total of six samples will be considered here, consisting of two total rocks, three K-feldspars, and one biotite. The Rb-Sr analytical data for these samples is listed in Table 6 and plotted on an isochron diagram in fig. 5.

Regression of this analytical data results in a Model I isochron (MSWD = 1.28 which is not significant at the 95% confidence level for 4 degrees of freedom) having an apparent age of 2067 ± 29 m.y. with an initial Sr$^{87}$/Sr$^{86}$ of 0.7036 ± 0.0010.

For five samples (deletion of 1099 biotite) the result is not significantly different (2031 ± 99 m.y.) which negates any suggestion that the slope of the isochron based on six samples is controlled by the biotite data.

Discussion

Certain anomalies regarding these results which need some explanation are:

1) The apparent age is significantly greater than the 1961 m.y. event defined in the last section for the same rock unit.

2) The indicated initial Sr$^{87}$/Sr$^{86}$ is also greater.
3) The total rocks for all samples, with the exception of 1367 K-feldspar for which none is available, can be fitted to within experimental error to the previously defined 1961 m.y. isochron.

4) This apparently excessive age is dominated by mineral analyses.

Turek (1966) found similar anomalies between total rock and mineral ages for granites from the Kalgoolie-Norseman Region of Western Australia. He discusses various models to explain the apparently excess age of the minerals and concluded that the preferred model involved loss of Rb from the minerals proportional to their Rb content.

The situation in the Kalgoolie-Norseman Region differs from the Kimberley Region in the following:

1) Turek found that the initial $\text{Sr}^{87}/\text{Sr}^{86}$ values for the total rock and mineral isochrons were identical, but for the Kimberley Region the indicated initial $\text{Sr}^{87}/\text{Sr}^{86}$ values are distinctly different.

2) The apparent difference in age between mineral and total rock isochrons was about 1% for the Kalgoolie-Norseman Region while it is greater than 5% in the Kimberley area. Turek suggests that it is possible that the 1% difference he detects could be the result of the particular statistical model used. While his total rock isochron is defined to within experimental error,
the mineral isochron exceeds this level. For the Kimberley area, both the total rock and total rock + mineral isochrons are defined to within experimental error and the 5% discrepancy cannot be the result of discrimination through comparison of various statistical models.

This anomalous situation where two equally valid isochrons of significantly different values define the same rock unit can be achieved in various ways. In this instance however, all hypotheses must take into account the fact that the total rocks have apparently remained closed chemical systems. The Model I isochron for 14 samples defining the 1961 m.y. event precludes the possibility that they have been open chemical systems since this event. The evidence is not so strong for the further three samples but a Model I isochron still results for seventeen samples.

An excessively high mineral age can be achieved by the internal redistribution between mineral phases of elements or isotopes: gain in Sr\textsuperscript{87}, or loss of Rb. For total rocks affected in this manner there is no internal redistribution but complete loss or gain of the particular isotope or element.

Gain in Sr\textsuperscript{87} is considered to be an unlikely mechanism in this instance. Arriens et al. (1966) have shown that microperthitic feldspars are more susceptible to loss
of Sr\textsuperscript{87} rather than gain. Micas tend to lose radiogenic Sr\textsuperscript{87} readily. In the general case it is normally found that Sr\textsuperscript{87} is depleted in most primary minerals subjected to a metamorphism, the excess being taken up by secondary mineral forms. Furthermore, to form an isochron having too old an apparent age those samples having the greatest initial enrichment of Sr\textsuperscript{87} are required to gain the greater amount. This is in direct opposition to the expectation which is that samples with the lower Rb/Sr values (e.g., plagioclase) are more likely to take up excess Sr\textsuperscript{87} than those already containing large amounts (e.g., biotites).

Loss of Rb with the retention of linearity to define an isochron, requires that the loss be proportional to the original amount of Rb contained in each sample. While the probability that proportional loss of Rb will be maintained through a suite of samples is no higher than for other redistribution models, Rb loss is still the most acceptable in this instance. The model has the distinct advantage of requiring the higher amount of redistribution from those samples with the greatest Rb/Sr value; under normal circumstances this means those samples with the greater absolute content of Rb, those with the greater amount of potentially exchangeable material. The micas are good examples: their comparatively high K and Rb contents coupled with their
particular crystallochemical structure allows for the relatively easy exchange or loss of appropriate atoms. Depending on the specific gradients operating, substitution could take place with relative simplicity.

Some evidence that a model of Rb loss may have been operative in the present situation is provided by the K-feldspar and biotite data from samples 970 and 1101. If it is assumed that the true age of the K-feldspar is given by the total rock isochron, and that the discordancy in age is due entirely to Rb loss from the K-feldspar, then the apparent loss in Rb can be calculated. If it is further assumed that this "lost" Rb is lodged in the coexisting biotite, then this apparent excess can also be calculated.

The nett result is that for material balance and concordancy of age to be achieved between the K-feldspar, biotite, and total rocks, the weight to weight ratio of K-feldspar/biotite has to be 8.06 and 5.52 for rocks 970 and 1101 respectively. This is equivalent to a modal K-feldspar/biotite of 7.3 - 6.0 for 970 and 5.0 - 4.1 for 1101, depending on the specific gravities assumed for the mineral phases.

While no accurate modal analyses are available for these rocks, these calculated ratios agree well with estimates of the mineral proportions based on inspection of a single thin section from each sample.
For 1099 biotite a reciprocal mechanism must be invoked involving loss of Rb from the biotite, rather than gain as in the previous instances. K-feldspar is virtually absent in this rock and therefore circumstances are changed. If the 2067 m.y. isochron is real then material balance has been achieved between the biotite and total rock of 1099 and the apparent loss of Rb reflected in the total rock can be due entirely to the loss from the biotite. In this particular instance the same could be said for any other redistribution model.

The evidence suggests that 1099 total rock has become an open chemical system, with loss of Rb at some time after the major metamorphism of the area. There is therefore further justification for excluding its data from the 1961 m.y. isochron regression.

No simple redistribution model will explain the discordancy existing between the biotite and total rock data for sample 958. The statistical evidence for the exclusion of the total rock data from the 1961 m.y. isochron regression is as valid as for 1099 total rock, i.e., comparably high Diff/SE values. The inclusion of 958 total rock data in the 2067 m.y. isochron regression is again statistical, but on the basis of the data for the other samples, open system chemistry is also indicated.

Rb loss as a model for this significantly older isochron is by no means proven, but is a likely
explanation for the discordancy. The model is acceptable in terms of the known compositions of the rocks and mineral components.

It is possible of course that both these isochrons are correctly registering two separate events. The older isochron would then reflect the apparent age of the Tickalara beds before the 1961 m.y. metamorphic event. During this latter event most total rocks would have lost isotopic or elemental material, most logically radiogenic Sr$^{87}$.

Such a hypothesis would give some real geological meaning to the 2067 m.y. age and confirm other events in the Kimberley area. Its acceptance would mean that the linearity and Model I fit of the majority of total rock data to the 1961 m.y. isochron is either accidental, or the result of Sr$^{87}$/Sr$^{86}$ homogenization.

It is hard to visualize the random loss of radiogenic Sr$^{87}$ from fourteen total rock samples of varying Rb/Sr values in such convenient amounts that an unequivocally Model I isochron results. It is therefore concluded that the uniformity of initial Sr$^{87}$/Sr$^{86}$ values and age of samples defining the 1961 m.y. isochron is not accidental.

Discussion has already been made of the significance of the initial Sr$^{87}$/Sr$^{86}$ of the 1961 m.y. isochron. It
was concluded that such a low value could only be explained in terms of complete loss of all radiogenic Sr$^{87}$ and homogenization of the Sr$^{87}$/Sr$^{86}$. This took place during the last major metamorphic event of the area.

Samples 1099 and 958 would then represent rocks which had survived this homogenization process; the K-feldspars from 970, 1101, and 1367 would also be relics. In the case of 970 and 1101, the total rocks have participated in the homogenization process. To balance the effect of the K-feldspars, excess Sr$^{87}$ loss must occur from some other mineral phase; mineral alteration products would be a likely phase.

There is not enough information available to decide which of these two alternatives is the correct interpretation. Analyses of the least metamorphosed material of the Tickalara beds should either confirm or refute the second alternative. Unfortunately suitable material is not available; either the rocks are crystalline and subjected to high-grade metamorphism, or they are relatively unmetamorphosed, deeply weathered, and unsuitable for reliable age determination analyses.

**Porphyritic and Coarse-Grained Granites**

Massive porphyritic and coarse-grained granites of batholithic proportions form part of the Lamboo Complex. They intrude mainly Tickalara Metamorphics but also
intrude basic and ultrabasic rocks of the McIntosh Gabbro and Alice Downs Ultrabasics. For the most part these granites are covered by the term Bow River Granite, but in some sections independent units, closely related to the main mass, have been given specific names. Within the scope of this thesis all porphyritic and coarse-grained granites have been collectively referred to as Bow River Granite.

East of the Halls Creek Fault a boss of granite is exposed which intrudes rocks of the Halls Creek Group. This outcrop has been given the specific name of Sophie Downs Granite. The relationships between this granite and other granitic rocks of the Lamboo Complex cannot be established from field evidence. Initially it was thought to be the oldest granitic intrusion in the Kimberley Region. Isotopic age determinations have now established that the Sophie Downs Granite and the Bow River Granite are coeval within the limits of the age determination technique.

In the area of the Cummins and McClintock Ranges, elongate bodies of granite (unnamed) intrude rocks of the Halls Creek Group. Contacts between the granite and country rocks are irregular and generally discordant; contact metamorphism has taken place in the intruded sediments. These granites have been referred by Roberts
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PORPHYRITIC and COARSE GRAINED GRANITES

FIGURE 6.
PORPHYRITIC and COARSE-GRAINED GRANITES

FIGURE 7
Model IV solution suggests a combination of both variation in the initial \( \text{Sr}^{87}/\text{Sr}^{86} \) between samples and post-emplacement movement of Rb and Sr.

The residual variance can be significantly reduced by deletion of certain data from the regression. The data which may be excluded on statistical grounds alone are from total-rock samples 1085, 1086, 1097, 5111, and 1081 biotite.

Regression of the remaining ten total-rock and three mineral samples gives a Model I isochron (MSWD = 0.94) with all error experimental (fig. 7). The age of the isochron is 1854 ± 14 m.y. with an initial \( \text{Sr}^{87}/\text{Sr}^{86} \) of 0.7029 ± 0.0015.

The results of the two regressions are not significantly different but that of the Model I solution is unequivocally within experimental error and can be regarded as the apparent age of the suite of samples. The initial \( \text{Sr}^{87}/\text{Sr}^{86} \) value of 0.7029 ± 0.0015 lies within the accepted limits for mantle-type material. Since there is no evidence to suggest metamorphism or some similar effect, and since the apparent age conforms to the pattern of events suggested by the field evidence, the age of 1854 ± 14 m.y. may be confidently regarded as the age of initial chemical closure of the granite masses, i.e., the age of crystallization.
Origin of the Bow River and Related Granites

The low mantle-type initial $^{87}\text{Sr}/^{86}\text{Sr}$ value of this coeval suite of samples suggests that these granites could have originated from the upper mantle. In this regard they would conform to the predictions of Dow et al. (1964) that the porphyritic and coarse-grained granites were not of anatetic origin.

In most other contexts, a combination of field evidence and mantle-type initial $^{87}\text{Sr}/^{86}\text{Sr}$ could be regarded as evidence in support of an upper-mantle origin for these granites. However, in the present situation the evidence for such an assumption is far from conclusive.

If it is assumed that the analysed samples from the Mabel Downs Granite, Tickalara Metamorphics, and the porphyritic and coarse-grained granites are representative, then an "average composition" for these major units of the Lamboo Complex can be calculated.

For nineteen total-rock samples of the combined Mabel Downs Granite and Tickalara Metamorphics, the calculated average composition has a $^{87}\text{Rb}/^{86}\text{Sr}$ of 1.623 and present day $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.7456. The seventeen samples of Bow River and Sophie Downs Granites have a calculated average $^{87}\text{Rb}/^{86}\text{Sr}$ of 6.741 and a present day $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.8732. Since the age and initial $^{87}\text{Sr}/^{86}\text{Sr}$ is known for each suite of samples, the data for the
average composition can be plotted on a radiogenic $^{87}\text{Sr}/^{87}\text{Rb}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ diagram (Compston and Jeffrey, 1959; Riley and Compston, 1961). Each average composition is represented by a line which depicts the decay history of the $^{87}\text{Rb}$ and the increase in radiogenic $^{87}\text{Sr}$ with time; therefore the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio is predictable for any particular point in time assuming that the rocks have remained closed chemical systems. Where chemical closure has not been continuous since the time of first crystallization of the body, e.g., the impression of a post-emplacement metamorphic event, estimates of the $^{87}\text{Sr}/^{86}\text{Sr}$ value prior to metamorphism will be erroneous.

As has been pointed out previously, faulting is the only event which has affected these granites and there is every reason to believe that the apparent age obtained is the age of chemical closure.

Fig. 8 shows the data for the average compositions of the two rock suites. It is immediately obvious that the two lines intersect close to the radiogenic $^{87}\text{Sr}/^{87}\text{Rb}$ and initial $^{87}\text{Sr}/^{86}\text{Sr}$ values equivalent to the age of the Bow River and Sophie Downs Granites. An independent calculation of the predicted $^{87}\text{Sr}/^{86}\text{Sr}$ for the combined Wabel Downs Granite and the Tickalara Metamorphics at 1854 m.y. shows that the expected ratio is equal to 0.7032. This value is well within the limits of
0.7029 ± 0.0015, the initial $\text{Sr}^{87}/\text{Sr}^{86}$ of the porphyritic and coarse-grained granites.

It is therefore possible for the porphyritic and coarse-grained granites to have been derived by differentiation from the melting of crustal material whose isotopic composition was equivalent to that of the combination of the Mabel Downs Granite and the Tickalara Metamorphics. Differentiation must also be invoked to explain the increased Rb/Sr value of the porphyritic and coarse-grained granites compared to that of the possible parent material.

Isotopic evidence alone cannot help in eliminating one or other of the two possible origins for these granites. It can only be concluded that while the porphyritic and coarse-grained granites could have been derived from the upper mantle, it is equally possible that, because of the peculiar composition of the "country rock", the granites were derived by anatexis and differentiation of a combination of the Mabel Downs Granite and Tickalara Metamorphics. If anatexis has been operative, then this process must necessarily have occurred at much deeper levels than are now exposed at the surface.

**McLintock and Cummins Ranges - Granites**

Roberts et al. (1965) correlated five elongate bodies of granite cropping out in the McLintock and Cummins
Ranges with the Sophie Downs Granite located some 70 miles further to the north. This latter granite has been shown to be equivalent in age to the Bow River Granite.

Three of the five granite bodies crop out in the cores of anticlines, and two are intruded parallel to and bordering on the Woodward Fault. All bodies are intrusive into rocks of the Halls Creek Group, and are associated with tin-bearing pegmatites.

The three bodies occurring in the cores of anticlines occupy a similar structural and stratigraphical position to that of the Sophie Downs Granite, and it is mainly on the basis of this that the correlations have been made.

The McLintock and Cummins Ranges granites are described by Roberts et al. (1965) as being equigranular coarse- to medium-grained granites which are white and massive in outcrop, with no change in grain size at their margins. The contacts with the country rocks are irregular and generally discordant, the granites being bounded by hornfels which pass outwards into biotite schist.

The granites are composed of microcline, quartz, subordinate plagioclase (oligoclase to andesine), and irregular clots of interlathed biotite and muscovite. The microcline poikilitically includes plagioclase, while the plagioclase is replaced by sericite-epidote-chlorite aggregates. Iron-ore minerals and tourmaline are accessories.
<table>
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<th>SR PPM</th>
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Pegmatite dykes are present in the sediments near these granites as randomly orientated discontinuous bodies which may be concordant or discordant with the strike of the country rock. They consist of varying amounts of microcline, lamellar albite, quartz, muscovite, and tourmaline. Minor accessories include garnet, ilmenite, and almost all carry tin and tantalum.

Two samples, 5101 and 5105, have been collected from two of the bodies cropping out in the cores of anticlines. 5105 is from the McLintock Range area, and 5101 from the Cummins Range. Sample 5105 has been affected by an event younger than its age of emplacement and is further discussed in another section under the heading of "Altered Rocks and Minerals".

A further sample, 5104, has been collected from one of the discontinuous pegmatite bodies associated with the granite. In this instance it is associated with the body from the McLintock Range, 5105 (maximum apparent age of 1638 m.y.) which shows evidence of open system chemistry (see later).

The analytical data for total rock samples 5101 and 5105 are listed in Table 8.

Discussion

The apparent ages obtained are dependent on the initial Sr\(^{87}/Sr\(^{86}\) assumed. A maximum apparent age of
2097 m.y. is obtained for 5101 assuming an initial $\text{Sr}^{87}/\text{Sr}^{86}$ of 0.70, and it is apparent that this granite is not related in time to the Sophie Downs Granite. For their ages to be equivalent, 5101 would have to have an assumed initial $\text{Sr}^{87}/\text{Sr}^{86}$ of 0.7169. This value is far greater than for any other granitic rock in the Kimberley Region, and far removed from that of the Sophie Downs or Bow River Granites. If the Cummins Range granite is to be coeval with either of these other units, then an abnormally high initial $\text{Sr}^{87}/\text{Sr}^{86}$ would have to be accepted. There seems little doubt that the granites from the Cummins and McLintock Ranges are significantly older than other dated granitic events.

Sample 5104 is enriched in radiogenic $\text{Sr}^{87}$ and the apparent age is virtually independent of the initial $\text{Sr}^{87}/\text{Sr}^{86}$. The maximum apparent age is 2251 m.y. for an initial $\text{Sr}^{87}/\text{Sr}^{86}$ of 0.70.

No direct relationship exists between this pegmatite and 5101 granite sample. The pegmatite has a close spatial association with granite 5105 which has been an open chemical system. The granite bodies located in the cores of anticlines are assumed to be comagmatic and coeval; the relationship between 5101 and 5104 is therefore inferred. The expectation is that these two samples should have similar apparent age.
The maximum values for the ages of these two units are significantly different. This difference becomes even more marked if apparent ages less than the maximum are calculated. Possible explanations of the discordancy are a) that the samples have been open chemical systems with respect to Rb and/or Sr, or b) that the spatial relationship between the pegmatite and granite is fortuitous and each unit reflects two separate and distinct events.

Open system chemistry is always likely in an environment such as the one represented here. If open system chemistry is invoked to explain the discordancy, then the following possibilities exist.

1) The pegmatite has retained its true age of formation while the granite has lost radiogenic strontium.

2) \(^{87}\text{Sr}\) enrichment has occurred in the pegmatite resulting in a maximum estimate for the age of this unit, while the granite reflects the true age of emplacement.

3) Rb loss has occurred in the pegmatite and the apparent age is a maximum estimate. Again the assumption is that the granite retains the true age of emplacement.

4) Both the pegmatite and granite have lost radiogenic \(^{87}\text{Sr}\), and both have minimal ages.

It is unlikely that the first alternative has been operative since an event of sufficient intensity to affect a relatively large granitic body could be expected.
to at least equally affect the smaller, more coarse-grained, pegmatite. The suggestion is made later that pegmatite has responded to a younger event of sufficient intensity to affect the granite, but that the relative differences in age between pegmatites and granites has been maintained. A real and significant difference in the ages of these two units is indicated.

Similarly Sr enrichment in the pegmatite is not considered likely. Loss of radiogenic Sr by weathering or response to some event is much more probable. Furthermore, enrichment in Sr would mean addition of material to a rock which was apparently already saturated in this component. In this instance Sr addition to the granite appears more likely to occur.

Rb loss from the pegmatite, or Sr loss from both the pegmatite and granite are equally plausible explanations of the discordancy. However, Rb loss as an explanation of the older age infers acceptance of synchronous emplacement of both pegmatite and granite. While this is a working hypothesis there is no real evidence for its acceptance since the pegmatites are discrete bodies; their relationship to the granites is only spatial and other equivalent pegmatite bodies are far removed from any present granitic exposures.

Likewise Sr loss from both bodies as the sole explanation of discordancy implies synchronous
emplacement. Furthermore, the greatest proportional amount would have to be lost from the granite. This is contrary to the expectation that the pegmatite with its significantly higher amount of Sr\textsuperscript{87} is more likely to lose a greater or equal proportion compared to the granite.

It appears that open system chemistry does not adequately resolve the apparent age discordancy if it is considered to be the sole explanation.

The possibility that each unit reflects a separate and discrete event has a certain amount of evidence to support it. In the first instance, the assumption that the pegmatite and granite are not synchronous makes open system chemistry feasible as a secondary mechanism. Secondly, another pegmatite body (5106 - see later) located some distance away from the one discussed here, has been dated. This body has an apparent age of about 2700 m.y.; the muscovite has an apparent age of 1755 m.y. The apparent ages of the two pegmatites are markedly different, but both are significantly greater than the granite. Either Sr\textsuperscript{87} loss or Rb gain must be invoked to explain the younger age of 5106 muscovite; neither mechanism can explain the higher total rock age.

If it is assumed that the granite retains the true age for all bodies, then to explain the higher pegmatite ages would necessitate approximately 8% loss of Rb for
5104, or 25% loss for 5106. If $\text{Sr}^{87}$ movement is assumed, approximately 5.6% gain for 5104 and 10% for 5106 is needed. These percentages represent large amounts of the particular isotope. Furthermore, the indicated gain or loss for the total rock sample 5106 contradicts the direction of movement of isotopes indicated by the muscovite data.

A third line of evidence is the comparison of the apparent ages of the granite and the rhyolite 5057 which intrudes the Ding Dong Downs Formation. Their maximum ages are of a similar order - 2097 m.y. for the granite and 2050 m.y. for the rhyolite. Both these values are similar to the 2067 m.y. isochron defined by some samples from the Tickalara Metamorphics. This similarity in age between these various units gives some geological meaning to the age for the granite.

The significantly greater age of the pegmatite 5104 is unlikely to have been solely the result of open system chemistry. The maximum apparent age of 2251 m.y. must be regarded as the minimum estimate for the time of emplacement of the dyke.

It is concluded that although a spatial relationship exists between granite and pegmatites in the McLintock and Cummins Ranges, these units are neither comagmatic nor coeval. Each independently reflects an age of chemical closure and these apparent ages are significantly different.
<table>
<thead>
<tr>
<th>G.A. SAMPLE NO.</th>
<th>RB PPM</th>
<th>SR PPM</th>
<th>RB/87/SR86</th>
<th>S87/SR86 CALC.</th>
<th>S87/SR86 MEAS.</th>
<th>AGE M.Y.</th>
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<td>5106 TOTAL ROCK-A</td>
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<td>1.1325</td>
<td></td>
<td>2750</td>
</tr>
<tr>
<td>5106 TOTAL ROCK-B</td>
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<td>11.236</td>
<td>1.1327</td>
<td></td>
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<td>5106 MUSCOVITE</td>
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<td>1.9</td>
<td>2180.102</td>
<td>54.5432</td>
<td></td>
<td>1755</td>
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McLintock and Cummins Ranges - Pegmatites

Two total rock samples of pegmatite have been analysed from the McLintock Range area; both samples have been mentioned in the previous section. However, the data for 5104 is reproduced, and that for 5106 listed for the first time in Table 9. Sample 5104 is sufficiently enriched in radiogenic Sr$^{87}$ for its apparent age to be virtually independent of the initial Sr$^{87}$/Sr$^{86}$ value. Sample 5106 is less enriched but still has sufficient enrichment for the apparent age to be meaningful within certain limits of initial Sr$^{87}$/Sr$^{86}$ values.

The maximum age given by the data for 5104 is 2251 m.y. For 5106 the maximum apparent age is about 2700 m.y.; this value is reduced to 2670 m.y. for an initial Sr$^{87}$/Sr$^{86}$ of 0.71. The muscovite from this latter sample has an apparent age of 1755 m.y. which is independent of the initial Sr$^{87}$/Sr$^{86}$.

If both pegmatites are assumed to be coeval and closed chemical systems since the time of emplacement, then they have a common age of 2158 m.y. at an initial Sr$^{87}$/Sr$^{86}$ of 0.7926. This is an extraordinarily high value for the initial Sr$^{87}$/Sr$^{86}$, but even at this level it will be noted that the apparent age is still greater than that of the associated granite and it is concluded that the minimum apparent age of the tin-bearing
The apparent age of about 2700 m.y. given by 5106 not only reflects the age of emplacement of the pegmatite but, more importantly, gives a minimum estimate
of the time of formation of the Halls Creek Group. This means that the "basement rocks" of the Kimberley Region are at least 2700 m.y. old and furthermore, the interpretations placed on the meaning of the apparent ages of other igneous rocks associated with this Group are substantiated.

**Rhyolite, Dacite, Microgranite Intrusions of the Lamboo Complex**

Leucocratic, fine-grained, acid, hypabyssal rocks intrude certain units of the Lamboo Complex. Similar rocks intrude the Halls Creek Group. Most are located about lat. 18°00' and crop out between long. 127°50' and 128°00'.

Samples from the two main areas of outcrop within the Lamboo Complex have been collected. One is representative of a rhyolitic dyke swarm which intrudes the Bow River Granite. The other sample is from the area of rhyolite-microgranite about the Armanda River, intrusive into rocks mapped as McIntosh Gabbro. The two sample localities are only about one mile apart.

The Armanda River outcrop has been tentatively correlated with the intrusive of the Ding Dong Downs Formation. The maximum age of this latter intrusive has been established as 2050 m.y.

Analytical data for sample 968, intruding the Bow River Granite, and 5223, intruding the McIntosh Gabbro,
<table>
<thead>
<tr>
<th>G.A. SAMPLE NO.</th>
<th>RB PPM</th>
<th>SR PPM</th>
<th>RB87/SR86</th>
<th>SR87/SR86</th>
<th>SR87/SR86</th>
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<td>968 TOTAL ROCK</td>
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<td>5223 TOTAL ROCK</td>
<td>163.2</td>
<td>65.1</td>
<td>7.207</td>
<td>0.8840</td>
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<td>1813</td>
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are listed in Table 10. The absolute values of the apparent ages are dependent on the values chosen for the initial Sr\textsuperscript{87}/Sr\textsuperscript{86}. For an initial Sr\textsuperscript{87}/Sr\textsuperscript{86} of 0.70 the apparent ages are 1811 m.y. and 1813 m.y. for 968 and 5223 respectively. At an initial Sr\textsuperscript{87}/Sr\textsuperscript{86} of 0.71, the apparent ages are reduced to 1735 m.y. and 1716 respectively.

Discussion

On the basis of the maximum apparent ages of these two samples, it seems unlikely that they can be related to the intrusive of the Ding Dong Downs Formation.

The ages obtained conform to the predicted values of these units, particularly those intrusive into the Bow River Granite. The age of the Granite has been established as 1854 m.y. The apparent ages also confirm the close relationship existing between the dyke rocks and the outcrops at Armanda River.

WHITEWATER VOLCANICS AND CASTLERBAGH HILL PORPHYRY

A total of fourteen samples have been collected from the Whitewater Volcanics (12) and Castlereagh Hill Porphyry (2) and twenty isotope dilution analyses of total rocks (14) and minerals (6) are available for interpretation. The twelve samples are considered to be representative of virtually all the known outcrops of the Whitewater Volcanics and sampling sites extend over 400 miles. Analyses of three of the minerals (956 K-feldspar, 964
<table>
<thead>
<tr>
<th>G.A. SAMPLE NO.</th>
<th>RB PPM</th>
<th>SR PPM</th>
<th>RB87/SR86</th>
<th>SR87/SR86</th>
<th>CALC. MEAS.</th>
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</thead>
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<td>960 TOTAL ROCK</td>
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<td>960 K-FELSPAR</td>
<td>474.8</td>
<td>34.0</td>
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<tr>
<td>964 TOTAL ROCK</td>
<td>235.4</td>
<td>128.8</td>
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<td>0.8389</td>
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</tr>
<tr>
<td>965 TOTAL ROCK</td>
<td>242.7</td>
<td>113.9</td>
<td>6.123</td>
<td>0.8896</td>
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</tr>
<tr>
<td>979 TOTAL ROCK-A</td>
<td>508.5</td>
<td>34.1</td>
<td>42.906</td>
<td>1.8206</td>
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<tr>
<td>979 TOTAL ROCK-B</td>
<td>516.7</td>
<td>33.4</td>
<td>44.476</td>
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<tr>
<td>979 K-FELSPAR</td>
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<td>70.0</td>
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<td>979 BIOTITE</td>
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<td>1107 TOTAL ROCK</td>
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<td>4.041</td>
<td>0.8150</td>
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</tr>
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<td>120.4</td>
<td>4.769</td>
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</tr>
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</table>
FIGURE 9.
biotite, 1107 biotite) can be rejected from this present discussion since they are not collinear with the remaining samples and have, at some time, become open chemical systems. The enrichment in the radiogenic Sr\(^{87}\) of these samples is such that an age may be calculated which is virtually independent of the assumed initial Sr\(^{87}/Sr^{86}\) value. The apparent ages obtained differ from each other and are markedly younger than the apparent isochron for the remaining samples.

Data from the seventeen remaining analyses are listed in Table 11 and plotted on an isochron diagram in fig. 9.

Discussion

Regression of the data for the seventeen analyses results in a Model IV isochron having an apparent age of 1788 ± 40 m.y. with an initial Sr\(^{87}/Sr^{86}\) of 0.7157 ± 0.0090. The residual variance of the regression is excessive, the MSWD being 31.10. The Model IV solution to the regression suggests both variation in the initial Sr\(^{87}/Sr^{86}\) between samples and redistribution of isotopic and/or elemental material (i.e., open system chemistry).

The residual variance can be significantly reduced by progressive deletion of certain of the data from the regression. Some indication of the data to be deleted is given by the ratio of the difference between the estimated and measured Sr\(^{87}/Sr^{86}\) divided by the standard
FIGURE 10.
error, which for ideal isochrons should be close to zero. Marked discrepancies in this quantity are significant.

Deletion of seven of the sets of analytical data results in a significant reduction of the MSWD to 3.31. A regression of the remaining 10 samples (5126, 5127, 5148, 1107, 5149, 5218, 5217, 5219, 979 - all total rocks - and 979 biotite) gives a Model IV isochron having an apparent age of 1823 ± 17 m.y. with an initial Sr$^{87}$/Sr$^{86}$ of 0.7121 ± 0.0034. This isochron has been plotted in fig. 10 and its apparent age is supported by the radiometric data of the younger Hart Dolerite (see later).

Regression of the nine total rock samples listed above gives a solution not significantly different to that obtained with 979 biotite included. The MSWD is 3.41 and the isochron (Model III) has an apparent age of 1829 ± 20 m.y. with initial Sr$^{87}$/Sr$^{86}$ of 0.7115 ± 0.0037. The biotite from 979 has apparently retained the age of the total rock systems and can therefore be included in the regression.

A Model III solution to the total rock regression can be expected particularly for volcanics. Variability in the value of the initial Sr$^{87}$/Sr$^{86}$ can occur within a single outcrop of limited exposure; the total rock isochron presented here is representative of material up to 400 miles apart.
It will be noticed that samples 964 and 956, the samples from the Castlereagh Porphyry have both been excluded from the final regression. This exclusion is based entirely on statistical grounds and has no geological bias. In fact, a regression based on the 10 "acceptable" samples plus 964 and 956 results in an isochron which is virtually no different to the $1823 \pm 17$ m.y. already quoted. For the twelve samples the regression has a Model IV solution ($MSWD = 6.76$), the isochron having an apparent age of $1814 \pm 21$ m.y. with an initial $\text{Sr}^{87}/\text{Sr}^{86}$ of $0.7118 \pm 0.0047$. For the eleven total rock samples (deletion of 979 biotite) the regression has a $MSWD = 7.49$ and Model IV solution, the isochron having an apparent age of $1820 \pm 37$ m.y. with an initial $\text{Sr}^{87}/\text{Sr}^{86}$ of $0.7110 \pm 0.0042$. The residual variance is increased but the confidence interval is still acceptable. These two samples are in fact more "correct" and fit the isochron to a higher degree than many of the excluded samples from the Whitewater Volcanics.

The above observations therefore support the assumption that the Whitewater Volcanics and the Castlereagh Porphyry are both coeval and comagmatic.

Origin of the Whitewater Volcanics and Castlereagh Hill Porphyry

The rather high initial $\text{Sr}^{87}/\text{Sr}^{86}$ (greater than 0.71) deserves comment. This value exceeds the limits usually
accepted for "mantle-type" material and the immediate inferences are that this Volcanic is really much older and has suffered "metamorphism" at a time equivalent to its $\text{Sr}^{87}/\text{Sr}^{86}$ value, or that the Volcanic has been derived from, or contaminated by, older crustal material.

An event causing the whole of the quite large exposure of Volcanics to become rehomogenized with respect to $\text{Sr}^{87}/\text{Sr}^{86}$ is theoretically possible. In practice however, it would appear to be extremely unlikely. The Volcanics show no petrographic evidence of such an event, and for such large-scale transfer of material one would expect some petrographic change to be evident. Neither is there any evidence for such an event in the closely related (both in space and time) Bow River Granite. Movement along the Greenvale Fault and its extensions is the only obvious source of the energy required for large scale transfer of material, but while it is known that localized areas close to fault systems have been affected, there has never been any suggestion that such movements could account for the massive alteration necessary to promote loss from the entire Whitewater Volcanics. For these reasons it is concluded that the high initial $\text{Sr}^{87}/\text{Sr}^{86}$ value of the Volcanics is a primary feature.

As stated above, the indicated initial $\text{Sr}^{87}/\text{Sr}^{86}$ exceeds the limits of typical mantle-type material
(e.g., oceanic basalts). Therefore either a crustal source or crustal contamination of mantle-type material is suggested. These suggestions are not supported by the petrographic evidence of the samples which shows that the composition of the Volcanics is normal and generally devoid of any component which would suggest contamination. This is in contrast to the composition of the Mabel Downs Granite which contains sillimanite and garnet in more than accessory amounts.

A further possibility is that the Volcanics were actually derived from mantle-type material and before emplacement the magma was held for a considerable length of time in the (say) lower crust. During this period the magma was isolated from the source region and the radiogenic Sr\(^{87}\) derived from the decay of Rb\(^{87}\) remained within the silicic magma. The Sr\(^{87}/\text{Sr}^{86}\) of the magma would be increased and this increased value would be retained on emplacement and consolidation as the "initial Sr\(^{87}/\text{Sr}^{86}\)".

Some support for the latter suggestion is given by the following:

1) All the lavas are porphyritic, containing phenocrysts of quartz and feldspar, with these minerals also occurring in the fine-grained groundmass. This sharp break in grain-size between phenocrysts and groundmass is
correlated with corresponding changes in conditions prevailing during freezing of the magma. "Such a break occurs where slow crystallization of magma deep within the crust has given way to rapid crystallization following uprise of the magma and extrusion at the surface...." (Turner and Verhoogen, 1951, p.55).

2) A strong similarity has been noted between certain phases of the porphyritic and coarse-grained granites and the Castlereagh Hill Porphyry. Contacts between the two units are usually obscured, and where present are contradictory, but even so it is obvious that gradation can exist from the Porphyry through to the granites. Border phases of the granite, where gradation is apparent, are so similar to the Porphyry that they become indistinguishable.

3) If the "average composition" (based on the analyses presented in this thesis) of the Whitewater Volcanics, Bow River Granite, and combined Mabel Downs Granite and Tickalara Metamorphics, is plotted on a radiogenic Sr$^{87}$/Rb$^{87}$ versus Sr$^{87}$/Sr$^{86}$ then each "average" line represents the Rb$^{87}$ decay history for each particular unit (fig. 8). From this diagram it is possible to predict the Sr$^{87}$/Sr$^{86}$ value for each unit at any particular time. It is immediately obvious that the projection of the decay line for the Whitewater Volcanics back in time (before
apparent crystallization) intersects the line for the Bow River Granite at that granites time of crystallization.

These reasons support the suggestion that the Whitewater Volcanics were derived from a magma held for some considerable time in the lower crust. Furthermore, the field and isotopic evidence (2 and 3) support the further suggestion that the Volcanics were a differentiate of the same parent magma as that from which the Bow River Granite was derived, and the period of time for which the differentiate lay "dormant" is the difference in apparent ages between the volcanics and Bow River Granite - some 30 m.y. or more. This is not an uncommonly lengthy period of time. Analyses of the Silurian Sutton Granite near Canberra, A.C.T., indicate a time difference of some 20 m.y. between the emplacement of the granite and aplite and the associated comagmatic pegmatites and microgranite (Bofinger - unpublished data).

ALTERED ROCKS AND MINERALS

Most of the minerals and some of the total rocks from samples of the igneous and metamorphic units within the Kimberley area have ages much younger than the apparent age of emplacement or formation of the parent body. Samples of rocks from the various granites, Tickalara Metamorphics, and Whitewater Volcanics are included. They represent a large portion of the map area and include rocks
ALTERED ROCKS AND MINERALS (1)

- Porphyritic Granite
- Gneissic Granite
- McLintock Range Granite
- Tidalara Metamorphics

FIGURE 11
from both the "mobile" and "stable" zones. They also represent a series of rocks which have been emplaced over a considerable period of geological time.

A total of nineteen separate mineral and total rock analyses will be considered in this section.

**Isochron I**

Eleven samples, consisting of three total rocks, five K-feldspars, and three biotites, define one isochron. The analytical data are listed in Table 12 and plotted on an isochron diagram in fig. 11.

Inspection of fig. 11 shows that linearity exists between these samples. Regression of the data confirms this linearity, resulting in a Model IV isochron (MSWD = 17.81) having an apparent age of $1681 \pm 63$ m.y. with an initial $\text{Sr}^{87}/\text{Sr}^{86}$ of $0.7025 \pm 0.0042$.

The Model IV solution suggests combined variation in the initial $\text{Sr}^{87}/\text{Sr}^{86}$ of samples and elemental and/or isotopic redistribution. This is to be expected since a) the regression is defined by samples derived from units with varying initial $\text{Sr}^{87}/\text{Sr}^{86}$ values, and b) the apparent age of the isochron is much less than that of any of the parental bodies and open system chemistry is obvious.

However, the isochron is significant in terms of geological events. The probability that random
<table>
<thead>
<tr>
<th>G.A. SAMPLE NO.</th>
<th>RB PPM</th>
<th>SR PPM</th>
<th>RB87/SR86</th>
<th>SR87/SR86</th>
<th>SR87/SR86</th>
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</thead>
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<td>28.445</td>
<td>1.5703</td>
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</tr>
</tbody>
</table>
FIGURE 11.
from both the "mobile" and "stable" zones. They also represent a series of rocks which have been emplaced over a considerable period of geological time.

A total of nineteen separate mineral and total rock analyses will be considered in this section.

**Isochron I**

Eleven samples, consisting of three total rocks, five K-feldspars, and three biotites, define one isochron. The analytical data are listed in Table 12 and plotted on an isochron diagram in fig. 11.

Inspection of fig. 11 shows that linearity exists between these samples. Regression of the data confirms this linearity, resulting in a Model IV isochron (MSWD = 17.81) having an apparent age of 1681 ± 63 m.y. with an initial Sr$^{87}$/Sr$^{86}$ of 0.7025 ± 0.0042.

The Model IV solution suggests combined variation in the initial Sr$^{87}$/Sr$^{86}$ of samples and elemental and/or isotopic redistribution. This is to be expected since a) the regression is defined by samples derived from units with varying initial Sr$^{87}$/Sr$^{86}$ values, and b) the apparent age of the isochron is much less than that of any of the parental bodies and open system chemistry is obvious.

However, the isochron is significant in terms of geological events. The probability that random
<table>
<thead>
<tr>
<th>G.A. SAMPLE NO.</th>
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<th>RB/SR87</th>
<th>SR/SR87</th>
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<td>1100 BIOTITE-A</td>
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</table>
ALTERED ROCKS AND MINERALS (2)

WEIGHTED MEAN AGE (including 1107 biotite)

1046 ± 26 m.y.

FIGURE 12.
Sample 5105 is from the granite in the McLintock Range area; the granite has been intruded into sediments of the Halls Creek Group. The sample site has been effected by faulting, and quartz reefs, aligned along the fault planes, are common.

Sample 5230 is located close to the Halls Creek Fault. The site is characterized by close set joint and fracture planes, and post-emplacement movement and alteration is indicated.

This age of 1681 ± 63 m.y. is therefore regarded as being that of a period of widespread diastrophism which affected large sections of the Kimberley Region. From what is known of the location of samples defining the isochron it is further suggested that this diastrophism was mainly expressed by faulting.

Isochron II

Analytical data for the remaining eight samples - four biotites, three K-feldspars, and one total rock - are listed in Table 13 and plotted on an isochron diagram in fig. 12.

Regression of the data results in a Model IV isochron (MSWD = 18.70) having an apparent age of 1046 ± 26 m.y. with an initial Sr\(^{87}/Sr^{86}\) of 0.7926 ± 0.0128. As with the previous isochron, combined variation in initial Sr\(^{87}/Sr^{86}\) and redistribution of material is suggested by the Model IV
solution, and is to be expected for such a heterogeneous suite of samples.

Two independent but not distinct isochrons can be defined by regressing certain groups of these eight samples. These isochrons give some indication of where material redistribution and variation in initial Sr$^{87}$/Sr$^{86}$ is most pronounced.

Regression of the four samples 954 total rock, 954 K-feldspar, 1086 K-feldspar, and 1100 biotite results in a Model III isochron (MSWD = 10.45) having an apparent age of 1067 ± 26 m.y. with an initial Sr$^{87}$/Sr$^{86}$ of 0.7888 ± 0.0175. The error is greater than experimental but is due to variation in the initial Sr$^{87}$/Sr$^{86}$ between samples (Model III).

Further regression of 956 K-feldspar, 976 K-feldspar, 1100 biotite, and 1240 K-feldspar results in a Model II isochron (MSWD = 20.49) having an apparent age of 1038 ± 114 m.y. with an initial Sr$^{87}$/Sr$^{86}$ of 0.8674 ± 0.5989. It will be noted that 1100 biotite is common to both regressions. This latter isochron is poorly defined, but the Model II solution, and the results, suggest extreme open system behaviour. Since three of these four samples are biotites, open system behaviour is to be expected.
As with Isochron I, the mean weighted Isochron II (1046 ± 26 m.y.) is considered to be related to a diastrophic event which was most probably expressed by faulting. It will be noted that all samples for Isochron II are contained within the Halls Creek Mobile Zone and possibly this later diastrophism was confined to this area leaving the "stable" blocks on either side of the Zone undisturbed.

Age Correlations

The 1681 m.y. diastrophic event may have had more far reaching effect than is indicated by the samples defining the isochron. Apparent ages of this order, which can be shown to be minimum values for the emplacement of the represented unit, are common.

The K-Ar data for the McIntosh Gabbro indicates an age of 1730 m.y. This age is a minimum since the Gabbro is known to be intruded by granite having a much older apparent age.

The age of the Halls Creek Group has been discussed previously and it was noted that the maximum apparent age retained by shales from the Olympio Formation is 1705 m.y. This is a minimum estimate of the time of deposition since the Group has been intruded by granites having ages of about 2,000 m.y. and pegmatite of about 2700 m.y. The muscovite from this pegmatite has an apparent age of 1755 m.y.
Data for glauconites from the Kimberley Group (see later) have a maximum age of about 1690 m.y. This value is also a minimum estimate of the time of formation of the Group since the depositional age is restricted to a well defined period between 1800 m.y. and 1823 m.y.

Within the Speewah Group (see later), which underlies the Kimberley Group, samples from the Valentine Siltstone have an apparent age of 1761 m.y. and glauconites from the O'Donnell Formation have an apparent age of 1732 m.y. The Speewah Group is also restricted in age to the same limits controlling the age of the Kimberley Group.

Wilson et al. (1960) report an age of about 1700 m.y. for muscovite from outcrops of the Lamboo Complex in the Leopold Ranges. They conclude that it is likely that a dominant metamorphism and granite injection took place in Northern Australia between 1600 and 1700 m.y. ago.

The 1046 m.y. event was apparently not as widespread as the earlier diastrophism. While ages comparable to 1046 m.y. are retained by the Glidden and Carr Boyd Groups and by a unit of the Wade Creek Sandstone (see later) this comparison is not considered to be significant. The ages of these sedimentary formations are still minimum estimates of the time of deposition, but their ages are not considered to be related to this younger diastrophism. The main evidence for this conclusion is given by the
data for the Carr Boyd Group. Here the order of superposition is retained by the ages of the various sedimentary units of the Group. If these minimum ages were the result of diastrophism or some similar event, this order of superposition of ages could be expected to be obliterated, or at least obscured.

