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PETROGENESIS OF THE PRECAMBRIAN BEVOS AND MUSCO GROUPS,
ST. FRANCOIS MOUNTAINS IGNEOUS COMPLEX, MISSOURI

by

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INTRODUCTION

The St. Francois Mountains in southeastern Missouri are an exposure of Precambrian plutonic and volcanic rocks of granitic composition which have chemical properties and isotopic ages similar to other Precambrian exposures extending from Wisconsin, through Missouri and Oklahoma to Texas (Fig. 1). Precambrian basement rocks to the northwest of these exposures are older than 1600 million years, whereas basement rocks to the south and east are younger, 1000-1200 million years (Bickford and Mose, 1975). A detailed study of these exposures should result in a better understanding of the formation of the continental crust during Precambrian time.

Accordingly, this study focuses on major and trace element contents of rocks from the St. Francois Mountains in order to help understand the petrogenesis of the complex. One unit in particular, the Munger Granite, was selected for field mapping, sample collecting, and major and trace element analyses. This granitic unit was selected for study because of its location in the western part of the complex in an area surrounded dominantly by volcanic rocks. The exact composition of the granite, its field relationships to the volcanic rocks, and to other granitic units in other parts of the complex was not definitely known.

The information obtained from this study for the Munger Granite is used to construct a theoretical model for the petrogenesis of this unit, and in addition, major and trace element data were obtained from other representative units of the complex in order to compare the petrogenesis of the Munger Granite to the rest of the complex. The samples for other rock units, excluding

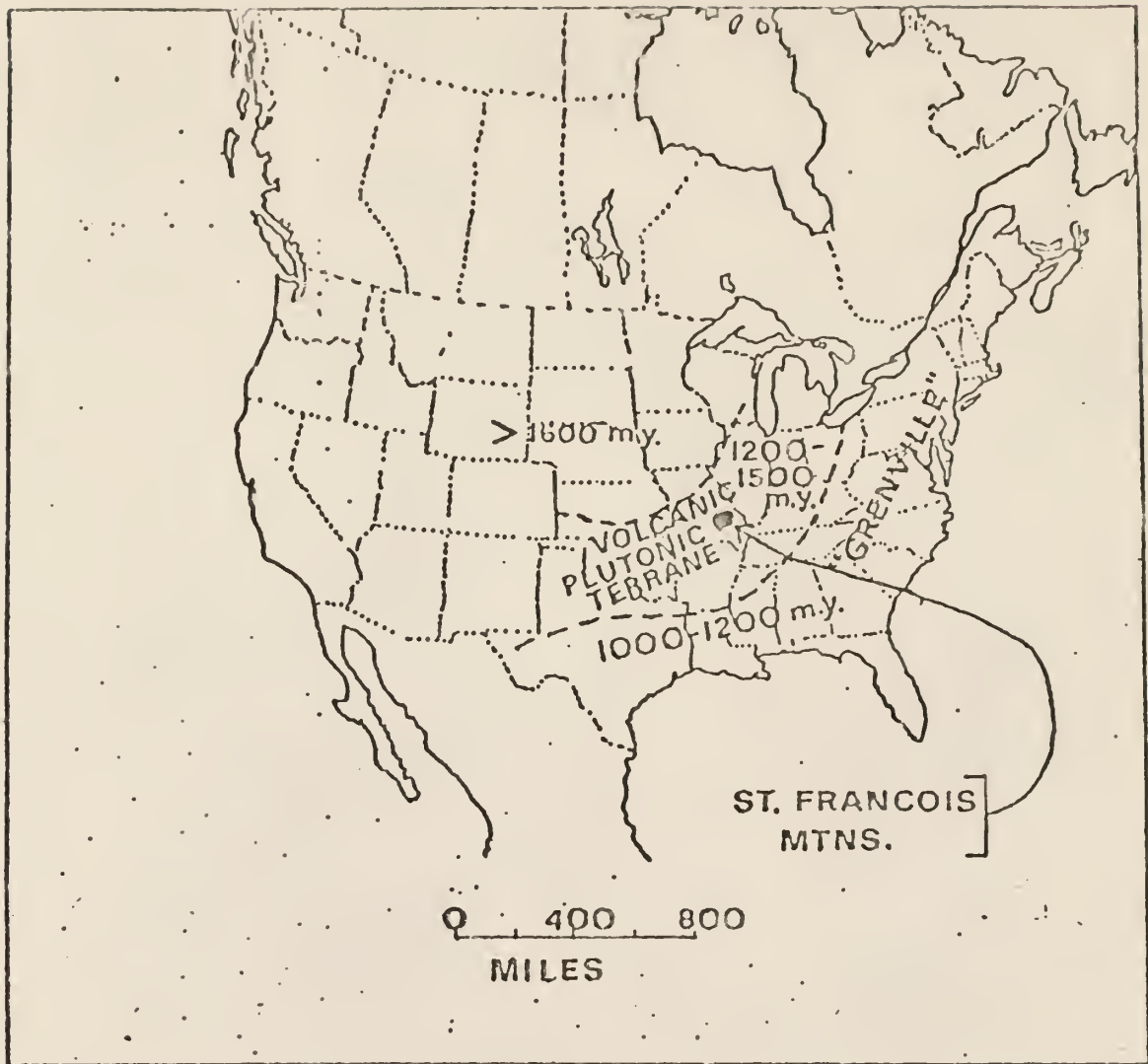


Figure 1. Map of North America showing the St. Francois Mountains in southeastern Missouri. The map also indicates the general ages of the Precambrian basement of North America, from Bickford and Mose (1975).

the Mungar Granite, were obtained from M. E. Bickford and assistants, Ronald Sides and Robert Nusbaum, from the University of Kansas, and they provided maps, major element, and isotopic data from many units in the eastern part of the complex.

Petrogenetic models are constructed from the trace element data by assuming a reasonable mineralogy and trace element content for a source rock of regional metamorphic facies, and then by predicting the trace element content of the melts as the source undergoes progressive fusion. The trace element contents of these primary melts may also be modified by fractional crystallization and the probability of this is also discussed. The predicted distributions can then be compared with the actual distributions in the samples to test the models.

GEOLOGY

General Geology



The St. Francois Mountains are an exhumed Precambrian terrain which have recently been exposed at the surface of the earth. In the immediate area, only the topographic highs are Precambrian rocks, and the valleys are underlain by Cambrian sandstone and dolomite. Throughout southeastern Missouri, the Precambrian rocks are undulating and irregular in the subsurface, reflecting the ancient erosional surface (Heyl, et al, 1965). The Paleozoic sedimentary rocks are locally horizontal and situated in the lower areas surrounding the Precambrian knobs. The sedimentary rocks range from only a few meters thick at the Precambrian contacts to much thicker in the valleys, and in every direction away from the Precambrian exposures. This illustrates the island-like character of the Precambrian surface during the Early Cambrian when seas advanced and eventually covered the hills, depositing as much as 1500 meters of sediment on top of the Precambrian. Today the St. Francois Mountains are considered to be the structural apex of the Ozark uplift (Heyl, et al, 1965).

Tolman and Robertson (1969) mapped the relationships between plutonic and volcanic rocks in the St. Francois Mountains (Fig. 2). Intrusive, batholithic rocks compose about one-third of the northeastern part of the complex, whereas volcanic rocks compose most of the southwestern two-thirds of the exposed rocks. The areal distribution of volcanic relative to intrusive rocks, along with the idea that the granites intruded their own ejecta (Hamilton and Meyers, 1967), make it appear that the whole batholith and associated volcanic rocks have been tilted to the southwest

Figure 2. Generalized geologic map of the St. Francois Mountains, after Tolman and Robertson (1969), and revised from Kisvarsanyi (1976). Figure 3 is of the Iron Mountain Lake, Lake Killarny, Fredricktown NW, and the Fredricktown SW quadrangles (heavily outlined). Figure 4 is of the area outlined in the Edgehill SE quadrangle.




