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Chemistry and Mineralogy of the Mt Falconer Pluton and  
Associated Rocks, Lower Taylor Valley, South Victoria Land,  
Antarctica

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*Abstract*

CHEMICAL and mineralogical data are presented for samples from the Mt Falconer quartz monzonite pluton, the wall rocks and the associated intrusions. A detailed account of petrography and structure was given in an earlier paper (Ghent and Henderson, 1968).

Chemical analyses of total rocks indicate that the major element chemistry of the Mt Falconer pluton is very similar to that of other granite bodies mapped as Irizar Granite.

Potassium-rubidium ratios of total rocks fall on the "main" trend (150-300), however, they do not indicate the complexity of the igneous events in the Mt Falconer area.

Mafic dykes are considered to be genetically related to the emplacement of the Mt Falconer pluton. Small amounts of mafic magma are inferred to have been mobilised by hot, water-undersaturated quartz monzonite magma.

Strontium partition between alkali feldspar and plagioclase is not a reliable geothermometer for the Mt Falconer pluton; this is likely to be due to subsolidus redistribution of strontium.

Field and chemical evidence indicate that the Skelton Group amphibolites in the Mt Falconer area are para-amphibolites.

Phase relations of alkali feldspar, plagioclase, and quartz in the Mt Falconer pluton, when compared to the experimental data, are compatible with early magmatic crystallisation of plagioclase followed by quartz and alkali feldspar.

INTRODUCTION

THE Mt Falconer quartz monzonite pluton is located in the Lower Taylor Valley, South Victoria Land, Antarctica (about 77°30'S, 163°08'E, see Ghent and Henderson, 1968: 852, for a location map). This pluton was studied during the summer of 1965-66 by Victoria University of Wellington Antarctic Expedition No. 10, and a paper on the petrography and structure, including a geological map, has been published elsewhere (Ghent and Henderson, 1968).

A brief summary of the geology will be given here: for details and for the locations of samples referred to in this paper see Ghent and Henderson (1968).

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The pre-Beacon Group rocks consist of, in order of decreasing age: (1) Skelton Group metasedimentary rocks (amphibolite facies); (2) granodiorite gneiss; (3) diorite "hybrid", microdiorite to trachydiabase, and granophyre dykes; (4) the discordant, epizonal Mt Falconer quartz monzonite pluton (about two square miles in outcrop area); and (5) silicic and camptonite dykes. The pluton and the dykes cut off the foliation and gneissosity of the Skelton Group rocks and the granodiorite gneiss at high angles, but there is no apparent deflection of earlier structural trends. Dykes of unit (3) are cut off at a low angle by the pluton, which is in turn cut by leucocratic and camptonite dykes of unit (5) along the same structural trend as the earlier dykes.

In this study total rock major and trace element data are reported for three samples of quartz monzonite, three samples of mafic dyke rocks, and one sample each of granophyre, diorite "hybrid", and Skelton Group amphibolite. In addition, major and trace element data on feldspars, biotites, and amphiboles from the Mt Falconer pluton and associated rocks are reported. As an indication of the accuracy of the analyses reported in this paper, U.S. Geological Survey silicate rock standards have been analysed and these analyses are reported in the appendix. A discussion of the accuracy of electron microprobe analyses is also contained in the appendix.

The chemical data are discussed with reference to the following problems: (1) crystallisation of the quartz monzonite in light of experimental data; (2) major-element chemistry and structural state of feldspar; (3) origin of mafic dykes; (4)

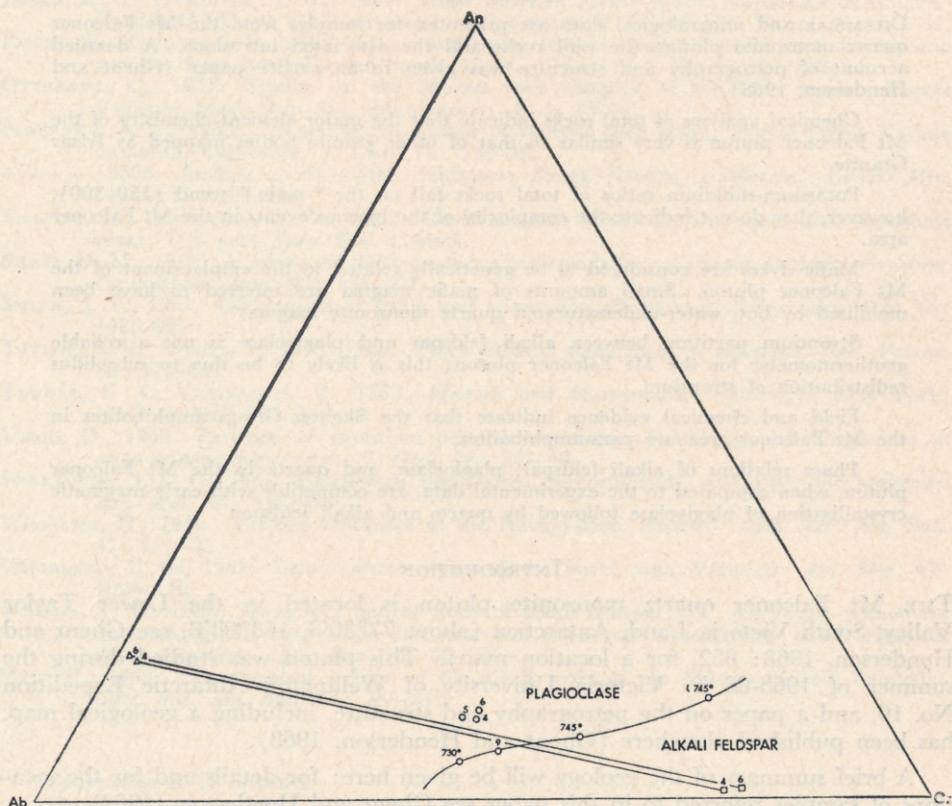


FIG. 1.—Quartz-saturated anorthite-albite-orthoclase systems at 1000 bars water vapour pressure (data from James and Hamilton, 1969). Squares indicate feldspars, circles with single numbers, e.g., 6, total rocks; and temperatures at 3 points on the cotectic line are also indicated; sample numbers refer to analysis numbers in Table I.