**SPEEWAH GROUP**

The Group consists of a succession of sandstones, siltstones, and shales, with minor tuff, and the five recognizable rock units within the Group are reported by Roberts *et al.* (1965) to be in conformable sequence. Dow *et al.* (1964) recognize strong angular unconformities between the basal units in the northern section of the area. The Group unconformably overlies rocks of the Halls Creek Group, Lamboo Complex, and Whitewater Volcanics, and is conformably overlain by rocks of the Kimberley Group.

Samples from two formations within the Group are available for isotopic age determinations. These are the O'Donnell Formation, the oldest unit, and the Valentine Siltstone, the middle unit of the Group.

1. **O'Donnell Formation**

In some sections of the Formation a ferruginous glauconitic sandstone crops out and three samples of glauconite (5201, 5202, 5203) have been separated from these beds. Glauconite separation has been attempted
<table>
<thead>
<tr>
<th>G.A. SAMPLE NO.</th>
<th>RB PPM</th>
<th>SR PPM</th>
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<th>SR87/SR86</th>
<th>SR87/SR86</th>
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<td>5202 GLAUCONITE</td>
<td>90.4</td>
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<td>5203 GLAUCONITE</td>
<td>530.6</td>
<td>6.9</td>
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</table>
FIGURE 13.
<table>
<thead>
<tr>
<th>G.A. SAMPLE NO.</th>
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<th>SR PPM</th>
<th>RB87/SR86</th>
<th>SR87/SR86</th>
<th>CALC. MEAS.</th>
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</thead>
<tbody>
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<tr>
<td>962 TOTAL ROCK-A</td>
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</tr>
<tr>
<td>962 TOTAL ROCK-B</td>
<td>219.3</td>
<td>182.2</td>
<td>3.461</td>
<td>0.7964</td>
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</tr>
</tbody>
</table>
Figure 14.
from other samples of the sandstone, but because of the ubiquitous iron, extraction of pure material proved impossible.

The data of Rb-Sr isotope dilution analyses of these three glauconites are listed in Table 14 and plotted on an isochron diagram, fig. 13.

The maximum apparent age is given by sample 5201. For an assumed initial Sr\(^{87}/Sr^{86}\) of 0.70, the apparent age is 1732 m.y. Data points for 5202 and 5203 lie close to this isochron, and assuming the same initial Sr\(^{87}/Sr^{86}\) value the corresponding ages are 1698 m.y. and 1725 m.y. for 5202 and 5203 respectively. The discrepancy between these three maximum apparent ages is about 2%.

(2) Valentine Siltstone

In the northern section of the area, tuffaceous material is preserved as an interbedded unit of this formation (Dow et al. 1964). In the southwestern section, this unit is absent (Dow et al., 1964; Roberts et al., 1965). Two samples (961, and 962) have been collected from a massive rhyolitic tuff which occurs near the top of the Siltstone.

Rb-Sr isotope dilution data are listed in Table 15 and plotted on an isochron diagram, fig. 14.

An isochron joining the two data points has an apparent age of 1761 m.y. with an initial Sr\(^{87}/Sr^{86}\) of
0.7118. Assuming a minimum initial Sr$^{87}$/Sr$^{86}$ of 0.70, then the maximum apparent age of each sample is 1807 m.y. and 1999 m.y. for 961 and 962 respectively. To obtain concordancy of "maximum" apparent ages at 1807 m.y., sample 962 would have an assumed initial Sr$^{87}$/Sr$^{86}$ of 0.7095.

Discussion

A maximum age for the emplacement of the Speewah Group is given by the age of the underlying Whitewater Volcanics. Likewise a minimum value can be obtained from the age of the Hart Dolerite (see later) which extensively intrudes this Group. The age of emplacement must lie between 1800 m.y. and 1823 m.y.

The maximum apparent age given by the glauconites of the O'Donnell Formation is some 4% too low to satisfy these limits to the age of the Group. This aspect of glauconite ages is well known, and is in fact predictable, and the apparent ages obtained for these minerals must necessarily be regarded as minima. A fuller discussion of the suitability of glauconites for age determinations will be made in the section on the Kimberley Group.

The close relationship between the maximum apparent ages (within 2%) deserves comment. The reproducibility lies within the limits of experimental error for minerals having high Rb$^{87}$/Sr$^{86}$ values (Brooks, 1966; McDougall et al.)
The enrichment in radiogenic Sr\textsuperscript{87} of these glauconites is such that this 2\% limit is still retained with higher (0.72) assumed initial Sr\textsuperscript{87}/Sr\textsuperscript{86} values.

This concordancy can be considered in two ways. It may be interpreted as reflecting a homogeneous environment during formation of these glauconites from quite separate areas, resulting in equivalent "time-delays" between deposition of the parent material and glauconitization, or it could represent the effect of some post-formational event in this area which has caused the glauconites to become temporary open chemical systems and reflect this event.

The apparent isochron of 1761 m.y. for data from rocks of the Valentine Siltstone must also be regarded as a minimum estimate of the time of emplacement since it is some 2-3\% lower than the predicted limit. However, the maximum value of 1807 m.y. obtained from the data of 961 falls within the limits. The maximum apparent age of 962 is ridiculously high and cannot be considered. Either the samples represent two open chemical systems which have responded to some event, or these samples are coeval and retain their age of emplacement but have differing initial Sr\textsuperscript{87}/Sr\textsuperscript{86} values. There is no real evidence to support either of these assumptions at the expense of the other.
The first hypothesis has to its credit the fact that the area about the sample sites has been subjected to faulting and folding and is relatively close (compared to the greater part and more stable section of the Kimberley Block) to the highly unstable Halls Creek Mobile Zone. Fine-grained volcanic ejecta (such as ash) would be more subject to alteration, such as redistribution or loss of elements, than the coarse-grained igneous equivalents, particularly in the interval between deposition and lithification.

The second possibility, that of variation in initial Sr$^{87}$/Sr$^{86}$ for coeval samples, can be supported for the following reasons.

1) The volcanic beds within the sequence are discontinuous; in most areas only one unit is present, while in others there are two. It is more than possible that these two samples are not from the same ash fall and variation in the parental composition is probable.

2) Lateral variation within a specific bed is reported by Dow et al., (1964). Williams, Turner, and Gilbert (1953) regard this variation as a common feature of pyroclastic rocks with "the coarser, more crystalline, and more basic materials and those richer in mafic minerals passing upward into finer materials richer in glass, feldspar, and quartz and therefore more siliceous
in composition. Corresponding lateral transitions may often be observed as a layer of ash or tuff is followed away from the parent volcano." (p.151). Such mineralogical variations could result in variations in the initial \( \frac{Sr^{87}}{Sr^{86}} \) ratio.

3) Variations in the \( \frac{Sr^{87}}{Sr^{86}} \) composition of sedimentary material deposited with and included in the volcanic ash beds will result in variations in the ultimate \( \frac{Sr^{87}}{Sr^{86}} \) of the lithified rock even for samples of ash having precisely the same parent.

The variation in the initial \( \frac{Sr^{87}}{Sr^{86}} \) values of 0.70 for 961, and 0.7095 for 962, necessary to obtain a common age of 1807 m.y. can be adequately explained in terms of any one, or a combination, of the above methods.

**KIMBERLEY GROUP**

Rocks of the Kimberley Group are the most extensively exposed of the younger Proterozoic material within the map area. The Group is conformably overlaid by the Bastion Group and lies with general conformity on the Speewah Group. It has been divided into five formations these being (youngest to oldest) the Pentecost Sandstone, Elgee Siltstone, Warton Sandstone, Carson Volcanics, and King Leopold Sandstone, and all are conformable. Minerals and rocks from three of these formations have been collected for isotopic age determination.
<table>
<thead>
<tr>
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<td>SR87/SR86</td>
<td>SR87/SR86</td>
<td>AGE M.Y.</td>
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<tr>
<td>----------------</td>
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<tr>
<td>5210 MUSCOVITE</td>
<td>511.1</td>
<td>32.1</td>
<td>45.753</td>
<td>1.9337</td>
<td>1.9337</td>
<td>1909</td>
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<tr>
<td>5211 MUSCOVITE</td>
<td>424.1</td>
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<td>30.990</td>
<td>1.5146</td>
<td>1.5146</td>
<td>1866</td>
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</table>
(1) **Carson Volcanics**

The formation consists of massive saussuritized and chloritized basalt, interbedded feldspatic sandstone and chloritic siltstone, and minor green chert. Two basaltic samples are available, these being selected from the least altered sections of the formation.

Data for Rb-Sr isotope dilution analyses of these samples is listed in Table 16 and displayed on an isochron diagram in fig. 15.

An isochron through the two data points has an apparent age of 1807 m.y. and an initial $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.7001.

(2) **Warton Sandstone**

The Sandstone is very uniform and consists of massive to blocky quartz sandstone, grading upwards into feldspatic sandstone. Minor interbeds of grit and purple shale also occur. In localized sections a highly micaceous sandstone is apparent towards the base of the formation. The assumption was that this mica was probably authigenic, and on this basis two samples were collected for age determination.

Data from the Rb-Sr isotope dilution analyses of these samples (5211 and 5210) is listed in Table 17.

The maximum age, assuming an initial $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.70, is 1909 m.y. for sample 5210, and 1866 m.y. for 5211.
<table>
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<th>SR87/SR86 MEAS.</th>
<th>AGE M.Y.</th>
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<tr>
<td>1008 GLAUCONITE</td>
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<td>98.756</td>
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<tr>
<td>1009 GLAUCONITE</td>
<td>336.7</td>
<td>20.3</td>
<td>51.868</td>
<td>1.8229</td>
<td>1541</td>
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<td>5205 GLAUCONITE</td>
<td>254.7</td>
<td>20.4</td>
<td>35.923</td>
<td>1.4777</td>
<td>1541</td>
</tr>
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</table>
The apparent ages are not markedly affected by variations in the assumed initial $\text{Sr}^{87}/\text{Sr}^{86}$ (although these micas are not as highly enriched in Rb relative to Sr as most) and for an assumed value of 0.72, the ages are reduced to 1883 m.y. and 1821 m.y. for samples 5210 and 5211 respectively. For sample 5210 to have an age comparable to its stratigraphic position relative to the apparent age of the Carson Volcanics, an initial $\text{Sr}^{87}/\text{Sr}^{86}$ of 0.77 would have to be assumed.

(3) Pentecost Sandstone

The Formation consists of quartz sandstone with minor interbeds of purple siltstone, micaceous siltstone, green shale, glauconitic sandstone, and ferruginous feldspathic sandstone.

A number of samples of the glauconitic sandstone have been collected but because of the excessive amount of iron usually associated with these beds, pure glauconite could be separated from only three of these. Rb-Sr isotope dilution analyses data for these three samples (1008, 1009, 5205) is listed in Table 18.

A wide variation exists in the maximum apparent age of these samples. Assuming an initial $\text{Sr}^{87}/\text{Sr}^{86}$ of 0.70, maximum apparent ages of 1696 m.y., 1541 m.y., 1541 m.y. are given for 1008, 1009, and 5205 respectively. All samples are highly enough enriched in radiogenic $\text{Sr}^{87}$
for the apparent ages to be virtually independent of reasonable variations in the initial $\text{Sr}^{87}/\text{Sr}^{86}$ value.

Discussion

Discordancy is apparent in the ages of these formations since the evidence of the relationships of rock sequences in the stratigraphic column is not reproduced by the age determinations.

Consider firstly the oldest apparent age, that given by the mica from the Warton Sandstone. Unless an extremely high initial $\text{Sr}^{87}/\text{Sr}^{86}$ is assumed, for which there is no available evidence, the ages are in excess of the maximum possible value of 1823 m.y. given by the Whitewater Volcanics. Therefore the apparent age of the mica cannot be considered as representing the age of deposition of the Sandstone.

The most logical hypothesis would be that this mica is detrital in origin, and that the apparent age reflects the age of the source material from which it was derived. Reasonable estimates of the age of 5210 (including, say, calculations based on an initial $\text{Sr}^{87}/\text{Sr}^{86}$ of 0.72) are still in excess of the age of the Bow River Granite. However, the maximum possible age is less than the limit for the age of the Mabel Downs Granite. Other evidence to be presented later shows that the Lamboo Complex is a likely provenance for all the younger Proterozoic
sedi mens. The apparent ages of the micas from the Warton Sandstone are consistent with the hypothesis that they represent "degraded" mica which has been derived from the Mabel Downs Granite. Goldich and Gast (1966) report reductions in ages of from 75% to 25% in weathered biotite.

The minimum estimate of the age of the Kimberley Group is obtained from the analytical data of the glauconites from the Pentecost Sandstone, and in this context the apparent ages are acceptable. However, the maximum estimate (1696 m.y.) is too small by some 100 m.y. The Hart Dolerite intrudes the Pentecost Sandstone and therefore the age of the Sandstone must be greater than that of the Dolerite. Evidence of the age of the Dolerite (see later) places the minimum estimate of the age of the Kimberley Group at 1800 m.y.

Much has been written regarding the suitability of glauconites for isotopic age determination studies and this information has been reviewed by McDougall et al. (1965). The work of Burst (1958) supports "the classical theory of glauconization as a mineralization process in which certain clay-like materials are converted or beneficiated to glauconite." (p.324). Hurley et al. (1960) suggest that this process could continue over a long period of time, citing as evidence the fact that in young glauconites there are 30% or more expandable layers which decrease to
about 10% in early Palaeozoic samples. It is this low
purification with time which Hurley et al. believe is
responsible for the fact that their measured ages on
glaucnites fall 10% to 20% short of the predicted value.
Similar conclusions were made by Evernden et al. (1961).
A concordance of K-Ar and Rb-Sr ages (Goldich et al. (1959))
is not considered to be evidence supporting the complete
retention of radiogenic daughter products and even concordant
ages must still be regarded as minima (McDougall et al.
(1965)).

In this particular case the maximum age is about 6%
too low and in this regard compares favourably with the
10% to 20% found by Hurley et al. (1960) for Phanerozoic
glaucnite samples. Assuming a relatively constant period
of time for glauconite to become a closed chemical system,
then the older the glauconite the closer the measured age
will be to the absolute value. Hence in older Precambrian
samples less discrepancy between the measured and the
predicted ages is expected.

The much lower measured ages of samples 1009 and 5205
are most likely due to the response of these widely
separated sampling sites to a later tectonic event. Both
samples come from near faults and are located in a
relatively mobile zone compared to the stability of the
1008 sample area. J.R. Richards (pers. comm.) reports a
K-Ar age of 1540 m.y. obtained on a biotite from granite of the Lamboo Complex (G.A. 158).

Knowing the limits within which the age of deposition of the Kimberley Group must lie (see above), the apparent age of 1807 m.y. given by the isochron for the Carson Volcanics must be close to the true age of emplacement of this unit. Unfortunately, since only two samples are available, the value of 1807 m.y. cannot be confidently accepted as the age of emplacement. However, since the only basis for doubt is statistical, and since the measured age conforms to the predicted limits, 1807 m.y. is considered to be the age of the Carson Volcanics.

HART DOLERITE

Detailed descriptions of the occurrence and petrography of the Hart Dolerite have been made by Gellatly et al. (1965). They describe the unit as one of the most extensively developed dolerites in the world, and consider it to be the most extensive Precambrian example. The total area of outcrop is given as 1800 square miles, which is less than the Karroo Dolerite of South Africa but of the same order of magnitude as the Tasmanian Dolerite. The unit intrudes the Pentecost Sandstone of the Kimberley Group but is best developed within the Speewah Group. The Dolerite is virtually unaltered; some late stage hydrothermal alteration is reported, and also sporadic veins of calcite, and minor quartz carrying traces of chalcopryite.
Granophyre is often developed as flat-lying sheets at, or near, the top of the dolerite sills. In the northern section of the area (Lissadell Sheet) granophyre is only developed at one stratigraphic level, but in the Lansdowne Sheet area recent work has shown that it is developed at no less than six horizons. Contact alteration of the intruded material is slight, but in local areas a metasomatized granophyre is developed between the normal granophyre and intruded arkose.

Gellatly et al. (1965) have discussed the petrogenesis of the granophyres and consider the most likely origin to be crystallization differentiation from a normal tholeiitic magma. Differentiation occurs within the dolerite and in one locality gradational transition from dolerite to granophyre is observed. This gradational contact between the two rock types is considered to be more widespread, but relationships are obscured. In general the rock types range from olivine dolerite and gabbro through to normal tholeiitic dolerite, granophyric dolerite and diorite to granophyre.

Samples have been collected from both the dolerite and the granophyre. 5215 and 65/16/7047 are from the granophyre proper, 5214 and 5241 from the granophyric dolerite, and 1241, 5131, 5133, 5132, and 5052 from the main mass of dolerite.
<table>
<thead>
<tr>
<th>G.A. SAMPLE NO.</th>
<th>RB PPM</th>
<th>SR PPM</th>
<th>RB87/SR86</th>
<th>SR87/SR86 CALC</th>
<th>SR87/SR86 MEAS</th>
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<tbody>
<tr>
<td>65/16/7047 TOTAL R.</td>
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<td>138.5</td>
<td>1.939</td>
<td>0.7507</td>
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<td>1241 PLAGIOCLASE</td>
<td>90.0</td>
<td>421.1</td>
<td>0.614</td>
<td></td>
<td>0.7167</td>
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<tr>
<td>5052 TOTAL ROCK</td>
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<td>191.3</td>
<td>0.548</td>
<td>0.7164</td>
<td>0.7167</td>
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<tr>
<td>5125 TOTAL ROCK-A</td>
<td>135.1</td>
<td>105.2</td>
<td>3.555</td>
<td>0.7903</td>
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</tr>
<tr>
<td>5125 TOTAL ROCK-B</td>
<td>133.6</td>
<td>108.0</td>
<td>3.557</td>
<td>0.7916</td>
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</tr>
<tr>
<td>5131 TOTAL ROCK</td>
<td>45.1</td>
<td>216.1</td>
<td>0.599</td>
<td>0.7201</td>
<td>0.7194</td>
</tr>
<tr>
<td>5132 TOTAL ROCK</td>
<td>52.8</td>
<td>194.2</td>
<td>0.781</td>
<td>0.7234</td>
<td>0.7225</td>
</tr>
<tr>
<td>5133 TOTAL ROCK</td>
<td>40.3</td>
<td>188.9</td>
<td>0.613</td>
<td>0.7196</td>
<td>0.7180</td>
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<tr>
<td>5214 TOTAL ROCK-A</td>
<td>224.8</td>
<td>43.9</td>
<td>14.707</td>
<td>1.0966</td>
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</tr>
<tr>
<td>5214 TOTAL ROCK-B</td>
<td>223.9</td>
<td>41.3</td>
<td>15.577</td>
<td>1.0996</td>
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<tr>
<td>5241 TOTAL ROCK</td>
<td>36.5</td>
<td>194.2</td>
<td>0.540</td>
<td>0.7176</td>
<td>0.7198</td>
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</table>
FIGURE 16.
Isotope dilution analyses of these samples are listed in Table 18 and plotted on an isochron diagram in fig. 16.

Discussion

Colinearity of the data points is shown in fig. 16 and a regression of the analytical data results in a Model I isochron (MSWD = 1.01) having an apparent age of 1800 ± 25 m.y. with an initial Sr$^{87}$/Sr$^{86}$ of 0.7026 ± 0.0006 at the 95% confidence level. This initial Sr$^{87}$/Sr$^{86}$ value lies within the limits for the composition of the earth's mantle (Gast, 1960), and supports the conclusions of Gellatly et al. (1965) that the magma from which the dolerites were derived was uncontaminated by crustal material.

The value of 1800 ± 25 m.y. is considered to be the age of initial consolidation and Sr$^{87}$/Sr$^{86}$ homogenization of the Hart Dolerite.

This determination is important in terms of the geochronology of the Kimberley Region since it represents the minimum limit to the period of emplacement of the Kimberley and Speewah Groups. It is also important in terms of subdivision of the Precambrian time-scale since the value is that of the proposed boundary between the "Carpentarian System" and "Lower Proterozoic System" (Dunn et al., 1966; McDougall et al., 1965).

SIGNIFICANCE OF AGES OF MAJOR IGNEOUS ROCK UNITS

The apparent ages of the Tickalara Metamorphics, gneissic granites and Bow River Granite are all
significantly different. Statistically each represents separate and discrete events in the geological history of the East Kimberley Region. Likewise the Whitewater Volcanics and Bow River Granite have apparent ages and initial $\text{Sr}^{87}/\text{Sr}^{86}$ values which are statistically distinct. The apparent age relationships between the Hart Dolerite and Bow River Granite are also significantly different.

The relationship between the Whitewater Volcanics and the Hart Dolerite is not so clear cut. The initial $\text{Sr}^{87}/\text{Sr}^{86}$ values are obviously distinct. The apparent ages are not distinct at the 5% level but are distinct at the 10% level, i.e., there are nine chances in ten of the apparent ages being distinct. Statistically the difference in apparent ages of these two units is not significant.

In circumstances such as this, a decision cannot be made purely on the basis of statistical significance; practical considerations must be paramount (Moroney, 1956). In this particular instance, the difference in initial $\text{Sr}^{87}/\text{Sr}^{86}$ between the rocks indicates that these units are predictably non-comagmatic. Furthermore the stratigraphic evidence shows that a definite period of time exists between the emplacement of the separate bodies. There being no evidence to the contrary, it is also concluded that both rock types have remained closed
chemical systems with respect to Rb and Sr since their times of emplacement.

The difference in the mean apparent ages of the Whitewater Volcanics and the Hart Dolerite is therefore considered to be real although this difference does not appear to be statistically distinct. The emplacement of each unit is regarded as being a separate and discrete event.

A Statement on the Interpretation of Rb-Sr Data from Shales

The radiometric ages detailed in the following pages are based on the interpretation of Rb-Sr data from shales. Within each section some attempt has been made to assess independently the data from each unit in the light of the known stratigraphy, mineralogy, and structural history. However, the interpretations are influenced by the results and conclusions contained in Appendix A. Some reference may therefore need to be made to this latter section.

BASTION GROUP

The Bastion Group conformably overlies the Kimberley Group in the northern portion of the map area, and is itself unconformably overlain by the Antrim Plateau Volcanics of Cambrian age. Radiometric control on the upper limit to the age of the Group is very poor and it is theoretically possible for the age of the rocks to
lie anywhere from about 600 to 1800 m.y. However, as the Group rests conformably on the Kimberley Group, and as the lowermost unit of the Bastion Group is transitional between the Pentecost Sandstone (uppermost unit of the Kimberley Group) and the Wyndham Shale (central unit of the Bastion Group), the age of the Bastion Group is considered to be close to that of the Kimberley Group.

The rocks of the Group are dominantly green shales and minor carbonates (siderite? and dolomite) overlain by quartz sandstone. The Wyndham Shale contains the only rocks suitable for age determination, and eight samples were collected from a cliff section at Wyndham. Carbonates were not present in the sample area.

After preliminary X-ray fluorescence analyses, five samples were selected for isotope dilution analyses. One notable thing about these shale samples is the extraordinarily low range in Rb/Sr values.

Narrow ranges in the Rb/Sr of a suite of samples leads to very wide confidence limits to the apparent age and initial $\text{Sr}^{87}/\text{Sr}^{86}$ value when the data are regressed. To offset this effect two of the total rock samples (those with the greatest and least Rb/Sr values) were treated in the following manner:

A weighed portion (approximately 1 g.) of crushed sample material was leached in a centrifuge tube by
stirring for one hour (using a teflon stirring rod) in 1.0N HCl. The residue and suspension was centrifuged and the supernatant liquid transferred to a clean Pyrex glass beaker. The operation was repeated twice more using demineralized water, each time the supernatant liquid being transferred to the original Pyrex glass beaker. The leached solid residue (LSR) was transferred to a tared platinum dish, dried slowly, and the loss in weight due to leaching recorded. The normal methods were then employed for Rb-Sr isotope dilution analyses of the LSR. The supernatant liquid (leach) was evaporated to dryness and an unspiked $\text{Sr}^{87}/\text{Sr}^{86}$ analysis made of the remaining solids.

Leaching of similar samples had been previously carried out using a buffered solution of sodium acetate and acetic acid, after the method of Dasch et al. (1966), but proved to be unsuitable since most of the carbonate in shales from the Kimberley area is in the form of dolomite.

The loss in weight for these two samples was less than 1.5%, which for a 1 g. sample is less than 15 mg. Unless the leached material is extremely highly enriched in both Rb and Sr, this amount of material is insufficient for a total Rb-Sr isotope dilution analysis. Since it might be expected that the major portion of the leach would be carbonate, a high Sr and low Rb concentration
could be expected. (In actual fact however, these particular samples proved to be abnormal in this respect and the supernatant contained about 10 p.p.m. Rb and 5 p.p.m. common Sr.) The Rb\(^{87}/Sr^{86}\) of the leach was then calculated.

The calculations are as follows. As the total rock is a mixture of the leach and solid residue, material balance shows that

\[
q = \frac{\text{Sr}_{LSR}^{86}}{\text{Sr}_{L}^{86}} = \left(\frac{f}{1-f}\right) \left(\frac{\text{Rb}_{TR}^{87}/\text{Sr}_{TR}^{86} - \text{Rb}_{L}^{87}/\text{Sr}_{L}^{86}}{\text{Rb}_{LSR}^{87}/\text{Sr}_{LSR}^{86} - \text{Rb}_{TR}^{87}/\text{Sr}_{TR}^{86}}\right)
\]

where \(f\) is the weight fraction of the leach. Of these quantities only \(\text{Rb}_{L}^{87}/\text{Sr}_{L}^{86}\) is unknown. Solving for this quantity we get

\[
\text{Rb}_{L}^{87}/\text{Sr}_{L}^{86} = (\text{Rb}_{TR}^{87}/\text{Sr}_{TR}^{86}) (1 + Q) - Q(\text{Rb}_{LSR}^{87}/\text{Sr}_{LSR}^{86})
\]

The adoption of this procedure results in two more data points for the regression for each leached sample, one of the points being much closer to, and the other further away from the "origin" than the total rock point. This effectively expands the \(\text{Rb}^{87}/\text{Sr}^{86}\) and \(\text{Sr}^{87}/\text{Sr}^{86}\) range of the samples and, assuming no chemical or geological effects, substantially reduces the ultimate confidence limits. This procedure is analogous to the
<table>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>5244A TOTAL ROCK</td>
<td>251.6</td>
<td>74.0</td>
<td>9.771</td>
<td>0.9436</td>
<td>0.9416</td>
</tr>
<tr>
<td>5244B TOTAL ROCK</td>
<td>263.1</td>
<td>65.8</td>
<td>10.837</td>
<td>0.9701</td>
<td>0.9701</td>
</tr>
<tr>
<td>5244C TOTAL ROCK</td>
<td>243.7</td>
<td>65.8</td>
<td>10.038</td>
<td>0.9517</td>
<td></td>
</tr>
<tr>
<td>5244E TOTAL ROCK</td>
<td>287.1</td>
<td>73.5</td>
<td>11.226</td>
<td>0.9769</td>
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</tr>
<tr>
<td>5244F TOTAL ROCK</td>
<td>269.3</td>
<td>73.1</td>
<td>10.595</td>
<td>0.9723</td>
<td></td>
</tr>
<tr>
<td>5244A LEACH SOLID R</td>
<td>243.6</td>
<td>68.8</td>
<td>10.186</td>
<td>0.9544</td>
<td></td>
</tr>
<tr>
<td>5244E LEACH SOLID R</td>
<td>279.3</td>
<td>68.8</td>
<td>11.668</td>
<td>0.9877</td>
<td></td>
</tr>
<tr>
<td>5244A LEACH</td>
<td></td>
<td></td>
<td>4.288</td>
<td>0.8029</td>
<td>0.8009</td>
</tr>
<tr>
<td>5244E LEACH</td>
<td></td>
<td></td>
<td>4.592</td>
<td>0.8184</td>
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</tbody>
</table>
FIGURE 17.
use of both total rocks and minerals in age determinations of igneous rocks.

The analytical data for these samples from the Wyndham Shale are listed in Table 20 and plotted on an isochron diagram in fig. 17.

Discussion

Firstly consider the total rock samples alone. A "two error" regression of the data for 5244 A, B, D, and E, results in a Model I isochron (MSWD = 2.83) having an apparent age of 1722 ± 371 m.y. and an initial Sr$_{87}$/Sr$_{86}$ of 0.7064 ± 0.0125. On the basis of the known geology and the age of the Kimberley Group (previously discussed), this apparent age should be regarded as a minimum estimate of the age of deposition of the Wyndham Shale. Further evidence to support this assumption can be gained from a consideration of the regression. Homogenization of the initial Sr$_{87}$/Sr$_{86}$ values of the samples has apparently taken place and this must be a post-depositional event (unless the Sr$_{87}$/Sr$_{86}$ composition of each layer on the shale was identical at the time of deposition) which, as will be suggested for other suites of samples, is most probably associated with diagenesis.

The presence of the 2M$_1$ mica polymorph is indicative of post-depositional crystallochemical reordering which Yoder (1959) believes to obtain in the progressive
metamorphism of materials of the requisite composition in a sediment, initiated perhaps in the earliest stages of diagenesis. This suggests that the uniformity in initial $\text{Sr}^{87}/\text{Sr}^{86}$ of these samples could be the result of a low-grade metamorphic event.

The other total rock sample 5244 F does not fit this regression and is regarded as an inhomogeneous member of the suite with a higher initial $\text{Sr}^{87}/\text{Sr}^{86}$ value. It would be represented by an isochron through its data point with a slope proportional to the common age as there is no reason to suggest that all samples are not coeval.

Inclusion of the data for the leach and LSR portions of samples 5244 A and B in the total rock regression results in a Model III (MSWD = 7.69) isochron with an apparent age of $1789 \pm 58$ m.y. and initial $\text{Sr}^{87}/\text{Sr}^{86}$ of $0.6963 \pm 0.0074$. These values are not significantly different to those obtained from the total rock regression and the process of leaching has effectively reduced the confidence limits.

The apparent age of $1789 \pm 58$ m.y. is more acceptable as an estimate of the time of deposition of the Bastion Group. Since the minimum age of the Kimberley Group is 1800 m.y., the expected age of the Bastion Group could be of the order of 1790 m.y. However, in view of the suggestion made later that the differentiation of the
Hart Dolerite infers a reasonable amount of overburden, and the mineralogical and isotopic information presented earlier, this apparent age given by the Wyndham Shale must still be regarded as a minimum estimate of the time of deposition.

**CROWHURST GROUP**

The Crowhurst Group conformably overlies the Kimberley Group in the Mt. Ramsay sheet area of the East Kimberleys, and is unconformably overlain by the Colombo Sandstone and rocks of the Louisa Downs Group. The base of the sequence has been selected at a lithological change similar to that marking the base of the Bastion Group (Dow et al. 1964) in the hope that the two boundaries may be isochronous (Roberts et al. 1965).

The maximum preserved thickness of the Group is of the order of 475 feet of which 150 feet is represented by the Liga Shale consisting of green fissile shale with minor interbeds of green micaceous siltstone and very fine-grained micaceous silty sandstone. Lateral variation in the lithology is not seen.

Exposures are poor since the unit erodes readily, and the Shale has been visibly affected by folding and faulting. A.R. Turner of Australian Mineral Development Laboratories describes (in Roberts et al. 1965, p.70) a thin section of a typical shale sample as consisting
<table>
<thead>
<tr>
<th>G.A. SAMPLE NO.</th>
<th>RB PPM</th>
<th>SR PPM</th>
<th>RB87/SR86</th>
<th>SR87/SR86</th>
<th>MEAS.</th>
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<tr>
<td>5109A TOTAL ROCK</td>
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<td>9.8</td>
<td>81.916</td>
<td>1.7233</td>
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<tr>
<td>5109B TOTAL ROCK</td>
<td>275.3</td>
<td>13.2</td>
<td>60.138</td>
<td>1.5337</td>
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</tr>
<tr>
<td>5109C TOTAL ROCK</td>
<td>254.4</td>
<td>11.6</td>
<td>63.275</td>
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<tr>
<td>5109D TOTAL ROCK</td>
<td>283.6</td>
<td>10.6</td>
<td>76.992</td>
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<tr>
<td>5109E TOTAL ROCK</td>
<td>262.8</td>
<td>17.4</td>
<td>43.513</td>
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<tr>
<td>5110F TOTAL ROCK</td>
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<td>16.7</td>
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<tr>
<td>5110G TOTAL ROCK</td>
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<td>5120A TOTAL ROCK</td>
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<td>19.0</td>
<td>40.541</td>
<td>1.5010</td>
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</tr>
<tr>
<td>5120B TOTAL ROCK</td>
<td>268.9</td>
<td>19.0</td>
<td>40.695</td>
<td>1.5046</td>
<td></td>
</tr>
</tbody>
</table>
FIGURE 18.
of "numerous angular to subangular quartz grains which have a size distribution in the range 0.04 to 0.02 mm. set in a recrystallized argillaceous matrix. The quartz has been recrystallized and many of the grains are elongated parallel to the laminations. The argillaceous matrix has been recrystallized to form muscovite, sericite, and chlorite. These minerals have a marked sub-parallel orientation and impart the fissility or incipient schistosity to the rock. The laminated texture is formed by alternate relatively high and relatively low concentration of finely disseminated iron oxide. In some layers the iron forms aggregates but in others only stains the individual mica laths."

A total of nine samples have been collected from two sampling sites; seven samples come from exposures in the Crowhurst Gorge (5109 and 5110) and two from a site south of the reference area (5120). All have been analysed for Rb and Sr by isotope dilution methods and the analytical results are listed in Table 21. Fig. 18 shows this data plotted on an isochron diagram.

Discussion

Data plotted on the isochron diagram (fig. 18) show a very wide scatter and quite a number of interpretations are possible. However none do much towards assessing the absolute age of the deposits.
The maximum apparent age is given by the data from 5120 A and B. Assuming the minimum initial $\text{Sr}^{87}/\text{Sr}^{86}$ value of 0.7057 (sea-water strontium - Hamilton (1966), data renormalized to $\text{Sr}^{87}/\text{Sr}^{86} = 8.3400$), the apparent age is 1397 m.y. A more predictable value for the initial $\text{Sr}^{87}/\text{Sr}^{86}$ would be about 0.72 (based on a consideration of the likely source of the sedimentary material, i.e., the Lamboo Complex) and this gives a maximum apparent age of 1373 m.y. It will be noted that samples 5120 come from a sampling site removed from the main group of samples and that they show little variation in Rb or Sr content. This could be interpreted as a complete homogenization during some event, but cannot be proved because of lack of evidence.

The maximum apparent age, although being of the right order, is still regarded by field geologists as being too young for the age of deposition of the formation.

Samples 5109 and 5110 come from the same sampling area and could be expected to reflect equally any event which may have affected the rocks of the area. It is obvious however, that homogenization (in terms of the "initial" $\text{Sr}^{87}/\text{Sr}^{86}$ between samples) has not occurred. The maximum apparent age of this particular suite is given by the isochron through samples 5110 F and 5109 E which has a value of 1061 m.y. and an initial $\text{Sr}^{87}/\text{Sr}^{86}$
of 0.7880. Data points 5109 D, B, and 5110 G define a Model I (MSWD = 0.04) isochron with an apparent age of 917 m.y. and an initial \( \text{Sr}^{87}/\text{Sr}^{86} \) of 0.7629. Similarly the join of 5109 A and C has an apparent age of 809 m.y. with initial \( \text{Sr}^{87}/\text{Sr}^{86} \) of 0.7966. Other alignments of data points are also possible.

Such a range of apparent ages is meaningless in terms of post-depositional history, rates of deposition, or geological events, and therefore the data should be reassessed to see if the samples, or the majority of samples, reflect some common period of equilibration. Suggested alignments of data points are 5120 A, B, 5110 F, 5109 A, and 5109 B, 5110 G, 5109 B. The first grouping results in a Model I isochron (MSWD = 1.84) with an apparent age of 384 ± 20 m.y. and an initial \( \text{Sr}^{87}/\text{Sr}^{86} \) of 1.2865 ± 0.0137. The second grouping defines a Model II isochron having an apparent age of 415 m.y. and an initial \( \text{Sr}^{87}/\text{Sr}^{86} \) of 1.1830.

The fact that both groupings result in approximately the same apparent ages must have some significance and could well show the response of this suite of samples to a Palaeozoic event. If this were so then 5109 D and 5109 C could be represented by isochrons through each individual point with slope proportional to something between 383 and 415 m.y. Some support for such an event
is given by the evidence of alteration and recrystallization seen in a thin section of a typical shale from this formation.

If none of the above interpretations are valid then the configuration of data points must be regarded as the variable response of independent samples to one or more events which have not been sufficiently active or long-lived to bring about $\text{Sr}^{87}/\text{Sr}^{86}$ homogenization between the samples. On the other hand the configuration could be regarded as representing marked primary variation in the initial $\text{Sr}^{87}/\text{Sr}^{86}$ of the samples which have been derived from various sources having markedly different $\text{Sr}^{87}/\text{Sr}^{86}$ values.

WADE CREEK SANDSTONE

The Mt. John Shale is a prominent Member of the Wade Creek Sandstone and in the reference area consists of 270 feet of laminated and thin-bedded black and grey shale containing interbeds of cherty siltstone. To the north, in the sample area, 450 feet of laminated and thin-bedded khaki-green and olive-green shale is preserved. The sequence here is usually silty and sometimes appears "glauconitic", always indurated, and minor fracture cleavage is the only apparent deformation. The shales are interbedded with micaceous silts and sands, and the sequence is overlain and underlain by quartz sandstone.
<table>
<thead>
<tr>
<th>G.A. SAMPLE NO.</th>
<th>RB PPM</th>
<th>SR PPM</th>
<th>RB87/SR86</th>
<th>SR87/SR86</th>
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<tr>
<td>5071B TOTAL ROCK</td>
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<td>70.8</td>
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<td>0.7836</td>
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</tr>
<tr>
<td>5072D TOTAL ROCK</td>
<td>62.5</td>
<td>123.4</td>
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<td>0.7347</td>
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</tr>
<tr>
<td>5072E TOTAL ROCK</td>
<td>36.1</td>
<td>205.3</td>
<td>0.505</td>
<td>0.7203</td>
<td></td>
</tr>
</tbody>
</table>
Mt. JOHN SHALE

FIGURE 19.
Samples were taken from a 100 feet cliff face where all deeply weathered material has been removed by seasonal rainstorms. A total of five samples were selected from the finest grained, least fractured, non-micaceous beds. Samples 5071 A, B, and C come from the basal, middle, and upper sections respectively of the cliff face. Capping the face and underlying the overlying sandstone is a narrow unit of thin-bedded very fine-grained, light grey shale containing some mica. Samples 5072 D and E were collected from the bottom and top (respectively) of the non-micaceous beds of this latter unit.

The mica within the shale beds is very fine-grained sericite or muscovite and there is every reason to believe that it has formed in situ by autometamorphic processes during diagenesis. However, since there is no certainty as to its origin, obviously micaceous shales were avoided in the collection in case the mica was of detrital origin.

Four of the five samples were selected for age determination after preliminary Rb-Sr X-ray fluorescence data had been obtained. The results of the Rb-Sr isotope dilution analyses are given in Table 22 and plotted on an isochron diagram in fig. 19. The indicated age at the 95% confidence level based on the statistical methods of McIntyre et al. (1966) is $1128 \pm 110$ m.y. with an initial Sr$^{87}$/Sr$^{86}$ ratio of $0.7121 \pm 0.0051$. 
Discussion

The mean square of weighted deviates of the four samples is 0.83 and all fit a Model I "two error" regression analysis. All error can therefore be attributed to experimental measurements and the samples fit a geological model of equal age, equal initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio, and chemical closure. The rather large plus and minus on the indicated age is the result of two factors:

1) the rather narrow range in $\text{Rb}^{87}/\text{Sr}^{86}$ exhibited by the suite (the range only being from about 0.5 to 5.0), and

2) the small number of samples and resultant high $t$ value.

Where a narrow range in $\text{Rb}^{87}/\text{Sr}^{86}$ exists, regardless of the absolute values, the S.E. (standard error) of the slope of the line is increased, and since the plus and minus is given by $t \times \text{S.E.}$, both factors have great influence. The plus and minus of the indicated initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio is similarly controlled by these factors.

Assuming the same S.E., one more sample would reduce the age limits to $\pm 81$ m.y. and the limits of the initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio to $\pm 0.0038$.

The apparent age is the age of homogenization (in terms of initial $\text{Sr}^{87}/\text{Sr}^{86}$ values) and chemical closure
of the samples, and this is considered to be close to or coincident with the time of deposition and diagenesis of the sediments although the stratigraphic control on the limits of time of deposition is very poor. Estimates of time based on the thicknesses of sediments do not give conclusive results. Variability of rates of deposition are indicated by the distinct and sudden changes in lithology. At least 16,000 feet of sediment are present between the Wade Creek Sandstone and the basement Lamboo Complex with at least three major periods of unconformity and one period of intrusion separating the units. About 500 feet of sediment and one unconformity separate the Sandstone from the younger Duerdin Group. Estimates of depositional rates based on figures given by Ninkovich et al. (1966) show that a discrepancy exists between the expected and actual time periods, and if the calculations are significant, the period of time represented by the unconformities must be of the order of 800 m.y.

A more complete discussion dealing with the significance of age determinations from shale material will appear in a later section, but some points will be mentioned here in regard to these rocks.

If the apparent age is not the age of deposition then the more usual conclusion is that it is greater than the depositional age, i.e., the rocks were deposited less than
1128 ± 110 m.y. ago. Since shales (and indeed most sedimentary rocks) are formed from the breakdown material of older pre-existing rocks it might be expected that some remnant or memory "age" relating to the source would remain with the breakdown products during transportation, sedimentation, and subsequent diagenesis. Whitney and Hurley (1964) have discussed this problem and conclude that ages obtained from shale samples must necessarily be regarded as maxima. Their conclusions are supported by the earlier work of Hurley et al. (1963) who obtained K-Ar "ages" from Recent deep-sea sediments which were compatible with the ages of older rocks in adjacent continental areas.

Samples of sedimentary material collected through a stratigraphic sequence represent both transgression of time and variability in source material, both the proportionate contribution of various units within a particular source area and also the proportionate contribution of a particular breakdown product from one single unit. Therefore variation in the value of the initial Sr$^{87}$/Sr$^{86}$ ratio is expected at different levels throughout the sedimentary sequence.

However, this is not considered to be the case in this particular instance. Since the "two error" regression of the analyses results in a Model I fit, the a priori assumption of equal initial Sr$^{87}$/Sr$^{86}$ ratios and chemical
closure of all samples is confirmed.

For a Model I fit to be applicable to a suite of samples, uniformity in the initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio must take place and this is either a primary feature reflecting homogeneity in the source area or it occurs during diagenesis or later metamorphism. With complete homogenization "memory ages" will be obliterated, and homogenization most probably takes place during diagenesis, a post-weathering, post-depositional event. As with the Bastion Group, the presence of the $2M_1^-$ mica polymorph within the Mt. John sequence supports this conclusion.

The $1128 \pm 110$ m.y. is therefore regarded as the minimum age of deposition of the Shale. Consideration of the relative amounts of sediment (and the number and degree of unconformities) representing a known interval of time suggests that the apparent age lies close to the expected value of the age of deposition. There is every likelihood then that the period of time between deposition and diagenesis was relatively short and that $1128 \pm 110$ m.y. can be regarded as the age of the Mt. John Shale.

The apparently high initial $\text{Sr}^{87}/\text{Sr}^{86}$ value of $0.7121 \pm 0.0051$ will be discussed in a later section. Here it is sufficient to say that it can be adequately explained in terms of the source area material without the necessity of recourse to metamorphic or like events.
GLIDDEN GROUP

The Glidden Group crops out in the Mt. Ramsay sheet area of the East Kimberley Region and has a total exposed thickness of about 1850 feet. Two sandstone units make up about 420 feet of the Group, the remaining 1430 feet being predominantly siltstone, claystone, and shale sequences of the Matheson and Maddox Formations. In terms of relative thicknesses of successions this Group is thin compared to others (e.g., Carr Boyd Group of 30,000 feet; Kimberley Group approximately 9,000 feet; etc.) and probably transgresses a much shorter time period. All units within the Group are conformable and only 200 feet of massive, well-sorted, fine-grained quartz sandstone separate the Matheson and Maddox Formations. On these bases the two Formations have been considered as one entity for the purpose of age determination. The analytical results support the assumption that this grouping is valid.

