THE GEOCHRONOLOGY OF THE PLUTONIC AND METAMORPHIC ROCKS OF NEW ZEALAND

Thesis by

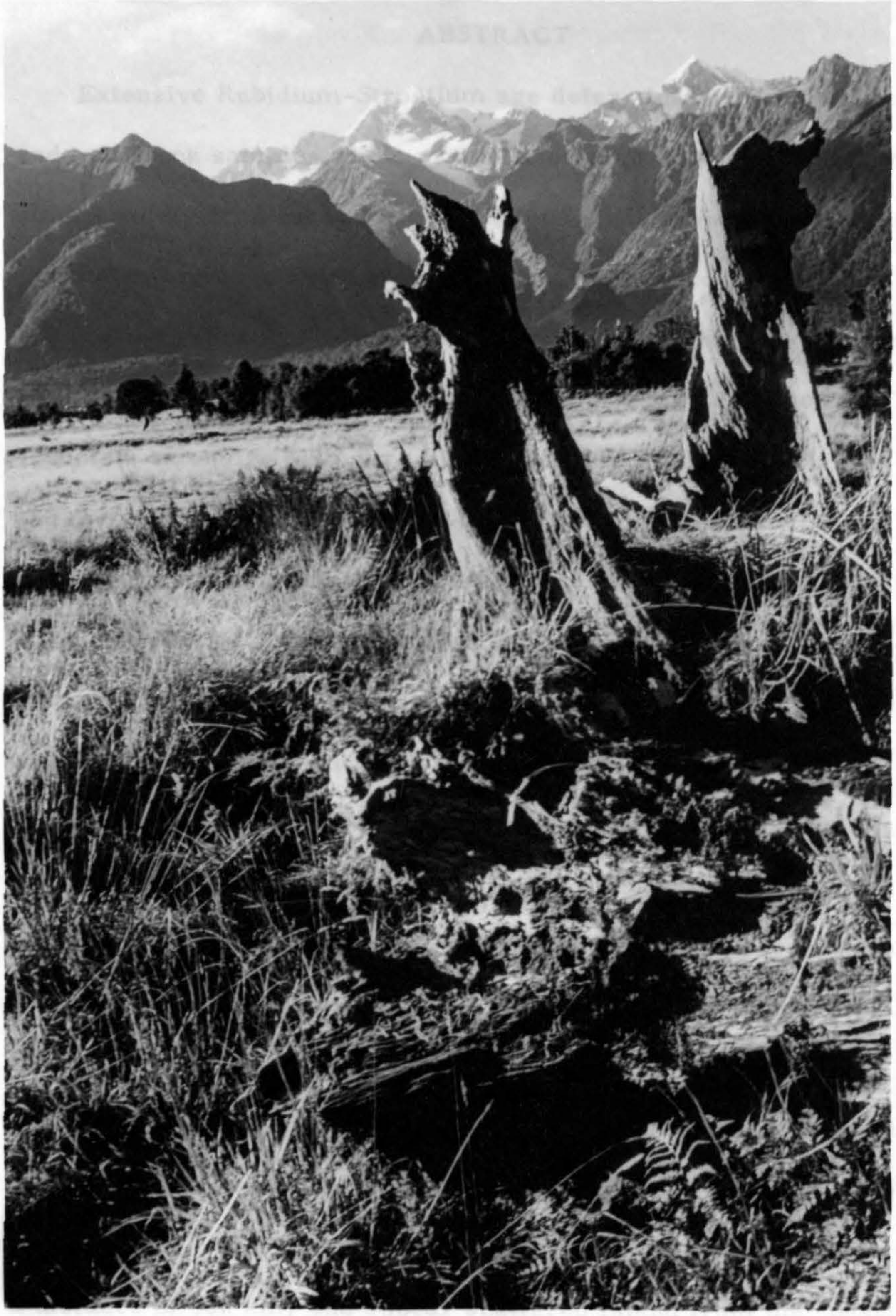
James Louis Aronson

In Partial Fulfillment of the Requirements
For the Degree of
Doctor of Philosophy

California Institute of Technology
Pasadena, California
1966
(Submitted May 10, 1966)

Frontispiece. Mt. Tasman (11,467') and Mt. Cook (12,349') reign over the Southern Alps, the backbone range of South Island. This rugged and steep range rises abruptly along the Alpine Fault from the narrow coastal strip of the North Block of the Foreland Province. The fault trends across the picture between the hills and the trees in the middle distance three km from the observer. The high peaks are comprised by relatively "unmetamorphosed" Alpine Zone greywacke, and the hills in the middle distance by oligoclase-almandine zone and biotite zone Alpine Schist of the Geosynclinal Province. The foreground consists of Pleistocene and Recent alluvium covering an extensive terrain largely comprised by the Greenland Series, the oldest known sedimentary unit in New Zealand. Six km behind the observer is the Tasman Sea underneath which the Lord Howe Rise extends toward Australia.

Photograph taken near Lake Matheson, Westland.



ABSTRACT

Extensive Rubidium-Strontium age determinations on both mineral and total rock samples of the crystalline rocks of New Zealand, which almost solely crop out in the South Island, indicate widespread plutonic and metamorphic activity occurred during two periods, one about 100-118 million years ago and the other about 340-370 million years ago. The former results date the Rangitata Orogeny as Cretaceous. They associate extensive plutonic activity with this orogeny which uplifted and metamorphosed the rocks of the New Zealand Geosyncline, although no field association between the metamorphosed geosynclinal rocks and plutonic rocks has been found. The Cretaceous plutonic rocks occur to the east in the Foreland Province in Fiordland, Nelson, and Westland, geographically separated from the Geosynclinal Province. Because of this synchronous timing of plutonic and high pressure metamorphic activity in spatially separated belts, the Rangitata Orogeny in New Zealand is very similar to late Mesozoic orogenic activity in many other areas of the circum-Pacific margin (Miyashiro, 1961).

The 340-370 million year rocks, both plutonic and metamorphic, have been found only in that part of the Foreland Province north of the Alpine Fault. There, they are concentrated along the west coast over a distance of 500 km, and appear scattered inland from the coast. Probably this activity marks the outstanding Phanerozoic

stratigraphic gap in New Zealand which occurred after the Lower Devonian.

A few crystalline rocks in the Foreland Province north of the Alpine Fault with measured ages intermediate between 340 and 120 million years have been found. Of these, those with more than one mineral examined give discordant results. All of these rocks are tentatively regarded as 340-370 million year old rocks that have been variously disturbed during the Rangitata Orogeny, 100-120 million years ago.

In addition to these two periods, plutonic activity, dominantly basic and ultrabasic, but including the development of some rocks of intermediate and acidic composition, occurred along the margin of the Geosynclinal Province at its border with the Foreland Province during Permian times about 245 million years ago, and this activity possibly extended into the Mesozoic.

Evidence from rubidium-strontium analyses of minerals and a total rock, and from uranium, thorium, and lead analyses of uniform euhedral zircons from a meta-igneous portion of the Charleston Gneiss, previously mapped as Precambrian, indicate that this rock is a 350-370 million year old plutonic rock metamorphosed 100 million years ago during the Rangitata Orogeny. No crystalline rocks with primary Precambrian ages have been found in New Zealand. However, Pb^{207}/Pb_{206} ages of 1360 million years and 1370 million years have

been determined for rounded detrital zircons separated from each of two hornfels samples of one of New Zealand's oldest sedimentary units, the Greenland Series. These two samples were metamorphosed 345-370 million years ago. They occur along the west coast, north of the Alpine Fault, at Waitaha River and Moeraki River, separated by 135 km. The Precambrian measured ages are most likely minimum ages for the oldest source area which provided the detrital zircons because the uranium, thorium and lead data are highly discordant. These results are of fundamental importance for the tectonic picture of the Southwest Pacific margin and demonstrate the existence of relatively old continental crust of some lateral extent in the neighborhood of New Zealand.

ACKNOWLEDGMENTS

I feel a great personal debt to Professor G. J. Wasserburg at the California Institute of Technology who has kindly been my teacher and advisor during this project. His vision has guided me whenever I became lost in a maze of details and it has been through his constant effort that I have been able to work under the most efficient conditions. His freely offered criticism has forced an alertness on my part that, I am certain, has greatly added to the worth of this work.

This study would not have been possible without an enormous amount of help generously offered me by several people in New Zealand and in the United States. A Fulbright Scholarship from the governments of New Zealand and the United States enabled me to spend one year during 1961-1962 at Victoria University of Wellington from which base the field work and sample collecting for this study were performed. The work was carried out as a research project leading toward a Ph. D. degree in the stimulating and, to be sure, exciting environment of the Division of Geological Sciences at California Institute of Technology. The work was supported largely by grants from the National Science Foundation and the Atomic Energy Commission and the author expresses his thanks to these agencies.

In New Zealand, assistance was offered in the field by the students and staff of Victoria University and by the staff of the New Zealand Geological Survey. From the University, Dr. H. W. Wellman, Mr. R. Brathwaite and Mr. E. Hardy were particularly helpful. I am indebted to Dr. Wellman for collecting the boulder from the Moeatoa Conglomerate. Professor R. H. Clark especially encouraged this project in its difficult beginning. From the New Zealand Geological Survey, B. L. Wood, Dr. W. A. Watters, Alec Mutch, Dr. John Reed, and John Rogers helped me collect important samples and discussed their significance with me. R. W. Willett, Director of the New Zealand Geological Survey made this cooperation possible and I always felt welcome in any of the Branch Offices.

Mr. C. A. Landis of the University of Otago has generously informed me of his discovery of glaucophane facies metamorphism in the Marginal Zone of the New Zealand Geosyncline. Malcolm Laird and Dr. G. Norris kindly offered me manuscripts of papers in press, and I especially want to extend thanks to Dr. Norris for his correspondence concerning palynological problems. Mr. G. Grindley and Dr. R. P. Suggate of the New Zealand Geological Survey provided many helpful suggestions and wisely cautioned me about overgeneralizing the preliminary results. Mr. Simon Nathan has informed me of his recent field results in the Paparoa Range.

Colleagues Richard S. Naylor, and R. E. Zartman discussed geological and technical problems with me, giving me much good advice. T. Wen and Dr. D. S. Burnett provided advice on analytical procedures. I am indebted to Dr. Arthur Boucot for information on the geology of Fiji and the paleontological dating of the New Zealand Devonian rocks. Mr. Joseph Brown advised me on mineral separation and sample preparation techniques and helped me crush some rock samples. Thanks are certainly due to Mr. Victor Nenow and Mr. Curtis Baumann who have maintained the mass spectrometer and general laboratory equipment throughout this project.

Dr. C. C. Patterson kindly sponsored me in his laboratory for a one-month study of lead chemistry and mass spectrometry just prior to my leaving for New Zealand. There, Dr. M. Tatsumoto first instilled in me the principles of ultra-clean analytical chemistry, which I have maintained throughout this work.

Professor L. T. Silver has generously made himself available for thought provoking discussions on many of the geochemical and geological aspects of this project. Both by direction and example, he has continuously stimulated my thinking of the present results in their proper geological framework.

I had the good opportunity of being able to spend two months in the Branch of Isotope Geology laboratories of the U. S. Geological Survey in Denver, Colorado, under Branch Chief, Dr. Robert Coleman. I am very grateful to Dr. Bruce Doe and Dr. M. Tatsumoto who cordially invited me into their laboratory and taught me the techniques of uranium, thorium and lead chemistry in zircons and feldspars. The zircon data presented here are some of the more important aspects of this thesis and I appreciate their generous aid in my acquiring this data.

I would like to express my thanks to my wife, Arlene, and to my parents, Mr. and Mrs. N. N. Aronson, for encouragement during this study. Special thanks are due Robert O'Daniel for his conscientious and careful typing of the final draft of this thesis.

TABLE OF CONTENTS

TABLE OF CONTENTS (contd)

I.

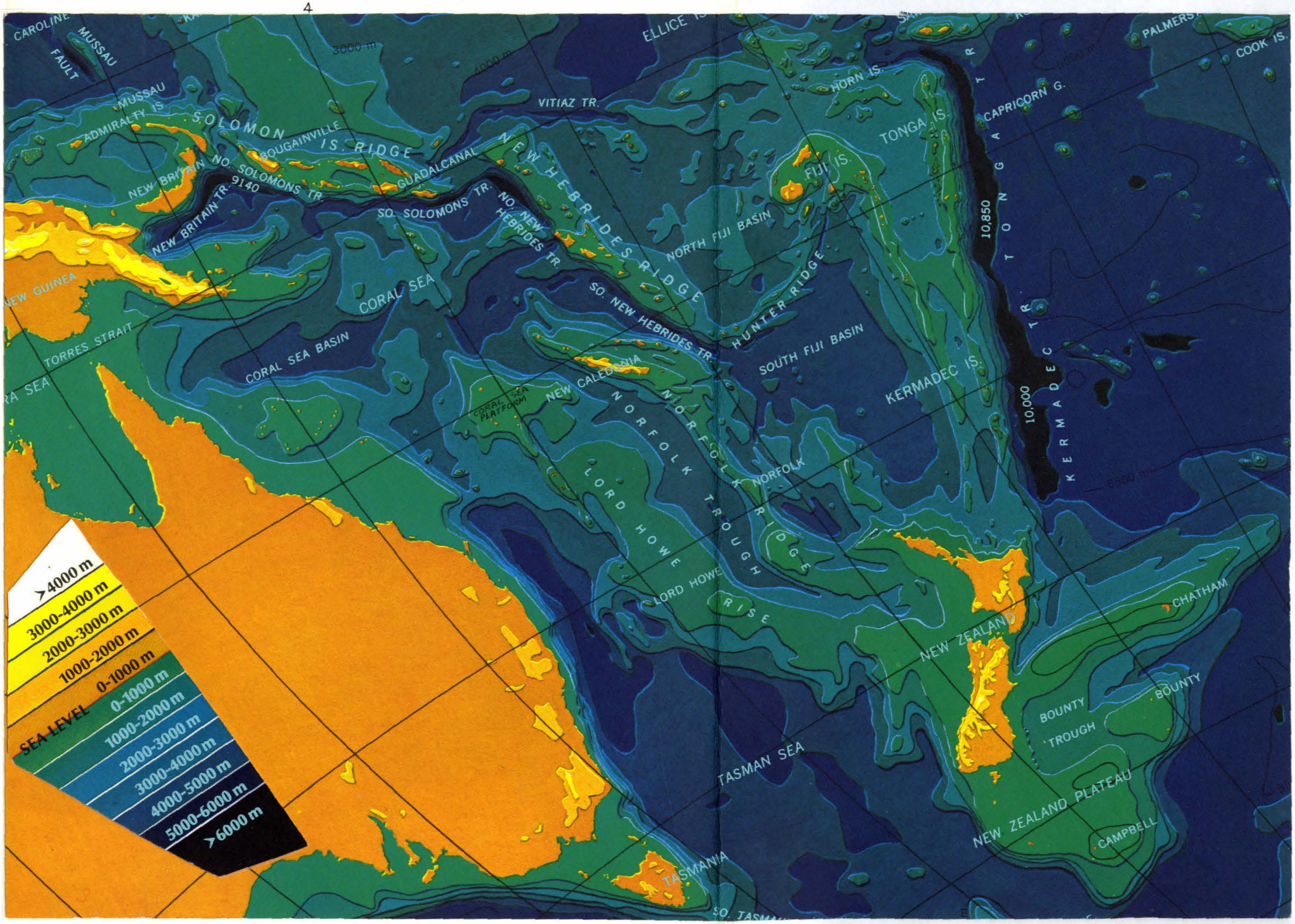
INTRODUCTION AND PURPOSE OF STUDY

I. Introduction and Purpose of Study

The crust of the earth is structurally organized on the basis of crustal thickness into continents and deep ocean basins and their few major subdivisions like oceanic rises and trenches. Because gross isostatic equilibrium has commonly obtained in the crust, this structural organization is also a topographic organization. Topographically one of the most complicated and least understood crustal areas of the earth is the region of the Southwest Pacific Ocean (Figure 1). This region of islands and complex alternating ridges and basins north and east of Australia comprises an area greater than that of the landmass of Australia. It stretches from northeastern Australia 5000 km southeast to Campbell and Bounty Islands beyond the landmass of New Zealand; 4000 km east to the Tonga-Kermedec Trench beyond New Caledonia and Fiji; and 1300 km northeast to the Solomon and New Hebrides Islands beyond the eastern end of New Guinea. A unifying feature of this large region is an average elevation that is intermediate between the continent and deep ocean basins which bound it.

The limited amount of geophysical work done in the region to determine its crustal structure has been mainly gravity (Woolard and Strange, 1962) and surface wave dispersion studies (Officer, 1955; Thompson and Evison, 1962; Adams, 1962); these indicate an intermediate crustal thickness of 15-20 km for much of the region. There is some conflict between the surface wave dispersion studies and

Figure 1. Bathymetry of the Southwest Pacific
(Menard, 1964). Color rendition by
Deep Submergence Systems,
North American Aviation
Co.


CAROLINE
FAULT
MUSSAU
MUSSAU
ADMIRALTY IS.
SOLOMON IS. RIDGE
BOUGAINVILLE
GUADALCANAL
NEW BRITAIN
NO. SOLOMONS TR.
NEW BRITAIN TR.
9140
SO. SOLOMONS TR.
NO. NEW HEBRIDES TR.
NEW HEBRIDES RIDGE
VITIAZ TR.
ELLICE IS.
3000 m
4000 m
NEW GUINEA
TORRES STRAIT
CORAL SEA
CORAL SEA BASIN
CORAL SEA PLATFORM
NEW CALEDONIA
SO. NEW HEBRIDES TR.
NORTH FIJI BASIN
HUNTER RIDGE
FIJI IS.
HORN IS.
TONGA IS.
CAPRICORN G.
TONGA TR.
10,850
KERMADEC TR.
10,000
KERMADEC IS.
SOUTH FIJI BASIN
NORFOLK RIDGE
NORFOLK
NORFOLK TROUGH
LORD HOWE
LORD HOWE RISE
PALMERSTON
COOK IS.
6000 m
6500 m
NEW ZEALAND
CHATHAM
BOUNTY
BOUNTY TROUGH
NEW ZEALAND PLATEAU
CAMPBELL
TASMAN SEA
TASMANIA
SO. TASMAN
ARAFURA SEA
>4000 m
3000-4000 m
2000-3000 m
1000-2000 m
0-1000 m
SEA LEVEL
0-1000 m
1000-2000 m
2000-3000 m
3000-4000 m
4000-5000 m
5000-6000 m
>6000 m

seismic refraction studies (Officer, 1955) over the crustal thickness of New Zealand, by far the largest landmass in the region. Officer, and more recently Eiby (1957), interpret the seismic refraction data as indicative of a 20-km crust, but Thompson and Evison (1962) interpret new surface wave dispersion data as indicating a more normal continental thickness of 30-35 km and reject the previous refraction study as incomplete. Adams (1962), using similar parameters as Thompson and Evison, determined by surface wave dispersion studies a 20-km crust for the shallowly submerged Campbell Plateau which adjoins New Zealand on the south and the east and which is about three times the size of the New Zealand land mass. Gravity data in New Zealand (Robertson and Reilly, 1958; Reilly, 1962) suggest a normal continental thickness.

Geologically, the larger landmass areas of the region demonstrate continental affinities. Thus, in New Caledonia during Mesozoic times, sediments were deposited in great thicknesses in a geosyncline and underwent relatively low temperature-high pressure metamorphism during the late Mesozoic. Thick geosynclinal sedimentation proceeded during the Tertiary in Fiji and has undergone relatively low grade burial metamorphism (Crook, 1963). The orogenic history of New Zealand is indeed continental and includes geosynclinal sedimentation in a huge belt, regional metamorphism of both the high and low pressure type (Miyashiro, 1961), and most important of all, the intrusion in quite some abundance of acidic plutonic rocks of batholithic dimensions. Granodiorite and schist crop out respectively at Bounty Islands and Campbell Island on the eastern and southern extremities of the Campbell Plateau greatly expanding the areal extent of the New Zealand subcontinent. The ages of the New Zealand plutonic and metamorphic rocks in general have been known only within wide limits and some have been tentatively mapped as Precambrian.

Because the Southwest Pacific Crust in many respects is a major region intermediate between oceanic and continental character, it may represent some transition between the two and, as such, may contain valuable clues to the origin of continents in general. In order to better understand the nature of this complex crustal region that has some continental affinities, it is important to determine the evolution of the continental aspects of the region.

This study has so far been limited to New Zealand, the most continental-like landmass of the region. Its purpose has been to determine by geochronological means the general history of plutonic and metamorphic activity in New Zealand and to determine if any of this activity has truly occurred as long ago as the Precambrian.

The author spent ten months during 1961-1962 in New Zealand doing field work and sampling for this study. Most of this time was spent in the South Island and Stewart Island where almost all of the plutonic and metamorphic rocks of New Zealand occur. It became necessary to adopt a particular sampling philosophy suitable for this problem because of the large region involved in this study of apparently complex geology, a general lack of detailed maps for much of the area of crystalline rocks, and various logistic problems. Among the latter are included a rugged topography and a low human population in the areas of crystalline rocks, these areas being among the least populous in all of New Zealand, with a consequent lack of roads and transportation to and from the crystalline rocks. However, a limited amount of transportation was possible by airplane and boat. The rainfall in the crystalline areas, mainly in the western part of South Island, is very high averaging 120-150 inches per year, and reaches over 300 inches per year in parts of Fiordland. As a result, thick plant overgrowth occurs and deep weathering of rocks is so common that fresh samples are obtained with difficulty.

Sampling was guided foremost by the following three factors:

(1) Mineralogy of rock samples was suitable for dating by Rb/Sr methods.

(2) Samples were taken from areas widely distributed throughout the South Island and Stewart Island and were representative of all of the geographically separated large bodies of crystalline rocks.

(3) Only large, fresh, unweathered samples were taken.

In general, plutonic rocks were favored over metamorphic rocks because of their implied simpler history.

Sampling for this study has been a "one-shot affair," the author having been unable to return to New Zealand during the progress of this study for further sampling or checking of field relations. An uncomfortably large number of samples (six) reported in this study were taken as boulders and not from outcrops because these were the only fresh samples available. In all but two cases these could be related to outcrops nearby. In all cases the boulders were large and the two which could not be related to nearby outcrops were larger than three meters in diameter, and almost certainly of local origin. However, considering the widespread effects of Pleistocene glaciation in the South Island, the source of these boulders should be further verified.

The data for this study are mainly Rb/Sr analyses, but include a few U, Th, and Pb isotopic analyses of zircons. The bulk of the Rb/Sr data has been taken on separated minerals but a few whole rocks have also been analyzed. None of the sampling was performed with the idea of doing cogenetic whole rock Rb/Sr studies. Considering that Rb/Sr ratios are prevalently low for New Zealand total rocks, such a study would involve several feedback stages between the X-ray fluorescense laboratory and sample collection sites. Most of the zircon concentration data is regarded as only an upper limit because of the use of a Pb^{206} enriched tracer and the consequent large effect of small post-aliquoting contamination. At this stage only the Pb^{207}/Pb^{206} ages are regarded as analytically reliable. Table 1 contains the uranium, thorium, and rubidium decay constants and relative isotopic abundances employed in this study.

In no way is it felt that this study represents a complete geochronology of New Zealand plutonic and metamorphic rocks. However, the results indicate significant aspects of this geochronology and in particular delineate four major periods of plutonic and metamorphic activity in New Zealand including at least one during the Precambrian.

The plan of this thesis will be to introduce the reader to the geology of New Zealand in a regional sense and in this context to present the geochronological evidence for the existence of these plutonic and metamorphic events. An appendix containing petrographic descriptions and localities of samples, and details of sample preparation and analytical procedure occurs at the end of the thesis.

TABLE 1

Constants Used in This Study

Decay Constants (10^{-10} y^{-1})	
Rb^{87}	0.139
U^{238}	1.537
U^{235}	9.722
Th^{232}	0.4881

Natural Isotopic Abundances	
Rb^{85}/Rb^{87}	2.59
U^{238}/U^{235}	137.7

II.

BRIEF INTRODUCTION TO THE GEOLOGICAL FRAMEWORK OF NEW ZEALAND

A. The Geosynclinal Province

B. The Foreland Province

BRIEF INTRODUCTION TO THE GEOLOGICAL FRAMEWORK OF NEW ZEALAND

The pre-Tertiary rocks of New Zealand can be divided into two distinct geological provinces, which the author shall call the Geosynclinal Province and the Foreland Province as shown in Figure 2. These occur as two broad adjoining northeastwardly trending bands. The first is completely comprised by the New Zealand Geosyncline which was an active site of thick geosynclinal deposition from the late Paleozoic through the middle part of the Mesozoic. The Foreland Province has generally been regarded as a stable upland region during this time partly shedding debris into the geosyncline. Almost all of the pre-Tertiary sedimentary rocks of the Foreland Province are lower Paleozoic or older in age and pre-date the oldest known sedimentary rocks of the New Zealand Geosyncline.

In areal extent the Geosynclinal Province is dominant comprising more than half of South Island and apparently the entire exposed pre-Cretaceous basement of the North Island. The Foreland Province crops out only in the South Island and southern Stewart Island, west of the Geosynclinal Province and is of much importance in this study because it contains most of the major bodies of acidic plutonic rocks which crop out in New Zealand.

In the South Island both provinces are cut by the Alpine Fault and right-laterally displaced along the Fault which is the dominant

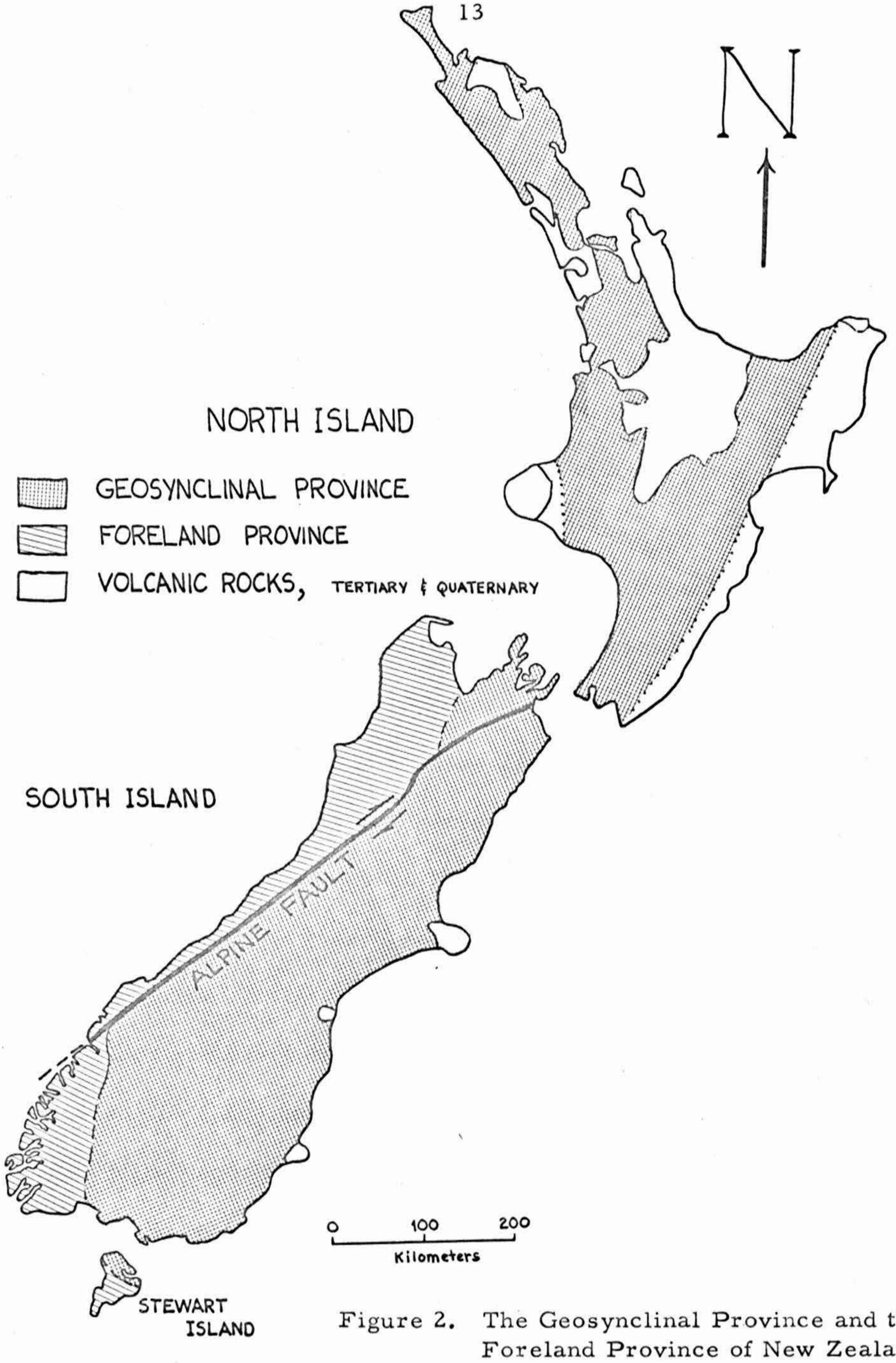


Figure 2. The Geosynclinal Province and the Foreland Province of New Zealand

structural feature of the South Island. The impressive evidence for Wellman's (1956) proposal of 500 km of right lateral displacement along the Alpine Fault has been recently summarized by Suggate (1963). The boundary between the Foreland Province and the Geosynclinal Province is largely covered by Tertiary and Cenozoic sedimentary rocks. This boundary in the one area where it is exposed, just south of the Alpine Fault, is a major fault, the Skelmorlie Fault.

A. The Geosynclinal Province

This province is entirely comprised by the New Zealand Geosyncline (Wellman, 1956). The Geosyncline has two parts, a Marginal Zone and an Alpine Zone (Figure 3). This geographical subdivision of the Geosyncline into the two zones presented here is a modification of Wellman's subdivision of the New Zealand Geosyncline which was based on the facies of its sedimentary rocks. The Marginal Zone as used here includes, along with Wellman's Marginal (Hokonui) facies of Mesozoic age, the geographically associated Permian deposits which underlie his Marginal facies. Both the Marginal Zone and the Alpine Zone received enormous thicknesses of sediments during the life of the New Zealand Geosyncline. On the order of 10 km of sediments were deposited in the Marginal Zone and this was almost certainly exceeded in the Alpine Zone (Coombs, 1950; Wellman, 1956; Wood, 1956; Mutch, 1957). The boundary between the two zones is formed by either major faults, mainly of a thrust nature, or else

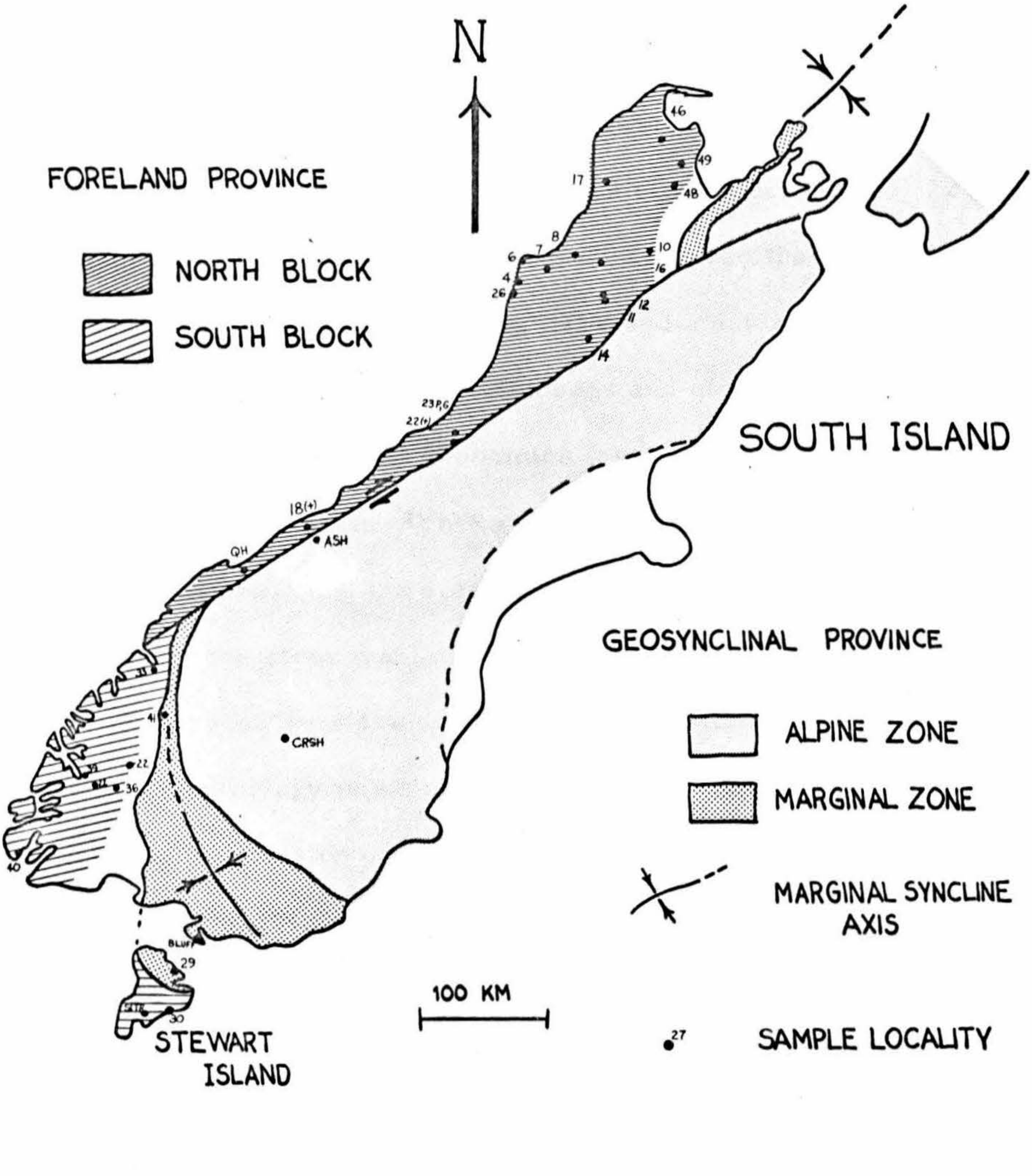


Figure 3. The Foreland Province and the Geosynclinal Province in South Island with sample localities.

complex zones of tight overturned folds (Wellman, 1956; Wood, 1956).

The Marginal Zone occurs along the western border of the Geosynclinal Province, nearest the Foreland Province, in the South Island, and along the west coast of the middle part of the North Island. All of the exposed plutonic rocks of the Geosynclinal Province occur in the South Island in the Marginal Zone and these are mainly ultrabasic or basic in composition. The sedimentary rocks of this zone are generally coarse and tuffaceous and of relatively shallow water facies containing not uncommon fossils (Wellman, 1956; Wood, 1956). These sedimentary rocks have been rather simply deformed on a regional scale and the stratigraphical control in them is good. Conversely, the stratigraphical control in the Alpine Zone is very poor. The rocks here are dominantly redeposited greywackes of monotonous lithology in which fossils are very uncommon. The structural deformation of these rocks has been intense. By necessity the history of the New Zealand Geosyncline has been mainly measured in the stratigraphy of the Marginal Zone. The scarce fossils found in the Alpine Zone greywackes do indicate these rocks are contemporaneous in deposition with the Marginal Zone, and the sedimentary rocks of the two zones are regarded as laterally equivalent in time but of different facies (Wellman, 1956).

Sometime during the late Mesozoic the Geosyncline was tectonically uplifted. During this uplift the sedimentary rocks of the Marginal Zone were rather simply deformed into a regional syncline that extends through the South Island both south and north of the Alpine Fault and into the North Island along its west coast. Meanwhile in the Alpine Zone, in addition to the complex and intense deformation of the sedimentary rocks throughout their extent, the bottom of the geosynclinal pile in this zone was regionally metamorphosed to the Otago and Alpine schists. This tectonic uplift of the New Zealand Geosyncline and the concomitant regional metamorphism have been termed the Rangitata Orogeny (see Kingma, 1959).

B. The Foreland Province

This province will be described in more detail later and a brief description will suffice here. The rocks of the Foreland Province differ greatly from those of the Geosynclinal Province. A large proportion of these are plutonic rocks of acidic-to-intermediate composition. These rocks occur in large, generally elongated bodies of batholithic dimensions. They are intrusive into either regional metamorphic schists and gneisses of low, medium, or high rank or into sedimentary rocks. The latter range in age from early Paleozoic possibly down into the Precambrian; the Paleozoic rocks are moderately fossiliferrous. Most of the sedimentary rocks are much more mature than the sedimentary rocks of the Geosynclinal Province being generally more quartz-rich (Reed, 1957). Limestones and quartzites are not uncommon in the section (Grindley, 1961).

III.

PREVIOUS GEOCHRONOLOGICAL WORK IN NEW ZEALAND

III. Previous Geochronological Work in New Zealand

Previous age determinations have been too limited in scope to provide a clear picture of the regional geochronology of the South Island. Hutton (1950) employed non-isotopic chemical and X-ray analyses to obtain a 119 million year age on uranothorites concentrated from South Westland beach sands, in the southern part of the Foreland Province north of the Alpine Fault, the source of which (Mason, 1961) was probably the Alpine Schists. By similar methods, Hutton (1951) calculated a maximum age of 15 million years for a pegmatitic allanite near Doubtful Sound in the South Block of the Foreland Province. A re-check of this calculation shows that this maximum age should be 200 million years*. The primary interest of the study by Hurley, Hughes, Pinson, and Fairbairn (1962) was to determine natural diffusion parameters of radiogenic argon in the Alpine Schist along the active Alpine Fault. However, their study included a North and a South Westland granitic rock from the southern half of the Foreland Province north of the Alpine Fault. A biotite with a chlorite impurity from the northern granite had a 70 million year potassium-argon age. The results of this present study suggest that this age may be a minimum value. The other results of their study will be

---

*Total lead, by X-ray fluorescence, did not exceed 0.01%; the ThO_2 content was 1.05% by chemical analysis. Calculation of maximum age assumes all lead is Pb^{208}.

discussed later. Wasserburg, Craig, Menard, Engel, and Engel (1963) determined an age of 190 million years by both potassium-argon and rubidium-strontium methods for biotite from a granodiorite from the Bounty Islands at the eastern edge of the Campbell Plateau. No rocks of this exact age were found in the present study and their results will be discussed briefly in summary sections later.

IV.

RESULTS OF THIS STUDY

A. GEOSYNCLINAL PROVINCE

1. Marginal Zone
2. Alpine Zone

B. FORELAND PROVINCE

1. Introduction
2. North Block
3. South Block

C. PRECAMBRIAN IN NEW ZEALAND

1. North Island
2. South Island,
   Greenland Series

IV. Results of This Study

Samples examined in this study were taken from areas widely distributed in South Island in the Foreland Province. Five samples also were examined from the Geosynclinal Province, three of which are from the Marginal Zone and two of which are from the Alpine Zone. These localities are shown in an index map as Figure 4. All of these samples include both plutonic and metamorphic types. In addition, two samples from the North Island were examined, shown in Figure 30.

The results of this study delineate four periods of plutonic and metamorphic activity in New Zealand:

(1) At least one in the Precambrian, of moderately old age, in the Foreland Province.

(2) One during the Devonian in the Foreland Province.

(3) One during the Permian, possibly extending into the Mesozoic in the Geosynclinal Province.

(4) One during the middle Cretaceous in both the Foreland and Geosynclinal Provinces.

The last three periods are indicated by the rubidium-strontium results and the tabulated data for these are shown in Tables 2, 3, 4, 5, and 6, organized by island, province, and age. Errors in the age have been approximately estimated by assigning a ± 0.25% error to the initial and present Sr^{87}/Sr^{86}; a ± 2% error to the rubidium content; and a ±0.4% error to the strontium content. The total error assignment is regarded as being very liberal and the reader is referred to data and discussion presented in the appendix concerning analytical reproducibility. The Rb-Sr results along with zircon results are discussed in detail below beginning with the Geosynclinal Province and followed by the Foreland Province.

Table 2.

RUBIDIUM - STRONTIUM DATA

SOUTH ISLAND	Sample Code	Phase	Rb^{87} 10^{-8} $\frac{\text{moles}}{\text{gm}}$	Sr^{88} 10^{-8} $\frac{\text{moles}}{\text{gm}}$	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86} Calculated	Sr^{87}/Sr^{86} Measured	Sr^{87}/Sr^{86} Initial	Sr^{87*} 10^{-8} $\frac{\text{moles}}{\text{gm}}$	Age Million Years
I. Geosynclinal Province										
A. Marginal Zone										
	Bluff. granite vein	biotite	169.2	14.290	99.14	1.045	1.053	0.706	0.5782(c)	246 ± 10(c)
	41 MacKay granodiorite	$biotite_1$	142.2	10.507	113.37	0.9452		0.706	0.3025	153 ± 5
		$biotite_2$	143.0	10.672	112.19	0.9411		0.706	0.3025	152 ± 5
	29. N. Stewart Island tonalite	biotite	114.76	8.837	108.76	0.9088	0.9085	0.703	0.2171(c)	136 ± 5(c)
B. Alpine Zone										
	CRSH. Otago schist	biotite	174.6	122.49	11.94	0.7236	0.7243	0.7063	0.2588(m)	104 ± 22(m)
		musc.	111.1	63.26	14.71	0.7306	0.7300	0.7063	0.1794(a)	116 ± 19(a)
		plag.	∼1.5	∼61	∼0.2		0.7063			
	ASH. Alpine schist pegmatite	biotite	166.4	2.772	502.7	0.886	0.883	0.7059	0.05971(c)	25.8 ± 1.0(c)
		musc.	78.15	36.23	17.95	0.7212	0.7226	0.7059	0.06672(c)	60 ± 14 (c)
		pot.feld.	149.5	58.84	21.29	0.7263	0.7236	0.7059	0.1249 (c)	60 ± 13 (c)
		plag.#	∼0	∼530	∼0		0.7059			

\# rubidium and strontium concentration determined by X-ray fluorescence.
(m)-calculated from measured Sr^{87}/Sr^{86}
(c)-calculated from calculated Sr^{87}/Sr^{86}
(a)-calculated from average of calculated and measured Sr^{87}/Sr^{86}
* -radiogenic strontium 87

Table 3. RUBIDIUM - STRONTIUM DATA

SOUTH ISLAND

II. Foreland Province

A. North Block

	Sample Code	Phase	Rb^{87} 10^{-8} moles/gm	Sr^{88} 10^{-8} moles/gm	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86} Calculated	Sr^{87}/Sr^{86} Measured	Sr^{87}/Sr^{86} Initial	Sr^{87*} 10^{-8} moles	Age Million Years
1. Paleosoic	QH. Quarts Hill granite	musc.	165.68	3.7206	372.95	2.6066		0.710	0.8426	365 ± 8
	18. Greenland Series hornfels, Moeraki Bluffs	biotite	241.3	9.566	211.3	1.571		0.7238	0.9669	288 ± 10
		musc.	108.0	29.41	30.74	0.8643	0.8647	0.7238	0.4915 (a)	326 ± 14(a)
		plag. #	~5	~350	~0.12			0.7238		
		whole rk.- 1	61.14	136.9	3.637	0.7409	0.7421	0.7238	0.2886	340 ± 73
		whole rk.- 2	51.87	135.1	3.215	0.7402	0.7398	0.7238	0.2492	345 ± 82
	22. Greenland Series hornfels, Waitaha River	biotite	157.99	5.4319	243.60	1.131		0.7223	0.2889	121 ± 3
		musc.	69.905	21.040	27.827	0.8402	0.8390	0.7223	0.2626 (c)	303 ± 15(c)
		plag. #	~0	~280	~0		0.7263			
		apatite #	~0	~60	~0		0.7300			
		whole rk.- 1	38.650	118.35	2.7351	0.7334	0.7335			
		whole rk.- 2	38.884	117.71	2.7667	0.7336	0.7344			
	230. Waitha medium granite	biotite	304.32	4.3479	586.2	1.7263		0.710	0.5250	124 ± 3
		whole rk.	56.10	170.84	2.750	0.7234	0.7240	0.710	0.2742 (c)	351 ± 95(c)
West Coast	23P. Waitha coarse granite	musc.	413.9	0.4915	7052.6	35.945		0.710	2.0678	358.5 ± 8
		pot. feld.	374.7	10.567	335.33	2.1945		0.710	1.8729	358.7 ± 9
		whole rk.- 1	91.34	4.549	168.19	1.5520	1.5549	0.710	0.4573 (c)	359 ± 10(c)
		whole rk.- 2	91.63	4.863	157.80	1.5285		0.710	0.4753	372 ± 10
	17. Karamea adamellite	musc.	169.4	11.276	125.83	1.3189	1.3191	0.7090	0.8204 (c)	348 ± 9(c)
		whole rk.	62.92	130.80	4.029	0.7287		0.7090	0.3071	350 ± 70
		plag. #	~3.2	~230	~0.12		0.7096			
	6a. Charleston - Geneiss, Tauranga Bay	biotite- 1	216.1	6.627	273.2	1.095	1.107	0.7136	0.3003 (c)	100.3 ± 3.0 (c)
		biotite- 2	227.1	3.516	541.0	1.448		0.7136	0.3077	97.4 ± 2.5
		pot. feld.	83.71	233.3	3.005	0.7186	0.7190	0.7136	0.1110 (m)	105 ± 66 (m)
		plag. #	20	370	0.50		0.7147			
	6b. Charleston - Geneiss, Tauranga Bay	biotite- 1	219.8	6.507	282.9	1.111		0.7117	0.3099	101.0 ± 3.0
		biotite- 3	218.6	7.064	259.2	1.0760		0.7117	0.3073	101.0 ± 3.0
		biotite- 4	219.3	6.983	263.0	1.0850		0.7117	0.3112	102.0 ± 3.0
		biotite- 5	224.7	6.683	281.6	1.1004		0.7117	0.3102	99.2 ± 3.0
		biotite- 6	221.5	7.242	256.1	1.0675		0.7117	0.3076	99.9 ± 3.0
		whole rk.- 1					0.7163	0.7117	0.0933 (m)	130 ± 100 (m)
		whole rk.- 2				0.7185	0.7169	0.7117	0.0922 (m)	150 ± 100 (m)
		apatite #	~0	~65	~0		0.7117			
	20. Charleston Gneiss, migmatitic granite	musc.- 1	126.1	9.827	107.47	1.0230		0.729	0.3450	197 ± 6
		musc.- 2	125.3	9.859	106.47	1.0249		0.729	0.3484	200 ± 6
		biotite	276.1	2.4530	942.6	2.0776		0.729	0.3950	102.9 ± 2.3
		plag. #	~5.6	~50	~1.0	0.7319				
	12. Marauia River granite	musc.	196.8	17.634	93.469	1.1442		0.710	0.91429	333 ± 9
		biotite	364.4	10.975	278.04	1.5915		0.710	1.5482	305 ± 7
		whole rk.	63.99	166.61	3.2167	0.7269		0.710	0.3362	377 ± 86
Inland	11. Marauia River hornfels	musc.	100.85	26.942	31.351	0.8557		0.7330	0.3947	282 ± 12
		plag., qts. #	~2.5	~80	~0.25		0.7341			
	49. Rocky River, Rameka diorite	biotite- 1	237.9	54.372	36.644	0.8503	0.8480	0.7037	0.9367 (m)	283 ± 12 (m)
		biotite- 2	237.2	56.179	35.358	0.8455		0.7037	0.9511	288 ± 13
		plag. #	~0	~1900	~0		0.7037			

\# rubidium and strontium concentration determined by X-ray fluorescence

(m)-calculated from measured Sr^{87}/Sr^{86}

(c)-calculated from calculated Sr^{87}/Sr^{86}

(a)-calculated from average of calculated and measured Sr^{87}/Sr^{86}

* -radiogenic strontium 87

Table 4.

RUBIDIUM - STRONTIUM DATA

SOUTH ISLAND (continued)

II. Foreland Province (continued)

A. North Block (continued)

2. Cretaceous

	Sample Code	Phase	Rb^{87} $10^{-8}\frac{moles}{gm}$	Sr^{88} $10^{-8}\frac{moles}{gm}$	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86} Calculated	Sr^{87}/Sr^{86} Measured	Sr^{87}/Sr^{86} Initial	Sr^{87*} $10^{-8}\frac{moles}{gm}$	Age Million Years
Western or Paporoa Belt	4. Nile River pegmatite	musc.	224.6	11.36	165.7	0.961	0.9572	0.706	0.3440(c)	110 ± 4 (c)
		pot. feld.	112.5	405.2	2.756	0.7083	0.7109	0.706	0.224 (m)	140 ± 100 (m)
		plag.	~3	~400	~0		0.7060			
	7B. Paparoa medium granite	whole rk. - 1	73.65	212.2	2.907	0.7197		0.714	0.1377	140 ± 106
		whole rk. - 2	75.41	212.3	2.975	0.7194	0.7178	0.714	0.1024(m)	100 ± 76 (m)
	7L. Paparoa coarse granite	whole rk. - 1	91.20	80.52	9.487	0.7300		0.714	0.15338	120 ± 29
		whole rk. - 2	92.07	80.85	9.538	0.7296	0.7288	0.714	0.14299(m)	100 ± 27 (m)
		musc. - 1	447.96	2.2797	1645.7	3.5238		0.714	0.69037	111 ± 2.5
		musc. - 2	468.06	2.1435	1828.8	3.2503		0.714	0.71913	111 ± 2.5
		pot. feld.- 1	221.42	70.752	26.21	0.7550	0.7522	0.714	0.3230 (m)	105 ± 17 (m)
		pot. feld.- 2	223.17	79.974	23.37	0.7485		0.714		106 ± 13
		plag.	4.125	40.583	0.85125	0.7150				
	8. Macley River qts. diorite	biotite	145.78	17.924	68.117	0.8136	0.8134	0.703	0.2367 (a)	117 ± 7 (a)
Karamea or Middle Belt	16. Buller River adamellite	musc.	288.6	31.772	76.077	0.8228	0.8241	0.704	0.4555 (m)	113 ± 5.5 (m)
		biotite	334.6	25.730	108.906	0.8726		0.704	0.5192	112 ± 4.5
		pot. feld,#	178.6	294.241	5.0838	0.7130	0.7119	0.704	0.278 (m)	112 ± 60 (m)
		whole rk.#	~30	326.26	~2.1		0.7069	0.704		100 ± 100
	14. Rahu Saddle adamellite	biotite	369.7	13.881	223.08	1.0448		0.704	0.5649	110 ± 3.5
		whole rk.	80	410.23	1.6		0.7062			
Eastern or Separation Point Belt	10. Rotoroa Complex quartz diorite	biotite	63.71	11.423	46.710	0.7783	0.7786	0.703	0.10275(c)	116 ± 8 (c)
	48. Motueka River pegmatite	musc.- 1	380.4	1.636	1935	3.538		0.7019	0.5527	105 ± 3
		musc.- 2	415.2	3.763	923.9	2.080		0.7019	0.6194	107 ± 3
		musc.- 4	485.6	0.6153	6610	10.226	10.	0.7019	0.6997	103.6 ± 2.3
		biotite	240.9	5.352	377.0	1.221		0.7019	0.3315	99.0 ± 2.7
		pot. feld.	166.4	330.15	4.222	0.7077	0.7075	0.7019	0.2235 (c)	97 ± 64 (c)
		plag. #	5	700	.06		0.7019			
	46. Anatoki River schist	biotite	138.53	2.8155	412.08	1.2912		0.7273	0.1896	98 ± 2.6
		musc.	66.98	22.644	24.774	0.7617		0.7273	0.09305	100 ± 12
		plag.(+) qts.	1.1	75	0.05		0.7273			

\# rubidium and strontium concentration determined by X-ray fluorescence.
(m)-calculated from measured Sr^{87}/Sr^{86}
(c)-calculated from calculated Sr^{87}/Sr^{86}
(a)-calculated from average of calculated and measured Sr^{87}/Sr^{86}
* -radiogenic strontium 87

Table 5.

