

THE UNIVERSITY OF MANITOBA

RUBIDIUM-STRONTIUM AGE DETERMINATIONS FROM
THE CHURCHILL PROVINCE OF NORTHERN MANITOBA

by

RICHARD KIME ANDERSON

A THESIS

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ABSTRACT

The ages of three rock units from the Churchill Structural Province of Manitoba were determined by the rubidium-strontium, whole-rock method. A minimum age of 2636 ± 163 million years, with an initial ratio of 0.7025 ± 0.0034 was obtained for a foliated quartz monzonite from the Kasmere Lake area in Northern Manitoba (^{87}Rb decay constant of $1.39 \times 10^{-11} \text{yr}^{-1}$). This unit probably represents an Archean basement for the metasedimentary rocks of the Wollaston Lake Belt in Manitoba. Also from the Kasmere Lake area, a grey quartz dioritic to granodioritic gneiss gave a minimum age of 1941 ± 25 million years and an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7038 ± 0.0003 . The isotopic data implies that this unit was formed from primary igneous material which was emplaced early in the Hudsonian Orogeny and underwent alkali metasomatism during a subsequent event.

A minimum age of 1818 ± 199 million years was obtained for a ferrohypersthene metatonalite, metadiorite and anorthositic gabbro from the Burntwood Lake area in central Manitoba. This age and the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7032 ± 0.0013 suggest that these ferrohypersthene rocks were derived from primary magma intruded during the Hudsonian Orogeny.

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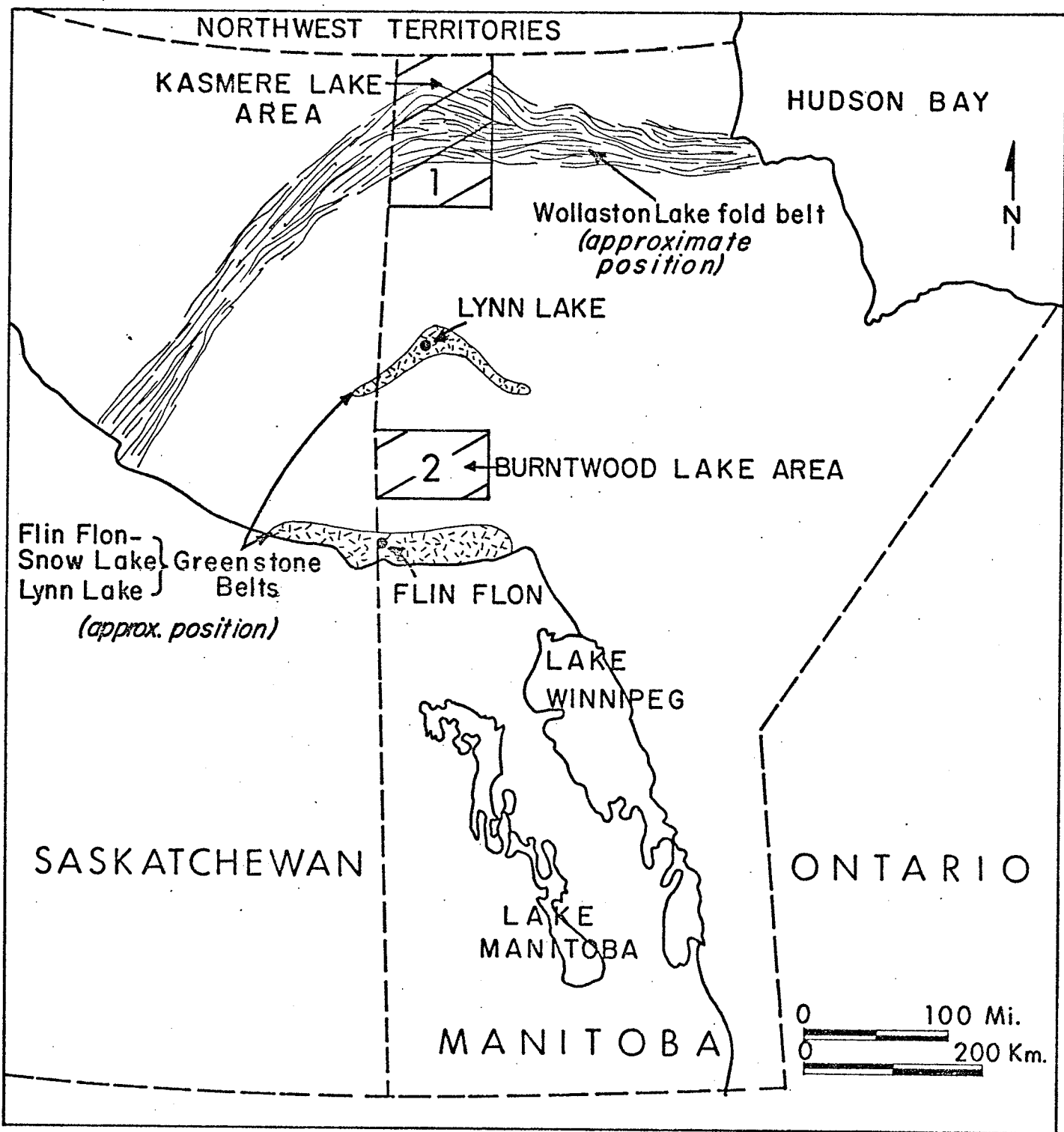
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I. INTRODUCTION

In order to solve common geological problems encountered in the study of the Churchill Structural Province of the Canadian Shield, it is often necessary to determine whether the rocks were: 1) crustal rocks formed during the Archean, 2) primary or anatectic intrusive rocks associated with the Kenoran Orogeny, 3) crustal rocks formed during the Aphebian or 4) primary or anatectic intrusive rocks emplaced during the Hudsonian Orogeny. Occasionally geologic evidence alone is not sufficient to confirm a rock unit's origin and history, particularly in those areas where outcrop is poor. In such cases, isotopic age determinations can be employed to obtain the rocks absolute age and, hopefully, the evidence necessary to confirm its genesis.

To assist in solving the mentioned problems, rubidium-strontium whole-rock age determinations were performed on three rock units from the Churchill Province in Manitoba. Two of these units are closely associated with the Wollaston Lake Belt, a linear zone of folded Aphebian metasediments and minor metavolcanics (Fig.1). The samples were collected from an area referred to as the Kasmere Lake area, which is situated in the northwest corner of Manitoba, and is bound by latitudes $58^{\circ} 30'$ and $60^{\circ} 00'$ north and by longitudes $100^{\circ} 00'$ and $102^{\circ} 00'$ west (Fig.1).

FIGURE 1. Location of Study areas
(positions of geologic features are
approximate, after Davidson, 1972)



The first geologic unit dated from this area is a foliated quartz monzonite. Similar rocks in Saskatchewan form the basement for the Wollaston Lake fold belt and gave an Archean age when dated by the rubidium-strontium whole-rock method (Money et al., 1970; Davidson, 1972). Age determinations were performed on the foliated quartz monzonite to confirm that it is also part of the basement rocks for the Wollaston Lake fold belt in Manitoba.

The second unit dated from the Kasmere Lake area is a grey quartz dioritic to granodioritic gneiss. This unit lies along the northwestern boundary of the Wollaston Lake Belt.

The third geologic unit investigated is a ferrohypersthene bearing metatonalite, metadiorite and anorthositic gabbro. Samples of this unit were collected from an area surrounding Burntwood Lake. (Fig.1) The area is bound by latitudes $55^{\circ} 15'$ and $56^{\circ} 00'$ north and longitudes $102^{\circ} 00'$ and $100^{\circ} 00'$ west.

The ferrohypersthene bearing rocks are intruded into the Kissenew gneiss complex that separates the Flin Flon greenstone belt from the Lynn Lake greenstone belt (Fig.1). Geologic evidence indicates that this unit is the oldest primary igneous intrusive unit in the Burntwood Lake area (McRitchie, personal communication). The age obtained for the ferrohypersthene bearing rocks may give the minimum age of deposition in the sedimentary basin between the two greenstone belts.

A. Acknowledgements

I would like to acknowledge the Faculty of Graduate Studies and the National Research Council for their financial assistance. I am also grateful to many individuals for their assistance in this study: Dr. G.S. Clark supervised the study. Dr. W.D. McRitchie supplied geologic information and maps for the Burntwood Lake area, and the ferrohypersthene bearing metatonalite, metadiorite and anorthositic gabbro. Dr. W. Weber, D. Schledewitz and C.F. Lamb supplied the geologic information and maps pertaining to the Kasmere Lake area. D. Schledewitz supplied the information for the description of the foliated quartz monzonite. C.F. Lamb supplied the necessary information for the geologic description of the grey quartz dioritic to granodioritic gneiss. Paul Beaudoin assisted in the chemistry of many of the samples. Drs. G.S. Clark, W. Weber and A.C. Turnock read the manuscript and offered many helpful suggestions.

II. GEOLOGIC DESCRIPTIONS

A. Geologic Settings of the Kasmere Lake and Burntwood Lake Areas

Both areas from which samples were collected for age determinations are in the Churchill Province of the Canadian Shield. The Churchill Province contains curved and linear belts of variably metamorphosed rocks, predominantly of Aphebian age, which are underlain by gneissic and granitoid rocks of great structural and petrologic complexity. Plutonic and crustal remnants of Archean age are rarely recognizable. The Hudsonian Orogeny caused slight to intense folding and metamorphism associated with granite intrusion; during this orogeny many of the Aphebian rocks were converted to granitic gneisses (Stockwell, et al., 1970; Davidson, 1972).