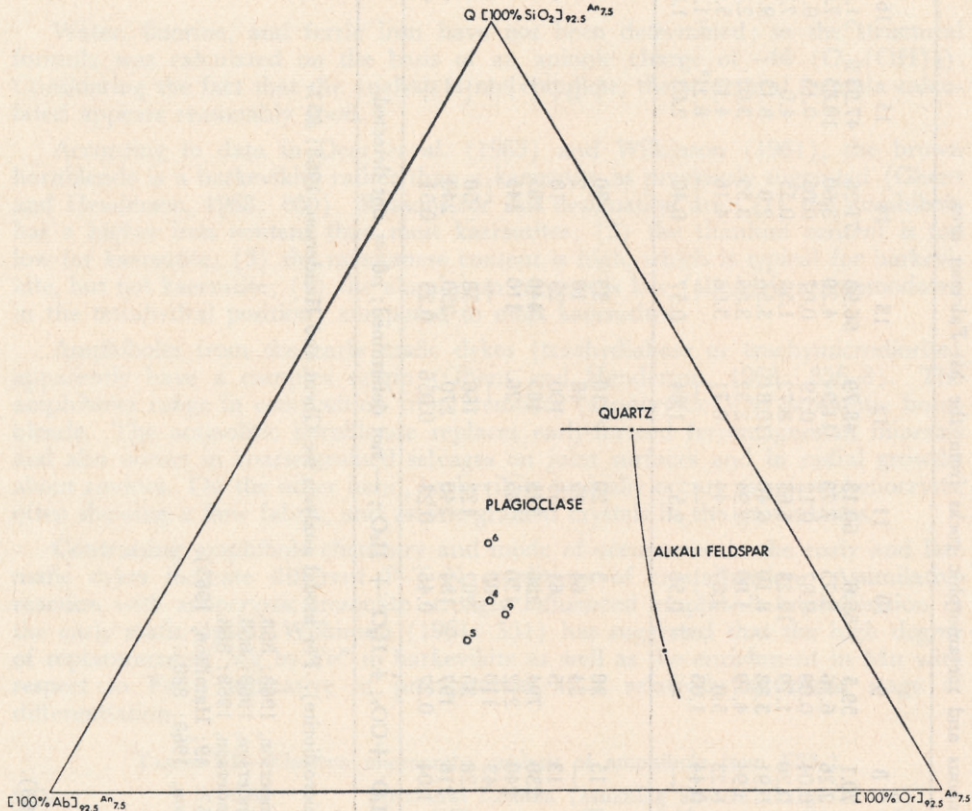


FIG. 2.—Quartz–albite–orthoclase system with a fixed (7.5 wt percent) anorthite content. Circles with adjacent numbers indicate total rock analysis and refer to the same samples which were plotted in Figure 1. (Experimental data from James and Hamilton, 1969.)

interpretation of K:Rb ratios in total rocks and minerals; (5) Sr partition between alkali feldspar and plagioclase; (6) the origin of the Skelton Group amphibolites.

#### MAJOR-ELEMENT CHEMISTRY OF TOTAL ROCKS

##### Introduction

Partial chemical analyses of nine total rock samples from the Mt Falconer area are presented in Table I. Analytical methods and estimates of reliability of analyses are presented in the appendix.

##### Mt Falconer Pluton

Ghent and Henderson (1968: 867–8) presented modal analyses suggesting that the Mt Falconer pluton was relatively homogeneous with respect to mineralogical composition. A comparison of three total-rock analyses from the pluton with the average of five analyses of Irizar Granite from elsewhere in Victoria Land indicate that the plutonic rocks which have been mapped as Irizar Granite have a limited spectrum of chemical variability.

Bottinga *et al.* (1966) have criticised the use of normative mineral compositions in experimental systems. In the present study a more realistic “norm” was calculated from the chemical analyses by subtracting  $K_2O$  and  $SiO_2$  for biotite<sup>1</sup> and

1. Analyses were corrected by subtracting 0.45 percent  $K_2O$  and 1.9 percent  $SiO_2$  for biotite in the quartz monzonites and granophyres.



allocating the appropriate amounts of  $\text{Na}_2\text{O}$ ,  $\text{K}_2\text{O}$ ,  $\text{CaO}$ , and  $\text{SiO}_2$  to albite, orthoclase, and anorthite respectively. The remaining  $\text{SiO}_2$  is taken as quartz. The single chemical analysis of a granophyre (No. 9) was treated in the same way. These data have been plotted in the An-Ab-Or-Qz system in Figs. 1 and 2 and the interpretation of these data is given below.

#### *Mafic Dykes*

Pre-Mt Falconer pluton dykes were termed biotite-hornblende (clinopyroxene) microdiorites by Ghent and Henderson (1968), but many of the samples contain abundant alkali feldspar and these rocks might be more appropriately termed trachydiabase or trachymicrodiorite.

Mafic dyke rocks of the lamprophyre clan show a wide variation in mineralogy and chemistry. For comparative purposes chemical analyses of a trachydiabase from Vermont (Woodland, 1962: 1098), a minette from north-east Arizona (Williams, 1936: 166), and the average basalt (Taylor and White, 1966) are presented in Table I. A discussion of the significance of these chemical data is given in the section on the origin of the mafic dykes.