RUBIDIUM - STRONTIUM DATA

SOUTH ISLAND (Continued)

	Sample Code	Phase	Rb^{87} 10^{-8} moles/gm	Sr^{88} 10^{-8} moles/gm	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86} Calculated	Sr^{87}/Sr^{86} Measured	Sr^{87}/Sr^{86} Initial	Sr^{87*} 10^{-8} moles/gm	Age Million Years
II. Foreland Province (continued)										
B. South Block										
Southwestern Tip	40. Kakapo adamellite	biotite	157.4	30.94	42.63	0.7621	0.7613	0.7029	0.2183 (c)	99.7 ± 8 (c)
		muscovite	105.1	41.30	21.59	0.7321	0.7321	0.7029	0.1418 (m)	97.1 ± 14 (m)
		pot. feld.	72.87	509.8	1.197	0.7031	0.7052	0.7029	0.12 (m)	180 ±180 (m)
		plag.	~4.8	~420	~0.10		0.7029			
		whole rk.- 1	27.76	334.6	0.6948		0.7041			
		whole rk.- 2	27.99	337.2	0.6952	0.7035	0.7035			
Main Crystalline Complex	36. Pomona Island granite	biotite	151.0	33.55	37.699	0.7690	0.7685	0.707	0.2484 (c)	118 ± 9.2(c)
		pot. feld.	121.9	49.49	20.627	0.7363	0.7359	0.707	0.1734 (c)	102 ± 14 (c)
		plag.	3.706	24.58	1.2625	0.7085				
		whole rk.- 1	42.91	44.68	7.556	0.7188	0.7172	0.707	0.05438(c)	109 ± 38 (c)
		whole rk.- 2	40.31	45.79	7.847	0.7186		0.707	0.06342	97 ± 29
	22. Lake Manapouri amphibolite	biotite 1	110.9	39.83	23.31		0.736	0.7026	0.1577	103 ± 12
		biotite 2	110.8	19.01	48.84	0.7693	0.773	0.7026	0.1554 (a)	101 ± 7 (a)
		diopside #	~0	~60	~0		0.7026			
	21. Lake Te Anau amphibolite	biotite	83.31	11.08	62.97	0.8086	0.8016	0.7012	0.1328 (m)	115 ± 6 (m)
		plagioclase	0	1200	0	0.7012				
	39. Doubtful Sound granite	biotite- 1†	140.7	10.158	116.0	0.8572		0.704	0.1846	94 ± 4
		biotite 2†	144.0	10.065	119.8	0.8576		0.704	0.1834	92 ± 4
		biotite 3‡	148.1	8.407	147.5	0.9036		0.704	0.1993	97 ± 4
	33. Milford Sound amphibolite	biotite	98.15	15.768	52.13	0.7558	0.7550	0.702	0.1012 (c)	74 ± 6 (c)
Stewart Island, Southern Part	SITR. Tin Range quartzite	muscovite 1	339.7	13.27	214.4	1.044	1.0276	0.706 0.730	0.5349 (c) 0.4970 (c)	113 (c) 105 (c)
		muscovite 2	301.3	17.05	148.0	0.9491	0.9355	0.706 0.730	0.4950 (c) 0.4447 (c)	118 (c) 106 (c)
	30. Lord's River gneissic granite	biotite	134.9	15.918	70.96	0.8021	0.1827	0.706	0.1827	97 ± 4

\# rubidium and strontium concentration determined by X-ray fluorescence
(m)-calculated from measured Sr^{87}/Sr^{86}
(c)-calculated from calculated Sr^{87}/Sr^{86}
(a)-calculated from average of calculated and measured Sr^{87}/Sr^{86}
* -radiogenic strontium 87
† - 80/100 mesh
‡ - (+)20 mesh

Table 6.

RUBIDIUM - STRONTIUM DATA

NORTH ISLAND

Sample Code	Phase	Rb^{87} 10^{-8}moles/gm	Sr^{88} 10^{-8}moles/gm	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86} Calculated	Sr^{87}/Sr^{86} Measured	Sr^{87}/Sr^{86} Initial	Sr^{87*} 10^{-8}moles/gm	Age Million Years
COR. Coromandel tonalite	biotite	196.8	4.453	370.2	0.7936		0.706	0.04657	17.0 ± 1.0
NICO. tonalite boulder, Moeatoa	biotite plagioclase#	76.38 ~3.1	18.64 ~540	34.32 ~0.05	0.8251	0.8266 0.7023	0.7023	0.2734(c)	257 ± 12(c)

rubidium and strontium concentration determined by X-ray fluorescence
(c)-calculated from calculated Sr^{87}/Sr^{86}
*-radiogenic strontium 87

A. Geosynclinal Province Results

Two of the significant features in the history of the New Zealand Geosyncline are:

(1) The intrusion of plutonic rocks, dominantly ultrabasic and basic in composition in the Marginal Zone.

(2) The metamorphism of the Otago and Alpine Schists in the Alpine Zone.

There is some geological evidence to suggest that at least some of the former was associated with volcanism during the early history of the Geosyncline, whereas the latter occurred during the Rangitata Orogeny which ended the Geosyncline. It is important to document the absolute age of both of these to understand their roles in the history of the Geosyncline, and to realize any possible orogenic links between the Geosynclinal Province and the Foreland Province.

1. Marginal Zone Results

The regional synclinal fold in this zone south of the Alpine Fault is very broad to the south in the southeastern corner of the South Island with about a 75-km separation of the oldest known beds of lower Permian age (Figure 5). Where the complete section is exposed these beds are overlain by upper Permian strata and thick sequences of Triassic and lower and middle Jurassic sedimentary rocks. To the north towards the Alpine Fault the regional syncline abruptly narrows and becomes much faulted with steeply dipping or

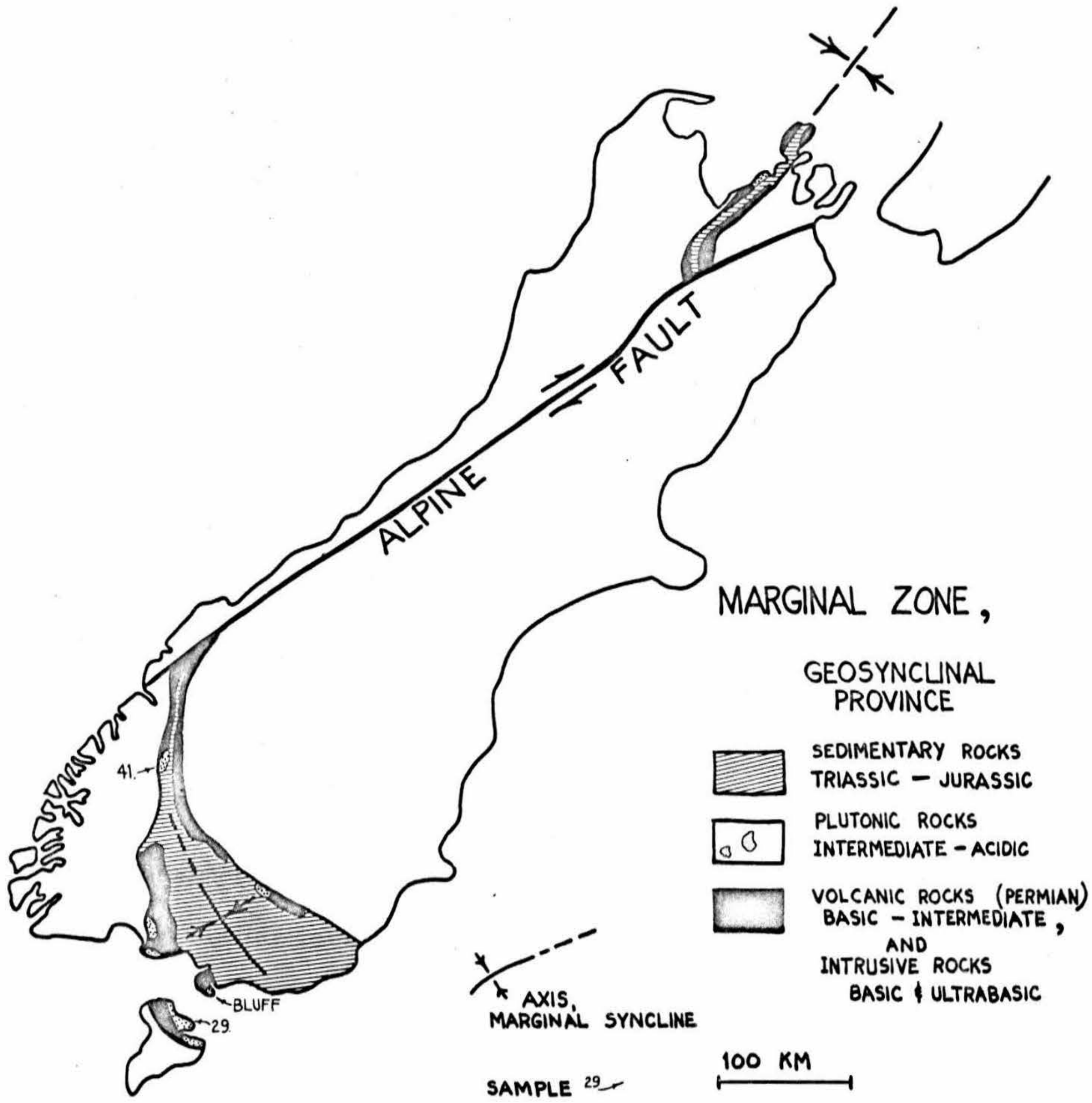


Figure 4. Marginal Zone of the Geosynclinal Province in the South Island.

vertical beds and generally complex structure; here most of the thick Triassic and Jurassic section is missing. The syncline is cut off at the Alpine Fault and occurs on the opposite side 500 km to the northeast where it is also very narrow and much faulted. From here the syncline has been extrapolated to the North Island (Wellman, 1956) where once again it is very broad with a thick section of Triassic and Jurassic marginal facies sedimentary rocks.

The plutonic rocks of the Geosynclinal Province are dominantly ultrabasic and basic in composition but include large amounts of intermediate and some acidic rocks (Figure 4). These plutonic rocks are ubiquitously associated with and intrusive into the oldest known deposits of the New Zealand Geosyncline. The latter are intermediate and basic volcanic rocks and volcanic-rich sedimentary rocks which occur along the flanks of the marginal syncline in the South Island. Fossils are known only in one locality, in the Takitimu Mountains, and these are lower Permian (Waterhouse, 1958). Here and in most other localities these rocks underlie fossiliferrous upper Permian sedimentary rocks (Waterhouse, 1964). In the long, narrow, faulted portion of the syncline near the Alpine Fault both north and south of the fault, partly serpentinized peridotites are the dominant intrusive. These occur as long belts which in places are continuous for greater than 80 km. In the broad portion of the syncline south of the Alpine Fault the dominant intrusive is gabbros occurring as isolated bodies with lesser amounts of associated ultrabasic, intermediate and acidic intrusives.

Because of the ubiquitous association of the plutonic rocks with either the lower Permian volcanic rocks or their lithological correlatives generally known to be pre-upper Permian, these plutonic rocks have been regarded as synchronously developed with the volcanic rocks and in part co-magmatic with them (Grindley, 1958; Wellman, 1956). However, others have called for a post-Permian intrusion of the belts of ultrabasic rocks; Benson (1940) and Turner (1934) (see Grindley, 1958) thought the belt south of the Alpine Fault was emplaced during the Rangitata Orogeny along the major fault (Livingston Fault) which bounds the Marginal Zone from the Alpine Zone; Lauder (1963) north of the Alpine Fault noted that the peridotite contact metamorphosed a marble correlated with upper Permian limestones, and suggested that the peridotites north of the Alpine Fault were also intruded during the Rangitata Orogeny.

Three samples of plutonic rocks were collected from widely separated areas of the Marginal Zone (Figure 5), all south of the Alpine Fault. One of these is from Bluff at the southeastern tip of the South Island, one from the Eglinton Valley and one from the northern part of Stewart Island. All of these occur on the west flank of the marginal syncline south of the Alpine Fault. From all of these rocks only biotite was favorable for Rb/Sr analysis.

a) The Bluff Intrusives (sample code: BLUFF)

At Bluff, norite and gabbro are intrusive into and contact-metamorphose basic volcanic and sedimentary rocks which contain an upper Paleozoic zaphrentid coral (Service, 1937). At this locality an important relationship exists with the gabbros that genetically links these basic rocks with ultrabasic rocks. A coarse scale interlayering between gabbro, peridotite and pyroxenite has been described (Harrington and McKellar, 1956) suggesting that at this locality on the syncline flank peridotite is coeval with gabbro. Also at Bluff lesser quantities of granite and diorite are associated with the gabbro. In the main Bluff quarry a very small quantity of coarse pegmatitic granite, in the form of thin reticulated veinlets, is intrusive into the norite.

The Rb/Sr age of coarse biotite*, hand-picked from the tiny veinlets, is 245 million years if an initial Sr^{87}/Sr^{86} of 0.706 is assumed, this assumption probably producing only a small uncertainty

---

*C. A. Landis of Otago University, Dunedin, New Zealand, informed the author that mica he had X-rayed from Bluff quarry was vermiculite. The mica analysed here is dark blackish-brown with $n_{x,z} > 1.60$ suggestive of biotite and not vermiculite, but X-ray analysis reveals the presence of both biotite and vermiculite in the sample with the biotite (001) peak being 1.5 times as large as the vermiculite (002) peak.

in the age (Table 2). Because the granite is post-norite and because the biotite shows some signs of alteration this age can only be taken as a minimum age for the norite and the associated ultrabasic rocks.

According to Holmes (1960) and Kulp (1961) the absolute age of 245 million years corresponds with the middle part of the Permian, and the lower part of the upper Permian, respectively. This agrees well with the stratigraphic evidence for the age of the gabbroic and associated intrusive rocks of the flanks of the broad part of the regional syncline south of the Alpine Fault. The rocks intruded by the norite at Bluff are correlated lithologically with the fossiliferrous lower Permian Takitimu Group, also on the west flank of the marginal syncline in the Takitimu Mountains, (Grindley, Wood, et al., 1959). The highly volcanic Takitimu Group grades down into basalts intruded by basic and ultrabasic crystalline rocks, chiefly gabbro (Mutch, in Lexicon Stratigraphique, 1957). North of Bluff on the opposite flank of the marginal syncline, near Gore, basic and acidic plutonic rocks of the Otama Intrusives also intrude basic volcanic and sedimentary rocks. The latter disconformably underlie fossiliferrous upper Permian sedimentary rocks and have been lithologically correlated with the Takitimu Group (Waterhouse, 1964). The Otama Intrusives are not observed to be intrusive into the overlying upper Permian sedimentary rocks of the same locality and are possibly represented as clasts in the upper Permian basal conglomerates (Wood, 1956).

If the relatively small mass of ultrabasic rocks grossly interlayed with the gabbro at Bluff is correlated with the huge belt of peridotites in the narrow part of the syncline to the north toward the Alpine Fault, then a Permian age is also suggested for the huge mass of ultrabasics. However, further geological and geochronological work is necessary to evaluate such a correlation of these two peridotites, both of which are associated with similar basic volcanic-rich rocks of lower Permian age.

b) MacKay Intrusives, Eglinton Valley (sample code: 41)

One of the largest masses of intermediate and acidic plutonic rocks developed on the flanks of the marginal syncline occurs south of the Alpine Fault on the west flank in the narrow portion of the syncline. These are centered at MacKay Creek in Eglinton Valley and are called the MacKay Intrusives. They are intrusive into the Eglinton Andesites and Basalts which conformably underlie upper Permian fossiliferrous sedimentary rocks (Grindley, 1958) and which probably correlate with the Takitimu Group (Waterhouse, 1964). The MacKay Intrusives are not associated with any basic or ultrabasic intrusive rocks. However, on the east flank, just opposite the MacKay Intrusives are the massive occurrences of peridotite and serpentine in the ultrabasic belt. Two separate splits of biotite from a slightly gneissic granodiorite sample of the MacKay Intrusives, mapped as "gneissic soda granite" by Grindley (1958), give ages of 153 and 152 million years if an initial Sr^{87}/Sr^{86} of 0.704 is assumed, this assumption probably producing only a small uncertainty in the age (Table 2).

c) Northern Stewart Island Tonalite (sample code: 29)

The northern third of Stewart Island contains abundant diorites and tonalities (Watters, 1959) and these have been correlated with the intermediate plutonic rocks at Bluff and in the Takitimu Mountains (Geological Map of New Zealand, Grindley, Harrington, and Wood, 1959 - see corrections). Because of the lack of any known fossiliferrous sedimentary rocks in northern Stewart Island this correlation is presently tentative. A probable fault contact separates the northern part of Stewart Island from the gneissic granites of the southern part which have been regarded as part of the Foreland Province (Grindley, Harrington, and Wood, 1959). A biotite from a gneissic tonalite from Horseshoe Bay, northern Stewart Island, gives an age of 136 million years if an initial Sr^{87}/Sr^{86} of 0.706 is assumed (Table 2).

d) Summary of Marginal Zone Results

Taken at face value the ages obtained for the three biotites from widely separated rocks of the western flank of the marginal syncline, of 245 my. at Bluff, 153 my. at MacKay Creek and 136 my. at northern Stewart Island suggest that plutonic activity occurred in the Marginal Zone during several periods during the life of the New Zealand Geosyncline. However, at least for the MacKay Creek sample, the possibility must be considered that the ages younger than Permian have resulted by post-crystallization metamorphic effects on the biotites. Coombs (1954), and Coombs, Ellis, Fife, and Taylor (1959), have shown that zeolite facies metamorphism grading at depth to prehnite-pumpellyite metamorphism is very common in the Marginal Zone of the Geosynclinal Province. Recently, C. A. Landis (personal communication) has found that the upper Permian sedimentary rocks of the narrow part of the marginal syncline both north and south of the Alpine Fault have been metamorphosed to glaucophane facies approximately in the area of the MacKay Intrusives. It is not known how much of the zeolite facies metamorphism is burial metamorphism and how much is associated with the Rangitata Orogeny. It would seem that the higher ranked glaucophane facies metamorphism in the Marginal Zone would be associated with the Rangitata Orogeny and not be due to burial metamorphism. As seen in thin section there are no obvious features in the particular sample of the MacKay Intrusive examined here which are suggestive of any secondary alteration by the glaucophane facies metamorphism. The biotite is only very slightly chloritized, probably less than in the average fresh New Zealand plutonic rock. However, Grindley (1958) describes microgranite varieties of the MacKay Intrusives (on the Eglinton Road) 0.6 km west of this samples's locality that display features suggestive of secondary alteration, but he attributed this to metasomatism of the microgranite by solutions from late crystallizing phases.

In the light of this metamorphism of the surrounding upper Permian sedimentary rocks to glaucophane facies it is possible to interpret the 152 million year apparent age of the MacKay Intrusive biotites by one of the following three explanations:

(1) The age is correct representing the time of intrusion and a subsequent glaucophane facies metamorphism has not affected the biotite Rb-Sr system.

(2) The age is correct, the granite being post-glaucophane facies metamorphism.

(3) The age is incorrect, the granite being older than the measured biotite age, set back by a subsequent glaucophane facies metamorphism.

Considering the well-known openness of the biotite Rb/Sr system during even light metamorphism the third hypothesis is certainly possible. The true age of the MacKay Intrusives may therefore also be Permian but further work on other mineral phases is necessary to verify this.

It is difficult to evaluate the single 136 million year apparent age on the biotite from northern Stewart Island both from the geochronological viewpoint and the geological viewpoint. Concerning the latter, the relationship of northern Stewart Island to the Marginal Zone plutonic rocks of the South Island and to the gneissic granites of the southern part of Stewart Island is not certain.

2. Alpine Zone Results

Because of the enormous thicknesses of sediments deposited in the New Zealand Geosyncline during the Permian, Triassic and Jurrassic, it has been proposed that the metamorphism of the Otago and Alpine Schists has been largely due to a burial metamorphism of the bottom of the geosynclinal pile (Wellman, 1956; Grindley, 1958). Under this proposal the maximum metamorphic rank was obtained for all sediments just prior to uplift of the geosyncline during the Rangitata Orogeny. It is evident that if this hypothesis is right and if deep burial during sedimentation is the cause of metamorphism then a measured age on the schists will be difficult to interpret. It is thus pertinent to discuss further the nature of the metamorphism of the Otago and Alpine Schists.

The central portion of the Alpine Zone has been regionally metamorphosed to the Otago and Alpine Schists. The Otago Schists occupy a huge broad band of chlorite zone shists 120 km wide in exposure in the south central part of the South Island, extending from the east (Pacific) coast to the Alpine Fault where they are gradational with the southern part of the northward swinging Alpine Schists (Figure 5). The latter extend 350 km north-northeast in a relatively narrow belt

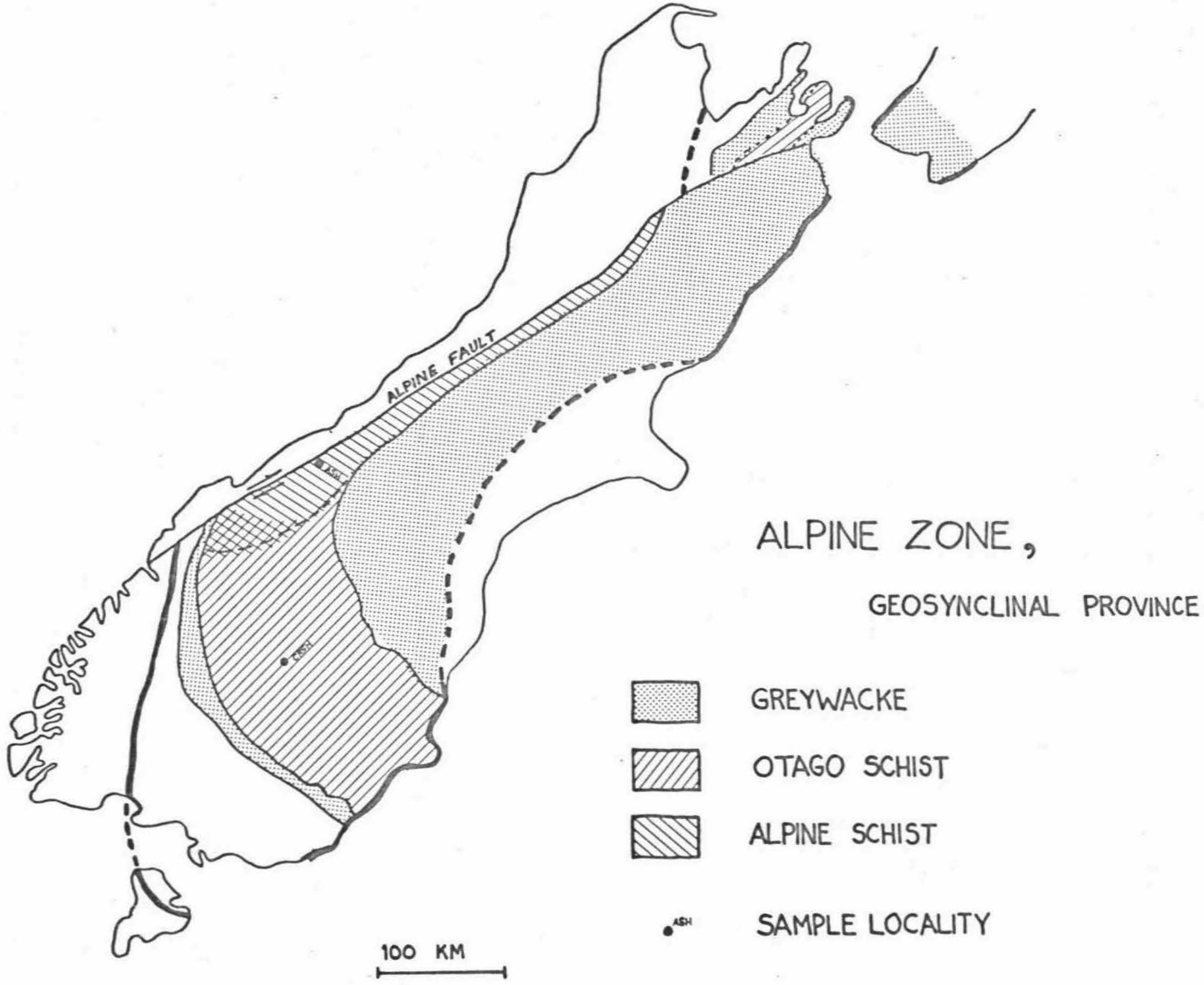


Figure 5. Alpine Zone of the Geosynclinal Province, South Island

bounded to the west by the Alpine Fault and along which they have been raised to form the Southern Alps backbone of the South Island. In contrast to the Otago Schists, the Alpine Schists contain closely spaced isograds increasing toward the Alpine Fault from chlorite zone through biotite zone to almandine-oligoclase zone. A correlative of the Otago and Alpine Schists, the Marlborough Schists occur north of the Alpine Fault bounded on both sides by relatively unmetamorphosed Alpine Zone greywacke. A small extension of these schists has been mapped in the central portion of the North Island (Grindley, Harrington, and Wood, 1958; Grindley, 1964).

The Otago and Alpine Schists are bounded on the north and east by "unmetamorphosed" greywacke (Figure 6) which contains very sparse Triassic and Jurassic fossils and fragments of possible Permian fossils. Also on the southwest the Otago Schist band is bounded by "unmetamorphosed" greywacke of the Alpine Zone. The greywackes, in turn, are thrust to the south over the sedimentary rocks of the Marginal Zone. Coombs (1954) and Coombs et al. (1959), besides showing that zeolite facies metamorphism is very common in the Marginal Zone, gradational at depth to prehnite-pumpellyite facies, presented evidence showing that much, if not all, of the "unmetamorphosed" Alpine Zone greywackes have been metamorphosed to prehnite-pumpellyite facies. The reconstitution within these rocks has been mainly mineralogical and not structural in contrast with the schists. Thus, essentially all of the sedimentary rocks of the New Zealand Geosyncline have undergone metamorphism.

There are three main hypotheses on the origin of the metamorphism of the Otago and Alpine Schists, listed historically as follows:

(1) Metamorphism due to subjacent granitic batholiths.
(2) Metamorphism due to deep burial during sedimentation.
(3) Metamorphism due to tectonic forces operative during the Rangitata Orogeny.

The first hypothesis was invoked by Finlayson in 1908 and Park in 1921 (referred to in Wood, 1963), Turner (1933, 1938), and Hutton (1940) before it was realized that the Alpine Fault separated the schists from the granites of the Foreland Province. This hypothesis has since been rejected because, except for a few sweat pegmatites in the Alpine Schists, no plutonic rocks have been found in association with the Otago and Alpine Schists in spite of the large relief carved in the schists.

The hypothesis of deep burial metamorphism was first proposed by Wellman (1956) who cited a general parallelism of schistosity and isograds to bedding. The discovery that the "unmetamorphosed" greywackes of the Alpine and Marginal Zones had been metamorphosed to prehnite-pumpellyite and zeolite facies and that in the latter, metamorphic grade increased with stratigraphic depth (Coombs, 1954; Coombs, et al., 1959) is not inconsistent with this hypothesis. However, this could also be explained by tectonic forces of the Rangitata

Orogeny preferentially bringing the lowest sediments of the geosynclinal pile into the hottest metamorphic environments. Alternatively, tectonic metamorphism of chlorite and higher grade during the Rangitata Orogeny may have been superimposed on rocks previously burially metamorphosed during deposition.

Burial metamorphism is progressive in time with no distinct beginning or end. Thus, the findings of Hurley, et al. (1962), of very anomalously low biotite K-Ar and Rb-Sr ages for the Alpine Schists are not inconsistent with burial metamorphism of the schists. They interpreted these low results as indicating that the deep regions from which these schists were recently uplifted are hot, and this suggests that some metamorphic effects may still be happening today in the deeply buried regions of the schist.

Recently much structural evidence has been accumulated that indicates that the major metamorphism of the Otago and Alpine Schists was not due to deep burial during deposition, but, instead, postdated a period of major deformation or was paratectonic with that deformation. In the Alpine Schists intense isoclinal folding preceded metamorphism (Lillie, Gunn, and Robinson, 1957, referred to in Coombs, et al., 1959). In the southern part of the Alpine Schists, Grindley (1963) has recognized multiple deformation including the formation of a major synclinal structure that is transected by later formed isograds. Evidence for paratectonic metamorphic crystallization of the Alpine and Otago Schists has been found by Wood (1963), Means (1963), Brown (1963), and Grindley (1963). Thus, the burial hypothesis does not appear to explain the major metamorphism of the schists, and the third hypothesis of metamorphism due to tectonic forces of the Rangitata Orogeny, first formulated in conjunction with subjacent batholiths by Turner (1933, referred to in Wood, 1963) and solely subscribed to by Mason (1962) does seem to explain the main metamorphism.

a) Otago Schists (sample code: CRSH)

A sample of the Otago Schists was collected from Cromwell, 120 km east of the Alpine Fault. Biotite and muscovite from this sample give consistent ages of about 104-116 million years (Figure 6; Table 2). There is a relatively large uncertainty in these apparent ages because of the low Rb/Sr ratios of the minerals and further geochronological work is warranted. This age range would be in the middle part of the Cretaceous (Kulp, 1961) (see discussion in summary section) and is in good agreement with most of the geological evidence for the age of the metamorphism and uplift of the schists. All evidence suggests that the schists are gradational with relatively unmetamorphosed greywackes of the Alpine Zone which in turn are thought to be laterally correlative with the fossiliferrous strata of the Marginal Zone. However, the contacts between the schists and the Alpine Zone greywacke, and between the Alpine Zone greywacke and the Marginal Zone are in general faulted. Mutch (1963) has mapped a gradational contact of

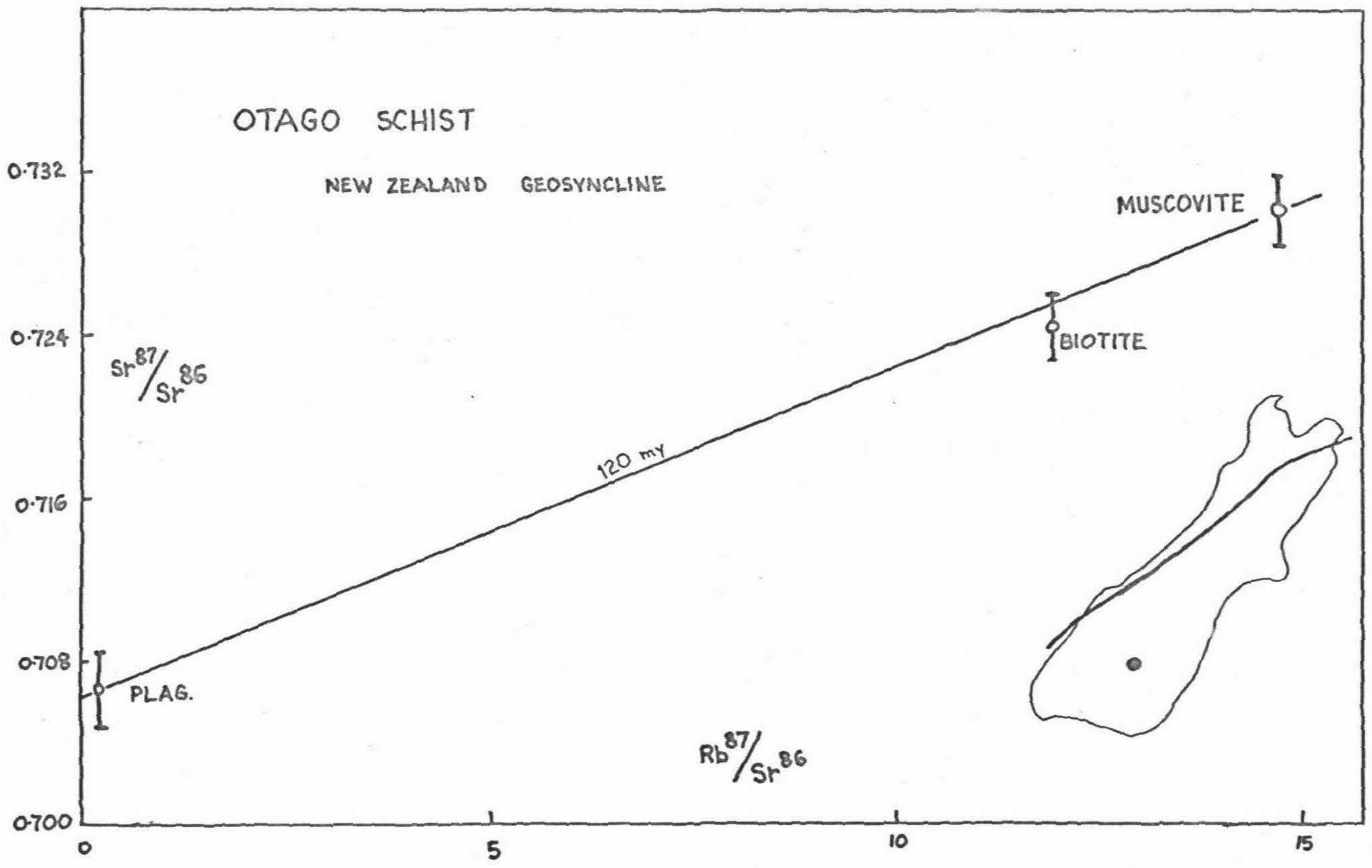


Figure 6. Rb-Sr isochron of Otago Schist, Cromwell

the schists with Permian and Middle Triassic greywackes of the Alpine Zone near the Waitaki River. Wood in the Gore Subdivision (1956) has noted a marked similarity between the basal Permian strata of the Marginal Zone and the overthrust Alpine Zone greywackes which to the northeast are gradational into chlorite zone Otago Schist. The main paratectonic and post-tectonic metamorphism of the schists must postdate the youngest sedimentary rocks of the New Zealand geosyncline into which the schists apparently grade. The youngest deposits which occur in the broad part of the Marginal Zone south of the Alpine Fault are upper Middle Jurassic marine sedimentary rocks and overlying non-marine plant-bearing beds. The terrestrial nature of the latter possibly signals the beginning of uplift of the geosyncline. Jurassic coal-bearing non-marine deposits also occur in Canterbury in the middle portion of the Alpine Zone just east of the axis of the geosyncline (Speight, 1928). However, belemnite-bearing upper Jurassic (Tithonian) marine sedimentary rocks have been found near the geosynclinal axis at its southwest end actually within the narrow neck of the Marginal Syncline (McKellar, Mutch, and Stevens, 1962). Also, fossiliferrous upper Jurassic (Tithonian) marine rocks have been found in several localities near the northeastern end of the geosynclinal axis in the South Island (McKellar, Mutch, and Stevens, 1962; Fleming, 1958) and this suggests that at that time the New Zealand Geosyncline was still an active depositional site at least in a narrow zone along the geosynclinal axis. The rapid retreat northward of that arm of the sea along the geosynclinal axis is suggested by the occurrence at the northern end of the axis of Cenomanian (Ngaterian) coals. These coals overlie with angular unconformity upper Albian (Motuan) marine sedimentary rocks which in turn overlie with angular unconformity Alpine Zone greywacke at least as young as Tithonian (Suggate, 1958). Further northeast at the northeastern end of the South Island and extending through the eastern part of the North Island marine deposition may have been continuous in the Geosyncline during the Cretaceous. However, at the northeastern end of the South Island uplift of a landmass to the south may be marked by basal conglomerates in the Albian and Turonian (Wellman, 1955; Hall, 1963). The youngest sedimentary rocks in the Marginal Zone of the North Island are also Tithonian and these again are suggestively overlain by plant-bearing terrestrial sedimentary rocks.

It thus seems likely that the final uplift of the New Zealand geosyncline must be post-Tithonian. According to Holmes (1960) and Kulp (1961) the upper Jurassic would have an age of about 135-145 million years.

An upper limit to the age of metamorphism of the Otago Schists is stratigraphically set by coarse terrestrial breccias and conglomerates which overlie the Otago Schists with profound unconformity in several localities in southeast Otago, containing large clasts of the schist.

These are interpreted to have been deposited in separated fault block basins as alluvial fans spreading from scarps along large faults which today partly bound these deposits (Harrington, in Fleming, 1958). These deposits have been dated by plant macro- and microfossils as being of various ages within the Cretaceous. The lower part of the Kyeburn Beds near Naseby is deemed the oldest because of the lack of angiosperms. All of the other Otago conglomerates and breccias unconformably above the schist, including the upper part of the Kyeburn beds, have yielded angiosperm micro- or macrofossils. Because the first known occurrence of angiosperms in New Zealand is in the lower part of the Ngaterian Stage which has been independently dated by marine fossils as Cenomanian (Hall, 1963; Vella, 1961), and because they are extremely rare as microfossils there (Wellman, 1959), an age determination based largely on the lack of angiosperms suggests, but does not prove, a pre-Cenomanian age.

A younger stratigraphic upper limit more firmly based is obtained from marine formations deposited by seas transgressive over quartzose coal measures, indicative of peneplaining conditions (Gage, 1952), which overlie the terrestrial breccias and conglomerates. The oldest of these marine rocks is Maestrichtian in age and occurs in southeast Otago at Shag Point (Gage, 1957). In Canterbury in the central part of the Geosynclinal Province rocks also of this age overlie rhyolites and plant beds which in turn unconformably overlie highly deformed Alpine Zone greywacke (Speight, 1928; 1938). Even younger uppermost Cretaceous and lower Tertiary marine deposits occur more widely spread inland in the Geosynclinal Province, marking a final subsidence of the land after the subsequent erosion and peneplaining of the areas tectonically uplifted during the Rangitata Orogeny.

Thus the geological evidence indicates a post-Tithonian, pre-Maestrichtian and possibly pre-Cenomanian age for the metamorphism of the Otago Schists, in good agreement with the 104-116 million year absolute age result recorded here.

Hurley, et al. (1962), measured a whole-rock K-Ar age of 133 million years on an argillite in gradational contact with Otago Schist (this age was misquoted by Mason (1961) as 166 million years). They argued that the 133 million year age was a minimum age of the potassium-bearing minerals in the argillite and implied that these minerals were diagenetically formed in the Triassic when the rock was deposited. However, it seems more likely, as was pointed out to the author (D. S. Coombs, personal communication), that most or all of these minerals are not of depositional age, but crystallized later during the Rangitata Orogeny. If so, this recrystallization of the argillite probably would have occurred at depths much shallower than those of the more thoroughly reconstituted Cromwell sample. Hence, the argillite micas may have begun retaining argon earlier than the schists, and therefore the 133 million year K-Ar whole-rock age may represent the beginning of orogenic uplift. It could be a maximum age for this event, however, because of the possibility of inherited radiogenic argon in clastic or diagenetic minerals.

b) The Alpine Schist (sample code: ASH)

As shown by Hurley et al. (1962), the Alpine Schist has had a complex history. They measured several K-Ar ages and one Rb-Sr age for biotites from samples of schist along the Alpine Fault. All biotites along the fault gave ages less than 10 million years old except for a large biotite from a pegmatite "shoot" structurally concordant with the schist at the Mica Mine in South Westland, which measured 25 million years by K-Ar. In the present work a complete Rb-Sr study of a related pegmatite "shoot" one mile south of the Mica Mine was made. Muscovite, biotite, potassium feldspar, and plagioclase were examined (Figure 7, Table 2). The age of the muscovite and potassium feldspar are both about 60 million years, but with a fairly large uncertainty; the biotite is 25 million years, in good agreement with the above-mentioned K-Ar determination.

These discordant results only confirm the complex history of the Alpine Schists that was revealed by the study of Hurley, et al. (1962), and the 60 million year ages represent the oldest ages so far obtained in the Alpine Schists, near the Alpine Fault. A good upper limit for the age of the Alpine Schist is the 104-116 million year age of the Otago Schist into which the higher-rank Alpine Schist imperceptively

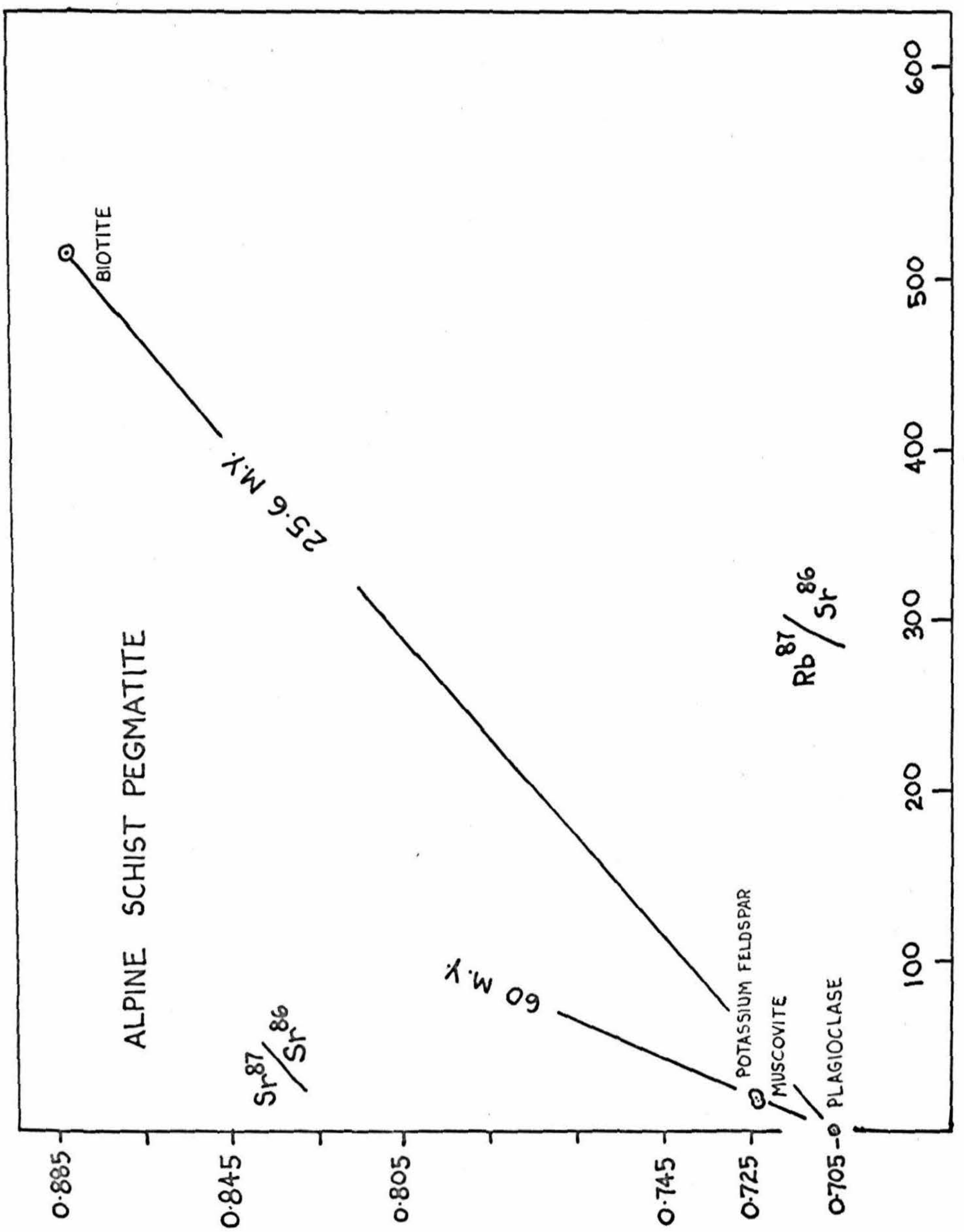


Figure 7. Rb-Sr isochron of
Alpine Schist pegmatite.

grades. An intermediate K-Ar age of 76 million years was determined by Hurley, et al. (1962), on a muscovite from a chlorite zone schist at Clark Bluff, intermediately located between the Alpine Fault and the Cromwell locality, though much closer to the Alpine Fault.

One cannot say whether ages younger than about 100 million years including those on the pegmatites represent times of distinct events or whether these ages simply reflect continuous diffusive loss of radiogenic daughters from older minerals, or some combination of both. Certainly the type of internal discordance presented here in which minerals from the same pegmatite give different ages, in addition to the external discordance of the pegmatite's having older apparent ages than the apparent ages measured by Hurley, et al., on the Alpine Schist in which the pegmatite is developed are suggestive that daughter loss has occurred. Hurley, et al. (1962), interpreted the low ages they obtained as due to diffusive losses and that only recently has uplift along the Alpine Fault brought these schists into cool enough regions where the already crystallized biotite could begin retaining its radiogenic daughter elements.

* * * *

Because no plutonic rocks have been found in field association with the Otago and Alpine Schists the Rangitata Orogeny has been regarded as unassociated with any plutonic activity. However, the geochronological results to be presented in the following section of numerous plutonic rocks from the Foreland Province indicate that a great many of these have ages of about 100-120 million years. These results, therefore, represent a major aspect of this work and associate a large amount of plutonism with the Rangitata Orogeny. This plutonism evidently occurred geographically separated from the Geosynclinal Province where, heretofore, the effects of the orogeny had mainly been recognized, or else occurred at such depth in the Geosynclinal Province that the vast relief carved in the schists has not exposed the plutonic rocks.

B. The Foreland Province

1. Introduction

At least during the latest stages of the Rangitata Orogeny a tectonic link existed between the Geosynclinal Province and the Foreland Province. This is indicated by the late Mesozoic and early Tertiary stratigraphic record of the Foreland Province which is similar to that of the Geosynclinal Province. In several separated areas mainly north of the Alpine Fault, terrestrial upper Mesozoic coal-bearing coarse sandstones, conglomerates and breccias overlie a basement of gneisses, granites, and possibly Precambrian sedimentary rocks. These locally derived deposits are lithologic and diastrophic correlatives of the terrestrial sedimentary rocks which overlie the Otago Schists in the Geosynclinal Province, both having been deposited as fanglomerates in separated fault block basins (Harrington in Lexique Stratigraphique, 1958). The plant microfossil evidence does not substantiate an exact time correlation of these deposits and this will be discussed in more detail later. Tectonic conditions continued in parallel, if not exactly synchronous, fashion in both the Geosynclinal and Foreland Provinces. In both, these deposits are overlain by quartzose coal measures indicative of peneplaining (Gage, 1952) and these in turn are succeeded by uppermost Cretaceous or lower Tertiary fossiliferrous marine sedimentary rocks deposited by seas transgressive over the peneplain (Figure 8).

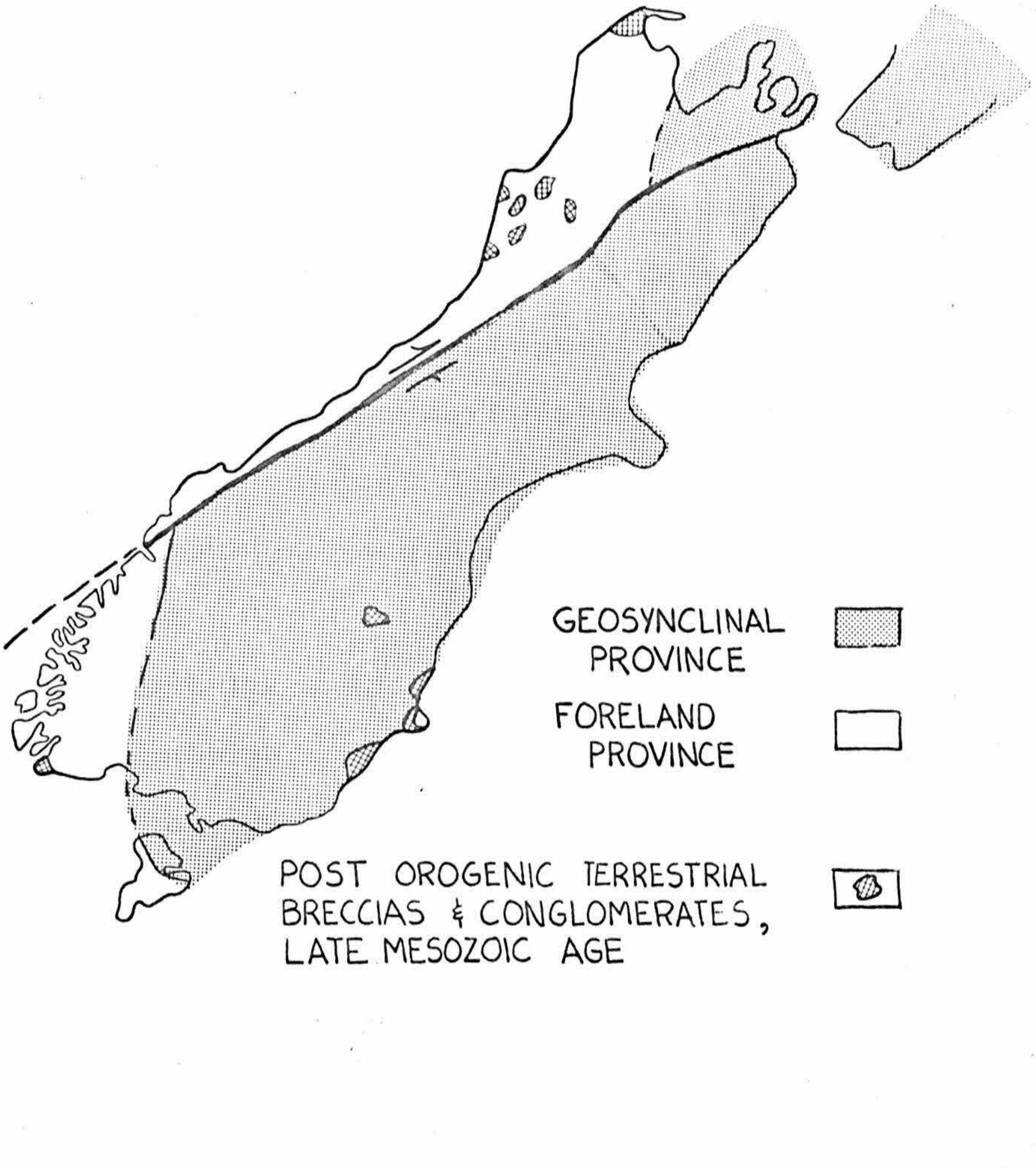


Figure 8. Distribution of post-Rangitata terrestrial breccias and conglomerates.

