THE UNIVERSITY OF MANITOBA

RUBIDIUM-STRONTIUM AGE DETERMINATIONS

FROM THE FILE-MORTON-WOOSEY LAKES AREA

OF THE FLIN FLON VOLCANIC BELT, WEST CENTRAL MANITOBA

BY

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ABSTRACT

Rubidium-strontium whole rock isochron ages have been determined on rock units from the File-Morton-Woosey Lakes area of the Flin Flon volcanic belt. A minimum age of emplacement is given by the radiometric age of 1860 $\pm$ 112 m.y. and an $^{87}Sr/^{86}Sr$ initial ratio of 0.7019 $\pm$ 0.0005 for the Ham pluton, a syn- to late kinematic 'granitic' intrusion (^{87}Rb decay constant of 1.39 x $10^{-11}yr^{-1}$). This age also provides a minimum age for the Amisk Group volcanic strata, the Missi Group sedimentary strata, and all other rocks, such as the Morton porphyry, and early deformation that predate the Ham pluton in the study area. The approximate age of 1737 $\pm$ 257 m.y. and an initial ratio of 0.7020 $\pm$ 0.0002 obtained for the Elmes Island Formation dacite flows, (an Amisk Group felsic volcanic), and the radiometric age of 1715 $\pm$ 83 m.y. and an initial ratio of 0.7027 $\pm$ 0.0001 for the Morton porphyry, (a pre- to early kinematic hypabyssal intrusion), are considered to be metamorphic ages and not emplacement ages, and that these units were updated during regional metamorphism.

The age of the regional metamorphism that affected the study area is given by the radiometric age of 1760 $\pm$ 43 m.y. obtained for the File gneiss dome, a granitoid paragneiss complex from the Kisseynew sedimentary gneiss belt.

The $^{87}Sr/^{86}Sr$ initial ratio for this unit is 0.7038 ± 0.0008.

The late pegmatite dykes are post-kinematic intrusions that postdate all other rocks in the study area. The calculated mineral ages of 1741 ± 55 m.y. and 1763 ± 55 m.y. (assumed initial ratio of 0.710), give the best approximation of the age of the youngest intrusive event in the study area.

The late Aphebian age of emplacement for the Ham pluton is consistent with the interpretation of Mukherjee (1971) and Sangster (1972) that the Flin Flon volcanic belt is late Aphebian. The area was subjected to regional metamorphism approximately 1760 m.y. ago, a late Aphebian event that may be representative of the Hudsonian orogeny.

ACKNOWLEDGEMENTS

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CHAPTER 1. INTRODUCTION

1.1. General Statement

      The File-Morton-Woosey Lakes area is located
within the southeastern portion of the Churchill geological
province of the Canadian Shield in west central Manitoba.
The area includes portions of two major easterly trending
lithological belts: the Flin Flon volcanic belt to the
south, and the Kisseynew metasedimentary gneiss belt to
the north (Bailes, 1971b). The study area is located 20
kilometers (12 miles) west of the town of Snow Lake, and
is bounded by latitudes $54^{\circ}45'$ and $55^{\circ}00'$ north, and longi-
tudes $100^{\circ}10'$ and $100^{\circ}30'$ west (see Figure 1).

      Traditionally, the Flin Flon volcanic belt (also
called the Flin Flon-Snow Lake greenstone belt) has been
considered Archean in age (e.g. Stockwell, 1963, 1964;
McGlynn, 1970; Bailes, 1971b; Tectonic Map of Canada,
G.S.C. Map 1251A). K-Ar age determinations of micas from
rocks of this belt by the Geological Survey of Canada gave
Hudsonian ages (e.g. Lowdon, 1961; Lowdon et al., 1963;
Wanless et al., 1965, 1967). These ages generally have
been attributed to updating of Archean rocks by the
Hudsonian orogeny (e.g. Stockwell, 1963, 1964). Archean
Rb-Sr whole rock isochron ages obtained by Coleman (1970)

Figure 1. Location map of the File-Morton-
Woosey Lakes study area.
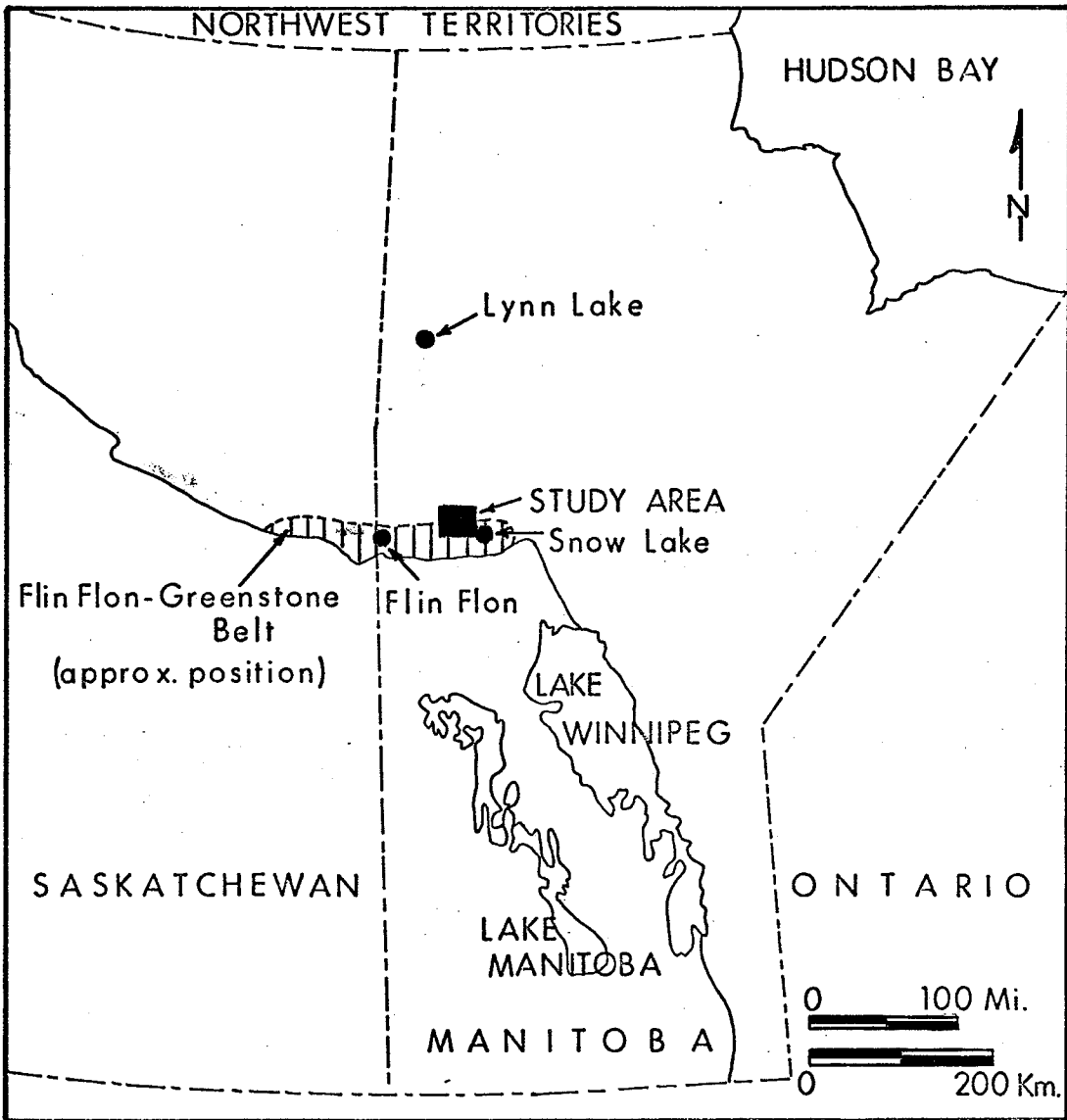
on volcanic and plutonic rocks at Hanson Lake, an area that
may be the western extension of the Flin Flon volcanic belt,
appear to support this Archean premise. However, more
recently, Aphebian Rb-Sr whole rock isochron ages have been
obtained by Mukherjee et al. (1971) on volcanic and plutonic
rocks near Flin Flon, and Aphebian common lead isotope ages
have been obtained by Sangster (1972) on galena from sul-
fide deposits that are considered by him to be coeval with
volcanism and to consist of single stage leads. Both
authors have interpreted these Aphebian dates as the age
of the Flin Flon volcanic belt. However, Slawson and
Russell (1973) have questioned the validity of Sangster's
lead ages, suggesting that they are multistaged leads and
that the secondary U/Pb system formed at least 2450 m.y.
(million years) ago.

1.2. Object of Study

The object of this study was to test the validity
of Mukherjee's and Sangster's conclusion that the Flin Flon
volcanic belt is Aphebian in age by preparing rubidium-
strontium whole rock isochron ages on rock samples from
the eastern portion of the belt. A paragneiss unit from
the Kisseynew sedimentary gneiss belt, located in the
north of the study area, was dated to obtain the age of
regional metamorphism. K-feldspar mineral concentrates
from late pegmatite dykes, that postdate the regional meta-
morphic event, were dated to obtain the youngest intrusive

event(s) in the study area. $^{87}Sr/^{86}Sr$ initial ratios obtained for igneous rocks have been interpreted to indicate the petrogenesis of the igneous rocks, and by inference, the petrogenesis of the rest of the Flin Flon volcanic belt.

CHAPTER 2.   GEOLOGY OF THE FILE-MORTON-WOOSEY LAKES AREA

2.1. Regional Setting

The Precambrian rocks of the File-Morton-Woosey Lakes area comprise rocks of two broad easterly trending belts of differing lithology, degree of deformation and grade of metamorphism: the Flin Flon volcanic belt to the south and the Kisseynew metasedimentary belt to the north (Bailes, 1971b). The geology of the File-Morton-Woosey Lakes area is shown in Figure 2, and the corresponding Table of Formations is given in Table 1.

The following discussion of the regional geology of the Flin Flon volcanic belt and Kisseynew metasedimentary gneiss belt is based on a regional compilation prepared by Bailes (1971b). Other reports of related interest are: Davies et al. (1962), Harrison (1949, 1951), McGlynn (1959, 1970), Robertson (1953), Williams (1966), Russell (1957), Kalliokoski (1952, 1953), Kornik (1968), Hunt (1970), Roussell (1970), Mukherjee (1971), Byers et al. (1954, 1965), and Moore and Froese (1971, 1972).

2.1.1. Flin Flon Volcanic Belt

The Flin Flon volcanic belt comprises Amisk Group volcanic and sedimentary rocks, Missi Group sedimentary rocks, and intrusive rocks that outcrop over a distance of

240 km (150 miles), extending from 32 km (20 miles) east of
Snow Lake to 48 km (30 miles) west of Flin Flon. The
average exposed width of the Flin Flon volcanic belt is
48 km (30 miles). The volcanic belt is bounded to the north
by the Kisseynew sedimentary gneiss belt and is overlain to
the south by flat-lying Paleozoic sedimentary rocks.

In the study area, Bailes (in preparation) has
subdivided the Amisk Group into Lower Amisk and Upper
Amisk Subgroups, consisting of volcanic and sedimentary
strata, respectively (see Table 1).

2.1.2. Kisseynew Metasedimentary Gneiss Belt

The Kisseynew sedimentary gneiss belt consists of
two major metasedimentary sequences: a lower meta-greywacke
unit and an upper unit of meta-arkose. Robertson (1953)
termed these units the Nokomis Group and the Sherridon
Group, respectively. In the study area, Bailes (in prepara-
tion) has termed these units the Upper Amisk Subgroup and
the Missi Group, respectively, due to the probable equiva-
lence of these strata to those of the Flin Flon volcanic
belt. The dimensions of the Kisseynew gneiss belt are
approximately 200 km (120 miles) in width and 500 km (300
miles) in length.

2.1.3. Metamorphism

The major metamorphic and tectonic event(s) post-
date deposition of all volcanic and sedimentary strata. The

Figure 2.   Generalized geological map of the
            File-Morton-Woosey Lakes area, with
            sample stations (after Bailes, 1971a).

100°30   100°15

LOONHEAD LAKE

CORLEY LAKE

958-1
957-1
950-1 956-1 966-2
955-1 967-1
954-1
953-1 969-1

1027-1
1028-1
1024-1
1021-1 1032-1 1030-1
1031-1

54°55

HAM LAKE

NORRISS LAKE

FILE LAKE

5344
5345 5348
5346
5347

54°50

MORTON LAKE
5192-1
5186-1
5180
1-3-5 5181-1
5448-1-2
5447-1

LEGEND

INTRUSIVE ROCKS

0   1   2

SYN-TO POST-KINEMATIC

Quartz diorite, granodiorite and porphyritic microcline quartz monzonite

N

PRE-TO EARLY-KINEMATIC

Felsic quartz feldspar porphyry

Feldspathic gabbro, ferrogabbro, quartz diorite and derived hornblende-plagioclase gneiss

MISSI GROUP

Meta-arkose and meta-subgreywacke

Granitoid gneiss derived from arkose and subgreywacke

AMISK GROUP

UPPER AMISK GROUP

Greywacke, argillite, local conglomerate and and derived paragneisses

LOWER AMISK GROUP

Felsic volcanic rock and derived gneisses

Mafic volcanic rocks and derived gneisses

TABLE 1. TABLE OF FORMATIONS [after Bailes (in preparation)]

Pleistocene & Recent					
				Great Unconformity	

Pleistocene & Recent

Great Unconformity

PROTEROZOIC APHEBIAN	Intrusive Rocks	Post kine-matic	‡Pegmatite Dykes

Intrusive Contact

Syn- to late kine-matic · Porphyritic microcline granite
●Granodiorite, tonalite, quartz diorite

Meta-Complexes
Anatectic Complex:
   Pegmatitic granodiorite and granite
File Gneiss Dome Complex:
■ Granitoid gneiss derived from the Missi Group

Intrusive Contact

Pre-to early kine-matic +Felsic quartz feldspar porphyry
Josland Formation: Differentiated gabbro sills

Intrusive Contact

Missi Group | Meta-arkose

?Disconformity?

Amisk Group

Upper Amisk Sub-Group ▲File Lake Formations: Interbedded greywacke and shale and derived
                                    paragneisses.
Yakimiw Formation: Interbedded greywacke and shale.

Lower Amisk Subgroup
Elmes Island Formation: Dacite Flows.   ⎫ "2nd" volcanic cycle
Storozuk Formation: Basalt and andesite flows.⎭
Dickstone Formation: Rhyolite and dacite flows and tuff⎫ "1st" volcanic cycle
Preaston Formation: Basalt and andesite flows   ⎭
Undifferentiated basalt and andesite flows

Units dated: ▲Elmes Island Formation of dacite flows.   ●Ham pluton.
                    +Morton porphyry.   ■File gneiss dome.
                                                                       ‡Late pegmatite dykes.

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intensity of deformation and grade of metamorphism is highest in the Kisseynew sedimentary gneiss belt and decreases into the volcanic belt. Middle to upper almandine-amphibolite facies assemblages and widespread migmatization and granitization, dominate the Kisseynew belt. It is highly deformed.

The Flin Flon volcanic belt is less deformed and metamorphosed than the Kisseynew belt. It is composed of rocks metamorphosed under greenschist to lower almandine-amphibolite facies conditions. The metamorphic grade increases northward towards the boundary contact zone with the Kisseynew belt. Much of the deformation in the volcanic belt was caused by emplacement of large granitic plutons. The plutons have thermal aureoles in which hornblende hornfels assemblages have been developed.

2.1.4. Stratigraphic Correlation

The Amisk and Missi sedimentary rocks have been correlated with rocks of the Kisseynew sedimentary gneiss belt by Bailes (1971b, p.13-14) north of Wekusko Lake, Manitoba, and by Byers and Dahlstrom (1954, p.50) north of Amisk Lake, Saskatchewan. In the study area, Bailes (in preparation) has shown that rocks of both belts are part of the same stratigraphic succession. The Nokomis Group is considered equivalent to the "flyschoid" greywacke-shale sequences of the Upper Amisk Subgroup, and the Sherridon Group to the arkosic rocks of the Missi Group.

2.2. Geology of the Study Area

The File-Morton-Woosey Lakes area straddles the boundary zone of the Flin Flon volcanic belt and the Kisseynew sedimentary gneiss belt. This boundary is considered to follow the south shore-line of File Lake in the study area (Figure 2). Geological mapping by Bailes (in preparation) has shown that rock units of both belts are part of the same stratigraphic succession. In the accompanying table of formations (Table 1), rocks belonging to the Nokomis and Sherridon Groups of the Kisseynew belt have been included by him with the Upper Amisk Subgroup and Missi Group of the Flin Flon belt, respectively. The rocks of the study area have been subdivided into three main groups (from oldest to youngest): the Amisk Group, the Missi Group, and the Intrusive Rocks.

The following description of the geology for the study area is based on information provided by Bailes from a geological report in preparation by him for the Manitoba Mines Branch.

2.2.1. The Amisk Group

The oldest rocks of the study area are the Amisk Group, which consist of volcanic strata (Lower Amisk Subgroup) and overlying sedimentary strata (Upper Amisk Subgroup). There are believed to be at least two mafic to felsic volcanic cycles in the Lower Amisk Subgroup. The volcanic

rocks comprise primarily subaqueous flows of calc-alkaline composition. Mafic volcanism consists largely of flows, whereas felsic volcanism is a mixture of flows and pyroclastic material.

Sedimentary rocks of the Upper Amisk Subgroup comprise immature deposits of interbedded greywacke and shale. The deposits consist of the Yakimiw and File Lake formations, which are composed primarily of volcanic detritus and likely were derived by erosion of loose debris from contemporaneous volcanic deposits. The formations were deposited rapidly in deep water by turbidity currents. The rocks north of File Lake have been regionally metamorphosed to garnet-staurolite-sillimanite bearing paragneisses (i.e., lower to middle almandine-amphibolite facies). The rocks south of File Lake have been regionally metamorphosed to greenschist facies mineral assemblages.

2.2.2. The Missi Group

The Upper Amisk metasedimentary rocks are overlain conformably by a meta-arkose sequence known as the Missi Group. The rocks are commonly crossbedded and are likely shallow-water deposits. They consist of arkose and subgreywacke deposits that have been metamorphosed to middle and upper almandine-amphibolite facies. North of File Lake, portions have been intensely recrystallized and homogenized to produce granitoid rocks, including the rocks of the File gneiss dome. The rocks of this domal complex are believed

to have been formed during the main regional metamorphism.

2.2.3. Intrusive Rocks

Several periods of metamorphism, deformation and intrusive rocks postdate the Missi Group. In the study area, the intrusive rocks have been subdivided according to their relation to the main culmination of deformation and metamorphism. The pre- to early kinematic intrusive rocks are large differentiated gabbroic sills. Chemical analyses of chilled margins from these gabbroic sills indicate that the original composition was basaltic (Bailes, personal communication). Also included in this group are plugs and dykes of tonalitic quartz-feldspar porphyry exposed east of Morton Lake.

Syn- to late kinematic intrusive rocks consist of large "granitic" plutons varying from quartz diorite to granite in composition. They have been emplaced along the entire length of the Flin Flon volcanic belt but not in the adjacent Kisseynew sedimentary gneiss belt, suggesting some major tectonic crustal control on their formation. They are calc-alkaline in composition and are true magmatic "granites" as they contain numerous angular stoped inclusions having thermal contact aureoles.

