

THE UNIVERSITY OF MANITOBA
RUBIDIUM-STRONTIUM WHOLE-ROCK AGES
FROM THE OXFORD LAKE - KNEE LAKE GREENSTONE BELT,
NORTHERN MANITOBA

BY
SHA-PAK CHEUNG

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
OF
MASTER OF SCIENCE
DEPARTMENT OF EARTH SCIENCES

WINNIPEG, MANITOBA

OCTOBER, 1978

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ABSTRACT

Rubidium-strontium whole rock ages have been determined on rock units from the Oxford Lake-Knee Lake greenstone belt within the Superior Province in northeastern Manitoba.

The Magill Lake Pluton, a post-Oxford Lake Group granitic intrusion gave an age of 2455 ± 35 Ma ($\lambda^{87}\text{Rb} = 1.42 \times 10^{-11} \text{ yr.}^{-1}$) and an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7078 ± 0.0043 . The Bayly Lake Pluton, believed to be a pre-Oxford Lake Group granodiorite gave an age of 2423 ± 74 Ma with an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7029 ± 0.0001 . Volcanic rocks, of the Hayes River Group, from Goose Lake (30 km south of Gods Lake Narrows) were dated at 2680 ± 125 Ma with an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7014 ± 0.0009 .

The age for the Magill Lake and Bayly Lake Plutons can be interpreted as the minimum ages of granitic intrusion in the area, while the age for the Hayes River Group volcanic rocks is consistent with Rb-Sr ages of volcanic rocks from other Archean greenstone belts within the northwestern Superior Province.

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INTRODUCTION

The study area lies within the Archean Oxford Lake-Knee Lake greenstone belt in the northern area of the Superior Province in Manitoba (Fig. 1). The granitic rock units investigated occur in the vicinity of southern Knee Lake, and east to the west shore of Gods Lake. A felsic volcanic unit from Goose Lake, 30 km south of Gods Lake Narrows, was also studied.

Previous to the present study, only K-Ar mineral dates have been published for some of the granitic bodies in the region between Oxford and Gods Lake, and these ranged from about 2600 to 1650 Ma. These dates suggest the possibility that post Archean thermal events affected this region and that granitic rocks were intruded during the Aphebian. The results of the present study suggest that the granitic intrusive rocks in this area which intrude the predominantly meta-sedimentary rocks of the Oxford Lake Group are late Archean in age.

The purpose of the present study is to present preliminary rubidium-strontium total-rock ages for the granitic bodies believed to represent pre- and post- Oxford Lake Group plutonic activity and therefore to place limits on the age of the Oxford Lake Group and the time of the major thermal activity in the area.

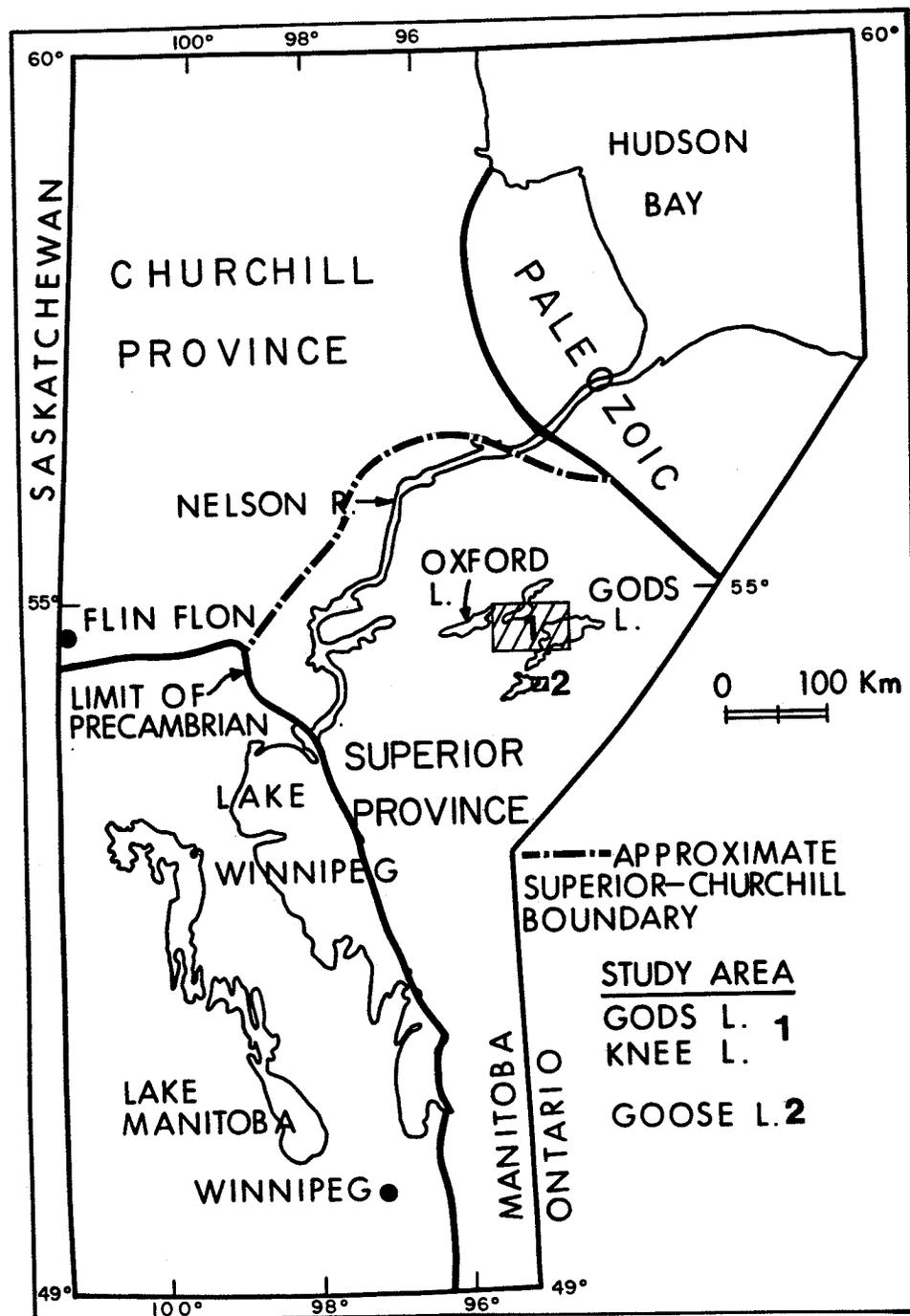


FIGURE 1. Location of area studied.

Acknowledgements

This work was made possible through financial assistance from the Geological Survey of Canada (CDA EMR 4-220/75), the National Research Council of Canada (NRC A3831), and a negotiated development Grant (NRC D-40).

The author would like to acknowledge the assistance of K. Ramlal (XRF analyses) and R. Pryhitko (drafting). P. Beaudoin assisted with the chemistry and isotope measurements while Carole Iverson and O. Stephenson assisted with the computer processing.

Paul Gilbert (Manitoba Mineral Resources Division) suggested the study and supplied most of the samples used in this work. He also made available unpublished information on the geology of the area. The study was supervised by Dr. G. S. Clark. Drs. W. Weber, A. C. Turnock, and R. C. Barber read the manuscript and their critical comments are gratefully acknowledged.

GENERAL GEOLOGY

A simplified geological map of the study area is given in figure 2. The major part of the map area shown involves the northwestern part of Gods Lake, west, to the southern area of Knee Lake and Magill Lake. The inset of figure 2 shows the geology in the vicinity of the Beaver Hill Lake-Goose Lake area.

