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RUBIDIUM-STRONTIUM MINERAL AND ROCK AGES AT SUDBURY, ONTARIO.

RUBIDIUM-STRONTIUM MINERAL AND ROCK AGES
AT
SUDBURY, ONTARIO.

BY

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A Thesis
Submitted to the School of Graduate Studies
in Partial Fulfilment of the Requirements
for the Degree
Doctor of Philosophy

McMaster University
September 1973

DOCTOR OF PHILOSOPHY (1973)
(Geology)

McMASTER UNIVERSITY
Hamilton, Ontario

TITLE: Rubidium-Strontium Mineral and Rock Ages at Sudbury, Ontario.

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NUMBER OF PAGES: 230, xviii

SCOPE AND CONTENTS:

Chemical and isotopic results have been used to calculate Rb^{87}/Sr^{86} and Sr^{87}/Sr^{86} ratios of both whole rock and mineral samples from the Sudbury Area of Northern Ontario. Using these ratios and the principles of radioactive dating, ages of various geologic events have been calculated.

These ages, along with results of other age dating and geologic studies in the area, are used to examine the origin and history of both the Nickel Irruptive and the Murray Granite. Finally, significant Rb-Sr mineral and whole rock ages from Sudbury and the geologic events they reflect are reviewed in chronological order and correlated with ages and events in adjacent areas.

ACKNOWLEDGEMENTS

Like many other geologists, the author is particularly indebted to numerous earlier and contemporary workers for techniques, information, ideas, and inspiration.

Robert H. McNutt acted as thesis supervisor and supplied much appreciated encouragement and criticism throughout the duration of the study.

Mike Marchand willingly provided invaluable help with X-ray fluorescence and data processing techniques.

Professors H. P. Schwarcz, C. J. L. Lock and J. H. Crocket served on my advisory committee and critically reviewed this manuscript. The kind help of all members of the Geology Department of McMaster University is cordially acknowledged. Amongst the many other people who also provided help and encouragement, the following deserve special mention. C. J. D. Adams - formerly of the University of Toronto, D. York, University of Toronto, J. V. Guy-Bray, T. Podolsky, and D. Phillips of the International Nickel Co., R. K. Wanless of the Geological Survey of Canada, and J. C. Cowan of Falconbridge Nickel Mines.

I would also like to acknowledge the warm hospitality of my uncle and aunt Mr. and Mrs. William Kelly of Azilda during the field work.

The International Nickel Company of Canada Ltd. and Falconbridge Nickel Mines Ltd. kindly gave permission and directions for sample collecting on their properties.

Financial support to the author was provided by an Ontario Government Fellowship and McMaster University.

Responsibility for any errors remains with the author.

ABSTRACT

Ages of rocks and minerals were calculated using a radioactive decay constant for Rb^{87} equal to 1.39×10^{-11} years $^{-1}$. They include:

(1) A norite whole rock isochron (15 samples) of 2,015 ± 64 m.y. (Ri = .7062 ± .0003). This is interpreted as representing the original intrusive age of the nickel irruptive.

(2) A micropegmatite whole-rock isochron (10 samples) of 1,680 ± 31 m.y. (Ri = .7083 ± .0007). Geologic evidence indicates that this represents a metamorphic age.

(3) Sub-layer whole rocks (5 samples) fall on a norite reference isochron.

(4) A Murray granite whole-rock errorchron (18 samples) of 2,257 ± 44 m.y. (Ri = .7171 ± .0043). The scatter of data points is probably geologic in origin, caused by open system metamorphism. The age is believed to be a minimum age for the Murray granite.

(5) A Murray granite whole-rock isochron (3 samples from the southeast portion) of 2,286 ± 29 m.y. (Ri = .7269 ± .0049). This may be the true age of the Murray granite.

(6) A Murray offshoot (granitic dikes which intrude the norite) whole rock errorchron of 1,798 ± 27 m.y. (Ri = .7122 ± .0013). The significance, if any, of this is uncertain. However, metamorphism definitely seems to have been involved.

(7) North range biotite-whole rock ages (1,620 - 1,820 m y.) are definitely older than those found on the south range (1,000 - 1,430 m.y.). These ages probably represent the time of uplift and cooling in their respective areas. Geologic evidence indicates that the south range has been uplifted relative to the north and these ages show that the uplift must have been after the Penokean orogeny.

(8) Potassium feldspar-whole rock ages from the Murray granite (1,281 - 1,324 m.y.) and Murray offshoot 1 (1,419 - 1,429 m.y.) are consistently higher than for coexisting biotites. The significance, if any, of these ages is not clear, but their consistency suggests that they may represent real events.

Comparison of these ages with results from other geochronologic and geologic studies affords a more complete picture of the geologic history of the Sudbury area. The Penokean orogeny appears to be the dominant feature in the Eastern Southern Province including the Sudbury Basin.

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Chapter 1 Introduction

> "... Obviously there are no well qualified students of Earth, and all of us in different degrees, dig our own small specialised holes and sit in them."
>
> Bullard 1960, p.92
> (quoted in Stacy 1969, vii)

It is important to remember that geochronologic studies do not always provide simple, unique answers. Depending on the methods used and the history of the samples analysed, they may also give criteria for accepting or rejecting certain hypotheses and/or ambiguous and inconsistent results. Needless to say careful isotopic and geologic interpretation is necessary during all phases of study.

1 - 1 Radioactive Dating and the Concept of Time

> "It (time) resists direct characterization in general terms and is involved in so many diverse disciplines that a complete and unified analysis based on these is all but impossible."
>
> Jones, 1973, p.599.

It is not the purpose of this study to discuss the numerous definitions, descriptions, and paradoxes of time which can be found in the fields of literature, philosophy, physics, and geology. However, an outline is presented in Table 1-1 which shows the relationship between geologic (serial) and isotopic (absolute) time.

Basic principles and equations of radioactive dating

TABLE 1 - 1 Time

	Geological (serial-time)	Isotopic (Absolute-time)
Tools	- field mapping - correlation	- measurement of certain radioactive decay schemes (i.e. parent and daughter nuclides)
Underlying principles	- law of superposition - law of cross cutting relationships	- law of constant rate of nuclear decay - law of statistical randomness of decay
Assumptions	- ability to correlate - ability to determine tops of units	- closed system behavior - initial abundance and uniformity of daughter nuclide
Ideal Conditions- (limited in nature) (limited in information obtainable)	definitive cross cutting relationships, chilled contacts, etc.	- equal ages from different dating schemes - true age
Non ideal Conditions. A) reject data B) multiple interpretations	- deformed and altered contacts - ambiguous field relationships - incorrect correlations	- open system behavior - incorrect assumptions - experimental error and measurement limitations

with respect to rubidium and strontium isotopes are presented briefly in Appendix A. More comprehensive treatments are given by Faure and Powell (1971) for rubidium-strontium and Dalrymple and Lanphere (1969) for potassium-argon.

Two values for the decay constant (or half-life) of radioactive Rb^{87} have been widely used (Table 1-2). Both values have their own merits and supporters. In this study, all ages have been calculated or recalculated using the 1.39×10^{-11} year $^{-1}$ or "geological" decay constant. This permits direct and simple comparison with most of the other rubidium strontium ages reported from Sudbury and adjacent areas.

An attempt has been made to apply the meaning of Aldrich et al. (1965, p.455) to the term 'age' in this study. This is simply the value of t calculated from the dating equation

$$t = (1/\lambda) \ln (1 + D/P)$$

where P is the present-day concentration of parent atoms, D is the concentration of radiogenic daughter atoms, and λ is the decay constant.

Some readers may wish to skip or skim quickly over the following chapter on analytical procedures, but all readers should keep in mind the following comment of Livingston (1968, p.6) when reading the results and discussion of this study.

TABLE 1 - 2 Rubidium -87 Decay Constants

Rb -87	Value	Method	Reference*
geological - λG	1.39×10^{-11} year $^{-1}$	Comparison with U-Pb or K-Ar dates of co-existing minerals	Aldrich et al. 1956
experimental λE	1.47×10^{-11} year $^{-1}$	1) Direct measurement of the specific beta-activity of Rb^{87}	Flynn and Glendenin 1959
		2) Measurement of the amount of Sr^{87} produced from a known quantity of Rb^{87} during a known time interval	McMullen et al. 1966

Conversion factor: age (λE) X 1.058 = age (λG)

*References are given in Faure and Powell (1972)

> "Rocks, however, are complicated systems and usually have experienced a complex series of events. It seems reasonable to believe that rocks have histories, not simply ages."

1 - 2 Purpose of Study

This study was begun with the general aim of making a critical up to date review of earlier Sudbury geochronolgy, obtaining additional age data using new samples and mineral and whole rock isochron techniques, and attempting to recognize and examine metamorphic events by means of their effect on rubidium and strontium isotopes. Several more specific objectives include:

1) an attempt to obtain a Rb-Sr whole rock isochron, using only norite samples from the nickel irruptive, in order to substantiate Souch and Podolsky's (1969) suggestion that the norite may be 2.0 b.y. (billion years) old

2) a test to see if and/or how the petrographic units within the norite, reported by Stevenson and Colgrove (1968) and Naldrett et al. (1970), differ in rubidium and strontium concentrations

3) an attempt to date the ore bearing "sub-layer" material

4) confirmation of the pre-nickel irruptive age of the Murray granite with a Rb-Sr isochron and examination of Fairbairn et al.'s (1965) suggestion that certain granite dikes, which intrude the norite and appear to have been formed by remobilization of the Murray granite, should give an age essentially

the same age as the norite.

1 - 3 The Importance of the Sudbury Area

The Sudbury District of Ontario is the world's greatest producer of nickel. All of the ore bodies, including some of the world's largest and richest individual deposits, occur within 25 miles of the City of Sudbury and are intimately associated with a layered complex of igneous rocks commonly referred to as the "nickel irruptive". In addition to nickel, an approximately equal tonnage of copper is produced and twelve additional elements are recovered as by-products. In over 80 years of mining, the value of production has passed 11 billion dollars and made a significant contribution to local, provincial, and national economies.

1 - 4 Introduction to the Geology of the Sudbury Basin

The Sudbury basin is defined and dominated by a large layered mafic intrusion, which is frequently referred to as the nickel complex or the nickel irruptive (Figure 1-1). Rocks of the irruptive outcrop in an elliptical ring 37 miles long and 17 miles wide, the width of the outcrop varies from one to four miles. The elliptical nature of the irruptive can be seen in the ring of hills formed from its resistant rocks and the distribution of mineral deposits and prospects along its outer margin. In most places the rocks and outer contacts of the irruptive dip steeply towards the center of

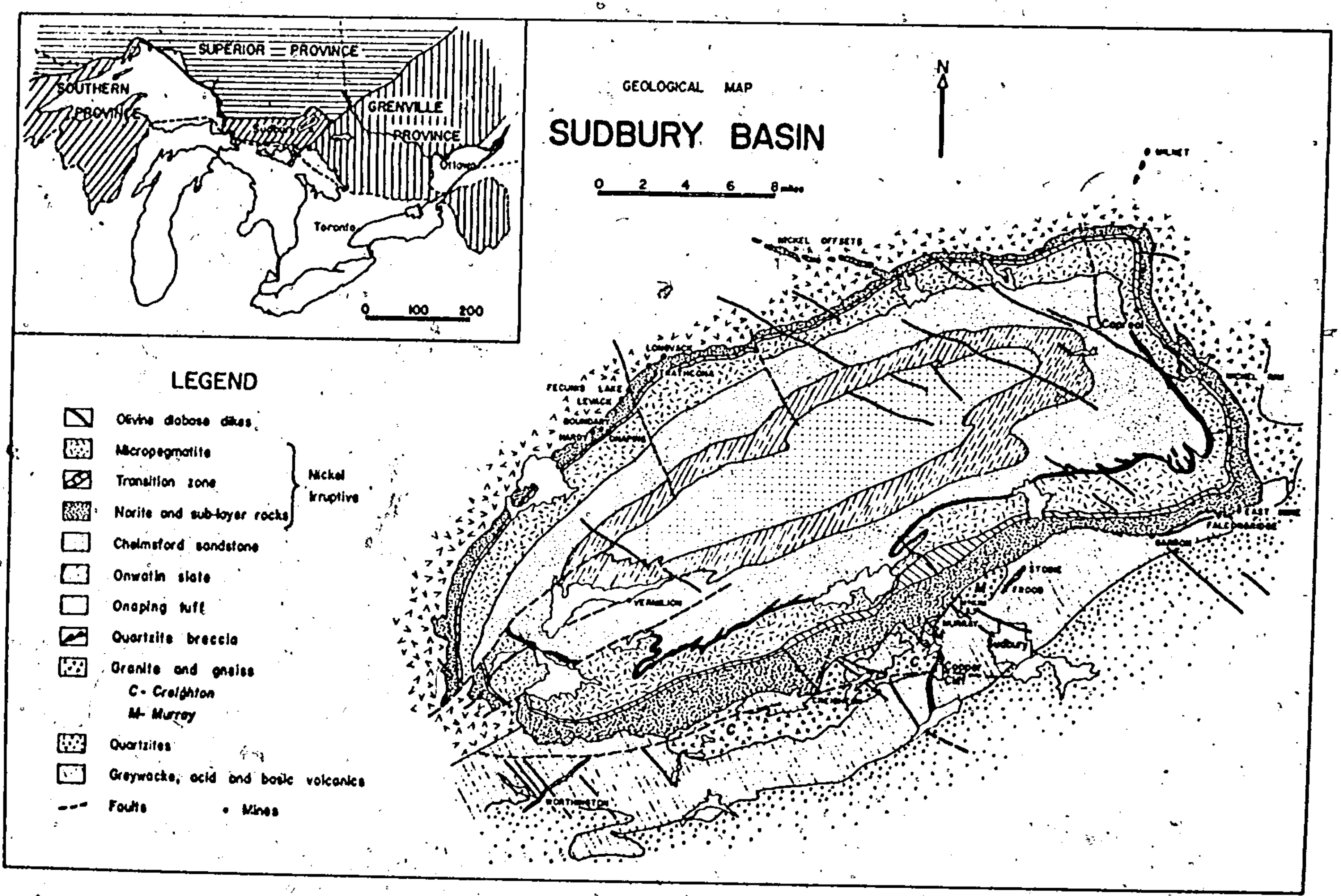
SUPERIOR PROVINCE
SOUTHERN PROVINCE
GRENVILLE PROVINCE
Ottawa
Toronto
0 100 200
GEOLOGICAL MAP
SUDBURY BASIN
N
0 2 4 6 8 miles
LEGEND
Olivine diabase dikes
Micropegmatite
Transition zone
Norite and sub-layer rocks
Nickel Irruptive
Chelmsford sandstone
Onwatin slate
Onaping tuff
Quartzite breccia
Granite and gneiss
C - Creighton
M - Murray
Quartzites
Greywacke, acid and basic volcanics
Faults
• Mines
MILNET
NICKEL OFFSETS
LONGVACK
STRATHCONA
FECUNIS LAKE
LEVACK
BOUNDARY
HARDY
ONAPING
Capreol
NICKEL RIM
EAST RIM
FALCONBRIDGE
GARSON
STOBIE
FROOD
VERMILION
MURRAY
Sudbury
Copper Cliff
CREIGHTON
WORTHINGTON
C
M

Figure 1 - 1

the basin (30-90 degrees). However, despite information from deep mining and drilling, we have little more than a two dimensional picture of the irruptive. Its true shape and original size can only be inferred. It is commonly believed to be funnel-shaped.

The irruptive itself can be divided into a lighter (sialic) upper layer called micropegmatite and a lower heavier and darker (mafic) layer called norite. Almost all of the ore occurs in inclusion rich breccias or quartz diorite known as "sub-layer". This occurs discontinuously around the base of the irruptive and in "offsets" - dikes which extend out into the surrounding rocks.[1]

Outside the basin, the irruptive is entirely surrounded by older rocks often called "foot-wall rocks." These include the earliest "basement" granites and gneisses to the north and steeply dipping Huronian meta-sedimentary and meta-volcanic rocks (Table 6-3) and the Creighton and Murray granites to the south. Sills, dikes, and irregular bodies of gabbro and diabase intrude and are deformed and metamorphosed along with the Huronian Series. These rocks are called Sudbury gabbro and are believed to be equivalent to the Nipissing diabase. All rock types surrounding the irruptive may be brecciated and some may contain shatter-cones.

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1. The irruptive and its petrology are discussed at length in Chapter 3.

A conformable sequence of sediments, the Whitewater Group, occurs above the irruptive in the centre of the Sudbury basin. They outcrop in concentric rings beginning with the lowermost Onaping formation, which has been called both a volcanic tuff and a fall back breccia, up to the Chelmsford formation which fills the center of the basin. No Whitewater Group rocks have ever been recognized outside the basin. Late WNW trending olivine diabase dikes cut all other rocks in the area.

Tectonicly the Sudbury basin lies in a unique position near the junction of three structural and age provinces (the Superior, Southern, and Grenville), two regional fault systems (the Murray and Onaping), and close to a third major tectonic discontinuity (the Grenville Front)(Figure 1-2). The basin itself is divided along its long axis by a series of faults related to the Murray fault system. Various effects of the Penokean Orogeny are widespread in most rocks of the south range (south half), which is believed to have been uplifted at least three miles relative to the north range.

1 - 5 A Review of Selected Studies of Sudbury Geology

This section is intended as a guide to the reader interested in more specific aspects of Sudbury geology. Many of of these are included in "New developments in Sudbury Geology", Geological Association of Canada Special Paper Number 10, 1972 edited by J.V.Guy-Bray.

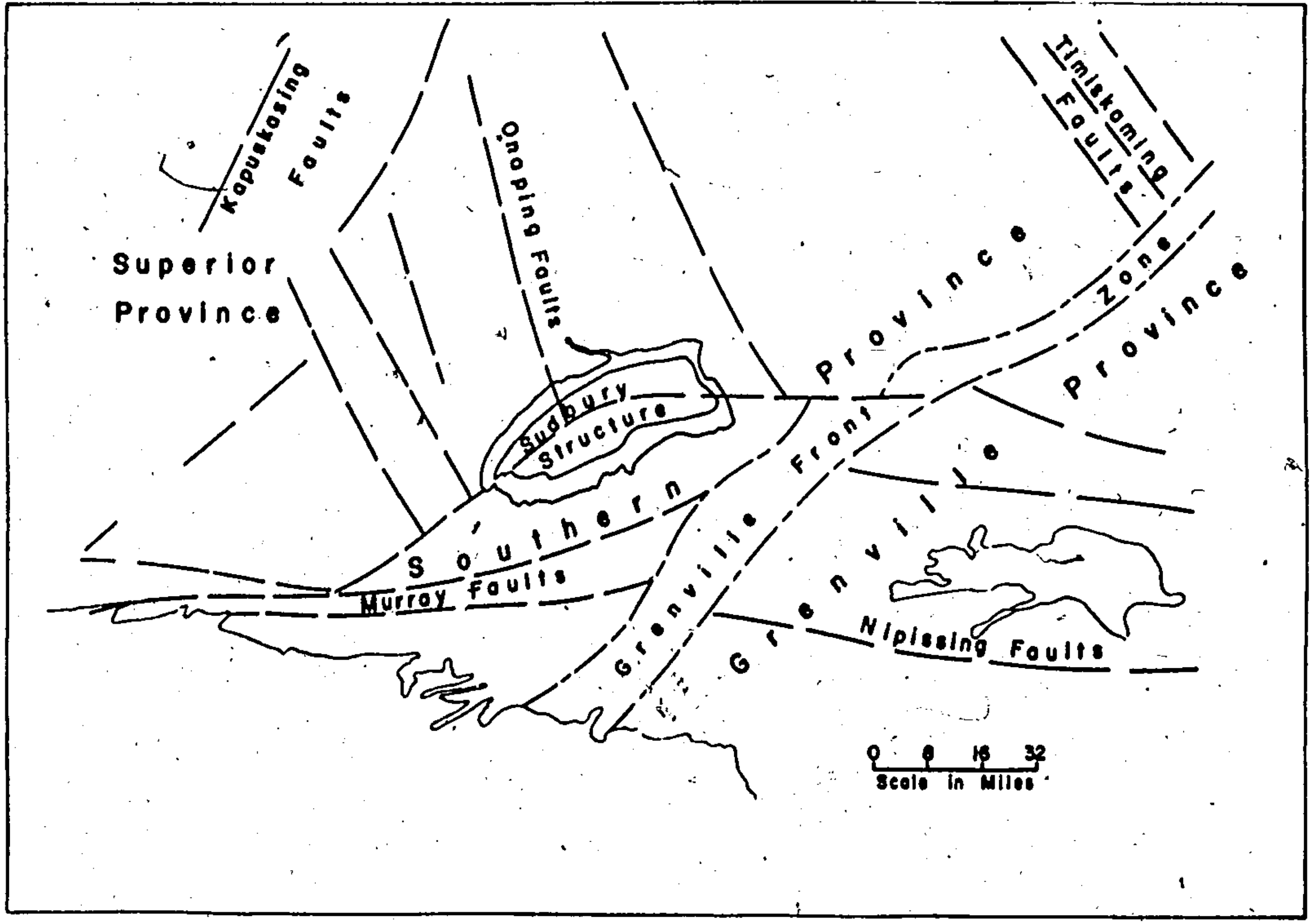

Figure 1-2 Location of the Sudbury structure with respect to structural province boundaries and major fault systems.

(from Card and Hutchinson, 1972)

Two classic works. W.H.Collin's 'Life History of the Sudbury Nickel Irruptive (1934, 1935, 1936 and 1937) and J.E.Hawley's 'The Sudbury Ores: Their Mineralogy and Origin' (1962) remain very clear and worthwhile reading. The pioneering studies of A.P.Coleman (1905-1913) and the first detailed petrographic study of the irruptive by T.C.Phemister (1925) are also worthy of note.

The best and most recent map available is Ontario Department of Mines Map 2170 - Sudbury Mining Area (1969). Several useful guide books which deal with Sudbury geology have recently become available. They include: Naldrett et al. (1971), Guy-Bray and Peredary (1971), Card and Robertson (1972), and Dence et al. (1972).

1 - 5 - 1 The Nickel Irruptive

The nickel irruptive is discussed in detail in Chapter 3. Following the work of Collins and others, Stevenson and Colgrove (1968) defined petrologic variations between and within north and south range norites. These units were confirmed by Naldrett et al. (1970), who also demonstrated cryptic variation and layering in the norite, using electron microprobe analyses of pyroxenes and plagioclase.

Souch and Podolsky et al. (1969) described the ore bearing "sub-layer" phase of the irruptive, and a detailed study of north range sub-layer and mafic norite has been made by Hewins (1971).

A recent summary of the geology of the nickel irruptive has been given by Naldrett et al. (1972 a).

1 - 5 - 2 The Murray Granite

The Murray granite is the subject of Chapter 4, which contains new geologic and geochemical data as well as geochronologic results. Usually the Murray granite has been studied in conjunction with the somewhat similar Creighton granite. Speers (1956) discussed the paradox of Murray granite-like dikes which intrude the irruptive and others which are cut by the irruptive and resolved it by recognizing two ages of Murray granite.

1 - 5 - 3 Structure, Metamorphism and Stratigraphy

Card et al. (1972a) review the structural geology and metamorphism of the Southern Province of the Precambrian Shield, including the Sudbury area. Brocoum and Dalziel (1973) emphasize the importance of the Penokean Orogeny in this area. Identification and correlation of isotopic ages with geologic events is presented in Chapter 5 for mineral ages and Chapter 6 for whole rock isochron ages.

Huronian stratigraphy and sedimentation (Table 6-2) are thoroughly reviewed by Young and Church (1966), Roscoe (1969), and Frarey and Roscoe (1970). Recent studies in the Whitewater series suggest that the Onaping formation represents a "fall back" breccia and related breccias (Peredery 1972) and the Chelmsford sandstone a proximal turbidite sequence deposited along the axis of a south-southwest dipping trough (Rousell 1972, Cantin and Walker 1972).

1 - 5 - 4 Geochronology

The first important isotopic age results from the Sudbury area were the K-Ar and Rb-Sr mineral and whole rock ages of Fairbairn et al. (1960) In later studies (Fairbairn et al., 1965, 1968, and 1969), they adopted the isochron method and extended their work. They were able to determine several metamorphic ages and relate them to the geology and demonstrate the effect of the metamorphism on various mineral and whole rock systems.

They obtained a 1,700 m.y (Ri = 0.7052) isochron from five micropegmatite and one norite whole rock samples from the north range, which they interpreted as the age of the nickel irruptive. Two north range norite samples reported by Souch and Podolsky et al. (1969) and Fairbairn et al.'s single norite fall along a line with a slope equal to 2,000 m.y. . This is in fairly good agreement with a minimum age of 1,900 m.y. they obtained from Pb^{207}/Pb^{206} ages of two zircon concentrates from south range norite and sub-layer. New irruptive data and ages are presented in Chapter 3.

1 - 5 - 5 Geophysics

Gravity and magnetic interpretation in the Sudbury area suggests that the main body of norite extends to a depth of 9 km. on the north range (i.e. north of the Fairbank Lake fault), whereas it probably extends to a depth of less than 5 km on the south range (Popelar 1972).

Paleomagnetic studies suggest that the norite acquired the major component of its remnant magnetization during original cooling (Sopher 1963, Larochelle 1969). A difference of 40 degrees in the mean direction of magnetism of north and south range norites is probably due to deformation of the basin.

1 - 5 - 6 The Meteorite Impact Theory

Deitz (1964) was the first to propose that the Sudbury basin is an astrobleme or meterorite impact structure. He used the distribution of breccias, overturned sediments and recognition of shatter cones as evidence. Additional evidence comes from Bray et al.'s (1966) work showing that the apices of most of the shatter cones point towards a common (explosion) center above the middle of the basin. French (1967, 1972) recognized a wide variety of shock-metamorphic features in the Onaping formation which overlies the irruptive as well as additional evidence in the relatively unmetamorphosed footwall rocks around the perimeter of the basin on the North range. Comparison of the Sudbury structure with other large meteorite impact craters is also convincing evidence (Dence 1972).

Card and Hutchinson (1972) compare the Sudbury irruptive with other differentiated mafic intrusions of well established terrestrial origin. They also point out the unique regional structural setting of the Sudbury basin, however, this argument is countered by pointing out that most of these structural elements developed after the impact. Lake Wanapitei at the northeast corner of the basin also appears to be a meteorite crater. This is the only known terrestrial example of a smaller impact impressed on a larger one (Dence et al, 1972) and makes the area even more unique.

The meteorite impact theory had always included a terrestrial origin for the silicate phase of the irruptive. However, some of its proponents, notably Dietz (1972), argue for an extra-terrestrial origin for some if not all of the ore material. This is called his "not only 'pennies from heaven,' but nickels as well" theory.

Chapter 2 Analytical Procedures

2 - 1 Sample Collection and Preliminary Preparation

2 - 1 - 1 Sampling Strategy

Preliminary work involved making a careful review of of pertinent published studies and holding discussions with people familiar and actively involved with Sudbury geology. Discussions with T.Podolsky and J.V.Guy-Bray led to the decision to study the Murray granite and associated dikes which intrude the norite. Subsequently it was discovered that C.J.A.Adams, then at the University of Toronto, was also studying the Murray granite and we combined efforts on the Murray granite study (Gibbins, Adams, and McNutt 1972). Discussions with A.J.Naldrett and J.V.Guy-Bray indicated that the Blezard and Strathcona (Levack) sections, of the south and north range respectively, offered the best combination of accessibility, exposure, fresh and typical material, as well as permitting direct correlation to Naldrett et al.'s (1970) detailed mineralogic and petrologic studies. Five sub-layer or ore bearing zone samples from the Murray and Copper Cliff North mines of the south range were collected and donated by R.H.McNutt.

2 - 1 - 2 Field Collection

Except for the sub-layer samples mentioned in the last section, all samples were personally collected in the field by the writer. A six pound sledge and two 1 1/2 pound geological hammers were used to break, pry apart, and trim samples. Emphasis was placed on obtaining large samples (10-30 lbs.) of fresh, representative material at each sample locality. Preliminary trimming away of weathered and joint surfaces was begun in the field and completed in the laboratory before crushing.

Brief descriptions of all samples and their locations are given in Appendix D. Locations are also shown in Figures, 3-3, 3-4, 4-1, 4-2, 4-3, and 4-4.

2 - 1 - 3 Laboratory preparation and crushing.

Once a sample was trimmed of all weathered material, it was broken up by sledge and hydraulic rock splitter, and fed into a self, pre-contaminated steel jaw crusher until a volume of approximately 1 1/2 pints (500-750 gm. of granite or 600-900 gm. of norite) of rock less than 1" x 1/2" x 1/4" in size was obtained and then reduced to less than 200 mesh by grinding 50-60 gm. portions for 10 minutes each in a tungsten carbide "Shatterbox" (Spex Industries Ltd., New Jersey). The ground sample was then homogenized by rolling on glazed paper for 10 to 15 minutes, split by combining opposite quarters, labelled, and stored for analyses. The uncrushed portion of the sample was stored for later use (i.e. thin section, mineral separation.)

2 - 1 - 4 Mineral Separation

Mineral separates were prepared by using the shatterbox for short periods (less than 30 seconds), and seiving through disposable 100 and 200 mesh nylon seives. The less than 200 mesh portion was discarded, 100 - 200 mesh was washed free of fines with distilled water and collected, and material coarser than 100 mesh recycled. Conventional separation techniques were used. A hand magnet was used to remove any magnetite and pyrrhotite, then a Frantz isodynamic separator was used to separate the more magnetic mafic minerals from quartz and feldspars. Several passes at slightly different current and slope settings effectively separated composite mineral grains from the concentrates. Next a heavy liquid (tetra bromoethane adjusted with acetone to the required specific gravity) was used to float off potassium feldspar or sink fluorite and zircon from the non magnetic concentrate. After further magnetic treatment, biotites were separated from concentrates of intermediate magnetic susceptibility using their tendency to slide slowly rather than roll quickly down inclined sheets of paper. Descriptions of the mineral separates given in Appendix D, Table D-2.

2 - 2 X-ray Fluorescence

2 - 2 - 1 Introduction

The X-ray fluorescence unit used consists of a Phillips manual 1540 spectrometer supplied with power by a PW 1010 60 KV., 1.6 Kw generator. Typical operating conditions used are given in Table 2-1. Pressed powder pellets were made by thoroughly mixing 3.0 to 3.5 gm. of sample with 2 or 3 drops of Moiwal (an organic binding agent), loading in a 1 1/4" diameter steel die, & adding a boric acid backing for strength. The die was subjected to 10 tons of pressure for 2-3 minutes in a hydraulic press.

Preliminary qualitative X-ray fluorescence analysis of pressed powder samples was made by scanning with a chart recorder a range of 2 θ values including Rb and Sr K_α peaks. This was done for three reasons: (1) to identify and select samples with the greatest spread in Rb/Sr values, (2) to determine approximate concentrations of Rb and Sr so that the optimum amount of spike solution can be added for isotope dilution analysis, and (3) to check the base line for the presence of interfering peaks which may affect the more rigorous analysis described below.

Quantitative determination of Rb/Sr, Rb, and Sr is described in the next two sections. A more exhaustive description of the analytical methods used at McMaster is given by Marchand (1973).

2 - 2 - 2 Rb/Sr Determination

The Rb/Sr ratio of all whole rock and feldspar samples were determined using an improved version of the method of Doering (1968). On a given day, peak positions and P.H.A. settings were checked, then NBS 70 a (potassium feldspar) and five U.S.G.S. whole rock standards (G-2, GSP-1, AGV-1, W-1, and BCR-1) were measured. This data was corrected for dead time

TABLE 2 - 1 Operating Conditions for X-Ray Fluorescence

Primary radiation:	Molydbenum
X-ray generator:	50KV. 30 ma.
Analysing crystal:	LiF (200) d = 4.028 A
Detector:	Scintillation counter - .82KV (1.95 scale divisions)
Collimator:	fine
Attenuation:	Z = 3
Sample spinner:	on
Counting time:	100 seconds

Peak positions:		Pulse height analysis settings (window = 12 V.):	
Peak	2θ (degrees)	Threshold Setting	Center of peak
Mo Compton	21.22	21.90	27.90
Background 1	24.37	17.50	23.50
Sr K_α	25.10	16.60	22.60
Background 2	25.84	16.05	22.05
Rb K_α	26.57	15.50	21.50
Background 3	27.17	15.00	21.00

TABLE 2 - 2 Values Used for X Ray Fluorscence Standards

Standard	Rb/Sr	Rb ppm	Sr ppm	Reference
NBS 70a (K-feldspar)	8.0000	531	66.2	(4)
G - 2 (granite)	0.3563	171	480	(1)
GSP - 1 (granodiorite)	1.0766	253	235	(1)
AGV - 1 (andesite)	0.1039	69	664	(3)
W - 1 (diabase)	0.1181	22.1	187.2	(2)
BCR - 1 (basalt)	0.1456	48.2	331	(1)

References:
(1) Fairbairn and Hurley (1971 - Table 5 "preferred values" ID and XRF
(2) Heier and Compston (1969) - Table 2 XRF
(3) Flanagan (1969)
(4) Compston et al. (1969) - Sr from XRF P. 756
Rb/Sr - average of (1) and (4)

(Gunn 1969) and background and then subjected to a least square linear regression treatment which computes an approximation of the calibration curve, i.e. ln(Rb/Sr) correct = slope x ln(Rb/Sr)x-ray + intercept. The slope is approximately 1 and the intercept very close to zero for a good set of data. Normally the 6 standards and 20 to 25 unknowns (including duplicate analyses of one of the standards) were analysed on a given day. A pure SiO_2 pellet was analysed 2 or 3 times to improve the background correction and all pellets have been analysed at least five times. The values used for x-ray fluorescence standards are given in Table 2-2.

Rb/Sr_{weight} values determined (by XRF) can be converted to $(Rb^{87}/Sr^{86})_{atomic}$, if we know $(Sr^{87}/Sr^{86})_{atomic}$, by using the equation:

$$(Rb^{87}/Sr^{86})_{atomic} = (Rb/Sr)_{weight} \times .2855 \times (9.43+(Sr^{87}/Sr^{86})_{atomic})$$

This equation is derived in Appendix A-5.

2 - 2 - 3 Rb and Sr Concentrations by XRF

By adding the molybdenum Kα Compton peak to those measured in the last section, the principles of Reynolds (1963) can be used to determine the concentration of Rb and Sr. He showed that for most common rocks and minerals, the mass absorption coefficient (μ) is linearly related to the reciprocal of the intensity of the Compton scattered Mo primary peak (I_{MoC}). As concentration of (x) is proportional to (I_x/I_{MoC}), a plot of (peak counts/Compton counts) vs. p.p.m. of several standards can be used to determine Rb + Sr in unknowns. (Powell et al, 1969, Marchand, 1978).

The concentrations of Rb and Sr in all whole rock and feldspar samples have been determined using this method (Table 2-9). Reynolds suggested that errors should be within ± 3%, comparison of Sr concentrations in potassium feldspars analysed by both isotope dilution and Compton peak scattering (Table 2-5) suggests this is a maximum error as most of the data show much closer agreement.

Less precise calculations of Rb and Sr concentrations can be made without measuring additional peaks. Moorbath et al. (1972) assumed background intensities to be inversely proportional to mass absorption coefficients. They consider their error to be ± 10%.

2 - 3 Chemical Preparation of Samples

2 - 3 - 1 Reagents

Reagents used include water, hydrochloric acid, nitric acid, hydrofluoric acid, perchloric acid and methanol.

Distilled demineralized water was prepared by passing "tap distilled" water through a mixed bed ion exchange resin (Barnstead Bantam Demineralizer Still).

Reagent grade HCl and HNO_3 were purified by mixing in 1:1 proportion with D.D. H_2O and collecting the first 75% from a vycor distillation apparatus. The normality of HCl was monitored with a specific gravity hydrometer.

Double vacuum distilled $HClO_4$ (70%) manufactured by the G.Fredrick Smith Chemical Co., 'Baker Analyzed' HF (48-50%), and Matheson Coleman and Bell spectroquality methanol were used.

2 - 3 - 2 Dissolution of Samples

Samples weighing from 100 mg. to 1 gm. were carefully weighed into 100 ml. teflon evaporating dishes on a five place Mettler single pan balance. A carefully weighed amount of spike solution was also added to samples to be used for isotope dilution analysis. (See appendix B for use of spike solutions).

The dishes were covered with teflon lids and transferred to the steam bath under the fume hood. To prevent cross contamination and eliminate spattering (samples were treated in batches of six), each sample was individually uncovered and wetted with a few drops of D.D. H_2O (distilled demineralized water), before addition of 25 ml. of HF and 3 ml. of $HClO_4$. The samples were covered, allowed to digest on the steam bath for a minimum of 8 hours, uncovered and evaporated to a perchlorate mush. About 25 mls. of D.D. H_2O were added to dissolve any insoluble fluorides, and again evaporated to a perchlorate mush. Next 25 ml. of 6 N HCl was added, the dish covered and allowed to reflux for a half hour, uncovered and evaporated to the last perchlorate fumes, removed from the steam bath and cooled. The sample was then treated with 5 - 15 ml. of spec pure methanol to remove most of the alkalies as an insoluable precipitate. Each sample was transferred to a centrifuge tube, centrifuged, the supernates poured into a 35 ml polyethylene "dispo" beakers, treated with 10 ml. of 6 N HCl, and evaporated to a volume of 5 ml.. If a radioactive tracer (i.e. Sr^{89}) was to be used, one or two drops of dilute tracer solution was added at this stage. The sample was then diluted with D.D. H_2O to a volume of 10 mls, ready to be loaded on ion exchange columns.

2 - 3 - 3 Ion Exchange Columns

Six 1.5 cm. inner diameter vycor glass columns, fitted with pinch cocks and 600 ml. polyethylene reservoirs were used. The columns consist of 20 cm. of sized (200-400 mesh) Dowex 50-X-12 cation exchange resin supported by a glass wool plug.

Each sample was added to the ion exchange column in a 10 ml. solution of 3 N HCl. Special care was taken not to disturb or stirr up the top of the resin. When the sample was completely absorbed on the column, a 10 ml. aliquot of 3 N HCl was added in a similar fashion and repeated three more times. After this initial 50 ml. passed through, the column was eluted with 200 ml. of 3 N HCl. Using the Sr^{89} tracer, the position of Sr in the column could be monitored with a Geiger counter. However, once the columns were calibrated, the tracer became unnecessary. When eluted with 3 N HCl, Sr came off in the 225 to 325 ml. portion and was collected in 30 ml. disposable polyethylene beakers. After elution, the columns were washed with 500 ml. of 6 N HCl and re-equilibrated with 50-100 ml. of 3 N HCl.

For each sample, the beakers containing the most strontium (radioactivity) were evaporated under infra-red heat lamps, combined, transferred to a small vycor beaker and evaporated to dryness. This residue was then treated with a few drops of $HClO_4$, evaporated to dryness and brought to red heat in a Meeker burner flame, to destroy any resin or other organic matter. The samples were cooled, converted to nitrate by a few mls. of 1:1 HNO_3, evaporated to dryness, cooled, covered with parafilm, re-labelled and stored for loading on the Ta filament.

2 - 3- 4 Filament Preparation

Filaments were prepared by welding .001" x .020" tantalum ribbon to the center posts of filament beads (A.E.I. style 237157). A small amount of a powdered Ta metal - Ta_2O_5 slurry was spread evenly on the center of the filaments. Then the single filament beads were degassed and decontaminated by passing 1.0 - 2.0 amperes of current through each filament for 1 hour, while under vacuum in a Varian PS 10 pumping station.

Chemically processed samples were dissolved in a small drop of 1:1 HNO_3 and loaded onto the center of a filament by means of a pyrex glass capillary pipette. A small current (~1 amp.) was passed through the filament to evaporate the sample, which was then ready to be loaded on the mass spectrometer.

2 - 3 - 5 Isotope Dilution

If one has a known amount of a sample containing an quantity (x) of an element and the natural ratio of two isotopes of that element is R_x, one can obtain a "spike" (an artificially prepared quantity of the element which is enriched in the isotope depleted in the natural element) of known isotopic ratio R_s, and add a known amount of it (s) to the unknown. Then the following equation holds:

$$x\ R_x + s\ R_s = (x + s)\ R_{MIX}$$

As R_{MIX} can be measured on a mass spectrometer, x becomes the only unknown and can be solved for. In practise one tries to make R_{MIX} close to 1 to minimize measurement errors. If x can be estimated, s can be varied so R_{MIX} becomes close to 1.

The spikes used in this study are discussed in Appendix B. Originally both Sr^{84} and Rb^{87} spikes were used, however, when the XRF method was adopted all previously analysed whole rock samples were redetermined using this latter method.

A Sr^{84} enriched spike was used to determine the strontium concentrations of biotite and potassium feldspar concentrates. This spike has the advantage that a Sr^{87}/Sr^{86} and a strontium determination can be made on the same mass spectrometer run. Van Schmus (1966) discusses the technique and includes a FORTRAN IV computer program for data reduction.

2 - 3 - 6 Atomic Absorption

Rubidium was determined in samples of biotite separates by Mr. John Muysson, analyst, Rock Analysis Laboratory, McMaster

University. Standard atomic absorption techniques were used in conjunction with a Perkin-Elmer 303 atomic absorption spectrophotometer equipped with an Osram vapour discharge Rb lamp.

2 - 4 Mass Spectrometry

Mass spectrometric analyses were done on a 10 inch radius, 90 degree single sector, solid source mass spectrometer in the Mass Spectrometer Laboratory, Geology Department, McMaster University. The system uses a Phillips type, tantalum, single filament source under an accelerating voltage of 5 KV, supplied by a Fluke 408B high voltage power supply. A high voltage-low amperage (475V, 110 ma) magnet is coupled with a Fluke 301C power supply. A N.J.E. Corp QR 10-10 D.C. current-stabilized filament power supply is used. All electronic components are stabilized with a Sorensen ACR 3000 voltage regulator. During operation vacuum conditions of at least 1 X 10 $^{-7}$ torr are maintained by two 50 L/S Ultek ion pumps. Beam intensities are measured with a Faraday cup coupled to a Cary 401 vibrating reed electrometer (VRE) equipped with 10^{-11} ohm and 10^{-12} ohm resistors. No significant difference was detected in a single run of the same sample between different VRE scales and resistors. However, most of the data presented in this study was collected on the 300 MV scale with the 10^{-12} ohm resistor.

Originally, data were collected by varying the magnetic field strength with a continuously variable heliopot, connected to a scan motor, across the peaks of intrest. Peak heights were measured directly from the mass spectrum obtained from a Brush Mark 10 strip recorder fitted with engineered chart paper. However, most of the data reported in this study was obtained by manually switching the accelerating voltage and recording background and peak tops with a Hewlett-Packard digital voltmeter (5326B) - digital recorder (5055A) system. The standard counting procedure was: 10 seconds counting, 2 seconds switching, and a 10 second delay before reading the next peak for the VRE to stabilize. Peak tops (8 volts wide and 58 volts apart) were measured at their center in the sequence 88 - 87 - 86.5 (background) -86 - 86 - 86.5 - 87 - 88. The mass 85 position was checked at the beginning and end of each run for the presence of rubidium. Data collected in this way is superior to using chart paper (errors can be introduced by paper which may shrink or wobble etc.) and far more efficient and less troublesome. Another advantage is that all peaks can be recorded on the same VRE scale.

In voltage switching Sr^{86} is accelerated through a greater potential difference than Sr^{87}, Sr^{87} greater than Sr^{88} etc., enhancing their measured values. At McMaster, this change appears to be linear (R.H.McNutt - personal communication), and normalization to $Sr^{86}/Sr^{88} = 0.1194$ compensates for any fractionation from the filament plus the voltage discrimination. This is demonstrated by obtaining accepted values for inter-laboratory standards (Table 2-3).

Normally 80 scans over the mass range of interest were collected for each sample. The steady sample emission required for the measurement of strontium isotope ratios normally occurred with filament currents between 1.8 to 2.1 amps.

2 - 5 Discussion of Errors, Accuracy, and Precision of Analytical Results

Analytical errors can be divided into two categories; (1) those related to accuracy or the true value we are trying to measure, and (2) precision or the reproducibility of what we are trying to measure. Errors in the first category often tend to be systematic, while those of the latter tend to be random. (Dalrymple and Lanphere 1969, p.100)

Systematic errors of the type which may affect accuracy are frequently calibration errors, e.g. improperly calibrated standards, spike solutions, or instruments. Another source of systematic error which may become important, especially with samples of very low concentration, and very young samples, is the blank value or amount of contamination introduced by the chemicals used in preparing the sample.

Errors in precision are frequently due to sample inhomogeneity, variations in operating conditions of instruments, sample chemistry, instrumental instabilities, and short term drift.

2 - 5 - 1 Accuracy

The accuracy of laboratory results is best evaluated by comparison of results obtained on interlaboratory standards with accepted values. Results obtained for two interlaboratory isotope ratio standards are given in Table 2-3, and compared to results from other laboratories in Table 2-4. The generally accepted value for the E and A standard is Sr^{87}/Sr^{86} = 0.7080, and camparison between laboratories is quite good. Values used for X-ray fluorescence standards are given in Table 2-2. These six standards were checked against each other for each set of data collected. Deviation from the accepted value was always less than 2 per cent, and usually much less.

Mitchell (1969) reported an average Sr blank of 0.026 μgms. Sr/100 mg. sample and average Rb blank of 0.008 μgms. Rb/100 mg. sample for this laboratory, using essentially the same procedures as used in this study. In the present study, a Sr blank, prepared and analysed along with Sr^{84} spiked biotites, gave ~~a~~ value of 0.0016 gms. Sr/100 mg. of sample. The consistently low values of blanks and the correct Sr isotope ratio values for the NBS 70a potassium feldspar standard (Table 2-3) indicate that laboratory contamination is insignificant.

2 - 5 - 2 Precision

The best way to estimate precision is to make replicate measurements. Replicate measurements of Sr^{87}/Sr^{86} and Rb/Sr have been made by (1) repeated measurements on the same portion of sample and (2) duplicate or replicate portions of sample individually prepared.

Nine separate measurements of the E. and A. standard

TABLE 2 - 3 Values obtained for inter laboratory isotope standards

Eimer and Amend $SrCO_3$ isotope standard:

	Sr^{86}/Sr^{88}	$(Sr^{87}/Sr^{86})_N$	1 sigma	
July 18/71	.1198	.7078	.0011(1)	
July 31/71	.1219	.7085	.0012	
Sept.13/71	.1231	.7079	.0008	
Sept.27/71	.1218	.7075	.0009	
Aug. 19/71	.1236	.7081	.0013	
Dec. 14/71	.1231	.7074	.0010	
Jan. 16/72	.1208	.7075	.0015	
Mar. 28/72	.1237	.7076	.0011	
May 3/72	.1195	.7083	.0006	
average	.1219	.7078	.0004(2) = (0.05%)	$\bar{x}$

NBS 70 a potassium feldspar:

				(Split)
Oct. 22/71	.1217	1.2005	.0018(1)	# 6
Dec. 2/71	.1226	1.2005	.0009	# 2
Mar. 27/72	.1218	1.2003	.0020	# 1
average	.1220	1.2004	.0001(2) = (0.01%)	$\bar{x}$

(1) for individual sets

(2) for individual analysis

TABLE 2 - 4 Comparison of some Results for Interlaboratory Isotope Standards

Eimer and Amend $SrCO_3$:

Reference	Laboratory	$\frac{Sr^{86}}{Sr^{88}}$	$\frac{Sr^{87}}{Sr^{86}}$ N	1 sigma	N
This work[1]	McMaster	.1219	.7078	.0004	9
Mitchell (1969)	McMaster	.1203	.7083	.0003	7
Spooner (1969)[2]	M.I.T.	.1199	.7083	.0004	7
Reesman (1968)	M.I.T.	.1191	.7086	.0004	21
Livingston (1969)	Arizona	.1192	.7080	.0002	25
Arriens & Compston (1968)[1]	A.N.U.	.1207	.7081	.0002[4]	21
Fullagar et al.(1971)	Goddard S.F.C.	-	.7075	.0007	5
Barton (1971)	McGill	.1173	.7080	.0003	3
Wanless & Loveridge (1972)[2]	G.S.C.	.1191	.7086	.0005	35
Moorbath et al. (1972)	Oxford	-	.7081	.0001	10
Brooks & Leggo (1972)	D.T.M.	-	.7085	.0001	17

NBS 70a Potassium Feldspar

This work[1]	McMaster	.1221	1.2004	.0001	3
McNutt & Crockett (1973)[3]	McMaster	-	1.2006	.0030	3
Compston et al. (1969)[2]	A.N.U.	-	1.1994	.0037	35
Barton (1971)	McGill	.1198	1.1957	.0015	2
Wanless & Loveridge (1972)	G.S.C.	-	1.1990	.0019	11

N = number of analyses
1 = voltage switching
2 = different instrument used
3 = personal communication
4 = single analysis

(Table 2-3) gave a value of 0.7078 ± 0.0004 or ± 0.05% (1 sigma). Twelve duplicate analyses made at McMaster (4 this study and 8 by McNutt - personal communication) gave an average error in Sr^{87}/Sr^{86} of 0.08% (1 sigma) (Table 2-7). This value of ± 0.08% (1 sigma) is considered to be a reasonable estimate of the error in $(Sr^{87}/Sr^{86})N$ for the values reported in this study.

Replicate X-ray fluorescence analysis of seven pairs of XRF. pellets gave an average error of ± 0.5% (1 sigma) for Rb/Sr (Table 2-6). The maximum error, 1.0% (1 sigma), has been tentatively accepted as the best estimate of error in Rb^{87}/Sr^{86} values reported in this study.

2 - 5 - 3 Error in Analytical Data

Replicate samples have been used to estimate a "blanket error". These are ± 0.08% (1 sigma) for Sr^{87}/Sr^{86} and ± 1.0% (1 sigma) for Rb^{87}/Sr^{86}.