#### *Potassium-rubidium Ratios*

Potassium-rubidium ratios have long been a major topic of research in the geochemistry of igneous rocks. Shaw (1968) has recently reviewed the subject, using a statistical approach. The main issue in K/Rb studies is whether the ratio remains constant or decreases steadily during igneous differentiation. According to Shaw (1968) there are three principal trends, one of which, called the main trend, closely fits a straight line with  $\log \text{ppm (Rb)} = 1.115 \log (\% \text{K}) + 1.597$ , i.e., in the K/Rb range of 150–300. The other trends are the oceanic tholeiite trend with K/Rb about 3000 and the pegmatite-hydrothermal trend with K/Rb about 50 or less. All of the K/Rb ratios from the Mt Falconer igneous rocks fall on the main trend. The ratios vary from 162 in the quartz monzonite to 228 in the mafic dykes and there appears to be a decrease in the K/Rb ratios with decreasing age of emplacement, fitting an apparent "fractionation trend". An examination of the field and petrographic evidence, however, indicates that there was a complex sequence of events during the emplacement of the igneous rocks. Early-formed mafic dykes are composed largely of biotite, amphibole, and feldspar. According to Shaw (1968: 592) ratios on the main trend are controlled largely by modal abundances of hornblende (high K/Rb) and biotite (low K/Rb). The mafic dykes then have K/Rb ratios which are largely an average of the contributions of hornblende and biotite (and feldspar). Diorite "hybrids" contain abundant late-stage potassium feldspar, sodic plagioclase, biotite, and quartz. Ghent and Henderson (1968: 864–5) noted that there appeared to be no correlation between the anorthite content of the plagioclase in these rocks and their modal abundance of alkali feldspar and quartz. They concluded that a fluid phase rich in K, Na, and Si had been introduced non-uniformly into the dioritic rocks. The K/Rb ratios of the diorite "hybrids" are intermediate between those of the mafic dykes and those of the quartz monzonite (FL-12 gives a ratio of 197). This value falls on the main trend and indicates, by itself, nothing unusual about the crystallisation of the rock. In addition, the volume relations of quartz monzonite, mafic dykes, and diorite "hybrid" are incompatible with a "normal" sequence of igneous differentiation. The conclusion to be drawn is that uncritical use of K/Rb ratios may lead to an erroneously oversimplified view of igneous petrogenesis.

#### *Origin of the Mafic Dykes*

The origin of mafic dykes associated with granitic plutons has long been debated, e.g., see Oftedahl (1957), Turner and Verhoogen (1960: 250–6) and Bateman *et al.* (1963: 25–7). The writer feels that the following points are critical in the interpretation of the origin of the mafic dykes in the Mt Falconer area: (1) the

thin mafic dykes and the quartz monzonite pluton are closely associated in space and time and they crystallised in a similar stress environment (Ghent and Henderson, 1968: 876); (2) the volume of mafic rocks, including the coarser diorite "hybrids", is far less than that of the quartz monzonite pluton; (3) chemically and mineralogically there are some rock types intermediate in composition between the mafic rocks and the quartz monzonites, but their volume is very small and they can be more reasonably interpreted in terms of reaction between quartz monzonite magma and partially crystallised mafic magma rather than by conventional fractionation; (4) the mafic dykes contain abundant quartz xenocrysts; (5) the early mafic dykes contain abundant inclusions of tremolite and actinolite amphibolite.

The following modes of origin for the mafic dykes seem to be worthy of discussion: (1) the mafic dykes crystallised from a contaminated basaltic magma, and the basaltic magma was derived from a deep source separate from that of the quartz monzonite; and (2) the dyke magma was mobilised from masses of older diorite, gabbro, mafic volcanic rock, or amphibolite.

The best argument against a deep independent source for the dyke magma is that only small amounts are intruded and that these are emplaced both before and after the emplacement of more silicic plutonic rocks. To regularly derive small quantities of mafic magma from a deep-seated source independently of the associated silicic magmas would seem to require an unnecessarily complex plumbing system. A local source for the mafic magma seems more probable and the next question is whether there is a genetic connection between the emplacement of the mafic dykes and the emplacement of the quartz monzonite pluton. Field data are compatible with a related genesis for the mafic and silicic rocks.

Experiments show that initial melting temperatures of mafic and silicic rocks converge at high water pressures (on the order of 10 kilobars) (Fig. 1). "Dry" and water-undersaturated rocks have beginning of melting curves with positive slopes on a pressure-temperature diagram. It is possible then to conceive of a hot, water-undersaturated silicic magma causing partial melting of water-rich mafic rocks.

The initial melting behaviour of Mt Falconer mafic rocks will probably be bracketed by the beginning of melting curves for water-saturated alkali basalt and tonalite (Fig. 1). Beginning of melting curves for water-saturated and "water-undersaturated" Sierra Nevada granite are considered to approximate the initial melting behaviour of Mt Falconer quartz monzonite.

What is the evidence for the water content of the Mt Falconer mafic and silicic magmas? Combined water in hydrous minerals is higher in the mafic dykes than in the quartz monzonite (Table I), but since the present water content may represent only a minimum value for each magma, this evidence can be considered only permissive. The presence of patchy zoning (Vance, 1965) in plagioclase in the quartz monzonite and the general lack of patchy zoning in the plagioclase of mafic dykes (Ghent and Henderson, 1968: 858) is consistent with a higher water content in the mafic magma. Patchy zoning is interpreted to have formed by resorption and later precipitation of plagioclase in a water-undersaturated magma which moved upward in the crust with a concomitant decrease in load pressure.

The mafic dykes locally contain abundant interstitial alkali feldspar and sodic plagioclase. One possible source of the alkalis and silica is a metasomatic addition from the quartz monzonite magma. In any case these components would also tend to lower the melting temperature of the mafic rocks.

In summary, the field, petrographic, chemical, and experimental data allow one to reasonably speculate that the quartz monzonite magma could have caused mobilisation of small volumes of mafic rocks.

The early mafic dykes are hybrid rocks in the sense that they are composed of material from more than one source. The presence of partially digested xenoliths of amphibolites and xenocrysts of quartz are the best evidence for a hybrid origin.