The area sampled lies within the Oxford Lake-Knee Lake greenstone belt - a typical Archean volcanic-sedimentary succession with associated plutonism and metamorphism. The first geological map of the area was compiled by Bruce (1919). Wright (1932) proposed the name Hayes River Group for the lower succession of predominantly volcanic flows and tuffs, with lesser sedimentary rocks. Barry (1959) further subdivided the Hayes River Group into two units (upper and lower). The overlying sedimentary rocks which Wright (1932) had termed the Oxford Lake Group were believed to lie unconformably on the Hayes River Group.

Campbell et al. (1972) suggested that the Hayes River Group and the Oxford Lake Group are not separated by a major unconformity and hence represent a continuous period of volcanism and sedimentation. Therefore, they referred to the Oxford Lake Group as the Oxford Lake Subgroup (of the Hayes River Group) and the upper and lower subdivisions of the Hayes River Group of Barry (1959) as the Knee Lake and Gods Lake Subgroups respectively (Baragar and McGlynn, 1976).

More recent work in the region has resulted in further revisions in the stratigraphy of the greenstone belt. The major unconformity as defined by Wright (1932) between the Hayes River Group and the Oxford Lake Group has now been recognized (Elbers, 1973), and the use of the two-fold division of the Hayes River Group into the Knee Lake

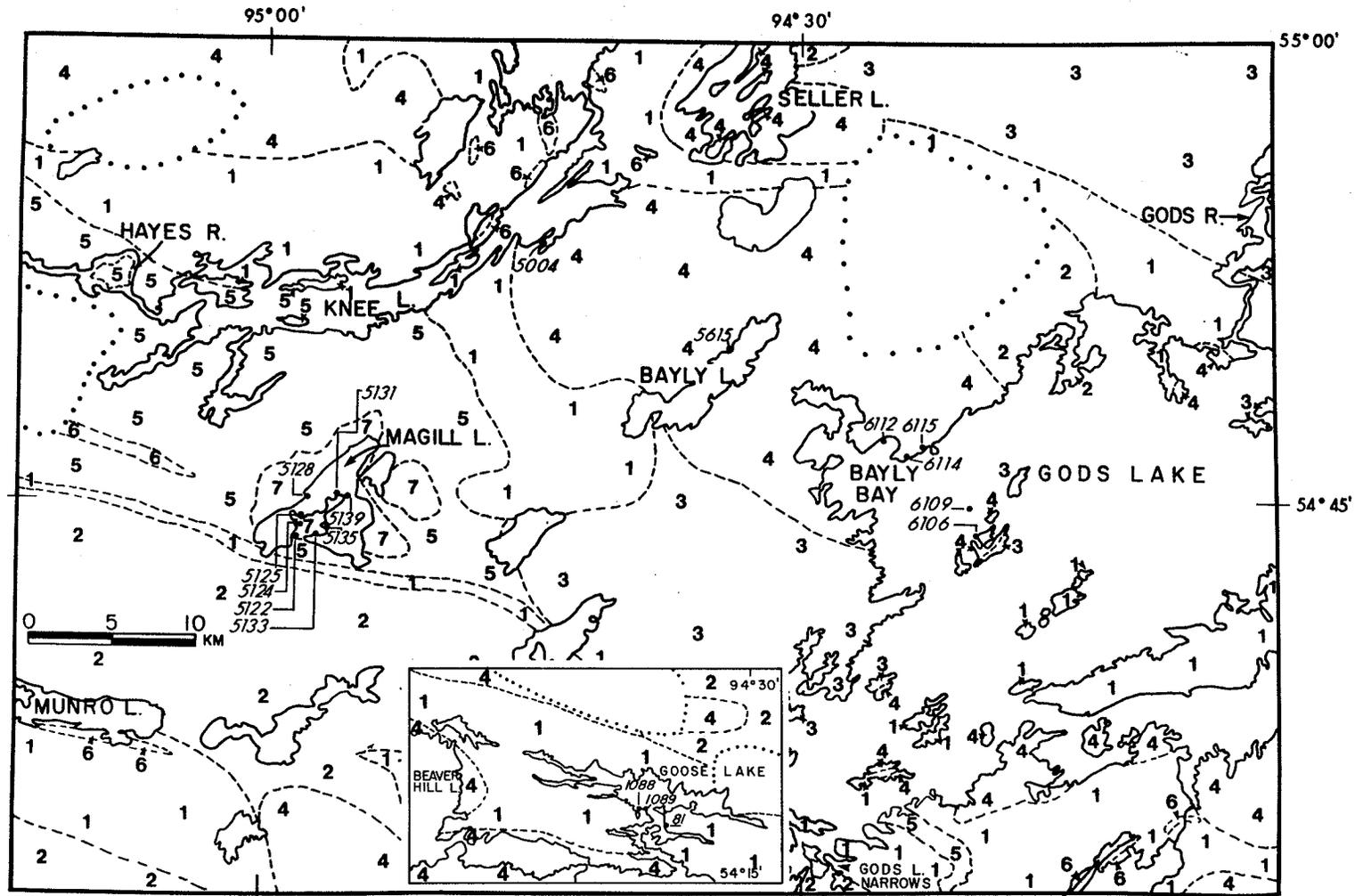


FIGURE 2. Simplified geological map of part of the Oxford Lake-Knee Lake greenstone belt with sample locations. Inset shows the Beaver Hill Lake-Goose Lake area. The legend is on page

and Gods Lake Subgroups is no longer recommended (H. P. Gilbert, pers. comm.).

The greenstone belt may be divided into the Hayes River Group, consisting mainly of volcanic rocks, and the unconformably overlying predominantly sedimentary Oxford Lake Group (see table 1).

The major aspects of the volcanism in the area have been described by Hubregtse (1976). Detailed mapping in the area has not revealed the presence of a basement below the Hayes River Group. Possible basement may be represented by a tonalitic gneiss which structurally underlies the greenstone belt south of Oxford Lake (Hubregtse, 1976), but possible sialic crust has not been recognized in this area. Baragar and McGlynn (1976) have reviewed the stratigraphy of Archean greenstone belts in this region and their possible relationship to an ancient sialic crust.

The Hayes River Group consists mainly of mafic to felsic volcanic flows, pyroclastics, sedimentary rocks, minor gabbro and peridotite. Intrusive into this are granitic rocks ranging from tonalite to granite. The Oxford Lake Group unconformably overlays these intrusions. The Oxford Lake Group consists mainly of sediments-conglomerate, siltstone, greywacke with minor hornblende schist and amphibolite. Gabbro and diabase intrusion preceded the intrusion of post-Oxford Lake Group granitic plutonism. This post-Oxford Lake Group intrusive activity consisted mainly of granite to granodiorite and pegmatite.

The Hayes River Group consists mainly of pillowed and massive basalts, intravolcanic gabbro and minor felsic pyroclastics and flows intercalated with greywacke, chert and iron formation. Five volcano-sedimentary cycles have been recognized in the Knee Lake area

(Hubregtse, 1976). The lower section of the Hayes River Group consists predominantly of mafic lavas with less than ten percent pyroclastic and epiclastic sediments, chert, rhyolite and dacite, while the upper section is mainly felsic and mafic volcanic fragmental rocks with subordinate sediments. The Hayes River Group forms a monoclinial, vertically dipping, south-facing structure which is bounded in the central Oxford Lake area by an east-west fault that seems to fade out to the east.