These estimates are comparable with those obtained in other laboratories (Table 2-8) and compatible with values obtained by replicate measurements on individual samples. These estimates mean only that if the analysis of any whole rock sample were repeated, the chances are two out of three that the result would fall within the stated limits.

2 - 6 Discussion of Isochron Calculation

Rb-Sr isochrons are constructed by plotting experimental data on rectangular or Cartesian co-ordinates, where Rb^{87}/Sr^{86}

TABLE 2 - 5 Comparison of Strontium Determinations of Potassium Feldspar by Isotope Dilution and XRF.

Sample	XRF (Compton peak)	Isotope Dilution	Difference	
W 7 KF	148.68 PPM	151.37 PPM	- 2.69	- 1.8 %
W 9 KF	45.05	45.83	- .78	- 1.7 %
W 10 KF	70.36	76.75	- .39	- .56 %
W 27 KF	20.30	18.74	+ 1.56	+ 8.0 %
W 64 KF	31.20	30.92	+ .28	+ .90 %
W 215 KF	31.75	31.86	- .11	- .35 %
W 35 KF	51.18	53.40	- 2.22	- 4.3 %
			|average|	2.5%

TABLE 2 - 6 Rb/Sr Replicates

ID	W 124	W 126	W 153	W 159	W 132	CCN-1	W 155
1	.2346	.23453	.4355	.3404	.2768	.9563	1.1492
2	.2363	.2351	.4335	.3415	.2735	.960	1.1414
	.2355	.2348	.4345	.3409	.2752	.9583	1.1453
	.0008	.0003	.0010	.0006	.0016	.0020	.0079
1 sigma	.00116	.00037	.00143	.00078	.00231	.00288	.01116
% 1 sigma	.49	.16	.33	.23	.84	.30	.97

average 7 = 0.5%

TABLE 2 - 7 REPLICATE SR-87/SR-86 VALUES

```
AVERAGE  0.06 PERCENT

NOTE - SAMPLES INDICATED WITH
W - THIS STUDY
SM AND MC - MCNUTT PERSONAL COMMUNICATION, 1973


W   1
              SR87-SR86  DEVIATION
              [illegible]  [illegible]
              [illegible]  [illegible]
              [illegible]  [illegible]
   AVERAGES     1.97115     .00175
  SS + STDVN     .00501     .00247        .157  PERCENT 1 SIGMA

W  103
              SR87-SR86  DEVIATION
              [illegible]  [illegible]
              [illegible]  [illegible]
              [illegible]  [illegible]
   AVERAGES      .71715     .01125
  SS + STDVN     .01100     .00025        .049  PERCENT 1 SIGMA

W  113
              SR87-SR86  DEVIATION
              [illegible]  [illegible]
              [illegible]  [illegible]
              [illegible]  [illegible]
   AVERAGES      .71370     .00040
  SS + STDVN     .01110     .01057        .079  PERCENT 1 SIGMA

W   53
              SR87-SR86  DEVIATION
              [illegible]  [illegible]
              [illegible]  [illegible]
              [illegible]  [illegible]
   AVERAGES      .71410     .00120
  SS + STDVN     .01010     .00020        .060  PERCENT 1 SIGMA

SM   60
              SR87-SR86  DEVIATION
                 .70520     .00033
                 .70580     .00030
   AVERAGES      .70550     .00030
  SS + STDVN     .00090     .01042        .061  PERCENT 1 SIGMA

SM  111
              SR87-SR86  DEVIATION
                 .70940     .00033
                 .70900     .00007
                 .70880     .00027
   AVERAGES      .70907     .00022
  SS + STDVN     .00000     .00031        .043  PERCENT 1 SIGMA

SM  163
              SR87-SR86  DEVIATION
                 .70840     .00015
                 .70870     .00015
   AVERAGES      .70855     .00015
  SS + STDVN     .00100     .00021        .030  PERCENT 1 SIGMA

SM  181
              SR87-SR86  DEVIATION
                 .70290     .00015
                 .70270     .00105
                 .70250     .00175
                 .70190     .00105
   AVERAGES      .70275     .00049
  SS + STDVN     .00600     .00066        .096  PERCENT 1 SIGMA

MC   6
              SR87-SR86  DEVIATION
                 .70640     .00020
                 .70610     .00020
   AVERAGES      .70620     .00020
  SS + STDVN     .00008     .00060        .050  PERCENT 1 SIGMA

MC  11
              SR87-SR86  DEVIATION
                 .70450     .00015
                 .70480     .00015
   AVERAGES      .70465     .00015
  SS + STDVN     .00100     .00021        .030  PERCENT 1 SIGMA

SM  178
              SR87-SR86  DEVIATION
                 .70608     .00090
                 .70420     .00090
   AVERAGES      .70518     .00090
  SS + STDVN     .00000     .00127        .181  PERCENT 1 SIGMA

SM  277
              SR87-SR86  DEVIATION
                 .70620     .00070
                 .70760     .00070
   AVERAGES      .70690     .00070
  SS + STDVN     .00080     .00099        .140  PERCENT 1 SIGMA
```

TABLE 2 - 8 Error Estimates of Some Geochronology Laboratories (1 sigma)

Reference	Laboratory	Sr^{87}/Sr^{86}	Rb^{87}/Sr^{86}
This work	McMaster	0.08%	1.0%
Adams (1970)[2]	Toronto	0.10%	1.0%
Barton (1972)	McGill	0.07%	0.3%
Moorbath et al. (1972)	Oxford	0.02%	0.5-1.0%
Brooks & Leggo (1972)	D.T.M.	0.05%	1.1%[2]
Pullagar et al. (1971)	Goddard SFC	0.20%	1.5%[2]
Wanless & Loveridge (1972)	G.S.C.	0.075%	1.5%[2]

1 personal communication

2 isottope dilution (others determined by XRF methods)

is plotted along the x-axis (abscissa) and Sr^{87}/Sr^{86} along the y-axis (ordinate) (Appendix A). If all the assumptions of the method are met, the slope of a straight line through the data points is proportional to the age of the rock and the y intercept represents the value of Sr^{87}/Sr^{86} when the rock crystallized (Appendix A). Because experimental error introduces scatter in the distribution of data points, a statistical model is required to fit an objective straight line to the data. Experimental error in both Rb^{87}/Sr^{86} and Sr^{87}/Sr^{86} precludes the use of simple linear regression and more sophisticated techniques (e.g. least squares cubic or quadratic) are needed. Several of these techniques are reviewed and compared by Brooks et al. (1972).

In this study, all sets of whole rock data have been tested with the multiple regression treatment of Brooks et al. (1972). This was used with 'blanket error" estimates and recommended correlation coefficients. The mean square of weighted deviates (MSWD) of the first treatment (McIntyre et al. 1966) can be used to distinguish between isochrons (data scatter is less than experimental error) and "errorchrons" (data scatter exceeds experimental error). As was shown by Brooks et al. (1972), all error treatments give essentially the same age, intercept, and error parameters when the data define an isochron. This can also be extended to include the York (1969) treatment with individual error estimates for data obtained in this study.

Unless indicated otherwise, all isochrons mentioned or plotted are based on the York (1966) (York 1 of Brooks et al. 1972) regression technique. In this case the error parameters of the regression line (age and intercept) are related to the actual scatter of the data points and will tend to zero as the data approaches an exact linear array. This choice is arbitrary, the York (1966) method has been used to calculate other whole rock ages in the Sudbury area (eg. Van Schmus 1965, Fairbairn et al. 1968, 1969) and precludes any error estimates, but is incapable of distinguishing between isochrons senso stricto (Brooks et al. 1972) and "errorchrons" or "scattercrons".

A computer program, based on the York (1969) techniques and using individual error estimates, was modified slightly and used to calculate mineral-whole rock ages.

All isochron errors given represent a one sigma (68%) confidence interval.

2 - 7 Analytical Results

Analytical results obtained in this study are given in Table 2-9.

TABLE 2-9 RB - SR DATA OBTAINED IN THIS STUDY

NOTE (1) THE SR ISOTOPE RATIOS OF ALL SAMPLES WITH A G IN THEIR ID WERE DETERMINED BY THE GEOCHRONOLOGY SECTION OF THE GEOLOGICAL SURVEY OF CANADA
(2) THOSE WITH A D ARE DUPLICATES.

SOUTH RANGE NORITE + TRANSITION ZONE

ID	(SR87/SR86)N	RB87/SR86	SR86/SR88	SR (PPM)	RB (PPM)
W 101	.7155	.3308	.1239	433.420	48.377
W 102	.7172	.3914	.1215	422.571	56.127
W103D	.7173	.3817	.1235	417.941	54.014
W 103	.7178	.3817	.1225	417.941	54.014
W 104	.7181	.4302	.1251	408.597	59.661
W 110	.7144	.3026	.1214	449.535	45.705
W113D	.7137	.2457	.1181	478.013	39.215
W 113	.7129	.2456	.1229	478.013	39.215
W 116	.7100	.1248	.1226	525.522	20.840
W 118	.7097	.1224	.1221	542.422	21.191
W 120	.7098	.1361	.1242	528.101	23.161
W 124	.7129	.2346	.1247	476.948	37.277
W 126	.7139	.2345	.1222	362.503	27.819
W 153	.7193	.4355	.1192	423.823	62.492
W 159	.7154	.3403	.1204	450.094	51.105

NORTH RANGE NORITE

ID	(SR87/SR86)N	RB87/SR86	SR86/SR88	SR (PPM)	RB (PPM)
W 129	.7153	.3278	.1206	464.401	51.488
W 134	.7143	.2930	.1200	476.686	47.019
W 136	.7148	.3111	.1220	454.309	47.443
W 127	.7109	.1948	.1196	477.843	30.454
W 132	.7124	.2768	.1197	451.280	41.995
W 311	.7067	.0996	.1211	263.180	7.811

TABLE 2-9 CONTINUED

SUB-LAYER

ID	(SR87/SR86)N	RB87/SR86	SR86/SR88	SR (PPM)	RB (PPM)
CCN 1	.7315	.9563	.1192	243.581	79.527
CCN 3	.7256	.7069	.1219	281.218	68.116
M 37	.7146	.3390	.1213	339.123	37.753
M 41	.7135	.2723	.1160	381.712	34.353
M 42	.7136	.3153	.1193	259.666	26.116

CONTACT NORITES – (MURRAY OFFSHOOT DIKE 1)

ID	(SR87/SR86)N	RB87/SR86	SR86/SR88	SR (PPM)	RB (PPM)
W 3	.7235	.7152	.1182	402.240	99.489
W 4	.7172	.4274	.1213	419.657	61.306
W 5	.7163	.3222	.1211	444.674	48.447
W 6	.7136	.2717	.1208	458.198	41.917

CONTACT NORITES – (LITTLE STOBIE MINE)

ID	(SR87/SR86)N	RB87/SR86	SR86/SR88	SR (PPM)	RB (PPM)
W 50	.7295	1.0084	.1224	94.170	32.010
W 51	.7185	.4642	.1205	369.201	58.342
W 52	.7199	.4358	.1232	402.635	59.894
W 53D	.7143	.2895	.1245	434.407	42.311
W 53	.7139	.2895	.1195	434.407	42.311

TABLE 2-9 CONTINUED

SOUTH RANGE MICROPEGMATITE

ID	(SR87/SR86)N	RB87/SR86	SR86/SR88	SR (PPM)	RB (PPM)
W 150	.7522	1.8531	.1197	166.625	108.997
W 154	.7278	.8138	.1199	218.824	61.422
W154G	.7285	.8139	.1202	218.824	61.422
W 155	.7361	1.1492	.1215	264.870	105.241
W155G	.7360	1.1492	.1215	264.870	105.241
W 156	.7455	1.6220	.1204	185.665	105.066

MURRAY GRANITE

ID	(SR87/SR86)N	RB87/SR86	SR86/SR88	SR (PPM)	RB (PPM)
W 27	1.1405	12.8702	.1203	49.702	218.837
W 28G	1.0189	9.0252	.1201	59.457	184.107
W 29	1.2997	17.6890	.1223	42.668	254.782
W 64	1.0802	11.6525	.1207	43.628	174.521
W 65	.9728	7.7016	.1203	45.908	120.847
W 66	.9304	6.5000	.1233	70.916	160.581
W 215	.9565	7.7703	.1219	72.608	195.377
W 35	1.1092	12.2016	.1219	46.039	192.756

SUDBURY BRECCIA

ID	(SR87/SR86)N	RB87/SR86	SR86/SR88	SR (PPM)	RB (PPM)
W 190	.9471	7.8667	.1200	78.073	214.497
W 227	.8547	4.1079	.1255	139.356	200.883

TABLE 2-9 CONTINUED

CONTACT MURRAY GRANITE - (LITTLE STOBIE MINE)

ID	(SR87/SR86)N	RB87/SR86	SR86/SR88	SR (PPM)	RB (PPM)
W 54	.8543	3.8863	.1266	91.007	122.374
W 55	.7418	.7060	.1224	199.079	48.379
W 56	.8316	4.3546	.1217	77.370	118.069
W 57	.9556	7.2468	.1221	73.464	185.274
W 58	.7999	2.3043	.1241	131.334	105.728

MURRAY OFFSHOOT DIKE 1

ID	(SR87/SR86)N	RB87/SR86	SR86/SR88	SR (PPM)	RB (PPM)
W 1	1.5763	37.1835	.1209	28.173	344.011
WD 1	1.5798	37.1953	.1220	28.173	344.011
W 7	.7496	1.6273	.1194	227.459	130.002
W 8G	1.0472	13.0646	.1203	66.539	298.228
W 9G	1.1226	15.4644	.1202	56.884	301.689
W 10	.8416	5.1521	.1209	110.921	199.738
84W11	.7539	1.6186	.1210	231.099	130.550
W 12	.7416	1.0166	.1255	289.294	102.427
W 19	.7202	.3895	.1200	285.249	37.600
W 20	1.1254	16.7862	.1210	53.694	305.301

MURRAY OFFSHOOT DIKE 2

ID	(SR87/SR86)N	RB87/SR86	SR86/SR88	SR (PPM)	RB (PPM)
W 302	.9621	9.7889	.1228	78.215	266.806
W 303	.9970	11.5389	.1200	67.021	269.102
W 304	.9154	8.2197	.1218	79.142	227.036
W 305	.7838	2.6703	.1226	169.153	158.589
W 306	.9668	10.1162	.1232	78.472	274.287

TABLE 2-9 CONTINUED

SYENITE

ID	(SR87/SR86)N	RB87/SR86	SR86/SR88	SR (PPM)	RB (PPM)
WA 67	.7835	2.0169	.1208	63.364	44.561
WB 67	.7667	1.1441	.1201	76.227	29.993

CARBONATITE

ID	(SR87/SR86)N	RB87/SR86	SR86/SR88	SR (PPM)	RB (PPM)
WW219	.7207	.0308	.1181	122.182	.747
PG219	.7277	.0701	.1211	75.174	1.080

BIOTITES - MURRAY GRANITE

ID	(SR87/SR86)N	RB87/SR86	SR86/SR88	SR (PPM)	RB (PPM)
W 27 B	12.7666	811.9733	.1239	14.647	1848.000
W 27 45B	8.0609	493.1432	.1219	17.470	1697.000
W 64 B	3.2578	167.0278	.1227	23.237	1052.000
W 215 B	6.7774	410.9382	.1265	15.906	1389.000
W 35 B	1.3248	11.6290	.1238	32.848	122.000

BIOTITES - MURRAY OFFSHOOT DIKE I

ID	(SR87/SR86)N	RB87/SR86	SR86/SR88	SR (PPM)	RB (PPM)
W 7 B	5.1985	283.7916	.1232	22.463	1500.000
W 9 B	7.9666	447.1092	.1239	22.609	2002.000
W 10 B	3.6988	184.6529	.1230	35.490	1717.000

TABLE 2-9 CONTINUED

BIOTITES – SUDBURY BRECCIA

ID	(SR87/SR86)N	RB87/SR86	SR86/SR88	SR (PPM)	RB (PPM)
W 190 B	7.1832	422.8589	.1213	12.364	1084.000
W 227 B	7.9226	479.4345	.1229	9.371	892.000

BIOTITES – NORITE

ID	(SR87/SR86)N	RB87/SR86	SR86/SR88	SR (PPM)	RB (PPM)
W 101 B	1.4640	40.7514	.1221	25.058	322.000
W 104 B	1.8757	71.5942	.1233	22.473	489.000
W 110 B	2.2072	85.8160	.1232	17.992	456.000
W 118 B	1.1519	24.9042	.1216	42.313	342.000
W 136 B	2.2330	65.2415	.1231	14.356	276.000
W 311 B	.7282	1.5063	.1222	45.178	23.000

K-FELDSPAR – MURRAY GRANITE

W 27 KF	1.9463	57.1825	.1190	20.301	359.762
W 64 KF	1.3759	27.8806	.1208	31.202	289.820
W215 KF	1.3682	29.9258	.1219	31.750	314.512
W 35 KF	1.2745	20.1100	.1175	51.180	349.422

K-FELDSPAR – MURRAY OFFSHOOT DIKE 1

ID	(SR87/SR86)N	RB87/SR86	SR86/SR88	SR (PPM)	RB (PPM)
W 7 KF	.8070	4.1606	.1220	148.683	218.234
W 9 KF	1.4713	32.0401	.1235	45.050	476.012
W 10 KF	1.0215	14.0332	.1206	70.361	342.373

TABLE 2-9 CONTINUED

PLAGIOCLASE - NORITE

ID	(SR87/SR86)N	RB87/SR86	SR86/SR88	SR (PPM)	RB (PPM)
118PL	.7203	.4801	.1219	181.422	30.018
311PL	.7073	.0519	.1154	511.349	8.112

FLOURITE

ID	(SR87/SR86)N	RB87/SR86	SR86/SR88	SR (PPM)	RB (PPM)
W 1FL	.8676	-	.1201	-	-
W29FL	.8456	-	.1162	-	-

CALCITE

ID	(SR87/SR86)N	RB87/SR86	SR86/SR88	SR (PPM)	RB (PPM)
W219C	.7184	-	.1184	-	-
W219R	.7193	-	.1205	-	-

Chapter 3 Geochronology and Geology of the Sudbury Nickel Irruptive.

3 - 1 Introduction

As mentioned in Chapter 1 and shown in Figure 3-1, the Sudbury irruptive is divided into a north and a south range by a series of south-dipping thrust faults which parallel the long axis of the basin. Mine-exploration records (Wilson 1956 and Souch and Podosky 1969) and magnetic and gravity studies (Popelar 1972) indicate a probable vertical displacement of the south range up 3 miles relative to the north range. Paleomagnetic studies (Sopher 1963, Larochelle 1969) indicate post-crystallization rotation which has decreased the angle between the north and south range limbs by 30 degrees. Brocoum and Dalziel (1973) suggested that the basin was originally circular in outline and deformation of the basin and the south range of the irruptive was coeval with major folding and flattening of rocks inside and outside the basin during the Penokean Orogeny (1.6 to 1.9 b.y. ago). However, Cantin and Walker (1972) presented sedimentologic evidence (paleocurrent studies) which indicate that the basin was elongate during deposition of the Chelmsford formation.

The irruptive itself can be divided into three distinct rock units, (micropegmatite, norite, and sub-layer), each of which may be further subdivided and may show differences between north and south range varieties (Figure 3-2 and Table 3-1). All three of these units and the overlying Onaping

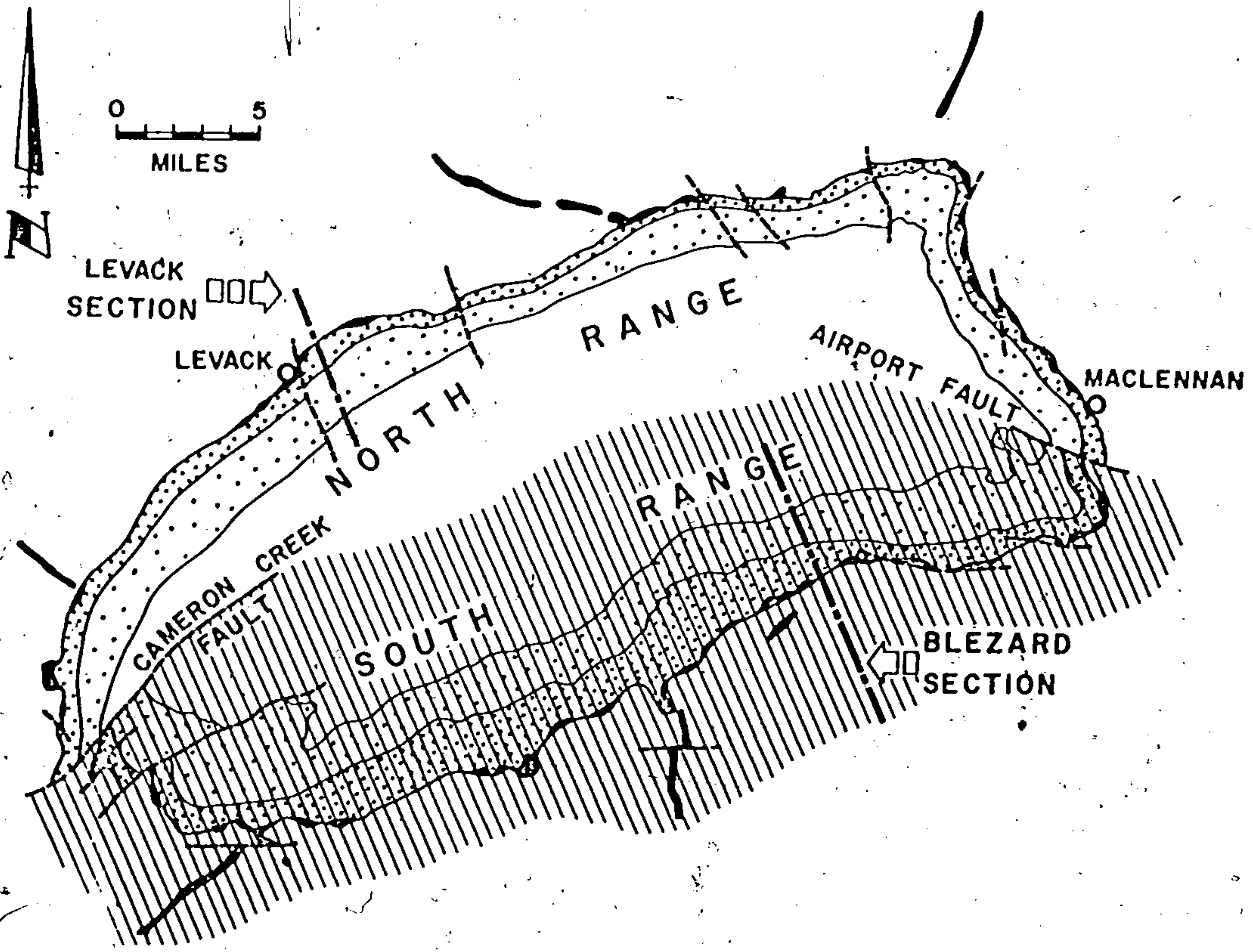

Figure 3 - 1: Map of the Sudbury basin showing distribution of sub-layer (solid) and north and south ranges. (after Souch and Podolsky 1969).

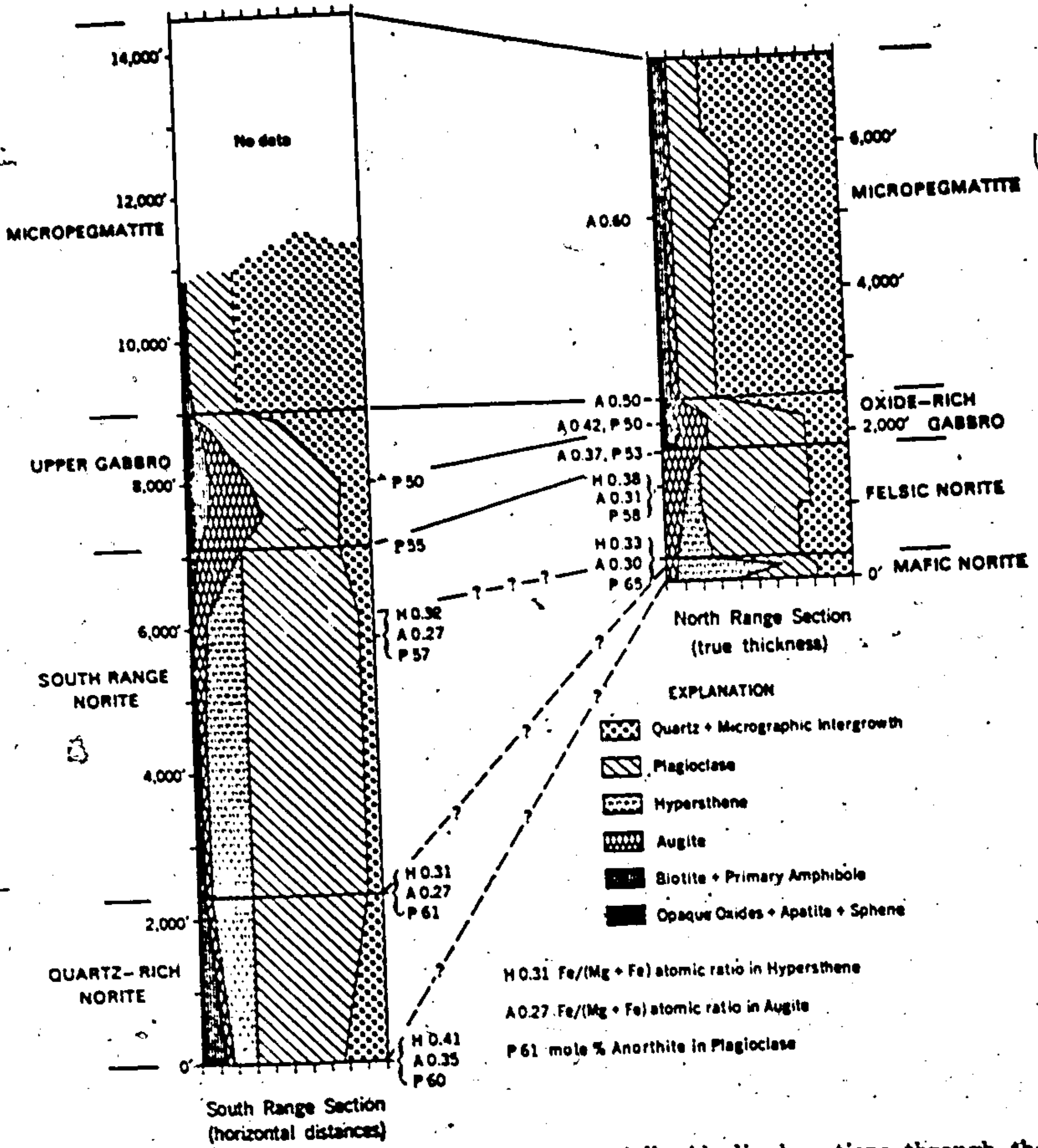

FIGURE 3-2 Comparison and correlation of partially idealized sections through the rocks of the north and south ranges. The columns indicate variation in modal composition of the rocks.

(after Naldrett et al. 1972a)

TABLE 3-1 ROCK UNITS OF THE SUDBURY IRRUPTIVE

UNIT	SOUTH RANGE	NORTH RANGE
MICROPEGMATITE[1]	MICROPEGMATITE (sheared)	MICROPEGMATITE
NORITE	UPPER GABBRO (sheared)	OXIDE RICH GABBRO
	SOUTH-RANGE NORITE[2] var. green (altered) var. black (fresh)	FELSIC NORITE
	QUARTZ RICH NORITE var. Biotite norite	MAFIC NORITE (discontinuous) var. hypidiomorphic var. poikilitic
SUB LAYER	SOUTH RANGE SUB-LAYER (discontinuous) var. interstitial sulf. in nor. sub-layer var. ragged disseminated sulf. var. gabbro-periodotite incln. sulf. var. inclusion massive sulf. var. massive sulfide	NORTH RANGE SUB-LAYER (discontinuous) var. mafic sub-layer var. leucocratic sub-layer breccia
	OFFSET SUB-LAYER Quartz diorite	

References: Naldrett et al. (1970), Hewins (1972), and Pattison and Phipps (1972)

[1] Stevenson and Colgrove (1968) and Peredery (1972) recognize distinct phases in the micropegmatite but they have not been mapped except locally due to their irregular nature.

[2] A hyphen is used to distinguish this petrologic unit from south range norite in the general sense.

formation, which frequently occurs as inclusions in the upper micropegmatite, appear to have been formed as a discrete series of events in a relatively short time.

The "micropegmatite" is actually a granophyre, as it is characterized by a fine-grained intergrowth of quartz and alkali feldspar (Barker 1970). The norite includes several varieties of gabbro as well as true norite and the "sub-layer" includes a variety of ore materials which may include matrix or breccia fragments of norite, quartz diorite, footwall granites and gneisses, or ultramafic rock types (e.g. peridotite and dunite).

The Sudbury irruptive can be defined as a mafic layered intrusion along with many other interesting and economically important rock masses. Their significance lies in the fact that they were not formed by the crystallization of a magma to give rocks of the same bulk composition as the liquid but by a process of fractional crystallization, i.e. the accummulation of crystals as they were formed and settled through the cooling body of liquid. The layering may vary from sharp monomineralogic layers to subtle variation of elemental ratios in certain minerals called cryptic layering. Study of the layering is undertaken in an effort to understand the physical and chemical processes and conditions involved in the crystallization of the parent magma.

3 - 2 Rubidium-Strontium Whole Rock Age Determinations

Irruptive samples used for whole-rock rubidium-strontium

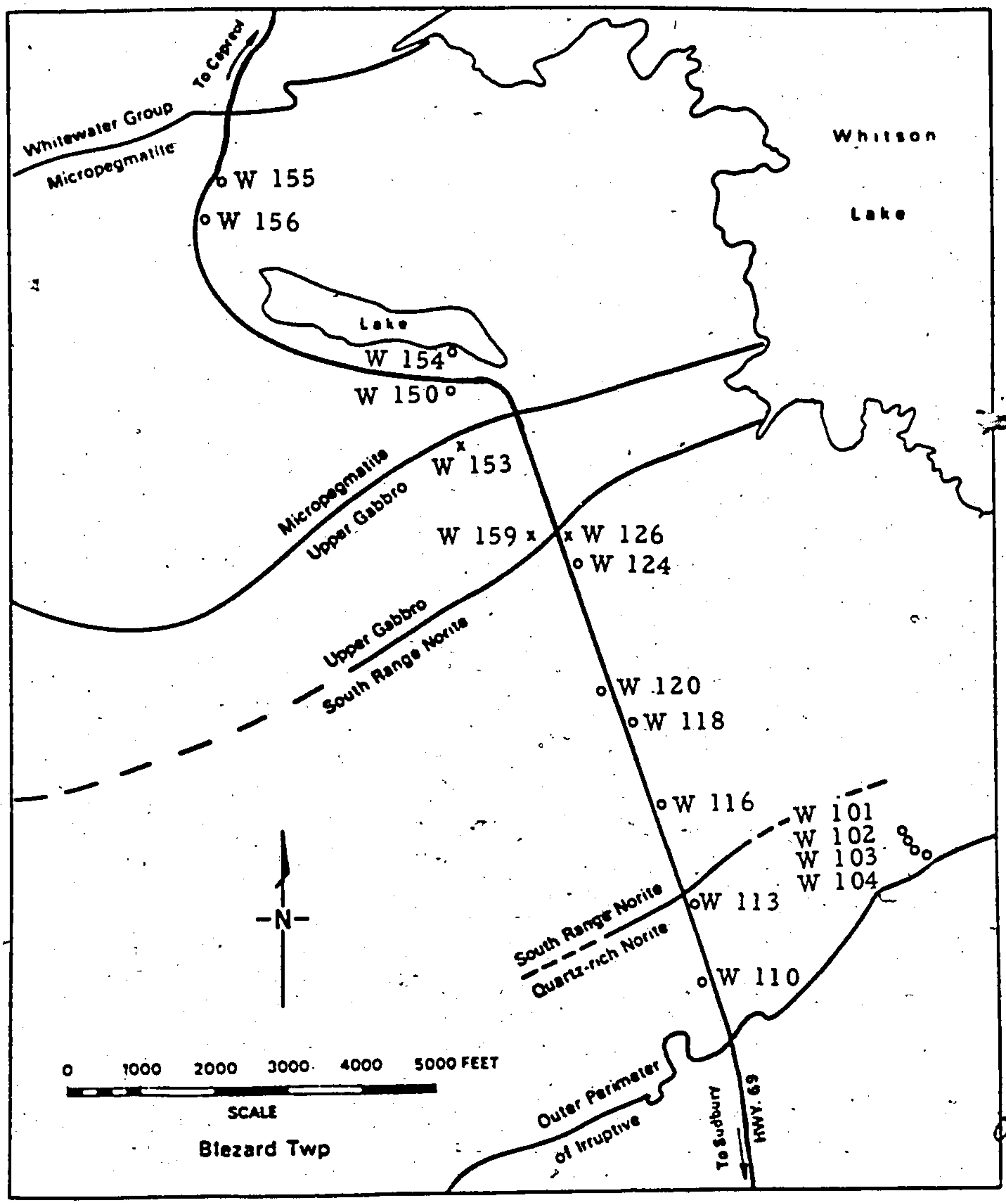

Figure 3-3 Map showing south range norite sample locations (Geology from Naldrett et al. 1970)

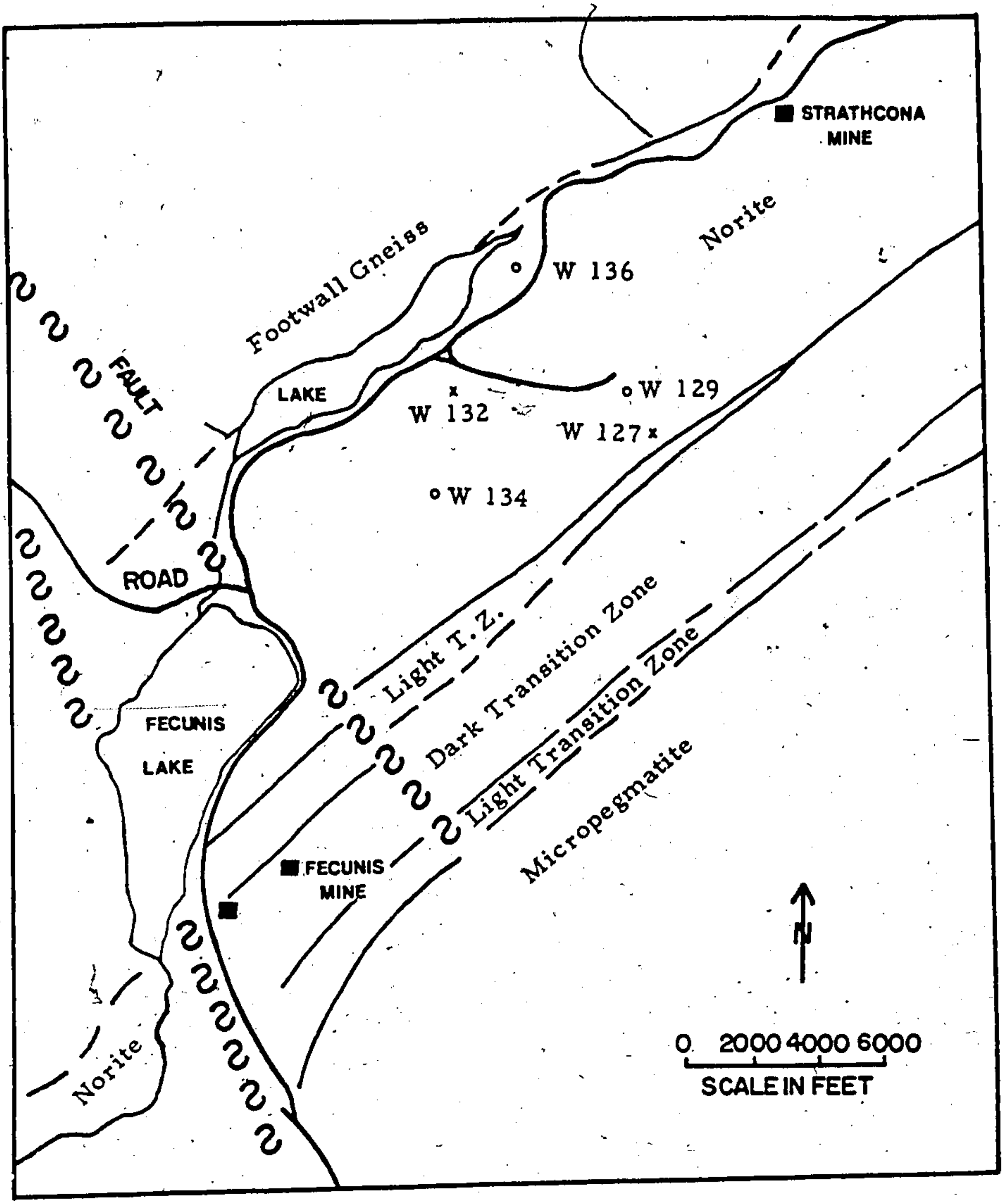

Figure 3-4 Map showing north range norite sample locations (Geology from O. D. M. Preliminary geological map No. P. 91)

analysis were collected along the Blezard traverse of the south range and the Levack-Strathcona traverse of the north range (Figures 3-1, 3-3, and 3-4). The collection and preparation of the samples is discussed in Chapter 2, the analytical results can be found in Table 2-9, and the sample descriptions in Appendix D. (Table D-1)

3 - 2 - 1 South and North Range Norites

Ten samples of norite from the south range give an isochron of 1,977 ± 58 m.y. and Ri (i.e. Sr^{87}/Sr^{86}) = 0.7063 ± 0.0002 (Figure 3-5A). Four samples of "biotite norite" are unusually rich in biotite and give the highest Rb^{87}/Sr^{86} values. They come from the base of the norite and are believed to represent a chilled phase of the norite magma, (Naldrett et al. 1970, p.133 and 1972a p.209), but there is a remote possibility of some country rock contamination. However, their removal does not change the isochron parameters appreciably, except to increase the error estimates, (i.e. 1,995 ± 146 m.y. and Ri = 0.7063 ± 0.0004).

Three north range samples are not enough to justify calling their regression line an isochron, especially with the small spread of values observed. However, this line is compatible with the south range isochron and gives t = 2,040 ± 20 m.y.:

FIGURE 3 - 5

A Norite south range

B Norite north range

squares - this study
triangles - after Souch and Podolsky 1969

C Norite combined

squares - south range
triangles - north range

D Norite combined

all data from this study

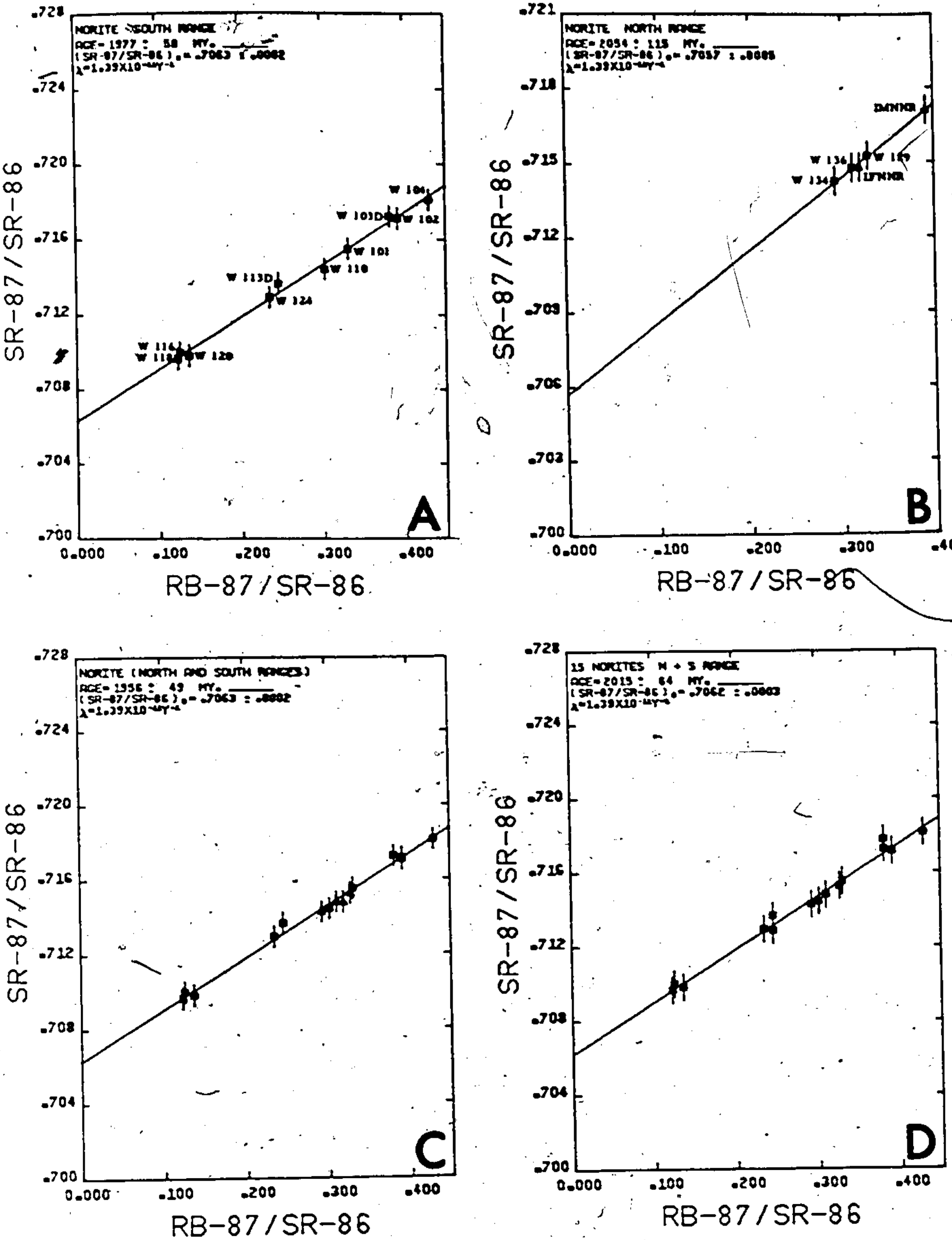
NORITE SOUTH RANGE
AGE= 1977 ± 58 MY.
(SR-87/SR-86)$_0$= .7063 ± .0002
λ=1.39X10^{-5}MY^{-1}
W 106
W 103D
W 102
W 101
W 110
W 113D
W 124
W 116
W 118
W 120
A
NORITE NORTH RANGE
AGE= 2054 ± 115 MY.
(SR-87/SR-86)$_0$= .7057 ± .0005
λ=1.39X10^{-5}MY^{-1}
DMNXR
W 136
W 139
W 134
LFNXR
B
NORITE (NORTH AND SOUTH RANGES)
AGE= 1956 ± 49 MY.
(SR-87/SR-86)$_0$= .7063 ± .0002
λ=1.39X10^{-5}MY^{-1}
C
15 NORITES N + S RANGE
AGE= 2015 ± 64 MY.
(SR-87/SR-86)$_0$= .7062 ± .0003
λ=1.39X10^{-5}MY^{-1}
D
SR-87/SR-86
RB-87/SR-86
.700
.704
.708
.712
.716
.720
.724
.728
.703
.706
.709
.712
.715
.718
.721
0.000
.100
.200
.300
.400

Figure 3 - 5.

Ri = 0.7059 ± 0.001. The addition of two north range data points reported by Souch and Podolsky (1969) increases the spread of points without altering the age and intercept values (Fig. 3-5B), 2,054 ± 115 m.y. and Ri = 0.7057 ± 0.0005.

The similar age and intercept for both north and south range norites has been taken as justification for combining the two sets of data. The 10 south range samples and 5 north range samples of norite give a 1,956 ± 49 m.y. age, Ri = 0.7063 ± 0.0002 (Fig. 3-5C). This appears to be a minimum age of the norite. An alternative regression includes two south range duplicate sample splits, but not the two INCO (Souch and Podolsky 1969) values. The 15 norite samples determined at McMaster give a 2,015 ± 64 m.y. age with Ri = 0.7062 ± 0.0003 (Figure 3-5D).

The data suggest a 2,000 m.y. age for the norite with an initial Sr^{87}/Sr^{86} value of 0.7062. A 2,000 m.y. Rb-Sr age of the norite was originally suggested by Souch and Podolsky (1969) on the basis of three colinear north range norite whole rock analyses.

3 - 2 - 2 Sub Layer

The "sub-layer" is a discontinuous layer of sulfide and inclusion bearing noritic rock which lies below the norite. Its distribution is shown in black in Figure 3-1). Three distinct environments are recognized: north range, south range, and offset dikes (Table 3-1).

Five whole rock samples of this material have been analysed. Again the small number of samples precludes calling the regression line an isochron, but again this line turns out to be compatible with norite isochrons (Figure 3-6A and B). One additional sub-layer sample, (IQDSR), reported by Souch and Podolsky (1969) has also been plotted. All of these samples are from the south range.

Three marginal samples of sub-layer material were collected from the Murray mine, (indicated by M in Figure 3-6A), near the top of the ore body and are classified as "interstitial sulfide in norite". Aside from the high sulfide content, they closely resemble norite and are no longer considered to be part of the sub-layer, but rather the base of the norite by INCO geologists, (D.Phipps and E.F.Pattison, personal communication 1973).

The other two samples from the Copper Cliff North mine (CCN) and the INCO sample are from quartz-diorite offset dikes. They have distictly higher isotopic ratios than the norite but still have the same age. This can be explained by the idea that the fine grained quartz diorite represents a chilled phase of the irruptive. Hewins and Pattison (1972) have reported fine grained and quench-textured varieties of sub-layer in the Foy offset on the north range. Sub-layer rocks closer

FIGURE 3 - 6

A Sub-layer

squares - marginal - Murray mine
triangles - offset - Copper Cliff North
diamond - after Souch and Podolsky 1969
(all samples from south range)

B Sub-layer compared to norite isochron

as above

C Contact norites compared to norite isochron

squares - Little Stobie mine
triangles - Murray offshoot 1

D Altered (green) norites and "transition zone" gabbros

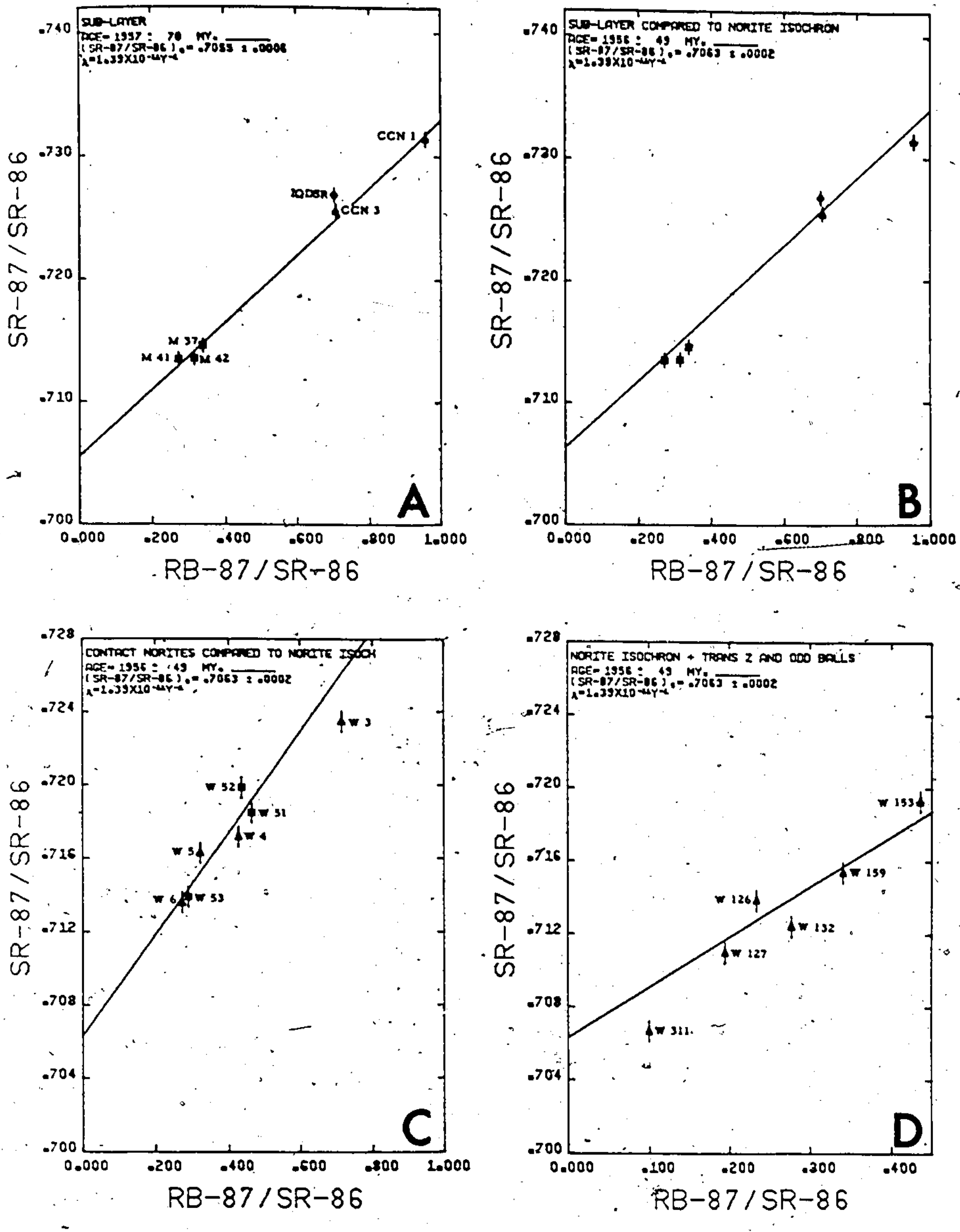
SUB-LAYER
AGE= 1957 ± 70 MY.
(SR-87/SR-86)$_0$= .7055 ± .0008
λ=1.39X10^{-11}Y^{-1}
CCN 1
IQDBR
CCN 3
M 37
M 41
M 42
A
SUB-LAYER COMPARED TO NORITE ISOCHRON
AGE= 1956 ± 49 MY.
(SR-87/SR-86)$_0$= .7063 ± .0002
λ=1.39X10^{-11}Y^{-1}
B
CONTACT NORITES COMPARED TO NORITE ISOCH
AGE= 1956 ± 49 MY.
(SR-87/SR-86)$_0$= .7063 ± .0002
λ=1.39X10^{-11}Y^{-1}
W 3
W 52
W 51
W 4
W 5
W 6
W 53
C
NORITE ISOCHRON + TRANS Z AND ODD BALLS
AGE= 1956 ± 49 MY.
(SR-87/SR-86)$_0$= .7063 ± .0002
λ=1.39X10^{-11}Y^{-1}
W 153
W 159
W 126
W 132
W 127
W 311
D
SR-87/SR-86
RB-87/SR-86
.740
.730
.720
.710
.700
.728
.724
.720
.716
.712
.708
.704
0.000
.100
.200
.300
.400
.600
.800
1.000

Figure 3 - 6.

to the irruptive lack distinctive quench features. A less likely explanation is early rubidium contamination. Subsequent contamination would undoubtedly affect the age.