One of the major tectonic belts in the Churchill Province in Manitoba is the Wollaston Lake Belt. This fold belt extends from the southern edge of the Canadian Shield in central Saskatchewan into Manitoba at Kasmere Lake (Fig.1). The Kasmere Lake area part of the fold belt trends east-northeast towards the Hudson Bay whereas the other part appears to plunge to the north (Weber, personal communication; Money, 1968; Money et al., 1970; Davidson, 1972)

The Wollaston Lake fold belt consists mainly of Aphebian supracrustal rocks which have been divided into

four groups (Money et al., 1970). The oldest recognized group comprises the metagreywacke, meta-arkose and meta-volcanic rocks of the Sandfly Lake Group. It is unconformably overlain by quartzite, oligomictic conglomerate, and pelitic metasedimentary rocks of the Meyers Lake Group. The Meyers Lake Group is unconformably overlain by metamorphosed arkose, greywacke and pelitic rocks of the Daly Lake Group. A fourth assemblage, assigned to the Meyers Lake Group consists of quartz pebble conglomerate, quartzite and pelitic schist (Money et al., 1970). The structure of the Wollaston Lake fold belt is characterized by closely spaced, northeast trending, isoclinal folds, commonly with steep limbs. The granitoid basement is exposed in anticlinal cores (Davidson, 1972).

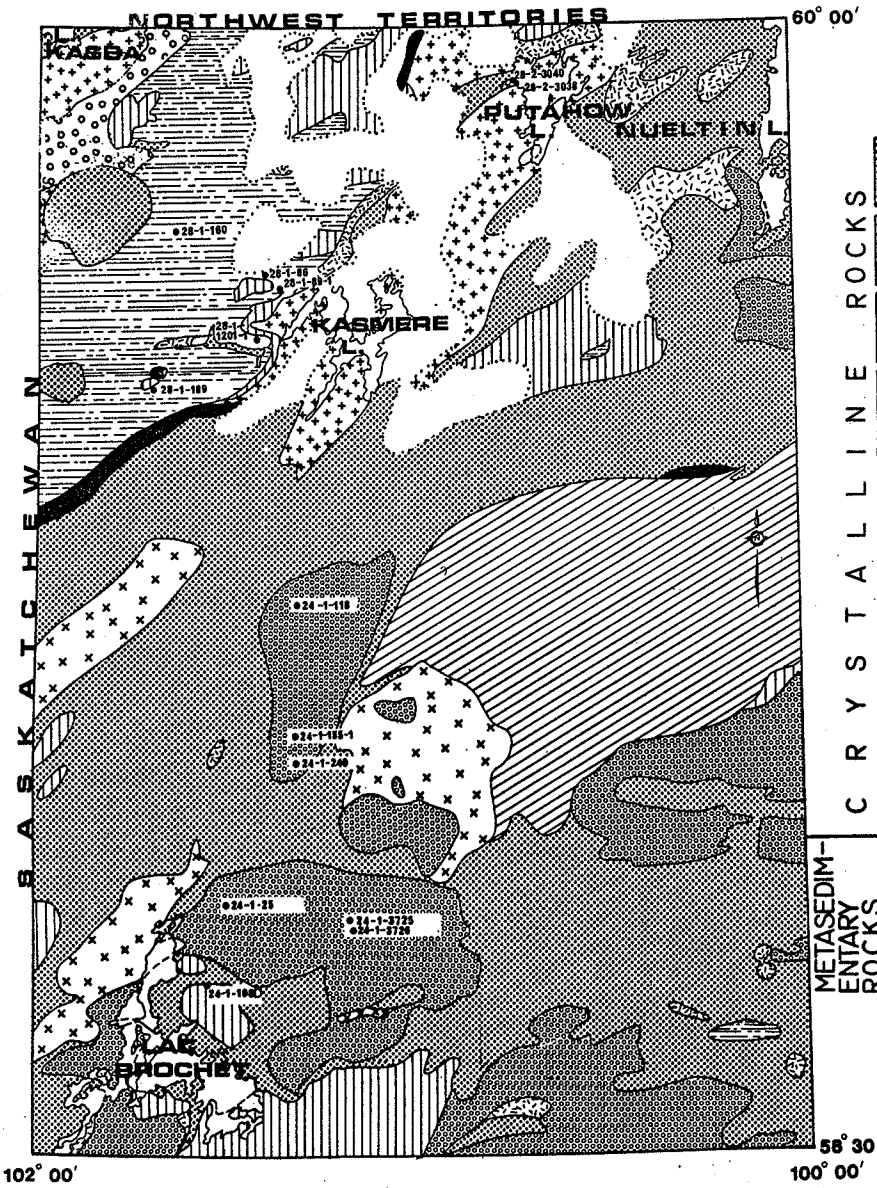
In the southern part of the Churchill Province in Manitoba, the Lynn Lake greenstone belt and the Flin Flon-Snow Lake greenstone belt are separated by the gneissic and granitoid rocks of the Kisseynew complex (Harrison, 1951; Davidson, 1972). These gneisses are believed to be the remnants of the sedimentary basin that existed between the two volcanic belts before deformation, metamorphism and intrusion by granitic rocks (Harrison, 1951; McRitchie, personal communication). The structure of the southern portion of this belt is dominated by tight, nearly isoclinal, easterly trending folds which are overturned to the south (Bailes, 1971).

B. Geology of the Kasmere Lake Area













Geologic mapping of the Kasmere Lake area has recently been completed at a scale of 1:50,000 by geologists with the Manitoba Mines Branch. The following summary of the geology of the area and the brief descriptions of the foliated quartz monzonite and the grey quartz dioritic to granodioritic gneiss are from the Summary of Geologic Field Work (Weber et al., 1972) and from W. Weber, C.F. Lamb and D. Schledewitz (personal communication).

The geology of the Kasmere Lake area is shown in Figure 2. With the exception of minor bodies of paragneiss, the oldest rocks in the area are granitic rocks which were probably intruded during the Archean. These granitic bodies are overlain by Aphebian metasedimentary rocks which are similar to those of the Wollaston Lake fold belt. Also overlying the Archean granitic rocks, but not otherwise associated with the Wollaston Lake Belt, are two units of metamorphic rocks of uncertain age and genesis. These two units, the grey quartz dioritic to granodioritic gneiss and the cataclastic biotite gneiss, separate the Wollaston Lake metasedimentary rocks from the younger sedimentary rocks of the Hurwitz Group in the northwest corner of the map area. Aphebian intrusive rocks and migmatites which were probably formed during the Hudsonian Orogeny are widespread in the Kasmere Lake area.

FIGURE 2. Generalized geologic map of the
Kasmere Lake area.
(after Weber et al., 1972; and
Weber, personal communication)



LEGEND

-  FLUORITE BEARING QUARTZ MONZONITE
-  PORPHYRITIC QUARTZ MONZONITE
-  PINK BIOTITE QUARTZ MONZONITE
-  MIGMATITE
-  WHITE GRANITE AND QUARTZ MONZONITE
-  CATACLASTIC BIOTITE GNEISS
-  GREY QUARTZ DIORITIC TO GRANODIORITIC GNEISS
-  FOLIATED QUARTZ MONZONITE
-  HYPERSTHENE-BEARING QUARTZ DIORITE AND QUARTZ MONZONITE
-  HURWITZ GROUP
DOLOMITE AND ARGILLITE
-  WOLLASTON LAKE METASEDIMENTARY ROCKS
MAINLY PELITIC GNEISSES AND
META-ARKOSES WITH MINOR CALC-SILICATE
ROCKS AND MARBLE
-  DRIFT

SCALE
1:350,000
18 MI.
10 K.