Several possible combinations of magma and xenoliths could give rise to the above relationships: (1) a mafic (basaltic) magma contaminated with amphibolite xenoliths and quartz xenocrysts; (2) a remobilised alkali and silica metasomatised amphibolite with quartz xenocrysts and undigested amphibolite remnants. A unique solution to the problem cannot be given, since the unaltered condition of each of the components, e.g., mafic magma, is not known. Amphibolite exposed in the Mt Falconer area may not be representative of amphibolite at depth. Examination of chemical analyses in Table I indicates that a simple combination of amphibolite, such as represented by analysis 10, with quartz monzonite magma or with "average" basaltic magma (Taylor and White, 1966) cannot produce the present chemistry of either the early or the late mafic dykes. Simple mobilisation of amphibolite, with additions of alkalis and silica, is also incompatible with the chemical data. (Compare, for example, the silica, iron, and lithium contents of the mafic dykes and the amphibolite.)

The hypothesis favoured by the writer is that mafic rocks (basaltic?) were partially melted and metasomatised by hot, water-undersaturated quartz-monzonite magma. This alkali-rich mafic magma later incorporated and reacted with amphibolite xenoliths similar to those in the Skelton Group rocks. The late mafic dykes could have had a similar origin, except that a source rock of slightly different composition was melted and the magma was not strongly contaminated with amphibolite. If the late mafic magma was mobilised by silicic magma the latter is not exposed as a crystallised pluton in the Mt Falconer area.

#### Major Element Chemistry and Structural State of Feldspar

*Plagioclase:* Plagioclase from the Mt Falconer pluton shows strong microscopic compositional zoning. Analyses of plagioclase-quartz mixtures are presented in Table II and are recalculated to plagioclase, assuming no CaO and Na<sub>2</sub>O in quartz. These analyses are considered to represent an approximation to the mean plagioclase composition of the total rocks.

TABLE II.—Atomic absorption analyses of plagioclase quartz mixtures. Data in ppm except where given as %.

Sample No.	CaO%	Na <sub>2</sub> O%	An wt % (corr) <sup>1</sup>	Sr	D <sup>2</sup>	X-ray <sup>3</sup>
FP-1	3.59	4.05	34	620	0.72	An <sub>30</sub>
FP2-1	1.25	3.31	18	1150	0.36	An <sub>24</sub>
FP2-4	1.76	3.71	22	820	0.56	An <sub>28</sub>
FP2-6	1.65	3.61	21	840	0.38	—
FP2-11	1.62	3.75	20	not det.	not det.	An <sub>24</sub>
FP2-17	1.62	3.38	22	890	0.37	—
FL 9	3.41	4.49	31	1820	0.42	—
FS 10	5.0	3.92	43	1160	0.56	—

not det. = not determined.

<sup>1</sup>Recalculated assuming all CaO and Na<sub>2</sub>O in plagioclase.

<sup>2</sup>D = wt in ppm Sr in alkali feldspar/wt in ppm Sr in plagioclase.

<sup>3</sup>Composition estimated from X-ray diffraction; see Ghent and Henderson, 1968: 867-8.

Microprobe analyses of plagioclase in thin section indicate about 1.5-2.0 wt percent Or (0.25-0.3 K<sub>2</sub>O) in solid solution. These results would change the An wt percent estimate by no more than 1 wt percent An.

In a previous study Ghent and Henderson (1968: 867-8) reported estimates of plagioclase composition based on X-ray diffraction, following procedures suggested by Hall (1965). This method assumes (1) the plagioclase is in the low-temperature

structural state, and (2) the composition of the plagioclase is not severely skewed. Data presented in Table II shows that the X-ray diffraction method overestimates the anorthite content of the plagioclase in three samples and underestimates it in a fourth. These data could be interpreted to mean that the composition of the plagioclase in the mineral separates are compositionally skewed toward more anorthite-rich compositions than the mean in three of the samples and toward less anorthite-rich compositions than the mean in the fourth sample. If the disagreement between the X-ray method and the chemical analysis were entirely due to the occurrence of intermediate structural state rather than low-temperature structural state, the anorthite content of *all* of the samples would have been overestimated.

### *Alkali Feldspar*

Alkali feldspars from the Mt Falconer pluton and associated rocks have been studied by a combination of X-ray diffraction, atomic absorption spectroscopy, and electron microprobe analyses.

In the earlier study the alkali feldspar was characterised as orthoclase microperthite with low (0.0–0.18)  $\Delta$  (obliquity) values. Three alkali feldspars have been restudied in more detail, following the methods outlined by Wright (1968). The results are presented in Table III.

TABLE III.—X-ray diffraction data on alkali feldspars.

Sample No.	204*	060	$\bar{2}01$ (observed)	$\bar{2}01$ (theoretical)	$\Delta \bar{2}01$ (difference)
FP2-6	50.75	41.745	21.035	21.35	0.30
FP2-1	50.763	41.726	21.075	21.35	0.28
FS-10	50.745	41.71	21.04	21.30	0.26

\* Reflection in  $^{\circ}2\theta$  Cu K alpha.

According to Wright (1968) the observed and predicted  $2\theta$  for  $\bar{2}01$  should agree to  $0.1^{\circ}$  or else the feldspar is termed "anomalous". Feldspars with anomalous cell dimensions can be labelled according to structural state, but the cell dimensions cannot be used to estimate composition. All of the Falconer samples fall near the orthoclase structural series on a 204–060 plot (Wright, 1968: 91).

Compositions estimated from homogenised alkali feldspar by the  $\bar{2}01$  method, however, agree to within 2–3 wt percent of the Or/Or + Ab + An values obtained from atomic absorption. Agreement with the electron probe analyses, however, is not as good. This can be attributed to the difference in sampling, since in the homogenisation and atomic-absorption study of mineral separates calcic plagioclase impurities were included in the analysis, whereas in the microprobe analyses they were avoided.