The 1,957 ± 78 m.y. age and 0.7055 ± 0.0006 Ri of the sub-layer regression line and the individual data points suggest that the sub-layer is contemporaneous with the norite within the limits of isotopic dating.

Geological evidence for the relative ages of the mafic sub-layer and the norite is not conclusive. On the north range contact relations between them may be sharp, but chilling and clear cross-cutting relations have not been found. On the south range it is difficult to recognize the exact contact between the sub-layer and the norite of the main irruptive (Naldrett et al. 1972 a and b).

3 - 2 - 3 South and North Range Micropegmatites

A regression line for four south range micropegmatites (1,625 ± 65 m.y.; Ri = 0.7094 ± 0.0012 - Figure 3-7A) is compatible within error estimates with a six point isochron of north range micropegmatites (1,717 ± 34 m.y.; Ri = 0.7074 ± 0.0008 - Figure 3-7B data from Fairbairn et al. 1968 and Souch and Podolsky 1969). The combined data yield an isochron of 1,680 ±31 m.y. age and 0.7083 ± 0.0007 initial ratio (Figure 3-7C).

This combined micropegmatite isochron gives a distinctly younger age and higher initial ratio than the norite

FIGURE 3 - 7

A Micropogmatite south range

B Micropegmatite north range

C Micropegmatite combined

squares - south range
triangles - north range

D Norites compared to micropegmatite isochron (b)

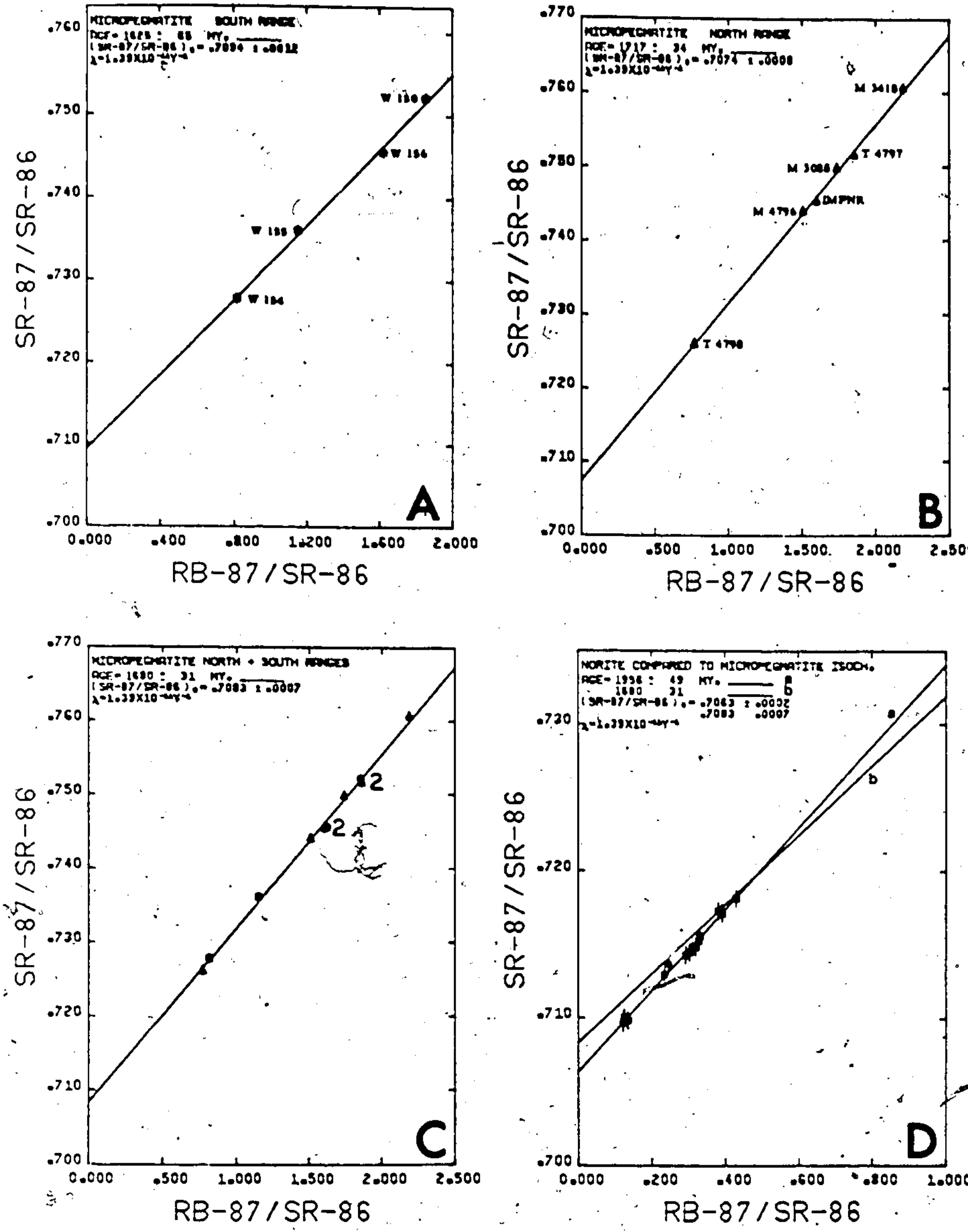
MICROPEGMATITE SOUTH RANGE
AGE= 1625 ± 65 MY.
(SR-87/SR-86)₀= .7094 ± .0012
λ=1.39X10⁻¹¹Y⁻¹
W 186
W 156
W 155
W 154
A
SR-87/SR-86
RB-87/SR-86
.700
.710
.720
.730
.740
.750
.760
0.000
.400
.800
1.200
1.600
2.000
MICROPEGMATITE NORTH RANGE
AGE= 1717 ± 34 MY.
(SR-87/SR-86)₀= .7074 ± .0008
λ=1.39X10⁻¹¹Y⁻¹
M 34186
T 4797
M 3088
DMPNR
M 4796
T 4798
B
.770
0.000
.500
1.000
1.500
2.000
2.500
MICROPEGMATITE NORTH + SOUTH RANGES
AGE= 1680 ± 31 MY.
(SR-87/SR-86)₀= .7083 ± .0007
λ=1.39X10⁻¹¹Y⁻¹
2
2
C
NORITE COMPARED TO MICROPEGMATITE ISOCH.
AGE= 1956 ± 49 MY. a
1680 31 b
(SR-87/SR-86)₀= .7063 ± .0002
.7083 .0007
λ=1.39X10⁻¹¹Y⁻¹
a
b
D
.200
.400
.600
.800
1.000

Figure 3 - 7.

(Figure 3-7D). These isochrons are compared statistically using the method suggested by McIntyre et al. (1966 p. 5466) in Table 3-2. Both ages and intercepts are signficantly different at the 90% confidence level. The age difference can actually be extended to the 98% level.

3 - 2 - 4 The Nickel Irruptive

Consideration of all 25 samples from the norite and micropegmatite, including the previously mentioned samples of Fairbairn et al. (1968) and Souch and Podolsky (1969), produces an isochron sensú stricto of age 1,722 ± 12 m.y. and intercept 0.7073 ± 0.0002 (Figure 3-8A). This is essentially the same as the irruptive isochron of Fairbairn et al. (1968) (Figure 3-8B) and the combined micropegmatite isochron (Figure 3-7C).

3 - 2 - 4 One or Two Ages of the Nickel Irruptive

3 - 2 - 4 - 1 The Problem

The problem arises in deciding whether one or two rubidium-strontium isochron ages are really represented by twenty-five whole rock samples from the irruptive. On one hand, norite and micropegmatite samples are very easily distinguished from each other and the resulting two populations

FIGURE 3 - 8

A Irruptive data combined

squares - norite (15)
triangles - micropegmatite (10)

B Irruptive data of Fairbairn et al. 1968

C Norites compared to "irruptive isochron"

D Bushveld data - after Davies et al. 1970

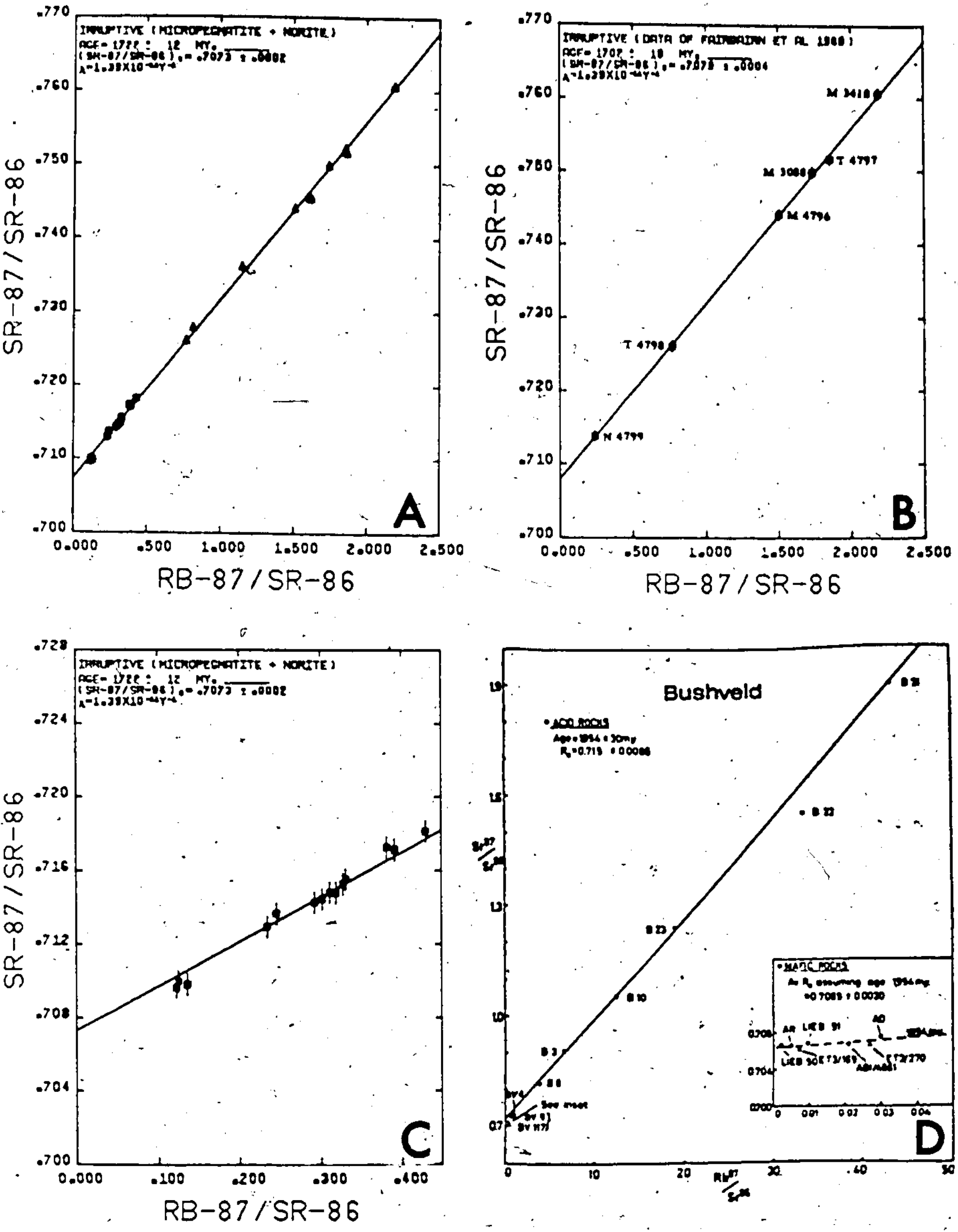
IRRUPTIVE (MICROPEGMATITE + NORITE)
AGE= 1722 ± 12 MY.
(SR-87/SR-86)o= .7073 ± .0002
λ=1.39X10⁻¹¹Y⁻¹
SR-87/SR-86
RB-87/SR-86
.700
.710
.720
.730
.740
.750
.760
.770
0.000
.500
1.000
1.500
2.000
2.500
A
IRRUPTIVE (DATA OF FAIRBAIRN ET AL 1968)
AGE= 1707 ± 18 MY.
(SR-87/SR-86)o= .7078 ± .0004
λ=1.39X10⁻¹¹Y⁻¹
M 3418
T 4797
M 3088
M 4796
T 4798
N 4799
B
IRRUPTIVE (MICROPEGMATITE + NORITE)
AGE= 1722 ± 12 MY.
(SR-87/SR-86)o= .7073 ± .0002
λ=1.39X10⁻¹¹Y⁻¹
.700
.704
.708
.712
.716
.720
.724
.728
0.000
.100
.200
.300
.400
C
Bushveld
• ACID ROCKS
Age = 1954 ± 30my
Ro = 0.715 ± 0.0086
B 32
B 23
B 10
B 3
B 8
See inset
Sr87/Sr86
Rb87/Sr86
0.7
1.0
1.3
1.5
1.9
0
10
20
30
.40
50
• MAFIC ROCKS
Av Ro assuming age 1954 my
= 0.7063 ± 0.0030
AR
LIEB 91
AO
LIEB 90
T3/169
T3/270
0.708
0.704
0.700
0
0.01
0.02
0.03
0.04
D

Figure 3 - 8.

TABLE 3 - 2 Statististical Comparison of Norite and Micropegmatite Isochrons

Rock Unit	# of samples	Age (m.y.)	Error (1 sigma)	Degrees of Freedom	Calculated t	t(90% Confidence level	Result
norite	15	2,015	125	16.1	2.58	1,746	significant difference.
micropegmatite	10	1,680	35				
		$(Sr^{87}/Sr^{86})_o$					
norite	15	0.7062	0.0005	17.4	2.04	1,740	significant difference.
micropegmatite	10	0.7083	0.0009				

$$t = \frac{X_1 - X_2}{(S_1^2 + S_2^2)^{1/2}}$$

Degrees of freedom calculated according to McIntyre et al. (1966, p.5466). Isochron and error parameters from York (1969) regression treatment.

each give isochrons sensu stricto (Table 3-2) which have age and initial Sr^{87}/Sr^{86} values that are significantly different at the 90% confidence level. On the other hand, all 25 norite and micropegmatite samples also define an isochron sensu stricto and visual inspection of this isochron, (Figure 3-8 A and C) shows that virtually all samples fall on it within the limits of experimental error.

3 - 2 - 4 - 2 Evidence for two ages

An explanation which favors two ages interprets the irruptive isochron (Figure 3-8C) as a micropegmatite isochron (Figure 3-7C). Empirically the two are not significantly different although a statistical comparison is not valid as both contain many of the same samples. The significance of norite samples is neutralized by the fact that the isochron is "anchored" or "pivoted" (1. where $Rb^{87}/Sr^{86} = 0$ and 2. where the norite and micropegmatite isochrons cross - Figure 3-7D), very close to the norite data points (Figure 3-8A). Consequently, they exert a much smaller "torque" or influence on the resulting regression line, while not showing any appreciable displacement from it. Somewhat similar conditions prevail in the Bushveld intrusion of South Africa (Figure 3-8D), but in this case the two isochrons have the same slope (age) but different intercepts (Ri's).

3 - 2 - 4 - 3 Lack of evidence of contamination and one age

Contamination seems to be the only possible explanation of how 1,700 m.y. old norites could be altered to give a 2,000 m.y. isochron. Mitchell and Crocket (1972) discussed the possibility that anomalously old isochrons with low initial ratios could be formed assuming "ideal assimilative processes involving complete mixing". Cliff's (1971) description of contamination of leucogranite within 30 cm. of its contract by common Sr from the enclosing tonalite indicates mixing, even though Long (1964) showed that anything less than complete isotopic exchange should destroy the collinearity of data points. Scattering of data has not taken place in the case of the norite and other evidence against Sr contamination is also present. There remains the possibility or even likelihood of some pre-intrusion contamination at depth, e.g. in the lower crust, (see section 3-5-2-1). This would not produce a false isochron.

Three black south-range norite samples (W116, W118, and W120) have the lowest isotopic ratios and show the greatest displacement from the micropegmatite isochron (Figure 3-7). These samples have been collected over a distance of 2,000 feet, yet cluster tightly, well within the limits of experimental error. Yet their displacement from the micropegmatite isochron is well in excess of estimated experimental error and consequently might be expected to show the greatest affects of contamination. The only reasonable contamination capable of creating an older apparent isochron position for these norites is a rather unique process of adding strontium having a Sr^{87}/Sr^{86} ratio less than 0.708 (i.e. lower their position from the micropegmatite isochron). There is no obvious source for strontium of this isotopic composition in the Sudbury area 1.7 b.y. ago. Other reasons suggestive of the lack of contamination of the south-range norites are:

(1) the fresh appearance, the distinct igneous mineral composition, and the igneous cumulate textures of these rocks

(2) the south-range norites are separated from non norite sources of contamination by the underlying biotite and quartz rich norites and the overlying green south-range norite and upper gabbro

(3) the high strontium content of these rocks

(A) would require a lot more strontium to be added or exchanged to change the Sr^{87}/Sr^{86} of these rocks the same amount as a low strontium rock (e.g. leucogranite of Cliff)

(B) concentration gradients favouring loss of strontium rather than gain would be expected

(C) preferential loss of radiogenic strontium 87 could cause the observed displacement, but the rocks with the lowest proportion of radiogenic Sr^{87} would have to lose the most.

It is difficult to understand how the north and south range norites could be contaminated in an exactly similar manner despite the many differences in origin, subsequent history, and country rocks. It has been pointed out in the beginning of this section that removal of four fine grained biotite norites, from the base of the norite and therefore most likely to be contaminated on geological grounds, does

TABLE 3 - 3 Contamination Effects in "Contact" Norites

Sample	Strontium (PPM.)	Rubidium (PPM.)	Distance from granite (feet)
A)Murray offshoot 1			
W - 3	402	99.5	3*
W - 4	420	61.3	7
W - 5	445	48.4	20
W - 6	458	41.9	36
B)Murray granite (Little Stobie mine)			
W - 51	369	58.3	45
W - 52	402	59.9	100
W - 53	434	42.3	470

not change the norite isochron age or intercept. Furthermore a fairly regular, probably primary, variation of rubidium and strontium with rock type occurs in the irruptive (Figures 3-9 and 3-10).

Where obvious contamination of norite has taken place, e.g. adjacent to older Murray granite in the Little Stobie mine or a younger granite dike (Figure 4-3), rubidium contamination is most noticeable and strontium is actually lost (Figure 3-6C and Table 3-3). These contact norites indicate that contamination is very limited in amount and extent, and that contaminated data can be recognized by high scatter and high ratios on Nicolaysen (isochron) diagrams, as well as geologically. This type of contamination does not produce anomalously old isochrons.

Altered norite samples also occur in the irruptive, especially near the micropegmatite-norite boundary on the south range. They are usually easy enough to recognize in the field and in thin sections. Isotopically they frequently show disequilibrium effects (scatter) and do not define isochrons. (Figure 3-6D).

3 - 2 - 4 - 4 Other Evidence of Two Ages

Other studies in the Sudbury area, using various isotopic systems, rocks and minerals, commonly document the same two ages as the norite and micropegmatite isochrons (Table 3-4).

The 2,000 m.y. event seems to be a relatively local event,

TABLE 3-4 EVIDENCE FOR 2,000 m.y. and 1,700 m.y. EVENTS AT SUDBURY
(number of samples in parenthesis)

Method and Material	Age I (m.y.)	Age II (m.y.)	Rock Unit	Location	Reference and interpretation
Pb^{207}/Pb^{206} zircon	1,915 (2)	1,740 (1)	Norite and sub-layer	south range	Recalculation of Souch and Podolsky 1969 Age I primary
Anomalous lead model various ore sulfides	1,920± 50	1,580± 50	Irruptive and Whitewater group	Sudbury basin	Ulrych and Russell 1964, p.467 I. Pb mineralization II.U & Th min.
Rb-Sr whole rock scatterchron	2,005±125 (5) 1,950±100 (29)		Basal Huronian mafic volcanics Combined Huronian	SW of irruptive Sudbury-Espanola	Fairbairn et al. 1969 metamorphic
		1,720± 40 (13) 1,685± 40 (24)	Whitewater sediments Combined sed. + tuff	mainly north range	Fairbairn et al. 1968 sedimentation - (metamorphic)
	2,100± 70 (15)	1,800± 30 (13) 1,800± 30 (3)	Murray granite Murray offshoot dikes Granite dikes	NW Murray granite south range norite south range norite	Chapter 4 (Figure 4-10 B & C) (Figure 4-10 D) (Figure 4-10 A) metamorphic ?
Rb-Sr feldspar Rb-Sr biotite	1,860-2,000 (4)	1,600-1,770 (4) 1,600-1,660 (4)	Basement (3) mpeg.(1) Chaping fm. Basement (2) norite (2)	north range north(east) range north range	Recalculated from Fairbairn et al. 1960 - metamorphic
K-Ar biotite	2,070 (1)	1,600-1,780 (7)	Copper Cliff rhyolite norite, mpeg., & granite	south range north + south range	Fairbairn et al. 1960 metamorphic

OTHER

Rb-Sr feldspar-isoch. Rb-Sr biotite Rb-Sr muscovite	A B S E N T	1,700 (7) 1,710 (1) 1,750±50	Nipissing diabase Basement granite Pegmatite	WEST OF SUDBURY (Blind River) (Cutler batholith)	Van Schmus 1965 - Fig. 4 "regional metamorphism" p.762 Wetherill et al. 1960 - primary
Rb-Sr whole rock Concordia-zircons		1,590(5)-1,700(8) 1,500(3)-1,700(3)	Chief Lake batholith + other Killarney gr.	SOUTH OF SUDBURY (Grenville Front)	Krogh and Davis 1969 + 1970. Age of penetrative mineral lineation

as might be expected to accompany intrusion of the irruptive. This event seems to have a slightly larger but concentric geographic distribution with respect to the Sudbury basin and the common Sudbury breccia (Speers 1956), shatter cones (Bray 1966), and other shock features. In this respect, it is compatible with a paired meteorite impact-irruptive intrusion. Structural investigations, (Brocoum and Dalziel 1973 and Card et al. 1972a), show that the irruptive has undergone deformation during the Penokean Orogeny (1,600 - 1,900 m.y.) and therefore must be older.

The 1,700 m.y. events have been recognized over a vast area. Van Schmus (1965) reported them from the Blind River area west of Sudbury and Krogh and Davis (1969,1970) in the Grenville Province to the SE . These events are closely associated with the Penokean Orogeny.

3 - 2 - 4 - 5 Conclusion

The evidence available indicates the existence of two ages of 2,000 m.y. and 1,700 m.y. in the Sudbury Area and the Sudbury irruptive. Accepting the 2,000 m.y. norite age as being primary, two possible explanations of the micropegmatite isochron are:

(1) it represents a metamorphic age produced by exchange and re-equilibration of strontium isotopes during the Penokean Orogeny, or (2) it represents separate intrusion of the micropegmatite during the Penokean Orogeny. These possibilities are examined in detail in section 3 - 4.

3 - 3 North Range versus South Range

3 - 3 - 1 Introduction

At the beginning of this chapter it was pointed out that the Sudbury basin is separated into a north and south range by a series of faults and the south range is believed to have been uplifted 4 km. in a vertical direction. These faults can be traced into the important Murray fault system (Figure 1-2). Vertical displacement of the south range and/or real differences in crystallization and subsequent metamorphism and deformation of the irruptive are responsible for the various differences observed. These differences may be: pre-, syn-, or post-intrusion and crystallization of the nickel irruptive.

3 - 3 - 2 Pre-Irruptive Differences

Pre-irruptive differences are simply differences in the lithology of the footwall rocks. Basement granites and gneisses of the Superior Province on the north range are easily distinguished from younger Huronian strata and post Huronian intrusions of the Southern Province and south range.

3 - 3 - 3 Syn-Irruptive Differences

The two uppermost units of the irruptive, the micropegmatite and upper-oxide rich gabbro (Table 3-1), are very similar on both ranges. The major difference is a high degree of shearing and alteration on the south range.

On the north range, the main norite unit is the felsic norite. It is a grey, medium grained, plagioclase-hypersthene orthocumulate, with a hypersthene to augite ratio of 2:1 and plagioclase grains characterized by a small unzoned core. It corresponds to the extreme upper part of the south-range norite (Figure 3-2). In contrast, the bulk of the south-range norite is a black or brown, medium to coarse grained plagioclase-hypersthene mesocumulate, which has a hypersthene to augite ratio of 5:1 and plagioclase grains with a large unzoned core and a thin zoned mantle.

Stratigraphically below and conformable with the south-range norite is the quartz rich norite. It is distinguished from the former by a progressive increase in quartz and decrease in grain size towards the outer margin of the irruptive. At the extreme outer margin, biotite becomes much more abundant giving rise to the variety known as biotite norite. On the north range, the lowermost unit is the mafic norite. It shows an abrupt change from the overlying felsic norite and occurs discontinuously along the footwall contact. (Figure 3-12). Hewins (1971) believed that it represents a rapidly cooled marginal facies and it has been tentatively correlated to the similarly fine grained quartz rich norite of the south range (Figure 3-2).

In Figure 3-9 the rubidium and strontium concentrations of norite samples from the Blezard traverse are compared with the modal data of Naldrett et al. (1970). These data were obtained from separate suites of samples and give good agreement and independent evidence for the petrologic units. Similar

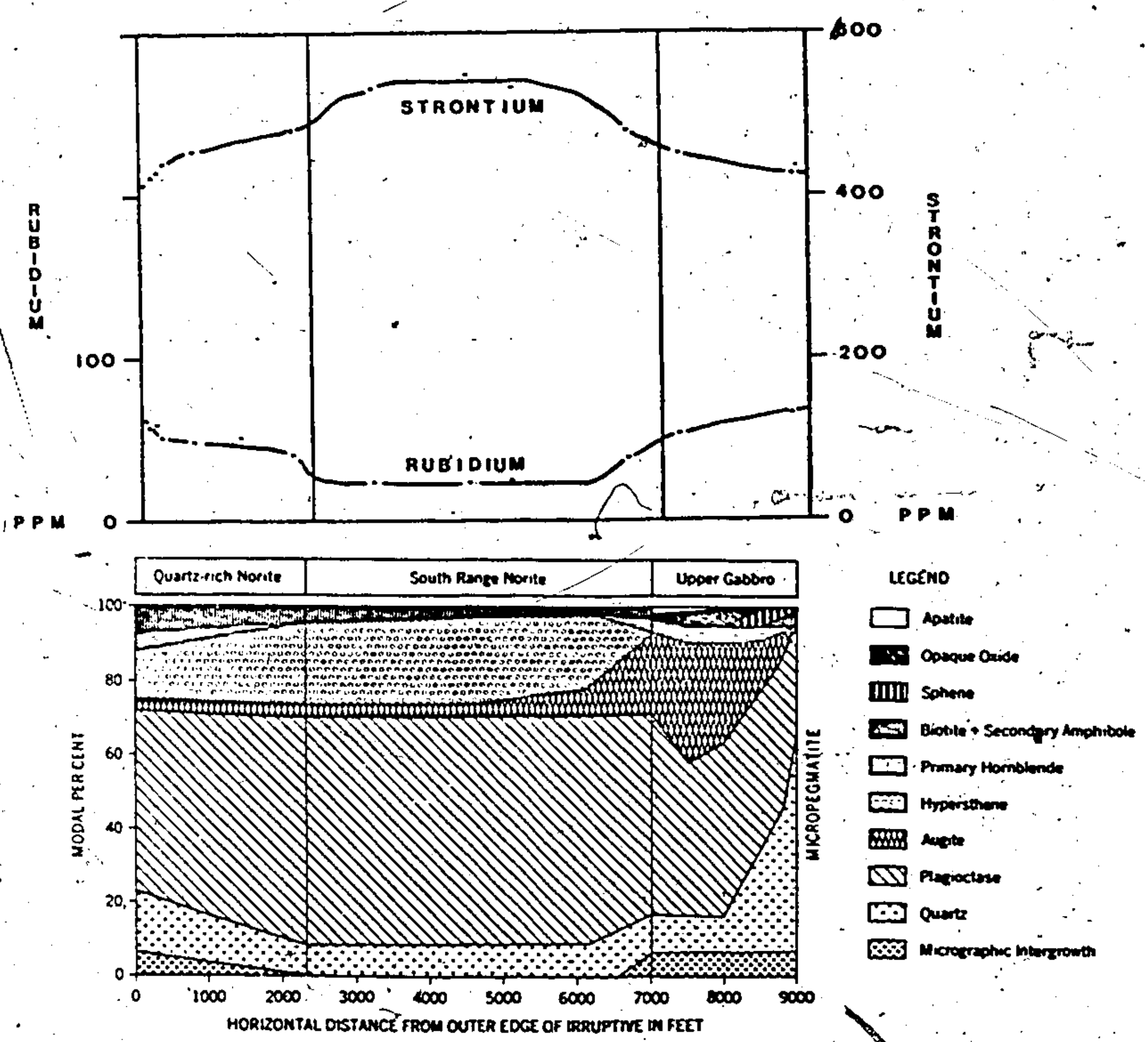

Figure 3 - 9: Variation of rubidium and strontium in the quartz-rich norite, south-range norites, and upper gabbro over the Blezard traverse compared with the modal data of Naldrett et al. 1970.

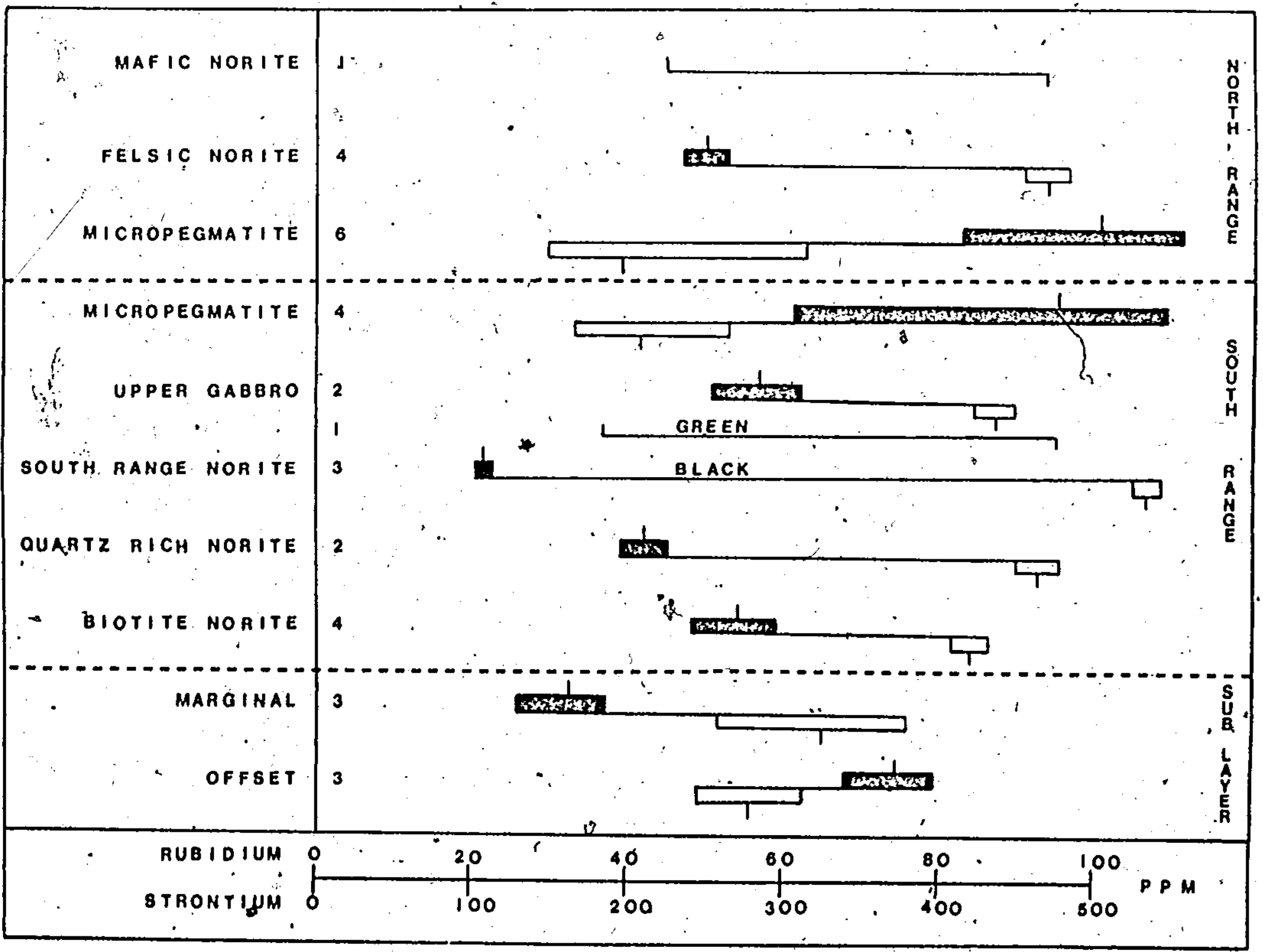

Figure 3 - 10: Range and average abundances of rubidium (solid-upper) and strontium (open-lower)

groupings can also be seen in Figures 3-10 and 3-5A and B. Similar values of Rb, Sr, Rb^{87}/Sr^{86}, and Sr^{87}/Sr^{86} from the mafic and quartz rich norites supports their correlation.

Wilson (1956) pointed out the high ratio of micropegmatite to norite exposed on the north range (3:1) relative to the south side (1:1). The sharply contrasting north and south range marginal sub-layer deposits have been described by Naldrett et al. (1972 a and b). Gasparrini and Naldrett (1972) studied and reported compositional differences in magnetite and ilmenite in various irruptive rock types. They calculated a much lower temperature for the final partitioning of iron and titanium between magnetite and ilmenite on the south range. This can be explained by metamorphism or a much slower cooling of the south range.

3 - 3 - 4 Post-Irruptive Differences

Metamorphic effects of the Penokean (deformation and recrystallization) and Grenville (thermal overprint) Orogenies are responsible for most of the post irruptive differences between the north and south ranges with or without help from faulting. Deformation on the north range is limited to late NNE trending faults (Figure 3-1), while the south range is highly sheared (along a WNW trend) and altered in many places. Distinctly different mineral ages are found on the north (1.6-2.0 b.y.) and south ranges (1.0 - 1.4 b.y.) (Figures 5-1 and 5-2). These are discussed in detail in Chapter 5. The more extensive metamorphism of the south range can also be recognized in recrystallized country rock breccias (Langford 1960, p.30).

Differences in paleomagnetic pole positions and dip of the base of the irruptive on either side of the basin must be related to major folding and/or faulting of the basin.

3 - 3 - 5 Conclusion

The concentration and isotopic ratios of Sr and Rb in norite and micropegmatite whole rock samples from both the north and south ranges do not appear to have been significantly affected by well documented differences in crystallization and subsequent metamorphism (recrystallization). Consequently, the north plus south range isochrons (Figures 3-5C & D and 3-7C) must be primary or have been isotopically re-equilibrated by a process that has affected the north and south range whole rocks in an identical manner.

The slightly younger ages of south range norites (Figure 3-5A and B) and micropegmatites (Figure 3-7 A and B) are not considered to be significant, even though they agree with a well defined tendency of south range mineral ages to be younger.

3 - 4 Norite versus Micropegmatite

3 - 4 - 1 Introduction

Like the north and south ranges, both original and later differences are recognizable in the upper (micropegmatite) and lower (norite) layers of the irruptive. They also show a few striking similarities; (1) their shape and geographic position,

(2) similar paleomagnetic directions within various sectors of the irruptive (Larochelle 1969), and (3) the same temperature of equilibration of oxides from the north range (Gasparrini and Naldrett 1972). These have been interpreted as showing that the two phases were probably intruded and cooled at the same time.

Cryptic layering and igneous textures (Naldrett et al. 1970) indicate that the norite is a primary igneous cumulate, whereas texture and mineralogy indicate that the micropegmatite has been metamorphosed during hydrothermal greenschist facies metamorphism (Section 3-4-4). This interpretation is consistent with the norite and micropegmatite isochrons reported earlier (Figures 3-5C or D and 3-7C)

3 - 4 - 2 The Norite Micropegmatite boundary: The "Transition Zone"

Recognition of the exact nature of the norite-micropegmatite boundary as hybrid contact or a transition zone is important to the proper assessment of the various hypotheses which have been proposed to explain the origin of the irruptive (Section 3-4-3). However, failure to reach agreement on the nature of the "transition zone" and inconsistent use of imprecise definitions (Table 3-5) has led to unnecessary confusion. This is reflected by frequent reference to "the so-called transition zone," (e.g. Hawley 1962 p.23)

Specific gravity data (Collins 1934) - (Figure 3-11),

TABLE 3 - 5 Descriptions of the Norite-Micropegmatite Boundary and Definitions of the "Transition Zone"

GEOLOGIST	CRITERIA	DEFINITION
Walker (1897) & Coleman (1913)	Chemical analysis & petrology	Recognized a complete gradation from norite to micropegmatite
Knight (1917)	Chemical analyses	Showed that a regular gradation from norite to micropegmatite does not exist.
Phemister (1925)	Quantitative mineral (modal analyses)	Showed a narrow contact or transition zone between fairly uniform norite and micropegmatite. He found one locality with a sharp contact and a maximum width of 80 yards at others. (1) The zone is defined by sudden changes in mineral abundances and composition of plagioclase feldspar
Collins(1934, p.125-126)	field appearance and thin sections	(2) The base of the transition zone is defined by "the color of the feldspar, which begins to change from a greenish or greyish white to a yellowish white". The top is where "the stout rectangular shape of the pyroxene gives place to less definite shapes.". Admitted that the chemical analyses of Coleman, Moore, and Walker, "tended to confirm Phemister's claim that an abrubt change in composition occurs where norite and micropegmatite join."
Langford (1960, p.38) (North Range)	field appearance	(3) "The transition zone should include all rocks lying between granophyre and typical grey norite. (It) is unlike either of them." He divided this into 4 sub-units.
Card (1968, p.31) (South Range)	field appearance	(4) "In the field, all rocks that did not have the megascopic appearance of either norite or granophyre were placed in this zone."
Stevenson & Colgrove (1968, p.31)		"The micropegmatite is transitional with the norite."
Naldrett et al. (1970, p.143)		Did not recognize the transition zone as a distinct unit, but referred to, "the abrupt transition between norite and micropegmatite as contrasted to the uniformity within these units."

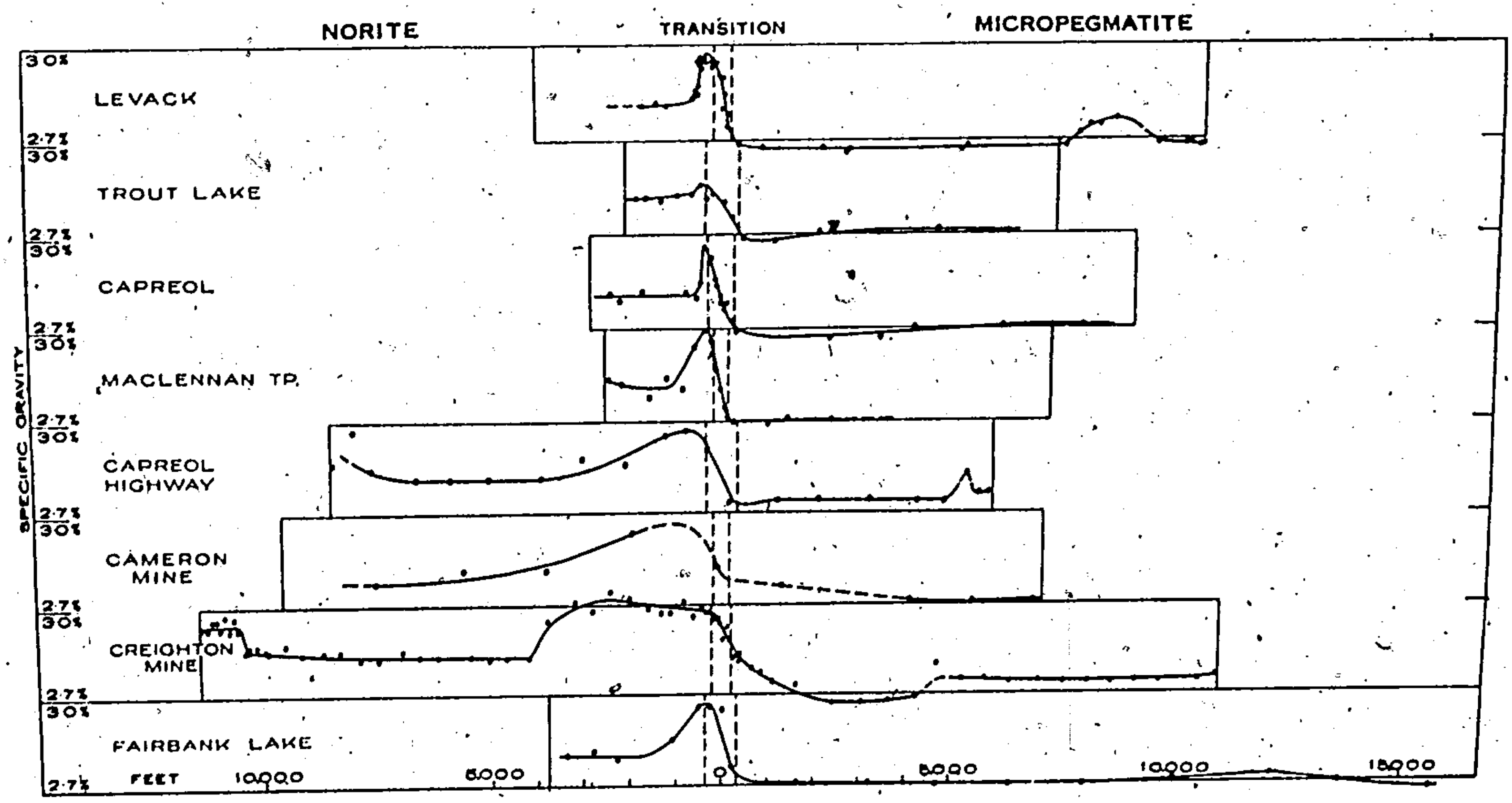

Figure 3 - 11: Curves of specific gravity variation across the nickel irruptive (after Collins 1934).

plagioclase compositions (Naldrett et al. 1970, figures 17-19), modal data (Phemister 1925, Naldrett et al. 1970) (Figure 3-2), and chemical analyses (Collins 1934) from various traverses across the irruptive, all indicate that the micropegmatite is not transitional with the oxide rich gabbros of the upper norite, but is in rather abrupt contact with it. Furthermore, the transition zone is not a layer parallel to other units in the irruptive as often implied. Hawley (1962, p.23) noted, "(It) is seldom exactly the same in any two localities and differences cannot be solely explained by either differentiation by crystallization or hybridization and must have involved late stage deuteric events as well as deformation in places."

3 - 4 - 3 The Origin of the Nickel Irruptive

Table 3-6 contains a summary of some of the many ideas about the origin of the irruptive and a list of some of the geologists who proposed and/or supported them. The structure of the irruptive is believed to be a folded sill, a funnel-shaped lopolith, or a ring dike. Possible explanations of the norite-micropegmatite origin are discussed below.

I Gravitational differentiation: Magmatic differentiation involving the settling out, under the influence of gravity, of earlier formed denser crystals would seem to adequately explain the cryptic layering in the norite portion of the irruptive. However, this does not explain the abrupt change from norite to micropegmatite relative to the uniformity within them. This led Collins (1934) to propose that a lighter,

TABLE 3-6 SUMMARY OF IMPORTANT CONCEPTS OF SUDBURY GEOLOGY

GEOLOGIST(S)	STRUCTURE OF IRRUPTIVE	ORIGIN OF NORITE -MICROPEGMATITE LAYERS	ORIGIN OF Cu-Ni ORES
Walker (1897) Coleman (1905, 1913)	Central collapse of a sill or laccolithic sheet to form the basin	gravitative, differentiation *in situ*	
Knight (1917) Phemister (1925)	ring dike	multiple intrusion	hydrothermal replacement
Collins (1934)	folded sill	gravitational differentiation and formation of three immiscible liquids - assimilation not important	
Wilson (1956)	funnel-shaped lopolith	differentiation of morite and assimilation	gravitational settling and separation of sulfide liquid
Hawley (1962)	sheet-like mass intruded into a down-sagged basin	gravity differentiation	immiscible sulfide liquid plus hydrothermal alteration and local remobilization
Stevenson & Colgrove (1968)		differentiation but assimilation for the bulk of micropegmatite	
Souch and Podolsky (1969)	Ore associated with sub-layer: a distinct inclusion and sulfide rich magma		

TABLE 3-6 Continued

GEOLOGIST(S)	STRUCTURE OF IRRUPTIVE	ORIGIN OF NORITE -MICROPEGMATITE LAYERS	ORIGIN OF Cu-Ni ORES
Naldrett et al. (1970, 1972)	Characteristics of both lopolith and sill	differentiation of norite and assimilation before and after intrusion	re-worked and re-intruded sulfide breccias containing ultra mafic or granitic inclusions form distinct sub-layer units
Dietz (1972)	meteorite impact crater	differentiation of a magma of deep crustal origin	Cosmogenic (at least in part) pre-irruptive meteorite splash

immiscible micropegmatite-liquid separated from the norite and then crystallized.

II Multiple Intrusion: The "narrow" transition zone" led Phemister (1925) to propose that the norite and micropegmatite had intruded separately. He interpreted a sharp increase in white mica and epidote in the upper norite as a contact metamorphic effect. However, lack of good intrusive contacts and quartz-feldspar intergrowths in each unit led him to include a common source and a short time interval between intrusions for the two magmas. Recent studies by Yoder (1973) indicate basalt and rhyolite magmas can coexist at depth at least for limited periods. He also pointed out that, "The paucity of intermediate rocks casts doubt on the production of contrasting magmas (rocks) by fractional crystallization." Phemister's second suggestion that the irruptive is a ring dike is not essential to the multiple intrusion hypothesis, even though it has often been treated as such.

III Assimilation: Collins (1934, p.150) considered it highly improbable that the nickel irruptive could have assimilated enough material to produce the large amount of micropegmatite. Ironically, Stevenson and Colgrove (1968, p.35) used the large amount of micropegmatite to rule out differentiation from the norite. They also cited the large number of country rock inclusions in varying stages of assimilation in the micropegmatite and the sharp to gradational contact between the micropegmatite and overlying country rocks as evidence in favor of forming the bulk of the micropegmatite by assimilation.

Hamilton (1960) showed chemical similarities, high alkalis and iron; low aluminum and calcium, of the micropegmatite and overlying Onaping fm. indicating that they are cogenetic. However, he interpreted the Onaping as an early silicic differentiate, rather than a source for assimilation.

None of the above ideas explain the differences in norite and micropegmatite whole rock isochrons, and conversely the isochrons do not support rejection or acceptance of any of the proposed origins. The Sudbury irruptive is more or less a unique layered intrusion, as are many others, and analogy to other granophyre-gabbro masses does not really help form a specific understanding of geologic events at Sudbury. For the purposes of this study, the recent model of Naldrett et al. (1970 and 1972a) (Figure 3-12) ~~can be~~ used as a working model. It most satisfactorily attempts to explain the origin of the irruptive using available information. It combines the processes of differentiation of silica rich basalt magma, assimilation of roof rocks, and subsequent faulting and metamorphism.

3 - 4 - 4 Metamorphism of the Micropegmatite

The micropegmatite may have been affected by more than one metamorphic event. However, greenschist metamorphism of late Penokean age (1.7 b.y.) has left the most obvious record (Table 3-7). The micropegmatite has a typical greenschist facies mineral assemblage including quartz-albite-epidote-biotite and/or chlorite, usually accompanied by minor muscovite and sphene. (Tables 3-7 and D-1 G).