GEOLOGIC BOUNDARY
DEFINED ——— APPROXIMATE - - - - -

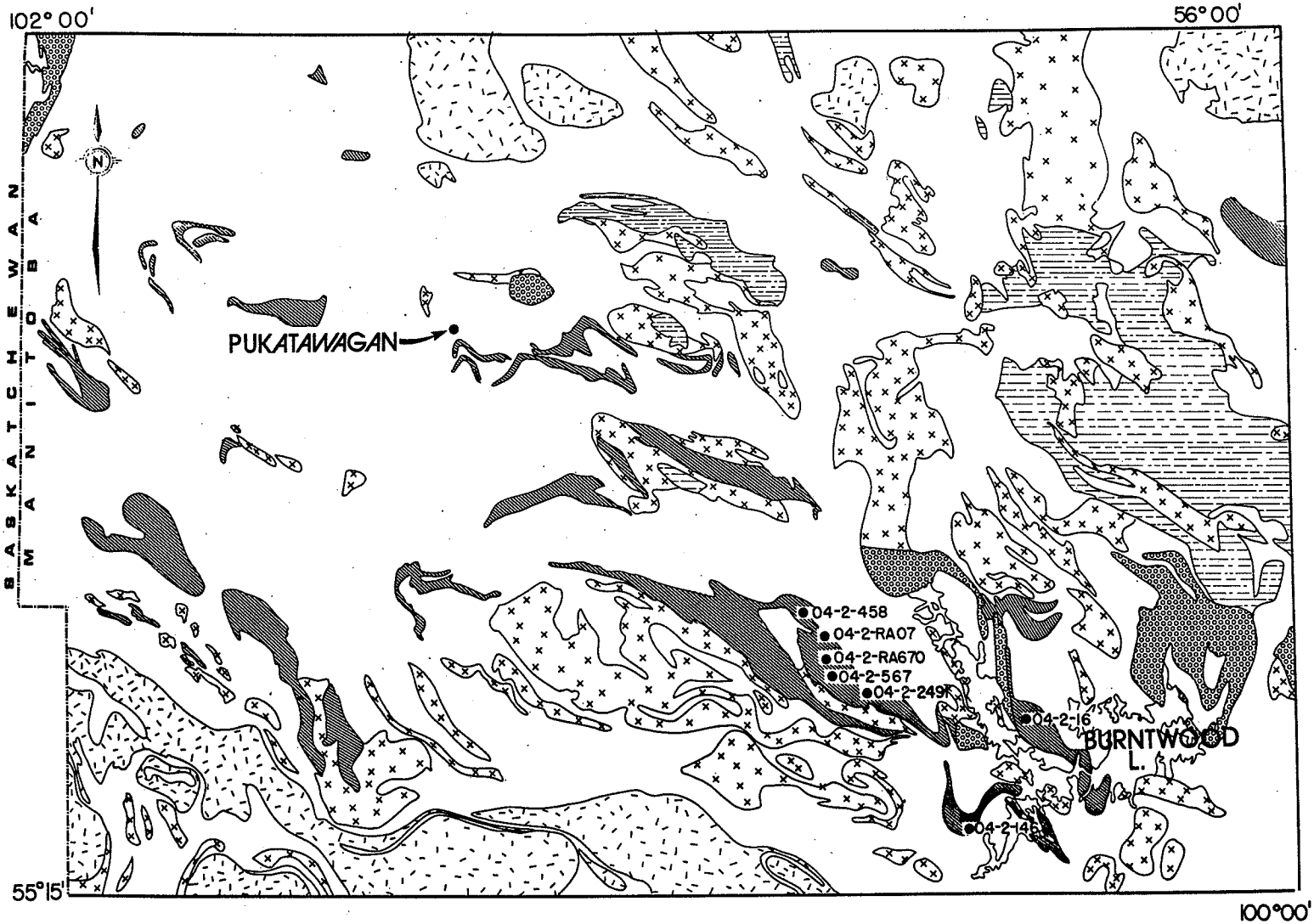
C. Geology of the Burntwood Lake Area







The geology of the Burntwood Lake area (Fig.3) has most recently been studied by the Manitoba Mines Branch. The majority of information necessary for this brief geologic description of the area, and of the ferrohypersthene bearing metatonalite, metadiorite and anorthositic gabbro was supplied by the Manitoba Mines Branch in their preliminary report (McRitchie et al., 1972) and by W.D. McRitchie (personal communication).

Much of the Burntwood Lake area is underlain by layered psammitic to pelitic paragneisses that have been metamorphosed to the middle or uppermost amphibolite assemblage. The majority of the paragneisses are greywacke gneisses, but isolated bodies of arkosic gneiss occur at the northern and southern limits of the area. As a result of metamorphism, the sedimentary rocks have been converted to a variety of lit par lit gneisses, diatexites, and wholly or partially anatectic and nebulitic granitic rocks.

Intrusive rocks of various ages are abundant throughout the Burntwood Lake area. The oldest intrusive rocks are probably large sills of ferrohypersthene bearing metatonalite, metadiorite and anorthositic gabbro. Where subjected to metamorphism, the ferrohypersthene bearing intrusive rocks grade into a tonalitic to granodioritic gneiss. Later alkali enrichment converted tracts of the tonalitic to granodioritic gneiss to a porphyritic quartz

FIGURE 3. Generalized geologic map of the
Burntwood Lake area
(after McRitchie, et al., 1972;
McRitchie, personal communication)



-  Granite to quartz diorite
-  Porphyritic granodiorite to quartz diorite
-  Granodiorite to quartz diorite gneiss
-  Ferrohypersthene bearing metatonalite, metadiorite and anorthositic gabbro
-  Meta-arkose group
-  Meta-graywacke group



monzonite. A complex of granites, quartz monzonites, pegmatites and aplites form the youngest intrusive complex in this area.

The gneissic belt in the Burntwood Lake area has a dominant west-northwest structural trend. This is overprinted in some areas by a younger northeast trend which results in northeast trending ellipsoidal bodies.

D. Rock Descriptions

1) Foliated Quartz Monzonite

The foliated quartz monzonite is present as three large bodies in the southern half of the Kasmere Lake area and as two smaller bodies in the northeastern portion (Fig.2). The quartz monzonite is pink on both the weathered and fresh surfaces. The rock has a schistosity which may be accompanied by a cataclastic foliation. The texture varies from a porphyroclastic texture, with aligned microcline or plagioclase porphyroblasts, to a well developed cataclastic texture with feldspar augen. A gneissosity may also be present in the form of granitic injections which strike parallel to the schistosity (Schledewitz, personal communication).

The mineralogy is generally constant throughout the foliated quartz monzonite bodies. Quartz constitutes twenty to thirty percent of the rock with feldspar making up sixty to eighty-six percent of the rock. Potassium feldspar is often more abundant than plagioclase and may make up to fifty-five percent of the rock. Biotite, which may be partially altered to chlorite, is present in abundances

varying from four to ten percent and is the only primary mafic mineral present in the rock (Schledewitz, personal communication).

The fabric and mineralogy of the foliated quartz monzonite suggest that the rock was affected by two metamorphic events. The first event was deformational, leading to cataclasis, and the second event caused recrystallization associated with minor mobilization of the alkalies and calcium (Schledewitz, personal communication).

2) Grey Quartz Dioritic to Granodioritic Gneiss

The grey gneiss is present in a northeast trending layer in the northwest corner of the Kasmere Lake area (Fig.2). It is generally medium grained but may be locally coarse grained and massive. The rock is commonly schistose with a foliation formed by the alignment of biotite. Elongate quartz and feldspar grains are also parallel to the foliation. Associated with the coarse grained variety of the grey gneiss are irregular veins and dikes of biotite granite which appear to have caused local areas of alkali enrichment (Lamb, personal communication).

The grey gneiss consists of quartz distributed in irregular patches, and generally subordinate microcline which may locally constitute up to twenty percent of the rock. Biotite, hornblende, and chlorite are also present in minor amounts (Lamb, personal communication).

The genesis of the grey gneiss is uncertain. Eade (1970) suggested that the predominant banding and composition

of some of the xenoliths, ten to thirty miles to the north, in the Northwest Territories, indicate a sedimentary origin for the grey gneiss. In Manitoba however, Lamb suggested that the composition of analyzed samples of the grey gneiss is that of a leucogranite rather than a metasediment; the SiO_2 contents are higher and the Al_2O_3 contents are lower than arkose, greywacke and subgreywacke.

3) Ferrohypersthene Bearing Metatonalite,
Metadiorite and Anorthositic Gabbro

Sill-like intrusive bodies of ferrohypersthene bearing intrusive rocks occur intermittantly over a large portion of the Burntwood Lake area (Fig.3). The sill complexes vary in size from three meters across to large sills three kilometers across and forty kilometers in length. The rock is typically medium grained, equigranular, homogeneous and weakly automorphic. The ferrohypersthene bearing metatonalite, metadiorite and anorthositic gabbro is a mesocratic rock comprising plagioclase, biotite and potassium feldspar. The most common accessory minerals are magnetite, apatite and zircon (McRitchie, personal communication).

The larger occurrences of the ferrohypersthene bearing intrusive rocks are cut by dykes of pink pegmatite, aplite and porphyritic quartz monzonite. Generally the dykes contain a one to ten centimeter thick silicified zone along their contact with the ferrohypersthene bearing rocks. The ferrohypersthene bearing metatonalite, where in contact with

the dykes, is recrystallized to a bleached, medium grained, equigranular, homogeneous, garnet-biotite-plagioclase-quartz gneiss (McRitchie, personal communication).

III PREVIOUS ISOTOPIC AGE STUDIES

A. Kasmere Lake Area

Previous isotopic age determinations for intrusive and metasedimentary rocks of the Wollaston Lake Belt, in Saskatchewan as well as Manitoba, are listed in Tables 1 and 2.

Of particular interest in this study are the ages obtained for the "Western Granites" in Saskatchewan and a hypersthene quartz diorite at Kasmere Lake. Lead-lead, uranium-lead and rubidium-strontium ages (Table 1) suggest that these crystalline rocks were intruded during the Archean, possibly as part of the Kenoran Orogeny (Money, 1968; Money et al., 1970; Sinha, 1970; Weber et al., in prep.).