Explanation

Cambrian and Younger Rocks






-  Post Lamotte Rocks
-  Lamotte Sandstone

Precambrian Batholithic Rocks


Musco Group

-  Buford Granite
-  Carver Creek Granite
-  Munger Granite


Bevos Group

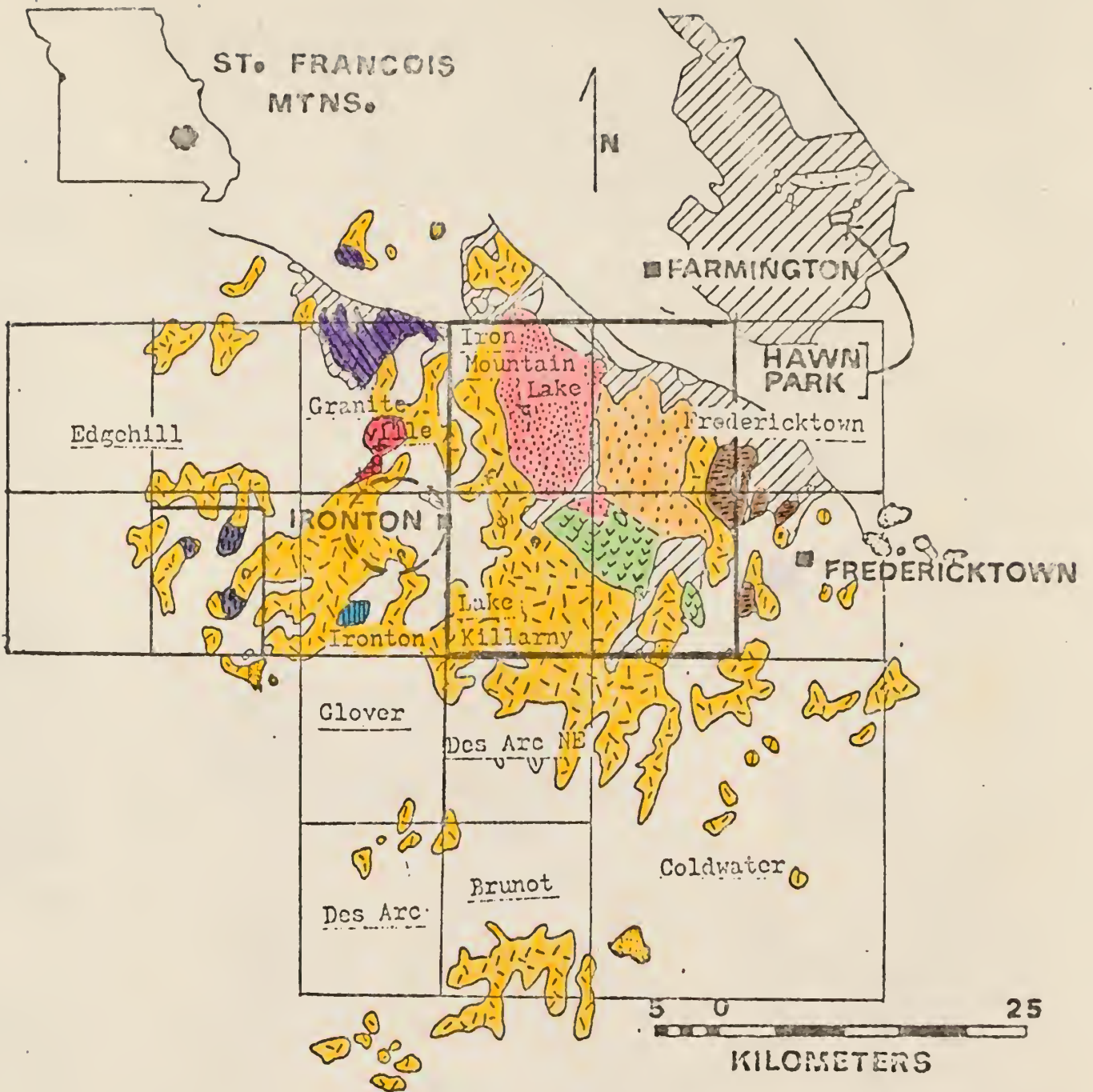
-  Graniteville Granite
-  Breadtray Granite
-  Butler Hill Granite
-  Slabtown Granite
-  Silvermine Granite

Precambrian Pre-Batholithic Rocks

-  Volcanic Rocks (Mostly silicic ash-flow tuff)

Symbols

-  Approximate location of hypothesized Taum Sauk Caldera



(Bickford, 1976, personal communication). This idea agrees with aeromagnetic interpretations by Allingham (1960) that the major volcanic-plutonic contacts dip to the southwest, and with petrochemical data of Kisvarsanyi (1972) that "...may indicate that progressively deeper levels of the batholith are exposed eastward."

Tolman and Robertson (1969) divided the intrusive rocks into two different episodes based on laboratory and field evidence. The granites of the first episode (Fig. 2) were called the Musco Group, and this group included the Slabtown, Stono, Buford, Munger, and Carver Creek granites, which they regarded as being genetically related to each other. The granites of the second episode were called the Bevos Group, and this group included the Graniteville, Breadtray, Butler Hill, Silvermine, and Knoblick granites, and the Brown Mountain Rhyolite Porphyry. Tolman and Robertson (1969, p. 33-34) stated that the Bevos Group of granites

"...immediately underlie(s) granites of the Musco Group on Stono Mountain and along Stouts Creek about 6 miles east of Ironton. The Bevos Group appears to have differentiated in place to form the strongly deuterically altered and commonly granophyric Breadtray Granite at the top, grading to Butler Hill, Knoblick, and Silvermine types at depth. The Graniteville Granite is similar in composition to the Breadtray Granite.... Upon differentiation, magma of Silvermine composition was squeezed into contact positions. Thus at some localities, granites grade in composition from Breadtray through Butler Hill to Silvermine granite and elsewhere Silvermine type granite is intrusive into older rocks."

Kisvarsanyi (1976, p. 73) reported that

"Recent studies indicate that the simple two-stage model proposed for the emplacement of the batholithic rocks of the St. Francois Mountains by Tolman and Robertson (1969) should be modified. G. Kisvarsanyi (1973, 1975) concluded that Musco Group granites (Slabtown and Stono Granites), previously interpreted as belonging to an earlier stage of granite emplacement, are marginal chilled facies and in-situ differentiates, and are transitional to Bevos Group granites with depth."

As a result of this, Figures 2 and 3 have been revised to comply with the new data. It also appears that the new data preclude any relative age determinations for the Musco and Bevos groups derived by Tolman and Robertson (1969).

M. E. Bickford and his assistants Ronald Sides and Robert Nusbaum from the University of Kansas mapped most of the intrusive rocks in the eastern part of the St. Francois Mountains. Figure 3 is the result of their mapping and shows locations of samples which they provided for analyses. A significant difference between Figure 3 and the map by Tolman and Robertson (Fig. 2) is that the contact between the granophyric Breadtray Granite and the hypidiomorphic-granular Butler Hill Granite (dotted line, Fig. 3) was revised to more accurately represent the textural change. Also, the mapping of the volcanic stratigraphy and structure done by Bickford, et al, is much more detailed than the map of Tolman and Robertson, however, much of the structure has been omitted from the map shown here (Fig. 3).

Basalt dikes transect parts of the St. Francois Mountains (Tolman and Robertson, 1969), but they are not considered to be related to the St. Francois Mountains igneous activity (Kisvaranyi, 1972; Wenner and Taylor, 1976).

Geology of the Munger Granite and Surrounding Intrusive and Volcanic Rocks

The Munger Granite occurs as three outcrops in the western part of the St. Francois Mountains (Figs. 2, 4); High Top, Goggins, and Proffit mountains, and have up to 200 meters of relief. The smallest exposure is at Goggins Mountain where the granite is only at the top of an isolated hill surrounded entirely by vol-

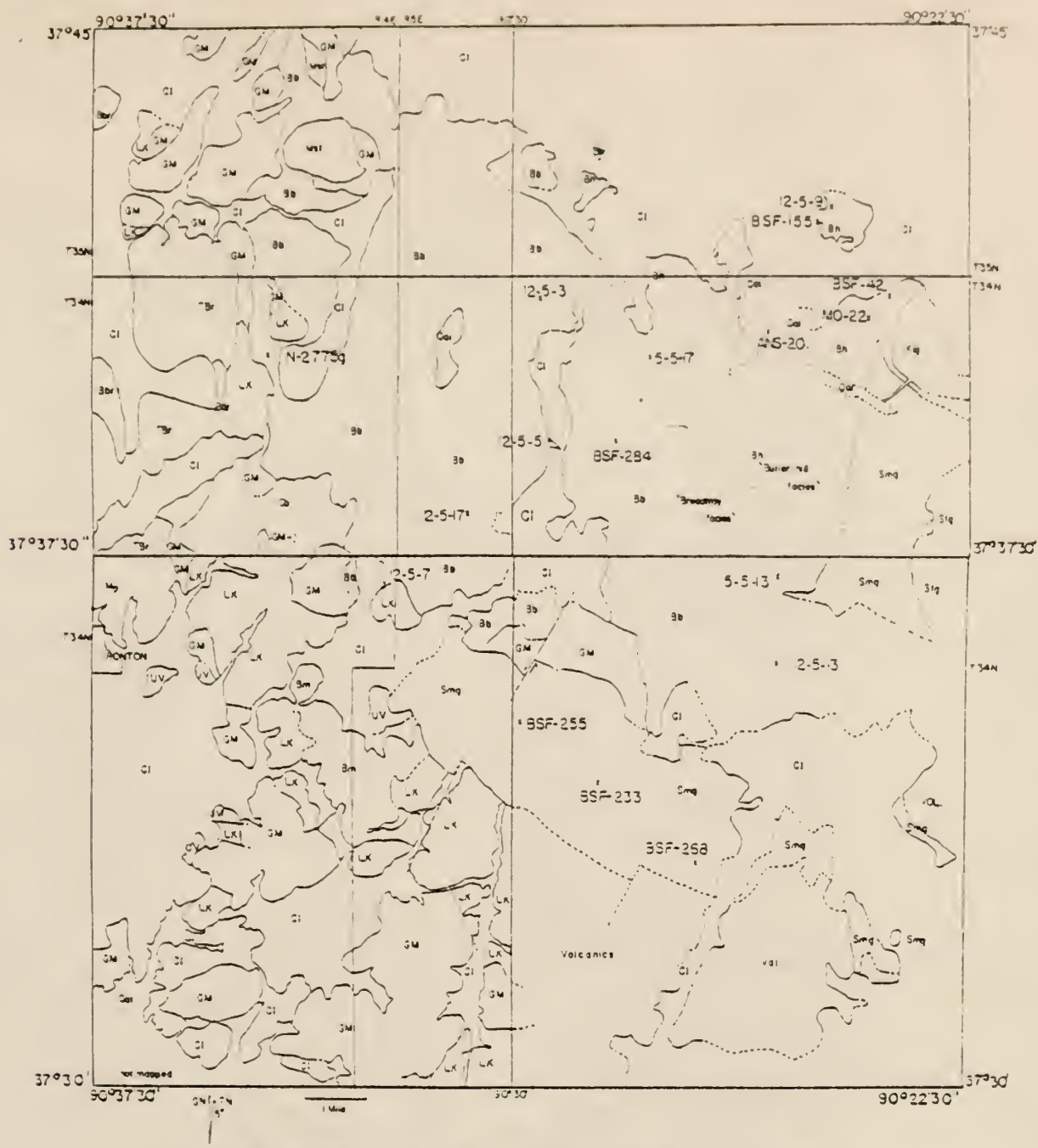


Figure 3. Generalized geologic map of the eastern St. Francois Mountains showing locations of samples (x). The map includes four 7.5 minute quadrangles and may be indexed with Figure 2. The mapping was done by M. E. Bickford, Ronald Sides, and Robert Nusbaum from the University of Kansas