The post kinematic intrusive rocks consist of granitic pegmatite dykes that locally intruded and fractured rocks of the area, such as the Ham pluton and the File gneiss dome.

CHAPTER 3.   PREVIOUS AGE DETERMINATIONS

The Churchill geological province, comprising rocks of predominantly Aphebian age, is largely underlain by gneissic and granitoid rocks of great structural and petrological complexity (Davidson, 1972, p.382). The geological complexity is reflected by radiometric determinations from the Churchill geological province. K-Ar mica ages, determined by the Geological Survey of Canada, generally have given a mean age of 1735 ± 95 m.y. which is presumed to reflect a major orogenic period, the Hudsonian (Stockwell, 1964, p.5; 1970, p.49). However, both Archean and Aphebian ages have also been determined on volcanic and plutonic rocks from the Churchill Province using the Rb-Sr whole rock isochron dating technique (e.g. Money, 1968; Money et al., 1970; Coleman, 1970; Davidson, 1972; Anderson 1974). Archean Rb-Sr whole rock isochron ages have been determined from granitic rocks believed to be basement to the metasedimentary strata of the Wollaston Lake fold belt (Money et al., 1970; Anderson, 1974).

Traditionally, the Precambrian rocks of the Flin Flon volcanic belt have been considered Archean in age, and were later deformed and updated by the Hudsonian orogeny (e.g. Stockwell, 1963, 1964; Tectonic Map of Canada, Map 1251A; McGlynn, 1970; Bailes, 1971b; Davidson, 1972).

Geologically, the assignment of an Archean age has been based on: 1) the lithological similarity of the Flin Flon volcanic belt and the Archean greenstone belts of the neighbouring Superior Province; and 2) the gross overall easterly trend of structural and aeromagnetic patterns of the volcanic belt parallels those of the adjacent Superior Province (the Churchill trends generally are considered to be north-easterly (Bailes, 1971b, p.19)).

K-Ar age determinations of micas from rocks of the Flin Flon volcanic belt by the Geological Survey of Canada gave Hudsonian ages (e.g., Lowdon, 1961; Lowdon et. al., 1963; Wanless et al., 1965, 1967). No date older than 1960 ± 60 m.y. has been determined (GSC 63-104, Wanless et al., 1965). These K-Ar mica ages have been attributed to updating of the Archean greenstone rocks by the Hudsonian orogeny (Stockwell, 1963, 1964).

Coleman (1970) obtained Archean ages on volcanic and plutonic rocks from the Hanson Lake area, which probably lies on the western extension of the Flin Flon volcanic belt. His dates appear to support the premise that the Flin Flon volcanic belt is Archean in age, and that the previously obtained K-Ar mica ages indicate updating of the volcanic belt by the Hudsonian orogeny. However, more recently, Aphebian ages have been obtained for the Flin Flon volcanic belt by Mukherjee et al. (1971) and Sangster (1972). Mukherjee et al. (1971) obtained two Rb-Sr whole rock isochron ages on a volcanic and plutonic suite,

respectively. Implicit in their interpretation is that
these dates represent "emplacement" ages for the volcanic
and plutonic rocks. Mukherjee et al. (1971, p.946) state
that "although an Archean age for the Amisk Group in the
Flin Flon-Amisk Lake area cannot be disproven there is no
direct evidence to suggest that it is older than Aphebian.
In any case, the main metamorphic and intrusive events are
early Hudsonian and no evidence of the Kenoran orogeny has
been observed in this region." Common lead isotope ages
by Sangster (1972) and Sinha (1970) on galena from sulfide
deposits from across the length of the volcanic belt are
considered by them to give the age of the host volcanic
strata. Their interpretation is based on the assumption
that: 1) the sulfide deposits are volcanogenic (i.e.
coeval with the volcanism); and 2) the lead is single-
stage. They feel that the geological and chemical data
are consistent with these assumptions. Aphebian ages were
obtained by this method for the sulfide deposits and their
host volcanic rocks. However, Slawson and Russell (1973)
and Ozard et al. (1973) have suggested that the Flin Flon
leads are multistaged (anomalous) leads. Slawson and
Russell (1973) indicate that the minimum age for the forma-
tion of the secondary U/Pb system (and maximum age for
mineralization), that is compatible with their anomalous
lead line, is approximately 2450 m.y. Ozard et al. (1973)
have proposed a modified three-stage model for the Flin
Flon leads to have occurred at 3040 m.y., 2630 m.y., and

1500 m.y. ago. The geological significance of these multi-stage leads and their corresponding model ages are reviewed by Thorpe and Sangster (1973).

Table 2 is a list of previously determined ages from the Flin Flon volcanic belt. Only Coleman's (1970) Rb-Sr whole rock isochron ages are Archean. The remaining age determinations are Aphebian. To the author's knowledge, no U-Th-Pb concordia ages nor K-Ar hornblende ages have been reported for rocks of the Flin Flon volcanic belt.

TABLE 2.   PREVIOUS AGE DETERMINATIONS: FLIN FLON VOLCANIC BELT

A) K-Ar Mineral Ages

Reference	Location	Sample Description	Material	Method	Age(m.y.)
Lowdon et al. (1963) (GSC 61-112)	Reynard Lake Lat: 54°41'N Long: 101°59'W	Quartz monzonite, intrudes the Amisk Group volcanics. (syn-kinematic intrusive rock)	Biotite	K-Ar	1705 ± 85
Lowdon (1961) (GSC 60-74)	Reed Lake Lat: 54°39'N Long: 100°15'W	Muscovite-biotite granite, from granite dyke related to granite pluton that intrudes Amisk Group volcanics. (Syn-kinematic)	Biotite	K-Ar	1745 ± 85
Lowdon et al. (1963) (GSC 61-118)	Reed Lake Lat: 54°39'N Long: 100°15'W	Same as GSC 60-74	Muscovite	K-Ar	1775 ± 90
Lowdon et al. (1963) (GSC 61-119)	Hat Lake Lat: 54°46'W Long: 99°32'W	Medium-grained impure meta-quartzite belonging to the Miss Group	Biotite	K-Ar	1770 ± 90
Lowdon et al. (1963) (GSC 61-120)	Hat Lake Lat: 54°46'W Long: 99°32'W	Same as GSC 61-119.	Muscovite	K-Ar	1620 ± 80
Wanless et al. (1965) (GSC 63-96)	Coronation Mine (1,050' level) Lat: 54°35'N Long: 102°00'W	Anthophyllite-garnet-biotite skarn, comprises metamorphosed and fragmental volcanic rock. (Amisk)	Biotite	K-Ar	1930 ± 100

Reference	Location	Description	Mineral	Method	Age
Wanless et al. (1965) (GSC 63-99)	Crowduck Bay, Wekusko Lake Lat: 54°52'N Long: 99°43'W	A post-Missi quartz-microcline mica pegmatite sill that intruded metamorphosed Missi sediments. Postdates main event of regional metamorphism.	Muscovite	K-Ar	1790 ± 60
Wanless et al. (1965) (GSC 63-100)	Crowduck Bay, Wekusko Lake Lat: 54°52'N Long: 99°43'W	Same as GSC 63-99	Biotite	K-Ar	1610 ± 50
Wanless et al. (1965) (GSC 63-104)	Goose Bay Wekusko Lake Lat: 54°43'N Long: 99°59'W	Massive biotite-quartz monzonite stock of variable composition; intrudes Missi sediments. (Syn-kinematic?)	Biotite	K-Ar	1960 ± 60
Wanless et al. (1965) (GSC 63-106)	Cliff Lake Lat: 54°48'N Long: 101°50'W	Medium-grained altered granitic rock with eyes of quartz; shows evidence of crushing.	Muscovite	K-Ar	1620 ± 80
Wanless et al. (1965) (GSC 63-108)	Phantom Lake Lat: 54°42'N Long: 101°52'W	Massive porphyritic granodiorite with phenocrysts of feldspar; youngest granite in Flin Flon area (late-to post kinematic?).	Biotite	K-Ar	1805 ± 65
Wanless et al. (1967)	Crowduck Bay, Wekusko Lake Lat: 54°51'N Long: 99°38'W	Lithium-bearing pegmatite	Muscovite	K-Ar	1735 ± 55
Moore et al. (1960)	Stall Lake Lat: 54°51'N Long: 99°56'W	Quartz-biotite gneiss, thought to be of sedimentary origin by Russell (1957), and an altered volcanic rock by Harrison (1949).	Biotite	K-Ar	1760

Lowdon (1961) (GSC 60-73)	Kisseynew Lake Lat: 54°57'N Long: 101°41'W	Medium-grained paragneiss, type area for Kisseynew metasedimentary gneiss belt.	Biotite	K-Ar	1735 ± 85
Hunt & Dennison (1971)	Iskwasum Lake Area Lat: 54°40'N Long: 100°51'W	Biotite fractions from post-Missi granitic plutons; whole rock sample from metamorphised Amisk sediments. (syn-to late kinematic)	4 Biotite Fractions whole rock biotite amphibolite	K-Ar	Average age 1749 + 24 (ranging from 1710-1785)

B) Rb-Sr Ages

Reference	Location	Sample Description	Material	Method	Age(m.y.)	$(^{87}Sr/^{86}Sr)i$
Mukherjee et al. (1971)	Flin Flon Area Saskatchewan Lat: 54°45'N Long: 101°55'W	Amisk Group metavolcanics.	Whole Rock	Rb-Sr Isochron	1775 ± 89	0.7039 ± 0.0013
Mukherjee et al. (1971)	Annabel Lake pluton Lat: 54°48'N Long: 102°10'W	Large, concordant, medium to coarse-grained granitic pluton that intrudes Amisk volcanics. (Post Missi and syn-kinematic).	Whole Rock	Rb-Sr Isochron	1805 ± 14	0.7023 ± 0.0007
Coleman (1970)	Hanson Lake area Saskatchewan Lat: 54°41'N Long: 102°54'W	Amisk-type metavolcanics.	Whole Rock	Rb-Sr Isochron	2521 ± 60	0.7013 ± 0.0006
Coleman (1970)	Hanson Lake area Saskatchewan Lat: 54°45'N Long: 102°54'W	Granitic rocks that intrude Amisk-type metavolcanics.	Whole Rock	Rb-Sr Isochron	2446 ± 16	0.7008 ± 0.0005

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Coleman (1970)	Hanson Lake area Saskatchewan Lat: 54°45'N Long: 102°54'W	Late pegmatites	Whole Rock	Rb-Sr Isochron	1799 ± 2	0.6980 ± 0.0015
Hunt & Dennison (1971)	Iskwasum Lake area Lat: 54°40'N Long: 100°51'W	Post-Missi granitic plutons (syn-to late kinematic).	Biotite	Rb-Sr Mineral	Average 1760 ± 35 range: 1630-1830	0.702 assumed ratio
Hunt & Dennison (1971)	Iskwasum Lake area Lat: 54°40'N Long: 100°51'W	Same as above	Feldspar concentrates, plus one whole rock	Rb-Sr Isochron	1904 ± 37	0.702
Sinha (1970)	Hanson Lake area Saskatchewan	Biotite granodiorite, included as a cogenetic sample with four K-feldspar concentrates and five whole rock samples from the "Eastern Granite" of the Wollaston Lake fold belt. This Hanson Lake granodiorite intrudes Coleman's (1970) Archean granite listed above.	Potassium Feldspar Concentrate	Rb-Sr Isochron	1846 ± 60	0.7040 ± 0.0005

C) Model Lead Ages

Reference	Location	Sample Description	Material	Method	Age(m.y.)
Sangster (1972)	Western Nuclear Mine, Hanson Lake area, Saskatchewan Lat: 54°42'N Long: 102°50'W	Massive economic sulfide deposit, considered coeval with host Amisk-type meta-volcanics. Contains visible galena.	Galena	Single-Stage Model Pb-Pb	1780 ± 44
Sangster (1972)	Flin Flon Mine Lat: 54°45'N Long: 101°52'W	Sulfide deposit coeval with Amisk metavolcanic host rocks; no visible galena.	Lead extract from massive sulfide ore	Single-stage model Pb-Pb	1850 ± 44
Sangster (1972)	Schist Lake Mine Lat: 54°44'N Long: 101°50'W	Same as for Flin Flon mine.	Lead extract from massive sulfide ore	Single-stage model Pb-Pb	1800 ± 44
Sangster (1972)	Osborne Lake Mine Lat: 54°58'N Long: 99°42'W	Same as above; contains visible galena.	Galena	Single-stage model Pb-Pb	1900 ± 44
Stacey et al. (1969)	Flin Flon Mine Lat: 54°45'N Long: 101°52'W	Massive sulfide deposit	Galena	Single-stage model Pb-Pb	1880
Doe (1967)	Flin Flon Mine	Massive sulfide deposit	Galena	Single-stage model Pb-Pb	1750 1920[a] [a]Sinha(1970)
Sinha(1969,70) Sinha & Tilton (1973)	Flin Flon Mine	Massive sulfide deposit, considered coeval with host rock volcanisms.	Galena	Single-stage model Pb-Pb	1920

Sinha (1970)	Phantom Lake Lat: 54°42'N Long: 101°52'W	Biotite granodiorite from the Phantom Lake pluton that is considered to be youngest intrusive in area. (late to post kinematic?)	Feldspar concentrates	Single-stage model Pb-Pb	1620
Sinha (1970)	Western Nuclear (54°42'N; 102°50'W)	Disseminated galena, considered coeval with host rock volcanism.	Galena	Single-stage model Pb-Pb	1850
(The listed ages were obtained from Sangster (1972), Fig. 4, p.508).	Hanson Lake (54°45'N; 102°45'W)	Massive sulfide deposit, considered coeval with host rock volcanism.			1880
	Flin Flon Mine (54°45'N; 101°52'W)	Massive sulfide deposit, considered coeval with host rock volcanism.			1880
	Stall Lake (54°52'N; 99°57'W)	Disseminated galena, considered coeval with host rock volcanism.			1920
	Chisel Lake (54°50'N; 100°08'W)	Disseminated galena, considered coeval with host rock volcanism.			1870
	Osborne Lake (54°58'N; 99°45'W)	Disseminated galena, considered coeval with host rock volcanism.			1920
Sinha and Tilton (1973)		Average galena sample, Churchill Province	Galena	Single-stage model Pb-Pb	1950
Russell and Farquhar (1960) p.139	Snow Lake 54°54°N; 100°01°W	Obtained from vein on south shore of Snow Lake on south side of Lake Fault.	Galena	Single-stage model Pb-Pb	1860

CHAPTER 4.   DISCUSSION OF ROCK UNITS DATED

Four rock units from the File-Morton Woosey Lakes
study area were dated. These units are: 1) Elmes Island
Formation dacite flows (Lower Amisk Subgroup); 2) Morton
porphyry (a pre- to early kinematic intrusion); 3) Ham
pluton (a syn- to late kinematic intrusion); and, 4) File
gneiss dome complex (a post-Missi granitoid complex of
arkosic composition). In addition, two K-feldspar mineral
concentrates from late pegmatite dykes, (post-kinematic
intrusions), were also dated. Descriptions of these units
are summarized from Bailes (in preparation).

4.1. Elmes Island Formation

Based on field evidence, the oldest geological
unit dated was the Elmes Island Formation, which is the
felsic member of the "second" volcanic cycle of the Lower
Amisk Subgroup (see Table of Formations, Table 1). It con-
sists of a monotonous sequence of calc-alkaline subaqueous
dacite flows. Metamorphism of these strata was slight,
producing upper greenschist facies mineral assemblages.
The purpose in dating this unit was to obtain the age of
Amisk volcanism.

4.2. Morton Porphyry

The Morton porphyry is a tonalitic quartz-feldspar porphyry that is exposed on the east shore of Morton Lake. It is one of the pre- to early kinematic intrusions that occur in small dykes and plugs and crosscut volcanic rocks. The unit is characterized by large subhedral to euhedral phenocrysts of blue quartz and delicately zoned plagioclase, up to 10 mm in size, that is set in a fine-grained felsic matrix. The porphyry bodies are probably high level intrusions, resembling hypabyssal or subvolcanic plugs. Their age relative to the other intrusive rocks is uncertain but they are considered to be pre- to early kinematic intrusions because: 1) they cross cut and are mutually crosscut by small subvolcanic gabbroic dykes; and, 2) they have been foliated and regionally metamorphosed to upper greenschist facies, thus predating the main periods of deformation and metamorphism in the study area. The purpose of dating this unit was to determine its age of emplacement, and a minimum age for the volcanic and sedimentary rocks of the study area.

4.3. Ham Pluton

The Ham pluton is an elongate north-northwesterly trending batholith that outcrops on the east side of File Lake. It is composed of medium to coarse-grained tonalite and granodiorite. The pluton intrudes the Amisk Group, but postdates the early folds that deformed the Missi strata

and the pre- to early kinematic intrusive rocks. The pluton
contains a north-northwesterly trending foliation defined by
flattening and crushing of quartz and plagioclase grains.
The northern portion of the pluton has been subjected to
high grade regional metamorphism. In areas sampled for age
determinations, the pluton generally has been metamorphosed
to lower almandine-amphibolite facies and in many instances
to upper almandine-amphibolite facies. The Ham pluton is
considered to be one of the "older" plutons in the study
area because it predates the main metamorphic event and
some of the associated deformation. The pluton is also
more deformed than the other plutons in the area. The
objective of dating the Ham pluton was to obtain an emplace-
ment age on one of the older "granitic" plutons in the study
area, a minimum age for the deposition of the volcanic and
sedimentary strata, and a minimum age for some of the
deformation.

4.4. File Gneiss Dome

The File gneiss dome is a complex of granitoid
gneisses exposed in a domal structure at the north end of
File Lake. These rocks consist of fine to medium-grained
foliated gneisses that have been derived by recrystalliza-
tion and metasomatism of arkosic gneisses of the Missi
Group. They were initially described as granites by
Harrison (1949) but are believed by Bailes (in preparation)
to have formed by metasomatism and recrystallization during

regional metamorphism. The objective of dating this unit was to obtain its age of metamorphism, which is the age of the main regional metamorphic event that has affected the Kisseynew sedimentary gneiss belt.

4.5. Late Pegmatite Dykes

The youngest unit dated consists of post-kinematic pegmatite dykes, which postdate all other rocks in the study area. They are randomly distributed and show no spatial association with igneous bodies, such as the Ham pluton, or metamorphic complexes, such as the File gneiss dome. Both bodies are intruded by these pegmatite dykes. The pegmatite dykes are composed mainly of perthitic microcline with minor quartz, plagioclase, and biotite. The age of the pegmatite dykes gives the age(s) of the youngest observed intrusive event in the study area.

CHAPTER 5. EXPERIMENTAL TECHNIQUES

5.1. Sample Collection, Preparation, and Selection

The samples analyzed in this study were collected by A. H. Bailes while mapping the File-Morton-Woosey Lakes area for the Manitoba Mines Branch during the summers of 1970 and 1971. Sample stations are shown in Figure 2. Individual sample descriptions are given in Appendix I.