With the exception of the ages determined for the "Western Granites" and the hypersthene quartz diorite, the ages obtained for the intrusive rocks correspond with the approximate 1850 million year age of the Hudsonian Orogeny (Stockwell, 1973). Bodies of flourite quartz monzonite, or Nuelton Lake granite, with an average rubidium-strontium age of 1807 million years are believed to have been emplaced during the final phase of the Hudsonian Orogeny (Eade, 1970). A porphyritic quartz monzonite, also referred to as a porphyritic granite, gives an age which corresponds with the Hudsonian Orogeny as well. Preliminary rubidium-strontium results suggest that the porphyritic quartz monzonite was formed from pre-existing crustal rocks and that the age obtained is a metamorphic

TABLE 1
Isotopic Ages of Granitic Rocks From
the Wollaston Lake Belt

<u>Rock Type</u>	<u>Location</u>	<u>Method</u>	<u>Age (M.Y.)¹</u>	<u>Reference</u>
"Western Granites"	Needle Falls Sask.	Rb-Sr	2220 \pm 70 ²	Money, 1968
	Geike River Sask.	Rb-Sr	2470 \pm 65 ²	Money, et al., 1970
	Needle Falls to LaRonge, Sask.	U-Pb	2700-3000	Sinha, 1970
Quartz Monzonite	Roper Bay Sask.	Pb-Pb	2405 ²	Money, et al., 1970
Hypersthene Quartz Diorite	Kasmere Lake Man.	Rb-Sr	2745 \pm 124 ²	Weber, et al., in prep.
"Eastern Granites"	Needle Falls Sask.	K-Ar	1740	Money, 1968
	Needle Falls to	Pb-Pb	1940-2030	Sinha, 1970
	LaRonge Sask.	Rb-Sr	1846 \pm 60	Sinha, 1970
Flourite Granite	Kasmere Lake Man.	K-Ar	1730	Lowden, et al., 1963
Nuelton Lake Granite	Ennadai Lake NWT	Rb-Sr	1799 \pm 16	Wanless, et al., 1972
	Kasmere Lake Man.	Rb-Sr	1814 \pm 59	Wanless, et al., 1972
Porphyritic Granite	Kasmere Lake Man.	K-Ar	1770	Leech, et al., 1963
Porphyritic Quartz Monzonite	Kasmere Lake Man.	Rb-Sr	1808 \pm 110 ²	Weber, et al., in prep.

¹All Rb-Sr ages reported in this thesis are Rb-Sr whole rock isochron ages calculated using a ⁸⁷Rb decay constant of 1.39 x 10⁻¹¹yr.⁻¹.

²Preliminary results.

TABLE 2

Isotopic Ages of Metasedimentary Rocks From
the Wollaston Lake Belt

<u>Rock Type</u>	<u>Method</u>	<u>Age(M.Y.)</u>	<u>Reference</u>
sillimanite paragneiss	K-Ar	1,670 \pm 90	Lowden, 1961
meta-arkose, Sandfly Lake Group	K-Ar	1,730 \pm 90	Money, 1968
biotite-muscovite- quartz schist, Meyers Lake Group	K-Ar	1,780 \pm 90	Money, 1968
hornblende-biotite gneiss, Sandfly Lake Group	K-Ar	1,570 \pm 80	Money, 1968
Pelitic Gneiss	Rb-Sr ¹	1,803 \pm 66 ²	Weber, et al., in prep.

¹Rb-Sr whole rock isochron age determination.

²preliminary result.

age (Clark, personal communication).

Potassium-argon results for the metasedimentary rocks give metamorphic ages that range from 1570 million years to 1780 million years (Table 2). These ages are believed to reflect the metamorphism of the Hudsonian Orogeny.

B. Burntwood Lake Area

Although ages have not been determined from the Kiskeynew gneiss complex in the Burntwood Lake area, potassium-argon age determinations were obtained from metasedimentary and intrusive rocks which are associated with the greenstone belts that bound the north and south limits of the gneiss complex.

Potassium-argon ages were obtained from granitic and metasedimentary rocks and were found, with one exception, to range from 1440 million years to 1730 million years (Wanless, 1970). A potassium-argon age of 2670 million years was obtained for a muscovite from a meta-arkose, but a biotite from the same sample gave an age of 1610 million years. These ages generally correspond to the average potassium-argon age of 1735 million years for the Hudsonian Orogeny (Stockwell, 1970).

To the south of the Burntwood Lake area, ages of the metasedimentary and igneous rocks near the Flin Flon-Snow Lake greenstone belt were determined by the potassium-argon method and were also found to correspond with the age of the Hudsonian Orogeny (Wanless, 1970).

IV. ANALYTICAL TECHNIQUES

A. Sample Collection and Preparation

Samples of the foliated quartz monzonite and the grey quartz dioritic gneiss were collected by D. Schledewitz and C.F. Lamb in the Kasmere Lake area during the summers of 1971 and 1972. These samples were collected primarily as geologic specimens and their weight varied from two to six pounds. The sample locations for the foliated quartz monzonite and the grey quartz dioritic to granodioritic gneiss are shown in Figure 2.

Samples of the hypersthene bearing metatonalite, metadiorite and anorthositic gabbro were collected by Dr. W.D. McRitchie during the summer of 1972. The sample locations are shown in Figure 3. Most of the samples were collected specifically for rubidium-strontium, total-rock analysis and each weighed eight to ten pounds when trimmed. During the collection of the ferrohypersthene bearing rock, care was taken to avoid alteration zones associated with the numerous granitic dikes.

All samples selected for analysis were examined for weathering, mineralogy, texture and structure (Appendix I). After this examination, the samples were crushed by a jaw crusher and pulverized in a disk grinder to approximately 100 to 200 mesh. Each sample was then coned and quartered and stored in a two ounce sample bottle.

B. Analytical Procedure

A detailed account of the rubidium-strontium analytical procedure and standard preparation is given in Appendix II. Briefly, the samples were dissolved in hydrofluoric and perchloric acids. After dissolution, the acids were evaporated and a predetermined amount of the appropriate spike was added to each sample. Rubidium samples were not purified further, except to separate any insoluble material. Strontium samples were leached with methanol, and centrifuged to remove the alkali elements. The final purification was attained using ion exchange columns.

C. Mass Spectrometry

The rubidium isotopic ratios and concentrations, and strontium isotopic ratios and concentrations, were determined separately on a triple filament, single focusing mass spectrometer. The instrument, which is described by Penner (1970), has a ten inch radius of curvature and a ninety degree deflection. A more detailed description of the mass spectrometer and the operating procedure is presented in Appendix III.

V. ANALYTICAL RESULTS

A. Calculation of Results

The calculations necessary to determine the rubidium and strontium concentrations and isotopic compositions are described by Penner (1970) and further discussion of the strontium isotope dilution calculation is given in Appendix IV. All strontium ratios were adjusted to the natural $^{86}\text{Sr}/^{88}\text{Sr}$ value of 0.1194.

The slope of each isochron was determined with the least squares regression analyses of York (1966) using the error limits of 0.15 per cent for the $^{87}\text{Sr}/^{86}\text{Sr}$ axis and 1.5 per cent for the $^{87}\text{Rb}/^{86}\text{Sr}$ axis. The ages were calculated employing the ^{87}Rb decay constant of $1.39 \times 10^{-11}\text{yr}^{-1}$.

B. Rubidium and Strontium Standards

Spikes enriched in ^{87}Rb were used in the rubidium analyses, and spikes enriched with ^{84}Sr were used for the strontium analyses. The concentration of the strontium spikes were calibrated with SrNO_3 (Baker analyzed, reagent grade) and the NBS 984 standard RbCl was used to calibrate the concentration of the rubidium spikes. The concentrations and compositions of the spikes used are listed in Tables 3 and 4.

Several analyses of the Eimer and Amend standard SrCO_3 were made over the period of this study to monitor the reproducibility of the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. The average $^{87}\text{Sr}/^{86}\text{Sr}$ ratio obtained over a period of thirteen months is 0.7081 ± 0.0004 for this laboratory.

TABLE 3

 ^{87}Rb Spike Compositions and Concentrations

<u>Spike</u>	<u>Date</u>	<u>^{87}Rb Percent</u>	<u>^{85}Rb Percent</u>	<u>Total Rb Concentration (micromoles/ml.)</u>
V	Sept., 1971	99.15	0.85	0.05883
VII	July, 1972	99.15	0.85	0.05902
VII/2	April, 1973	99.16	0.84	0.05913
VII/3	Oct., 1973	99.15	0.85	0.05880

TABLE 4

 ^{84}Sr Spike Compositions and Concentrations

<u>Spike</u>	<u>Date</u>	<u>^{84}Sr Percent</u>	<u>^{86}Sr Percent</u>	<u>^{87}Sr Percent</u>	<u>^{88}Sr Percent</u>	<u>Total Sr Concentration (Micromoles/ml)</u>
IV/2	Aug., 1971	82.2	3.67	1.56	12.5	0.01110
IV/3	Dec., 1972	81.5	3.66	1.56	12.2	0.01126
IV/4	Aug., 1973	82.4	3.67	1.58	12.4	0.01123

Three strontium and five rubidium analyses were performed by the author and P. Beaudoin on the NBS 70a standard potassium feldspar (Table 5). The average of the concentrations obtained for radiogenic ^{87}Sr was 3.0334 ± 0.0183 ppm. The average total strontium concentration was determined to be 65.97 ± 0.52 ppm. The average rubidium concentration was 527.9 ± 1.8 ppm.

A discussion on the use of the NBS 70a potassium feldspar as a standard was presented by Compston et al., (1969). For several isotope dilution analyses for total strontium they obtained a value of 65.1 ppm, with a coefficient of variation of less than 0.1 per cent. From the same analyses they found that the radiogenic ^{87}Sr concentration was 3.0197 ppm with a coefficient of variation of 0.06 per cent. The average rubidium concentration, calculated from all of their analyses, was 529 ppm within the error limits of 0.45 per cent.

C. Results from Geologic Units Collected in the Kasmere Lake Area

1) Foliated Quartz Monzonite

Seven samples of the foliated quartz monzonite were analyzed. The results of these analyses are shown in Table 6, and the isochron is plotted on Figure 4. The age was calculated without sample 24-1-108D which may not be a foliated quartz monzonite (Weber, personal communication). The age derived for the foliated quartz monzonite is 2637 ± 163 million years and the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio is 0.7025 ± 0.0034 .