The Oxford Lake Group is composed of sedimentary rocks but locally contains up to forty percent of lavas, and associated volcanoclastic rocks. It is characterized by a lower mixed volcanic unit, overlain by a basal conglomerate and relatively uniform epiclastic rocks which, although locally well sorted, are dominantly greywacke suite. The conglomerate clasts consist of mafic to felsic volcanic rocks, sedimentary rocks of various types, granitoid rocks and quartz grains.

Metamorphism and Structure

The Hayes River Group forms a broad synclinal, vertically dipping south-facing structure. The rocks exhibit varying degrees of schistosity and faulting has been prominent.

The pre-Oxford intrusive rocks are largely gneissic in character while the younger, post-Oxford granitic rocks exhibit a massive nature although, locally, a weak foliation is evident. Pegmatite dykes associated with the younger granitic rocks are locally folded and disrupted suggesting a syn- to pre-kinematic age of intrusion (Gilbert and Elbers, 1972; Elbers and Gilbert, 1972; Gilbert, 1972).

Two metamorphic events have been recognized in the region (Weber

and Scoates, in press). The older event occurred prior to the deposition of the Oxford Lake Group while the later event postdated this sedimentary sequence. The latter event may be related to the intrusion of the younger granites. The range of metamorphism in the Oxford Lake-Knee Lake greenstone belt (associated with both events) ranges from lower greenschist to lower amphibolite facies.

Discussion of Rock Units Dated

Rubidium-strontium whole-rock ages were determined on three rock units in the area:

- (1.) Hayes River Group Volcanic rocks from the Goose Lake Area.
- (2.) Bayly Lake Pluton (pre-Oxford Lake Group intrusion).
- (3.) Magill Lake Pluton (post-Oxford Lake Group intrusion).

1. Hayes River Group Volcanic Rocks (Goose Lake)

These rocks occur in the Beaver Hill-Goose Lake greenstone belt. The major area sampled occurs about 40 km south of Gods Lake Narrows (Fig. 2). Due to multiple deformation and metamorphism in the lower to middle amphibolite facies, most rocks in the Beaver Hill Lake-Goose Lake greenstone belt have lost most of their primary characteristics. Mafic flows, tuffs, and greywacke have been recrystallized to amphibolite. Felsic volcanic rocks in the area sampled consist mainly of quartz-biotite schist (Elbers, 1972). The felsic volcanics sampled consist largely of fine-grained rhyolitic tuff containing plagioclase and quartz fragments. Some fragments, however, consist of rhyolite porphyry up to 10 cm in length.

2. Bayly Lake Pluton

The Bayly Lake Pluton is believed to be part of the pre-Oxford

Lake Group intrusive series. This intrusion (Unit 4, Fig. 2) is chiefly granodiorite in composition. The area of the body sampled for the present study extends from the western part of Gods Lake, northwestward to southern Knee Lake. Most of the information on this unit is taken from unpublished reports of the Manitoba Dept. of Mines, Resources and Environmental Management (H. P. Gilbert, per. comm.). The body intrudes volcanics of the Hayes River Group at southern Knee Lake and earlier tonalitic rocks at Gods Lake.

The pluton is leucocratic, medium-grained, massive to slightly foliated, and generally porphyritic. Microcline phenocrysts often contain oriented inclusions of plagioclase and quartz. The rock varies locally from granite to tonalite. Mafic schlieren and amphibolite xenoliths are not common, being confined mostly to the contact zones in the southern Knee Lake area. The body is intruded locally by a grey granodiorite as dykes and irregular masses which have been foliated with the Bayly Lake Pluton.

The basal Oxford Lake Group conglomerate contains clasts of the Hayes River Group volcanics as well as clasts identified as belonging to the Bayly Lake Pluton. This, together with the absence of any intrusive relationships between the Oxford Lake Group and the Bayly Lake Granodiorite, strongly indicate a pre-Oxford Lake Group age for this unit.

3. Magill Lake Pluton

The Magill Lake Pluton (Unit 7, Fig. 2) probably represents the youngest major granitic activity in the area. The body investigated in the present study occurs at Magill Lake. Another granitic body in the northern Oxford Lake area, to the northwest, may belong to the same intrusive phase.

The pluton ranges from granite to granodiorite in composition and is a pear-shaped body. The rocks of this body are massive to slightly foliated, white to pink and the texture ranges from medium-grained to pegmatitic. The medium-grained phases and the pegmatitic granite occur as both clearly defined separate layers and as gradational zones. The Magill Lake Pluton intrudes metasedimentary rocks (largely greywacke) of the Oxford Lake Group at Magill Lake. The contacts between the intrusion and the host rocks are sharp and contact metamorphic zones have been recognized at Magill Lake.

The foliation trend in the pluton is consistently east-west and foliated greywacke xenoliths up to several meters in length occur within the intrusion. Granitic dykes associated with the Magill Lake Pluton are folded and disrupted, and show a weak foliation along with the pluton (Gilbert and Elbers, 1972).

The rocks of the pluton are composed of quartz, plagioclase, microcline and biotite. The quartz occurs as strained, interstitial grains, as irregular masses several centimeters in diameter and as graphic intergrowth with plagioclase and microcline. The plagioclase in the main granite body is usually An_5 - An_{11} in composition but more calcic plagioclase (andesine-labradorite) occurs in granite dykes intruding calc-silicate rocks at central Magill Lake. Biotite is commonly partially chloritized and locally contains epidote inclusions.

PREVIOUS ISOTOPIC AGES

The only published ages from the region of Oxford Lake and Gods Lake are K-Ar dates on biotite separated from granitic rocks. Some of these ages are summarized in Table 1 and a brief description follows.

The oldest K-Ar age reported from the study area is 2620 Ma for a pre-Oxford Lake Group granodiorite at Gods Lake (Burwash et al., 1962). The same authors report an age of 2380 Ma from a granodiorite at Gods Lake Narrows. Moore et al. (1960) obtained an age of 1640 Ma on biotite separated from the Magill Lake Pluton.

A gneissic granite from the south shore of Oxford Lake was dated at 2200 Ma (Moore et al., 1960). Wanless et al. (1973) have reported a K-Ar age of 1900 Ma from Bigstone River (95 km NNW of Gods Lake). Also, Lowdon et al. (1962) obtained an age of 1970 Ma near Robinson Portage (130 km SW of Gods Lake) and Lowdon (1961) has reported an age of 2190 Ma from Playgreen Lake (240 km S of Gods Lake). Leech et al. (1963) have reported an age of 2005 Ma on a granite from Seller Lake (50 km NNE of Gods Lake).

Although some of these ages are reported from areas far removed from the present study area, the ages suggest strongly that late Archean and possibly post-Archean reheating of this area of the northern Superior Province in Manitoba has occurred.

Evidence for middle and late Proterozoic igneous activity within the Superior Province of Northeastern Manitoba is offered by two dyke swarms which cut the Archean rocks.

The Molson Dyke Swarm is a northeasterly trending set of mafic to ultramafic dykes believed to have intruded between 1800 and 2000 Ma. Ermanovics and Fahrig (1975) discuss the more recent whole-rock K-Ar dates obtained from this dyke swarm.

TABLE 2.

Previously Published Biotite K-Ar ages from the Northern Superior Province in Northern Manitoba, Including the Present Study Area.