Explanation

Sedimentary Rocks		Symbols	
<u>Qal</u>	Quaternary Alluvium	---	contact, dashed where inferred
<u>Bb</u>	Cambrian Bonneterre Dolomite		
<u>Ci</u>	Cambrian Lamotte Sandstone		
Precambrian Intrusive Rocks		Precambrian Extrusive Rocks	
Beros Group		<u>Uv</u>	Unknown Volcanics
<u>Bb</u>	Breadtray Granite	<u>Mp</u>	Pilot Knob Group
<u>Bm</u>	Brown Mountain Rhyolite Porphyry	<u>Trb</u>	Tribby Breccia
<u>Bb</u>	Butler Hill Granite	<u>Bbr</u>	Black Breccia
<u>Stg</u>	Stono Granite	<u>Gm</u>	Grassy Mountain Ignimbrite
<u>Stg</u>	Slabtown Granite	<u>Lk</u>	Lake Kilarney Felsite
<u>Sbx</u>	Silvermine Granite		
<u>Kis</u>	Knoblick Granite		

canic rocks, and the granite at this exposure is granophyric (Appendix II). The other two exposures, at High Top and Proffit mountains, are at the southwestern end of northeast-southwest trending volcanic ridges and are hypidiomorphic-granular except for one sample (6-28-10) from the very top of High Top Mountain which is granophyric like the granite at Goggins Mountain.

Anderson (1970) mapped many of the volcanic rocks in the area surrounding the Munger Granite and found at least ten mappable volcanic units ranging from 20 to 600 meters thick each, and a possible total thickness of three kilometers. Three of Anderson's major units are in Figure 4. The Stouts Creek Rhyolite (600 meters) is reported to be the oldest and lowest stratigraphic unit. This unit is in contact with the Munger Granite on High Top Mountain. The Taum Sauk Tuff (800 meters) overlies the Stouts Creek Rhyolite and it is exposed at Proffit and Lee mountains, dipping about 20 degrees to the northeast. Structures in the Taum Sauk Tuff indicate that the lava flowed to the southwest (Anderson, 1970). The Johnson Shut-ins Tuff conformably overlies the Taum Sauk Tuff so they have similar dips. The Johnson Shut-ins Tuff is in contact with the Munger Granite on the west side of Proffit Mountain along the Black River at Johnson Shut-ins.

Anderson, et al, (1969) believed that the volcanic rocks in this area are part of a collapsed caldera, the Taum Sauk Caldera (Fig. 2). The center of the caldera was presumed to be near Ironton, Missouri. The volcanic rocks appear to dip to the center of the collapsed structure with the oldest units outcropping on the periphery. The faults mapped in this area resemble fault patterns of other collapse calderas (Berry, 1970).

Figure 4. Geologic map of the Munger Granite and surrounding volcanic rocks showing sample localities. Indicated sample localities are:

A = 6-28-1
C = 6-28-3
F = 6-28-6
G = 6-28-7
H = 6-28-8
J = 6-28-10
N = 6-28-14
O = 6-15-9

Explanation
(Symbols after Anderson, 1970)

Sedimentary Rocks

QEs Cambrian sedimentary rocks with Quaternary Aluvium along streams

Precambrian Intrusive Rocks

Mm Munger Granite

Precambrian Extrusive Rocks (in stratigraphic order, youngest on top)

pEj Johnson Shut-ins Tuff

pEt Taum Sauk Tuff

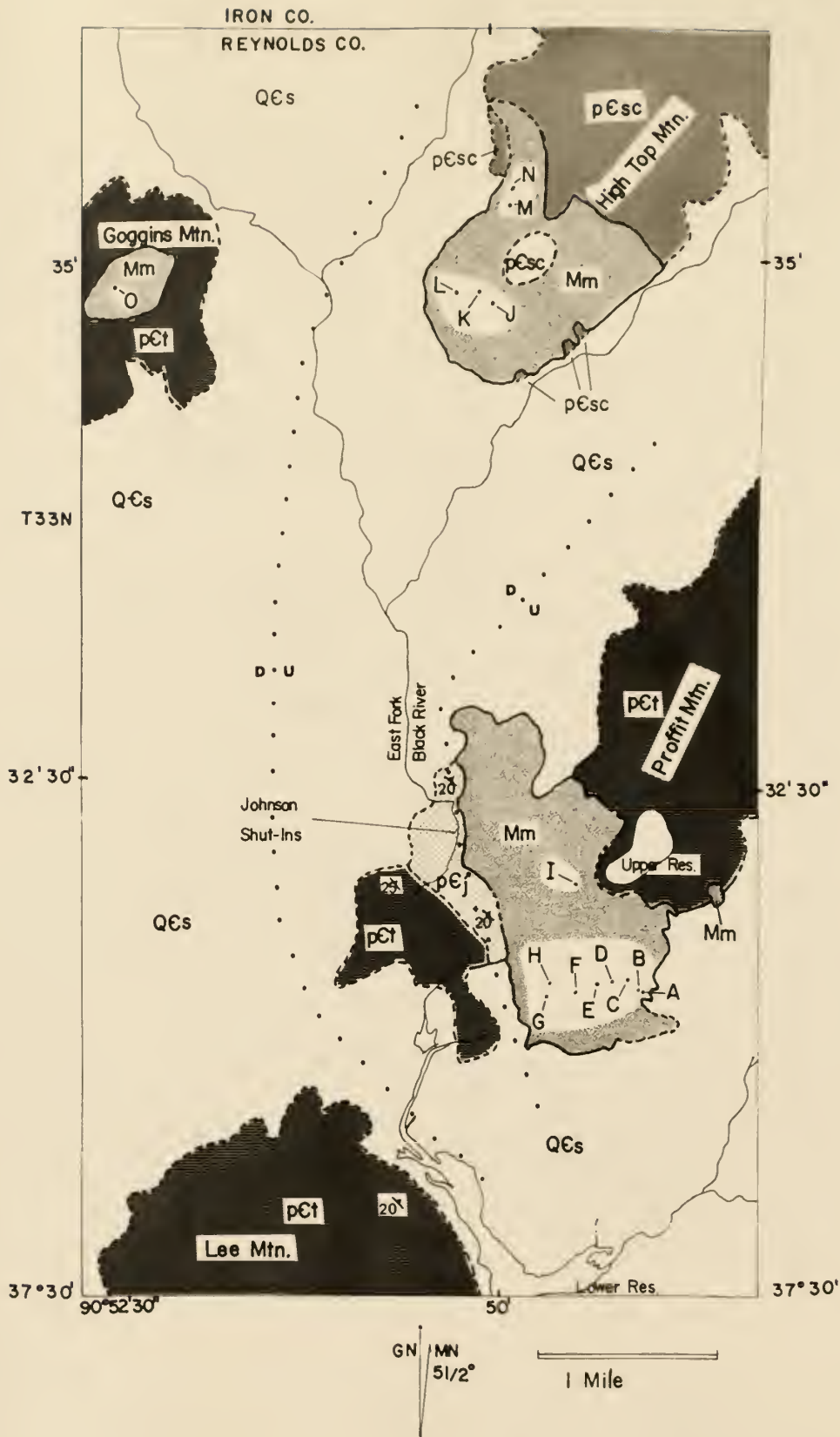
pEsc Stouts Creek Rhyolite

Symbols

↙ Strike and dip of compaction foliation or flow layering

— — — — Contact, dashed where approximate

••••• Inferred faults



The Carver Creek and Buford granites are relatively small exposures of granite in the western part of the St. Francois Mountains (Fig. 2). Consistent with the caldera theory, the Carver Creek, Munger, and Buford granites are hypothesized to be ring fracture dikes which intruded into arcuate fractures surrounding the collapsed caldera (Anderson, et al, 1969).

This theory by Anderson, et al, is in direct contradiction with O'Brien (1961) because during a construction project he found the Taum Sauk Tuff had undoubtedly flowed on top and baked the weathered surface of the Munger Granite. If O'Brien is correct, and the Taum Sauk Tuff, the middle stratigraphic volcanic unit, did flow onto the granite on Proffit Mountain, and the upper volcanic unit is in contact with the Munger Granite at the valley floor approximately 200 meters below, then the volcanic rocks to the west must be faulted downward (Fig. 4). Using Anderson's stratigraphic thicknesses, this faulting would represent net vertical displacement of about 1 kilometer.

Tolman and Robertson (1969) reported yet another type of occurrence for the Munger Granite, Carver Creek Granite, and Buford Granite outcrops. They termed these units sills which intruded into the layers of the volcanic pile. At the present state of mapping in this area, it has not definitely been determined what kind of intrusive units these granites are, and perhaps only a drilling campaign will resolve the differences.

PREVIOUS GEOCHEMISTRY

Major Elements

Hayes (1959) analyzed major elements of rocks from the St. Francois Mountains, and later, Kisvarsanyi (1972) summarized the major element petrochemistry in the area. Using rock classifications based on chemical analyses, Kisvarsanyi related different granitic units to each other genetically, and generally concluded that the Musco Group of granites were less acidic, less salic, less alkalic, and more calcium-rich than granites from the Bevos Group. However, Kisvarsanyi found that the Knoblick and Silvermine granites, previously assigned to the Bevos Group, had closer chemical affinities to the Musco Group than to the Bevos Group.

Sides (1977) analyzed the Breadtray and Butler Hill granites for major elements and some of his data are reported in Appendix V. He used variations in the major elements of these plutons to define batholithic tilt planes based on the theory that when the magma intruded differentiation of the major elements occurred in horizontal layers due to mineral fractionation. Subsequent tilting and erosion of the batholith could then expose different portions of the batholith. His data "...indicate that if the pluton was originally more mafic downward, the azimuth of tilt lies between $S24^{\circ}W$ and $S58^{\circ}W$."