TABLE 5

Analytical Results for NBS 70a Standard K-feldspar

Strontium Data

<u>Date</u>	<u>Sr (ppm)</u>	<u>⁸⁷Sr (ppm)¹</u>	<u>⁸⁷Sr/⁸⁶Sr (norm.)²</u>
31/1/73	66.11	3.0378	1.1983
29/3/73	66.41	3.0491	1.1980
29/7/73	65.40	3.0133	1.2001

¹Radiogenic strontium.

²Strontium isotope ratios were normalized to a value of 0.1194 for the natural ⁸⁶Sr/⁸⁸Sr ratio.

Rubidium Data

<u>Date</u>	<u>Rb (ppm)</u>
29/1/73	528.9
27/4/73	526.7
29/5/73	529.8
6/6/73	526.1

TABLE 6

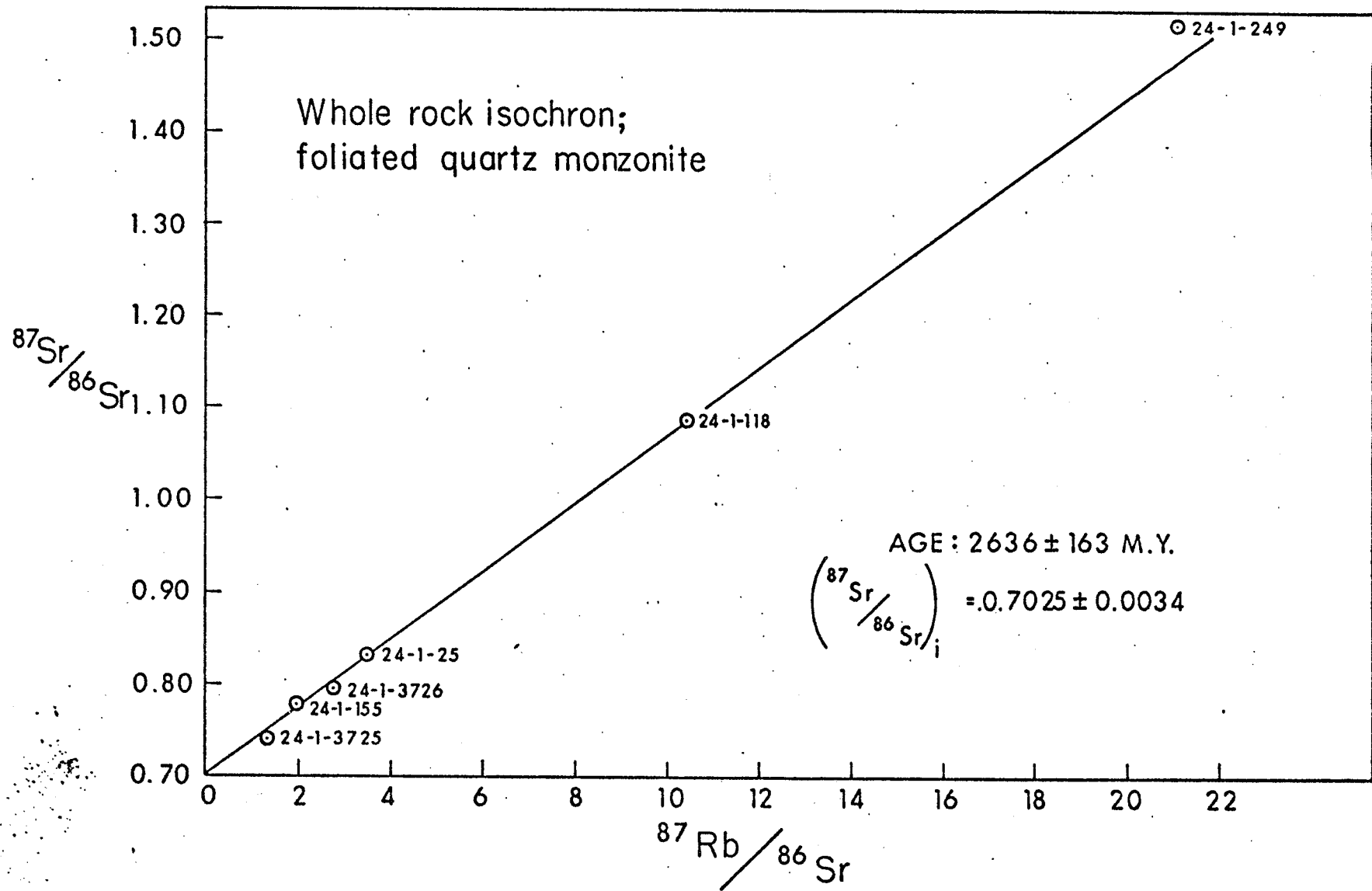
Analytical Results for the Foliated Quartz Monzonite

<u>Sample</u>	<u>Rb(ppm)</u>	<u>Sr(ppm)</u>	$\frac{^{87}\text{Rb}}{^{86}\text{Sr}}$	$^{87}\text{Sr}/^{86}\text{Sr}$ Calculated	$^{87}\text{Sr}/^{86}\text{Sr}^2$ Normalized
24-1-25	175.1	145.5	3.479	0.8302	0.8315
		146.4	3.456	0.8298	0.8314
24-1-155	165.9	239.6	2.002	0.7778	0.7789
		241.2	1.988	0.7779	0.7791
24-1-249	352.2	48.22		1.5134	1.5167
		48.22		1.5134	1.5178
24-1-108D	109.0	186.8	1.083	0.7333	0.7347
		108.5	287.9	1.092	0.7328
24-1-3726	166.6	177.6	2.681	0.7927	0.7939
				0.7920	0.7935 ¹
24-1-3725	100.0	294.6	0.9813	0.7388	0.7413
			100.1	0.9813	
24-1-118	304.3	83.45	10.42	1.0844	1.0875

¹Unspiked run.

²All $^{87}\text{Sr}/^{86}\text{Sr}$ values normalized with the $^{86}\text{Sr}/^{88}\text{Sr}$ value of 0.1194.

FIGURE 4. Whole rock isochron; foliated quartz
monzonite



2) Grey Quartz Dioritic to Granodioritic Gneiss

Eight samples of the grey quartz gneiss were analyzed. The results, together with the replicate determinations are shown in Table 7. The age was calculated without the results from sample 28-1-189 which was collected from an outcrop that contained a large amount of pegmatite (Lamb, personal communication). The age of the grey gneiss was found to be 1941 ± 25 million years, with an initial ratio of 0.7038 ± 0.0003 (Fig. 5).

D. Results from Geologic Units Collected from the Burntwood Lake Area

1) Ferrohypersthene Bearing Metatonalite, Metadiorite and Anorthositic Gabbro

Data from the analyses and replicate analyses of seven samples of the ferrohypersthene bearing rocks are shown in Table 8. An age of 1818 ± 199 million years, and an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7032 ± 0.0013 was determined for the ferrohypersthene bearing rocks (Fig.6).

TABLE 7

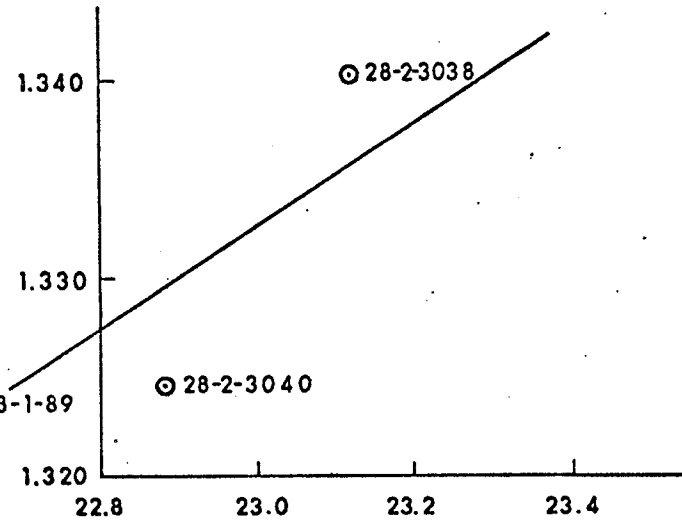
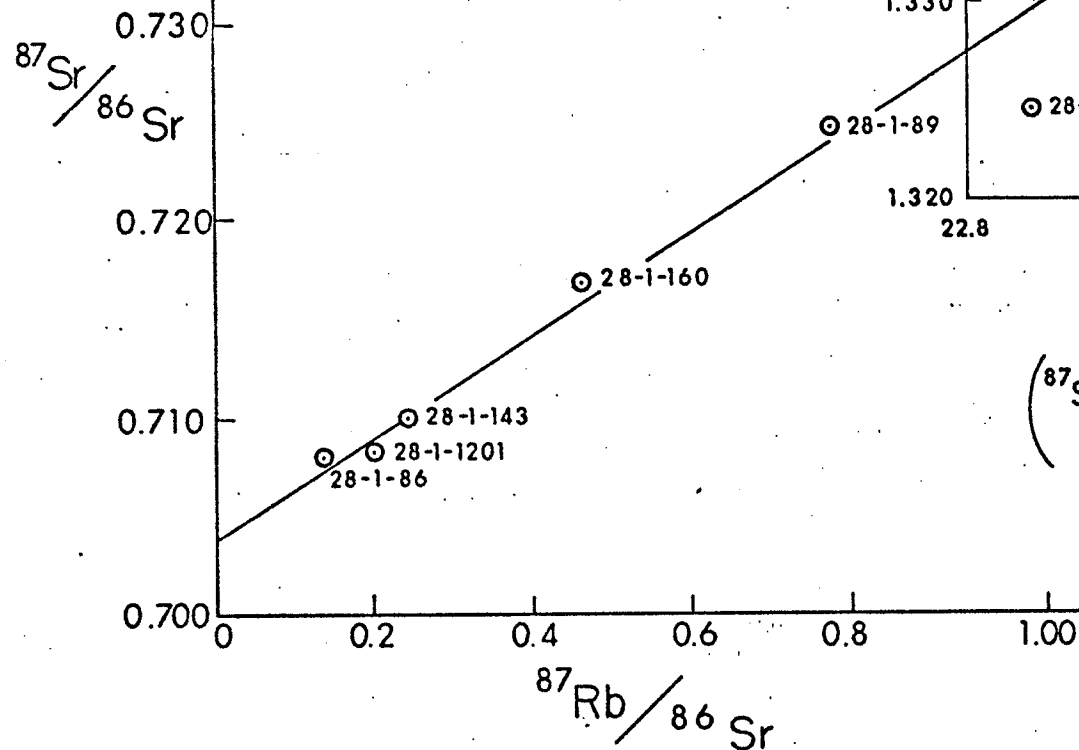
Analytical Results for the Grey Quartz Dioritic to
Granodioritic Gneiss