### *Trace Elements from Alkali Feldspars*

Trace-element ratios in alkali feldspars have been considered to be useful in estimation of the degree of fractionation of magmas (e.g., Kolbe and Taylor, 1966). Trace-element data on alkali feldspars from the Mt Falconer area are presented in Table IV, and data from the feldspars of the Cape Granite are included for comparison. According to Kolbe and Taylor (1966) the differentiation sequence in the high level Cape Granite is coarsely porphyritic granite, medium-grained granite, fine-grained granite. The K/Rb and Rb/Sr ratios of the alkali feldspars from the Mt Falconer pluton are comparable to those from the early coarsely porphyritic granite of the Cape Granite. Ca/Sr ratios are difficult to compare, because Kolbe and Taylor based their analyses entirely on mineral separates. Electron microprobe study of the mineral separates from the Mt Falconer pluton indicates that they contain antiperthite and other calcium plagioclase impurities.



TABLE IV.—Analyses of alkali feldspar from the Mt Falconer area. Data in ppm except where given as %.

Sample No.	1	2	3	4	5	6	7	8	9	10
CaO%	0.23(0.12)	0.29(0.10)	0.38(0.14)	0.41(0.12)	0.35(0.12)	0.67(0.06)	0.96(0.10)	0.22	0.19	0.22
Na <sub>2</sub> O%	2.43(2.75)	2.15(2.59)	2.56(2.36)	2.64(2.82)	2.54(2.51)	2.23(1.85)	1.59	2.38	1.89	2.21
K <sub>2</sub> O%	(12.97)	(12.9)	(13.4)	(12.9)	(13.3)	(14.0)	(14.1)	13.12	13.96	13.27
Li	3.4	3.1	2.5	4.8	2.9	4.2	5.2	4.7	4.8	6.4
Sr	444	412	456	315	329	767	647	166	94	44
Rb	439	479	415	490	458	372	480	410	540	640
Or wt %	76.9	76.6	79.4	76.4	78.6	82.8	83.6	77.79	82.77	78.71
Ab wt %	23.2	21.9	19.9	23.8	21.2	15.6	16.0	20.06	15.96	18.70
An wt %	0.6	0.5	0.7	0.6	0.6	0.3	0.5	1.09	0.96	1.07
Total wt %	100.7	99.0	100.0	100.8	100.4	98.7	100.1			
Ratios										
K/Rb	246	224	269	219	241	312	244	267	215	173
Rb/Sr	0.99	1.16	0.91	1.55	1.39	0.48	0.74	2.5	5.7	14.5
Ca/Sr	1.93	1.73	2.19	2.74	2.6	0.6	1.1	9.5	14.8	3.5

\* Electron probe analyses on alkali feldspars given in parentheses, all other analyses of Falconer samples by atomic absorption.

1. FP-1 from quartz monzonite, 201 method gives Or 75 Ab + An 25.
2. FP2-1 from quartz monzonite.
3. FP2-4 from quartz monzonite, bulk probe analyses on all grains CaO 0.38, Na<sub>2</sub>O 2.79.
4. FP2-6.
5. FP2-17.
5. FL-9 "Diorite hybrid".
7. FS-10 from Skelton Group schist near contact with pluton, contains diopside, tremolite, plagioclase, quartz, biotite, alkali feldspar.
8. Average of 35 analyses of feldspars coarsely porphyritic granites, Kolbe and Taylor, 1966, p. 213-14.
9. Average of nine analyses of feldspars medium grained granitic, Kolbe and Taylor, 1966, p. 213-14.
10. Average of nine analyses of feldspars fine grained granites, Kolbe and Taylor, 1966, p. 213-14.

## STRONTIUM PARTITION BETWEEN ALKALI FELDSPAR AND PLAGIOCLASE

*Introduction*

Barth (1961) suggested the possibility of using the distribution of strontium between alkali feldspar and plagioclase as a geothermometer. Virgo (1968) has presented evidence that strontium partition between alkali feldspar and plagioclase shows a regular behaviour with increase in metamorphic grade from the middle amphibolite facies to the granulite facies. The distribution coefficient  $K_d$  ( $K_d = X^k_{sr}/X^p_{sr}$  where  $X =$  mole fraction and  $K =$  alkali feldspar and  $p =$  plagioclase) is usually near 1 for amphibolite facies rocks and greater than 1 for granulite facies rocks. Virgo also quotes unpublished experimental data suggesting that  $K_d$  increases with increasing temperature. Iiyama (1968) has recently presented experimental data on partitioning of several trace elements between alkali feldspar and plagioclase at 1000 bars water pressure and 600°C for feldspars of differing composition. The fractionation coefficient  $D$ , where  $D =$  Sr ppm in alkali feldspar/Sr ppm in plagioclase ranges from 0.80 to 0.85.

*Application to Mt Falconer Plagioclase:*

Data for co-existing feldspars from the Mt Falconer pluton and the associated Skelton Group and diorite "hybrid" are presented in Table III. The fractionation co-efficient  $D$  for the feldspars of the pluton varies from 0.36 to 0.72, with the highest value coming from a fine-grained sample (FP-1) near the contact with the wall rocks. A schist from the Skelton Group has a  $D$  value of 0.56, which is lower than any of the amphibolite facies fractionations quoted by Virgo (1968).

If the strontium feldspar "geothermometer" were taken literally, one would infer temperatures of crystallisation of less than 600°C with little temperature variation between pluton and wall rock. Can we account for this apparent contradiction?