The stratigraphic relationship of the Group to other sequences in the area is rather vague. The Group unconformably overlies Carson Volcanics of the Kimberley Group. Roberts et al. (1965) infer that the unit post-dates the Crowhurst Group and that profound erosion of the Kimberley and Crowhurst Groups took place before the deposition of the Glidden Group. In places the succession rests directly on rocks of the Halls Creek Group and the Lamboo Complex.
<table>
<thead>
<tr>
<th>G.A. SAMPLE NO.</th>
<th>RB PPM</th>
<th>SR PPM</th>
<th>RB87/SR86</th>
<th>SR87/SR86</th>
<th>CALC.</th>
<th>MEAS.</th>
</tr>
</thead>
<tbody>
<tr>
<td>5094A TOTAL ROCK</td>
<td>226.1</td>
<td>47.6</td>
<td>13.666</td>
<td>0.9197</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5094B TOTAL ROCK</td>
<td>242.0</td>
<td>44.6</td>
<td>15.587</td>
<td>0.9548</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5094C TOTAL ROCK</td>
<td>251.2</td>
<td>44.2</td>
<td>16.328</td>
<td>0.9644</td>
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<td></td>
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<tr>
<td>5094D TOTAL ROCK</td>
<td>237.8</td>
<td>47.3</td>
<td>14.455</td>
<td>0.9234</td>
<td></td>
<td>0.9233</td>
</tr>
<tr>
<td>5094E TOTAL ROCK</td>
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<td>40.1</td>
<td>16.436</td>
<td>0.9468</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5113A TOTAL ROCK</td>
<td>65.6</td>
<td>43.8</td>
<td>4.309</td>
<td>0.7831</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5113C TOTAL ROCK</td>
<td>76.5</td>
<td>127.1</td>
<td>1.729</td>
<td>0.7541</td>
<td></td>
<td>0.7538</td>
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<tr>
<td>5113E TOTAL ROCK</td>
<td>97.9</td>
<td>15.3</td>
<td>18.462</td>
<td>0.9949</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5113F TOTAL ROCK</td>
<td>214.6</td>
<td>39.5</td>
<td>15.598</td>
<td>0.8971</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
MATHESON and MADDOX FORMATIONS
SHALES

FIGURE 20.
FIGURE 21.
The lowermost unit of the Louisa Downs Group unconformably overlies the Glidden Group and the relationship of this latter Group with the Kuniandi Group cannot be demonstrated. However, Roberts et al. (1965) consider that the contrasting lithologies of the Glidden and Kuniandi Groups prove non-contemporaneity and that the absence of glacigene strata in the Glidden Group lends weight to their assumption that the Glidden Group pre-dates the Kuniandi Group. Dow and Gemüts (in prep.) support this assumption to some degree by pointing out a stratigraphic correlation which may exist between the Glidden Group and the Wade Creek Sandstone.

Of the samples collected a total of 9 were selected for Rb-Sr isotope dilution analyses; 4 from the Maddox Formation (5113), and 5 from the Matheson Formation (5094). Analytical results are listed in Table 23 and plotted on isochron diagrams in figs. 20 and 21.

Discussion

Inspection of fig. 20 shows that the data points are quite widely scattered, but that this scattering is not correlated with the Formation from which the various samples were obtained. However an alignment of data points does exist between samples 5113 A, C, and E, and 5094 A, B, and C. Regression analyses of these data (MSWD = 10.33) results in a Model III isochron having an
apparent age of $1042 \pm 51$ m.y. and an initial $\text{Sr}^{87}/\text{Sr}^{86}$ of $0.7246 \pm 0.0092$; variability of the initial $\text{Sr}^{87}/\text{Sr}^{86}$ between samples is indicated.

Deletion of samples 5113 A and 5094 A from the regression substantially reduces the MSWD to 0.17 and results in a Model I isochron with an apparent age of $1031 \pm 23$ m.y. and an initial $\text{Sr}^{87}/\text{Sr}^{86}$ of $0.7288 \pm 0.0024$ (fig. 21). Data from samples 5113 C, E, and 5094 B, C, lie well within experimental error and represent both the Formations. This isochron confirms the validity of considering both Formations as a single unit, and further suggests that both sets of samples have a similar source area.

Uniformity of the initial $\text{Sr}^{87}/\text{Sr}^{86}$ values between samples is apparent and, as with the other successions already discussed, this is considered to be in part a post-depositional effect consistent with diagenesis, which is supported by the presence of the $2M_1$ mica polymorph. The apparent age of $1031 \pm 23$ m.y. then represents the minimum age of deposition of these sediments.

The fact that uniformity of the initial $\text{Sr}^{87}/\text{Sr}^{86}$ occurs does not necessarily mean that homogenization has taken place between the Formations. In fact it is inconceivable to think in terms of the diffusion of $\text{Sr}^{87}$ across a 200 feet quartz-sandstone division. An event capable of such large scale transfer would be expected
to leave some mark on the rocks of the Formations but there is no evidence of any such event. The most logical explanation is that both Formations were derived from the same, or similar, source areas with the result that the "average" $\text{Sr}^{87}/\text{Sr}^{86}$ values were virtually the same at the time of homogenization.

Since the MSWD can be significantly reduced by the deletion of samples 5113 A and 5094 A from the regression this data must be considered in some other context.

Consider firstly samples 5094 A, D, E, and 5113 A. Two possible interpretations of the analytical data can be suggested. In the first instance they may represent a non-homogeneous (in terms of the initial $\text{Sr}^{87}/\text{Sr}^{86}$) suite of samples which would be represented on the diagram by isochrons having slopes proportional to 1031 m.y. drawn through each separate point. Secondly, the samples may have been open chemical systems during some post-depositional period. As for sample 5113 F, only one interpretation is possible and that is that the sample has been a post-depositional open chemical system. An isochron with slope proportional to 1031 m.y. drawn through this data point results in an impossibly low initial $\text{Sr}^{87}/\text{Sr}^{86}$ value.

The concept of inhomogeneity of initial $\text{Sr}^{87}/\text{Sr}^{86}$ is more than possible but not enough evidence is available to substantiate it. The evidence of 5113 F indicates that
these samples may have most logically been open chemical systems and responded to a similar event.

An isochron through the data points for samples 5094 A, D, and E, has an apparent age of 732 m.y. with an initial \( ^{87}\text{Sr} / ^{86}\text{Sr} \) of 0.7780. Similarly an isochron defined by samples 5113 and F has an apparent age of 723 m.y. and initial \( ^{87}\text{Sr} / ^{86}\text{Sr} \) of 0.7396. The similarity in these two apparent ages is unlikely to be pure coincidence and it is suggested that these samples have responded to a late Precambrian event which caused redistribution of radiogenic Sr and rehomogenization of the \( ^{87}\text{Sr} / ^{86}\text{Sr} \) in selected sections of the two Formations.

**CARR BOYD GROUP**

The Group consists of six Formations with regional unconformities separating all but two of them. The unconformities have been brought about by movement along major faults of the Halls Creek Mobile Zone during sedimentation, and locally up to 1,000 feet of sediment has been eroded. The Group unconformably overlies Whitewater Volcanics, Halls Creek Group, and Lamboo Complex rocks. It is itself unconformably overlain by Palaeozoic rocks within the Mobile Zone and rocks of the Duerdin Group east of the Halls Creek Fault; the Mt. Parker Sandstone is also reported to overlie the Carr Boyd Group in this area. Stratigraphic control on the age of the Group is poor and the minimum period of time
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>5245B TOTAL ROCK</td>
<td>247.1</td>
<td>44.5</td>
<td>16.429</td>
<td>0.9888</td>
<td></td>
</tr>
<tr>
<td>5245D TOTAL ROCK</td>
<td>266.3</td>
<td>48.3</td>
<td>16.312</td>
<td>0.9887</td>
<td></td>
</tr>
<tr>
<td>5245E TOTAL ROCK</td>
<td>168.9</td>
<td>34.4</td>
<td>14.491</td>
<td>0.9619</td>
<td></td>
</tr>
<tr>
<td>5245F TOTAL ROCK</td>
<td>187.2</td>
<td>36.6</td>
<td>15.065</td>
<td>0.9663</td>
<td></td>
</tr>
<tr>
<td>5245J TOTAL ROCK</td>
<td>233.7</td>
<td>35.1</td>
<td>19.793</td>
<td>1.0492</td>
<td></td>
</tr>
<tr>
<td>5245I TOTAL ROCK</td>
<td>195.0</td>
<td>40.0</td>
<td>14.362</td>
<td>0.9593</td>
<td></td>
</tr>
</tbody>
</table>
FIGURE 22.

GOLDEN GATE SILTSTONE

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

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

$1182 \pm 89$ m.y.
between the overlying and underlying units is of the order of 1,100 m.y. The maximum thickness of the Group is 30,000 feet.

Collections of samples have been made from the Golden Gate Siltstone, Glenhill Formation, and Pincombe Formation which are predominantly interbedded siltstone, shale, and minor sandstone units. However, in the Pincombe Formation shale is minor and normally micaceous, and massive quartz sandstone is the most prominent rock. Only the finest-grained, least altered beds were sampled.

A total of 27 samples were collected and after preliminary X-ray fluorescence data had been obtained, 20 were selected for Rb-Sr isotope dilution analyses. Six samples come from the Golden Gate Siltstone (5245), 6 from the Glenhill Formation (5236), and 8 from the Pincombe Formation (5246, 5247).

Data for each group of samples is given in Tables 24, 25, 26 and plotted on isochron diagrams in figs. 22, 23, 24.

(1) Golden Gate Siltstone

The six samples define a Model I isochron (MSWD = 2.10 which is not significant for four DF) having an apparent age of $1182 \pm 89$ m.y. and an initial $\text{Sr}^{87}/\text{Sr}^{86}$ of $0.7193 \pm 0.0197$ at the 95% confidence level.

If it is assumed that a MSWD = 2.10 is significant, regression of the data results in a Model III isochron
having an apparent age of 1184 ± 123 m.y. and initial Sr\(^{87}/Sr^{86}\) of 0.7188 ± 0.0276. The results of the two Models are virtually identical.

The uncertainty in both the age and the initial Sr\(^{87}/Sr^{86}\) ratio is high but more or less to be expected from shale material. The uncertainty is contributed to by a) the small variation in the Rb\(^{87}/Sr^{86}\) of the samples with the result that all samples lie close to the mean point of the isochron, and b) the uncertainty in the initial Sr\(^{87}/Sr^{86}\) is further increased by the probable variability in the content of inherited radiogenic Sr in each sample.

As previously stated, the stratigraphic control on the predicted age of the formation is poor, and the apparent age of the isochron must be interpreted on the basis of the experimental results alone. The reasons for concluding that the apparent age of the Mt. John Shale represents the age of diagenesis apply equally well to the Golden Gate Siltstone. The value of 1184 ± 123 m.y. (taking the most conservative estimate of the confidence limits) must therefore be regarded as a minimum age for the deposition of the Siltstone.

(2) **Glenhill Formation**

Two distinctly separate isochrons are defined by the six samples of the Glenhill Formation. Two duplicated analyses define one line (4 points) and one duplicate and three single analyses (5 points) define the other.
<table>
<thead>
<tr>
<th>Sample No.</th>
<th>RB PPM</th>
<th>SR PPM</th>
<th>$\text{Rb}<em>{87}/\text{Sr}</em>{86}$</th>
<th>$\text{Sr}<em>{87}/\text{Sr}</em>{86}$</th>
<th>$\text{Rb}<em>{87}/\text{Sr}</em>{86}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5236A TOTAL ROCK-A</td>
<td>131.5</td>
<td>26.9</td>
<td>14.444</td>
<td>0.9699</td>
<td>0.9475</td>
</tr>
<tr>
<td>5236A TOTAL ROCK-B</td>
<td>130.9</td>
<td>27.0</td>
<td>13.916</td>
<td>0.9383</td>
<td></td>
</tr>
<tr>
<td>5236B TOTAL ROCK</td>
<td>98.5</td>
<td>25.7</td>
<td>11.200</td>
<td>0.8698</td>
<td></td>
</tr>
<tr>
<td>5236C TOTAL ROCK</td>
<td>150.5</td>
<td>122.2</td>
<td>3.549</td>
<td>0.7597</td>
<td></td>
</tr>
<tr>
<td>5236D TOTAL ROCK-A</td>
<td>70.9</td>
<td>9.2</td>
<td>23.126</td>
<td>1.1783</td>
<td></td>
</tr>
<tr>
<td>5236D TOTAL ROCK-C</td>
<td>70.5</td>
<td>9.0</td>
<td>22.415</td>
<td>0.9906</td>
<td></td>
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<tr>
<td>5236E TOTAL ROCK-A</td>
<td>104.7</td>
<td>23.7</td>
<td>12.976</td>
<td>0.9040</td>
<td></td>
</tr>
<tr>
<td>5236E TOTAL ROCK-B</td>
<td>103.7</td>
<td>21.4</td>
<td>13.942</td>
<td>0.9197</td>
<td></td>
</tr>
<tr>
<td>5236H TOTAL ROCK</td>
<td>127.9</td>
<td>57.5</td>
<td>6.461</td>
<td>0.8079</td>
<td>0.8064</td>
</tr>
</tbody>
</table>
Normally it is invalid to consider duplicate analyses as separate entities in a regression analysis. In this instance however their inclusion can be justified. A glance at Table 25 and fig. 23 will show that "error" in these duplicates lies well outside the limits of experimental variation and that the plot of each lies on the isochron predicted by previous analyses. What is being dealt with here is a sampling problem where homogeneity of the crushed rock sample has not been achieved. Since these shales were prepared in precisely the same way as all other samples (samples which have not shown this effect) no reason can be given for the appearance of this problem. The only known way in which the shales from this Formation (and from other formations in the Group) differed from sedimentary samples in other parts of the Kimberley area was in their excessively high zirconium content (greater than 200 p.p.m.). While this factor caused some inconvenience during the chemical preparation of the samples there is no reason to suspect that it could be responsible for the apparent error in sampling.

Four of the samples (one in duplicate) define a Model II isochron with an apparent age of 1080 ± 80 m.y. and an initial $\text{Sr}^{87}/\text{Sr}^{86}$ of 0.7064 ± 0.0072 at the 95% confidence level. The MSWD of the Model I regression is 9.29.
The MSWD can be substantially reduced by deletion of 5236 B data. With three samples (2 degrees of freedom) the MSWD is reduced to 2.74 and a Model I isochron is appropriate with an apparent age of 1100 ± 40 m.y. and an initial Sr\textsuperscript{87}/Sr\textsuperscript{86} of 0.7056 ± 0.0036.

Addition of data from one more sample (5236 B) substantially increases the MSWD and results in a Model II isochron. The inference here is that redistribution of material at an isotopic or elemental level has occurred through the suite of samples. Knowing that this is unlikely to have occurred in three of the samples (because of the Model I isochron), 5236 B can now be singled out as the most logical example of an open chemical system.

For these reasons it would be valid to accept the older age of 1100 m.y. with the lower confidence limits of ± 40 m.y. as the apparent age of this suite, but erring on the side of caution the less precise value of 1080 ± 80 m.y. is accepted as the apparent age of the samples.

This apparent age, as with the age of the Golden Gate Siltstone, is considered to be a minimum estimate for the time of deposition of the Glenhill Formation.

Two other duplicated samples define a Model III isochron (2 degrees of freedom) with an apparent age of 417 ± 111 m.y. and an initial Sr\textsuperscript{87}/Sr\textsuperscript{86} of 0.8605 ± 0.0292; variability in the initial Sr\textsuperscript{87}/Sr\textsuperscript{86} between samples is indicated.
This interpretation of the data is not necessarily valid since sample 5236 A could be defined equally well by an isochron with a slope proportional to 1080 m.y. and an apparent initial $\text{Sr}^{87}/\text{Sr}^{86}$ value of approximately 0.728.

The latter interpretation is by far the simpler and does not need to invoke movement of elements and isotopes to explain the data points. If sample 5236 A had been an open chemical system then addition of radiogenic Sr, loss of Rb, or a combined loss of Rb and radiogenic Sr is necessary to explain the analytical results. While it is recognised that such elemental and isotopic dispersion does take place under certain circumstances it is not considered to be likely in this particular instance. Even though duplication of analyses of the sample are widely different, homogenization of the initial $\text{Sr}^{87}/\text{Sr}^{86}$ has apparently occurred and the duplicates plot on an isochron paralleling the 1080 m.y. isochron.

Sample 5236 D has obviously been an open chemical system since an isochron drawn through either of the points with slope equivalent to 1080 m.y. gives a ridiculously low intercept on the $\text{Sr}^{87}/\text{Sr}^{86}$ axis. $\text{Sr}^{87}/\text{Sr}^{86}$ homogenization of an inhomogeneous sample, with or without the loss of radiogenic Sr, is the simplest explanation of the configuration. The apparent age of the duplicate samples is 464 m.y. with an initial $\text{Sr}^{87}/\text{Sr}^{86}$ of 0.8456.
<table>
<thead>
<tr>
<th>G.A. SAMPLE NO.</th>
<th>RB PPM</th>
<th>SR PPM</th>
<th>R887/SR86</th>
<th>SR87/SR86</th>
<th>CALC.</th>
<th>MEAS.</th>
</tr>
</thead>
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<tr>
<td>5247A TOTAL ROCK</td>
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<td>101.9</td>
<td>3.954</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5247B TOTAL ROCK-A</td>
<td>216.2</td>
<td>137.0</td>
<td>4.535</td>
<td>0.8591</td>
<td>0.7953</td>
<td></td>
</tr>
<tr>
<td>5247B TOTAL ROCK-C</td>
<td>217.8</td>
<td>126.7</td>
<td>4.944</td>
<td>0.7954</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5247B TOTAL ROCK-D</td>
<td>216.8</td>
<td>125.3</td>
<td>4.974</td>
<td>0.7966</td>
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<tr>
<td>5247C TOTAL ROCK</td>
<td>222.4</td>
<td>107.6</td>
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<td>0.7974</td>
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<tr>
<td>5247D TOTAL ROCK-A</td>
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<td>0.8013</td>
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<tr>
<td>5247D TOTAL ROCK-C</td>
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<td>100.9</td>
<td>6.085</td>
<td>0.8014</td>
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<tr>
<td>5247E TOTAL ROCK-A</td>
<td>237.7</td>
<td>125.3</td>
<td>5.454</td>
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<tr>
<td>5247E TOTAL ROCK-C</td>
<td>231.2</td>
<td>122.1</td>
<td>5.443</td>
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<td></td>
</tr>
<tr>
<td>5247F TOTAL ROCK</td>
<td>102.9</td>
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<td></td>
</tr>
<tr>
<td>5246A TOTAL ROCK</td>
<td>161.1</td>
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<tr>
<td>5246B TOTAL ROCK</td>
<td>126.4</td>
<td>53.1</td>
<td>6.844</td>
<td>0.8198</td>
<td>0.8187</td>
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</tbody>
</table>
FIGURE 24

PINCOMBE FORMATION

$\frac{Rb^{87}}{Sr^{86}}$ vs $\frac{Sr^{87}}{Sr^{86}}$

$872 \pm 123$ m.y.

$911 \pm 149$ m.y.
Regardless of which interpretation is accepted it is apparent that at least one or possibly both samples reflect a Palaeozoic event.

(3) Pincombe Formation

The eight samples of shale from two sampling localities in the Pincombe Formation suggest two lineations. Regression of the data from each of these alignments support the assumption of two distinct isochrons.

Samples 5247 D, C, A, and F, (2 degrees of freedom) define a Model I isochron with a MSWD of 2.54 which is not significant for 2 degrees of freedom. The apparent age is $911 \pm 149$ m.y. with an initial $\text{Sr}^{87}/\text{Sr}^{86}$ of $0.7229 \pm 0.0118$, at the 95% confidence level.

Samples 5247 B, E, and 5246 A, B, define a Model I isochron having a MSWD of 1.95 which is not significant for 2 degrees of freedom. This isochron has an apparent age of $872 \pm 123$ m.y. with an initial $\text{Sr}^{87}/\text{Sr}^{86}$ of $0.7346 \pm 0.0108$, at the 95% confidence level.

The high confidence limits placed on these results are again a function of the small number of samples, the possible variation in initial $\text{Sr}^{87}/\text{Sr}^{86}$, the narrow range in $\text{Rb}^{87}/\text{Sr}^{86}$, and the possibility of there being some open chemical systems.

The slopes of the two isochrons are not significantly different and, based on the assumption that the samples are in fact coeval, the slopes of the isochrons can be
pooled to determine the mean weighted common age.

The pooled slope is 0.012423 with S.E. of 0.000306; the t value for a 95% confidence limit is 2.74. The common age of the samples is then 888 ± 60 m.y.

As with other formations from the Carr Boyd Group, this age is considered to represent the minimum age of deposition of the sediments of the Pincombe Formation.

The assumption of a bimodal distribution of initial $\text{Sr}^{87}/\text{Sr}^{86}$ within the samples has been based entirely on the statistical evidence. However, this assumption can be further justified on "geological grounds". X-ray diffraction analyses of these total rock samples (Appendix D, Table D-1) show that they can be divided into two groups depending on whether or not the samples contain microcline. Furthermore, this division conforms to that already made based on the isotopic data, i.e., those samples without K-feldspar define the lower isochron while those containing this mineral define the upper isochron. Since K-feldspar normally contains appreciable amounts of radiogenic $\text{Sr}^{87}$, this division conforms to the expectation.

**Significance of the Apparent Ages**

It has already been suggested that the apparent ages obtained from the isochrons of each of the three formations represent the minimum age of deposition of the sediments. Furthermore they reflect a time of $\text{Sr}^{87}/\text{Sr}^{86}$ homogenization (to within experimental error) of each suite, and reproduce the order of deposition.
A single event is unlikely to be responsible for the homogenization since redistribution would have to be directly proportional to the age of the samples for the stratigraphic order to be retained; if a single event was responsible then one age would be common to all suites.

The isochron data suggests that three separate events were responsible for this uniformity of initial $\text{Sr}^{87}/\text{Sr}^{86}$ of samples defining each isochron, each event being discrete and peculiar to a particular formation. This being the case the most likely period is during the deposition and diagenesis of each particular formation, a time which is considered to be close to the age of deposition. Assuming the apparent ages represent the age of deposition of each formation, then the Carr Boyd Group and the regional unconformities separating each Formation transgress something like 300 m.y. of time.

**DUBRDIN AND KUNIANDI GROUPS**

**Glacial Rocks**

The Duerdin Group crops out discontinuously east of the Halls Creek Fault and is extensively exposed in the Osmond Range area. The basal units of this Group are of undoubted glacial origin and have been described in detail by Dow (1965) and Dow et al. (1964). Equivalent rocks are included in the Western Succession, and the basal units of the Kuniandi Group contain rocks of glacial origin. There is little doubt that the glacials are stratigraphic
<table>
<thead>
<tr>
<th>GA. SAMPLE NO.</th>
<th>RB PPM</th>
<th>SR PPM</th>
<th>RB87/SR86</th>
<th>SR87/SR86 CALC.</th>
<th>SR87/SR86 MEAS.</th>
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<td>0.7719</td>
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<td>5080B TOTAL ROCK</td>
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<tr>
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<tr>
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<td>5085A TOTAL ROCK</td>
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FIGURE 25.
equivalents and there is every reason to suppose that before deformation and erosion these glacials were much more widespread and probably contiguous, covering much of the Lamboo Complex.

Both Groups lie unconformably on much older material; the Duerdin Group overlies material as old as the Halls Creek Group and as young as the Helicopter Siltstone, and the Kuniandi Group rests on Kimberley Group rocks. Stratigraphic control on the maximum age of the Groups is poor.

Of the many samples of shale collected from the glacial-bearing units, a total of 18 have been selected for Rb-Sr isotope dilution analyses. Seven of the samples are from the Moonlight Valley Tillite of the Duerdin Group, nine from the Landrigan Tillite and two from the Wirara Formation of the Kuniandi Group.

The analytical data for all samples is set out in Table 27 and plotted on an isochron diagram in fig. 25.

Discussion

Fig. 25 shows that there is apparently a wide scatter in the analytical results, which is not directly related to differences in the geographical location of the samples. The discrepancy in one collection site (such as between 5118 and 5119, or 5085 A and 5085 B) is in fact greater than that between the major localities. It is obvious
that there is present here either marked redistribution of elements (i.e., open chemical systems) or marked variations in initial Sr$^{87}$/Sr$^{86}$ values which reflect differences in provenance between samples.

Many interpretations are possible for such a configuration of data points and, based on analytical results alone, any one of these could be correct. The interpretation of these results will therefore have to be based on prior knowledge of the stratigraphy, intuitive assessment of the possible age, and knowledge of the apparent ages of the material stratigraphically related to these glacial deposits.

A maximum possible age to the glaciation is given by the Helicopter Siltstone which unconformably underlies the glacial in the Eastern Succession. The Siltstone conformably overlies the Wade Creek Sandstone in which the Mt. John Shale Member has an age of 1128 m.y. It would be reasonable then to expect the glacial rocks to be something less than 1,000 m.y. old. In fact it would be reasonable to say that the glacial should be younger than the rocks of the Carr Boyd Group (i.e., less than 870 m.y. in age), since no evidence of climatic change indicating the onset of glaciation is present in the sediments of this Group.

In the Duerdin Group, the Ranford Formation which conformably overlies the Moonlight Valley Tillite has an apparent age of 686 m.y. (see later). No similar data is
available for units of the Kuniandi Group, but further to the west the Throssell Shale, overlying glacials of the Mt. House Group, has an apparent age of 685 m.y. (see later). A minimum value for the glaciation period seems to be fairly firmly established.

Interpretations of the analytical data for these glacial sequences must therefore take into account the maximum and minimum limits placed on the period of deposition, i.e., the age should lie between 685 and 870 m.y. Furthermore, since units within the Groups are conformable, the expected age should be close to the minimum value, i.e., close to 685 m.y.

Only one combination of analytical data satisfies these conditions, and that is the combination 5080 A, B, C, D, E, and 5216 B, C, D. A regression of the data for these samples results in a Model III isochron having an apparent age of 739 ± 30 m.y. with an initial Sr\(^{87}/\text{Sr}\(^{86}\) of 0.7331 ± 0.0060. The MSWD is equal to 47.59. Variation in the initial Sr\(^{87}/\text{Sr}\(^{86}\) between samples is indicated by the Model III isochron and obvious from an inspection of the data. Since there is no reason for assuming that the remaining samples have not been closed chemical systems, they would be represented by lines through their data points having slopes proportional to 739 m.y.

In fig. 25 this latter hypothesis has been graphically indicated, and three factors become noticeable. Firstly,
the fact that a single line can represent several points and that the data points are fairly closely grouped about this line; secondly that at least three distinct provenances have contributed to the formation of these glacial shales, and thirdly, the grouping is independent of geographical location.

Complete homogenization of the initial $\text{Sr}^{87}/\text{Sr}^{86}$ has not taken place between samples and is not expected to because of the areal distribution. Even in the one sample locality this has not occurred. Yet all samples apparently have the same age. Furthermore variations in provenance are indicated by the variable initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratios, yet, while their identity has remained, the differences in the ages of the provenances (which might reasonably be expected) have been completely obliterated. Many other examples support this conclusion and will be discussed in more detail later. These observations are considered to be further proof of the hypothesis previously suggested that the apparent ages of shales reflect post-depositional events and the Rb-Sr radiometric ages are therefore minima.

The assumed multimodal distribution of initial $\text{Sr}^{87}/\text{Sr}^{86}$ values within these samples can be supported in part by variations which exist in the mineralogical composition of the various samples. X-ray diffraction analyses of the total rock samples indicate basic differences which
generally conform to the isochron groupings outlined above. However, the divisions are not as clear cut as those of the Pincombe Formation. The diffraction analyses are listed in Table D-2 and their significance discussed in Appendix D.

The age of 739 m.y. which is suggested for the older glacial rocks of the Kimberley Region is acceptable to most geologists and may be favourably compared with apparent ages given for other known Precambrian glacial deposits. In the Adelaide System two widespread Precambrian glaciations are recognised (Thomson, 1966). Isotopic age determinations on shales from the underlying Burra Group (Compston et al., 1966) placed a maximum limit to the age of the glacials of about 800 m.y. The minimum value is given by the Cambrian-Precambrian boundary at about 600 m.y. (Kulp, 1961).

Comparisons may also be made with other Precambrian glacial sequences throughout the world. Harland (1964) states (p.122): "Many geosynclinal successions are known, passing down from fossiliferous Cambrian rocks into thousands of metres of concordant, largely unfossiliferous strata with a pair of tillite horizons a few hundred or thousand of metres beneath proved Cambrian rocks. This double horizon appears to be characteristic and may therefore prove to be of use in correlation." He then described occurrences of glacigene rocks from throughout the world which bear a remarkable similarity to the sequences in the
Kimberley area. In an article published in 1964, Harland and Rudwick consider the majority of the "Infra-Cambrian" glacigene rocks were emplaced 650-700 m.y. ago.

**DUERDIN GROUP**

**Ranford Formation**

The Ranford Formation conformably overlies the Moonlight Valley Tillite, and consists of sandstone, siltstone, and shale. Two Members are recognised within the Formation, the Jarrad Sandstone at the base (210 feet) which is overlain by the Johnny Cake Shale Member, 600 feet of dominantly thin-bedded or laminated shale. The Shale is best developed in the Osmond Range area (which is the type locality) but also appears as poorly exposed outcrops north and south of this main area.

A total of sixteen samples of shale from three widely separated collection areas have been selected from the Formation, the majority coming from the Johnny Cake Shale Member. Samples 5239 and 5062 come from a site in the Albert Edward Range and represent rocks originally mapped by Smith (1963) as the Duerdin Shale. Samples 951, 952, 5070, and 5242 are from the Osmond Range area, and excepting 5242, are from the type locality. Sample 5250 is a single example from the Mt. Brooking area where the Formation is fossiliferous (Dunnet, 1965). Although the areal extent of the samples is large, there is no doubt that the deposits they represent are isochronous, and that
<table>
<thead>
<tr>
<th>G.A. SAMPLE NO.</th>
<th>RB PPM</th>
<th>SR PPM</th>
<th>Rb87/Sr86</th>
<th>Sr87/Sr86</th>
<th>CALC.</th>
<th>MEAS.</th>
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<td>5.080</td>
<td>0.7832</td>
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<td>952 TOTAL ROCK</td>
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<td>4.150</td>
<td>0.7815</td>
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<td></td>
</tr>
<tr>
<td>5070B TOTAL ROCK</td>
<td>200.6</td>
<td>137.4</td>
<td>4.196</td>
<td>0.7867</td>
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<td></td>
</tr>
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<td>8.613</td>
<td>0.8138</td>
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<td></td>
</tr>
<tr>
<td>5239C TOTAL ROCK</td>
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<td>11.096</td>
<td>0.8356</td>
<td>0.8346</td>
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<tr>
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<td>0.8367</td>
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<td>182.5</td>
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<td>12.271</td>
<td>0.8511</td>
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<td>2.039</td>
<td>0.7458</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
RANFORD FORMATION

FIGURE 26.
deposition took place over a relatively restricted period of time.

After preliminary X-ray fluorescence analyses twelve total rocks have been chosen from this collection and isotope dilution analyses carried out. The analytical data for these samples is listed in Table 28 and plotted on an isochron diagram in fig. 26.

Discussion

The data plotted in fig. 26 shows quite a large scatter, but a general trend towards alignment of the data points is also obvious. Further evidence of such a lineation is given by the regression. A "two-error" regression of all data results in a MSWD of 33.69 and a Model III isochron having an apparent age of 695 ± 90 m.y. with an initial Sr$^{87}$/Sr$^{86}$ value of 0.7348 ± 0.0112. Variation in the initial Sr$^{87}$/Sr$^{86}$ between samples is indicated by both the configuration of the data points and the Model III solution to the regression.

Deletion from the regression of the data for those samples which apparently have errors in excess of experimental variation does not alter the apparent isochron or substantially reduce the MSWD. A regression based on eight samples (deletion of 5070 B, 5239 D, C, and 5250) still has a MSWD = 12.49 and a Model III isochron having an apparent age of 698 ± 90 m.y. with an initial Sr$^{87}$/Sr$^{86}$ value of 0.7340 ± 0.0118.
There is one combination of analytical data which will result in a Model I solution. This is the combination 951, 5062 A, 5239 B, and 5239 B. Regression of the data from these samples results in a MSWD of 1.65 and an isochron having an apparent age of $686 \pm 72$ m.y. with an initial $\text{Sr}^{87}/\text{Sr}^{86}$ value of $0.7333 \pm 0.0082$. The result is not significantly different to that obtained from all samples and is independent of variations between collection sites since the two main areas are represented in this regression. It is apparent that these samples are coeval and have remained closed chemical systems.

On the assumption that all systems have a common age and that the analytical data for each has equal significance, then samples whose data does not fit the defined Model I isochron may be represented by isochrons through each individual point with slopes proportional to about 690 m.y.

This is graphically displayed in fig. 26 and it is immediately obvious that a single line can be common to more than one sample. Pooling of the slopes of the three dashed lines results in a common age of 684 m.y. with a S.D. of 12.5 m.y. This apparent age is identical to that given by the Model I isochron and the interpretation of the analytical data is to some extent justified.

It is also apparent that there is a multimodal distribution of initial $\text{Sr}^{87}/\text{Sr}^{86}$ values between samples of this Formation which is independent of geographical
location. Variations in the provenance of different levels and areas of the sedimentary sequence are suggested. If the ages of the provenances were to be reflected in the apparent ages of the sediments then a wide distribution of values could be expected rather than a common age as is apparent in this instance.

This common age is regarded as a minimum estimate of the time of deposition of the sediments; consideration of the known stratigraphy suggests that this estimate is close to the actual age of deposition. The assumption that the common age is a minimal value is supported by the existence in the samples of the $2M_1$ mica polymorph, the significance of which has been previously mentioned.

Unfortunately the existence of a multimodal distribution of the initial $\text{Sr}^{87}/\text{Sr}^{86}$ cannot be supported by any known "geological" information. X-ray diffraction analyses of the total rock samples used in the isotopic study are listed in Table D-3 and discussed in Appendix D. No significant difference in the mineralogical composition can be detected which conforms to the distribution indicated by the isochrons.

MT. HOUSE GROUP

Throssell Shale

The Mt. House Group crops out in the Lansdowne Sheet area and is exposed outside the limits of the map used in
this thesis. The Group has been formally defined by Gellatly, Derrick, and Plumb (1965) and consists of four formations. The oldest unit, the Walsh Tillite (recognised by Guppy et al., 1958) rests with slight angular unconformity on the Kimberley Group and consists of massive tillite overlaid by dolomite. The overlying Traine Formation is a relatively thin unit consisting of dominantly dolomitic, chloritic sandstone. The Throssell Shale, which rests conformably on the Traine Formation, is described as consisting of flaggy green siltstone and fine-grained sandstone towards the base, with uniform, flaggy, chloritic and micaceous shale with interbeds of laminated fine-grained, micaceous sandstone in the upper section. The youngest beds, the Estaugh Formation, are dominantly subgreywacke and siltstone, and are overlain by Cainozoic soil cover.

Stratigraphic control on the maximum age of the Group is poor, but the lithology and the palaeoclimatic evidence are indicative of a younger Precambrian period of deposition. Dow et al. (1964) consider the Group to be the stratigraphic equivalent of the Duerdin Group, and Roberts et al. (1965) equate the Mt. House Group with the Kuniandi Group. All these sequences have tillite capped by dolomite as the basal section; other similarities also exist. The correlation of all three Groups appears to be reasonably well established.
<table>
<thead>
<tr>
<th>G.A. SAMPLE NO.</th>
<th>RB PPM</th>
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<th>RB87/SR86</th>
<th>SR87/SR86</th>
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<td>5137B TOTAL ROCK</td>
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<tr>
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<td>53.9</td>
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</table>
Figure 27.
A suite of shale samples have been collected from two collection sites in the Throssell Shale. One set (5137) comes from the reference area for the formation (Mt. Clifton); the other set, 5213, comes from Mt. House itself. Outcrop is virtually continuous between these two sites.

After preliminary X-ray fluorescence analyses, seven samples were selected for Rb-Sr isotope dilution analyses. The results are listed in Table 29 and plotted on an isochron diagram in fig. 27.

Discussion

Inspection of fig. 27 shows that linearity exists between the data points for the samples. Regression of the analyses results in a Model I isochron (MSWD = 1.26) having an apparent age of 686 ± 75 m.y. and an initial Sr\(^{87}/Sr\(^{86}\) value of 0.7285 ± 0.0121.

Uniformity of the initial Sr\(^{87}/Sr\(^{86}\) between samples is apparent and the rocks have remained closed chemical systems. 686 m.y. is therefore regarded as the minimum estimate for the age of deposition of these sediments and probably refers to the time of diagenesis of the sedimentary pile. The existence of the 2M\(_1\) mica polymorph supports this interpretation.

The stratigraphic correlation of the Mt. House and Duerdin Groups (Dow et al. 1964) is upheld by the apparent ages obtained; 686 m.y. for both the Throssell Shale and the Ranford Formation.
Significance of the Glacial and Post-Glacial Shale Data

It has been established that the Duerdin and Mt. House Groups contain shales which are geochronologically equivalent. The samples defining the two isochrons can therefore be considered as a coeval suite.

Pooling of the results of the two isochrons results in a common slope of 0.009576 with S.E. of 0.000203; the t value for 95% confidence limits is 3.04. These results are equivalent to a mean weighted common age of 686 ± 44 m.y. The common age is identical to those already defined by the separate isochrons, but the confidence limits have been substantially reduced.

Comparison of this result with that obtained for the glacial shales shows that there is an overlap in the confidence limits. Testing of these results shows however, that these isochrons are significantly different at the 1% level, i.e., there is only one chance in a hundred that they have the same apparent age.

The isochrons can now be accepted with much greater confidence since the order of superposition has definitely been retained and the results show a distinct age difference representing a finite period of time. Furthermore this period of time is of the order expected from a consideration of the stratigraphic relationships.
<table>
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<th>G.A. SAMPLE NO.</th>
<th>RB-PPM</th>
<th>SR-PPM</th>
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<th>SR87/SR86 CALC.</th>
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<td></td>
</tr>
</tbody>
</table>
ALBERT EDWARD GROUP

Elvire Formation

The Formation overlies the basal unit (Mt. Forster Sandstone) of the Group and is separated from the younger Timperley Shale by the Boonall Dolomite. The Formation consists of shale and silstone beds generally less than two inches thick; rare beds of medium-grained quartz sandstone occur throughout. The boundary with the overlying Boonall Dolomite is gradational and the Elvire Formation generally has interbedded dolomite near the top (Dow et al. 1964).

Samples of shale have been collected from the Formation and eight have been selected for isotopic age determination. Two sampling sites, relatively close to each other, are represented.

Analytical data for the eight total rock samples is listed in Table 30 and plotted on an isochron diagram in fig. 28.

Discussion

Relatively wide scatter is shown by the plotted data points and it is obvious that all the samples will not define a single isochron. A regression of the data for seven of the samples (exclusion of 5240 D) results in a Model III isochron (MSWD = 25.01) having an apparent age of 607 ± 174 m.y. with an initial Sr$^{87}$/Sr$^{86}$ value of 0.7396 ± 0.0366. Further deletion of the data for 5063 C
results in a Model II isochron (MSWD = 10.50) having an apparent age of 670 ± 102 m.y. and initial Sr$^{87}$/Sr$^{86}$ value of 0.7244 ± 0.0203.

A regression of the data for samples 5063 A, 5240 B, G, 5063 B, and 5240 E, results in a Model I solution (MSWD = 1.06), the isochron having an apparent age of 653 ± 48 m.y. with an initial Sr$^{87}$/Sr$^{86}$ value of 0.7262 ± 0.0100. The initial Sr$^{87}$/Sr$^{86}$ of these five samples is uniform and the apparent age of 653 m.y. is regarded as a minimum estimate of the time of deposition.

This mean value of 653 m.y. is less than that obtained for the younger Timperley Shale (see later) although the two results are not significantly different. However, this reversal contradicts the observation (based on the previous data for other shales) that stratigraphic position has been retained by the apparent ages.

ALBERT EDWARD AND LOUISA DOWNS GROUPS

Timperley and McAlly Shales

Roberts et al. (1965) consider the Albert Edward and Louisa Downs Groups to be stratigraphic equivalents, and further that the Timperley and McAlly Shales, respective units of the Groups, are direct equivalents, (Table 15). In fact, although continuity of outcrop is not present, there is evidence to suggest that they are precisely the same shale unit.
<table>
<thead>
<tr>
<th>GA SAMPLE NO.</th>
<th>RB PPM</th>
<th>SR PPM</th>
<th>RB87/SR86</th>
<th>SR87/SR86</th>
</tr>
</thead>
<tbody>
<tr>
<td>5088 TOTAL ROCK</td>
<td>230.1</td>
<td>35.1</td>
<td>16.932</td>
<td>0.8910</td>
</tr>
<tr>
<td>5089 TOTAL ROCK</td>
<td>213.6</td>
<td>53.5</td>
<td>11.482</td>
<td>0.8403</td>
</tr>
<tr>
<td>5090 TOTAL ROCK</td>
<td>236.0</td>
<td>40.9</td>
<td>16.602</td>
<td>0.8839</td>
</tr>
<tr>
<td>5091 TOTAL ROCK</td>
<td>207.9</td>
<td>38.0</td>
<td>15.713</td>
<td>0.8764</td>
</tr>
<tr>
<td>5092 TOTAL ROCK</td>
<td>217.3</td>
<td>44.4</td>
<td>14.056</td>
<td>0.8697</td>
</tr>
<tr>
<td>5093 TOTAL ROCK</td>
<td>194.9</td>
<td>38.2</td>
<td>14.675</td>
<td>0.8714</td>
</tr>
<tr>
<td>5117 TOTAL ROCK</td>
<td>219.5</td>
<td>29.6</td>
<td>21.331</td>
<td>0.9233</td>
</tr>
</tbody>
</table>

**Timperley Shale**

<table>
<thead>
<tr>
<th>GA SAMPLE NO.</th>
<th>RB PPM</th>
<th>SR PPM</th>
<th>RB87/SR86</th>
<th>SR87/SR86</th>
</tr>
</thead>
<tbody>
<tr>
<td>5064A TOTAL ROCK</td>
<td>174.9</td>
<td>56.2</td>
<td>8.956</td>
<td>0.8064</td>
</tr>
<tr>
<td>5064B TOTAL ROCK</td>
<td>169.6</td>
<td>51.6</td>
<td>9.455</td>
<td>0.8187</td>
</tr>
<tr>
<td>5065 TOTAL ROCK</td>
<td>207.0</td>
<td>39.9</td>
<td>14.892</td>
<td>0.8719</td>
</tr>
<tr>
<td>5066 TOTAL ROCK</td>
<td>238.1</td>
<td>44.6</td>
<td>15.355</td>
<td>0.8673</td>
</tr>
</tbody>
</table>
FIGURE 29.
The Albert Edward and Louisa Downs Groups overlie with probable unconformity the Duerdin and Kuniandi Groups respectively; both sequences are unconformably overlaid by (?) Lower Cambrian units.

Samples have been collected from the Timperley and McAlly Shales and from these a total of eleven have been selected for age determination. These consist of four from the Timperley Shale (5064 A, B, 5065, 5066) and seven from the McAlly Shale (5088, 5089, 5090, 5091, 5092, 5093, and 5117). Analytical data for these samples are listed in Table 31 and plotted on an isochron diagram in fig. 29.

Discussion

Linearity of the data points is apparent in fig. 29. For eleven samples a Model III solution (MSWD = 13.5) is given, the apparent age being 661 ± 75 m.y. with an initial Sr$^{87}$/Sr$^{86}$ of 0.7316 ± 0.0155. The Model III solution suggests variation in the initial Sr$^{87}$/Sr$^{86}$ value between samples, which can be expected for rocks of heterogeneous parentage.

Deletion of certain of the sample data can significantly reduce the MSWD and also the confidence limits. A regression of the data for samples 5064 B, 5065, 5088, 5090, 5091 results in a Model I isochron (MSWD = 1.93) having an apparent age of 665 ± 43 m.y. with an initial Sr$^{87}$/Sr$^{86}$ value of 0.7321 ± 0.0084 (Fig. 30).
FIGURE 30.

MCALLY and TIMPERLEY FORMATIONS
SHALES

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

$665 \pm 43 \text{m.y.}$
The mean values for the age and the initial Sr$^{87}/$Sr$^{86}$ are not significantly different to those given by the Model III regression for all samples. Furthermore the Model I regression includes samples from both shale formations and supports the initial suggestion of correlation and continuity between the two units.