<u>Sample</u>	<u>Rb(ppm)</u>	<u>Sr(ppm)</u>	$\frac{^{87}\text{Rb}}{^{86}\text{Sr}}$	$\frac{^{87}\text{Sr}}{^{86}\text{Sr}}$ <u>Calculated</u>	$\frac{^{87}\text{Sr}}{^{86}\text{Sr}}$ <u>Normalized</u>
28-1-86	29.32	643.9	0.1322	0.7063	0.7079
		641.3	0.1327	0.7050	0.7080
28-1-189	66.29	411.6	0.4649	0.7185	0.7208
			66.06	0.4635	0.7187
28-1-89	68.18	334.9	0.7760	0.7237	0.7251
				0.7232	0.7246 ¹
28-1-1201	26.05	371.5	0.1990	0.7062	0.7083
				0.7068	0.7083 ¹
28-1-160	73.82	457.6	0.4608	0.7154	0.7169
28-2-3040	372.8	46.73	22.80	1.3233	1.3241
				373.1	46.45
28-2-3038	370.4	45.81	23.12	1.3402	1.3409
28-1-143	32.87	390.2	0.2405	0.7077	0.7102

¹Unspiked run.

FIGURE 5. Whole rock isochron, grey quartz
dioritic to granodioritic gneiss

Whole rock isochron;
grey quartz dioritic to
granodioritic gneiss



AGE: 1941 ± 25 M.Y.

$$\left(\frac{^{87}\text{Sr}}{^{86}\text{Sr}} \right)_i = 0.7038 \pm 0.0003$$

TABLE 8

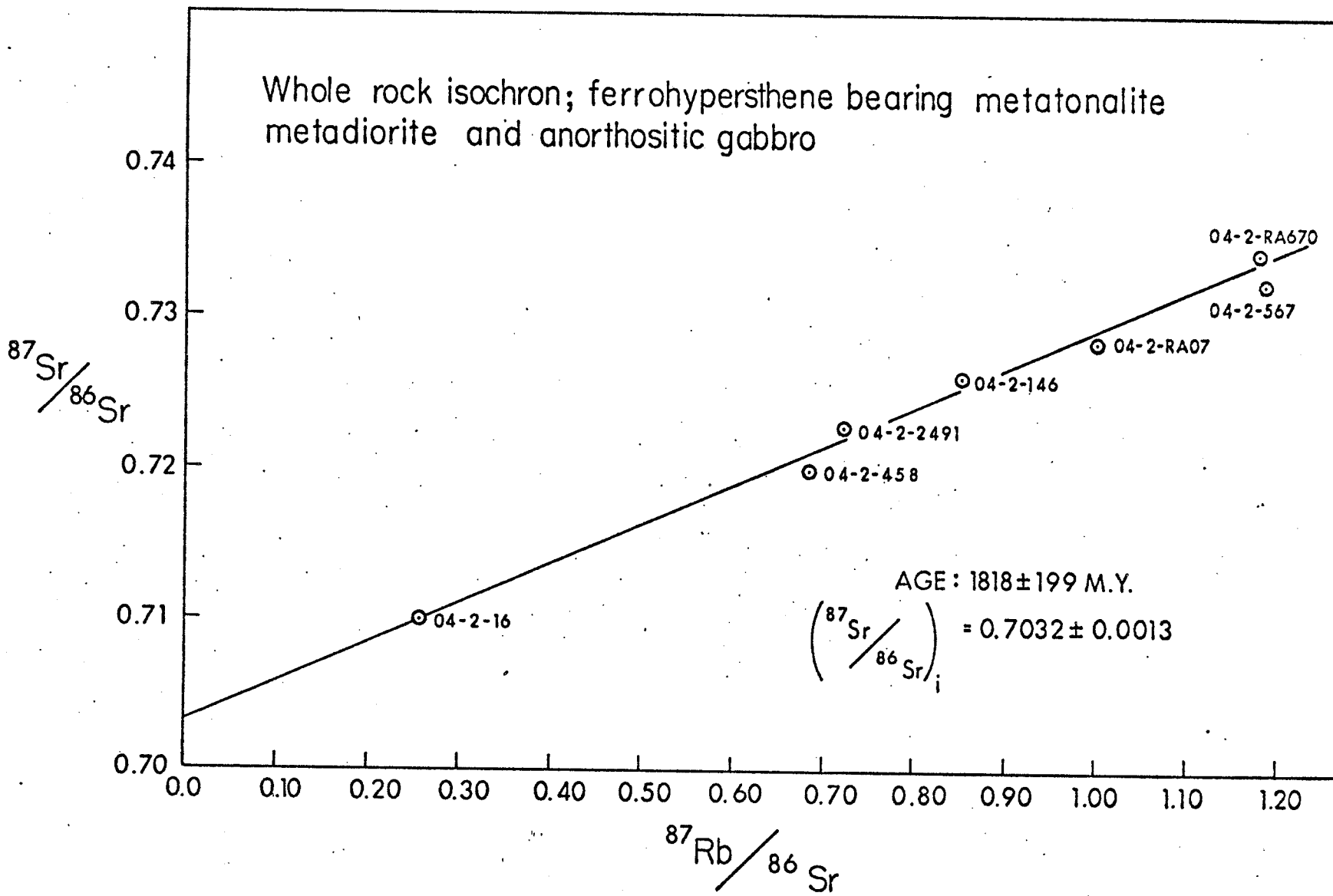
Analytical Results for the Ferrohypersthene Bearing
Metatonalite, Metadiorite and Anorthositic Gabbro

<u>Sample</u>	<u>Rb(ppm)</u>	<u>Sr(ppm)</u>	$\frac{^{87}\text{Rb}}{^{86}\text{Sr}}$	$\frac{^{87}\text{Sr}}{^{86}\text{Sr}}$ <u>Calculated</u>	$\frac{^{87}\text{Sr}}{^{86}\text{Sr}}$ <u>Normalized</u>
04-2-16	48.07	537.2	0.2586	0.7074	0.7098
		542.7	0.2559	0.7077	0.7097
04-2-RA670	138.7	345.0	1.178	0.7333	0.7340
04-2-567	141.1	346.3	1.183	0.7300	0.7327
				0.7310	0.7321 ¹
04-2-2491	82.09	323.9	0.7246	0.7196	0.7228
04-2-RA07	123.9	349.1	1.016	0.7261	0.7289
	124.6			0.7265	0.7282 ¹
04-2-146	111.3	377.4	0.8521	0.7225	0.7261
04-2-458	90.53	382.7	0.6879	0.7172	0.7194

¹Unspiked run.

FIGURE 6. Whole rock isochron; ferrohypersthene bearing metatonalite, metadiorite and anorthositic gabbro

Whole rock isochron; ferrohypersthene bearing metatonalite
metadiorite and anorthositic gabbro



V. INTERPRETATION OF RESULTS

A. Interpretation of Kasmere Lake Results

1) Foliated Quartz Monzonite

The age of 2636 million years obtained for the foliated quartz monzonite is direct evidence that Archean crystalline rocks underlie the Wollaston Lake fold belt. This evidence is supported by work done on the "Western Granites" in Saskatchewan and by work completed on the hypersthene quartz diorite in Manitoba (Table 1) which appear related to the foliated quartz monzonite (Weber, personal communication).

Geologic evidence that the foliated quartz monzonite did not remain a closed system subsequent to its formation is supported by the scatter of sample points about the isochron. This unit has obviously undergone a complex crustal history, probably being affected by both the Kenoran and Hudsonian orogenies. This metamorphism may have lead to a decrease in the apparent age (Moorbath, 1967), therefore the age obtained for the foliated quartz monzonite should be interpreted as a minimum age.

The initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7025 ± 0.0034 does not preclude the possibility that the quartz monzonite originated from material having a previous crustal history. For example, if we assumed a possible parent material having an average $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.701 and an average $^{87}\text{Rb}/^{86}\text{Sr}$ ratio of 2, probably an upper limit, then it

could conceivably have had a precrustal history of 200 to 300 million years prior to remobilization and isotopic homogenization 2636 million years ago.

2) Grey Quartz Dioritic to Granodioritic Gneiss

The information obtained for the grey gneiss suggests that it was derived from primary igneous material which was emplaced during the Hudsonian Orogeny and was subsequently metamorphosed.