Reference	Location	Sample Description	Age (Ma)
Wanless et al. 1973 G.S.C. 72-77	55°37'25"N 95°04'15"W Bigstone River, 95 km NNW of Gods Lake	Quartz monzonite	1900
Lowdon et al. 1962 G.S.C. 61-127	54°15'N 96°16'W Robinson Portage 130 km SW of Gods Lake	Microcline granite gneiss	1970
Lowdon 1961 G.S.C. 60-85	53°45'40"N 97°55'30"W Playgreen Lake 240 km S of Gods Lake	Quartz monzonite	2190
Leech et al. 1963 G.S.C. 62-100	55°02'00"N 94°27'40"W Seller Lake 48 km NNE of Gods Lake	Granite	2005
Burwash et al. 1962	54°38'N 94°16'W Gods Lake	Granodiorite	2620
Burwash et al. 1962	54°32'N 94°30'W Gods Lake Narrows	Granodiorite	2380
Moore et al. 1960	54°18'N 95°35'W S shore of Oxford Lake	Gneissic granite	2200
Moore et al. 1960	54°45'N 94°55'W Magill Lake	Granite	1640

A north-northwesterly striking dyke swarm referred to as the Mackenzie Dyke Swarm consists mainly of diabase dykes and appears to be considerably younger than the Molson Dyke Swarm. Whole-rock K-Ar ages on this set of dykes suggest an emplacement age of about 1200 Ma (Fahrig and Jones, 1969).

EXPERIMENTAL PROCEDURES

Sample Collection and Preparation

The samples used in this study were collected by H. P. Gilbert and F. J. Elbers during the 1972 and 1973 field seasons in the Manitoba Department of Mines, Resources and Environmental Management's "Greenstone Project" mapping program. The sample locations are shown in Figure 2.

All weathered surfaces were carefully trimmed from all samples as a first step in the analytical procedure. The samples were then crushed and pulverized to approximately - 100 mesh. A representative aliquot was taken of the pulverized material and stored in two ounce glass sample bottles.

Samples for isotopic analysis were selected on the basis of rapid X-ray fluorescence analysis to offer the optimum range in Rb/Sr ratios, and to provide estimates for appropriate tracer additives.

Analytical Procedures

The experimental methods used in the present study are similar to those described elsewhere (for example, Penner, 1970 and Anderson, 1974). A brief description of the techniques used here follows and a more detailed description is presented in the appendix.

1. Chemical Techniques

An appropriate aliquot of the sample powder was carefully weighed and transferred to a teflon beaker. The sample was digested slowly in 20 ml of 40% Hf and 3 ml of HClO₄. The final perchlorate "mush" was then taken up in about 20 ml double distilled water and again taken slowly to dryness. After adding an appropriate amount of ⁸⁷Rb or ⁸⁴Sr

tracer, about 20 ml of 6.2 N HCl ("vycor" distilled) was added and the sample was again taken to dryness. In the case of rubidium, no further chemistry was required prior to the mass spectrometric measurements. For strontium, further purification was obtained using a methanol leach as a first stage in separating the alkali metals. Final purification was obtained using cation exchange resin (AG 50 W-x12, 200-400 mesh).

2. Isotopic Measurement

Both Rb and Sr concentrations were determined by isotope dilution mass spectrometry. The mass spectrometer is a single focusing instrument with a 25 cm radius of curvature and 90° sector magnet. It has a triple filament thermal ionization source slightly modified from that described by Craig (1959). Some modifications have been made to the mass spectrometer since the description given by Josse (1974). Signal detection and amplification is obtained with a Cary vibrating reed electrometer (model 401), as before. However, the data is recorded using a timer-counter DVM (HP model 5326B) and a thermal printer (HP model 5150A). Measurements are made by magnet peak switching between two peaks and each signal is counted for 10 seconds. Magnetic switching is controlled automatically by the DVM.



ANALYTICAL RESULTS

Rubidium and Strontium Standards

During this study, the accuracy of the strontium isotope measurements were frequently monitored by analyzing a prepared solution of Eimer and Amend (E & A) SrCO_3 standard (lot No. 492 327). This allows an interlaboratory comparison of our results. Several analyses of this standard during the course of this work, gave a $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7084 ± 0.0003 (1σ) when normalized to a $^{86}\text{Sr}/^{88}\text{Sr}$ value of 0.1194. A solution of the National Bureau of Standard (Washington, D.C.) standard Reference Material 987 (SrCO_3) has been recently prepared and a single measurement obtained toward the end of this study gave a $^{87}\text{Sr}/^{86}\text{Sr}$ value of 0.7103 ± 0.0004 (1σ) when normalized as above. Both the values agree favourably with results obtained by other laboratories, within the precision quoted.

Analyses of the NBS 70a K-feldspar standard (Compston et al., 1969) gave average values of 531 ppm and 65.3 ppm for Rb and Sr respectively.

Rubidium and Strontium Blanks

In order to check the levels of contamination in the chemical procedures, total process blanks are measured periodically. The average values in this laboratory are 0.0027 microgram for rubidium and 0.007 micrograms for strontium. These levels are considered negligible for the sample levels measured.

Composition and Concentration of Spike Solutions

All rubidium measurements were made using a ^{87}Rb -enriched tracer. The isotopic composition and concentration of the spike was measured

periodically during the present work. The spike concentration was determined by comparing it to a prepared solution of the National Bureau of Standard reference material (SRM) 984 (99.90% \pm 0.02 wt. % RbCl).

The concentration of the ^{87}Rb spike solution used in this work is 0.05935 micromole/ml and the isotopic composition is (in atoms %):

$$^{87}\text{Rb} = 99.15$$

$$^{85}\text{Rb} = 0.85$$

The strontium concentration and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were determined for single, spiked sample aliquots using a ^{84}Sr -enriched tracer (Oak Ridge National Laboratory). During the early stage of this work, the ^{84}Sr spike was calibrated against a standard solution prepared from SrCO_3 (Baker analyzed, reagent grade). More recently, it has been compared to a standard solution made up from the National Bureau of Standard (SRM) 987 (99.98 \pm 0.02 wt. % SrCO_3). The spike concentration used in this work is 0.01126 micromole/ml and the composition (in atom %) is:

$$^{88}\text{Sr} = 12.480$$

$$^{87}\text{Sr} = 1.560$$

$$^{86}\text{Sr} = 3.710$$

$$^{84}\text{Sr} = 82.240$$

Constants used in the Isotopic Measurements and Age Calculations

All the isotopic results have been reported using the following data:

$$^{85}\text{Rb}/^{87}\text{Rb} = 2.593$$

$$^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$$

$$^{84}\text{Sr}/^{86}\text{Sr} = 0.05697$$

The majority of geochronologists using the rubidium-strontium method have been reporting the ages based on the decay constant for ^{87}Rb of $1.39 \times 10^{-11} \text{ yr}^{-1}$ as determined by Aldrich et al. (1956) by adjusting the rubidium-strontium ages obtained from pegmatite minerals to agree with uranium-lead ages obtained from the same minerals. Although the precision is poor for this value, the physical determination of the ^{87}Rb decay constant was subject to large systematic errors due to the low energy β^- particles emitted by this isotope.

More recently, however, superior measurements have been made resulting in the recommendation that the value of $1.42 \times 10^{-11} \text{ yr}^{-1}$ be adopted at the present time (Steiger and Jager, 1977). This recommended value is based on measurements by several workers, which include; Neumann and Huster (1976) and Davis et al. (1977).

All ages reported in this study are based on the value of $1.42 \times 10^{-11} \text{ yr}^{-1}$.

Results Obtained from Present Study

On the basis of replicate determinations on samples and standards, the errors used in calculating the ages and initial ratios are 1.5% for the $^{87}\text{Rb}/^{86}\text{Sr}$ ratios and 0.15% for the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. The errors quoted for the ages are at the 2σ level while the errors in the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are 1σ . The ages are calculated using the least squares regression method of York (1966). If these ages are to be compared with the $1.39 \times 10^{-11} \text{ yr}^{-1}$ decay constant of ^{87}Rb , the latter should be multiplied by the factor 0.9789.