Berlin and Henderson (1969) have reported that analyses of Sr in co-existing plagioclase and alkali feldspar phenocrysts, rock groundmasses, and total rocks of porphyritic trachytes and phonolites indicate that plagioclase is a better solvent for Sr than alkali feldspar at liquidus temperatures, i.e.,  $D$  is less than 1. They point out that data reported from coarse-grained plutonic rocks are often contradictory, e.g.,  $D$  greater than 1 for gneisses and granite in Northern Norway and  $D$  generally less than 1 for Donegal granites. They (p. 248) suggest that these contradictory data may be due to "subsolidus rearrangements". The discrepancy between the experimental data on fractionation and the observed fractionation between feldspar phenocrysts in trachytes and phonolites, however, remains unexplained. One possibility is that the experimental data do not represent equilibrium fractionation and a second possibility is that the observed fractionation in natural feldspars is not a simple function of temperature. It is difficult to evaluate these two possibilities, but some data are available to speculate on the subsolidus re-arrangement of Sr.

Arriens *et al.* (1966), report examples of discordant Rb-Sr mineral ages in granitic rocks from Australia, from which they present strong evidence for expulsion of radiogenic strontium from K-feldspar and its accumulation in plagioclase and other calcium minerals. The extent of the expulsion and whether it includes much common strontium as well as radiogenic strontium depends at least in part on the intensity of the subsolidus event. Arriens *et al.* report (p. 4993) that the change of state from a high temperature K-feldspar to a low temperature K-feldspar is accompanied by the expulsion of Sr (K-feldspars with low obliquities gave younger Rb-Sr ages). Presumably perthitic exsolution of albite from K-feldspar would also result in expulsion of Sr. Strontium is unlikely to substitute readily into the perthitic albite and a likely accumulator is myrmekitic oligoclase and other grains of groundmass plagioclase. Expulsion of Sr from K-feldspar at low temperatures would result in lowering of  $D$  values, and because this is likely to be a non-

equilibrium process the D values would show wide scatter. The Sr distribution between feldspars in granitic rocks would thus seem to be an unreliable geothermometer.

#### CRYSTALLISATION OF QUARTZ MONZONITE IN LIGHT OF EXPERIMENTAL DATA

Ghent and Henderson (1968) have presented field and petrographic evidence that the emplacement of the Mt Falconer pluton could be reasonably interpreted in terms of magmatic crystallisation. Chemical data on total rocks and feldspars can be used to interpret the crystallisation history of the Mt Falconer pluton in light of recent studies in the "granite" system.

The feldspar boundary curve in the quartz-saturated albite-anorthite-orthoclase system at 1000 bars water pressure is plotted in Fig. 1 (James and Hamilton, 1969). Compositions of co-existing feldspars for two samples and recalculated analyses of three total rocks are plotted in the same figure.

Lines connecting feldspar compositions should pass through the points representing the recalculated total rocks analyses. Two possible reasons for this slight inconsistency are: (1) the mineral analyses are not representative of the average feldspar composition of the total rock; (2) recalculation of the rock analyses to the albite-anorthite-orthoclase system is in error.

Ghent and Henderson (1968: 870) have concluded from petrographic evidence that plagioclase began to crystallise before alkali feldspar. This conclusion is consistent with the fact that the recalculated analyses plot in the plagioclase field.

Plagioclase from the Mt Falconer pluton is chemically zoned and consequently the feldspar analyses represent the "average" composition of plagioclase that crystallised and the line connecting the composition of plagioclase to the composition of alkali feldspar cannot be a true tie line. The composition of the existing feldspars, however, is comparable to that reported from other granitic rocks (Piwinskii, 1968a) and from hydrothermal experiments on granitic melts (Piwinskii, 1968b).

If the rock analyses are recalculated and plotted in the albite-orthoclase-quartz system with fixed anorthite content (7.5 weight percent) (Fig. 2, from James and Hamilton, 1969), they also plot in the field of plagioclase and are far removed from the projected plagioclase-quartz boundary curve at 1000 bars water pressure. Unfortunately the petrographic evidence is not clear as to the time relations of crystallisation of quartz and alkali feldspar so that a crystallisation path cannot be suggested.

One porphyritic granophyre (Fig. 3) has been analysed and the recalculated analysis is plotted in Figs. 1 and 2 (Analysis 9). In the quartz-saturated anorthite-albite-orthoclase system (Fig. 1) the analysis plots very near the feldspar boundary curve. This plot is consistent with the occurrence of phenocrysts of plagioclase and alkali feldspar. A possible interpretation is that plagioclase and alkali feldspar crystallised together from a granitic liquid, which later, because of a change in physical conditions, crystallised to yield a micrographic intergrowth of alkali feldspar and quartz.

#### BIOTITE

The composition of biotite in certain mineral assemblages is potentially useful in the estimation of physical conditions of crystallisation (Wones and Eugster, 1965; and Rutherford, *J. Petrol.*, in press). In the present study ferrous and ferric iron determinations were made on two mineral separates (Table V). Electron microprobe study indicates strong Fe-Mg zoning in the biotites, consequently the wet chemical analyses represent "average" compositions for the biotites.

Ilmenite, magnetite, and hematite occur in the Mt Falconer pluton, but the magnetite and hematite are associated with secondary minerals such as chlorite and

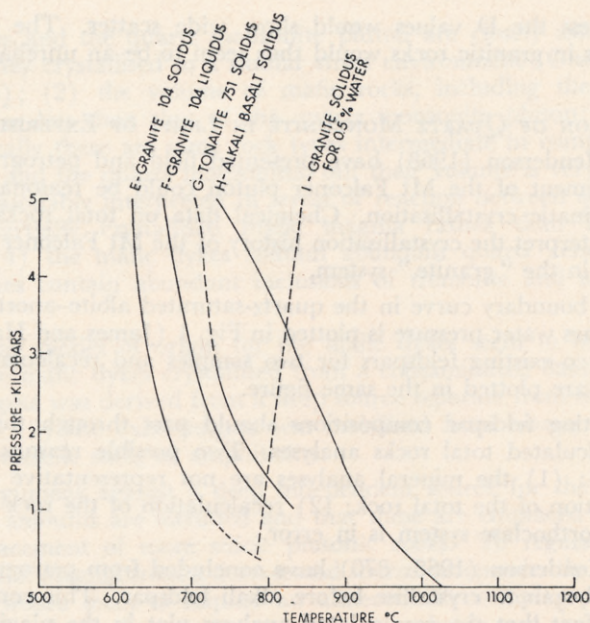


FIG. 3.—Solidus and liquidus curves for granite, tonalite, and alkali basalt as a function of pressure, temperature, and water content (data from Piwinski, 1968a).