Partial uniformity of the initial Sr$^{87}/$Sr$^{86}$ is apparent between all samples, and complete uniformity (within experimental error) is apparent between six of the samples. Those samples which do not fit the Model I isochron can be adequately represented by isochrons through each data point with slopes proportional to 665 m.y. In fig. 29 this has been indicated and it is noticeable that 5064 A, 5066, and 5117, lie on the same isochron, having an apparent age of 665 m.y., to within $\pm$ 0.1%.

The samples have apparently remained closed chemical systems and the apparent age of the suite is regarded as a minimum estimate of the age of deposition.

When both the mean age and the 95% confidence limits are taken into consideration, this apparent age is not significantly different (statistically) to that given by the pooled estimate for the Ranford Formation and Throssell Shale. However, if only the mean age is considered, it is noted that the order of superposition of the rocks is retained by the apparent ages and that the indicated
### TABLE 32

**DYKE ROCKS**

<table>
<thead>
<tr>
<th>GA. SAMPLE NO.</th>
<th>RB PPM</th>
<th>SR PPM</th>
<th>R87/SR86</th>
<th>S87/SR86</th>
<th>AGE M.Y.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1103 TOTAL ROCK</td>
<td>40.7</td>
<td>182.8</td>
<td>0.641</td>
<td>0.7210</td>
<td>2320</td>
</tr>
<tr>
<td>1105 TOTAL ROCK</td>
<td>56.9</td>
<td>166.1</td>
<td>0.983</td>
<td>0.7246</td>
<td>1778</td>
</tr>
<tr>
<td>1106 TOTAL ROCK</td>
<td>136.5</td>
<td>239.5</td>
<td>1.638</td>
<td>0.7213</td>
<td>929</td>
</tr>
<tr>
<td>1239 PLAGIOCLASE</td>
<td>14.8</td>
<td>413.5</td>
<td>0.103</td>
<td>0.7030</td>
<td>0.7038</td>
</tr>
<tr>
<td>1239 BIOTITE</td>
<td>426.0</td>
<td>5.8</td>
<td>210.323</td>
<td>6.4527</td>
<td>1940</td>
</tr>
<tr>
<td>5068 TOTAL ROCK</td>
<td>37.5</td>
<td>127.2</td>
<td>0.847</td>
<td>0.7262</td>
<td>0.7245</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>GA NO.</th>
<th>MINERAL</th>
<th>% K</th>
<th>4CAR*40K</th>
<th>%AR ATM.</th>
<th>AGE M.Y.</th>
</tr>
</thead>
<tbody>
<tr>
<td>971</td>
<td>PYROXENE</td>
<td>0.048-ID</td>
<td>0.3502</td>
<td>7.4</td>
<td>2696</td>
</tr>
<tr>
<td>971</td>
<td>PYROXENE</td>
<td>0.048-ID</td>
<td>0.3675</td>
<td>6.2</td>
<td>2766</td>
</tr>
</tbody>
</table>
period between their times of deposition or diagenesis conforms to the expectation. Mean ages can therefore be meaningful in terms of geological processes and should not be disregarded because of high confidence limits which may be the result of statistical bias. Moroney (1956) sums up this attitude by stating that the result "not significant" from a statistical test is not so much a complete acquittal as a verdict of "not proven".

**Dyke Rocks**

Various dyke rocks, intrusive into both older and younger units of the Kimberley Region, have been collected for age determination. The analytical results for these samples are listed in Table 32.

**G.A. 971**

The sample is from a tholeiitic dolerite body which has been mapped as belonging to the series of dolerite dykes and sills intruding Whitewater Volcanics and the O'Donnell Formation (Dow et al., 1964; Dunnet and Plumb, 1964). According to these authors, "this dolerite differs from the Hart Dolerite and is probably older". On the basis of this interpretation of the field evidence and the previously reported ages of the various units, sample 971 should have an apparent age less than the 1800 m.y. to 1823 m.y. range.

Duplicate K-Ar analyses (determined by A.W. Webb) of pyroxene from the sample give apparent ages of 2696 m.y.
and 2766 m.y.; the discrepancy between duplicates is due to variation in Ar\(^{40}\) content.

Obviously these apparent ages do not agree with the reported geology within the area. Therefore either the apparent ages of the pyroxene are excessive, or the interpretation of field evidence is incorrect.

Excessively high ages determined by the K-Ar method can result from either loss of K from the mineral or gain of Ar\(^{40}\). Preferential loss of K compared to Ar has never been reported; the expectation is that Ar will preferentially diffuse from the mineral while all or most of the K is retained. Kulp and Engels (1963) cite laboratory results to support their conclusion that K-Ar ages are not appreciably affected by removal of as much as 50% of the potassium.

Pyroxenes containing excess Ar\(^{40}\) have been previously reported (Hart and Dodd, 1962; McDougall and Green, 1964; Lovering and Richards, 1964), but these were all from rocks derived from high pressure-temperature environments - eclogites and high-grade metamorphics. The general conclusion appears to be that the excess Ar\(^{40}\) was introduced and held in the pyroxene lattice during a metamorphic event.

There is no evidence from inspection of sample 971 to suggest that excess Ar\(^{40}\) may have been introduced to the
pyroxene. In fact petrographic study indicates that Ar\textsuperscript{40} may well have been lost since the time of initial emplacement. Some pyroxene grains show exsolution textures and strongly developed parting parallel to (001). Fracturing of mineral grains is common, and alteration of pyroxene to chlorite is marked in many instances. The rock as a whole has been visibly epidotized and chloritized. Under such conditions the apparent age is expected to be a minimum estimate of the time of emplacement of the dolerite.

Misinterpretation of field relationships appears to be the most logical explanation of this anomalous situation. In the sample collection area, no evidence of intrusive relationships was seen. In the light of these age determination results, it seems more probable that the exposure is that of "basement" rocks and that this dolerite should be correlated with the older basic rocks which are contained in the Halls Creek Group and Lamboo Complex.

This is not to say that dyke rocks within the 1800 m.y. to 1823 m.y. range do not intrude the Whitewater Volcanics and the O'Donnell Formation. The discussion above merely points out that the blanket correlation of basic rocks exposed within or near a particular stratigraphic horizon is not necessarily valid.

It is of interest to note that the mean apparent age of this particular dolerite and that of the tin-bearing
Pegmatite 5106 are the same to within 0.5%, well within the combined limits of the K-Ar and Rb-Sr methods of age determination. The apparently excessive age of the dolerite has some geological meaning and confirms the previous estimate of the minimum age of the Kimberley "basement" rocks.

G.A. 1103

This sample is representative of a dolerite dyke which intrudes rocks of the Lamboo Complex. The strike is approximately NW-SE which differs from the regional trend by some 60°. Tickalara Metamorphics, Mabel Downs Granite, and Bow River Granite are all cut by the dyke; the maximum age of the dyke is therefore 1854 m.y.

The maximum apparent age of the dyke, 2320 m.y., is obviously too great. The enrichment of the sample in Sr\(^{87}\) is low and the apparent age is greatly dependent on the initial Sr\(^{87}/Sr^{86}\) value chosen.

For an initial Sr\(^{87}/Sr^{86}\) of 0.7045, the apparent age is substantially reduced to 1828 m.y. a value which conforms to the limitations for the age of this rock. The initial Sr\(^{87}/Sr^{86}\) assumed is not excessive and lies within accepted limits for mantle-type material.

However, since the apparent age is so dependent on the initial Sr\(^{87}/Sr^{86}\) assumed, and since there is no minimum control to the age of emplacement, little meaning can be placed on this present determination.
G.A. 1105

The sample is from a dolerite which intrudes the Whitewater Volcanics. The maximum age is therefore 1823 m.y. Enrichment in radiogenic Sr$^{87}$ is low and the apparent age is dependent on the initial Sr$^{87}$/Sr$^{86}$. For an initial value of 0.70, the maximum age of the dolerite is 1778 m.y. This value is acceptable in terms of the limitations placed on the age of emplacement.

The maximum age of this sample confirms the remarks concerning 971, namely that the overall correlation of basic rocks occupying a particular stratigraphic position may be invalid. 1105 is representative of the rocks with which 971 has been correlated, but there is no doubt that these two samples represent discrete events widely separated in time.

G.A. 1106

This sample is representative of a doleritic body which is intrusive into units of the Speewah Group - the O'Donnell Formation and possibly the Lansdowne Arkose. The dolerite has been correlated with other doleritic bodies represented by 1105 and 971.

Enrichment in radiogenic Sr$^{87}$ is again low and the apparent age is dependent on the initial Sr$^{87}$/Sr$^{86}$. However, the maximum age (initial Sr$^{87}$/Sr$^{86}$ = 0.70) is only 929 m.y. The maximum possible limit to the age is within the 1800 m.y. to 1823 m.y. range, or if the sample is coeval with 1105, 1778 m.y.
Either the correlation is incorrect or the sample has been an open chemical system. There is reason to believe that the rock was an open chemical system, in which case the apparent age of 929 m.y. represents the minimum age of emplacement.

G.A. 1239
This sample is from a quartz dolerite in which most of the pyroxene has been altered to biotite, hornblende, and chlorite; the plagioclase is mostly fresh with some slight sericitization. Petrographically there is some suggestion that the rock may have undergone metamorphism.

As far as is known, the sample is intrusive into rocks of the Halls Creek Group. Doleritic-dioritic rocks are fairly widespread within the area but relationships between these intrusives and the sediments is obscured. The degree of metamorphism of sediments near to the contacts, and the apparent lack of deformation within the intrusives suggests that this present dolerite sample is much younger than the age of major folding of the Halls Creek Group.

The biotite from this dolerite is sufficiently enriched in radiogenic Sr\(^{87}\) for the apparent age to be independent of the initial Sr\(^{87}/\)Sr\(^{86}\). The data for the plagioclase indicates that there are apparently no abnormal values for the initial Sr\(^{87}/\)Sr\(^{86}\) of this rock. However, the value of 1940 m.y. must be considered to be a minimum estimate of the time of emplacement of the body
since possible metamorphism is suggested.

The apparent age of the biotite and the established age of the Tickalara Metamorphics and gneissic granite are remarkably similar. It would be reasonable to assume that the biotite reflects the time of major metamorphism of the Tickalara Metamorphics.

G.A. 5068

The sample is that of a pegmatite which is intrusive into Tickalara Metamorphics and closely associated with the Mabel Downs Granite; no direct connection between granite and pegmatite is exposed.

The enrichment in radiogenic Sr$^{87}$ is unusually low for a rock of this type, and the apparent age is dependent on the initial Sr$^{87}$/Sr$^{86}$ assumed. The maximum apparent age is 2050 m.y. for an initial Sr$^{87}$/Sr$^{86}$ of 0.70. For an initial Sr$^{87}$/Sr$^{86}$ of 0.701, the indicated initial Sr$^{87}$/Sr$^{86}$ of the Tickalara Metamorphics and gneissic granites, the apparent age is 1968 m.y.

This latter age and initial Sr$^{87}$/Sr$^{86}$ is identical to that of the Metamorphics and Granite, and suggests a genetic relationship between these units and this pegmatite.

MISCELLANEOUS MINERALS

Table 33 lists the analytical data for minerals from various rock units, the majority being biotite. The table also lists the maximum apparent age of each sample assuming an initial Sr$^{87}$/Sr$^{86}$ of 0.70.
<table>
<thead>
<tr>
<th>G.A. SAMPLE NO.</th>
<th>RB PPM</th>
<th>SR PPM</th>
<th>RB87/SR86</th>
<th>SR87/SR86</th>
<th>AGE M.Y.</th>
</tr>
</thead>
<tbody>
<tr>
<td>957 Biotite</td>
<td>291.2</td>
<td>21.8</td>
<td>38.417</td>
<td>1.1719</td>
<td>878</td>
</tr>
<tr>
<td>958 Biotite</td>
<td>430.6</td>
<td>4.7</td>
<td>265.327</td>
<td>4.3072</td>
<td>971</td>
</tr>
<tr>
<td>959 Biotite</td>
<td>412.9</td>
<td>15.7</td>
<td>75.813</td>
<td>2.5639</td>
<td>1747</td>
</tr>
<tr>
<td>964 Biotite</td>
<td>979.3</td>
<td>5.2</td>
<td>544.390</td>
<td>10.3500</td>
<td></td>
</tr>
<tr>
<td>967 Biotite</td>
<td>742.9</td>
<td>5.5</td>
<td>388.788</td>
<td>7.4639</td>
<td>1368</td>
</tr>
<tr>
<td>969 Biotite</td>
<td>239.0</td>
<td>21.9</td>
<td>31.374</td>
<td>1.5147</td>
<td>1844</td>
</tr>
<tr>
<td>972 Muscovite</td>
<td>871.1</td>
<td>12.9</td>
<td>193.449</td>
<td>5.5573</td>
<td>1784</td>
</tr>
<tr>
<td>973 Biotite</td>
<td>698.2</td>
<td>14.1</td>
<td>142.331</td>
<td>2.4671</td>
<td>887</td>
</tr>
<tr>
<td>1098 Biotite</td>
<td>358.1</td>
<td>1.1</td>
<td>938.516</td>
<td>22.6064</td>
<td>1428</td>
</tr>
<tr>
<td>1104 K-Felspar</td>
<td>610.6</td>
<td>18.7</td>
<td>93.800</td>
<td>2.6929</td>
<td>1511</td>
</tr>
<tr>
<td>1104 Biotite</td>
<td>246.7</td>
<td>4.1</td>
<td>173.171</td>
<td>4.5948</td>
<td>1600</td>
</tr>
<tr>
<td>1366 Biotite</td>
<td>1481.2</td>
<td>8.5</td>
<td>499.577</td>
<td>11.1306</td>
<td>1486</td>
</tr>
<tr>
<td>1101 Biotite</td>
<td>523.6</td>
<td>9.5</td>
<td>158.563</td>
<td>3.7347</td>
<td>1364</td>
</tr>
<tr>
<td>1102 Biotite</td>
<td>360.9</td>
<td>5.0</td>
<td>206.865</td>
<td>5.8313</td>
<td>1762</td>
</tr>
</tbody>
</table>
The apparent ages given by the minerals do not reflect any single event. Individually considered, some of the minerals do reflect what are apparently major events in the geochronological history of the area. For instance 969 biotite probably reflects the age of intrusion of the Bow River Granite; 959 biotite and 972 muscovite may reflect some post-Hart Dolerite event leading up to the main 1700 m.y. (approximately) diastrophism.

However, since these are all independent analyses which are not supported by either their total rock data or specific groupings, any interpretation of the apparent ages is open to criticism.

Since the interpretation of these ages make no significant contribution to the general geological history, they are lumped together and listed for the sake of the record.

Taken as a group, they may be considered to represent the variable response of different rocks over a wide geographical area to a series of events of variable proportion and loci of intensity.

**SUMMARY OF THE PRECAMBRIAN GEOCHRONOLOGY WITHIN THE EAST KIMBERLEY REGION**

A diagrammatic display of the Precambrian geochronology of the East Kimberley Region is given in Fig. 31. Each
<table>
<thead>
<tr>
<th>Age (my)</th>
<th>Kimberley Block</th>
<th>Halls Creek Mobile Zone</th>
<th>Sturt Block</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LOUISA DOWNS GROUP</td>
<td>THROSSELL SHALE</td>
<td>ALBERT EDWARD GROUP</td>
</tr>
<tr>
<td></td>
<td>KUNIANDI GRP.</td>
<td>MOONLIGHT VALLEY GLACIATION</td>
<td>RANFORD FORMATION</td>
</tr>
<tr>
<td>600</td>
<td>EGAN GLACIATION</td>
<td>DUERDIN GROUP</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>GLIDDEN GROUP</td>
<td>CARR BOYD GROUP</td>
<td>HELICOPTER SILTSTONE</td>
</tr>
<tr>
<td></td>
<td>DIASTROPHISM</td>
<td>(1080)</td>
<td>WADE CREEK SANDSTONE</td>
</tr>
<tr>
<td>1500</td>
<td>COLOMBO SANDSTONE</td>
<td>DIASTROPHISM</td>
<td>BUNGLE BUNGLE DOLomite</td>
</tr>
<tr>
<td></td>
<td>(1031)</td>
<td>(1184)</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>CROWHURST GRP.</td>
<td>RHYOLITE INTRUSION</td>
<td>RED ROCK BEDS</td>
</tr>
<tr>
<td></td>
<td>DIASTROPHISM</td>
<td>(1540)</td>
<td></td>
</tr>
<tr>
<td>2500</td>
<td>MANT DOlERITE</td>
<td>MEINTOSH GABBRO</td>
<td>+ GRANITE &amp; RHYOLITE</td>
</tr>
</tbody>
</table>
sedimentary unit is represented by a block, the height of which gives some indication of what is thought to be the time span represented by the unit. Dashed lines represent major unconformities: from the diagram the inference is that these unconformities represent a period of time equal to or greater than that of the rock record. While there is no absolute proof of this, consideration of all available data leads one to suspect that it is a more than reasonable assumption.

Question marks indicate doubt. This may refer to either the age of a particular unit (especially where there is little stratigraphic control and no age determinations have been made) or to the existence of a particular event. For instance it has not been possible to date the Fish Hole Dolerite and, according to its relationships with other rocks, it could be any age between 2700 and 1200 m.y. Similarly some of the diastrophisms which have been inferred have been based purely on the isotopic response of some minerals: there is no obvious geological evidence which will support a specific event although the general concept of diastrophism can be supported.

The Precambrian history of the East Kimberleys may be summarized as follows.

1) Prior to 2700 m.y., geosynclinal-type sediments and extrusives of the Halls Creek Group were deposited
over a wide area. This area encompassed the greater part of the East Kimberleys and probably extended over most of the West Kimberleys and into the areas south-west and south-east of the Kimberley area as a whole.

2) Around 2700 m.y., pegmatites were intruded into portion of these already consolidated and folded sediments. Just what else happened at this time is not known, but it is more than probable that some faulting occurred and that the two major fault systems of the area, the Halls Creek and Greenvale Faults, were delineated.

3) At some time prior to 2100 m.y., intrusion of quite large amounts of basic and ultrabasic rocks occurred. These rocks generally show some layering and are relatively coarse-grained, indicating that they crystallized reasonably slowly under appreciable cover of overburden. Dolerite accompanied these intrusions.

4) The first suggestion of a metamorphic event is given by relic total rock and mineral ages within the Tickalara Metamorphics, considered to be the unmetamorphosed equivalents of the Halls Creek Group. At the same time coarse-grained granite was intruded into the Halls Creek Group together with rhyolite dykes.

5) The main metamorphism (granulite facies) took place 1960 m.y. ago and was localized within the central and northern parts of the Halls Creek Mobile Zone.
Associated with this metamorphic episode was the emplacement of gneissic granite (Mabel Downs and McHale bodies) which is considered to represent the end product of the metamorphism, i.e., the granites are considered to have been formed by the melting of the Tickalara Metamorphics. The intensity of this episode was high enough to cause almost complete loss of pre-existing \(^{87}\text{Sr}\) within the affected area.

6) Intrusion of the Bow River and Sophie Downs Granites took place some 100 m.y. later (1850 m.y.). These bodies are massive, coarse-grained or porphyritic, and the first body covers a large portion of the Halls Creek Mobile Zone. The Sophie Downs Granite, intrusive into the Sturt Block, is comparatively small when compared to the Bow River Granite.

7) Intrusion of granite was followed closely by the intrusion and extrusion of vast amounts of acid porphyry and volcanics - the Whitewater Volcanics and the Castlereagh Hill Porphyry. These were emplaced in the Mobile Zone and the Kimberley Block, and it is possible that their emplacement was a continuation of the episode of granite intrusion and not an entirely separate event.

Movement along the major fault lines occurred at this time and depositional basins were formed on the Kimberley and Sturt Blocks.

8) The period from 1823 m.y. to 1800 m.y. is represented by thick accumulations of sediments and basic
volcanics (the Speewah and Kimberley Groups) deposited on the Kimberley Block. Similar deposits, thought to be of equivalent age, also occur on the Sturt Block. Rhyolite, dacite, and microgranite intrusion took place in localized areas within the Mobile Zone.

9) The emplacement of the Hart Dolerite occurred 1800 m.y. ago and marked the end of major igneous activity in the region. This body is very widespread and, since differentiation in place occurred with the formation in upper levels of granophyre, a reasonable amount of overburden is inferred.

10) The Hart Dolerite does not intrude the Bastion Group which conformably overlies the Kimberley Group and is gradational from it. However in view of the observation concerning overburden, it is possible that the Bastion Group was deposited before the Dolerite intrusion and should have an age slightly greater than 1800 m.y. The correlation with the Crowhurst Group is based on stratigraphic evidence only; the Crowhurst Group has apparently responded to some event with the rocks becoming open chemical systems.

11) A widespread diastrophism of some form affected large areas of the East Kimberleys about 1700 m.y. ago, and minerals and rocks have responded. Some faulting at least took place during this period which apparently
extended intermittently over tens of millions of years.

12) Between 1500 and 1600 m.y. ago a further diastrophic event apparently affected localized areas; this may have been associated with local rhyolite intrusion. On the other hand, the rhyolite may be much older and the apparent age reflect the diastrophism. Evidence for this diastrophism is not as clear as it is for the 1700 m.y. event.

13) The period between about 1700 and 1200 m.y. is not represented by very much in the way of rocks; some erosion of older material took place and it is possible that the whole period of time is represented by unconformities. Deposition of the Colombo Sandstone on the Kimberley Block and the Mt. Parker Sandstone and Bungle Bungle Dolomite on the Sturt Block took place, but it is thought that these sediments formed close to the 1200 m.y. mark. In any case their thicknesses are unlikely to account for 500 m.y. of time.

14) About 1200 m.y. ago deposition commenced in the northern part of the Mobile Zone and continued for another 300 m.y. (Carr Boyd Group). Equivalent sedimentation of much shorter duration took place on the Kimberley Block (Glidden Group) and Sturt Block (Wade Creek Sandstone and Helicopter Silstone). During this period of sedimentation, faulting and other diastrophic events occurred locally
and intermittently in areas removed from the area of deposition. This series of movements is largely reflected in the response of minerals within igneous rocks.

15) Another hiatus appears in the period between about 900 m.y. and 740 m.y. No sedimentation took place and unconformities are the only relic of the time involved.

16) 740 m.y. ago marks a distinct change in the type and mode of sedimentary deposition. Widespread glaciation which affected most of the Kimberleys and most probably large areas beyond, occurred at this time. This was followed by a further period of lutite and arenite sedimentation. A slight unconformity separates this sedimentation from a second phase of glaciation which was probably not as widespread as the first. Normal sedimentation followed.

17) An unconformity separates the top of these Precambrian sediments from the overlying (?) Lower Cambrian Antrim Plateau Volcanics.
APPENDIX A

THE USE AND INTERPRETATION OF Rb-Sr DATA

OBTAINED FROM ARGILLACEOUS MATERIAL
Introduction

The ability to obtain meaningful radiometric ages from sedimentary material is one of the major steps made in recent years to further the understanding of geological processes. Since some 70% of the continental surface of the earth's crust is sedimentary in origin, the use of this material and the understanding and interpretation of the radiometric data is of prime importance. For Precambrian rocks, radiometric dating is virtually the only method available for determining the relative ages of separated sequences and for making correlations. As at least two thirds of Australia is Precambrian of predominantly sedimentary origin, greater reliance is having to be placed on the results of radiometric dating in order to interpret the field geology.

Earlier attempts at using sedimentary material were confined to the specific use of diagenetic minerals such as glauconite and illite; both K-Ar and Rb-Sr methods were used. In general it was found that the apparent ages obtained from glauconite were significantly less than the predicted value based on radiometric data on associated igneous rocks, or estimates based on the known stratigraphy in relation to the presently suggested time scale.

Hurley et al. (1960) found that both K-Ar and Rb-Sr age determination methods when applied to glauconites
showed a consistent variation with geological age which was 10-20% younger than the predicted age. They have related this anomaly to the degree of interlayering present within the mineral and the fact that the K content is inversely proportional to the percentage of expandable layers (montmorillonite). They further found that the percentage of expandable layers was decreased in older samples and suggested that the development of pure glauconite took some considerable time.

Superimposed on this is the possible variable effect of both diffusive loss of argon, and loss of radiogenic Sr in deeply buried sediments. Hurley et al. (1960) do not consider this latter possibility to be as significant as the effect of the reordering of the mineral lattice in the development of anomalously young apparent ages because of the concordance obtainable by both K-Ar and Rb-Sr age determination methods. The nett result appears to be that the older a glauconite is, the closer will be the real and apparent ages. This is supported by the work of McDougall et al. (1965) on Precambrian glauconites.

Evernden et al. (1961) find similar results for glauconite, but stress that the burial history of glauconite samples is one of the major items to be evaluated prior to dating. They consider that the heating which occurs with burial may be sufficient to cause
excessive argon loss. Since the diffusion coefficients for illite are similar to those of glauconite, burial and heating will also influence the argon retention in illite. Comparable forms of alteration could be expected to influence the Rb-Sr apparent age in Palaeozoic and older authigenic minerals.

One major problem associated with the use of authigenic minerals is their availability. In most instances glauconite is rare or absent, and where present is "imperfectly" developed; extraction of a pure concentrate in quantities sufficient for reliable analyses becomes almost impossible. Illite, or its equivalent, is much more abundant but again there is the problem of mineral separation. Normally the mica is so fine-grained that the usual methods of separation are ineffective. Techniques (i.e., flotation) which may enable separation to be made also run the risk of introducing contamination and/or exchange of the determinative elements.

Compston and Pidgeon (1962) introduced the concept of dating sedimentary sequences by using total rock samples of shale. The use of total rocks minimised contamination, the effect of intergranular elemental or isotopic diffusion, and significantly reduced the problem of availability of material. In almost any area of interest, fine-grained sediments which can be effectively called
shales occur. The use of total rocks has been continued by persons involved in the Rb-Sr method of dating, and has been successfully used by some working with the K-Ar method (e.g., Harper, 1964, 1966).

The apparent ages obtained using total rock shales are variable in their significance, and the interpretation of the results also varies considerably. These will be discussed in more detail later.

**Composition of Shales**

The basic mineralogical composition of shales is relatively simple compared to the variations possible in igneous rocks of comparable chemical composition. Subsequent alteration brought about by weathering or diagenesis may affect the basic mineralogy to some degree but not to any marked extent.

Most shales consist of varying proportions of representatives of the hydromica, kaolin, montmorillonite, and chlorite groups, together with detrital quartz. Other detrital minerals such as feldspar and mica can also be present. The actual composition of any particular bed will be dependent to a large extent on the composition of the source area (Weaver, 1958; Milne and Barley, 1958) with modifications to the basic mineral lattice being secondary and reflecting the depositional environment and post depositional history. Terrestrial deposits are subject
to more variation in the depositional environment than marine deposits. However, since we are only interested in marine sediments at this stage, the possible variations associated with terrestrial sedimentation will not be considered.

These clay minerals are derived from the weathering of igneous or metamorphic silicates. In some instances, the minerals present in a particular bed may represent reworked and redeposited clay minerals from pre-existing sediments. However, the ultimate origin of all clays must be igneous in origin.

Studies of the weathering of granitic rocks by Grant (1963) and Harriss and Adams (1966) show that the stabilities of minerals during weathering are the inverse of the general crystallization sequence. Grant (1963) found that the least stable mineral was biotite followed by oligoclase; residual microcline still existed in the base of the soil horizon while muscovite was only slightly weathered and quartz appeared quite stable. Harriss and Adams (1966) give the relative mineral stabilities as plagioclase, biotite, K-feldspar, quartz from least to most stable. They state that this sequence is consistently observed regardless of the climatic and/or local physiochemical conditions. This means that Sr, Ca, Na, K and Rb should be released and mobilized during the early
stages of weathering while K, Rb, and Sr are retained in the relatively stable K-feldspar.

There is always the possibility therefore, that detrital or incompletely weathered K-feldspar and muscovite may be present together with clay minerals as constituents of a sedimentary bed. Furthermore, these minerals will be stable in an environment chemically equivalent to that existing in oceanic sediments (Hess, 1966).

The feature which distinguishes the clay mineral groups from other minerals is their pronounced ability to absorb cations. In a marine environment these minerals absorb and exchange large amounts of K, Mg, Ca, Na, Al, Fe, etc. Under suitable conditions, degraded and fragmental mineral lattices take up K and Mg to form, principally, illite and chlorite (Burst, 1959) during progressive diagenesis. Keller (1963) envisages this alteration as a two stage process; in the first stage, cation absorption is driven by the energy of the ions in solution, while the second stage is the rearrangement of ions in the clay minerals to produce (say) illite. This second stage may be aided by mechanical and thermal energy which, as they become more effective, may develop into metamorphism.

The interesting thing is that most ancient illites are of the 2M structural type (Weaver, 1958), the high temperature form. This would be interpreted by some
(e.g. Weaver, 1958, 1959) as indicating that all mica in ancient sediments was of detrital origin. However, Yoder (1959) has shown that progressive metamorphism will transform the 1Md type to 1M and thence to 2M₁ and he believes that this "progressive metamorphism" is perhaps initiated in the earliest stages of diagenesis. Some workers (e.g. Weaver, 1959; Milne and Earley, 1958) consider, however, that burial alone will not promote these transformations and that some other force, such as a shearing force, is necessary.

The combined presence of the 2M polymorph mica and the ever present possibility of detrital K-feldspar and muscovite has led many people to believe that the apparent age obtained from argillaceous rocks must of necessity be a maximum estimate of the time of deposition of the sediments. It was further considered that the apparent age reflected the age of the provenance area, and that the degree to which the apparent age of the sediments was erroneously high depended on the relative difference in age between the source and the time of deposition of its derivatives.

The work of Hurley et al. (1963) supported these theories. They obtained K-Ar "ages" from Recent deep-sea deposits in the North Atlantic which ranged from 200 to 400 m.y., values which were compatible with the ages of rocks in adjacent continental areas. A Pacific deep-sea
sample which retained an "age" of 80 m.y. reflected the generally younger rocks rimming the Pacific basin.

Peterman and Tourtelot (1966) similarly report Rb-Sr "ages" equivalent to the Permian for Cretaceous sediments, and concluded that the anomaly was due to inherited radiogenic strontium.

The majority of Rb-Sr data available for shales indicates initial $\text{Sr}^{87}/\text{Sr}^{86}$ values significantly different to those values accepted for sea-water strontium. Since it was generally assumed that isotopic homogenization of clay particles and sea-water should occur, at least in part, the presence of radiogenic Sr$^{87}$ in excess of sea-water Sr was regarded as being indicative of a maximum apparent age. Where the observed initial $\text{Sr}^{87}/\text{Sr}^{86}$ value was less than that of sea-water it could be explained by the absorption of common Sr. Since it would be more concentrated in the samples of low Rb/Sr ratio, it exerts a statistical leverage upon the isochron and depresses the initial Sr$^{87}/\text{Sr}^{86}$, thus increasing slope and the apparent age (Whitney and Hurley, 1964).

Other generalized observations which can be made are the following.

1) The range in Rb/Sr values of a suite of shales is generally less than that for igneous rocks of comparable composition, and reflects the complex process of ion
absorption associated with weathering, transportation, and deposition.

2) Compston and Pidgeon (1962) first pointed out that a definite range in initial $\text{Sr}^{87}/\text{Sr}^{86}$ occurred in their coeval shale samples. This is borne out by the work presented in this thesis: variations can occur in the initial $\text{Sr}^{87}/\text{Sr}^{86}$ of a suite of samples unless some process has brought about complete isotopic homogenization.

3) The Rb/Sr of shales is normally significantly greater than estimates of this value for the assumed source area.

The first really definitive work on the dating of shales was carried out by Whitney and Hurley (1964). They took 19 samples of shale from the Middle Devonian Hamilton Group of New York and Pennsylvania and defined an isochron whose apparent age was not more than 15% in excess of estimates for the Middle Devonian. They considered that their "relatively small error" was due primarily to the derivation of the sediments from a source area not much older than the Middle Devonian. They also found that there was no significant concentration of inherited radiogenic Sr in the coarser fractions of the shale; an empirical correction could not therefore be applied. While they recommended the use of total rock Rb-Sr chronology for ancient unfossiliferous sediments, part of their conclusion is
quoted since it has had such a strong influence on subsequent interpretations of shale data. They state (p.433): "Application of the whole-rock Rb-Sr age measurement technique to argillaceous sediments yields results in excess of the true age of sedimentation due to the presence of inherited radiogenic strontium in the clastic components of the sediment. The magnitude of this effect is dependent upon the provenance of the detritus and the degree to which it has been altered during weathering, transportation, and sedimentation".

The interpretation of data presented earlier in this thesis is contradictory to the above conclusion. Interpretation of the apparent ages has been based on consideration of the geological history of the samples and a statistical assessment of the data: the following points have therefore been assumed in the interpretations.

1) The apparent age obtained for total rock shale data will be a minimum estimate of the time of deposition, and will reflect the period of diagenesis or some more recent event.

2) All analytical data has equivalent significance with respect to precision and accuracy. Therefore any scatter of data points will be due to geological rather than experimental causes.

3) All samples taken from the one shale bed are considered in the first instance to be coeval.
4) The most accurate estimate, within the bounds of geological limitations, of the apparent age of a suite of total rock shale samples will be given by a Model I isochron where all error is experimental.

5) Samples not defining the initial isochron can be accommodated on a similar isochron having identical slope but differing in the initial $\text{Sr}^{87}/\text{Sr}^{86}$.

6) Variation in the initial $\text{Sr}^{87}/\text{Sr}^{86}$ of samples is a primary feature, normally indicating the presence of inherited radiogenic Sr but having no effect on the apparent age. This variation reflects differences in the provenance area which may be intensified or sharpened by diagenetic processes.

To test the validity of these various theories listed above and discussed earlier, detailed work was carried out on selected suites of samples. For ease of comparison with previously published work, $\lambda_{\text{Rb}} = 1.47 \times 10^{-11} \text{yr}^{-1}$ has been employed throughout this section.

(1) **Hamilton Group, New York and Pennsylvania**

*Middle Devonian*

Since the conclusions of Whitney and Hurley (1964) are so important to the interpretation of the apparent ages of shales, a reassessment of their data was attempted in the light of more advanced statistical techniques. The statistical techniques of McIntyre et al. (1966), when
computerized, allowed for rapid determination of the significance of a set of data, and also gave definite procedures for the interpretation of the results.

Inspection of the analytical results of Whitney and Hurley shows that the published data for R4742 and R4741 will never fit an isochron defined by the remaining eighteen samples. No explanation can be given for R4742, but for R4741 the $\text{Sr}^{87}/\text{Sr}^{86}$ has apparently been incorrectly reported (Whitney, pers. comm.).

Using the "two-error" regression method of McIntyre et al. (1966) and the estimated variances obtained in this laboratory, treatment of the eighteen acceptable samples results in a Model IV isochron (MSWD = 8.26) having an apparent age of 401 ± 19 m.y. with an initial $\text{Sr}^{87}/\text{Sr}^{86}$ of 0.7067 ± 0.0010 at the 95% confidence level. The apparent age and intercept are not significantly different to that given by Whitney and Hurley, but the confidence limits have been increased, a result of the statistical treatment. The Model IV isochron suggests that the extent to which the analyses lie outside experimental error can be attributed to a combination of variation in the initial $\text{Sr}^{87}/\text{Sr}^{86}$ and elemental redistribution.

Inspection of the data plotted on an isochron diagram (Fig. A-1) shows that these apparent errors may be resolved by the fitting of two isochrons having similar
Figure 1.

WEIGHTED MEAN ISOCHRON AGE VALUE
384 ± 9 m.y.

FIGURE A-1.
slope but differing initial $\text{Sr}^{87}/\text{Sr}^{86}$ values. The procedure appears to be justified by the results of the respective regressions.

Regression of the analytical data for samples R4727, R4727 A, R4732, R4743, R4749 A and B, R4760, R4917, R4921 and R4997, results in a Model I isochron (all error experimental) with MSWD = 1.10. This isochron has an apparent age of $383 \pm 11$ m.y. with an initial $\text{Sr}^{87}/\text{Sr}^{86}$ of $0.7071 \pm 0.0007$ at the 95% confidence level for eight degrees of freedom.

The separate regression of the analytical data for samples R4729, R4734, R4739, R4740, R4755, R4916 and R4918, also results in a Model I isochron with a MSWD = 1.35. The isochron has an apparent age of $386 \pm 21$ m.y. with an initial $\text{Sr}^{87}/\text{Sr}^{86}$ of $0.7094 \pm 0.0020$ at the 95% confidence level for five degrees of freedom.

The estimates of the slopes of the two isochrons are not significantly different. On the assumption that the ages of each group are in fact identical, the two estimates may be pooled to obtain a more precise estimate for the common age.

The pooled slope is $0.005657$ with S.E. = $0.000063$; the approximate degrees of freedom (K) are equal to 12.2. This is equivalent to an apparent age of $384 \pm 9$ m.y.; if the higher half-life value of Aldrich et al. (1956) is used
the result is 406 ± 10 m.y. Both sets of values are quoted to the 95% confidence level.

Sample R4749 C has been excluded from both of these regressions on statistical grounds; if it is included in either one, there is a significant increase in residual variance. However its inclusion would not make any difference to the conclusions since the apparent age of the first isochron which it would best fit, would then be 378 ± 17 m.y. (Model III) with an initial Sr$^{87}$/Sr$^{86}$ of 0.7072 ± 0.0010 at the 95% confidence level for nine degrees of freedom.

Further refinement of the data for the two isochrons could be made so that the results are unequivocally within experimental error, by deletion of the data for sample R4740 from the upper isochron and samples R4743 and R4732 from the lower isochron. Treatment of the remaining data in exactly the same way as before results in MSWDs of 0.29 and 0.23 for the upper and lower isochron respectively. Pooling of the results gives a mean weighted apparent age of 377 ± 11 m.y. or 399 ± 11 m.y. at the 95% confidence level for 9.8 degrees of freedom using the lower and higher half-life values of Rb$^{87}$ respectively.

Discussion

The fitting of two parallel isochrons to this data of Whitney and Hurley (1964) instead of the conventional single
Figure 2

[Graph showing Sr\(^{87}\)/Sr\(^{86}\) and Rb\(^{87}\)/Sr\(^{86}\) ratios with data points labeled as D4742, D4732, and approx. 0.705.]

FIGURE A-2.
isochron is based entirely on the statistical estimate of the regressions. There is no apparent (published) geological relationship to support this procedure, although some discussion on the possibilities can be promoted.

Parallel isochrons can result from the proportional admixture of some material (e.g. carbonate), having a differing \( \text{Sr}^{87}/\text{Sr}^{86} \) to that of the host rock, to certain samples in a suite. The proportions must be identical for each sample. Two isochrons having identical slopes but differing intercepts on the \( \text{Sr}^{87}/\text{Sr}^{86} \) axis will be generated, one representing the unaltered rock, and the other the admixture of host rock and secondary material. Some evidence of such an operation is apparent in a few of the samples from the Hamilton Group. Whitney and Hurley have separated some of the samples and analysed the + 5 \( \mu \) solid residue. The analytical data for the solid residue from samples R4727 and R4732 plot close to the upper isochron and the indicated initial \( \text{Sr}^{87}/\text{Sr}^{86} \) of the leach is about 0.705 (Fig. A-2). The total rocks of the two samples seem to be true admixtures with the - 5\( \mu \) fraction (carbonate?) and + 5\( \mu \) residue each retaining their separate identity. However this is not the case for sample R4734 where the analytical data for the + 5\( \mu \) residue plots on the same isochron as the total rock. The indication here is that the \( \text{Sr}^{87}/\text{Sr}^{86} \) of the - 5\( \mu \) fraction equilibrated with that of the other constituents of the sample.
The different behaviour of these separated samples, coupled with the fact that both calcareous and non-calcareous rocks define each of the isochrons, makes this mixing model rather unconvincing. Furthermore, the probability that the carbonate Sr will be a constant proportion of the total Sr in each sample seems very low.

The more usual interpretation of parallel isochrons would imply uniformity in the initial $\text{Sr}^{87}/\text{Sr}^{86}$ for the samples which define each isochron. This then becomes a primary feature of the rocks, reflecting cyclic variations in the material being derived from the provenance. For instance, two rivers having separate watersheds within a common provenance area would be expected to show variations in the relative proportions of materials being deposited. Depending on the possible differences between the watersheds, differences in the bulk $\text{Sr}^{87}/\text{Sr}^{86}$ of material being deposited would be expected. This variation could be heightened by limited homogenization during diagenesis.

The remaining possibility would be homogenization in situ, probably associated with diagenesis of the sedimentary pile - the age on this model would be a minimum estimate of the time of deposition. The initial $\text{Sr}^{87}/\text{Sr}^{86}$ value would reflect the source area and in this instance its value is consistent with the observations quoted by Whitney and Hurley (1964) that the Hamilton
Group sediments were derived from Cambrian and Ordovician material.

Homogenization of the initial $\text{Sr}^{87}/\text{Sr}^{86}$ has been complete for at least one of the samples (R4734), but incomplete for others; in both instances the same apparent age is reproduced by the total rock isochrons. The uniformity of initial $\text{Sr}^{87}/\text{Sr}^{86}$ values of samples defining each isochron is the important feature but no single explanation, applicable to all samples, can be advanced at present to explain all the features displayed in the isochron diagram.

The revised estimate of a minimum value of $362 \pm 6$ m.y. for the age of the Devonian-Carboniferous boundary (McDougall et al. 1966) agrees well with this reassessment of the age of the Hamilton Group. Even if it is assumed that the true lower limit of the Devonian can be defined by the data from Lower Devonian biotites (Hamilton et al., 1962; Kulp et al., recalculated by Hamilton et al., 1962) as about $386 \pm 10$ m.y. then the Middle Devonian would be expected to be of the order of $374$ m.y. Since the Devonian-Carboniferous boundary could be as old as $369 \pm 11$ m.y. (McDougall et al., 1966) and the value for the lower limit of the Devonian most likely a minimum estimate, $374$ m.y. would also be a minimum estimate of the Middle Devonian. The recent work of Bottino and Fullager (1966) support this assumption. They obtained an age of $390 \pm 5$ m.y.
(recalculated to $\lambda \text{Rb}^{87} = 1.47 \times 10^{-11} \text{yr}^{-1}$) for the Silurian-Devonian boundary of North America and state (in a footnote to the publication) that if recent investigations by Boucot are confirmed, this value must be regarded as a minimum age for the boundary.

The recalculated age of $384 \pm 9$ m.y. for the Middle Devonian Hamilton Group lies within the presently accepted limits (362 - 390 m.y.) for the age of the Devonian, and these limits could well be minimum estimates. Thus the evidence for the conclusions of Whitney and Hurley (1964), that whole rock Rb/Sr age measurements of argillaceous sediments yields results in excess of the true age of sedimentation, is no longer applicable. In the opinion of the author, this apparent age of $384 \pm 9$ m.y. is most likely to be itself a minimum estimate reflecting diagenesis. Apparently, however, very little time is represented by the hiatus between deposition and diagenesis, and $384 \pm 9$ m.y. can be effectively regarded as the age of the Middle Devonian with the possibility that this value could be reduced to $377 \pm 11$ m.y.

(2) **State Circle Shale - Upper Lower Silurian**

In the previous section, the reassessment of the data for the Hamilton Group, no specific geologic reason could be proposed to explain the bimodal distribution of initial $\text{Sr}^{87}/\text{Sr}^{86}$ within the suite of samples, although some
suggestions were made. This was due mainly to the fact that only limited information on these samples was available from the published work. However, there is always the possibility that no obvious reason, determinable by our present methods of analysis, exists to explain this observed bimodal distribution. In order to test the various hypotheses outlined previously and to see if some valid reason could be given for the non-uniformity of initial \( \text{Sr}^{87}/\text{Sr}^{86} \) values between coeval samples, the present work on the State Circle Shale was attempted.

The total rock samples used in this study have been selected from a core penetrating fossiliferous upper Lower Silurian shale within the Canberra City area, A.C.T., Australia. The various samples represent material from the weathered surface, oxidized zone, and unaltered shale. Consequently a further contribution to the understanding of the apparent ages derived from total rock Rb-Sr analyses of shales is the possible effect of weathering. This is of vital importance since the majority of sedimentary samples available for age determination purposes are derived from surface outcrops.

A summary of the geology of the Canberra City district was prepared by Opik in 1954, and published in greater detail by the same author in 1958. These publications represent the most recent and detailed work available for this area.
The Lower Silurian is represented by a conformable sequence of sediments, the Camp Hill Sandstone, State Circle Shale, and Canberra Group; the first two units together represent the beginning of Silurian marine transgression. This sequence, whose total thickness is about 1400 feet, overlies the pre-Silurian rocks with strong angular unconformity. A hiatus exists between the Ordovician and Silurian rocks during which the pre-Silurian was plicated, uplifted, and eroded (Benambran Orogeny - Browne, 1950). The Lower Silurian sequence is therefore representative of only the upper Llandovery with the possibility that the upper portion of the Canberra Group may be transgressive to the Middle Silurian.