Some major element chemical data from Kisvarsanyi (1972) for granites from the St. Francois Mountains are summarized in Figures 5 and 7. A summary of the modal analyses for the Bevos Group (Kisvarsanyi, 1972) and of the Mungler Granite (Appendix II) is

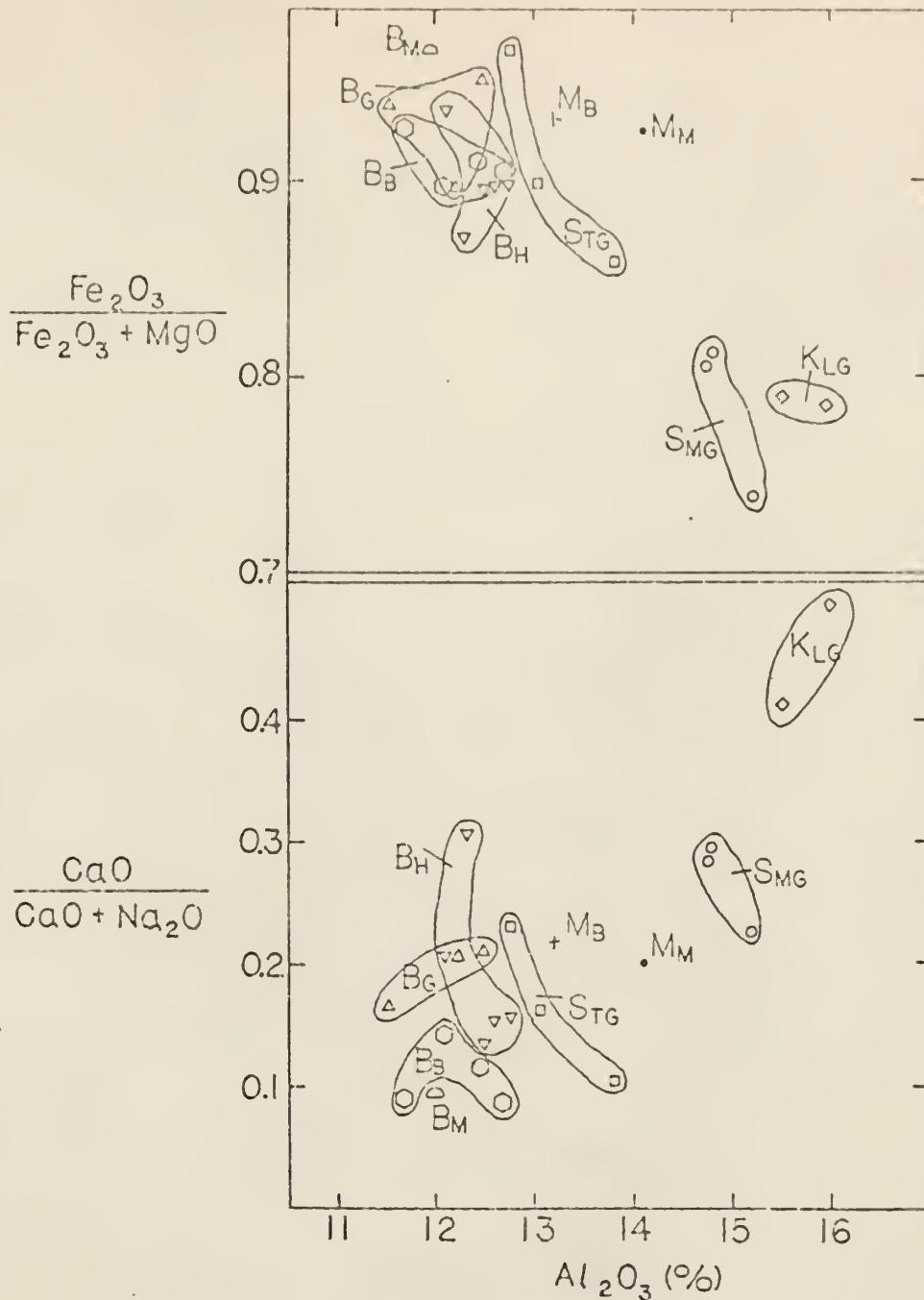


Figure 5. Major element variation diagram for the St. Francois Mountains using data from Kisvarsanyi (1972), weight percent oxides. Musco Group: Mm, Munger Granite (\cdot); Mb, Buford Granite (+). Bevos Group: Eg, Graniteville Granite (Δ); Bb, Breadtray Granite (\circ); Bh, Butler Hill Granite (∇); Stg, Slabtown Granite (\square); Smg, Silvermine Granite (\circ); Klg, Knoblick Granite (\diamond).

Table 1. Summary of the modal mineralogy for St. Francois Mountains intrusive rocks, volume percent.
(after Kisvarsanyi, 1972)

Intrusion	Quartz	Perth. Feld.	Plag- icoclase	Horn- blende	Bio- tite
Musco Group					
Munger Granite*	27-39 (32)	2-15 (11)	41-49 (44) An ₁₀₋₂₀	0-3 (2)	6-15 (8)
Bevos Group					
Graniteville Granite	36	33	29 An ₄	0	0
Breadtray Granite	36-40 (38)	49-51 (57)	1-8 (5) An ₅	0	0-3 (1)
Butler Hill Granite	27-37 (32)	45-60 (50)	0-22 (14) An ₈	1	1-4 (2)
Slabtown Granite	22-34 (28)	8-51 (32)	15-68 (36) An ₈	-	-
Silvermine Granite	29	27	36 An ₁₇	3	0
Knoblick Granite	23	41	27 An ₂₄	2	7

() Indicates average modal mineralogy.

* From Appendix II, this report.

included in Table 1 and Figure 6. The chemical data from Kisvarsanyi (Fig. 5) will later be shown to agree with data obtained in this report, and the mineralogic data (Table 1) will be used in conjunction with the chemical data to explain the petrogenesis of the St. Francois Mountains.

Isotopic Studies

Muehlberger, et al, (1966), Anderson, et al, (1969), Bickford and Mose (1975), and Bickford (1976) reported isotopic analyses of rocks from the St. Francois Mountains. Muehlberger, et al, (1966) obtained Rb-Sr ages for the Precambrian basement rocks of Missouri ranging from 1200 to 1350 million years. Anderson, et al, (1969) found two different Rb-Sr ages representing two episodes of igneous activity. The first activity occurred at about 1415 million years (the Butler Hill and Silvermine granites), while a second activity gave younger ages of about 1320 million years (the Munger and Graniteville granites).

Bickford and Mose (1975) and Bickford (1976) obtained U-Pb as well as Rb-Sr ages for samples from many of the units in the complex (Table 2). The U-Pb dates for the Butler Hill, Bread-tray, and Silvermine granites (Bevos Group) are about 1500 million years, while the Rb-Sr ages for the same units ranged from 1273 to 1408 million years with initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratios of 0.7036 to 0.7254. The Munger Granite (Musco Group) gave U-Pb dates of 1408 million years and Rb-Sr dates of 1280 million years with an initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio of 0.7040.

Bickford and Mose (1975) and Bickford (1976) concluded that the Rb-Sr dates were about ten percent less than the U-Pb dates,

Table 2. Summary of Geochronology of the St. Francois Mountains
(ages in years $\times 10^6$)

Units	Rb-Sr age	$(\text{Sr}^{87}/\text{Sr}^{86})_0$	U-Pb age
From Anderson, et al, (1969)			
Younger Intrusions			
Munger Granite	1318 \pm 12	0.700	
Graniteville Granite	1319 \pm 26	0.704	
Older Intrusions			
Silvermine and Butler Hill Granites	1415 \pm 31	0.702	
From Bickford and Mose (1975) and Bickford (1976)			
Musco Group			
Munger Granite	1280 \pm 50	0.7040	1408 \pm 12
Bevos Group			
Graniteville Granite	1273 \pm 92	0.7254	
Breadtray Granite	1289 \pm 69	0.7070	1500 \pm 20
Butler Hill Granite	1408 \pm 72	0.7036	1500 \pm 20
Slabtown Granite	1321 \pm 98	0.7045	
Silvermine Granite			1501 \pm 40

presumably due to radiogenic strontium loss, indicating, perhaps that a later low grade metasomatism of the system may have occurred, probably about 1300 million years ago. Bickford also surmised that the Mungler Granite (Musco Group) may have been part of a later igneous activity. Wenner and Taylor (1976) did oxygen isotope studies on the St. Francois Mountains and concluded that a later metasomatic event did occur, supporting Bickford's conclusion.

PROCEDURE

Sample Collection and Preparation

Samples of the Munger and Carver Creek granites were collected in the field and prepared for analyses by the author. The freshest parts of samples for geochemical analyses were ground to pass through a 200 mesh sieve and stored as fine powders in airtight vials. A detailed description of the sample preparation is in Appendix I. Thin sections of some samples were prepared commercially. Thin section descriptions of samples of the Munger Granite are in Appendix II and are summarized in Table 1. Other rock samples analyzed in this project were previously prepared in a similar manner by M. E. Bickford from the University of Kansas, and the rock units were described petrographically by Tolman and Robertson (1969).