The pre-Tertiary rocks of the Foreland Province south of the Alpine Fault are somewhat different from those north of the Alpine Fault, although the proposed 500 km right lateral displacement would correlate these two halves. These will be referred to here, respectively, as the South Block and the North Block of the Foreland Province (Figure 2). The South Block is almost entirely comprised by crystalline rocks. These are dominated by gneisses metamorphosed to medium and high rank, largely amphibolites, and these are intruded by lesser amounts of concordantly emplaced acidic plutonic rocks. Only in the very southwestern tip of this block have pre-Tertiary sedimentary rocks been found. There lower Ordovician rocks are intruded and contact metamorphosed by granite (Benson, Bartrum, and King 1934).

In the North Block acidic plutonic rocks by far dominate in extent over metamorphic rocks which here are mainly schists metamorphosed to low and medium rank. These plutonic rocks, which occur mainly in batholithic belts are intrusive into and contact metamorphose parts of extensively developed sedimentary rocks. It is these sedimentary rocks which are in part regionally metamorphosed to schists; they range in age from lower Devonian down to the Greenland Series of possible Precambrian age but do not include any known Silurian rocks. A small patch of Permian sedimentary rocks has recently been found in the northern part of this block (Waterhouse and Vella, 1965).

The ages assigned to the plutonic and metamorphic rocks of the Foreland Province have always been regarded as tentative because of the lack of limiting stratigraphic evidence. In general the plutonic rocks have been divided into separate belts (Reed, 1958; Grindley, Harrington, and Wood, 1959; Wood, 1960), and these have been treated as possibly being of separate origin and consequently have been given separate ages. These commonly range from Precambrian to late Paleozoic. Those plutonic rocks classed as late Paleozoic have been correlated with definitely post-Ordovician granites of both the North and South Blocks for which an upper limit had been set by the occurrence of plutonic boulders in Triassic conglomerates of the Marginal Zone of the Geosynclinal Province both north and south of the Alpine Fault.

The Charleston Gneiss which occurs in the middle part of the North Block on the west coast and just inland (Figure 10) has been mapped as Precambrian. This complex gneissic terrain has been regarded as a possible basement for the Greenland Series, although field relationships have been unclear.

The results of this study indicate that the plutonic and metamorphic rocks of the Foreland Province both north and south of the Alpine Fault essentially all crystallized during two fairly short periods, one about 100-120 million years ago during the mid-Cretaceous, and the other about 345-370 million years ago during the Devonian. No crystalline rocks with primary Precambrian ages have been found in the Foreland Province. All of the results for the Foreland Province are shown in summary form as a histogram in Figure 9. The two peaks of this histogram are obvious and seem to define major relatively sharp pulses of plutonic and metamorphic activity in New Zealand. The older group of measured ages disperse toward young ages with some rocks showing apparent ages intermediate between the 120 and 345 million year events. Of these, those with both biotite and muscovite show internal discordance of their apparent ages and the interpretation at this stage is that these are 345-370 million year rocks variously affected by plutonism and metamorphism during the Cretaceous event. Because of these effects the limits on the age of the older period are not as well known as for the younger period.

The 100-120 million year age corresponds to the age measured for the metamorphism of the Otago Schist during the Rangitata Orogeny. The association of plutonic activity with this orogeny was not heretofore generally recognized. Only C. A. Cotton (referred to in Wellman, 1959) and J. Henderson (referred to in Reed, 1958) suggested that most or all of the plutonic rocks of the South Island were of late Mesozoic age. The 345-370 million year plutonic event probably is equivalent to middle Devonian and, if so, marks the outstanding stratigraphic gap during Phanerozoic time in New Zealand.

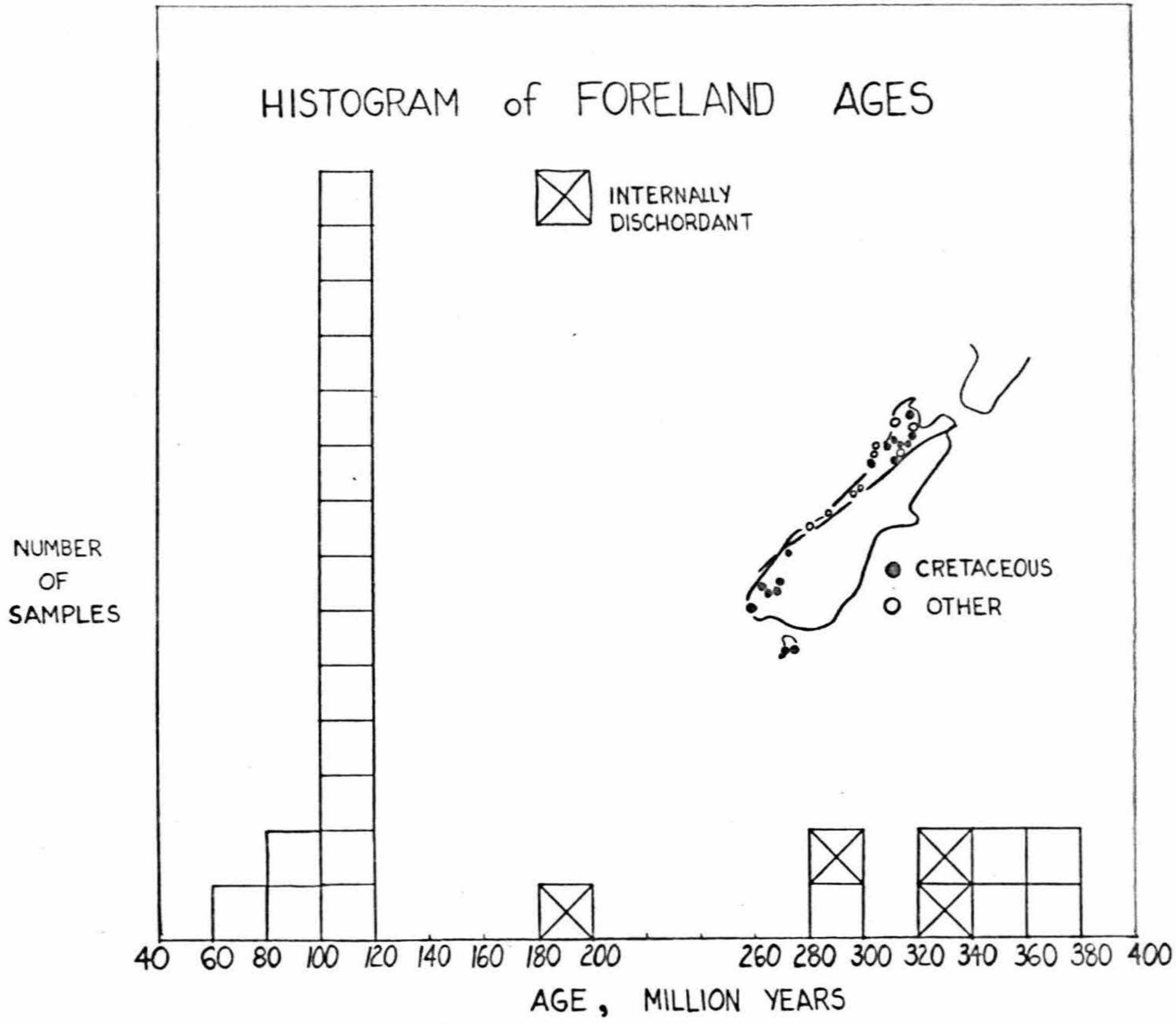


Figure 9. Foreland Ages.

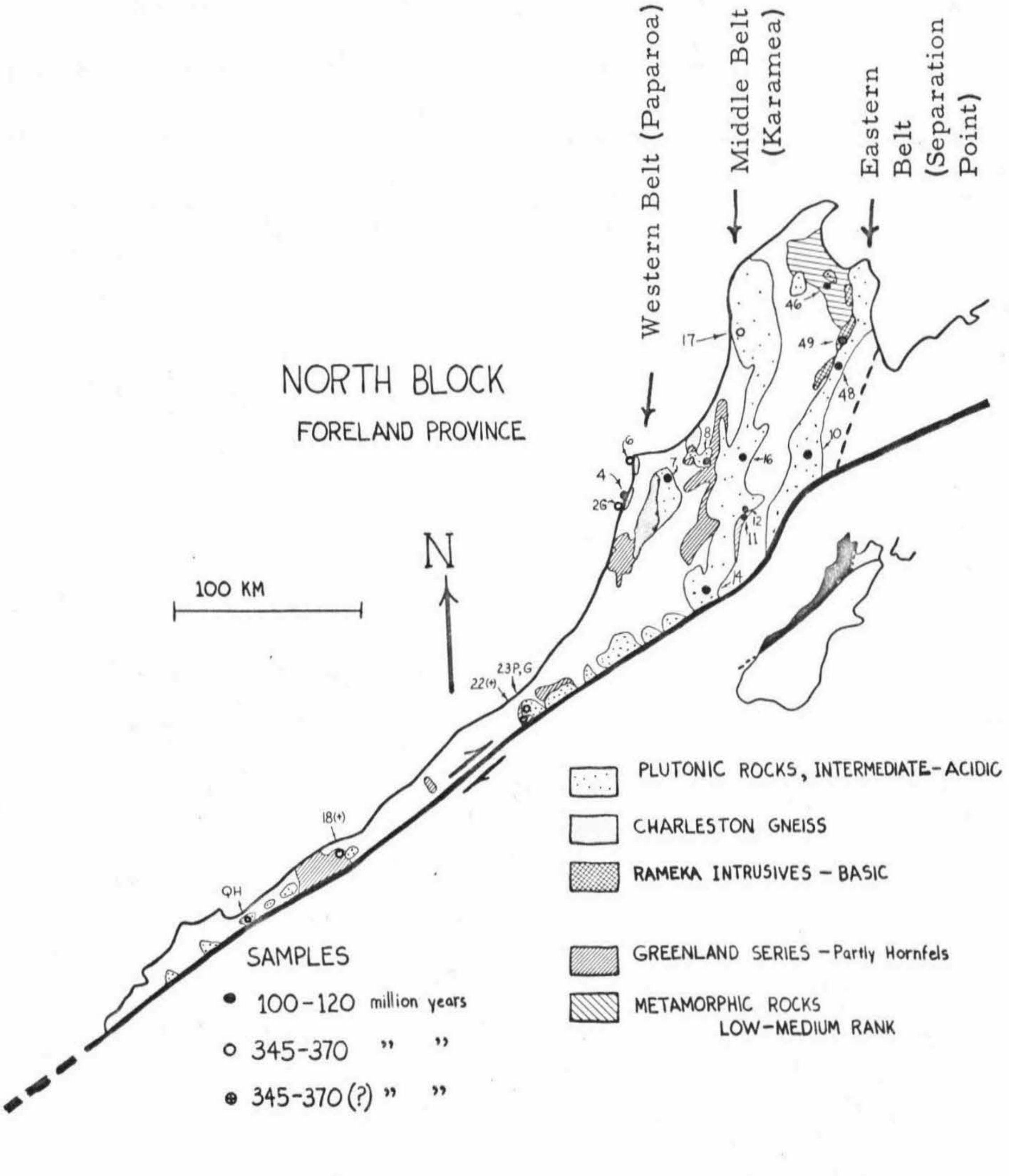


Figure 10. North Block of Foreland Province, showing sample locations.

The distribution of the two age groups of rocks seems somewhat complicated and it is difficult to generalize at this stage of work. No evidence of 345-370 million year rocks has been found in the South Block. In the North Block these rocks are concentrated along the west coast and appear scattered inland where the 100-120 million year rocks may be more concentrated. The distribution is complicated by the occurrence of rocks like the Charleston Gneiss in which both events are registered.

The following is a detailed discussion of these results from the Foreland Province, first focusing on the North Block and then proceeding to the South Block.

2. Detailed Discussion of Results From the North Block

In the northern part of the North Block the plutonic rocks crop out as three separated elongate belts trending roughly north-south, with the middle belt meeting the western belt at its top and the eastern belt at its bottom (Figure 10). Proceeding inland from the coast these belts have been named Paparoa, Karamea, and Separation Point by Reed (1958) and this terminology was followed in the Bulletin which accompanied the 1 : 2,000,000 Geological Map of New Zealand (Grindley, et al., 1959). The Middle Belt (Karamea) is the largest extending continuously for 200 km in length and 30 km in width. The Western Belt (Paparoa) includes the Charleston Gneiss as its western part. The three belts lose their distinctness in about the middle of this block, southward from which, in the narrow coastal strip of the southern half of the North Block, the plutonic rocks no longer crop out as large continuous bodies. They are separated into smaller masses by extensive Plio-Pleistocene and recent alluvial deposits shed from the Southern Alps, or else further south occur as small isolated stocks.

In the north the large masses of granitic rocks in the middle and eastern belts are intrusive into and contact metamorphose fossiliferrous rocks of Ordovician age which dominate an extensive sedimentary sequence also containing known Cambrian and lower Devonian rocks. The very northern part of the lower Paleozoic sequence of sedimentary rocks has been regionally metamorphosed to schists of low and medium rank and these bridge the northern parts of the middle and eastern granitic belts. Along the western border of the Eastern Belt (Separation Point) of granitic rocks occurs a discontinuous narrow belt of basic plutonic rocks and associated volcanics which are in part metamorphosed (Figure 10). These are mapped as Rameka Intrusives and Riwaka Metamorphics (Grindley, 1961; Cooper, 1965).

In the middle and southern part of the North Block the acidic plutonic rocks are intrusive into the Greenland Series which except for a small patch of infaulted Lower Devonian is the only sedimentary rock present. In the very south the Greenland Series is dominant in extent over the stock-like bodies of acidic plutonic rocks intrusive into it. Most of the Greenland Series in the southern half of this block is metamorphosed to a biotite, muscovite hornfels. This has been described as contact metamorphism by the stocks intrusive into the Greenland Series, but the hornfels is so extensive that their metamorphism can be considered as regional (personal communication, R. P. Suggate).

In the following discussion of the geochronological results of the North Block the detailed results from the 345-370 million year crystalline rocks will be examined first, beginning in the south of this block, proceeding along the west coast and then inland. Then the 100-120 my. rocks which occur mainly inland in the north of this block will be discussed.

(a) 345-370 Million Year Crystalline Rocks

(1) West Coast

Quartz Hill (sample code: QH): Coarse muscovite from a sample of coarse pegmatitic granite at Quartz Hill in the southern part of this block (Figure 10) was analyzed and gives an age of 365 million years if an initial Sr^{87}/Sr^{86} of 0.710 is assumed or 364 million years if 0.702 is assumed (Table 3). Quartz Hill is one of the several isolated small stocks of the southern part of this block. The contacts of the granite with the surrounding rock have not been reported but it is likely that it intrudes Greenland Series, the only pre-Cretaceous sedimentary rock known from the southern part of this block. Healy (1938) has described small granite bodies intruding Greenland Series not far south of

Quartz Hill; 60 km northeast a small body of granite intrudes the Greenland Series at Paringa (Wellman, 1955).

Moeraki Bluffs, Greenland Series (sample code: 18+): A sample of metamorphosed Greenland Series from near Paringa at Moeraki Bluffs (Figure 11) was examined in this study. The sample is a biotite and muscovite hornfels showing poor schistosity. The progressively increasing metamorphism of these rocks as the contact of the granite intrusive into the Greenland Series is approached has been noted (Wellman, 1955). Biotite, muscovite, total rocks, and plagioclase were analyzed from this sample and the results are shown on a strontium evolution diagram in Figure 11 and Table 3. The data for the biotite and muscovite are discordant, the muscovite-whole rock age being 330 million years and the biotite-whole rock age being 290 million years. The results of analysis of two aliquots of the whole rock show a relatively large spread. Both of these lie slightly above the muscovite-biotite-plagioclase triangle, this being due to experimental error or else suggesting the presence of another radiogenic strontium-bearing phase in the rock not examined here. The biotite age is in good agreement with a K-Ar determination by Hurley, et al. (1962), of 286 million years on a biotite from the granite intrusive into the Greenland Series in this same area. The internal discordance between the muscovite and biotite ages determined here indicates that this rock has been disturbed and suggests that the 320 million year

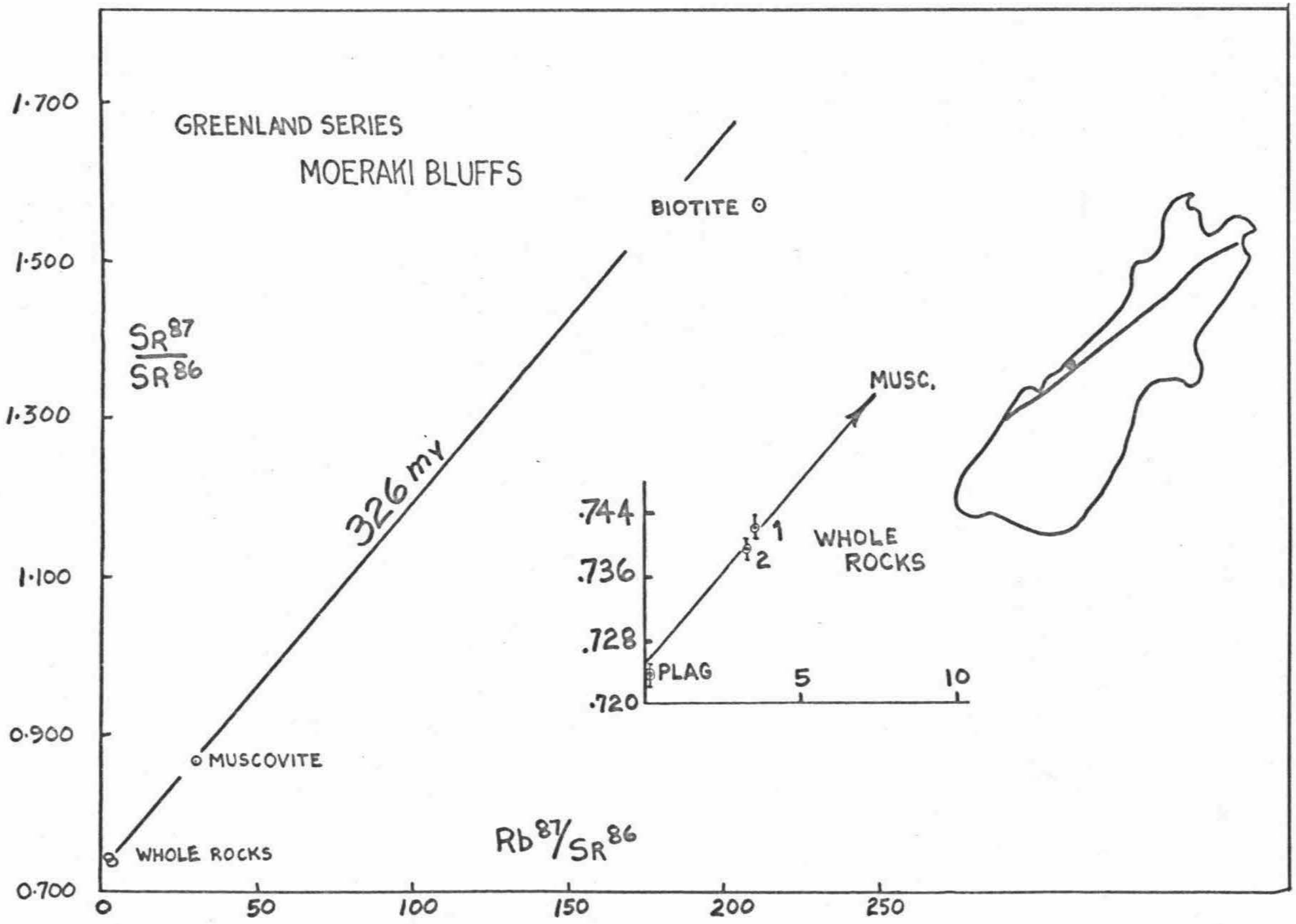


Figure 11. Rb-Sr isochron for Greenland Series, Moeraki Bluffs.

muscovite age can only be taken as a minimum indication of the age of metamorphism of this rock and intrusion of the nearby granite. The nature of the post-crystallization disturbance at this stage can only be inferred to be the Rangitata Orogeny.

Waitaha River, Greenland Series (sample code: 22+); and Intruding Granites (sample codes: 23P, 23G): One hundred thirty-five km northeast of Moeraki at the Waitaha River (Figure 10), granitic rocks are intrusive into the Greenland Series. Two phases of the granitic rocks collected from the same locality 5 km from the Alpine Fault and a hornfels sample of the intruded Greenland Series collected about 0.7 km from the fault were examined here. The hornfels, of poor schistosity, bears a strong resemblance to the Paringa hornfels. The two samples from widely separated localities have a similar mineralogy and texture. Both rocks contain small brown euhedral tourmaline as an accessory mineral; both contain sieve-structured muscovite porphyroblasts which are crudely foliated athwart the biotite foliation. The wide extent of this type of rock in the Greenland Series terrain is indicated by descriptions (Turner, 1930; and in Healy, 1938) of similar tourmaline-bearing hornfels phases of the Greenland Series 20 km south of Quartz Hill. These are also intruded by tourmaline-bearing pegmatites and pegmatitic granites.

The results of analysis of the Waitaha River hornfels are shown in Figure 12 and Table 3, and these indicate that this hornfels has

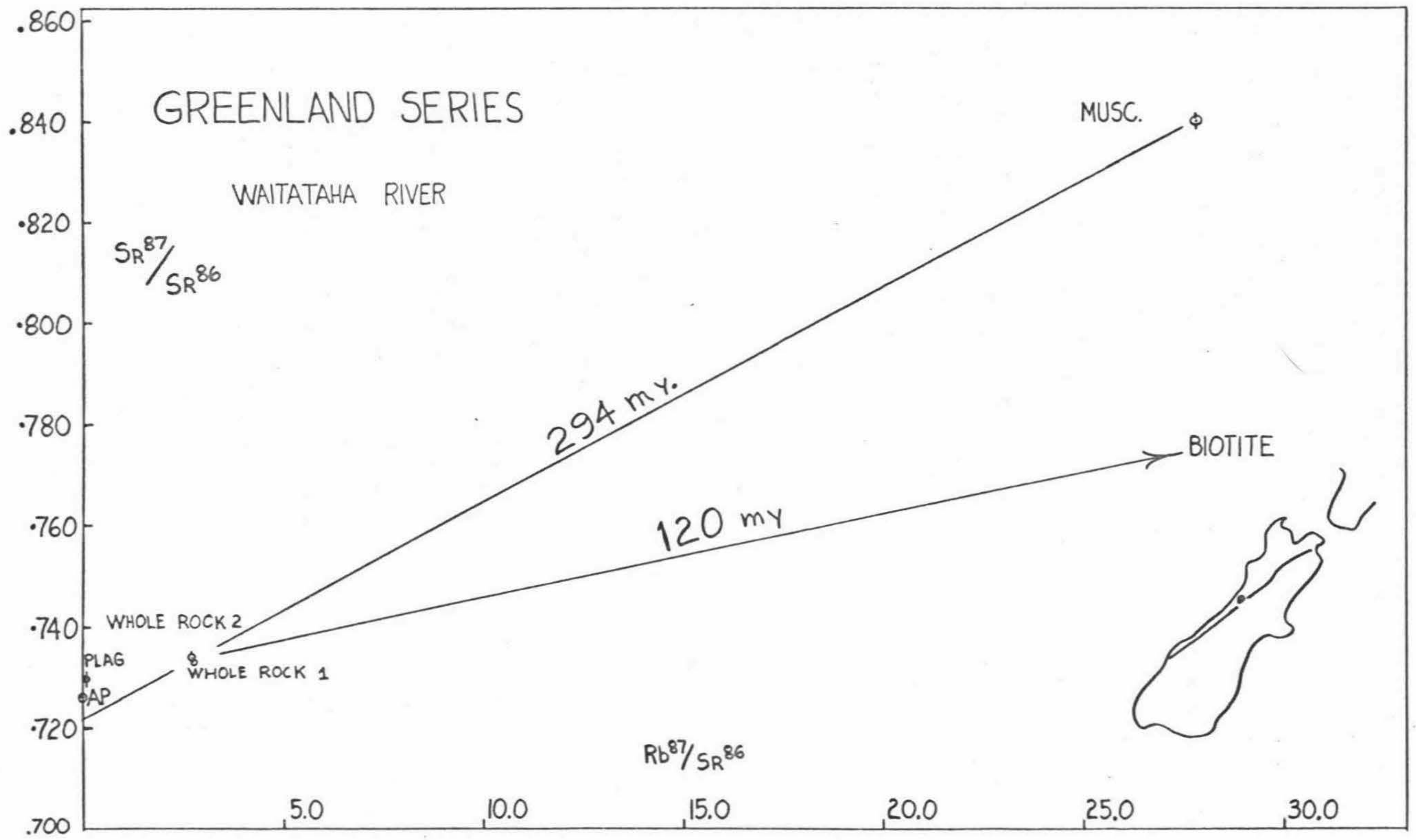


Figure 12. Rb-Sr isochron of Greenland Series, Waitaha River.

experienced a similar history as was inferred by rubidium-strontium evidence for the Moeraki sample to the south. The biotite-total rock age of 120 my., the magnitude of this discordance being much greater than at Moeraki Bluffs, and both the muscovite and biotite apparent ages are much lower. Because this sample locality is only about 0.7-0.8 km west of the Alpine Fault, movements along the fault may have caused some of this discordance. However, this seems unlikely when one considers that biotite from the granite, discussed below, intrusive into the Greenland Series and taken a much farther distance from the fault has a similar age.

One of the granites intrusive into the Greenland Series is a coarse tourmaline-bearing pegmatitic granite and the other is a medium-grained granite. The two granites occur at the same locality and the former is believed to be a pegmatitic phase of the latter although no detailed field relation between the two was observed. These have been described as being intrusive into the Greenland Series (Morgan, 1908). It is assumed that the two phases of granite are cogenetic but this should be confirmed by further field work.

The data for these two granites are plotted in the same strontium evolution diagram (Figure 13 and shown in Table 3). The coarse granite and its constituent minerals have very high Rb/Sr ratios permitting precise measured ages. The potassium feldspar and muscovite, both coarse-grained, give concordant ages of 359 my. and these

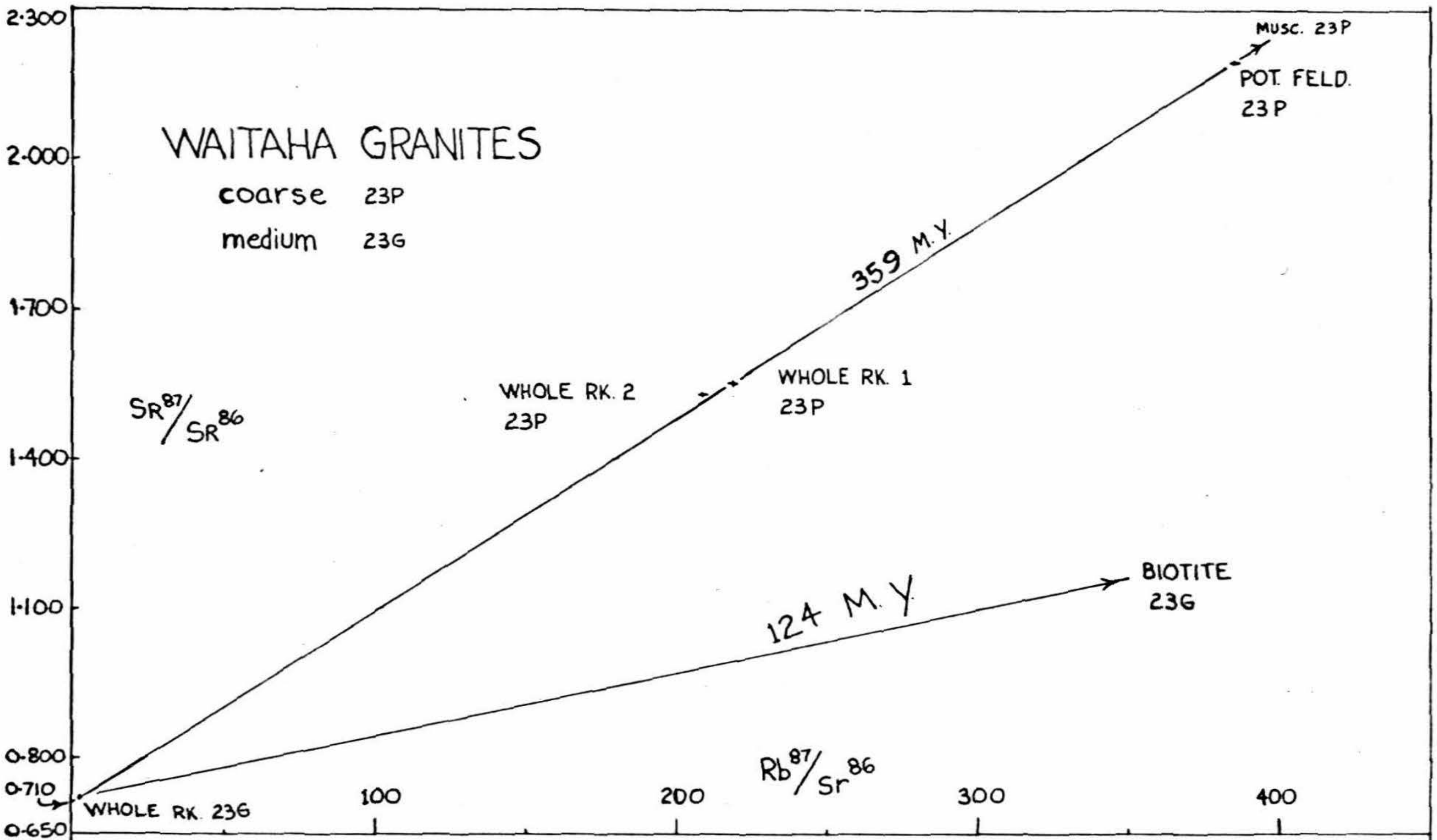


Figure 13.
Rb-Sr isochron of Waitaha River granites.

essentially fall on the isochron determined by whole rocks of the coarse granite and a whole rock of the medium-grained granite. However, the discrepancy between the two coarse total rocks is rather large, between 359 million years and 372 million years. An initial Sr^{87}/Sr^{86} of 0.710 is indicated for these two rocks and their minerals. The biotite from the medium-grained granite gives an age of 123 million years, much younger than the other minerals of the coarse-grained granite and similar to the biotite from the Greenland hornfels.

The possibility that the medium-grained granite is only 123 million years old, and not cogenetic with the coarse granite, arises. However, this age would imply a rather high initial Sr^{87}/Sr^{86} for this granite of 0.719. Field work and more geochronology is necessary, of course, to verify the relative ages of the two granites. At this stage of work the most favorable interpretation of the present data suggests that the medium-grained granite is of the same generation as the 360 million year coarse pegmatitic granite. The biotite from the medium-grained granite and from the nearby Greenland Series hornfels have both been disturbed at least 120 million years ago, after the emplacement of the granites. This disturbance is best inferred as the Rangitata Orogeny.

Karamea Adamellite, Northern Middle Belt (sample code: 17): Granitic rocks crop out discontinuously for a distance of 100 km north of Waitaha River, further north of which begins the occurrence of granitic rocks as continuous batholithic belts. The Western Belt

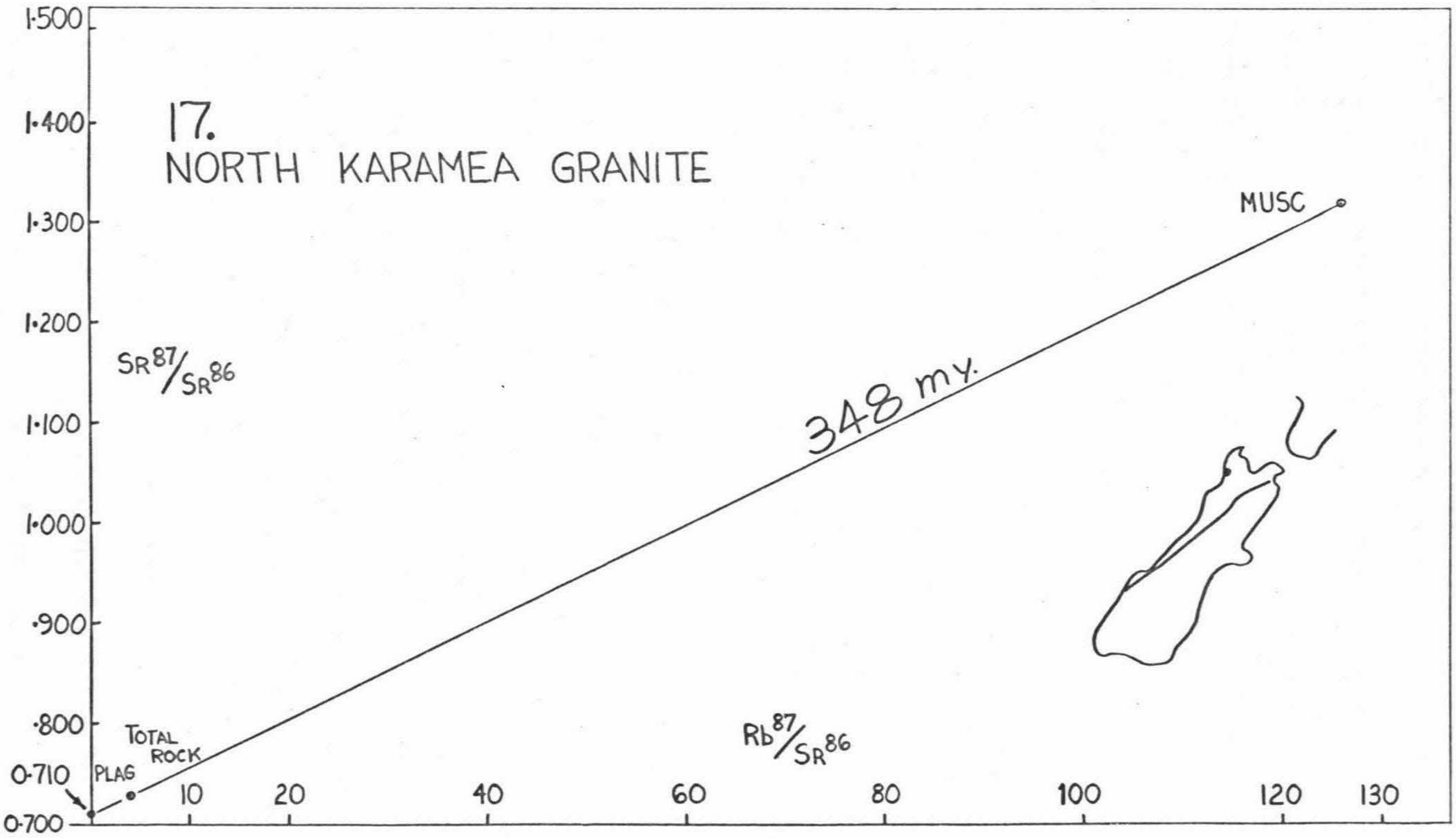


Figure 14. Rb-Sr isochron of North Karamea adamellite.

(Paparoa) is gneissic on the west and massive on the east (Figure 10), the gneissic part being the Charleston Gneiss which extends west from the Paparoa Range under alluvium to patchy outcrops on the coast. At its northern end the Western Belt intersects the Middle Belt (Karamea) of massive granites. Inland, granites on the eastern border of this Middle Belt intrude and contact metamorphose Ordovician sedimentary rocks (Grindley, 1961). An adamellite from this Middle Belt near the west coast just north of Karamea and north of the Charleston Gneiss was examined here. The results for plagioclase, total rock and muscovite are shown in the strontium evolution diagram of Figure 14 and Table 3, and indicate an age of 347 million years with an initial Sr^{87}/Sr^{86} of 0.710. Thus, it appears as if the west coast belt of 345-370 million year plutonic rocks that occurs in the southern half of the North Block may extrapolate northward across the Charleston Gneiss to the massive granites at the north end of the middle batholithic belt, a total distance greater than 500 km from southern end to northern end.

Charleston Gneiss (sample code: 6): The Charleston Gneiss comprises a terrain of highly twisted granitic gneisses, schists, and migmatites which on the west coast are intruded by abundant pegmatites (Figure 10). Historically there have been two views on the age of this gneiss. Morgan and Bartrum (1915) thought the gneiss was a Precambrian basement over which the possibly Precambrian Greenland Series was deposited. Henderson (1917) noted the lack of good exposed contact relations with other units and suggested that the gneiss was an orthogneissic phase of the Paparoa Range Granite (the eastern massive part of the western granitic belt). The two most recent geological maps of New Zealand (Grindley, et al., 1959, Bowen, 1964) show the Charleston Gneiss as Precambrian (?) and Precambrian, respectively.

Two adjacent samples of a coarsely crystalline feldspathic augen gneiss phase of the Charleston Gneiss at Tauranga Bay near Wesport on the west coast were examined in this study (Figure 10). These samples are judged to be metaplutonic and not metasedimentary on the basis of (1) a very coarse grain size (potassium feldspar augen up to 4 cm) with a well developed mortar texture that suggests the grain size may have been originally coarser and (2) a chemical composition inferred from the approximate mode (see Appendix) of relatively high Na_2O and K_2O and low SiO_2. Total rocks, biotite, and apatite were taken from sample (A) and biotite, potassium feldspar, and plagioclase were taken from sample (B) of these two adjacent samples. The results are shown in Figure 15 and Table 3. The +20 mesh biotite from rock (A) was used as a standard intermittently run during the course of this study and hence its apparent age is well known at 100 million years. Two other biotite separates from rock (B) agree with this. There is some scatter of the potassium feldspar, apatite, and plagioclase from the total rock-biotites isochron which may be real suggesting an older age for the potassium feldspar, or else may either be due to experimental error or a different initial Sr^{87}/Sr^{86} in these two adjacent samples. In any case a moderately high initial Sr^{87}/Sr^{86} between 0.712 and 0.715 is indicated and this suggests that the 100 million year age may represent a secondary event in the history of the Charleston Gneiss. If the gneiss total rock has remained a closed system during this event then a maximum age for the original rock, inferred to be igneous, is obtained from an isochron through the total rock to a very low initial Sr^{87}/Sr^{86} of 0.702, if it is assumed that the total rock has remained closed since crystallization. This maximum age is 450 million years (Table 7). The choice of 0.702 for an initial Sr^{87}/Sr^{86} is appropriate because this is the lowest observed for any acidic or intermediate rock in this study and only one value in the entire study, 0.701, obtained for an amphibolite, is lower. If 0.706 is used instead of 0.702 then a maximum age of about 300 million years is indicated (Table 7). The Rb-Sr data therefore suggest that the Charleston Gneiss is not Precambrian, but very likely is older than the 100 million year mineral ages.

In order to further verify the age of this important unit it was deemed necessary to analyze the zircons which occur abundantly in the above samples. These zircons comprise a very uniform suite of euhedral grains with a very light brown color when acid-washed (Figure 16). The euhedral nature and general uniformity of these separated zircon grains are consistent with this sample's having been originally an

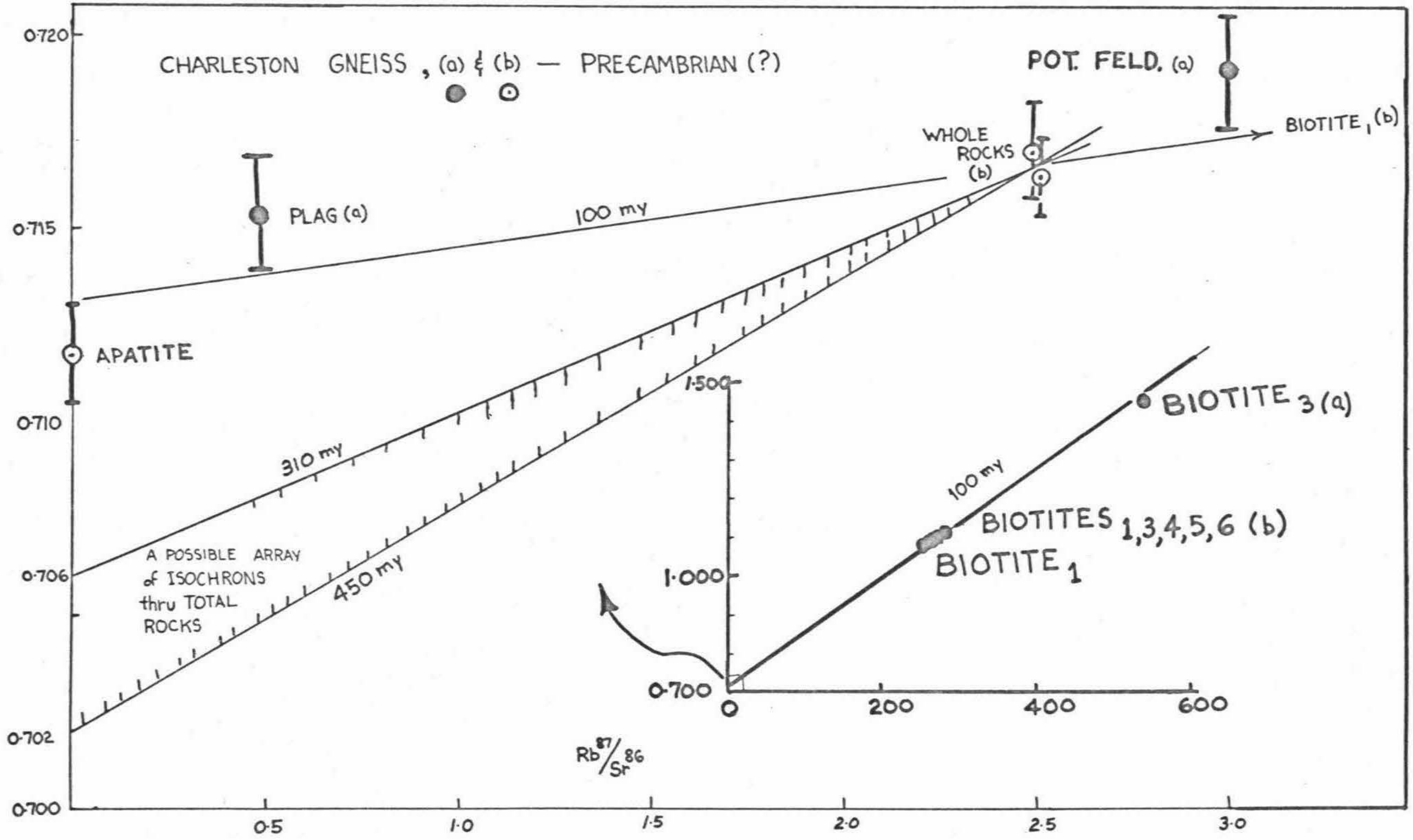


Figure 15. Rb-Sr isochron of Charleston augen gneiss.

TABLE 7

Rubidium-Strontium
Whole Rock Data
Charleston Gneiss, Tauranga Bay

Sample Code	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86}	Primary Whole Rock Age T (10^6 years)	
			Initial Sr^{87}/Sr^{86} = 0.706	Initial Sr^{87}/Sr^{86} = 0.702
6B				
Whole Rock 1	2.516	0.7163	290 ± 55	410 ± 50
Whole Rock 2	2.496	0.7169	320 ± 60	480 ± 55
Average			305 ± 60	445 ± 55

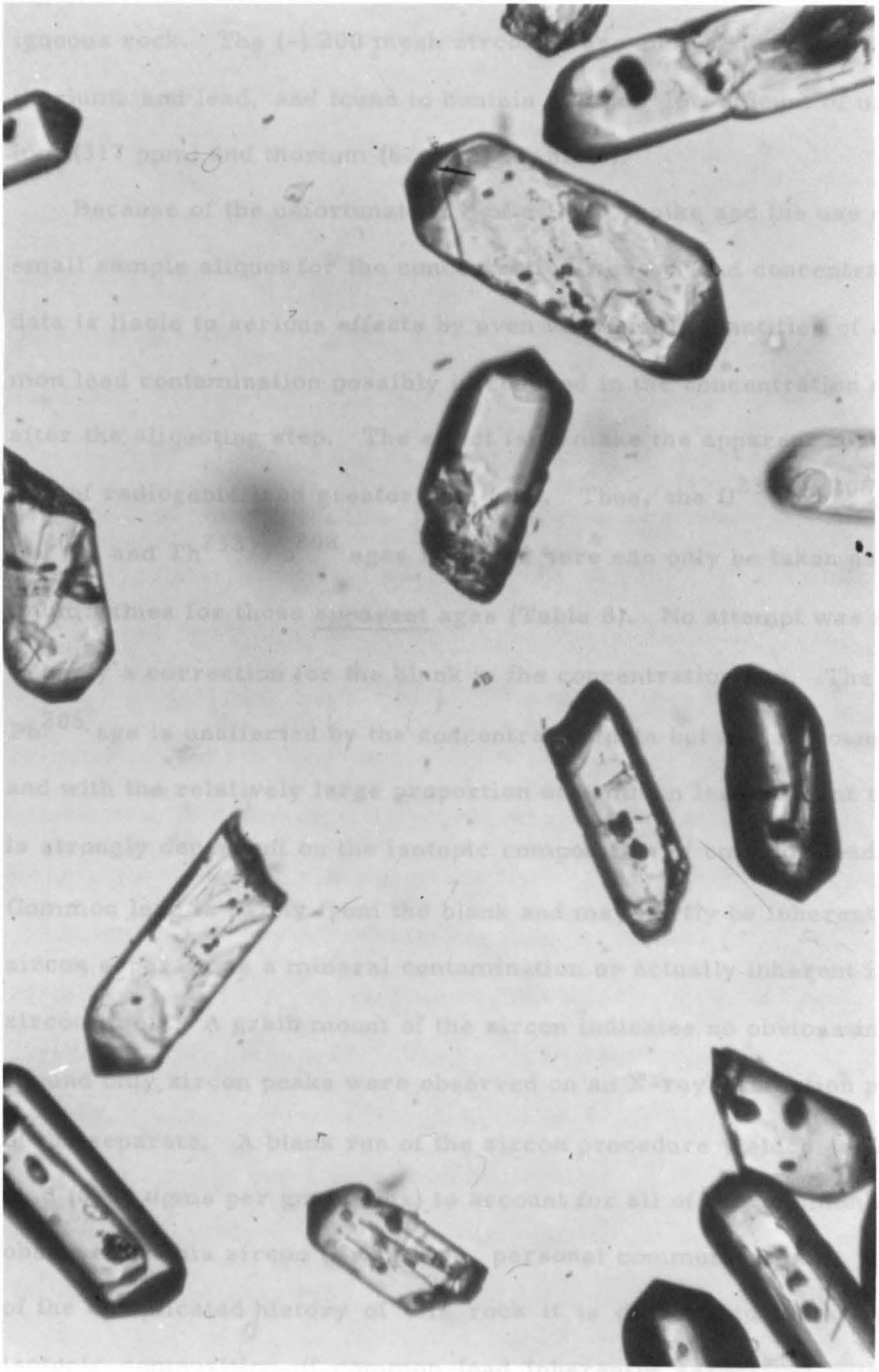


Figure 16. Euhedral zircons (-200 mesh), Charleston Gneiss.
Photo by L. T. Silver

igneous rock. The (-) 200 mesh zircons were analyzed for uranium, thorium, and lead, and found to contain a rather low amount of uranium (317 ppm) and thorium (87 ppm) (Table 8).

Because of the unfortunate use of a Pb^{206} spike and the use of a small sample aliquot for the concentration run the lead concentration data is liable to serious effects by even very small quantities of common lead contamination possibly introduced in the concentration aliquot after the aliquoting step. The effect is to make the apparent concentration of radiogenic lead greater than true. Thus, the U^{238}/Pb^{206}, U^{235}/Pb^{207}, and Th^{232}/Pb^{208} ages reported here can only be taken as maximum values for those apparent ages (Table 8). No attempt was made to apply a correction for the blank in the concentration run. The Pb^{207}/Pb^{206} age is unaffected by the concentration data but at this young age and with the relatively large proportion of common lead present this age is strongly dependent on the isotopic composition of common lead. Common lead is partly from the blank and may partly be inherent in the zircon separate as a mineral contamination or actually inherent in the zircon itself. A grain mount of the zircon indicates no obvious impurity and only zircon peaks were observed on an X-ray diffraction pattern of the separate. A blank run of the zircon procedure yielded enough lead (0.54 μgms per gm of flux) to account for all of the common lead observed in this zircon (Bruce Doe, personal communication). Because of the complicated history of this rock it is difficult to know the isotopic composition of common lead inherently associated within the zircon. The isotopic composition of lead in the potassium feldspar from the rock is $Pb^{204} : Pb^{206} : Pb^{207} : Pb^{208}$; 1 : 18.57 : 15.82 : 38.96. Three Pb^{207}/Pb^{206} ages are reported in Table 8. One, 427 million years, uses an average of acid wash and reagent lead compositions determined by Professor L. T. Silver at C.I.T. (Banks, 1963) as common lead correction. Another, 376 million years, uses the lead from the feldspar from the same rock as common lead correction. The third Pb^{207}/Pb^{206} age reported of 365 million years uses potassium feldspar lead from the 350 million year Karamea granite (sample code: 17). Because of the possibility that the U^{238}/Pb^{206}, U^{235}/Pb^{207}, and Th^{232}/Pb^{208} apparent ages are discordant with the Pb^{207}/Pb^{206} apparent age, the Pb^{207}/Pb^{206} apparent age may be only a minimum value for the original age of the Charleston Gneiss. The zircon results definitely confirm the whole rock Rb-Sr data that the Charleston Gneiss is older than the 100 million year biotite ages. Probably the rock is not much older than the largest Pb^{207}/Pb^{206} age of 427 million years reported above, but this must be confirmed by a zircon analysis using a Pb^{208} spike. The relatively low U and Th content of this zircon means that it had probably only received mild radiation damage prior to the 100 million year metamorphism, and hence was capable of remaining nearly closed during the metamorphism (Silver and Deutsch, 1962; Silver and McKinney, 1962).

TABLE 8

Zircon Data

Charleston Gneiss

	Observed Ratios					
6B zircon (-)200 mesh	Pb^{206}/Pb^{204}	Pb^{207}/Pb^{204}	Pb^{208}/Pb^{204}		Uranium (ppm)	Thorium (ppm)
	177.5 ± 0.2	24.38 ± .03	53.15 ± .06		317.4	87.42
			Ages (million years)			
	Pb^{206}/U^{238} †*	Pb^{207}/U^{235} †*	Pb^{208}/Th^{232} †*	Pb^{207}/Pb^{206} *	Pb^{207}/Pb^{206} **	Pb^{207}/Pb^{206} ***
	376 ± 20	368 ± 25	397 ± 50	427	376	365

† These apparent ages are regarded as maximum values for the true apparent ages because of the use of a Pb^{206} tracer. The errors reported above are only those associated with uncertainties in the mass spectrometry and in the composition of common lead and do not include the concentration error incurred by the use of a Pb^{206} tracer. A hypothetical large post-aliquoting blank of 0.1 μgm. of blank lead would cause these ages to be high by about 15%.