sericite and are considered to be postmagmatic. If the ilmenite is magmatic, oxygen fugacities less than that of the magnetite-hematite buffer are suggested (Buddington and Lindsley, 1964). According to Wones and Eugster (1965: 1264) the ratio of  $Fe^{IV}/Fe^{III} + Fe^{II}$  is about 0.25 for hematite-magnetite buffer conditions, 0.10 for nickel-nickel oxide buffer conditions, and 0.05 for fayalite-magnetite-quartz buffer conditions. The ferric iron content of biotite from FP2-17 appears to be too high to be in equilibrium with ilmenite and suggests the possibility of oxidation during late-stage hydrothermal alteration (see Ghent and Henderson, 1968: 866). The ferric iron content of biotite from FP2-6 appears compatible with the presence of ilmenite, and presumably this biotite was more resistant to late-stage oxidation.

Estimations of water fugacity during the crystallisation of the Mt Falconer pluton based upon biotite composition have not been attempted. Until the effects of Ti and F on the stability of biotite have been experimentally determined, estimates of the fugacity of water are of limited reliability.

TABLE V.—Partial chemical analyses of biotite from the Mt Falconer pluton.

Sample No.	FP2-6	FP2-17
$Fe_2O_3$	4.67*	7.94
FeO	23.29	20.52
$Fe^{IV}/Fe^{III} + Fe^{II}$	0.16	0.26

\* Analyses by Technical Services Laboratories, Toronto.

#### AMPHIBOLES

Electron microprobe analyses of amphiboles from the Mt Falconer pluton and early mafic dykes and xenoliths were presented in an earlier paper (Ghent and Henderson, 1968: 859, 872). In the present study, electron microprobe analyses of brown hornblende from one camptonite dyke (FB3-2) were obtained. The analyses and a calculated structural formula are presented in Table VI.

Water, fluorine, and ferric iron have not been determined; so the structural formula was calculated on the basis of an anionic charge of  $-46$  ( $O_{22}(OH)_2$ ). Considering the fact that the analysis is not complete, the structural formula calculated appears reasonably good.

According to data in Deer *et al.* (1963) and Wilkinson (1961), the brown hornblende is a barkevikite rather than a kaersutite as previously suggested (Ghent and Henderson, 1968: 880). Reasons for this designation are: (1) the amphibole has a higher iron content than most kaersutites; (2) the titanium content is too low for kaersutite; (3) the manganese content is high, which is typical for barkevikite, but not kaersutite; (4) the aluminium content is low (all Al is accommodated in the tetrahedral position) compared to most kaersutites.

Amphiboles from the early mafic dykes (trachydiabase or trachymicrodiorite) apparently have a complex origin (Ghent and Henderson, 1968: 856–8). The amphiboles range in composition from tremolite (xenocrystic?) to actinolitic hornblende. The actinolitic hornblende replaces early-formed ferromagnesian minerals and also occurs in coarse-grained selvages on joint surfaces and in radial growths about cavities. On the other hand, barkevikite typically occurs as microphenocrysts, often showing a flow fabric, and as fine-grained crystals in the groundmass.

Contrasting amphibole chemistry and mode of occurrence in the early and late mafic dykes indicate different P–T–X conditions of crystallisation. Assimilative reaction with xenocrystic tremolite strongly influenced amphibole crystallisation in the early mafic dykes. Wilkinson (1961: 351) has suggested that the high degree of replacement of Mg by Fe<sup>2+</sup> in barkevikite as well as the enrichment in Mn with respect to Fe is indicative of precipitation at a relatively advanced stage of differentiation.

TABLE VI.—Electron microprobe analysis of amphibole from FB3-2.

SiO <sub>2</sub>	40.62	Structural formula	(assuming anionic charge of -46)		
TiO <sub>2</sub>	4.14	Si	5.93	Ti	0.45
Al <sub>2</sub> O <sub>3</sub>	11.85	Al	2.04	Fe <sup>2+</sup>	1.85
FeO*	15.19			Mg	2.40
MnO	1.63		7.93	Mn	0.20
MgO	11.03				
CaO	8.29				4.90
Na <sub>2</sub> O	2.27				
K <sub>2</sub> O	1.32				
Total	96.36				

\* Total iron as FeO.

Examination of total rock analyses of two early mafic dyke and one camptonite sample indicate very little difference in Mg/Fe ratios, but the camptonite does have a slightly higher Mn content. Silica, however, is lower in the camptonite than in the early mafic dykes, suggesting a less advanced stage of differentiation.

#### AMPHIBOLITES

Amphibolites of the Skelton Group in the Mt Falconer area are associated with metamorphic rocks of undoubted sedimentary origin (Ghent and Henderson, 1968: 854). They occur as thin concordant layers within the metasedimentary rocks. Marbles have not been observed in the Mt Falconer area, but are associated with amphibolite and calc-silicate rock elsewhere in the Taylor Valley, e.g., at Bonney Riegal. Field relationships thus strongly suggest that the amphibolites were originally sedimentary in origin, e.g., a carbonate–shale mixture, or else were thin mafic tuffs.

It is of interest to see if the limited chemical data are compatible with a sedimentary origin. Chemical distinction between a para-amphibolite tuff and a para-amphibolite flow is not possible (see Evans and Leake, 1960: 360).

The following chemical data are strongly suggestive of a sedimentary origin for some of the Skelton amphibolites:

(1) Rb/Sr of Sample FS-4 is 0.46; the average for shales given by Faure and Hurley (1963) is 0.50, whereas the average for basalt is 0.056 (Taylor and White, 1966).