All units of the sequence are fossiliferous but the State Circle Shale is the more definitive. The occurrence of the Monograptus turriulatus, M. spiralis, M. exiguus, etc., establishes the unit as zone 22 (Elles and Wood, 1901-1918), and upper Llandovery in age. This shale is described by Špík (1958) as consisting of non-calcareous sandy shale and black shale, with beds of fine-grained sandstone.

The Canberra Group represents a change in environmental and depositional conditions. Calcareous matter becomes common; volcanic activity is common and steadily increases with the advance of time throughout the Silurian. The
total visible thickness of the Silurian sequence in Canberra is 3,800 feet, but the real thickness is considered to be over 4,800 feet. Consolidation of this sedimentary and volcanic pile is considered by Öpik (1958) to have been achieved by "a relatively moderate Bowning deformation". This "moderation" refers only to conditions in the immediate Canberra City area where intrusive rocks are insignificant; to the east and west, granitic bodies are dominant. In Canberra, the consolidating phases of the Bowning Orogeny (Browne, 1950) occurred during lower Ludlow time.

After the Bowning Orogeny, no depositional or tectonic events of major importance are recorded.

Sample Selection and Preparation

During 1964, a borehole was commissioned by the Australian National University to be drilled in the State Circle Shale near to the type locality. The first 9 feet of the bore penetrated soil and soft, friable, heavily altered shale, but after this the dipping (45° - 50°) shale was well compacted to the total depth of the bore - 211 feet. Almost 100% core recovery was obtained.

Study of the core showed that for the upper 100 feet the material was oxidized and iron-stained, the staining and degree of oxidation being more marked towards the surface. The deeper section of the core penetrated grey, well consolidated shale showing no signs of weathering or oxidation. This unaltered material showed thin-bedding
and the intercalation of sandy and fine-grained shale as described by Öpik.

The following petrographic descriptions of the shale have been supplied by Dr G.A. Joplin. The unaltered rock is strongly laminated with extremely fine argillaceous bands alternating with slightly coarser and more sandy ones. The coarser bands consist of small equidimensional grains of quartz and rare grains of feldspar in a matrix difficult to resolve. This matrix appears to be rather similar to the finer argillaceous bands and contains a good deal of white mica, a little chlorite, and a flaky mineral with low birefringence, possibly a clay mineral. Sphene and rutile are present as heavy minerals together with a little carbonaceous matter and iron ore. The fine bands consist largely of small orientated flakes of white mica, rather more carbonaceous matter than the coarser bands, and a few grains of quartz of similar size to those of the coarser bands. There is also the possibility of a little chlorite and clay mineral. The very abundant white mica in these bands may be muscovite (sericite). No lime minerals, other than sphene, have been detected.

The oxidized rock resembles closely the unaltered rock. Quartz and mica are not stained by limonite but much of the chloritic material and clay material is stained. Iron ores are oxidized, and veins of oxidation
cut the rock which is badly stained in their vicinity.

Joplin notes further that the parallel arrangement of
the very numerous mica flakes in the fine bands of both
rocks may have been brought about by compaction and
diagenesis. On the other hand these rocks may have
suffered very slight metamorphism and, if the mineral really
is muscovite, she would attribute its formation to a slight
metamorphism.

In either instance, the general consensus of opinion
would regard the phyllosilicates in these rocks as being
of secondary rather than primary origin, formed \textit{in situ}
through diagenetic or metamorphic processes.

X-ray diffraction patterns of samples used for the
isotope dilution analyses support the observations and
conclusions of Joplin. The shale samples consist
essentially of quartz, 2M\textsubscript{1} muscovite (sericite), and
chlorite (?chamosite), associated in certain instances with
K-feldspar (microcline), plagioclase, kaolinite, and
montmorillonite or mixed layer structures.

50 g. samples were taken from each foot of the core
from 5 feet to 211 feet inclusive. Each was crushed to
pass 100 B.S. mesh sieve size and thoroughly mixed using
a Siebtechnik vibratory grinder with a tungsten carbide
grinding stone and ring.

Rb and Sr X-ray fluorescence analyses were made of
each powered sample and on the basis of these results,
19 were chosen for complete Rb-Sr isotope dilution analyses, 10 being from the zone of oxidation and 9 from the unaltered shale material. The choice was based on the range in Rb/Sr values shown by the X-ray fluorescence analyses with the intention of forming, if necessary, independent isochrons from the unaltered and oxidized zones. Range in Rb/Sr was the only criterion on which the selection was made. The isotope dilution analyses were made according to the method outlined in Appendix B.

Results

The X-ray fluorescence analyses were carried out by Dr B.W. Chappell of the Department of Geology, Australian National University, according to the methods of Norrish and Chappell (1967). The Rb/Sr values, considered to be accurate to within $\pm 3\%$, have been plotted against sample depth and are displayed in Fig. A-3. It is apparent that, in general, the range in Rb/Sr of all samples lies within a relatively well defined zone.

This limited zone infers a degree of homogeneity with respect to Rb and Sr and reflects the complex cycle of weathering, transportation, deposition, and diagenesis, coupled with the influence of ion absorption and exchange (Grim, 1958; Weaver, 1958) to which the shale components are subjected. However, it does not infer uniformity of isotopic composition.
FIGURE A-4.
FIGURE A-5.

Sr X.R.F. Counts + 10
Variation in Rb/Sr within this zone is due almost entirely to differences within the Sr, rather than Rb, content of samples. Figures A-4 and A-5 are histograms of the frequency distribution of Rb and Sr for 201 samples based on the X-ray fluorescence analyses. It can be seen that for Rb (Fig. A-4) the distribution is normal with a relatively narrow standard deviation which can be compared to the slightly skewed Sr distribution (Fig. A-5) with appreciably larger standard deviation. This may be a reflection of the high capacity of the clay minerals for absorption of K and Rb ions from a marine environment, and the higher mobility and earlier release of Na and Ca (and Sr) during the initial weathering of the parent material (Harriss and Adams, 1966).

Samples chosen for complete Rb-Sr isotope dilution analyses are indicated on Fig. A-3 by full circles. For the most part the selection is random insofar as a vast number of possible combinations exist. Certain particular samples have been chosen however, which fall outside the general range of Rb/Sr of the shale as a whole. The intention was to ascertain whether apparent enhancement and depletion in Rb and Sr exhibited by some of the specimens had any effect on their apparent age.

Isotope dilution analytical data for the specimens are listed in Table A-1 and displayed on an isochron
<table>
<thead>
<tr>
<th>Sample Depth</th>
<th>Rb  p.p.m.</th>
<th>Sr  p.p.m.</th>
<th>Rb$^{87}$/Sr$^{86}$</th>
<th>Sr$^{87}$/Sr$^{88}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 Total Rock</td>
<td>195</td>
<td>19</td>
<td>30.055</td>
<td>0.9041</td>
</tr>
<tr>
<td>18</td>
<td>194</td>
<td>12</td>
<td>46.758</td>
<td>1.0162</td>
</tr>
<tr>
<td>23</td>
<td>174</td>
<td>14</td>
<td>36.485</td>
<td>0.9544</td>
</tr>
<tr>
<td>30</td>
<td>186</td>
<td>17</td>
<td>31.959</td>
<td>0.9253</td>
</tr>
<tr>
<td>33</td>
<td>198</td>
<td>14</td>
<td>40.379</td>
<td>0.9759</td>
</tr>
<tr>
<td>44</td>
<td>182</td>
<td>18</td>
<td>28.379</td>
<td>0.9052</td>
</tr>
<tr>
<td>50</td>
<td>193</td>
<td>20</td>
<td>27.107</td>
<td>0.8943</td>
</tr>
<tr>
<td>58</td>
<td>164</td>
<td>38</td>
<td>12.238</td>
<td>0.8049</td>
</tr>
<tr>
<td>65</td>
<td>197</td>
<td>24</td>
<td>23.314</td>
<td>0.8745</td>
</tr>
<tr>
<td>78</td>
<td>159</td>
<td>25</td>
<td>18.568</td>
<td>0.8416</td>
</tr>
<tr>
<td>103</td>
<td>202</td>
<td>21</td>
<td>28.172</td>
<td>0.8990</td>
</tr>
<tr>
<td>120</td>
<td>180</td>
<td>18</td>
<td>28.057</td>
<td>0.9027</td>
</tr>
<tr>
<td>128</td>
<td>77</td>
<td>28</td>
<td>8.057</td>
<td>0.7702</td>
</tr>
<tr>
<td>144</td>
<td>57</td>
<td>29</td>
<td>5.571</td>
<td>0.7563</td>
</tr>
<tr>
<td>151</td>
<td>146</td>
<td>21</td>
<td>19.787</td>
<td>0.8570</td>
</tr>
<tr>
<td>160</td>
<td>163</td>
<td>26</td>
<td>17.986</td>
<td>0.8438</td>
</tr>
<tr>
<td>166</td>
<td>159</td>
<td>29</td>
<td>15.894</td>
<td>0.8230</td>
</tr>
<tr>
<td>174</td>
<td>149</td>
<td>31</td>
<td>13.783</td>
<td>0.8106</td>
</tr>
<tr>
<td>203</td>
<td>188</td>
<td>25</td>
<td>21.970</td>
<td>0.8690</td>
</tr>
<tr>
<td>12 C&amp;P</td>
<td>192</td>
<td>43</td>
<td>11.420</td>
<td>0.7877</td>
</tr>
<tr>
<td>13 C&amp;P</td>
<td>164</td>
<td>23</td>
<td>20.720</td>
<td>0.8472</td>
</tr>
<tr>
<td>17 C&amp;P</td>
<td>178</td>
<td>32</td>
<td>15.870</td>
<td>0.8185</td>
</tr>
</tbody>
</table>

Sr$^{87}$/Sr$^{86}$ normalized to a Sr$^{86}$/Sr$^{88}$ value of 0.1194
diagram in Fig. A-6; the reference numbers for each sample refers to the depth in the borehole from which it was selected. The present day Sr\textsuperscript{87}/Sr\textsuperscript{86} values have been normalized to a Sr\textsuperscript{86}/Sr\textsuperscript{88} value of 0.1194.

Three further samples have been included and these are designated 12 C&P, 13 C&P, 17 C&P, and refer to the previously published analyses of Compston and Pidgeon (1962). These samples are representative of the weathered surface exposures of the State Circle Shale. For purposes of comparison their published present day Sr\textsuperscript{87}/Sr\textsuperscript{86} values have been normalized to the Sr\textsuperscript{86}/Sr\textsuperscript{88} constant used here.

Inspection of Fig. A-6 shows that a certain lineation exists in the sample data points and this is borne out to some degree by a statistical assessment of the analytical results. Using the "two-error" regression method of McIntyre et al. (1966), a regression of the data for the 22 samples results in a Model III solution (MSWD = 38.04) having an apparent age of 426 ± 14 m.y. and initial Sr\textsuperscript{87}/Sr\textsuperscript{86} of 0.7232 ± 0.0053 at the 95% confidence level.

The Model III solution to the above regression suggests variation in the initial Sr\textsuperscript{87}/Sr\textsuperscript{86} of samples included in this isochron. Some indication of those samples which are more likely to fit the isochron with the least precision is given by the value of the Difference/SE of each sample (McIntyre et al., 1966).
The residual variance can be substantially reduced by deletion of the data for samples 10, 128, 144, and 12 C&P, 13 C&P, 17 C&P from the assessment. A regression based on the remaining 16 total rock samples still results in a Model III solution but the MSWD has been reduced to 15.28. The resultant isochron has an apparent age of $413 \pm 12$ m.y. with an initial $\frac{\text{Sr}^{87}}{\text{Sr}^{86}}$ of $0.7300 \pm 0.0048$. The Model III solution still suggests that there is a variation in the initial $\frac{\text{Sr}^{87}}{\text{Sr}^{86}}$ of the samples which is greater than experimental error.

Further refinement of the data suggests that the age of the samples can be best considered in terms of a series of essentially parallel isochrons having the same slope but varying in their initial $\frac{\text{Sr}^{87}}{\text{Sr}^{86}}$ values.

On this basis, a Model I (all error experimental) isochron can be formed by samples 78, 103, 166, and 174, having an apparent age of $416 \pm 23$ m.y. and an initial $\frac{\text{Sr}^{87}}{\text{Sr}^{86}}$ of $0.7256 \pm 0.0062$. The MSWD of this regression is 2.39 which is not significant for 2 degrees of freedom.

Similarly, samples 18, 23, 30, 33, 44, 50, 58, and 120, define a Model I isochron (MSWD = 1.30 which is not significant for 6 degrees of freedom) having an apparent age of $413 \pm 7$ m.y. and an initial $\frac{\text{Sr}^{87}}{\text{Sr}^{86}}$ of $0.7300 \pm 0.0022$.

Likewise samples 10, 13 C&P, 17 C&P, 128, and 144, have a Model I solution (MSWD = 0.97) having an apparent
age of 408 ± 8 m.y. with an initial Sr$_{87}$/Sr$_{86}$ of 0.7221 ± 0.0017. It will be noted that the data for 12 C&P has not been included in this regression: its inclusion results in a Model III isochron having a significantly high residual variance (MSWD = 8.02) but the apparent age (413 m.y.) is virtually identical. However, the 95% confidence limits are increased to ± 16 m.y.

In a similar manner it will be found that regression of the data for samples 65, 151, 160, and 203, results in an isochron having an apparent age of 389 m.y. The isochron is Model III and the 95% confidence limits are excessively high at ± 130 m.y. The indicated initial Sr$_{87}$/Sr$_{86}$ of the isochron is 0.7411, again with high confidence limits of ± 0.0400.

Disregarding for the moment the data for samples 65, 151, 160, and 203, we find that three Model I isochrons have been defined whose slopes are not significantly different. On the assumption that the ages of each group are in fact identical, these estimates may be pooled to obtain a more precise estimate of the common age.

The pooled slope of the isochrons is 0.006097 and the S.B. of this slope is 0.000028; the approximate degrees of freedom K are equal to 10.0. These values are equivalent to an age of 413 m.y. with 95% confidence limits of ± 4.3 m.y. The pooled age is identical to that
obtained for 16 total rock samples, but the confidence limits have been substantially reduced. Similarly it is not significantly different to the age obtained for the five samples originally deleted to obtain the regression for 16 samples.

Treatment of the isochron data obtained for groupings of 16 and 5 total rock samples in precisely the same manner as outlined above, results in a pooled slope of 0.006062 with S.E. of 0.000034 and 4.36 degrees of freedom. This is equivalent to an apparent age of 411 m.y. with 95% confidence limits of ± 6 m.y. As far as the apparent age of the State Circle Shale is concerned, it is irrelevant as to whether or not a bimodal or multimodal distribution of initial Sr$^{87}$/Sr$^{86}$ values is assumed.

On the basis of these pooled estimates of the apparent age there is some justification for assuming that samples 65, 151, 160, and 203, would be represented by "isochrons" through each of their data points having a slope proportional to 413 m.y. In Fig. A-6 such a single isochron has been drawn which encompasses these four samples, indicating that they are also considered to be coeval with the remainder of the sample suite and consequently reflect the same apparent age.

Discussion

The Palaeozoic time scale of Kulp (1961) concludes that the Silurian Period lies between the limits of 405 ± 10 m.y.
and 425 ± 10 m.y., both values being rather arbitrarily chosen estimates based on data for the Lower - Middle Devonian boundary and on the Trenton of the Ordovician Period. As has been noted previously by Compston and Pidgeon (1962), the absolute age of the Silurian is the least well known. Holmes (1960) suggested 440 m.y. as the base of the Silurian and is supported by Bvernden and Richards (1962) who propose an age of 435 m.y. As with Kulp's estimates, these suggestions for the age of the Ordovician-Silurian boundary are quite arbitrary.

For convenience, Compston and Pidgeon have assumed that no age uncertainty exists in the Palaeozoic time scale beyond the limits of these arbitrary boundaries, and estimated that the upper Lower Silurian, zone 22, should be about 420 m.y. to 430 m.y. in age. Their original interpretation of data for the State Circle Shale support these estimates.

The various age results suggested previously in this work are all acceptable in terms of presently recognized Silurian boundaries. The apparent age of 426 m.y. given by a single regression of all samples is furthermore quite acceptable in terms of the estimates for the upper Lower Silurian made by Compston and Pidgeon (1962).

The ages of 413 ± 4 m.y., or 411 ± 6 m.y. proportional to the pooled mean slope of the isochrons, are too young
in terms of the above estimates, but these values are still considered to be the most acceptable estimate of the apparent ages given by the State Circle Shale. Their acceptance can be justified on statistical grounds but not on any easily recognizable lithologic, stratigraphic, or structural grounds. It will be noted that samples from both the oxidized and unaltered zones, and from various stratigraphic positions, define each of the various isochrons.

A similar situation exists with the available analytical data for the Hamilton Shale of New York and Pennsylvania (Whitney and Hurley, 1964). Treatment of their data in precisely the same manner as outlined above (Bofinger and Compston, 1967) showed no apparent geological reason for the distribution of data points: the assumption of bimodal distribution of initial $\text{Sr}^{87}/\text{Sr}^{86}$ was considered justified on the basis of the statistical reassessment. Bofinger and Compston (1967) have suggested that this bimodal distribution could be a primary feature reflecting cyclic variation in the detritus from a provenance area, or that it was generated, or at least intensified by in situ homogenization of Sr isotopes during diagenesis or later metamorphism.

The assumption of coevality of samples from the State Circle Shale is not unreasonable. On this basis the initial $\text{Sr}^{87}/\text{Sr}^{86}$ which conforms to the common age can be
FIGURE A-7.

Initial $\frac{\text{Sr}^{87}}{\text{Sr}^{86}}$ of the two major isochrons 0.7221 0.7285
All percentages are relative and based on comparison with a synthetic mix of known composition; they are not a quantitative measure of the mineralogical composition of the rocks.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Muscovite</th>
<th>Chlorite</th>
<th>K-feldspar</th>
<th>Plagioclase</th>
<th>Mixed layer</th>
<th>Kaolinite</th>
<th>Goethite</th>
</tr>
</thead>
<tbody>
<tr>
<td>(00) Musc.</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
</tr>
<tr>
<td>(002) Chlor.</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
</tr>
<tr>
<td>7Å Chlor.</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
</tr>
<tr>
<td>7Å Kaol.</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
</tr>
<tr>
<td>10Å Chlor.</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
</tr>
<tr>
<td>2.6Å Micr.</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
</tr>
<tr>
<td>Quartz</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
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</tr>
<tr>
<td>Microcline</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
</tr>
<tr>
<td>Quartz %</td>
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<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
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<tr>
<td>Microcline %*</td>
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<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
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<tr>
<td>Muscovite %*</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
</tr>
<tr>
<td>Chlorite %</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
</tr>
<tr>
<td>Kaolinite + Goethite %*</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
</tr>
</tbody>
</table>

**TABLE A-2**
calculated for each sample. Fig. A-7 is a histogram of these calculated Sr$^{87}$/Sr$^{86}$ values assuming a common age of 413 m.y. It is obvious that, at the least, a bimodal distribution of initial Sr$^{87}$/Sr$^{86}$ values exists based on groupings of 6 and 16 total rock samples.

X-ray diffraction analyses of the mineralogical content of each sample defining these isochrons shows that definite differences exist which strongly support a bimodal distribution model. Additional information is also available which indicates the effects of oxidation and weathering on shales of these compositions.

Table A-2 lists the specific mineralogical composition of each sample, indicated by a cross in the appropriate column. Quartz is ubiquitous and has been omitted from the Table.

Muscovite (sericite) is the 2M$_1$ polymorph and is present in equivalent amounts in all samples except 128 and 144. In these it exists in less than half the usual proportions and shows a positive correlation with the Rb concentration of the total rock.

Chlorite, which bears a strong resemblance to chamosite, is common to all samples but variable in amount. The (002) muscovite to (002) chlorite ratio (10Å : 7Å) is consistently greater than 1.0 in the surface samples and zone of oxidation, and less than 1.0 in the region of
unaltered material. This marked difference in concentration is mirrored by the presence of kaolinite and goethite in the altered samples and its absence in the unaltered rocks, and is in accordance with the statement of Deer, Howie, and Zussman (1962) that chamosite is readily converted by oxidation to yellow, yellow-brown, and red-brown alteration products consisting essentially of kaolinite and goethite.

Mixed layer structures, strongly resembling montmorillonite and exhibiting a marked 12Å reflection, exist in small amounts in most samples; their presence does not seem to be related to any particular mineralogical composition or state of alteration.

Plagioclase is present only in samples below the 144 feet level. In most instances it appears to have the composition of albite; sample 144 contains the only Ca-rich plagioclase.

K-feldspar, exhibiting the 3.26Å reflection of microcline, is present in all samples except 10, 128, 144, 12 C&P, 13 C&P, and by extrapolation, 17 C&P. The samples which are devoid of K-feldspar are those with define the lowermost isochron. Furthermore the presence or absence of K-feldspar is independent of the Rb/Sr ratio, compared to the rough correlation shown between this ratio and the mica content.

K-feldspar normally has an appreciable Rb/Sr and, through time, will develop a significant increase in the
value $\text{Sr}^{87}/\text{Sr}^{86}$. Addition of such older material to various levels of a sedimentary pile substantially increases the $\text{Sr}^{87}/\text{Sr}^{86}$ of selected samples.

Variation in the initial $\text{Sr}^{87}/\text{Sr}^{86}$ then becomes a primary feature of a suite of samples, the value of this ratio being a reflection of cyclic variation in the detritus from a provenance area (Bofinger and Compston, 1967).

The above observations support the statistical suggestion of a bimodal distribution in the initial $\text{Sr}^{87}/\text{Sr}^{86}$ of the samples. The lack of K-feldspar in those samples having a low initial $\text{Sr}^{87}/\text{Sr}^{86}$ value as compared to its presence in the majority of samples having higher initial $\text{Sr}^{87}/\text{Sr}^{86}$ values gives a geological reason to the statistical assessment. Unfortunately, the X-ray diffraction method, when applied to total rock samples, is not precise enough to allow for accurate quantitative estimates of the various mineral phases. The further assumption of a multimodal distribution of initial $\text{Sr}^{87}/\text{Sr}^{86}$ values cannot be proved by the mineralogical evidence.

The acceptance or rejection of a multimodal, as distinct from a bimodal, distribution of the initial $\text{Sr}^{87}/\text{Sr}^{86}$ makes no real difference to the apparent age of the samples. The pooled slope of the two isochrons based on groupings as indicated by the histogram (Fig. A-7) is proportional to 411 m.y. with 95% confidence limits of
+6 m.y. This result is not significantly different to that obtained for the multimodal Sr\(^{87}\)/Sr\(^{86}\) distribution model. However, it is important in terms of the general principles underlying the model.

A bimodal distribution would be generally accepted since it can be supported by both mineralogical and statistical evidence. The principle of its original selection is, however, purely statistical and based on the fact that the analytical precision of all data is equivalent and that the optimum result is the attainment of very small residual variances to the regressions and, if possible, Model I isochrons. If a bimodal distribution of initial Sr\(^{87}\)/Sr\(^{86}\) can be accepted on the basis of the statistics and evidenced by mineralogical information, then the concept can be equally well extended to include a multimodal distribution model. The lack of data to support a multimodal model does not mean that such a model does not exist.

It is therefore considered justified to propose a sequence of Model I isochrons having essentially the same slope but varying in their initial Sr\(^{87}\)/Sr\(^{86}\) to explain the distribution and pattern of the analytical data for the State Circle Shale.

**Interpretation of the Apparent Age**

Geologic, petrographic, and isotopic criteria indicate that the apparent age of 413 \(\pm\) 4 m.y. is a minimum estimate.
of the time of deposition of the upper Lower Silurian sediments.

The uniformity of initial $^{87}\text{Sr}/^{86}\text{Sr}$ of samples defining an isochron, particularly in the case of potentially heterogeneous material such as sediments, infers some form of $^{87}\text{Sr}/^{86}\text{Sr}$ homogenization. This uniformity is substantially a primary feature of the various levels of the unconsolidated sedimentary pile. It is more than possible however, that this uniformity is intensified by the process of diagenesis and the apparent age would then reflect this post-depositional event.

Inherited radiogenic $^{87}\text{Sr}$, present within these samples, is indicated by the relatively high initial $^{87}\text{Sr}/^{86}\text{Sr}$ of the various isochrons. According to the proposals of Whitney and Hurley (1964), the presence of inherited radiogenic $^{87}\text{Sr}$ infers that the apparent age must be a maximum estimate of the time of deposition, and reflect the age of the provenance area.

This is unlikely to have occurred in the case of the State Circle Shale. In the first instance, the apparent age obtained is significantly less than the predicted value according to Kulp's time scale. This aspect becomes even more marked if other suggested time-scales are considered. Secondly, estimates of the approximate age of the provenance show that the source material must be
older than Middle Ordovician, i.e., the State Circle Shale was not derived from its immediate basement which is in accordance with the predictions of Öpik (1958).

If it is assumed that the shales samples used in this study are representative of the source material, then the average Rb and Sr concentrations of the source are 181 and 22 µg/g respectively (based on the average of 201 X-ray fluorescence analyses); the Rb\(^{87}/\)Sr\(^{86}\) would then be 23.45. The average Sr\(^{87}/\)Sr\(^{86}\) of the source area at the time of deposition of these sediments would be given by the mean initial Sr\(^{87}/\)Sr\(^{86}\) of the shales. This value would be 0.7285 assuming that the State Circle Shale samples are coeval.

Assuming an initial Sr\(^{87}/\)Sr\(^{86}\) of 0.70 for the provenance, the age of the source would be 83 m.y. older than the apparent age of the derived sediments. These calculations do not take into account the fact that Rb, in excess of that derived from the source, is absorbed by the clay minerals (together with potassium from sea-water) during transport and diagenesis. The actual age of the provenance is undoubtedly older than 500 m.y. in age.

If the inherited radiogenic Sr\(^{87}\) was to contribute to an excessively high apparent age for the State Circle Shale, the expectation would be that the apparent age obtained should be greater, and not less, than the predicted estimate.
Petrographic evidence supports the suggestion of minimality of the apparent age of the State Circle Shale, since the shale now consists almost entirely of secondary phyllosilicates. This is consistent with mineralogical alterations brought about during normal diagenesis and load metamorphism. Under such conditions, homogenization of $\text{Sr}^{87}/\text{Sr}^{86}$, at least within the range of samples of 50 g size, could be expected to take place. Since this is a post-depositional event, the resultant apparent age would then be a minimum estimate of the time of deposition.

X-ray diffraction data is in agreement with the petrographic information. The mica is dioctahedral and of the 2M form which is normal for Palaeozoic sediments (Weaver, 1958, 1959), while the 1M polymorph is common to Recent sediments. Yoder (1959), in experimental studies on micas, effected the transformation $1\text{Md} \rightarrow 1\text{M} \rightarrow 2\text{M}_1$ for muscovite and paragonite and believes that this growth sequence obtains in the progressive metamorphism of materials of the requisite composition in sediments, initiating perhaps as early as the beginning of diagenesis. However, Weaver (1959) considers that mere burial will not effect this transformation but that low-grade metamorphism or shearing-type forces are necessary.

The indications are that the mica in these shales has been subject to a degree of metamorphism. It is
reasonable to assume that the other mineral phases in the rocks have suffered similar changes.

The geologic aspects indicate that the apparent age must indeed be a minimum. Accepting the absolute ages of the upper and lower boundaries of the Silurian, it is realised that if the apparent age of 413 m.y. represents a maximum estimate, or even the absolute age, of the upper Lower Silurian, the Lower Silurian accounts for an inordinately large portion of the Silurian Period. This is contrary to stratigraphic evidence available throughout the world. Furthermore, as more accurate determinations of the ages of the Palaeozoic boundaries are made, it is apparent that the tendency is to push these boundaries further back in time. Such a trend would increase this apparent imbalance in the subdivision of the Silurian.

It must therefore be accepted that the apparent ages of $413 \pm 4$ m.y. or $411 \pm 6$ m.y. given by the total rock data of the State Circle Shale is a minimum estimate for the upper Lower Silurian and for the time of deposition of these rocks.

The question is, just how much younger than the absolute age is this estimate?

According to Opik (1958) the Canberra Region was folded in a phase of the Bowning Orogeny during the lower Ludlow. The dating of the orogenic phase is quite accurate since
it occurred after the deposition of lower Ludlow sediments and before the intrusion of a lower Ludlow porphyry. Immediately following the consolidation of the porphyry and still in lower Ludlow time, a second phase of the Orogeny faulted large portions of the Canberra Region; throws of not less than 4,000 – 5,000 feet are recorded.

Öpik considers that the final consolidation of the Silurian and Ordovician rocks of the Canberra region was achieved "by a relatively moderate Bowning deformation". Pre-Silurian rocks were partially consolidated by plication and subsequent uplift and erosion during the Lower Silurian Benanbram Orogeny, but Silurian rocks were not effected until the Bowning deformation.

This latter phase of folding and faulting did not have a marked effect on the State Circle Shale of the sample area, and the deposit was only slightly deformed. However, in view of the relatively shallow depth of burial (approximately 3,000 feet), the geologic interpretation of Öpik (1958), and the available petrographic information, it is conceivable that the State Circle Shale did not become a closed chemical system with respect to Rb and Sr until the "consolidating" events of the Bowning Orogeny, which would be in accordance with the views of Weaver (1959).

If this is so, then it infers that not only is $413 \pm 4$ m.y. a minimum estimate for upper Lower Silurian time, but
| K-Ar age determinations from Evernden and Richards (1962) | |
|---|---|---|---|---|
| Sample  | P.p.m. | P.p.m. | Sr 87/Sr 86 | Sr 87/Sr 86+ | Age | Age | Y. | Y. | Age | Age |
| Pegmatite KT | 37 | 57 | 523 | 255 | 0.40 | 0.52 | 1.45 | 1.60 | 7.49 | 7.49 |
| Pegmatite KT | 37 | 57 | 523 | 255 | 0.40 | 0.52 | 1.45 | 1.60 | 7.49 | 7.49 |
| Pegmatite SR | 37 | 57 | 523 | 255 | 0.40 | 0.52 | 1.45 | 1.60 | 7.49 | 7.49 |
| Pegmatite SR | 37 | 57 | 523 | 255 | 0.40 | 0.52 | 1.45 | 1.60 | 7.49 | 7.49 |

TABLE A-3
it reflects the age of the lower Ludlow. In terms of the present and possibly projected estimates for boundaries of the Silurian Period, $413 + 4$ m.y. as the age of the lower Ludlow would be more than acceptable. This latter interpretation of the apparent age of the State Circle Shale is considered to be the most probable.

Further support for the suggested interpretation of the age is given by the analytical data for igneous bodies associated with sediments of known age; limits can be placed on the stratigraphic age of these intrusives. The analytical data for these granites is listed in Table A-3; their reference numbers refer to the A.N.U. collection. For details of locations and descriptions of all samples except the Sutton Granite, the reader is referred to Evernden and Richards (1962).

The Sutton Granite is located some 13 miles N.N.E. of Canberra and intrudes and hornfelses Ordovician sediments of the Cullarin Horst (Opik, 1958) which were folded during the Benambran Orogeny. It is therefore post-lowermost Silurian in age: Opik places the granite in the Middle Silurian.

G.A. 252 and 253 intrude Upper Ordovician sediments and possibly (?) Silurian; both predate the Upper Devonian (Griffin, 1957; Hall, 1956; Browne, 1950). G.A. 274 intrudes Ordovician and (?) possibly Upper Silurian; it is
overlain by Lower Devonian Snowy River Volcanics.

G.A. 187 and 290 (195 in Evernden and Richards) are considered by Vallance (1953) and Snelling (1960) to be early or Middle Silurian, and Upper Silurian or Lower Devonian respectively.

Öpik (1958) considers all these granites belong to the Bowning "granitorogeny" which he recognizes as extending over a period of time from the Middle Silurian to possible Lower Devonian.

The Silurian intrusions in the immediate Canberra area are represented by the Sutton Granite and the Shannon's Flat Granodiorite (G.A. 290). The apparent age of the total rock granite and aplite from the Middle Silurian Sutton Granite is 422 m.y. This age then represents a minimum estimate for the time of deposition of the State Circle Shale, and a maximum estimate for the beginning of the Bowning Orogeny within the local area.

The apparent ages of 397 m.y. given by the pegmatites and micropegmatites associated with the Sutton Granite could represent the waning phase of the Bowning Orogeny. The apparent ages of samples G.A. 186, 187, 252, and 253, and the biotite data for G.A. 290 would also be interpreted as representing this phase of the orogeny.

G.A. 274 has an apparent age equivalent to that of the Sutton Granite. The K-feldspar data for G.A. 290 is
Effects of Weathering on the Apparent Age of Total Rock Shale Samples

An important feature which is indicated by the analytical data and isochron diagram for this Shale is that weathering and oxidation have no apparent effect on the age indicated by the samples.

Fig. A-6 shows that there is no systematic difference between the analytical data of weathered surface samples (the three samples of Compston and Pidgeon, 1962), those from the zone of oxidation (0 - 100 feet) and apparently unaltered fresh material (100 - 211 feet).

This is contrary to expectation based on the work of Kulp and Engels (1963), Marvin et al. (1965), and Goldich and Gast (1966). They found that weathering drastically reduced the Rb-Sr age of biotites compared to the estimates based on K-Ar determinations and considered that this was due to the removal of radiogenic strontium by groundwater solution. While certain portions of the State Circle Shale have obviously been subjected to solution, the samples have not responded with preferential loss of radiogenic Sr$^{87}$.

Bottino and Fullagar (1966) and Fullagar and Bottino (1966) have found that for total rock samples of granite and gneiss which show obvious effects of weathering, leaching, and Rb and Sr enhancement and depletion, the
apparent age has remained unaffected. These observations agree with the evidence presented here.

Peterman (1966) found a systematic difference in the ages of oxidized and unaltered metasediments in Minnesota. In this instance the oxidized samples indicated an apparent age which was some 17% less than the apparent age of unoxidized samples. State of oxidation was, apparently, the only basis on which a division of supposedly coeval samples was made.

Conclusions based on the data of this present work are entirely contradictory to the observations of Peterman. Oxidation and weathering has strongly modified the mineralogical composition of some of these shales, but the apparent age remains unaltered. Any degrading which may have occurred within the mica, or alteration of the chlorite, has not resulted in any detectable loss of Rb or Sr from the total rocks themselves. Even though the alteration has been instigated by external sources, the rocks themselves have remained effectively closed chemical systems with respect to Rb and Sr.

In the case of shales, this retentivity is probably due to the fact that as the rocks are composed of material which has undergone at least one weathering cycle, the components are in "equilibrium" with a weathering environment. Subsequent cycles of weathering may have little effect on the chemical stability of the shale material.
Conclusions

Statistical treatment of the Rb-Sr data for the State Circle Shale indicates that a multimodal distribution of initial $^{87}\text{Sr}/^{86}\text{Sr}$ exists between the total rock samples: a bimodal distribution is supported by mineralogical evidence. On this basis, the data is best resolved by considering a series of isochrons having essentially identical slopes but differing in their initial $^{87}\text{Sr}/^{86}\text{Sr}$. Pooling of these slopes results in a weighted mean estimate of the common age for all samples.

The weighted mean apparent age of this upper Lower Silurian shale is $413 \pm 4$ m.y. This is considered to be a minimum estimate of the time of deposition of the shale, and a minimum age for the upper Lower Silurian even though it is obvious that the rocks have inherited $^{87}\text{Sr}$ from the source area. The only effect of this inherited $^{87}\text{Sr}$ is to increase the initial $^{87}\text{Sr}/^{86}\text{Sr}$ of the samples.

Further consideration of the geologic and petrographic information suggests that this minimum estimate of $413 \pm 4$ m.y. reflects the Upper Silurian deformation which influenced the region. It is proposed that $413 \pm 4$ m.y. is most probably a reliable estimate for the age of the lower Ludlow. This suggests that some significant period of time may be necessary to bring about chemical closure within shale and that in the absence of thick overburden
some degree of metamorphism appears to be necessary.

The data also indicates that weathering and oxidation has no deleterious effect on the apparent age given by shale samples.

(3) **Dullingari No.1 Well - Middle Ordovician**

The previous two examples, both of which are considered to have minimum apparent ages, represent samples which have apparently been subject to no more than "normal" diagenesis, or only the slightest metamorphism. The shales from Dullingari No.1 well have responded to an event which, while it may still be regarded as within the realms of diagenesis, has an intensity which borders on low-grade metamorphism. In such a case the apparent age can be expected to represent a minimum estimate of the time of deposition and reflect the age of the metamorphic event. As will be seen, the minimum apparent age is at least 10% greater than the presently suggested limits for the Middle Ordovician. This provides a strong argument for the necessity of a complete reappraisal of the Lower Palaeozoic time boundaries. Unfortunately too much data is being interpreted in the light of Kulp's (1961) time scale which is now outdated and based in many instances on results of doubtful reliability or arbitrarily chosen boundaries. The end result is that many theories are proposed to explain discrepancies between the suggested time scale and new data, theories which may not necessarily be justified if some other time-scale was proposed.
Introduction

The Delhi-Santos Dullingari No.1 well, located in the Great Artesian Basin of Australia at latitude 28°07'55.6"S and longitude 140°52'30"E, was drilled to a depth of 11,588 feet from the surface, the interval from 9050 to 11,588 feet being in Ordovician sediments dipping at 60° to 45°. These sediments are described (Harrison & Greer (1963)) as dark grey, very hard, fissile, thinly bedded, calcareous to dolomitic, pyritic shale with very fine calcite and quartz veins; abundant thin interbeds and lenses of siltstone occur throughout.

Biserial graptolites (Diplograptids) have been found to be abundant in some layers within the 9191' - 9211' interval, indicating a Middle to early Upper Ordovician age (Opik & Jones, 1963). Fragments of graptolites are present also in the 9496' - 9506' and 9802' - 9812' intervals. Fragmentary uniserial graptolites occur in cores recovered from depths greater than 10,143 feet, and a Lower Ordovician age is indicated for this deeper section.

Rb-Sr analyses of ten samples selected from cores from the 9191' to 9506' interval were made in an attempt to determine the radiometric age of portion of the Ordovician. Petrological examination of thin sections from this depth interval show that the originally angular quartz has been modified by recrystallization, and that the original
clay minerals have been completely recrystallized and now consist of well aligned, parallel laths of muscovite. The rocks could be classed as slates owing to their fissility, degree of recrystallization and grain size. However, Harrison and Greer (1963) state that there is no evidence to suggest that the present state of the rocks is due to any factor other than simple load metamorphism or normal diagenesis associated with depth of burial.

**Sample Preparation**

50 - 100 g samples were selected from the available core material, selection being confined to the finest-grained, most uniform sections free from veins and silt bands. Each was crushed to pass 100 B.S. mesh sieve size and thoroughly mixed. Rb-Sr isotope dilution analyses were carried out on 0.5 g splits of each sample by standard methods.

Two of the samples were further treated by leaching in HCl. 1.0 g samples were agitated in 1.0N HCl for 5 minutes, centrifuged, and the supernatant liquid stored. The residue was thoroughly washed in demineralized water, centrifuged, dried and weighed, and the supernatant liquid removed and added to the original. Complete Rb-Sr isotope dilution analyses were carried out on the residues, while $\frac{\text{Sr}^{87}}{\text{Sr}^{86}}$ measurements were made of the leach (supernatant). The $\text{Rb}^{87}$ and $\text{Sr}^{86}$ concentrations within the leach were calculated by difference between the absolute amounts within the total rock and residue.
<table>
<thead>
<tr>
<th>Sample</th>
<th>Rb p.p.m.</th>
<th>Sr p.p.m.</th>
<th>Rb$^{87}$/Sr$^{86}$</th>
<th>Sr$^{87}$/Sr$^{86}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>9191 Total Rock</td>
<td>199</td>
<td>127</td>
<td>4.536</td>
<td>0.7516</td>
</tr>
<tr>
<td>9193 Total Rock</td>
<td>210</td>
<td>121</td>
<td>4.997</td>
<td>0.7546</td>
</tr>
<tr>
<td>9199 Total Rock</td>
<td>213</td>
<td>110</td>
<td>5.579</td>
<td>0.7590</td>
</tr>
<tr>
<td>9203 Total Rock</td>
<td>185</td>
<td>120</td>
<td>4.472</td>
<td>0.7508</td>
</tr>
<tr>
<td>9205 Total Rock</td>
<td>222</td>
<td>113</td>
<td>5.686</td>
<td>0.7588</td>
</tr>
<tr>
<td>9207 Total Rock</td>
<td>192</td>
<td>122</td>
<td>4.545</td>
<td>0.7516</td>
</tr>
<tr>
<td>9496 Total Rock</td>
<td>*216</td>
<td>144</td>
<td>*4.340</td>
<td>0.7493</td>
</tr>
<tr>
<td>9498 Total Rock</td>
<td>213</td>
<td>146</td>
<td>4.212</td>
<td>0.7474</td>
</tr>
<tr>
<td>9502 Total Rock</td>
<td>240</td>
<td>109</td>
<td>6.370</td>
<td>0.7650</td>
</tr>
<tr>
<td>9506 Total Rock</td>
<td>197</td>
<td>124</td>
<td>4.591</td>
<td>0.7512</td>
</tr>
<tr>
<td>9496 Leach</td>
<td>*0.778</td>
<td></td>
<td></td>
<td>0.7237</td>
</tr>
<tr>
<td>Leach calculated</td>
<td></td>
<td></td>
<td></td>
<td>0.7237</td>
</tr>
<tr>
<td>9496 Residue</td>
<td>215</td>
<td>78</td>
<td>7.967</td>
<td>0.7754</td>
</tr>
<tr>
<td>9502 Leach</td>
<td>0.293</td>
<td></td>
<td>0.7255</td>
<td></td>
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<tr>
<td>Leach calculated</td>
<td></td>
<td></td>
<td>0.7257</td>
<td></td>
</tr>
<tr>
<td>9502 Residue</td>
<td>246</td>
<td>71</td>
<td>9.962</td>
<td>0.7884</td>
</tr>
</tbody>
</table>

*These values are in error - see Addendum*
DULLINGARI No.1 Well

Middle Ordovician Shales

FIGURE A-8.
Results

The Rb-Sr analytical data is listed in Table A-4 and plotted on an isochron diagram in Fig. A-8. Reference numbers refer to the depth from which the samples were selected.

Linearity of data points is shown by the 10 total rock samples. Application of the "two-error" regression method of McIntyre et al. (1966) results in a Model I isochron in which all error can be attributed to experimental variability. The apparent age is 514 ± 318 m.y. and initial Sr$^{87}$/Sr$^{86}$ is 0.7165 ± 0.0027 at the 95% confidence level. The large values of the confidence limits are due to the restricted range in Rb$^{87}$/Sr$^{86}$ of the total rock samples.

In an attempt to increase the Rb$^{87}$/Sr$^{86}$ range of the regression, leaching was carried out on samples 9496 and 9502 representing one of the least enriched and the most enriched in Rb$^{87}$ relative to Sr$^{86}$. Material balance between the total rock, leach, and residue of each sample has been retained, but linearity of all the data points has been lost. The exact alignment of the components of each leached sample is a result of the calculation and the low sampling error, but the excellent agreement between the measured and calculated Sr$^{87}$/Sr$^{86}$ of each leach is an independent check at least for the Sr data.

The leach for 9502 can never fit an isochron defined by the remaining samples and therefore the solid residue...
from 9502 most probably shows some equivalent effect. Excluding the data for these two analyses but including 9496 leach and residue, a Model I isochron is defined having an apparent age of 490 ± 14 m.y. This value is not significantly different to that of the total rock isochron but considerably more precise. However, if the discordancy indicated by 9502 is present to any extent in 9496, then this value of 490 ± 14 m.y. will be too young.

Two possibilities to explain this discrepancy are

1) that initial Sr\textsuperscript{87}/Sr\textsuperscript{86} homogenization of the HCl soluble fraction (the majority most logically being carbonate) and the residue has not taken place, or

2) preferential leaching of Sr\textsuperscript{87} relative to Sr\textsuperscript{86} has occurred with the leach fraction being enhanced and the residue depleted in Sr\textsuperscript{87}.