1. Hayes River Group Volcanic Rocks

The regression of the results of six samples of rhyolite tuff gives an age of $2441 \pm 182 \text{ Ma}$ and an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of $0.7056 \pm$

0.0018 (dashed line, Fig. 3).

The samples were collected from a single felsic tuff horizon at Goose Lake which contains clasts of porphyritic rhyolite and rhyolite.

The large error on the age is due largely to the low range in the Rb/Sr ratios which results in a large extrapolation to the ordinate (relative to this range).

Due to the restricted range of Rb/Sr values for the rhyolite tuff, two samples of basalt from the same volcanic sequence have been included in the age calculation. The samples of basalt were collected 2.5 km due south of sample 81. The regression of seven points results in an age of 2680 ± 125 Ma and an initial ratio of 0.7014 ± 0.0009 (solid line, Fig. 3). Sample 81-I is omitted from this plot since it falls considerably below the regressed line of the other samples.

2. Bayly Lake Pluton

Seven samples of this granitic unit have been analyzed. The analytical results are listed in Table 4. The regression of the seven points defines a whole-rock isochron age of 2424 ± 74 Ma and an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7029 ± 0.0001 . The results are plotted in Figure 4. The results all lie about the best-fit line within the uncertainty used in the calculation.

3. Magill Lake Pluton

The analytical results for this unit are listed in Table 5. The slope of the best-fit line through all eight points defines an age of 2450 ± 35 Ma with an initial ratio of 0.7078 ± 0.0043 (Fig. 5). The fit of the points is good, and this, together with the extreme range of the Rb/Sr values has resulted in the very low error in the age. The inset of Figure 4 shows the distribution of the four least radiogenic

TABLE 3. Analytical Results for the Hayes River Group Volcanic Rocks
(Goose Lake)

Sample	Rb(ppm)	Sr(ppm)	$^{87}\text{Rb}/^{86}\text{Sr}$ ¹	$^{87}\text{Sr}/^{86}\text{Sr}$ ²
1089 - I	81.59	148.5	1.596	0.7631
1089 - II	133.6	366.9	1.057	0.7434
81 - I	156.3	231.8	1.957	0.7732
81 - II	92.7	306.8	0.8760	0.7371
81 - III	113.2	204.1	1.610	0.7632
1088	118.8	356.3	0.9667	0.7383
1013	29.72	272.5	0.3154	0.7139
1011	75.43	461.9	0.4723	0.7186

¹Atomic ratio

²Normalized to $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.1194

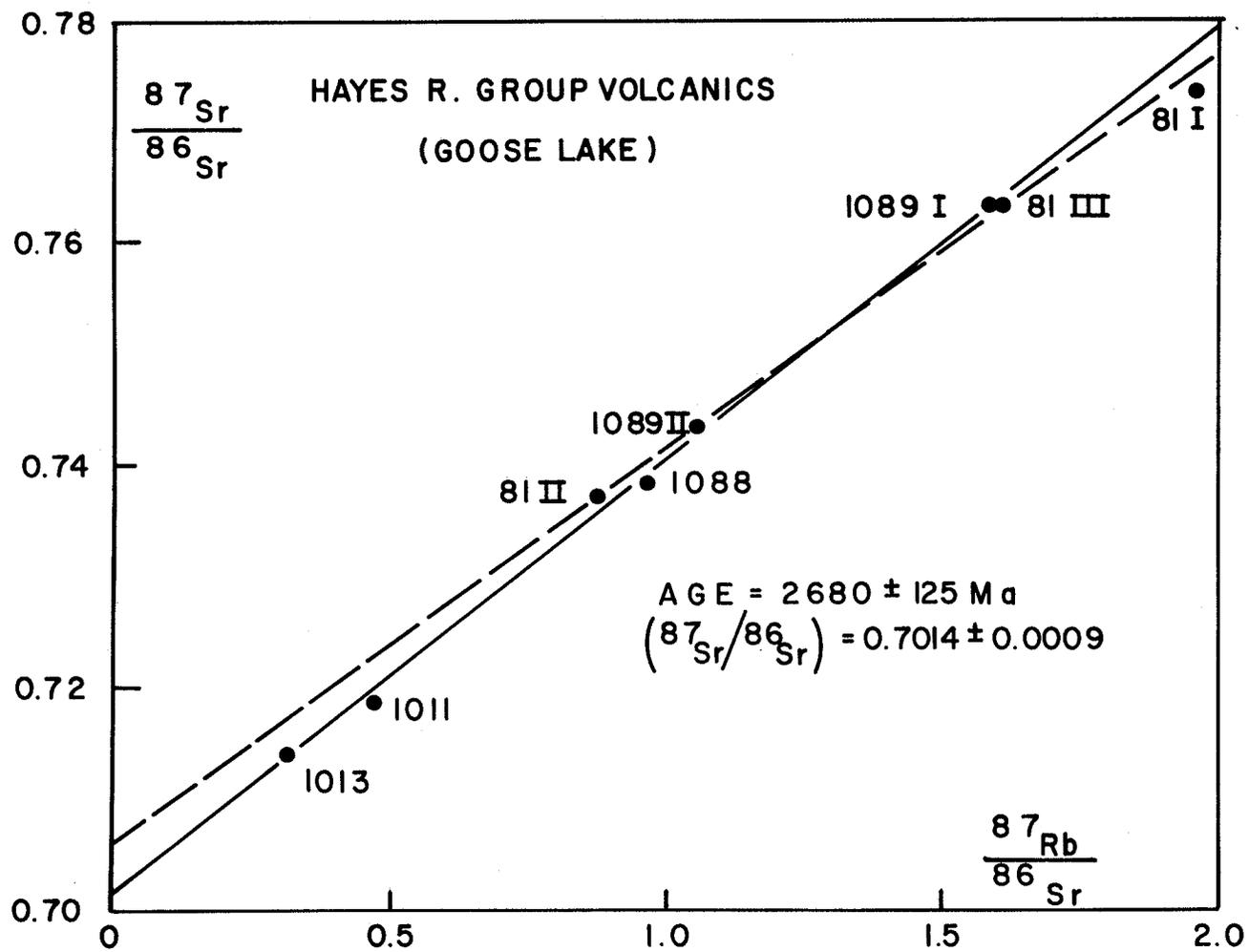


FIGURE 3. Whole-rock isochron for the Hayes River Group volcanic rocks.

samples. Because the regression of the points involves a large extrapolation of the line to the ordinate, the initial ratio of 0.7078 should not be interpreted necessarily as reflecting a pre-crustal history.

This extrapolation results from the absence of samples having low Rb/Sr ratios. In fact, all the samples are greatly enriched in rubidium relative to strontium.

Further discussion of the results is given in a later section.