Weathered surfaces were trimmed from the individual samples prior to sample preparation. Each sample was crushed by a jaw crusher and pulverized by a Bleuler grinder to approximately 100 to 200 mesh size. A representative aliquot of approximately 100 g. was obtained by "cone and quartering" the bulk pulverized rock powder, and stored in a two ounce sample bottle.

Sample selection for mass spectrometric analysis was based on: 1) the value of the sample Rb/Sr ratio that was calculated from preliminary x-ray flourescence analysis of rubidium and strontium concentrations; and, 2) the degree of sample weathering.

All samples prepared for mass spectrometric analyses were for whole rock analysis, with the exception of the late pegmatite dykes. K-feldspar mineral concentrates were prepared from the pegmatite samples.

5.2. Isotope Dilution Analysis

The method of stable isotope dilution analysis was used to determine the concentration of strontium and the $^{87}Sr/^{86}Sr$ ratio from spiked strontium analysis, and to determine the concentration of rubidium from rubidium analysis. A detailed discussion of the method is given in Appendix III.

5.3. Chemical Procedure

A detailed description of the chemical procedure used in this study is outlined in Appendix II.

Briefly, three accurately weighed aliquots of a sample were dissolved and digested separately in teflon beakers: one portion was used for spiked strontium analysis, the second for unspiked strontium analysis, and the third for rubidium analysis. Dissolution and digestion was effected by refluxing each aliquot with hydrofluoric acid and perchloric acid. After digestion, a predetermined volume of the rubidium spike solution was added volumetrically to one portion, and a predetermined volume of the strontium spike solution was added to a second portion. The respective mixtures were equilibrated by refluxing the resulting solutions with hydrochloric acid. No spike solution was added to the third portion, which was to be used for direct determination of the $^{87}Sr/^{86}Sr$ ratio present in the sample.

No further extraction or purification, such as cation exchange chromatography, was made on the rubidium

portion. The resulting rubidium residue, in the chloride form, was analyzed mass spectrometrically.

After the spiking procedure, the two aliquots used for strontium analysis were treated similarly. The alkali perchlorates were leached by methanol and were removed from solution in a precipitate form by centrifuging the resulting slurry. Further purification of the strontium fraction was attained by cation exchange chromatography. The resulting strontium sample was analyzed in the chloride form as purified strontium chloride.

5.4. Mass Spectrometry

A triple filament solid source assembly, single-focusing, sector-type mass spectrometer with a 10-inch radius of curvature and a ninety degree deflexion was used to determine all rubidium and strontium isotope analysis. The instrument was described by Penner (1970) and by Anderson (1974). A detailed discussion of the operating procedure is given in Appendix IV.

5.5. Analytical Precision

Two interlaboratory standards were used to monitor the precision and accuracy of analyses made. Replicate analyses of the Eimer and Amend (E&A) $SrCO_3$ standard (lot no. 492 327) were made to determine the precision in the measurement of $^{87}Sr/^{86}Sr$ ratios obtained from strontium analysis of samples. To determine the precision and accuracy

in the measurement of rubidium and strontium concentration obtained from spiked rubidium and spiked strontium analyses, replicate analyses of the NBS 70a K-feldspar standard (Compston et al., 1969) were made separately for rubidium and strontium analyses.

Periodic rubidium and strontium "blank" analyses were made to monitor contamination levels that may be present in rubidium and strontium analyses of samples.

CHAPTER 6. ANALYTICAL RESULTS

6.1. Rubidium and Strontium Standards

Twenty-six replicate analyses of the Eimer and Amend $SrCO_3$ standard (lot No. 492 327) were made over a twenty-four month period to monitor the precision in the measurements of the $^{87}Sr/^{86}Sr$ ratio in both spiked and unspiked strontium analyses. The average value of the $^{87}Sr/^{86}Sr$ ratio was 0.7082 $\pm$ 0.0006 (1 sigma), and the standard deviation of a single measurement was 0.12% (1 sigma).

The precision and accuracy in the measurements of rubidium and strontium concentration determinations was obtained from replicate analyses of the NBS 70a K-feldspar standard. Data for the replicate analyses of this standard is listed in Table 3. The precision of the mean value (528.5 ppm) for eight rubidium analyses was 0.23% (2 sigma). The five total strontium concentration analyses yield a precision on the mean value (65.59 ppm) of 1.25% (2 sigma). The precision on the mean value (1.1980) for the determination of $^{87}Sr/^{86}Sr$ ratio from spiked strontium analyses was 0.23% (2 sigma).

Student's "t" distribution statistics with (n-2) degrees of freedom, where n is the number of analyses, was

Table 3. Analytical Results for the NBS 70a II K-Feldspar Standard

Rubidium Data

Analyst[1]		Rb (ppm)
GRJ	18/7/71	528.8
"	28/8/72	529.7
"	29/8/72	530.9
"	7/12/72	526.9
RKA	29/1/73	528.9
PRB	27/4/73	526.7
"	9/5/73	529.8
"	20/6/73	526.1

mean: 528.5 ± 1.7 ppm

Strontium Data

Analyst[1]	Date	Total Sr (ppm)	$^{87}Sr*$[2] (ppm)	^{86}Sr (micromoles/g)	$(^{87}Sr/^{86}Sr)_N$[3]
RKA	31/1/73	66.11	3.037	0.07000	1.1983
"	29/3/73	66.41	3.049	0.07134	1.1980
"	21/5/73	65.14	3.055	0.06987	1.2093
"	29/7/73	65.40	3.015	0.07024	1.2001
		65.77 ± 0.59 ppm			1.2014 ± 0.0053

[1] Analyst: RKA (R. Anderson), PRB (P. Beaudoin), GRJ (G. Josse).

[2] Radiogenic Sr.

[3] $^{87}Sr/^{86}Sr$ values normalized to $^{86}Sr/^{88}Sr$ = 0.1194.

Table 4. Blank Analysis

Rb Data

Analyst[1]	Date	Rb (micrograms)	^{87}Rb (micrograms)
GRJ	24/7/72	0.038	0.011
"	7/12/72	0.101	0.028
PRB	8/5/73	0.014	0.004
GRJ	6/6/73	0.028	0.008

0.045 ± 0.038 micrograms

Sr Data

Analyst[1]	Date	Sr (micrograms)
GRJ	12/12/72	0.0024
"	"	0.0114
"	"	0.0173

0.0104 ± 0.0075 micrograms

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[1]Analysts: PRB (P. Beaudoin),
GRJ (G. Josse).

used to convert the standard deviation to 2 sigma confidence limits (Spiegel, 1961, p.188).

6.2. Rubidium and Strontium Blank Analyses

To monitor the contamination levels present in rubidium and strontium analyses, rubidium and strontium blank analyses were made periodically. The determined contamination levels are listed in Table 4. The average contamination levels were: 0.045 ± 0.038 micrograms Rb, and 0.0104 ± 0.0075 micrograms Sr. The Rb "blank" correction was applied to the Elmes Island Formation because the average concentration level was low, (i.e., less than 10 ppm). The Rb "blank" correction was considered non-limiting, and hence negligible for the other units analyzed. Similarly, the Sr "blank" correction was found to be non-limiting and was considered negligible for the units analyzed.

6.3. Composition and Concentration of Spike Solutions

Isotope tracers enriched in the ^{87}Rb isotope and isotope tracers enriched in the ^{84}Sr isotope were supplied by Oak Ridge National Laboratories as salts of RbCl and $Sr(NO_3)_2$, respectively. The procedure for preparation of the respective spike solutions from these salts is given in Appendix II. The concentration of the strontium spike solution was calibrated with a gravimetrically prepared laboratory solution of $Sr(NO_3)_2$ and the concentration of the rubidium spike solution was calibrated with a standard solution of

the NBS 984 standard RbCl. The isotope composition of each spike solution was measured directly on a mass spectrometer from dried aliquots of each spike solution. The concentrations and composition of each spike solution are listed in Table 5. During the course of this study, four solutions of the ^{87}Rb-enriched spike solution and three solutions of the ^{84}Sr-enriched spike solution were prepared.

6.4. Duplicate Analyses

The standard deviation of replicate analyses was obtained by using the method of Youden[1], a method that was illustrated by Reesman (1968, p.23). For example, replicate analyses for the Ham pluton yield a standard deviation on the mean of 0.83% and 0.28% for the analyses of rubidium and strontium concentration, respectively. From these coefficients of variation, a standard deviation on the mean of 0.88% for the determination of the ^{87}Rb/^{86}Sr values was obtained. The standard deviation on the mean in the measurement of ^{87}Sr/^{86}Sr ratios from replicate analyses was 0.14%.

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[1]Youden (1951), p.16.

$$\text{standard deviation} = \pm \sqrt{\sum_{i=1}^{n} \frac{\left| x_1^1 - x_1^2 \right|^2}{2n}}$$

where,
n = number of duplicate analyses,

x_1^1, x_1^2 = values for a duplicate analysis.

Table 5. Composition and Concentration of Spike Solutions

^{87}Rb-Enriched Solutions

Spike	Date	Percent Composition		Total Rb Concentration (micromoles/ml)
		^{87}Rb	^{85}Rb	
IV		99.15	0.85	0.05898
V	Sept. 1971	99.15	0.85	0.05883
VII	July 1972	99.15	0.85	0.05902
VII/2	April 1973	99.14	0.84	0.05913

^{84}Sr-Enriched Solutions

Spike	Date	^{84}Sr	^{86}Sr	^{87}Sr	^{88}Sr	Total Sr Concentration (micromoles/ml)
IV/1		82.24	3.71	1.56	12.49	0.01110
IV/2	Aug. 1971	82.2	3.67	1.56	12.5	0.01110
IV/3	Dec. 1972	81.5	3.66	1.56	12.1	0.01126

6.5. Analytical Results from the File-Morton-Woosey Lakes Area

York's (1966) least squares cubic regression
analysis program was used to calculate the respective iso-
chrons. Constant percentage experimental errors of 0.15%
and 1.5% were assigned to the $^{87}Sr/^{86}Sr$ and $^{87}Rb/^{86}Sr$ ratios,
respectively, from which the weighting factors required for
the program were obtained. These values were used in all
isochron fits because the exact values used as weighting
factors were found to have little effect on the determined
age and intercept ($^{87}Sr/^{86}Sr$) values. For each isochron,
the error in age was quoted at 95% confidence limits (1.96
sigma), whereas the corresponding error quoted for the
$^{87}Sr/^{86}Sr$ initial ratio (i.e. the intercept value) was at
1.0 sigma limits. To convert the standard deviation of the
intercept value to 95% confidence limits, Student's "t" dis-
tribution was employed using n-2 degrees of freedom, where
n is the number of sample points regressed.

6.5.1. Elmes Island Formation

Seven samples were analyzed from the Elmes Island
Formation of dacite flows (Table 6). A definitive isochron
fitting of the sample points was not obtained because of the
narrow spread in the range of the Rb/Sr values, the low
mean value of the Rb/Sr ratio, and the excessive scatter
of sample points about a best-fit least squares regression
line. However, regression of four of the seven samples

Table 6. Analytical Results from the Elmes Island Formation

Sample	Rb(ppm)	Sr(ppm)	$^{87}Rb/^{86}Sr$ (atomic)	$(^{87}Sr/^{86}Sr)N$[+]	$(^{87}Sr/^{86}Sr)$mean
5344-2	6.09 <u>5.90</u> <u>6.00±0.10</u>	226.9	0.0763	0.7039±0.0006	0.7039
5344-3	4.61	179.9 <u>182.0</u> <u>181.0±1.0</u>	0.0737	0.7055±0.0006 0.7052±0.0005 0.7040±0.0003*	0.7048±0.0006
5345-1	18.60 <u>18.34</u> <u>18.47±0.13</u>	163.2 <u>165.5</u> <u>164.4±1.1</u>	0.3246	0.7094±0.0003 0.7092±0.0009*	0.7093±0.0001
5347-2	6.27 <u>6.20</u> <u>6.23±0.03</u>	172.2	0.1043	0.7057±0.0006 0.7051±0.0004*	0.7054±0.0003
5347-3	8.61 <u>7.66</u> <u>8.14±0.48</u>	167.4	0.1405	0.7050±0.0007 0.7063±0.0004* 0.7052±0.0002*	0.7055±0.0005
5348-2	12.64 <u>12.74</u> <u>12.69±0.05</u>	274.2 <u>274.9</u> <u>274.6±0.3</u>	0.1332	0.7052±0.0004 0.7049±0.0005*	0.7051±0.0002
5348-3	6.91 <u>6.78</u> <u>6.84±0.06</u>	306.5	0.0646	0.7049±0.0006 0.7026±0.0007* 0.7027±0.0010*	0.7035±0.0010

*Unspiked Sr Analysis.

+All $^{87}Sr/^{86}Sr$ values were normalized to the $^{86}Sr/^{88}Sr$ value of 0.1194.

Figure 3.   Partial regression of some of the analytical
data from the Elmes Island Formation dacite
flows.   Regressing samples 5344-2, 5347-3,
5348-2, and 5348-3, an isochron age of
1737 ± 257 m.y. and an initial ratio of
0.7020 ± 0.0002 are defined (solid line).
Regression of samples 5344-2, 5345-1, 5347-3,
5348-2, and 5348-3, gives an age of
1570 ± 95 m.y. and an initial ratio of
0.7022 ± 0.0001 (dashed line).

Elmes Island Formation
Dacite Flows

AGE: 1737 ± 257 m.y.
$(^{87}Sr/^{86}Sr)_i$: 0.7020 ± 0.0002

AGE: 1570 ± 95 m.y.
$(^{87}Sr/^{86}Sr)_i$: 0.7022 ± 0.0001
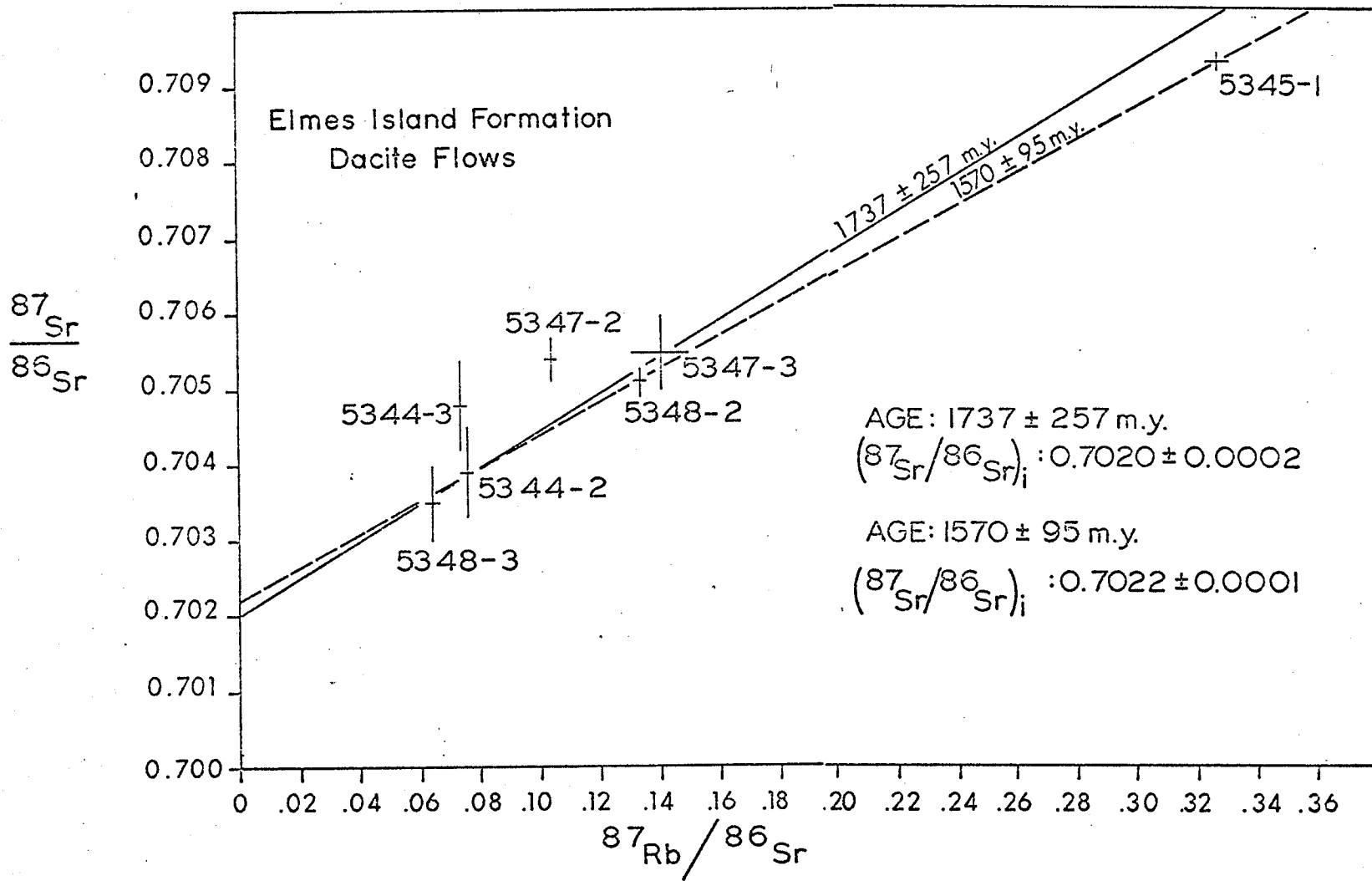
analyzed, (samples 5344-2, 5347-3, 5348-2, and 5348-3), yields an isochron age of 1737 ± 257 m.y. and an $^{87}Sr/^{86}Sr$ initial ratio of 0.7020 ± 0.0002 (solid line, Figure 3). Regression of five of the seven samples analyzed, (samples 5344-2, 5345-1, 5347-3, 5348-2, and 5348-3), gives an age of 1570 ± 95 m.y. and an $^{87}Sr/^{86}Sr$ initial ratio of 0.7022 ± 0.0001 (dashed line, Figure 3).

Samples 5344-3 and 5347-2 were omitted from either regression treatment because both points occur outside the assigned experimental error limits. This is illustrated by the error bars in Figure 3.

6.5.2. Morton Porphyry

Eight samples were analyzed from the Morton porphyry (Table 7). An isochron age of 1715 ± 83 m.y. and an $^{87}Sr/^{86}Sr$ initial ratio of 0.7027 ± 0.0001 are defined by the sample points (Figure 4).