If lack of homogenization of the initial Sr\textsuperscript{87}/Sr\textsuperscript{86} of the carbonate (leach) and residue fractions is the cause of the non-linearity then there must be at least two generations of carbonate with significantly different initial Sr\textsuperscript{87}/Sr\textsuperscript{86} values. The estimate of the time of deposition of the sediments would then be given by the carbonate-free residue joins, i.e., about 443 m.y.

For lack of homogenization, and the apparent existence of at least two generations of contaminant, to be acceptable as explanations of the non-linearity, they must also explain
the marked colinearity of the total rock data points. This can only be done if proportional addition of Sr$^{87}$ relative to the absolute amount of Sr$^{86}$ is assumed for each total rock sample. This is hard to envisage under the most optimum conditions, but it is made even more unlikely by the apparent existence of at least two additives having significantly different Sr$^{87}$/Sr$^{86}$ values.

Complete recrystallization of all the original clay minerals, and partial recrystallization of the quartz, has occurred and these conditions are not consistent with a concept of inhomogeneity. In such circumstances homogenization of the initial Sr$^{87}$/Sr$^{86}$ of all components could be expected, coupled with the concentration and segregation of certain constituents such as dolomite. Even if the carbonate was introduced at some time after the initial diagenesis of the sediments, the load metamorphism continuing from that time - and still existing to the present - should be sufficient to promote homogenization.

The remaining possibility is that of preferential removal of Sr$^{87}$ from the residue during the leaching process. This means that the leach portion is enhanced in Sr$^{87}$ in excess of the amount that can be accounted for by the Rb concentration. A similar effect could be obtained by the preferential retention of Rb by the residue fraction but in this instance it cannot wholly account for the
discrepancy and, furthermore, such retention would be contrary to expectation.

Support for the above suggestion can be gained from consideration of the total rock-leach-residue relationships of the two leached samples. In the first instance it is apparent that if preferential movement of Sr\(^{87}\) has occurred, then the greater amount has been removed from the sample having the greater amount available. This is in accordance with the expectation. Secondly, if inhomogeneity of the sample fractions is assumed, and if addition of a single Sr\(^{87}\)/Sr\(^{86}\) composition is considered, then the apparent age of the additive is a negative quantity - an impossible situation. Thirdly, the apparent initial Sr\(^{87}\)/Sr\(^{86}\) of this carbonate is greatly in excess of any predictions so far made for solution material in a marine environment.

Further support for a suggestion of preferential leaching of Sr\(^{87}\) is given by the recent work of Faure and Chaudhuri (1967). They dissolved samples of powdered limestone in HCl of different strengths over different periods of time. They found a marked correlation between the magnitude of the Sr\(^{87}\)/Sr\(^{86}\) ratio, the normality of the acid, and the duration of attack by the acid. The measured Sr\(^{87}\)/Sr\(^{86}\) varied far in excess of the reproducibility of measurements. They suggest that (p.23) "a possible explanation of this phenomenon may be that radiogenic Sr\(^{87}\)
is leached from the insoluble clay mineral fraction by the acid treatment".

The amounts of Sr$^{87}$ involved in preferential leaching would be relatively small in the present situation and well within the capabilities of the leaching process. For sample 9496, the amount of apparently excess Sr$^{87}$ in the leach is 0.00011 μm, and for sample 9502 the amount is 0.00033 μm based on the isochron formed by the total rock data alone.

Discussion

The youngest estimate of the time of deposition of these Ordovician sediments, 443 m.y. is given by the join of the residues of 9496 and 9502, and compares favourably with Kulp's (1961) estimate for the Middle to Upper Ordovician. Kulp quotes a value of 445 m.y. for the Trenton and upper Caradoc.

However, while this age does represent a minimum estimate of the time of deposition it is not considered to be valid. The reasons for this consideration have been outlined above. A more precise estimate of the time of deposition is given by the isochron formed by the total rocks plus the leach and solid residue of 9496.

This result (490 m.y.) is clearly in excess of those values presently suggested for the age of the Middle Ordovician and even for the Cambrian-Ordovician boundary. Kulp (1961) places the boundary at 500 ± 10 m.y., while
Snelling (1964) quotes Fairbairn et al. (1960) and considers 518 m.y. to be the most reliable estimate; more recently Fairbairn et al. (1967) place the age of the Lower Cambrian at 550 m.y.

The only available data which bears any resemblance to the age obtained here is that of Poole et al., 1963. They obtained K-Ar dates of 481 m.y. and 477 m.y. as minimum ages for the Middle Ordovician rocks of Southern Quebec. However, the stratigraphic relations of these rocks have been the subject of considerable debate and are generally considered to be unreliable.

The possibility remains that the shale samples presented here are reflecting a maximum age for their time of deposition due to the presence of inherited radiogenic Sr$^{87}$, but it is suggested by Bofinger and Compston (1967) that the only contribution inherited radiogenic strontium makes is to an increase in the initial Sr$^{87}$/Sr$^{86}$, reflecting the Sr$^{87}$/Sr$^{86}$ of the provenance.

Hart and Tilton (1966) have shown that the isotopic compositions of sediments are not in equilibrium with the depositional environment and that the Sr$^{87}$/Sr$^{86}$ of the sediments reflect the strontium isotopic composition of the provenance area. Similar relationships are reported by other workers, e.g., Peterman (1966), Dasch et al. (1966).

In the case of the shales from the Dullingari No.1 well, the indicated initial Sr$^{87}$/Sr$^{86}$ is significantly
greater than that of present day sea-waters (Compston and Pidgeon, 1962; Hamilton, 1966), but the petrologic information from these rocks suggests that the apparent age of 490 m.y. is a minimum estimate of the time of deposition of these sediments. The degree of "metamorphism" brought about by diagenetic processes is more than sufficient to bring about the equilibration of the \( \text{Sr}^{87}/\text{Sr}^{86} \) values of the various components of any sample-sized specimen. Furthermore, the remarkably good alignment of the total rock data points indicates uniformity of the initial \( \text{Sr}^{87}/\text{Sr}^{86} \) over at least 311 feet of shale, which represents a stratigraphic interval of about 200 feet. In "unmetamorphosed" sediments, this uniformity is not always found and a multimodal distribution of initial \( \text{Sr}^{87}/\text{Sr}^{86} \) values is not uncommon.

It is therefore considered that \( 490 \pm 14 \) m.y. represents a minimum age of deposition of these Middle Ordovician shales and most probably reflects the time of diagenesis of the sediments. If redistribution of \( \text{Sr}^{87} \), suggested by the data for 9502, has occurred between the leach and solid residue of 9496 then the minimum age can be justifiably increased to \( 514 \pm 38 \) m.y.

(4) **Heavitree Quartzite - Precambrian: "Upper Proterozoic"**

The previous examples have apparent ages which are minima but close to the age of deposition of the sediments.
For the Dullingari shales it was inferred that the close fit of the analytical data to a single isochron was brought about by homogenization of the samples during slight metamorphism.

The Heavitree Quartzite is an example of a sediment which has suffered post-depositional silicification and alteration. The apparent age reflects an event which is much younger than the age of deposition, and complete homogenization of the initial $^{87}\text{Sr}/^{86}\text{Sr}$ has occurred.

Wells et al. (1964, 1965) describe the Quartzite as a medium-grained, silicified quartz sandstone which unconformably overlies older Precambrian metamorphic and igneous rocks. It is conformably overlain by the Bitter Springs Limestone which, in turn, is disconformably overlain by the Areyonga and Pertatataka Formations or some younger unit. Wells et al. consider the Heavitree Quartzite to be "Upper Proterozoic" in age. Isotopic data on shales from the Pertatataka Formation indicate that the absolute age of the Quartzite should be in excess of 800 m.y. (Bofinger - unpublished results).

Complete Rb-Sr isotope dilution analyses were carried out on four samples from the Quartzite; the data are listed in Table A-5 and plotted on an isochron diagram in Fig. A-9.

Regression of the analytical data results in a Model I isochron, MSWD = 1.75 which is not significant for 2 degrees
HEAVITREE QUARTZITE

FIGURE A-9
of freedom. The slope of the isochron is proportional to 
506 ± 30 m.y. with an initial Sr\textsuperscript{87}/Sr\textsuperscript{86} of 0.7538 ± 0.0104; confidence limits are quoted to the 95% level.

The apparent age is significantly less than the predicted value while the indicated initial Sr\textsuperscript{87}/Sr\textsuperscript{86} is quite high even for shales.

The Model I fit of the data to a single isochron suggests that the apparent age represents the age of Sr\textsuperscript{87}/Sr\textsuperscript{86} homogenization of the samples; this is known to be a minimum estimate of the time of deposition of the sediment.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Rb p.p.m.</th>
<th>Sr p.p.m.</th>
<th>Rb\textsuperscript{87}/Sr\textsuperscript{86}</th>
<th>Sr\textsuperscript{87}/Sr\textsuperscript{86}</th>
</tr>
</thead>
<tbody>
<tr>
<td>5249 A</td>
<td>184</td>
<td>21</td>
<td>24.683</td>
<td>0.9382</td>
</tr>
<tr>
<td>5249 B</td>
<td>143</td>
<td>29</td>
<td>13.994</td>
<td>0.8602</td>
</tr>
<tr>
<td>5249 D</td>
<td>151</td>
<td>20</td>
<td>21.138</td>
<td>0.9103</td>
</tr>
<tr>
<td>5249 F</td>
<td>273</td>
<td>21</td>
<td>36.953</td>
<td>1.0323</td>
</tr>
</tbody>
</table>

Reflections and Conclusions

Certain conclusions based on the results, and the discussion of the results, of the examples previously detailed may be considered here.
1) In these instances at least, the apparent age obtained is a minimum estimate of the time of sedimentation. This conclusion can be independent of the actual value of this apparent age, and based solely on consideration of the statistical and geological information available. This is not to suggest that the apparent ages of shales are never too great, but to point out that, in these instances, the ages are considered to be minima. Since the older, generally more deformed, shale material from the Kimberley area has been subjected to at least as much, and in most cases more, deformation and alteration than the examples used here (with the possible exception of the Heavitree Quartzite), it appears reasonable to assume that they too will define minimum ages. This assumption is justified by the fact that the order of superposition of the sediments is reproduced by their apparent ages, the apparent order of time between the sedimentary phases conforming to expectation.

2) The presence of inherited radiogenic strontium has had no detectable effect on the apparent ages of the examples. The presence of excess or inherited Sr$^{87}$ is indicated by the high initial Sr$^{87}$/Sr$^{86}$ defined by the isochrons. However, for low values of initial Sr$^{87}$/Sr$^{86}$, the decision as to whether inherited radiogenic strontium is present appears to be very arbitrary. Values greater than seawater strontium are considered by most authors to
be proof of the presence of inherited radiogenic Sr; values less than that of seawater strontium may still be considered to show excess Sr\textsuperscript{87} depending on the interpretation placed on the data by the particular authors (e.g. Whitney and Hurley, 1964; Peterman and Tourtelot, 1966).

The initial Sr\textsuperscript{87}/Sr\textsuperscript{86} of a suite of samples reflects the Sr\textsuperscript{87}/Sr\textsuperscript{86} of the provenance area from which the sediments were derived, at the time of their derivation.

In the case of the examples previously quoted, no real knowledge of the provenance area is available. For the Hamilton Group, a Cambrian and Ordovician source terrain is proposed, but no data on this provenance is available. For the State Circle Shale, some estimate of the possible age of the provenance can be made, but there is no knowledge of its location. All that is known is that the shale has not been derived from the Ordovician rocks in the immediate region. The source for the Dullingari samples is completely unknown.

However, the data for the Kimberley sediments provides excellent control on both an acceptable source area and its sedimentary derivatives. It is reasonable to assume that the post 1800 m.y. old sediments were derived from the Lamboo Complex or a mass of similar composition. Available information on the structure and lithology of the Complex together with information on the possible provenance directions of the sediments supports this hypothesis.
FIGURE A-10.
If it is further assumed that the samples of crystalline rock selected from the Complex for the age determination programme are representative of the various rock types, then an average composition for each rock type can be derived from the available analytical data. In Fig. A-10 these computed compositions have been plotted on a radiogenic $\text{Sr}^{87}/\text{Rb}^{87}$ versus $\text{Sr}^{87}/\text{Sr}^{86}$ diagram. Each line then represents the $\text{Rb}^{87}$ decay history for each particular composition from its time of chemical closure to the present day. Since only very limited data is available for the metabasic rocks of the Complex, the "basic rocks" mean of the diagram has been calculated including the data for the Hart Dolerite and Carson Volcanics, rocks of equivalent composition to the metabasics.

Also included on this diagram is a plot of age against initial $\text{Sr}^{87}/\text{Sr}^{86}$ for each dated sedimentary unit. Certain features are immediately obvious.

a) The initial $\text{Sr}^{87}/\text{Sr}^{86}$ values of the sediments are generally encompassed by the $\text{Sr}^{87}/\text{Sr}^{86}$ of the gneissic granites, metamorphics, and basic rocks at the time given by the apparent ages of the sediments. Only during the period of glaciation does it appear that the porphyritic and coarse-grained granites made any contribution to the formation of the sediments. Sediments derived from the Whitewater Volcanics do not appear to be represented.
b) In cases where the initial $\text{Sr}^{87}/\text{Sr}^{86}$ of the sediments are not covered by the source rocks listed above, the ratio is less than that expected. In such instances it is possible that partial loss of radiogenic $\text{Sr}^{87}$ has occurred during weathering, transportation, and sedimentation. The other possibility is of course that the actual source rocks are not represented by the selection which has been made from the Complex. Since they would be very basic rocks, they would have been avoided in the initial collection which was specifically for the purpose of determining the age of various units.

c) The general trend shown by the initial $\text{Sr}^{87}/\text{Sr}^{86}$ of the sediments is increasing value with decreasing age. The increase in value is to be expected if the sediments are to reflect their source, a prediction made by almost all clay mineralogists although they refer specifically to the mineralogy. However, the fact that the $\text{Sr}^{87}/\text{Sr}^{86}$ increases with decreasing age is contradictory to the suggestions of previous authors. If the measure of inherited radiogenic Sr is to be found in the initial $\text{Sr}^{87}/\text{Sr}^{86}$, and if this necessarily results in a maximum age for the sediments (Whitney and Hurley, 1964) then in cases where a common source for a sequence of sediments is indicated (representing in this case something like 1100 m.y.) the expectation would be that all sediments should have similar
apparent ages or maybe that the younger sediments should have the older apparent ages (depending on the relative Rb and Sr concentrations of the source and derived sediment). This is obviously not the case, the superposition of rocks being reflected by their radiometric age which particularly for the younger Precambrian sediments, conform to the expectation. There seems to be no evidence to support the contention that the presence of inherited radiogenic Sr will result in a maximum estimate for the time of deposition.

3) The range in initial $^{87}\text{Sr}/^{86}\text{Sr}$ between coeval samples can be quite significant. This may be due to various causes: variation in the detritus being fed to a depositional basin, brought about by the presence of more than one feeder channel, would possibly be the most common cause; the idealized situation where there is only one feeder transporting material from a restricted homogeneous source is seldom seen in nature. Associated with this would be variation in the type of detritus. This is shown by the State Circle Shale where the samples defining the upper isochrons have microcline as a component which is non-existent in samples defining the lower isochron. Such a situation could be brought about by either multiple feeder channels or heterogeneity within a single source area. Initial $^{87}\text{Sr}/^{86}\text{Sr}$ variation could also be achieved through the effect of proportional preferential common Sr
absorption on certain clay minerals (e.g. montmorillonite) which would depress the Sr$^{87}$/Sr$^{86}$ of those samples containing such a mineral (Hurley et al., 1960).

4) It would appear that, in general, those samples with the lowest Rb/Sr values also have the lower initial Sr$^{87}$/Sr$^{86}$. If in a case such as this the data from a whole suite of samples is included in a single regression, then the initial Sr$^{87}$/Sr$^{86}$ for the isochron will be depressed and an erroneously high age will result (c.f. Whitney and Hurley, 1964). While inherited radiogenic Sr is usually regarded as the cause of such discrepancies, it is normally due to the fact that these various populations, based on the initial Sr$^{87}$/Sr$^{86}$, have not been recognized. Where a sufficient number of samples are available, these populations may be recognized and defined by a statistical assessment of all the data. Inspection of the isochron diagrams usually gives some initial indication of which samples define specific populations, but it is possible to make these decisions purely on statistical grounds. In the first instance the intention is to significantly reduce the residual variance to a minimum. An indication of those samples which fit the isochron with the least precision and are most likely to contribute to a high residual variance is given by the value Diff/SE (McIntyre et al., 1966). Repetition of this procedure will normally result
in a minimum value for the residual variance being achieved for as many samples as possible. Those samples excluded are then tested in the same manner to determine whether or not they define one or more isochrons which have slopes that are not significantly different to the already defined isochron. If the various isochrons are not significantly different, a pooled estimate of the common age for all samples can then be calculated. These procedures can be subjective and it is possible to derive erroneous results through use although this usually becomes obvious. In all cases however, all available information concerning the stratigraphy and geological history of the samples should be taken into consideration during interpretation of the shale data.

5) It is obvious from the work presented previously and from the discussion above that for the interpretation of data from total rock shales large number of samples are usually necessary. However, since most collections can be regarded as random, a scatter of data points representing the various populations could be expected for a small number of samples. Therefore, when lineation of a small number of samples is achieved (such as for the Mt. John Shale) it can be confidently assumed that the apparent age obtained and probably the initial Sr\(^{87}/Sr^{86}\) are representative of the unit as a whole.
6) The Rb/Sr range of a suite of shale samples is usually low compared to (say) igneous rocks of equivalent chemical composition. In this regard the samples for the State Circle Shale and the Hamilton Group are abnormal; the range shown by the Dullingari shales are much closer to what could be regarded as the norm. The sediments from the Kimberley area generally show ranges similar to that of the Dullingari shales. Again, the mean of this restricted Rb/Sr range is generally much higher than for equivalent igneous rocks: samples which have very low Rb/Sr values relative to the average rock and would help to define more accurately the initial Sr$^{87}$/Sr$^{86}$ are very rare.

7) The Rb/Sr of shales is normally higher in value than the source area from which they were derived. This point is brought out quite strongly in Fig. A-10 where the average Rb/Sr composition of each shale unit has also been plotted. The assumption again is that the shale samples for which analyses are available are representative of their respective units. It is obvious that for most units there is a marked Rb enrichment compared to the source material. Only the Mt. John Shale and Pincombe Formation have Rb/Sr values comparable to the Lamboo Complex, but even these do show some Rb enrichment. This diagram emphasizes the role that ion absorption and exchange plays in the formation of clay minerals in a marine environment, a point strongly stressed by clay mineralogists.
8) Isotopic homogenization of the shale components with the marine environment is rare. Where it appears to have occurred this could well be fortuitous and represent a source area which, by chance, had a $\text{Sr}^{87}/\text{Sr}^{86}$ value equivalent to that of seawater, or it could be the partial degrading of the clay components during weathering, etc. Very few examples are available where the initial $\text{Sr}^{87}/\text{Sr}^{86}$ values of sediments are unequivocally the same as that of the marine environment. Only material precipitated directly or biogenically extracted from sea water would be expected to have its $\text{Sr}^{87}/\text{Sr}^{86}$.

9) Results obtained by leaching experiments on shales must be interpreted with caution. Selective removal of isotopes or elements can occur when acid treatment is used. In the case of the Dullingari shales, enhancement of the leach in $\text{Sr}^{87}$ has apparently occurred, the resultant age being less than a minimum estimate of the time of deposition.

10) A most important point which comes from the detailed work on the State Circle Shale, is that weathering and oxidation appear to have no effect on the apparent age given by the shale material. This has far-reaching consequences on the data for the Kimberley rocks; the analyses can now be accepted with much greater confidence. Since the majority of all sedimentary samples are extracted from surface outcrops, this applies to all shale dating work. Just why this is so is not known, but it is possible
that since the components have been derived through at least one cycle of weathering, they may be relatively isotopically stable in such an environment.
ADDENDUM

Further work carried out into the effects of leaching on the Dullingari shale samples since the printing of this thesis shows that an error has been made in the data for 9496 total rock. This alters the interpretation previously given. The full results of these latest experiments will be reported elsewhere.

The Rb$^{87}$/Sr$^{86}$ ratio of 9496 total rock now has a value of 4.104; the leach portion of this sample then has a Rb$^{87}$/Sr$^{86}$ of 0.314 which plots close to the data for 9502. The further results for the leaching of other total rock samples confirms this latter alignment of data points. There is therefore no evidence from this data to justify the suggestion that preferential movement of Sr$^{87}$ has resulted from the chemical treatment. In fact the indications are that with increased normality of acid or increased time of leaching Rb is increased in the supernatant liquid without any significant increase in the common Sr content. However, the radiogenic Sr$^{87}$ is increased proportional to the Rb content so that linearity is retained.

This is not to say that preferential enhancement in radiogenic Sr$^{87}$ never occurs but merely points out that it cannot be supported in this instance. The author still considers that the mechanism is theoretically possible.
particularly in cases where initial Sr\(^{87}/Sr^{86}\) homogenization has not occurred between the mineral phases of a total rock shale sample.

In the case of the Dullingari shales initial Sr\(^{87}/Sr^{86}\) homogenization has apparently occurred since the leach - total rock - residue joins of each sample define a common age. This age is very close to the suggested value of Kulp (1961) and reflects the period of Sr\(^{87}/Sr^{86}\) equilibration within each sample. This event will most logically have taken place after the deposition of the sediments and the age must therefore be considered as a minimum estimate of the time of deposition.

This alteration in interpretation does not effect the general conclusions made concerning the interpretation of Rb-Sr results from argillaceous material.
APPENDIX B

Rb-Sr METHOD OF AGE DETERMINATION CALCULATION
ERROR MAGNIFICATION
TREATMENT OF RESULTS
TESTING AND POOLING ISOCHRON RESULTS
MASS SPECTROMETRY
COLLECTION OF SAMPLES
PREPARATION OF SAMPLES
CHEMICAL PREPARATION
CONTAMINATION
Rb-Sr METHOD OF AGE DETERMINATION

Calculation

When nuclear disintegration of a radioactive nuclide takes place, the rate of decay is proportional to $N$, the number of reactant nucleii present, i.e.,

$$\frac{-dN}{dt} = \lambda N$$

where $N$ is the number of radioactive atoms of original parent material remaining after time $t$, and $\lambda$ is a decay constant representing the probability that an atom will disintegrate in unit time (Hamilton, 1965).

Integration of the above gives

$$N = N_0 e^{-\lambda t}$$

the explicit number of parent atoms remaining after time $t$, where $N_0$ is the original number of atoms.

Since it is convenient to measure time backwards from the present, the basic equation of geochronology becomes

$$\frac{D}{P} = e^{\lambda t} - 1$$

where $D$ is the present number of atoms of daughter nuclide formed during a time $t$, and $P$ is the present number of atoms of parent nuclide, $\lambda$ is the decay constant of the parent nuclide, and $t$ is the time measured from the present. The apparent age $(t)$ of a sample is then given by the equation

$$\lambda t = \log_e(1 + \frac{D}{P})$$
In terms of the Rb-Sr method of age determination, the $\beta^-$ decay of $\text{Rb}^{87}$ to $\text{Sr}^{87}$ may be written as

$$\text{Rb}_i^{87} = \text{Rb}_p^{87} e^{\lambda t}$$

where $\text{Rb}_i^{87}$ is the number of atoms of $\text{Rb}^{87}$ initially present at time $t = 0$, and $\text{Rb}_p^{87}$ is the number of atoms now present after the elapse of time $t$.

Hence $\text{Rb}_p^{87} + r\text{Sr}^{87} = \text{Rb}_p^{87} e^{\lambda t}$

where $r\text{Sr}^{87}$ is the radiogenic $\text{Sr}^{87}$ produced between the initial and present time, and

$$\lambda t = \log_e (1 + \frac{r\text{Sr}^{87}}{\text{Rb}_p^{87}})$$

or

$$\lambda t = \theta - \theta^2/2 + \ldots.$$ 

where $\theta = \frac{r\text{Sr}^{87}}{\text{Rb}_p^{87}}$. The higher terms of the expansion can be ignored.

For Palaeozoic and younger samples, it is customary and legitimate for the assumption to be made that $\lambda t \neq (e^{\lambda t} - 1)$ for all but the oldest rocks, and the above equation becomes

$$\lambda t = \frac{r\text{Sr}^{87}}{\text{Rb}_p^{87}}$$

Expansion of the above equation results in an equation of familiar form, i.e.,

$$\lambda t = \frac{r\text{Sr}^{87}}{\text{Rb}_p^{87}}$$
The basic assumption is, of course, that the parent and daughter isotopes have comprised a closed chemical system from the time of generation of the system.

To solve this equation it is necessary to determine the amounts of $\text{Sr}^{86}$ and $\text{Rb}^{87}$ present within the samples for which an age is desired, and also to measure or calculate the $R_p$. The quantity $R_i$ must either be assumed or determined by some independent method.

The age determination technique depends on the use of mass spectrometers which, because of the large numbers of variables involved, are not suited to absolute calibration. However, they are ideal for the measurement of isotope ratios. It is therefore necessary to incorporate an internal standard (spike or tracer) into the sample being measured so that the absolute amounts of isotopes in which we are interested can be calculated by comparison with the spike. (This, in short, is the method of isotope dilution.) For this calculation to be made and related to the age equation, it is necessary to express the quantities $\text{Sr}^{86}$ and $\text{Rb}^{87}$ in
terms of measurable ratios which will be a combination of both sample and spike.

The general form of this expansion has been detailed by Riley and Compston (1962) and is reproduced here.

Consider a mixture of the isotopes a and b where any number of sources \( j \) contribute. Let \( Z \) be the number of atoms of a particular isotope present, and let \( R_m \) be the resulting isotopic ratio \( a/b \) of the mixture, i.e.,

\[
R_m = \frac{Z_1^a + Z_2^a + Z_3^a + \ldots}{Z_1^b + Z_2^b + Z_3^b + \ldots}
\]

\[
= \frac{\sum_j Z_j^a}{\sum_j Z_j^b}
\]

but

\[
R_j = \frac{Z_j^a}{Z_j^b}
\]

so that

\[
R_m = \frac{\sum_j R_j Z_j^b}{\sum_j Z_j^b}
\]

whence

\[
\sum_j Z_j^b (R_j - R_m) = 0
\]

Applying this to the isotopes of Sr for age determination where the Sr\(^{86}\) spike (s) and sample (sa) are the only contributors to the dilution, and \( m \) is the mixture, we get

\[
Z_{sa}^{86} (A_s - A_m) + Z_{sa}^{86} (A_{sa} - A_m) = 0
\]
where \( A = \frac{\text{Sr}^{88}}{\text{Sr}^{86}} \)

\[
Z_{86}^{sa} = \frac{Z_s^{86}(A_m - A_s)}{A_{sa} - A_m}
\]

\[
= Q \times Z_s^{86}
\]

where \( Q = \frac{\frac{\text{Sr}^{88}}{\text{Sr}^{86}}_m - \frac{\text{Sr}^{88}}{\text{Sr}^{86}}_s}{\frac{\text{Sr}^{88}}{\text{Sr}^{86}}_sa - \frac{\text{Sr}^{88}}{\text{Sr}^{86}}_m}
\]

the concentration (\( \mu m/g \)) of \( \text{Sr}^{86} \) in the sample is then equal to

\[
Q \times \mu_s \times \frac{W_s}{M}
\]

where \( \mu_s \) is the concentration (\( \mu m/g \)) of \( \text{Sr}^{86} \) in the spike solution; \( W_s \) is the weight of spike solution used; \( M \) is the weight of mineral or rock sample used.

Also \( Z_s^{86}(R_s - R_m) + Z_{sa}^{86}(R_{sa} - R_m) = 0 \)

where \( R = \frac{\text{Sr}^{87}}{\text{Sr}^{86}} \)

\[
Z_{sa}^{86}(R_{sa} - R_m) = Z_s^{86}(R_m - R_s)
\]

Substituting from above

\[
Q Z_s^{86}(R_{sa} - R_m) = Z_s^{86}(R_m - R_s)
\]

\[
R_{sa} = R_p = \frac{(R_m - R_s) + Q R_m}{Q}
\]

\[
= \frac{R_m (1 + Q) - R_s}{Q}
\]
Rb$^{87}$ is calculated in a manner exactly analogous to the calculation for Sr$^{86}$, the difference being that the ratio used is Rb$^{85}$/Rb$^{87}$.

The use of a double spike composed of Sr$^{86}$ and Sr$^{84}$ for Sr analyses allows correction of the measured ratios to offset the effects of mass discrimination between various mass spectrometers, and mass fractionation. Since the Sr$^{86}$/Sr$^{84}$ of the spike is known, usually by gravimetric determination, the "true" Sr$^{86}$/Sr$^{84}$ of the mixture of spike and sample can be calculated and compared with the actual measurement of this ratio. Proportional corrections are then applied to all measured ratios. This is an iterative method of correction.

The "true" value of the mixture of spike and sample Sr$^{86}$/Sr$^{84}$ may be calculated as follows.

$$Z_s^{86}(B_s - B_m) + Z_{sa}^{86}(B_{sa} - B_m) = 0$$

where $B = Sr^{84}/Sr^{86}$

Then $Z_s^{86}(B_s - B_m) = Z_{sa}^{86}(B_m - B_{sa})$

Substituting $Z_s^{86}(B_s - B_m) = Z_s^{86}Q(B_m - B_{sa})$

$$B_m = \frac{B_s + Q B_{sa}}{1 + Q}$$

Then the "true" Sr$^{86}$/Sr$^{84}$ = Sr$^{86}$/Sr$^{84}$ $\times \frac{1 + Q}{1 + kQ}$

where $K = \frac{B_{sa}}{B_s}$
In the case of the double spike used for the majority of this work, \( \text{Sr}^{88}/\text{Sr}^{86} = 0.1309, \text{Sr}^{86}/\text{Sr}^{84} = 10.521, \) and \( k = 0.6053. \)

This "true" value of \( \text{Sr}^{86}/\text{Sr}^{84} \) is then compared with the actual measured value and iterative corrections applied. Correction of the \( \text{Sr}^{88}/\text{Sr}^{86} \) will be of the same order as for \( \text{Sr}^{86}/\text{Sr}^{84} \); the corrections for \( \text{Sr}^{87}/\text{Sr}^{86} \) (one mass unit apart) will be half this value.

Calculation of the \( \text{Sr}^{86} \) concentration for the corrected \( Q \) value will then be independent of machine discrimination but directly dependent upon any error in the value taken for \( \text{Sr}^{88}/\text{Sr}^{86} \).

For analyses where a single \( \text{Sr}^{86} \) spike has been used, correction for the machine discrimination is not easily calculated. Some measure of this correction factor can be gained by comparison of the measured and calculated values for \( \text{Sr}^{87}/\text{Sr}^{86} \) but this method is not very satisfactory since it is subject to inherent errors. The more usual treatment is to apply a blanket correction factor to the ratios measured, the value of this factor being based on previous knowledge gained from the mass spectrometric analyses of multiple samples of known isotopic composition.

Using a single \( \text{Sr}^{84} \) spike, corrections can be applied similar to those already detailed for the double spike; in this case the corrections are applied using the ratio
Sr\textsuperscript{88}/Sr\textsuperscript{86} as the internal standard which will consist almost entirely of sample material with negligible contribution from the spike. Theoretically the same procedure could be used for the single Sr\textsuperscript{86} spike, comparisons being made with the Sr\textsuperscript{88}/Sr\textsuperscript{84} of the mixture, but because of the increased errors involved in measuring ratios between isotopes of markedly different concentrations the method is unsatisfactory.

The method of iterative correction may be avoided by expressing the correction procedure in terms whereby the value of the corrected ratio can be rapidly and accurately determined. The introduction of a computer service facilitated the calculations.

Calculations based on the use of a double spike may be expressed in the form of a quadratic equation \((AX^2 + BX + C = 0)\) whose solution is the positive root of the equation, i.e.,

\[
X = \frac{-B + \sqrt{B^2 - 4AC}}{2A}
\]

where \(X\) is the "true" \textsuperscript{88}Sr/\textsuperscript{86}Sr value (\(= U_{\text{mix}}\)) of the mixture of sample and spike. The basic equations are

\[
\frac{U_m - U_{\text{mix}}}{U_m} = \frac{P_m - P_{\text{mix}}}{P_m} \quad \text{................ (1)}
\]

\[
P_{\text{mix}} = \frac{P_S (1 + Q)}{(1 + Q P_S/P_{sa})} \quad \text{................ (2)}
\]

\[
Q = \frac{U_{\text{mix}} - U_s}{U_{sa} - U_{\text{mix}}} \quad \text{................ (3)}
\]
where \( U = \frac{Sr^{88}}{Sr^{86}} \) and \( P = \frac{Sr^{86}}{Sr^{84}} \).

Substituting (3) in (2)

\[
P_{mix} = \frac{\left(1 + \frac{U_{mix} - U_s}{U_{sa} - U_{mix}}\right)}{\left(1 + \frac{P_{mix}}{P_{sa}}\right)\left(\frac{U_{mix} - U_s}{U_{sa} - U_{mix}}\right)} = \frac{P_s (U_{sa} - U_s) P_{sa}}{P_{sa} (U_{sa} - U_{mix}) + P_s (U_{mix} - U_s)} \quad \ldots \quad (4)
\]

From (1) \( P_{mix} = \frac{U_{mix} P_m}{U_m} \) \quad \ldots \quad (5)

Then \( \frac{U_{mix} P_m}{U_m} (P_{sa} U_{sa} - P_{sa} U_{mix} + P_{mix} U_{mix} - P_{sa} U_s) \)

\[
= P_s P_{sa} (U_{sa} - U_s) + U_{mix} 2 \left(\frac{P_m (P_s - P_{sa})}{U_m}\right) + U_{mix} \left(\frac{P_m (P_{sa} U_{sa} - P_{sa} U_s)}{U_m}\right) + P_s P_{sa} (U_{sa} - U_s) = 0
\]

This is the equation for the case where no allowance is made for discrimination between ratio measurements. In the general case

\[
A = \frac{P_m (P_s - P_{sa})}{U_m}
\]

\[
B = \frac{P_m (P_{sa} U_{sa} - P_{sa} U_s)}{U_m} + P_m (f - 1)(P_s - P_{sa})
\]

\[
C = P_m (f - 1)(P_{sa} U_{sa} - P_{sa} U_s) - f P_s P_{sa} (U_{sa} - U_s)
\]
where \( f \) is the mass discrimination factor between measurements of the ratios \( \text{Sr}^{88}/\text{Sr}^{86} \) and \( \text{Sr}^{86}/\text{Sr}^{84} \). In most instances \( f \) is very close to unity in value and the added terms in the expressions become negligible.

In a manner similar to that above, expressions may be derived for the "true" \( \text{Sr}^{88}/\text{Sr}^{86} \) value of the mixture of spike and sample when the single \( \text{Sr}^{84} \) spike is used. The basic equations are

\[
\frac{S_{\text{mix}}}{S_m} = \frac{U_m}{U_{\text{mix}}} \quad \ldots \ldot
When allowance is made for discrimination in ratio measurement the general values are

\[
A = \left( \frac{1}{P_s} - \frac{1}{P_{sa}} \right)
\]

\[
B = \frac{U_s}{P_{sa}} - \frac{U_{sa}}{P_s} + \frac{(U_{sa} - U_s)(1 - 1/f)}{P_m}
\]

\[
C = \frac{U_m(U_{sa} - U_s)}{fP_m}
\]

In the above case the relationship is expressed as a quadratic equation but it may be equally well expressed as a linear equation such as

\[
U_{mix} = X = \frac{U_m(U_sP_{sa} - U_{sa}P_s)}{U_m(P_{sa} - P_s) - P_m(U_{sa} - U_s)}
\]

or for the general case,

\[
U_{mix} = X = \frac{fU_m((U_sP_{sa} - U_{sa}P_s) + P_m(f-1)(U_{sa} - U_s))}{fU_m(P_{sa} - P_s) - P_m(U_{sa} - U_s)}
\]

Having established the "true" value for Sr\(^{88}/\text{Sr}\(^{86}\), correction of other measured ratios and the calculation of the various quantities follows as outlined before.

Measurements of unspiked Sr\(^{87}/\text{Sr}\(^{86}\) (to independently determine \(R_P\)) may be normalized directly from the accompanying measurement of Sr\(^{88}/\text{Sr}\(^{86}\). The correction is half the percentage difference between the Sr\(^{88}/\text{Sr}\(^{86}\) measured and that value of Sr\(^{88}/\text{Sr}\(^{86}\) assumed for the sample, i.e., \((A_{sa} - A_m)100/2 A_{sa}\).
In this work, the data for the major portion dealing with the geochronology of the Kimberley rocks have been normalized to a Sr^{88}/Sr^{86} value of 8.340 (Compston et al., 1965). Since the measurements were made on the same mass spectrometer as used by Compston et al. and the same laboratory techniques were used, the use of this value was considered to be justified.

During the later work on the State Circle Shale, etc., the more commonly used value of 8.3752 (Faure and Hurley, 1963) for Sr^{88}/Sr^{86} was used. These samples were also analysed on different mass spectrometers.

Use of either one of these Sr^{88}/Sr^{86} values makes no significant difference to the apparent age of the sample given by the isochrons. There is a difference of about 0.0015 in the Sr^{87}/Sr^{86} however, for most samples with ratios less than 1.0, the lower value for Sr^{88}/Sr^{86} giving the lower Sr^{87}/Sr^{86}. For samples having Sr^{87}/Sr^{86} greater than about 1.0, the difference becomes greater.

The value of Rb^{85}/Rb^{87} = 2.600 has been used throughout (Shields et al., 1963).

ERROR MAGNIFICATION

The accuracy of the determination of Rb^{87} and Sr^{86} depends on errors in the factors μs, ws, and M, and Q. The 95% confidence limits for μs are approximately ± 1.0% for long term variations, and ± 0.1% for ws and M. These
percentage errors are directly reflected as the same percentage errors in Rb$^{87}$ or Sr$^{86}$.

However, the errors in Q are somewhat magnified by a factor termed error magnification which depends on the values of $A_m$, $A_s$, and $A_{sa}$, where $A$ is either Rb$^{85}$/Rb$^{87}$ or Sr$^{88}$/Sr$^{86}$. For mixtures where $A_s$ and $A_{sa}$ are known, the fractional error in Q will exceed the fractional error in $A_m$ by the error magnification factor, i.e.,

$$\frac{\Delta Q}{Q} = \frac{\Delta R}{R} \times B$$

For the analysis of Rb or Sr, $B$ is given by the equation

$$B = \frac{R_m(R_{sa} - R_s)}{(R_{sa} - R_m)(R_m - R_s)}$$

which for the particular spikes used in this work, have a minimum value of 1.2 for Rb ($A_{sa} = 2.600$) and 1.35 for Sr ($A_{sa} = 8.34$). Predetermined knowledge of the Sr content of the samples, coupled with the known isotopic composition of the spike allows for $A_m$ to be chosen for each particular sample so that $B$ is very close to the minimum.

**TREATMENT OF RESULTS**

Rb-Sr age determinations may be treated in two ways. Firstly the data for each sample may be considered independently and an apparent age calculated. To do this it is necessary to assume a value for the initial Sr$^{87}$/Sr$^{86}$. For samples having high present day Sr$^{87}$/Sr$^{86}$ values the age will be virtually independent of reasonable estimates
of this assumed initial value. However, for samples with low $\text{Sr}^{87}/\text{Sr}^{86}$ the age can be markedly dependent on the value of the assumed initial $\text{Sr}^{87}/\text{Sr}^{86}$. Apparent ages obtained in this manner must be interpreted on the basis of the expectation derived from a knowledge of geological relationships or consideration of data from other coeval samples.

Restrictions to the usefulness of this method are the usual dependence of the age on the assumed initial $\text{Sr}^{87}/\text{Sr}^{86}$ value, or where the age is dependent of this value (e.g., biotite, muscovite, K-feldspar), the reliability of the material used. Where coeval samples exist which have been closed chemical systems and have identical initial $\text{Sr}^{87}/\text{Sr}^{86}$ values, then it is possible to solve the simultaneous equations for a common initial $\text{Sr}^{87}/\text{Sr}^{86}$ and common age.

The second method of treatment which is much more valuable is the graphical expression of the data. Compston and Jeffery (1959) expressed their data on a graph with axes of $\frac{r\text{Sr}^{87}}{\lambda \text{Rb}^{87}}$ and $\frac{\text{Sr}^{87}}{\lambda \text{Rb}^{86}}$. The relationship

$$T \frac{r\text{Sr}^{87}}{\lambda \text{Rb}^{87}} = \frac{\text{Sr}^{86}}{\lambda \text{Rb}^{87}} (R_p - R_i)$$

is the equation of a straight line with gradient $\frac{\text{Sr}^{86}}{\lambda \text{Rb}^{87}}$ and $R_i$ the independent variable. Data for each sample can therefore be expressed as a straight line. Convergence of a series of data lines to a single point indicates the
common initial $\mathrm{Sr}^{87}/\mathrm{Sr}^{86}$ for the suite of samples; from this information a common age can be calculated. Where convergence does not occur, it is immediately obvious and suggests that the samples may not be coeval, or that some have been open chemical systems, or that the samples have varying initial $\mathrm{Sr}^{87}/\mathrm{Sr}^{86}$ values. The method is extremely useful for the study and interpretation of systems such as a total rock and its component minerals.

A more widely used method of graphical expression is that introduced by Hales (1960) and discussed by Nicolaysen (1961). From the relationship

$$\frac{r_{\mathrm{Sr}^{87}}}{\mathrm{Rb}^{87}} = \frac{\mathrm{Sr}^{86}}{\mathrm{Rb}^{87}} (R_p - R_i)$$

we get

$$R_p = \frac{r_{\mathrm{Sr}^{87}} (\mathrm{Rb}^{87})}{\mathrm{Rb}^{87} (\mathrm{Sr}^{86})} + R_i$$

which is the equation of a straight line with slope $r_{\mathrm{Sr}^{87}}/\mathrm{Rb}^{87}$ and $\mathrm{Rb}^{87}/\mathrm{Sr}^{86}$ the independent variable.

The method of Nicolaysen is to represent the analytical data for each sample on a diagram by plotting $\mathrm{Rb}^{87}/\mathrm{Sr}^{86}$ vs $R_p$. Coeval and cogenetic samples which have remained closed chemical systems with respect to Rb and Sr since formation, will plot along a straight line called an isochron. This method of graphical expression lends itself readily to statistical treatment, the fitting of a line by the least squares method of analysis.
The slope of the line will be proportional to the age of the samples, and the intercept of this line with the $R_p$ axis gives the initial $\text{Sr}^{87}/\text{Sr}^{86}$ common to all samples at the time of their chemical closure with respect to Rb and Sr. For samples of igneous or metamorphic origin, the value of this common $R_1$ is of marked importance in terms of the possible genesis of these rocks. The study and interpretation of these values has now developed into a line of research in its own right.

For sedimentary rocks (shales) the common value of $R_1$, or variations in this ratio (i.e., multimodal distribution of $R_1$ values), gives important information on the possible provenance area of the samples and/or the post-weathering history. Consideration of this information in conjunction with added data on the stratigraphy and geological history of an area gives further information on the reliability of the apparent ages in terms of the time of deposition of the sediments. Similar considerations also apply to the reliability of the apparent ages of igneous rocks.

The failure of coeval and cogenetic samples to fit an isochron to within experimental error implies that some form of elemental and/or isotopic redistribution has taken place, the further inference normally being that this redistribution has occurred subsequent to the initial chemical closure of the samples. For igneous rocks these
assumptions are usually correct but there is always the possibility that those samples which lie outside the acceptable confidence limits of the isochron may be relics reflecting some previous period of chemical closure. In such instances the isochron formed by the majority of samples would represent a period of $^{87}\text{Sr}/^{86}\text{Sr}$ homogenization, such as a metamorphic event, which had taken place more recently than the real time of formation of the samples.

The interpretation of discordancy in sedimentary samples such as shales is much more complex. In the first instance there is always the possibility of situations occurring such as those already mentioned for igneous rocks. However, a further and more far-reaching complication is the nature of shales themselves. It will be shown later that a multimodal distribution of initial $^{87}\text{Sr}/^{86}\text{Sr}$ values is not uncommon within a suite of shale samples. This distribution is a primary feature probably reflecting variations in the provenance of various levels of the sedimentary pile and incomplete $^{87}\text{Sr}/^{86}\text{Sr}$ homogenization in situ. Shale samples which do not fit an isochron to within experimental error should therefore be considered carefully in the light of this new information.