Common lead correction

Pb^{204}	Pb^{206}	Pb^{207}	Pb^{208}	
1	18.22	15.60	37.92	* average blank (Banks, 1963)
1	18.59	15.82	38.96	** feldspar, Charleston Gneiss
1	18.83	15.87	39.48	*** feldspar, Buller River Adamellite

Some approximate information on the age of the Charleston Gneiss can also be obtained from the model Pb^{207}/Pb^{206} versus Pb^{207}/Pb^{204} diagram (Figure 17, Table 9) showing some closed system lead evolution curves that employ the constants of Murthy and Patterson (1961). The model age of the feldspar lead using these constants is ~100 million years. Pb^{207}/Pb^{206} ages which use this simple closed system model have been found to be less than or equal to the true age of crystallization of many crustal materials, particularly those of relatively young age (Chow and Patterson, 1961; Patterson and Tatsumoto, 1963).

Also plotted in Figure 17 and shown in Table 9 is the composition of lead from potassium feldspar from the Karamea Granite of 350 million years age and from the Buller River Granite of 112 million years age. The U and Th contents of both these feldspars was measured and found to be low enough to produce negligible radiogenic lead. The U and Th content was not measured for the Charleston Gneiss feldspar but assumed very low because of the high purity of the separate. The model ages of the two feldspars are ~200 and ~0 million years, respectively, for the 350 million year Karamea granite and 112 million year Buller River granite. That the range of feldspar ages bounded by these two feldspar model ages contains the model age from the Charleston Gneiss feldspar lead is consistent with the Charleston Gneiss's being a 350 million year old plutonic rock

TABLE 9

Lead Composition

New Zealand Potassium Feldspars

Sample	Pb^{204}	Pb^{206}	Pb^{207}	Pb^{208}
Buller River adamellite, 112 my.	1	18.83	15.87	39.48
Charleston Gneiss Tauranga Bay	1	18.59	15.82	38.96
Karamea adamellite, 350 my.	1	18.38	15.80	38.78

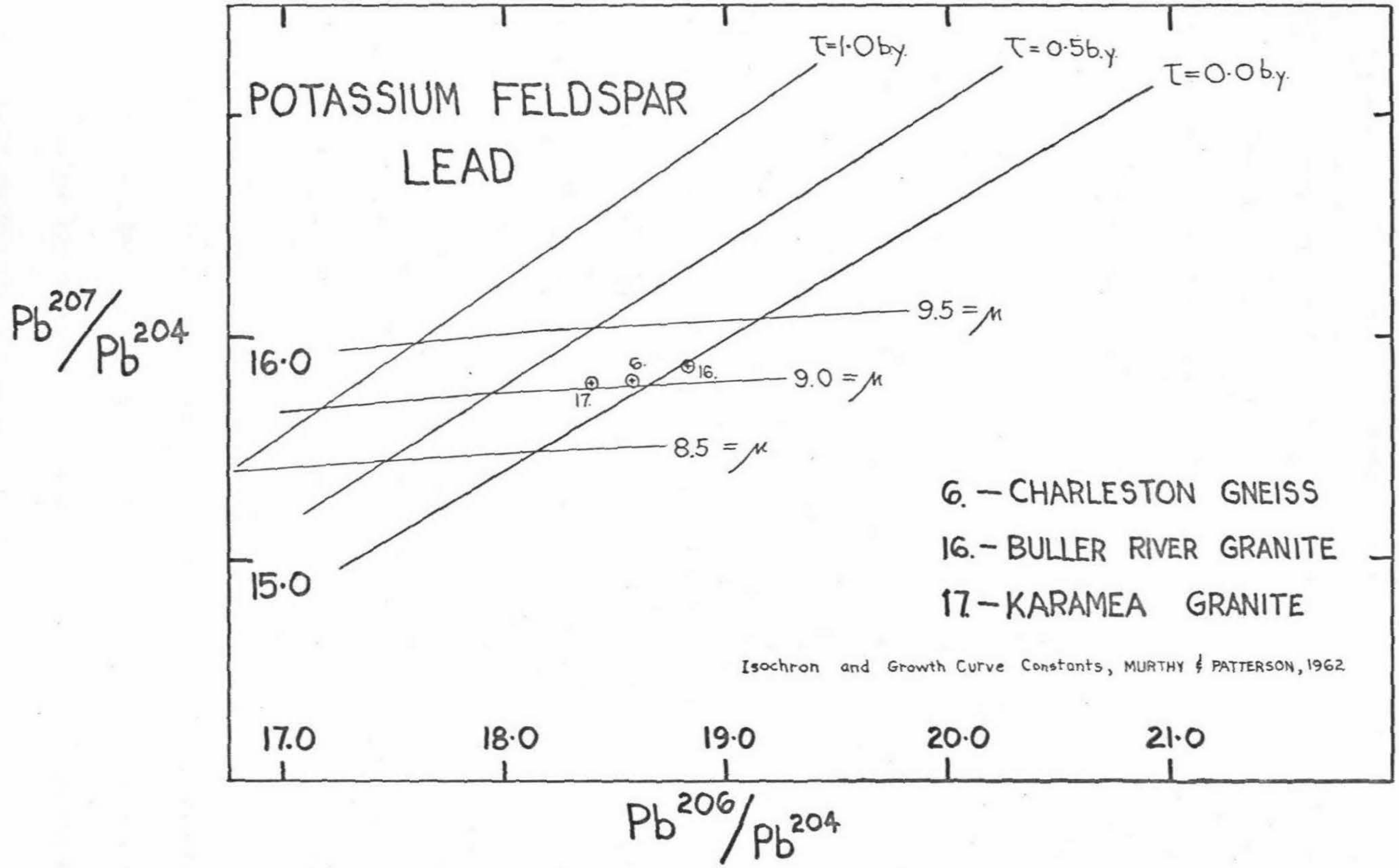


Figure 17. Common lead in New Zealand potassium feldspars.

metamorphosed 100 million years ago. Further work is necessary to confirm this, including measurements of U/Pb for the Charleston Gneiss and lead composition measurements of feldspars from several New Zealand 350 million year old granites.

Charleston Gneiss, Migmatitic Granite (sample code: 2G)

Twenty-five km south of the above samples of the Charleston Gneiss and also mapped as Charles Gneiss (Bowen, 1964), is a slightly gneissic saccroidal biotite and muscovite granite occurring in a coarse-scale migmatite relationship with medium-coarse-grained biotite, muscovite schist. In thin section there is textural evidence suggesting that muscovite in both schist and gneissic granite is of two generations. One form of the muscovite is normal medium-grained flakes and the other, which is texturally late, occurs as patches of very fine-grained matted aggregates rimming biotite or in interstitial veinlets. Because samples of both schist and granite, though separated by several meters, show this unusual second generation muscovite, it is suggestive that its formation postdates the intrusion of the granite into the schist and may represent a distinct second event in the history of both the schist and intruding granite.

The Rb-Sr analyses of biotite and muscovite from the granite (Table 3) indicate that this rock has been disturbed since crystallization. The biotite age of 102 million years is in good agreement with the biotites from the above-mentioned adjacent samples of the

Charleston Gneiss, but internally discordant with the coexisting muscovite's apparent age of 198 million years. The latter was determined twice on separate aliquots of a 40/80 mesh muscovite separate that includes only a small amount of the fine-grained muscovite. The internal discordance indicates that the rock has been disturbed and that the muscovite age can only be taken as a minimum indication of the rock's original age. A probable upper limit for the initial Sr^{87}/Sr^{86} for this rock is taken from the plagioclase at 0.729 and was used to compute the above ages.

The total data presently accumulated for these samples of the Charleston Gneiss both Pb^{207}/Pb^{206} on the zircon and potassium feldspar and Rb/Sr on minerals and total rock suggest a history for the Charleston Gneiss that is very consistent with the other general geochronological results of this study. They suggest that the gneiss is at least 350 million years old but not as old as about 450 million years and has been disturbed or metamorphosed 100 million years ago. Therefore, the Charleston Gneiss probably is not Precambrian but represents the 100 million year metamorphism of the terrain common to the south of 345-370 million year granitic rocks intrusive into Greenland Series sedimentary rocks. The Charleston Gneiss thus completes a link in what now appears to be a continuous linear extension along the west coast of rocks of this age to the north.

In independent support of these conclusions are the recent field observations of Laird (in press) who has traced metasedimentary portions of the Charleston Gneiss in the Paparoa Range continuously with no obvious break across a very steep metamorphic gradient into relatively unmetamorphosed Greenland Series. He noted parallel structures occurring in the two units. He has concluded that this portion of the Charleston Gneiss is not a basement for the Greenland Series, which commonly had been held previously, but instead represents metamorphosed Greenland Series.

(2) Possible Occurrence of 345-370 Million Year Rocks in the Northern Block

No other plutonic or metamorphic rocks have been found in this study which presented definite evidence that they crystallized 345-370 million years ago. However, plutonic rocks from two areas inland in the North Block with ages intermediate between these ages and the Cretaceous ages of the Rangitata Orogeny may represent 345-370 million year rocks disturbed by the Cretaceous Orogeny.

Marauia River, Middle Belt Granite (sample code: 12); Hornfels (sample code: 11): A sample of white-colored granite near Ruffe Creek at its meeting with the Marauia River in the middle part of the Middle Belt of granites (Figure 10) has biotite and muscovite which in isochrons with the total rock give internally discordant ages of 305 and 333 million years, respectively, indicating a post-crystallization disturbance of the rock and that, therefore, the 333 million year muscovite-total rock age is probably a minimum age (Figure 17, Table 3). The initial strontium for this rock indicated by the muscovite-total rock isochron is 0.710. Until further data are available, the best interpretation of the age of this rock is that it is 345-370 million years old and has been disturbed by the Rangitata Orogeny.

This sample of granite is one of two samples collected as boulders for which no similar rock could be found immediately present as in situ country rock. A fine-grained hornfels, mapped as Greenland Series (Bowen, 1964), was collected nearby in situ and this rock is in fault contact with different reddish granite that is weathered. Muscovite from the hornfels gives an age of 287 million years if an initial Sr^{87}/Sr^{86} of 0.727 as measured in the plagioclase is used, Table 3. This result indicates the local terrain has similar ages to the granite and that the granite boulder is probably of local origin.

Basic Plutonic Rocks, Eastern North Block (sample code: 49): Another plutonic rock inland in the North Block which may be of the 345-370 million year vintage is mapped as the Rameka Intrusives and the Riwaka Metavolcanics which comprise a discontinuous north-south belt of basic igneous rocks, both plutonic and volcanic, and their metamorphic equivalents. These occur along the western border of the eastern belt (Separation Point) of granites (Figure 10). At the northern

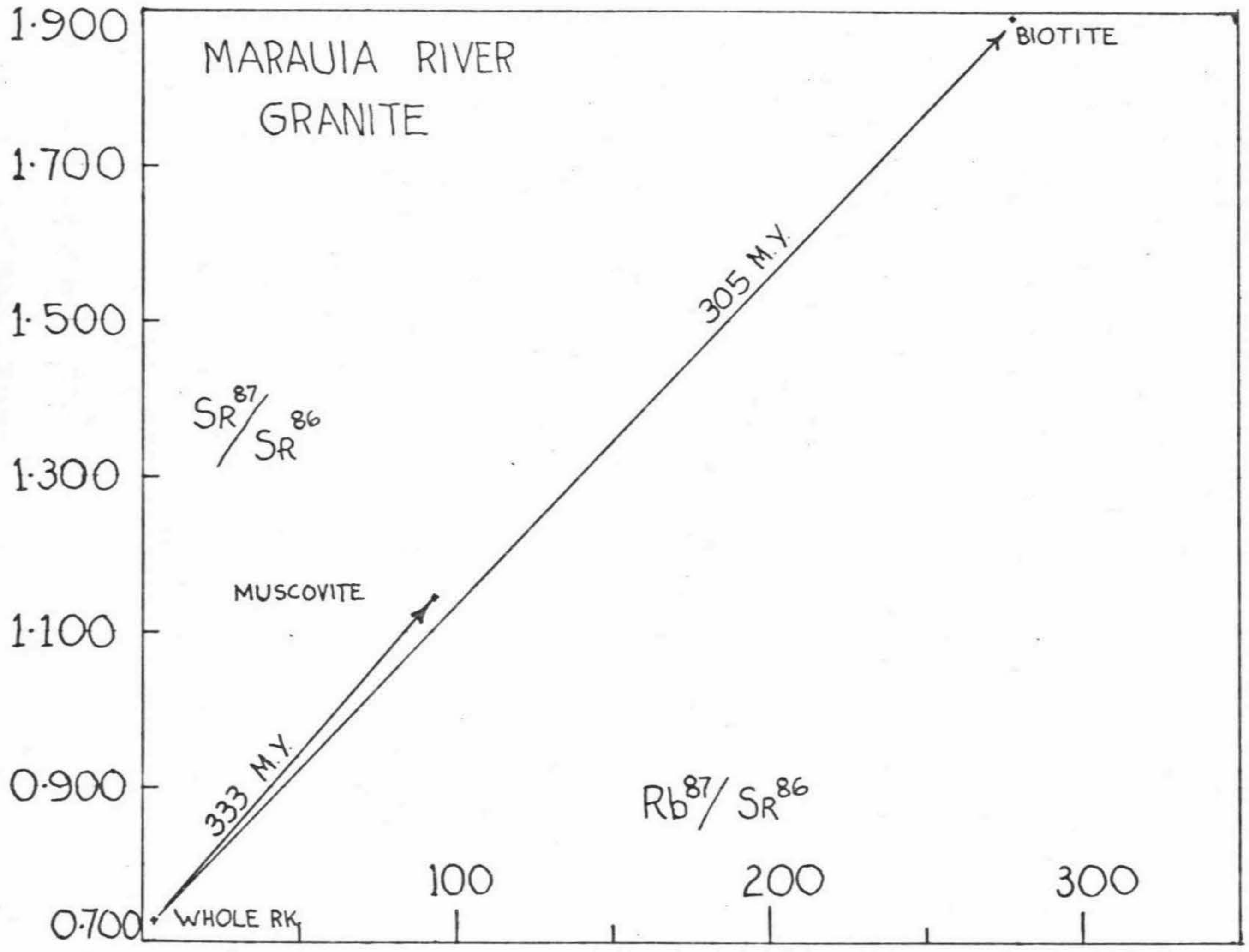


Figure 18. Rb-Sr isochrons of Marauia granite.

end of this belt of basic rocks, basic plutonic rocks intrude and skarn-metamorphose the surrounding Upper Ordovician Mount Arthur Marble (Grindley, 1961). These intrusives are thought to be magmatically related to basic amphibolitic metavolcanics to the south (Grindley, 1961) which stratigraphically overlie meta-sedimentary rocks which in turn overlie the Mount Arthur Marble (Cooper, 1965). Cooper notes the general increase in metamorphism of the Mount Arthur Marble as its contact with the eastern belt of granites is approached to the east, suggesting that the metamorphism of the marble and the stratigraphically overlying basic volcanics is due to the emplacement of the eastern belt of granites. Near the southern end of these basic rocks at Baton River, Willis (1965) mentions the contact metamorphism of fossiliferrous lowermost Lower Devonian (Boucot, Caster, Ives, and Talent, 1963) by basic intrusives mapped as Rameka Intrusives by Grindley (1961). Thus, if the Rameka Intrusives do constitute a coeval belt of magmatically related basic volcanics and intrusives their age is less than the Lower Devonian rocks they intrude and probably greater than the age of the eastern belt granitic rocks by which they are apparently metamorphosed.

A boulder of a very distinctive hypersthene-augite-anorthoclase medium-grained dioritic igneous rock was collected from the lower middle reaches of Rocky River, a western tributary to Motueka River. The headlands of Rocky River 2. 5 km west of the boulder locality upstream are mapped as basic metavolcanics by Grindley (1961), but had previously been mapped as basic intrusives by Henderson, MacPherson, and Grange (1959). These are mapped by Grindley as being in fault contact with the eastern belt of granites which comprise most of the drainage of Rocky River. Essentially 80% of the boulders, some of which are up to two meters in diameter, that occur in the river at the sample locality, are this distinctive basic rock which is very fresh and rings to a hammer blow in contrast to the bedrock of Separation Point Granite which, typical of this rock, is deeply weathered. It seems likely that these boulders come from the basic rocks which comprise the river headlands, although these rocks have not been observed by the author for comparison. The occurrence of anorthoclase* in the rock indicates a rather rapid cooling time for this diorite suggestive of a hypabyssal origin. This in turn is consistent with the occurrence of both volcanic and plutonic rock types in the basic belt.

Two biotites examined from this rock have Rb/Sr ages of 285 million years using the initial Sr^{87}/Sr^{86} measured in the plagioclase as 0.704 (Table 3). This age may be true and is consistent with the geological evidence that the rocks of the basic belt are post-Lower Devonian. However, because part of the basic belt in the north has

---

*$2V = 35^{o}$; X-ray analysis indicates sanidine or anorthoclase.

been metamorphosed to amphibolites by the intrusion of the Separation Point Granite, and because to the south this belt of basic rocks remains geographically close to the Separation Point Belt of granites although largely in fault contact, it is certainly possible that the intrusion of the granites has affected the biotite Rb-Sr system in the sample examined here. As will be shown later the Separation Point Belt of granites appears to be about 100-115 million years in age. If the biotite ages are minimum ones then perhaps these post lowermost Lower Devonian belt of basic igneous rocks are coeval with the acidic plutonic rocks to the west of 345-370 million years. The latter absolute age is probably a stratigraphic equivalent of either uppermost Lower Devonian or Middle Devonian, as discussed later.

(b) 100-120 Million Year Plutonic and Metamorphic Activity

(1) Western Belt

Pegmatites Intrusive Into the Charleston Gneiss (sample code: 4): On the west coast pegmatites are commonly intrusive into the Charleston Gneiss, which as shown above was metamorphosed about 100 million years ago. One of these pegmatites, from the mouth of the Nile River at Charleston, was examined here (Figure 10). Muscovite gives an age of 110 million years and the results on potassium feldspar of low Rb/Sr ratio are not inconsistent with this (Figure 19, Table 4). This age is older than the 100-102 million year ages on biotites from Charleston Gneiss samples not too far distant from the Nile River to

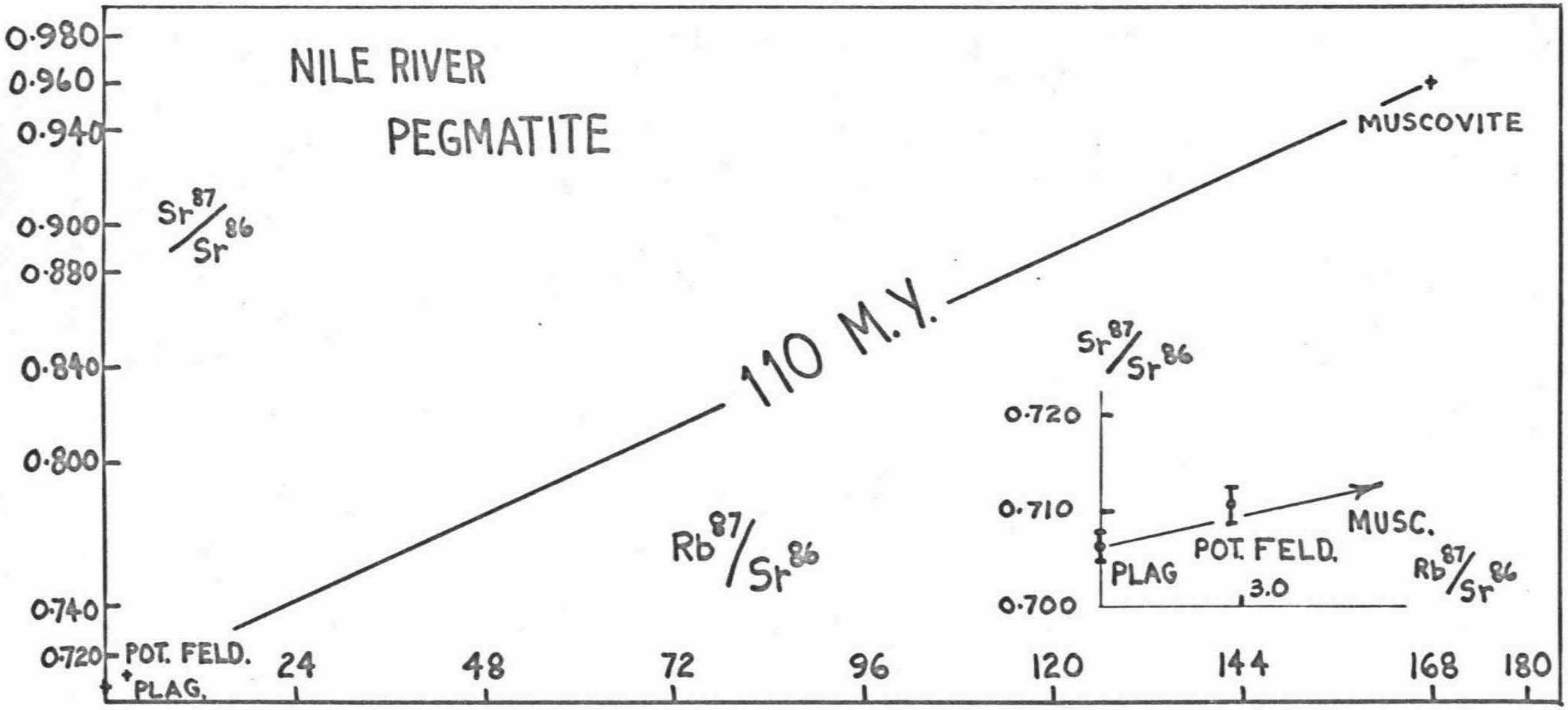


Figure 19. Rb-Sr isochron of Nile River pegmatite.

the north (sample: 6) and south (sample: 2G) reported above and hence somewhat inconsistent with this pegmatite's intruding Charleston Gneiss. This inconsistency may reflect a cooling off period during which the biotites were losing radiogenic strontium. The initial Sr^{87}/Sr^{86} of the pegmatite is 0.706 as measured in the plagioclase and is measurably lower than the 0.712-0.715 and 0.729 measured in the Charleston Gneiss samples. This suggests that the pegmatite did not originate in a simple way by melting of the Charleston Gneiss although measurements on more samples of the gneiss are necessary before the isotopic composition of its strontium may be regarded as characteristically high. The pegmatite may be related in origin to the Paparoa Range granitic rocks on the eastern part of the Western Belt (Paparoa) which, as discussed below, is at least in part 100-120 million years old.

Paparoa Range Migmatite (sample code: 7): A sample of an adamellite augen gneiss and intimately associated migmatitic granite near the border of the Charleston Gneiss with the Paparoa Range Granite was examined (Figure 10). The massive granitic rock occurs as irregular patches several cm thick and up to 50 cm long and comprises perhaps 5% of the massive road cutting from which the sample came, but probably 15% of the biased sample examined here. The two rock phases were separated and total rock aliquots of each analyzed along with mineral separates of the coarse granite. The total rocks and minerals, including two potassium feldspar separates, two muscovite separates, and a plagioclase, all lie on an isochron of about 115 million years, with a relatively high initial Sr^{87}/Sr^{86} of 0.714 (Figure 20, Table 4). These results are consistent with the coarse granite migmatite phase and enclosing augen gneiss being cogenetic 115 million years ago. This rather high initial Sr^{87}/Sr^{86} suggests that the granite phase of the migmatite may have formed by melting of the gneissic phase at that time.

Mackley River Quartz Diorite (sample code: 8): In the Mount William Stream Gorge of the northern Paparoa Range, granite is intrusive into a porphyritic quartz diorite containing rounded phenocrysts of quartz. The intrusive contact is inferred by the author from the following evidence: abundant red potassium feldspar crystals occur in the quartz diorite both in long narrow trains and as isolated poikolitic crystals only within one-half meter of its contact with the granite which contains 30% of red potassium feldspar. The quartz diorite is tentatively considered here as a coarser grained phase of the Berlins quartz porphyry very common in the Mount William Gorge and in the whole general region of the northern Paparoa Range, south to the Buller River. This correlation is based on the rounded quartz phenocrysts common to both rocks; the subhedral shape of biotite grains in both rocks; and the geographical closeness of both rock types in the Mount William Gorge. The Berlins Quartz Porphyry is noted in many places for the abundance of small fine-grained argillite inclusions. Rounded one cm fine-grained inclusions were noted in the quartz diorite but they are uncommon. It

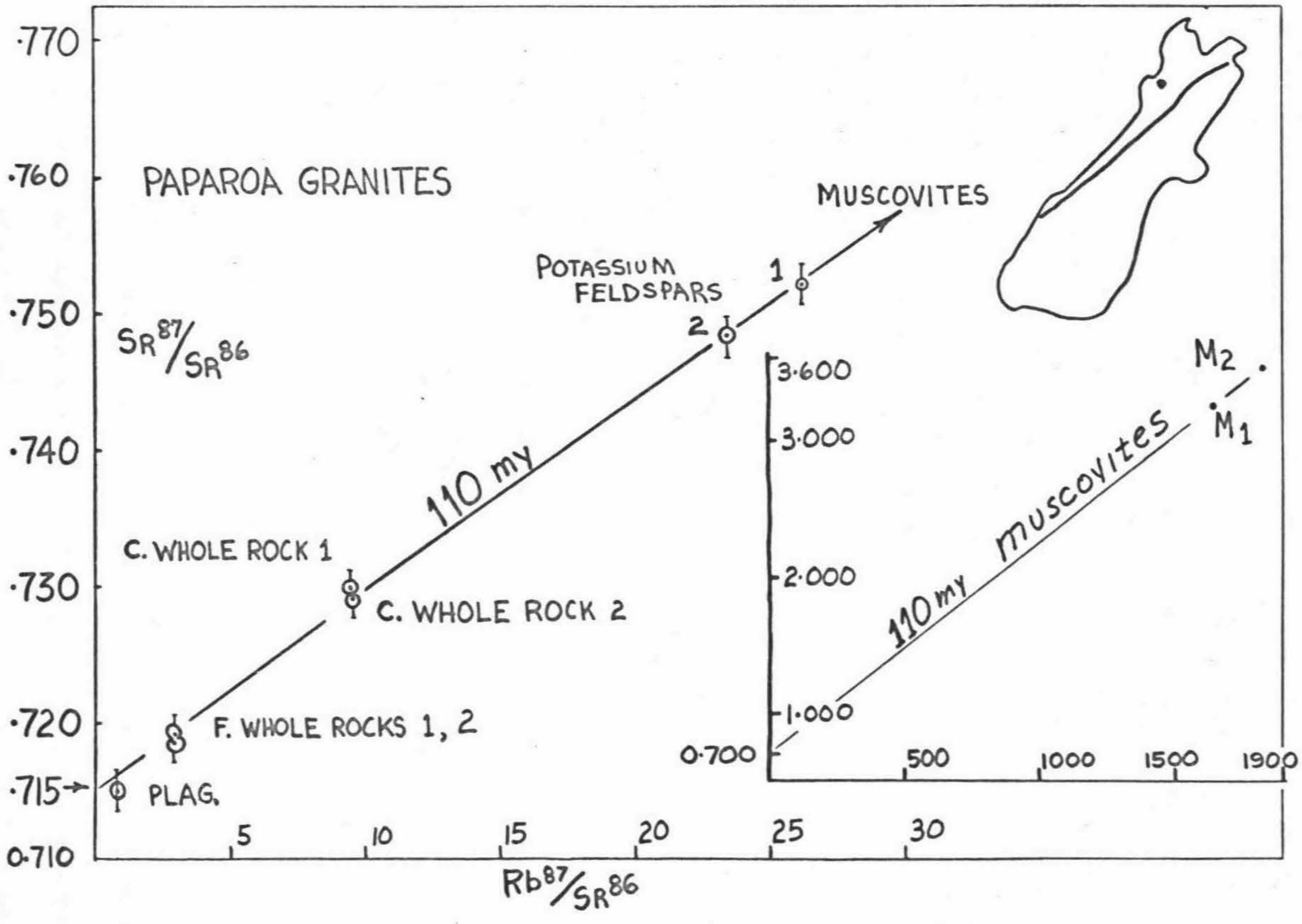


Figure 20. Rb-Sr isochron of the Paparoa Range augen gneiss and migmatitic granite.

should be noted that no Charleston Gneiss was observed by the author in the eastern half of the Mount William Gorge although it has been mapped there (Morgan and Bartrum, 1915; Bowen, 1964).

A large boulder of similar quartz diorite with rounded quartz phenocrysts and subhedral biotite was collected as a stream boulder from the Mackley River at the mouth of Blue Duck Stream, 3. 5 km downstream from the mouth of Mount William Stream (Figure 10). Biotite from this sample gives an age of 117 million years assuming an initial Sr^{87}/Sr^{86} of 0. 703 or 113 my. if 0. 707 is assumed (Table 4).

(2) Middle Belt of Granitic Rocks

Quartz Monzonite, Buller River (sample code: 16): A sample of quartz monzonite from the middle portion of the Middle Belt on the south shore of the Buller River near the White Creek Fault (Bowen, 1964) was examined (Figure 10). Biotite and muscovite from this rock show concordant ages of 112 million years (Figure 21, Table 4). The initial Sr^{87}/Sr^{86} as indicated by the isochron through the potassium feldspar is 0. 704. Rubidium in the total rock analysis has been estimated by X-ray fluorescence, the isotope dilution run having been lost. An estimated error of ±20% is shown in the Rb^{87}/Sr^{86} ratio of the total rock for this reason. If the total rock has been a closed system then the maximum age it could possibly be, extrapolating back to 0. 702, is about 200 ±100 million years (present Sr^{87}/Sr^{86} is 0. 7069, $Rb^{87}/Sr^{86} \sim 2. 1$).

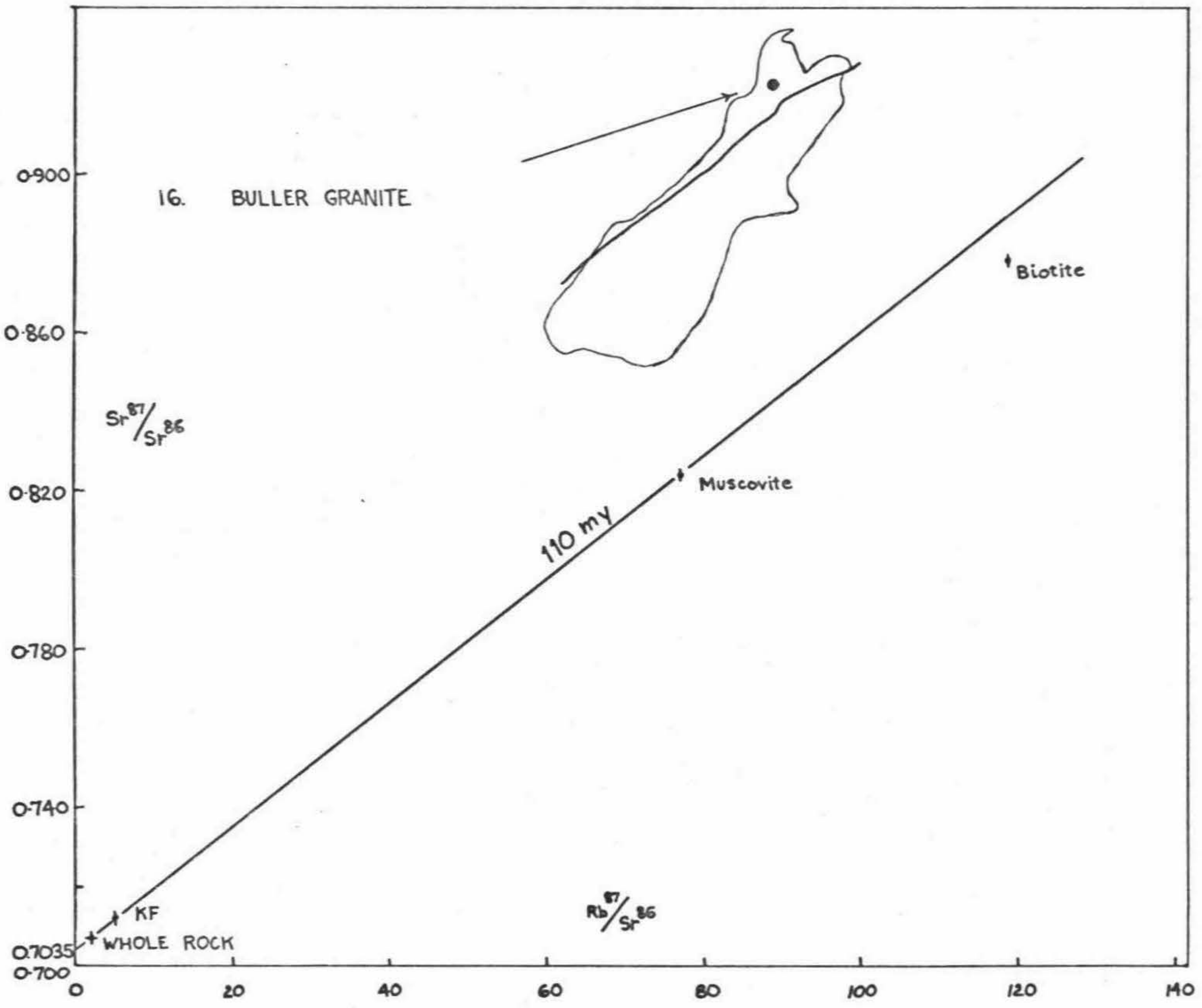


Figure 21. Rb-Sr isochron of Buller River quartz monzonite.

Rahu Saddle Adamellite (sample code: 14): A coarse-grained granite was collected as a large four-meter diameter boulder from the road near Rahu Saddle in the southern end of the middle belt of granites (Figure 10). No granite was found in situ at this locality where a biotite-muscovite-garnet schist does occur in situ. Quartz diorite crops out 1 km to the west of the sample locality. It is assumed that the source of the granite is nearby because of the large size of the boulder and the small amount of drainage area that is above the sample locality.

An initial Sr^{87}/Sr^{86} of 0.704 and age of 110 million years is indicated by an isochron through the total rock,for which the rubidium content has been estimated by X-ray fluorescence, and the biotite. If the total rock has remained a closed system then the maximum age it could possibly be, extrapolating back to 0.702, is about 250 $\pm$100 million years (present Sr^{87}/Sr^{86} is 0.7064, $Rb^{87}/Sr^{86} \sim 1.6$).

(3) Eastern Belt of Granites

Rotoroa Igneous Complex (sample code: 10): The southern quarter of this belt is comprised of dioritic plutonic rocks and amphibolitic gneisses that are called Rotoroa Igneous Complex (Bowen, 1964). A sample of quartz diorite from a road cut near the junction of the Howard and Buller Rivers (Figure 10) was examined and has biotite that gives an age of 116 million years if 0.703 is assumed as the initial Sr^{87}/Sr^{86} or 111 million years if 0.707 is assumed (Table 4).

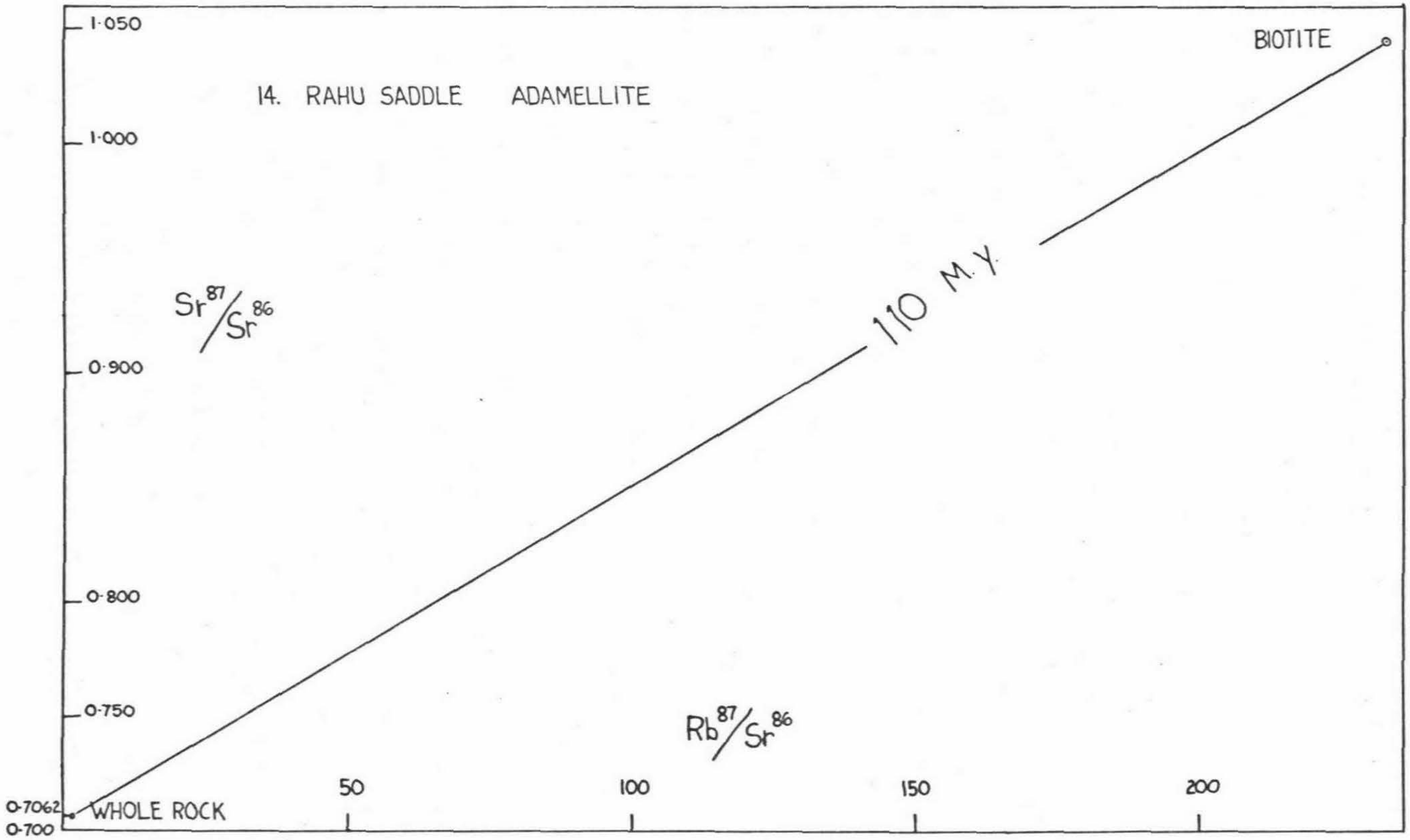


Figure 22. Rb-Sr isochron of Rahu Saddle adamellite.

Motueka River Pegmatite (sample code: 48): Further north in the middle part of this belt a large pegmatite is intrusive into hornblende quartz diorite (Figure 10). The results of analyses of several minerals from this pegmatite give very good indications of an age of 104 million years (Figure 23, Table 4). Three muscovites, a biotite, potassium feldspar and plagioclase were examined from this pegmatite. The muscovites have extremely high Rb/Sr ratios that enable a very precise measurement of their age. The rubidium content of these muscovites which were hand-picked and -trimmed from separate books is inherently quite variable and hence their Rb/Sr ratios are also inherently variable and not simply due to contamination by common strontium. Thus, each muscovite gives an independent measure of the age of the rock and the isochron along which their analyses fall is more fully confirmed as the age of an event during which the strontium isotopic composition in the rock was homogeneous. Considering the rather strong resistance muscovite generally displays to strontium isotopic exchange during metamorphism, especially coarse muscovite, this event can only be the original crystallization of the pegmatite. The biotite, which is partly inelastic and may be slightly weathered, gives a somewhat lower age of 99 million years. The potassium feldspar apparent age is consistent with that of the biotite and muscovite, but imprecisely known because of a low Rb/Sr ratio. The initial Sr^{87}/Sr^{86}

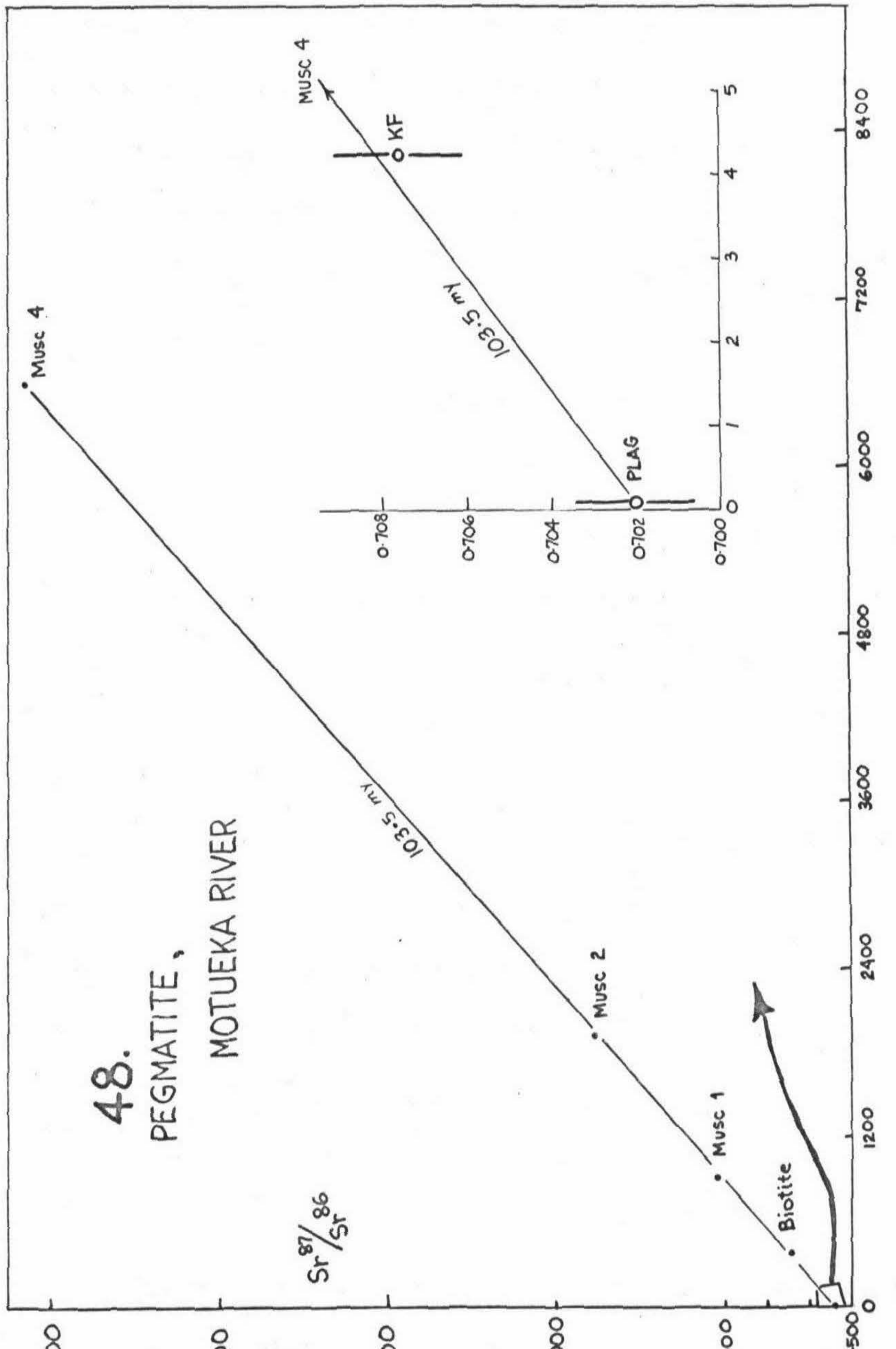


Figure 23. Rb-Sr isochron of Motueka River pegmatite.

of this pegmatite is well indicated both by the plagioclase and the isochron through the potassium feldspar as a low 0.702.

Schist, Anatoki River (sample code: 46): A sample possibly associated with the northern end of the eastern belt of granite rocks is a quartzose biotite, muscovite schist from the banks of the Anatoki River, mapped as Onekaka Schist (Grindley, 1961) (Figure 10). The sample is located 12 km west of the western exposed margin of the eastern granitic belt and separated from it by the broad alluvial and glacio-alluvial deposits of Takaka Valley, and by Mount Arthur Marble and Pikikiruna Schist. The latter two immediately border the granite and 15 km to the south have been described as increasing in metamorphic rank toward the granite contact (Cooper, 1965). However, the Onekaka Schist itself, 3 km north of the sample locality, is in contact with what is mapped as a small isolated body (4 km by 4 km) of Separation Point (eastern belt) granite (Grindley, 1961).

Biotite and muscovite from this schist give concordant ages of 98 and 100 million years, respectively (Figure 24, Table 4). The initial Sr^{87}/Sr^{86} as measured in a mixture of plagioclase and quartz from this sample is high at 0.727, reflecting the metamorphic nature of this rock.

Recently, the first known occurrence of Permian sedimentary rocks in the Foreland Province was discovered (Waterhouse and Vella, 1965). Only 8 km northwest of the Anatoki River schist sample and separated

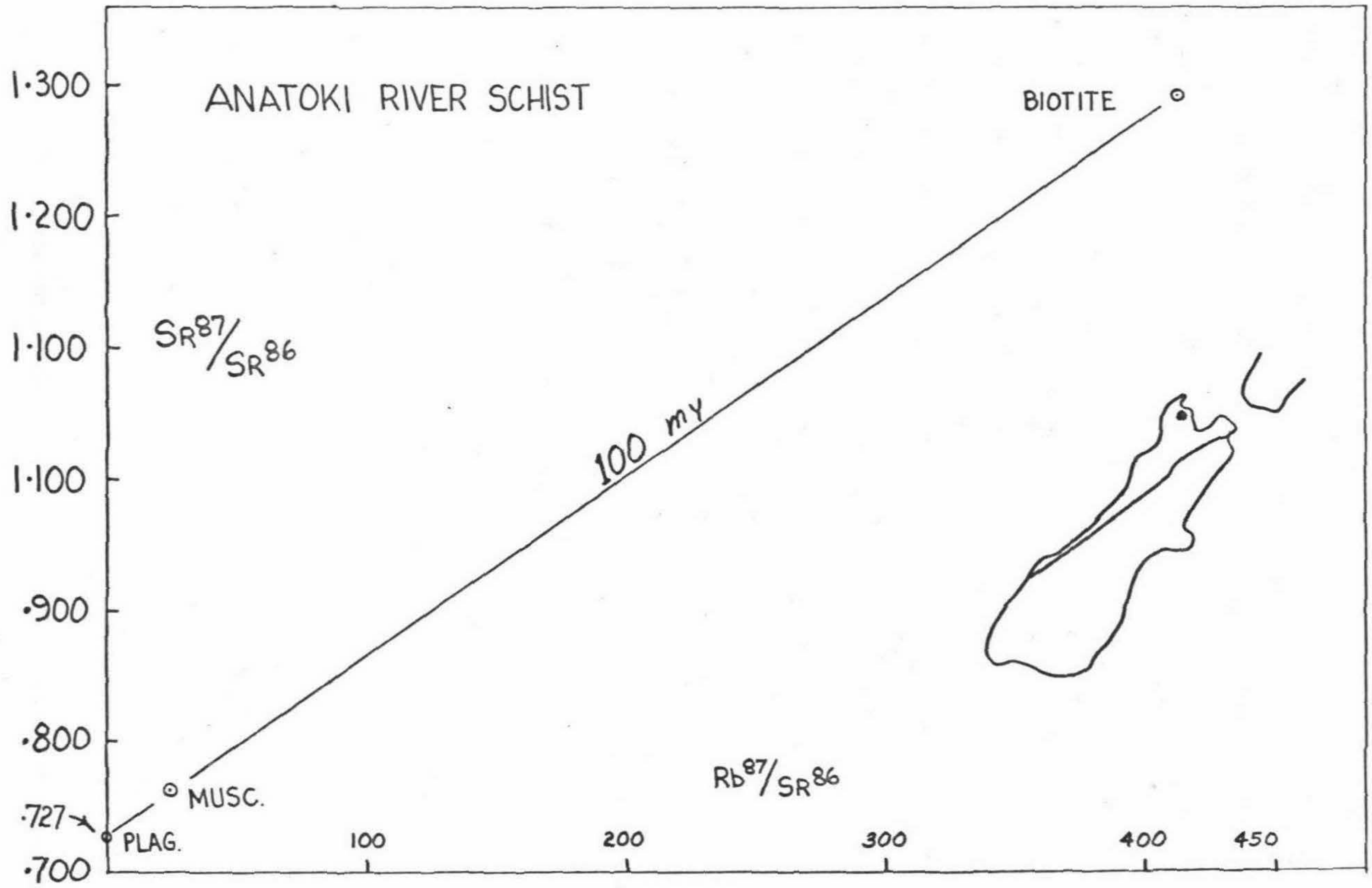


Figure 24. Rb-Sr isochron of the Anatoki River schist.

from it by the Golden Bay Fault (Grindley, 1961), Upper Permian fossiliferrous beds are described as overlying a conglomerate that rests on garnetiferrous slate. This implies that the metamorphism of the latter is pre-Upper Permian. This seems anomalous with the geochronological results on the Anatoki River Schist and the general association of low and medium rank regional metamorphic rocks with the western margin of the 100-116 million year Eastern Granite Belt. In contrast only a narrow zone of contact metamorphic rocks occurs along the eastern border of the northern Middle Belt (Karamea) of granitic rocks the western part of which was shown to be about 350 million years old. However, schists do occur to the west and north-west of the Anatoki River sample in contact with isolated small patches of granite (i. e., Lead Hills) which may be extensions of the Middle Belt (Karamea) of granites (Grindley, 1961). Thus, perhaps the regional metamorphism of the western schists is associated with the intrusion of the 345-370 million year northern Middle Belt of granites, or perhaps associated with the intrusion of the more easternly Rameka Basic Intrusives for which a pre-Upper Permian age has been obtained. More field and geochronological work is necessary to resolve this apparent conflict of having both pre-Permian and 100 million year metamorphic rocks so close to each other. Meantime, it appears as if regional low-medium grade metamorphism may have accompanied intrusion of both the Devonian and Cretaceous age plutonic rocks in in the North Block of the Foreland Province.

A Summary of Distribution of the Two Age Groups of Crystalline Rocks in the North Block

In summarizing the distribution of the two groups of plutonic and metamorphic rocks of different age in the North Block it must be emphasized that the geographic density of samples examined in this study is very low and the pattern that has emerged from these few points is not simple, considering that in terrains like the Charleston Gneiss both ages are represented in the same hand specimen of plutonic rock. The following summary is offered as the best interpretation at this stage of work.