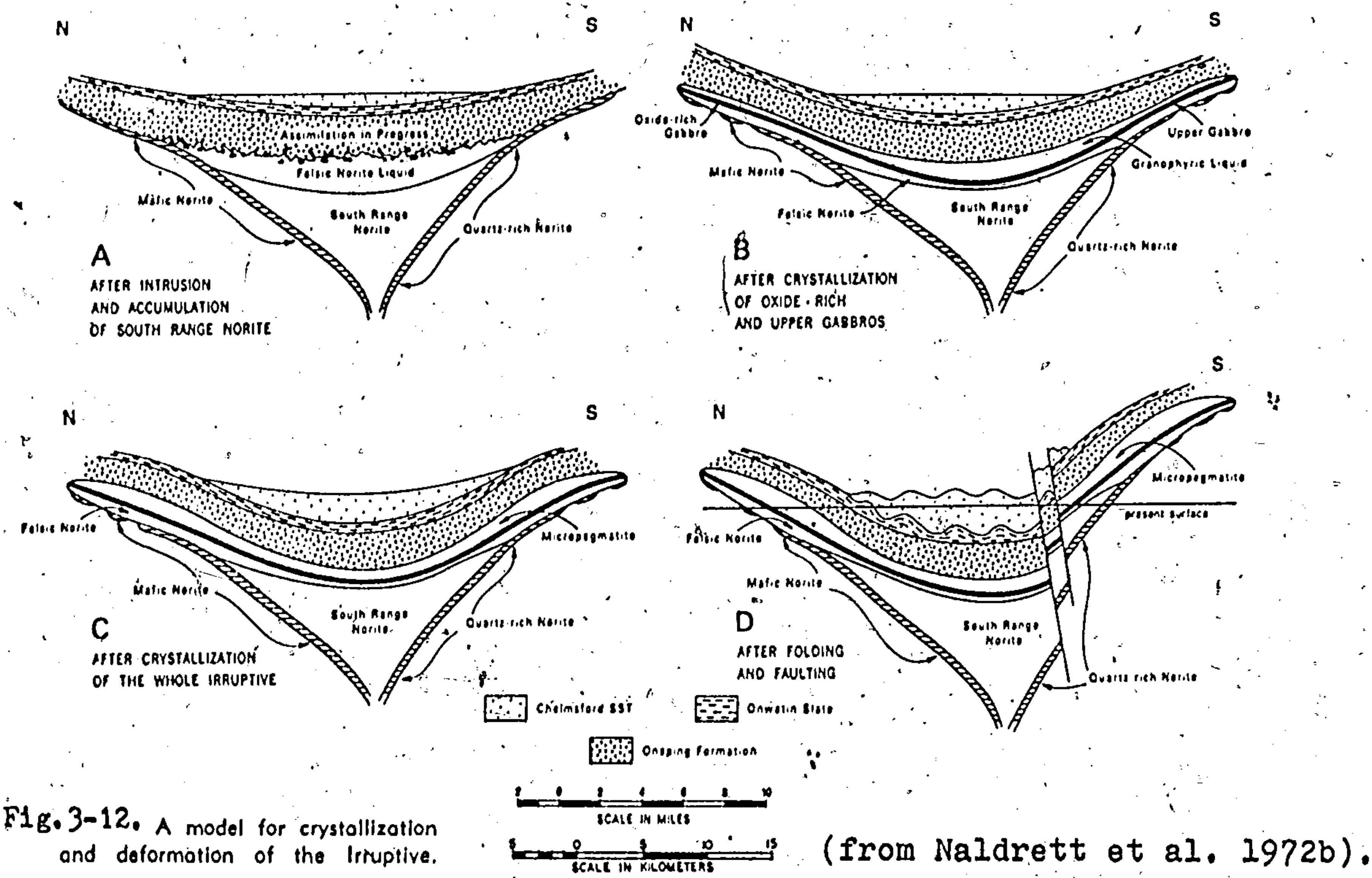

Fig. 3-12. A model for crystallization and deformation of the Irruptive. (from Naldrett et al. 1972b).

TABLE 3-7 EVIDENCE OF GREENSCHIST FACIES METAMORPHISM OF THE MICROPEGMATITE

EVIDENCE	DESCRIPTION	REFERENCE
Plagioclase - albite + epidote	1) An abrupt change from calcic plagioclase to albite plus epidote occurs at the norite - micropegmatite boundary. 2) The very low orthoclase content of albite coexisting with potassium feldspar indicates a metamorphic origin for the albite	Naldrett et al. 1970, p. 137.
Mafic minerals	Pyroxenes and hornblende change to chlorite and/or biotite across the norite-micropegmatite boundary	Phemister 1925, Langford 1960, Naldrett et al. 1970, etc.
Granophyric intergrowth	The abundance and variation of granophyric and myrmekitic intergrowth suggests a metamorphic origin for at least some of the intergrowth. It occurs as porphyroblasts, fine grained ground mass, cracks in feldspar crystals, replacing feldspar margins or cores. It has regular graphic, radial, irregular wormy and "poikelitic" forms. In the norite it is much less abundant and occurs mainly as mesostasis.	
Paleomagnetism	"The considerably lower magnetic homogeneity of the micropegmatite suggests that an appreciable percentage of its remnant magnetism may in fact reside in minerals formed long after the original cooling phase of this part of the irruptive."	Larochelle 1969, p. 21-22

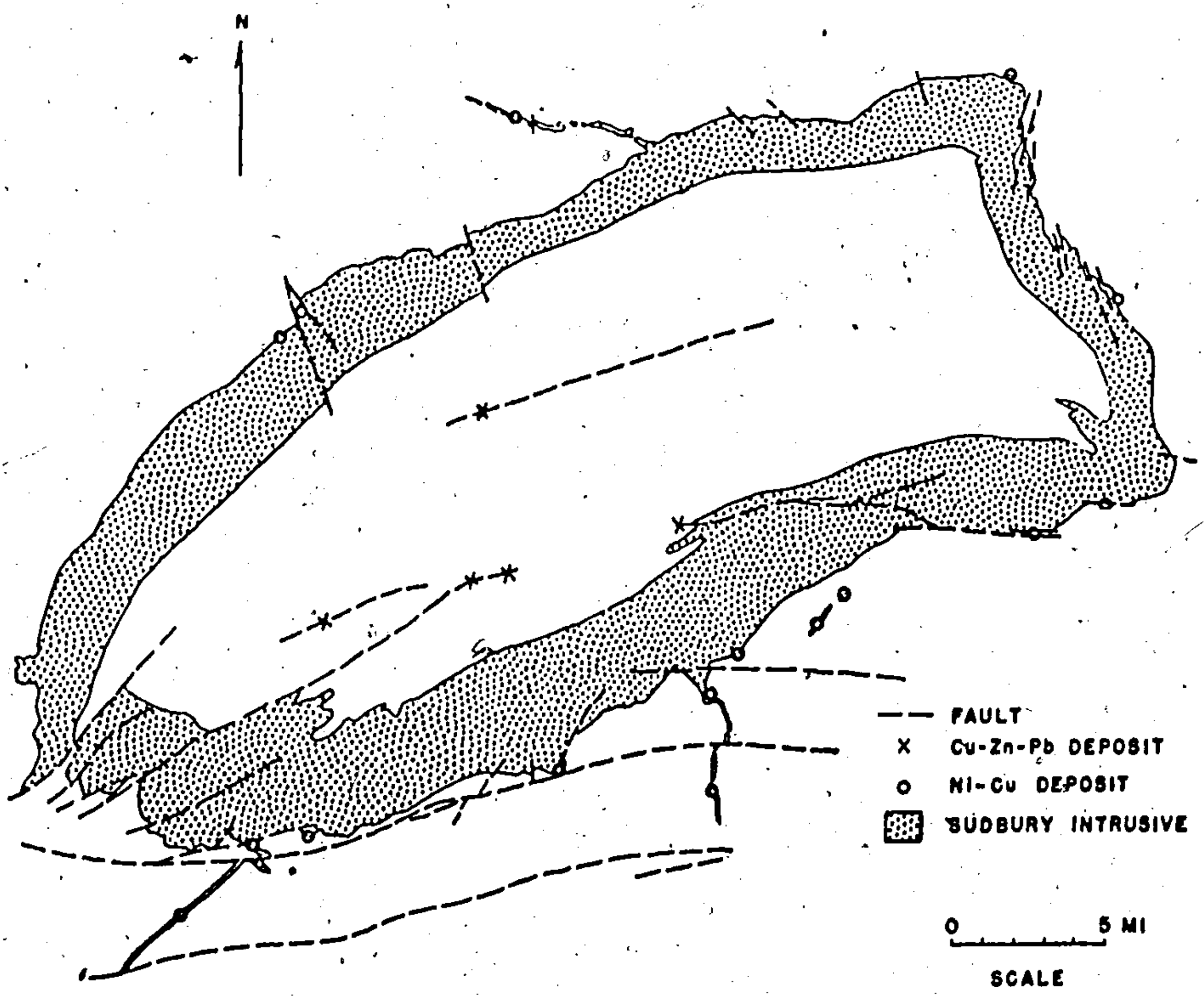

Figure 3 - 13: Distribution of copper-nickel and zinc-copper-lead deposits in the Sudbury District, Ontario. (from Wilson 1953)

Stilpnomelane, actinolite and calcite have also been reported. Evidence for the same Penokean greenschist metamorphism is also found in the overlying Whitewater Group (Table 3-8 and Figures 3-14 and 3-15).

Associated hydrothermal ore deposits, the presence of hydrous minerals, and the likelihood of connate and/or juvenile water in the rock units involved are indicative of the "wet" or hydrothermal nature of the metamorphism. This is also indicated by the behaviour of Rb-Sr whole-rock data. (Fig.3-14). This diagram shows that the most complete metamorphism has taken place in the micropegmatite and overlying units, while the norite has acted as an impermeable barrier to the hydrothermal solutions and only the upper most sections (upper gabbro and green norite) have been affected. This effect appears to be quite common, Turner (1968, p. 80) noted that many thick gabbroic sills have a relatively unaltered central zone margined by a border of greenschist or amphibolite. The same type of metamorphism is present in the Nipissing diabase (Sudbury Gabbro) (Card and Pattison 1973).

Deuteric effects, related to intrusion, are distinct and/or limited. In the green norite and oxide rich gabbro, they are represented by large dark green pleochroic hornblende crystals, while very fine grained uralite (amphibole and epidote) is metamorphic. The hornblende also mantles pyroxenes in the south range norite. The turbid plagioclase of some irruptive rocks (Naldrett et al. 1970, p. 137) may be deuteric and/or hydrothermal in origin.

TABLE 3-8 EVIDENCE OF GREENSCHIST FACIES METAMORPHISM OF THE WHITEWATER GROUP

EVIDENCE	DESCRIPTION	REFERENCE
Petrography	1) Chelmsford fm: "The presence of chlorite oriented parallel to the secondary foliaton indicates that the Chelmsford fm. has undergone low grade metamorphism."	Rousell 1972, p.81.
	2) Onaping fm: "The mineralogy of the Onaping fm. indicates only mild metamorphism to the chlorite grade."	Fullagar et al. 1971, p.439.
Cu-Zn-Pb mineralization	Major, pre-olivine diabase, copper-zinc-lead deposits occur along the intersection of post irruptive faults within the basin (Figure 3-13). The micropegmatite appears to be the source of this mineralization.	Wilson 1953, p. 399-400 and Martin 1957, p. 368.
Mineral ages	Despite possible obscuring by later events and the limited number of mineral ages available, the inferred 1.7 b.y. age of greenschist metamorphism can still be recognized from Rb-Sr feldspar ages of the Onaping fm. (see Figure 5-5 and Table 5-1).	Fairbairn et al. 1960.
Rb-Sr whole rock	Rb-Sr whole rock data from the micropegmatite and the Whitewater sediments fall along or close to a reference isochron of age 1.7 b.y. and intercept (Ri=0.708). The Onaping data also fall close to the reference isochron (Figure 3-15).	Fairbairn et al. 1968.

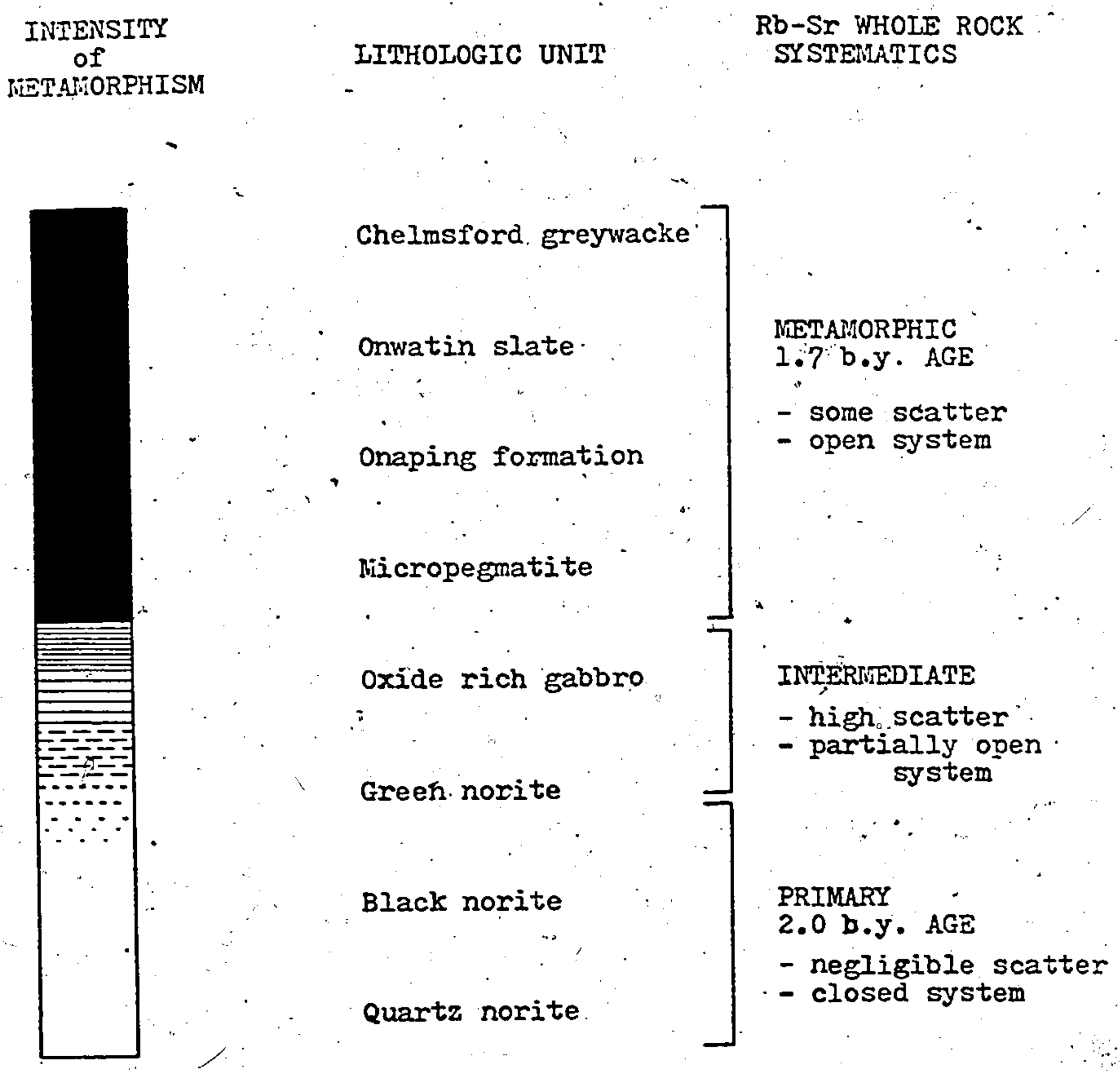

Figure 3 - 14: Hydrothermal Metamorphism in the Sudbury basin
Note: The stratigraphic location of the green norite-black norite transition may vary from section to section.

Normally whole rock samples are not expected to show open system behaviour with respect to Rb and Sr during greenschist facies metamorphism (section 6-1). However, water content and/or water pressure are capable of producing different metamorphic assemblages at the same rock temperature and rock pressure (Yoder 1955). Even at comparatively low temperatures saline water will approach equilibrium with alkali bearing crystalline phases and become capable of transporting various elements as shown by various hydrothermal ore deposits (Orville 1962, 1963). Brooks (1968, p. 4757) concluded, "feldspar alteration petrographically revealed in a rock must be taken to be suggestive of isotopic movement (between feldspars) and of potential total-rock open-system behaviour." As plagioclase feldspar(the main Sr bearing phase) has been completely altered to albite and epidote and trace elements (ie. Sr and Rb) are more effectively redistributed than major elements (De Vore 1955), it seems likely that strontium, (the only element required to be isotopically re-equilibrated), could readily enter or leave the hydrous fluid phase and provide the necessary movement and isotopic exchange observed in the basin.

If a common origin is assumed for the norite and the micropegmatite (age = 2.0 b.y.; initial $Sr^{87}/Sr^{86} = 0.706$), then the micropegmatite would be expected to have a $Sr^{87}/Sr^{86} = 0.712$($\pm$ 0.002 1.7 b.y. ago (Table 3-9). This value is slightly higher, (within the limits of error), than the observed value obtained from the micropegmatite isochron and can be interpreted as evidence for a certain amount of open-system behaviour. Potassium feldspar veinlets in some micropegmatite samples (e.g. W 156) also indicate this. Similar Sr^{87}/Sr^{86} relation-

TABLE 3 - 9 Values of $Sr^{87}/Sr^{86}{}_o$ in the Sudbury Basin

Time (b.y.)	$Sr^{87}/Sr^{86}{}_o$ Micropegmatite	$Sr^{87}/Sr^{86}{}_o$ Basement[1]
present	0.740 ± 0.010	0.721 ± 0.005
1.7 (calculated)	0.712 ± 0.002[2]	0.711 ± 0.005
1.7 (observed)	0.7083 ± 0.007	0.709 ± 0.0015[3]
2.0 (assumed)	0.7063 ± 0.0002[4]	
2.5 (assumed)		0.706

1. After Fairbairn et al. 1968
(Basement = average Superior Province)
2. Calculated using: $(Sr^{87}/Sr^{86}) = (Sr^{87}/Sr^{86})_o + (Rb^{87}/Sr^{86})\lambda t$

where $(Rb^{87}/Sr^{86})\lambda t = (1.5 \pm 0.5)(1.39 \times 10^{-11})(0.3 \times 10^{9})$

or 0.006 ± 0.002

3. Whitewater group

4. Norite

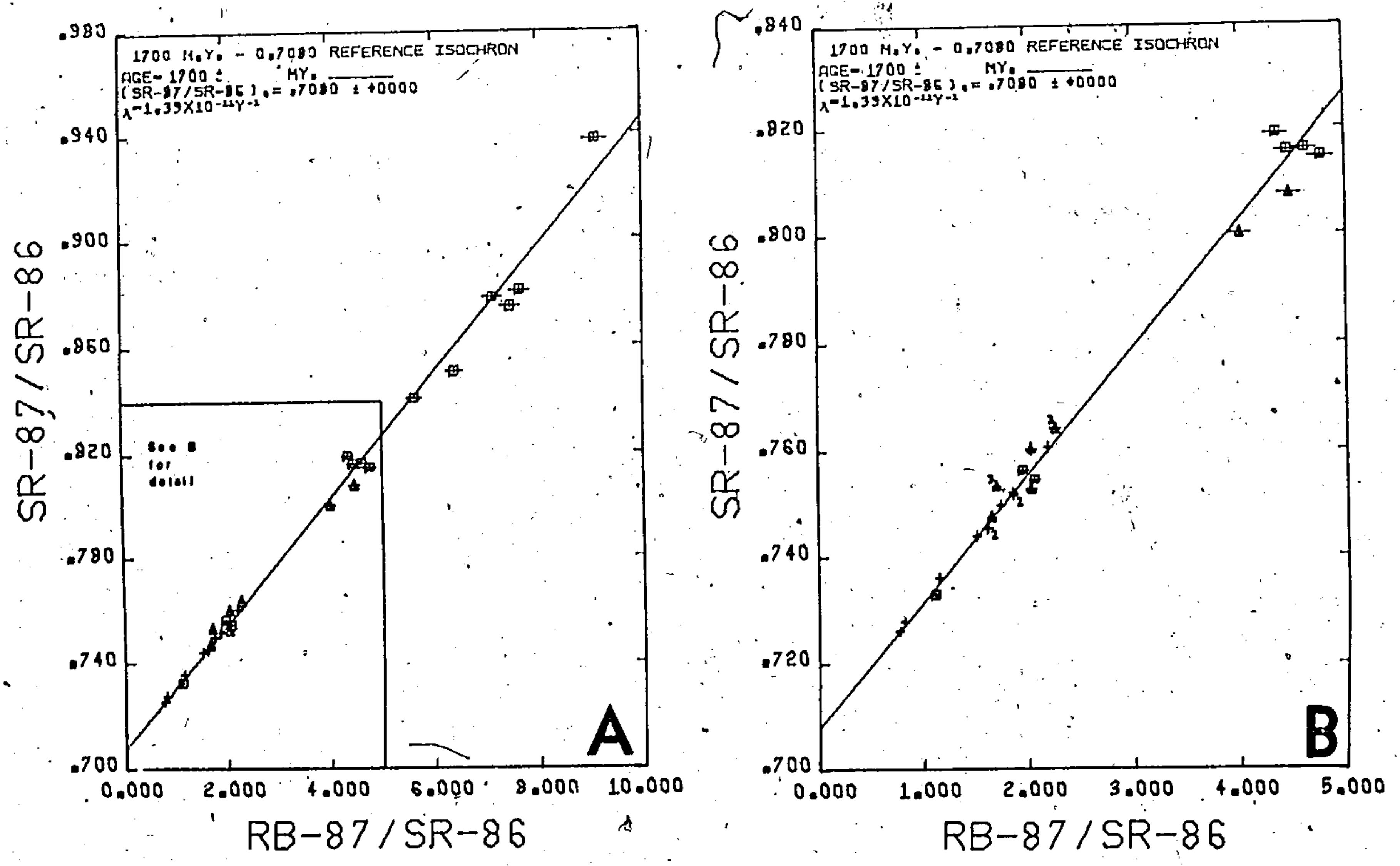

Figure 3 - 15: Comparison of Whitewater Group and Micropegmatite Rb-Sr Whole Rock Analysis. (Micropegmatite = crosses, Onaping fm. = triangles, and Whitewater sediments = squares).

ships hold for the basement - Whitewater system (Table 3-9)

Outside the basin, 1.7 b.y. mineral ages are common where they have not been obliterated by later events, but whole rock systems (Fairbairn et al.) may remain partially unaffected due to lack of water (which may have been driven off by an earlier event) and/or lack of proper "plumbing".

A 1.4 - 1.5 b.y. (Fullagar et al. 1971) or 1.3 - 1.4 b.y. (Fairbairn, 1969) age for the greenschist metamorphism seems to be ruled out by its apparent close relationship to Penokean deformation and metamorphism e.g. chlorite oriented parallel secondary foliation in the Chelmsford formation (Rousell, 1971), structural control of the Cu-Pb-Zn mineralization (Wilson 1953, Martin 1957), and scarcity of 1.3 - 1.5 b.y. mineral ages on the north range. The metamorphism is also earlier than the late olivine diabase dikes (1.46 ± 0.13 b.y. Gates & Hurley 1973) which cut the Cu-Pb-Zn deposits and earlier foliation.

3 - 4 - 5 Discussion

In the previous sections a contemporaneous origin of the norite and micropegmatite 2.0 b.y. ago has been presented. This was then followed by greenschist metamorphism 1.7 b.y. ago. An alternate conceptual model involving intrusion of the micropegmatite as a separate intrusion 1.7 b.y. ago and metamorphism at the same time and/or shortly thereafter would not require isotopic resetting of whole rocks, but seems to be ruled out by the evidence in section 3 - 4 - 1 favoring a contemporaneous origin for the norite and micropegmatite.

Fairbairn et al. (1968) proposed the "consanquinity of all rocks of the (Sudbury) structure" 1.7 b.y. ago on the basis of major element chemical and Rb-Sr isotopic data. However, this does not explain: (1) the 2.0 b.y. norite isochron age, (2) the various peculiarities - including petrographic shock features found in the Onaping fm. or (3) how the layered irruptive can be logically related to or derived from the same source as the overlying Chelmsford turbidite sediments.

3 - 5 Contrast and Comparison of the Sudbury Nickel Irruptive to Other Intrusions

The uniqueness of the Sudbury irruptive is shown by its tectonic or structural position and its rich copper-nickel ore deposits, nevertheless certain similarities and differences with respect to other intrusions may be worth noting.

3 - 5 - 1 The Sudbury Irruptive versus Other Intrusions in the Area

The geographic proximity, relatively similar ages (2.00 ± 0.07 b.y. vs, 2.16 ± 0.08 b.y.), and identical initial Sr^{87}/Sr^{86} values (0.706) suggest a common source and similar origin for the Sudbury norite and the Nipissing diabase (Sudbury gabbro). Other similarities in petrography, chemistry, mineralization, structure, and metamorphism also occur. Their respective Rb-Sr isochron ages are in agreement with the geological evidence of Cooke (1946) who reported that the norite bevels granite-Sudbury gabbro contacts, and Speers (1956) and others who showed that the Sudbury gabbro is cut by pre-irruptive breccias.

Late, northwesterly trending, olivine diabase dikes are distinctly alkaline in composition (Fahrig et al. 1965). This and a distinctly lower age (1.46 ± 0.13 b.y.) and initial Sr^{87}/Sr^{86} (0.7034 ± 0.0004) (Gates and Hurley 1973) indicate a later and different type of origin. A deep mantle source for the olivine diabase dikes is a reasonable explanation of the chemical differences. The diabase age is not well established,[1] but geological evidence is compatible with a late Penokean to Elsonian origin.

The Rb and Sr contents of north and south range micropegmatite samples are comparable with each other (Figure 3-10), but chemically and petrographically they are quite distinct from other rocks in the area. However, the micropegmatite must have had the same Sr^{87}/Sr^{86} value as the Chelmsford and Onaping fms. 1.7 b.y. ago.

3 - 5 - 2 The Sudbury Irruptive versus other Mafic Layered Intrusions

The term "layered intrusion" encompasses a large number of separate rock masses. They are usually mafic in composition and assumed to have been derived from all the earth's mantle. Despite many general similarities, vast differences in age,

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[1] Geological contamination, the low spread in isotopic ratios, and many samples collected near the Grenville Front have contributed to the large uncertainty reported - See Gates & Hurley (1973) for additional discussion.

size, shape, chemical and mineral composition, geologic and tectonic setting, differentiation-crystallization, and subsequent history can occur. This has led to a great number of individual combinations within the broad definition of layered intrusion.

3 - 5 - 2 - 1 The Initial Sr^{87}/Sr^{86}

The initial Sr^{87}/Sr^{86} values of layered intrusions and various basalts have frequently been interpreted as representing the value of Sr^{87}/Sr^{86} in the mantle at the time these rocks crystallized. Various single - multiple, linear - non linear, and dynamic - steady state models of Sr isotope evolution in the mantle have been proposed, (e.g. see Chapter XII in Faure and Powell 1972). Many of the criteria in these models are rather arbitrary and the available data does not provide a conclusive answer (see Figure 8, Davies et al.1970 and/or Figure XII,2, Faure and Powell 1972). Moorbath (1972) pointed out that the assumption "that the observed Sr data are solely related to the ultimate source region of an igneous rock" may be invalid and the observed data "reflect the sum total of <u>all</u> processes" including: "- i) differentiation or melting of mantle derived sources, ii) partial melting of continental crust, iii) contamination by, and assimilation of, country rock by magma, iv) various types of wall-rock reaction leading to isotope migration and exchange between magma and wall-rock, v) interaction with circulating ground waters, etc.

Obviously more than one of these processes may have occurred in the evolution of a given rock."

Certainly more than one of these processes may have been in operation during the formation of the Sudbury norite (0.7063 - section 3-2), the Nipissing diabase (0.7061 - Fairbairn et al. 1969, Van Schmus 1965), and the mafic-rocks of the Bushveld and Losberg intrusions (0.7065 - Davies et al. 1970), as these values are considerably higher than the 0.7020 ± 0.0005 assumed for the upper mantle 2.0 b.y. ago (e.g. Figure XII.2., Faure and Powell 1972, p.134). Additional evidence for the previously mentioned processes affecting the Sudbury irruptive is the quartz rich nature of all its rocks (Naldrett et al. 1970, p.147 and 1972a, pp. 212-214).

3 - 5 - 2 - 2 Gabbroic versus Granitic Portions of Layered intrusions

In addition to treating each layered intrusion separately, their mafic and granitic (granophyric) portions should also be individually tested. Failure to do so may be a common pitfall of Rb-Sr geochronology. Table 3-10 shows significant mafic-granite differences found in the Sudbury and Bushveld intrusions. Other intrusions showing distinct mafic-granitic differences in Sr isotopes are the Newer Gabbros of Northeast Scotland (Pankhurst 1969), the Skaergaard intrusion, East Greenland (Hamilton 1963) and preliminary results from the Muskox intrusion, North West Territories (R.K.Wanless and T.N.Irvine, personal communication).

The Ushwana complex (Davies et al. 1970), the Nipissing diabase (Fairbairn et al, 1969 and Van Schmus 1965), and the Duluth gabbro (Faure et al. 1969) seem to have been homogenous

TABLE 3 - 10 Comparison of Mafic and Granitic Rocks in the Sudbury Irruptive and Bushveld Intrusion

	Unit	Geology	isochron age (b.y.)	$(Sr^{87}/Sr^{86})_o$
SUDBURY	granitic (micropegmatite)	Greenschist metamorphism obscures origin	1.7	0.7083
	mafic (norite)	Essentially igneous (Naldrett et al.1970)	2.0	0.7063
BUSHVELD	granitic	Probably formed by anatexis of the epicrustal rocks (felsites and granophyres) and Transvaal Sediments (Willemse 1969)	1.95	0.715
	mafic	Igneous	1.95	0.7065
			Davies et al. 1970	

closed systems, while Sr isotope data from many other layered intrusions is incomplete or non existent.

Granitic or granophyric rocks associated with layered intrusions can also be expected to vary from intrusion to intrusion as well as within each intrusion, depending on their origin and subsequent history.

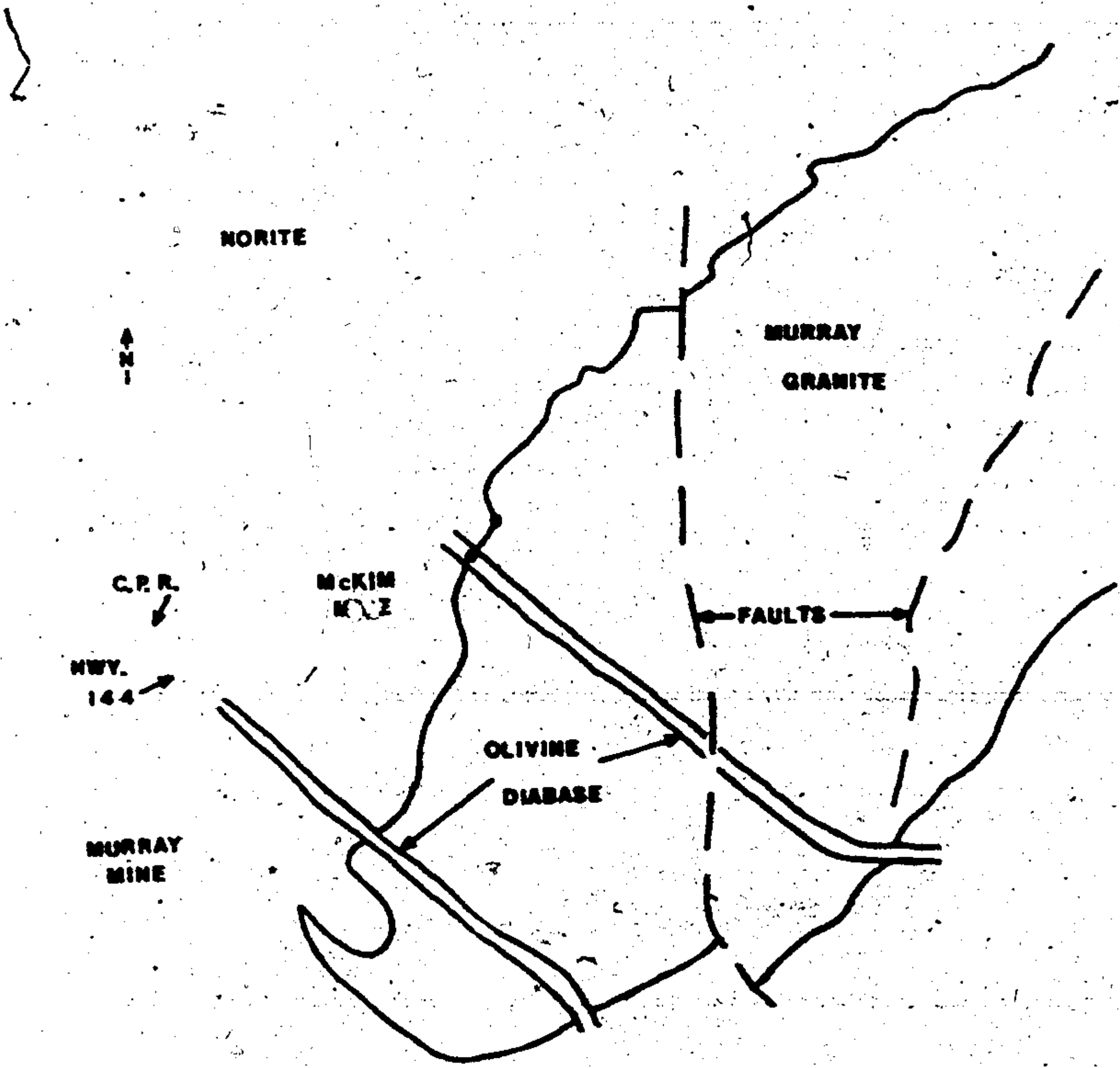
3 - 6 Conclusions

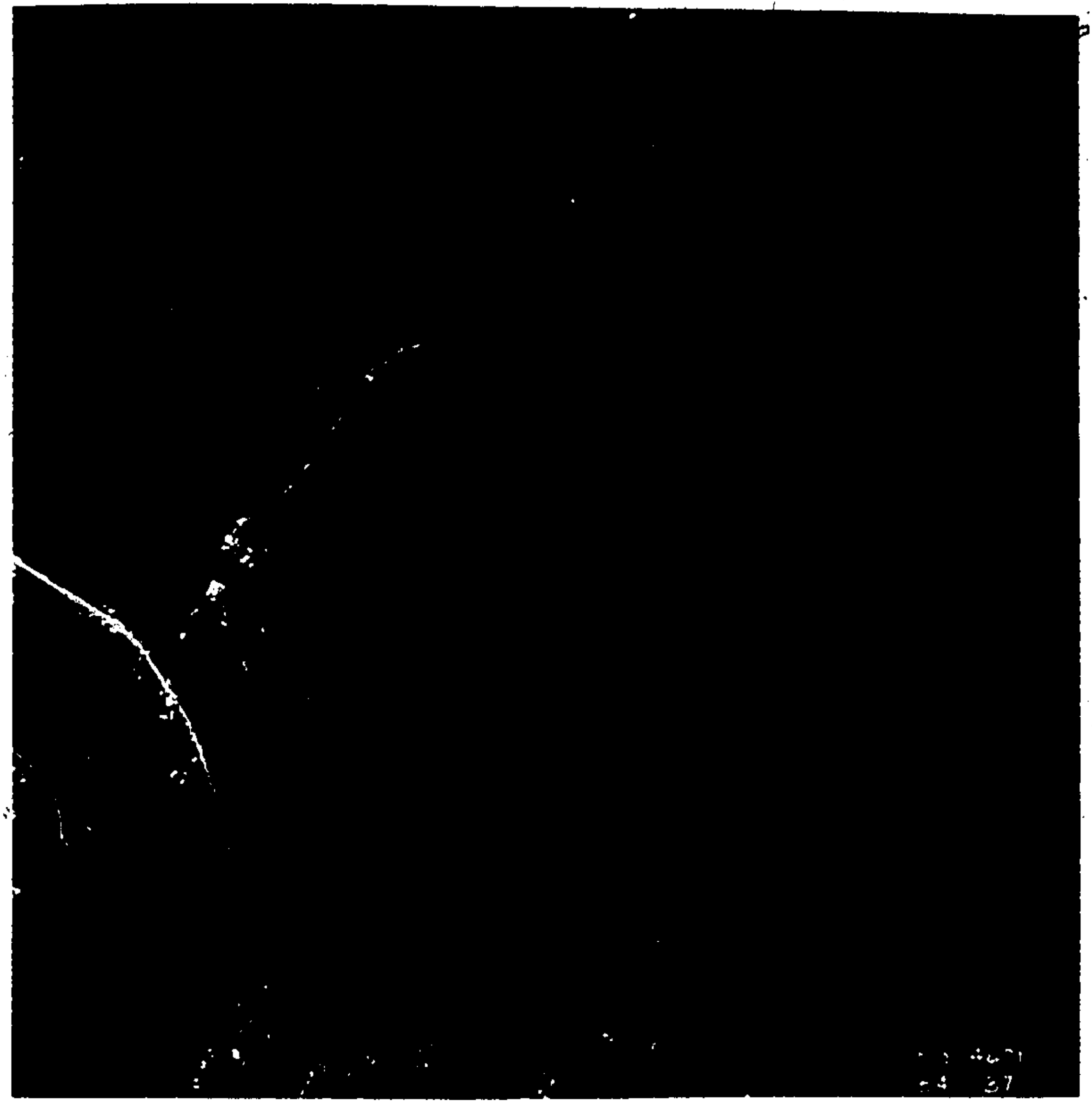
Rubidium-strontium whole-rock data indicate that the Sudbury norite, (and probably the sub-layer as well,) was intruded 2.00 b. y. ago. The micropegmatite, which also seems to have been intruded at this time, has been affected by hydrothermal greenschist facies metamorphism 1.7 b.y. ago. This obviously involved some open system chemical behaviour. These ages are also represented in other rocks and minerals and by other isotopic dating techniques (Table 3-4).

The Rb-Sr data cannot distinguish which of several hypotheses regarding the origin of the nickel irruptive is most important, but they are incompatible with a simple mantle source and closed system differentiation. The relatively high 0.7063 initial Sr^{87}/Sr^{86} of the norite strongly suggests contamination with complete mixing of Sr isotopes, an inhomogenous mantle source, and/or a deep crustal source.

The writer is impressed by Naldrett et al.'s (1972a) comment: "future studies are unlikely to make the complicated history of the Irruptive appear any less complicated."

Plate 4 - 1 Area photo of the Murray granite.
(area shown is approx. 2 mi. x 2 mi.)


NORITE
N
MURRAY
GRANITE
C.P.R.
McKIM
MINE
FAULTS
HWY.
144
OLIVINE
DIABASE
MURRAY
MINE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Chapter 4 The Murray Granite

4 - 1 Introduction

The Murray granite (Plate 4-1) is approximately three miles long by one mile wide and located two miles north-west of the city of Sudbury. ~~It~~ intrudes meta-volcanics and meta-sediments of the Huronian sequence between the southern margin of the nickel irruptive (norite) and the Frood-Stobie offset. Two northwesterly trending olivine diabase dikes cut across the granite at its southwest end.

Early timbering operations, sulfide roasting, and forest fires in the area have removed most of the heavy vegetation and subsequent erosion by running water has removed considerable amounts of glacially derived clay. This has produced excellent exposure of most of the Murray granite (Plates 4-1 and 4-2).

The neighboring Creighton granite (C in Figure 1-1) has been intruded into a similar environment and shows similar conflicting field relations with respect to the nickel irruptive. The two granites are considered to be broadly related in time and environment of intrusion, as well as subsequent history, but having certain dissimilarities in level of intrusion, source material, crystallization history, and alteration (Tables 4-1 and 4-2).

4 - 2 The Relationship of the Murray Granite to the Nickel Irruptive: The Controversy and its Importance

Field relations between the Murray granite and the nickel

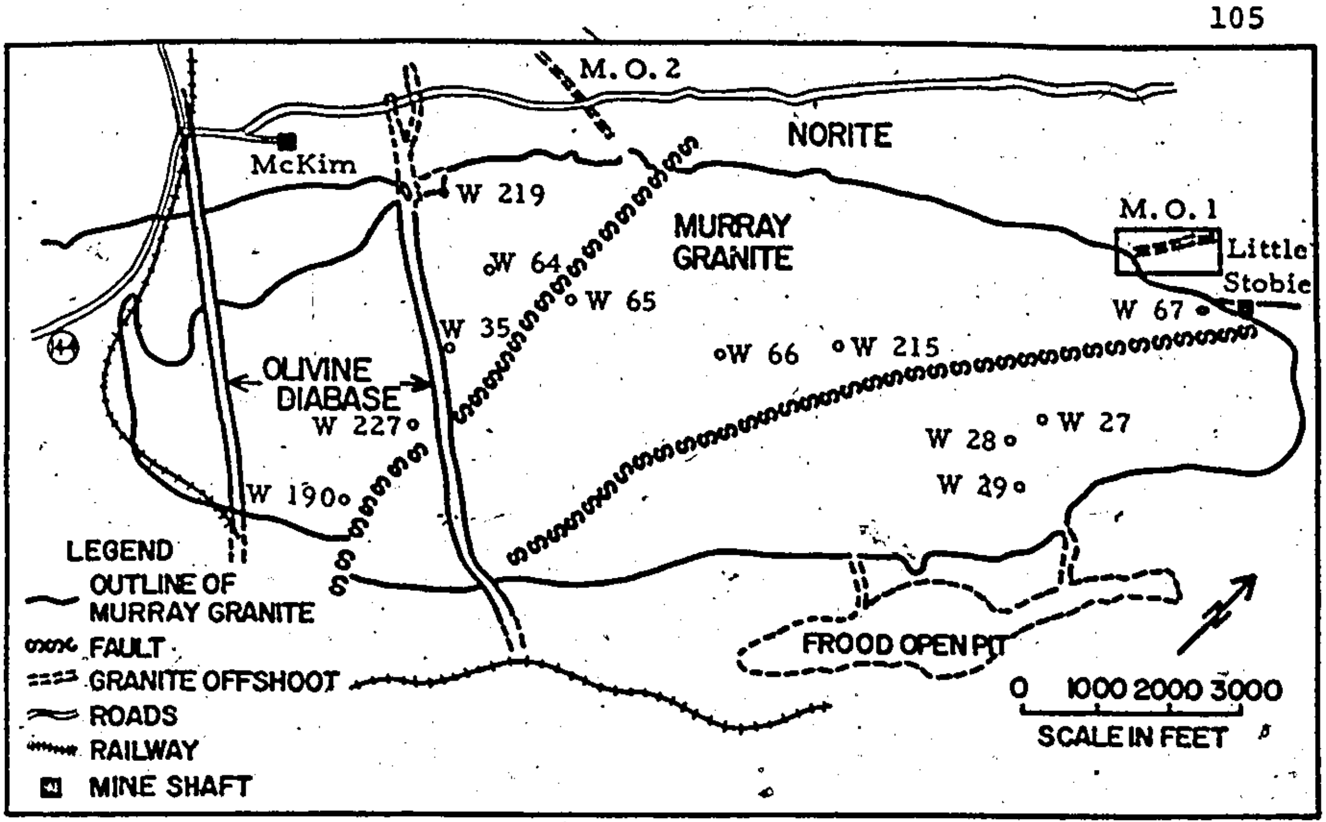

Figure 4-1 Map of Murray granite showing sample locations (this study)

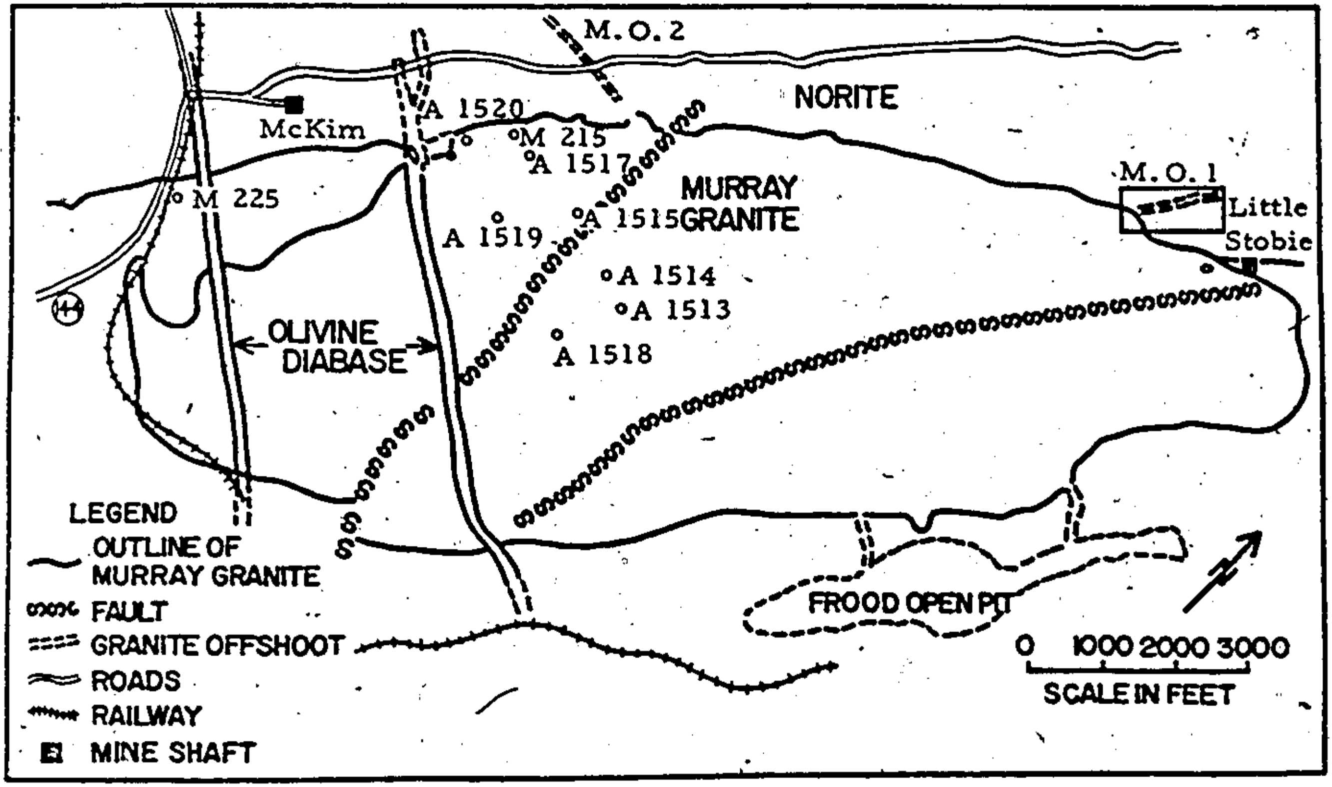

Figure 4-2 Map of Murray granite showing sample locations (after Gibbins, Adams, and McNutt 1972)

TABLE 4 - 1 Petrologic Phases in the Murray and Creighton Granites (after Speers 1956)

	Murray granite	Creighton granite
Late Phase		pegmatite
Post-norite phase	granite # 2	grey to pink granite grey granite black porphyry breccia
norite		
	← Common Sudbury breccia →	
Main phase (pre-norite)	granite # 1	massive gneiss porphyritic gneiss
(inclusions)	mafic rocks	gneiss

TABLE 4 - 2 Comparison of Murray and Creighton Granites (after Speers 1956 and Ginn 1958)

Similarities:

- mineralogy
- major element composition
- field relationships with the nickel irruptive
- sulfides along nickel irruptive contact
- pre- and post-irruptive breccias

Differences:

- accessory minerals
- texture (Creighton is more variable and includes porphyritic phases)
- alteration (Creighton has more altered plagioclase)
- petrology (see Table 4 - 1)
- structure (Creighton is commonly gneissic)

irruptive present contradictory evidence with respect to their relative ages. Briefly, the confusion largely stems from granite dikes which appear to originate in the Murray granite. One set of dikes extends northwesterly into the norite-suggesting a post-irruptive age, while other southeasterly trending dikes are cut by the quartz diorite (sub-layer of Chapter 3) and ore-bearing breccia zones of the Frood-Stobie offset, indicating a pre-irruptive age for the granite. (Figure 4-1). Similar relationships are found in the Creighton granite (Collins 1936).

Yates (1938, 1948) believed that the Frood-Stobie offset was much younger than the norite and Murray granite, but this idea has not been popular with later workers. A second explanation, based on conventional geologic data, invokes the concept that at least two ages are present in the Murray granite (and Creighton granite). This concept seems to have originated with Coleman.

> "Coleman (1905,1913) refers to the Creighton granite as partly older and partly younger than the nickel irruptive, thus implying that it is not a single intrusion but is composed of two or more granites of different ages. This opinion is shared by later workers."
>
> Collins,1936,p.35

Speers (1956) extended the two age concept to the Murray granite (Table 4-3).

The importance of the granite-irruptive age relations has been described by Collins (1936, p.29):

> "Settlement of this question is a necessary step towards knowing the origin of the nickel-copper ore

TABLE 4 - 3 Definition and Evidence for more than One Type of Murray Granite (after Speers 1956)

	Granite # 1 (pre-nickel irruptive)	Granite # 2 (post nickel irruptive)
1) Occurence	- most of the Murray pluton (>90%)	- minor, includes a 30-100 foot wide band along norite contact plus various granitic dikes and veinlets
2) Field relations	- cut by Frood offset & breccia zone - contains dark common Sudbury breccia - shows evidence of metamorphism and gradation into Granite # 2 near the norite	- includes granite veinlets which cut dark breccia of of granite # 1 - contains post norite injection breccias, replacement veins, and sulfides - contains possible inclusions of granite # 1 and dark breccia
3) Petrography	- commonly shows evidence of deformation (eg crushing) - 2 plagioclases[1] (albite + oligoclase An_{28})	- usually massive, may show evidence of recrystalization (annealling, remelting &/or metasomation) - one plagioclase (An_{4-20}) but more abundant
4) Chemistry	- usually no difference	

1 - Note: Other petrographic criteria of Speers (1956, p.171) seem to be partly invalid and/or not definative to the present writer - a more detailed study may be required.

> deposits, because one of the largest ore bodies, the Creighton, is partly in the granite, and hence younger than the granite. If the granite is older than the nickel irruptive all or almost all of the large docket of evidence indicating that the ore came from the nickel irruptive is in harmony with such a relationship of granite and nickel irruptive and can be accepted with confidence. But if the granite is younger than the nickel irruptive it would follow that the ore deposits are so much younger than the irruptive that they could not have come from it."