Atomic Absorption Spectrophotometry

Seven major element and three trace element concentrations were determined using atomic absorption spectrophotometry (AA). The method was adapted from Buckley and Cranston (1971), and is in Appendix III. The results of analyses of U.S.G.S. standard rocks G-2, AGV-1, and GSP-1 determined in this study and by Bickford (1977, personal communication) are compared with published values for these rocks in Table 3. The agreement among analyses is generally good although silica analyses are not reported for the standard rocks analyzed in this study because they were inaccurate. This probably was due either to the inherent matrix differences between the synthesized standard solutions and the dissolved rock solutions, or to the complexing of silica in the

Table 3. Comparison of analyses of U.S.G.S. standard rocks
(weight percent oxides)

Oxide	from Flanagan (1969)		this report+		from Kansas University*		
	G-2	GSP-1	G-2	GSP-1	G-2	GSP-1	
SiO ₂	69.19	67.28	58.99	---	69.0	67.4	59.7
Al ₂ O ₃	15.35	15.12	17.01	15.43	15.44	15.24	17.32
Fe as Fe ₂ O ₃	2.77	4.33	6.80	2.92	4.42	4.11	6.53
CaO	1.99	2.03	4.98	1.96	2.05	4.79	4.99
MgO	0.78	0.96	1.49	0.74	0.92	1.47	1.49
K ₂ O	4.51	5.49	2.90	4.53	5.54	2.86	2.95
Na ₂ O	4.16	2.88	4.33	4.12	2.85	4.28	4.31
Ba (ppm)	1500-3000 (1950)	855-2000 (1360)	1050-2700 (1410)	2550	1900	2470	NA
Rb (ppm)	108-513 (234)	200-690 (343)	68-130 (89)	204	310	77	NA
Sr (ppm)	235-680 (463)	150-400 (247)	350-1050 (657)	550	260	760	NA

+ Average of four analyses
 * Average of five analyses
 () Indicates recommended values
 NA Not available

rock solutions.

Silica analyses were obtained for the granites by dissolving the three U.S.G.S. standard rocks along with five granites in each run. The absorption values determined by AA plotted against SiO_2 content of the standards were linear and used as a calibration to determine unknown SiO_2 contents. In this way, the U.S.G.S. standard rocks and the granite solutions had similar matrix compositions and were dissolved at the same time, so if any complexing of silica occurred, equal amounts of complexing occurred in both standards and samples. This method proved itself in repeated analyses, and avoided the problems involved with using synthesized standard solutions for silica analyses.

Also, barium results are slightly higher than values recommended for standard rocks by the U.S.G.S. There is wide variability in barium values among different analysts as reported by Flanagan (1969, Table 3) and successive trials by the author for barium analysis were consistent.

Neutron Activation Analyses

The concentrations of the REE and some other elements were determined by radiochemical neutron activation analyses (RNAA) and instrumental neutron activation analyses (INAA) methods. The samples were irradiated at full power (1×10^{13} n/cm²sec.) in the central thimble of the Kansas State University Triga Mark II reactor for about four hours. For the RNAA, the samples were processed chemically (after Denechaud, et al, 1970) about 24 hours after irradiation, and then radioassayed 1, 3, 10, and 40 days after irradiation, and later reirradiated and assayed for deter-

mination of chemical yield. The INAA involved radioassaying the whole rock samples 4, 10, and 40 days after irradiation without reirradiation. The RNAA is slightly more precise than INAA for analyses of the REE (Cullers, et al, 1974), but INAA is useful for analyses of iron, sodium, manganese, barium, and rubidium, as well as for most of the REE.

Detailed descriptions of RNAA procedures was given by Yeh (1973), Arnold (1977), and Roden (1977); the INAA procedure is in Appendix IV. Tables 4a and 4b show results of analyses done by other workers and by the author for U.S.G.S. standard rocks BCR-1 and G-2, and good agreement was obtained for all the elements reported.

Table 4a. Comparison of abundances of the REE (ppm) in BCR-1 using RNAA

Reference	La	Ce	Sm	Tb	Eu	Lu	Yb	Iu
This work, RNAA	27.7	50.4	6.5	0.99	2.0	0.62	3.27	0.62
Cullers, et al, (1974), RNAA	26.4	54.9	7.25	1.21	2.05	0.54	3.33	0.54
Gordon, et al, (1968), INAA	23.	46.	5.9	1.0	1.95	0.60	3.2	0.60
Flanagan (1969), various methods	28.8	49.	7.3	1.0	2.2	0.60	4.4	0.60

Table 4b. Comparison of abundances of the REE and other elements in G-2 (ppm) using INAA

Reference	La	Ce	Sm	Eu	Tb	Yb	Lu	Fe ₂ O ₃	Na ₂ O	MnO	Ba	Rb
This work, INAA	84.6	163.	6.94	1.51	0.41	0.66	0.12	2.71	4.2	.034	1700	140
Flanagan (1969), various methods	112.	166.	8.3	1.5	0.52	1.0	0.18	2.77	4.16	.037	1950	168
Jacobs, et al, (1977), INAA	87.9	163.	7.17	1.64	0.44	0.74	0.111	2.65	4.12	-----	-----	----
Gordon, et al, (1968), INAA	81.	144.	8.7	1.37	0.52	0.8	0.18	2.46	3.98	.030	1800	130

* weight percent oxide

ANALYTICAL RESULTS

Introduction

The results of the analyses using the AA and NAA techniques on the Munger, Carver Creek, and Buford granites, and the data from the University of Kansas on other plutons are reported in Appendix V. The results are shown to be comparable with other published data on this complex, as well as with another similar granitic complex.

Chemical Characteristics of Plutons
of the St. Francois Mountains

Quartz, albite, orthoclase, and anorthite modal compositions were recalculated to 100 percent and plotted on a quartz-alkali feldspar-plagioclase (Q-A-P) ternary diagram (Fig. 6) after Streckeisen (1967). The granites of the St. Francois Mountains show variation ranging from the alkali granite field for the Graniteville and Breadtray granites, to the granite field for the other Bevos Group, and to the granodioritic field for the Munger Granite.

The alkali-lime differentiation index may be determined by plotting $(\text{Na}_2\text{O} + \text{K}_2\text{O})$ versus SiO_2 , and CaO versus SiO_2 on the same graph (Fig. 7). The intersection of the lines joining the two plots defines a SiO_2 content which is used to categorize igneous complexes. The data plotted in Figure 7 are from this report and from Kisvarsanyi (1972). The data from both sources agree, but the lines joining the data points do not intersect in this range of SiO_2 contents, indicating that these rocks are at least alkali-calcic, and probably alkalic. Also shown on the

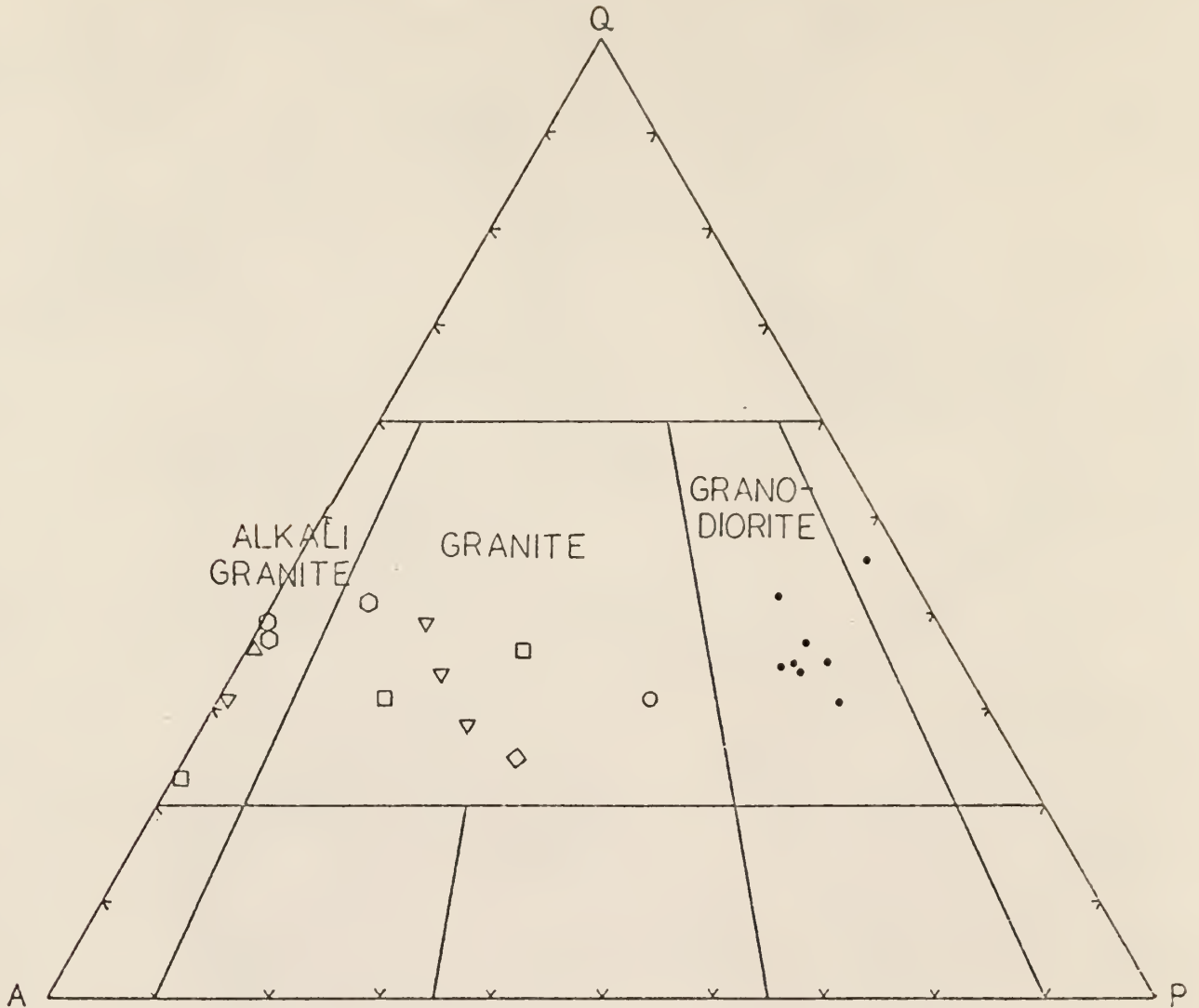


Figure 6. Q-A-P ternary diagram for the St. Francois Mountains. Q represents the quartz mode, A represents the sum of the alkali feldspar and albite (An_{0-5}), and P represents the plagioclase (An_{5-100}) mode, after Streckeisen (1967). Symbols indicate the Munger Granite (\cdot), Graniteville Granite (Δ), Breadtray Granite (\circ), Butler Hill Granite (∇), Slabtown Granite (\square), Silvermine Granite (\circ), and Knoblick Granite (\diamond).