6.5.3. Ham Pluton

The seven samples analyzed from the Ham Pluton (Table 8) define an isochron age of 1860 ± 112 m.y. and an $^{87}Sr/^{86}Sr$ initial ratio of 0.7019 ± 0.0005 (Figure 5). By deleting sample 1027-1 and regressing the remaining six samples, the resulting isochron defines an age of 1880 ± 85 m.y. and an initial ratio of 0.7019 ± 0.0004. Although an improved definition of confidence limits is the result, sample 1027-1 should be retained in the

Table 7. Analytical Results from the Morton Porphyry

Sample	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$ (atomic)	$(^{87}Sr/^{86}Sr)_N{}^+$	$(^{87}Sr/^{86}Sr)$ Mean
5180-1	12.06 <u>12.54</u> 12.30±0.24	540.7 <u>537.7</u> 539.2±1.5	0.0660	0.7052±0.0011* 0.7034±0.0003*	0.7043±0.0009
5180-3	8.23 <u>7.84</u> 8.03±0.21	550.4 <u>547.0</u> 548.7±1.7	0.0423	0.7034±0.0006 0.7043±0.0006 0.7038±0.0004*	0.7038±0.0004
5180-5	16.16	437.7	0.1067	0.7052±0.0004*	0.7052
5181-1	9.84	531.2	0.0536	0.7035±0.0004 0.7042±0.0005*	0.7038±0.0003
5186-1	18.40	439.1	0.1211	0.7054±0.0008 0.7062±0.0004	0.7058±0.0004
5192-1	30.05	222.4	0.3905	0.7125±0.0007 0.7117±0.0004*	0.712±0.0004
5448-1	23.41 <u>24.13</u> 23.77±0.36	497.4 <u>504.7</u> 500.7±3.3	0.1372	0.7064±0.0007 0.7052±0.0004 0.7054±0.0004*	0.7057±0.0005
5448-2	22.71	507.9 <u>519.1</u> 513.5±5.6	0.1278	0.7068±0.0009 0.7054±0.0004* 0.7058±0.0007*	0.7060±0.0005

*Unspiked Sr analysis.

$^+$All $^{87}Sr/^{86}Sr$ values were normalized to $^{86}Sr/^{88}Sr = 0.1194$.

Figure 4:   Rb-Sr whole rock isochron for the Morton
              Porphyry, a pre-to early kinematic intru-
              sion.

Morton Porphyry

AGE: 1715 ± 83 m.y.

$\left(^{87}Sr/_{86}Sr\right)_i$: 0.7027 ± 0.0001
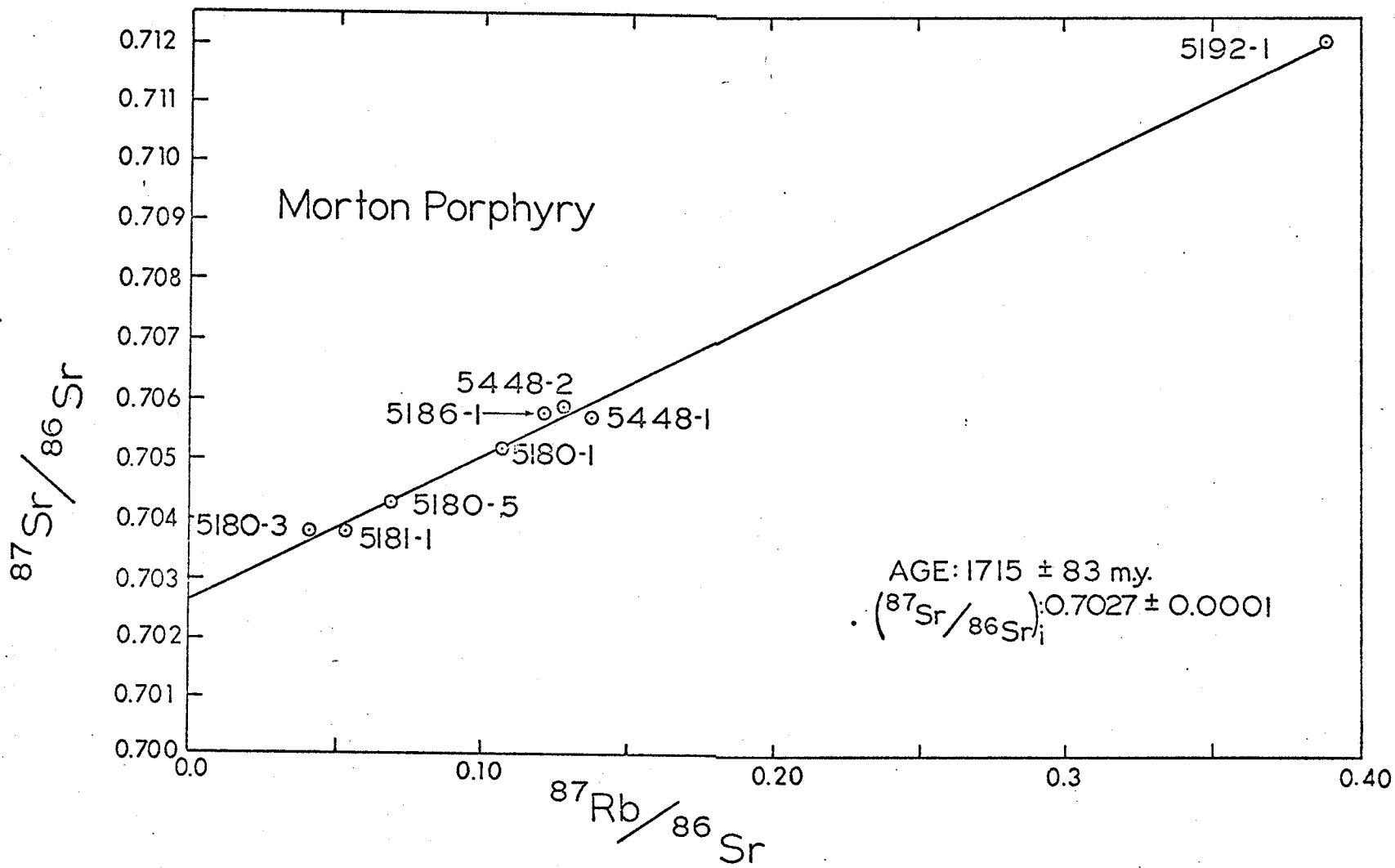
Table 8. Analytical Results from the Ham Pluton

Sample	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$ (atomic)	$(^{87}Sr/^{86}Sr)N^+$	$(^{87}Sr/^{86}Sr)$ Mean
1021-1	122.5	276.6 276.8 276.7±0.1	1.2798 1.2790 1.2794	0.7361±0.0010 0.7359±0.0007 0.7370±0.0006*	0.7363±0.0004
1024-1	48.1 48.4 48.3±0.2	270.2	0.5150 0.5169 0.5159	0.7159±0.0010*	0.7159
1027-1	54.9 55.9 55.4±0.5	213.9	0.7424 0.7549 0.7487	0.7204±0.0004 0.7209±0.0006*	0.7206±0.0003
1028-1	59.4	277.4	0.6214	0.7188±0.0006 0.7165±0.0003* 0.7176±0.0004*	0.7176±0.0007
1030-1	42.8 43.2 42.4 42.8±0.3	374.1 373.0 373.5±0.5	0.3393	0.7105±0.0002 0.7117±0.0007	0.7111±0.0006
1031-1	47.9 48.3 48.1±0.2	374.8	0.3714	0.7132±0.0006 0.7108±0.0009*	0.7120±0.0012
1032-1	49.2 49.9 48.6 49.2±0.5	324.0 322.9 323.0±1.0	0.4416	0.7139±0.0010 0.7127±0.0004*	0.7133±0.0006

*Unspiked Sr run.

$^+$All $^{87}Sr/^{86}Sr$ values were normalized to $^{86}Sr/^{88}Sr$ = 0.1194.

Figure 5.   Rb-Sr whole rock isochron for the Ham pluton,
a syn- to late kinematic intrusion.

Ham Pluton

1021·1

1027·1

1028·1

1024·1

1032·1

1031·1

1030·1

AGE: 1860 ± 112 m.y.

$\left(^{87}Sr/_{86}Sr\right)_i$: 0.7019 ± 0.0005

$^{87}Sr/_{86}Sr$

$^{87}Rb/_{86}Sr$
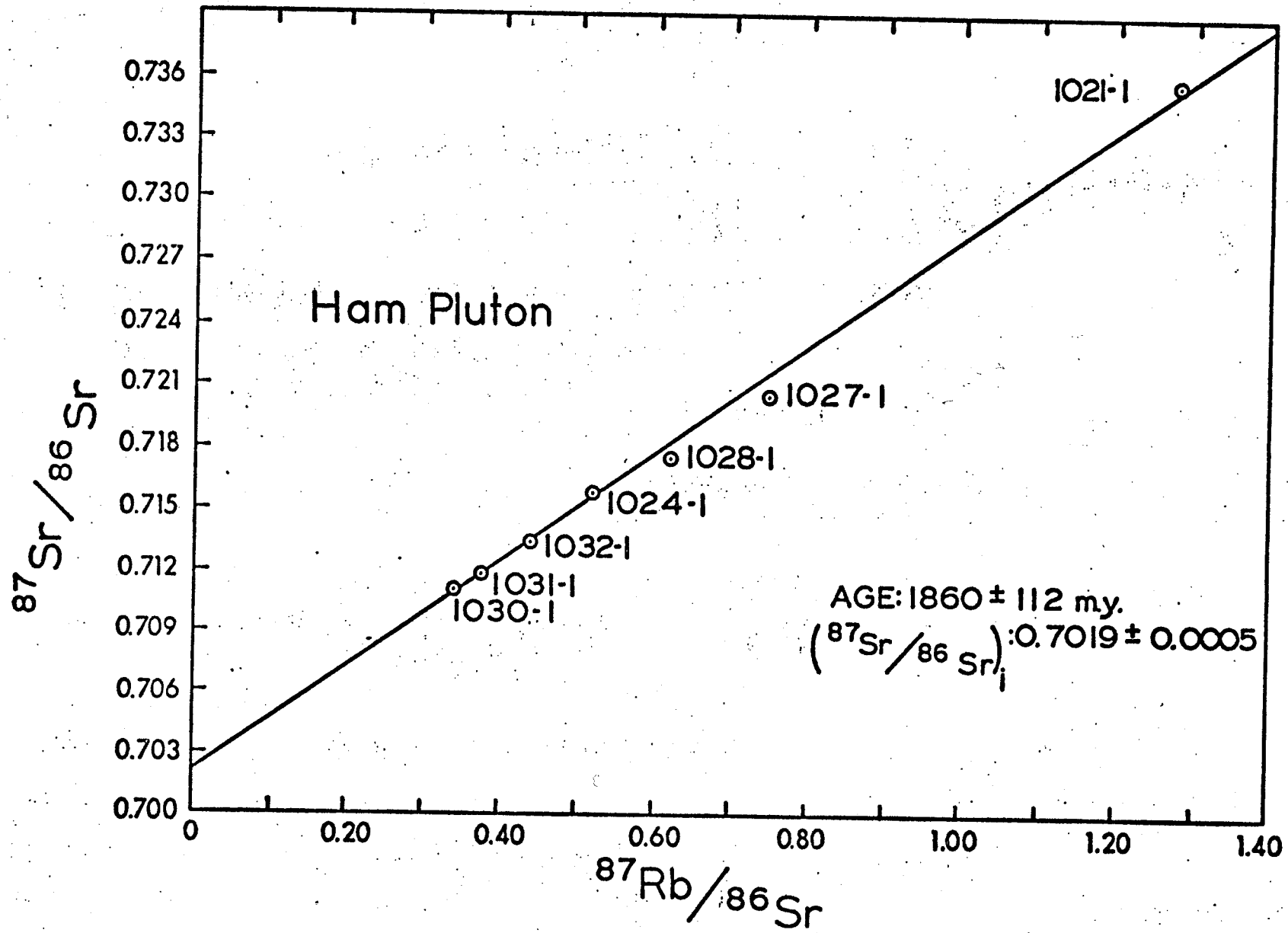
regression because the sample lies within the experimental
error limits.

6.5.4. File Gneiss Dome

Ten samples were analyzed from the File gneiss
dome (Table 9). An isochron age of 1760 $\pm$ 43 m.y. and an
$^{87}Sr/^{86}Sr$ initial ratio of 0.7038 $\pm$ 0.0008 are defined by
the isochron (Figure 6).

6.5.5. Late Pegmatite Dykes

The potassium feldspar mineral concentrates of
two pegmatite samples from the pegmatite dykes were analyzed
(Table 10). Assuming the $^{87}Sr/^{86}Sr$ initial ratio to be
0.710, individual mineral ages of 1741 $\pm$ 55 m.y. and
1763 $\pm$ 55 m.y. were calculated for samples 966-1 and 1021-3,
respectively.

Table 9. Analytical Results from the File Gneiss Dome

Sample	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$ (atomic)	$(^{87}Sr/^{86}Sr)_N$[+]	$(^{87}Sr/^{86}Sr)$ Mean
950-1	118.6 118.9 118.8±0.2	149.2 151.9 150.6±1.4	2.2959 2.2620 2.2779	0.7602±0.0014 0.7609±0.0010	0.7606±0.0004
953-1	119.3	137.9	2.4963	0.7641±0.0012	0.7641
954-1	125.6 123.3 124.5±1.2	121.2 123.2 122.0±1.0	2.9778 2.8924 2.9455	0.7779±0.0006 0.7799±0.0003	0.7789±0.0010
955-1	92.4	222.8	1.1892	0.7344±1.0010	0.7344
956-1	176.8	78.1 78.8 78.4±0.4	6.5521 6.4831 6.5176	0.8643±0.0011 0.8665±0.0006	0.8654±1.0011
957-1	112.7 113.3 113.0±0.3	184.1	1.7698 1.7794 1.7746	0.7473±0.0011	0.7473
958-1	130.0 130.6 130.3±0.3	119.9 119.7 119.8±0.1	3.1499 3.1388 3.1439	0.7842±0.0010 0.7834±0.0012*	0.7838±0.0004
966-2	102.5 106.9 104.7±2.2	235.8 230.3 233.1±2.7	1.2567 1.3404 1.2986	0.7376±0.0012 0.7352±0.0007	0.7364±0.0012
967-1	121.3	157.0	2.2151	0.7572±0.0010	0.7572
969-1	116.7 116.0 116.3±0.3	222.5	1.5164 1.5062 1.5112	0.7409±0.0009	0.7409

*Unspiked Sr analysis.

[+]All $^{87}Sr/^{86}Sr$ values were normalized to $^{86}Sr/^{88}Sr$ = 0.1194.

Figure 6.   Rb-Sr whole rock isochron of the File
gneiss dome, a granitoid gneiss complex
that was formed by the main regional
metamorphic event.

File Gneiss Dome

AGE: 1760 ± 43 m.y.

$\left(\dfrac{^{87}Sr}{^{86}Sr}\right)_i : 0.7038 \pm 0.0008$

Y-axis: $^{87}Sr/^{86}Sr$

X-axis: $^{87}Rb/^{86}Sr$

Data points labeled: 956-1, 954-1, 958-1, 950-1, 953-1, 967-1, 957-1, 966-2, 969-1, 955-1
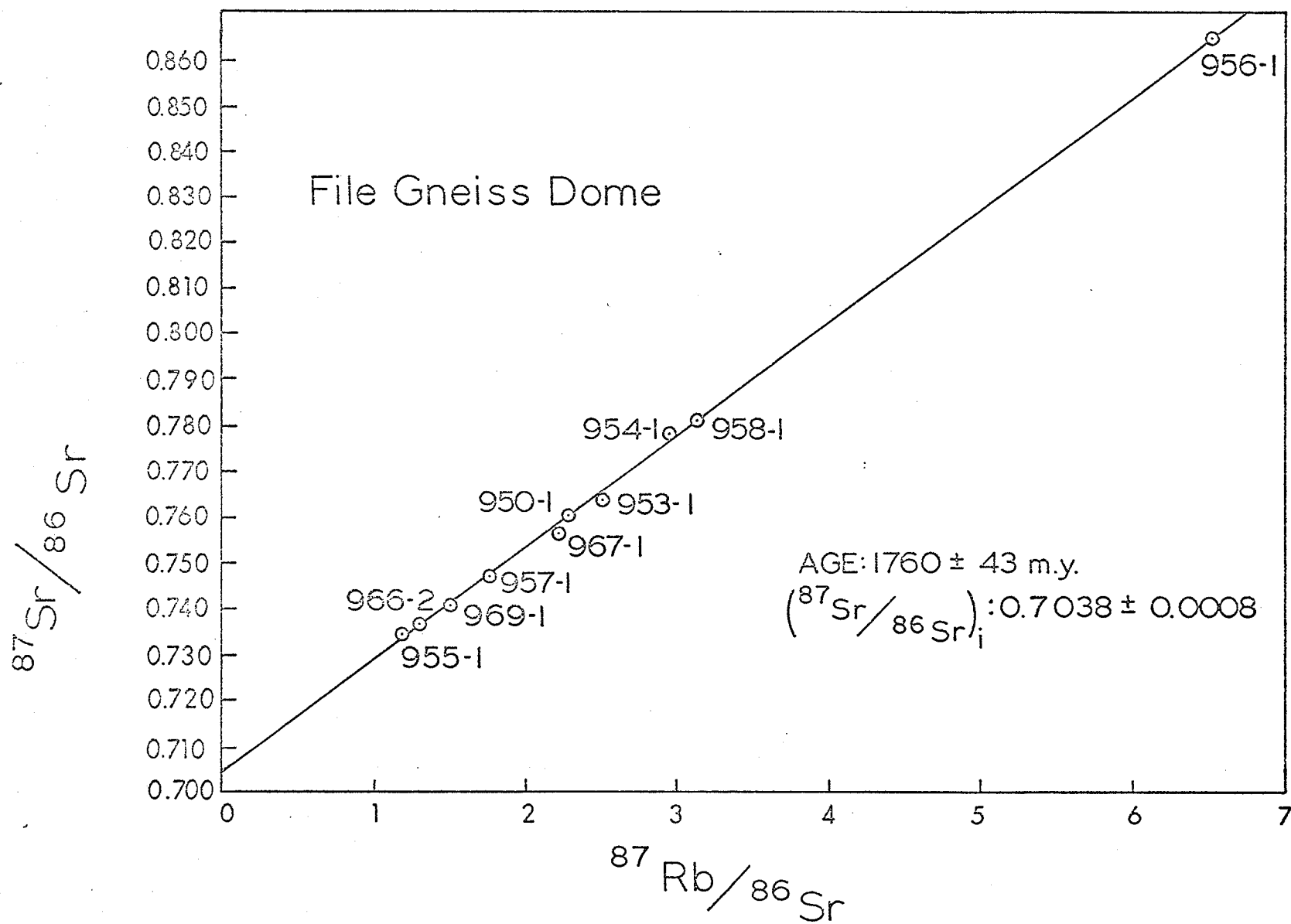
Table 10. Analytical Results from the Late Pegmatite Dykes

Sample	Rb (ppm)	Total Sr (ppm)	^{87}Sr* (ppm)	^{86}Sr (micromoles/g)	$(^{87}Rb/^{86}Sr)$ Atomic	$(^{87}Sr/^{86}Sr)N$	Age+ (m.y.)
966-1	325.4	72.1	2.268	0.07862	13.461	1.0393±0.0010	1741 ± 55
1021-3	363.1	53.8	2.568	0.05773	20.458	1.2185±0.0018	1763 ± 55

*Radiogenic Sr.

+Age calculations were obtained by assuming the ^{87}Sr/^{86}Sr initial ratio to be 0.710.

CHAPTER 7. INTERPRETATION OF ISOTOPIC DATA

Rubidium-strontium age determinations obtained from
the File-Morton-Woosey Lakes area of the Flin Flon volcanic
belt are listed in Table 11. The $^{87}Sr/^{86}Sr$ initial ratios
from these results are plotted in Figure 7, which is an iso-
tope evolution diagram of strontium with time in the source
regions of oceanic basalt and of continental crust. For
comparative purposes, the initial ratios obtained by
Mukherjee et al. (1971) at Flin Flon and by Coleman (1970)
at Hanson Lake are included in Figure 7. This diagram can
sometimes be used to distinguish between primary and recycled
crustal material and to suggest a possible source region for
the corresponding magma (Faure and Powell, 1972; Bruwash
et al., 1973).