The age of 1941 ± 25 million years is probably a minimum age as samples, 28-2-3040 and 28-2-3038, have undergone alkali metasomatism (Lamb, personal communication). The five relatively unmetasomatized samples fall on an isochron that gives an age of 1953 ± 192 million years. This information suggests that the effect of metasomatism has not been large, and that the original rock, which was emplaced early in the Hudsonian Orogeny, was also metamorphosed during a Hudsonian event.

The $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratio of the grey gneiss, 0.7038 ± 0.0003 , is compatible with that of primary igneous intrusions of comparable age (see for example, Faure and Powell, 1972). This information suggests that the grey gneiss was formed by the metamorphism of primary igneous material, but it does not preclude the possibility that the observed initial ratio for the grey gneiss could have been effected by: alkali metasomatism, incorporation of older crustal material, or a cooling period of 200 to 300

million years, assuming a maximum $^{87}\text{Rb}/^{86}\text{Sr}$ ratio of 0.50.

Although the initial ratio of the grey gneiss suggests that these rocks had a primary igneous origin, the isotopic data does not eliminate the possibility that the grey gneiss may have originated from the metamorphism of sedimentary rocks. If these gneisses are metasedimentary rocks, the emplacement of the source rocks, the sedimentary cycle, and the palingenesis cycle would probably have occurred within 300 million years for the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio to be at its observed value.

B. Interpretation of Burntwood Lake Area Results

1) Ferrohypersthene Bearing Metatonalite, Metadiorite and Anorthositic Gabbro

The age of 1818 ± 199 million years, obtained for the ferrohypersthene bearing metatonalite indicates that these rocks were emplaced during the Hudsonian Orogeny. The scatter of sample points around the isochron and the presence of quartz monzonite dykes in the area suggest that the samples have not remained a closed system throughout their history and an introduction of alkalis seem likely (McRitchie, personal communication). An addition of rubidium would cause a lowering of the apparent age, therefore the observed age is a minimum age.

The initial ratio of 0.7032 ± 0.0013 is in keeping with the geologic information that the ferrohypersthene bearing metatonalite was formed from primary igneous material (McRitchie, personal communication).

VI SUMMARY AND CONCLUSIONS

In the Kasmere Lake area, the foliated quartz monzonite occurs as five large bodies. The age of 2635 ± 163 million years represents the first Archean age found in the Churchill province of Manitoba and agrees with ages obtained from similar rocks further to the southwest in Saskatchewan. The results confirm the theory that the Wollaston Lake fold belt is underlain by Archean intrusive rocks. The initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7025 ± 0.0034 does not preclude the possibility that the quartz monzonite originated from material having a previous crustal history of 200 to 300 million years.

The 1941 ± 25 million year age, obtained for the grey quartz dioritic to granodioritic gneiss probably reflects the effect of the Hudsonian Orogeny in the Kasmere Lake area. The initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7038 ± 0.0003 suggests that the grey gneiss was formed from primary igneous material having a previous crustal history of less than 300 million years. The isotopic data suggests that the grey gneiss was intruded into crustal rocks early in the Hudsonian Orogeny and was effected by a later metasomatic event during the same orogeny. The isotopic data, however, does not preclude the possibility that the grey gneiss was formed from sediments eroded from mantle derived rocks, deposited and metamorphosed within 300 million years.

In the Burntwood Lake area, the ferrohypersthene

bearing metatonalite, metadiorite and anorthositic gabbro gave an age of 1818 ± 199 million years. The initial ratio of 0.7032 ± 0.0013 , along with the age, indicate that the ferrohypersthene bearing rocks were derived from a primary igneous source and were intruded into crustal rocks during the Hudsonian Orogeny.

APPENDIX I

Sample Descriptions

Foliated Quartz Monzonite: Kasmere Lake Area

- 24-1-3726 Quartz, feldspar and biotite are the major minerals in this sample. Mortar texture can be seen between some of the feldspar grains in thin section.
- 24-1-3725 Quartz, feldspar and biotite are the main rock forming minerals in this sample. The majority of the feldspar is microcline with lesser amounts of perthite. Mortar texture can be seen in thin section.
- 24-1-118 This sample consists of coarse grained feldspar, mainly microcline and perthite, with lesser amounts of biotite. Mortar texture is present around some of the larger feldspar grains.
- 24-1-155-1 Coarse grained feldspar and quartz form the majority of this sample. Some hornblende is present as well as biotite. Much of the hornblende is altered to biotite.
- 24-1-25 This sample has a coarse grained to pegmatitic texture with quartz, feldspar, biotite and hornblende. This sample displays a slight foliation. Some weathering is noticeable on this sample.
- 24-1-249 Quartz and feldspar, with some minor quantities of biotite and hornblende are the main constituents of this sample. The sample has a medium grained texture with some fracturing evident in the feldspar grains.
- 24-1-108D This sample consists primarily of quartz and feldspar with hornblende ranging in quantities up to ten per cent. The sample has a coarse grained texture with some fracturing of feldspar and quartz grains.

Grey Quartz Dioritic to Granodioritic Gneiss:

Kasmere Lake Area

- 28-1-86-1 This sample is a fine grained grey rock consisting mainly of quartz and plagioclase with

minor amounts of potassium feldspar and biotite. On the weathered surface, a well developed alignment of biotite is evident.

- 28-1-89-1 Quartz and plagioclase constitute the majority of this sample. The sample is fine grained and massive.
- 28-1-189-1 This sample is fine grained and grey with major quantities of plagioclase and quartz, and minor amounts of biotite and potassium feldspar.
- 28-1-160-1 This fine grained, grey sample contains up to eighty per cent plagioclase and quartz with smaller amounts of potassium feldspar and biotite. Alignment of biotite causes a slight foliation in this sample.
- 28-1-120-1 This sample is a grey, fine grained rock consisting mainly of quartz and plagioclase. A slight gneissosity was formed by the separation of mafics from the quartz and plagioclase.
- 24-1-143-1 This sample is a grey, fine grained, slightly gneissic rock which contains primarily quartz and feldspar with minor biotite.
- 28-2-3038-1 This rock consists mainly of plagioclase and quartz with minor potassium feldspar. The potassium feldspar occurs in thin, coarse grained veins.
- 28-2-3040-1 This sample is a fine grained, grey to slightly pink rock consisting mainly of potassium feldspar, plagioclase and quartz with minor amounts of biotite. The texture is medium to coarse grained with potassium feldspar porphyroblasts.

Ferrohypersthene Bearing Metatonalite, Metadiorite
and Anorthositic Gabbro: Burntwood Lake Area

- 04-2-16 The primary minerals in this sample are quartz, feldspar, biotite, hypersthene, with approximately five per cent sericite associated with the plagioclase.
- 04-2-146 This sample consists of feldspar, quartz and biotite as well as hypersthene in amounts up to ten per cent of the rock.

Some of the feldspar has been altered to sericite. Mortar texture is noticeable between some of the larger grains.

- 04-2-458 This sample consists of feldspar, quartz, biotite and hypersthene. The rock is medium grained with an equigranular, interlocking texture.
- 04-2-RA670 The main constituents of this sample are feldspar, quartz, biotite and hypersthene. The rock is medium grained with some alignment of biotite laths.
- 04-2-RA07 The main constituents of this sample are feldspar, quartz, biotite and hypersthene with some garnets.
- 04-2-567 The primary constituents of this sample are feldspar, quartz, biotite, hypersthene and sericite. The sample is fine to medium grained with the coarser grained portion primarily interlocking, and the finer grained portion mortared. In thin section, biotite and hypersthene inclusions could be found in some of the larger feldspar grains.
- 04-2-2491 The main constituents of this sample are feldspar, quartz, biotite and hypersthene. The rock has a medium grained, equigranular texture.

APPENDIX II

Detailed Analytical Procedure

Using x-ray fluorescence results, the proportion of sample and spike required to produce a measured ($^{84}\text{Sr}/^{86}\text{Sr}$) or ($^{85}\text{Rb}/^{87}\text{Rb}$) value of approximately 0.5 was calculated. The sample was weighed in aluminum foil boats with an electric balance and was then transferred to a 200 ml. teflon beaker. Twenty ml. of 40% HF (E. Merck, Suprapur) and 3 ml. of 70% HClO_4 (G. Frederick Smith, double distilled) were added to the sample. The sample was allowed to digest for at least eight hours. The cover was removed and the sample was allowed to evaporate to a perchlorate mush. Twenty ml. of double distilled water were then added and the sample was allowed to evaporate to dryness.

The sample, at this time was ready for spiking. To each rubidium or strontium sample, the appropriate amount of rubidium or strontium spike was added. The amount of spike to be used was determined from the x-ray fluorescence results. To insure equilibrium of the sample and the spike, 20 ml. of 6.2 N HCl were added. The sample was allowed to digest at low heat for at least two hours. The cover was then removed and the sample was evaporated to dryness.

After spiking, five ml. of methanol (G.C. spectrophotometric quality) were added to the sample to separate the alkaline earths. The sample was then centrifuged until

the supernatant was clear. It was then poured into a 30 ml. hysil beaker with 10 ml. of 6.2 N HCl. The sample was allowed to evaporate at low heat.

The final isolation of strontium from the rest of the sample was achieved in an ion exchange column. The strontium was separated by analytical grade cation exchange resin (AG 50W-X12). The ion exchange column was previously calibrated with an atomic absorption spectrophotometer to determine when the strontium fraction would appear. The dried strontium sample was dissolved in 5 ml. of 6.2 N HCl, and then transferred to the column. After the first 5.0 ml. of HCl had passed through the column, and the sample was absorbed, two more 5.0 ml. aliquots and one 35 ml. aliquot of HCl were added. After a total of 50 ml. of HCl had passed through the column, the strontium was collected with 45 ml. of HCl in a 50 ml. hysil beaker. The sample was then allowed to dry until 2 ml. of sample remained, which was transferred to a 10 ml. hysil beaker for the final drying. After the sample was completely evaporated, it was ready for isotopic measurement.