The Charleston Gneiss occurs on the west coast and just inland in the middle of an elongate band of 345-370 million year granitic rocks. This band stretches along the west coast. South of the Charleston Gneiss the band occurs as discontinuous bodies of granite, and north of the gneiss as large granitic masses in the northern Middle Belt (Karamea). The gneiss was metamorphosed 100 million years ago but the original rocks which are now meta-plutonic parts of the gneiss were originally 345-370 million year granitic rocks. The Charleston Gneiss thus provides a link for a batholith that extended over a distance of 500 km along the entire west coast of this block. Inland from the west coast, the middle part of the Middle Belt (Karamea) is comprised in part of rocks of similar age. The Rameka Belt of basic intrusives and extrusives along the western border of the Eastern Belt (Separation Point) may also be of this same age.

The pegmatites which commonly intrude the Charleston Gneiss of the western half of the Western Belt (Paparoa) of granitic rocks are about 110 million years old as are the plutonic rocks that comprise the eastern half of this belt. Much of the middle and southern sections of the Middle Belt (Karamea) is also of this age. It appears as if all of the Eastern Belt (Separation Point) of acidic-to-intermediate plutonic rocks is of this age including the Rotoroa Igneous Complex at its southern end.

(3) Detailed Geochronological Results of the South Block of the Foreland Province

(a) Introduction

In this study only Cretaceous ages have been found for the plutonic and metamorphic rocks of the South Block of the Foreland Province and no evidence of 345-370 million year rocks has been found. It is thought that the samples in this study from this block are generally representative of the plutonic and metamorphic rocks which comprise this block. However, it should be noted that almost none of this region of rugged topography and thick overgrowth, remote from civilization, has been mapped in any detail and the first general maps of the region have only recently been completed (Wood, 1960; 1962). Much more geological and geochronological work will be necessary before it is known if the Devonian age crystalline rocks are indeed absent from the Foreland Province south of the Alpine Fault.

Considering that this block is almost entirely comprised of phaneritic crystalline rocks, the bulk of which are medium-rank metamorphic rocks, the stratigraphic data on the age of these rocks are necessarily very limited. Only in one small area at the southwestern tip of the South Island (Figure 25) do pre-intrusive sedimentary rocks, not regionally metamorphosed, occur. There, at Preservation and Chalky Inlets, the Kakapo Granite (Wood, 1960) intrudes and contact metamorphoses Lower Ordovician graptolite-bearing sedimentary rocks (Benson, et al., 1934). Unconformably overlying the granite are terrestrial conglomeratic coal measures, similar to those overlying the basement rocks of the North Block, and these are overlain by fossiliferrous marine rocks of Lower Tertiary age. On the basis of plant microfossils, the terrestrial sedimentary rocks have been classed as Lower to Middle Cretaceous, but no floral assemblage was published (Cooper in Wood, 1960).

A fault separates this southwestern area from the main crystalline mass of this block (Wood, 1960). Therefore, the relationship of the Lower Ordovician rocks and the Kakapo Granite intrusive into them to the medium rank regional metamorphic complex that constitutes the main part of this block is not certain. A correlation of some of the

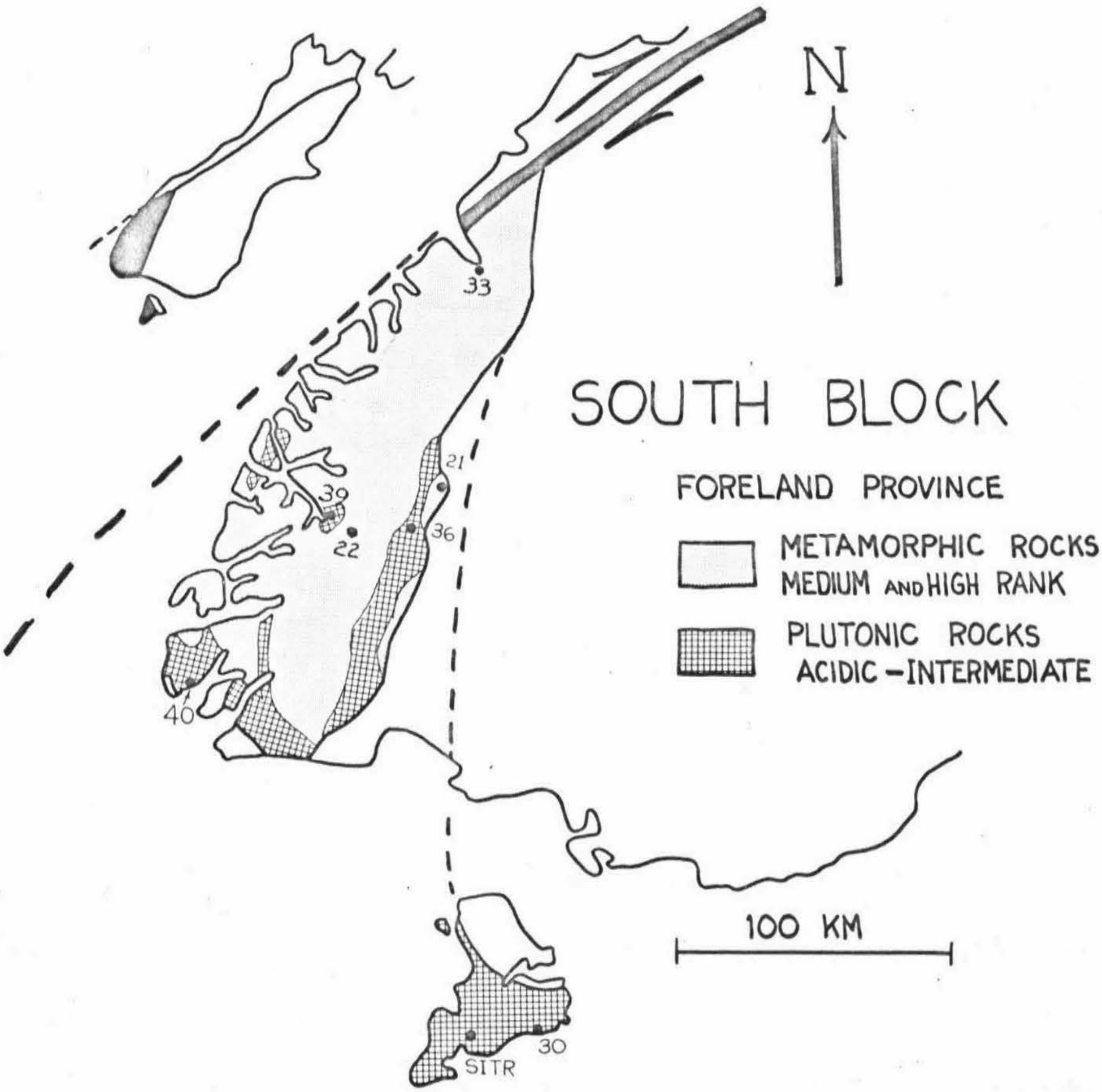


Figure 25. South Block of Foreland Province showing sample localities.

of the regional metamorphic rocks with the Ordovician sedimentary rocks has been only tentatively made (Wood, 1960).

b) Southwestern Tip--Kakapo Granite (sample code: 40)

A sample of the Kakapo Granite from Chalky Inlet was examined here (Figure 25). These results are shown in Figure 26 and Table 5. The ages on biotite and muscovite are concordant at 100 million years, the latter being somewhat imprecise because of a rather low Rb/Sr ratio. The data for the potassium feldspar and total rocks are consistent with a 100 million year age and provide excellent control in determining a low initial Sr^{87}/Sr^{86} of 0.702. This Middle Cretaceous age (Kulp, 1961) therefore conflicts some with the plant microfossil Lower Cretaceous assignment of the overlying terrestrial sedimentary rocks.

c) Main Crystalline Complex of South Block

There is some suggestion that this large crystalline complex is of one age. The recent regional mapping by Wood (1960, 1962) of this crystalline complex suggests that structures and metamorphic units can be traced continuously over large portions of the region. One of the very few areas in this crystalline complex studied in detail is the shoreline region of Lake Manapouri and Doubtful Sound in the middle part of the complex (Figure 25), studied by Turner (1937 a, b; 1948, p. 291-293). He has shown that the granites in that area have intruded into the enveloping amphibolitic gneisses synchronously with the metamorphism of those gneisses. They show concordant contacts and the

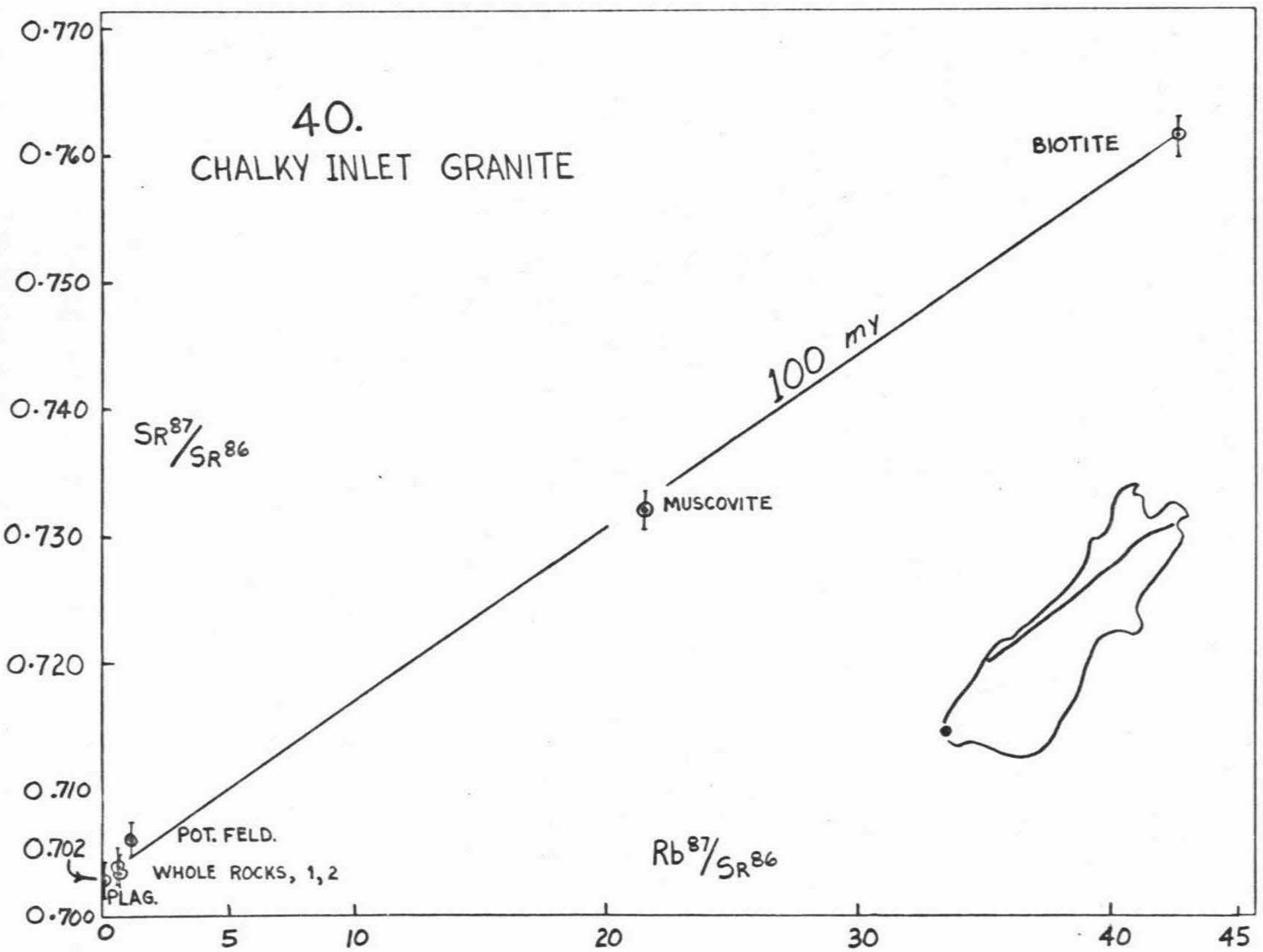


Figure 26. Rb-Sr isochron of Kakapo Granite.

gneisses show no increase in metamorphic grade as these contacts with the intruding granite are approached. On a regional scale Wood (1960) has noted the concordant nature of the intrusion of the granites throughout the whole complex. Thus there is some suggestion that (1) the plutonic and metamorphic rocks are synchronous in development in the entire crystalline complex and (2) that the metamorphic units occur continuously over much of the region. This geological picture of a single period of crystallization for the whole South Block has so far been borne out by the geochronological work that has been done in the present study.

Pomona Granite, Lake Manapouri (sample code: 36): This concordantly emplaced granite from Pomona Island in the eastern part of Lake Manapouri studied by Turner was examined here (Figure 25) and the data are shown in Figure 27 and Table 5. The data from this sample constitute good evidence that its age is about 102-118 my. The relatively large spread between the biotite and potassium feldspar apparent ages is outside experimental error and not understood, particularly because the biotite apparent age of 118 million years, is greater than the potassium feldspar apparent age of 102 million years, this relationship being contrary to the usual observation that a potassium feldspar Rb/Sr measured age is greater than or equal to a biotite Rb/Sr age. Part of the errors shown in Table 5 for the above two ages is the estimated error in the initial Sr^{87}/Sr^{86} ratio. This error is the

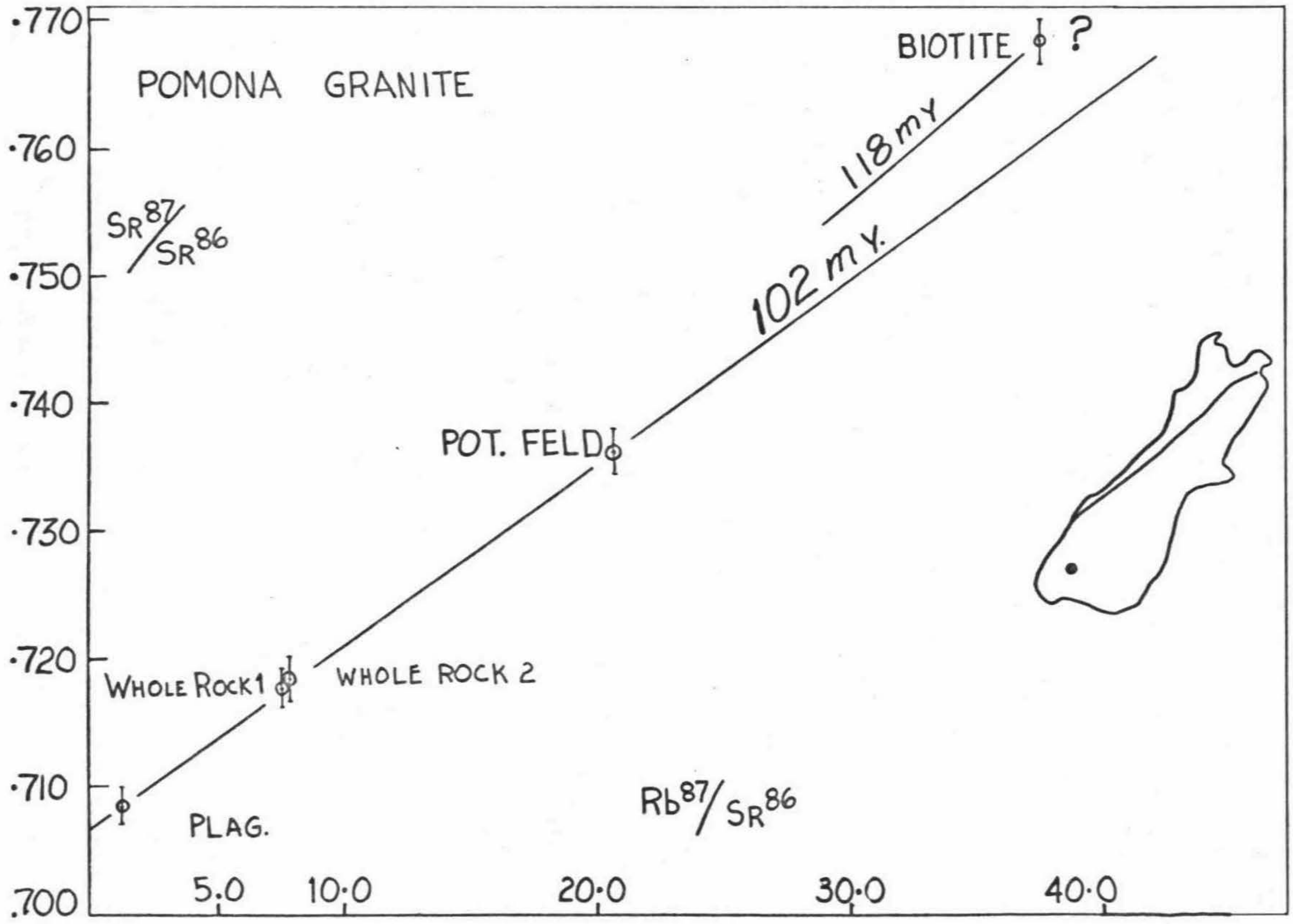


Figure 26. Rb-Sr isochron of Kakapo Granite.

same for the cogenetic biotite and potassium feldspar. Hence, relative to each other, the ages and errors are 118 ±6 million years for the biotite and 102 ±10 million years for the potassium feldspar. It should be noted that the biotite from this rock is somewhat more altered to chlorite than in other rocks of this study.

The Pomona Granite is the only plutonic rock of possible Cretaceous age examined in this study that has a moderately high total rock Rb/Sr ratio so that its total rock age is analytically meaningful. The Rb^{87}/Sr^{86} in the total rock is 0.719 as compared to 0.707 initially present in the plagioclase 102 million years ago. If this total rock has remained a closed system since its origin then the oldest it could possibly be, extrapolating back to a low 0.702, would be 150 ±20 million years (Table 10) and not as old, for instance, as the older granites of the North Foreland Block of 345-370 million years ago. Thus this data on the Pomona Granite in combination with the field and petrographic data of Turner have great importance for the interpretation of the age of the whole South Block. If one accepts Turner's conclusion that the Pomona Granite is indeed synchronous in origin with the metamorphism of the surrounding gneisses and also accepts that there is a general field continuity of the metamorphic units throughout this block as is implied in the regional mapping of Wood, then the suggestion is that a large part of the South Foreland Block has a maximum age of 155 million years and probably is actually 100-120 million years old.

TABLE 10

Whole Rock Data, Pomona Granite 36

	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86}	Age (million years)	
			Initial Sr^{87}/Sr^{86} = 0.707	Initial Sr^{87}/Sr^{86} = 0.702
Whole rock 1	7.556	0.7172	97	145 ± 19
Whole rock 2	7.847	0.7186	109	152 ± 19
Average			103	148 ± 19

This suggestion is made further by the results of the relatively few representative samples of wide separation from this block that were examined in this study (discussed below).

Amphibolite, Lake Manapouri (sample code: 22) and Lake Te Anau (sample code: 21): A sample of amphibolitic gneiss from the western shores of Lake Manapouri 17 km west of the Pomona Granite locality was examined (Figure 25). This rock has been mapped as Bradshaw Gneiss (Wood, 1960). Two different biotite separates from this rock give ages of 101 and 103 million years using an initial Sr^{87}/Sr^{86} of 0.703 registered in the plagioclase (Table 5). The former age is analytically more precise. North of Lake Manapouri an amphibolitic gneiss was examined from the mouth of the South Arm of Lake Te Anau (Figure 24). This sample has been mapped as Princess Formation (Wood, 1960). A biotite from this rock gives an age of 115 million years using an initial Sr^{87}/Sr^{86} of 0.701 measured in the plagioclase (Table 5). This is the lowest value of Sr^{87}/Sr^{86} measured in this study.

Doubtful Sound Adamellite (sample code: 39): West of Lake Manapouri an adamellite was collected from the base of Helena Falls at the head of Doubtful Sound (Figure 25) as a large fresh boulder in Helena Stream. This rock was uncommon amongst the boulders at the base of the falls, the dominant type being light colored gneisses. However, similar highly weathered granite was found in situ 1-2 km east of the sample locality along the Doubtful Sound-Lake Manapouri track, and constitutes a major part of the cobbles in Stella Stream 3 km west of the sample locality. Three biotites were examined, two of which are splits of the same 40/80 mesh separate and a third is a +20 mesh separate. Their ages are relatively low at 92, 94, and 97 million years, respectively, displaying a somewhat large, but possible, internal variation to attribute to analytical error (Table 5). It may be significant that the coarser biotite gives the highest age and this may indicate a type of internal discordance and that the rock has been disturbed after crystallization. All of these ages are calculated assuming a low initial Sr^{87}/Sr^{86} of 0.703; if the true initial Sr^{87}/Sr^{86} were greater than this then the above variation would accordingly increase. This possible discordance will be further discussed with results obtained from a sample near the northern end of the South Block, at Milford Sound (below).

Amphibolite, Milford Sound (sample code: 33): This sample, taken from the head of Milford Sound (Figure 25) is a biotite amphibolite. The biotite in this sample gives an age of 74 million years assuming an initial Sr^{87}/Sr^{86} of 0.702 or 68 million years if 0.706 is assumed (Table 5). Considering the general continuity of the metamorphic units of the northern part of the South Block with those to the south (Wood, 1960; 1965), this result seems anomalously low when compared with the 94-118 million year ages obtained from samples to the south.

This sample is only 16 km east of the Alpine Fault on the uplifted side. Highly sheared and intensely folded mylonitic gneisses occur with a 4-5 km-wide zone immediately east of the Alpine Fault with boundaries parallel to the just-offshore fault (Wood, 1962), demonstrating the effect movement along this fault has had on these rocks. It seems likely that the same explanation invoked by Hurley, et al. (1962), to explain anomalously young biotite K-Ar and Rb/Sr ages in the Alpine Schist may well be extrapolated for regions further south in the Foreland Province which also has been uplifted a great height along the Alpine Fault. In this regard, if the biotite ages obtained here (excluding the Pomona Granite biotite which is suspect because it gave an older age than the coexisting potassium feldspar) for the South Foreland Block are arranged according to their distance from the inferred position of the fault, the farthest first the following age-distance order is obtained:

Lake Te Anau amphibolite	115 my.	- 61 km
Chalky Inlet Granite	100 my.	- 55 km
Lake Manapouri Amphibolite	98-103 my.	- 55 km
Doubtful Sound Granite	92-97 my.	- 40 km
Milford Sound Amphibolite	74 my.	- 16 km

Some of this spread in measured ages in the South Block may reflect a real spread in the true ages of crystallization, but there is a suggestion that uplift along the Alpine Fault may also be a cause of young apparent ages here as well as in the Geosynclinal Province.

Stewart Island (sample code: SITR): The crystalline rocks that comprise the southern two-thirds of Stewart Island have been regarded as extensions of the South Block of the Foreland Province (Grindley, et al., 1959) (Figure 27). These rocks are largely granitic and most of the rocks observed by the author in the eastern part of this part of Stewart Island are gneissic and garnet is a common constituent. The schists and quartzites which comprise the Tin Range have been interpreted as a roof pendant enclosed by the granite and in which the intrusion of the granite has developed a cassiterite-bearing greisen (Williams, 1934). Two samples from the southern part of Stewart Island were examined here, one from the greisen in the Tin Range and one from the gneissic granite. Thick books of muscovite occur in the Tin Range quartzites (Figure 24). Two hand-picked and -trimmed separates of this mineral were analyzed separately and give ages of 113 million years and 118 million years if an initial Sr^{87}/Sr^{86} of 0.706 is assumed (Table 5). The two muscovites show large and therefore certainly real inherent variations in rubidium and normal strontium content. Because of the metamorphic nature of this rock perhaps the assumed initial Sr^{87}/Sr^{86} is too low. If, for instance, the initial ratio were 0.730 then both muscovites would give the same age of 106 million years.

A biotite was examined from a gneissic adamellite (sample code: 30) that is slightly crumbly to a hammer blow, although of unaltered appearance in thin section, from the middle east coast of Stewart Island at the mouth of Lord's River (Figure 25). This biotite gives an age of 97 million years if an initial Sr^{87}/Sr^{86} of 0.706 is assumed (Table 5), somewhat young in comparison to the Tin Range muscovites. The two ages, however, do seem to confirm the correlation of southern Stewart Island with the crystalline complex of the South Block of the Foreland Province in the main South Island. The results contrast with the older age of 136 million years for a biotite obtained from sample: 29 from the intermediate-composition rocks from northern Stewart Island. As previously mentioned, these rocks of northern Stewart Island have been mapped as part of the Marginal Zone plutonic rocks of the Geosynclinal Province (Grindley, et al., 1959).

C. Precambrian in New Zealand

One of the foremost purposes of this study has been to determine whether or not crystalline rocks of Precambrian age comprise any of the New Zealand basement.

No crystalline rocks with primary Precambrian age have been found in the South Island. The evidence presently accumulated suggests that the Charleston Gneiss, formerly mapped as Precambrian, is Paleozoic and not Precambrian in age.

(1) North Island

In a further effort to establish whether or not Precambrian occurs in the New Zealand crust, two possible samples were examined from the North Island. The North Island is essentially entirely comprised of the Geosynclinal Province, a large portion of which has been covered by Tertiary--Recent volcanics (Figure 28). Basement for the geosyncline has been proposed to exist only in one area, the Coromandel Peninsula.

(a) "Coromandel Granite" (sample code: COR)

In the northern part of the North Island on the northwest side of Coromandel Peninsula (Figure 28), a small body of fine-grained hypersthene tonalite occurs in the Moehau Range. It is generally referred to as the "Coromandel Granite," but has recently been mapped as Paritu Tonalite (Thompson, 1960). Field evidence has been insufficient to determine whether this rock is a basement for fossiliferrous

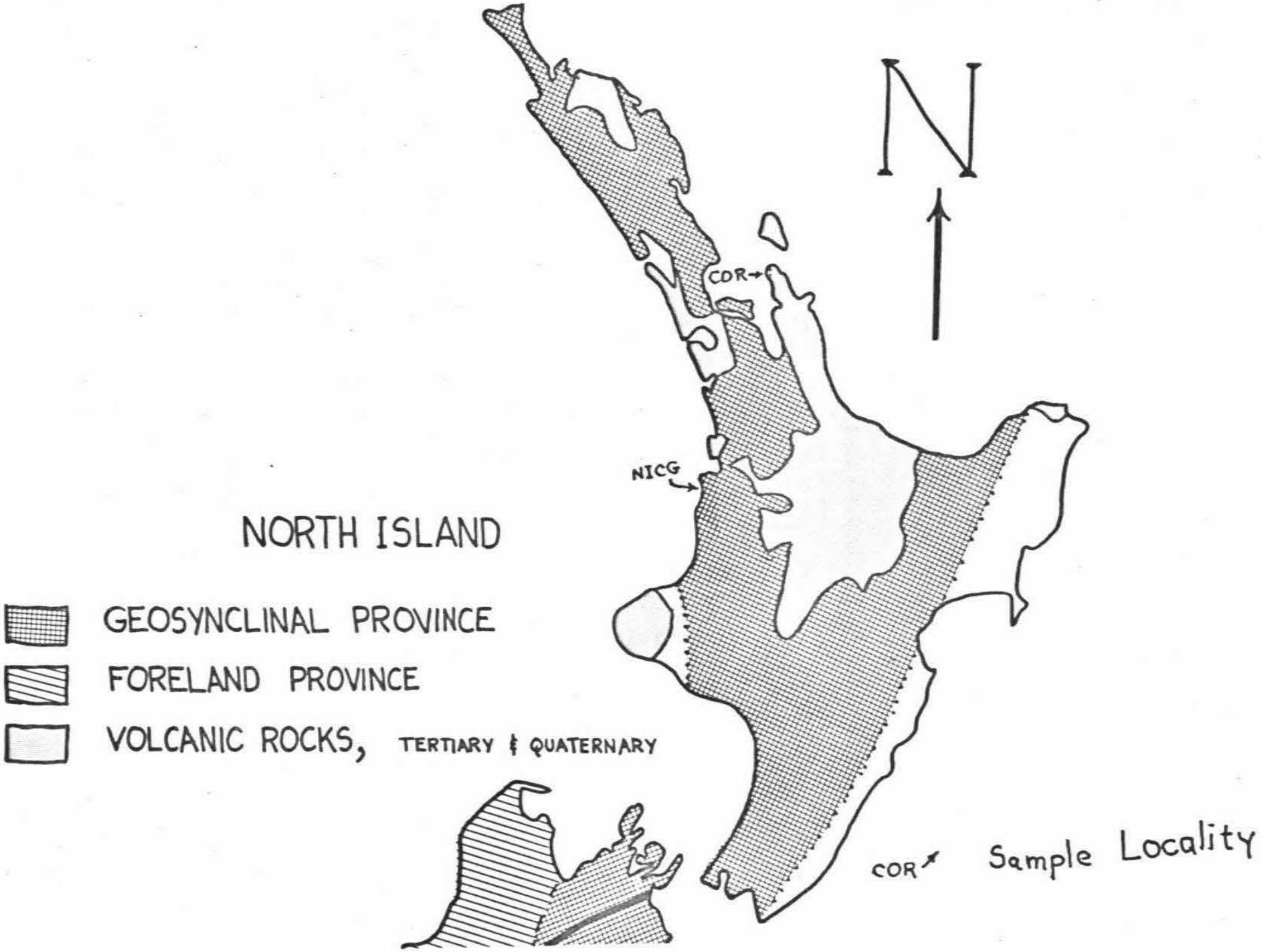


Figure 28. Sample localities in North Island.

Jurassic sedimentary rocks in the area, or else a hypabyssal equivalent of one of two Tertiary, either Eocene (?) or Miocene (?), hypersthene andesites which unconformably overlie the Jurassic rocks (Fraser, 1907). Fraser had tentatively assigned these rocks as pre-Jurassic in age mainly on the basis that the Jurassic sedimentary rocks are rarely intruded by igneous dikes and sills whereas the underlying pre-Jurassic (?) sedimentary rocks are commonly intruded by these.

A Rb/Sr analysis of biotite from this tonalite gives an age of 17.0 million years assuming an initial Sr^{87}/Sr^{86} of 0.706 (Table 6). This absolute age, according to Kulp (1961), is equivalent to Miocene and constitutes good evidence that this fine-grained tonalite is a hypabyssal equivalent of Fraser's Second Period Volcanics. Leaf impressions that occur in these volcanics have been assigned a Miocene age (Fraser, 1907). The fine-grained sub-ophitic texture of this intrusive rock is consistent with such a hypabyssal origin, and its chemical composition is very similar to that of the andesites (Fraser, 1907).

(b) Tonalite Boulder, Moeatoa Conglomerate (sample code (NICG)

The other sample examined from the North Island occurs as a large boulder of medium-grained tonalite in the Moeatoa Formation, a marine fossiliferrous conglomerate of middle Triassic age. This formation is in the Marginal Zone of the Geosynclinal Province on the west coast, south of Kawhia Harbor (Figure 28). Coarse marine conglomerates containing large boulders of plutonic rocks are characteristic of the Marginal Zone Triassic throughout the extent of this zone in New Zealand in both the North and South Islands. The occurrence of plutonic rocks as boulders in the Triassic conglomerates of the South Island, both north and south of the Alpine Fault had often been cited (Wood, 1956; Reed, 1958; Grindley, 1961) as evidence of a pre-Triassic age for the crystalline rocks of the Foreland Province. This study has shown that a probably major part of the plutonic and metamorphic rock now exposed in the Foreland Province is Cretaceous, but that a large amount of pre-Triassic plutonic rock does occur in the Foreland Province, at least north of the Alpine Fault.

In the Moeatoa Conglomerate, rudely sorted, rounded-to-angular boulders are very coarse, some as large as 2. 5 meters in diameter (Marwick, 1946), suggesting a nearby source area that is now either to the west, just off shore, submerged in the Tasman Sea, or else buried beneath sedimentary and volcanic rocks to the east. Because of the complete lack of any exposed crystalline basement or Foreland Province in the North Island, it is of much importance to determine the age of the crystalline source area now represented as boulders in this North Island conglomerate.

The biotite from this boulder gives a Rb-Sr age of 257 million years using an initial Sr^{87}/Sr^{86} of 0.702 measured in the plagioclase (Table 6). This biotite is inelastic in hand specimen and is partly altered to iron oxides. Its X-ray pattern shows vermiculite is present, but subordinate to biotite. Otherwise, the rock appears fresh in thin section and hand specimen. Until further work is done this mid-Permian age (Kulp, 1961) is regarded as a true age or minimum age for the source area which provided the boulder and is consistent in being older than Triassic. If the age is true then it is likely that the source is a continuation from the South Island of the belt of largely basic and ultrabasic with lesser intermediate plutonic rocks associated with the flanks of the Marginal Zone regional syncline; this would possibly occur off shore to the west of the Moeatoa Conglomerate. Further, the suggestion that the plutonic intrusives within the flanks of the marginal syncline are a source for the coarse boulders in the Triassic conglomerates not only in the North Island but also in the South Island is not unreasonable if one considers the close distance which separates outcrops of the Triassic strata from outcrops of such Marginal Zone intrusives in the South Island. On the other hand, if the biotite age is a minimum age, then the source of the conglomerates may be a northward continuation of the exposed 500-km belt of 345-370 million year plutonic rocks that occur along the west coast of the South Island, now possibly shallowly submerged just west of the North Island in the

Tasman Sea. This sample merits further work, including K-Ar on the hornblende.

(2) South Island, Greenland Series*

There are good geological indications that Precambrian acidic crust does exist, or at least did exist, in New Zealand. The oldest sedimentary rocks of known age in New Zealand are limestone lenses in the Haupiri Group of the northern part of the North Block which have yielded Middle Cambrian trilobites and Middle or Upper Cambrian brachiopods (W. N. Benson, referred to in Lillie, Lexique Stratigraphique, 1958). Thought to be in association with these limestone lenses are conglomerates with dominantly volcanic clasts, but also rare clasts of granite and mica schist (Grindley, et al., 1959). The latter suggest the presence of a pre-existing acidic basement for the Cambrian rocks that has not yet been found.

As previously noted, the Greenland Series, areally extensive in the southern part of the North Block, is regarded as possibly of Precambrian age. Reed (1957) has postulated an acidic source for this sedimentary rock on the basis of its uniform quartz-rich character (averaging about 72% SiO_2 in the chemical analysis). He suggested

---

*Wellman (1946) divided the Greenland Series into two units on the basis of a difference in regional strike. One of these was termed the Waiuta Series (Suggate, 1957). In this study, both the Waiuta Series and Greenland Series are considered simply as Greenland Series.

from the available evidence that the source may have been the Charleston Gneiss, but the evidence from the present study indicates this is unlikely.

It is important to try to determine the age of deposition of the Greenland Series, certainly one of New Zealand's oldest sedimentary rocks. The widespread distribution of this important unit in New Zealand is shown in Figure 29. A maximum age of deposition for the Greenland Series is represented by an isochron through the total rock points of two metamorphosed Greenland hornfels samples examined in this study to a very low initial Sr^{87}/Sr^{86}, assuming the total rocks have remained closed systems. The two samples are from Moeraki Bluffs (sample code: 18+) and Waitaha River (sample code: 22+), previously discussed. Total rocks of the Marauia River Greenland Series (sample code: 11) have not been analyzed. Because of the low spread in the Rb/Sr ratio of the whole rocks of the two samples examined, the points do not determine an isochron in themselves. If an initial Sr^{87}/Sr^{86} of 0.702 is assumed then a maximum age of deposition of 820 million years is indicated; if 0.706 is used then this age would be 750 million years. Thus, an age of deposition sometime between these maximum ages in the late Precambrian and the probable Devonian age of metamorphism is suggested for the Greenland Series. The geological basis for the Precambrian assignment to the Greenland Series has been that over its wide extent it is non-fossiliferrous and

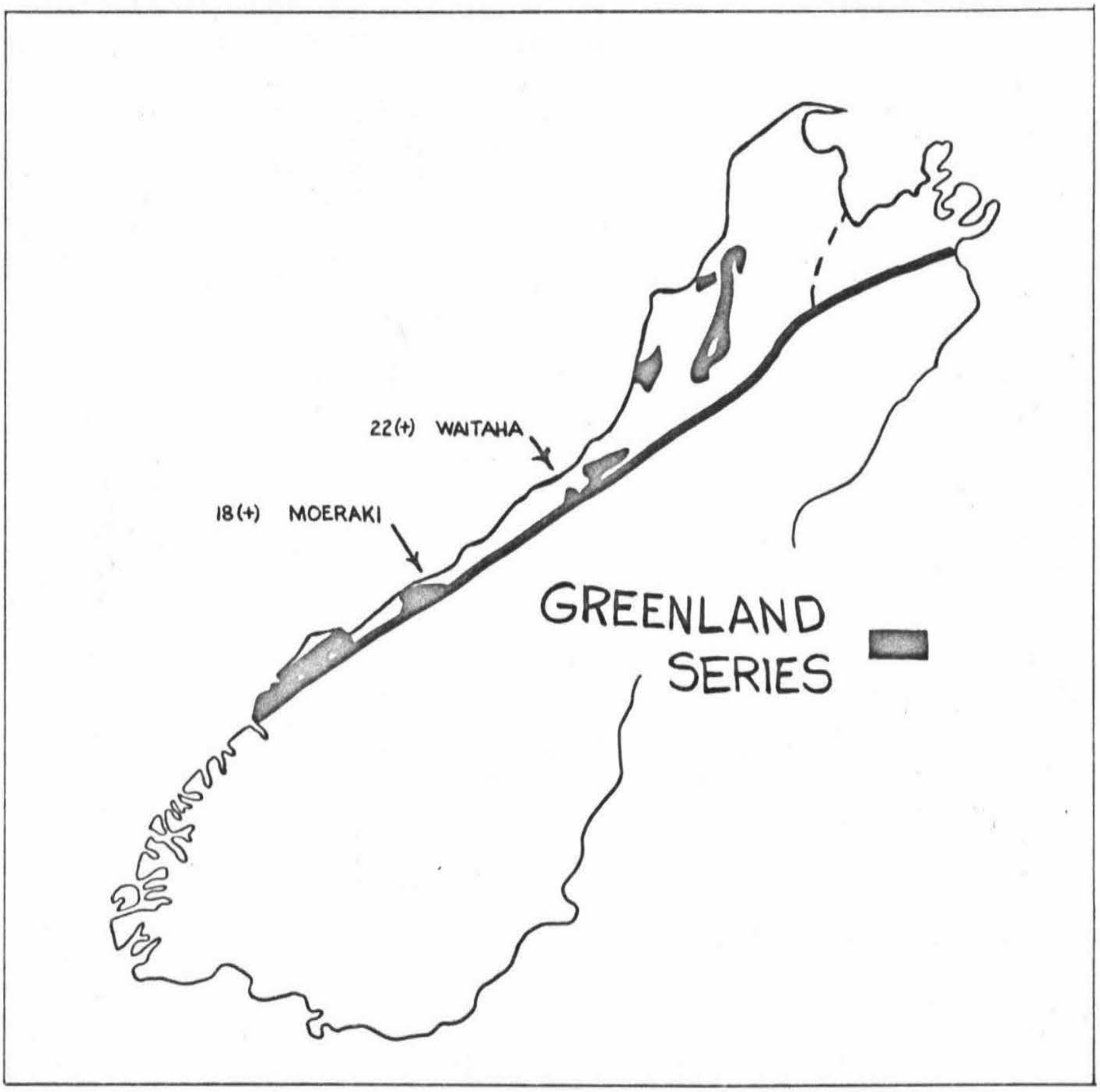


Figure 29. Distribution of the Greenland Series in New Zealand.

TABLE 11

Rubidium-Strontium

Whole Rock Data

Greenland Series

Sample Code	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86}	Primary Whole Rock Age T (10^6 years)	
			Initial Sr^{87}/Sr^{86} = 0.706	Initial Sr^{87}/Sr^{86} = 0.702
18(+), Moeraki Bluffs				
Whole rock 1	3.637	0.7421	710 ± 50	790 ± 50
Whole rock 2	3.215	0.7398	770 ± 55	840 ± 55
Average			740 ± 55	815 ± 55
22(+), Waitaha River				
Whole rock 1	2.735	0.7335	720 ± 60	825 ± 60
Whole rock 2	2.767	0.7344	735 ± 60	835 ± 60
Average			730 ± 60	830 ± 60

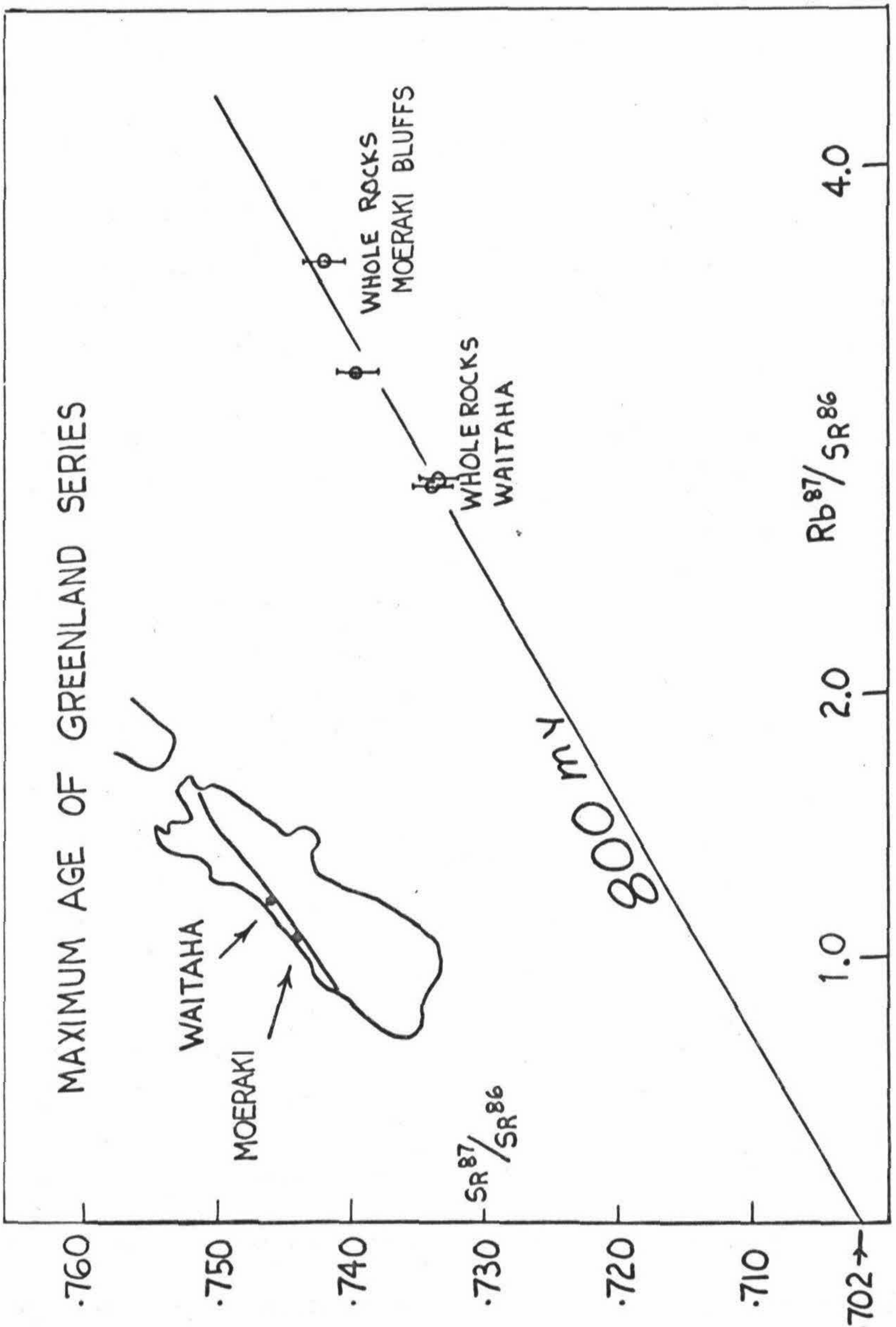


Figure 30. Whole rock maximum age of deposition of the Greenland Series.

that near Reefton it is believed to underlie the Lower Devonian rocks (Suggate, 1957). The data presented here are not in conflict with this assignment.

In addition to being typically quartz-rich, the three samples of Greenland Series hornfels examined in this study from widely spaced localities in the North Block of the Foreland Province (Moeraki, Waitaha and Marauia Rivers, Figure 29), contain moderate amounts of rounded zircon additionally suggestive of the presence of a widespread pre-existing acidic crust. In a final effort in the present search for Precambrian in New Zealand, it was decided to date the remnants of that pre-existing crust conveniently preserved in the Greenland Series as detrital zircons.

Zircons were separated from the Waitaha River sample, previously described as being intruded by 360-370 million year granites. These zircons, photographs of which are shown in Figures 31, 32 comprise a very nonuniform suite with variable color, size, shape, and degree of roundedness. The shape varies from euhedral prisms pyramidally terminated with slightly rounded edges to almost completely spherical grains with no crystal outlines. The finer grains on the average are rounder than the coarser grains. The color of the acid-washed grains varies from clear to dark purple and the color of the grain aggregates is light purple. The separate was split into two parts, one (+) 250 mesh and the other (-) 250 mesh, in the hope of obtaining a separation

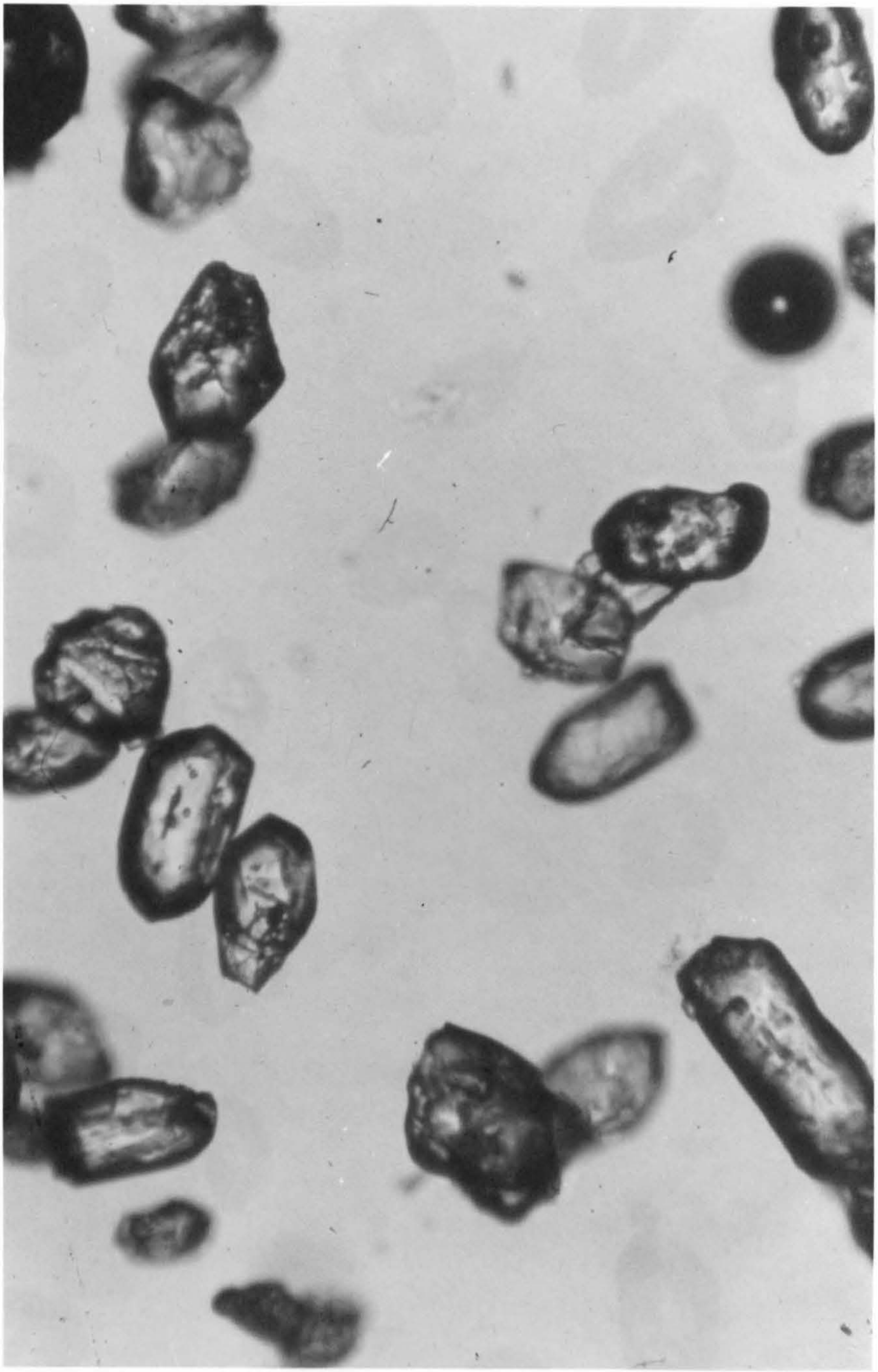


Figure 31 (+) 250 mesh zircons, Greenland Series
Waitaha River, Photo by L. T. Silver

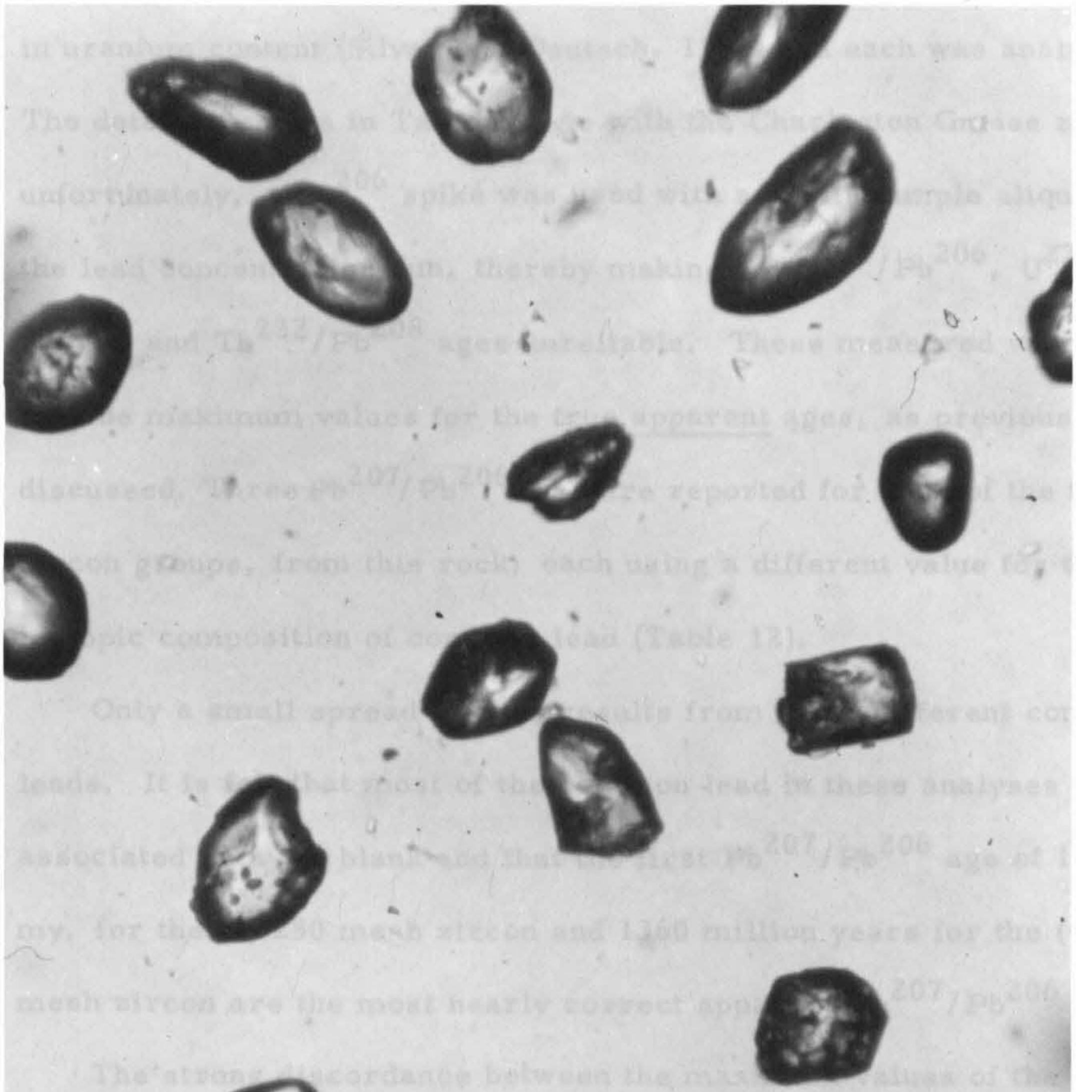


Figure 32. (-) 250 mesh zircons from Greenland Series, Waitaha River. Photo by L. T. Silver

in uranium content (Silver and Deutsch, 1963) and each was analyzed. The data are shown in Table 12. As with the Charleston Gneiss zircon, unfortunately, a Pb^{206} spike was used with a small sample aliquot for the lead concentration run, thereby making the U^{238}/Pb^{206}, U^{235}/Pb^{207}, and Th^{232}/Pb^{208} ages unreliable. These measured values can only be maximum values for the true apparent ages, as previously discussed. Three Pb^{207}/Pb^{206} ages are reported for each of the two zircon groups, from this rock, each using a different value for the isotopic composition of common lead (Table 12).