7.1. Discussion of Isotopic Data and Age Relations
7.1.1. Elmes Island Formation

Dacite flows of the Elmes Island Formation repre-
sent the felsic member of the 'second'volcanic cycle of
Amisk volcanism recognized in the study area (Table 1).
Because of the narrow range of Rb/Sr values and the low
mean value of Rb/Sr ratios in this unit, least-squares regres-
sion of the sample points is characterized by a considerable
scatter of sample points about the best-fitting mean

Table 11.   Rb-Sr Age Determinations, File-Morton-Woosey
            Lakes Area

Unit Dated	Age (95%) Confidence)	$(^{87}Sr/^{86}Sr)$ initial
Elmes Island Formation[1] ($54^{\circ}50'N$ by $100^{\circ}27'W$)	1737 ± 257 m.y.	0.7020 ± 0.0002
Morton porphyry[1] ($54^{\circ}55'N$ by $100^{\circ}26'W$)	1715 ± 83 m.y.	0.7027 ± 0.0001
Ham pluton[1] ($54^{\circ}55'N$ by $100^{\circ}15'W$)	1860 ± 112 m.y.	0.7019 ± 0.0005
File gneiss dome[2] ($54^{\circ}55'N$ by $100^{\circ}20'W$)	1760 ± 43 m.y.	0.7038 ± 0.0008
Late pegmatite dykes[3] calculated mineral ages:		
sample 966-1	1741 ± 55 m.y.	0.710, assumed
sample 1021-3	1763 ± 55 m.y.	0.710, assumed

---

[1]Units representing the Flin Flon volcanic belt.

[2]Units representing the Kisseynew sedimentary gneiss belt.

[3]Late pegmatite dykes that intrude both the Ham pluton and
the File gneiss dome.

isochron. Consequently, the data does not yield a defini-
tive isochron (Figure 3), and the resulting age determination
has a large uncertainty. For example, regression of four of
seven samples analyzed, (samples 5344-2, 5347-3, 5348-2, and
5348-3), yields an isochron with an apparent age of 1737 $\pm$
257 m.y. and an $^{87}Sr/^{86}Sr$ initial ratio of 0.7020 $\pm$ 0.0002.
The three samples, (samples 5344-3, 5345-1, and 5347-2),
that were excluded lie outside the experimental limits of
error. If sample 5345-1 is included with the four previously
regressed samples, the resulting isochron calculation yields
an age of 1570 $\pm$ 95 m.y. and an initial ratio of 0.7022 $\pm$
0.0001. However, this apparent age of 1570 m.y. is con-
sidered to be too low for the Amisk Group and is discarded.

The radiometric age of 1737 $\pm$ 257 m.y. for the
Elmes Island Formation may represent the age of deposition
of the dacite flows, or an updated age due to regional meta-
morphism during the Hudsonian orogeny. However, it is diffi-
cult to distinguish between the two possible interpretations
because of the large uncertainty associated with the deter-
mined age. Since the age of 1737 $\pm$ 257 m.y. is less than
that of 1860 $\pm$ 112 m.y. for the Ham pluton, a pluton that
intrudes the volcanic strata but predates the regional meta-
morphism, and since the age of 1737 $\pm$ 257 m.y. statistically
overlaps the metamorphic age of 1760 $\pm$ 43 m.y. for the File
gneiss dome, the apparent age of 1737 $\pm$ 257 m.y. can be
interpreted to be a metamorphic age for the Elmes Island
Formation that was updated during regional metamorphism.

The $^{87}Sr/^{86}Sr$ initial ratio of 0.7020 $\pm$ 0.0002 plots within the basalt field of Figure 7, suggesting that the parent material for the Elmes Island Formation dacite flows may have been derived from a similar source region. This does not preclude any crustal pre-history that may have occurred between the geological age of deposition for the dacite flows and its radiometric age of 1737 $\pm$ 257 m.y.

7.1.2. Morton Porphyry

The Morton porphyry is considered to have been intruded as pre- to early kinematic hypabyssal intrusions, that predate the main periods of deformation and metamorphism in the study area, but postdate the volcanic rocks in which they are set. However, according to Bailes (personal communication), its geological age relative to the gabbroic sills of the Josland Formation (Table 1) is not well established, and it could in fact be older. The porphyry bodies appear to be high level intrusions and may be subvolcanic, as indicated by their texture and mode of occurrence as numerous small dykes and plugs. The determined radiometric age of 1715 $\pm$ 83 m.y. gives an age that is younger than the age of 1860 $\pm$ 112 m.y. determined for the Ham pluton, a syn- to late kinematic intrusion that postdates the Morton porphyry. At 95% confidence limits, there is a statistical overlap of both ages, but there also is a statistical overlap with the age of 1760 $\pm$ 43 m.y.

determined for the File gneiss dome. The radiometric age
obtained for the Morton porphyry does not preclude a pre- to
early kinematic time of intrusion. However, the radiometric
age may also represent an updating of the rocks in response
to the main regional metamorphic event that affected the
area. The Morton porphyry has been foliated and regionally
metamorphosed to upper greenschist facies conditions. The
small dykes and plugs of tonalitic quartz feldspar porphyry
composition that comprise the Morton porphyry could have
responded as 'open' geochemical systems at this time. There-
fore, the determined radiometric age of 1715 ± 83 m.y. for
the Morton porphyry should be interpreted as a possible
minimum age of intrusion.

The $^{87}Sr/^{86}Sr$ initial ratio of 0.7027 ± 0.0001
(Figure 4) plots within the basalt field of Figure 7, sug-
gesting that the parent material for the Morton porphyry
may have been derived from a similar source region. The
interpreted source region for oceanic basalts is the upper
mantle (Faure and Powell, 1972, p.24). However, the initial
ratio of 0.7027 does not preclude the possibility of a
crustal pre-history for the Morton porphyry that may have
occurred between its geological age of emplacement and its
determined radiometric age. For example, if one assumes a
possible parent material having a $^{87}Sr/^{86}Sr$ ratio of 0.7020
and a maximum Rb/Sr ratio of 0.1, then the Moron porphyry
could conceivably have had a crustual pre-history of approxi-
mately 250 m.y. prior to isotopic homogenization 1715 m.y.

ago as a result of metamorphism.

7.1.3. Ham Pluton

The Ham pluton is considered to be one of the older syn- to late kinematic 'granitic' plutons in the study area. The pluton is foliated and probably was meta-morphosed to lower almandine-amphibolite facies, or even in part to upper almandine-amphibolite facies. Since intrusion of the pluton predates the main regional metamorphic event, but postdates Amisk volcanism and Missi sedimentation, its radiometric age of 1860 $\pm$ 112 m.y. gives a minimum age for Amisk volcanism and Missi sedimentation, and all other rocks which predate the Ham pluton in the study area, such as the Morton porphyry. It also provides a minimum age for any early deformation that predates the Ham pluton.

The $^{87}Sr/^{86}Sr$ initial ratio of 0.7019 $\pm$ 0.0005 (Figure 5) for the Ham pluton plots within the basalt field of Figure 7. The low initial ratio suggests that the Ham pluton could not have been derived from much older continen-tal crust material, but rather the pluton was derived from a source depleted in rubidium relative to strontium, such as the mantle. The value of the initial ratio is similar to the $^{87}Sr/^{86}Sr$ ratio of 0.7018 which was calculated for the source regions of oceanic basalt having an average Rb/Sr ratio of 0.025 (Faure and Powell, 1972, p.25). How-ever, the low initial ratio for the Ham pluton does not preclude the possibility that the pluton was affected by

the main regional metamorphic event or by a cooling period
of some duration of time following intrusion. Either possi-
bility is suggested by the scatter of sample points about
the isochron that is indicated by the uncertainty of ±112
m.y. in the determined radiometric age. As a result, the
determined age of 1860 $\pm$ 112 m.y. is interpreted as a mini-
mum age of intrusion for the Ham pluton.

7.1.4. File Gneiss Dome

The File gneiss dome is a granitoid complex derived
from the Missi Group arkosic sedimentary rocks by recrystal-
lization and potassium metasomatism. The radiometric age of
1760 $\pm$ 43 m.y. is interpreted as the age of metamorphism for
the File gneiss dome and the age of the main regional meta-
morphic event that affected the Kisseynew sedimentary gneiss
belt. The radiometric age is comparable with the K-Ar bio-
tite age of 1735 m.y. (GSC 60-73, Lowdon, 1961) obtained from
a paragneiss at Kisseynew Lake, Bruce's (1918) type area for
the Kisseynew gneisses. Both ages probably represent the
age of the main regional metamorphic event of the Hudsonian
Orogeny.

The $^{87}Sr/^{86}Sr$ initial ratio of 0.7038 $\pm$ 0.0008
(Figure 6) for strata of the File gneiss dome statistically
overlaps the source regions for oceanic basalt and the
source region for continental crust in Figure 7. The
moderately high initial ratio appears to reflect this unit's
complex crustal pre-history which includes metasomatic and

metamorphic generation from Missi Group arkosic sedimentary rocks.

7.1.5. Late Pegmatite Dykes

The late pegmatite dykes represent the youngest intrusive event(s) of the study area. They postdate the main regional metamorphic event. The dykes intrude foliated bodies of rocks, such as the Ham pluton and the File gneiss dome, that were affected by the main regional metamorphism. By assuming the value of the $^{87}Sr/^{86}Sr$ initial ratio to be 0.710, individual mineral ages of 1741 $\pm$ 55 m.y. and 1763 $\pm$ 55 m.y. were calculated for the two K-feldspar mineral concentrates analyzed. Thus, the individual mineral ages of 1741 m.y. and 1763 m.y. represent the best approximation of the age of the youngest intrusive event for the study area.

7.2. $^{87}Sr/^{86}Sr$ Initial Ratios from the Flin Flon Volcanic Belt

In the application of strontium isotopes to the petrogenesis of igneous rocks, $^{87}Sr/^{86}Sr$ initial ratios can be used to suggest the source regions for the material from which the igneous rocks crystallized. The value of the initial ratio depends upon the nature, the previous history, and in particular, the Rb/Sr ratio of the source regions. The nature of the source regions is represented by two generalized fields of initial ratios that are outlined in Figure 7, a development diagram of strontium isotope evolution with time in the source regions of oceanic basalt and the continental crust. The initial ratios of uncontaminated

Figure 7. Sr isotope evolution diagram for the Flin Flon
volcanic belt, adapted from Faure and Powell
(1972, p.26). The confidence limits for the
$^{87}Sr/^{86}Sr$ initial ratios are expressed at one
sigma levels.

File-Morton-Woosey Lakes area (this work)

J-1 Elmes Island Formation dacite flows:
1737 ± 257 m.y, 0.7020 ± 0.0002.

J-2 Morton porphyry: 1715 ± 83 m.y., 0.7027 ± 0.0001.

J-3 Ham pluton: 1860 ± 112 m.y., 0.7019 ± 0.0005.

J-4 File gneiss dome: 1760 ± 43 m.y., 0.7038 ± 0.0008.

Flin Flon area (Mukherjee et al., 1971)

M-1 Amisk volcanics: 1775 ± 89 m.y., 0.7039 ± 0.0007.

M-2 Annabel Lake pluton: 1805 ± 14 m.y.,
0.7027 ± 0.0004.

Hanson Lake area (Coleman, 1970)

C-1 Metavolcanics: 2521 ± 60 m.y., 0.7013 ± 0.0003.

C-2 Granitic pluton: 2446 ± 16 m.y., 0.7008 ± 0.0003.

CONTINENTAL CRUST (Rb/Sr = 0.18)

$^{87}Sr / ^{86}Sr$

M-1 ⊙ J-4

M-2 ⊙ ⊙ J-2

J-3 ⊙ ⊙ J-1

C-1 ⊙

⊙ C-2

Source regions of basalt
(upper mantle)

.711
.710
.709
.708
.707
.706
.705
.704
.703
.702
.701
.700
.699

3000   2500   2000   1500   1000

TIME IN MILLION YEARS MEASURED FROM THE PRESENT
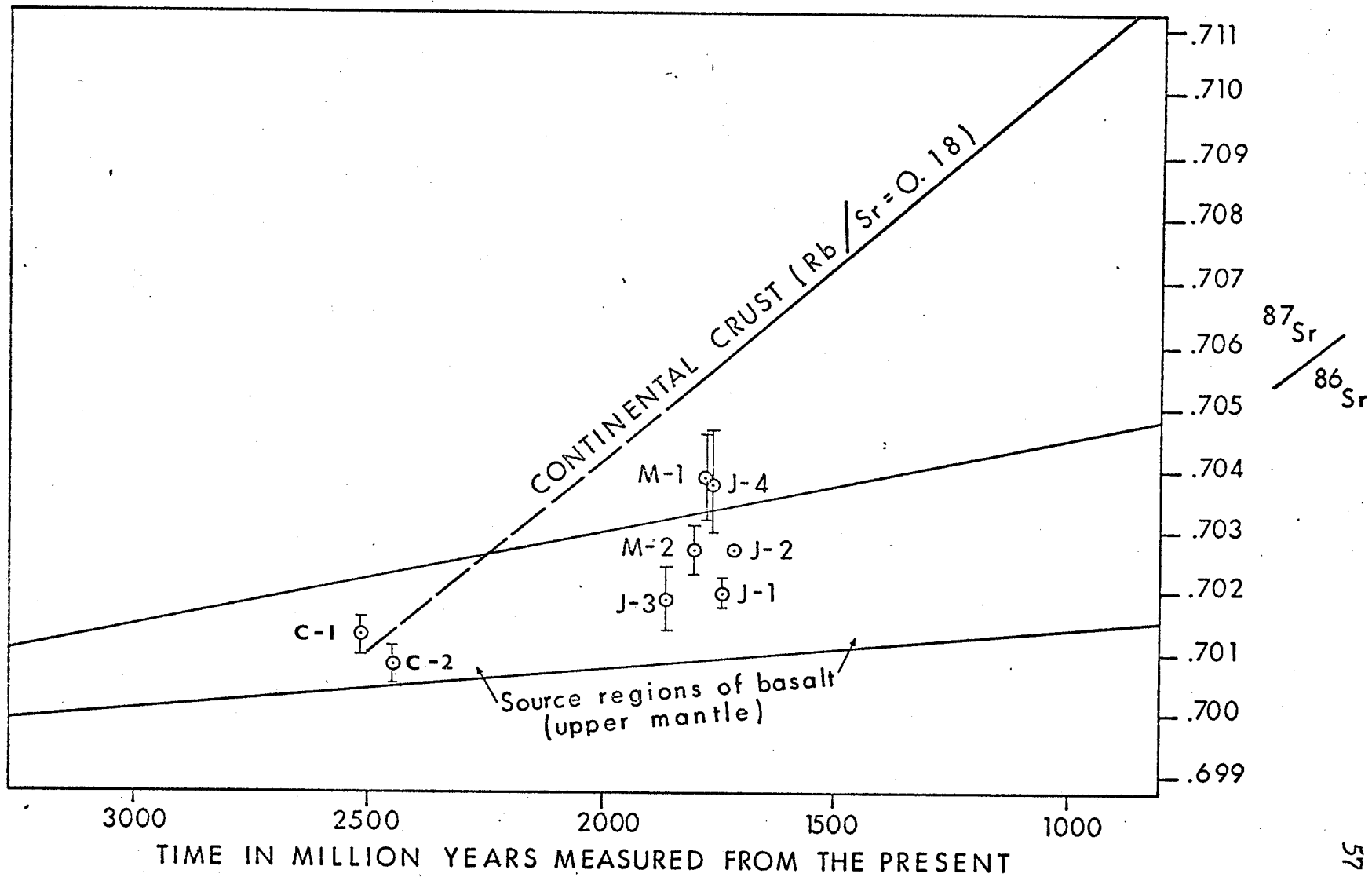
oceanic basalt are considered to be the same as that of its source region in the upper mantle. The 'basalt field' in Figure 7 is defined by the initial ratios of oceanic basalt, that range in value from 0.702 to 0.706 and have a mean value of 0.7037. On the other hand, the "continental crust field' is more difficult to define because the $^{87}Sr/^{86}Sr$ and Rb/Sr ratios are more difficult to determine. The $^{87}Sr/^{86}Sr$ ratios of the continental crust are quite variable since its range of values are determined by such variable factors as the Rb/Sr ratios present and the crustal history of the rocks. Faure and Powell (1972, p.26) obtained an estimate of 0.719 for the average $^{87}Sr/^{86}Sr$ ratio in the continental crust having an average Rb/Sr ratio of 0.18. Initial ratios of igneous rocks that plot within the continental crust field of Figure 7 suggest that the parent material may have been derived from the reconstitution of older sialic material, from primary igneous material that was contaminated by a considerable amount of older crustal material, or, from the isotopic equilibration of strontium on a whole-rock scale by a metamorphic event.

For a more detailed discussion on the significance and use of $^{87}Sr/^{86}Sr$ initial ratios as 'geological tracers' in the petrogenesis of igneous rocks, the reader is referred to the review by Faure and Powell (1972) and the application by Burwash et al. (1973).

In general, the low initial ratios obtained for the Elmes Island Formation (0.7020), the Morton porphyry (0.7027), and the Ham pluton (0.7019) plot within the basalt field of

Figure 7. The low initial ratios suggest that these rocks
could not have been derived from much older continental
crustal material, but rather from a source region depleted
in rubidium relative to strontium, such as the upper mantle.
However, as previously discussed, this interpretation does
not preclude the possibility of any crustal pre-history that
may have occurred between their geological ages of emplace-
ment and the main regional metamorphic event that may have
caused these units to undergo partial or complete isotopic
homogenization.

The exception to this trend of low ratios is that
obtained for the File gneiss dome (0.7038) which statis-
tically overlaps the basalt and continental crust fields in
Figure 7. The moderately high initial ratio indicates a
crustal pre-history prior to isotopic homogenization of the
Missi Group arkosic sedimentary rocks during regional meta-
morphism.

The $^{87}Sr/^{86}Sr$ initial ratios obtained from volcanic
and plutonic units by Mukherjee et al. (1971) at Flin Flon
and by Coleman (1970) at Hanson Lake also plot within the
basalt field in Figure 7. Coleman's Archean ages and
Mukherjee's Aphebian ages are considered, by them, to repre-
sent igneous ages for the respective rock units. In dis-
cussing the significance of the low initial ratios obtained
at Flin Flon, Mukherjee (1971, p.144) states that "it may be
interpreted that previously existing continental crustal
material did not contribute significantly to the Annabel Lake
granodiorites or to Amisk volcanism."

CHAPTER 8. SUMMARY AND CONCLUSIONS

Radiometric age determinations have been obtained by the rubidium-strontium whole rock isochron method from the File-Morton-Woosey Lakes area. The study area, which is located within the southeastern portion of the Churchill geological province of the Canadian Shield, straddles the boundary between two major easterly trending lithological belts: the Flin Flon volcanic belt (in the south), and the Kisseynew sedimentary gneiss belt (in the north).