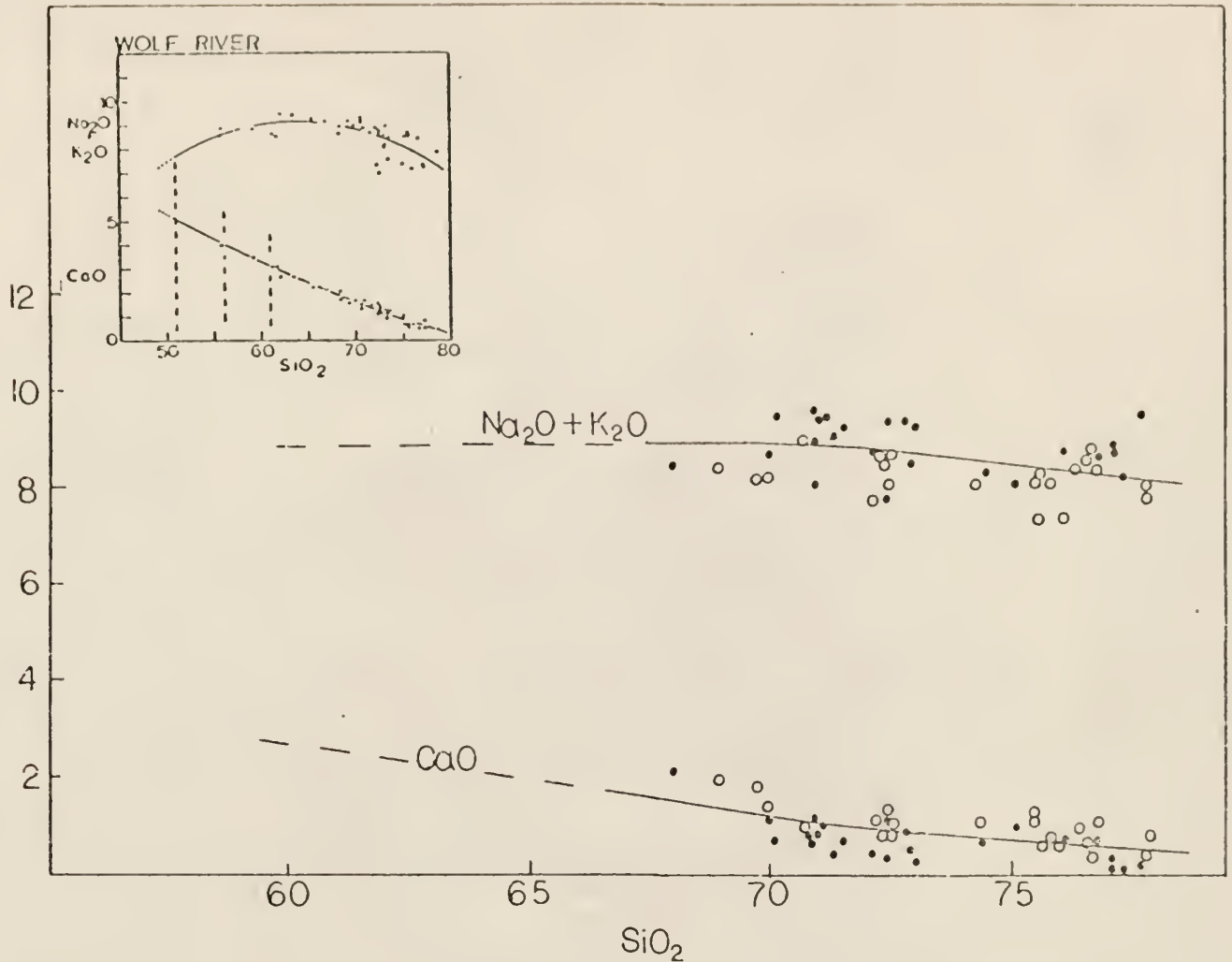


Figure 7. Alkali-lime differentiation index. Data are from this report (\cdot), and from Kisvarsanyi (1972) (\circ). Also shown is the differentiation plot from Anderson and Cullers (1973).

figure is the differentiation index derived by Anderson (1975) for the Wolf River Batholith of similar age in Wisconsin. He also concluded that the batholith was at least alkali-calcic and probably alkalic. Of special interest is the lack of intermediate rocks in the plutons of the St. Francois Mountains. Unlike the Wolf River Batholithic rocks, which contain anorthosites and monzonites with lower SiO_2 values, the St. Francois Mountain plutonic rocks do not contain values below about 68 percent SiO_2 .

The $\text{Fe}_2\text{O}_3/(\text{Fe}_2\text{O}_3 + \text{MgO})$ and $\text{CaO}/(\text{CaO} + \text{Na}_2\text{O})$ ratios are plotted versus Al_2O_3 in Figure 8. Some data for the granites of the Bevos Group were provided by Bickford (1977, personal communication) and are not tabulated in Appendix V. The chemical trends in Figure 8 are similar to the older analyses in Figure 5 (Kisvarsanyi, 1972), and demonstrate the similarity of the chemical data among independent analysts.

A summary of the trace element contents of the granites from the St. Francois Mountains is in Table 5, and Ba and Rb values are plotted versus Sr, and Eu/Sm is plotted versus Ba in Figure 9. Also, the chondrite normalized REE plots of granites from the St. Francois Mountains are in Figure 10. The REE values of the chondrites, after Haskin, et al (1968), are considered to be equal to the average terrestrial REE distributions. The Eu/Sm and Eu/Eu^* ratios (Table 5) are indications of the degree of Eu depletion relative to other REE next to Eu. Eu^* is determined by extrapolation of Sm and Tb (or Gd) on the chondrite-normalized curve to estimate the Eu present assuming no Eu was fractionated. Negative Eu anomalies may be arbitrarily defined as a Eu/Eu^* ratio less than 0.8.

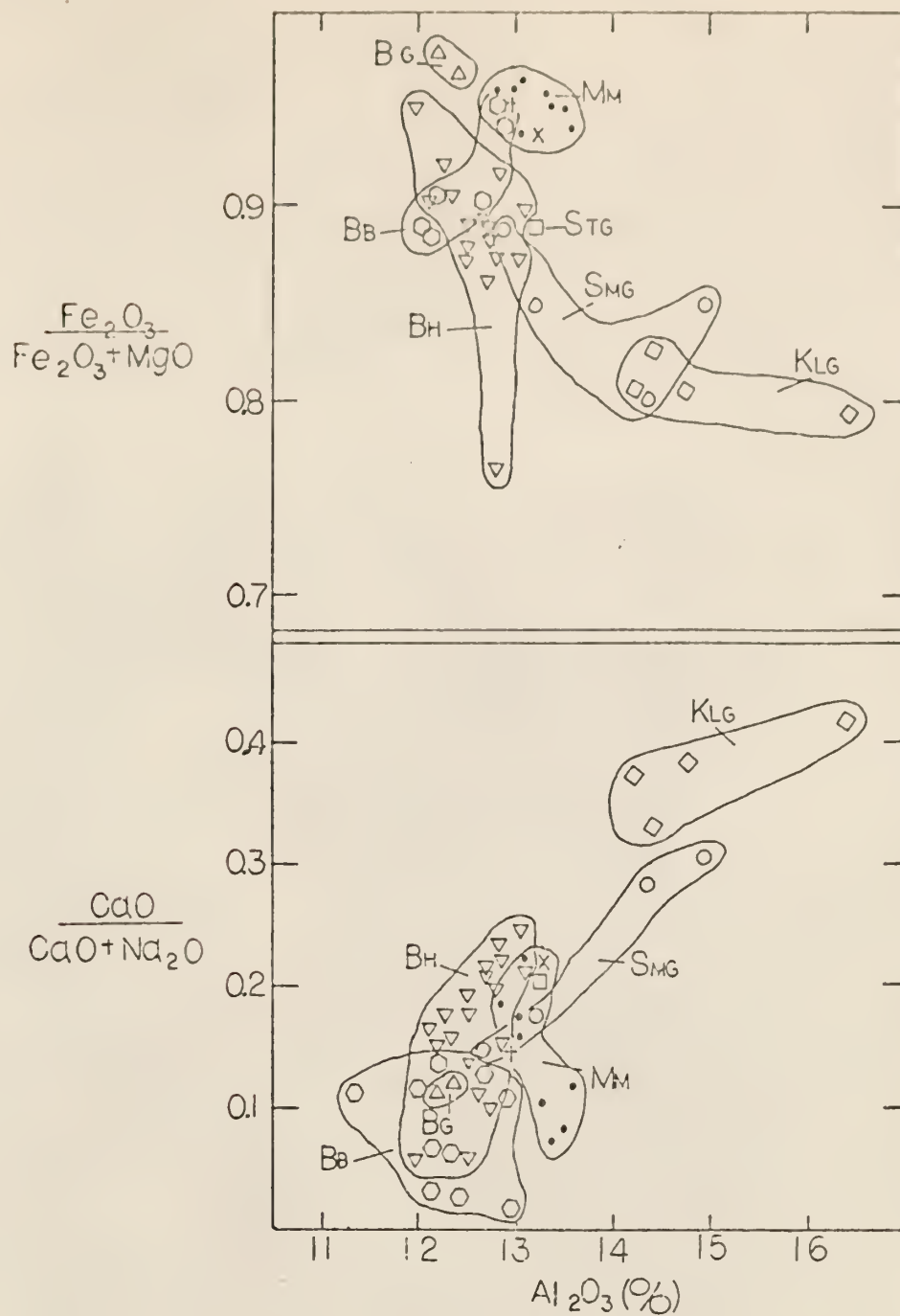


Figure 8. Major element variation diagrams, Musco Group: Mm, Munger Granite (\cdot); Carver Creek Granite (\times); Buford Granite ($+$). Bevos Group: Bg, Graniteville Granite (Δ); Bb, Breadtray Granite (\circ); Bh, Butler Hill Granite (∇); Stg, Slabtown Granite (\square); Smg, Silvermine Granite (\circ); Klg, Knoblick Granite (\diamond).