4 - 3 The Nature of the Murray Granite Contact

4 - 3 - 1 The Northwestern Margin of the Murray Granite

Over most of its exposed northwestern margin, the Murray granite is separated from the nickel irruptive by a thin belt of greenstone (Basal Huronian), which is generally a few feet to a hundred feet wide.

Collins (1936, p.33) pointed out that many small granitic dikes cut the greenstone (Figure 4, Clarke and Potapoff 1959, p. 70), some cut the Murray granite (Plate 4-2B), and a few extend a short distance into the norite. The latter dikes at least are post-norite and are probably related to other granitic dikes reported to be found throughout the irruptive (Card 1968, p.33 and Hawley 1962, p.14) and not necessarily related to the Murray granite. Most of these dikes are from one to ten feet wide and may be albitite, aplite, or pegmatite as well as granite.

Two larger granitic dikes also intrude the norite. These dikes, called the "Murray offshoots" (1 & 2) [1], appear to

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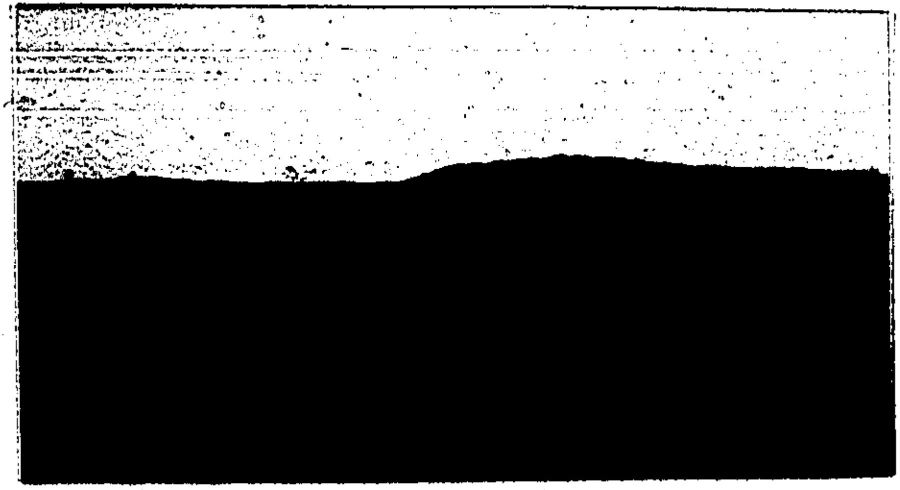
[1] Not to be confused with "offset" dikes which are part of the nickel irruptive.

Plate 4 - 2. Nature of the Murray granite in the field



A. General topography and outcrop.
Note: black color due to smelter gases.

B. Late aplite dike.

originate from the Murray granite, although 25 to 100 feet of swamp separate both of them from the main body of Murray granite (Figures 4 - 1 to 4 - 4).

The first of these, the Murray offshoot 1, extends into the norite in a northeasterly direction from the north end of the Murray granite in the vicinity of the Little Stobie mine. It is up to 50 feet wide and almost a quarter of a mile long. The norite-dike contact is sharp and dips 45 degrees in a southeasterly direction (Plate 4-3 A). Mega - and microscopically only minor recrystallization and alteration is present (Plate 4-3 B).

A second dike, the Murray offshoot 2, intrudes the norite in a westerly direction from a point approximately mid-way along the northeast margin of the Murray granite. This dike is up to 30 feet wide and extends about a quarter of a mile into the norite.

The Murray granite and offshoot dikes are similar in appearance and major element chemistry (Collins 1936, p.33 and Sutton 1972) (see Figure 4-5). An exception to this is shown by a few dike samples (e.g.W 19), which show a relative decrease in K_2O related to albitization.

This similarity has led some workers to conclude that the entire Murray granite is younger than the irruptive.

Collins (1936, p.33) has described the Murray granite-irruptive contact as follows:

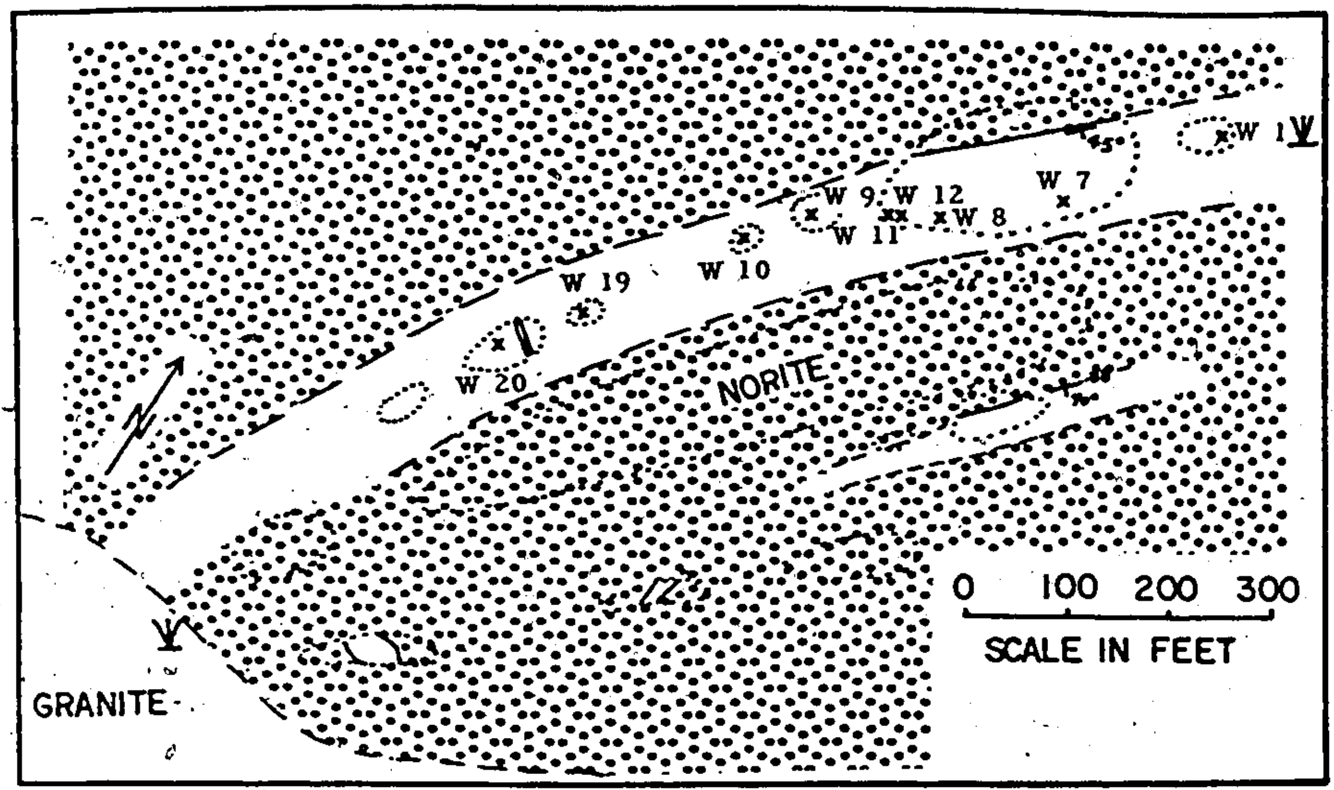


Figure 4-3 Map of Murray offshoot 1 showing sample locations

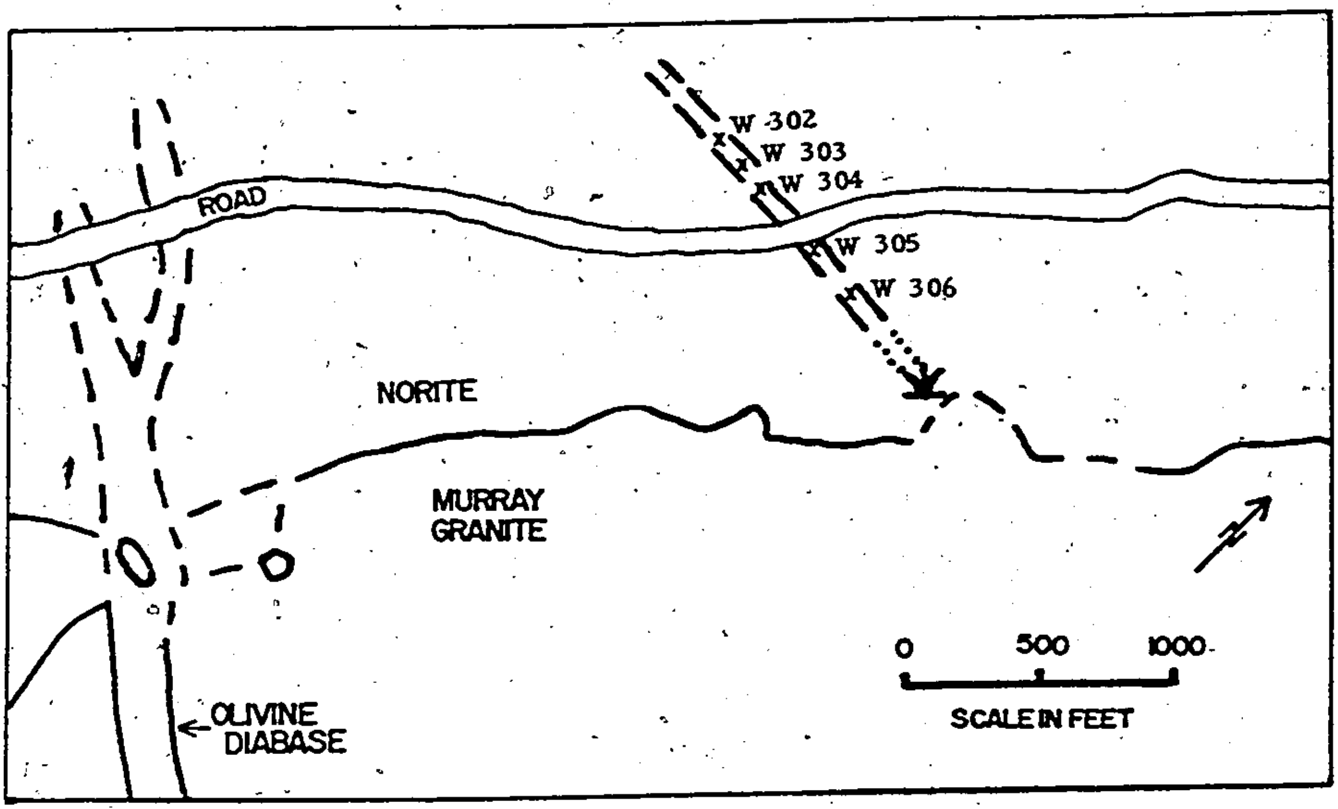
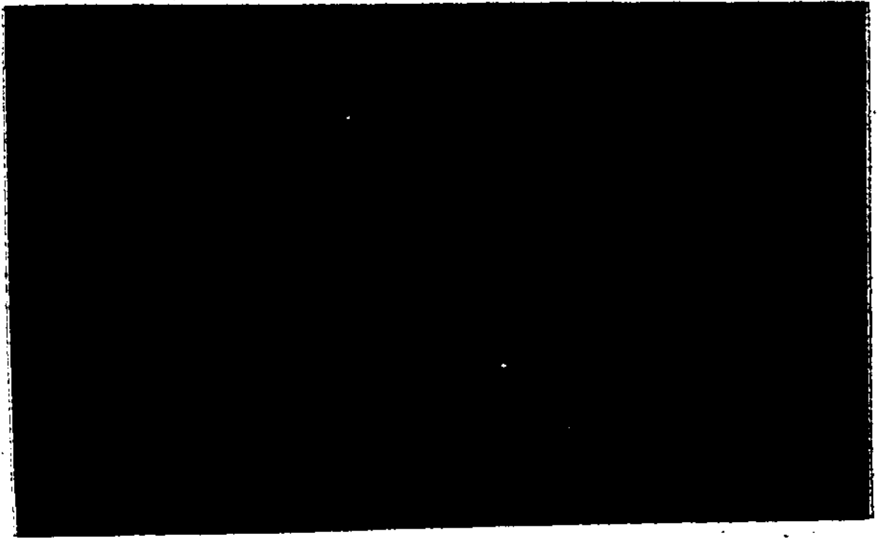


Figure 4-4 Map of Murray offshoot 2 showing sample locations

Plate 4 - 3. Contact of Murray offshoot 1
and norite (near W-7 in Figure 4-3)
(Norite on left)

A. Outcrop.



B. Thin section. (3/4 x 1 1/2 inches)

> "It is almost a straight line. Neither rock is appreciably finer grained near the contact, and neither one has produced any apparent contact alteration in the other. Even under the microscope in specimens showing both sides of a knife-edge contact such slight differences of grain and mineral composition as can be seen are hard to interpret and contradictory. We could find no unquestionable inclusions of either formation in the other."

Collins also noted that small bodies of nickel-copper sulfides occur almost continuously along the contact and the improbability that a younger Murray granite would have stopped exactly at the base of the irruptive.

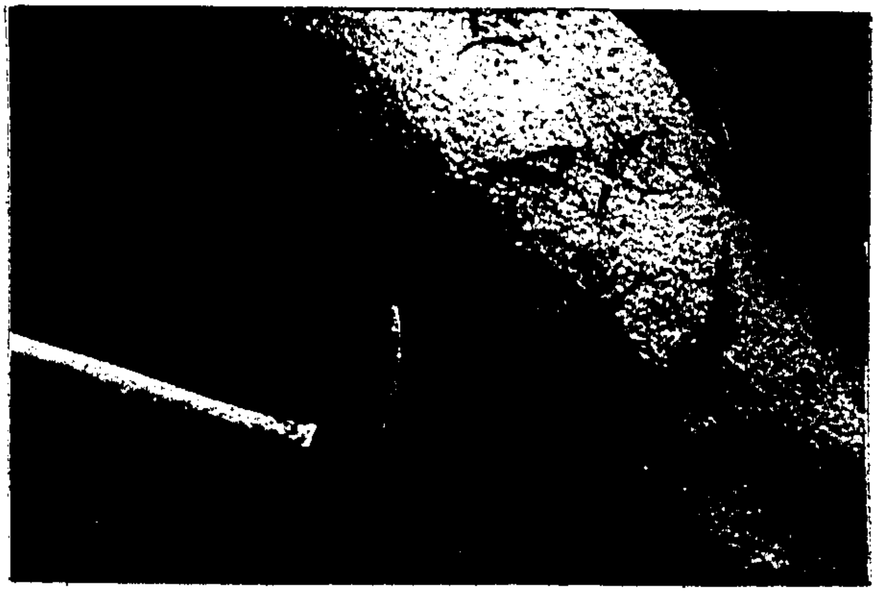
Speers (1956, pp. 179-180 and Plate 45) reported inclusions of granite in norite. He described these inclusions as being distinct from the small dikes in the norite, but microscopically similar to the main mass of Murray granite. He also described inclusions of granite in granite near the Murray granite-norite contact (idem. pp. 177-178 and Plate 44) and interpreted this phenomenon as evidence of two ages in the Murray granite.

Speers (1956) suggested that the common Sudbury breccia, which is fairly typical of the main Murray mass, is absent in the vicinity of the norite-granite contact. This is generally true, however, a few sharp angular fragments of somewhat feldspathized dark Sudbury breccia have been found "floating" in remobilized granite near the contact (Plate 4-4 A).

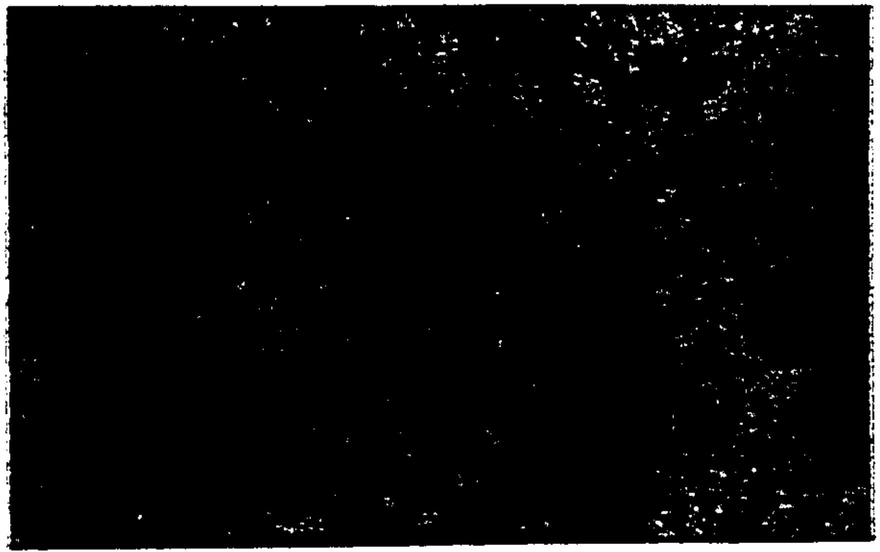
4 - 3 - 2 The Southeastern Margin of the Murray Granite

The most noticeable feature of the eastern half of the southeastern margin of the Murray granite is the occurrance of

Plate 4 - 4.



A. Angular fragments of broken and recrystallized dark Sudbury breccia "floating" in Murray granite near the norite contact.



B. Thin section (3/4 x 1 1/2 inches) of a small vein of dark Sudbury breccia in the center of the slide. (Plain light - potassium feldspar stained yellow) granite dikes which extend in a southeasterly direction from the main body of Murray granite towards the Frood offset and breccia zone. These dikes have become inaccessible and obliterated by mining operations in the Frood open pit. However, Zurbrigg (1957, Figure 2) and Speers (1956, pp. 172-175) give a detailed map and description of them. The dikes are cut off by the quartz diorite and breccias of the Frood offset, indicating that they were formed before the nickel irruptive.

Along the western part of the southeastern Murray granite contact, the writer found several examples of knotted hornfels-like rock in the adjacent Huronian meta-sediments. These rocks have been altered by retrograde metamorphism, making relationships unclear, but it is possible that they represent contact metamorphism of the sediments during intrusion of the Murray granite.

4 - 4 The Nature of the Murray Granite

4 - 4 - 1 Description of the Murray Granite

In general the Murray granite is a pink equigranular rock which has an average grain size of 1 mm diameter and contains abundant quartz, microperthite, plagioclase (albite and/or oligoclase), with minor biotite, magnetite and other accessory minerals. The texture is usually granoblastic and the structure varies from massive to well foliated even within a single thin section. Specimens of the Murray offshoots are usually more massive and may show evidence of sodium metasomatism.

More detailed petrographic information and discussion of the samples used in Rb-Sr studies is given in Appendix D, Tables D-1 and D-3.

4 - 4 - 2 Sudbury Breccia in the Murray Granite

Dark breccias (Plate 4-4 A), composed of sub-angular to rounded granite fragments enclosed in a very fine grained matrix of angular mineral fragments, are found throughout the Murray granite, but arenoticeably more common in the southwest. They are equivalent to the common Sudbury breccias which occur in most of the pre-irruptive rocks surrounding the Sudbury basin (Speers 1956, 1957) and occur in the form of sinuous and tenuous "dikes" of variable size and shape.

Speers (1956, p.164) reported that the coarser grain size and amphibole in the matrix of Murray granite - Sudbury breccia near the norite were produced by metamorphism caused by the younger norite.

4 - 4 - 3 Two Ages of Murray Granite

Criteria for two types and ages of Murray granite are listed in Table 4-3. Speers' granite # 2 may intrude or grade into granite # 1. Needless to say, it is not precisely defined and may include more than one age itself.

4 - 4 - 4 Igneous and Metamorphic Aspects of the Murray Granite

Both igneous and metamorphic features exist in the Murray granite, (Table 4-4). In the past, metamorphic features were not always recognized and some (e.g. remobilized granite and sulfides) have been misinterpreted as igneous and evidence for a post-norite age of the Murray granite.

Evidence for the primary igneous nature of the Murray granite includes the general appearance, chemistry, (Fig. 4-5) and mineral composition of the rocks and field relations with the enclosing Lower Huronian meta-sediments and volcanics. A concentric internal structure is shown by contouring the specific gravity of hand specimens (Figure 4-6) and is probably igneous in origin.

Metamorphic features of the Murray granite are diverse in character as well as in manner and age of formation. (Table 4-5). These features may be local and affect only a small area, or regional and extend well beyond the limits of the Murray granite.

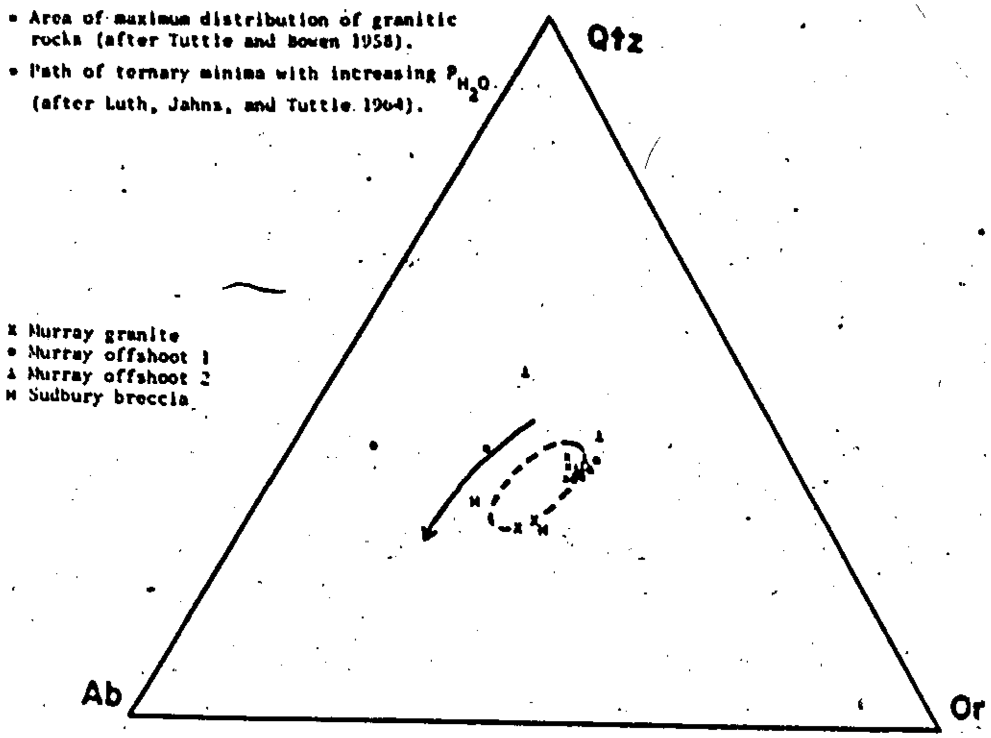
X-ray diffraction studies of the 131 and $1\bar{3}1$ reflections (Figure 4-6) of potassium feldspar (see Wright 1967 and/or Tilling 1968) showed only one sample (W35) of orthoclase, while the remainder were maximum microcline (Table D-4). The single sample of orthoclase has resulted from contact metamorphism caused by the adjacent olivine diabase 1.46 b.y. ago (Figure 4-1). All other samples, including samples collected adjacent to the norite and from granitic dykes in the norite uniformly show maximum triclinicity which may have developed during the Penokean orogeny.

Analysis of the most prominent joints from each of three sub-divisions of the Murray granite indicate five systemmatic

A. Qtz - Ab - Or normative diagram.

Dashed line = Area of maximum distribution of granitic rocks (after Tuttle and Bowen 1958).

Solid line = Path of ternary minima with increasing P_{H_2O} (after Luth, Jahns, and Tuttle 1964).



B. An - Ab - Or normative diagram.

Dashed line = Area of maximum distribution of granitic rocks (after Tuttle and Bowen 1958).

Solid line = Thermal trough (after Kleeman 1965).

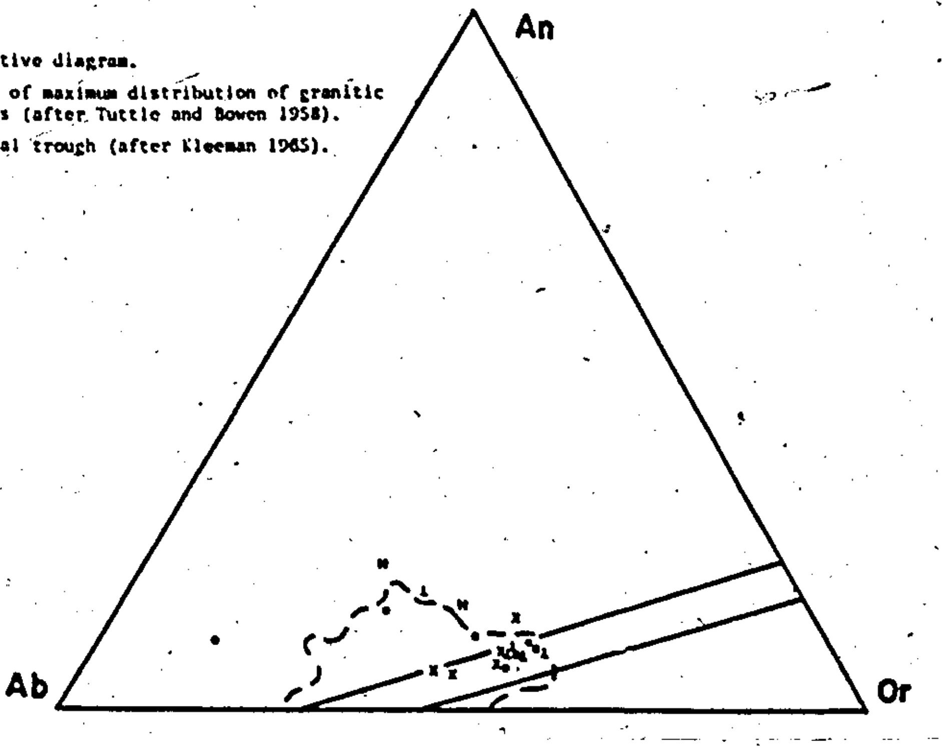


Figure 4 - 5: Comparison of normative data from the Murray granite and offshoots (after Sutton 1972), with experimentaly and empirically determined thermal valleys.

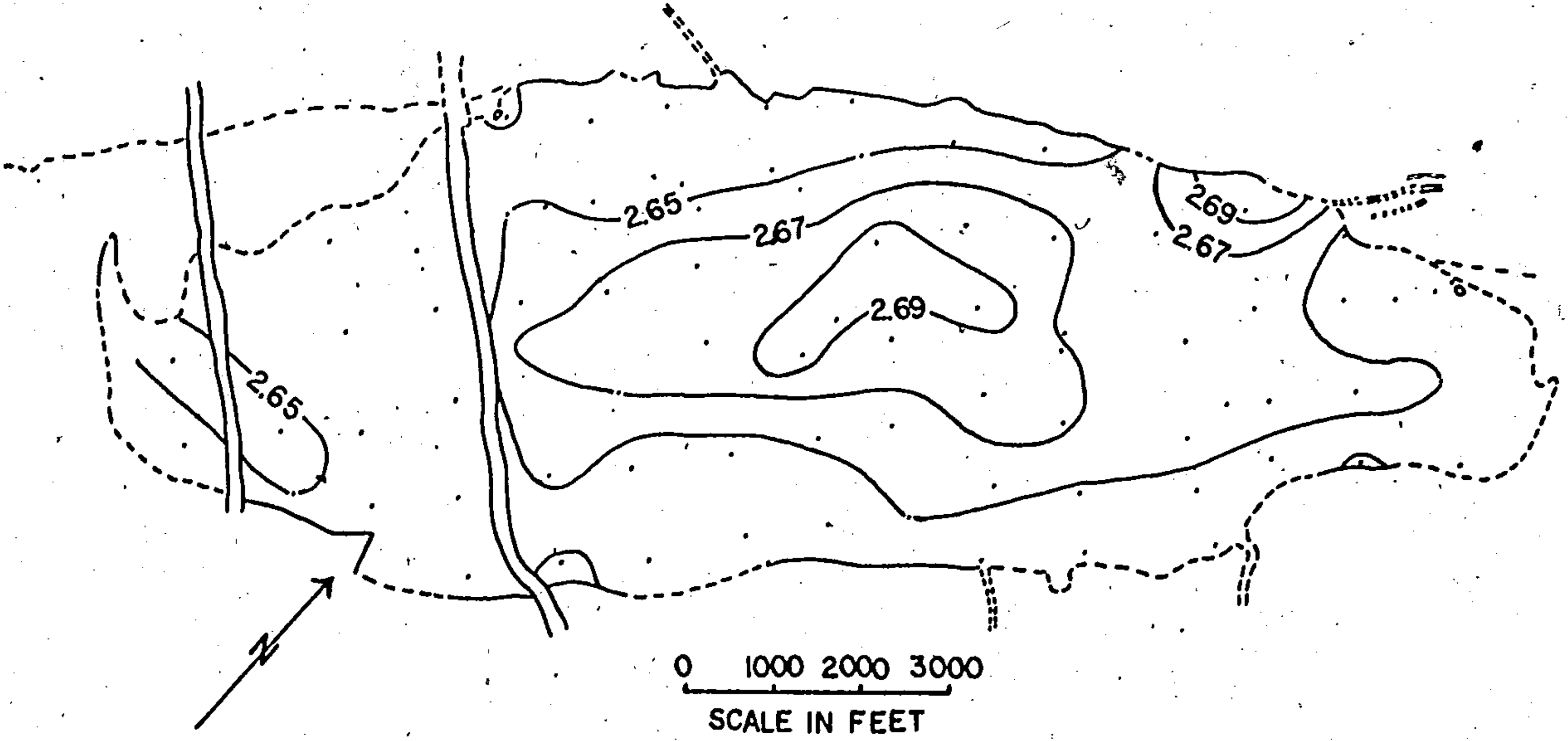


Figure 4 - 6: Variation of specific gravity in the Murray granite.

TABLE 4 - 4 Suggested Igneous and Metamorphic Features of the Murray Granite

A) IGNEOUS FEATURES

- general igneous appearance
- typical igneous mineral assemblage
- typical igneous chemical composition (Figure 4-5)
- concentric zoning (specific gravity contours) (Figure 4-6)
- field relations with Huronian rocks
    - sub-concordant to discordant contact
    - granite dikes in Huronian rocks
    - possible contact aureole

B) REGIONAL METAMORPHIC FEATURES

- widespread cataclastic features and development of dark common Sudbury breccia.
- almost ubiquitous distribution of maximum microcline
- systematic joints which are related to regional structures (Figure 4-8)
- widespread minor alteration of certain minerals (e.g. sericitization of plagioclase cores)
- low K-Ar and Rb-Sr mineral ages (Chapter 5)
- "geologic" scatter in Rb-Sr whole rock data (Section 4-5)
- recognition of regional metamorphism in adjacent rock units. (Card et al. 1972)

C) LOCAL METAMORPHIC FEATURES

- development of orthoclase in granite adjacent to late olivine diabase dikes
- late fault or mylonite zones
- introduction of sulfides and development of breccias along granite-norite contact (e.g. McKim and Little Stobie mines
- local evidence of metasomatism and remobilization of granite

---

TABLE 4-5 Petrographic effects of Local Metamorphism of the Murray Granite

A) Dark Common Sudbury breccia
(commonest in southwest Murray granite)
- (1) granoblastic and porphyroclastic textures.
- (2) extreme granulation and recrystallization of matrix

B) Contact effects of the nickel irruptive
(e.g. Little Stobie mine)
- (1) brecciation by narrow veinlets of chlorite and epidote
- (2) introduction of sulfides

C) Contact effects of late olivine diabase dikes
- (1) Microcline (grid twinning) replaced by orthoclase (Carlsbad twinning)
- (2) Evidence for the reaction
  biotite + plagioclase + quartz ⟶
  K feldspar + albite + hornblende
  (Winkler 1967, p.214)
- (3) Pink - orange color of rock

D) Late faulting - as recognized in long linear valleys and displacements of the Murray granite contact
- (1) protomylonite in valley walls.

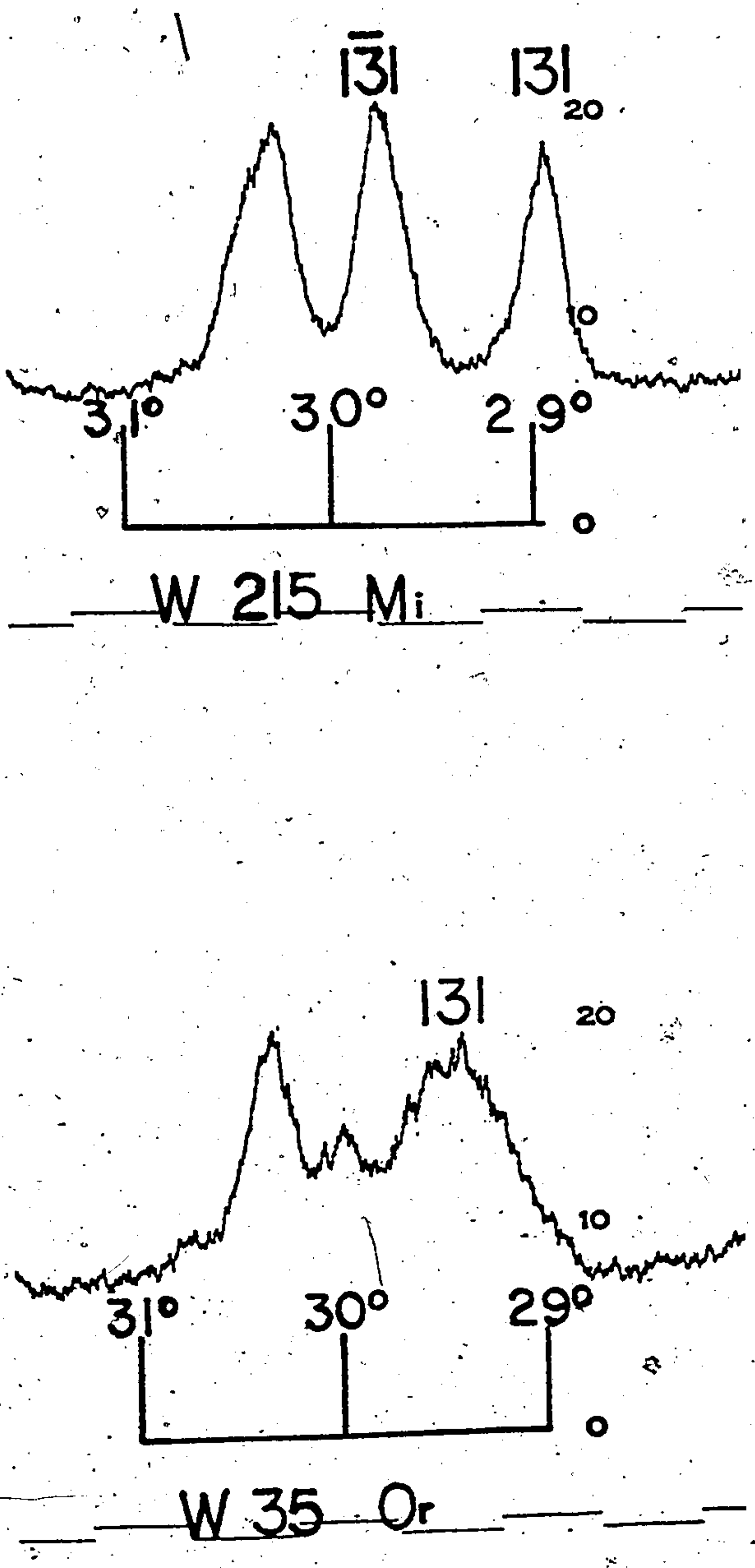


Figure 4 - 7: X-ray diffractograms of potassium feldspar polymorphs (microcline and orthoclase) based on 131 peak splitting.

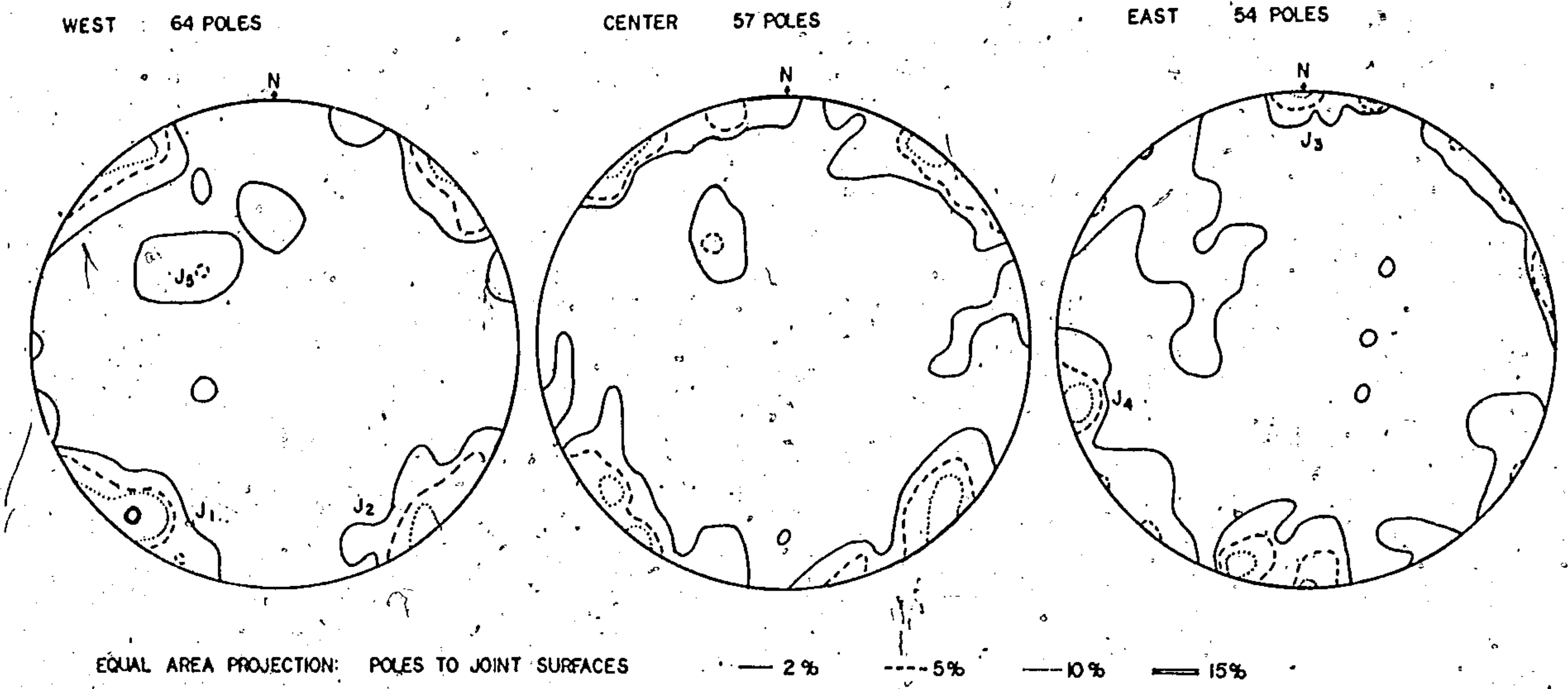


Figure 4 - 8: Distribution of joints in the Murray granite.

joint sets (Figure 4-8). NW-SE (J_1), and NE-SW (J_2) sets may have formed at a different time or depth than E-W (J_3) and N-S (J_4) sets/ A fifth set (J_5) is not as well developed but occurs in all three zones. All five of these joint sets may be related to major structures (folds and faults) found in the Sudbury-Espanola area (Card et al. 1972a, p.353). Any primary or igneous joints, which may have existed, have been resealed and obliterated. The former existence of fracture surfaces is shown by offset quartz veins.

Deformational features in the Murray granite range from spectacular examples of pre-irruptive common Sudbury breccia and post-irruptive mylonitic fault zones to microscopic examples showing great variation of deformation within a single thin section.

Petrographic evidence of metamorphism (i.e. recrystallization, remelting, replacement etc.) is given in Table 4-5.

4 - 4 - 5 Discussion

The geological evidence presented in this chapter affords an adequate explanation of the seemingly contradictory field relations between the Murray granite and the nickel irruptive. It also supports a pre-irruptive and pre-ore age for the bulk of the Murray granite. Again, similar arguments can be applied to the Creighton granite.

Before going on to consider the isotopic evidence, the reader is referred to Table 4-6 for correlation of lithologies

TABLE 4-6 CORRELATION OF MURRAY GRANITE LITHOLOGIES

<table>
<tr><th colspan="2">Speers 1956</th><th colspan="2">This Study</th></tr>
<tr><td rowspan="3">Murray granite #2</td><td rowspan="3">(7) granitic veinlets, sand and "ghost" breccias
? ? ?
(6) pink granite dikes
(5) grey granite dikes
(4) injection breccia dikes
(3) marginal strip 30-600 feet wide</td><td>Sodium metasomatism ?</td><td>carbonatite
albitite</td></tr>
<tr><td>(2)Murray offshoots ≀ (3)granitic dikes
(1.7-2.0 b.y.)</td><td>pegmatite
aplite
granite</td></tr>
<tr><td rowspan="2">(1) Murray granite
(includes Sudbury breccia)
(≥2.26 b.y.)</td><td rowspan="2">(C)marginal strip (2.10±.07 b.y.)
(B)Northwest half (2.10±.07 b.y.)
(A)Southeast half (2.29±.03 b.y.)
Regional metamorphism increasing (A) to (C).</td></tr>
<tr><td>Murray granite #1</td><td>(2) Common dark Sudbury breccia
(1) fine grained pink granite</td></tr>
</table>

recognized in this study with those of Speers (1956). One should also keep in mind an appreciation of the obvious difficulty to impossibility of distinguishing between unaltered granite, recrystallized (in the solid state) granite, partially melted granite, and completely remelted granite, even though their separate existence can be reasonably inferred. In addition more than one episode of metamorphism and/or melting has taken place.

4 - 5 Rubidium-Strontium Whole Rock Age Determinations

Sample locations for the Murray granite samples are given in Figures 4-1 and 4-2 and for the Murray offshoots in Figures 4-3 and 4-5.

Almost all the data regressed resulted in "errorchrons" (Brooks et al. 1972) or "scatterchrons", i.e. the data do not fit an exact linear array within the limits of experimental error. Increasing the error estimate from 1 sigma to 2 sigma did nothing to help the problem. The geological error or scatter may be due to the failure of either or both fundamental assumptions of isochron dating to be valid. Either the value of Sr^{87}/Sr^{86} (Ri) at the time the rocks were formed was not constant and/or the individual whole rocks have acted as open systems at some time during their subsequent history (e.g. metamorphism).

Although the writer is fully cognizant of the fact that the "ages" obtained are not justifiable statistically, the data is not completely random. Results from the York (1966) regression technique, (based solely on the actual scatter of data points), have been used to obtain "approximate ages" which are suitable for the conclusions drawn from them. Some justification for this position may be given by the fact that three independent sample collections, analysts, and laboratories have produced similar results for the Murray granite. Geological data and interpretation frequently fail to fit strict mathematical models.

4 - 5 - 1 The Murray Granite

Fairbairn et al. (1960, p.53) determined the age of Murray and Creighton granite whole rock samples to be 2,060 m.y. old (using a Rb-87 decay constant = 1.47 x 10^{-11} year $^{-1}$ and assuming Ri = 0.702). Later (Fairbairn et al. 1965), they re-examined their data using the isochron method and the "geological" Rb-87 decay constant (= 1.39 x 10^{-11} year $^{-1}$) to obtain an age of 2,140 ± 60 m.y. and Ri = 0.712 ± 0.010. These data have also been regressed and plotted in Figure 4-10A. Only three whole rock samples were used and two of these came from the Creighton granite. They now give an age of 2,203 ± 59 m.y., Ri = 0.7096 + 0.0044.

Gibbins, Adams, and McNutt (1972) presented Murray granite age values of 2,150 ± 60 m.y.: Ri 0.729 ± .010 and 2,230 ± 20 m.y.: Ri = 0.719 ± .003 based on 7 and 9 samples respectively. The two extra samples (M 225 and M 225), collected near the granite contact, were considered to be atypical and probably contaminated. A new regression of their 9 samples is given

FIGURE 4 - 9

A Murray granite - this study

triangle - Sudbury breccia not regressed

B Murray granite - Gibbins, Adams & McNutt, 1971

C Murray granite - compared

squares - this study
triangles - Gibbins, Adams & McNutt
* diamonds - Fairbairn et al. 1968
*(not regressed)

D Murray granite - combined

as above

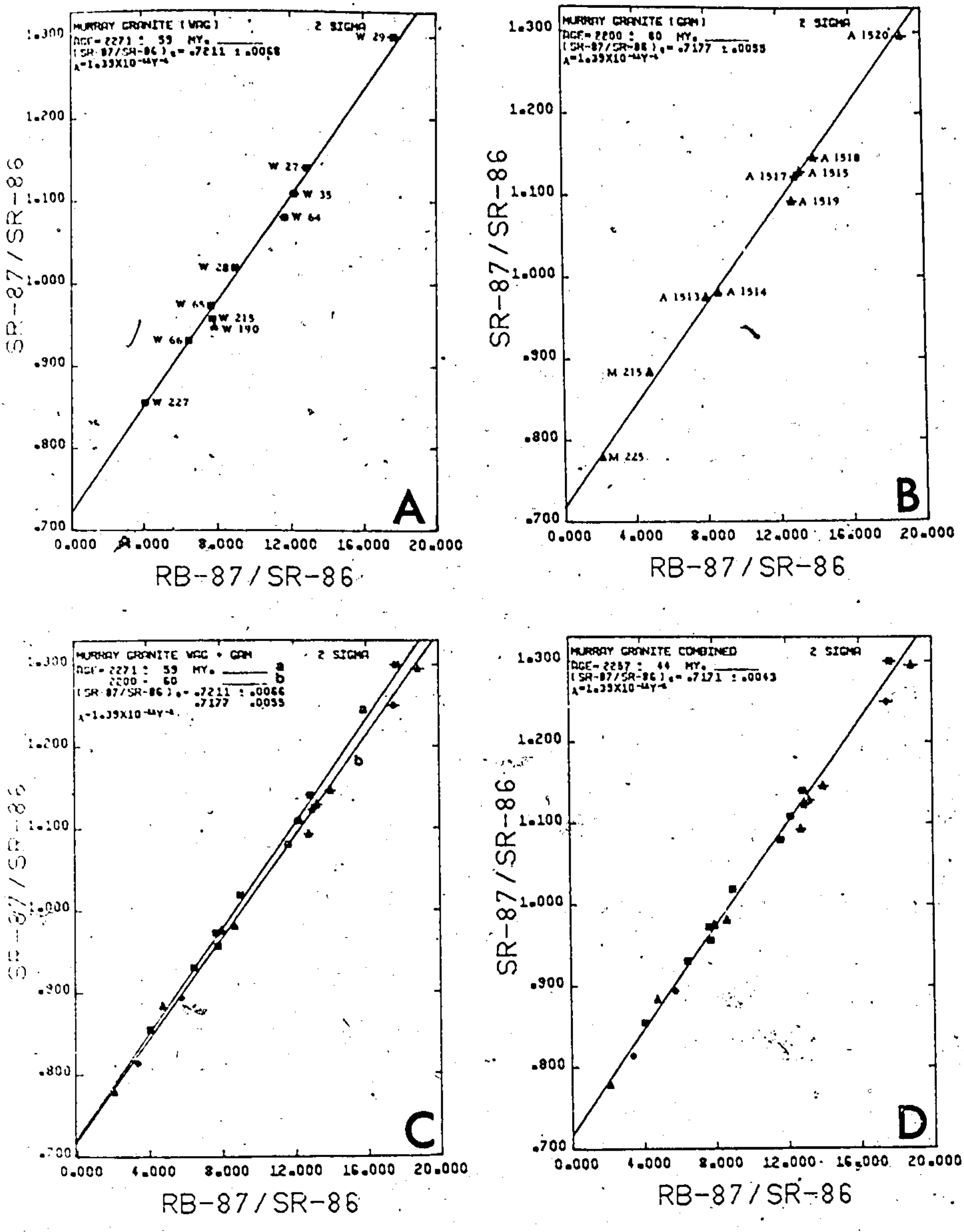

MURRAY GRANITE (VRG)
2 SIGMA
AGE= 2271 ± 59 MY.
(SR-87/SR-86)0= .7211 ± .0068
λ=1.39X10-11Y-1
W 29
W 27
W 35
W 64
W 28
W 65
W 215
W 190
W 66
W 227
A
SR-87/SR-86
RB-87/SR-86
.700
.800
.900
1.000
1.100
1.200
1.300
0.000
4.000
8.000
12.000
16.000
20.000
MURRAY GRANITE (GRM)
2 SIGMA
AGE= 2200 ± 60 MY.
(SR-87/SR-86)0= .7177 ± .0055
λ=1.39X10-11Y-1
A 1520
A 1518
A 1517
A 1515
A 1519
A 1513
A 1514
M 215
M 225
B
MURRAY GRANITE VRG + GRM
2 SIGMA
AGE= 2271 ± 59 MY. a
2200 ± 60 b
(SR-87/SR-86)0= .7211 ± .0066
.7177 .0055
λ=1.39X10-11Y-1
a
b
C
MURRAY GRANITE COMBINED
2 SIGMA
AGE= 2257 ± 44 MY.
(SR-87/SR-86)0= .7171 ± .0043
λ=1.39X10-11Y-1
D

Figure 4 - 9.

in Figure 4-9B. These samples were determined at the University of Toronto by Adams.

Nine samples of Murray granite, collected and analysed in this study, give an errorchron or scatterchron of 2,270 ± 60 m.y.: Ri = 0.721 ± 0.007 (Figure 4-9A). These include one orthoclase bearing sample (W 35) collected adjacent to an olivine diabase dike (Figure 4-1) and an altered sample of Sudbury breccia (W 227). A fresh sample of Sudbury Breccia (W 190) plots off the regression line well outside experimental error and has not been used.