Only a small spread in ages results from these different common leads. It is felt that most of the common lead in these analyses is associated with the blank and that the first Pb^{207}/Pb^{206} age of 1270 my. for the (-) 250 mesh zircon and 1360 million years for the (+) 250 mesh zircon are the most nearly correct apparent Pb^{207}/Pb^{206} ages.

The strong discordance between the maximum values of the U^{238}/Pb^{206}, U^{235}/Pb^{207}, and Th^{232}/Pb^{208} apparent ages and the Pb^{207}/Pb^{206} ages indicates the latter are minimum ages for the zircons. Only under the very unusual conditions, never before reported for other zircons, of uranium loss without lead loss in the history of these zircons would the Pb^{207}/Pb^{206} age not represent a minimum age. Such a history is ruled out because the U-Pb ages are less than the Pb^{207}/Pb^{206} age and hence inconsistent with uranium loss. Part of

TABLE 12

Data for Detrital Zircons, Greenland Series

Sample	Observed Ratios				
22(+)-Waitaha River	Pb^{206}/Pb^{204}	Pb^{207}/Pb^{204}	Pb^{208}/Pb^{204}	Uranium (ppm)	Thorium (ppm)
(-)250 mesh	1037 ± 4	99.50 ± 0.4	204.0 ± 0.8	951.0	647.7
(+)250 mesh	1680 ± 10	158.7 ± 0.9	193.6 ± 1.0	699.6	175.8
18(+)-Moeraki Bluffs					
(-)270 mesh	3570 ± 66	322 ± 6	393 ± 7	840 ± 100	

	Ages (million years)					
	Pb^{206}/U^{238*}	Pb^{207}/U^{235*}	Pb^{208}/U^{238*}	Pb^{207}/Pb^{206*}	Pb^{207}/Pb^{206**}	Pb^{207}/Pb^{206**}
22(+)						
(-)250 mesh	$711 \pm 15^{\dagger}$	$860 \pm 15^{\dagger}$	$516 \pm 20^{\dagger}$	1276	1275	1269
(+)250 mesh	$846 \pm 15^{\dagger}$	$1000 \pm 15^{\dagger}$	$995 \pm 20^{\dagger}$	1363	1362	1358
18(+)						
(-)270 mesh	780 ± 100	950 ± 100		1368	1367	1364

---

† Maximum values for true apparent age because of use of Pb^{206} tracer. A large post aliquoting hypothetical blank of 0.1 μgm. of blank lead would cause these ages to be high by about 10%.

Common lead correction

Pb^{204}	Pb^{206}	Pb^{207}	Pb^{208}		
1	18.22	15.60	37.92	*	average blank, (Banks, 1963)
1	16.23	15.50	35.89	**	model 1500 my. (Catanzaro and Gast, 1961)
1	18.83	15.87	39.48	***	Buller River adamellite feldspar, 112 my.

the discordance may be due to younger detrital zircons diluting the oldest detrital zircons or to overgrowths of new zircon during metamorphism as pointed out to the author by L. T. Silver.

In order to examine the possible lateral extent of this Precambrian source area, zircons were separated from the similar sample of the Greenland Series at Moeraki River (sample code: 18+) 135 km south of the Waitaha River, and analyzed for uranium and lead. The uranium data are only preliminary. In this analysis a Pb^{208} spike was employed. In physical aspect the zircon concentrate from this rock is almost identical to that separated from the Waitaha Greenland Series with rounded zircons being dominant. Euhedral zircons, only slightly rounded, are perhaps more common in this sample than in the other sample. They comprise about 15% of the (-) 270 mesh concentrate. The pyramidally-terminated prisms of these euhedral zircons tend to be rather uniformly elongate with a length-width ratio of about six. The highly discordant age pattern obtained for this zircon from the Moeraki River sample is very similar to those obtained for the Waitaha sample and these results are also shown in Table 12. The Pb^{207}/Pb^{206} age of 1370 million years for this zircon is particularly reliable because of the rather highly radiogenic lead separated from this zircon and the consequent small common lead correction.

Because of the complicated history of these twice-metamorphosed detrital zircons from both samples of the Greenland Series hornfelses,

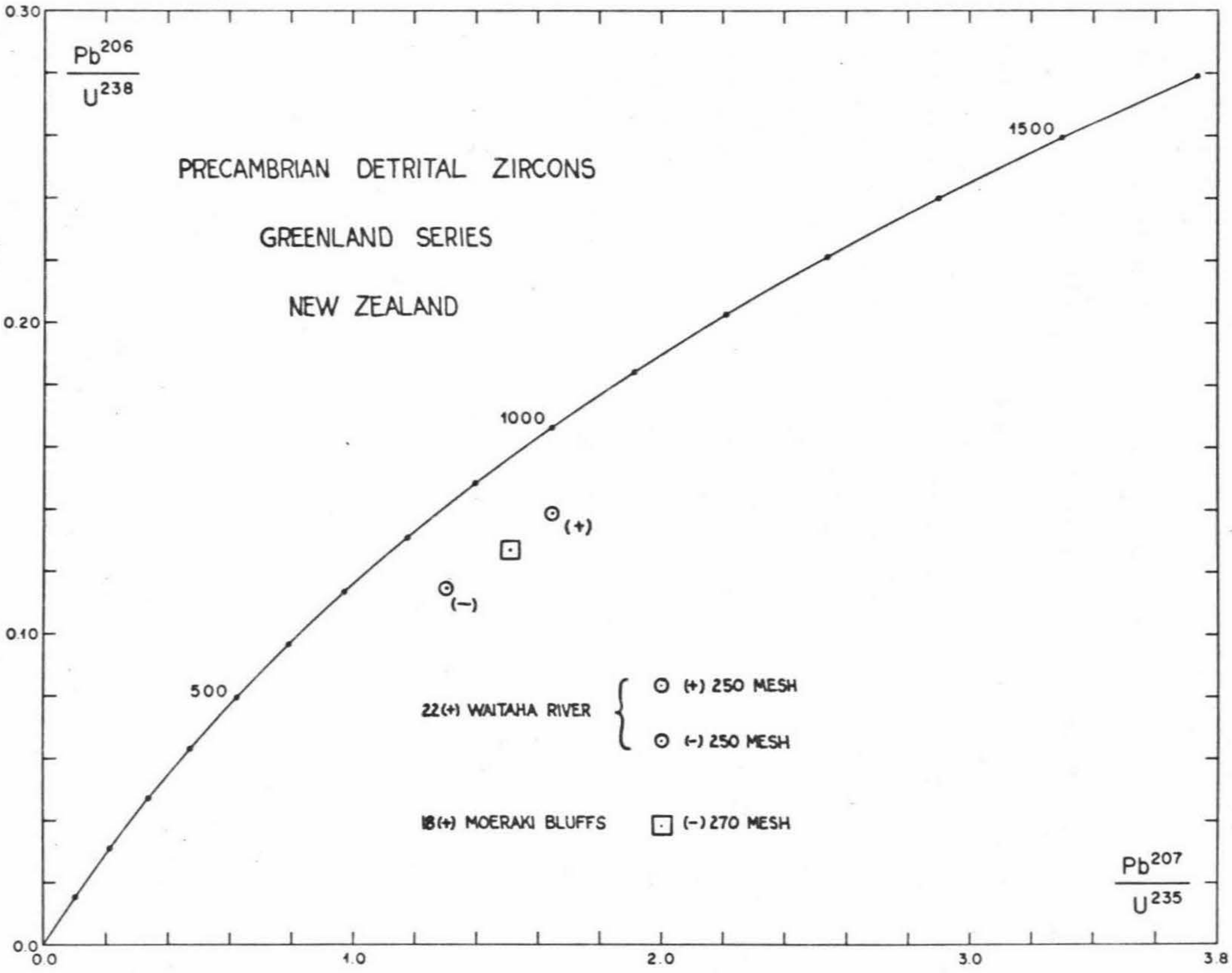


Figure 33. U/Pb data from Greenland Series zircons on concordia plot.

it is impossible to make any extrapolation to the oldest age represented by these zircons and all that can be said is that the older Pb^{207}/Pb^{206} age of 1370 million years is almost certainly a minimum age for the oldest source area which provided the zircons. For convenience, these results are shown in a concordia plot (Figure 33), it being stressed that the concentration data are not reliable. These results demonstrate the presence of moderately old Precambrian acidic crust in, or in the neighborhood of, New Zealand of wide enough extent to have shed abundant zircons into sediments now separated by 135 km. This has fundamental importance for the tectonic picture of the southwest margin of the Pacific Ocean. The implications of these results are discussed in the following section.

V.

GENERAL ASPECTS OF GEOCHRONOLOGICAL RESULTS AND CONCLUSIONS

A. Cretaceous Plutonic and Metamorphic Activity

B. 345-370 Million Year Plutonic Activity

C. Permian and Possible Younger Plutonic Activity of the Marginal Zone, Geosynclinal Province

D. Precambrian

E. Future Work

V. GENERAL ASPECTS OF GEOCHRONOLOGICAL RESULTS AND CONCLUSIONS

The results of this study reveal major aspects of the geochronology of plutonic and metamorphic activity in New Zealand. They indicate that most of the plutonic and metamorphic rocks now exposed in New Zealand crystallized during two events, one during the Devonian about 345-370 million years ago, and the other during the Cretaceous about 100-120 million years ago. The latter results date the Rangitata Orogeny and associate much plutonic activity with that orogeny.

In addition, plutonic activity occurred in the Marginal Zone of the New Zealand Geosyncline during the Permian and possibly extended into the Mesozoic. At least one plutonic event in the Precambrian of moderately old age is indicated for the New Zealand crust by the occurence of detrital zircons in the Greenland Series at least as old as 1370 million years.

A. Cretaceous Plutonic and Metamorphic Plutonic Activity

The results presented here indicate that extensive plutonic activity widely scattered throughout the Foreland Province accompanied the Rangitata Orogeny. From many of the samples of this apparent age examined in this study, biotite was the only phase with a high enough Rb/Sr ratio for an analytically precise age determination. In reviewing the results on the Charleston Gneiss, if biotite alone had been examined, the rocks could have been classified as plutonic rocks produced during the 100-120 million year orogeny. The interpretation of the age of rocks from which only biotite has been examined must therefore be made with caution. Possibly any individual 100-120 million year result obtained for a sample with only a biotite analysis cannot be regarded with a high degree of confidence. However, the overwhelming uniformity of 100-120 million year apparent ages obtained for many samples of varying rock types widely distributed throughout the Foreland Province is a strong argument in itself that some of these rocks are indeed of this age and have not just suffered a metamorphic disturbance at this time. If this age represented just a metamorphism of the older rocks, then a distribution of apparent age values dispersed between the 345 million years and the 120 million years should have been obtained. Of those relatively few rocks which do show an intermediate age, every one of those with both biotite and muscovite give apparent ages which are markedly discordant. Many of the 100-120 million year samples examined here do contain both biotite and muscovite which give reasonably concordant ages. It is felt that the age of these individual samples may be regarded with a high degree of confidence. Only for two 100-120 million year samples were total rocks of sufficiently high Rb/Sr ratio to enable analytically precise dates. Total rocks of the augen-gneiss and associated migmatite phase from the Paparoa Range were analyzed separately and constitute an isochron that includes several minerals from the migmatite. These results suggest that the granite phase of the migmatite originated by melting of the gneissic phase 100-120 million years ago. The other radiogenic total rock is the Pomona Granite from the South Block, the total rock of which indicates a maximum age of 150 ±20 my., if it has remained a closed system.

In addition to these two rocks, two other probable 100-120 million year granitic rocks, the Buller River granite (sample code: 16) and the Rahu Saddle granite (sample code: 14) have total rock Rb/Sr ratios that are relatively high compared to the other probable Cretaceous samples in this study. Sample 16 has a present Sr^{87}/Sr^{86} of 0.7069 and Rb^{87}/Sr^{86} of about 2.1; sample 14 has a present Sr^{87}/Sr^{86} of 0.7064 and a present Rb^{87}/Sr^{86} of about 1.6. If extrapolated back initially to a Sr^{87}/Sr^{86} of 0.702 with a closed system assumption, these results indicate maximum ages of about 200 ±100 and 250 ±100 million years for these rocks. This suggests these rocks cannot be as old as the 345-370 million year rocks common in the North Block of the Foreland Province.

For the Foreland Province it should be noted that 116 million years is probably a better estimate of the maximum apparent age of the plutonic and metamorphic activity. In this province only one determination is greater than this, the 118 million year age on biotite from the Pomona Granite, the potassium feldspar of which is only

102 million years. It may be significant that one of the oldest Cretaceous ages comes from the Otago Schist muscovite of the Geosynclinal Province, at 116 million years. Because of a low Rb/Sr ratio, however, this age is rather imprecise.

The absolute age of 100-120 million years probably corresponds stratigraphically to uppermost Albian and Lower and Middle Cenomanian. Silver, Allen, and Stehli (1961) report concordant U, Th, Pb ages of 116 million years for a monazite from a post-Early and Middle Albian, pre-Upper Campanian or Lower Maestrichtian intrusive rock in Baha California, Mexico. Folinsbee, Baadsgaard, and Lipson (in Kulp, 1961) from a stratigraphically well dated Cretaceous section in western Canada have estimated the Middle Albian is 117 million years old and the Upper Cenomanian is 96 million years old, using K-Ar techniques on biotites from volcanics intercalated in the section.

At this stage of work, it is not known just how much of the spread in Cretaceous ages obtained for the New Zealand plutonic and metamorphic rocks is real and how much is due to a complicated post-crystallization geological history. For instance, some evidence suggests that some of the spread of apparent ages in the South Foreland Block may be caused by relatively recent uplift along the Alpine Fault. In the North Block muscovite from the west coast pegmatite at Nile River, which intrudes the Charleston Gneiss, gives an age of 110 million years in contrast to 100-102 million years of apparent age on biotites from samples of the Charleston Gneiss north and south of the pegmatite.

One of the major contributions of this work is the association of large amounts of plutonic activity with the Rangitata Orogeny. The Otago Schist sample at Cromwell, which was metamorphosed during the orogeny, was shown to have a mid-Cretaceous age of about 104-116 million years. Numerous plutonic rocks of varied rock-type throughout both blocks of the Foreland Province have ages essentially within this same range and hence are certainly associated in origin with the Rangitata Orogeny. It now becomes apparent that this orogeny is similar to other orogenies which occurred at about the same time during the Late Mesozoic in other circum-Pacific areas. Typical of at least some other parts of this circum-Pacific orogeny, the plutonic activity and associated relatively high temperature and low pressure regional metamorphism in New Zealand occurs in a belt (Foreland Province) inland from a Pacific-ward belt of coeval regional metamorphism under relatively high pressure and low temperature conditions. Miyashiro (1961) first recognized this feature of parallel belts as common to the circum Pacific Mesozoic orogenies. He included New Zealand as a type area along with Japan, California, and the Celebes. However, he noted that New Zealand was not exactly typical because the plutonic activity in the inland belt was probably older than the

Late Mesozoic high pressure regional metamorphism in the Pacific-ward New Zealand Geosyncline, because at the time he published his ideas, this plutonic activity in New Zealand was generally regarded as Late Paleozoic in age. The results of the present study demonstrate the Rangitata Orogeny is also similar to the Japan and California orogenies in the synchronous timing of spatially separated plutonic activity and high pressure metamorphic activity.

The fact that only plutonic and metamorphic rocks of 100-120 million years of age have been found in the South Block of the Foreland Province and no evidence has been found there of the 345-370 million year rocks common in the North Block may seem to conflict with the hypothesis of 500 km right lateral displacement along the Alpine Fault. This hypothesis would correlate the North Block with the South Block. The conflict is resolved by considerations of the vertical movement that has occurred along this fault in addition to its dominant horizontal movement. The South Block has undergone a large amount of uplift along the upthrown side of the Alpine Fault and probably an enormous quantity of material has been stripped by erosion from the top of this uplifted block, and a deeper view of the crust is now exposed. Thus, it is likely that the North Block and the South Block of the Foreland Province considered together provide a vertical cross section into the 100-120 million year relatively high temperature--low pressure regional metamorphic and plutonic belt of New Zealand. In the downthrown North Block, the higher levels of this cross section are exposed: regional metamorphism is not really extensive and has mainly produced only schists of low and medium rank; abundant plutonic intrusions are structurally discordant with and contact metamorphose the intruded sedimentary rocks and schists. In the South Block, all of this upper level of this crustal section, including the pre-existing 345-370 million year old rocks could well have been removed by erosion and the deep zone of the 100-120 million year high temperature belt of medium-to-high rank gneisses is now exposed throughout the entire block, except for the faulted southwestern tip. In this deep zone acidic plutonic rocks are developed as structurally concordant bodies of relatively small extent within what is essentially an extensive gneissic terrain. Their emplacement has not altered the metamorphic rank of those gneisses. The occurrences of plutonic rocks as boulders in Mid-Triassic conglomerates in the Marginal Zone south of the Alpine Fault do not constitute a conflict with the lack of Pre-Triassic plutonic rocks in the South Block, even if it is agreed that these clasts were derived from the South Block. There is a good possibility that such rocks did exist in the South Block and have since been removed by erosion from this uplifted block.

Interpretation of stratigraphic and palynological evidence presents a conflict with the 100-120 million year absolute ages measured for the plutonic and metamorphic rocks developed during the Rangitata

Orogeny. An upper limit to the age of the Otago Schists and the granites of the Foreland Province are the numerous terrestrial, locally derived, breccias and conglomerates that were deposited in separated fault block basins over the crystalline basement. The widely spread occurrence of these deposits is shown in Figure 8. Previous to Cooper's pioneer work (1953) on New Zealand Mesozoic and Cenozoic palynology these terrestrial deposits had all been correlated as time equivalent. As stated at that time by Gage (p. 23, 1952) in a summary of the similarities of all of these deposits to each other, "correlation... is valid only if it is accepted that the conditions favorable for production of such beds are likely to be regional rather than local in effect, and in an area as small as New Zealand, are not likely to have occurred in different localities at different times in the recorded geological history."

However, plant micro- and macro-fossil evidence, largely the former, has not substantiated the exact time correlation of these separated lithologically similar deposits. They have been assigned ages which vary from locality to locality from Middle Jurassic through the lower and middle part of the Upper Cretaceous (Cooper, 1953, 1960; in Wood, 1960; in Harrington, 1955; Norris, in press). The older of these ages conflicts with the ages measured in this study.

In discussing the micro-floral dating of these Late Mesozoic terrestrial beds in the Foreland Province north of the Alpine Fault, Norris (in press) noted the difficulties involved: "No marine beds are known in the Ohika Beds, Hawks Crag Breccia, or Topfer Formation (the three units of these terrestrial deposits regarded on palynological grounds as the oldest in New Zealand*). Consequently, age determinations of these formations are based almost entirely on spore assemblages. Assessment of the exact age of these micro-floras is difficult owing to the geographically restricted nature of some of the constituent spores and little or no information on spore range in the Jurassic and early Cretaceous in New Zealand." The plant ages apparently weigh heavily on the presence or absence of angiosperms in the floral assemblage. The oldest known occurrence of angiosperm micro- and macro-fossils in New Zealand that has been independently dated by marine fossils is in Lower Ngaterian strata (Cooper, in Wellman, 1955; Hall, 1963), which is most likely equivalent to Cenomanian times (Vella, 1961). There they form an extremely rare part of the micro-floral assemblage, comprising one grain in 500 examined (Wellman, 1959). Thus, an age based largely on the absence of angiosperms at best suggests, but does not prove, a pre-Cenomanian age. It seems probable that the Ohika Beds, the Hawks Crag Breccia, and the Topfer Formation, in many samples of which no angiosperm micro-flora have been found, may well be older than those similar geographically

---

*Inserted by present author.

separated deposits in which angiosperms do occur. However, only recently has evidence been presented that indicates just how much older these deposits may be, by correlation with independently well dated sections in the North Island and in Australia. This evidence is the work of Norris (in press), which will now be discussed.

The main purpose of Norris' study was to date the Hawks Crag Breccia at Fox River on the west coast of the North Foreland Block (Figure 8) which probably overlies the Charleston Gneiss there and contains large boulders of the granitic gneiss. Norris' effort is one of the first Mesozoic micro-floral studies in which a large proportion of the forms has been recognized in overseas areas, particularly Australia.

From Norris' statement, above, of the difficulty of using indigenous New Zealand micro-flora to date the terrestrial deposits, it would seem legitimate to base the age of the Hawks Crag Breccia on those micro-flora which are also common to Australia, the closest overseas continental landmass. In all, Norris reported 30 species from the Hawks Crag. Of the 13 species not confined to New Zealand and of age significance, 12 occur in Australia; the other one Podosporites ohikaensis, occurs elsewhere in New Zealand in the Upper Cretaceous and in the Lower Cretaceous of Canada. Of the 12 Australian forms, nine are restricted there to either the Lower Cretaceous of the entire Cretaceous, but some of these do occur in the Middle or Upper Jurrasic of Britain or, less commonly, Canada. The other three occur in both the Upper Jurassic and Lower Cretaceous of Australia. In comparing the Hawks Crag micro-flora with the definite Tithonian micro-flora of Southwest Auckland in the North Island, which has been independently dated by marine fossils, Norris concluded that the Hawks Crag Breccia was older and he assigned a Kimmerdigian age to the Fox River Hawks Crag Breccia. However, the reasons for the older choice were not elucidated. He mentions, in what is apparently an incomplete listing, four of the above nine Fox River micro-floral forms restricted in Australia to the Lower Cretaceous which do not occur in the North Island Tithonian. Having assigned the Fox River beds as Kimmerdigian the absence of these forms in the Tithonian is unusual and Norris suggests their absence may be due to either (1) the presence of a distinctive floral province in northwestern South Island or else (2) a migration of these forms away from New Zealand during the Kimmerdigian. It would seem that a much simpler explanation of Norris' collection of data would be that the Fox River Hawks Crag Breccia is not Kimmerdigian, but instead, Lower Cretaceous. This would be in agreement with the bulk of the 12 correlations with Australian micro-floral forms of which nine occur only in the Cretaceous and three in both the Lower Cretaceous and Upper Jurassic. Thereby the absence of the Fox River Hawks Crag Breccia forms from the North Island

Tithonian is easily explained because these forms would not necessarily have arrived in either New Zealand or Australia until the Cretaceous.

Further work, both paleontological and geochronological, is necessary to completely resolve the conflict of micro-floral dating of the late Mesozoic New Zealand terrestrial sedimentary rocks and the absolute age determinations of the underlying basement. Of much importance, though, assuming both methods are approximately correct, is the indication they present together that in some places an extremely short time span during the Rangitata Orogeny separated the following succession of events: (1) relatively high temperature--low pressure regional metamorphism with concomittant intrusion of abundant acidic plutonic rocks in the Foreland Province and high pressure--low temperature regional metamorphism in the Geosynclinal Province, (2) uplift of these deep-seated crystalline rocks in both provinces, and (3) their erosion into the coarse late Mesozoic breccias. It is interesting to note that a similar brief period is evidenced for the intrusion, uplift, and erosion of the Southern California Batholith (Beal, 1948; Jahns, 1954) of Cretaceous age (Banks, 1963; Silver, Stehli and Allen, 1963) on an opposite part of the circum-Pacific belt.

B. 345-370 Million Year Plutonic Activity

To relate this period of plutonism, for which evidence has only been found in the North Block of the Foreland Province, to the known stratigraphic history in New Zealand, it is necessary to determine its equivalent stratigraphical age. The age almost certainly falls within the Lower or Middle Devonian (Kulp, 1961); exactly where in this stratigraphic interval is important. The outstanding Phanerozoic stratigraphic gap in New Zealand occurs above the Lower Devonian. No sedimentary rocks are known in New Zealand of Middle Devonian up to Lower Permian age. At this latter time the oldest known sediments of the New Zealand Geosyncline were deposited, commencing a style of thick greywacke sedimentation completely different from the Lower Paleozoic and possibly Precambrian relatively near shore sedimentation of varied lithology that had previously occurred in the Foreland Province. In the Foreland Province, per se, except for a thin onlap of Upper Permian (Waterhouse and Vella, 1965) no sedimentary rocks are known up to the post-Rangitata Orogeny Late Mesozoic terrestrial sedimentary rocks. Possibly this large stratigraphic gap in the Foreland Province is marked at its beginning by the 345-370 million year plutonic activity.

The Lower Devonian sedimentary rocks of New Zealand occur in two localities, both in the North Foreland Block. The two appear to be of somewhat different age. The oldest occurs at Baton River where Shirley (1938) assigned an Upper Siegenian or Lower Coblenzian age and later Boucot, et al. (1963), assigned an Upper Gedinnian age as most likely for what they termed an undoubtedly Lower Devonian fauna.

At Reefton, the other locality, south of Baton River, Allan (1947) determined a Coblenzian age for the Reefton Mudstone Beds and Hill (1956) determined an early Middle Devonian age for corals in overlying beds, but Suggate (1958b) mentions the Lower Devonian character of brachiopods immediately overlying the corals. Boucot, et al. (1963), indicated a probable early Emsian age for the Reefton Mudstone and an Emsian or Couvinian age for the overlying limestone. Thus, it appears as if the Reefton Beds are younger than the Baton River Beds and are upper Lower Devonian and possibly lower Middle Devonian.

The absolute stratigraphic time scale has not achieved sufficient resolution in the Lower Paleozoic to determine the relative time position of these youngest Lower Paleozoic sedimentary rocks in New Zealand on the one hand, and the 345-370 million year plutonic activity on the other. Many of the ages currently being used to define this part of the time scale have been determined as K-Ar and Rb-Sr ages on minerals and rocks in Maine and Nova Scotia, North America, where the paleontological control for the Lower Paleozoic has been good. However, this region lies at the northern end of the Appalachian belt of later Acadian metamorphism, and possibly as a result of this, there is an inconsistency in the absolute data which suggests an unusually long period of time for the Lower Devonian from 410 million years ago through 360 million years ago (Bottino, Schnetzler, and Fullagar, 1965). The time points obtained for the Devonian from other regions outside the New England--Nova Scotia area suggest that the older absolute ages in the latter are probably more correct than the younger ages. In Greenland, a biotite K-Ar age of 393 million years has been obtained for a post-Lower Devonian, pre-Middle Devonian intrusion (Kulp, 1961); in Gaspé Peninsula, Quebec, concordant K-Ar ages of 385 ±10 million years have been obtained for biotite and sanidine from a stratigraphically well dated bentonite of middle Lower Devonian (Lower Coblenzian) age (Smith, Baadsgaard, Folinsbee, and Lipson, 1962); at Snobs Creek, Australia, K-Ar ages of 345 million years have been determined for biotites from a lava at the Upper Devonian-Lower Carboniferous boundary (Evernden and Richards, 1962).

It thus seems that the younger part of the 345-370 million year time range falls stratigraphically within the Middle Devonian or even Upper Devonian and that the older part of this range is probably in the lower part of the Middle Devonian, but may be in the upper Lower Devonian. Thus, it is likely, but not certain, that this plutonic activity, perhaps associated with an orogenic event, ended the possibly late Precambrian and early Paleozoic depositional period in New Zealand.

Another presently unfilled stratigraphic gap in New Zealand occurs for the entire Silurian period. Suggate (1957) associated the development of auriferous quartz reefs in the Greenland Series at Reefton with the intrusion of Victoria Range granites of the middle part of the Middle Belt (Karamea) of granites. On the basis of (1) the lack of these reefs in the much small smaller volume of infaulted Lower Devonian sedimentary rocks; (2) the lower degree of metamorphism of the Devonian rocks; and (3) the correlation of the Victoria Range granites with definite Post-Ordovician granites in the northern Karamea Belt, he suggested these granites may be Silurian in age. The absolute ages determined in this study suggest that many of the Foreland granites are as old as Devonian but no evidence of any as old as Silurian has been found. The Rameka Basic Intrusives are definitely later than the Lower Devonian sedimentary rocks at Baton River which they intrude and contact metamorphose. However, it is not known if the 345-370 million year acidic plutonics are coeval with the Rameka Intrusives.

It should be noted that plutonic activity with absolute ages in the range of 345-370 million years has been recorded in the Tasman Geosyncline in southeastern Australia including Tasmania (Evernden and Richards, 1962; McDougall and Leggo, 1965).

C. Permian and Possible Younger Plutonic Activity of the Marginal Zone

The geochronological data taken in this study from plutonic rocks of the flanks of the Marginal Syncline of the Geosynclinal Province do not avail themselves of a simple interpretation. The spread in biotite measured ages of 136, 155, and 245 million years for plutonic rocks from the Marginal Zone south of the Alpine Fault either are true and reflect the occurrence of plutonic activity in this zone during several periods extending well into the Mesozoic or else are not all true, the younger ones set back by the very low grade metamorphism recorded in the Marginal Zone. If the latter is so, it may be possible that all of the plutonic rocks, which are dominantly ultrabasic or basic in composition, may be Permian in age as suggested by the ubiquitous association of these plutonic rocks with the Lower Permian volcanic-rich strata in the syncline flanks.

Two other rocks, one examined in this study and one reported in a previous study by other workers, may belong to the Marginal Zone plutonic rocks. The former is the boulder of granodiorite from the Triassic Marginal Zone Moeatoa Conglomerate in the North Island, which has a biotite age of 257 million years.

The other sample possibly belonging to this group is a granodiorite examined from the Bounty Islands by Wasserburg, et al. (1963). The Bounty Islands lie just north of the trend of the northern flank of the Marginal Syncline of the South Island, but 700 km removed from the South Island on the eastern edge of the Campbell Plateau (see Figure 1). Biotite from this rock gave concordant K-Ar and Rb-Sr ages of 190 million years. No rocks of this age have been found in the main islands of New Zealand, but this age falls within the range of ages observed for the plutonic rocks of the Marginal Zone of the

Geosynclinal Province. One hundred fifty km north of Bounty Island at Chatham Island, on the end of the Chatham Rise (Figure 1), greywackes and low grade schists similar to those of the Alpine zone occur (Boreham, 1959), not inconsistent with an extrapolation of the New Zealand Geosyncline to the edge of the Campbell Plateau, and therefore not inconsistent with the Marginal Zone of the Geosyncline being to the south of Chatham Island, at the Bounty Islands.

D. Precambrian

The occurrence of detrital zircons of moderately old Precambrian age in the Greenland Series has important relevance to the origin of New Zealand crust. First and foremost it strongly reinforces the view that the crust of New Zealand is continental. The Greenland Series zircons not only indicate the old age of the source area, but they also trace the acidic nature of that old crust from which they were eroded. The presence of this crust indicates one of two obvious possibilities. Either New Zealand has remained an isolated "sub-continent" at least for the last 1370 million years or else there is some relationship of New Zealand crust to the Precambrian-rich crust of Australia. Such a relationship, this author believes, may exist that does not necessarily involve continental drift. Extensive areas of Precambrian rocks have been mapped in northeastern Australia in the Northern Territory and in northern Queensland (Figure 34). The western portion of these rocks in the Carpentaria region of the Northern Territory and northwestern

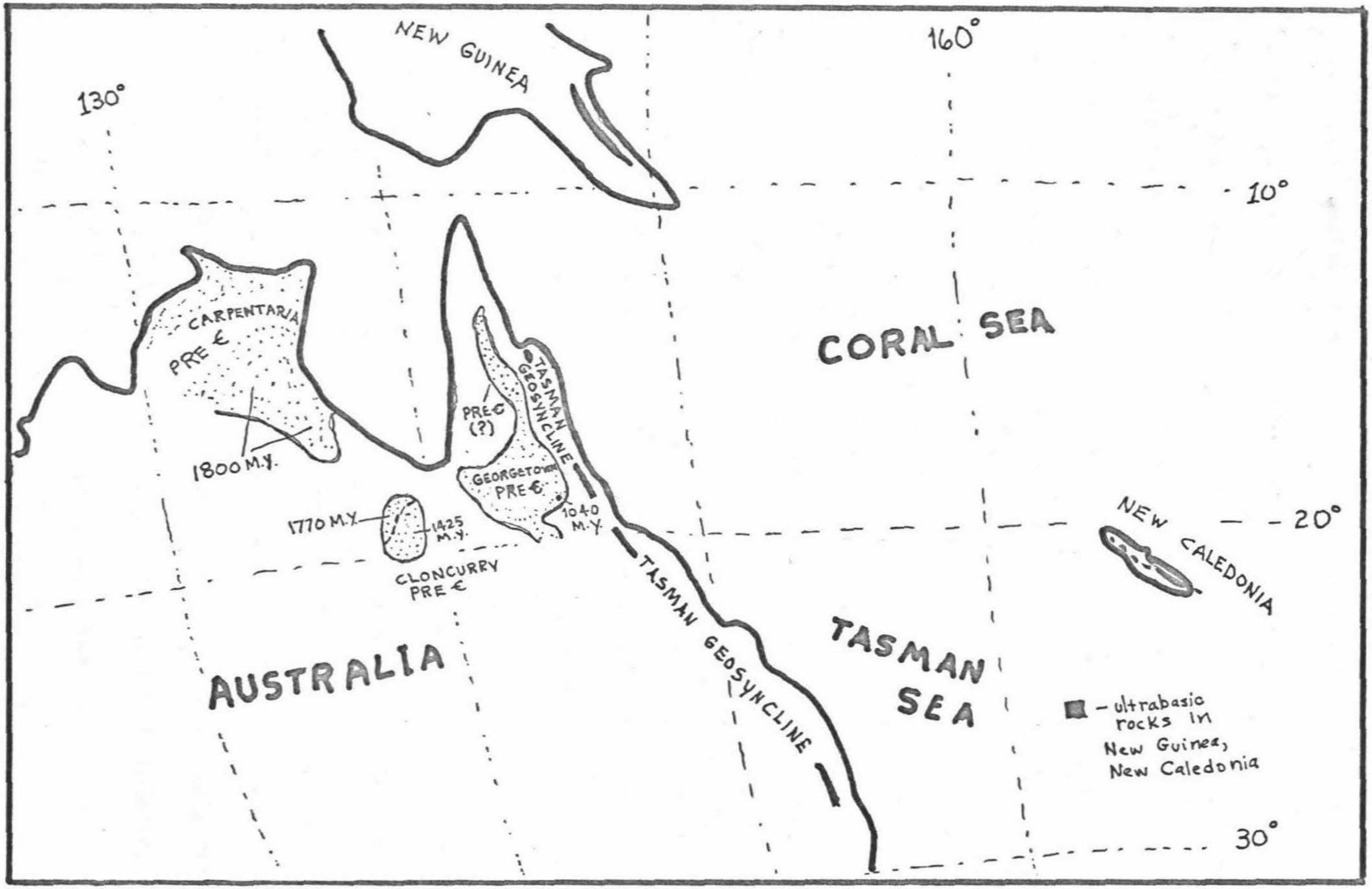


Figure 34. Precambrian terrains in Australia and ultrabasic belts in New Guinea and New Caledonia.

Queensland consists of a crystalline basement overlain by unmetamorphosed Proterozoic sedimentary and volcanic rocks. The basement has been confirmed as Precambrian in age by extensive consistent age determinations of 1800 ±50 million years for granites intrusive into metamorphic rocks of the basement (McDougall, Dunn, Compston, Webb, Richards, and Bofinger, 1965). East of there, in the Mount Isa region of northwestern Queensland, granites intrusive into the Proterozoic sedimentary rocks which have been partly metamorphosed give consistent results indicating an age of 1400-1450 million years (Richards, Cooper, and Webb, 1963). Further east in the Georgetown region near the east coast of Australia large areas of metamorphic rocks are overlain by sedimentary rocks believed to be Proterozoic in age (D. A. White and D. H. Wyatt in Hill and Denmead, 1960). Only one absolute age from these rocks has been recorded, that being a 1044 million year K-Ar age on a granite from the eastern edge of these rocks in the Dargalong Metamorphics, 170 km from the Australian east coast (de Keyser and Wolff, 1964). No other details about the age have been published including the type of mineral analyzed. The sample locality is about six km from a large area of later intrusives documented on stratigraphic and extensive consistent geochronologic grounds as Permian (de Keyser and Wolff, 1964), however, and the 1044 million year age may be a minimum one.

Beneath the Tasman Sea, stretching from northeastern Australia to the South Island of New Zealand, is a complex oceanic structure comprised by the Lord Howe Rise and the Coral Sea Platform. This structure which is continuous with the New Zealand landmass is slightly separated from the Australian continental shelf (Figure 1). It rises from normal deep ocean depths of greater than 4000 meters in the Tasman Sea to the top of the Lord Howe Rise at an average depth of about 1500 meters (Standard, 1961) and to the top of the Coral Sea Platform contoured at an average depth of less than 1000 meters (Menard and S. M. Smith in Menard, 1964). A narrow channel 2500 meters deep separates the Coral Sea Platform from the northern end of the Lord Howe Rise (Standard, 1961) and the Coral Sea Platform is separated from the Australian shelf by a narrow saddle between 2000 and 3000 meters deep as shown by Menard's and Smith's contours (1964).

Surface wave dispersion studies of a New Zealand earthquake recorded in Brisbane, Australia, with a path partly over the normal 5 km oceanic Tasman Sea crust and partly over the southern flank of the Lord Howe Rise indicates that the flank of the rise has a crustal thickness of 20 km (Officer, 1955). The crest of the rise may well be thicker, as pointed out by Officer. Only two islands occur along the Lord Howe Rise, these close together on its southern flank. Both are composed of alkali olivine basalt (Standard, 1961). Several coralline islands dot the Coral Sea Platform, and near-shore islands on the northeastern Australian continental shelf, per se, are composed of metamorphic rocks (Jones and Jones, 1960). The maps of Gutenberg and Richter (1954) designate the Lord Howe Rise and Coral Sea Platform as aseismic areas, as well as the Tasman Basin.

The northern part of the eastern edge of the Australian landmass with its broad shelf leading to this oceanic rise structure contrasts markedly with the middle and southern parts of the eastern edge, where the continent abruptly drops over the space of a few km to normal deep ocean depths in the Tasman Sea. Also somewhat unusual in this northern part of the Australian east coast is the extension of a widespread Precambrian terrain to within nearly 170 km of the east coast. This terrain is separated from the coast by Paleozoic sedimentary rocks of the Tasman Geosyncline and intruding Permian granites. The near-shore islands southeast of the Cape York peninsula have tentatively been classed as Precambrian structural highs in the Tasman Geosyncline because of a relatively high metamorphic rank (Jones and Jones, 1960). However, arguments have been presented for at least some of these occurrences being Paleozoic metamorphic equivalents of some of the Tasman Geosyncline sedimentary rocks (de Keyser, 1965).

Because the Lord Howe Rise--Coral Sea Platform structure displays the above-mentioned unusual, non-oceanic-crustal characters and because, as shown in the present work, it physically connects an extensive terrain of moderately old Precambrian rocks in northeastern Australia with moderately old acidic Precambrian crust in, or in the neighborhood of, New Zealand, it is suggested that it may be comprised, at least in part, by moderately old acidic Precambrian crust and as such constitutes an integral part of an Australian--Lord Howe--New Zealand continent.

Other workers in the past have discussed the extension of the Australian continent to Marshall's "Andesite Line" (Gutenberg and Richter, 1954). Gill (1952, 1958; see Standard, 1961) states that "geologically, New Zealand has been regarded as the eastern edge of a great continent which includes Australia and New Zealand as well as the area between them," and previously had extended this great Austzelandic continent south to Antarctica (1952). The proposal of a Lord Howe Rise--Coral Sea Platform continental link of New Zealand to Australia presented here builds upon the suggestion of Kingma (1959) that the Lord Howe Rise portion may represent a continuation of the northwestern part of the South Island of New Zealand, and later that of Standard (1961) that the Lord Howe Rise portion may be in part as old as Paleozoic in age. Neither of these workers suggested a connection to Australia and Standard (1961) referred to the area between the Lord Howe Rise and the circum-Pacific belt as a unit separated from the Australian continent.

If one looks now east of the New Zealand landmass, it would seem that there is no doubt that the Campbell Plateau -- Chatham Rise, which, like the Lord Howe Rise are continuous with the New Zealand landmass, is a contiguous part of the New Zealand continental crust. Its eastern and southern edges crop out in Chatham Island as greywacke and low grade schist (Boreham, 1959), in Bounty Island as granodiorite (Reed, 1949; Wasserburg, et al., 1963), in Campbell Island as schist (Reed, 1949) and in Auckland Islands as granite (Fleming in Lexique Stratigraphique, 1948). By analogy it would seem that the Lord How Rise may hold a similar relationship to the New Zealand crust on the west. The depth of submergence is greater for the Lord Howe Rise, generally being about 1500 meters as compared to an average depth of only 500 meters for the Campbell Plateau, but this may well be explained as being due to uplift of the eastern side of the Alpine Fault, certainly a major fracture in the earth. Brodie (1958) proposed that the Alpine Fault system and Kermedec Trough displace the southern edge of the Campbell Plateau from the southern edge of the Lord Howe Rise. Brodie proposed that the existence of New Zealand as a landmass may be a function of its being located at the intersection of three structural trends comprised by the Lord Howe Rise, the Campbell Plateau and Chatham Rise and the Kermedec Trough. Perhaps New Zealand, or at least South Island, pokes up as a window of an anomalous landmass along the Lord Howe Rise--Campbell Plateau simply because of uplift along the great fault.

E. Future Work

This proposal of an Australian--New Zealand continental link via the Lord Howe Rise and Coral Sea Platform constitutes a proposed framework for the whole Southwest Pacific crust and suggests a path of future geochronological studies in the region. North of the Coral Sea Platform--Lord Howe Rise ridge system and separated from it by the Norfolk Trough and Coral Sea Basin is a parallel discontinuous ridge system extending from the North Island of New Zealand to the eastern part of New Guinea (see Figure 1). The Norfolk Ridge portion of this system, continuous with the North Island of New Zealand, bridges more than half the distance and crops out as New Caledonia near its northwestern end. A deep trough separates the Norfolk Ridge from a submerged platform in the northern Coral Sea that is joined to the narrow continental shelf extending east from New Guinea (Bathymetric Map in Menard, 1964). Several islands crop out along this shelf and Rennel Island crops out from the northern Coral Sea platform. The North Island of New Zealand is entirely comprised by the Geosynclinal Province, as previously discussed, which in the South Island has undergone regional metamorphism at least in part under high pressure conditions (Landis, personal communication; Miyashiro, 1961), typical of Miyashiro's Pacific-ward belt. Likewise, a belt of geosynclinal sedimentary rocks occurs in New Caledonia (Piroutet, 1917-see Benson, 1927; Avias and Routhier, 1962), metamorphosed to glaucophane facies and a belt of geosynclinal sedimentary rocks also occurs in northeastern New Guinea, that has undergone regional metamorphism with the probable development of glaucophane (Smith and Green, 1961). In both of these latter areas continuous belts of peridotite occur (for New Guinea, see Dow and Davies, 1964; Smith and Greene, 1961) similar to the occurrences of peridotite belts in the Geosynclinal Province of New Zealand. The age assignments to the regional high pressure metamorphism and peridotite emplacement in New Caledonia and New Guinea are not certain, as indeed is still the situation with the New Zealand peridotites and Marginal Zone plutonic rocks. It seems as if the peridotite emplacements in New Caledonia may be as young as Tertiary (Avias and Routhier, 1962). Dow and Davies (1964) cite the lack of limiting evidence for the age of Papuan Ultrabasic Belt. A Tertiary age has been given for some serpentine pods in the North Island of New Zealand

Hess and Maxwell (1949) have proposed that the North Island of New Zealand, New Caledonia, and New Guinea are parts of a single orogenic belt. It is important to justify whether this extension of the New Zealand Geosynclinal Province is warranted by further geological and geochronological work in these areas. If a continuous orogenic belt can be justified by a systematic age pattern, determined both geochronologically and geologically, then the regularities of the circum-Pacific Late Mesozoic orogenies (Miyashiro, 1961) predict a coeval inner belt of plutonism and low pressure regional metamorphism as is shown in this paper to occur in the Foreland Province in New Zealand. This inner belt should be sought in southeastern New Guinea and possibly in the future along the Lord Howe Rise and Coral Sea Platform by deep drilling. Also, in light of the geochronological results presented in this paper, it is evident that the inner belt (the Foreland Province) at least in New Zealand, includes plutonic and metamorphic rocks of Devonian and of moderately old Precambrian age. The author has predicted, largely on the basis of the Greenland Series zircons, that the Lord Howe Rise--Coral Sea Platform is a submerged continental link of New Zealand to Australia and comprised, at least in part, of Precambrian acidic plutonic rocks. It is of much importance that evidence of this inner belt crystalline basement be sought by analyzing detrital zircons in the Mesozoic sedimentary rocks in New Caledonia.

An apparent obstacle to projecting Precambrian continental crust continuously from Australia to New Zealand arises along the northeast coast of Australia itself. As mentioned, the known Precambrian of the Australian Georgetown area extends close to the east coast, but is actually separated from the coast by a major Paleozoic geosyncline trending parallel to the coast, the Tasman Geosyncline. However, several areas of metamorphic and plutonic rocks do occur in the coastal islands east of the York Peninsula and along the central part of the peninsula. These have been tentatively regarded as Precambrian in age on generally minimal evidence, and de Keyser (1965) has argued for a Paleozoic age for the metamorphic rocks on many of the islands. It is important to geochronologically document the ages of all of these Australian east coast crystalline rocks to determine whether or not Precambrian crust, in fact, extends within and beyond the Tasman Geosyncline.

In New Zealand itself this work suggests combined geochronological and geological studies that should be done in several areas. Of foremost interest are the following:

(1) The possibility of regional metamorphism during the Devonian as well as in the Cretaceous in the northern part of the North Foreland Block should be investigated.

(2) This work suggests that the Middle Belt of plutonic rocks (the Karamea Belt) in the North Block contains both age groups. The relationship between these two should be sought in the field and confirmed by geochronological work. It would be interesting to determine whether or not a "Charleston Gneiss type" boundary zone exists in this belt as it does in the Western Belt (Paparoa).

(3) It is important to further define the time relationship between the spatially separated Rameka Basic Intrusives and the 345-370 million year acidic plutonic rocks of the North Block.

(4) Whether or not the Precambrian source which supplied the Greenland Series zircons was extensive, should be further tested by examining zircons from more widespread samples of this unit. Less metamorphosed samples of this unit may yield zircons with less disturbed U, Th-Pb systems and permit better estimates of their true age. Possible in situ Precambrian basement for the Greenland Series should be sought in the field, possibly in the very southern part of the North Block (South Westland).

(5) Zircons should be examined from several Cretaceous plutonic rocks to confirm their age. A whole rock study of cogenetic samples of the Pomona granite, shown to have a fairly high Rb/Sr ratio, should be performed.

(6) The age of the rocks in the Campbell and Auckland Islands should be measured to possibly determine the relationship of the southern Campbell Plateau to the South Block of the Foreland Province.

(7) The South Block of the Foreland Province should be more thoroughly investigated, geologically and geochronologically for possible existence of 345-370 million year crystalline rocks.

(8) The plutonic rocks of the Marginal Zone of the Geosynclinal Province should be further investigated, including rocks from that part of the zone north of the Alpine Fault. Other phases from these rocks, in addition to biotite, like hornblende and zircon, should be analyzed. Some attempt should be made to date basic rocks directly associated with the ultrabasic rocks of the Marginal Zone of the very northern part of North Island.

(9) The nature of the source area of the New Zealand Geosyncline, a typical circum-Pacific late Mesozoic geosyncline, should be sought by further examining the plutonic boulders, both geochronologically and petrologically, deposited extensively in the Triassic conglomerates of the Marginal Zone of the Geosyncline. Detrital zircons in the geosynclinal sediments will provide important evidence of the age of the source of these sediments and may indicate whether the Precambrian source of the Greenland Series was still significantly exposed during the life of the Geosyncline.

(10) More detailed work is necessary to date the metamorphism of the Otago Schists more precisely than was done here, in order to determine the exact time relation of the regional metamorphism in the Geosynclinal Province to the plutonic activity in the Foreland Province. This work will certainly involve K-Ar measurements, and is necessary to provide the detailed temporal framework necessary for understanding a type "circum-Pacific orogeny."

(11) Basic and acidic volcanic activity in large quantities immediately postdated the Rangitata Orogeny in the Geosynclinal Province (Inland Kaikouras, Malvern Hills and Mount Somers). The time relationship of this activity to the plutonic activity in the Foreland Province should be determined by dating these volcanics.

LIST OF REFERENCES

Adams, R. D. (1962) "Thickness of the earth's crust beneath the Campbell Pleateau," New Zealand Jour. Geology and Geophysics, 5, pp. 74-85.

Allan, R. S. (1947) "A revision of the Brachiopoda of the Lower Devonian strata of Reefton, New Zealand," J. Paleont., 21, pp. 436-452.

Avias, Jacques and Routhier, Pierre (1962) Notice Explicative, Feuille no. 5, Carte Geologique de la Nouvelle Caledonia, Paris.

Banks, P. O. (1963) Some Systematics of Uranium and Lead Distribution in Relation to the Petrology of the Mt. Rubidoux Granites, Riverside County, California, unpublished thesis, Div. of Geol. Sci., Calif., Inst. of Tech.