Table 5. Summary of trace element data (ppm), parenthesis indicate average value.

Units	ΣREE	La/Lu	Eu/Sm	Eu/Eu*	Ba	Rb	Sr
Musco Group							
Munger Granite	145-256 (203)	48-65 (54)	0.17-0.25 (0.21)	0.58-0.77 (0.72)	1460-1610 (1515)	146-320 (213)	35-115 (67)
Carver Creek Granite	311	35	0.13	0.43	1140	157	82
Buford Granite	303	47	0.22	0.70	2050	230	75
Bevos Group							
Granite-ville Granite	288-328 (309)	18-22 (20)	0.02 (0.02)	0.05-0.06 (0.06)	140-263 (202)	320-380 (350)	17-23 (20)
Breadtray Granite	174-301 (247)	7-49 (31)	0.03-0.11 (0.06)	0.06-0.29 (0.18)	390-560 (460)	190-250 (210)	14-68 (46)
Butler Hill Granite	201-330 (283)	44-57 (48)	0.05-0.08 (0.07)	0.17-0.28 (0.23)	350-699 (452)	190-259 (230)	56-141 (84)
Slabtown Granite	208-256 (232)	39-57 (48)	0.23 (0.23)	0.75-0.77 (0.76)	810-1600 (1205)	104-134 (119)	112
Silvermine Granite	154-160 (156)	43-71 (58)	0.15-0.24 (0.20)	0.41-0.78 (0.62)	700-1165 (938)	114-167 (138)	95-208 (152)

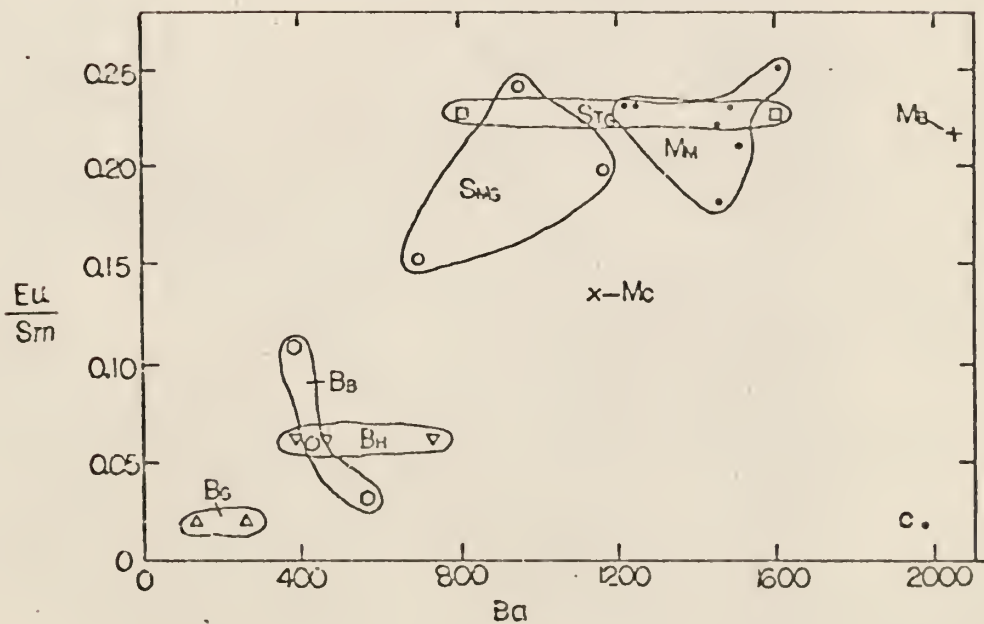
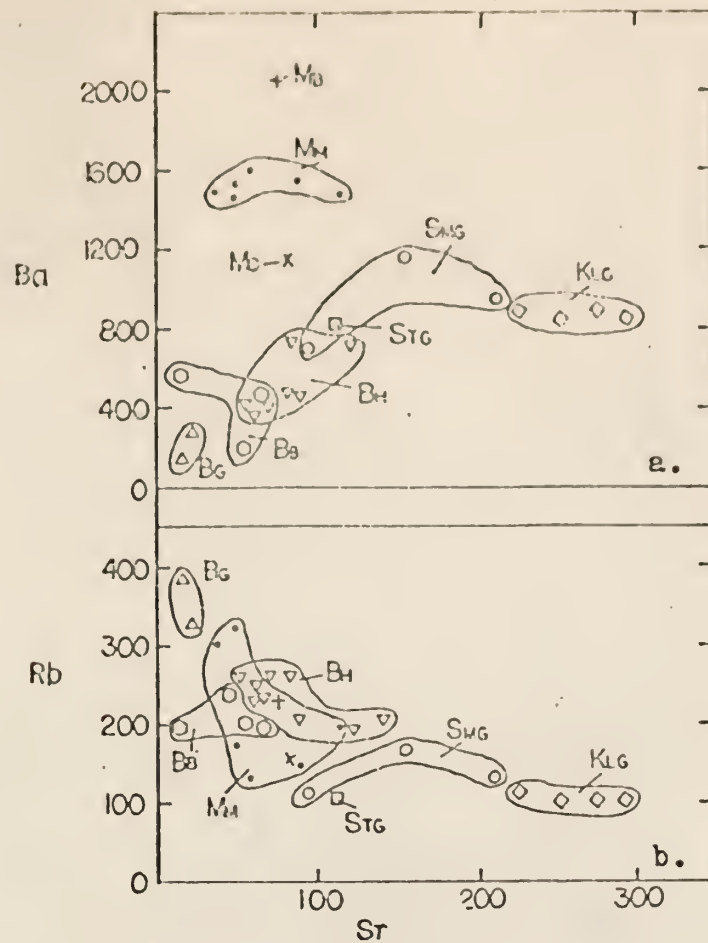


Figure 9. Trace element variation diagrams (ppm). Musco Group: Mm, Munger Granite (\cdot); Mc, Carver Creek Granite (x); Mb, Buford Granite (+); Bevos Group: Bg, Graniteville Granite (Δ); Eb, Breadtray Granite (\circ); Bh, Butler Hill Granite (∇); SMG, Silvermine Granite (\circ); STG, Slabtown Granite (\square).

Figures 9 and 10 are similar to diagrams obtained by Anderson and Cullers (1978) for differentiated and undifferentiated granites of the Wolf River Batholith in Wisconsin. The general chemical characteristics of the two groups of granites from this complex are stated below.

Bevos Group

The Bevos Group contains the widest variation in chemical trends in the St. Francois Mountains. The Graniteville and Breadtray granites contain relatively low Ca/Na, Al, Ba, Sr, La/Lu, Eu/Sm, and Eu/Eu*, and relatively high Fe/Mg, Rb, and REE compared to the other Bevos Group units (Fig. 8, 9, Table 5). In contrast, the Knoblick Granite, and parts of the Silvermine and Slabtown granites contain higher Al, Ca/Na, Ba, Sr, La/Lu, Eu/Sm, and Eu/Eu*, and relatively lower Fe/Mg, Rb, and REE compared to the other units of the Bevos Group.

The Butler Hill Granite is generally intermediate in chemical composition between the Graniteville and Breadtray granites on one end of the chemical trends, and the Slabtown, Silvermine, and Knoblick granites on the other end. The chemical variations in the Bevos Group will later be used to determine which minerals could have caused the magma differentiation.

Musco Group

Kisvarsanyi (1972) emphasized that the Musco Group is less salic than the Bevos Group. The granites in this group, the Mungler, Carver Creek, and Buford granites, have major element chemistry similar to one another, and thus, plot in the same fields in Figures 8 and 9, although some variation exists in Ba and