TABLE 4. Analytical Results for the Bayly Lake Pluton

Sample	Rb(ppm)	Sr(ppm)	$^{87}\text{Rb}/^{86}\text{Sr}$ ¹	$^{87}\text{Sr}/^{86}\text{Sr}$ ²
6114	12.15	1065	0.03280	0.7042
6112	9.61	585.2	0.04750	0.7044
5615	50.15	1129	0.1286	0.7076
6109	48.17	809.8	0.1775	0.7094
6106	66.62	513.6	0.3754	0.7160
6115	40.23	908.4	0.1280	0.7073
5004	127.6	1066	0.3461	0.7151

¹Atomic ratio

²Normalized to $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.1194

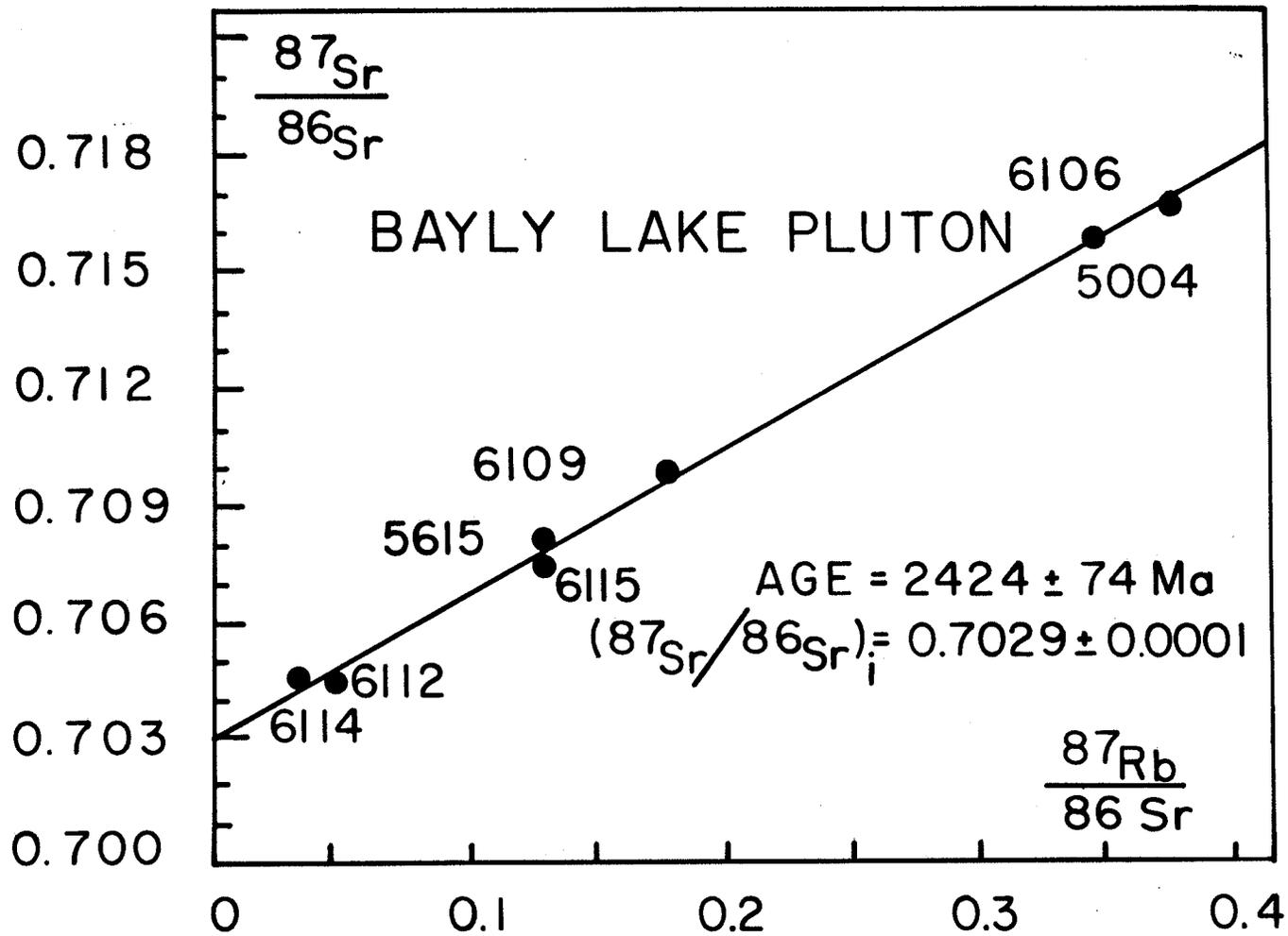


FIGURE 4. Whole-rock isochron for the Bayly Lake Pluton.

TABLE 5. Analytical Results for the Magill Lake Pluton

Sample	Rb (ppm)	Sr (ppm)	$^{87}\text{Rb}/^{87}\text{Sr}$ ¹	$^{87}\text{Sr}/^{86}\text{Sr}$ ²
5122	437.8	7.099	487.2	18.288
5124	691.6	11.22	482.8	18.065
5125	519.2	12.59	203.8	7.887
5131	260.3	83.27	8.909	1.0298
5139	268.1	72.37	11.12	1.0990
5135	238.0	45.80	15.84	1.2654
5128	267.2	52.02	15.63	1.258
5133	311.9	6.578	260.2	9.817

¹Atomic ratio

²Normalized to $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.1194

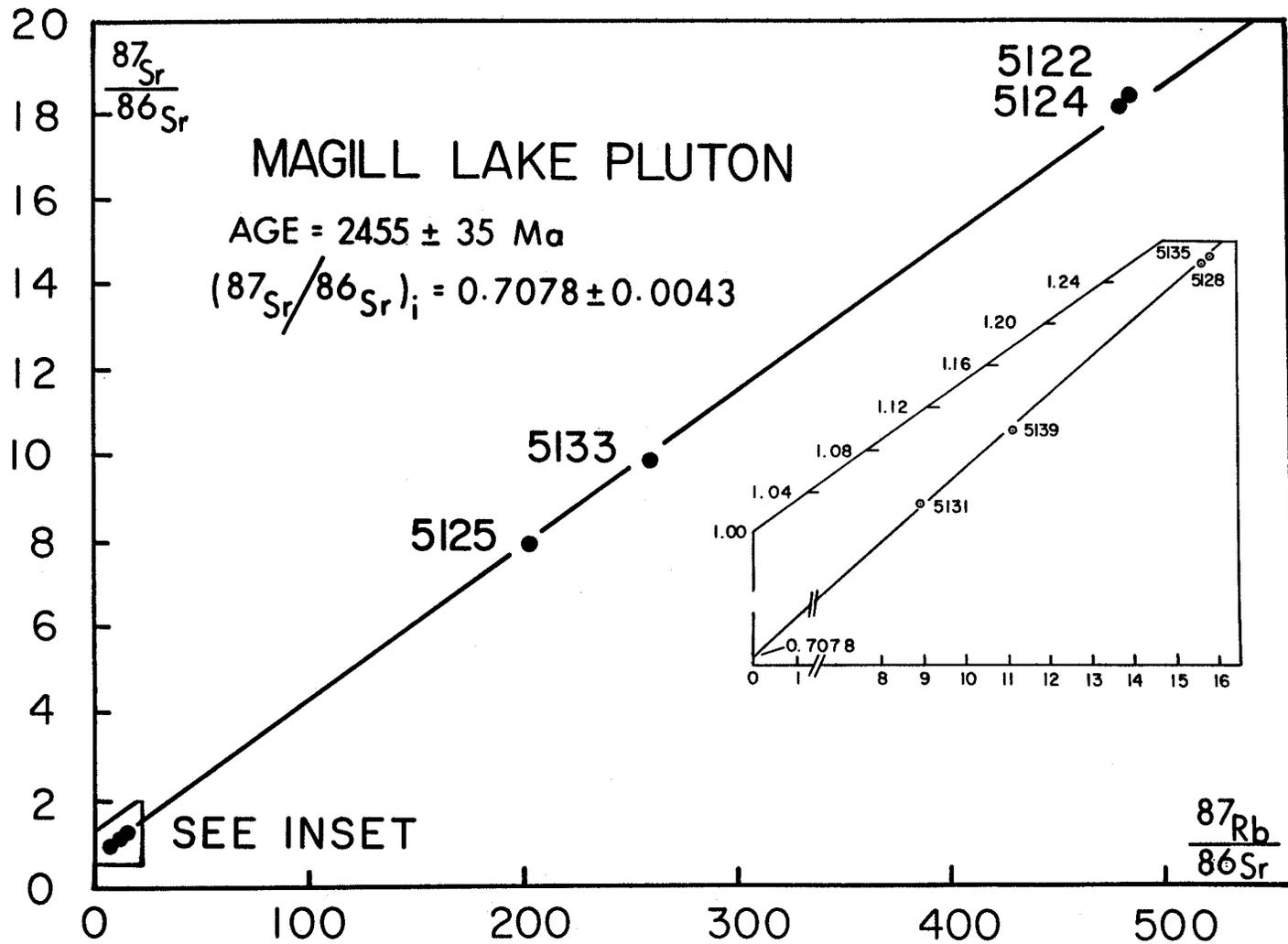


FIGURE 5. Whole-rock isochron for the Magill Lake Pluton.