The normal method of statistical analysis is that of least squares fitting of the isochron to the data. In the classical model, the assumption is that $X (\text{Rb}^{87}/\text{Sr}^{86})$ is
free of error and that all deviation occurs in $Y (\text{Sr}^{87}/\text{Sr}^{86})$. The line of "best fit" occurs when the sum of squares of the difference between the observed and estimated values of $Y$ is a minimum. Taking the equation of a straight line to be $y = mx + b$, the expression to be minimized is

$$\sum (Y_i - b - mX_i)^2$$

This model is not valid for use in Rb-Sr age determination work since it is known that error also exists in the $\text{Rb}^{87}/\text{Sr}^{86}$ parameter. The statistical treatment used throughout this thesis is the "two-error" regression method of McIntyre et al. (1966). This method takes into account the known variance in $Y$ which may have two values depending on whether the $\text{Sr}^{87}/\text{Sr}^{86}$ is directly measured or calculated, and allows for the non-uniform variance in $X$. McIntyre et al. have shown that the variance in $\text{Rb}^{87}/\text{Sr}^{86}$ is proportional to $(\text{Rb}^{87}/\text{Sr}^{86})^2$, i.e., the variance in $X_i$ is equal to $C(X)^2$ where $C$ is a constant.

The expression to be minimized is now

$$\sum W_i(Y_i - b - mX_i)^2 = FU$$

where $X_i$ and $Y_i$ are the means of $\text{Rb}^{87}/\text{Sr}^{86}$ and of $\text{Rb}^{87}/\text{Sr}^{86}$ over $ND_i$ replicate analyses from a rock specimen.

$W_i = 1/(\text{Var}Y_i + m^2 \text{Var}X_i)$; $\text{Var}Y_i$ is the replicate variance of $\text{Sr}^{87}/\text{Sr}^{86}$ divided by $ND_i$; $\text{Var}X_i = CX_i^2/ND_i$. $M$ and $b$ are the parameters to be determined.

The normal equations are
\[ \sum_i W_i(Y_i - b - mX_i) = 0 \quad \ldots \quad (1) \]

and

\[ \sum_i W_i(Y_i - b - mX_i)X_i + m \sum \text{Var}_XW_i(Y_i - b - mX_i)^2 = 0 \quad \ldots \quad (2) \]

Substituting for b from (1) in (2) gives a cubic equation in m which can be solved iteratively commencing with an approximate estimate of m.

This is the Model I isochron of McIntyre et al. which assumes all error to be experimental. A test of the goodness of fit of points to the isochron is given by the weighted sum of squares of the residual using values for b and m determined from the normal equations, divided by the expectation, i.e., \( \text{FU/N-2} \) which is equal to the mean square of weighted deviates (MSWD). The significance of this value may then be tested as an F variate with N-2 and the number of degrees of freedom of the estimates of VarX and VarY.

In the treatment of McIntyre, the limit to the value of MSWD for a Model I isochron has been placed at 1 which is equivalent to an F variate with infinity, infinity degrees of freedom. When the MSWD is greater than 1, the amount by which the residual variance exceeds experimental error is considered to be due to "geological effects". The calculation is then repeated up to three times using different models of distribution of this geological effect with recommendations as to which model is the more appropriate.

Model II assigns the geological variance to the \( \text{Sr}^{87}/\text{Sr}^{86} \) co-ordinate but in addition relates it
proportionally to the variance in X. This model is believed to be applicable to isochrons of cogenetic and coeval samples that have undergone slight redistribution of radiogenic Sr since crystallization and to more extreme cases of open-system behaviour.

Model III is based on the assumption that the geological effect assigned to the \( \text{Sr}^{87}/\text{Sr}^{86} \) is independent of the \( \text{Rb}^{87}/\text{Sr}^{86} \). This model is considered to be applicable to samples having different initial \( \text{Sr}^{87}/\text{Sr}^{86} \) values such as shales, some metamorphic rocks, and even samples from extensively distributed igneous rocks of the same suite.

Model IV is a combination of Models II and III allowing for both primary variation in the initial \( \text{Sr}^{87}/\text{Sr}^{86} \) values and post-chemical closure isotopic or elemental redistribution. The majority of igneous suites appear to fit this model and it is implicit in the assessment that samples defining this model are both coeval and cogenetic.

The ideal set of analytical data will define a Model I isochron and it is regarded as valid to at least consider the data in this light. In cases where the MSWD has a high value it is usually profitable to test any particular sample to see if it actually belongs to the population. An indication of those samples which are least likely to belong to the population is given by the ratio of \( (Y - b - mX)/\text{standard error}, \text{i.e.}, \text{Diff}/\text{SB} \), where the value
of this ratio is high compared to the value for the remaining samples. If after deleting such analyses a regression based on the remaining samples has a MSWD which is significantly reduced (at the 5% level), then there is a statistical justification for exclusion of the deleted samples.

Such treatment has been applied to the data throughout this thesis. This is particularly so for suites of shale samples where, because of the possible variation in the initial $^{87}\text{Sr}/^{86}\text{Sr}$ between samples, this treatment becomes necessary to obtain meaningful apparent ages. While the Model III assessment is designed to cope with such contingencies it is limited in its application to instances where a "small geological effect" (Turek, 1966) exceeds the known experimental errors. In many instances, the variation in initial $^{87}\text{Sr}/^{86}\text{Sr}$ of shales greatly exceeds what could be regarded as a small deviation.

The values for $\text{Var}_Y$ and $\text{Var}_X$ used throughout this work are those of McIntyre et al. (1966) and Turek (1966). It has been previously stated that $\text{Var}_X = C(X_i)^2$ where $C$ is a constant. The value of $C$ used throughout is $25.51 \times 10^{-6}$ (Turek, 1966) which is a pooled variance based on 34 degrees of freedom. $\text{Var}_Y$ has two values: for the calculated ratio the value is $1.73 \times 10^{-6}$ (73 DF) and for the measured ratios the value is $0.22 \times 10^{-6}$ (53 DF). Use of these values is justified since
a) much of the present work contributed to the assessments,

b) all analyses were carried out on the same MS2-SG mass spectrometer, and

c) all analyses took place under identical conditions in the same laboratory.

For data derived from the NAA or MS-X mass spectrometers, a maximum VarY of $0.22 \times 10^{-6}$ is applicable for both measured and calculated values of $\text{Sr}^{87}/\text{Sr}^{86}$; this is due to higher machine precision.

Based on the above estimates of the variances, the conservative test of the significance of the MSWD of the various Model I isochrons would be as an F variate with $N-2, 34$ DF.

TESTING AND POOLING OF ISOCHRON RESULTS

Throughout this thesis, the limits placed on the isochron ages and intercepts are calculated for the 95% level of confidence. Where no overlap occurs in these uncertainties, the results of each isochron can be said to be significantly different. However, in cases where overlap of the confidence limits does occur it is still possible for the ages and/or intercepts to be statistically distinct. A test of this distinction is given by the expression (Turek, 1966)

$$t_{\text{calc.}} = \frac{B_1 - B_2}{\left(\frac{\text{SE}_{B_1}}{2} + \frac{\text{SE}_{B_2}}{2}\right)^{\frac{1}{2}}}$$
where $B_1$ and $B_2$ are the slopes and $SE_{B_1}$, $SE_{B_2}$ the standard errors of the slopes of the respective isochrons. $t_{calc.}$ is approximately a "student's t" distribution with $K$ degrees of freedom given by the relationship
\[
\frac{((SE_{B_1})^2 + (SE_{B_2})^2)^2}{K} = \frac{(SE_{B_1})^4}{N_1 - 2} + \frac{(SE_{B_2})^4}{N_2 - 2}
\]
where $N_1$ and $N_2$ are the numbers of samples defining the respective isochrons.

$t_{calc.}$ is then compared with $t_{actual}$ for the appropriate degrees of freedom $K$ and the significance level of the slope differences determined.

An identical calculation is used to determine the significance of differences between intercepts.

The pooling and averaging of isochrons can be accomplished by regression of the sample populations. However, this is only valid if both the gradients and intercepts of the separate isochrons are identical or at least statistically indistinct.

The usual situation is that where the slopes of the isochrons are not significantly different but the intercepts are distinct. In such instances a mean weighted common age can be calculated which will satisfy the slope requirements of the various statistically indistinct contributory isochrons.

The mean weighted common slope is given by the relationship
B-23.

Mean \( B = \frac{B_1}{(SE_{B_1})^2} + \frac{B_2}{(SE_{B_2})^2} + \ldots \)

and the standard error of this common slope will be

\[
\text{SE of Mean } B = \left( \frac{1}{(SE_{B_1})^2} + \frac{1}{(SE_{B_2})^2} + \ldots \right)^{\frac{1}{2}}
\]

The approximate degrees of freedom (\( K \)) of the pooled slope are given by the relationship (Settenthweite, 1946)

\[
\left( \frac{B_1}{(SE_{B_1})^2} + \frac{B_2}{(SE_{B_2})^2} + \ldots \right)^2
\]

\[
\left( \frac{N_1 - 2}{(SE_{B_1})^2} + \frac{N_2 - 2}{(SE_{B_2})^2} + \ldots \right)
\]

The calculation is identical for pooling statistically indistinct intercepts from different isochrons.

**MASS SPECTROMETRY**

The machine used for the major portion of this work was a Metropolitan-Vickers type MS2-SG mass spectrometer, modified to allow for greater precision and sensitivity. The machine and modifications, together with statements of the efficiency and precision, have been described by Compston et al. (1965) and only a general statement will be made here.

The MS2-SG is a 6 inch radius of curvature, 90° sector machine in which the source is operated at a constant 2 kV.
Modification of the standard high voltage supply allowed for positive and negative variation of about 10 V between the centre and two side filaments of the triple filament bead, and a voltage variation of approximately 0-300V between the filament block and "D plates". Restrictions to the length of the beam divergence slit and the incorporation of a 0.004 inch defining slit further improved the resolution. Tail correction due to beam scatter was less than 0.1% under mass 87 and could be further reduced by overnight pumping.

The original d.c. amplifiers were replaced by a Carey Model 31 electrometer equipped with turret switch selection of input resistors and critical damping. The electrometer output was digitized to obtain maximum sensitivity and precision, and also monitored by chart recorder. The digitizing system comprises a Dymec Model 2211B voltage-to-frequency converter, a Hewlitt-Packard Model 522B counter and Hewlitt-Packard Model 560A digital recorder.

The different isotopes were compared by rapid peak switching of the magnetic field of the electromagnet. This peak switching was effected by push-button selection of pre-set values for the reference voltage of the magnet power supply. Field hysteresis was negligible after a short period of cycling of the magnet between the isotopes to be measured. The beam voltage was "counted" for 1 sec., immediately switched, and the second beam counted for the
same period of time after a fixed interval of 5 secs. This
delay time was found to be the time required for full and
consistent response of the magnetic field and amplifier.

Using the above system of comparison of beam intensities,
Compston et al. found that the sensitivity, using the
electronic equipment consistently in use for the measurement
of Sr isotopes, to be better than 0.05% for the ratios
$\text{Sr}^{88}/\text{Sr}^{86}$ and $\text{Sr}^{87}/\text{Sr}^{86}$.

Use was also made of a second commercially built mass
spectrometer. This machine, a 60° sector, 12 inch radius
Nuclide Associates Analysis mass spectrometer, was also
considerably modified to suit the particular needs of those
involved in radiometric age determinations. Full details of
these modifications and the precision of the machine are
being prepared by Dr P.A. Arriens of the Department of
Geophysics and Geochemistry, Australian National University.

However, while it may be said that the precision of a
single set of ratio measurements on the NAA machine is
superior to that of the MS2-SG, the ultimate results are
not significantly different. That is, the "geological
error" inherent in a suite of samples is much greater than
any error attributable to variation between machine precision.

The NAA machine differs radically from the MS2-SG in
the following features. The Nuclide utilizes a 6 kV
accelerating voltage which results in generally improved
sensitivity and resolution. This is further improved by the double pumping system, "independent" pumping of both source and analyzer tube, which results in a better ultimate vacuum and consequently a negligible gas-scatter and higher turnover of samples. The tail under mass 87 is at least 5 times smaller than for comparative conditions in the MS2-SG. The incorporation of extra defining slits to which adjustable potential differences can be applied also improve beam definition.

However, the major difference lies in the method of peak-switching. This is by push-button control of pre-set accelerating voltages. The response time of the magnet (some 20 secs.) makes magnet switching impracticable. Use of voltage switching introduces a constant mass discrimination effect which must be corrected for.

Measurement of the ion-beam intensities is again by Carey Model 31 electrometer connected to a digitized output and monitored on a chart recorder. The digitizing system is basically the same as for the MS2-SG except that superior models are used. The counter is a six-digit Hewlitt-Packard Model 5232A and the recorder is a Hewlitt-Packard Model 562A.

Modification of the voltage-to-frequency converter allows for "counting" of the peak intensities for 2 seconds rather than 1 sec. A 2 second period has been found to be the optimum for Sr analyses. Slight variations which may
occur in the beam intensity during counting are "smoothed"
using a 2 sec. count without impairing the precision obtained
through making comparisons with as little time between as
possible.

A third solid source mass spectrometer now in general use
has been designated the MS-X. All the mass spectrometer
analyses for the State Circle Shale and the Dullingari shales
were made on this machine. The unit was assembled from
commercially built parts and pieces fabricated by departmental
technicians. The working drawings, supervision of fabrication,
and assembly of all mechanical portions of the machine were
carried out by the author during the tenure of his post­
graduate work; the design and fabrication of the electronic
components were the responsibility of Mr E. Penikis of this
Department. The design of the machine was based on the
original ideas of Dr W. Compston.

The MS-X is a 6 inch, 90° sector, mass spectrometer
designed to incorporate what were considered to be the better
features of each of the machines previously discussed. The
machine has a double pumping system which produces vacuums
of better than $10^{-7}$ mm. of Hg in the source region during
operation, and better than $10^{-8}$ mm. of Hg at the collector
after approximately 15 mins. of pumping. The source design
is based on the MS2 pattern except that it operates at 6 kV
and the defining slit (0.004 inch) is fixed into the tube.
This offsets one disadvantage of the MS2 arrangement which is that beam alignment will vary between loadings because of slight misalignment of the ion-gun. The voltage between the "D plates" and filament block is variable as is the voltage between the side and centre filaments; this allows for maximum alignment of the ion beam before it passes through the defining slit.

The method of measuring the ion-beam intensities is precisely the same as for the Nuclide, incorporating a reed electrometer and digitizing equipment.

Peak-switching is by push-button preselection of the magnet current reference voltage as for the MS2. However, the magnet is different in that it is basically a permanent magnet with a field strength of 6,500 gauss. Secondary windings allow for a field shift of a maximum of + 200 gauss. Since the machine was designed specifically for Rb-Sr isotopic analyses, it covers only a restricted mass range. Peak switching is carried out by preselection within the + 200 gauss range; slight fluctuations in the magnet current supply then have little effect on the position of the peak centre. In all there is negligible drift and very little hysteresis: the latter may be removed after a few cycles between the particular mass units to be measured.

Resolution is far superior to that of the MS2, but not as good as for the Nuclide; tails of the order of 0.02% under
mass 87 are normally measured after 20 minutes of pumping. A simple method of adjustment of magnet-tube relationships makes the attainment of optimum peak shape (flat-topped) relatively easy. Under normal running conditions it is possible to resolve the mass 88 peak so that it is 10-15 volts wide at maximum intensity and is 20 V across the peak at half intensity. This is usually better than that routinely gained from the Nuclide. The precision of measurements obtained from the MS-X is equivalent to that obtained from the NAA machine.

Regardless of which mass spectrometer is used, a minimum of 10 comparisons of each pair of mass units is made for each set of ratios. For Rb measurements, the $\text{Rb}^{85}/\text{Rb}^{87}$ was determined independently on each side filament, the standard deviation of each set determined, and a weighted mean calculated. The procedure now is to take two or more sets of data from each side filament under varying running conditions and then calculate a weighted mean. This procedure helps to offset as far as is possible the effects of discrimination during measurements.

Strontium isotope ratio measurements were more complex because of the necessity (and ability) to normalize ratios by the equations quoted earlier, thus correcting for mass discrimination and fractionation.

Using double spike (combined $\text{Sr}^{86}$ and $\text{Sr}^{84}$) and normalizing ratios to the "gravimetric" value of the spike
Sr$^{86}$/Sr$^{84}$, the usual sequence of ratio measurements was $86/84$, $88/86$, $87/86$, $86/84$. Correction for Rb$^{87}$ contamination of the Sr$^{87}$ peak was made by measuring the Rb$^{85}$ before and after the $87/86$ set of ratios, correcting to Rb$^{87}$ by dividing Rb$^{85}$ by the isotope ratio of Rb$^{85}$/Rb$^{87}$ (2.600), and, by linear interpolation, subtracting the appropriate amount from each mass 87 peak before calculation of the Sr$^{87}$/Sr$^{86}$.

Fractionation was corrected for by extrapolating between the difference in measurements of the internal standard (in this case Sr$^{86}$/Sr$^{84}$) taken at the beginning and end of the run.

The use of a single Sr$^{84}$ spike is basically the same as for the double spike: corrections, numbers of comparisons, etc., are precisely the same. The major difference lies in the fact that normalization and fractionation corrections are now made by comparison of the measured Sr$^{88}$/Sr$^{86}$ ratio with the assumed value of this ratio for the sample (i.e., either 8.340 or 8.3752). The sequence of ratio measurements is therefore $88/86$, $86/84$, $87/86$, $88/86$. Corrections for within-run fractionation can be more accurately determined by measuring a further set of 88/86 ratios between the 86/84 and 87/86 sets. The sequence then becomes $88/86$, $86/84$, $88/86$, $87/86$, $88/86$.

Percentage tail corrections for each ratio set are estimated from the chart record of the mass spectra.
COLLECTION OF SAMPLES

Igneous and high-grade metamorphic rocks were sampled by drilling and blasting. Well exposed areas, free from joints, veins, and fractures were selected, drilled to a depth of from 18" to 2', and blasted using A.N. gelignite "60". Approximately 50 pounds of "fresh" rock was then collected from the exposed face.

The depth of weathering is unknown in the Kimberley region, but it can be assumed by comparison with similar areas where drilling or mining has determined the depth, that it is of the order of hundreds of feet. Therefore, while the outer shell of strongly weathered material is avoided, the material collected is still within the weathering zone and can only be regarded as the freshest available.

The collection of suitable material from shale beds is a problem. All exposures show marked fracture or slaty cleavage and shear jointing; weathering and deposition of secondary material are sometimes obvious along the parting planes. The resultant blocks of shale vary considerably and are friable; decomposition through various agencies is marked.

To decrease the possible effects surface weathering and leaching may have on the apparent age of the rocks, only cliff sections were sampled where possible. The outer 6" to 1' was removed and samples taken from the more compact and less altered material. Each block of shale extracted
was chipped until a compact central (usually ovoid in shape) portion was exposed. This was the sample used for analysis. Sampling was done at approximately 10' vertical intervals through each site.

**PREPARATION OF SAMPLES**

**Crystalline Rocks**

Handspecimen size samples (greater than 300 g.) were crushed using jaw and roller crushers, to pass through B.S. sieve No.36 (422μ). A portion of approximately 40 g. weight was taken from this crush by repeated use of a modified Jones type splitter (c.f. Otto, 1937). The split was further crushed to pass through a B.S. sieve No.100 (152μ). Crushing was done by hand using an agate mortar and pestle; mechanically using a sample mixer mill with tool steel vial and ball, or a Siebtechnik vibratory grinder, type T100 with tungsten carbide grinding stone and ring. A final sample (of approximately 10 g.) was extracted by repeated use of a microsplitter.

The use of both mechanical mills and repetitive splitting ensured, as far as possible, homogeneity and representativeness of the final rock sample. Contamination was kept to an absolute minimum by meticulous cleaning of all apparatus and the crushing of large quantities of sample. In this way any remnant material was diluted to such a high degree that it became negligible. Later analyses gave no indication of any cross contamination.
Shales

Samples of shale were crushed to less than B.S. sieve No.100 (152μ) using either an agate mortar and pestle, sample mixer mill, or Siebtechnik vibratory grinder. Preliminary crushing was by hand in a manganese steel mortar and pestle. A microsplitter, used repeatedly, extracted the final sample of about 20 g.

The size of the initial handspecimen varied considerably from the 20 g. minimum to approximately 150 g. and depended entirely on the availability of suitable material.

Minerals

The amount of whole rock sample crushed for mineral extraction was governed by the modal composition of the rock, 1 g. of 99% pure mineral concentrate being considered a minimum quantity. To obtain this purity, most separations were carried out in the B.S. sieve No.60 to 100 (251μ - 152μ) grainsize range.

Normal methods, involving heavy liquids (tetrabromoethane and methylene iodide) and magnetic separation, were used for the separation of K-feldspar, plagioclase, biotite, muscovite, and pyroxene from the various samples.

Glauconite was separated without using heavy liquids. Burst (1958) discusses the variable mineral composition of "glauconite" and Weaver (1958) has shown the ability of clay minerals to absorb cations. To cut possible reagent contamination to a minimum, "dry" methods of separation were employed.
CHEMICAL PREPARATION

The standard method of chemical preparation of rock samples and extraction of Rb and Sr for isotope dilution analyses as used in this laboratory is described in detail in Compston, Lovering, and Vernon (1965). The method is outlined below, with modifications where necessary for the particular samples used in this work.

A minimum 0.5 g. quantity of the powdered rock sample was weighed into a 100 ml. platinum dish, wet with demineralized water, and 100 ml. of 48% hydrofluoric acid added. The mixture was allowed to stand for at least one hour at room temperature and then slowly brought to dryness on a water bath. 5 ml. of hydrofluoric acid and 5 ml. of 70% perchloric acid were added, the hydrofluoric acid evaporated on the water bath, and the remainder brought to dryness on a hot plate. The residue was dissolved in about 30 ml. of 2.5N HCl, transferred to a tared 100 ml. Pyrex glass beaker with Parafilm cover, and demineralised water added to bring the nett weight of solution to approximately 45 g. The solution was warmed to ensure complete mixing, then left to cool.

The cool solution was weighed, and separate aliquots for each element weighed into 30 ml. Pyrex glass beakers, the amount of solution being chosen to contain 7.5 μg. of common Sr and 15 μg. of Rb for strontium and rubidium determination respectively. Tracer solutions containing
about 3.5 µg. of Sr$^{86}$ and Sr$^{84}$, and 6 µg. of Rb$^{87}$ were added to the respective aliquots and the "spiked" aliquots taken to dryness. These proportions of common Sr to spike Sr were found to be the optimum values for minimum error magnification. The residues were dissolved in 5 ml. of hydrochloric acid, transferred to cation exchange columns, eluted with hydrochloric acid and the required fraction collected. This was evaporated to dryness and the sample transferred in one drop of demineralized water to the two side filaments of triple filament bead assemblies using a Pyrex glass pipette. The loaded beads were dried and stored in an oven kept at a temperature of about 80°C.

The ion-exchange columns are of Pyrex glass, 30 cm x 1.2 cm i.d., fitted with a stopcock with a P.T.F.E. key at the bottom and with a B14 socket at the top. The resin was retained by an acid-washed glass wool plug, and now by a polypropylene wool plug. The resin used is Dowex 50W-X8, 200-400 mesh and each column contains 8 g. of dry resin. Above the column is a pressure head consisting of a 150 ml. reservoir joined by 50 cm. of 2 mm. i.d. tube to a B14 cone fitted with a P.T.F.E. sleeve. Columns used for Rb separation were eluted with 1.0 N HCl (Rb cut at 155-185 ml.) and columns for Sr separation eluted with 2.50 N HCl (Sr cut at 80-110 ml.), the flow rate on each column being adjusted to approximately 1 ml./minute.
After each separation the columns are cleaned by washing with 100 ml. of 6.0 N HCl, 50 ml. of demineralised water, followed by 100 ml. of the appropriate normality HCl. The columns are never allowed to run dry, and 5 ml. of acid is left above the resin surface. This acid is run out before a sample is loaded onto the column and ensures that any contaminating ions that have diffused out of the resin after the washing cycle are eluted down the column ahead of the sample.

Column calibration was carried out in two ways. In the first instance, 10 mg. amounts of the respective elements were eluted through the columns and the residues of 5 ml. fractions weighed. To check this calibration and also to evaluate the effect other ions may have on the calibration a whole rock sample containing a known amount of strontium was eluted through the column and 5 ml. fractions collected over a range in excess of the assumed calibration. Each 5 ml. fraction was then spiked with a known amount of tracer Sr and the absolute amount of common strontium per fraction calculated from the mass spectrometer data. It was found that all strontium was accounted for and that the initial calibration was verified.

To avoid the possibility of cross-contamination, separate columns were reserved for spiked and unspiked samples with particular ones used exclusively for high- and low-level strontium 87 contents. All glassware, except
the ion-exchange columns, exposed to spiked material was discarded after use.

Preliminary Separations

The efficiency of the ion-exchange columns and the purity of the final separation were found to depend considerably on the total amount of material and the relative amounts of Rb and Sr in any one aliquot.

In basic rocks, the alkaliis may be excessively diluted by iron. Where this possibility existed, the samples were converted back to perchlorates after spiking and heated strongly to convert most of the iron and aluminium to oxides. The alkalies were then dissolved in hot demineralised water, any suspended oxides centrifuged out, and a much smaller residue obtained which could be efficiently separated by the ion-exchange process.

For samples containing excessive amounts of Rb relative to Sr, a preliminary separation using ion-exchange columns was used. A strontium column (normally 2.5 N HCl) was converted to 1.0 N HCl by draining and washing with 100 ml. 1.0 N HCl. The sample was loaded onto the column and eluted with 200 ml. of 1.0 N HCl which was allowed to run to waste, and then collected from the column by eluting with 30 ml. of 6.0 N HCl. This was dried down and the residue (now virtually free of Rb) loaded onto the column which had been reconverted to 2.5 N HCl by washing with 50 ml. of demineralised water followed by 100 ml. of 2.5 N HCl.
This method was found to be excellent for high Rb samples such as biotites and muscovites and resulted in strontium separations almost completely free of Rb contamination.

For samples having a high calcium content it was found that normal elution through a 2.5 N HCl ion-exchange column did not adequately extract the strontium; calcium was always present resulting in dilution of the strontium and the suppression of emission during mass spectrometric analysis. Eluting the residue a second time through the column sometimes brought the calcium content of the strontium sample down to a workable level. In other cases it was found profitable to convert the column to 2.0 N HCl and elute with this normality acid. The amount of acid used is much greater than that used for 2.5 N elution but the degree of separation is also greater (for 2.5 N HCl the centres of the elution curves for calcium and strontium are 91 and 102 ml. respectively, while for 2.0 N HCl they are 97 and 142 ml. respectively).

With one suite of shale samples, adequate separation of strontium could not be achieved using any of the above methods of ion-exchange separation. The effect was that of reduced column capacity. X-ray fluorescence analyses of the samples indicated a high proportion (compared to all other samples handled) of zirconium (approximately 200 μg/g), which has a high $K_d$ value even in the divalent state.
(Strelow, 1960). An element such as this would tend to remain static in the columns and would have the effect of reducing column capacity.

To remove such material, a small column of the same internal diameter as the normal ion exchange columns but having only one quarter the capacity was used. The column was fitted with a quartz sinter (to retain the resin) and had a 25 ml. capacity reservoir fitted to the top. Approximately 2 g. of cleaned resin (stored in 2.5 N HCl in a polypropylene bottle) was placed in the column and washed with 20 ml. of 2.5 N HCl to remove any contamination. The sample was loaded onto the column and eluted with 15 ml. of 2.5 N HCl which was run to waste. A further 20 ml. of acid was collected, the residue dried down, and loaded onto a normal strontium ion-exchange column. The strontium was then extracted in the normal way. By using the above method, the concentration of iron, magnesium, etc., and particularly rubidium is greatly reduced in the residue and zirconium, thorium, etc. is retained in the resin in the small column. This resin is removed from the column and the column and sinter thoroughly cleaned by washing in 6.0 N HCl followed by 2.5 N HCl. New resin is used for each preliminary separation. This method has proved to be very satisfactory and comparatively rapid. A complete preliminary separation can be performed in less than 10 minutes.
CONTAMINATION

Corrects for the possible contamination of Rb and Sr analyses by external sources have not been applied during this work. Previous investigations by Compston et al. (1965) show that for the relatively high levels of Rb and Sr handled in this work, contamination will be negligible compared to other sources of error assuming that normal precautions have been taken.

The main sources of possible contamination are to be found in the bead and filament block assemblies, laboratory utensils used during the preparation of the samples, and the reagents used.

Common elemental contamination and cross-contamination between samples was virtually eliminated by the adoption of the following procedures. Each filament bead was stripped of used filaments, thoroughly cleaned, refilamented with fresh rhenium ribbon which was used because it was found to contain very small amounts of alkali, cleaned again, and finally outgassed in vacuum by subjecting the filaments to currents far in excess of those of normal operation. The alkali level was monitored during the outgassing operation so that only minute amounts of contaminant remained.

Cleaning of the filament block assembly and parts exposed directly to the filaments also eliminated contamination from this source.
Laboratory utensils were thoroughly acid cleaned after use, and any glassware (excluding the ion exchange columns) in contact with spike solution were discarded. During filament and source loading procedures, gloves were worn to avoid possible contamination from the hands, and all beads, etc., were handled with cleaned tweezers.

The reagents used during chemical preparation of the samples were very low in contaminants. The data of Compston et al. (1965) indicates this and is shown in Table B-1. Independent analyses of the reagents were made by this author during the course of this work, the results being the same as those listed.

Possible cross-contamination from the ion-exchange columns was tested by running blanks through the entire procedure using the minimum amount of spike. The results of Compston et al. are listed in Table B-2.

The details outlined above support the assumption that correction for contamination in samples containing reasonable amounts of Rb and Sr is unnecessary when the techniques in operation in this laboratory are used. They justify the fact that such corrections have not been applied to the work outlined in this thesis.
### TABLE B-1

<table>
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<tr>
<th></th>
<th>Rb µg/g</th>
<th>Sr µg/g</th>
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<tr>
<td>Hydrochloric acid, 6.2 N</td>
<td>$0.52 \times 10^4$</td>
<td>$1.11 \times 10^{-4}$</td>
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<tr>
<td>Demineralized water</td>
<td>$0.34 \times 10^{-4}$</td>
<td>$0.14 \times 10^{-4}$</td>
</tr>
<tr>
<td>Hydrochloric acid, 2.5 N</td>
<td>$0.41 \times 10^{-4}$</td>
<td>$0.53 \times 10^{-4}$</td>
</tr>
<tr>
<td>Perchloric acid, 72%</td>
<td>$3.10 \times 10^{-4}$</td>
<td>$22.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>Hydrofluoric acid, 48%</td>
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<td>3.3</td>
</tr>
<tr>
<td>English Pyrex glass</td>
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<tr>
<td>American Pyrex glass</td>
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<td>14.0</td>
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</table>

Pyrex glass

*Wasserburg et al.* (1964)

### TABLE B-2

<table>
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<th></th>
<th>Rb µg</th>
<th>Sr µg</th>
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<tr>
<td>Blank 1</td>
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<td>*0.13</td>
</tr>
<tr>
<td>Blank 2</td>
<td>*0.019</td>
<td>*0.13</td>
</tr>
<tr>
<td>Blank 3</td>
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<td>0.09</td>
</tr>
<tr>
<td>Blank 4</td>
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</tr>
<tr>
<td>Blank 5</td>
<td>0.0007</td>
<td>0.054</td>
</tr>
<tr>
<td>Ion-exchange process</td>
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<td>-</td>
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</tbody>
</table>

*determined without the ion-exchange process*

*All data above from Compston et al.* (1965)
APPENDIX C.

Total Rock Sample Descriptions.
Ding Dong Downs Formation.
G.A.5057 - Rhyolite: Sample of the acid volcanic from the Ding Dong Downs Formation. The rock is fresh and shows little disturbance, and is well jointed. Its relationship to the surrounding sediments is not known, and it may be either intrusive or extrusive. In thin section it consists of anhedral grains of quartz and anhedral (with rare subhedral) grains of both K-feldspar (microperthite) and plagioclase with interstitial chlorite and clear mica. The grains all exhibit corroded margins with the development of replacement sericite. Chloritized biotite also occurs as small individual flakes. Clinopyroxene, altered to tremolite in part, occurs throughout the rock as a primary constituent. Magnetite forms quite a large proportion of the mineral assemblage. The rock has not suffered any regional metamorphism, but hydrothermal alteration is apparent in the alteration of the feldspars, quartz, and pyroxene.

Biscay Formation.
G.A.5055 - Sodic rhyolite: Sample of an acid volcanic from the Biscay Formation of Lower Proterozoic age. The rock is well jointed, retains its flow structure, and is conformable with the regional trend; it is most probably intrusive. It is overlain and underlain by carbonaceous "shale". In thin section the rock is fine-grained, allotriomorphic granular, and consists of quartz, plagioclase, microcline (perthite), riebeckite, fluorite, altered muscovite, and secondary carbonate. Riebeckite is evenly distributed throughout the rock and aligned so that it reflects the flow structure. It is altered in rare instances to iron-stained quartz. Muscovite or bleached biotite is rare and may be secondary; it is much altered. Quartz occurs as evenly distributed anhedral grains showing some graphic intergrowth with perthite. Plagioclase is albite in composition and occurs as anhedral to subhedral grains. Perthite is the most abundant feldspar evenly distributed throughout the rock. Fluorite occurs as small anhedral grains, evenly distributed, and in more than accessory amounts. Carbonate is secondary and is associated with secondary quartz veining.

G.A.5058 - Alkali microgranite: Sample of an acid intrusive of the Biscay Formation. It is fairly fresh, well jointed, porphyritic, and almost amygdaloidal in parts. Some faulting is shown by the outcrop and the general strike transgresses the regional trend by a few degrees; this would indicate that the body is intrusive and therefore much younger than the Biscay Formation. The body is in contact with low-grade metasediments. In thin section, the rock is medium to fine-grained, hypidiomorphic granular, and shows large-scale growth of spherulitic feldspar. Biotite is a ragged brown-green variety with even distribution. Quartz occurs in anhedral grains and also graphically intergrown with K-feldspar. Albite is anhedral to subhedral in form and is also apparent as exsolved material from the perthite. Microcline is perthitic with
marked exsolution of albite. Fluorite occurs in more than accessory amounts. Calcite is present as a secondary mineral. Muscovite is quite common as very small flakes, normally around feldspar grains, and is most probably formed from their breakdown. The feldspars are relatively clear, and quartz shows no obvious strain. However, there is some possibility of greisenization which may account for the apparently low age.

Olympio Formation.
G.A. 5102 and 5232 - Shales: Samples 5102 are of black shales which have been metamorphosed to phyllite in many instances. The sequence is normally very silty, and these specimens are from the finest beds. The area surrounding these samples is mainly one of schists and phyllites showing marked cross-cleavage and some shearing. Samples 5232 actually come from the fault plane of the Halls Creek Fault and can be expected to reflect the movement along this fault. The rocks have been metamorphosed to phyllite with the marked development of mica along the parting planes; slickensiding is also obvious.

McIntosh Gabbro. Information and description by I. Gemus.
G.A. 5221 and 5222 - Gabbro: Differentiated basic sills, with or without basal ultrabasic segregations, were intruded into the Halls Creek Group before the formation of the Tickalara Metamorphics. This is indicated by the fact that the basics are metamorphosed themselves and do not have contact aureoles. Some of the intrusions are large and form roughly circular or elliptical sill-like bodies which are folded into shallow synclines or basins. The rock types found include gabbro, troctolite, norite, uralitized basic rocks, amphibolites, and pyroxene granulites. The fabric in all rocks is medium to coarse-grained allotriomorphic granular. Rhythmic mineral banding, outlined by single or cumulative layers of irregular olivine crystals, are present in some specimens. Olivine forms euhedral to anhedral fractured crystals or glomeroporphyritic aggregates. It is marginally replaced by brown hornblende or has yellow coronas of spinel. Anhedral schillerized hypersthene contains exsolution lamellae or myrmekitic intergrowths of clinopyroxene; in rare cases it pseudomorphs euhedral olivine crystals. Clinopyroxene anheda are partly schillerized and have a prominent parting (diallage). Large anhedral and tabular plagioclase laths range in composition from labradorite to anorthite; the feldspar is cloudy. Some of the mafic minerals are partly altered to a pale brown and greenish-brown amphibole which is associated with black iron oxide and green spinel.
Gneissic Granites and Tickalara Metamorphics.

G.A.957 - Granodiorite - Mabel Downs Granite: A coarse-grained hypidiomorphic granular rock containing amphibole, epidote, biotite, plagioclase, and quartz. Plagioclase is the most abundant mineral and occurs as subhedral, well twinned unaltered crystals. Amphibole occurs in minor amounts as green hornblende, but has been altered to epidote. Epidote occurs in more than accessory amounts. Part has been formed at the expense of the amphibole but much could be primary. Biotite occurs as rather ragged green and light brown flakes which are fairly evenly distributed. Quartz is normally fine-grained and mosaic-like, interstitially situated and having undulose extinction. Some recrystallization may have taken place. Rare larger grains have incipient zoning developed.

G.A.958 - Biotite Granite - Tickalara Metamorphics: Similar in composition to G.A.1098 when hand-samples are compared, i.e., biotite rich with no apparent K-feldspar.

G.A.959 - Pyroxene Granulite - Tickalara Metamorphics: Augite is the most abundant pyroxene occurring as anhedral grains with lobate and subophitic relationships with plagioclase. It is widely and evenly distributed showing parallelism of the grains, imparting to the rock a marked gneissic structure. Orthopyroxene occurs in minor amounts associated with the clinopyroxene. Amphibole is minor and has formed from the alteration of the pyroxenes. Biotite is present as two varieties: the first is bright green and has apparently formed at the expense of the pyroxenes and is in optical continuity with them, and the second is a brown variety which appears to be primary. The primary form is dominant. Plagioclase occurs as subhedral laths and prisms, subophitically intergrown with pyroxene; its composition is in the andesine-labradorite range. Cordierite occurs in minor amounts associated with the pyroxene. Ilmenite is present mainly in contact with biotite-pyroxene areas and is surrounded by and intergrown with biotite. Some alteration to leucoxene has taken place.

G.A.969 - Granodiorite - Mabel Downs Granite: A coarse-grained hypidiomorphic granular rock with slight to moderate foliation. The plagioclase is basic oligoclase (An27), anhedral to subhedral in form, showing little alteration. Quartz occurs in anhedral interstitial grains showing undulose extinction. Bright green hornblende is present as ragged anhedral grains. Biotite is a brown variety associated closely with the hornblende. Some strain is obvious throughout the rock with wavy extinction in the plagioclase and some distortion, together with the undulose extinction in the quartz. Gneissosity is apparent in the parallelism of the biotite.
G.A.970 - Granitic Gneiss - Tickalara Metamorphics:
Medium-grained, hypidiomorphic granular, foliated rock of granitic composition. Quartz occurs in subhedral to anhedral grains having undulose extinction and marked shattering. Inclusions of K-feldspar and biotite are included in the quartz. The K-feldspar is a perthitic microcline with marked albite exsolution. The mineral appears completely fresh. Plagioclase occurs as small unaltered, smaller, discrete crystals which are subhedral in form and in the oligoclase range of composition. Biotite is fresh with little alteration, evenly distributed, and red-brown in colour. Sillimanite occurs in minor amounts throughout the rock. Cordierite is fairly abundant as subhedral crystals. Alteration to chlorite has occurred on borders and cleavage areas. The mineral is usually associated with the biotite. Epidote occurs as minor subhedral crystals also associated with the biotite.

G.A.973 - Granodiorite - Tickalara Metamorphics:
Even, medium-grained, slightly to moderately foliated granodiorite containing plagioclase, quartz, biotite, K-feldspar, epidote and hornblende. In thin section the rock has been fractured and the quartz recrystallized, and both the plagioclase and biotite crystals are bent or contorted. This appears to be the result of post-crystallization shearing. Plagioclase has the composition of andesine with slight to moderate sericitization and secondary epidote along the fractures. Twin lamellae are bent and in some cases the crystals are fractured. Quartz occurs in anhedral grains with typical recrystallized seriate texture; moderate strain effects are noted. Biotite occurs in clusters and streaks together with abundant epidote. In places the biotite is seen replacing hornblende. Epidote is relatively abundant and is probably secondary after both hornblende and biotite. Hornblende is present in only small quantities, mostly altered to biotite and epidote.

G.A.975 - Garnet Cordierite Biotite Gneiss - Tickalara Metamorphics:
Even, medium-grained, moderately foliated non banded gneiss, containing quartz, K-feldspar, plagioclase, cordierite, biotite, garnet and sillimanite with accessory epidote and iron oxide. K-feldspar consists of fresh anhedral grains of moderately twinned microcline containing abundant film and string perthite lamellae. Myrmekite is very abundant but is not restricted to microcline-plagioclase contacts. Plagioclase is present as fresh anhedral grains of oligoclase simply twinned only. Cordierite occurs as anhedral grains, slightly pinnitized along cracks and close to biotite. Biotite occurs as small flakes with sub-parallel orientation. Vermicular intergrowths occur together with biotite clusters and in many places the biotite appears to be replacing sheaves of sillimanite. Garnet occurs in fresh anhedral grains which tend to occur in clusters of bands. Sillimanite occurs in small sheafs, usually associated with biotite.
G.A.976 - Garnet Biotite Granite - (?) Transitional:
Even, medium-grained granite or granite gneiss containing K-feldspar, plagioclase, quartz, biotite, garnet and accessory magnetite andapatite. K-feldspar occurs as fresh anhedral grains with wavy extinction over most of the area and with minor domains containing moderately to well developed microcline twinning. Perthite is abundant. Plagioclase is in fresh subhedral grains with complex twinning, some lamellae being bent. The composition is andesine. Myrmekite is well developed at contacts with K-feldspar (and biotite in some cases) and also occurs as discrete lobate grains. Biotite occurs in large flakes usually in clusters of sub-radial growth; some flakes have been distorted. Garnet is present as anhedral rounded grains occurring in clusters surrounded by biotite flakes.

G.A.1098 - Biotite Granite - Mabel Downs Granite:
Hypidiomorphic granular, coarse-grained rock containing quartz, K-feldspar, plagioclase, biotite, muscovite, sillimanite, cordierite, and amphibole. Quartz occurs as large anhedral grains showing undulose extinction. Plagioclase occurs in rare small grains showing little alteration. Biotite is abundant occurring in large flakes and also as areas of small matted lath-like grains which are apparently the result of complete alteration of amphibole. Amphibole occurs in minor amounts as small equant euhedral crystals. Muscovite is relatively common; the flakes are normally bent and tend to be equant in form rather than the usual elongate grains. Sillimanite is common and occurs as areas of radiating fibrous and acicular crystals associated with the biotite alteration areas. Cordierite is quite abundant and associated closely with the biotite and sillimanite. The rock is obviously much contaminated by sedimentary and persilicic igneous rocks.

G.A.1099 - Garnet Gneiss - Tickalara Metamorphics:
A coarse grained rock with granitoid fabric and containing megacrysts of garnet. Mineralogically the rock consists of quartz, biotite, muscovite, plagioclase, garnet, microcline, and (?)scapolite.

G.A.1100 - Gneissic granodiorite - Mabel Downs Granite:
Hypidiomorphic granular, coarse-grained rock consisting of quartz, plagioclase, biotite, amphibole, K-feldspar, and accessory epidote,apatite and zircon. Quartz occurs in anhedral grains showing some fracturing and elongation of the grains. Undulose extinction is marked and parallelism of the elongate grains noticeable. Plagioclase is the most abundant feldspar and the composition lies within the range of oligoclase. Overall it is relatively fresh but shows some sericitization. Sub-parallelism of the crystals is apparent with some distortion. Biotite is abundant showing elongation and sub-parallelism of the flakes; there is no distortion. Amphibole occurs in minor amounts, shows twinning, is associated with the biotite, and shows no distortion. K-feldspar, in anhedral grains, occurs in minor amounts.
G.A.1101 - Biotite Granulite - Tickalara Metamorphics:
Medium-grained, massive granulite containing plagioclase, biotite, quartz, K-feldspar, and possibly hypersthene with secondary sericite and amphibole and some magnetite. The rock has a slight microscopic foliation due to the alignment of biotite clusters. Plagioclase occurs in anhedral to subhedral grains of andesine which is fresh. Quartz occurs in anhedral grains with slight to moderate strain effects. Biotite is fairly abundant usually occurring in elongate clusters associated with magnetite. K-feldspar is present as rather sparse anhedral microcline grains. Ragged crystals which may be hypersthene also occur; most crystals are strongly altered, enclosed in sericite material and in some cases rimmed by amphibole.