The radiometric age of 1860 ± 112 m.y. obtained for the Ham pluton, a syn- to late kinematic intrusion, is interpreted to be its minimum age of emplacement. The age is considered Aphebian, according to Stockwell's (1964, 1972) definition. It also is considered to provide a minimum age for the extrusion of the Amisk volcanic strata and deposition of the Missi sedimentary strata, rocks which it intrudes. In addition, it gives a minimum age for all other rocks in the study area that predate the Ham pluton, such as the Morton porphyry, and a minimum age for any early deformation that predates the pluton.

The age of regional metamorphism that affected the study area during the Hudsonian orogeny is given by the radiometric age of 1760 ± 43 m.y. that was determined for the File gneiss dome, a granitoid gneiss complex.

The radiometric ages determined for the dacite flows of the Elmes Island Formation (1737 ± 257 m.y.), representing the Amisk volcanics, and for the Morton porphyry (1715 ± 83 m.y.), representing pre- to early kinematic intrusions, are interpreted to be probably metamorphic ages and not emplacement ages, and that these units were updated during regional metamorphism. The metamorphic age interpretation is preferred because: 1) the determined radiometric ages are younger than that obtained for the Ham pluton, an intrusion that postdates the Elmes Island Formation and the Morton porphyry, but predates the main regional metamorphic event; 2) both units were metamorphosed under greenschist facies conditions during regional metamorphism; and, 3) both ages statistically overlap the metamorphic age obtained for the File gneiss dome.

The late pegmatite dykes are post-kinematic intrusions that postdate all other rocks in the study area. The calculated mineral ages of 1741 ± 55 m.y. and 1763 ± 55 m.y. give the best approximation of the age of the youngest intrusive event in the study area.

The age determinations for the rock units analyzed can be subdivided according to their relation to the geological events recognized in the study area (Table 1). They are: 1) the Aphebian age of emplacement for the Ham pluton, which also provides a minimum age for Amisk volcanism, Missi sedimentation, and all other rocks and early deformation that predate the Ham pluton; 2) the age of regional metamorphism

during the Hudsonian orogeny is given by the metamorphic
age of the File gneiss dome; 3) the probably metamorphic
ages for the Elmes Island Formation dacite flows and the
Morton porphyry; and, 4) the post-kinematic age determina-
tions for the late pegmatite dykes.

Two trends are given by the $^{87}Sr/^{86}Sr$ initial
ratio values determined from the rock units analyzed. The
rock units from the Flin Flon volcanic belt are characterized
by low initial ratio values: Elmes Island Formation dacite
flows (0.7020 ± 0.0002), Morton porphyry (0.7027 ± 0.0001),
and the Ham pluton (0.7019 ± 0.0005). This characteristic
trend suggests that these rocks could not have been derived
from much older continental crustal material, but rather
from a source region depleted in rubidium relative to stron-
tium, such as the upper mantle. However, this does not
exclude the possibility of any crustal pre-history that may
have occurred between their geological ages of emplacement
and the corresponding radiometric ages. For example, such
a possibility is indicated for the Elmes Island Formation and
the Morton porphyry, two rock units whose radiometric ages
are considered metamorphic.

The exception to this trend of low initial ratios
is given by the File gneiss dome (0.7038 ± 0.0008), a grani-
toid gneiss complex from the Kisseynew sedimentary gneiss
belt. This moderately high initial ratio suggests a crustal
pre-history for the paragneiss prior to isotopic homogeniza-
tion of the Missi Group arkosic sedimentary rocks by recrystal-
lization and metasomatism during regional metamorphism.

REFERENCES CITED

Anderson, R. K.   Rubidium-strontium age determinations
    1974   from the Churchill Province of northern
                           Manitoba; unpub. M.Sc. thesis,
                           University of Manitoba.

Bailes, A. H.   Geology of the File-Morton-Woosey
(in preparation)   Lakes area, Manitoba; Man. Mines Br.
                          Publication.

    1971a: File-Morton Woosey Lakes area Manitoba;
                          Man. Mines Br., Preliminary Maps:
                          1971B-1, 1971B-2, with descriptive
                          notes.

    1971b: Preliminary compilation of the geology
                          of the Snow Lake-Flin Flon-Sherridon
                          area; Man. Mines Br., Geol. Paper
                          1/71, 27 pages.

Bruce, E. L.   Amisk-Athapapuskow Lake district;
    1918:   Geol. Surv. Can., Mem. 105.

Burwash, R. A., Krupicka, J., Colbert, R. B.
    1973:   Cratonic reactivation in the
                          Precambrian basement of western Canada.
                          III. Crustal evolution; Can. J. Earth
                          Sci., V.10, p.283-291.

Byers, A. R., Kirkland, S. J. T., Pearson, W. J.
    1965:   Geology and mineral deposits of the
                          Flin Flon area, Saskatchewan; Sask.
                          Dept. Mineral Resources, Geol.
                          Sciences Br., Rept. No. 62, 95 pages.

_____, Dahlstrom, C. D. A.
    1954:   Geology and mineral deposits of the
                          Amisk-Wildnest Lakes area, Saskatchewan;
                          Sask. Dept. Mineral Resources, Geol.
                          Sciences Br., Rept. No. 14, 177 pages.

Coleman, L. C.   Kenoran orogeny in the Hanson Lake
    1972:   area of the Churchill province of
                          the Canadian Shield; Geol. Soc. Am.,
                          Mem. 132, p.149-157.

Coleman, L. C.
1970:
Rb/Sr isochrons for some Precambrian rocks in the Hanson Lake area, Saskatchewan; Can. J. Earth Sci., V. 7, p.338-345.

Compston, W., Chappell, B. W., Arriens, P. A., Vernon, M. J.
1969
On the feasibility of the NBS 70a K-feldspar as a Rb-Sr reference sample; Geochim. Cosmochim. Acta, V.33, p.753-757.

Craig, R. D.
1959:
Surface ionization source for mass spectrometry; J. Sci. Inst., V.36, p.38-39.

Damon, P. E.
1966:
Strontium isotope analysis, in Correlation and Chronology of ore deposits and volcanic rocks; University of Arizona Annual Progress Report No. C00-689-60, U.S. Atomic Energy Commission Contract AT (11-1)-689, p.15-22.

Davidson, A.
1972:
The Churchill Province; in Variations in tectonic styles in Canada, ed., Price, R. A., Douglas, R. J. W.; Geol. Assoc. Can., Spec Paper No. 11, p.381-434.

Davis, J. F., Bannatyne, B. B., Barry, G. S., McCabe, H. R.
1962:
Geology and mineral deposits of Manitoba; Man. Mines Br. (not numbered).

Doe, B. R.
1967:
The bearing of lead isotopes on granitic magma; J. Petrol., V.8, p.51-83.

Farquharson, R. B., Clark, G. S.
1971:
Rb-Sr geochronology of some granitic rocks in southeastern Manitoba; Geol. Assoc. Can., Spec. Paper No. 9, p.111-117.

Faure, G., Powell, J. L.
1972:
Strontium isotope geology; Springer-Verlag, New York, 188 pages.

Harrison, J. M.
1951:
Precambrian correlation and nomenclature and problems of the Kisseynew gneisses, Manitoba; Geol. Surv. Can., Bull. 20.

Harrison, J. M.   Geology and mineral deposits of File-
    1949:   Tramping Lakes area, Manitoba; Geol.
                         Surv. Can., Mem. 250.

Hunt, G.   Iskwasum Lake (west-half), Manitoba,
    1970:   Man. Mines Br., publ. 65-3.

_____, Dennison, R.   K-Ar and Rb-Sr ages of Precambrian
    1971:   rocks in the Iskwasum Lake area,
                         northern Manitoba; Geol. Assoc. Can.,
                         Spec. Paper No. 9, p.137-142.

Kalliokoski, J.   Interpretation of the structural
    1953:   geology of the Sherridon-Flin Flon
                         Region, Manitoba, Geol. Surv. Can.,
                         Bull. 25.

    1952:   Weldon Bay map-area, Manitoba;
                         Geol. Surv. Can., Mem. 270.

Kerr, P. D.   Optical Mineralogy, 3rd edition;
    1959:   McGraw-Hill Book Co., New York,
                         442 pages.

Kornik, L. J.   Guay Lake (west-half); Man. Mines
    1968:   Br., Publ. 64-6.

Lowdon, J. A.   Age determinations by the Geological
    1961:   Survey of Canada, Report 2, Isotopic
                         ages; Geol. Surv. Can., Paper 61-17,
                         p.44-54.

_____, Stockwell, C. H., Tupper, H. W., Wanless, R. K.
    1963:   Age determinations and geological
                         studies, Isotopic ages, Report 3;
                         Geol. Surv. Can., Paper 62-17,
                         p.67-75.

McGlynn, J. C.   Churchill Province; in Geology and
    1970:   economic minerals of Canada, ed.,
                         Douglas, R. J. W.; Geol. Surv. Can.,
                         Econ. Geol. Rept. 1, p.85-107.

    1959:   Elbow-Heming Lakes area, Manitoba;
                         Geol. Surv. Can., Mem. 305.

Money, P. L.   The Wollaston Lake Fold-Belt system,
    1968:   Saskatchewan and Manitoba; Can. J.
                         Earth Sci., V.5, p.1489-1504.

Money, P. L., Baer, A. J., Scott, B. P., Wallace, R. H.
1970:   The Wollaston Lake belt Saskatchewan,
               Manitoba, Northwest Territories; in
               Basins and Geosynclines of the Canadian
               Shield, ed., Baer, A. J.; Geol. Surv.
               Can., Paper 70-40, p.170-200.

Moore, J. M., Froese, E.
1972:   Geological setting of the Snow Lake
               area; Geol. Surv. Can., Paper 72-1,
               Part B, p.78-81.

1971:   Tectonic and metamorphic environment
               of mineral deposits in the Snow Lake
               area, Manitoba; paper presented at
               the 74th Annual Meeting of the C.I.M.,
               Ottawa, April, 1971.

Moore, Jr., J. M., Hart, S. R. Barnett, C. C., Hurley, P. M.
1960:   K-Ar ages in northern Manitoba; Bull.
               Geol. Soc. Am., V.71, p.225-230.

Mukherjee, A. C.
1971:   The precambrian geology of the Flin
               Flon area, northern Saskatchewan and
               Manitoba, Canada; unpubl. Ph.D.
               thesis, University of Saskatchewan,
               Saskatoon.

_____, Stauffer, M. R., Baadsgaard, H.
1971:   The Hudsonian orogeny near Flin Flon,
               Manitoba; A tentative interpretation
               of Rb/Sr and K/Ar ages; Can. J. Earth
               Sci., V.8, p.939-946.

Nilsson, Borghild
1967:   Separation of perthite microcline by
               heavy liquid separation - A too sensi-
               tive method? Nor. Geol. Tidskr.,
               V.47, No. 2, p.149-157.

Ozard, J. M., Slawson, W. F., Russell, R. D.
1973:   An integrated model for lead isotopic
               evolution for samples from the
               Canadian Shield; Can. J. Earth Sci.,
               V.10, p.529-537.

Penner, A. P.
1970:   Rubidium-strontium age determinations
               in the Bird River area, southeastern
               Manitoba; unpubl. M.Sc. thesis,
               University of Manitoba.

Penner, A. P., Clark, G. S.
    1971:   Rb-Sr age determinations from the
                         Bird River area, southeastern Manitoba;
                         Geol. Assoc. Can., Spec. Paper No. 9,
                         p.105-109.

Pringle, I. R.
    1970:   A graphical method for removing rubi-
                         dium contamination from strontium iso-
                         topic data; Geophys. J. R. Astro. Soc.,
                         V.19, p.103-105.

Reesman, R. H.
    1968:   A rubidium-strontium investigation of
                         the possibility of dating hydrothermal
                         mineral deposits; in Mass. Inst.
                         Technol. 16th Annual Progress Report
                         for 1968, U. S. Atomic Energy Commission
                         Contract AT (30-1)-1381, p.15-24.

Robertson, D. S.
    1953:   Batty Lake map area, Manitoba;
                         Geol. Surv. Can., Mem. 271.

Rousell, D. H.
    1970:   Iskwasum Lake (east half), Manitoba;
                         Man. Mines Br., publ. 66-3.

Russell, G. A.
    1957:   Structural studies of the Snow Lake-
                         Herb Lake area, Manitoba; Man. Mines
                         Br., publ. 55-3.

Russell, R. D. Farquhar, R. M.
    1960:   Lead isotopes in geology; Interscience
                         Publishers Inc., New York, 243 pages.

Sangster, D. R.
    1972:   Isotopic studies of ore-leads in the
                         Hanson Lake-Flin Flon-Snow Lake mineral
                         belt, Saskatchewan and Manitoba; Can.
                         J. Earth Sci., V.9, p.500-513.

Shields, W. R. (editor)
    1966:   Analytical mass spectrometry section:
                         Instrumentation and procedures for
                         isotopic analysis; NBS Technical Note
                         277, National Bureau of Standards,
                         U.S. Dept. of Commerce, Washington,
                         D. C., p.11-13.

Sinha, A. K.
    1969:   Removal of radiogenic lead from potas-
                         sium feldspars by volatilization;
                         Earth Planet. Sci. Lett., V.7,
                         p.109-115.

    1970:   Model lead and radiometric ages from
                         the Churchill Province, Canadian
                         Shield; Geochim. Cosmochim. Acta, V.34,
                         p.1089-1106.

Sinha, A. K., Tilton, G. R.
1973:   Isotopic evolution of common lead;
                         Geochim. Cosmochim. Acta, V.37,
                         p.1823-1849.

Slawson, W. F., Russell, R. D.
1973:   A multistage history for the Flin Flon
                         lead; Can. J. Earth Sci., V. 10,
                         p.582-583.

Spiegel, M. R.   Statistics; Schaum's Outline Series,
1961:   McGraw-Hill Publishing Co., New York,
                         359 pages.

Stacey, J. S., Delaveaux, M. E., Ulrych, T.
1969:   Some triple-filament lead isotopic
                         ratio measurements and an absolute
                         growth curve for single stage leads;
                         Earth Planet. Sci. Lett., V.6,
                         p.15-25.

Stockwell, C. H.   Revised Precambrian time scale for
1972:   the Canadian Shield; Geol. Surv. Can.,
                         Paper 72-52.

1970:   Geology of the Canadian Shield -
                         Introduction; in Geology and economic
                         minerals of Canada; ed., Douglas, R.
                         J. W., Geol. Surv. Can., Econ. Geol.
                         Rept. 1, p.44-54.

1964:   Fourth report on structural provinces,
                         orogenies and time-classification of
                         rocks of the Canadian Shield; Geol.
                         Surv. Can., Paper 64-17, part II.

1963:   Interpretative note on sample GSC
                         62-99; in Age Determinations and
                         geological studies, Isotopic ages,
                         report 4; Geol. Surv. Can., Paper
                         63-17, p.65-66.

1969:   Tectonic map of Canada; Geol. Surv.
                         Can., Map 1251A.

Thorpe, R. I., Sangster, D. F.
1973:   An integrated model for lead isotopic
                         evolution for samples from the
                         Canadian Shield: Discussion; Can. J.
                         Earth Sci., V.10, p.1693-1696.

Wanless, R. K., Stevens, R. D., Lachance, G. R.,
Rimsaite, J. Y. H.

    1967:   Age determinations and geological studies, K-Ar isotopic ages, report 7; Geol. Surv. Can., Paper 66-17, p.78-82.

    1965:   Age determinations and geological studies, Isotopic ages, report 5; Geol. Surv. Can., Paper 64-17, pt. I, p.75-79.

Williams, H.
    1966:   Geology and mineral deposits of the Chisel Lake map area, Manitoba; Geol. Surv. Can., Mem. 342.

York, D.
    1966:   Least squares fitting of a straight line; Can. J. Physics, V.44, p.1079-1086.

————, Farquhar, R. M.
    1972:   The earth's age and geochronology; Pergamon Press, Toronto, 178 pages.

Youden, W. J.
    1951:   Statistical methods for chemists; John Wiley & Sons, Inc., New York, 126 pages.

APPENDICES

APPENDIX I. SAMPLE DESCRIPTION

I.1. Elmes Island Formations (54°50' N by 100°27'W)

5344-2   A light-grey, white weathering, fine grained to
          aphanitic dacite with a weak biotite foliation
          and disseminated pyrite. Iron oxide staining
          is present along fractures in the sample.

5344-3   A medium-grey, white weathering, fine-grained
          to aphanitic dacite with a weak biotite folia-
          tion and disseminated pyrite. Iron oxide
          staining is present along fractures in the
          sample.

5345-1   A medium-grey, white weathering, fine-grained
          to aphanitic dacite with a weak biotite folia-
          tion. It contains disseminated pyrite and
          chalcopyrite. Iron oxide staining is present
          along fractures in the sample.

5347-1   A light-grey, fine-grained to aphanitic dacite
          with small flattened phenocrysts of quartz.
          It contains disseminated pyrite. A small
          amount of iron oxide staining is present along
          the fractures in the sample.

5347-2   A light-grey, white weathering, fine-grained to
          aphanitic dacite with disseminated pyrite. No
          evidence of biotite foliation is present. Iron
          oxide staining occurs along fractures in the
          sample.

5347-3   A light-grey, white weathering, fine-grained to
          aphanitic dacite with disseminated pyrite. No
          evidence of biotite foliation is present. A
          small amount of   iron oxide staining is present.

5348-2   A light-grey, fine-grained to aphanitic dacite
          with a strong biotite foliation and disseminated
          pyrite. A large amount of iron staining is pre-
          sent along fractures in the sample.

I.2. <u>Morton porphyry</u> (54°49'N by 100°26'W)

5180-1   A light grey, white weathering, felsic quartz feldspar, biotite-bearing porphyry with well developed phenocrysts of blue quartz and plagioclase (up to 10 m.m. in size), set in a fine-grained matrix. It contains disseminated pyrite. Iron oxide staining is present along cracks in the sample.

5180-3   A weakly foliated, light-grey, white weathering, felsic quartz feldspar, biotite-bearing porphyry with large subhedral to euhedral phenocrysts of plagioclase and blue quartz (up to 10 m.m.), set in a fine-grained matrix. It contains disseminated pyrite. A large amount of iron oxide staining is present throughout the sample.

5180-5   A weakly foliated, light-grey, white weathering, felsic quartz feldspar, biotite-bearing, porphyry with well developed phenocrysts of plagioclase and blue quartz (up to 10 m.m. in size), set in a fine-grained matrix. It contains accessory disseminated pyrite. A large amount of iron oxide staining is present.

5181-1   A light-grey, white weathering, felsic quartz feldspar, biotite-bearing porphyry with large well developed phenocrysts of plagioclase and quartz (up to 10 m.m.), set in a fine-grained matrix. It contains accessory disseminated pyrite. A large amount of iron oxide staining is present.

5186-1   A weakly foliated, medium-grey, felsic quartz feldspar, biotite bearing porphyry, with large subhedral to euhedral phenocrysts of plagioclase and blue quartz (up to 8 m.m. in size), set in a fine-grained to aphanitic matrix. It contains accessory disseminated pyrite. A small amount of iron oxide staining is present.