The rubidium sample, after spiking, was dissolved in 5 ml. of 6.2 N HCl. It was centrifuged to separate any insoluble material that may not have been dissolved by the HF acid. When the supernatant was clear it was transferred to a 10 ml. hysil beaker and was baked to complete dryness. The dried rubidium sample was then ready for isotopic measurement.

The strontium and rubidium spikes were supplied by Oak Ridge Laboratories as $\text{Sr}(\text{NO}_3)_2$ and RbCl , and were prepared by Dr. G.S. Clark. They were dried for at least six hours at 120°F ., and were allowed to cool in a dessicator. The spikes were carefully weighed and then diluted to 200 ml. with 0.5 N HCl . A one ml. aliquot of this solution was transferred to a 1000 ml. volumetric flask, and was diluted to volume with double distilled water. A sample for composition determination was obtained by drying a 10 ml. aliquot of the spike at low heat. The strontium concentration was calibrated with $\text{Sr}(\text{NO}_3)_2$ (Baker analyzed, reagent grade) and the rubidium spike concentration was calibrated with RbCl (NBS 984 RbCl , assay-isotopic standard). The isotopic ratios necessary to determine concentration and composition were measured on a mass spectrometer using the same procedure as is described in Appendix III.

APPENDIX III

Detailed Description of Mass Spectrometry

Description of Mass Spectrometer

All isotopic measurements were made on a triple filament, single focusing mass spectrometer, with a ten inch radius of curvature and a ninety degree deflection.

Strontium and rubidium analyses were run using separate ionization sources, similar to the type described by Craig (1959). Two tungsten sample filaments and one rhenium centre filament were welded to the posts of Picker nuclear beads (style #297157), which are held in the source with non-magnetic stainless steel blocks.

The vacuum is maintained at the source end with a mechanical pump and an oil diffusion pump, while the vacuum in the collector end is maintained with a 50 l/s Vac Ion pump. On-line gate valves isolate the source for venting and changing samples.

Amplification of the signal is attained with a Cary vibrating reed electrometer, and the signal is recorded on a strip chart recorder equipped with an expanded scale.

The voltage required for the magnets is supplied through a Fluke high voltage power supply (Model 410B). The filament currents and vibrating reed are stabilized using a Sola transformer and a Sorensen voltage regulator.

Operating Procedure

The operating procedure was begun by outgassing

the filament to be used for each run. Filaments designated for rubidium runs were outgassed with the side filament current at two amp. and centre filament current at four to five amp. The side and centre filaments to be used for the strontium runs were outgassed at 2.5 amp. and 5.5 amp. respectively. The duration of the outgassing period was 20 minutes.

Prior to mounting on the outgassed filament, the sample was dissolved in five to six drops of double distilled water. A small glass pipette was used to place three or four drops of sample on each of the two tungsten side filaments. The sample was dried on the tungsten filaments using an electric current. The filament bead was then placed in the source.

The procedure of mounting and removing the source from the mass spectrometer was aided by isolating the source region from the collector end and diffusion pump. For removal of the source, the source region was vented with dry nitrogen while a constant pressure was maintained in the diffusion pump region, the tube, and at the collector end. When the source was mounted in the mass spectrometer, a pressure of 50 microns of mercury was attained with a mechanical roughing pump. When this pressure was achieved, the valve leading to the diffusion pump was opened and the roughing pump was isolated.

After the oil diffusion pump attained a pressure of 2.0×10^{-7} millimeters of mercury, preliminary outgassing

of the sample was achieved by passing a current through the sample and centre filaments. A current of 0.1 amp. on the side filaments and 1.0 amp. on the centre filament was usually sufficient to outgas the rubidium samples, but centre filament currents of 3.5 amp. to 4.0 amp. were necessary for the strontium samples. The source region remained isolated for approximately one-half hour after degassing to assure that the pressure was below 2.0×10^{-7} millimeters of mercury.

During a strontium measurement the side filament currents were between 0.1 and 0.3 amp., and the centre filament current was normally between 4.5 and 5.0 amp. An accelerating voltage of 4.0 kilovolts was generally used. During each measurement, the three strontium ratios, $^{84}\text{Sr}/^{86}\text{Sr}$, $^{87}\text{Sr}/^{86}\text{Sr}$, and $^{88}\text{Sr}/^{86}\text{Sr}$ were measured separately at expanded scale. Seven to ten scans of each ratio were taken. The base line was scanned between each set of ratios, as well as at the beginning and end of the measurement, in order to check for possible changes due to variations in the pressure or filament characteristics. These base line checks also enabled the operator to monitor any rubidium present in the sample.

The rubidium ratio was measured with the sample filament current maintained between 0.30 and 0.50 amp. and the centre filament at 1.9 to 2.2 amp. using an accelerating voltage of 3.5 kilovolts. Fourteen to sixteen scans were generally taken of the ^{85}Rb and ^{87}Rb peaks.

APPENDIX IV

Isotope Dilution Calculation

The notations used in the strontium isotope dilution calculations are listed below:

m = concentration of each isotope or total strontium in the mixture of spike and sample

t = concentration of each isotope or total strontium in the spike

s = concentration of each strontium isotope in the sample

A = total concentration of strontium in the sample

The calculations required in the calculation of the atomic abundance of each of the four strontium isotopes are shown below.

$$(1) \left(\frac{{}^{84}\text{Sr}}{{}^{86}\text{Sr}} \right)_m = \frac{({}^{84}\text{Sr})_t + ({}^{86}\text{Sr})_s}{({}^{86}\text{Sr})_t + ({}^{86}\text{Sr})_s}$$

$$(2) ({}^{84}\text{Sr})_s = 0.0056A$$

$$(3) ({}^{86}\text{Sr})_s = 0.0986A$$

$$(4) A = \frac{({}^{84}\text{Sr}/{}^{86}\text{Sr})_m ({}^{84}\text{Sr})_t - ({}^{84}\text{Sr})_t}{0.0056 - 0.0986 ({}^{84}\text{Sr}/{}^{86}\text{Sr})_m}$$

$$(5) (\text{Sr})_m = A + (\text{Sr})_t$$

$$(6) (\text{Sr}/{}^{86}\text{Sr})_m = ({}^{84}\text{Sr}/{}^{86}\text{Sr})_m + ({}^{87}\text{Sr}/{}^{86}\text{Sr})_m + ({}^{88}\text{Sr}/{}^{86}\text{Sr})_m + 1$$

$$(7) ({}^{88}\text{Sr}/\text{Sr})_m = \frac{({}^{88}\text{Sr}/{}^{86}\text{Sr})_m}{A/({}^{86}\text{Sr})_m}$$

$$(8) \left(\frac{^{87}\text{Sr}}{\text{Sr}} \right)_m = \frac{\left(\frac{^{87}\text{Sr}}{^{86}\text{Sr}} \right)_m}{A / \left(^{86}\text{Sr} \right)_m}$$

$$(9) \left(\frac{^{86}\text{Sr}}{\text{Sr}} \right)_m = \frac{1}{A / \left(^{86}\text{Sr} \right)_m}$$

$$(10) \left(\frac{^{84}\text{Sr}}{\text{Sr}} \right)_m = \frac{\left(\frac{^{84}\text{Sr}}{^{86}\text{Sr}} \right)_m}{A / \left(^{86}\text{Sr} \right)_m}$$

$$(11) \left(^{88}\text{Sr} \right)_s = \left(\text{Sr} \right)_m \left(\frac{^{88}\text{Sr}}{\text{Sr}} \right)_m - \left(^{88}\text{Sr} \right)_t$$

$$(12) \left(^{87}\text{Sr} \right)_s = \left(\text{Sr} \right)_m \left(\frac{^{87}\text{Sr}}{\text{Sr}} \right)_m - \left(^{87}\text{Sr} \right)_t$$

$$(13) \left(^{86}\text{Sr} \right)_s = \left(\text{Sr} \right)_m \left(\frac{^{86}\text{Sr}}{\text{Sr}} \right)_m - \left(^{86}\text{Sr} \right)_t$$

$$(14) \left(^{84}\text{Sr} \right)_s = \left(\text{Sr} \right)_m \left(\frac{^{84}\text{Sr}}{\text{Sr}} \right)_m - \left(^{84}\text{Sr} \right)_t$$

In the above calculations, equations (1), (2), (3) and (4) lead to the determination of the total strontium concentration in the sample (A). In equation (2) the figure 0.0056 is the fraction of ^{86}Sr in natural strontium and in equation (3) the value 0.0986 is the fraction of ^{84}Sr in natural strontium. Equations (5) through (14) lead to the determination of the concentration of ^{88}Sr , ^{87}Sr , ^{86}Sr and ^{84}Sr in the sample. The three ratios $\left(\frac{^{88}\text{Sr}}{^{86}\text{Sr}} \right)_s$, $\left(\frac{^{87}\text{Sr}}{^{86}\text{Sr}} \right)_s$, and $\left(\frac{^{84}\text{Sr}}{^{86}\text{Sr}} \right)_s$ are found by dividing the value of $\left(^{86}\text{Sr} \right)_s$ into the concentration of each of the other three ratios.

The method of applying the normalization factor and other adjustments are described by Penner (1970).

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