The two sets of data were compared in Figure 4-9C and combined in Figure 4-9D (2,260 ± 40 m.y.: Ri = 0.717 ± 0.004). Samples from the southeastern part of the Murray granite (W 27, W 28 , W 29) consistently fell to the upper left side of the scatterchrons. Separate regression of these three defines a line equal to 2,290 ± 30 m.y.: Ri = 0.727 ± 0.005, while 12 samples from the north east part continue to give a scatterchron of 2,100 ± 70 m.y. and Ri = 0.735 ± 0.009 suggestive of resetting (Figure 4-10B).

Five samples of Murray granite (W 54 to W58) were collected at increasing distances from the contact with the nickel irruptive on the 1200 level of the Little Stobie mine. They all show definite foliation, brecciation by dark biotite rich veinlets, and up to 1 per cent sulfide. Isotopically they all show lower than normal values of Rb^{87}/Sr^{86} and Sr^{87}/Sr^{86}, but except for W 56, and possibly W 55 they would indicate a whole

FIGURE 4 - 10

A Creighton - Murray granite data of Fairbairn et al regressed (a) and granitic dikes of Gibbins, Adams, and McNutt 1971 (b)

B Murray granite - NW versus SE

squares - NW Murray granite (b)
triangles - SE Murray granite (a)

C Murray granite from Little Stobie mine near norite-granite contact

(a) Murray granite combined regression
(b) SE Murray granite regression

D Carbonate (W 219) and syenite (W 67) data compared to Murray granite and Murray offshoot regressions

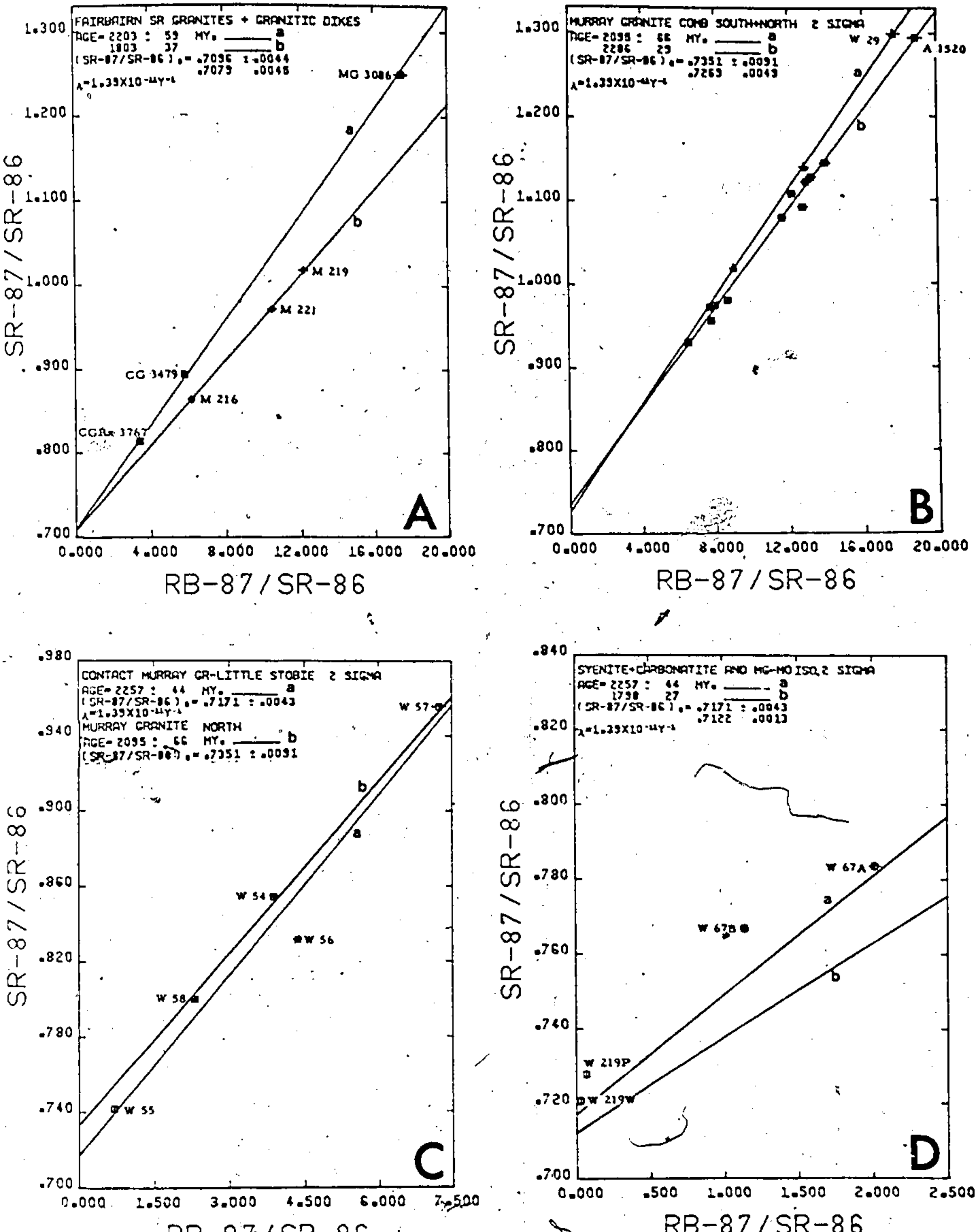

FAIRBAIRN SR GRANITES + GRANITIC DIKES
AGE= 2203 ± 59 MY. a
1803 37 b
(SR-87/SR-86)$_0$= .7096 ± .0044
.7079 .0046
λ=1.39X10^{-11}Y^{-1}
MG 3086
M 219
M 221
CG 3479
M 216
CGRx 3767
a
b
A
SR-87/SR-86
RB-87/SR-86
1.300
1.200
1.100
1.000
.900
.800
.700
0.000
4.000
8.000
12.000
16.000
20.000
MURRAY GRANITE COMB SOUTH+NORTH 2 SIGMA
AGE= 2095 ± 66 MY. a
2286 29 b
(SR-87/SR-86)$_0$= .7351 ± .0091
.7263 .0043
λ=1.39X10^{-11}Y^{-1}
W 29
A 1520
a
b
B
CONTACT MURRAY GR-LITTLE STOBIE 2 SIGMA
AGE= 2257 ± 44 MY. a
(SR-87/SR-86)$_0$= .7171 ± .0043
λ=1.39X10^{-11}Y^{-1}
MURRAY GRANITE NORTH
AGE= 2095 ± 66 MY. b
(SR-87/SR-86)$_0$= .7351 ± .0091
W 57
W 54
W 56
W 58
W 55
b
a
C
.980
.940
.900
.860
.820
.780
.740
.700
0.000
1.500
3.000
4.500
6.000
7.500
SYENITE+CARBONATITE AND MG-MO ISO.2 SIGMA
AGE= 2257 ± 44 MY. a
1798 27 b
(SR-87/SR-86)$_0$= .7171 ± .0043
.7122 .0013
λ=1.39X10^{-11}Y^{-1}
W 67A
W 67B
W 219P
W 219W
a
b
D
.840
.820
.800
.780
.760
.740
.720
.700
0.000
.500
1.000
1.500
2.000
2.500

Figure 4 - 10.

rock age equal to or greater than the Murray granite scatterchrons (Figure 4-10C). The sulfides and isotopic data indicate chemical exchange across the irruptive contact, probably related to the brecciation.

4 - 5 - 2 The Murray Offshoots

Eight whole rock samples from the Murray offshoot 1 yield an errorchron of 1,820 ± 40 m.y.: Ri = 0.712 ± 0.002 (Figure 4-11A).[1] and five whole rock samples from the Murray offshoot 2 give an errorchron of 1,730 ± 30 m.y.: Ri = 0.719 ± 0.002 (Figure 4-11B). Samples from the two offshoots show considerable overlap (Figure 4-11C) and produce a 15 point 1,800 ± 30 m.y.: Ri 0.712 ± 0.001 errorchron (Figure 4-11D) when combined.

An additional sample of Murray offshoot 1 (W-1) has extremely high isotopic ratios (Figure 4-12). It falls below the errorchron (possibly due to weathering?) and has not been used. When it is used, it lowers the errorchron age to 1,780 m.y. Sample (W 19) on the other hand is completely free of potassium feldspar and has extremely low isotopic ratios. W 19 also has low K_2O and W 1 low CaO)(Sutton 1972). Both are extremely unusual and indicate special conditions were required to produce or modify them.

---

[1] A 2.05 b.y.: Ri= .711 age for six of these samples reported by Gibbins et al. (1972) was found to be in error. (Large discrepencies in Rb values indicate an incorrectly calibrated Rb spike was the main source of this error). All of these samples have been re-analysed.

FIGURE 4 - 11

A Murray offshoot 1

B Murray offshoot 2

C Murray offshoots - compared

squares - Murray offshoot 1
triangles - Murray offshoot 2

D Murray granite - combined

as above
diamonds - granitic dikes (Figure 4-11A)

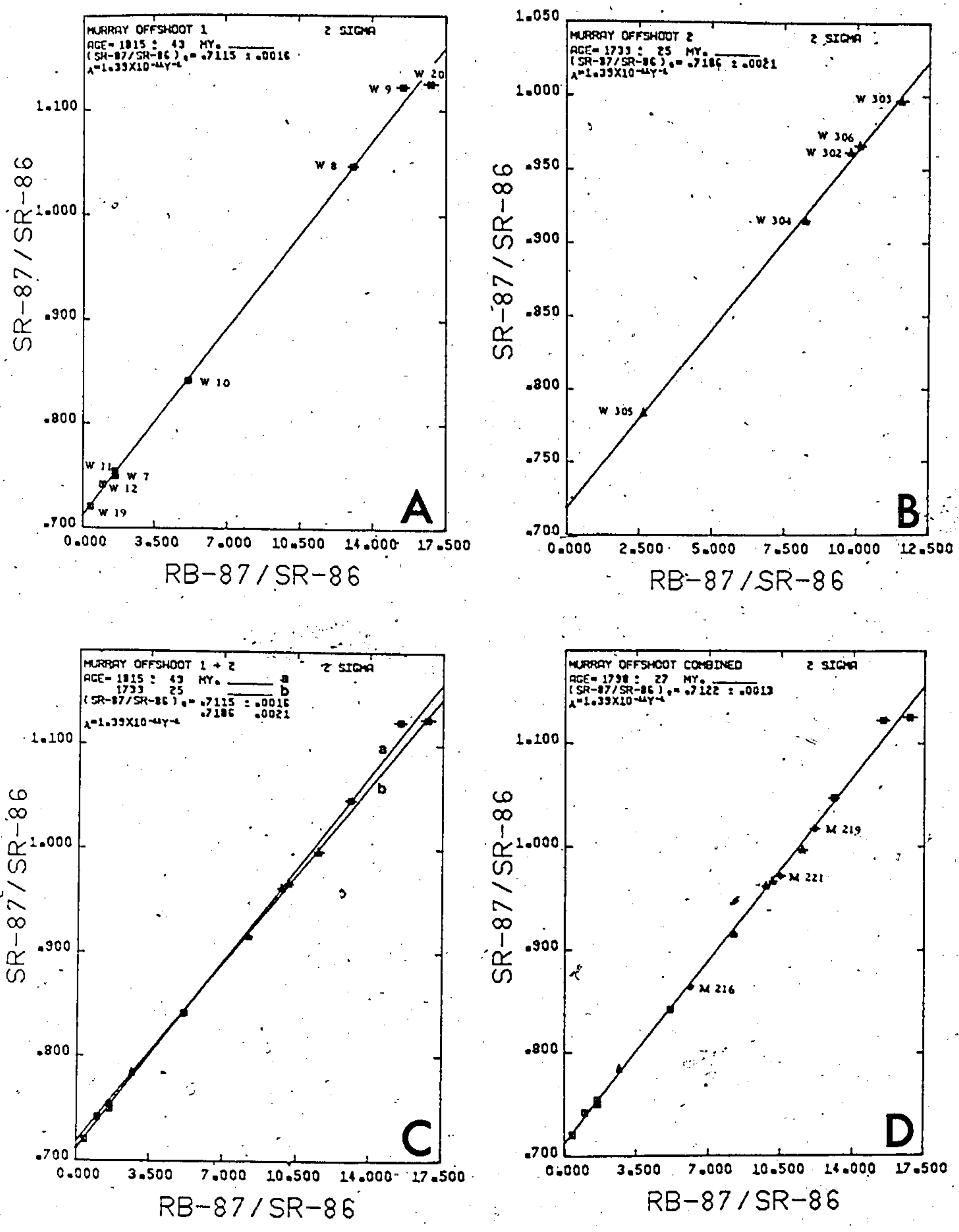

MURRAY OFFSHOOT 1
2 SIGMA
AGE= 1815 ± 43 MY.
(SR-87/SR-86)$_0$= .7115 ± .0016
λ=1.39X10^{-11}Y^{-1}
W 20
W 9
W 8
W 10
W 11
W 7
W 12
W 19
A
1.100
1.000
.900
.800
.700
0.000
3.500
7.000
10.500
14.000
17.500
SR-87/SR-86
RB-87/SR-86
MURRAY OFFSHOOT 2
2 SIGMA
AGE= 1733 ± 25 MY.
(SR-87/SR-86)$_0$= .7186 ± .0021
λ=1.39X10^{-11}Y^{-1}
W 303
W 306
W 302
W 304
W 305
B
1.050
1.000
.950
.900
.850
.800
.750
.700
0.000
2.500
5.000
7.500
10.000
12.500
SR-87/SR-86
RB-87/SR-86
MURRAY OFFSHOOT 1 + 2
2 SIGMA
AGE= 1815 ± 43 MY. a
1733 25 b
(SR-87/SR-86)$_0$= .7115 ± .0016
.7186 .0021
λ=1.39X10^{-11}Y^{-1}
a
b
C
1.100
1.000
.900
.800
.700
0.000
3.500
7.000
10.500
14.000
17.500
SR-87/SR-86
RB-87/SR-86
MURRAY OFFSHOOT COMBINED
2 SIGMA
AGE= 1798 ± 27 MY.
(SR-87/SR-86)$_0$= .7122 ± .0013
λ=1.39X10^{-11}Y^{-1}
M 219
M 221
M 216
D
1.100
1.000
.900
.800
.700
0.000
3.500
7.000
10.500
14.000
17.500
SR-87/SR-86
RB-87/SR-86

Figure 4 - 11.

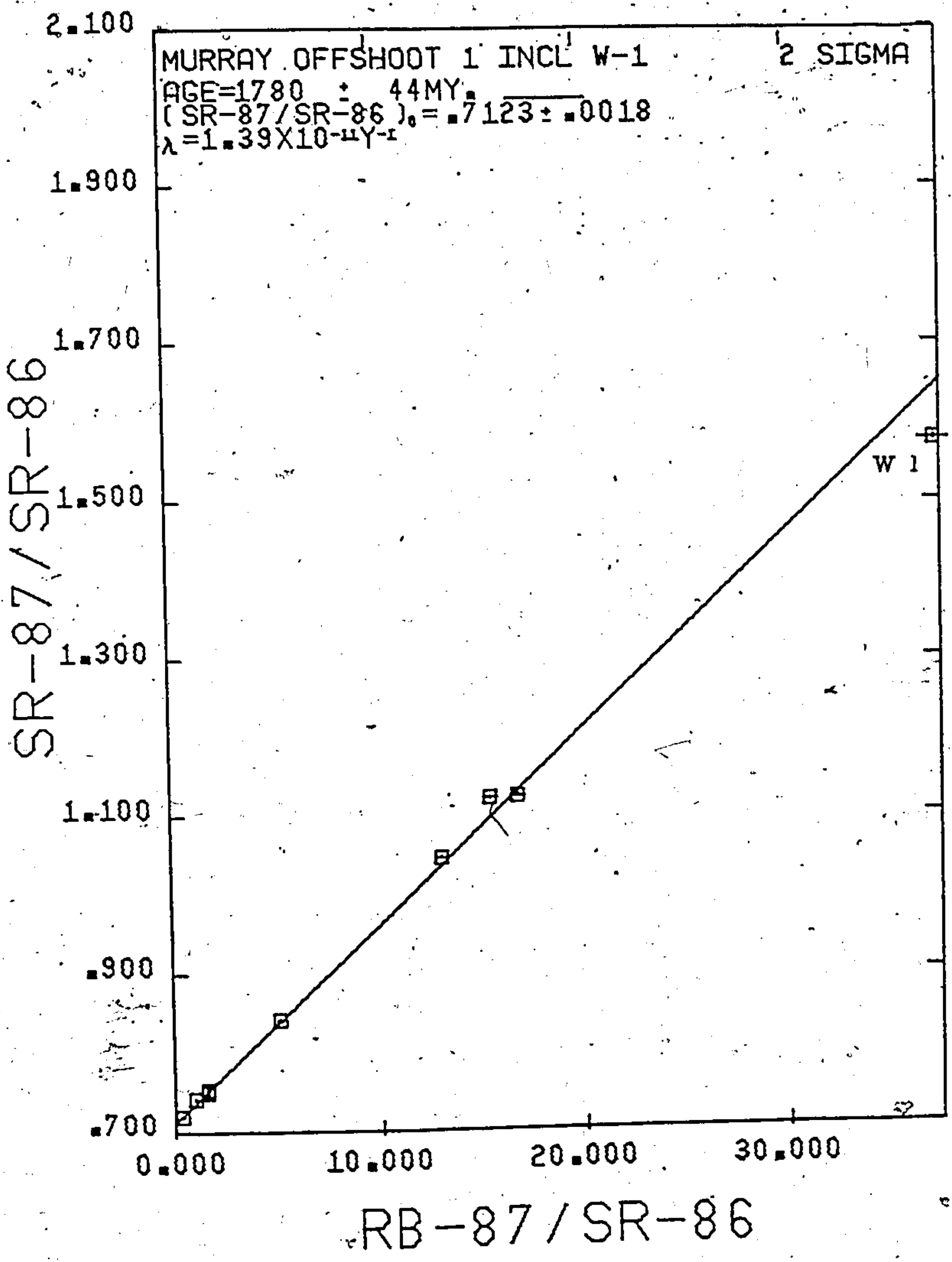


Figure 4 - 12: Comparison of sample W - 1 (not regressed) with other Murray offshoot samples.

4 - 5 - 3 Granitic Dikes

Three samples of late aplitic pegmatitic dikes which cut the norite and Murray granite give an age of 1,800 ± 40 m.y.: Ri = 0.708 ± .05 (Gibbins et al. 1972 and Figure 4-10A). They appear to be isotopically equivalent to the Murray offshoot dikes (Figure 4-11D).

4 - 5 - 4 Minor Intrusions

Two small plugs (about 100 feet in diameter) appear to intrude the Murray granite near its contact with the irruptive. The first (W 67) is all albitite which occurs near the Little Stobie mine and the second (W 219) a carbonatite occurring near the McKim mine (Figure 4-1). They are composed mainly of albite and albite plus carbonate (see appendix D). Lack of petrologic and isotopic variation and open system behavior has made it impossible to date them (Figure 4-10D). The origin and possible relationship of these two intrusions to each other is not clear, they may be related to fenetization found elsewhere in the Sudbury area.

4 - 6 Discussion of Isotopic Analyses

4 - 6 - 1 Murray Granite versus Murray Offshoots

Figure 4-13 shows the distribution of 18 whole rock samples of Murray granite (squares), 13 samples of Murray offshoot (M.O. 1 = triangles, M.O. 2 = diamonds), and their

FIGURE 4 - 13

Murray granite and offshoots compared

squares - Murray granite
triangles - Murray offshoot 1
diamonds - Murray offshoot 2

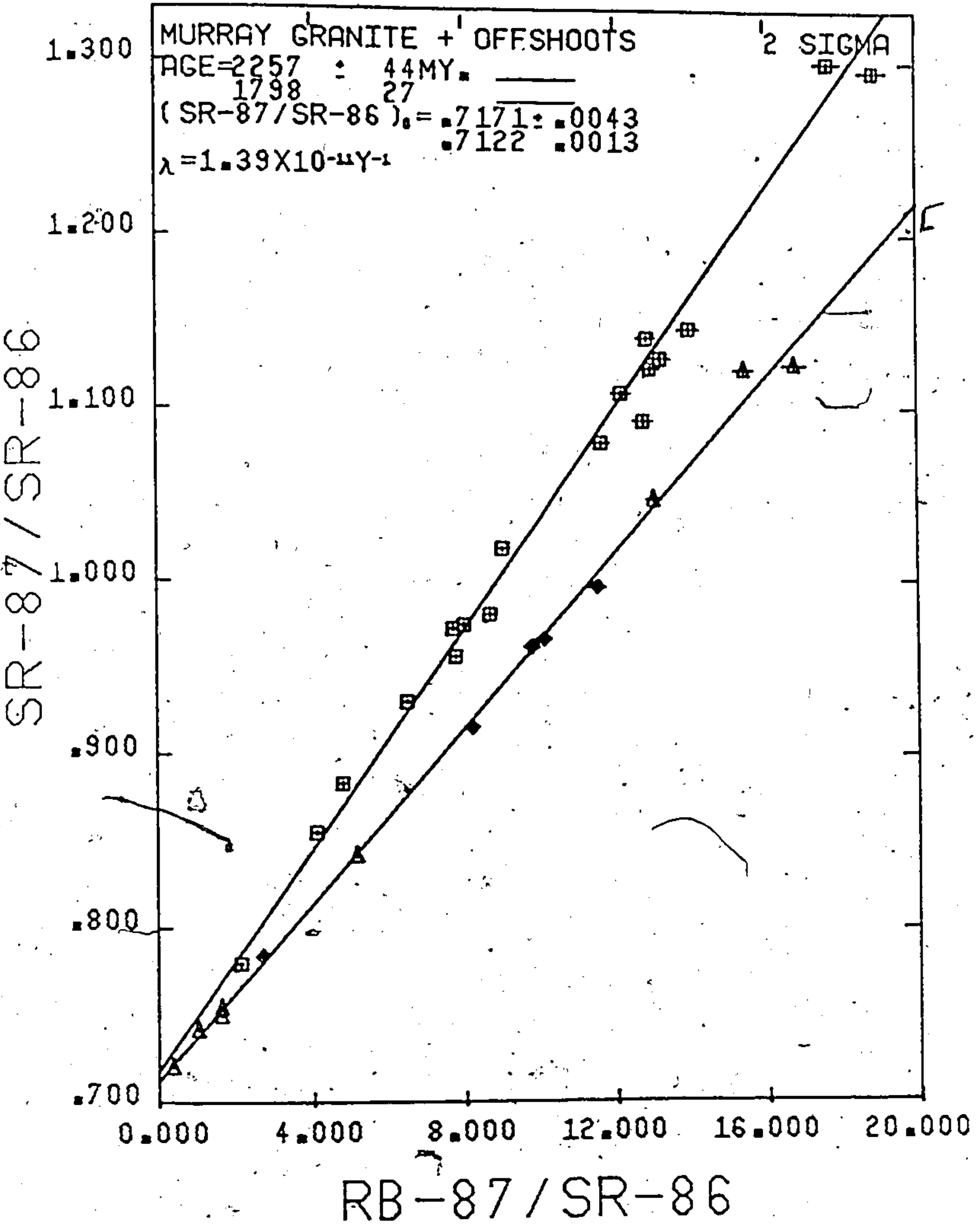


Figure 4 - 13: Comparison of Murray granite samples (squares) with Murray offshoot 1 (triangles) and Murray offshoot 2 (diamonds).

respective regression lines. Although the two sets of data show a similar range in isotopic ratios and scatter about their regression lines, they are well defined and show no overlap.

The offshoots are also unique in that they show extreme values of isotope ratios (W 1 and W 19) and do not contain sulfides or Sudbury breccia and other well developed deformational features.

4 - 6 - 2 The Murray Granite

The Murray granite data indicate a pre-irruptive origin (Figure 4-9D). This is in accord with the geologic evidence and interpretation discussed previously. The high initial Sr^{87}/Sr^{86} of the Murray granite (0.717) is unusual for rocks of this age. It is higher than any comparable granites listed in Faure and Powell (1972, pp. 139-142). This high initial ratio seems to indicate a source region in the crust, i.e. melting of older crustal material, e.g. Archean basement granites and gneisses. Rejection of probably contaminated marginal samples (M 215 and M 225) and Sudbury breccia samples (W 190 and W 227) of low isotopic ratios gives an even higher initial ratio.

Division of the remaining Murray granite samples according to location, (northwest and southeast sections of the Murray granite), produces results in accordance with Speers' (1956) concept of two ages of Murray granite. Three samples from the southeast section (W 27, W 28, and W 29) indicating a pre-irruptive age of 2,290 ± 30 m.y., Ri = 0.727 ± 0.005 and the remaining 12 samples from the northwest part give a regression line of slope equal to 2,100 m.y. and intercept of 0.735 (Figure 4-10B). This is not a geologically or statistically valid age, but suggests and is compatible with partial resetting of whole rocks by metamorphism related to intrusion of the nickel irruptive and the Sudbury event. This metamorphism is indicated by the higher data scatter, the higher initial Sr^{87}/Sr^{86}, and the lower age of the northwestern samples, as well as the geological evidence presented in Section 4-4. In addition, W 29, the farthest, and A 1520, the closest sample to the norite, have comparative isotopic ratios and also indicate metamorphism by the norite. Three of five brecciated Murray granite samples, collected near the norite in the Little Stobie mine, also fall on the 2,100 m.y. scatterchron, the other two fall to show isotopic equilibrium (Figure 4-10C).

Contact metamorphism of the Murray granite by the norite approximately 2.0 b.y. ago is indicated by geologic and isotopic evidence. Other subsequent metamorphic events in the area are demonstrated and discussed in Chapters 5 and 6.

4 - 6 - 3 The Murray Offshoots

Collins (1936, p. 45) suggested remobilization and injection of granitic material during and slightly after intrusion of the norite. Gabbroic magma, of higher melting point, could conceivable melt parts of an adjacent granite, which then filled cracks in the newly crystallized norite at temperatures between their respective melting points. Fairbairn et al. (1965, p.100) suggested that the isotopic age of these granitic dikes should be the same as the norite. The 1.73 b.y. Murray offshoot 2 age is compatible with their 1.72 b.y. irruptive age, but not the 2.0 b.y. norite age of Chapter 3. A lower initial Sr^{87}/Sr^{86} for the offshoots (0.712) as compared to the Murray granite (0.717 - 0.727) is not compatible with the remelting idea, although addition or exchange of strontium with the norite may be able to resolve this problem.

Collins (1936, pp. 36-37) recognized two types of granitic dykes adjacent to the norite. One type is porphyritic like the Creighton granite. These dikes are less than 5 feet wide and extend less than 40 feet into the norite. These may also be present near the norite and appear to be equivalent to the injection breccia dikes of Speers (1956), which may contain abundant inclusions and sulfides similar to the marginal metamorphic zone of the Murray granite or Speers' Murray granite # 2.

The Murray offshoots are not like the above (section 4-6-2), but seem to be equivalent in many ways to Collins' second type. These are fine grained, with sharp parallel contacts and possible chilling. They may be found at greater distances from the contact and may show low potassium values. They are also separated from the main granite mass by swamp and have led Collins (1936, p.37) to note: "It is possible that they are much later intrusions unrelated to the Creighton mass."

The 1.7 to 1.8 b.y. whole rock "ages" of the Murray offshoots and granitic dikes, coupled with their relatively undeformed nature suggest a unique post-norite and post-Murray granite, late Penokean time of crystallization. The Cutler batholith to the west and some of the Killarney and French River granites to the south and east are also Penokean (1.7 b.y.) in age. Less clear are: (1) the exact relationship of the Murray offshoots and the granitic dikes (a pegmatite dike in the Murray offshoot 1, near W 20 in Figure 4-3, may represent a late stage of the offshoot), (2) the relationships within "granitic dikes," (3) the ultimate source and origin of the dikes, (4) the origin of the large fissures in the norite which the dikes occupy, and (5) the apparent alkali metasomatism in some offshoot samples and the chemical similarity of others to the Murray granite.

4 - 7 Conclusions

New isotopic and geologic evidence and a review of earlier evidence and concepts confirms and/or indicates the following conclusions:

(1) The Murray granite (2.26 b.y.) is older than the nickel irruptive (2.0 b.y.)

(2) The Murray granite appears to have been metamorphosed by the nickel irruptive along their mutual contact. This is in accordance with the concept of two ages of Murray granite.

(3) The Murray offshoot dikes (1.7 - 1.8 b.y.) are post norite and post Murray granite. They appear to have formed

during late Penokean time.

(4) Geological evidence indicates additional metamorphic effects in the Murray granite are widespread in nature, time and degree.

Chapter 5 Rubidium-Strontium Mineral Ages from the Sudbury Area

5 - 1 Introduction

As mentioned in Chapter 1, "age" is used in this study to refer to the value of t in the solution of the basic age dating equation. In the ideal case, no excess radiogenic daughter nuclide is present when the system (mineral or rock) becomes closed at t = 0 and it remains closed with respect to parent and daughter nuclides and their respective elements until t = present. In minerals, this closure is commonly accomplished by cooling through a characteristic "blocking temperature". This cooling is frequently related to crystallization and/or tectonic uplift of the rocks involved.

Ideality however, is not always the case in nature, examples of excess daughter product and various types of open system behavior in minerals are well established. Common causes of complete or partial resetting of minerals include contact metamorphism (e.g. Hart, 1964 and Hanson and Gast 1967), regional metamorphism (e.g. Wetherill et al. 1967 and Aldrich et al. 1965), and chemical weathering (e.g. Goldich and Gast 1966). Discordant mineral ages may be the only recognizable effect of open system behavior of minerals in a rock, e.g. exchange of radiogenic Sr^{87} with pore fluid in the rock or diffusion of radiogenic Sr^{87} out of the mineral structure) or they may be accompanied by obvious mineralogic, petrographic and/or chemical changes (e.g. widespread metasomatism and recrystallization involving the gain or loss of other elements besides rubidium and strontium).

5 - 2 Types of Rubidium-Strontium Mineral Ages

5 - 2 - 1 Mineral-Assumed Initial Ratio Ages

Due to experimental limitations, the earliest rubidium-strontium age determinations were made on rubidium rich minerals (e.g. micas). Each sample was analysed for Sr^{87}/Sr^{86} on a mass spectrometer and rubidium and strontium contents were determined by gravimetric methods. The amount of radiogenic strontium in the sample ($*Sr^{87}$) was determined using the equation:

$$*Sr^{87} = \frac{Sr^{87} - A}{1 - A} C \qquad \text{(Schreiner, 1958)}$$

where: C = measured concentration of Sr
A = the initial Sr^{87}/Sr^{86} value

then the age was calculated using the equation:

$$*Sr^{87} = Rb^{87} (e^{\lambda t} - 1)$$

or the approximation $t \cong \frac{1}{\lambda} \frac{*Sr^{87}}{Rb^{87}}$

Later isotope dilution and X-ray fluorescence techniques were introduced and the method extended to whole rocks and other minerals.

The mineral-assumed initial ratio age can be calculated from the equation:

$$Sr^{87}/Sr^{86} = (Sr^{87}/Sr^{86})_{initial} + Rb^{87}/Sr^{86} (e^{\lambda t} - 1)$$

On a Nicolaysen or strontium evolution diagram (Appendix A), this is equivalent to plotting the sample and joining it with a straight line to the assumed initial Sr^{87}/Sr^{86} at $Rb^{87}/Sr^{86} = 0$. The slope of this line is then related to the age by, $m = e^{\lambda t} - 1$.

Normally the initial Sr^{87}/Sr^{86} value is assumed to be similar to values obtained from oceanic basalts (0.702 to 0.706), which are believed to be representative of mantle values.

Frequently ages derived in this manner give reasonable and reproducible results, as is the case when the sample has remained closed and not been subject to metamorphic (i.e. resetting) events and/or the Sr^{87}/Sr^{86} of the sample is considerably greater than the Sr^{87}/Sr^{86} assumed (i.e. 0.702 - 0.706). On the other hand, strontium isotope re-equilibration or resetting by metamorphism may raise the Sr^{87}/Sr^{86} of the system (rock unit or whole rock sample) considerably (Appendix A) and lower the ages of their components correspondingly. An example of this can be seen in Figure 5-2A where four potassium feldspar-whole rock pairs from the Murray granite give consistent (1.28 - 1.32 b.y.) ages, but assumption of a 0.706 initial Sr^{87}/Sr^{86} would produce considerably older and inconsistent ages. (1.45-1.71 b.y.) However, biotites from the same rock samples, because of their high isotope ratios, are relatively unaffected by assuming any initial Sr^{87}/Sr^{86} value between 0.700 and 1.000 (Figure 5-2C)

Original rubidium free mineral phases (e.g. fluorite, apatite, epidote) contain only common strontium and can provide a useful check of the initial Sr^{87}/Sr^{86} of isochrons of undisturbed rocks. In metamorphic rocks, their use as an initial (Sr^{87}/Sr^{86}) is not always warranted. Examples are known where rubidium poor phases have Sr^{87}/Sr^{86} values which are too high (e.g. garnet) or too low (apatite and fluorite) (e.g. Jaeger 1970). As far as metamorphic minerals are concerned, an assumed initial Sr^{87}/Sr^{86} is often just as good if not better than a rubidium free phase.

The traditional method of determining potassium-argon ages contains some of the same disadvantages mentioned above. Because the radiogenic daughter Ar^{40} is an inert gas, it is often (but not always) completely expelled from the system and the age calculation assumes that there was no excess argon at the time the system was closed.

5 - 2 - 2 Mineral Isochrons

A mineral isochron is simply an isochron derived by plotting the analytical results for each of several separated mineral phases and the whole rock (composite value) of a single rock sample. In undisturbed systems, the minerals simply plot along the same straight line isochron as whole rock samples.

In other systems isotopic re-equilibration may take place between mineral phases without disturbing the rubidium-strontium systematics of whole rock samples. In the ideal case of complete isotopic re-equilibration, the various minerals from each whole rock will define an isochron giving the time of the re-equilibration and recrystallization (i.e. the metamorphic event) and a new initial Sr^{87}/Sr^{86} (i.e. the Sr^{87}/Sr^{86} value of each mineral after re-equilibration, q.v. Appendix A and/or Faure and Powell 1972, Chapter IX).

In nature, mineral scatterchrons are common (e.g. Wetherill et al. 1967). This is not totally unexpected, as different minerals are known to lose or gain radiogenic daughter nuclides at different temperatures, rates, etc.. The actual isotopic redistribution produced depends on a number of factors such as the intensity and type of processes involved, the chemical and physical properties of the mineral phases present and the atoms of elements of the parent and daughter nuclides. The relative proportions of elements and/or minerals may also be important.

5 - 2 - 3 Mineral-Whole Rock Pairs

A third approach to mineral dating is to analyze both the mineral and the whole rock sample from which it was separated. The slope of the line joining the two points on a strontium evolution line can then be used to calculate an age. The consistency of these ages can be checked by analyzing additional whole rock-mineral pairs from the same rock unit and (1) comparing the resultant ages for that particular mineral (e.g. Figure 5-1A or 5-2A), or (2) normalizing all the whole rock samples to a common value and regressing the adjusted mineral points (e.g. Figure 5-2D or Figure 4 - Van Schmus 1965, p.763).

Whole rock-mineral ages are most useful when the mineral has considerably higher values of Rb^{87}/Sr^{86} and Sr^{87}/Sr^{86} than the whole rock. Micas almost always fall into this category. (e.g. Figure 5-1A and B). This plus their ability to lose radiogenic Sr^{87} quantitatively in a manner similar to Ar^{40} and to become relatively easily isotopically reset before they become closed again makes them particularly useful for detecting and dating late metamorphic events, which might otherwise go unnoticed.

When a mineral has roughly the same isotopic ratios as the whole rock, (for example some potassium feldspar), it may plot on or very near the whole rock isochron and give no clue of a younger event. Alternately mineral-whole rock lines may indicate that the mineral was open, but unreasonable slopes (negative or ages older than the earth), make it impossible to determine when it was open. This would seem to be the case for potassium feldspar from the Baltimore gneiss (Wetherill et al. 1967) and orthoclase-whole rock and sericite-whole rock pairs from the garnet sillimanite gneisses of the Willyama Complex (Pidgeon 1967, pp. 289-290).

Other minerals may also give unreasonable results, even biotite-whole rock pairs may give completely unreasonable ages. Jaeger (1970, pp. 167-168) found unexpectedly low biotite-whole rock ages and unexpectedly high biotite-assumed initial ratio (0.7091) ages in an admittedly unusual sample of aplite from the Alps.

5 - 3 Discussion of Sudbury Mineral Ages

Biotite and potassium feldspar-whole rock ages determined in this study are given in Figure 5-1 to 5-4 and Table 5-1. These and are indicated by the letter W.

TABLE 5-1 SUDBURY MINERAL AGES

Note: All ages given in billions of years (b.y.)
K-Ar ages in parenthesis, others Rb-Sr(λ= 1.39x10-11y.)
*indicates assumed initial ratio (Ri = 0.706)

ID.	ROCK	BIOTITE	FELDSPAR	REFERENCE
A-1	SOUTH RANGE NORITE			
W104	biotite norite	1.16		1
W101	biotite norite	1.32		1
W110	quartz rich norite	1.25		1
W118	south-range norite	1.27	PL 2.10	1
3192	norite-Murray mine	1.43*(1.63)		2C
3423	norite-Falconbridge mine	(1.40)		2A
A-2	NORTH RANGE NORITE			
W136	felsic norite-Fecunis L.	1.66		1
3197	norite-Hardy mine	1.66*(1.70)		2C
B-1	SOUTH RANGE MICROPEGMATITE			
3191	mpeg.-Snider twp.	1.27*(1.70)		2B
B-2	NORTH RANGE MICROPEGMATITE			
3418	mpeg.-Norman twp.		1.99*	2B
3425	" -Capreol twp.		1.62*	2C
3478	" -Dowling twp.	1.36*(1.67)		2C
C-1	SOUTH RANGE GRANITIC ROCKS			
W 27	Murray granite	1.04	1.30	1
W 27-45	" "	1.03		1
W 64	" "	1.00	1.30	1
W215	" "	1.03	1.32	1
W 35	" " adj.ol.diab.	-33.99	1.49 Or.	1
3086	" " McKim twp.	1.29(1.70)	1.28	2B (A)
W190	" " breccia	1.07		1
W227	" " "	1.06		1
W 7	Murray offshoot 1	1.12	1.28	1
W 9	" " 1	1.13	1.43	1
W 10	" " 1	1.14	1.42	1
3089	Creighton granite	1.23*(1.36)	1.80*	2A
3479	" "	1.28	1.14	2B
3767	" " brecca		1.63	2B
3768	Birch L.gr.-Drury twp		1.33	2B
3094	Copper Cliff rhyolite	1.10(2.07)	2.11*(1.08)	2B(A)
3774	" " " -McKim twp		1.63	2B

TABLE 5-1 continued

ID.	ROCK	BIOTITE	FELDSPAR	REFERENCE
C-2	NORTH RANGE GRANITIC ROCKS			
3471	granite - MacLennan twp.			
3477	" Moncieff "		1.40*	2A
3480	" Porter "		2.04*(1.40)	2A
3481	" " "	(1.50)	1.98*(1.26)	2A
3769	gneissic granite - Trill "	1.82 (1.53)		2B (A)
3770	" " Cascaden"		1.86*	2A
3092	" " " "	(1.35)		2A
3777	" " Norman "	(1.33)		2A
3205	" " Hart "	1.64*(1.82)		2A
3204	" " Levack "	1.62*(1.60)		2A
D-1	SOUTH RANGE NIPISSING DIABASE			
3196	Sudbury gabbro-McKim twp.	1.32*(1.78)		2A
D-2	NORTH (COBALT) NIPISSING DIABASE			
82,(61-157)	Nip.diab.-Cobalt	2.18*(21.10)		3, (4)
E-1	SOUTH RANGE MISCELLANEOUS			
3039	biotite garnet gneiss	0.90*(0.96)		2A
3203	kyanite " bio. "	0.98*(0.99)		2A
3884	granophyre from ol.diab.	(1.02)		2A
E-2	NORTH RANGE MISCELLANEOUS			
3771	Onaping rhyolite		1.03*	2A
3419	" tuff		1.75*	2A
3420	" rhyolite		1.77*	2A
3424	" "		1.66*	2A
3476	Onwatin slate-whole rock	(1.61)		2A

References:

1	This study (Table 2-9)	
2A	Fairbairn et al.	1960
2B	" " "	1961
2C	" " "	1962
3	Van Schmus	1965
4	Lowden et al.	1962

These figures and Table 5-1 also contain data from Fairbairn et al. (1960, 1961, 1962 and 1965) many of which have been recalculated using the 1.39 x 10^{-11} $year^{-1}$ decay constant for Rb^{87} and mineral-whole rock pairs whenever possible. These can be identified by Fairbairn's original sample numbers and letters indicating the rock unit. In an few cases of data recalculated from the literature, an initial Sr^{87}/Sr^{86} (0.706) was assumed in lieu of published whole rock data. They are indicated by an asterisk in Table 5-1. Some of these feldspar ages may be too high.

Selected K-Ar ages from Fairbairn et al. (1960) are also given in Table 5-1 and are indicated by parentheses.

Sample locations can be found in Figures 3-3, 3-4, 4-1, and 4-3. Fairbairn et al.'s sample locations are given in Figure 1, page 43 of their 1960 paper.

In the present study, the effect of grain size on mineral age has been tested by analyzing and comparing biotite separated from the 100-200 mesh fraction (W 27 B) with the 45-100 mesh fraction (W 27 45B) of the same specimen of Murray granite (Figure 5-1A). The finer grained biotite concentrate (W 27 B) has slightly higher Rb^{87}/Sr^{86} and Sr^{87}/Sr^{86} values (possibly due to less inert contaminants), but the two concentrates give the same mineral-whole rock age as do two other biotite whole rock pairs from the Murray granite.

This result, coupled with the consistency of mineral-whole rock ages for each mineral, locality, and rock unit or rock

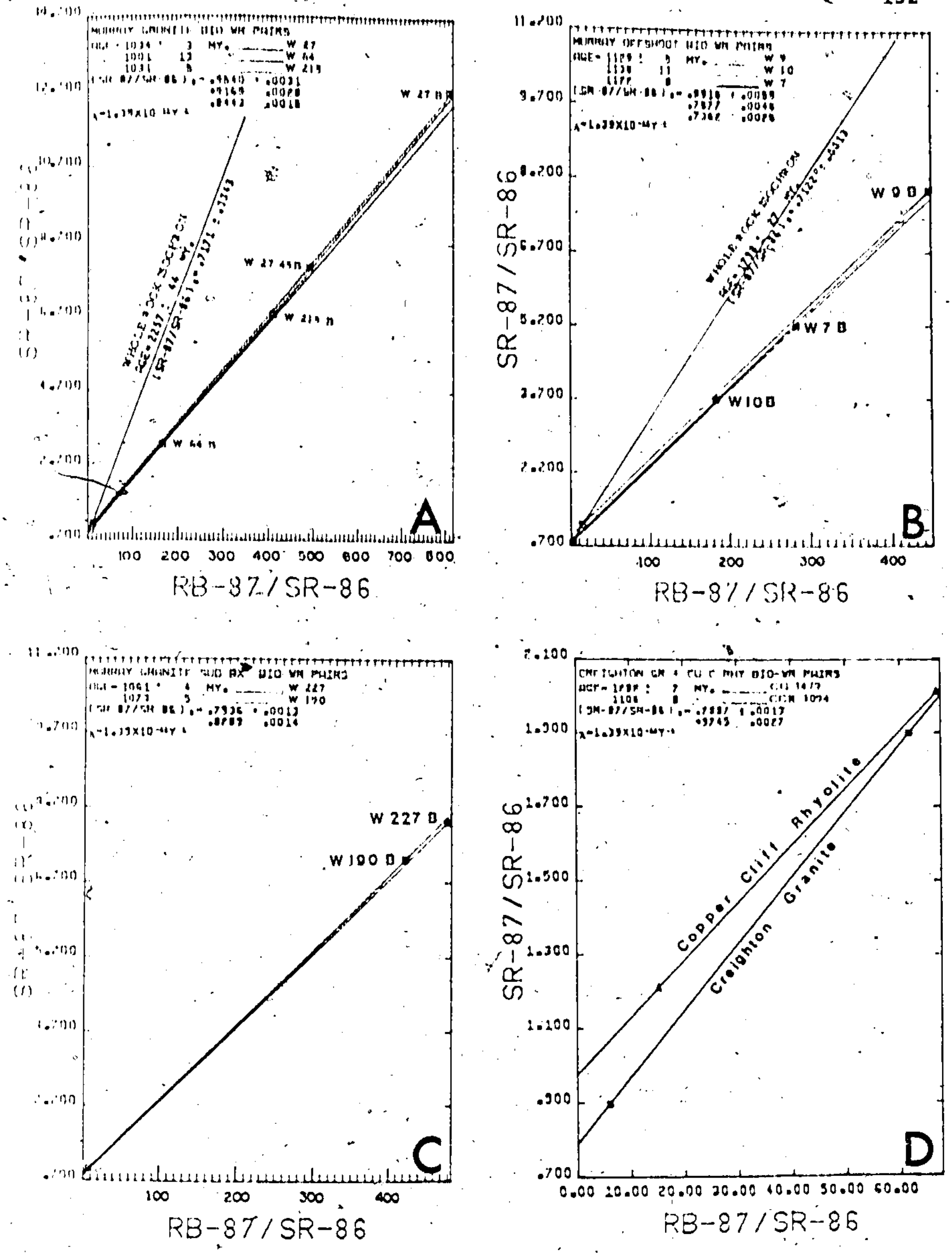

MURRAY GRANITE BIO WR PAIRS
W 27
W 64
W 219
λ=1.39X10 MY
WHOLE ROCK ISOCHRON
W 27 B
W 27.45 B
W 219 B
W 64 B
A
100
200
300
400
500
600
700
800
RB-87/SR-86
MURRAY OFFSHOOT BIO WR PAIRS
W 9
W 10
W 7
λ=1.39X10 MY
WHOLE ROCK ISOCHRON
W 9 B
W 7 B
W 10 B
B
SR-87/SR-86
100
200
300
400
RB-87/SR-86
MURRAY GRANITE SUD RX BIO WR PAIRS
W 227
W 190
λ=1.39X10 MY
W 227 B
W 190 B
C
100
200
300
400
RB-87/SR-86
CREIGHTON GR + CU C RHY BIO-WR PAIRS
CCR 1094
λ=1.39X10 MY
Copper Cliff Rhyolite
Creighton Granite
D
SR-87/SR-86
2.100
1.900
1.700
1.500
1.300
1.100
.900
.700
0.00
10.00
20.00
30.00
40.00
50.00
60.00
RB-87/SR-86

Figure 5 - 1.

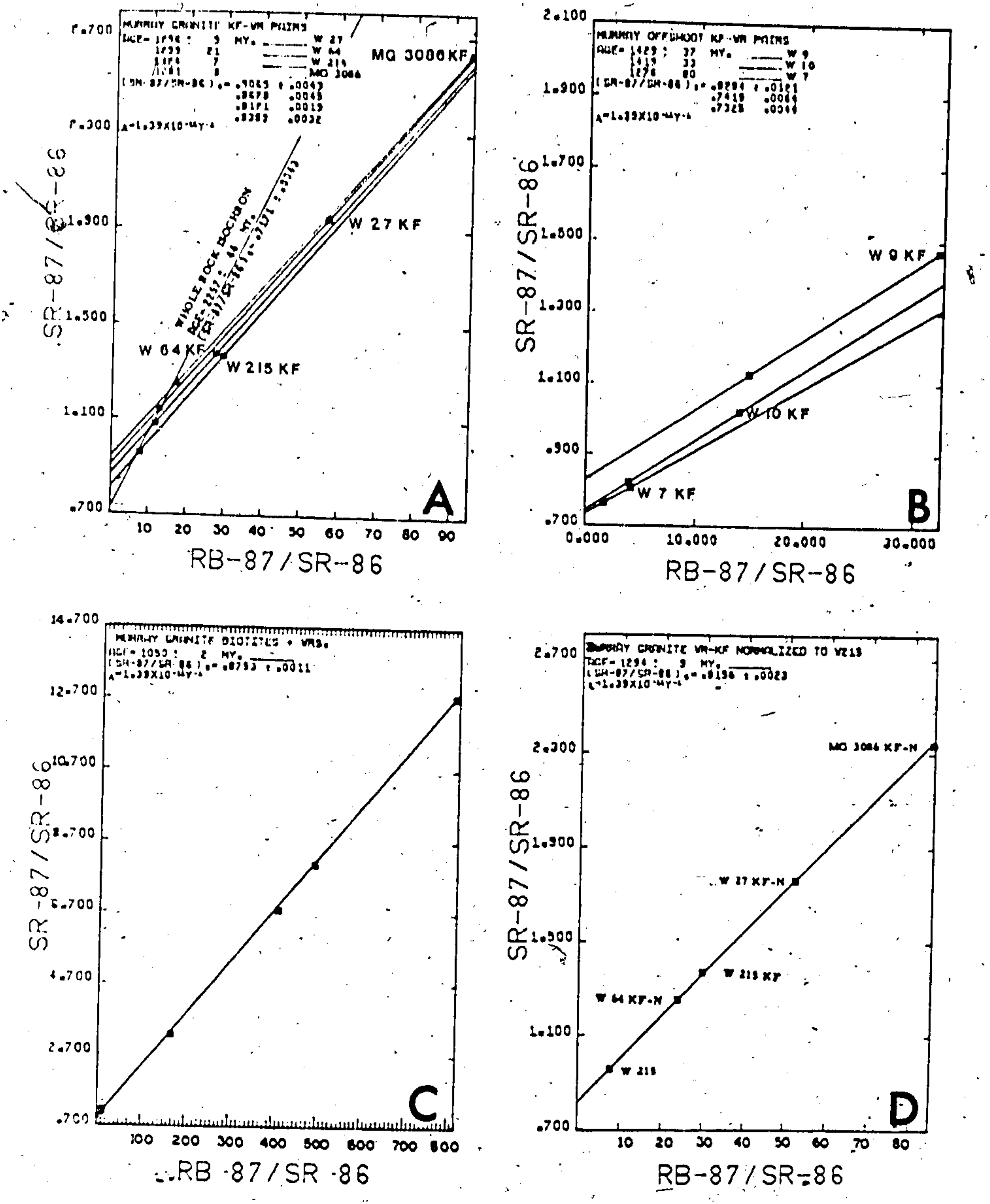

MURRAY GRANITE KF-WR PAIRS
AGE= 1296 ± 9 MY. W 27
1239 21 W 64
1276 7 W 215
1281 8 MO 3086
(SR-87/SR-86)₀= .9065 ± .0043
.8678 .0045
.8171 .0019
.8383 .0032
λ=1.39X10⁻¹¹Y⁻¹
MQ 3086KF
WHOLE ROCK ISOCHRON
AGE=2257 ± 46 MY.
(SR-87/SR-86)₀=.7131 ±.0063
W 27 KF
W 64 KF
W 215 KF
A
SR-87/SR-86
RB-87/SR-86
.700
1.100
1.500
1.900
2.300
2.700
10 20 30 40 50 60 70 80 90
MURRAY OFFSHOOT KF-WR PAIRS
AGE= 1429 ± 37 MY. W 9
1419 33 W 10
1276 80 W 7
(SR-87/SR-86)₀= .8284 ± .0121
.7419 .0064
.7328 .0046
λ=1.39X10⁻¹¹Y⁻¹
W 9 KF
W 10 KF
W 7 KF
B
SR-87/SR-86
RB-87/SR-86
.700
.900
1.100
1.300
1.500
1.700
1.900
2.100
0.000 10.000 20.000 30.000
MURRAY GRANITE BIOTITES + WRS.
AGE= 1050 ± 2 MY.
(SR-87/SR-86)₀= .8733 ± .0011
λ=1.39X10⁻¹¹Y⁻¹
C
SR-87/SR-86
RB-87/SR-86
.700
2.700
4.700
6.700
8.700
10.700
12.700
14.700
100 200 300 400 500 600 700 800
MURRAY GRANITE WR-KF NORMALIZED TO W215
AGE= 1294 ± 9 MY.
(SR-87/SR-86)₀= .8156 ± .0023
λ=1.39X10⁻¹¹Y⁻¹
MO 3086 KF-N
W 27 KF-N
W 215 KF
W 64 KF-N
W 215
D
SR-87/SR-86
RB-87/SR-86
.700
1.100
1.500
1.900
2.300
2.700
10 20 30 40 50 60 70 80

Figure 5 - 2.