INTERPRETATION OF ISOTOPIC RESULTS

The Rb-Sr total rock ages reported here represent the first such ages to be obtained from granitic rocks of this region. The area lies within the Cross Lake subprovince, as defined by Stockwell (1964). This subprovince was recognized largely on the basis of several low K-Ar dates (about 1650-2190 Ma) which are lower than the predominant Kenoran dates (about 2500-2600 Ma) obtained elsewhere in the Superior Province of Manitoba and adjacent N.W. Ontario. Some of these ages are listed in Table 2.

Bell (1966, 1971) considered these younger dates to be the result of overprinting of the Hudsonian orogeny on Archean rocks to the south of the Churchill-Superior boundary. Bell (1971) speculated that the overprinting resulted in retrogressive metamorphism causing argon loss from Archean rocks throughout the Cross Lake subprovince. However, one of the problems with this interpretation is the considerably older K-Ar ages from granulites (average K-Ar age is about 2600 Ma) that occur in the northern part of this subprovince.

If some of these low K-Ar dates are due to a distinct post-Archean thermal event, then it is possible that the Rb-Sr systems may be disturbed in some of the plutons in the Oxford Lake-Gods Lake region.

The Bayly Lake Pluton is believed to belong to the oldest group of granitic intrusions which immediately predate the Oxford Lake Group in this area. This largely tonalitic to granodioritic body is characterized by low Rb/Sr ratios and the seven points analyzed all fall on the isochron, well within the analytical precision stated above. Although the samples were collected across the entire width of the intrusion (a distance of about 30 km), which shows varying degrees of foliation,

the Rb-Sr system appears to have been essentially undisturbed. The age of 2424 ± 74 Ma is interpreted as the time of intrusion of this igneous body. The Bayly Lake Pluton intrudes volcanics of the Hayes River Group in the vicinity of southern Knee Lake and tonalitic rocks at Gods Lake.

Although a pre-Oxford Lake Group age for this unit is not conclusive from field evidence, conglomerate at the base of the Oxford Lake Group contains clasts identified as belonging to the Bayly Lake Pluton. In any case, the age places a lower limit on the time of volcanism and sedimentation of the Hayes River Group.

The isochron age for the Magill Lake Pluton is 2455 ± 35 Ma. This age does not differ statistically from that of the Bayly Lake Pluton. The age of 2455 Ma is based on the regression of eight points for samples collected over a small area at Magill Lake. In this area, the granite clearly is intrusive into metasedimentary rocks of the Oxford Lake Group and this age, therefore, places a lower limit on the time of deposition of the sedimentary rocks in this group.

The colinear nature of the data points supports the conclusion that the age corresponds to the time of crystallization of the granite. As mentioned above in the description of this granite, pegmatitic phases are common within the pluton both as clearly defined layers and as zones gradational with the main granite body. Although pegmatitic phases were avoided during the sampling, all the samples available are highly radiogenic. The least radiogenic samples have $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of about 1 to 1.3 while two of the samples having extreme enrichment in radiogenic ^{87}Sr yielding $^{87}\text{Sr}/^{86}\text{Sr}$ values of about 18.

Field evidence suggests that alkali metasomatism of the Magill Lake Pluton has occurred. If this process was active, it probably

occurred during crystallization of the granite or as a late stage event, perhaps during the formation of the pegmatites. Also, the isotopic system seems to have been little affected by the subsequent metamorphism responsible for the slight foliation present in the pluton as well as the pegmatite phases.

The enrichment of Rb relative to Sr in this pluton is striking and could be caused by alkali metasomatism or reflect the derivation of the granite from the remelting of alkali-rich phases of pre-existing crustal material. The initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7078 ± 0.0043 does not help to resolve this problem since the initial value is masked by the high radiogenic strontium component and the large extrapolation of the isochron to the $^{87}\text{Sr}/^{86}\text{Sr}$ axis.

As mentioned above, K-Ar dates which clearly post-date the Archean are common throughout this region. Of particular interest is the 1640 Ma date from the Magill Lake Pluton (Moore et al., 1960). Results from the present work do not support this date as being due to Aphebian plutonism or to a distinct thermal event corresponding to the Hudsonian orogeny. This date, together with other anomalously low K-Ar dates in this region could be a result of mild heating due to deep burial or the intrusion of "young" dykes (in this case not evident from surface exposure). Studies on the retention of Ar by minerals have been reviewed by Dalrymple and Lanphere (1969). Biotite is quite sensitive to argon loss at relatively low temperatures. For example, if held at a temperature of about 200°C for one million years, biotite could lose nearly all of its argon. This low temperature would probably not affect the Rb-Sr total-rock system.

In any event, the Rb-Sr results for the Magill Lake Pluton suggest

that the last pulse of granitic intrusion in this area occurred 2450 Ma ago marking the last stage of the Kenoran orogeny.

The samples used to construct the Rb-Sr isochron for the Hayes River Group volcanics at Goose Lake were collected from a single tuff horizon within the volcanic sequence (see inset map, Fig. 2) and from a basalt unit in the same sequence. The tuff is siliceous and clasts of rhyolite are common. The regression of the six samples gives an age of 2440 ± 180 Ma and an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7056 ± 0.0018 . The plot indicates some scatter of the data points which cannot be accounted for by analytical errors. The large uncertainty in the age is chiefly due to the low spread in the Rb/Sr ratios ($^{87}\text{Rb}/^{86}\text{Sr}$ values range from about 0.9 to 1.6) and the resulting large extrapolation of the regression line to the $^{87}\text{Sr}/^{86}\text{Sr}$ axis. However, the inclusion of the two basalt samples, as explained above, results in an age of 2680 ± 125 Ma and an initial ratio of 0.7014 ± 0.0009 . This age is achieved if sample 81-I is omitted from the regression. This sample falls considerably below the best-fit line of the other seven points. Rb-Sr ages for Archean volcanics are usually interpreted as minimum ages due to their susceptibility to metamorphic recrystallization even during greenschist facies metamorphism because of their fine grain size. On the other hand, zircon U-Pb ages seem to yield ages which tend to date the time of crystallization (Krogh and Davis, 1971).

Although there is no direct field evidence to relate the volcanic rocks of the Beaver Hill Lake-Goose Lake area to those in the Oxford Lake-Knee Lake greenstone belt, the former are presumed equivalent to the latter and are included in the Hayes River Group. This Rb-Sr age is in agreement with an unpublished U-Pb age for zircons separated

from metadacite occurring in the southern Knee Lake area (G. Hanson, pers. comm.). Two zircon fractions yield a $^{207}\text{Pb}/^{206}\text{Pb}$ age of about 2700 Ma. Both zircon suites, however, are highly discordant and the age could be interpreted as a minimum age, at least until more results are obtained.