(2) The  $\text{TiO}_2$  content is rather low (0.58 percent) for mafic igneous rock (Evans and Leake, 1960: 356, table I, analysis 12).

(3)  $\text{K}_2\text{O}$  is greater than  $\text{Na}_2\text{O}$ , which is common in shales but rare in mafic igneous rocks.

(4) For the  $\text{SiO}_2$  content the Mg/Fe ratio is high for a mafic igneous rock.

#### CONCLUSIONS

On the basis of chemical and mineralogical data presented in this paper several conclusions regarding the genesis of these rocks have been reached. In summary these are:

(1) In major-element chemistry the Mt Falconer pluton is very similar to other granite bodies mapped as Irizar Granite elsewhere in Victoria Land.

(2) The mafic dyes are considered to be genetically related to emplacement of the Mt Falconer quartz monzonite pluton. Small amounts of mafic magma are inferred to have been mobilised by hot, water-undersaturated quartz monzonite magma.

(3) Field and chemical evidence indicate that the Skelton Group amphibolites in the Mt Falconer area are para-amphibolites, i.e., of sedimentary origin.

(4) K/Rb ratios for total rocks fall on the "main trend" as defined by Shaw (1968); however, they cannot be used to unravel the complex sequence of igneous events.

(5) Strontium partition between alkali feldspar and plagioclase is not a reliable geothermometer for the Mt Falconer pluton; this is likely to be due to subsolidus redistribution of strontium.

(6) Phase relations of alkali feldspar, plagioclase, and quartz can be compared with those in the experimental system orthoclase–albite–anorthite–quartz–water. Chemical analyses of co-existing feldspars and total rocks, when compared with experimental results, indicate (a) the compositions of co-existing feldspars in the Mt Falconer pluton are comparable to those found in the experimental "granite" system; (b) the petrographically determined order of crystallisation: plagioclase, alkali feldspar (quartz) is consistent with the plots of total rock analyses in both the quartz-saturated orthoclase–albite–anorthite–water system and the albite–orthoclase–quartz–water system (7.5 weight percent anorthite).

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#### APPENDIX: METHODS OF CHEMICAL ANALYSIS

Wet chemical analyses of rocks and minerals reported in this paper were done at the Department of Geology, University of Calgary, and at the Institute of Sedimentary and Petroleum Geology, except for ferrous–ferric iron determinations on biotite, which were done by Technical Service Laboratories, Toronto. Silica was done by the rapid spectrophotometric method outlined by Shapiro and Brannock (1962). All other analyses were done on a Perkin Elmer Model 303 atomic absorption spectrophotometer following the methods outlined by Billings and Adams (1964).

As a check on the accuracy of the analyses, we have obtained analytical data on the new U.S. Geological Survey silicate rock standards. Our results and the averages compiled by Flanagan (1969) are listed in Table VII.

TABLE VII.—Comparison of analyses on U.S. Geological Survey silicate standards done by the University of Calgary with those of other analysts. Data in ppm except where indicated as %. Average of data reported by Flanagan (1969) given in parentheses.

Constituent	G-2	GSP-1	AGV-1	PCC-1	DTS-1	BCR-1
Cu	15 (11)	47 (35)	74 (64)	14 (10)	10 (8)	25 (22)
Li	27 (43)	25 (36)	10.5 (12)	2.4 —	2 —	14.5 (17)
Rb	211 (234)	284 (343)	74 (89)	bd (0.5)	bd (2.8)	61 (73)
Sr	453 (463)	237 (247)	722 (657)	bd (0.3)	bd —	356 (345)
Zn	81 (75)	101 (143)	88 (112)	34 (53)	34 (61)	150 (132)
Fe <sub>2</sub> O <sub>3</sub> **%		4.35 (4.33)				13.59 (13.51)
MnO%	0.04 (0.04)	0.04 (0.04)	0.10 (0.10)	0.12 (0.12)	0.11 (0.13)	0.18 (0.18)
MgO%	0.74 (0.78)	1.08 (0.96)	1.41 (1.49)			3.21 (3.28)
CaO%	1.98 (1.98)	1.84 (2.03)	4.70 (4.98)	0.54 (0.53)	0.11 (0.15)	6.80 (6.95)
Na <sub>2</sub> O%	3.78 (4.15)	2.86 (2.88)	4.37 (4.33)	0.02 (0.05)	0.01 (0.05)	3.21 (3.31)
K <sub>2</sub> O%		5.96 (5.48)				1.77 (1.68)
TiO <sub>2</sub> ***		0.67 (0.69)	1.01 (1.08)			

\*\* Total iron as Fe<sub>2</sub>O<sub>3</sub>; — not given; bd, below determination.

\*\*\* Done at Institute of Sedimentary and Petroleum Geology.

#### APPENDIX 2: ELECTRON MICROPROBE ANALYSIS

Electron microprobe analyses were done on carbon-coated polished thin sections and grain mounts on an ARL EMX-SM microanalyser at the Department of Geology, the University of Calgary.

Operating conditions were: 15kv accelerating potential, 0.1μ amp beam current, and a spot size of 10μ. Drift was corrected by the use of beam current integration. A list of standards used can be obtained from the author.

Correction procedures used were those outlined by Bence and Albee (1968). As a check on the accuracy of the microprobe technique and the data-correction procedure, several analysed mineral standards were run as unknowns. An example is set out in Table VIII.

TABLE VIII.—Comparison of an electron microprobe analysis and wet chemical analysis of an olivine.

Constituent	Probe	Chemical
SiO <sub>2</sub>	40.9	40.8
Al <sub>2</sub> O <sub>3</sub>	0.0	0.0
FeO	9.45	9.37
MgO	49.5	49.2
MnO	0.13	0.13
CaO	~ 0.01	0.02
NiO	not det.	0.40
Total	99.99	99.92

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