Benson, W. N. (1927) "The tectonic conditions accompanying the intrusion of basic and ultrabasic igneous rocks," Natl. Acad. Sci. 19, pp. 1-90.

Benson, W. N., J. A. Bartum, and L. C. King (1934) "The geology of the region about Preservation Inlet, Southern Fiordland, New Zealand. Part II," Trans. Roy. Soc. N. Z. 64, pp. 51-85.

Boreham, Anne U. E. (1959) "Cretaceous fossils from the Chatham Islands," Roy. Soc. New Zealand Trans. 86, pp. 119-125.

Bottino, M. L., C. C. Schnetzler, and P. D. Fullagar (1965) "Rb-Sr whole-rock age of the Traveler and Kineo rhyolites, Maine, and its bearing on the duration of the Early Devonian," Meetings of Geol. Soc. America.

Boucot, A. J., K. E. Caster, D. Ives and J. A. Talent (1963) "Relationships of a new Lower Devonian Terebratuloid (Brachiopoda) from Antarctica," Bull. Amer. Paleont. 46, pp. 81-151.

Bowen, F. E. (1964) Sheet 15-Buller, Geological Map of New Zealand, 1 : 250,000, Dep. Sci. Indust. Res., Wellington.

Brodie, J. W. (1958) "Structural significance of sea-floor features around New Zealand," Geol. Rundsch. 47, pp. 662-667.

Brown, E. H. (1963) "The geology of the Mt. Stoker area, eastern Otago," N. Z. J. Geol. Geophys. 6, pp. 847-71.

Catanzaro, E. J. and P. W. Gast (1960) "Isotopic composition of lead in pegmatitic feldspars," Geochim. et Cosmoschim. Acta 19, pp. 113-126.

Chow, T. J. and C. R. McKinney (1956) "Mass spectrometric determination of lead in manganese nodules," Analytical Chem. 30, pp. 1499-1503.

Chow, T. J. and C. C. Patterson (1962) "The occurrence and significance of lead isotopes in pelagic sediments," Geochim et Cosmoschim Acta 26, pp. 263-290.

Coombs, D. S. (1954) "The nature and alteration of some Triassic sediments from Southland, New Zealand," Trans. Roy. Soc. N. Z. 82, pp. 65-109.

Coombs, D. S., A. J. Ellis, W. S. Fyfe, and A. M. Taylor (1959) "The zeolite facies, with comments on the interpretation of hydrothermal syntheses," Geochimica et Cosmochimica Acta 17, pp. 53-107.

Cooper, R. A. (1965) "Lower paleozoic rocks between Upper Takaka and Riwaka, North-west Nelson," N. Z. J. Geol. Geophys. 8, pp. 49-61.

Couper, R. A. (1953) "Upper mesozoic and cainozoic spores and pollen grains from New Zealand," N. Z. Geol. Surv. Pal. Bull. 22.

Couper, R. A. (1960) "New Zealand Mesozoic and Cainozoic Plant Microfossils," N. Z. Geol. Surv. Pal. Bull. 32.

Crook, K. A. W. (1963) "Burial metamorphic rocks from Fiji," N. Z. J. Geol. Geophys. 6, pp. 681-704.

de Keyser, F. (1965) "The Barnard Metamorphics and their relation to the Barron River Metamorphics and the Hodgkinson Formation, North Queensland," J. Geol. Soc. Aust. 12, pp. 91-103.

de Keyser, F. and K. W. Wolff (1964) "The geology and mineral resources of the Chillagoe Area, Queensland," Bur. Min. Resour. Aust. Rep. 70, pp. 1-136.

Dow, E. B. and H. L. Davies (1964) "The geology of the Bowutu Mountains, New Guinea," *Bur. Min. Resour. Aust. Rep.* 75, pp. 1-31.

Eiby, G. A. (1957) "Crustal structure project. The Wellington profile," *N. Z. Dep. Sci. Industr. Res. Geophys. Mem.* 5.

Evernden, J. F. and J. R. Richards (1962) "Potassium-argon ages in eastern Australia," *J. Geol. Soc. Aust.* 9, pp. 1-50.

Finlayson, A. M. (1908) "Some observations on the schists of central Otago," *Trans. N. Z. Inst.* 40, pp. 72-79.

Fleming, C. A. (1958) editor, "Lexique Stratigraphique International, Oceanie," 6.

Fleming, C. A. (1958) "Upper Jurassic fossils and hydrocarbon traces from the Cheviot Hills, North Canterbury," *N. Z. J. Geol. Geophys.* 1, pp. 375-94.

Folinsbee, R. E., H. Baadsgaard and J. Lipson (1961) "Potassium-argon dates of Upper Cretaceous ash falls, Alberta, Canada," *New York Acad. Sciences Annals.* 91, pp. 352-363.

Fraser, C. (1907) "The Geology of the Coromandel Subdivision, Hauraki, Auckland," *N. Z. Geol. Surv. Bull.* 4 (n. s.), pp. 1-154.

Gage, M. (1952) "The geology of the Greymouth Coalfield," *N. Z. Geol. Surv. Bull.* 55 (n. s.).

Gill, E. D. (1952) "Paleogeography of the Australian-New Zealand region in Low Devonian time," *Trans. Roy. Soc. N. Z.* 80, pp. 171-185.

Gill, E. D. (1958) "Australian Lower Devonian paleobiology in relationship to the concept of continental drift": Continental Drift--a symposium, Geology Dept. Univ. Tasmania, 375 p.

Grindley, G. W. (1958) "The geology of the Eglinton Valley, Southland," *N. Z. Geol. Surv. Bull. 58 (n. s.)*.

Grindley, G. W. (1960) Sheet 8--Taupo. Geological Map of New Zealand, 1 : 250,000, Dep. Sci. Indust. Res., Wellington.

Grindley, G. W. (1961) Sheet 13--Golden Bay. Geological Map of New Zealand, 1 : 250,000, Dep. Sci. Indust. Res., Wellington.

Grindley, G. W. (1963) "Structure of the Alpine Schists of South Westland, Southern Alps, New Zealand," N. Z. J. Geol. Geophys. 6, pp. 872--930.

Grindley, G. W., H. J. Harrington, and B. L. Wood (1959) "The geological map of New Zealand," N. Z. Geol. Surv. Bull. 66 (n. s.).

Guttenberg, B. and C. F. Richter (1954) Seismicity of the Earth and Associated Phenomena: 2d. ed., Princeton Univ. Press, 273 p.

Harrington, J. J. (1955) "The geology of the Naseby district Central Otago," N. Z. Journ. Sci. Tech. 36, pp. 581-99.

Harrington, J. J. and I. C. McKellar (1956) "A preliminary account of layering in gabbroic rocks at Bluff Peninsula, Southland," N. Z. J. Sci. Tech. 38B, pp. 103-8.

Harrington, H. J. (1958) in "Lexique Stratigraphique International," ed. C. A. Fleming 6, pp. 185-186.

Hall, W. D. M. (1963) "The Clarence Series at Coverham, Clarence Valley," N. Z. J. Geol. Geophys. 6, pp. 28-37.

Healy, J. (1938) "The geology of the coastal strip from Big Bay to Professor Creek, Northwest Otago, N. Z. J. Sci. Tech. B. 20, pp. 80-94.

Henderson, J. (1917) "The geology and mineral resources of the Reefton Subdivision, Westport and North Westland divisions," N. Z. Geol. Surv. Bull. 18 (n. s.).

Henderson, J., L. I. Grange, and E. O. Macpherson (1959) "The geology of Motucka Subdivision," N. Z. Geol. Surv. Bull. 35.

Hess, H. H. (1955) "Serpentine, orogeny and epeirogeny, Geol. Soc. America Special Paper 62, pp. 391-407.

Hess, H. H. and J. C. Maxwell (1949) "Major structural features of the Southwest Pacific, 7th Pacific Science Congress Proceedings 2, pp. 14-17.

Hill, D. (1956) "The Devonian corals of Reefton. Part I of paleozoic corals from New Zealand," N. Z. Geol. Surv. Pal. Bull. 25, pp. 5-14.

Holmes, Arthur (1960) "A revised geological time-scale," Trans. Edinburgh Geol. Soc. 17, pp. 183-216.

Hurley, P. M., H. Hughes, W. H. Pinson, Jr., H. W. Fairbairn (1962) "Radiogenic argon and strontium diffusion parameters in biotite at low temperatures obtained from Alpine Fault uplift in New Zealand," Geochim. Cosmochim. Acta 26, pp. 67-81.

Hutton, C. O. (1940) "Metamorphism in the Lake Wakatipu Region, Western Otago, New Zealand," N. Z. Dep. Sci. Industr. Res. Geol. Mem. 5.

Hutton, C. O. (1950) "Studies of heavy detrital minerals," Bull. Geol. Soc. Amer. 61, pp. 635-716.

Hutton, C. O. (1951) "Allanite from Wilmot Pass, Fiordland, New Zealand," Amer. J. Sci. 249, pp. 208-214.

Jahns, R. H. (1954) "Geology of the Peninsular Range Province, Southern California and Baja California," Geology of Southern California Bull. 170, vol. 1, Dept. of Natural Resources, pp. 29-52.

Jensen, H. I. (1960) "Cape York Peninsula," J. Geol. Soc. Aust. 7, pp. 77-78.

Jones, O. A. and J. B. Jones (1960) "The coastal islands and adjacent coastal strip," J. Geol. Soc. Aust. 7, pp. 78-79.

Kingma, J. T. (1959) "The tectonic history of New Zealand," N. Z. J. Geol. Geophys. 2, pp. 1-55.

Kulp, J. L. (1961) "Geologic time scale," Science 133, pp. 1105-14.

Laird, M. G. (in press) "The field relations of Constant Gneiss and Greenland Group in the central Paparoa Range, West Coast, South Island," N. Z. J. Geol. Geophys. 8, pp. 3-34.

Lillie, A. R., B. M. Gunn, and P. Robinson (1957) "Structural observations in central Alpine region of New Zealand," Trans. Roy. Soc. N. Z. 85, pp. 113-29.

Lillie, A. R. (1958) in Lexique Stratigraphique International," ed. C. A. Fleming, 6, pp. 122-123.

Mason, Brian (1961a) "Some analyzed rocks from Westland, New Zealand," *N. Z. J. Geol. Geophys.* 4, pp. 347-51.

Mason, Brian (1961b) "Potassium-argon ages of metamorphic rocks and granites from Westland, New Zealand," *N. Z. J. Geol. Geophys.* 4, pp. 352-6.

Mason, Brian (1962) "Metamorphism in the Southern Alps of New Zealand," *Bull. Amer. Mus. Nat. Hist.* 123, pp. 211-48.

McDougall, I., P. R. Dunn, W. Compston, A. W. Webb, J. R. Richards and V. M. Bofinger (1965) "Isotopic age determinations on Precambrian rocks of the Carpentaria Region, Northern Territory, Australia," *J. Geol. Soc. Aust.* 12, pp. 67-90.

McDougall, I. and P. J. Leggo (1965) "Isotopic age determinations on granitic rocks from Tasmania," *J. Geol. Soc. Aust.* 12, pp. 295-332.

McKellar, I. C., A. R. Mutch, and G. R. Stevens (1962) "An upper Jurassic outline in the Pyke Valley, North-west Otago, and a note on upper Jurassic belemnites in the South Island," *N. Z. J. Geol. Geophys.* 5, pp. 487-92.

Means, W. D. (1963) "Mesoscopic structures and multiple deformation in the Otago Schists," *N. Z. J. Geol. Geophys.* 6, pp. 801-16.

Menard, H. W. (1964) Marine Geology of the Pacific, New York, McGraw-Hill, 271 p.

Miyashiro, A. (1961) "Evolution of Metamorphic Belts," *J. Petrol.* 2, pp. 277-311.

Morgan, P. G. (1908) "The geology of the Mikonui Subdivision, North Westland," *N. Z. Geol. Surv. Bull.* n. s. 6.

Morgan, P. G. and J. Bartrum (1915) "The geology and mineral resources of the Buller-Mokihinui Subdivision, Westport Division," *N. Z. Geol. Surv. Bull.* 17.

Murthy, V. Rama, and C. C. Patterson (1962) "Primary isochron of zero age for meteorites and the earth," *J. Geophys. Research* 67, pp. 1161-1167.

Mutch, A. R. (1957) "Facies and thickness of the upper paleozoic and Triassic sediments of Southland," Trans. Roy. Soc. N. Z. 84, pp. 499-511.

Mutch, A. R. (1963) Sheet 23--Oamaru. Geological Map of New Zealand, 1 : 250,000, Dep. Sci. Indust. Res., Wellington.

Nier, A. O. (1938) "Isotopic Constitution of Strontium, Barium, Bismuth, Thallium, and Mercury," 54, pp. 275-278.

Norris, G. (in press) "Plant microfossils from the Hawks Crag breccia, south-west Nelson, New Zealand," N. Z. J. Geol. Geophys.

Officer, C. B. (1955) "Southwest Pacific crustal structures," Am. Geophys. Union Trans. 36, pp. 449-459.

Park, J. (1921) "The geology and mineral resources of western Southland," N. Z. Geol. Surv. Bull. 23.

Patterson, C. and M. Tatsumoto (1964) "The significance of lead isotopes in detrital feldspar with respect to chemical differentiation within the earth's mantle," Geochimica et Cosmochimica Acta 28, pp. 1-22.

Piroutet, M. (1917) Etude Stratigraphique sur la Nouvelle Caledonie, Macon, 1917.

Reed, J. J. (1957) "Petrology of the Lower Mesozoic rocks of the Wellington district," N. Z. Geol. Surv. Bull. 57.

Reed, J. J. (1958) "Granites and mineralization in New Zealand," N. Z. J. Geol. Geophys. 1, pp. 47-64.

Reed, F. R. (1949) "Geology of the British Empire," London, Edward Arnold.

Reilly, W. I. (1962) "Gravity and crustal thickness in New Zealand," N. Z. J. Geol. Geophys. 5, pp. 228-33.

Richards, J. R., J. A. Couper, and A. W. Webb (1963) "Potassium-argon ages on micas from the precambrian region of north-western Queensland," J. Geol. Soc. Aust. 10, pp. 299-312.

Robertson, E. I. and W. I. Reilly (1958) "Bouguer anomaly map of New Zealand," N. Z. J. Geol. Geophys. 1, pp. 560-4.

Service, H. (1937) "An intrusion of norite and its accompanying contact metamorphism at Bluff, New Zealand," Trans. Roy. Soc. N. Z. 67, pp. 185-217.

Shirley, J. (1938) "The fauna of the Baton River Beds (Devonian) New Zealand," Quart. J. Geol. Soc. Lond. 94, pp. 459-506.

Silver, L. T., and Sara Deutsch (1963) "Uranium-lead isotopic variations in zircons: a case study," New York Acad. Sciences Annals. 71, pp. 721-758.

Silver, L. T., and C. R. McKinney (1962) "U-Pb isotopic age studies of a Precambrian granite, Marble Mountains, San Bernardino County, California," Geol. Soc. America Special Paper 73, p. 65.

Silver, L. T., F. G. Stehli, and C. R. Allen (1963) "Lower Cretaceous Pre-Batholithic rocks of northern Baja California, Mexico," Bull. Amer. Assoc. Petroleum Geologists 47, pp. 2054-2059.

Smith, D. G. W., H. Baadsgaard, R. Folinsbee, and J. Lipson (1961) "K-Ar age of Lower Devonian bentonites of Gaspe, Quebec, Canada," Bull. Geol. Soc. Amer. 22, pp. 171-173.

Smith, J. W., and D. H. Green, "The geology of the Musa River area, Papua," Bur. Min. Resour. Aust. Rep. 52, pp. 1-41.

Speight, R. (1928) "The geology of the Malvern Hills," N. Z. Dep. Sci. Ind. Res. Geol. Mem. 1.

Speight, R. (1938) "The geology of the Mount Somers District," N. Z. Dep. Sci. Ind. Res. Geol. Mem. 3.

Standard, J. C. (1961) "Submarine geology of the Tasman Sea," Geol. Soc. America Bull. 72, pp. 1777-1788.

Suggate, R. P. (1957) "The geology of the Reefton Subdivision," N. Z. Geol. Surv. Bull. 65.

Suggate, R. P. (1958a) "The geology of the Clarence Valley from Gore Stream to Bluff Hill," Trans. Roy. Soc. N. Z. 85, pp. 397-408.

Suggate, R. P. (1958b) in "Lexique Stratigraphique International, 6, pp. 350-351.

Suggate, R. P. (1963) "The Alpine Fault," Trans. Roy. Soc. N. Z. Geol. 2, pp. 105-29.

Thompson, B. N. (1960) Sheet 2B--Barrier. Geological Map of New Zealand, 1 : 250,000, Dep. Sci. Indust. Res. Wellington.

Thomson, A. A., and F. F. Evison (1962) "Thickness of the earth's crust in New Zealand," N. Z. J. Geol. and Geophys. 5, pp. 29-45.

Turner, F. J. (1930) "The metamorphic and ultrabasic rocks of the lower Cascade Valley, South Westland," Trans. N. Z. Inst. 61, pp. 170-201.

Turner, F. J. (1933) "The metamorphic and intrusive rocks of southern Westland," Trans. N. Z. Inst. 63, pp. 178-284.

Turner, F. J. (1937) "The metamorphic and plutonic rocks of Lake Manapouri, Fiordland, New Zealand," Trans. Roy. Soc. N. Z. 67, pp. 83-100; 227-49.

Turner, F. J. (1948) "Mineralogical and structural evolution of the metamorphic rocks," Mem. Geol. Soc. Amer. 30.

Vella, Paul (1961) "An occurrence of an Albian ammonite in the motuan stage in the upper Awateri Valley," Trans. Roy. Soc. N. Z. 1, pp. 1-4.

Wasserburg, G. J., H. Craig, H. W. Menard, A. E. J. Engel, and Celeste G. Engel (1963) "Age and composition of a Bounty Islands granite and age of a Seychelles Islands granite," Jour. Geol. 71, pp. 785-789.

Wasserburg, G. J., T. Wen, and J. Aronson (1964) "Strontium contamination in mineral analyses," Geochim. Cosmochim. Acta 28, pp. 407-10.

Waterhouse, J. B. (1958) "The age of the Takitimu Group of western Southland," N. Z. J. Geol. Geophys. 1, pp. 604-11.

Waterhouse, J. B. (1964) "Permian stratigraphy and faunas of New Zealand," N. Z. Geol. Surv. Bull. n. s. 72.

Waterhouse, J. B. and Paul Vella (1965) "A Permian fauna from north-west Nelson, New Zealand," Trans. Roy. Soc. N. Z. Geol. pp. 57-84.

Watters, W. A. (1959) "An association of hornblende and cummingtonite from Ringarina, Stewart Island, New Zealand, N. Z. J. Geol. Geophys. 2, pp. 248-256.

Wellman, H. W. (1955a) "A Revision of the type Clarentian Section at Coverham, Clarence Valley," Trans. Roy. Soc. N. Z. 83, pp. 93-118.

Wellman, H. W. (1955b) "The geology between Bruce Bay and Haast River, South Westland, N. Z. Geol. Surv. Bull. 48.

Wellman, H. W. (1956) "Structural Outline of New Zealand," N. Z. Dep. Sci. Industr. Res. Bull. 121.

Wellman, H. W. (1959) "Divisions of the New Zealand Cretaceous," Trans. Roy. Soc. N. Z. 87, pp. 99-163.

White, D. A., and D. H. Wyatt (1960) "Etheridge-Einasleigh-Cardoss area, J. Geol. Soc. Aust. 7, pp. 62-74.

Williams, G. (1934) "A granite-schist contact in Stewart Island," Quart. J. Geol. Soc. Lond. 90, pp. 322-51.

Willis, I. (1965) "Stratigraphy and structure of the devonian strata at Baton River, New Zealand," N. Z. J. Geol. Geophys. 8, pp. 35-48.

Wood, B. L. (1956) "The geology of the Gore Subdivision," N. Z. Geol. Surv. Bull. 53.

Wood, B. L. (1960) Sheet 27--Fiord. Geological Map of New Zealand, 1 : 250,000 Dep. Sci. Indust. Res., Wellington.

Wood, B. L. (1962) Sheet 22--Wakatipu (1st Ed.). Geological Map of New Zealand, 1 : 250,000, Dep. Sci. Indust. Res., Wellington.

Wood, B. L. (1963) "Structure of the Otago Schists," N. Z. J. Geol. Geophys. 6, pp. 641-80.

Wood, B. L. (1963) "Structure of the Otago Schists," N. Z. J. Geol. Geophys. 6, pp. 641-80.

Woolard, G. P., and W. E. Strange (1962) "Gravity anomalies and the crust of the earth in the Pacific Basin," The Crust of the Pacific Basin: Geophysical Monograph no. 6, American Geophysical Union, pp. 60-80.

Zartman, R. (1964) "A geochronological study of the Lone Grove Pluton from the Llano Uplift, Texas," J. Petrol. 5, pp. 359-409.

APPENDIX

I. SAMPLE PROCESSING.

Minerals were separated from crushed rock samples by standard techniques using heavy liquids and a Frantz isodynamic magnetic separator. Pegmatite minerals were hand-picked. Mineral purity in the former case was assessed for all minerals except feldspars by eye under a binocular microscope as being greater than about 95% pure. Grain mounts of some potassium feldspar separates were shown by staining to be comprised by greater than 99% potassium feldspar grains but intergrown perthitic plagioclase as indicated by X-ray diffraction was always present. That feldspar-quartz fraction which gave the optimum compromise of maximum strontium content and minimum Rb/Sr ratio by X-ray fluorescence was usually taken as a sufficient plagioclase separate and only occasionally further verified by index oils. All binary biotite and muscovite impurity in the feldspars was removed by slow runs through the Frantz at minimum side tilt and maximum amperage. All mineral separates were thoroughly rinsed in reagent-grade acetone.

Total rock aliquots were selected from large volumes of crushed sample which generally weighed from 10-40 kg. The ground rock was well mixed by hand. In the beginning of the study aliquots of the total rock were selected by using joint-free sample splitters. Later it was shown that simple grabbing of numerous random spatula-fulls of mixed rock powder produced just as representative samples.

II. EXPERIMENTAL PROCEDURES.

A. Rubidium and Strontium.

The rubidium and strontium analytical procedure is essentially the basic isotope dilution procedures currently used in several laboratories, and described by Lanphere (1963). A brief description will suffice here.

Dissolution of silicate samples with HF and $HClO_4$ was followed by complete solution in HCl except for zircon residues in some biotites and in all total rocks. At an early stage in this work it was realized in collaboration with G. J. Wasserburg and T. Wen that use of low-strontium laboratory glassware contributed significant amounts of strontium contamination (Wasserburg, Wen, and Aronson, 1964). It is felt that this possible contamination did not alter significantly the ages of the samples so processed (ASH, SITR, 22, 4, and parts of 18(+), 6, and 48), and in all subsequent work teflon vessels were used in the post-dissolution, pre-ion exchange column steps. Dissolved samples were thoroughly mixed and aliquoted by weighing into a rubidium concentration aliquot, a strontium concentration aliquot and, for most lowly-radiogenic strontium samples, a strontium isotopic composition aliquot. Weighed amounts of calibrated Rb^{87} enriched tracer and Sr^{86} or Sr^{84} enriched tracer were added to their respective aliquots. The mixtures were then thoroughly mixed by vigorous stirring.

Samples were evaporated dry under heat lamps. The rubidium concentration was washed with two drops of water and the remaining undissolved perchlorate crystals were ready for the mass spectrometer run. A few rubidium samples were completely dissolved in 2 ml of 1% hydrochloric acid and K and Rb were precipitated with sodium tetraphenyl borate. This precipitate was converted to perchlorates and then to sulfates by addition and evaporation of perchloric and sulfuric acid, respectively. The sulfates were run in the mass spectrometer.

The strontium aliquots were picked up in 2.5N HCl and loaded on conditioned Dowex 50 columns 15-20 cm in length and 1 cm in diameter. The strontium aliquots were collected in glass beakers, evaporated dry, and loaded on a filament for the mass spectrometer.

The Rb^{87} tracer contained rubidium that was 99.2% Rb^{87}. The Sr^{86} tracer, used in the early stages of this work (see samples listed with glassware, above), was about 84% pure. The Sr^{84} tracer was used for all other samples. This "single" isotope tracer of about 83% purity enables the determination of discrimination-corrected isotopic compositions during the spiked run. Details of the discrimination calculation are contained in a later section of this appendix. The tracers were calibrated regularly against normals carefully prepared by the author from "spec-pure" $SrCO_3$ and RbCl supplied by Johnson and Matthey, Ltd. of England. A slow drift toward an 0.6% increase in concentration in the Sr^{84} tracer was noted over a 2.5 year period of constant use. No drift toward increased concentration was observable in the Rb^{87} tracer over a 3 year period of constant use. This is probably only due to a lack of precision in the measurement of rubidium concentration as explained below.

All mass spectrometer runs were made on the same 12-inch radius of curvature, 60° sector, single focusing, solid source mass spectrometer described by Chow and McKinney (1956). The ion beam was accelerated by a 5 kilovolt potential. A ten stage electron multiplier received the ion current and the resulting current was passed through a $2 \cdot 10^9$ resistor and a vibrating reed electrometer. All samples were run on single outgassed tantalum filaments.

Blanks were processed regularly during the course of this study. These indicate a strontium contamination which averages 0.012 μ gm per gram of sample processed and ranged from 0.007 μ gm/gm to 0.021 μgm/gm. The rubidium blank ranged from 0.0005 μ gm/gm to 0.006 μ gm/gm.

B. Lead, Uranium and Thorium.

Zircon separates were carefully purified by several passes through 3.30 S.G. methylene iodide, discarding the floats. Visual inspection of grain mounts and X-ray diffraction analysis showed no impurity, other than pyrite. The zircons were washed in 1-1 hot nitric acid until all pyrite was dissolved, and then rinsed several times with pure water. About 0.5-0.6 grams were fused in ten times their weight of purified borax. The entire fusion was generally complete within one hour at temperatures monitored by an optical pyrometer as between 930° C -1000°C. Continuous agitation apparently eased the fusion.

The fused zircon was transferred completely with hydrochloric acid and dissolved in 250-500 ml of hydrochloric acid. Small amounts of flaky insoluble residue were centrifuged down, transferred to a teflon vessel and treated with HF and $HClO_4$, dissolved in hydrochloric acid, and returned to the main solution. The solution was partitioned by either weighing or volume into two parts, one containing about 90% for the lead composition run and the other 10% for the lead, uranium, and thorium concentration run. The lead, uranium, and thorium were coprecipitated with $Zr(OH)_4$ by passing NH_3 gas through the solution. The precipitate was dissolved in hydrochloric acid and the final normality was 1.2N-1.5N. This solution was loaded on a 17 x 1 cm Dowex 100-200 mesh anion exchange column. Lead was retained on the column during the loading and subsequent washing of the column by 1.2N hydrochloric acid, while zirconium, uranium, and thorium and most other elements were eluted. This eluate was collected from the spiked concentration aliquot for subsequent treatment for uranium and thorium. The lead was eluted with water and collected. The lead was further purified by standard dithizone procedures extracting in chloroform from a pH 9, cyanide-citrate solution, and back-extracting into dilute nitric acid. The latter, containing ionic lead, was evaporated dry, picked up in 2% NH_4NO_3 and lead precipitated with H_2S gas. The sulfide was loaded on a rhenium single outgassed filament and run in the U.S.G.S. solid source mass spectrometers with simple collectors in Denver or in the C.I.T. machine on a tantalum filament with electron multiplier.

Lead from feldspars was extracted similarly, only the feldspar was more easily dissolved using standard treatment by HF and $HClO_4$.

The eluate containing the spiked uranium and thorium was again coprecipitated with $Zr(OH)_4$. This was dissolved in 6N nitric acid and loaded on a new Dowex 17 x 1cm Dowex anion exchange column, previously conditioned with nitric acid. The sample-loaded column was washed with 6N nitric acid. Uranium was eluted with water,and thorium with 6N hydrochloric acid into the same catch beaker. The solution was evaporated to near dryness, picked up in 6N HNO_3, and the above column procedure was repeated using a smaller 17 x 0.6 cm column. The uranium and thorium in the final evaporation were picked up in nitric acid and loaded on two side filaments of a triple filament source.

At the U.S.G.S. the average lead blank incurred in separating lead from feldspar is about 0.1 gm or less. A blank run by Bruce Doe on the borax used for the fusion of zircons from samples 22(+) and 6 produced 0.54 gm of lead per gram of flux. However, a total common lead concentration one-half this value was observed for one borax fusion which included 0.5 gm of zircon sample in addition to the borax. At the California Institute of Technology, the blank on borax used for zircon from sample 18(+) was 0.065 ppm.

III. PRECISION AND ACCURACY OF RUBIDIUM-STRONTIUM AGES.

The rubidium-strontium age equation is

$$T = \frac{1}{\lambda} \ln \left\{ 1 + \frac{Sr^{86}}{Rb^{87}} \left[\left(\frac{Sr^{87}}{Sr^{86}} \right)_{today} - \left(\frac{Sr^{87}}{Sr^{86}} \right)_{initial} \right] \right\}$$

The precision of an age measurement varies from sample to sample because the uncertainty in the term $\left[\left(\frac{Sr^{87}}{Sr^{86}} \right)_{today} - \left(\frac{Sr^{87}}{Sr^{86}} \right)_{initial} \right]$, which measures how radiogenic sample strontium is, varies depending on how large the term is. The relative error in measuring a single Sr^{87}/Sr^{86} is suggested by a very low mean deviation of ± 0.10% obtained during this work for nine independent runs of a strontium composition standard. The mean deviation obtained for these independent runs is about equal to the average mean deviation obtained within a single run in which 10 to 20 sets of ratios are normally taken at the same filament temperature. The standard is Johnson and Matthey "spec-pure" strontium dissolved as the normal shelf solutions. Two composition runs on this sample were made and the composition was calculated in seven separate calibrations of the Sr^{84} tracer by the normals. These results are shown in Table 1A. In addition, the M.I.T. interlaboratory standard was run once. T. Wen made several analyses of strontium separated from a mid-ocean seawater sample during the latter portion of this study. These results are also shown in Table 1A. The results of the numerous runs on Johnson and Matthey strontium indicate the high precision with which the isotopic composition of strontium can be measured and calculated. In general, it is felt that strontium separated from most mineral samples gives a more stable, equally intense run in the mass spectrometer than does the purer standard strontium. Hence

TABLE A-1

Isotopic Composition of Strontium Standards on CIT OLD 12" Mass Spectrometer

All data normalized so that Sr^{86}/Sr^{88} = 0.1194

Standard	Sr^{87}/Sr^{86}	Date
$SrCO_3$ Johnson and Matthey	0.7091	2-1963
	0.7091	1-1964
" " "	0.7089[‡]	6-1963
" " "	0.7081[‡]	6-1963
" " "	0.7079[‡]	7-1963
" " "	0.7081[‡]	7-1963
" " "	0.7076[‡]	5-1965
" " "	0.7083[‡]	11-1965
" " "	0.7076[‡]	11-1965
Average of calculated compositions	0.7081 ± .0003[‡]	
M.I.T. Eimer and Amend Sr lot 492327	0.7060	11-1965
Sea Water (analyses by Ted Wen)		
Average of 4 runs	0.7072	4-65—10-65

[‡] Calculated from calibration of Sr^{84} tracer by strontium normal solution.

the uncertainty of measurement of isotopic composition of mineral sample strontium is probably just as low as for the strontium standard. Therefore it is felt that ± 0.25% is a generous estimate of the precision obtainable for the measurement of the isotopic composition of sample strontium.

The composition of the two interlaboratory strontium standards, M.I.T. and Seawater, reported in Table A1, are about 2 parts in 700 lower than the results reported by the M.I.T. laboratory (Faure et al., 1965). The cause for this difference may be due to imperfect resolution because of low vacuum, and to observed saturation of the electron multiplier by intense Sr^{88} beams in the Caltech old mass spectrometer.

It is easily seen that as the $\left(Sr^{87}/Sr^{86}\right)_{today}$ term gets large in comparison to $\left(Sr^{87}/Sr^{86}\right)_{initial}$, the uncertainty in their difference approaches the estimated uncertainty in a single strontium measurement of about 0.25%. Conversely, when their difference is small, this error becomes large. Thus, if the difference is only 30 parts in 700, the estimated uncertainty in their difference is about ± 10%.

The uncertainty in the measurement of Sr^{86}/Rb^{87} is essentially independent of the nature of the sample, being about ± 2%. Most of this is contributed by the Rb^{87} determination. As shown in many calibrations of the Rb^{87} tracer, rubidium contents can not be measured better than about ± 1.5% under mass spectrometer filament conditions more uniform than in sample rubidium runs. On the other hand, regular calibrations of the Sr^{84} tracer indicate that strontium contents can be measured with a precision of about ± 0.3%. This difference in precision of measurement is due to the fact that accurate machine discrimination corrections can be applied for strontium and not for rubidium.

The best idea of precision of age measurement can be had by comparing the results of multiple analyses on the same mineral from the same rock. A standard biotite which was regularly run during the course of the study was a +20 mesh biotite from the Charleston Gneiss. The results of analysis of this biotite, of two other finer-grained biotite separates from this rock, and of a biotite from Llano, Texas analysed several times by Zartman (1964), are shown in Table 2A. Because of its coarse size, the +20 mesh biotite was a poor standard. Included in it was a rich content, and hence probably variable content, of included apatite and zircon crystals, as seen in thin section. Several euhedral zircon crystals always remained after dissolution of this biotite, and these were almost certainly accompanied by apatite, which did dissolve.

Several other minerals were repeated during the study. These results are shown together for comparison in Table 3A. The variation in the ages of the biotites from Doubtful Sound, as discussed in the text, may be due to a post-crystallisation metamorphic disturbance, the effect of which was variable, depending on the grain size of the biotite. The variation reported in the SITR muscovite may result from an incorrect choice of the initial strontium composition, also discussed in the text.

The accuracy of an age analysis is dependent on the accuracy with which the decay constant is known and the accuracy of the tracer concentrations. The rubidium decay constant used in this study is $\lambda = .139 \times 10^{-10}$ year^{-1}. There is probably a 5% uncertainty in this value, but it is the same value used for making the geological time scale of Holmes (1960) and Kulp (1961), and is the value most commonly used in geochronological studies. It is felt that the tracer concentrations are known in an absolute sense to within ± 0.3% for strontium and ± 1.5%

TABLE A-3

Rb-Sr Data for Standard Biotite, 6B(+)20

	Rb^{87} $10^{-8}\ \frac{\text{moles}}{\text{gm.}}$	Sr^{88} $10^{-8}\ \frac{\text{moles}}{\text{gm.}}$	Sr^{87*} $10^{-8}\ \frac{\text{moles}}{\text{gm.}}$	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86}	T million years
No. 1	219.8	6.507	0.3099	282.9	1.111	101
No. 3	218.6	7.064	0.3073	259.2	1.076	101
No. 4	219.3	6.983	0.3112	263.0	1.085	102
No. 5	224.7	6.683	0.3102	281.6	1.100	99
No. 6	221.5	7.242	0.3076	256.1	1.0675	100
Biotite 6A 40/80 (from adjacent sample of same rock)						
No. 1	216.1	6.627	0.3003	273.2	1.095	100
No. 2	227.1	3.516	0.3077	541.0	1.448	97
ZL3 Biotite (Zartman, 1964)						
This paper	265.4	6.575	3.901	338.0	5.676	1050
Zartman (1964)	260.9	6.608	3.895	329.1	5.651	1070

TABLE A-4

Rb-Sr Data for Repeated Analyses

Sample	Rb^{87} 10^{-8} $\frac{\text{moles}}{\text{gm.}}$	Sr^{88} 10^{-8} $\frac{\text{moles}}{\text{gm.}}$	Sr^{87*} 10^{-8} $\frac{\text{moles}}{\text{gm.}}$	$\mathrm{Rb}^{87}/\mathrm{Sr}^{86}$	$\mathrm{Sr}^{87}/\mathrm{Sr}^{86}$	T million years
SITR. musc. 1	339.7	13.27	0.5349	214.4	1.044	113[‡]
SITR. musc. 2	301.3	17.05	0.4950	148.0	0.9491	118[‡]
48. musc. 1	380.4	1.636	0.5527	1935	3.538	105
48. musc. 2	415.2	3.763	0.6194	923.9	2.080	107
48. musc. 3	485.6	0.6153	0.6997	6610	10.226	103.6
2G. musc. 1	126.1	9.827	0.3450	107.47	1.0230	197
2G. musc. 2	125.3	9.859	0.3484	106.47	1.0249	200
41. biotite 1	142.2	10.507	0.3025	113.4	0.9452	153
41. biotite 2	143.0	10.672	0.3022	112.2	0.9411	152
49. biotite 1	237.9	54.37	0.9464	36.64	0.8480	283
49. biotite 2	237.2	56.18	0.9457	35.36	0.8455	288
7. pot. feld.	221.4	70.75	0.3467	26.21	0.7550	113[†]
7. pot. feld.	223.2	79.97	0.3290	23.37	0.7485	106
39. biotite 1	140.7	10.158	0.1846	116.0	0.8572	94
39. biotite 2	144.0	10.065	0.1834	119.8	0.8576	92
39. biotite 3	148.1	8.407	0.1993	147.5	0.9036	97[†]
7. musc. 1	448.0	2.280	0.6904	1645.7	3.5238	110.8
7. musc. 2	468.1	2.144	0.7191	1828.8	3.2503	110.5
22. biotite 1	110.9	39.83	0.1577	23.31	0.736	103
22. biotite 2	110.8	19.01	0.1513	48.84	0.769	101

[‡] Initial $\mathrm{Sr}^{87}/\mathrm{Sr}^{86}$ of this metamorphic rock unknown.

[†] Grain size coarser than that of other separate(s) of same mineral from same rock.

for rubidium. The author's normal solutions of spectroscopically pure salts were cross-checked by isotope dilution against tracers prepared by T. Wen. Mr. Wen had calibrated these tracers with normals of the spectroscopically pure salts, the anion content of which was analytically checked as pure (T. Wen, personal communication).

IV. ISOTOPE DILUTION WITH A Sr^{84} TRACER.

A Sr^{84} tracer was employed in most of the analyses reported in Tables 2, 3, 4, 5, and 6. This tracer has the following composition:

83.48%	Sr^{84}
11.35%	Sr^{88}
3.86%	Sr^{86}
1.31%	Sr^{87}

One can calculate the machine discrimination during a mass spectrometer run of natural strontium that has been spiked with this tracer. Thereby a precise calculation of the Sr^{87}/Sr^{86} in the sample can be made from the concentration run. The results shown in Tables 2, 3, 4, 5, 6, and A1 strongly affirm the verity of this statement.

Briefly, the formula for the calculation is derived as follows:

$$(1.)\qquad \frac{84_N}{84_T} = \frac{\left(\frac{88}{84}\right)_{\mu}^{\text{True}} - \left(\frac{88}{84}\right)_T}{\left(\frac{88}{84}\right)_N - \left(\frac{88}{84}\right)_{\mu}^{\text{True}}} = \frac{\left(\frac{86}{84}\right)_{\mu}^{\text{True}} - \left(\frac{86}{84}\right)_T}{\left(\frac{86}{84}\right)_N - \left(\frac{86}{84}\right)_{\mu}^{\text{True}}}$$

$$(2.)\qquad \left(\frac{88}{84}\right)_{\mu}^{\text{True}} = \left(\frac{88}{84}\right)_{\mu}^{\text{measured}} (1 + D)^2$$

$$\text{and}\qquad \left(\frac{86}{84}\right)_{\mu}^{\text{True}} = \left(\frac{86}{84}\right)_{\mu}^{\text{measured}} (1 + D)$$

$$\text{where}\qquad (1 + D) = \frac{\left(\frac{86}{88}\right)_N^{\text{measured}}}{\left(\frac{86}{88}\right)_N^{\text{True}}} = \frac{\left(\frac{86}{88}\right)_N^{\text{measured}}}{0.1194}$$

(3.) $$\underbrace{\left(\frac{88}{84}\right)_{\mu}\left[\left(\frac{86}{84}\right)_{N}-\left(\frac{86}{84}\right)_{T}\right]}_{C_1}(1+D)^2+\underbrace{\left(\frac{86}{84}\right)_{\mu}\left[\left(\frac{88}{84}\right)_{T}-\left(\frac{88}{84}\right)_{N}\right]}_{C_2}(1+D)\ +$$

$$+\ \underbrace{\left(\frac{88}{84}\right)_{N}\left(\frac{86}{84}\right)_{T}-\left(\frac{86}{84}\right)_{N}\left(\frac{88}{84}\right)_{T}}_{C_3}=0$$

or

$$C_1\,(1+D)^2+C_2\,(1+D)+C_3=0$$

(4.) Solving for D

$$D=\frac{-C_3-C_1-C_2-D^2C_1}{2C_1+C_2}$$

This is solved by successive approximations. First the D^2C_1 term is neglected and an approximate D is calculated. Then D is refined by including the term D^2C_1. Generally, one additional recalculation is sufficient for calculating a discrimination for two mass units (1 + D) that is correct to 10^{-6}. It should be noted for this calculation that $(88/84)_T$ and $(86/84)_T$ can not be normalized and therefore the spike to normal ratio should be adjusted so that $(86/84)_\mu$ is large compared to $(86/84)_T$. An optimal spiking ratio is such that $(88/84)_\mu$ is about 20.

It is necessary to know the value of $(88/84)_N$. Nier (1938) reports a value of $(88/84)_N = 147.45$ for $(Sr^{86}/Sr^{88}) = 0.1194$. Nine independent measurements of this quantity were made for various samples of this study (Table 2A) on the old twelve-inch C.I.T. mass spectrometer. These indicate an average $(88/84)_N$ of 147.80 ± 0.35, for an $(86/88)$ of 0.1194.

TABLE A-2

Sr^{88}/Sr^{84} in Normal Strontium

All values normalized so that $Sr^{86}/Sr^{88} = 0.1194$

Sample	Sr^{88}/Sr^{84}
1. CRSH.-plagioclase	148.10
2. 21.-plagioclase	147.80
3. SITR.-muscovite	148.30
4. 40.-muscovite	148.40
5. 40.-whole rock	147.85
6. 48.-pot. feld.	147.10
7. 48.-plagioclase	147.20
8. 4.-plagioclase	147.55
9. 6.-whole rock	147.85
Average	147.80 ± 35

V. SAMPLE LOCATION AND DESCRIPTION.

Following are locations and brief petrographic descriptions of samples examined in this study. One reference set of hand specimens is lodged in the Division of Geological Sciences at the California Institute of Technology and another in the Geology Department at Victoria University of Wellington, New Zealand.

A. South Island, Geosynclinal Province, Marginal Zone

Bluff.

Bluff coarse granite - This sample was collected from the main Bluff quarry about 1 kilometer west of the Bluff Railway Station. The rock is intimately intrusive into the Bluff norite, and is formed in thin 1-5 cm thick reticulated veinlets. It consists approximately of 50% plagioclase, 30% quartz, 10% potassium feldspar, and 10% biotite ($n_{y,z} > 1.60$) and minor pyrite. X-ray diffraction indicates some vermiculite in the biotite.

* * *

41.

McKay Intrusive - This sample was collected as a 30 Kg boulder 0.8 km up the eastern branch of McKay Creek from the fork in McKay Creek. In hand specimen the sample is a grey and black granodiorite with pink scattered potassium feldspar grains. A slight alignment of biotite lends the rock a slight foliation. The rock is a common consitituent of the boulders in McKay Creek and occurs in place along the banks 1.5 km up from the fork in the creek. The collected sample in hand specimen has a very fresh appearance, unlike the highly altered varieties of the McKay Intrusives that occur in the Eglinton Valley road cuts east of McKay Creek.

In thin section the following mineralogical composition is observed:

50% 1. Plagioclase - up to 1 cm, anhedral grains; slightly zoned, sodic oligoclase, carlsbad twinned; generally clear and only lightly altered.

15% 2. Potassium Feldspar - up to 1/2 cm; anhedral; slightly perthitic; poikilitically includes one or two plagioclase grains; slight dusty appearance.

30% 3. Quartz - sutured aggregates, up to 0.5 cm.

5% 4. Biotite - up to 5 mm; very slight (1%) chlorite alteration.

1% 5. Apatite - large euhedral crystals.

6. Zircon - large euhedral crystals, up to 0.25 mm; common.

7. Magnetite.

This rock is a holocrystalline, hypidiomorphic, granular, medium-grained granodiorite. Biotite occurs both interstitially and in aggregates, the grains in which are slightly aligned from aggregate to aggregate.

About 20 Kg of crushed rock was aliquoted for total rock Rb/Sr samples.

* * *

29.

Gneissic Hornblende Diorite - This sample was collected from an outcrop in the middle of the beach at Horseshoe Bay, Northern Stewart Island. In hand specimen this sample is a dark green and grey slightly gneissic dioritic rock. The gneissic structure is more apparent in one direction and tends toward being lineation. The rock is intruded by an 8 cm vein of fine-grained massive light-colored granodiorite without hornblende.

The thin section shows the following mineralogy:

40% 1. Plagioclase - moderately zoned, calcic-sodic andesine; cores are in places sericitized but generally fresh and unaltered; carlsbad twinned, albite twin lamellae are bent; 3-6 mm anhedral laths .

20% 2. Quartz - isolated 1 mm grains, fairly uniform extinction.

15% 3. Hornblende - light tan to dark olive green; 5 mm.

10% 4. Biotite - light brown to almost opaque.

15% 5. Potassium Feldspar - interstitial, up to 1.5 mm, angular grains that are amoebic on edges.

1% 6. Apatite.

1% 7. Sphene - 0.1 mm; along edges or within cleavages of biotite; commonly completely rims anhedral magnetite.

8. Magnetite - includes apatite.

9. Zircon - uncommon, rounded, mild halo in biotite.

This rock is a gneissic hornblende granodiorite with an intersertal to subophitic texture formed largely by larger laths of andesine and lesser amounts of 1 cm equant clusters of ferromagnesian minerals in a finer-grained matrix of quartz, plagioclase and interstitial potassium feldspar. Hornblendes show good sieve structure, particularly at edges, including mainly rounded quartz.

B. South Island, Geosynclinal Provine, Alpine Zone

Otago Schist (CRSH).

Sample collected from road cut 300 meters south of the junction of Clutha and Kawarau Rivers near Cromwell. It is mapped as being in the chlorite

IV zone (Wood, 1962). In hand specimen the rock is fine-grained with occasional 1-5 cm thick bands of coarser quartz, with minor coarser biotite and muscovite. Rock has well developed schistosity and two lineations; one is formed by tiny fold axes along which muscovite and biotite trains may occur, and the other is 70° athwart this and is formed by gentle ripples or microfolds.

The thin section reveals the following mineralogical composition:

(?) 45% 1. Quartz - average size 0.1-0.2 mm, can be elongate.

(?) 35% 2. Plagioclase - albite (?)

10% 3. Muscovite - 0.2 mm average.

2% 4. Biotite - light yellow to brown (dark), normal interference colors.

2% 5. Chlorite - light purple-dark blue interference colors; optically negative clear-light green pleochroism; Fe/Mg chlorite (Albee, 1965).

5% 6. Epidote - 0.5 mm, optically negative.

1/2% 7. Sphene

8. Calcite - uncommon.

9. Apatite - common.

Rock is a fine-grained greenschist. Biotite and chlorite occur in separate grains and intergrown in the same grain. In the latter biotite tends to be on edge of grain surrounding or fringing chlorite. Foliation is well marked by alignment of muscovite, biotite, and chlorite flakes and elongated quartz. Schistosity is well developed by separation into mica rich layers (1-1.5 mm thick) and 1 mm thick quartz-feldspar layers. A few coarse quartz (1 mm) layers and lenses with interstitial calcite, coarse muscovite (1 mm) occur. Plagioclase in these layers has interlocking edges. Muscovite occurs in elongate patches that have an outer sheath parallel to the schistosity of medium-grained muscovite over an inner zone of very fine-grained muscovite aligned athwart the foliation about 70°.

* * *

<u>Pegmatite, Alpine Schist (ASH).</u>

This sample is from a pegmatite "shoot", or large vein, in the biotite-zone Alpine Schist of the Mataketake Range 1.3 km southwest of Old Mica Mine and 2 km east of the Alpine Fault. The pegamatite, conchordant with the schistosity (Wellman, 1955),consists mainly of bull quartz, white potassium feldspar, and muscovite. The latter is in coarse books up to 10 cm wide and is associated with minor biotite that occurs intergrown within muscovite books. The muscovite cleavages are distorted and show radial strain patterns. Plagioclase occurs in a relatively finer-grained intergrowth with quartz. The thin section shows that the potassium feldspar has a regular intergrowth of 0.2 mm subhedral laths of plagioclase optically aligned. From comparisons of the index of refraction (closer to potassium feldspar than quartz) the plagioclase is judged as albite. In the plagioclase and quartz intergrown rock phase both minerals occur as 0.5 cm grains . Finer-grained quartz (0.3-l mm) occurs in a semi-mortar texture with sutured borders around larger plagioclase and quartz grains. Some plagioclase grains include microcline (grid twinned). The plagioclase is probably oligoclase and is sericitized in this rock phase.

C. South Island, Foreland Province, North Block, 345-370 Million-Year-Old Rocks, West Coast

Quartz Hill Granite (QH).

This sample was collected by John Rogers and Alec Mutch from Quartz Hill, just north of the Arawata River near Jackson Bay, about 3 km west of the Alpine Fault. The sample is a white pegmatitic granite with muscovite quartz and feldspar. The latter consists of white plagioclase and white potassium feldspar. The muscovite books are up to 8 cm in diameter. The rock is highly fractured; muscovite and potassium feldspar cleavages are bent.

* * *

18(+).

Greenland Hornfels (Figure 35) - This sample was collected from road cuttings at Moeraki Bluffs near the north bank of the Moeraki River about 3.5 miles west of the Alpine Fault in the south part of Westland. The sample is a medium-grained brownish purple moderately schistose hornfels, schistosity being formed by aligned biotite; coarser-grained muscovite is subaligned as isolated grains athwart the general foliation of the rock. In thin section the rock is seen to have the following mineralogical composition:

50% 1. Quartz - anhedral up to 0.6 mm.
27% 2. Plagioclase - slightly dusty alteration, sodic oligoclase or albite.
20% 3. Biotite - up to 2 mm.
3 % 4. Muscovite - sieve structure, poikilitic.
5. Apatite
6. Zircon
7. Magnetite uncommon.

Figure 35. Greenland Series hornfels; Moeraki River (l.), Waitaha River (r.).

8. Tourmaline - not seen in thin section but observed as euhedral prisms in heavy mineral concentrate.

The total rock Rb/Sr aliquot of this sample was taken from 10 Kg of crushed rock. A chemical analysis was published by Mason (1961) of a sample of metamorphosed Greenland Series at Paringa River Bridge 13 km north of, and continuous with, the Greenland Series at Moeraki Bluffs (Table A5).