5192-1   A weakly foliated, light-grey, felsic quartz feldspar, biotite bearing porphyry, with large well developed phenocrysts of plagioclase and quartz (up to 10 m.m.), set in a fine-grained to aphanitic matrix. It contains disseminated pyrite. Iron oxide staining is present.

5448-1   A weakly foliated, light-grey felsic quartz
           feldspar, biotite bearing porphyry with well
           developed phenocrysts of plagioclase and quartz
           (up to 10 m.m.), set in a fine-grained matrix.
           It contains accessory disseminated pyrite.
           Iron oxide staining is prominent.

5448-2   A weakly foliated, light-grey felsic quartz
           feldspar, biotite-bearing porphyry with sub-
           hedral to euhedral phenocrysts of blue quartz
           and plagioclase (up to 10 m.m.), set in a fine-
           grained matrix. It contains accessory dis-
           seminated pyrite. Iron oxide staining is
           prominent.

I.3. Ham pluton (54°55'N by 100°15'W)

1021-1   A white coloured, white weathering, massive
           medium-to coars-grained, biotite bearing,
           tonalite.

1024-1   A pink, massive, equigranular medium-grained,
           biotite-bearing, tonalite to granodiorite.

1027-1   A pink, massive porphyritic, medium-grained,
           biotite-bearing, tonalite to granodiorite,
           with small phenocrysts of potassium feldspar.

1028-1   A pink, massive, porphyritic, coarse-grained,
           biotite-bearing, tonalite to granodiorite,
           with phenocrysts of potassium feldspar. It
           also is weakly foliated.

1030-1   A pink, massive, weakly foliated, medium-to
           coarse-grained biotite-bearing, tonalite to
           granodiorite.

1031-1   A pink, massive porphyritic, coarse-grained,
           biotite-bearing, tonalite to granodiorite with
           phenocrysts of potassium feldspar.

1032-1   A pink, massive, equigranular, medium-grained,
           biotite-bearing, tonalite to granodiorite.

I.4. File gneiss dome (54°55'N by 100°20'W)

950-1   A pink, gneissic, strongly foliated, fine-
           grained quartzo-feldspathic biotite gneiss
           with small porphyroblasts of potassium feld-
           spar.

953-1   A pink, gneissic, weakly foliated, fine-grained, quartzo-feldspathic biotite gneiss with small porphyroblasts of potassium feldspar.

954-1   A pink, white weathering, gneissic, weakly foliated, fine-grained, hornblende bearing, quartzo-feldspathic biotite gneiss with small porphyroblasts of potassium feldspar.

955-1   A greyish-pink, gneissic, moderately foliated, fine-grained, quartzo-feldspathic biotite gneiss with small porphyroblasts of potassium feldspar and accessory magnetite.

956-1   A pink, equigranular, massive, fine-to medium-grained, "granitic" gneiss with porphyroblasts of quartz and plagioclase. It is a quartzo-feldspathic biotite gneiss that does not possess a typical gneissic texture.

957-1   A greyish-pink gneissic, weakly foliated, fine-grained, equigranular, quartzo-feldspathic biotite gneiss with small porphyroblasts of potassium feldspar.

958-1   A pink, gneissic, weakly foliated, fine-grained, equigranular quartzo-feldspathic biotite gneiss with small porphyroblasts of potassium feldspar. It contains accessory disseminated pyrite.

960-2   A medium-grey gneissic, equigranular, moderately foliated, fine-grained quartzo-feldspathic biotite gneiss with porphyroblasts of potassium feldspar.

967-1   A greyish-pink, gneissic, strongly foliated, fine-grained, quartzo-feldspathic biotite gneiss with small porphyroblasts of potassium feldspar.

969-1   A pinkish-grey, gneissic, strongly foliated, fine-grained, quartzo-feldspathic biotite gneiss with small porphyroblasts of potassium feldspar.

I.5. Late pegmatite dykes

966-1   A pink, very coarse-grained pegmatite of granitic composition, containing large phenocrysts of perthitic microcline with graphic intergrowths of quartz and large phenocrysts of plagioclase with graphic intergrowths of quartz. It contains a small amount of biotite and accessory pyrite.

1021-3   A pink, coarse-grained, biotite-bearing, granitic pegmatite with large phenocrysts of microline and quartz.

APPENDIX II.   DETAILED DISCUSSION OF CHEMICAL PROCEDURES

This treatment for preparation, selection, and
chemical procedures is similar to the method outlined by
Penner (1970).

II.1. Sample Preparation and Selection

The weathered surfaces of the rock samples,
weighing from 1 to 2 kilograms, were removed prior to
sample processing. Each sample was ground to chip-size
using a jaw crusher, and the sample chips were washed
with distilled water. After drying, the chips were pul-
verized to a rock powder using a Bleuler grinder. Approxi-
mately 100 g. of the rock powder was selected from the bulk
quantity by the process of "cone and quartering" to ensure
homogeneity of the sample.

Preliminary rubidium and strontium concentrations
were obtained from x-ray fluorescence analysis, (an ARL
Quantometer x-ray fluorescence spectrometer was used). In
general, these preliminary concentrations were from 25%-30%
lower in value than the corresponding concentrations
obtained from subsequent isotope dilution analysis. No
correction factors for such effects as instrument drift,
background, and absorption effects (such as electron
shielding, secondary fluorescence, matrix effects), were

used for these preliminary concentrations.

These preliminary results were used for the selection of samples possessing a range of rubidium and strontium concentrations, expressed as a Rb/Sr ratio, suitable for whole-rock isochron studies. In addition to sample selection, the determination of sample weight required for precise mass spectrometric analysis and the corresponding volume of enriched spike selection needed to yield optimum isotopic ratios in the mixture of sample and spike were based on these preliminary results. The optimum spiking ratio used for the mixture of spike and sample was 0.5 for both the $^{84}Sr/^{86}Sr$ ratio and $^{85}Rb/^{87}Rb$ ratio measured for the respective mixtures.

II.2. Chemical Procedure

II.2.1. Dissolution and Digestion

Three separate aliquots, per sample, of a predetermined weight (0.2 to 0.5 g. on the average), were precisely weighed on aluminum foil weighing boats and were carefully transferred to separate 100 ml. teflon beakers. These aliquots represent chemical preparations for a spiked Rb analysis, a spiked Sr analysis, and for an unspiked Sr analysis. The samples were dissolved in 20 ml. of 40% HF (manufactured by E. Merck: Suprapur) and were covered with teflon disks to allow the samples to reflux for 30 minutes at approximately $250^{\circ}F$ on hot plates. 3 ml. of 70% $HClO_4$ (G. Frederick Smith Chemical Co., double distilled) were

added to each aliquot to convert the sample to the perchlorate form, and the samples were refluxed for 8 hours at 250°F for sample digestion. In general, little or no undissolved matter remained at this point. The teflon covers were removed, and the samples were evaporated to a perchlorate mush. 20 ml. of double-distilled H_2O was added to dissolve the mush, and the samples were evaporated to a perchlorate cake to remove any lingering HF acid from the sample. Care was taken to evaporate the samples to dryness without actually burning the sample brown.

II.2.2. Spiking Procedure

The appropriate volumes of [87]Rb-enriched spike solution and of [84]Sr-enriched spike solution were added volumetrically to the respective Rb and spiked Sr samples. In general, 2 ml. or 5 ml. were added to Sr samples and 5 ml. or 10 ml. to Rb samples. No spike solution was added to the unspiked Sr sample. 20 ml. of vycor distilled (constant boiling) 6.2N HCl were added to each spiked sample, the beakers were covered with the teflon disks, and the mixtures of sample and spike were equilibrated by refluxing on a hot plate for 30 minutes. The teflon covers were removed, and the spiked samples were evaporated to dryness.

II.2.3. Preparation of the Rb Sample

For the majority of rubidium samples prepared, the samples were not purified by the procedure of ion

exchange column chromatography. Originally, a number of samples from the File gneiss dome and the Ham pluton were concentrated and purified by eluting the Rb samples through calibrated ion exchange columns.

The Rb sample was taken into solution in 5 ml. of 1N HCl, and was transferred to a centrifuge tube. After centrifuging for 5 minutes, the liquid was decanted directly into a 10 ml. Hysil beaker and evaporated to dryness, as a chloride. The prepared sample contained iron, calcium, and other elements, but it was found that adequate mass spectrometric analysis could be made on this residue without necessitating the separation of the Rb fraction by ion exchange column chromatography.

In the original treatment, the supernatant liquid was decanted directly into a prepared ion exchange column. Once the sample was absorbed by the resin, one 5 ml. portion, two 10 ml. portions, and one 85 ml. portion of 1N HCl were added, allowing each portion to be completely absorbed, before adding the next. The desired Rb fraction was collected in the next 40 ml. portion of 1N HCl added. The collected 40 ml. fraction of eluted sample was evaporated to dryness as a sulfate by adding a drop of 10% H_2SO_4 during evaporation.

II.2.4. Preparation of the Sr Samples

After the spiking procedure, the preparation of the spiked and unspiked Sr samples were treated similarly.

During the course of this work, the procedure for ion exchange column chromatography was altered. In the original method, an 8% cation exchange resin was used, whereas a 12% cation exchange resin was subsequently used (see following section on ion exchange columns).

The Sr samples were taken into solution in 5 ml. of methanol (Baker Instra-Analyzed, GC-Spectrophotometric Quality Solvent) to leach out the alkaline earth perchlorates, and were transferred to centrifuge tubes. After centrifuging, the supernatant liquids were decanted into 30 ml. Hysil beakers where 10 ml. of 6.2N HCl were added. The solutions were evaporated to dryness.

For elution of the samples using the 8% cation exchange resin, the dried samples were taken into solution in 5 ml. of 2.5N HCl, and were transferred directly to the prepared columns. After allowing the solution to be absorbed, one 5 ml. portion, two 10 ml. portions, and one 85 ml. portion of 2.5N HCl were added, allowing each portion to be completely absorbed before adding the next. The desired Sr fraction was collected in the next 40 ml. portion of 2.5N HCl added. This collected fraction was evaporated to dryness in the perchlorate form by adding a few drops of 10% $HClO_4$ during evaporation.

For elution of samples using the 12% cation exchange resin, the dried Sr samples were taken into solution in 5 ml. of 6.2N HCl and were transferred to the prepared columns. Two 5 ml. portions and one 40 ml.

portion of 6.2N HCl were added, allowing each portion to be completely absorbed before adding the next. The Sr fraction was collected in the next 30 ml. portion of 6.2N HCl added. The collected Sr fraction was evaporated to dryness in the chloride form.

II.3. Ion Exchange Columns

The columns used were made of 10 m.m. I.D. glass tubing fitted with a coarse fritted disc positioned about 3 cm. above the lower tapered end. The flow rate was fixed at approximately 5-10 ml. per hour by the porosity of the frit and the length of the resin used in the column. Two sets of columns, of a different design, were used for strontium extraction. On one set, the top of the column was terminated in a standard taper 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 taper male ground glass joint by a 10 inch (25 cm.) length of narrow glass tubing. The purpose of this extension was to create a hydrostatic pressure to increase the flow rate of the acid through the resin to approximately 10 ml. per hour. The second set of columns were designed so that the top of the column was connected directly to the 200 ml. flask that was used to hold the acid. The set of columns used for rubidium separation were similar in design to this second set of strontium columns. Provision was made for all three sets of columns to have a resin length in the

column that varied from 9 to 10 inches (22 to 25 cm.).

Analytical reagent grade cation exchange resin AG-50W-X8-200-400 mesh, hydrogen form (Bio-Rad Laboratories), was used for the three sets of ion exchange columns in the original procedure. For the strontium columns, the resin was given a preliminary washing in 2.5N HCl, and then was added to the columns. Subsequent washing with 50 ml. of 6.2N HCl was made; this was followed by a washing with 150 ml. of 2.5N HCl. The columns were then ready for calibration and for use. In a similar manner, the resin for the rubidium columns was washed with 50 ml. of 1N HCl instead of the 2.5N HCl, and then was added to the columns to be washed with 50 ml. of 6.2N HCl and with 150 ml. of 1N HCl.

Analytical reagent grade cation exchange resin AG-50W-X12-200-400 mesh, hydrogen form (Bio-Rad Laboratories), was used for the modified procedure of ion exchange column chromatography for strontium separation. All washings of the 12% cation exchange resin were made with 6.2N HCl.

Calibration of the respective columns was made individually by eluting a suitably prepared sample through the columns. 10 ml. fractions of the elutant were collected, and each portion was analyzed on an atomic absorption spectrophotometer to determine the portions when the strontium fraction came out on the strontium columns, and when the rubidium fraction came out on the rubidium columns.

Following an extraction during the use of the columns, the strontium columns using the 8% cation exchange resin were cleaned by passing consecutive volumes of 50 ml. of 6.2N HCl and 100 ml. of 2.5N HCl; the strontium columns using the 12% cation exchange resin were cleaned with 100 ml. of 6.2N HCl; and, the rubidium columns were cleaned with 50 ml. of 6.2N HCl and 100 ml. of 1N HCl. The resin in the columns, when not in daily use, was kept moist by adding several ml. of 1N HCl, 2.5N HCl, and 6.2N HCl to the rubidium columns, to the strontium columns using the 8% cation exchange resin, and to the strontium columns using the 12% cation exchange resin, respectively.

II.4. Preparation of Potassium Feldspar Mineral Concentrates
from Pegmatite Samples

The procedure for the separation of the potassium feldspar mineral concentrates, from other constituent minerals present in the pegmatite samples, was based on Nilssen's (1967) method and that used previously in this laboratory.

The two pegmatite samples analyzed (samples 966-1 and 1021-3) were crushed and pulverized to a rock powder in the manner previously outlined for the preparation of the whole rock samples. The rock powder was passed through a sieve and the -60=100 mesh fraction was collected. The very fine particle or dust fraction was carefully removed by washing with distilled water and by decanting several times. After drying, the -60+100 mesh fraction was

suspended in bromoform (specific gravity = 2.89), contained in a separatory funnel, and the mafic mineral fraction was removed as the "sink" fraction. The specific gravity of the heavy liquid was lowered by dropwise addition of acetone to the bromoform. The "sink" fraction was removed. Repetition of this procedure gave a series of "sink" fractions of steadily decreasing specific gravity. These respective "sink" fractions were washed with acetone, to remove any lingering traces of bromoform and to dry the fractions. The last and lightest "sink" fraction was considered to comprise pure potassium feldspar. The purity of the feldspar concentrate was checked by refractive index measurements using the method of Kerr (1959, pp.57-63).

II.5. Preparation of the Spike Solutions

Isotope tracers enriched in the ^{87}Rb isotope and isotope tracers enriched in the ^{84}Sr isotope were supplied by Oak Ridge National Laboratories as salts of RbCl and of $Sr(NO_3)_2$, respectively. The respective spike solutions were prepared by G. S. Clark from these isotopically enriched tracer salts. The salts were dried overnight at $120^{o}F.$, and were allowed to cool in a dessicator. The spike salts were carefully weighed and carefully transferred to 200 ml. volumetric flasks where they were diluted to volume with 0.5N HCl. A 10 ml. aliquot of the ^{84}Sr-enriched spike solution was transferred volumetrically to a 1000 ml. volumetric flask, where the stock solution was

diluted to volume using 60 ml. of 6.2N HCl and double-distilled water. A 15 ml. aliquot of the ^{87}Rb-enriched spike solution was transferred volumetrically to a separate 1000 ml. volumetric flask, and the stock solution was diluted to volume with 60 ml. of 6.2N HCl and double-distilled water.

Composition analysis of the respective spike solutions were measured mass spectrometrically on dried 10 ml. aliquots of each spike solution separately.

The concentration of the strontium spike solution was calibrated with a gravimetrically prepared laboratory standard solution of $Sr(NO_3)_2$ (Baker analyzed, reagent grade), and the concentration of the rubidium spike solution was calibrated with a solution of RbCl (NBS 984 RbCl, assay-isotopic standard). The isotopic ratios necessary to determine the concentration and composition of these spike solutions were measured mass spectrometrically.

APPENDIX III.   ISOTOPE DILUTION ANALYSES

An isotope dilution analysis is an addition
analysis in which a precisely measured volume of a tracer
(spike) solution (whose concentration and isotopic composi-
tion are precisely known) is added to an accurately weighed
sample to be analyzed. In applying this method to age deter-
minations, the isotopic abundances of rubidium or strontium
present in a rock sample are determined, in addition to the
total concentration of rubidium or strontium. The corres-
ponding isotopic ratios are calculated from the isotopic
abundances.

III.1. Isotope Dilution Calculation for Rubidium

The method used for isotope dilution calculations
of rubidium is described by Penner (1970). The notations
used for this method are given below:

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

t = concentration of each isotope or total rubidium
    in the spike;

s = concentration of each rubidium isotope in the
    sample; and

A = total sample concentration of rubidium, in units
    or micromoles.

The isotope dilution equation used for rubidium calculations was:

(1) $(^{85}Rb/^{87}Rb)m = \dfrac{(^{85}Rb)t + (^{85}Rb)s}{(^{87}Rb)t + (^{87}Rb)s}$

From the natural composition of rubidium:

(2) $(^{85}Rb)s = 0.722A$

(3) $(^{87}Rb)s = 0.278A$

Using the isotopic composition, concentration, and volume of the rubidium spike solution used, both $(^{85}Rb)t$ and $(^{87}Rb)t$ are determined. Therefore, equation (1) is reduced to a single unknown, the total concentration (A) of rubidium in the sample. From equation (1), the concentration (A) of rubidium is calculated uniquely in terms of the measured ratio $(^{85}Rb/^{87}Rb)m$. Given the concentration of rubidium (A), the concentration of ^{87}Rb, in micromoles/g., was calculated from equation (3) using the natural composition of rubidium and the sample weight used.

All rubidium isotope dilution calculations were made using a data reduction program written by A. Penner for use on an Olivetti-Underwood Programma 101 desk calculator.

III.2. Isotope Dilution Calculation for Strontium Analysis

The following discussion of isotope dilution calculation for strontium is similar to that outlined by Penner (1970) and Anderson (1974). The notations described by Anderson (1974, p.47) are listed below:

m = pertaining to the mixture of spike and sample,

such as the concentration of each isotope or
total strontium, the isotopic composition of
each isotope, or the isotopic ratio of an iso-
tope pair;

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,
in units of micromoles.