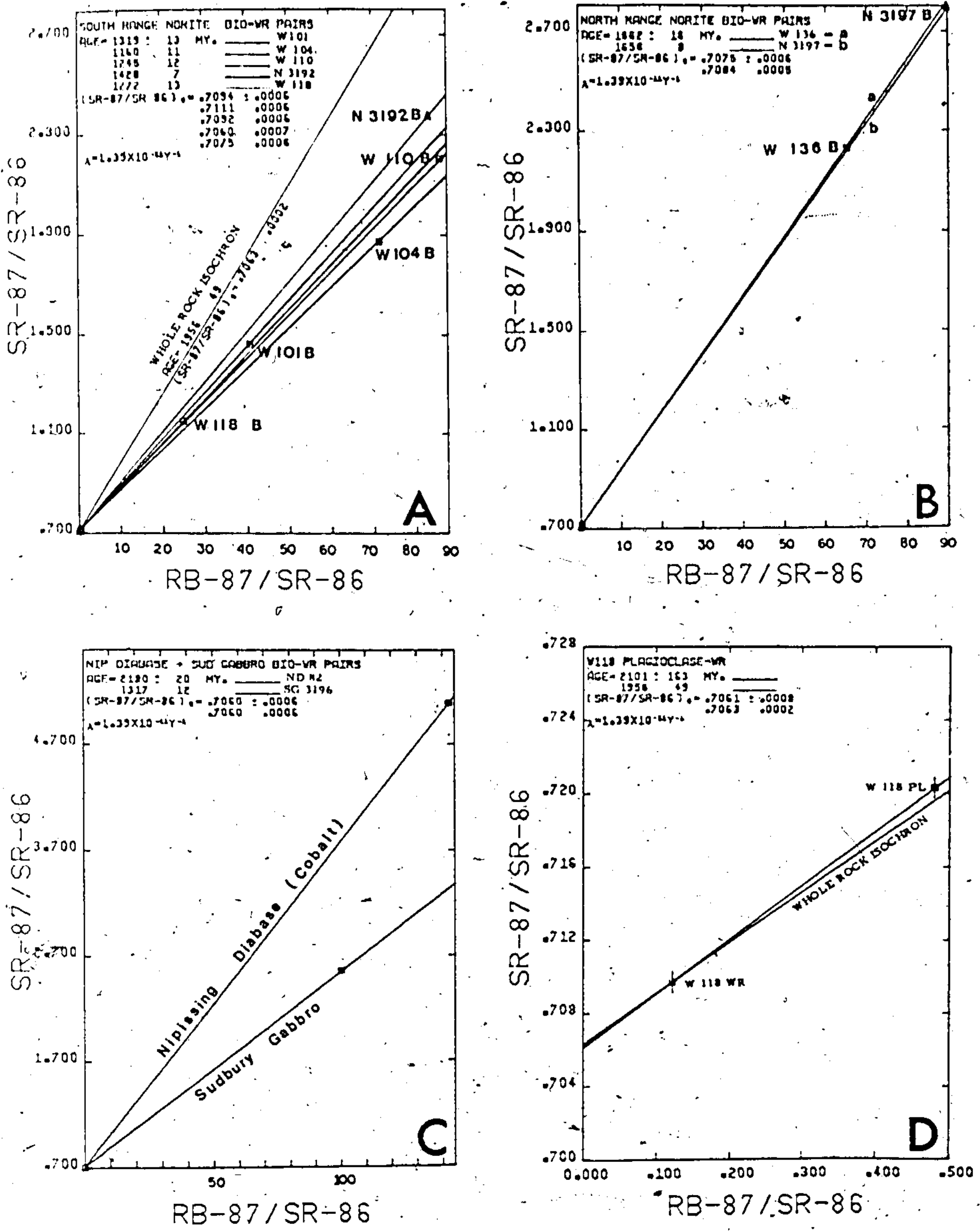

SOUTH RANGE NORITE BIO-WR PAIRS
AGE= 1319 ± 13 MY. W101
1160 11 W 104
1745 12 W 110
1428 7 N 3192
1772 13 W 118
(SR-87/SR-86)₀= .7094 ± .0006
.7111 .0006
.7092 .0006
.7060 .0007
.7075 .0006
λ=1.39X10⁻¹¹Y⁻¹
WHOLE ROCK ISOCHRON
AGE= 1956 49
(SR-87/SR-86)₀=.7063 ± .0002
N 3192 B
W 110 B
W 104 B
W 101 B
W 118 B
A
2.700
2.300
1.900
1.500
1.100
.700
10
20
30
40
50
60
70
80
90
SR-87/SR-86
RB-87/SR-86
NORTH RANGE NORITE BIO-WR PAIRS
AGE= 1662 ± 18 MY. W 136 = a
1656 9 N 3197 = b
(SR-87/SR-86)₀= .7075 ± .0006
.7084 .0008
λ=1.39X10⁻¹¹Y⁻¹
N 3197 B
a
b
W 136 B
B
2.700
2.300
1.900
1.500
1.100
.700
10
20
30
40
50
60
70
80
90
SR-87/SR-86
RB-87/SR-86
NIP DIABASE + SUD GABBRO BIO-WR PAIRS
AGE= 2180 ± 20 MY. ND 82
1317 12 SG 3196
(SR-87/SR-86)₀= .7060 ± .0006
.7060 .0006
λ=1.39X10⁻¹¹Y⁻¹
Nipissing Diabase (Cobalt)
Sudbury Gabbro
C
4.700
3.700
2.700
1.700
.700
50
100
SR-87/SR-86
RB-87/SR-86
W118 PLAGIOCLASE-WR
AGE= 2101 ± 163 MY.
1956 49
(SR-87/SR-86)₀= .7061 ± .0008
.7063 .0002
λ=1.39X10⁻¹¹Y⁻¹
W 118 PL
WHOLE ROCK ISOCHRON
W 118 WR
D
.728
.724
.720
.716
.712
.708
.704
.700
0.000
.100
.200
.300
.400
.500
SR-87/SR-86
RB-87/SR-86

Figure 5 - 3.

FIGURE 5 - 4 C

squares	biotite from granite
triangles	biotite from norite
diamonds	biotite from micropegmatite

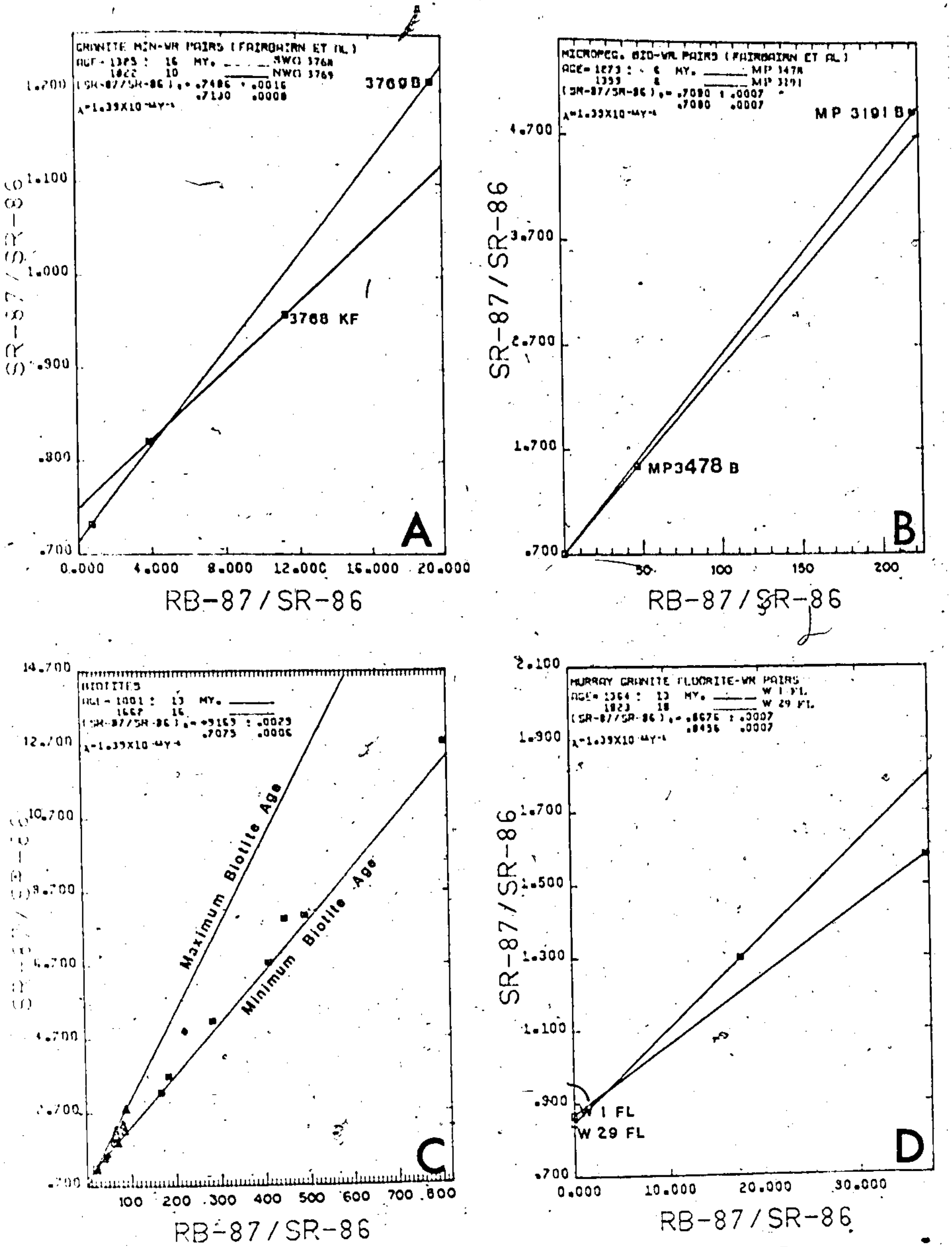

GRANITE MIN-WR PAIRS (FAIRBAIRN ET AL)
AGE= 1325 ± 16 MY. SWO 3768
1022 10 NWO 3769
(SR-87/SR-86)₀= .7486 ± .0016
.7130 .0008
λ=1.39X10 MY
3769B
3768 KF
SR-87/SR-86
1.200
1.100
1.000
.900
.800
.700
0.000
4.000
8.000
12.000
16.000
20.000
RB-87/SR-86
A
MICROPEG. BIO-WR PAIRS (FAIRBAIRN ET AL)
AGE= 1273 ± 6 MY. MP 3478
1353 8 MP 3191
(SR-87/SR-86)₀= .7090 ± .0007
.7080 .0007
λ=1.39X10 MY
MP 3191 B
MP3478 B
SR-87/SR-86
4.700
3.700
2.700
1.700
.700
50
100
150
200
RB-87/SR-86
B
BIOTITES
AGE= 1001 ± 13 MY.
1667 16
(SR-87/SR-86)₀= .9163 ± .0029
.7075 .0006
λ=1.39X10 MY
Maximum Biotite Age
Minimum Biotite Age
SR-87/SR-86
14.700
12.700
10.700
8.700
6.700
4.700
2.700
.700
100
200
300
400
500
600
700
800
RB-87/SR-86
C
MURRAY GRANITE FLUORITE-WR PAIRS
AGE= 1364 ± 13 MY. W 1 FL
1823 18 W 29 FL
(SR-87/SR-86)₀= .8676 ± .0007
.8436 .0007
λ=1.39X10 MY
SR-87/SR-86
2.100
1.900
1.700
1.500
1.300
1.100
.900
.700
W 1 FL
W 29 FL
0.000
10.000
20.000
30.000
RB-87/SR-86
D

Figure 5 - 4.

TABLE 5 - 2 Consistency of Sudbury Rb-Sr Mineral Ages

No. of samples	Rock Unit	Mineral	Range (b.y.)
4	Murray granite	biotite	1.00 - 1.04
4	" "	feldspar	1.28 - 1.32
2	" " breccia	biotite	1.06 - 1.07
3	Murray offshoot 1	"	1.12 - 1.14
2	" "	feldspar	1.42 - 1.43
2	Creighton granite	biotite	1.23 - 1.28
2	North range norite	"	1.66
5	South " "	"	1.16 - 1.43
3	North " granite	"	1.62 - 1.82
3	" " "	feldspar	1.86 - 2.04

type (Table 5-1 to 5-3 and Figures 5-1 to 5-6), suggests that the hypothesis that those ages represent the time since the minerals last became closed and passed through their respective blocking temperatures may be tentatively accepted.

5 - 3 - 1 Comparison of Mineral Ages from the North and South Ranges

Careful examination of Table 5-1 and/or Figures 5-1 to 5-4 or rapid examination of Table 5-3 shows a remarkable difference in mineral ages from the north and south ranges. This difference can also be seen in the map of Rb-Sr mineral ages (Figure 5-5) and the section (Figure 5-6) of Rb-Sr biotite whole-rock ages. Other mineral ages (e.g. Rb-Sr potassium feldspar and K-Ar biotite) show similar but more diffuse trends due, at least in part, to incomplete data. Micropegmatite data (Figure 5-4B) unfortunately are hopelessly inadequate and fresh, chlorite-free concentrates might be very difficult to obtain. Nevertheless, the remaining data show virtually no overlap (Table 5-3) and appear to be adequate enough to attempt meaningful interpretation.

A geological basis for the observed ages and their distribution is given by correlation with well established structural and metamorphic features. Arealy these are (1) an ENE trending series of SE dipping thrust faults which divide the Sudbury basin and define the north and south ranges, (2) a regional trend of increasing deformation and grade of metamorphism in a southeasterly direction towards the Grenville

TABLE 5 - 3 Summary of the North and South Range Mineral Ages (b.y.)

Mineral	rock type	North Range			South Range		
		No.	Average	Range	No.	Average	Range
Biotite	norite	2	1.66	1.66	5	1.29	1.16-1.43
Biotite	granite	3	1.69	1.62-1.82	13	1.11	1.00-1.28
Potassium Feldspar	granite	3	1.96	1.86-2.04	12	1.41	1.14-1.80

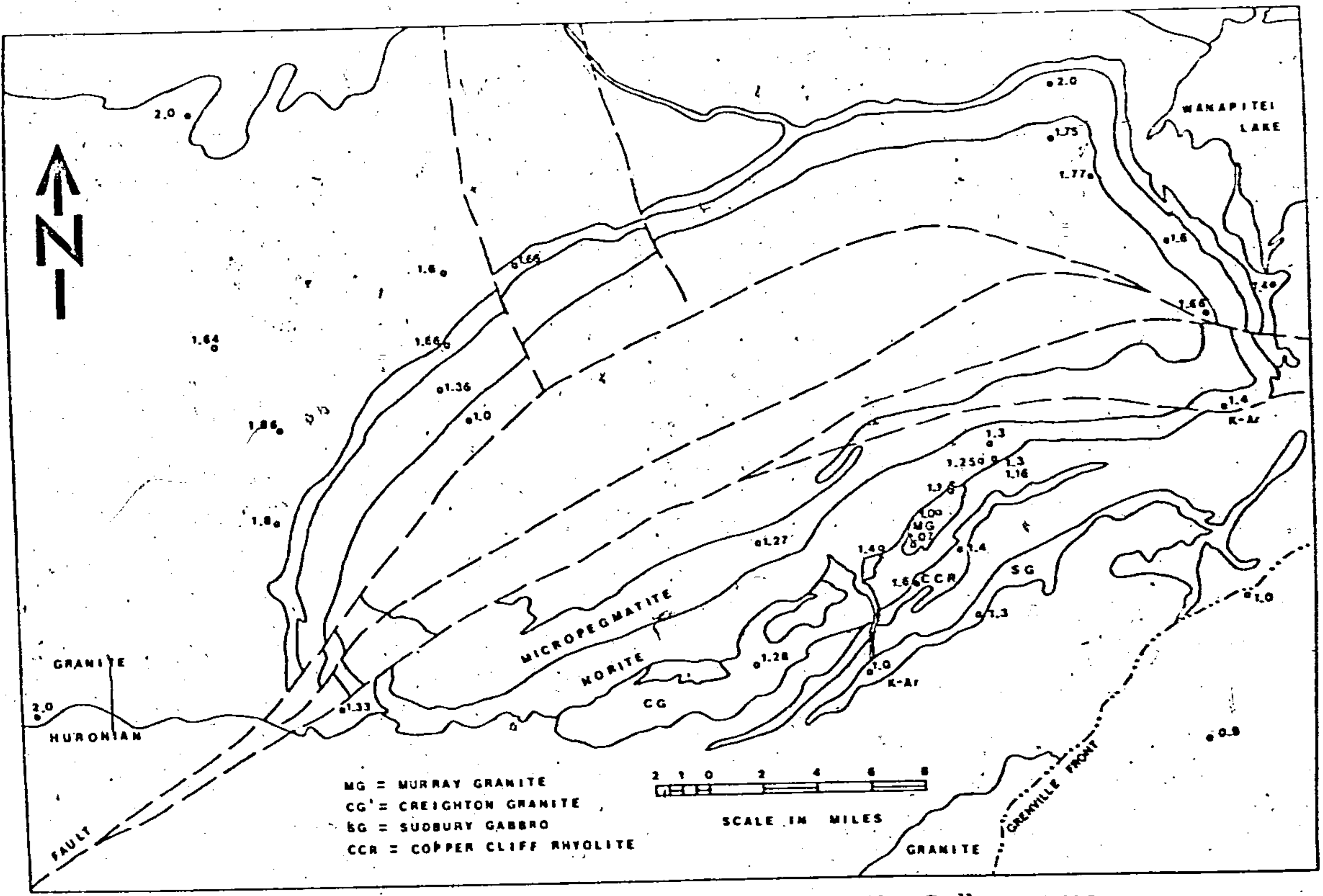


Figure 5 - 5: Distribution of Rb-Sr mineral ages in the Sudbury area. Solid circles = K feldspar ages, open circles = biotite ages. (Most data recalculated from Fairbairn et al. 1960)

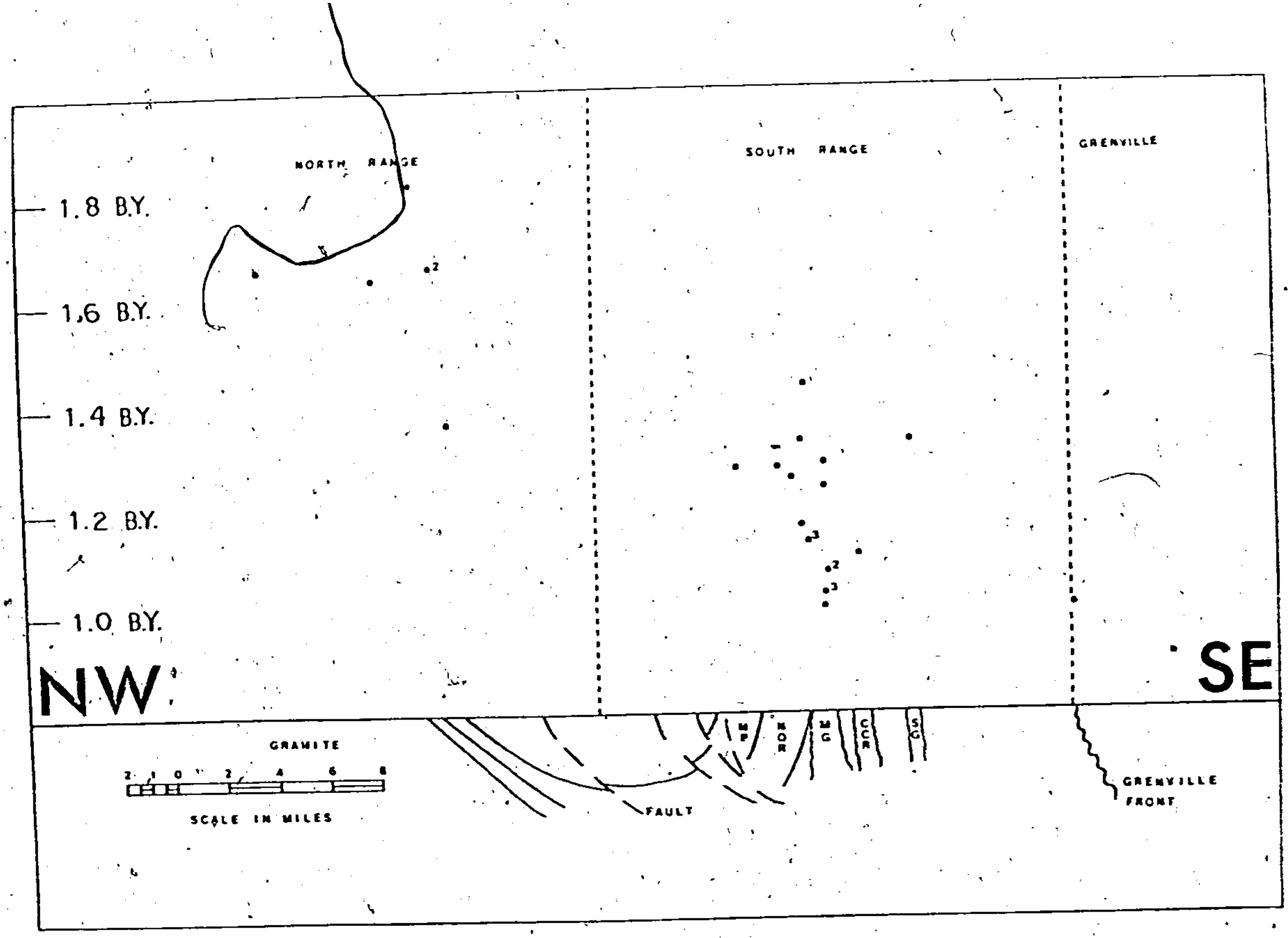


Figure 5 - 6: Generalized cross section of the Sudbury basin showing Rb-Sr biotite ages.

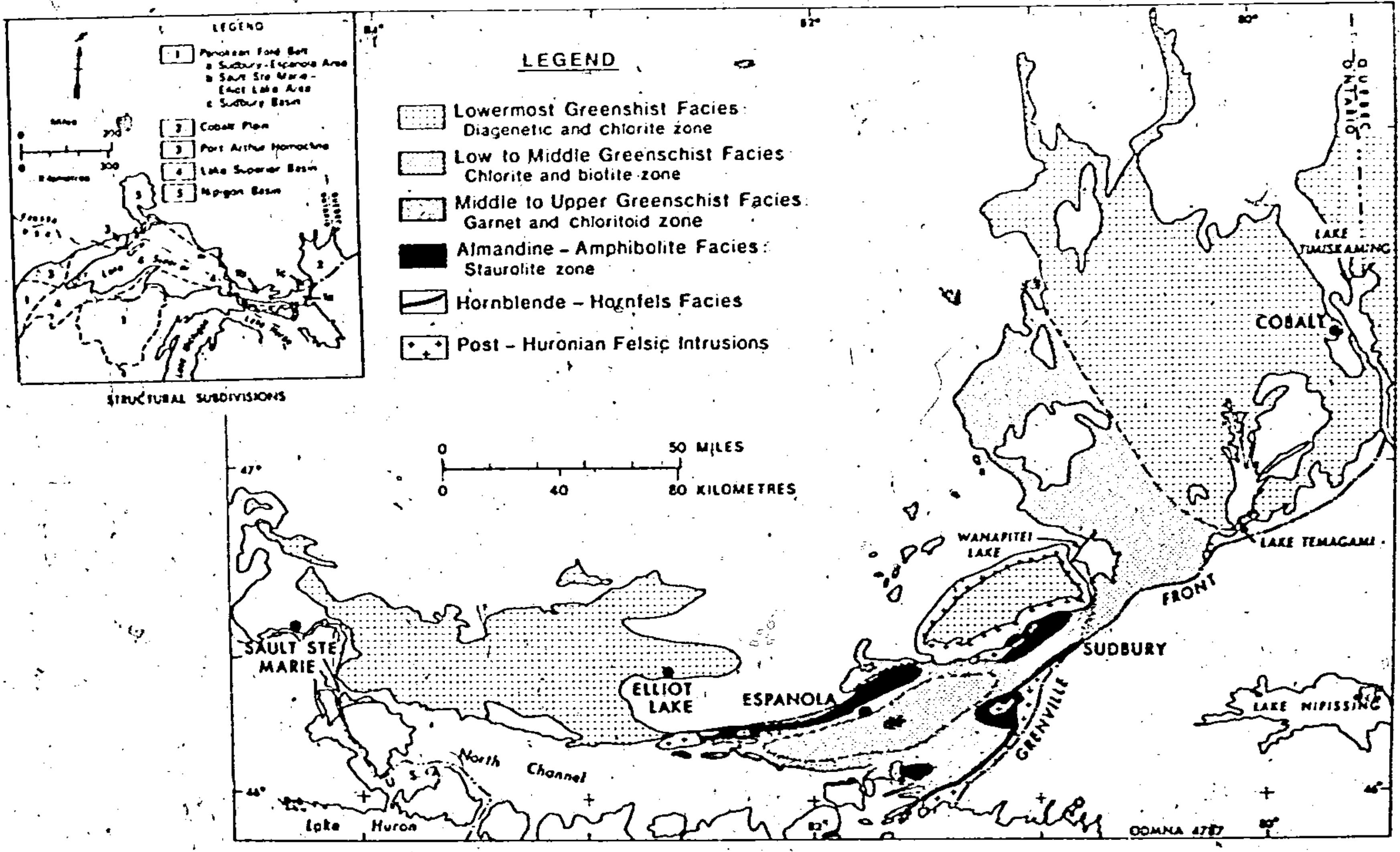


Figure 5-7: Distribution of metamorphic facies and post-Huronian intrusions in the Cobalt Plate and Penokean Fold Belt in Canada. (From Card et al. 1972).

Front (Figures 3-1 and 5-7), and (3) a high grade metamorphic node, of almandine amphibolite facies superimposed on a lower grade greenschist facies terrain, centered in or near the Murray granite (Figure 5-7 after Card et al. 1972a). Mineral ages are easily correlated with well known events recognized by myself and others (Tables 5-4, and 6-2), including: (1) a 1.95 - 2.05 b.y. Sudbury event, (2) the 1.65 - 1.80 b.y. Penokean Orogeny, (3) a 1.30 - 1.45 b.y. "cryptic" thermal event and (4) the 0.90 - 1.10 b.y. Grenville Orogeny or thermal overprint as it is referred to northwest of the front.

Either regional metamorphism and/or faulting with uplift of the south range may explain the difference in north and south range mineral ages. Card et al. (1972a) cite evidence that many of these faults show repeated movements from Huronian deposition (2.2 b.y. ago) to post olivine diabase dikes (1.46 ± 0.13 b.y. ago). This is compatible with uplift, cooling, and resetting of mineral ages of the south range due to faulting approximately 1.4 b.y. ago. This suggests that the 1.3 - 1.45 b.y. "cryptic" thermal event of the south range is related to late faulting in the basin and/or late olivine diabase intrusion.

A similar situation is demonstrated by the Simplon Centovalli fault zone in the Monte Rosa of the Western Alps, described by Hunziker (1970). This fault appears to have a vertical displacement (5-8 km.) as shown by different metamorphic facies and different mica ages on either side of the fault (i.e. 11 m.y. Rb-Sr ages and amphibolite facies metamorphism on the northeast side of the fault and 15 m.y. increasing to 22 m.y. away from the fault and greenschist metamorphism on the southwest side.

Most of the 2.0 and 1.65 b.y. mineral ages from the north range are younger than their respective whole rock isochrons. They all come from a greenschist metamorphic terrain (Figure 5-7) compatible with their being metamorphosed during the Sudbury and/or Penokean events.

The 1.0 b.y. Rb-Sr biotite-whole rock age of the Murray granite (3 samples - 4 biotites), apparently surrounded by 1.3 - 1.4 b.y. ages (Figure 5-5) may be related to a metamorphic node here, but could also be coincidental or due to other causes.

5 - 3 - 2 Comparison of Biotite and Potassium Feldspar-Whole Rock Ages

Rb-Sr potassium feldspar-whole rock ages from the Murray granite and Murray offshoot tend to be 0.3 b.y. older than their corresponding biotite ages (Figures 5-1 A & B and 5-2 A B C D). This also appears to be true for the north range granitic rocks (Table 5-1 section C-2).

Several explanations seem possible, for example radiogenic Sr^{87} could have leaked out of biotite and/or into feldspar since the last event or potassium feldspar may have been only partially reset during the last metamorphic event without losing all of its radiogenic Sr^{87}. However, the striking consistency of all the mineral-whole rock pairs for a particular rock unit (Figures 5-1 A B and 5-2 A and B) and the correspondence between the ages and independently defined events (Table 5-4) suggests that the different ages could be real.

Rubidium and strontium of potassium feldspars seems to be able to behave differently in different rocks and environments and can be very stable. Hart (1964) found Rb-Sr ages of potassium feldspar apparently unaffected beyond about 50 feet of the contact with the intrusive Eldora stock, even though samples as far as 248 feet away were converted from microcline to orthoclase and K-Ar ages of potassium feldspar had been effectively reset at 1000 feet from the contact. Biotite Rb-Sr ages, on the other hand, are frequently almost as easily reset as biotite K-Ar ages (Hanson and Gast 1967).

If the potassium feldspar ages in Table 5-1 are geologically significant, they would indicate that the Sudbury and cryptic thermal events were much more effective at resetting Rb-Sr potassium feldspar ages (e.g. higher temperature), than the Penokean and Grenville events. However, the real explanation may be more complicated than this.

One sample of Murray granite (W 35) was collected in the thermal contact aureole of a late olivine diabase dike less than three feet from the dike (Figure 4-1). Thermal metamorphism in this sample is indicated by the conversion of microcline to orthoclase and most of the biotite to hornblende. The Rb-Sr orthoclase-whole rock age of 1.49 ± .02 b.y. is in good agreement with Gates & Hurley's (1973) 1.46 ± .13 b.y. whole rock scatterchron for the dikes, but this age is not well established yet.

5 - 3 - 3 Comparison of Biotite-Whole Rock Ages

Murray granite biotite-whole rock ages (1.00 - 1.03 b.y.) are consistently lower than Murray offshoot biotite ages (1.12 - 1.14 b.y.) (Figure 5-1 A and B). The Creighton granite (1.23 - 1.28 b.y.) and south range norite (1.16 - 1.43 b.y.) also show minor differences in Rb-Sr biotite ages. These ages seem to reflect partial to complete resetting due to the Grenville thermal overprint as samples closer to the Grenville front tend to have lower ages (Figures 5-5 and 5-6).

Another possible contributing factor is the thermal conductivity of various rock units. Rocks of lower thermal conductivity (e.g. norite and gabbro) could be expected to have lower maximum temperatures (higher "ages") in their interiors than rocks of higher thermal conductivity (e.g. granite). This concept is compatible with the distribution of Rb-Sr biotite ages of the south range and can be extended to explain the intermediate ages of the Murray offshoot by thermal shielding or insulation of the surrounding norite (Figure 4-3).

Another possible explanation is based on the work of Wones and Eugster (1965) on the stability of biotite.

"Biotites occurring in K-feldspar, muscovite, or magnetite free assemblages (e.g. norite) should have less tendency to recrystallize and might be expected to yield older ages" (p. 1268). Rb content (Table 2-9) and isotopic ratios (Figure 5-4C) indicate that there is the expected difference between granite and norite biotites and the Rb-Sr biotite ages (Table 5-1) are in agreement with the suggestion of Wones and Eugster.

5 - 3 - 4 Miscellaneous Minerals

Only one plagioclase sample (W 118 PL) has been isotopically determined. The plagioclase-whole rock age calculated is 2.10 ± .16 b.y., Ri = 0.7061 ± 0.0008 in reasonable agreement with the norite whole rock isochron (Figure 5-3D). It is obvious that more work needs to be done on plagioclase.

Fluorite was found in a few samples of Murray granite and the Murray offshoot 1. Two samples, (W 1 FL and W 29 FL) were analyzed for Sr^{87}/Sr^{86} (Figure 5-4D). Their Sr^{87}/Sr^{86} values, 0.8676 and 0.8456, indicate isotopic redistribution of strontium amongst minerals of their whole rock and they fall within the range of initial strontium ratios of corresponding biotite-whole rock pairs. An attempt was made to calculate fluorite-whole rock ages (Figure 5-4D), but their significance if any, is highly conjectural.

Calcite from the carbonatite (W 219 in Figure 4-1) gave Sr^{87}/Sr^{86} values of 0.7184 and 0.7193. In view of the very low rubidium content of the carbonatite, these values indicate a crustal source and/or crustal contamination of the carbonatite.

5-4 The Relationship of Sudbury Mineral-Whole Rock Ages to Regional and Local Geologic History

Mineral-whole rock ages indicate a long polymetamorphic history in the Sudbury area. Polymetamorphism can also be demonstrated by whole-rock data (Chapter 6) and field geology (Card et al. 1972 a and b). Some of these metamorphic events can be recognized and traced over great distances (e.g. Penokean and Grenville (Keweenawan) activity), while others are only suggested in one or two areas of rather limited geographic distribution (e.g. the Sudbury and cryptic thermal events) (Table 5-4).

A 2.18 b.y. Rb-Sr biotite-whole rock age (Figure 5-3 D, after van Schmus 1965) and a 2.10 b.y. K-Ar biotite age (Lowden et al. 1962) from the Nipissing diabase near Cobalt Ontario corresponds to its 2.16 b.y. Rb-Sr whole rock isochron. These results are typical of what could be expected in an unmetamorphosed part of the Southern Province.

In the Sudbury area, the oldest mineral ages are the 2.0 b.y. potassium feldspar - assumed initial ratio ages of north range granitic rocks. The age is equivalent to the "Subdury event" (Chapter 3). This seems to be a very intense but local metamorphic event (e.g. relatively short-lived shock

TABLE 5-4 Inter-Regional Summary of Mineral Ages and Metamorphic Events (along the Eastern Penokean Fold Belt.)

EVENT	AGE b.y.	NORTHERN MICHIGAN	BLIND RIVER	SUDBURY BASIN NORTH	SUDBURY BASIN SOUTH	GRENVILLE FRONT AREA	GRENVILLE GEORGIAN BAY
Grenville Orogeny (Keweenawan)	1.0-1.2	Keweenawan K-Ar hornblende Granite K-Ar feldspar			Murray granite Rb-Sr biotite Sudbury gabbro Rb-Sr biotite	Granite Rb-Sr K-Ar many minerals	Paragneiss & granite Rb-Sr plagioclase, biotite, etc.
Cryptic Thermal Event(s)	1.3-1.5	Granite, gr. gneiss & slate K-Ar+Rb-Sr biotite Granite + slate K-Ar musc.	Cutler gr. Rb-Sr biotite Croker complex Rb-Sr mica etc.		Norite Rb-Sr biotite Murray granite Rb-Sr feldspar Onaping tuff Rb-Sr inclusions		
Penokean Orogeny	1.6-1.8	Gabbro + gneiss K-Ar Hornblende Granite Rb-Sr feldspar + muscovite	Cutler gr. Rb-Sr muscovite Nip. Diabase Rb-Sr feldspar	Norite Rb-Sr biotite Granite Rb-Sr biotite Onaping Rb-Sr feldspar	Murray granite K-Ar biotite	Granites 1.6 and 1.7 (bracket major deformation)	<u>Paragneiss</u> and <u>granite</u>
Sudbury Event	1.9-2.05			Granite Rb-Sr feldspar <u>Norite</u>			
Kenoran Orogeny?	2.4-2.6			↓ 3 miles	↑	Note Rb-Sr whole rock ages are underlined	

References

Northern Michigan - Aldrich et al. (1965)

Blind River - Van Schmus (1965)
Wetherill et al. (1960)

Sudbury Basin - Fairbairn et al. (1960)
This Study

Grenville Front and Northwest Grenville Areas
- Davis et al. (1970)
Krogh et al. (1971)

metamorphism followed by intrusion of the nickel irruptive).

The Penokean Orogeny can be seen in the 1.6 to 1.8 b.y. Rb-Sr biotite ages of the north range, where the metamorphism has not reached a very high grade. Open whole rock systems and geological evidence (extensive deformation and recrystallization) indicate a higher grade of metamorphism on the south range.

The cryptic thermal event (1.3 - 1.45 b.y. ago) was first recognized in the Sudbury area by Fairbairn et al. (1969). It is best demonstrated by Rb-Sr potassium feldspar ages from the south range. This data is suggestive of a fairly high temperature regime due to an originally deeper level of the present south range, followed by uplift relative to the north range 1.4 b.y. ago.

The Grenville Orogeny in the Sudbury area is represented by a thermal overprint (Henderson 1972 and Brocoum and Dalziel 1973). The relatively minor importance of the Grenville event in the Sudbury basin is indicated by failure of south range potassium feldspars and many biotites to be effectively reset. It has not affected the north range.

Chapter 6 - A Review of Rb-Sr Whole-Rock Ages from Sudbury and Adjacent Areas.

6 - 1 - Introduction

> "The behaviour of Rb-Sr whole rock systems during metamorphism is apparently not simply dependent on intensity of metamorphism. Open-system behaviour of whole-rock systems has been described in hydrothermally altered granite (e.g. Arriens et al., 1966; Brooks 1966, 1968), in low grade metamorphic rocks (e.g. Hansen et al., 1969; Hunziker, 1970; Jager, 1970) and in medium grade gneisses (Lanphere et al., 1964; Wasserburg et al 1964). On the other hand whole-rock systems that have remained closed up to amphibolite-facies metamorphism have also been described from several localities (e.g. Long, 1964; Lambert, 1964). In some of these cases closed-system behaviour is observed down to hand specimen-sized samples, despite the fact that the individual minerals have reequilibrated during the metamorphism. The explanation for this variable response to metamorphism remains obscure."
>
> Cliff 1971, p.274

Many other studies could also be cited in the above discussion. Metamorphic events may affect the Rb-Sr systematics of a lithologic unit or area in one or more of the ways listed in table 6-I.

In some instances metamorphism of whole rock samples may be suggested by a high initial Sr^{87}/Sr^{86} and/or data scatter greater than experimental error. In any case, a sound knowledge of the geology of the rocks and area involved is a necessary prerequisite to competent interpretations of isotopic results.

Cases of almost all types of Rb-Sr whole rock disturbance

TABLE 6-1 PROCESS - RESPONSE MODELS OF METAMORPHISM AND Rb-Sr WHOLE ROCK AGES

PROCESS	RESPONSE	LITERATURE EXAMPLE	SUDBURY EXAMPLE
1. Whole rocks closed, minerals may be reset (isochrons)	original age	Baltimore gneiss	Sudbury norite
2. Whole rocks partially open (scatterchrons)	A. original age	Torset granite	Copper Cliff rhyolite? SE Murray granite
	B. metamorphic age	Aston-Hospitalet gneiss	NW Murray granite kyanite gneiss
	C. intermediate age and/or inconsistent data	Doodoman migmatites	Huronian group green norite and gabbro
3. Whole rocks open, but re-equilibrated (reset isochrons)	metamorphic age	Roffna gneiss	Micropegmatite
SPECIAL CASES			
A. (1) original age = metamorphic age		Palmer granite	Murray offshoots?
(2) original age ≅ metamorphic age		Twilight gneiss	Chief L. batholith
B. Failure of assumptions to be valid.			
(1) non uniform initial Sr87/Sr86 (2) alteration or continued open system		Palmer granite	Whitewater group
(3) geological contamination		Zentral gneiss leucogranite	Murray granite samples M225 & M215
C. Polymetamorphism		Bamble area - Norway Southern Arizona etc.	Sudbury area esp. south range

REFERENCES - TABLE 6-1

A) LITERATURE

Wetherill et al. (1967)
Brueckner (1971)
Jaeger and Zwart (1968)
Wendt et al. (1972)
Hansen et al. (1969)
White et al. (1967)
Barker et al. (1969)
Cliff (1971)
O'Nions and Baadsgaard (1971)
Shakel (1972)

B) SUDBURY

This study - Chapters 3 and 4
Fairbairn et al. (1965)
" " " (1968)
" " " (1969)
Krogh and Hurley (1968)
Krogh and Davis (1970)

have been recognized in the Sudbury Area (Table 6-1), as well as many of the same metamorphic events shown by mineral ages. These are shown in Table 6-2 and discussed below.

6 - 2 - 1 Archean Basement and the Kenoran (Algoman) Orogeny (2.4 - 2.7 b.y.)

Archean basement rocks in the Sudbury area are represented by the Levack migmatite complex, the Levack granite, and the Wanapitei granite which occur immediately north of the nickel irruptive (Langford 1960, Ginn 1958). These rocks have not been adequately dated by the Rb-Sr whole rock method as yet, but can be reasonably inferred to be Archean on geological grounds. The closest documented Archean Rb-Sr ages are 2.35 to 2.70 b.y. old granites near the Grenville Front northwest of Sudbury (Grant 1964, Krogh and Hurley 1968) and various 2.4 - 2.8 b.y. old mineral ages from granitic basement rocks of the Blind River area (Van Schmus, 1965).

The Kenoran Orogeny is an important and widespread event which has affected almost all Archean rocks of the Canadian Shield.

6 - 2 - 2 Huronian Volcanism and Sedimentation (2.15 - 2.4 b.y.)

The Huronian supergroup of the Southern Province is a thick sequence of Proterozoic sedimentary and volcanic rocks (Table 6-3). The detailed sedimentation and stratigraphy of these rocks has been reviewed recently by Card et al. (1972).

TABLE 6-2 Summary of Whole Rock Data - Sudbury and Adjacent Areas

EVENT	AGE (b.y.)	SOUTHERN PROVINCE			SUDBURY AREA			NW. GRENVILLE PROV.		
Grenville Orogeny	1.0							Wanapitei kyanite gneiss	•1.0	.726
	1.2							paragneiss	•1.1 •1.3	
Cryptic Thermal Event	1.4	Lamprophyre dikes Eagle granite (Croker cplx.)	1.42 1.45	.708 .705	Olivine diabase	1.46	.703	Granite	? •1.50	
	1.6							Paragneiss Young Granite lineation-deformation	•1.56 1.59	 .706
Penokean Orogeny		Cutler granite Mongowin granophyre?	1.75 •1.77	 .711				Old Granite	1.70	.703
	1.8				Granite dikes	? •1.80	.712	Paragneiss	•1.80	
Sudbury Event	2.0				Whitewater sed. Onaping fm. Micropegmatite Norite	•1.68 •1.52 •1.68 2.00	.708 .715 .708 .706			
		Nipissing diabase	2.16	.706	Sudbury Gabbro	-	-			
					Murray granite	2.28	.727			
Huronian Sedimentation	2.2	Gowganda fm. Espanola fm. Bruce fm. McKim fm. Copper Cliff rhy. Sudbury series balt.	2.28	.706		•1.81 •1.80 •2.04 •2.17 2.35 •2.00	.714 .723 .712 .707 .706 .705	References: Davis et al. 1969, 1970 Fairbairn et al. 1968, 1969 Fullagar et al. 1971 Gates and Hurley 1973 Krogh and Hurley 1968 Krogh et al. 1971 Van Schmus 1965, 1971 This Study, Chapter 3 and 4		
	2.4									
Kenoran Orogeny?										
Archean	2.6	Basement granite	2.40 2.80		Basement granite	-	-	Basement granite	2.60	.702

Note • indicates metamorphic

TABLE 6-3.

SUMMARY OF HURONIAN STRATIGRAPHY

Group	Formation	Lithology	Thickness (Feet)	Depositional Mode Environment	Source	Mineralization
Cobalt	Bar River	Sandstone, siltstone.	1000-4000	Shallow marine	North (Northwest to northeast)	Silica source
	Gordon Lake	Siltstone, sandstone, chert.	1000-3000	Shallow marine	Northwest	
	Lorrain	Sandstone	2000-6000	Shallow marine	North, northwest	Silica source Th-U
	Gowganda	Conglomerate, greywacke, sandstone.	500-4500	Glacial in north; marine glacial in south	North, northwest	
Quirke Lake	Serpent	Sandstone.	0-2400	Fluvial, fluvial-deltaic, shallow marine	Northwest, north	
	Espanola	Dolomite, limestone, sandstone, siltstone.	0-1500	Tidal mudflat, shallow marine	West, northwest, north	Copper tungsten near diabase
	Bruce	Conglomerate.	0-450	Glacial marine	North?	
Hough Lake	Mississagi	Sandstone.	0-4000	Fluvial, fluvial-deltaic	Northwest, west, north	Uranium near basement
	Pecors	Argillite, sandstone.	40-1500	Fluvial-deltaic	North, northwest	Minor uranium near basement
	Ramsay Lake	Conglomerate	5-600	Glacial marine	North, northwest?	Minor uranium
Elliot Lake	McKim	Argillite, siltstone, sandstone.	0-2500	Shallow water turbidite	Northwest, north	Minor uranium near basement
	Matinenda	Sandstone, conglomerate.	0-2000	Fluvial, fluvial-deltaic	Northwest, north	Uranium, thorium near basement
	Volcanic rocks	Basalt, andesite, rhyolite.	local	Marine?		Copper in flows and intercalated sediments. Uranium in conglomerate interbeds.

Includes
Copper Cliff rhyolite
Sudbury Series basalt

Modified from Robertson and Card 1972.

Huronian rocks unconformably overly Archean basement rocks and are derived from them. Detrital monazite and zircon from the Matinenda fm. (Table 6-3) give a Pb^{207}/Pb^{206} age of 2.5 ± 0.1 b.y. (Mair et al. 1960). The end of Huronian deposition is bracketed by the 2.155 b.y. age of the Nipissing diabase (Van Schmus 1965, Fairbairn et al. 1969) which everywhere intrudes Huronian rocks. Rb-Sr whole rock isochrons from (1) unmetamorphosed Gowganda fm. at Gowganda (2.29 ± 0.09 b.y.) - Fairbairn et al. 1969, (2) Copper Cliff rhyolite (basal Huronian) at Sudbury (2.35 ± 0.06 b.y - Fairbairn et al 1965), and (3) the maximum age of the Murray granite, which intrudes the basal Huronian (2.29 ± 0.03 b.y. - Chapter 4) all fall within the limits outlined and are believed to represent the true ages of these rocks.

Fairbairn et al. (1969) found 1.80 to 2.17 b.y. isochrons (scatterchrons) for various Huronian units in the Sudbury-Espanola area. These are obviously due to metamorphism and variable susceptibility or response of the various lithologies to metamorphism.

According to Card et al. (1972), faulting accompanied Huronian deposition and early major folding took place before and during intrusion of the Nipissing diabase west of Sudbury.

6 - 2 - 3 The Sudbury Event (2.00 ± 0.10 b.y.)

Isotopic evidence for the 2.00 b.y. Sudbury event is given in Chapter 3. (Table 3-4). The most important evidence in this connection is the 2.0 b.y. isochron age of the Sudbury norite (Figure 3-5).

The pre-irruptive Sudbury breccias (Speers 1957), the micropegmatite, and the Whitewater group can be related to the Sudbury event by geological arguments. As mentioned previously, this event appears to have a relatively local distribution.

6 - 2 - 4 The Penokean (Hudsonian) Orogeny (1.6 - 1.8 b.y.)

Post-norite (2.0 b.y. - Chapter 3) and pre-Cutler (1.7 b.y. - Van Schmus 1965) and Killarney granite (1.6 - 1.7 b.y. - Krough and Davis 1969, 1970). Penokean metamorphism and deformation is well developed and clearly recognizable in the Sudbury - Espanola area (Card et al. 1972, Brocoum and Dalziel 1973). More than one period and/or type of activity is indicated by:

(1) "There is general correspondence between "nodes" of higher grade metamorphism (almandine-amphibolite facies), relatively intense deformation, felsic plutonic intrusions, and the thickest parts of the Proterozoic supracrustal sequence" (Card et al. 1972, p. 365). This metamorphism is superimposed on previously deformed rocks and restricted to the rocks south of the basin (Figure 5-7). The 1.80 - 2.17 b.y. whole rock scatterchrons of Huronian sediments and volcanics (Fairbairn et al 1968) are likely due to Penokean and/or Sudbury event metamorphism. They suggest variable time, degree, location, and lithologic response of metamorphism.