SUMMARY AND CONCLUSIONS

Rubidium-strontium whole-rock ages reported here establish a late Archean age for granitic plutonism in the Oxford Lake-Knee Lake greenstone belt. Field evidence has established that the Magill Lake Pluton is intrusive into the Oxford Lake Group. The age of 2455 ± 35 Ma for this alkali-rich pluton establishes a minimum age for the final deposition of sediments of the Oxford Lake Group and sets an age of about 2450 Ma as the time of the last major granitic plutonism in the area (based on the ^{87}Rb decay constant of $1.42 \times 10^{-11} \text{ yr.}^{-1}$). Taking the Rb-Sr age from this study, and the preliminary $^{207}\text{Pb}/^{206}\text{Pb}$ zircon age mentioned above into account, the age of the Magill Lake Pluton suggests a time interval of about 250 Ma from the time of volcanism associated with the Hayes River Group and the cessation of granitic igneous activity in the area.

Although the stratigraphic age of the Magill Lake Pluton is well established, the interpretation of the Bayly Lake Pluton as being pre-Oxford Lake Group in age is based on less direct evidence. The Rb-Sr age reported here for this unit does not do much to resolve this problem. The ages for the two plutons agree within the quoted errors, but it is possible, considering the maximum range of error limit, that the Bayly Lake Pluton predates the Magill Lake Pluton by as much as 75 Ma. The isotopic results presented here do not preclude a post-Oxford Lake Group age for the Bayly Lake Pluton.

The age of 2680 Ma for the Hayes River Group volcanic rocks at Goose Lake (in the Beaverhill Lake area) should be considered a minimum age for the Hayes River Group since previous work has indicated that such ancient, fine-grained rocks are susceptible to recrystallization

even under low grades of metamorphism, which may result in updating of the Rb-Sr whole rock age (Hart and Davis, 1969; Krogh and Davis, 1971). However, the Rb-Sr age reported here is consistent with Rb-Sr ages obtained in other Archean greenstone belts from the northwestern Superior Province.

APPENDIX. DETAILS OF CHEMICAL PROCEDURESample Preparation

The chemical procedure used for this work was similar to the ones used by Penner (1970) and Josse (1974).

The weathered surfaces of the rock samples were first removed. Each sample was then crushed to chip size by using a jaw crusher. The chips were then pulverized to powders using a Bleuler grinder. Approximately 100 g of the rock powders were selected from the bulk quantity by the process of 'cone and quartering' to ensure homogeneity. X-ray fluorescence analyses of rubidium and strontium were made for each sample using an ARL Quantometer X-ray fluorescence spectrometer. These preliminary results were used for the selection of samples possessing a range of rubidium and strontium concentrations expressed as Rb/Sr ratios suitable for whole rock isochron studies. The X-ray results were also used to determine the sample weight required to produce a $^{84}\text{Sr}/^{86}\text{Sr}$ ratio and $^{85}\text{Rb}/^{87}\text{Rb}$ ratio of at least 0.5, a ratio which represents the optimum spiked ratio for the composition of the spikes used in a mixture of spike and sample.

The appropriate amount of each sample was accurately weighed out in an aluminum foil boat and transferred to a 100 ml teflon beaker. 20 ml of 40% hydrofluoric acid was added to the sample, covered with a teflon disk, and heated for half an hour at approximately 120°C . 3 ml of perchloric acid was added, the sample covered again and allowed to digest at 120°C for at least eight hours. Generally, the sample would be dissolved by this time. The cover was removed and the sample was heated and evaporated to dryness. If there was any sample still undissolved the above pro-

cedures were repeated until the sample was totally dissolved. 20 ml of double distilled water were added and the sample again evaporated to a mush to eliminate any remaining hydrofluoric acid. An appropriate amount of spike solution was added to the rubidium or strontium sample, using a pipette. 20 ml of vycor distilled (constant boiling) 6.2N hydrochloric acid was added and the solution was covered and heated for two hours to equilibrate sample and spike. After refluxing, the teflon cover was removed and the solution was evaporated to dryness.

The rubidium sample was dissolved again in 6.2N HCl and transferred to a 10 ml Hysil beaker and evaporated to dryness, as a chloride and was stored for mass spectrometer analysis.

For the strontium sample, 10 ml of methanol was added to the dried sample to leach out the alkaline earths. The supernate was transferred to two 5 ml centrifuge tubes and centrifuged until the supernate was clear. The supernate was poured into a 30 ml beaker with 10 ml of 6.2N HCl added. The solution was heated and the sample was again evaporated to dryness. The sample was then redissolved again in 5 ml 6.2N HCl and poured directly to a cation exchange column (Cation exchange resin AG 50W-x12, 200-400 mesh hydrogen form) which had been previously calibrated using an atomic absorption spectrometer to determine when the strontium fraction would come out. Once the sample was absorbed, three 5 ml portions of 6.2N HCl were added allowing each portion to be completely absorbed before adding the next portion. Further HCl was added until the predetermined volume, the volume of HCl required to wash the strontium fraction out, was reached. The sample was collected in the next 90 ml of 6.2N HCl

and was evaporated to dryness. The column was then regenerated with 200 ml of 6.2N HCl and constantly kept moist with 6.2N HCl. For samples with high Rb/Sr ratios the samples were put through a second time. The sample was dissolved again in 3 ml of HCl and transferred to a 5 ml Hysil beaker and the solution was again brought to dryness by slow heating. The sample was then stored for analysis.

Preparation of the Spike Solutions

The spike salts were obtained from Oak Ridge National Laboratory as $\text{Sr}(\text{NO}_3)_2$ and RbCl and were prepared by Dr. G. S. Clark. These were dried at 120°C overnight and allowed to cool in a dessicator. Each spike salt was accurately weighed out and transferred to a 200 ml volumetric flask and diluted to volume in 0.5N HCl. 10 ml of the aliquot of ^{84}Sr spike solution was transferred to a 1000 ml volumetric flask and the solution was diluted to volume with 0.5N HCl. 15 ml of the ^{87}Rb spike solution was similarly diluted to obtain the appropriate concentration required.

Ion Exchange Columns

The columns used were made of 10 mm I.D. glass tubing fitted with a coarse fritted disc positioned about 5 cm above the lower taper end. The length of the column is about 30 cm and packed with about 20 cm of resin. The flow rate is approximately 10 ml per hour. The top of the column was terminated in a standard female ground glass joint to facilitate the positioning of a 200 ml flask used to hold the acid, the flask was connected to a standard male ground glass joint by a 25 cm long capillary tube. The acid that flowed through the column was controlled by a stopper at the lower end of the column. Analytical reagent grade cation exchange resin AG-50W-X12-200-400 mesh,

hydrogen form (Bio Rad Laboratories) was used. After the resin had been packed in the column 200 ml of 6.2N HCl was passed through to wash the resin. Calibration of the column was made individually by eluting a suitable prepared sample through the column. 5 ml fractions of the eluant were collected and each portion was analyzed on an atomic absorption spectrometer to determine the portions containing the strontium fractions. This volume was used to determine the amount of acid required to wash through the column before the strontium sample was collected. After use, the column was regenerated by washing with 200 ml of 6.2N HCl and the resin was kept moist with the acid between each use. Resin was exchanged periodically to ensure maximum efficiency.

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