The calculations required in the calculation of
the atomic abundance of each of the four strontium isotopes
are from Anderson (1974, p.47-48). However, Anderson's
equations (7) through (10) contain an erratum. The denomi-
nator should read $(Sr/^{86}Sr)m$ and not $A/(^{86}Sr)m$. The equa-
tions are:

(4) $(^{84}Sr/^{86}Sr)m = \dfrac{(^{84}Sr)t + (^{84}Sr)s}{(^{86}Sr)t + (^{86}Sr)s}$

(5) $(^{84}Sr)s = 0.0056A$

(6) $(^{86}Sr)s = 0.0986A$

(7) $A = \dfrac{(^{84}Sr)t - (^{84}Sr/^{86}Sr)m(^{86}Sr)t}{0.0986(^{84}Sr/^{86}Sr)m - 0.0056}$

(8) $(Sr)m = A + (Sr)t$

(9) $(Sr/^{86}Sr)m = (^{84}Sr/^{86}Sr)m + (^{87}Sr/^{86}Sr)m + (^{88}Sr/^{86}Sr)m + 1$

(10) $(^{88}Sr/Sr)m = \dfrac{(^{88}Sr/^{86}Sr)m}{(Sr/^{86}Sr)m}$

(11) $(^{87}Sr/Sr)m = \dfrac{(^{87}Sr/^{86}Sr)m}{(Sr/^{86}Sr)m}$

(12) $(^{86}Sr/Sr)m = \dfrac{1}{(Sr/^{86}Sr)m}$

(13) $(^{84}Sr/Sr)m = \dfrac{(^{84}Sr/^{86}Sr)m}{(Sr/^{86}Sr)m}$

(14) $(^{88}Sr)s = (Sr)m(^{88}Sr/Sr)m - (^{88}Sr)t$

(15) $(^{87}Sr)s = (Sr)m(^{87}Sr/Sr)m - (^{87}Sr)t$

(16) $(^{86}Sr)s = (Sr)m(^{86}Sr/Sr)m - (^{86}Sr)t$

(17) $(^{84}Sr)s = (Sr)m(^{84}Sr/Sr)m - (^{84}Sr)t$

In the above calculations, equations (4) through (7) lead to the determination of the total concentration of strontium in the sample (A). In equations (5) and (6), the values 0.0056 and 0.0986 refer to the fractional isotopic composition of ^{84}Sr and ^{86}Sr in natural strontium, respectively. The total concentration of strontium in the mixture of spike and sample, (Sr)m, is determined from equation (8). The sum of the four isotope ratios present in the mixture, $(Sr/^{86}Sr)m$, is given by equation (9), where $(^{86}Sr/^{86}Sr)m$ is assumed equal to 1.0. Equations (10) through (13) lead to the calculation of the fractional composition of each strontium isotope in the mixture of spike and sample. The isotope concentration of $(^{88}Sr)s$, $(^{87}Sr)s$, $(^{86}Sr)s$, and $(^{84}Sr)s$ are determined by equations (14), (15), (16), and (17). The isotope ratios $(^{88}Sr/^{86}Sr)s$, $(^{87}Sr/^{86}Sr)s$, and $(^{84}Sr/^{86}Sr)s$ are obtained from the following calculations:

(18) $(^{88}Sr/^{86}Sr)s = (^{88}Sr)s/(^{86}Sr)s$

(19) $(^{87}Sr/^{86}Sr)s = (^{87}Sr)s/(^{86}Sr)s$

(20) $(^{84}Sr/^{86}Sr)s = (^{84}Sr)s/(^{86}Sr)s$

At this stage of data reduction, the determined isotope ratios of $(^{88}Sr/^{86}Sr)s$, $(^{87}Sr/^{86}Sr)s$, and $(^{84}Sr/^{86}Sr)s$ are approximate in value because neither the normalizing factor, to correct for isotopic fractionation, nor the "alpha" correction factor, to adjust the relative isotopic composition of the four strontium isotopes, has been applied. If the "alpha" correction factor is to be applied, it was applied at this stage of data reduction. If no "alpha" correction is necessary, the following procedure of applying the "alpha" correction factor was omitted, and the procedure of applying the normalizing factor was made directly.

The "alpha" correction is an adjustment of the isotopic composition of the relative isotope abundances of strontium in the sample, and this correction is applied to a sample that has a much larger than natural value of $(^{87}Sr/^{86}Sr)s$. Such a condition is present in rubidium-rich phases such as pegmatites, where the presence of radiogenic $(^{87}Sr)s$ is reflected in the larger than natural value of $(^{87}Sr/^{86}Sr)s$. The relative atomic abundance of $(^{86}Sr)s$ in the sample is a function of the $(^{87}Sr/^{86}Sr)s$ composition in the sample, since the other isotope ratios of $(^{88}Sr/^{86}Sr)s$ and $(^{84}Sr/^{86}Sr)s$ are invariant in nature. It was shown by Penner (1970, p.16) that the use of the "alpha" correction factor will increase the calculated total strontium concentration in the sample, and will significantly improve the calculated $(^{84}Sr/^{86}Sr)s$ value that is very sensitive to this correction. On the other hand, it will not affect the

calculated concentration of $(^{86}Sr)s$, and will only affect the $(^{87}Sr/^{86}Sr)s$ value very slightly.

The calculations required to apply the "alpha" correction factor are listed below.

(21) $(^{84}Sr)s = 0.0056$ (alpha) A

(22) $(^{86}Sr)s = 0.0986$ (alpha) A

(23) alpha $= \dfrac{(^{84}Sr/^{86}Sr)n+(^{87}Sr/^{86}Sr)o+(^{88}Sr/^{86}Sr)n+1.0}{(^{84}Sr/^{86}Sr)n+(^{87}Sr/^{86}Sr)s+(^{88}Sr/^{86}Sr)n+1.0}$

where,

$\quad (^{84}Sr/^{86}Sr)n = 0.0568,$

$\quad (^{88}Sr/^{86}Sr)n = 8.375,$ and

$\quad (^{86}Sr/^{86}Sr)n = 1.0,$

are the natural isotopic ratios in the sample;

$\quad (^{87}Sr/^{86}Sr)s$ = the determined preliminary value from

$\qquad\qquad$ equation (19), and

$\quad (^{87}Sr/^{86}Sr)o = 0.706,$ an arbitrary value.

The value of "alpha" obtained from equation (23) is substituted into equations (21) and (22). Equations (21) and (22) then are substituted into equation (7), and the calculations associated with equations (7) through (20) are repeated. From this iteration, a new set of adjusted values for the total concentration of strontium in the sample (A), and the sample isotope ratios $(^{88}Sr/^{86}Sr)s$, $(^{87}Sr/^{86}Sr)s$, and $(^{84}Sr/^{86}Sr)s$ are determined. More than one iteration of equations (7) through (20) may be required until two successive estimates of $(^{87}Sr/^{86}Sr)s$ are of equivalent value.

To correct for the variable degree of isotopic fractionation that occurs during mass spectrometric analysis, the application of the normalizing factor was used. The measured isotope ratios, $(^{88}Sr/^{86}Sr)m$, $(^{87}Sr/^{86}Sr)m$, and $(^{84}Sr/^{86}Sr)s$ are proportionally adjusted (i.e. normalized) to $(^{88}Sr/^{86}Sr)s$ = 8.375. The calculations required for the normalization procedure are listed below.

(24) $(88/86)N = 8.375/(^{88}Sr/^{86}Sr)s$

(25) $(^{88}Sr/^{86}Sr)m,N = (88/86)N \ (^{88}Sr/^{86}Sr)m$

(26) $(^{87}Sr/^{86}Sr)m,N = (1/2) \left[1.0 + (88/86)N \right] \ (^{87}Sr/^{86}Sr)m$

(27) $(^{84}Sr/^{86}Sr)m,N = \left[1.0/(88/86)N \right] (^{84}Sr/^{86}Sr)m$

In the above calculations, $(88/86)N$ is the normalizing factor that is determined uniquely for that particular strontium mass spectrometric analysis. In equations (25), (26), and (27), the three measured isotope ratios of the mixture of spike and sample are proportionally adjusted (normalized).

Equations (25), (26), and (27) are substituted into equations (7) through (13), and the overall calculation procedure from equations (7) through (20) was repeated. If the "alpha" correction factor was used, equations (21) and (22) are used instead of equations (5) and (6). The "alpha" factor determined above was used. If no "alpha" correction was used, equations (21) through (23), and the procedure associated with them, was omitted. If the "alpha" correction was used, the total concentration of strontium in the sample (A) was obtained from equations (7), (21), (22), and

(27). In addition, $(^{86}Sr)s$ was determined from equation
(22). The respective concentration values for A and $(^{86}Sr)s$
were divided by the sample weight used in the analysis. The
purpose was to standardize the concentration unit to micro-
moles/g. If no "alpha" correction was used, (A) and $(^{86}Sr)s$
were determined directly from equations (6), (7), and (27),
and from the sample weight used.

III.3. Calculation of the Radiogenic ^{87}Sr Content

Radiogenic ^{87}Sr content was calculated from
rubidium-rich samples, such as K-feldspar mineral concen-
trates from pegmatite samples, or from the NBS 70a K-feldspar
standard. The calculation used, was after York and Farquhar
(1972, p.31, 57), and is listed below.

$$(28) \quad (^{87}Sr)^*_s = (^{86}Sr)s \left[(^{87}Sr/^{86}Sr)s - (^{87}Sr/^{86}Sr)i \right]$$

where $(^{87}Sr)^*_s$ = concentration of radiogenic strontium in the
sample, $(^{86}Sr)s$ = concentration of ^{86}Sr in the sample;
$(^{87}Sr/^{86}Sr)s$ = determined sample ratio, and $(^{87}Sr/^{86}Sr)i$ =
initial ratio at the time of crystallization, assumed to be
0.710.

The concentration of $(^{86}Sr)s$ must be determined
before equation (28) can be used. Since the relative iso-
topic composition of ^{88}Sr: ^{86}Sr: ^{84}Sr is constant in
nature, the relative isotopic abundance of ^{86}Sr in the sample
is dependent upon the abundance of ^{87}Sr; the abundance of
^{87}Sr is reflected by the value of $(^{87}Sr/^{86}Sr)s$. Two
methods of similar result can be used to calculate the

relative isotopic abundance of ^{86}Sr, that in turn determines the concentration value for (^{86}Sr)s. To calculate the relative isotopic abundance (and concentration) of (^{86}Sr)s, equations (22) and (23) can be used. Alternatively, the relative isotopic abundance of ^{86}Sr can be determined directly from the isotopic composition of strontium in the sample. To illustrate both procedures, the pegmatite sample 966-1, a K-feldspar mineral concentrate, is used. For sample 966-1, the total strontium concentration is 72.1 ppm, and the (^{87}Sr/^{86}Sr)s ratio is 1.0393. Since the nonradiogenic isotopes of strontium are considered invariant in nature, then (^{88}Sr/^{86}Sr)n = 1.0. These three isotope ratios, plus that for (^{87}Sr/^{86}Sr)s are summed:

$$\sum = (8.375 + 1.0393 + 1.0 + 0.0568) = 10.4711.$$

The following tabular calculation was made to calculate the relative isotopic abundance of strontium and to calculate the atomic weight of strontium. The relative isotopic abundance of ^{86}Sr was found to be 0.0955 and the corresponding atomic weight of strontium was found to be 87.58.

Isotope	Relative Isotopic Abundance in Sample		Isotopic[1] Atomic Mass(amu)		Atomic Weight
^{88}Sr	8.375/$\sum$ = 0.7998	x	87.9056	=	70.3087
^{87}Sr	1.0393/$\sum$ = 0.0993	x	86.9089	=	8.6257
^{86}Sr	1.0/$\sum$ = 0.0955	x	83.9094	=	8.2043
^{84}Sr	0.0568/$\sum$ = 0.0054	x	83.9134	=	0.4397
	1.0000				87.5784

[1]Handbook of Chemistry and Physics, 49th edition, The Chemical Rubber Co., Cleveland, Ohio, (1968), p. B24-B26.

The concentrations of $(^{86}Sr)s$ was obtained from the following calculation:

(29) $(^{86}Sr)s$ = (abundance of ^{86}Sr) (Total common Sr)

$= (0.0955) (72.1 \text{ ppm}) = 6.886 \text{ ppm.}$

Alternatively, from equation (22), the "alpha" value for the sample was 0.9685. Substituting this value into equation (22), the concentration of $(^{86}Sr)s$ was also obtained.

(22) $(^{86}Sr)s$ = 0.0986 (alpha) A

$= (0.0986) (0.9685) (72.1 \text{ ppm})$

$= 6.886 \text{ ppm.}$

This value is identical to that determined above using equation (29). Substituting the values of $(^{86}Sr)s$ = 6.886 ppm, $(^{87}Sr/^{86}Sr)s$ = 1.0393, and $(^{87}Sr/^{86}Sr)i$ = 0.710 into equation (28), the radiogenic concentration of ^{87}Sr present in the sample then was calculated.

$(^{87}Sr)^{*}_{s}$ = 6.886 ppm (1.0393 - 0.710)

$= 2.268 \text{ ppm.}$

APPENDIX IV. MASS SPECTROMETRY

IV.1. <u>Description of the Mass Spectrometer</u>

The following description of the mass spectro-
meter is similar to that described by Penner (1970) and
Anderson (1974).

All isotopic measurements were made on a triple
filament thermal ionization solid source assembly, single
(direction) focusing mass spectrometer with a ten inch
radius of curvature and a ninety degree deflexion.

The ionization source assembly used was similar
to that described by Craig (1959). Picker nuclear beads
(style #297157) were used as filament beads. Two tantalum
sample filaments and one rhenium center filament were
welded to the posts of the Picker nuclear filament bead.
The dimensions of the filament material used was 0.030"
wide and 0.001" thick (H. Cross and Company). The prepared
filament beads were mounted in the source assembly with non-
magnetic stainless steel blocks. Separate ionization
sources were used for rubidium and strontium analysis.

The vacuum system consists of an oil diffusion
pump backed by an oil-sealed mechanical fore pump at the
source end, and a Varian Vac Ion Pump (50 liters/sec.) at
the collector end. On-line gates valves were used to iso-
late the collector end and oil diffusion pump from the

source end of the vacuum system for venting and changing samples.

Signal detection and amplification of the ion current was attained with a Cary Model 401 vibrating reed electrometer (VRE). The signal was recorded on a Leeds and Northrup Speedomax Model W/L ten inch strip chart recorder equipped with an expanded scale measurement recording circuit to integrate the VRE output with the chart recorder. The principle of operation of the expanded-scale has been described by Damon (1966, p.13) and Shields (1966, pp.11-13).

A Fluke high voltage power supply (Model 410B) was used to provide the voltage (D.C.) required for the "accelerating" voltage of the produced ion current in the ionization source assembly. The filament currents and vibrating reed electrometer were stabilized using a Sola transformer and a Sorensen voltage regulator.

IV.2. Operating Procedure

The filament bead to be used for either rubidium or strontium analysis was outgassed in the source region of the mass spectrometer for a period of 30 minutes. The side and centre filaments were outgassed by passing a current of 2.5 amp. and 5.0 amp., respectively.

The prepared sample to be analyzed, stored in a beaker, was taken into solution by adding a few drops of double-distilled water. A clean glass micropipette, that

was discarded after use, was used to transfer the sample slurry and solution to the surface of the outgassed tantalum side filaments. The sample was evaporated to dryness by passing an electric current of 1.8 amps.

The procedure of mounting the source was aided by the use of on-line gate valves to isolate the source region from the oil diffusion pump, the ion beam tube, and the collector end, where a constant vacuum was maintained. A mechanical roughing pump was used for rapid pumpdown of the source region. Once a pressure of 50 microns was attained, the on-line gate valve to the oil diffusion pump was opened, and the mechanical roughing pump was isolated. For removal of the source, the source region was isolated from the oil diffusion pump, the ion beam tube, and the collector end where a constant vacuum will be maintained. The source region was then vented with dry nitrogen to facilitate removal of the source from the source end.

After a pressure of 2.0 x 10^{-7} millimeters of mercury was attained in the source end by the oil diffusion pump, the sample was outgassed by passing a current through the side and centre filaments. A current of 0.1 amp. on the side filaments and 1.8 amp. on the centre filament was used to outgas rubidium samples, whereas 4.0 amp. on the centre filament was used to outgas strontium samples. Outgassing of the samples for 30 minutes was usually sufficient to ensure that the pressure in the source region was below 2.0 x 10^{-7} millimeters of mercury necessary for analysis.

During mass spectrometric analysis, magnetic peak switching was used to measure a set of isotope pairs.

During strontium analysis, the operating mode was to use: 1) an accelerating voltage of 4000 volts (D.C.); 2) filament currents between 0.1 and 0.5 amp. for the side sample filaments, and 3) a filament current between 4.5 and 5.5 amp. for the centre ionizing filament. For spiked strontium measurements, three separate sets between 10 and 12 scans of the isotope ratios, $^{88}Sr/^{86}Sr$, $^{87}Sr/^{86}Sr$, and $^{84}Sr/^{86}Sr$, were measured at expanded scale. The base line was scanned between each set of isotope ratios measured to monitor base line resolution of the isotope peaks, and to monitor the presence of any rubidium contamination that may be present. In addition, the base line was scanned before and after the measurement of the three sets of isotope ratios. The procedure for unspiked strontium measurements was similar to that outlined for spiked strontium measurements, with the exception that no measurement of the $^{84}Sr/^{86}Sr$ ratio was made.

For rubidium analysis, an accelerating voltage of 3500 volts (D.C.) was used. Filament currents between 0.3 to 0.7 amp. on the side sample filaments and between 1.8 to 2.2 amp. on the centre ionizing filaments were maintained. During a rubidium measurement, one set of 10 or 12 scans of the isotope pair $^{85}Rb/^{87}Rb$ was taken.

IV.3. Reproducible Analysis

The quality of analysis made by mass spectrometric

analysis often is influenced by a number of variable factors.
Controlling the variability of these factors where possible,
generally results in consistent and improved reproducible
data. The stability and sensitivity of ionic emission during
an analysis were dependent on such factors as: 1) the
quality of the prepared sample, 2) the consistency in the
manner of sample mounting onto the side filaments; 3) the
position of the side filaments relative to the centre fila-
ment, 4) the quality of vacuum maintained during analysis;
5) the degree of matrix effects; and, 6) the alignment of
the centre filament with the principal slit of the source
assembly.

By outgassing the sample before an analysis, the
risk of pressure surges during an analysis was minimized
and the pressure of the vacuum system was maintained con-
stant. Proper resolution between the isotope mass peaks
was maintained when the pressure was kept constant without
the system being subject to pressure surges.

Matrix effects were evident in rubidium analysis
because the sample was prepared as a residue. Care was
exercised while mounting the sample residue onto the side
filaments. If too much residue was mounted, the resulting
sample sensitivity generally was decreased. This would
necessitate a larger than average sample filament current.
In addition, the sample would remain gassy during analysis,
and the vacuum system often would be subject to pressure
surges.

Proper centre filament alignment with the principal slit of the source assembly was necessary in attaining a workable resolution between the isotope mass peaks. Good resolution was necessary for the resolution of the mass 87 peak from the mass 88 peak in strontium analysis.

IV.4. <u>Rubidium Contamination</u>

In strontium isotope analysis containing rubidium contamination (as recognized by the presence of the mass 85 peak), the standard correction procedure of assuming the isotope ratio of the contaminating rubidium to be of normal composition was used (i.e. $^{87}Rb/^{85}Rb = 0.385$). However, Pringle (1970) suggests that such a procedure is invalid because the isotope ratio of the contaminating rubidium is not of normal composition. This would be particularly evident if such contamination was caused by a "memory effect" of a previous spiked rubidium analysis. As a result, strontium isotope analyses were discarded if the contaminating rubidium contained 1) the presence of a spiked rubidium composition (i.e. a "memory effect"); 2) the presence of the mass 85 peak in a "growing" mode; and 3) the presence of ^{85}Rb greater than or equal to 1% of the measured mass 87 peak.