* * *

22(+)

Greenland Hornfels (Figure 35) - This sample was collected from the quarry at the west end of the Waitaha River in the Waitaha Sugarloaf, 0.5 miles west of the Alpine Fault in the middle part of Westland. The sample in hand specimen is a brownish purple medium-fine-grained massive hornfels with subaligned biotite. Muscovite porphyroblasts are isolated and subaligned athwart the biotite alignment. Portions of the rock grade abruptly from purplish color to green color, the latter forming green patches.

In thin section the following mineralogical composition is observed:

42% 1. Quartz - anhedral, many grains elongate.

23% 2. Plagioclase - albite (?)

25% 3. Biotite or Chlorite - average 0.7 mm, up to 1.5 mm.

3% 4. Muscovite - poikilitic; optically continuous fragments which encompass 2.5 mm on average, but up to 1 cm.

4% 5. Magnetite - associated with biotite and chlorite; 0.3 mm.

2% 6. Epidote - associated with chlorite.

1/2% 7. Calcite - 0.3 mm in association with biotite and muscovite.

TABLE A5

PUBLISHED CHEMICAL ANALYSES OF THE GREENLAND SERIES

	Paringa River*	Waitaha River**
SiO_2	71.80	76.6
Al_2O_3	12.54	10.6
Fe_2O_3	0.48	0.50
FeO	4.12	2.40
CaO	3.51	1.90
MgO	2.28	1.90
K_2O	2.27	2.95
Na_2O	1.17	0.50
TiO_2	0.60	0.35

*Mason (1961)

**Morgan (1908)

1/2% 8. Tourmaline - 0.5 mm, euhedral prisms, yellow brown to clear.

9. Apatite

10. Zircon - rounded.

Foliation in this rock is marked by alignment of isolated biotite and chlorite flakes and subalignment of elongate quartz. One thin section of the green-purple boundary indicates the sharpness (1 cm or less) of this boundary. The green portion contains chlorite and associated epidote with no biotite. Plagioclase in this portion is sericitized, whereas it is fresh and unaltered in the purple (biotite) zone. Muscovite occurs in both zones. Within the 1 cm border, the following transitions are observed:

fresh plagioclase + biotite → moderately sericitic plagioclase + biotite → sericitic plagioclase + biotite interleaved with chlorite →

sericitic plagioclase + chlorite + epidote.

The Rb/Sr total rock aliquots were 2 grams taken from about 25 Kg of crushed rock.

A chemical analysis of the metamorphosed Greenland Series from this locality was published by Morgan (1908) (Table A5).

* * *

23P.

Waitaha Coarse Granite - This sample was collected from the quarry on the north bank of Ellis Creek along with 23G, and is believed a late stage rock associated with the more abundant medium-grained granite. In hand specimen the sample is a white coarse-grained pegmatitic granite distinguished by about 4% of elongate tourmaline prisms that are aligned. Rock crumbles easily to the hammer blow.

The thin section reveals the following mineralogical composition:

38% 1. Potassium Feldspar - very coarse, 2 cm and larger; grid twinned, poikilitically includes quartz, anhedral.

20% 2. Plagioclase - albite, up to 1 cm, generally fresh, slightly zoned, cores replaced partly by isolated muscovite grains.

34% 3. Quartz - 4-5 mm, sutured aggregates.

4% 4. Muscovite - 0.5 mm - 10 mm.

4% 5. Tourmaline - dark greyish green to clear, euhedral prisms up to 20 mm by 1 mm.

6. Garnet - red in hand specimen, 0.15 mm.

Rock is a very coarse-grained pegmatitic granite with 2-3 cm phenocrysts of potassium feldspar which is amoebically interstitial at its edges and poikilitically includes plagioclase and quartz. Euhedral elongate prisms of tourmaline are aligned. In contrast to the more abundant medium-grained granite (23G) at the same locality, 23P is fresh, including most of the plagioclase which has coarse sericite developed along fractures. Coarser muscovite veinlets occur in potassium feldspar.

The Rb/Sr total rock aliquots were taken from 8.5 Kg of crushed rock.

* * *

23G.

Waitaha Granite - This sample was collected from the quarry on the north bank of Ellis Creek, 2.5 miles west of the Alpine Fault near the Waitaha River in Westland. In hand specimen the sample is a medium-grained very slightly foliate grey and black granitic rock. The rock crumbles easily to the blow of a hammer. This rock is believed to be genetically associated with rock 23P, a very coarse-grained pegmatitic granite, (Morgan, 1908, p. 132), although the contacts at this locality were not observed.

In thin section the following mineralogical composition is observed:

37% 1. Potassium Feldspar - fresh and unaltered, carlsbad twinned, some grains up to 3 cm, poikilitically includes 1 mm plagioclase and quartz. Smaller 1 mm grains occur interstitially.

30% 2. Quartz - 4 mm and less in 1-2 cm aggregates with sutured boundaries.

25% 3. Plagioclase - highly sericitized, muscovite in core of grain, lightly zoned, albite.

5% 4. Biotite - 5% altered to chlorite.

3% 5. Muscovite - replacing plagioclase; feathery aggregates on edge of biotite, and associated with biotite.

6. Zircon
7. Apatite
8. (?) - reddish brown, zoned, high relief, biaxial.
9. Epidote - replacing plagioclase, in association with biotite and chlorite.
10. Sphene - uncommon, associated with biotite.

This rock is a medium-coarse-grained holocrystalline porphyritic hypidiomorphic granular granite. Phenocrysts to 3 cm of anhedral potassium feld-

spar poikilitically include quartz and plagioclase. Quartz is aggregated in large patches up to 3 cm as are some potassium feldspars. Alteration of this rock is suggested by heavy sericitization of plagioclase cores and replacement of plagioclase by epidote and biotite by chlorite.
The Rb/Sr total rock aliquot was taken from about 12 Kg of crushed rock.

* * *

17.

Karamea Granite - In hand specimen of this rock is a coarse-grained pink and white porphyritic biotite granite, dominated by phenocrysts of pink carlsbad twinned potassium feldspar in subhedral and euhedral crystals ranging in size from 1.5 cm to 5 cm. These phenocrysts are randomly arranged. The biotite is surrounded by a brownish green stain. This sample was collected from the abandoned quarry two miles west of the town of Oparara on the south bank of the Opara River near Karamea.
From the thin section the following minerals were identified and their proportions were visually estimated.

30% 1. Quartz - isolated anhedral grains, 3-10 mm in size.
30% 2. Plagioclase - moderately zoned, albite in composition; 3-10 mm in size, sericitic alteration.
27% 3. Potassium Feldspar - fresh, carlsbad twinned.
10% 4. Biotite - average size 2 mm; some grains interlayered with chlorite.
3% 5. Muscovite - average size is 0.6 mm. Finer interstitial grains occur.
6. Apatite - euhedral.

7. Zircon - euhedral; generally tiny; in biotite they are surrounded by pleochroic haloes.
8. Epidote - rare.

Rock is a holocrystalline, hypidiomorphic granular, massive medium-grained porphyritic adamellite. Potassium feldspar phenocrysts up to 5 cm in size are poikilitic, including biotite, quartz and euhedral laths of plagioclase, all about 0.6 mm. Biotite occurs in 5 mm clusters with associated muscovite. Muscovite also occurs replacing plagioclase that is generally altered to sericite. Myrmekite texture is present. Alteration of the rock is suggested by sericitized plagioclase and chloritized biotite. Epidote (rare) may be secondary.

The Rb/Sr total rock was a 2 gm aliquot of a 25 Kg crushed sample.

* * *

6.

Charleston Gneiss (Figure 36) - This sample was collected from the quarry on the coast 200 meters south of Taurana Bay. In hand specimen the sample is a grey and black augen gneiss, carlsbad twinned. Feldspar augen up to 5 cm are common and these are enwrapped by subparallel discontinuous foliae of biotite in which tiny brown crystals are not uncommon (sphene). The thin section reveals the following mineralogical composition:

40% 1. Potassium Feldspar - 1 cm or greater, porphyroclasts; fresh, either free of inclusions or poikilitically including aligned rounded laths of plagioclase (2 mm).

25% 2. Plagioclase - slightly zoned, mid oligoclase; up to 1-2 mm porphyroclasts and smaller grains.

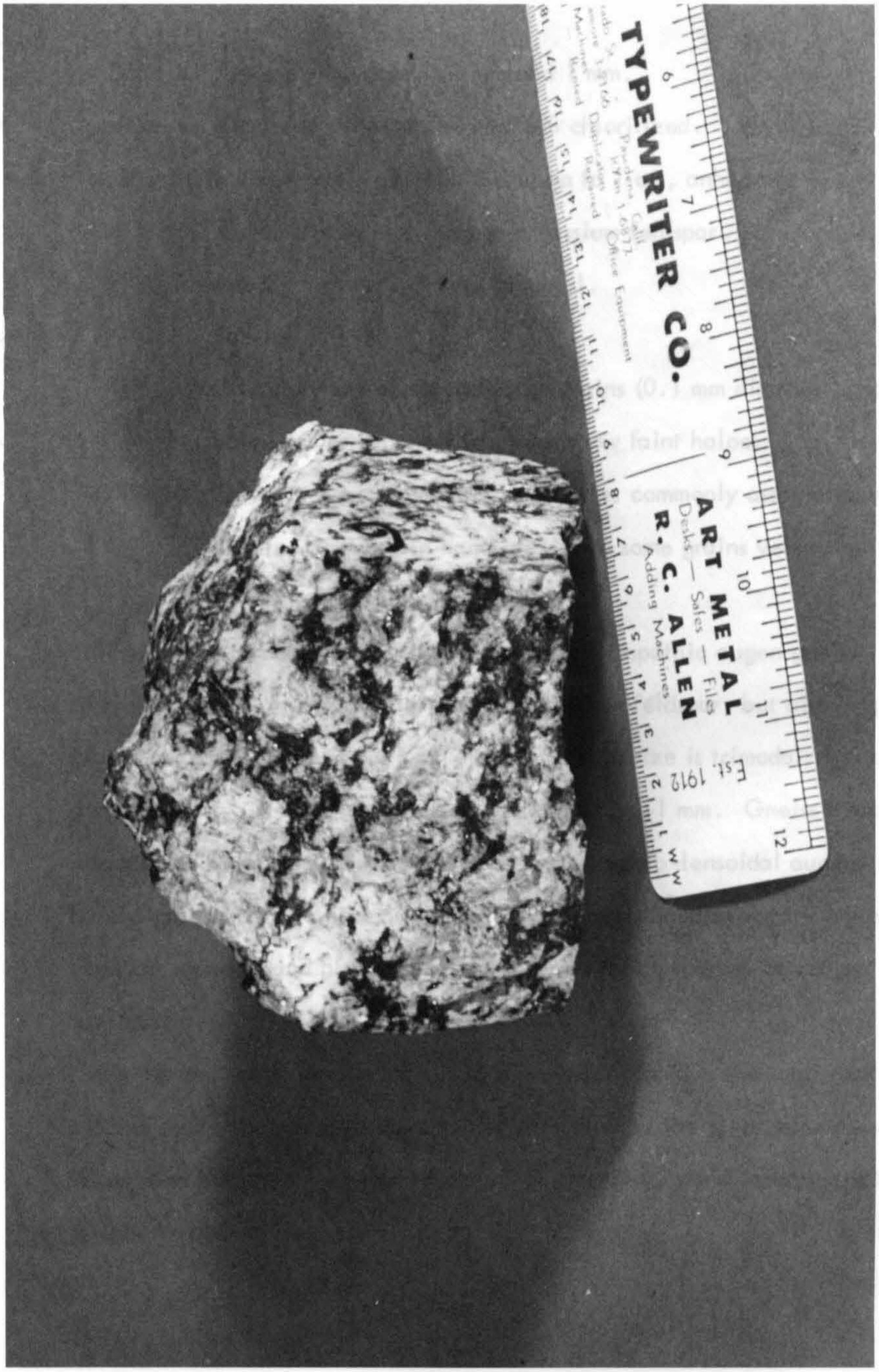


Figure 36. Charleston Gneiss, Tauranga Bay.

20% 3. Quartz - bimodal 0.2 mm and 1 mm.

8% 4. Biotite - average 2-3 mm; 3% chloritized.

3% 5. Hornblende - average 3 mm; up to 1 cm, anhedral.

6. Calcite - veinlet through potassium feldspar.

1% 7. Apatite - up to 0.3 mm, euhedral.

1/2% 8. Sphene

1/4% 9. Zircon - very abundant; large grains (0.1 mm diameter) show no haloe in biotite; smaller grains show faint haloe.

1/4% 10. Garnet - 2 mm anhedral, aggregates commonly associated with biotite; light red in hand specimen; some grains veined by chloritized biotite.

This rock is a coarse- to very coarse-grained feldspathic augen gneiss. One to five cm augen are formed largely by potassium feldspar, but also by plagioclase. Mortar texture is well developed. Grain size is trimodal: 1-5 cm porphyroclasts, 1-2 mm groundmass, and mortar, 0.1 mm. Gneiss structure emphasized by aligned biotite which enwraps the sub-lensoidal augen, and by elongate quartz. These augen are in part surrounded by mortar potassium feldspar, quartz, and plagioclase, and in part by aggregates of coarser (1-2 mm) quartz.

Two adjacent large samples of this rock were processed. The total rock aliquots and some minerals were taken from one and the other minerals were taken from the other. The one from which the total rock aliquots were taken weighed about 35 Kg.

* * *

2g.

Charleston Gneiss - This sample was collected 16 road kilometers south of Charleston from outcrops on the beach. The sample in hand specimen is a leucocratic massive light grey medium-fine-grained granitic rock. The rock is in a coarse (granite pods and veins up to 1 meter thick) migmatitic relationship with a biotite-muscovite schistose gneiss.

The thin section reveals the following mineralogical composition:

35% 1. Quartz - 1-1.5 mm average size; aggregates with sutured and non-sutured borders.
30% 2. Potassium Feldspar - 2-6 mm, anhedral.
23% 3. Plagioclase - sericitized, mid oligoclase, anhedral.
10% 4. Muscovite - bimodal, 1-2 mm and less than .05 mm.
2% 5. Biotite
6. Apatite
7. Zircon - uncommon, pleochroic halo in biotite.

This rock is a holocrystalline, fine- to medium-grained, leucocratic adamellite with somewhat of a saccroidal texture. Potassium feldspar, quartz, and plagioclase are anhedral, the foremost poikilitically including the latter two. Plagioclase is often coarsely altered to coarse sericite which grades up to muscovite. Muscovite occurs with very unusual textural relations in this rock. It is bimodal in size with normal 1-2 mm grains and very fine (.05 mm and less) grains which occur in large feathery matted aggregates, up to 3 mm. Feathery muscovite fringes and rims biotite. In places interlayered with fine and normal muscovite are semi-opaque iron-stained patches. Some normal muscovite shows sieve structure poikolitically includding graphic quartz. Some normal muscovite has the fine feathery muscovite rimming it. In places the fine-grained muscovite is aligned and intergrown with tiny fingers of quartz (?). Perhaps the muscovite represents two generations, the feathery muscovite being younger than the normal muscovite. It is interesting to note the occurrence of muscovite in the associated schistose gneiss. Both matted fine-grained feathery muscovite and normal muscovite also occur in this rock, but the former is much less common. It is found also rimming and perhaps replacing biotite, and also, in contrast to the granite rock, as cores of normal muscovite, rather than at its edges. In this rock plagioclase, perhaps more sodic than in the granite, is fresh and only very mildly sericitized, and can occur completely unaltered.

D. South Island, Foreland Province, North Block, Possible 345-370 Million Year Old Rocks, Inland

11.

Hornfels - Sample is collected from road cutting immediately south of Ruffe Creek along the Murchison-Matakitaki Road. This metamorphic sample is a massive fine-grained purplish brown rock that is finely jointed on a scale of a few inches. N.Z. Lands and Survey locality code: Murchison S.D. 532 5638-7456. South of Ruffe Creek one-half mile the hornfels is separated by a fault from large extensive outcrops of reddish granite.

In thin section this rock has the following mineralogical composition:

50% 1. Quartz - 0.1-0.4 mm, anhedral, undulent extinction.

20% 2. Plagioclase - 0.2 mm, anhedral, dusky alteration.

20% 3. Muscovite - occurs as patches of feathery very fine grains associated with biotite and as individual 0.5 mm grains.

10% 4. Biotite - 4% altered to chlorite.

5. Magnetite - in association with muscovite.

6. Apatite (?) - coarse rounded anhedral outlines 0.1-0.2 mm; shadowy core.

7. Zircon - fairly large rounded grains; 0.1-0.08 mm.

8. Tourmaline - uncommon.

This is a fine-grained quarzose hornfels or subschist with foliation formed by aligned discontinuous streaks of biotite and muscovite and aligned slightly elongate quartz grains. Muscovite occurs in an unusual texture. 60% of the muscovite occurs in 0.7 mm patches of feathery unoriented very fine grains with slightly coarser muscovite and biotite in them. These patches have a slightly brownish tinge and may be biotite in part. They possibly represent crystallizing spots of biotite and muscovite from clay minerals (?). The occurrence of tourmaline suggests this rock may be a contact metamorphic hornfels.

* * *

12.

Granite - Sample collected from boulder 5 meters in diameter along the Murchison-Matakitaki Road near the junction of McWha Creek with the Marauia River. This is about 1.5 miles north of Ruffe Creek, where sample number 11 (schist) was collected. No country rock was observed in the immediate locality of sample 12, but massive outcrops of slightly weathered granite with red potassium feldspar occurs just south of sample 11. In hand specimen this sample is a medium-grained porphyritic granititic rock with a light grey color. The phenocryst are elongate subaligned 2-3 cm carlsbad twinned white potassium feldspar.

In thin section this rock has the following mineralogical composition:

25% 1. Quartz - anhedral grains 2-10 mm in size; clusters of a few grains common with fine sutured borders; some clusters up to 4 cm.

40% 2. Potassium Feldspar - carlsbad twinned; fresh; poikilitically includes plagioclase and biotite; the former is rimmed and altered to sericite, the latter to chlorite; grains elongate subhedral up to 3 cm, euhedral to subhedral.

25% 3. Plagioclase - mildly zoned, cores sericitized, mid oligoclase-calcic albite; 1-7 mm in size.

6% 4. Biotite - slightly chloritized (about 3%).

3% 5. Muscovite - associated in biotite clusters; occurs as coarsest alteration of plagioclase and possibly partly replacing potassium feldspar.

6. Zircon - abundant, inclusions in biotite give definite pleochroic halo.

7. Apatite

8. Magnetite - rare.

This rock is a coarse-grained holocrystalline, hypidiomorphic porphyritic granite with elongate phencrysts of subhedral potassium feldspar poikilitically including biotite and plagioclase that are slightly altered. Quartz and biotite occur in separate clusters, muscovite being associated with the latter. Alteration is indicated by sericitization of plagioclase and partial replacement of biotite by chlorite. Feathery muscovite with associated magnetite rims biotite and possibly replaces potassium feldspar.

The Rb/Sr total rock aliquot of this sample was taken from about 30 Kg of crushed sample.

* * *

49.

Rocky River Sample - This unusual sample was collected as a large boulder about 1-2 km up Rocky River, a tributary to Motueka River south of Brooklyn. This hard, very distinctive rock comprised almost 100% of the boulders in Rocky River, and almost certainly comes from the unit mapped as Riwaka metavolcanics by Grindley (1961), separated from the Separation Point Granite by the Motueka Fault. In hand specimen the sample is a medium-grained dark black crystalline rock with black biotite. The rock is hard to break with a hammer.

The thin section shows that this rock has an unusual mineralogy:

57% 1. Plagioclase - 2-6 mm, carlsbad twinned, calcic andesine, slight zoning; some bending of albite lamellae; under uncrossed Nicols plagioclase has a dusky dark look that is not an alteration but probably fine magnetic inclusions (plagioclase was magnetic during Franz mineral separations); anhedral blocky grains.

13% 2. Potassium Feldspar* - 1-2 mm, interstitial angular grains; not dusky; 2V $> 35^{\circ}$, anorthoclase.

2% 3. Quartz - interstitial isolated grains 1/2 - 1 mm.

2% 4. Hornblende - dark greenish olive to greenish brown; occurs isolated and with pyroxenes; 1-5 mm; interstitial on edges.

* X-ray diffraction indicates anorthoclase or sanidine

5% 5. Biotite - up to 1 cm.

4% 6. Magnetite

7. Sphene

2% 8. Apatite - large euhedral crystals.

9. Pyroxene - pleochroic light green to light pink, opt(+), 2V about 55°, 2nd order birefringence, schiller structure, - augite (?); 3 mm.

10. Pyroxene - pleochroic light green to light pink, opt(-), 2V about 45°, low 1st order birefringence, no schiller structure - hypersthene (?), 3 mm.

The rock is medium-grained holocrystalline, hypidiomorphic pyroxene, hornblende, biotite, anorthoclase diorite. Rock has a sub-sacchroidal texture formed by blocky plagioclase and pyroxene grains with interstitially developed anorthoclase and biotite. Biotite also occurs as large poikolitic grains including pyroxene, magnetite, and hornblende; it also is developed around the edges of pyroxene. Magnetite is associated with pyroxene interstitial to it or rimming it. Myrmekite is common between plagioclase and potassium feldspar.

E. South Island, Foreland Province, North Block, 100 - 120 Million Year Old Rocks

4.

Pegmatite - This sample was collected from the north bank of the mouth of the Nile River near Charleston. N.Z. Lands and Survey locality code is S 30-4949 7554. The pegmatite is 2/3 - 1 meter wide and cross cuts the Charleston Gneiss with sharp contact. It consists dominantly of large crystals (up to

40 cm) of fresh light tan potassium feldspar with lesser amounts of bull quartz. Muscovite is common as booklets 1 mm - 1 cm in diameter. Weathered chalky plagioclase is relatively minor, occurring as 1-2 mm grains. Small weathered inelastic biotite is also minor.

The thin section shows that the potassium feldspar is coarsely perthitic. The perthite laminae are lightly sericitized, whereas the potassium feldspar is unaltered. Myrmekite is abundant at borders of plagioclase with potassium feldspar.

* * *

7.

Paparoa Granite (2 Phases) - This sample was collected from the first massive road cuts east of Westport in Buller Gorge east of Windy Point on the south side of the Buller River. N.Z. Lands and Survey locality code is approximately S-31 5178 7630. In hand specimen the sample is an augen gneiss with light pink-grey augen 1 cm long of potassium feldspar. The augen are roughly aligned in a generally grey medium-grained matrix with a gneissic texture. The rock is intimately injected with irregular veins up to 20 cm thick of a light colored pink and white coarse granite that is generally massive. The feldspar and mica cleavages in this coarse granite phase are strongly bent.

The microscopic descriptions of these two phases will be discussed separately below.

A. Augen Gneiss (7D)

40% 1. Quartz - seriate, very fine to 1 cm porphyroclasts.

32% 2. Plagioclase - mid oligoclase, sericitized, muscovite (coarser than sericite) can replace plagioclase along (010) and perpendicular to (010), giving a rectangular pattern.

22% 3. Potassium Feldspar - porphyroclasts 1-2 cm, carlsbad twinned, fresh and unaltered.

3% 4. Muscovite - highly bent lamellae giving wavy extinction; occurs in association with biotite with the latter partially enwrapping coarser muscovite.

2% 5. Biotite

1% 6. Chlorite - light purple interference color; occurs both as separate flakes with opaque needles and intergrown with biotite; light yellow to green.

7. Zircon - rounded, mild halo in biotite.

Rock is an augen gneiss of adamellite composition. It consists of 15% 1-2 cm lensoid porphyroclasts of plagioclase, quartz, and potassium feldspar, enwrapped by fine-grained quartz, plagioclase, potassium feldspar, muscovite, biotite. Quartz is particularly abundant in this matrix and mainly occurs as stretched-out streaky single and aggregate grains.

The grain size of this matrix extends down to very small, almost indistinguishable grains constituting good mortar structure. Elongate quartz aggregates have highly sutured joined boundaries. The elongate quartz and the augen-enwrapping micas are aligned, giving the rock good foliation. Post-crystallization straining of the rock is evidenced by the strongly bent mica and feldspar cleavages.

B. Coarse Light Colored Granitic Rock (7L)

50% 1. Potassium Feldspar

38% 2. Quartz

6% 3. Muscovite

1% 4. Biotite and Chlorite

5% 5. Plagioclase

This rock also shows mortar structure, but is dominantly coarse-grained, 5 mm to 1 cm. Lensoid porphyroclasts form 50% of the rock and are essentially all formed by potassium feldspar. Fine-grained potassium feldspar partially or entirely enwraps the feldspar augen in contrast to the more gneissic rock phase described above, where mica, myrmekitic plagioclase, and elongate quartz dominantly enwrap the augen. The rock has a poor gneissic structure mainly developed by sub-parallel lensoidal feldspar augen. The high abundance of augen give the rock a massive appearance. As such, the rock is a cataclastic coarse-grained granite.

* * *

8.

This sample was collected as a fresh rounded 25 Kg boulder from the Mackley River at the mouth of the Blue Duck stream. The rock, identified by its distinctive features, was a common constituent of the stream boulders at this locality, and crops out at many places within the gorge of Mount William stream, where it has been mapped as Charleston Gneiss. In hand specimen the sample is a slightly porphyritic medium-grained dark grey dioritic rock with rounded quartz phenocrysts and euhedral hexagonally outlined biotite.

In thin section the following mineralogical composition is observed:

50% 1. Plagioclase - rounded equant grains, strongly zoned, mid-andesine , generally seriate in size 0.5 mm--10 mm with 3 mm a common size.

35% 2. Quartz - equant rounded phenocrysts, 1/2-1 cm.

3% 3. Potassium Feldspar (?) - tiny 0.2 mm angular pieces.

12% 4. Biotite - light brown to opaque, 1-2% chloritized, subhedral 0.8-1.0 mm, can be interstitial.

5. Apatite - to 0.5 mm.

6. Zircon - not uncommon, euhedral, long prisms; large, to 0.1 mm in width; none to very slight halo observed in biotite.

7. Magnetite - euhedral, silver reflection.

8. Sphene - anhedral, 0.4 mm, associated with biotite.

9. Calcite - rare, observed with sphene.

10. Hornblende (?) - one grain observed, altering to biotite, included in quartz; green.

Rock is a holocrystalline, medium-grained, slightly porphyritic, granular hypidiomorphic tonalite. Phenocrysts of plagioclase and larger rounded quartz. The latter poikilitically includes rounded grains of plagioclase, biotite and rounded aggregates of plagioclase and biotite. Some quartz grains are embayed by the finer-grained matrix, and some appear to be finely amoebic into the matrix. This matrix consists of very fine (0.1 mm) to fine (0.5 mm) quartz, plagioclase that is slightly zoned and angular potassium feldspar. The latter is confined to the fine-grained matrix. Plagioclase forms some 1 cm rounded lath phenocrysts, but is mainly seriate in size, averaging 0.4 mm. The plagioclase, being so abundant, gives the rock an intersertal or sub-ophitic appearance.

* * *

16.

This sample was collected from the north bank of the Buller River at Whale Flat, seven miles west of Murchison between Maruia River and Newton Flat. The White Creek Fault passes several meters west of the sample locality. Locality NZGS code: Matiri S.D. S-25 5631-7701.

In hand specimen this is a pink and grey medium-grained granite. The rock is coarsely jointed (spacing one foot), along which weathering and staining has progressed.

In thin section the following mineralogical composition has been observed:

33% 1. Quartz - anhedral 4 mm average size, up to 2 cm.

33% 2. Plagioclase - moderately zoned, cores strongly sercitized; sodic oligoclase; 1-5 mm rounded laths. Albite lamellae curved.

25% 3. Potassium Feldspar - up to 1.5 cm in size; perthitic.

3% 4. Biotite - up to 4 mm; 40% altered to chlorite, mainly along edges.

3% 5. Muscovite - interstitial between plagioclase grains; 1/3 mm flakes replace cores of highly sericitized plagioclase; in association with biotite and along edges of biotite possibly replacing biotite.

1/2% 6. Apatite

1% 7. Magnetite - euhedral, silver reflection, up to 2 mm cubic or equilateral triangular sections. Slight alteration to reddish brown semi-opaque material on edge (hematite?).

8. Zircon - euhedral; produces distinct halo in biotite.

9. Epidote - uncommon; in association with chlorite and replacing

plagioclase (see diagram).

Rock is a medium-grained allotriomorphic, holocrystalline granular adamellite. The minerals tend to aggregate with their own kind. Potassium feldspar, up 1.5 cm, is poikilitically including plagioclase and biotite, the former rounded and zoned. Most grains have a general rounded appearance with edges that are amoebicly interstitial. Myrmekite occurs.

The Rb/Sr total rock was a 2 gram aliquot of approximately 25 Kg of crushed rock.

* * *

14.

Quartz Monzonite - Sample collected from a boulder 4 meters in diameter along the south side of the Lewis Pass Road, 2 miles northwest of Rahu Saddle. The large boulder occurred in a mass of slip material, the country rock in the immediate vicinity being muscovite, biotite, garnet, quartz schist, with diorite occurring just west of the schist. In hand specimen this rock is a coarse-grained white and black granitic rock with 2-5 cm euhedral phenocrysts of white potassium feldspar.

In thin section the following mineralogical composition is observed:

30% 1. Quartz - anhedral sutured aggregates.

25% 2. Potassium Feldspar - up to 5 cm in size; fresh, unaltered, grid twinned; poikilitic.

30% 3. Plagioclase - zoned, cores sericitized, up to 1.5 cm in size; smaller grains more strongly zoned; carlsbad and albite twinned; calcic albite.

10% 4. Biotite - partly chloritized (3%).

2% 5. Epidote - replacing plagioclase along liner and rectangular zones and occurring in association with biotite.

6. Sphene - in association with epidote and biotite (see diagram). anhedral.

7. Apatite - large euhedral inclusions in biotite .

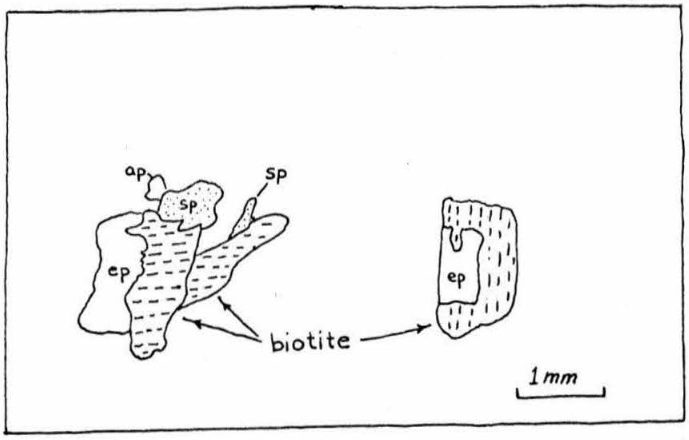
8. Muscovite - trace, interstitial or associated with biotite or alteration of plagioclase cores.

9. Magnetite

10. Zircon - large euhedral, up to 0.1 mm diameter; mild pleochroic halo in biotite.

Rock is a coarse-very coarse-grained holocrystalline, hypidiomorphic granular porphyritic quartz monzonite. Subhedral phenocrysts to 5 cm of potassium feldspar and subhedral laths of plagioclase to 1.5 cm poikilitically include quartz and biotite. Quartz occurs as aggregates of grains with sutured boundaries. Biotite occurs in aggregates associated with eipdote and sphene. Alteration of the rock is indicated by sericitization of plagioclase, replacement of plagioclase by epidote, and biotite by chlorite. The rock is somewhat crunchy and brittle to the hammer blow. The Rb/Sr total rock aliquot was taken from a crushed sample weighing about 10 Kg.

Diagram illustrating typical biotite, epidote, sphene association: (see next page):



10.

Rotoroa Gneiss - This sample was collected from a large road cutting on the Kawatiri-Blenheim Road along the south bank of the Buller River, about one mile north of the junction of the Howard River with the Buller River. The N.Z. Lands and Survey locality code is S-26 6069-7774. In hand specimen this sample is a fine-medium grained grey dioritic rock. The rock has a very slight foliation with subaligned thin tabular dark fine-grained inclusions up to 30 cm long.

In thin section the following mineralogical composition is noted:

63% 1. Plagioclase - moderately zoned mid-andesine to calcic oligoclase; carlsbad twinned anhedral laths 4-5 mm.

22% 2. Quartz - interstitial aggregates of anhedral 0.5 mm grains.

10% 3. Biotite - some places this is interstitial, no chlorite observed 0.5-1 mm.

5% 4. Hornblende - 1/2-1 mm.

1% 5. Epidote - alters cores of plagioclase (0.1 mm); and associated with biotite (0.2-0.4 mm).

2% 6. Sphene - euhedral wedges 0.8-1.0 mm; often magnetite core, sphene rim has mammillary edges extending into biotite and filling cracks in hornblende. One sphene observed with epidote core.

1% 7. Magnetite

8. Zircon - uncommon.

No potassium feldspar observed.

Rock is a fine- to medium-grained holocrystalline, hypidromorphic, granular quartz diorite. Slight foliation marked by slight alignment of biotite and lesser alignment of plagioclase laths. Rock has an intersertal - sub-ophitic texture formed with subaligned anhedral plagioclase laths, which are amoebic on their edges, into an interstitial matrix of quartz aggregates and finer plagioclase. Biotite and hornblende occur as grains with sieve structure poikilitically including quartz or as smaller interstitial grains.

* * *

<u>48.</u>

Motueka River Pegmatite - This sample was collected from the west bank of the Motueka River, 3 kilometers north of Baton Bridge. The pegmatite, a few meters thick, cross-cuts a hornblende diorite mapped as Separation Point Granite. It consists approximately of 60% salmon colored potassium feldspar up to 40 cm, and 30% bull quartz, with plagioclase, biotite, and muscovite. The biotite, altered to chlorite on the edges, occurs in twisted aggregates of very coarse grains that form monomineralic veins cross-cutting the other minerals of the pegmatite. N.Z. Lands and Survey locality code is S13 - 6212 8339.

* * *

46.

Hornfels or Subschist - Sample collected from road cutting along Kotinga-Anatoki River road on the south bank of the Anatoki River. The exact locality is 100 meters west of the fence blocking the end of the public road from the short primitive road. Grindley (1961) mapped this as Onekaka schist which is separated by the Golden Bay Fault from the Golden Bay Schist to the west. In hand specimen the sample is a fine-grained massive purple-grey hornfels with no schistosity. The rock is very hard to break with a hammer.
In thin section the following mineralogy is observed:

(?) 60% 1. Quartz - bimodal in size .05 mm and 0.3-1 mm.
(?) 20% 2. Plagioclase - slightly zoned, calcic oligoclase (?).
10 % 3. Biotite - 0.1-0.2 mm.
3 % 4. Muscovite - up to 1 mm.
5 % 5. Calcite - isolated angular grains 0.2-0.5 mm.
1/2 % 6. Sphene (?) - high relief and birefringence, anhedral.
1 % 7. Magnetite - silver reflection.
1/2 % 8. Apatite - up to 0.2 mm, with shadowy core, common.
9. Zircon - not uncommon, mild pleochroic halo in biotite, rounded to euhedral.
10. Tourmaline (?) - one possible grain observed, 0.2 mm

euhedral lath, strongly pleochroic yellow brown - clear.

This rock is a fine-grained subschist with average grain size of 0.2 mm. Coarser grains (1 mm) of quartz and muscovite and (rarely) plagioclase occur. Foliation is well marked by parallel muscovite and biotite flakes which are isolated and not in layers.

F. South Island, Foreland Province, South Block

40.

Kakapo Granite - Sample collected as a 60 Kg boulder lying on a rocky shore of similar composition at Honey's Garden on the north shore of Chalky Inlet just opposite the western end of Great Island. In hand specimen the sample is a very slightly gneissic medium-grained light colored granitic rock. The gneissic structure is formed by a slight alignment of biotite. The thin section reveals the following mineralogical composition:

40% 1. Quartz - 10 mm patches of sutured aggregate of 0.2-4 mm anhedral individuals.

30% 2. Potassium Feldspar - up to 5 mm, anhedral equant grains that are interstitial on edges; poikilitically includes plagioclase and biotite.

25% 3. Plagioclase - up to 4 mm, slightly zoned, albite, slightly zoned, carlsbad twinned.

4% 4. Biotite - 5% chloritized on edges, also some isolated whole flakes of chlorite occur.

1% 5. Muscovite - occurs as plates associated with biotite and as coarse alteration of plagioclase; possibly also alters potassium feldspar.

6. Apatite
7. Epidote - associated with biotite, up to 1 mm in size; one grain has core of apatite.
8. Zircon - common, fairly large grains, .08 mm, mild halo in biotite; tiny zircons have stronger halo.
9. Sphene or monazite (?) - low 2V, about 10-12°, cleavage, biaxial (+), low birefringe.
10. Magnetite

This rock is a holocrystalline, hypidiomorphic, granular adamellite. It is medium-grained but seriate down to 0.5 mm. Microcline, lightly dusted with kaolinite (?) poikilitically includes plagioclase and biotite and is interstitial on its edges. Muscovite and biotite associated in stretched-out clusters. Epidote occurs both as an associate of biotite and as an alteration of plagioclase. Plagioclase is also fairly heavily sericitized.

The total rock Rb/Sr aliquots were taken from 40 Kg of crushed rock.

* * *

36.

Pomona Granite - This sample was collected from a glaciated surface on the north-eastern shore of Lake Manapouri. In hand specimen the sample is a medium-grained pinkish grey massive granitic rock. The quartz has a bluish tinge.

The thin section reveals the following mineralogical composition:

35% 1. Quartz - bimodal in size; 2.5-5 mm equant anhedral grains are commonly partly surrounded by sutured aggregates of the finer-grained quartz. Undulent extinction.

32% 2. Potassium Feldspar - 0.5 cm-1 cm, strongly perthitic, grid twinned;

altered to kaolinite (?), dusty.

30% 3. Plagioclase - up to 5 mm, slightly zoned, calcic oligoclase - sodic oligoclase sericitized, intergrown with potassium feldspar.

2% 4. Biotite - fine-grained 0.2 mm; green to brown pleochroism; 50% chloritized.

1/2% 5. Muscovite - veinlets between plagioclase grains.

1/4% 6. Calcite - isolated grains.

7. Zircon (?) - may be epidote, uncommon, tiny.

8. Apatite - uncommon.

9. Sphene - large independent crystals, 2 mm and larger, magnetite and chlorite veins through cracked center.

10. Magnetite - 0.2 mm, euhedral cubic section, silver reflection.

This rock is a fine-medium grained holocrystalline, hypidiomorphic granular adamellite. A very unusual textural relation between plagioclase and potassium feldspar occurs. Almost all of the plagioclase occurs within the potassium feldspar grain as a patchy albite twinned intergrowth so that 30-40% of each feldspar grain is plagioclase. (It was very difficult to obtain an 80/100 mesh heavy liquid separate of plagioclase free from potassium feldspar.) Fine grained quartz, 0.5 mm and less, and biotite and muscovite commonly surrounds larger quartz and potassium feldspar. Potassium feldspar is strongly kaolinized and plagioclase heavily sericitized; 50% of biotite has altered to chlorite.

The total rock Rb/Sr aliquots of this rock were taken from 9 Kg of crushed rock.

39.

Doubtful Sound Granite - This sample was collected as a 50 Kg boulder at the base of Helena Falls in Deep Cove of Doubtful Sound. Almost all of the boulders at the base of the falls are marble gneisses. This was the only granitic rock observed among all of the boulders. However, about 0.5-1 km south of Deep Cove, deeply weathered granite very similar to the collected sample occurs just below the Wilmot Pass track. One-and-one-half kilometers south of Deep Cove, granite essentially identical in hand specimen to the collected granite comprises a major portion of the cobbles and boulders in Stella Creek. In hand specimen these samples are medium-coarse-grained grey and black granitic rocks. A very slight foliation of the biotite occurs.

The thin section of the collected sample shows the following mineralogy:

40% 1. Potassium Feldspar - 1.5 cm, patchy perthite; grid twinned.

15% 2. Plagioclase - sericitized, up to 5 mm, subhedral; carlsbad twinned; calcic albite or sodic oligoclase.

40% 3. Quartz - sutured aggregates; some aggregates are continuous for several cm.

4% 4. Biotite - brown to dark brown; only one small patch of chlorite observed in biotite.

1/2% 5. Calcite - common, in association with biotite and in veinlets through potassium feldspar.

6. Muscovite - trace, in association with biotite.

7. Apatite - abundant.

8. Zircon - abundant, 0.1 mm x .25 mm; no pleochroic halo in

biotite.

9. Magnetite
10. Allanite (?) - wedge-shaped euhedral grains up to 2 mm long; reddish brown, translucent in lateral section; pleochroic light brown to dark brown.

This rock is a holocrystalline, hypidiomorphic granular granite. Rock is generally equigranular except for mortar texture of fine quartz and potassium feldspar that is developed around larger grains of potassium feldspar. Biotite grains envelop potassium feldspar and plagioclase and are crudely aligned. Biotite displays an unusual texture of growth into plagioclase, quartz and potassium feldspar grains. Possible alteration of this rock is marked by patchy sericitization of plagioclase, slight development of chlorite and calcite veinlets and patches in perthitic potassium feldspar.

* * *

22.

Schistose Amphibolite - This rock was collected from the shaft at the northwest end of the west arm of Lake Manapouri. The sample, in hand specimen, is a brownish green and grey medium-grained gneiss with poorly developed layers of close spacing.

The thin section shows the following mineralogy:

43% 1. Plagioclase - very fresh, unaltered; slightly zoned, anhedral, up to 1 cm in size; oligoclase; carlsbad twinned.

30% 2. Quartz - anhedral, 3 mm-1 cm in size, interstitial.

12% 3. Biotite - light yellow brown to dark reddish brown; no chlorite; elongate plates.

12% 4. Hornblende - 0.2 mm-1 cm; anhedral, rounded.

3% 5. Sphene - up to 0.3 mm, euhedral wedges, and anhedral.

6. Apatite

7. Magnetite - enwrapping hornblende.

8. Zircon - not uncommon, rounded, no halo to very faint halo in biotite.

9. Diopside - optically (+); X-rayed.

This rock is a schistose biotite amphibolite. Hornblende and biotite are associated. These wrap around coarser quartz and plagioclase but do not form continuous layers. The foliation is most apparent in one direction, so that foliation is intermediate toward being a lineation. Diopside is poikilitic including biotite, hornblende, and sphene.

* * *

21.

Amphibolite - The sample was collected from the west shore of Lake Te Anau about 1.5 kilometers south of the South Arm entrance. In hand specimen, the sample is a dark green and grey, medium-grained amphibolite. The structure is tending from foliation toward lineation.

In thin section the following mineralogy is observed:

40% 1. Quartz - angular shaped grains up to 4 mm in size, grains are interstitial on edges.

46% 2. Plagioclase - 3-5 mm anhedral grains, zoned, carlsbad twinned, sodic andesine.

8% 3. Hornblende - up to 1 cm, dark green - yellow brown, anhedral; amoebic on edges.

5% 4. Biotite - no chlorite, very light brown to greenish brown; 1/2-1 mm.

1/2% 5. Epidote - in association with biotite and altering plagioclase on edge.

6. Apatite

7. Zircon (?) - high relief, optically (+).

This rock is a medium-grained biotite amphibolite. Foliation is crudely marked by subaligned anhedral plagioclase laths, and roughly aligned separated biotite flakes. Hornblende and quartz are anhedral and interstitial to plagioclase. The former is poikilitic.

* * *

<u>33</u>.

Darran Diorite - This sample was collected from a freshly blasted large slip block, 3-5 meters throug, that had fallen down onto the south side of the road from the outcrops above the north side of the road leading into Milford Sound. The exact locality is about 400 meters south of the Milford Hotel in the first massive rock outcrops east of where the road bends to go north along the shore of Milford Sound. In hand specimen, the sample is a gneissic medium-grained biotite amphibolite. Yellowish green epidote is common. The color of the rock is black and white.

In thin section the following mineralogy is observed:

47% 1. Plagioclase - 0.5-0.6 mm, anhedral, zoned, calcic andesine to calcic oligoclase (carlsbad twin); partly replaced by epidote, and muscovite, the latter up to 0.2 mm.

15% 2. Hornblende - average 3 mm, anhedral lens-shaped, dark green to light brownish green; sieve structure including plagioclase and quartz.

15% 3. Epidote - average 2 mm, up to 4 mm in size, subhedral; sieve structure including plagioclase and quartz.

3% 4. Sphene - 0.5-4 mm, sieve structure, including rounded plagioclase and quartz.

10% 5. Biotite - average 2 mm, not chloritized, fine opaque needle inclusions, very light brown to dark brown.

10% 6. Quartz - anhedral aggregates 0.2 mm, up to 1.0 mm; also isolated grains.

7. Muscovite - replacing plagioclase, uncommon.

This rock is a medium-grained biotite, epidote amphibolite. The plagioclase and quartz are separated from the ferromagnesian minerals which occur associated in lensoidal clusters up to 1.5 cm. The plagioclase and quartz are generally equant and anhedral. The ferromagnesians may be elongate (sphene and biotite) and subhedral; hornblende tends to be lens-shaped. Plagioclase is generally fresh but shows isolated areas replaced by epidote and muscovite.

* * *

SITR.

Stewart Island Tin Range Quartzite - Coarse 1-2 cm books of muscovite were hand-picked from a medium-coarse grained relatively pure recrystallized meta-quartzite that occurs at the mine-tunnel dump at the south end of the Tin Range about 4 kilometers north of Pegasus Inlet. The quartzite is interlayered with minor layers of biotite-rich schist.

30.

This sample was collected from the eastern coast of the middle part of Stewart Island at the northern point of the mouth of Lord's River. In hand specimen, the sample is a medium-grained white and black lineated granitic rock. The feldspars have a chalky appearance and the rock is crunchy to the hammer.

In thin section the following mineralogy is observed:

35% 1. Quartz - very undulent extinction; average 1 mm, up to 1 cm.
30% 2. Plagioclase - carlsbad twinned, mid oligoclase, slightly zoned.
30% 3. Potassium Feldspar - perthitic, moderate to strong; anhedral phenocrysts 1/2 to 1 cm; one patch of heavy sericite observed.
4. Muscovite - fine-grain fringe of biotite.
5. Magnetite
6. Apatite
7. Epidote
8. Sphene - partly altered to leucoxene (?).
9. Zircon - rounded elongate grains; no pleochroic halo in biotite.

The rock is a holocrystalline medium-grained hypidiomorphic granular lineated adamellite. Lineation, not foliation, of biotite aggregates occurs. A biotite-rich (10%) gneissic layer 20 cm thick occurs parallel to this lineation. Average grain size is 1-2 mm, with equant grains. Quartz and potassium feldspar also occur as amoebic anhedral grains up to 1 cm enveloping other grains on their edges.

G. North Island

Coromandel Granite (Cor).

This sample was collected by the N.Z. Geological Survey from the quarry on the northeastern shore of the Coromandel Peninsula in Moehau Survey District at Paritu Point (David Kear and John Reed, personal communication). The unit has been mapped as Paritu Tonalite (Thompson, 1960).

In hand specimen, the sample is a fresh fine- to medium-grained grey and black dioritic rock. Occasional rounded inclusions, 1-2 cm, of darker finer-grained rock occur. A chemical analysis is shown in Table A6.

In thin section, the following mineralogy is noted:

62%	1.	Plagioclase - seriate 6 mm-0.3 mm, strongly zoned, subhedral laths, carlsbad twinned; mid labradorite to calcic oligoclase on edge; average composition probably mid andesine or sodic andesine.
20%	2.	Quartz - generally small anhedral interstitial isolated grains.
10%	3.	Hypersthene - anhedral, up to 5 mm; altering to uralite (?); poikilitically includes biotite and magnetite.
7%	4.	Potassium Feldspar - fresh and unaltered, small grains to 1 mm; angular interstitial grains.
1%	5.	Magnetite
	6.	Apatite
	7.	Zircon - uncommon.
	8.	Muscovite - rare.

This rock is a fine-grained holocrystalline, hypidiomorphic tonalite. Subophitic texture is well developed with plagioclase subhedral laths being

TABLE A6

PUBLISHED CHEMICAL ANALYSIS OF COROMANDEL GRANITE[*]

SiO_2	57.32
Al_2O_3	17.69
Fe_2O_3	2.24
FeO	5.62
MnO	0.21
CaO	6.50
MgO	3.66
K_2O	1.25
Na_2O	4.04
TiO_2	0.85

---

[*] Fraser (1908)

roughly stacked in subparallel fashion, and all other grains being interstitial except for a few large hypersthene grains. Potassium feldspar is associated with biotite and may rim or partially enclose biotite. Some fine-grained auto-inclusions (?) up to 3 cm in diameter occur consisting mainly of fine-grained (0.1-0.3 mm) hypersthene and plagioclase, biotite being scarce. The inclusion rim is rich in hypersthene and biotite, the latter rimming magnetite and is occasionally itself rimmed by hypersthene. Rare fine muscovite is seen to rim magnetite. Rock appears very fresh although hypersthene is reacting to uralite (?) and biotite and chlorite.

* * *

Moeatoa Conglomerate Boulder (NICG)

This sample was collected by Professor H. W. Wellman as an at least 45 Kg boulder which occurred in the Moeatoa Formation. The locality is 150 meters north of Kaitangata Point on the west coast of the North Island south of Kawhia Harbor. In hand specimen, the sample is a medium-grained massive greenish-grey granitic or dioritic rock.

The thin section reveals the following mineralogical composition:

42% 1. Plagioclase - variously zoned lightly to moderately, calcic oligoclase to sodic andesine, albite and carlsbad twinned; 0.5 mm-1 cm, seriate.

20% 2. Quartz - mainly isolated 1-4 mm grains, anhedral; some quartz grains include plagioclase and hornblende.

18% 3. Potassium Feldspar - interstitial, angular average 1 mm; up to 1 cm; larger grains poikilitically include plagioclase, hornblende, quartz and biotite.

10% 4. Biotite - average 5 mm, isolated grains, 5% chloritized (chlorite: light brown-dark green anomalous brown interference color). Biotite has a strange non-fresh appearance. Broad dusky zones of ironstaining along cleavages. Abnormal irregular mottled extinction optically (-).

8% 5. Hornblende - average size 3 mm, dark olive green-light straw brown, anhedral.

2% 6. Magnetite - euhedral square outlines.

7. Apatite

1/2% 8. Sphene - euhedral flattened diamonds up to 3 mm.

9. Zircon - not uncommon - fairly large, no halo seen in biotite.

10. Chlorite - intergrown with hornblende and biotite, may be alteration of these.

Rock is a holocrystalline hypidiomorphic medium-grained intergranular granodiorite. The coarse intergranular texture is dominated by plagioclase laths with interstitial quartz and potassium feldspar. Less common coarser grains of the latter two minerals show an ophitic relationship with the plagioclase laths. Alteration of the rock is shown by the slight sericitization of plagioclase and unusual mottled ironstained appearance of biotite.