(2) Apparently syn-or post-deformational 1.68 b.y. low grade

hydrothermal (greenschist facies) metamorphism of the micropegmatite and Whitewater series of the Sudbury Basin (Chapter 3, Tables 3-7 and 3-8, and Figure 3-15).
(3) 1.60 - 1.66 b.y. biotite ages from the north range of the basin probably are related to late cooling and/or uplift of this otherwise undeformed area.

In the Sudbury area, the Penokean Orogeny is rivalled only by the Sudbury event in importance. However, regionally it is far more important, and extensive, 1.6 - 1.8 b.y. events have been found far greater distances in all directions. (Table 6-2).

6 - 2 - 5 The Cryptic Thermal Event (1.3 - 1.5 b.y.)

Rb-Sr whole rock evidence for a cryptic thermal event at Sudbury includes:
1) a 1.46 ± 0.13 b.y. scatterchron from olivine diabase dikes collected a short distance south of the basin (Gates & Hurley, 1973)
(2) a 1.515 ± 0.065 b.y. scatterchron from whole rocks and inclusions from the Onaping fm. (Fullagar et al. 1971).

The event is apparently of local importance and best recognized in mineral ages. It has been recognized as a local phenomenon at Sudbury and Cutler, Ontario and Iron Mountain, Michigan.

6 - 2 - 6 The Grenville Orogeny (0.9 - 1.25 b.y.)

Three of four whole rock samples of Wanapitei kyanite gneiss, collected less than one mile south of the Grenville Front, plot along a 1.0 b.y., Ri = 0.726 Rb-Sr reference isochron (Krogh and Hurley 1968). This indicates Grenville metamorphism and isotopic resetting of whole rocks has taken place along the Grenville Front.

Whole rock samples collected northwest of the Grenville Front have remained closed to Rb and Sr migration. However, most south range Rb-Sr biotite ages have been reset by the Grenville event (Figures 5-5 and 5-6). North range samples are apparently unaffected. Structural investigations along the Grenville Front (e.g. Henderson 1972, p.515) indicate that "no penetrative deformation overprints the (1590 m.y. southwest plunging) lineation in the Chief Lake area." Thus Grenville activity can be recognized as a thermal event between the Grenville Front and the axis of the Sudbury basin, but cannot be recognized north of this area. The reset biotite ages are due to late to post Grenville cooling and uplift.

Chapter 7 - Summary of Conclusions and Suggestions for Future Study

7 - 1 Summary of Conclusions

Probably the most significant results of this study is the 2.00 b.y. Rb-Sr whole rock isochron age of the Sudbury irruptive norites and the interpretation of the the 1.68 b. y. age of the micropegmatite and Whitewater Series as metamorphic. Rb-Sr whole rock data also indicate that the north and south range irruptive are essentially the same age, as are the norite and ore bearing sub-layer. This part of the study is rewarding in so much as the data can be related to petrologic (Stevenson and Colgrove 1968, Naldrett et al. 1970), isotopic (Souch and Podolsky 1963), and metamorphic and tectonic studies of other workers (Card et al. 1972, Brocoum and Dalziel 1973). However, these results have not been able to distinguish between the various theories of origin of the nickel irruptive except to rule out a simple mantle source for the norite and suggest at least some open system behaviour. (e.g. assimilation and/or metasomatism) for the micropegmatite.

Important aspects of the Murray granite study include the recognition of the various igneous and metamorphic features present, the recognition of remobilized granite, and the confirmation of the pre-irruptive origin (Table 7-1). The significance of granitic dikes in the norite is still somewhat problematical. The suggestion that they might independently

TABLE 7 - 1 Geologic History of the Sudbury Basin Area

NR - North Range
SR - South Range

Event	Rock Unit	Deformation and Metamorphism	Radiometic Age(m.y.)	Nickel Irruptive	Murray Granite
Grenville Orogeny	Wanapitei kyanite gneiss	Final uplift and cooling- late faulting	1000	Faulted contacts	Faulted contacts Mylonite zones
		Thermal event	1000 - 2000	Rb-Sr biotite SR	Rb-Sr biotite
Cryptic Thermal Event	Olivine diabase dikes	Thermal met. of glassy and shocked Onaping inclusions Deformations along the Grenville Front Zone & faulting	1300 - 1450	Rb-Sr biotite SR	Rb-Sr K-feldspar Development of joints?
Penokean Orogeny	Killarney granite (young)	Ductile non penetrative deformation	1600 - 1700		
		Greenschist facies met. in center of Sudbury basin	1700	Micropeg. + Whitewater Rb-Sr whole rocks Rb-Sr biotite NR	K-Ar biotite Murray offshoots Rb-Sr whole rock?
	Killarney granite (old) Chief Lake batholith	Major penetrative deformation SR + amphibolite to Greenschist facies met. of Huronian	1700-1800	Folding and shearing SR	
Sudbury Event (meteorite impact?)	Whitewater Group Nickel Irruptive	Mafic intrusion and contact metamorphism	2000 ± 100	Rb-Sr norite whole rock isochron	N.W. Murray granite remelted? Sulfides
	Sudbury Breccias	Shock metamorphism and brecciation			Sudbury breccias
"Early Orogeny"	Nipissing Diabase Murray Granite	Intrusion of sills Intrusion of SR granites	2150 2280 ± 100		S.E. Murray granite Rb-Sr whole rocks
Huronian Sedimentation & Volcanism	Huronian Super-group	Folding and faulting	2150 - 2400		
?			≥ 2250	Mafic magma separates from mantle?	Crustal source of Murray granite magmas
Kenoran Orogeny	Basement granites and gneisses	Probably major met. and deformation	2400 - 2700		

indicate the age of the nickel irruptive seems to be no longer promising.

Mineral ages from this study extend the usefulness of those reported previously (e.g. Fairbairn et al 1960). Collectively they are interpreted as evidence for the recognition of the Penokean and Grenville Orogenies, and the Sudbury and 1.30-1.45 b.y. cryptic thermal events, plus the nature and distribution of metamorphism in the area. (i.e. increasing in degree and decreasing in age to the southeast). Rb-Sr studies of the Murray granite and Murray offshoot 1 show that potassium feldspar ages are greater than biotite ages from the same samples. This difference could be due to geochemical and/or time-temperature relationships.

Finally this study has permitted a comprehensive review of Rb-Sr whole rock data from the Sudbury area. These data can be related to geology, mineral ages, and ages from other decay schemes in the Sudbury area and adjacent areas. The geological history of the area is summarized in Table 7-1.

7-2 Recommendations for Future Studies

There are an unlimited number of potentially worthwhile investigations of Sudbury geology (e.g. re-examination of the Sudbury breccia problem or study of the deformation and metamorphism of south range ore deposits). Isotopically additional Rb-Sr whole rock data from the following units would be useful; the sub-layer, the mafic norite, ultramafic xenoliths

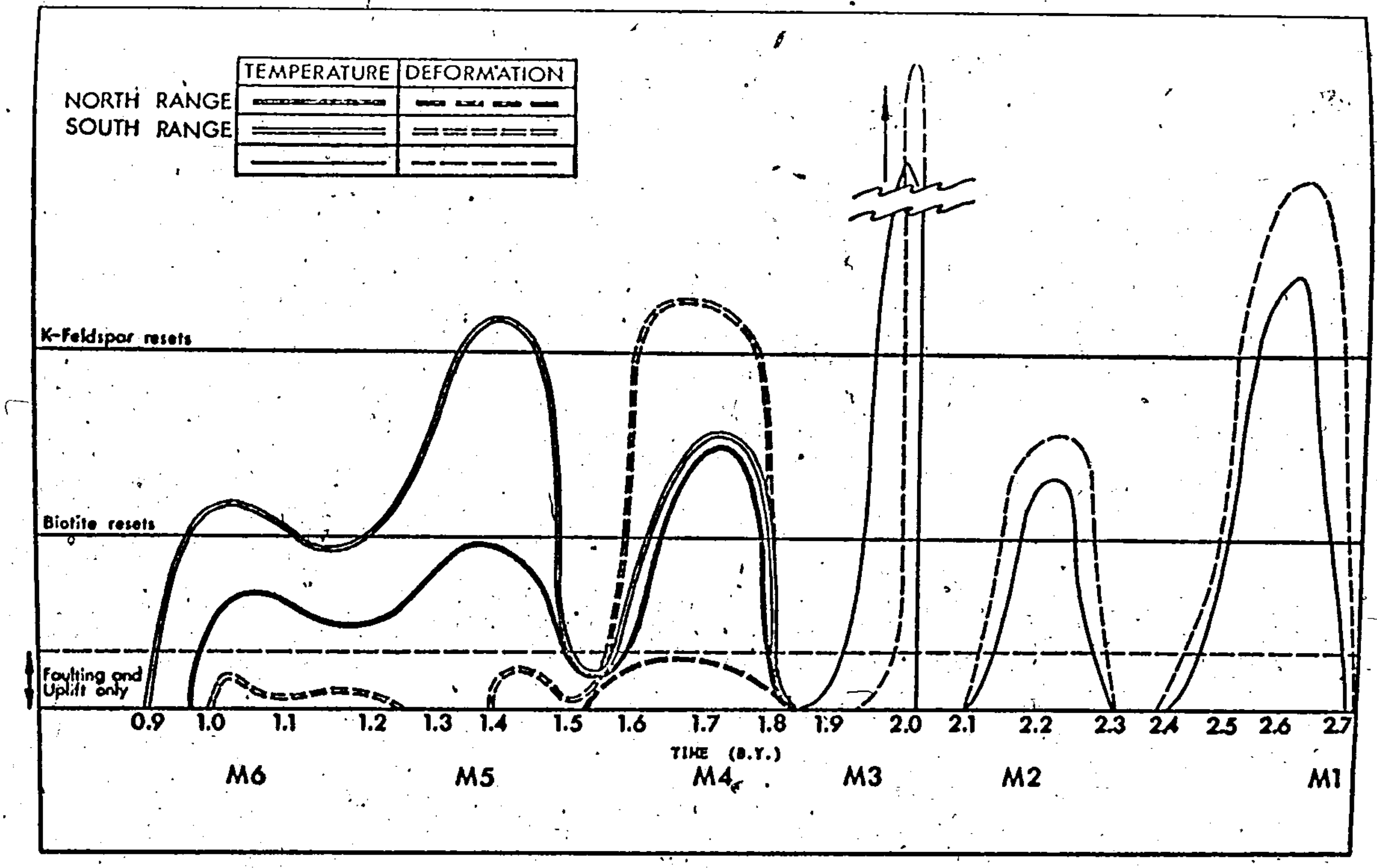


Figure 7 - 1 Speculative Temperature vs. Time and Deformation vs. Time in the Sudbury Basin Area

in the irruptive, melt rocks from the base of the Onaping fm., the Sudbury gabbro, olivine diabase dikes from the north range, north range basement rocks including breccias, the Copper Cliff rhyolite, and the Creighton granite. Additional data from minerals (e.g. plagioclase) and other dating techniques (e.g. Pb^{207}/Pb^{206} and uranium-lead ages of zircon and model lead ages from sulfides) would also be useful. $Re^{187} - Os^{187}$ isochrons are also feasible (J.N.Schindler - personal communication 1973). Some of these studies have already begun.

Recent advances in equipment and technique have made the Rb-Sr whole rock method applicable to most layered mafic intrusions. Such studies have been successfully carried out on mafic intrusions from Africa (Davies et al. 1970) and North America (e.g. the Duluth gabbro - Faure et al. 1969, the Stillwater complex - Fenton and Faure 1969, and the Sudbury norite - Chapter 3). These studies should be extended to the nickel and chromium bearing mafic rocks of Manitoba and Northwestern Ontario. Potentially datable intrusions in Manitoba include; the Bird River sill, the Fox River sill, the Lynn Lake gabbro, and the Thompson-Moak Lake Peridotites (Scoates 1971), in Northwestern Ontario, the Gordon Lake, Shebandowan and Great Lakes Nickel deposits should be considered. With the cooperation of the mining companies involved, accessibility to mine workings and/or diamond drill core should ensure suitable fresh material. There is also the possibility that the time of intrusion may be represented in the country rocks (e.g. Powell et al. 1969)

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Appendix A - Basic Concepts of Rb-Sr Age Dating

A - 1 Basic Principles of Radioactive Decay

Rb^{87} is naturally radioactive and decays spontaneously to Sr^{87} accompanied by beta emission. Radioactive decay is a random, statistical process in which the number of atoms that disintegrate per unit of time ($-dN/dt$) is proportional to the number ~~of~~ atoms of parent nuclide present (N), (i.e. $-dN/dt = \lambda N$) where λ, the decay constant, represents the probability that an atom will decay in a given interval of time. Integrating the above equation between $N = N_o$ at $t = t_o$ and $N = N$ at $t = t$, we get:

$$\int_{No}^{N} \frac{dN}{N} = -\lambda \int_{to}^{t} dt$$

or

$$\ln N/No = -\lambda t$$

or

$$N = No\, e^{-\lambda t}.$$

In geochronology, the rate of radioactive decay is often expressed in terms of the half life ($t_{1/2}$) of the radioactive decay. This is defined as the time required for half of a given quantity of radioactive atoms to decay, (i.e. $N/No = 1/2$). then

$$\ln \frac{N}{No} = -\lambda t$$

becomes $\ln 2 = \lambda t_{1/2}$

or $t_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}$

The number of radiogenic daughter atoms (*D) which have formed from the decay of parent (N) in a rock or mineral since the time of its origin as a closed system is

$$*D = No - N \quad .$$

The total number of daughter atoms present is

$D = Do + *D$ (where Do = the original amount of daughter atoms).

Then

$$D = Do + No - N$$

$$D = Do + Ne^{\lambda t} - N$$

$$D = Do + N(e^{\lambda t} - 1).$$

For the $Rb^{87} - Sr^{87}$ decay, this becomes

$$Sr^{87} = (Sr^{87})_o + Rb^{87}\,(e^{\lambda t} - 1) \quad .$$

Dividing by stable, non radiogenic (i.e. constant) Sr^{86}, because it is easiest to measure isotopic ratios, we obtain

$$\frac{Sr^{87}}{Sr^{86}} = \frac{Sr^{87}}{Sr^{86}} + \frac{Rb^{87}}{Sr^{86}}\,(e^{\lambda t} - 1)$$

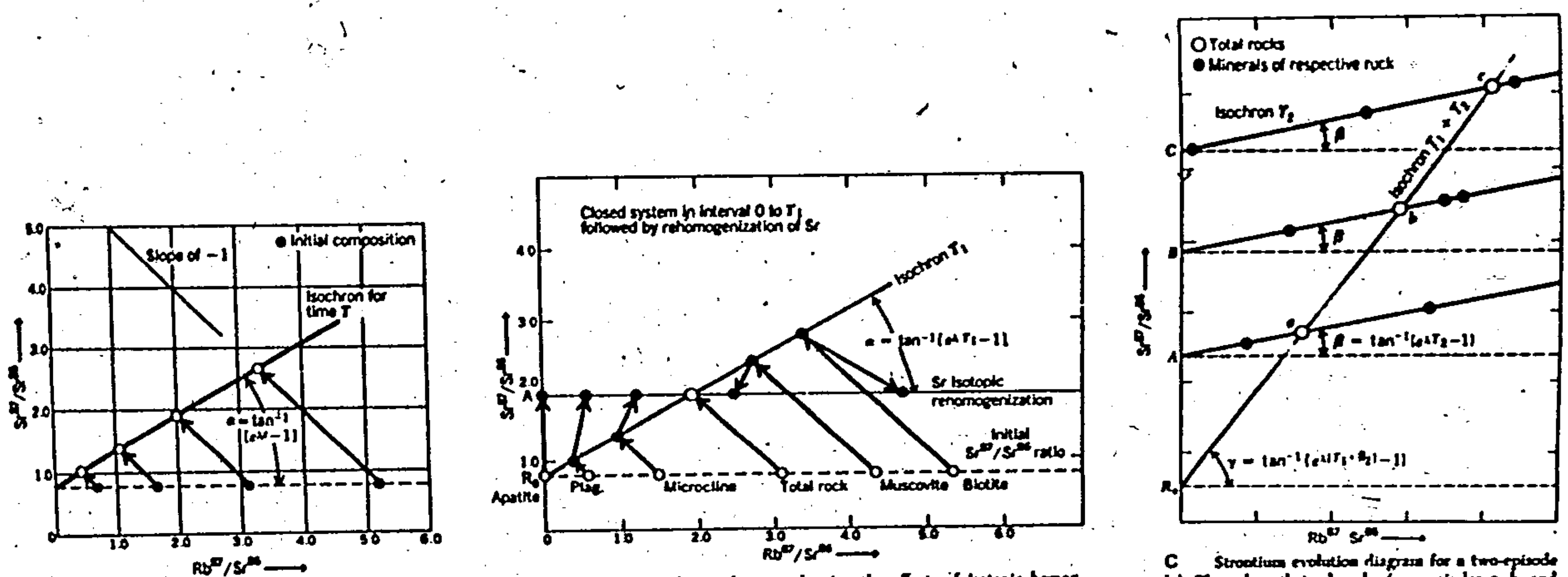
which is the basic dating equation for the Rb^{87}-Sr^{86} system. When t is small, the following approximation is commonly made for convenience

$$\frac{Sr^{87}}{Sr^{86}} \cong \frac{Sr^{87}}{Sr^{86}}_o + \frac{Rb^{87}}{Sr^{86}}\lambda t \quad .$$

Sr^{87}/Sr^{86} is measured on a mass spectrometer, Rb^{87}/Sr^{86} calculated from (Rb/Sr) weight and Sr^{87}/Sr^{86}, and $(Sr^{87}/Sr^{86})_o$ assumed or determined (see next section), then the dating equation can be solved for the age of the system t.

A - 2 The Isochron Method

Use of the isochron method, requires a suite of cogenetic rocks or minerals, (i.e. having the same age and initial Sr^{87}/Sr^{86}) which have different Rb/Sr values and have remained closed, chemical systems with respect to rubidium and strontium since their formation (i.e. $t = 0$). By determining Rb^{87}/Sr^{86}



A Strontium evolution diagram showing the development of the Sr^{87}/Sr^{86} ratio in time T as a result of the rubidium decay in four hypothetical minerals of some crystalline rock. (*After Lanphere, Wasserburg, and Albee,* 1964)

B Strontium evolution diagram showing the effects of isotopic homogenization for a two-episode model. (*After Lanphere, Wasserburg, and Albee,* 1964.)

C Strontium evolution diagram for a two-episode model. Three hypothetical rocks (open circles *a*, *b*, and *c*) were isolated from a common environment $T_1 + T_2$ years ago. Their initial Sr^{87}/Sr^{86} ratio was R_0. Each rock, taken as a whole, remained a closed system, but T_2 years ago the strontium in each of them was homogenized by a metamorphic event. The mineral isochrons of each rock are drawn through the mineral points (solid circles) and intercept the ordinate at the homogenized Sr^{87}/Sr^{86} values A, B, and C. (*After Lanphere, Wasserburg, and Albee,* 1964.)

Figure A - 1: Rb-Sr Isochron or Evolution Diagrams (from Faul 1966).

(x values) and Sr^{87}/Sr^{86} (y values) for each sample and plotting them on a strontium evolution diagram (Figure A-1) a straight line of the form y = mx + b is defined. This line, called an isochron, is analogous to the basic dating equation, where m, the slope, is related to t, the time since last isotopic homogenization, by

$$m = e^{\lambda t} - 1$$

or

$$t = 1/\lambda \ln (m + 1)$$

and b, the y - intercept, defines the initial Sr^{87}/Sr^{86}.

In practice, the straight line is calculated and tested for validity by using various regression techniques (McIntyre et al. 1966, York, 1966, 1969, and Brooks et al. 1972).

A - 3 The Intersection Method

Using the same data and assumptions as the last section, it is possible to use a slightly different approach and construct strontium development diagrams (Figure A-2). For each sample, the Sr^{87}/Sr^{86} measured is plotted on the y axis and a straight line of slope (Rb^{87}/Sr^{86}) is drawn through it. If all assumptions are satisfied the family of lines intersect at a common point with coordinates (age, $(Sr^{87}/Sr^{86})_o$).

A - 4 Isotopic Homogenization of Strontium

In addition to primary ages, secondary or metamorphic ages due to strontium homogenization (resetting of isotopic "clocks")

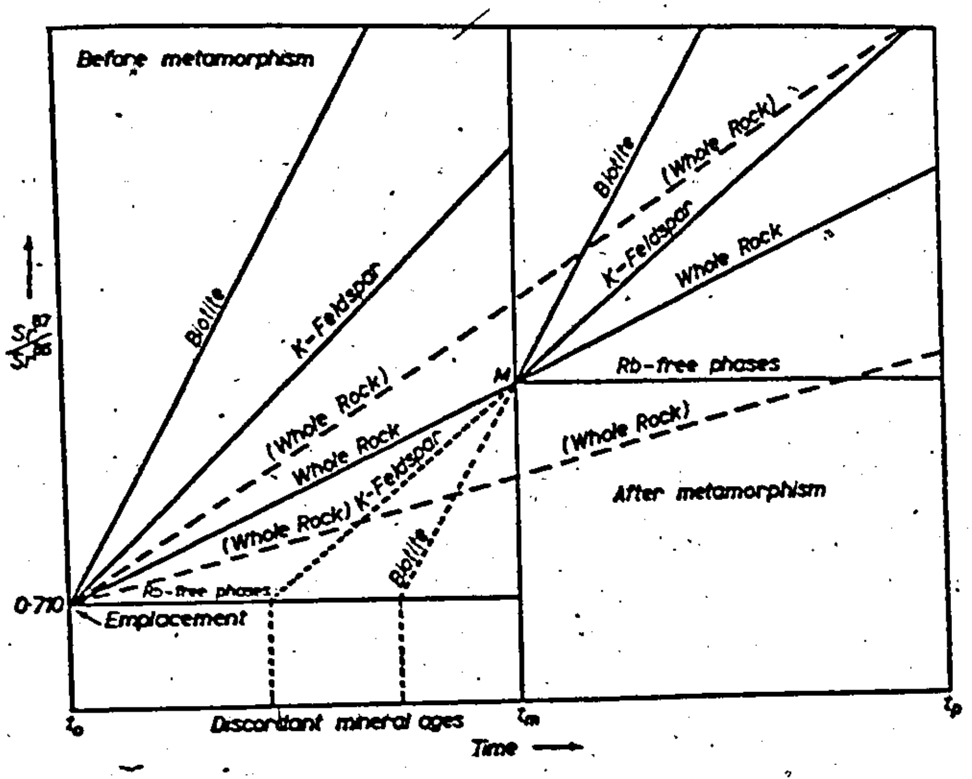


Figure A - 2: Rb-Sr Development Diagram (after Moorbath 1964)

Schematic diagram of Sr^{87}/Sr^{86} growth lines for a granitic whole-rock specimen and its component mineral phases (continuous lines), showing a metamorphic break at time t_m with complete isotope homogenization of strontium. Other whole-rock samples from the same intrusive are indicated by the discontinuous, dashed lines. Discordant, apparent ages for metamorphic potassium feldspar and biotite are indicated by discontinuous, dotted lines, with the assumption that the initial Sr^{87}/Sr^{86} ratio is 0·710.

can be recognized and defined on isochron and intersection diagrams (Figures A-1 B and C and A-2). In fact, in some instances (e.g. Lamphere et al. 1964) isotopic homogenization may be the only evidence of metamorphism.

Often a metamorphic event is defined by mineral ages, while whole rock samples continue to give older primary ages like the theoretical examples in Figure A-1 and A-2. However, different lithologic layers or even whole rocks may also produce secondary isochron ages. Metamorphism and isotopic homogenization must be considered whenever high initial Sr^{87}/Sr^{86} values are found.

A - 5 Conversion of (Rb/Sr) weight to (Rb^{87}/Sr^{86}) atomic.

It is obvious that

$$Rb^{87}/Sr^{86} = (Rb/Sr)\ (Rb^{87}/Rb)\ (Sr/Sr^{86})$$

and

$$Sr/Sr^{86} = Sr^{88}/Sr^{86} + Sr^{87}/Sr^{86} + Sr^{86}/Sr^{86} + Sr^{84}/Sr^{86},$$

because the ratios Sr^{88}/Sr^{86}, Sr^{86}/Sr^{86}, and Sr^{84}/Sr^{86} are constant and known.[1]

$$Sr/Sr^{86} = 8.3832 + Sr^{87}/Sr^{86} + 1.0000 + 0.0568$$

$$Sr/Sr^{86} = 9.4300 + Sr^{87}/Sr^{86} \quad \text{---- (1)}$$

also

$$(Rb/Sr)_{atomic} = (Rb/Sr)_{weight}) \times \frac{\text{atomic weight Sr}}{\text{atomic weight Rb}}$$

$$(Rb/Sr)_{atomic} = (Rb/Sr)_{weight} \times \frac{87.62}{85.47}$$

$$(Rb/Sr)_{atomic} = (Rb/Sr)_{weight} \times 1.0252 \quad \text{---- (2)}$$

and

$$Rb^{87}/Rb = \text{a constant} = 0.2785 \quad \text{---- (3)}$$

Substituting (1), (2) and (3) in the original equation gives the required equation

$$\mathrm{Rb}^{87}/\mathrm{Sr}^{86} = (\mathrm{Rb}/\mathrm{Sr})_{\mathrm{weight}} \times 0.2855\ (9.4300 + \mathrm{Sr}^{87}/\mathrm{Sr}^{86})$$

Barton's (1971, p.19) equation for the error in $\mathrm{Rb}^{87}/\mathrm{Sr}^{86}$ (1 sigma) is

$$\sigma\ \mathrm{Rb}^{87}/\mathrm{Sr}^{86} = \left[\sigma^2\ (\mathrm{Rb}/\mathrm{Sr})_{\mathrm{wt.}}\ (0.2855\ (9.400 + \mathrm{Sr}^{87}/\mathrm{Sr}^{86})\ )^2 + \sigma^2\ \mathrm{Sr}^{87}/\mathrm{Sr}^{86}\ \ (0.2855 \times (\mathrm{Rb}/\mathrm{Sr})_{\mathrm{wt.}}\ )^2 \right]^{1/2}$$

---

1. Values calculated from Appendix E, Friedlander et al.(1964).

Appendix B Composition and Use of Spike Solutions

The compositions and concentrations of the spike solutions used in this study are given in Tables B-1 and B-2.

It was pointed out in Chapter 2 that the ratio of two isotopes used in an isotope dilution should be near unity. If the amount of the element in the sample can be estimated (e.g. by XRF), the amount of spike required to produce a ratio of unity can be determined.

The number of atoms of Rb^{85} in any mixture is the sum of the number of atoms of Rb^{85} from N amount of normal Rb (the sample) plus the number of atoms of Rb^{85} of spike Rb. Similarly for Rb^{87}, hence

$$R = \frac{Rb^{85}}{Rb^{87}} = \frac{Rb^{85}(N) + Rb^{85}(S)}{Rb^{87}(N) + Rb^{87}(S)}$$

substituting values from Table B-7

$$R = \frac{.7215(N) + .0084(S)}{.2784(N) + .9916(S)}$$

when R = 1

$$.2784(N) + .9916(S) = .7216(N) + .0084(S)$$

$$.9832(S) = .4432(N)$$

and $N/S_{\text{atomic}} = \frac{.9832}{.4432} = 2.2 = N/S_{\text{weight}}$

Knowing the amount of Rb in the sample (e.g. 200 p.p.m. x 0.5 gm = 100 μgm Rb(N)) and the concentration of the spike solution (e.g. 15 μgm/ml) the amount needed is given by

$$\text{amount of spike (ml)} = \frac{\text{sample Rb(μgm)}}{2.2} / \text{spike conc.(μgm/ml)}$$

$$= \frac{100}{2.2} / 15 = 3.0 \text{ ml.}$$

The same method was used to obtain N/S = 8.5 for the Sr^{84} spike in Table B-8. In this case Sr^{84}/Sr^{86} is adjusted to unity.

TABLE B - 1 Isotopic Composition of Rb

Normal Rb[1]:

isotope	atomic weight	x	atomic percent		
Rb^{85}	84.9117		72.15	=	61.2638
Rb^{87}	86.9092		27.84	=	24.1955

atomic weight of normal Rb 85.4593

Rb^{87} spike ORNL[2] LY1448 (A) - RbCl:

isotope	atomic weight	x	atomic percent		
Rb^{85}	84.9117	x	.84	=	.7133
Rb^{87}	86.9092	x	99.16	=	86.1792

atomic weight of spike Rb 86.8925

Concentration
March 1969
15.095 ugm Rb/gm 2 N HCl[3]

or

14.971 ugm Rb^{87}/gm 2 N HCl

1. data from Friedlander et al. (1964)
2. Oak Ridge National Laboratory
3. Mitchell (1969)

TABLE B - 2 Isotopic composition of Sr

Normal Strontium:

isotope	atomic weight	x	atomic percent		
Sr^{84}	83.9134		.56	=	.4699
Sr^{86}	8[illegible].9093		9.86	=	8.4707
Sr^{87}	86.9089		6.99	=	6.0749
Sr^{88}	87.9056		82.59	=	72.6012

atomic weight of normal Sr 87.6167

Sr^{84} spike ORNL Lh1368(A) - $Sr(NO_3)_2$:

isotope	atomic weight	x	atomic percent		
Sr^{84}	83.9134		82.24	=	69.0103
Sr^{86}	85.9093		3.71	=	3.1872
Sr^{87}	86.9089		1.56	=	1.3558
Sr^{88}	87.9056		12.49	=	10.9794

atomic weight of spike Sr 84.5327

Concentration March 1969 9.031 ugm Sr/gm of 2 N HCl
May 1972 9.531 ugm Sr/gm of 2 N HCl
or 7.800 ugm/Sr^{84} of 2 N HCl

Appendix C - Summary of Data Processing

C - 1 Introduction

All data processing was carried out with the facilities of the McMaster University Computation Center. Facilities include a Model 6400 Control Data Corporation computer and various software equipment. Most computer programs used were modified so that output from one program would be compatible as input to succeeding ones.

C - 2 Isotope Dilution Analysis

Mass spectrometer results from spiked samples used for isotope dilution analysis were converted elemental abundances (ppm Rb and/or Sr) and normalized Sr^{87}/Sr^{86} ratios using a modified form of the Fortran IV program described and discussed by Van Schmus (1966). The principle modification was to define error as one standard deviation rather than the average deviation from the mean originally used.

C - 3 X-ray Fluorescence Analysis

Two programs have been used to process X-ray fluorescence data. The first, called RBSRR, calculates Rb/Sr values for data collected using the method of Doering (1968); the second, called RBSRPPM, calculates rubidium and strontium concentrations for data collected by the Compton peak method of Reynolds (1963, 1967). These programs were written by Michael Marchand. Their use is described by him in a Technical Memo 73-3, Geology Department, McMaster University. Another program converts $(Rb/Sr)_{weight}$ to $(Rb^{87}/Sr^{86})_{atomic}$ using the method described in Appendix A-5.

C - 4 Isochrons

All whole rock isochrons or errorchrons have been calculated using a multiple regression program REGROSS which has been described by Brooks et al. (1972). This program is written to use errors estimated from replicate or duplicate analyses. Another program written by D.York (1969) which permits use of errors based on repeated measurements on a single sample was also available and used, to calculate the age of WR - min. pairs and occasionally to compare results from REGROSS.

The Brooks et al. program calculates isochrons based on each of several regression treatments. When deviation from linearity by data points can be explained in terms of experimental error, all treatments give essentially identical regression parameters (age, intercept and errors). Several of the treatments also include provision for distinguishing between isochrons and errorchrons or scatterchrons.

Appendix D - Description of Samples and Summary of Petrography.

D - 1 Introduction

Descriptions of all whole rock samples are given in Table D-1, and all mineral concentrates in Table D-2. Sample locations are listed in terms of the Universal Transverse Grid or the name of the mine where they were collected. The color the rock describes the fresh surface of a hand specimen. Texture is given by (1) an estimate of the grain size (unaided eye), (2) structure of the hand specimen, and (3) a genetic interpretation of the texture (thin section). The effects of cataclasis have caused some samples of the Murray granite to show a much finer grain size when observed through a microscope using crossed nichols than when observed under ordinary light. Estimates of the amounts of the major minerals present are only approximate and some trace minerals (e.g.zircon or hematite) are not given.

D - 2 The Nickel Irruptive

The interested reader is referred to the work of Naldrett et al.(1970) and Stevenson and Colgrove (1968) for detailed description and discussion of irruptive petrography. The south range samples used in this study were collected along Naldrett et al.'s (1970) Blezard traverse, while north range samples correspond to their Strathcona section.

Towards the top of the Blezard traverse altered green norite replaces fresh black norite. One sample of green norite (W 124) still contains relatively fresh plagioclase and falls on the norite isochron. A second sample (W 126) contains highly altered plagioclase, micrographic intergrowth, and a secondary foliation. Two transition zone or upper grabbo samples (159 and 153) show similar effects. Isotopic data from these three samples show scatter greater than can experimentally be accounted for and have not been used in isochron calculations.

Felsic norite samples from the north range show some plagioclase alteration, and two of five samples do not fit the norite isochron. No clear petrographic evidence distinguishes these two, but they are darker in color and tend to contain less quartz and biotite, and more micrographic intergrowth than the others. One sample of mafic norite (W 311) is extremely altered and probably should never have been analysed.

Only deformed south range micro-pegmatites have been analysed in this study. However, isotopic results agree favourably with north range samples reported in the literature (Fairbairn et al, 1968; Souch and Podosky, 1969)

D - 3 . The Murray Granite

The petrography of the Murray granite has been briefly discussed in studies by Speers (1956) and Ginn (1958). A striking uniformity of hand specimens of Murray granite, normally pink, fine to medium grained, and massive to slightly foliated, is in contrast to the frequently more variable nature of thin sections. In thin sections, notable variations occur in the average grain size of the granoblastic texture, the degree that foliation is developed, the grain size, the shape and amount of perthite in potassium feldspars, the form, alteration, and abundance of plagioclase feldspars.

In some thin sections the predominance of microcline microperthite suggests the Murray granite may have originally been a one feldspar (hypersolvus granite), in other thin sections plagioclase (oligoclase and abite) is more abundant. More careful study is required to separate plagioclase of igneous and metamorphic origin. Murray granite petrography is summarized in table D-3.

In addition to the cataclastic granulation which has affected the Murray granite as a whole, several localized metamorphic effects can also be recognized petrographically. These are summarized in Table 4-5.

D - 4 Murray Offshoot Dikes

The petrography of the Murray offshoots is very similar to that of the Murray granite. The most striking difference is the replacement of potassium feldspar by albite in some specimens of the offshoot dikes (e.g. W 19, W 12, W 305). The replacement may be absent to complete. In two samples this alteration appears to be related to tiny veinlets in the rock. Some biotite may also be removed. Secondary albite grains can be recognized from earlier albite by peculiar "checkerboard twinning" and large anhedral crystal forms.

More subtle differences include, more massive, finer grained hand specimens, less granulation (due to annealing?), more intense alteration of plagioclase, more muscovite, and less amphibole in the offshoot dikes compared with the Murray granite.

TABLE D-1 PETROGRAPHIC DESCRIPTION OF WHOLE ROCK SAMPLES

NOTE. LOCATIONS ARE GIVEN IN TERMS OF THE UNIVERSAL TRANSVERSE MERCATOR GRID
POTASSIUM FELDSPAR IS MICROCLINE UNLESS INDICATED AS ORTHOCLASE.
MODES ARE ESTIMATES ONLY

ABREVIATIONS

FG	FINE GRAINED
MG	MEDIUM GRAINED
CG	COARSE GRAINED
M	MASSIVE
F	FOLIATED
GB	GRANOBLASTIC
PC	PORPHYROCLASTIC
RX	RECRYSTALLIZED
PI	PRIMARY IGNEOUS
BX	BRECCIATED
A	ALTERED
P	PERTHITE
AB	ALBITE
ACT	ACTINOLITE
AMPH	AMPHIBOLE
AP	APATITE
AUG	AUGITE
BIO	BIOTITE
CARB	CARBONATE
EPD	EPIDOTE
INT	GRANOPHYRIC INTERGROWTH
KF	POTASSIUM FELDSPAR
MTE	MAGNETITE
MUSC	MUSCOVITE
PLAG	PLAGIOCLASE
QTZ	QUARTZ
SPH	SPHENE
SULF	SULFIDE

TABLE D-1 CONTINUED

A MURRAY GRANITE (FIGURE 4-1)

ID	LOCATION	COLOR	TEXTURE	QTZ	KF	PLAG	BIOAMPH		EPD	SPH	PERCENT
W - 27	17T MB 991537	GREY-PINK	MG/M/GP	30	45P	15	5		5		
W - 28	17T MB 990534	PINK	F-MG/F/GB-RX	30	25	30A	8		7		
W - 29	17T MB 992532	RED-PINK	MG/M/GB	30	40P	25	5		TR		
W - 35	17T MB 969520	PINK-ORANGE	MG/M/GB-RX	30	40	15	5	10			ORTHOCLASE
W - 64	17T MB 969524	PINK	MG/F/GB-RX	30	50P	10	5	5	TR		
W - 65	17T MB 973527	PINK	F-MG/F-M/RX	35	40	15	3	10			
W - 66	17T MB 980527	PINK	F-MG/M/GB	30	30P	20	5	15			
W 215	17T MB 983533	GREY-PINK	FG/F/GB-RX	20	15	45	10	10	TR		

B MURRAY GRANITE (SAMPLES FROM GIBBINS, ADAMS, AND MCNUTT-1972) (FIGURE 4-2)

ID	LOCATION	COLOR	TEXTURE	QTZ	KF	PLAG	BIOAMPH		EPD	PERCENT
M 215	MB967 527	NO SAMPLE								
M 225	MB 959 513	NO SAMPLE								
A 1513	MB 977 521	PINK	MG/M/GB	30	30P	25	6	9		
A 1514	MB 975 522	PINK	MG/M/GB	30	30P	25	10	5		
A 1515	MB 971 524	PINK	MG/M/GB/RX	35	35P	25	5	TR		
A 1517	MB 968 527	PINK	MG/F/GB	30	35,	25	3	7		
A 1518	MB 975 519	PINK	FG/M/GB	35	35P	25	10			
A 1519	MB 970 521	PINK	MG/M/GB	30	30P	30	5	5	TR	
A 1520	MB 965 525	PINK	FG-MG/M/GB	35	35P	20	10	TR		

C SUDBURY BRECCIA - FROM THE MURRAY GRANITE

ID	LOCATION	COLOR	TEXTURE	QTZ	KF	PLAG	BIOAMPH		EPD	SPH	PERCENT
X 190	17T MB 971511	BLACK	FG/F/PC-RX	30	15	15	20	10	10		
W 227	17T MB 971516	BLACK	FG/F/PC-RX	40		25	25		15		

TABLE D-1 CONTINUED

C MURRAY OFFSHOOT 1 (FIGURE 4-3)

ID	LOCATION	COLOR	TEXTURE	QTZ	KF	PLAG	BIO	MUSC	EPD	CHL	PERCENT
W - 1	17T MB 991[illegible]45	PINK	F-MG/M/GB	35	35P	25A	4	1			
W - 7	17T MB 991545	GREY	F-MG/M/GB	25	35AP	30A	5	4	1		
W - 8	17T MB 991545	PINK-GREY	F-MG/M/GB	30	40P	20A	8	2			
W - 9	17T MB 991545	ORANGE-GREY	F-MG/M/GB	40	40P	15A	5	TR			
W - 10	17T MB 991545	ORANGE-GREY	F-MG/M/GB	30	35P	20A	7	8			
W - 11	17T MB 991545	ORANGE-GREY	F-MG/M/GB	25	30P	30A	9	3	3	TR	
W - 12	17T MB 991545	GREY	F-MG/M/GB	30	30AP	30	10				
W - 19	17T MB 991545	PINK-GREY	F-MG/M/GB	40		50A	10				
W - 20	17T MB 991545	PINK-GREY	F-MG/M/GB	30	35P	20A	15	TR	TR	TR	

D MURRAY OFFSHOOT 2 (FIGURE 4-4)

ID	LOCATION	COLOR	TEXTURE	QTZ	KF	PLAG	BIO	MUSC	EPD	CHL	PERCENT
W 302	17T MB 978532	PINK-GREY	F-MG/M/GB	25	30P	30A	10	3			
W 303	17T MB 978532	PINK-GREY	F-MG/M/GB	30	25P	35A	8	2		TR	
W 304	17T MB 978532	PINK	F-MG/M/GB	30	25P	40	4	1	TR		
W 305	17T MB 978532	GREY	F-MG/M/GB	30	-A	60A	5	4	TR		(1 CARB)
W 306	17T MB 978532	PINK-GREY	F-MG/M/GB	30	30P	30A	10	1	TR		

TABLE D-1 CONTINUED

F SOUTH RANGE NORITES (FIGURE 3-3)

	ID	LOCATION	COLOR	TEXTURE	QTZ	PLAG	BIO	AMPH	HYP	AUG	MTE	INT	EPD
W	104	17T NB 017559	BLACK	MG/M/PI	15	40	25	20			1		
W	103	17T NB 017559	BLACK	MG/M/PI	15	40	25	20			1		
W	102	17T NB 016560	BLACK	MG/M/PI	15	40	20	5	15	5	TR		
W	101	17T NB 016560	BLACK	F-MG/M/PI	15	40	15	25			5		
W	110	17T NB 012558	BLACK	MG/M/PI	15	40	10	10	20	5	TR		
W	113	17T NB 012560	BLACK	MG/M/PI	15	40	8	20	5	2			
W	116	17T NB 010564	BLACK	MG/F/PI	5	45	5	15	25	5	TR		
W	118	17T NB 009568	BLACK	MG/F/PI	5	52	3	5	20	10	TR		
W	120	17T NB 008570	BLACK	MG/F/PI	5	52	3	5	20	10	TR		
W	124	17T NB 007575	GREEN-BLACK	M-CG/M/RX	5	50		40	-A	-A			
W	126	17T NB 006576	GREEN-GREY	M-CG/F/RX	5	48A	1	35	-A	-A	2	TR	10

F SOUTH RANGE **UPPER GABBRO** (FIGURE 3-3)

	ID	LOCATION	COLOR	TEXTURE	QTZ	PLAG	BIO	AMPH	HYP	AUG	MTE	INT	EPD
W	159	17T MB 005580	PINK-DK.GREY	MG/M-F/RX	5	35A	2	30			(2APATITE)6	5	15
W	153	17T MB 003577	PINK-BLACK	F-MG/F/RX		35A	10	21			(2 SPHENE)2	15	15

G SOUTH RANGE MICROPEGMATITE (FIGURE 3-3)

	ID	LOCATION	COLOR	TEXTURE	QTZ	INT	AB	EPD	CHL -BIO	KF	SPH	MUSC	MTE
W	150	17T NB 002582	PINK-GREY	F-MG/F/RX	10	46	20	10	13	4	TR	2	TR
W	154	17T NB 002584	PINK-GREY	F-MG/F/RX	10	44	20	15	9	1	TR	1	TR
W	156	17T MB 991589	PINK-GREY	F-MG/M-F/RX	10	25	23	15	14	10	2	1	TR
W	155	17T MB 992591	DARK GREY	F-MG/F/RX	10	30	27	12	15	3	2	1	TR

TABLE D-1 CONTINUED

(FIGURE 3-4)

H NORTH RANGE NORITE

ID	LOCATION	COLOR	TEXTURE	QTZ	PLAG	BIOAMPH		HYP	AUG	MTE	INT	EPD
W 136	17T MB 733687	GREY	MG/M/PI	TR	55	5	10	20A	10A		TR	
W 132	17T MB 732684	DARK GREY	MG/M/PI	3	55	5	25	-A	10A		2	
W 134	17T MB 731681	GREY	MG/F/PI	2	50	10	18	10	10	TR	TR	
W 129	17T MB 735683	GREY	MG/M/PI	5	53	10	15		10A		5(2KF)	
W 127	17T MB 736682	DARK GREY	MG/M/PI		55	TR	20	5A	15A		5	
W 311	LONGVACK S MINE	BLACK	F-MG/M/RX		40	5	25		20A	10		

I SUB-LAYER (SOUTH RANGE)

ID	LOCATION	COLOR	TEXTURE	QTZ	PLAG	BIOAMPH		EPD	CHL	MTE	SULF
M - 37	MURRAY MINE		MG/M/PI	10	30A	15	5	10	15		15
M - 41	MURRAY MINE		MG/M/PI	10	50	10	20		TR		10
M - 42	MURRAY MINE		M-CG/M/PI	10	20	10	20	5	5		30
CCN 1	CU.CLIFF N.M.		F-MG/M/RI-RX	10	25	20	40	5	5	TR	TR
CCN 3	CU.CLIFF N.M.		F-MG/M/RI-RX	10	30A	20	30	5	5	TR	5
W - 50	LITTLE STOBIE M.	BLACK	F-MG/M/RX		10	TR	(90 ACTINOLITE + TALC)				

J CONTACT NORITES

ID	LOCATION	COLOR	TEXTURE	QTZ	PLAG	BIOAMPH		MTE	FEET FROM CTCT
W 3	MURRAY OFF.1	BLACK	MG/M/PI		50	20	25A	5	3
W 4	MURRAY OFF.1	BLACK	MG/M/PI		50	20	30A	TR	7
W 5	MURRAY OFF.1	BLACK	MG/M/PI		55	20	30A	TR	20
W 6	MURRAY OFF.1	BLACK	MG/M/PI	3	52	20	30A	TR	36
W - 51	LITTLE STOBIE	BLACK	MG/M/PI	10	40	20	30A	TR	45
W - 52	LITTLE STOBIE	BLACK	MG/M/PI	15	40	20	25A	TR	100
W - 53	LITTLE STOBIE	BLACK	MG/M/PI	10	40	15	30A	5	470

TABLE D-1 CONTINUED

K CONTACT GRANITES

ID	LOCATION	COLOR	TEXTURE	QTZ	KF	PLAG	BIO	MUSC	EPD:	FEET FROM CTCT
W - 54	LITTLE STOBIE	PINK-GREY	F-MG/F+BX/GB	30	35	20	15	2	13	2
W - 55	LITTLE STOBIE	PINK	MG/F+BX/GB	40	25	15RX	3	1	8(2 CARB)	12
W - 56	LITTLE STOBIE	PINK	MG/F+BX/GB	35	25P	25	6	TR	7	18
W - 57	LITTLE STOBIE	PINK-GREY	MG/F/GB	30	30P	25	8	3	2	42
W - 58	LITTLE STOBIE	PINK	F-MG/F+BX/GB	30	30P	30	5			80

L MISCELANEOUS

CARBONATITE

ID	LOCATION	COLOR	TEXTURE	QTZ	AB	CARB	MUSC	MTE	BIO
W 219W	17T MR 965524	WHITE	F-MG/M/GB		65	35	TR		
W 219P	17T MR 965524	PINK	CG/M/PI	5	85	10	TR		

ALBITITE

ID	LOCATION	COLOR	TEXTURE	QTZ	AB	CARB	MUSC	MTE	BIO
W - 67	17T MR 994544	PINK	F-MG/M/GB	10	80		4	2	4

Table D-2 Description of Mineral Concentrates

I Biotite

A) Granites	Purity %
W 7 B	99
W 9 B	99
W 10 B	99
W 27 B	99
W 27 B 45	99
W 64 B	99
W 215 B	99
W 35 B	80-85
W 190 B	99
W 227 B	98

Traces of amphibole; chlorite muscovite, quartz and zircon.

B) Norites	Purity %
W 101 B	90
W 104 B	90
W 110 B	80
W 118 B	85
W 136 B	60

Minor chlorite, traces of plagioclase, amphibole, and pyroxene

II Potassium feldspar
Microcline microperthite W 7 KF, W 9 KF, W 10 KF
W 27 KF, W 64 KF, W 215 KF

Orthoclase W 35 KF
Impurities other than albite - less than 1%

III Plagioclase - W 118 PL
Impurities less than 1%; trace of sulfide, biotite, pyroxene.

IV Fluorite W 1 FL, W 29 FL
Essentially 100% pure purple fluorite

TABLE D - 3 Summary of Murray Granite Petrography

Mineral	Northwest & Central	Southeast
Quartz 30-35%	- granoblastic, variable grain size - clear, some undulose extinction - smooth grain boundaries more common than sutured	
Potassium feldspar 25-50%	- may or may not be perthitic and twinned - often pockiloblastic - may be recrystallized i.e. finer grained with rims of albite e.g. W 66	- usually perthitic and gridiron twinning - often poikiloblastic
Plagioclase feldspar 10-25%	- contains (A) oligoclase & (B) albite. (A) discrete laths, often saussurite in cores (B) clear small grains, rims on other feldspar and string pethite or inclusions in K feldspar	- similar
Biotite 5-10%	- fine grained, anhedral - occur in "clots" - may be associated with epidote, amphiboles and/or magnetite - some alteration to chlorite or muscovite	
Amphibole 0-15%	- pleochroic dark green to blue green - not always present	- rare
Accessory Minerals	- usually epidote, muscovite, magnetite, sphene, zircon - occasionally chlorite, hematite, amphibole or fluorite	

TABLE D - 4 Potassium Feldspar Polymorphs

a) Orthoclase

Murray granite: W 35

b) Maximum microcline

Murray granite: W 27 W 29 W 64
W 65 W 215

Murray granite: W 54 W 56
(near norite contact Little Stobie mine)

Sudbury breccia: W 190

Murray offshoot 1: W 1 W 7 W 20