G.A.1102 - Pyroxene Granulite - (?) Transitional:
Hypidiomorphic granular rock, coarse-grained, with sub-ophitic texture and distinct foliation. Hypersthene occurs in subhedral to anhedral grains ophitic intergrown with plagioclase and closely associated with biotite. Schiller inclusions are marked, as is exsolution of augite on the (100) planes. Clinopyroxene is the lesser pyroxene occurring in anhedral grains associated with the orthopyroxene. The amphibole is a strongly pleochroic green hornblende which forms as a replacement of pyroxene with which it is in optical continuity. Biotite is a red-brown variety occurring as discrete equant grains and also as laths; it also replaces amphibole. Plagioclase is abundant and has the composition in the labradorite-biotite, some zoning is shown. The majority are discrete crystals but some intergrowth with pyroxene is also present. Quartz occurs in minor amounts, often interstitially but often enclosing plagioclase. The clarity and nature of the rock suggests recrystallization of a norite with some metasomatism.

G.A.5078 - "Basic Metasediment" - (?) Transitional:
No thin section is available for this sample but in hand specimen it is basically the same as G.A.1102. The area from which this sample was taken is strongly foliated along the regional north-south trend and shows much small scale folding (ptygmatic veins?).

G.A.5079 - Biotite Granulite - (?) Transitional:
This sample comes from the same area as G.A.5078 and is an example of the "acid phase metasediments" of the Lamboo Complex. The rock is fine-grained, hypidiomorphic granular, with marked gneissosity and a granitic composition consisting of quartz, biotite, K-feldspar, and plagioclase. The K-feldspar is a perthitic microcline and occurs in anhedral equant slightly sericitized grains. Plagioclase is the subordinate feldspar occurring in anhedral equant grains of oligoclase composition. Biotite is a green-brown variety, fine-grained, with marked parallelism of the flakes. They have a relatively even distribution with some areas of lineal concentration. Minor areas where coarser crystallization has occurred are seen. Preferred orientation of the quartz and feldspar is not marked.
G.A. 5150 – Granodiorite – Mabel Downs Granite: Coarse-grained hypidiomorphic granular rock containing plagioclase, quartz, amphibole, biotite, epidote, clinopyroxene; K-feldspar is apparently absent. Plagioclase occurs as subhedral oligoclase-andesine with some slight saussuritization; the feldspar has wavy extinction. Quartz has marked undulose extinction and some inclusions. Amphibole is distinctly orientated in one direction and is secondary after pyroxene; there is apparently no primary amphibole. Clinopyroxene occurs as small remnant crystals and grains. Biotite occurs in two forms: a primary brown variety which is well formed, and a ragged green variety which is secondary after amphibole. Epidote is a common alteration product associated with amphibole-pyroxene areas. Rare cordierite and sphene occur as accessories. There is obvious parallelism of biotite and amphibole grains which is less apparent, but present, in the quartz and feldspar.

G.A. 5074 – Granodiorite – McHale Granite: The granite is intrusive into knotted schists etc. of the Olympio Creek Formation. Weathering is deep and iron-staining marked in the outcrop; foliation is not seen. Plagioclase and K-feldspar occur in subhedral grains showing some preferred orientation. The feldspars have suffered alteration to sericite and kaolin. Quartz is shattered and has marked undulose extinction. Orientation of the grains and recrystallization is seen. Chlorite occurs as the alteration product of biotite; no original biotite remains in the rock. Epidote is minor but most probably formed from the alteration of amphibole. Muscovite is minor and amount and most probably secondary in origin. The rock is stressed and shows an impressed microscopic gneissosity which is particularly apparent in the areas of quartz.

G.A. 5097 – Granite Aplite – Tickalara Metamorphics: Allotriomorphic granular rock consisting of quartz, K-feldspar, plagioclase, and biotite. The quartz shows marked undulose extinction. K-feldspar is microperthitic and relatively fresh. Some graphic intergrowth of quartz and K-feldspar occurs. Plagioclase shows minor alteration to sericite and kaolin. Biotite is a minor constituent of the rock and is fresh. A definite parallelism of the long axes of all minerals is noticeable.
G.A.1367 - "Granite" - (?) Transitional: Microperthite is the most abundant feldspar and occurs as large megacrysts, subhedral in form, with marked albite exsolation. Grain borders are embayed and reaction rims formed. Plagioclase is the subordinate feldspar occurring in large crystals and also as smaller euhedral forms in the groundmass. Biotite is ragged and patchy in distribution through the rock. Sillimanite is present in large amounts; cordierite occurs as minor small crystals. Muscovite is distributed throughout in both large and small flakes. In some instances it appears to have formed at the expense of K-feldspar and is aligned along two exsolution planes of the feldspar; it is apparently of secondary origin. Garnet occurs in minor amount and in some instances may be altered to biotite; it is normally associated with biotite. Intergrowths of quartz and feldspar are common as are quartz-biotite intergrowths. Garnet-quartz intergrowths also occur but these are more lobate. Quartz does not show marked strain but the K-feldspar has wavy extinction. K-feldspar is altered in most instances with the development of a reaction rim of sillimanite, quartz, and minor muscovite.

Porphyritic and Coarse-grained Granites.

G.A.963 - Porphyritic Granite - Bow River Granite: Coarse-grained hypidiomorphic granular rock consisting of quartz, K-feldspar, plagioclase, biotite, amphibole, and minor muscovite. The K-feldspar occurs as large phenocrysts of microperthite normally surrounded by a rim of quartz and K-feldspar intergrowth. The feldspar is usually perfectly euhedral in the phenocrysts, but also occurs as anhedral and subhedral grains. It has been altered in some sections to kaolin. Quartz occurs as intergrowths with K-feldspar and also as evenly distributed anhedral grains which are, for the most part, unstrained. Plagioclase occurs in euhedral to subhedral grains which are mostly altered to saussurite and sericite. Biotite is green in colour, ragged in parts, and chloritized to some degree. Relic amphibole remains, but most has been altered to epidote.

G.A.966 - Adamellite - Bow River Granite: Coarse-grained hypidiomorphic granular rock, massive, containing quartz, K-feldspar, plagioclase, amphibole, biotite, and epidote. Quartz is anhedral, interstitial, shattered, and has marked undulose extinction. K-feldspar is perthitic, anhedral to subhedral, and has wavy extinction. Minor graphic intergrowth with quartz exists. The plagioclase is anhedral oligoclase, some zoned with overgrowths of K-feldspar. Much has been saussuritized and/or sericitized. The amphibole is hornblende which has been mostly altered to epidote. Biotite occurs in ragged green-brown flakes, much of it showing distortion, shearing and bending. Epidote, together with minor clinzoisite, occurs as an alteration product of amphibole and plagioclase. Definite effects of stress and shearing are seen in the rock.
G.A.967 - Porphyritic Granite - Bow River Granite :
Coarse-grained hypidiomorphic granular rock containing
large phenocrysts of microperthite showing marked albite
exsolution, surrounded by clusters of quartz and biotite.
Between these large megacrysts, a fine-grained mosaic of quartz
and feldspars contain phenocrysts of very strained quartz
and ragged biotite stringers. The biotite usually wraps around
garnet (which is minor but rare in this granite type). The
fine quartz mosaic suggests recrystallization and the garnet
points to contamination. Graphic intergrowth of quartz and
K-feldspar is obvious in both the fine-grained material and
also on the borders of the large microperthite megacrysts.
The plagioclase lies in the range of composition of oligoclase
to andesine. The sample comes from near the contact with the
Tickalara Metamorphics and could well be contaminated by these.

G.A.972 - Adamellite (Porphyritic) - Bow River Granite :
Massive, medium to coarse-grained granite containing
scattered ovoid megacrysts of K-feldspar. Other minerals
present are quartz, plagioclase, biotite, chlorite and epidote,
magnetite and muscovite. The K-feldspar occurs as large
irregular anhedral grains of orthoclase, frequently with a
subhedral or ovoid core surrounded by patches or zones of
graphically intergrown K-feldspar and quartz. The K-feldspar
of the core is in optical continuity with the graphic feldspar.
The feldspar is fresh to moderately kaolinitized with slight to
moderate undulatory extinction. Biotite flakes occur in
small clusters, strongly bleached and intergrown with chlorite
and epidote. Muscovite occurs in small clusters, usually
interstitial, and appear to be of primary origin.

G.A.974 - Granite - Bow River Granite :
Hypidiomorphic granular, medium-grained rock which has suffered a degree of
deuteric alteration. All biotite has been altered to pennine
and possibly talc. Relic amphibole remains but most has been
altered to epidote. Minor plagioclase exists in the rock.
The K-feldspar is microcline which has been kaolinitized and
iron-stained; it is anhedral to subhedral in form. The quartz
is relatively clear and unstrained. The graphic intergrowth
of quartz and K-feldspar is obvious and characteristic; this
feldspar has not suffered alteration.

G.A.1081 - Hornblende Biotite Tonalite - Bow River Gr. :
Medium-grained, slightly to moderately foliated tonalite
containing plagioclase, quartz, biotite, hornblende, epidote
and magnetite. The foliation is due to crystal alignment and
is a primary flow foliation. Plagioclase occurs in subhedral
grains with moderately bent twin lamellae; the composition is
andesine. Zoning is slightly to moderately developed; most
grains are fresh but there is some sericitization. Quartz is
anhedral, interstitial, and has moderate strain effects.
Biotite occurs in fresh to slightly chloritized flakes, frequently in elongate clusters together with epidote. Many flakes are slightly bent. Hornblende is present both as relatively fresh and also as chloritized grains, associated with the biotite. Epidote is present in greater than accessory amounts, occurring in clusters and also associated with the biotite. It is not clearly secondary after any mineral.

G.A.1085 - Graphic Adamellite - Bow River Granite:
Massive, medium-grained adamellite, containing K-feldspar, quartz, plagioclase, chlorite, magnetite and epidote. The rock has been altered and contains thin fracture veins. The K-feldspar occurs in fresh to slightly kaolinized anhedral grains which are mostly orthoclase and frequently graphically intergrown with quartz. Some crystals have incipiently developed microcline twinning. Quartz occurs in anhedral grains, much of it graphically intergrown with the K-feldspar, and showing strong strain effects. Plagioclase occurs in subhedral grains, strongly sericitized and slightly replaced by epidote. Chlorite is the only Fe/Mg mineral present and is of secondary origin. The epidote is an alteration product of the plagioclase and occurs in thin veinlets cutting the rock. The rock is a high level orthoclase granite which has been fractured and retrogressively metamorphosed producing chlorite and epidote with incipiently developed microcline.

G.A.1086 - Porphyritic Granite - Bow River Granite:
No thin section has been examined from this rock, but in handspecimen it is similar to the other porphyritic granites and adamellites already described.

G.A.1097 - Granodiorite - Bow River Granite:
Coarse-grained hypidiomorphic granular rock consisting of quartz, microcline, plagioclase, biotite, and muscovite. Microcline occurs in euhedral crystals which are virtually unaltered. Plagioclase is in the compositional range of oligoclase, unaltered, and with relatively even distribution. Biotite is a green-brown variety, fresh and unaltered, and with relatively even distribution. Muscovite is rare, associated with the biotite, and occurs also as small patches of alteration in the feldspar. Quartz occurs as anhedral grains showing undulose extinction.

G.A.1104 - Muscovite Granite - Bow River Granite:
No thin section has been examined from this rock but it is known to consist of quartz, microcline, plagioclase, biotite, and muscovite. The muscovite occurs in appreciable quantities. The rock shows no evidence of strain or alteration either in hand specimen or in mass in the field; it may be regarded as typical high level granite representative of that type intruded in the Kimberley area.
G.A.1240 - Biotite Adamellite - Bow River Granite:
Medium to coarse-grained, massive adamellite containing microcline, plagioclase, quartz, epidote and chlorite. K-feldspar occurs in anhedral crystals varying in size from small interstitial grains to megacrysts up to 6 mm., in diameter. The megacrysts semi-poikilitically enclose other minerals and appear to be digesting plagioclase. The feldspar appears to be mainly monoclinic with scattered porphyroblasts of microcline twinning developed at the margins. Plagioclase is present in subhedral tabular crystals of oligoclase; they are lobate and corroded where in contact with K-feldspar and are usually strongly sericitized. The crystals vary from fresh to strongly altered and contain abundant sericite together with varying amounts of epidote; some twin lamellae are slightly bent. Biotite occurs in small irregular clusters together with epidote; it is fairly fresh to strongly altered. Epidote is present in more than accessory amounts as an alteration product of the plagioclase.

G.A.1242 - Porphyritic Granite - Bow River Granite:
Medium to coarse-grained massive granitic rock containing megacrysts of K-feldspar up to 22 mm., in length. The K-feldspar also occurs as anhedral interstitial grains. It is fresh and has wavy extinction, and contains abundant perthite lamellae. Quartz occurs as large subhedral crystals up to 6 mm., and also as anhedral interstitial grains. Locally intergrowth with K-feldspar can occur. Plagioclase is present in subhedral crystals, completely altered, and partially replaced by K-feldspar. Biotite is ragged and bleached and also strongly chloritized. It is associated with epidote in small clusters.

G.A.5053 - Granodiorite (Granulitic) - Sophie Downs Granite:
A sample of the border phase of this granite which is strongly cleaved and foliated throughout the area. In thin section the rock is hypidiomorphic granular and consists of biotite, plagioclase, quartz. Plagioclase occurs as subhedral phenocrysts showing some marginal corrosion; it also occurs as rare grains in the groundmass. The composition lies within the oligoclase-andesine range, and the crystals are only slightly sericitized. Quartz occurs as phenocrysts which are angular and strained. It is mainly concentrated in the groundmass where it is intergrown with feldspar; this is most marked along the margins of the plagioclase. Biotite is relatively low in concentration and occurs as a fine-grained brown variety with fairly even distribution. The biotite is fresh and chlorite is rare. Minor muscovite is associated with the biotite and also occurs along the margins of the feldspar grains. The rock appears to have been formed from the dynamothermal metamorphism of a rock of type G.A.5054.
G.A.5054 - Granite - Sophie Downs Granite: The rock is composed almost entirely of graphically intergrown quartz and microcline (perthite) with occasional plagioclase intergrowths. Plagioclase is usually discrete subhedral grains with replacement K-feldspar along the margins. Biotite occurs in areas of concentration as relatively small stumpy flakes; it also occurs scattered in the interstices. Chlorite is rare. Some undulose extinction is apparent in the quartz.

G.A.5059 - Porphyritic Granite - Bow River Granite: Massive, unfoliated, coarse-grained, hypidiomorphic granular rock containing K-feldspar, quartz, plagioclase, biotite, and muscovite. The K-feldspar is perthite and occurs in anhedral to subhedral crystals which are both megacrysts and phenocrysts. It is altered for the most part to kaolin. Quartz is present as anhedral grains with undulose extinction; it is also apparent in graphic intergrowth with the K-feldspar. Plagioclase has the composition of oligoclase and occurs in anhedral to subhedral crystals, zoned in part, and altered to muscovite in the cores. Biotite is a green variety and is present in relatively small flakes, normally ragged, with even distribution. Muscovite is a minor constituent occurring as an alteration product of the plagioclase.

G.A.5060 - Porphyritic Granite - Bow River Granite: No thin section of this sample has been examined, but in the field and in hand specimen it is similar to the other rocks of this type already described. Its description would be almost identical to that of G.A.5059.

G.A.5111 - Leucogranite(?) - Bow River Granite: This sample occurs as veins intruding the basic metasediments of the Tickalara Metamorphics. In thin section this hypidiomorphic granular rock is seen to consist of K-feldspar, quartz, plagioclase, (?)clinopyroxene, clinozoisite and non-ferrian zoisite. Microcline is the more abundant feldspar and is slightly kaolinized and sericitized. The quartz shows marked undulose extinction. Plagioclase is in the oligoclase range of composition it is well twinned and the bending and shearing of some crystals is obvious. The (?)clinopyroxene occurs as interstitial phenocrysts which have for the most part been completely altered to pennine. Zoisite occurs in about the same amount as the pyroxene as is apparently a primary mineral.

G.A.5231 - Porphyritic Granite - Sophie Downs Granite: No thin section is available for this rock but it is considered to be identical to G.A.5054 already described.
McLintock and Cummins Ranges Granites.

G.A. 5101 and 5105 - Granites: Sample 5101 is from the Cummins Range area and is representative of a massive, coarse, even-grained granite outcropping in the core of an anticline. Sample 5105 is similarly situated and is representative of the rocks of the McLintock Range area. In this latter area faulting has effected some of the granites resulting in shearing and granulation of the bodies, particularly near the margins. Also in this latter area, pegmatites are associated with the granite though they bear no definite relationship to each other. Description of the granites is taken from Roberts et al. (1965). They describe the bodies as consisting of equigranular coarse to medium-grained granites which are white and massive in outcrop; there is no change in grainsize at their margins. In thin section the granites consist of microcline, quartz, subordinate plagioclase (oligoclase to andesine), and irregular clots of interlathed biotite and muscovite. The microcline shows poikilitic inclusions of plagioclase, while the plagioclase is replaced by sericite-epidote-chlorite aggregates. Iron ore minerals and tourmaline are accessories.

McLintock Range and Environs, Pegmatites.

G.A. 5104 - Pegmatite: This pegmatite intrudes sediments of the Olympio Formation and is spatially associated with G.A. 5105. The pegmatite dykes are discontinuous randomly orientated bodies which may be concordant or discordant with the strike of the sediments. In thin section this rock consists almost entirely of microperthite with minor amounts of plagioclase. Quartz and mica are also present, the quartz showing marked undulose extinction. The particular sampling site is veined by secondary quartz and closely associated with quartz "blows" and reefs, indicative of planes of faulting.

G.A. 5106 - Pegmatite: A sample of a pegmatite dyke which intrudes rocks of the Olympio Formation and is aligned parallel to the regional trend of the area. This particular pegmatite is apparently completely independent of any association with an intrusive granitic body. It consists of quartz, muscovite, and perthitic microcline, is extremely coarse-grained having large megacrysts of feldspar and the development of books of mica. The rock is associated with, and probably forms part of, and area of tin bearing pegmatites.
Rhyolite, Dacite, Microgranite.

G.A.968 - Rhyolite: Part of the minor intrusives of acid material which have been included in the Lamboo Complex. This sample is representative of a dyke swarm which intrudes Bow River Granite. The dykes are aligned more or less parallel to the regional trend of the area. The rock consists essentially of phenocrysts of plagioclase with lobate, corroded and rounded margins (and to a lesser extent K-feldspar) set in a fine-grained mosaic-like groundmass of quartz, plagioclase, and K-feldspar. Stringers of biotite in parallel orientation reproduce the flow structure. Slight alteration of the phenocrysts exists but for the most part the rock is fresh.

G.A.5223 - Quartz-feldspar Porphyry: The sample is representative of the porphyries which intrude the basic rocks of the Armanda Sill. The description is taken from Gemuts (1965). The fabric ranges from porphyritic to ophitic and the most common rock type consists of phenocrysts of feldspar and quartz set in a fine-grained siliceous groundmass. In thin section the plagioclase feldspar is poorly developed and is replaced by sericite. K-feldspar forms large irregular phenocrysts, partly replaced by sericite. Most sections contain amphibole which is replaced by biotite along the cleavage. The groundmass consists of a cryptocrystalline mosaic of quartz, feldspar, and mica. Accessory sphene, epidote, magnetite and garnet also occur.

Whitewater Volcanics and Castlereagh Hill Porphyry.

G.A.956 - Quartz-feldspar Porphyry - C.H.P.: The sample is from a porphyry which has been equated to the Whitewater Volcanics but which intrudes and forms part of the Lamboo Complex. In the general area of sampling, the porphyry has margins which are chilled against the Bow River Granite. The site from which this sample was taken lies a few miles east of the Greenvale Fault and the outcrop is strongly lineated parallel to the regional trend of the area. No thin section is available for description.

G.A.960 - Rhyodacite - W.W.V.: Fine-grained, massive, reddish-brown, silicified rhyodacite containing a few small phenocrysts of pale green plagioclase and pink orthoclase. These are set in an extremely fine-grained, silicified, felsic groundmass which appears to have reacted and digested feldspar phenocrysts. Quartz occurs in small euhedral to subhedral phenocrysts. Plagioclase is in subhedral to anhedral crystals, many being veined and digested by the groundmass. The K-feldspar is subhedral to anhedral orthoclase with uneven patchy twinning. It is also kaolinized and digested by the groundmass. Chlorite occurs scattered through the groundmass and in small patches together with magnetite. The whole rock appears to have been recrystallized and silicified at some period.
G.A. 964 - Granitic Mylonite - C.H.P. : This sample comes from a similar area to that of 956 and shows the effect of shearing associated with faulting. It is a transitional rock insofar as it grades into true porphyry to the east. The rock is of granitic composition with rounded orbs of sericitized K-feldspar, plagioclase and quartz set in a fine-grained crystalline groundmass of quartz and biotite. The biotite also occurs in aggregates associated with muscovite and relic (?)amphibole orbs. The rock has been formed from the shearing of the quartz-feldspar porphyry.

G.A. 965 - Feldspar Porphyry - W.W.V. : This rock is lithologically the same as that of the porphyry forming part of the Lamboo Complex, i.e., the Castlereagh Hill Porphyry, and occurs in the lower section of the Whitewater Volcanics in the Greenvale area. It consists of phenocrys ts of subhedral K-feldspar (orthoclase) and plagioclase set in a groundmass of microcrystalline quartz and (?)K-feldspar. Epidote occurs as an accessory alteration product together with chlorite which probably represents the alteration of amphibole. The rock is xenolithic containing epidotized granoblastic material consisting of minor K-feldspar, plagioclase, and relic Fe-Mg minerals. Flow texture is apparent in the sub-parallel alignment of the primary minerals. The rock shows secondary veining by calcite and chlorite. However, it is overall quite fresh.

G.A. 979 - Quartz-feldspar Porphyry - W.W.V. : The rock comes from the northern area (Lissadell Sheet) of outcrop of the Whitewater Volcanics and is of undoubted authenticity as to the rock group to which it belongs. The whole of the Volcanics in the sample area have been sheared and weakly cleaved, and it is possible that the rock could give anomalous age results. No thin section has been examined from the specimen.

G.A. 1107 - Porphyry - W.W.V. : The sample has been selected from relatively isolated outcrops of the Volcanics in the Cambridge Gulf Sheet area. Some faulting is noticed about the sample area but the specimen itself does not appear to be effected Nothin section has been examined.

G.A. 5126 and 5127 - Porphyries - W.W.V. : Sample 5126 comes from an area which shows some fracturing and faulting but is overall relatively undisturbed, the alteration apparently being localized rather than regional. Sample 5127 is taken from the border zone of the Volcanics which is apparently in contact with porphyritic granite (Bow River Granite). The area is intensely sheared. No thin sections are available of these rocks.

G.A. 5148 and 5149 - Porphyries - (?) W.W.V. : These samples come from a fault area (?) on the Lennard River Sheet. This section has not yet been mapped and the actual formational names of the rocks are still in doubt. The collection sites are near Mt. Hart and Inglis Gap. In this area the Volcanics
have been intensely sheared and it is possible that the rocks may give anomalous age results.

**G.A.5217 to 5220 - Quartz-feldspar Porphyry - W.W.V.**

The samples have been selected as a suite through one portion of the outcrop of Volcanics. They are undeformed and relatively unaltered by weathering. In handspecimen the rocks are red, coarse-grained and porphyritic, and generally show some form of banding (flow or compaction). The thin section description is taken from Roberts *et al.* (1965). The rocks contain euhedral to anhedral embayed and marginally resorbed quartz phenocrysts, sericitized euhedral feldspar phenocrysts (probably plagioclase), irregular chloritic patches (altered ferromagnesian minerals), and accessory zircon, magnetite and ilmenite. They may contain small angular, ragged and embayed fragments of granite, altered dolerite, greywacke, and quartz-feldspar porphyry. The phenocrysts are set in a chlorite and mica rich siliceous groundmass. The mineralogical composition and primary structures suggest that the rocks are deuterically altered dacitic lavas.

**Altered Rocks, (according to the age determination data).**

**G.A.954 - Porphyritic Granite - Bow River Granite:** The specimen has been taken from a fault area which is confined to the granite; as such it may indicate the time of this faulting. In thin section the rock consists of microperthite occurring in megacrysts up to 2 cm across in which albite exsolution is prominent. The mineral is relatively clear and unaltered with only minor sericitization; a slightly wavy extinction is noted. Graphic intergrowth with quartz exists. Quartz occurs in pseudo-hexagonal crystals but for the main part is anhedral. Some 50% is intergrown with K-feldspar. Undulose extinction exists in the quartz. Plagioclase is invariably altered, normally saussuritized with some sericitization and replacement by K-feldspar. Biotite occurs in ragged green flakes which are for the most part chloritized. Muscovite occurs as clean clear well defined flakes associated with the biotite. Clinozoisite occurs in parallel vein-like areas cutting through other minerals, the dissected minerals remaining in optical continuity.

**G.A.1366 - Granite - Bow River Granite:** Coarse-grained hypidiomorphic granular rock consisting of large crystals of microperthite and characterized by the graphic intergrowth of quartz and K-feldspar. The biotite is an olive-green variety. Plagioclase is euhedral and sericitized. The K-feldspar is relatively unaltered.
G.A. 5073 - Granodiorite - McHale Granite: The granite is intrusive into knotted schists of the Olympio Formation and this sample has been selected from the contact section where the rock is xenolithic, veined with quartz, and shows jointing 2 to 3 feet apart. There is some evidence of shearing but this is not marked. In thin section the rock is very similar to 5074 except that the biotite (a brown variety) is relatively unaltered with rare chloritization compared to the complete chloritization occurring in 5074. Impressed gneissosity is marked with the recrystallization of quartz quite apparent. The muscovite could well be of secondary origin.

G.A. 5230 - Porphyritic Granite - Sophie Downs Granite: This sample has been selected from almost the same point as 5231 and there is no apparent reason for this rock to have been an open chemical system when compared to other samples. No thin section has been examined but it can be assumed that this specimen is virtually the same as those previously described from this rock mass.

Valentine Siltstone.

G.A. 961 - Tuffaceous Siltstone: The rock is a tuffaceous siltstone of rhyolitic composition, banded and even-grained within the bands. It consists essentially of quartz and biotite set in a finer matrix of colourless mica. The banding is brought about by predominantly quartz bands associated with biotite bands alternating with beds of matrix. The matrix consists of quartz and K-feldspar which has been altered to mica. Relic K-feldspar, now completely altered to mica, existed in the coarser sections of the rock. The biotite has in part been altered to chlorite. Opaques are accessory minerals.

G.A. 962 - Tuffaceous Siltstone: Fragments of angular quartz, altered amphibole (chloritized) and orthoclase (kaolinized and sericitized) are set in a fine-grained matrix of quartz (minor), plagioclase (albite-oligoclase), and authogenic mica. The alteration of the orthoclase is almost complete in many sections. The quartz is relatively clear with little undulose extinction. The matrix mica may have formed from the alteration of K-feldspar. Interstitial opaques make up about 5% of the rock. Linearity of the elongate fragments reflect the sedimentary structure of the rock.
Carson Volcanics.
G.A. 5083 and 5136 - Dolerite: Samples of dolerite from the uppermost section of the Carson Volcanics which may be intrusive and therefore younger than the rocks they invade. The samples are comparatively fresh, as compared to the general volcanic which may be heavily veined with calcite and quartz, chloritized and epidotized. It is possible that these samples are actually from the Hart Dolerite or at least closely related to it. In thin section the dolerite is medium to coarse grained with a sub-ophitic texture, and consisting of clinopyroxene, plagioclase, and alteration products. The pyroxene is augite, strongly cleaved, and exhibiting undulose extinction. The plagioclase is andesine, sericitized and kaolinized, and also showing strain effects. Chlorite occurs as an alteration product of the plagioclase. The accessories are opaques occurring as interstitial grains and also as exsolution blebs from the pyroxene.

Hart Dolerite.
G.A. 1241, 5052, 5125, 5131, 5132, 5133, 5214, 5241: The Hart Dolerite is a widespread doleritic sill which is found intruding rocks as young as the Pentecost Sandstone but is mainly concentrated within rocks of the Speewah Group. The dolerite is tholeiitic in composition and there is extensive development of granophyre in the upper sections of some exposures. Samples have been collected from both the dolerite proper and the granophyre. The dolerite is massive, medium to coarse-grained, hypidiomorphic granular, with sub-ophitic texture, and composed of plagioclase, pyroxene, magnetite, quartz, K-feldspar, and chlorite. The plagioclase has the composition of labradorite and occurs in anhedral to euhedral prismatic crystals. Alteration is variable, some crystals being fresh while others are kaolinized or sericitized. The pyroxene is an augite which ranges from fresh to moderately chloritized. The grains may show sutured and embayed margins. Magnetite is a very abundant accessory, evenly distributed throughout the rock. Often the magnetite is poikilitically enclosed by mainly plagioclase but also pyroxene. The granophyre exists as a medium to fine-grained allotriomorphic granular rock with marked granophyric texture. K-feldspar occurs as discrete subhedral crystals and, more commonly, as graphic intergrowths with quartz. The mode of occurrence is similar to that in the dolerite. The K-feldspar is a perthite and some exsolved albite lamellae are present. Plagioclase occurs as discrete subhedral to euhedral crystals which are for the most part saussuritized to some degree. The composition lies within the range of oligoclase. Quartz occurs intergrown with the K-feldspar but also as anhedral grains. Undulose extinction is seen but is not as marked as in the granites. The pyroxene is mostly altered to epidote and chlorite with much exsolution of hematitic iron.
Wyndham Shale.

G.A.5244A-H - Bastion Group: The sampling locality is from Bastion Hill near the township of Wyndham where the samples have been selected from a 100' cliff face, sampling being at approximately 10' intervals. Deposition of secondary carbonate is evident in some sections but only fine-grained beds free of carbonate have been selected. The sample area is closely jointed with evidence of fracture cleavage and (?) slaty cleavage. The deformation is considered to be due mainly to load metamorphism but localized faulting could have accentuated the feature. The mineralogy, based on the X-ray diffraction analysis of 5244B is essentially quartz, 2M, muscovite, and chlorite and (?) kaolinite with possible minor amounts of goethite, microcline, and the mineral represented by the 2.79A peak.

Crowhurst Group.

G.A.5109A-D, 5110F and G, 5120A and B - Liga Shale: The samples are from the least disturbed areas of outcrop of the Shale. However the main sampling area (represented by 5109 and 5110) is quite complexly folded and local faulting is marked both in the outcrop and through the region. It is more than probable that the apparent age given by these samples will be too young. Sample 5120 was supplied by H.G.Roberts and comes from a less disturbed area to the north, but these latter samples are more weathered than those normally selected for radiometric dating. The mineralogy of the Shale, based on the X-ray diffraction data for 5110F, indicates that it is basically composed of quartz, 2M, muscovite, and kaolinite, with microcline and minerals represented by 2.79A and 2.70A. Chlorite is rare or absent and has apparently been altered to a mixture of kaolinite and iron oxide.

Wade Creek Sandstone.

G.A.5071A, B, and C, 5072D and E - Mt. John Shale: The site represents a collection of samples from the bottom to the top of a cliff face, the samples being taken at approximately 10' intervals. The sequence consists of sandy, silty, and shaley beds, of which samples were collected from the latter only. The rocks are well lithified and appear micaceous; normal fracture cleavage is apparent. The area about has been broadly folded and the outcrop dips at about 30°. X-ray diffraction of 5071A and 5072D show that the rocks consist of quartz, 2M, muscovite with chlorite rare and apparently replaced by kaolinite or dickite; possible microcline and the mineral represented by the 2.79A peak are also present. Montmorillonite or interlayered silicates also appears to be present.

Glidden Group.

G.A.5094A-E, 5113A-F - Matheson and Maddox Formations: The former suite is from the Matheson Formation and the latter from the Maddox Formation; the collection areas are
within a few hundred yards of each other. Both sequences are low dipping at about 10°, relatively undeformed and fairly silty. Samples have been taken from the finer beds but even so they would strictly be silts. X-ray diffraction of 5094C and 5113E indicate that the Mtheson Formation rocks are essentially of quartz-muscovite composition while the Maddox Formation has additional chlorite and possibly goethite and kaolinite.

Carr Boyd Group.

G.A.5245A-J - Golden Gate Siltstone: The samples have been collected from a disturbed but apparently unaltered area near the proposed Ord River Dam site. Strong faulting occurs close by but according to the engineering geologists of the West Australian Geological Survey these shales have not been metamorphosed. X-ray diffraction indicates that they are composed of quartz, 2M1 muscovite, chlorite, and kaolinite, with microcline and the mineral represented by the 2.79A peak.

G.A.5236A-H - Glenhill Formation: Rocks of the Formation in the area of sampling are quite silty, siliceous, and generally deeply weathered. X-ray diffraction of 5236E indicates that the samples are composed of quartz, 2M1 muscovite, and kaolinite plus the mineral represented by the 2.70A peak. Chlorite is apparently absent and replaced by kaolinite and probably goethite.

G.A.5246A-B, 5247A-F - Pincombe Formation: The former samples were collected from a relatively isolated outcrop of the Formation. In this area, weathering appears to be deep and the exposure is dominated by sands and silts. Samples 5247 come from the reference area in the Pincombe Range and were supplied by K.A.Plumb; the outcrop is similar to that of 5246. Full details of the mineralogy of these samples are listed in Table D-1 of Appendix D.

Duerdin Group.

G.A.980, 5080A-E, 5243 - Moonlight Valley Tillite: Samples 5080 and 5243 are from identical sites in the reference area for the Moonlight Valley Tillite. The section is relatively undeformed but fracture cleavage is apparent in the shale samples. Sample 980 is again from an outcrop of the Tillite to the north but the area of sampling is sheared and impressed schistosity is apparent in the sample. The mineralogical composition of the suite is listed in Table D-2 of Appendix D.

Kuniandi Group.

G.A.5085, 5086, 5087, 5118, 5119, 5216: Two units are represented in this suite. Samples 5085, 5086, and 5216 are representative of the Landrigan Tillite, the two former samples being derived from an area of relatively tight folding so that the samples show the effects of axial plane and fracture cleavage.
Samples 5087, 5118, and 5119 are from the overlying Wirara Formation, the latter two samples being supplied by H.G. Roberts. Details of the mineralogical composition of the various samples is listed in Table D-2 of Appendix D.

**Duering Group.**

**G.A. 951, 952, 5062, 5070, 5239, 5242, 5250 - Ranford Formation:** Two main sampling areas are represented in this suite and their locality is indicated on the sample locality overlay. Both areas are relatively undeformed and fracture cleavage is the only apparent effect impressed on the shales. Details of the mineralogical composition of each sample is listed in Table D-3 of Appendix D.

**Mt. House Group.**

**G.A. 5137 and 5213 - Throssell Shale:** Samples 5137 were collected from the Mt. Clifton area (reference section for the Group) and 5213 from Mt. House itself. The outcrop of the Shale is virtually continuous over both areas and fracture cleavage is the only apparent deformation. The mineralogical composition of the Shale, based on the X-ray diffraction analysis of 5137A, is essentially quartz, 2M₁ muscovite, and chlorite with some plagioclase and a small amount of the mineral represented by the 2.79A peak.

**Albert Edward Group.**

**G.A. 5063 and 5240 - Elvire Formation:** Two sampling sites are represented both of which form banks to dry creek beds. The area is relatively undeformed and the samples show only fracture cleavage effects although large scale faulting is apparent within a mile from the sampling sites. The mineralogical composition, based on the X-ray diffraction data for 5240B, is quartz, 2M₁ muscovite, chlorite, kaolinite and dickite, plus the minerals represented by refections at 2.70, 2.79, and 2.90A.

**G.A. 5064, 5065, 5066 - Timperley Formation:** Sampling sites form the banks of dry creeks and often show the effects of deep weathering. Samples considered suitable for age determination are hard to find. Apart from fracture cleavage, the area is undeformed and flat lying. The mineralogical composition, based on X-ray diffraction analysis of 5065, is quartz, 2M₁ muscovite, chlorite, kaolinite, and dickite plus the mineral represented by the 2.79A reflection. Small amounts of microcline could also be present.
Louisa Downs Group.

G.A.5088, 5089, 5090, 5091, 5092, 5093, 5117 – McAlly Shale: The majority of samples represent a suite taken through a sequence of the McAlly Shale where it forms the bank to a dry creek. Dips of approximately 20° are recorded; cross-cleavage is not marked in the section. Elsewhere cleavage has resulted in the development of wide areas of pencil shale. Sample 5117 comes from an area of outcrop to the north and was supplied by R.Halligan. This latter area is probably more representative of the areas where cleavage is marked. No determination has been made of the mineralogical compositions but it is assumed that this shale is identical to the Timperley Shale described above.
APPENDIX D

X-RAY DIFFRACTION OF SHALE SAMPLES
Analyses of total rock shale samples were made on a Phillips X-ray diffractometer comprised of a PW1009 1Kw power supply, PW1050/30 goniometer and PW1051 diffractometer using a pulse-height discriminator and proportional counter. CuKα radiation with a Ni filter was used with slit widths of 1°, 0.2°, and 1°; scanning speed was 1°/min. from 2θ of 5° to a minimum of 40° up to 65°.

The total rock samples used were those previously prepared for isotope dilution analyses, i.e., less than 100 B.S. mesh size. Splits from these powders were pressed into aluminium holders for diffraction analyses and the minerals can be regarded as randomly orientated.

The use of multicomponent samples presents problems in diffraction pattern interpretation. For instance it is difficult to distinguish kaolin in the presence of chlorite because of the overlap of identifiable peaks. Consequently certain reflections, considered to be peculiar to particular minerals, were used to determine their presence.

The identification of quartz, abundant in all specimens, is no problem since virtually all peaks are represented. A similar situation exists with the mica. Identification of the mica type was based, in the first instance, on whether it was dioctahedral or trioctahedral indicated by reflections about 1.50Å and 1.53Å respectively. The presence of a reflection at 3.72Å further signifies that the mica is the 2M₁ polymorph.
Chlorite was determined mainly on the presence of 14Å and 4.7Å reflections. Kaolin has reflections at about 7Å and 3.5Å which almost coincide with the chlorite peaks. However, it is possible to discriminate between these two minerals at a 1°/min. scanning speed if the kaolin is present in reasonable amounts relative to the amount of chlorite.

The presence of plagioclase was based on the reflection at about 4.04Å, a peak common to the whole solid solution range. Microcline was distinguished by the 3.25Å reflection. Calcite was considered to be present if a reflection at about 3.03Å was seen. Expandable layered silicates such as montmorillonite occur in some samples, but normally their major peaks about the 12Å region are diffuse and probably represent the interlayering of clays and (say) illite.

In some samples peaks occur at 2.70, 2.79, and 2.90Å; these peaks are quite intense and independent of each other. The actual compositions of the minerals that they represent have not been determined but some possibilities are suggested. The 2.70Å reflection is most probably given by hematite or goethite, with the unlikely possibility that hornblende or some such mineral could be contributing. The 2.79Å can result from calcium silicate, potassium carbonate, sodium chloride, sodium silicate, siderite etc., of which all are strong possibilities in a sedimentary environment. The 2.90Å may represent ferroan dolomite (ankerite), pumpellyite,
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etc., of which the former is considered to be the most probable.

Based on the above information, interpretation of the diffraction patterns of the samples used for determining the age of the Pincombe Formation are listed in Table D-1. The shales are essentially composed of quartz and $2M_1$ muscovite, with varying amounts of chlorite, kaolinite, goethite; the 2.79 Å peak is common to all samples. However, samples 5246 A and B, and 5247 B and E are distinguished from the remaining four samples in that they contain microcline. It will have been noted that this mineralogical separation conforms to the previously defined isotopic separation based on the assumption of a bimodal distribution of initial $^{87}\text{Sr}/^{86}\text{Sr}$ values within the suite. Those samples containing microcline define the isochron having the higher initial $^{87}\text{Sr}/^{86}\text{Sr}$ value and their average Rb/Sr is greater than that of samples defining the isochron with lower initial $^{87}\text{Sr}/^{86}\text{Sr}$. These observations conform to the expectation and give some geological meaning to the parallel isochrons previously statistically assessed. An analogous situation exists for samples from the State Circle Shale, discussed in Appendix A.

Table D-2 lists the X-ray diffraction information for shales from the glacials belonging to the Moonlight Valley Glaciation. The samples have been grouped according to
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their assumed initial $\text{Sr}^{87}/\text{Sr}^{86}$ based on the isotopic data and isochrons defined in the main text of this thesis. Basically the shales are composed of quartz, $2M_1$ muscovite, and a mixture of chlorite, kaolinite and dickite, with variable amounts of plagioclase, microcline, and minerals represented by the 2.70 and 2.90 Å peaks. The possibility of some small amount of calcite is not excluded.

Differences between the groups appears to be indicated by the 2.70 and 2.90 Å peaks, and the presence or otherwise of microcline. However, some discrepancies exist since 5216 B, C, and D should then theoretically be grouped with the uppermost isochron defined by samples 980 etc. rather than with samples 5080 which they apparently fit.

While there are mineralogical differences which conform to the majority of the isotopic data in suggesting a multimodal distribution of initial $\text{Sr}^{87}/\text{Sr}^{86}$, it is also apparent that the differences cannot be completely resolved by total rock X-ray diffraction. More detailed work is necessary to find out if the problem can be solved; research into the differences in the bulk chemistry of the samples or more particularly within the various mineral species may prove profitable.

Table D-3 lists the X-ray diffraction data for samples of shale from the Ranford Formation. With the exception of 951, all samples used in the determination of the age
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of this formation are represented; none of the original 951 sample remains.

The shales are composed essentially of quartz, $2M_1$ muscovite, and combined chlorite-kaolinite-dickite, with or without plagioclase and the mineral represented by the 2.70Å peak. The mineral represented by the 2.79Å reflection appears to be common to all samples, and the possibility of calcite as a minor constituent is not excluded.

The listing shows that there does not seem to be any correlation between the qualitative mineralogy and the particular isochron on which the samples lie. In this regard the diffraction results cannot be used to support the previous interpretation of the isotopic data. A more involved situation than was found for the glacial shales appears to be operative in these Ranford Formation samples. More detailed work is necessary before the problem can be solved.

In Table D-4 a listing is made of X-ray diffraction results of selected samples from each of the main shale units discussed in the text of the thesis. Usually only one sample has been selected from each unit, this sample being considered to be "average" (based on the isotopic data) and possibly representative of the unit as a whole. The listing gives the qualitative mineralogy of each sample only and no predictions or real conclusions based on comparative mineralogy can be made. However it is interesting
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to note that sample 5232 B which reflects a minimum age for the metamorphosed Olympio Formation is extremely rich in muscovite (and quartz) compared to other shales with other minerals being relatively minor. It is not known whether this is a primary feature of the sample or a secondary feature reflecting the response to metamorphism, but the inference is that this increased mica content could be secondary in part. If this is so, then the fact that other shale samples have significantly lower muscovite contents may be indicative of the fact that they have not been unduly metamorphosed and have suffered little more than "normal diagenesis".
APPENDIX E

SAMPLE LOCATIONS AND CROSS-REFERENCE

LISTING THE A.N.U. AND B.M.R.

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REFERENCES


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Marvin, R.F., Wright, J.C., and Walthall, F.G. (1965) The K-Ar and Rb-Sr ages of biotite from the Middle Jurassic part of the Carmel Formation, Utah, U.S. *Geol. Surv. Prof. Paper* 525-B.


PRECAMBRIAN GEOLOGY of the
EAST KIMBERLEY REGION, W.A.

LEGEND

Lowick Group
Athabasca Group
Kurnool Group
Dundie Group
Helicopter Siltstone
Wade Creek Sandstone
Glidden Group
Carr Boyd Group
Bungle Bungle Dolomite
Mt. Parker Sandstone
Colombo Sandstone
Hart Dolomite
Fish Hole Dolomite
Crawshay Group
Bostjan Group
Kimberley Group
Spearach Group
Bawber Creek Formation

Red Rock Beds
Moora Bulka Formation
Rhyolite, dacite, microgranite
Whittaway Volcanics
Caterwings Hill Porphyry
Violet Valley Tonalite
Bow River Granite
Sophie Downs Granite
Mabel Downs Granite
McIntosh Granodiorite
Tuckadlin Metamorphics
McIntosh Gabbro
Alice Downs Ultrabasics
Woodward Dolomite
Halls Creek Group

Major Fault
Fault
Shear Zone
Geological Boundary

Based on a compilation by
D.B. Drew, (Carnegie), and A.J. Wadley (1976)
M.A. and G.S.I.W.A.)