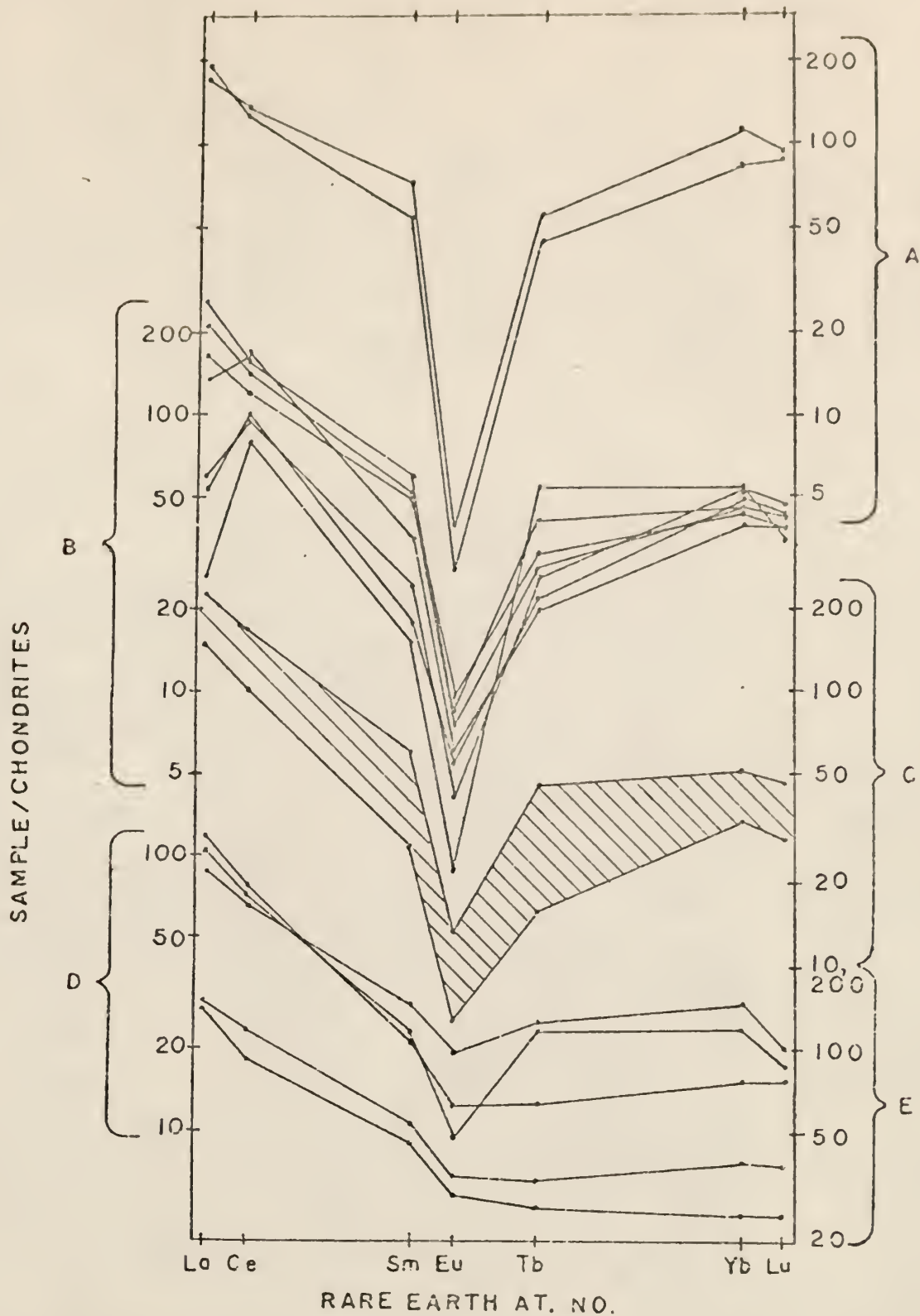


Figure 10a. Chondrite normalized REE plots for the Bevos Group. (A) Graniteville Granite; (B) Breadtray Granite; (C) Butler Hill Granite ranges (shaded); (D) Silvermine Granite; (E) Slabtown Granite.

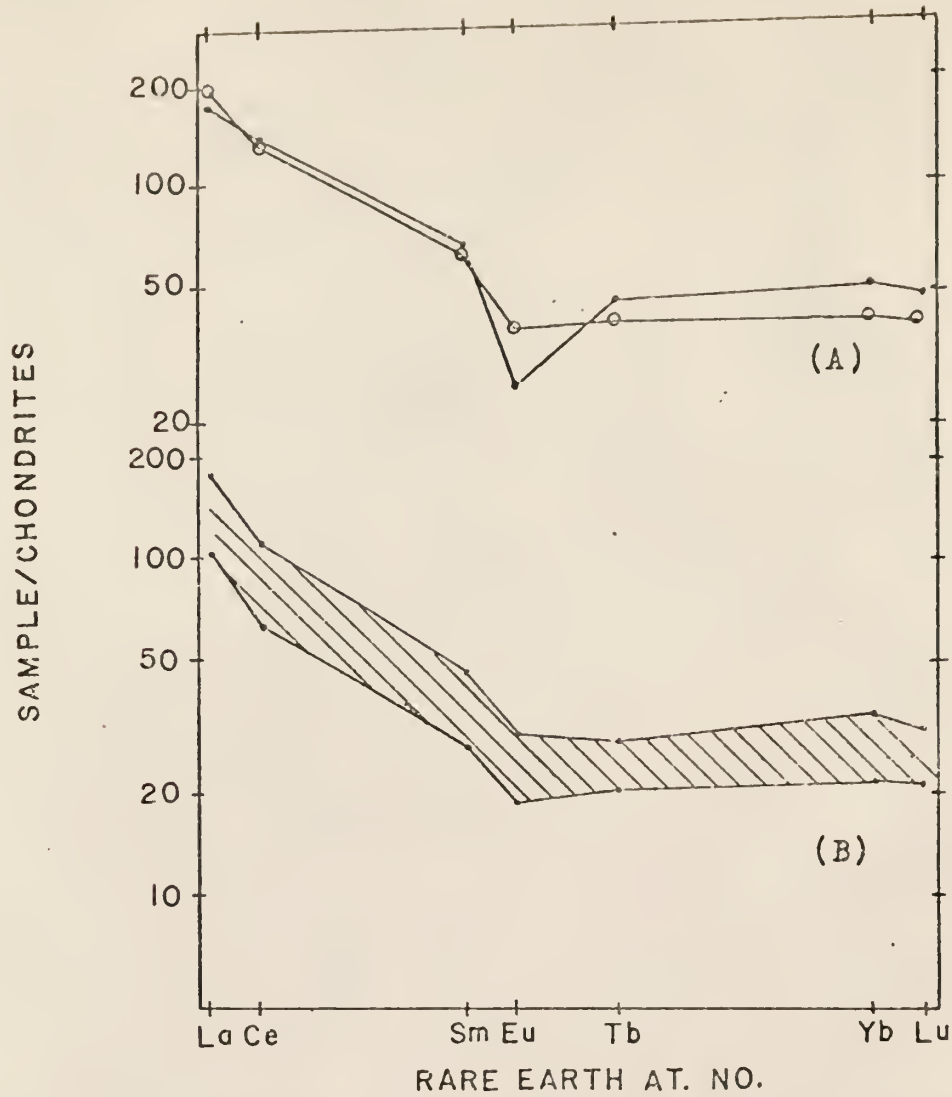


Figure 10b. Chondrite normalized REE plots for the Musco Group. (A) Carver Creek Granite (•), and Buford Granite (o); (B) Munger Granite ranges (shaded).

Eu/Sm values among these granites (Fig. 9c). The Ca/Na, Rb, Sr, and La/Lu values are similar to intermediate values obtained for the Bevos Group (like the Butler Hill Granite), but Fe/Mg, Al, Ba, Eu/Sm, and Eu/Eu* values are generally higher in the Musco Group than in the Bevos Group. These chemical characteristics will later be used to explain the formation of the Musco Group in relation to the Bevos Group.

DISCUSSION

Bevos Group Differentiation

Tolman and Robertson (1969) and later Kisvarsanyi (1972) referred to the Bevos Group as a composite body of differentiated magma. Sides (1977) discussed major element variations in the Breadtray and Butler Hill granites and tried to relate the trends to dip planes of the batholith based on magma differentiation. One may go one step further with the available major and trace element data in relation to the mineralogic data (Table 1) and geographic location of the units (Figs. 2, 3) to make qualitative predictions about the mineral differentiation which could have caused the variations observed in the Bevos Group.

The model proposed here is that magma similar in composition to the Butler Hill Granite and parts of the Slabtown and Silvermine granites could have fractionally crystallized plagioclase, K-feldspar, and biotite and/or hornblende to form the other granites of the Bevos Group. The Knoblick and parts of the Slabtown and Silvermine granites could have formed by accumulation of the above minerals mixed with some of the original magma, and the Graniteville and Breadtray granites could have formed from residual liquids. The following discussion will summarize evidence for the proposed fractionation model.

Major Elements

The relatively high Fe/Mg ratios and low Al contents of the Graniteville Granite (Fig. 8), combined with the apparent lack of ferromagnesium minerals and low K-feldspar content (Table 1), compared to the Butler Hill Granite, suggest that it could have

formed from a residual magma left from the fractional crystallization of Mg-rich biotite and/or hornblende and possibly some K-feldspar. The Ca/Na ratios and plagioclase contents of this unit are similar to the Butler Hill Granite and do not suggest that plagioclase was involved in the differentiation which led to the formation of this unit.

The low Ca/Na ratios and relatively high Fe/Mg ratios of the Breadtray Granite (Fig. 8), along with high K-feldspar and lower plagioclase and anorthite contents, compared to the Butler Hill Granite (Table 1), suggest that it could have resulted from a residual magma after the crystallization of Mg-rich biotite and/or hornblende along with Na-rich plagioclase (An₅₋₁₀). The high K-feldspar contents in the Breadtray Granite could have resulted from the accumulation of K-feldspar grains during the simultaneous formation of the Graniteville Granite (see above).

The Butler Hill Granite has highly variable Fe/Mg and Ca/Na ratios as well as variable amounts of K-feldspar and plagioclase (Fig. 8, Table 1). Qualitatively, this variation could also be caused by fractional crystallization of Na-rich plagioclase (An₅₋₁₅), Mg-rich biotite and/or hornblende, and K-feldspar. Sides (1977) found the variations in major element chemistry to be consistent from southwest to northeast, and data from this report (Figs. 2, 3, 8; Table 1) show this unit to be intermediate between the Graniteville and Breadtray granites on the west, and the Slabtown, Silvermine, and Knoblick granites on the east in mineralogy and major element chemistry. Kisvarsanyi (1973, 1975) reported the Butler Hill Granite to be in contact with and transitional to the Breadtray, Slabtown, and Silvermine granites,

and this is also indicated by overlap in the major element chemistry in Figure 8.

The Slabtown and Silvermine granites have somewhat similar major element chemistry and mineralogy. These granites tend to have higher Al, Ca, Mg, and therefore higher Ca/Na, but lower Fe/Mg ratios than most of the Butler Hill Granite. They also contain higher amounts of plagioclase and anorthite, and slightly less K-feldspar than the Butler Hill Granite (Table 1), and could have been formed by accumulation of plagioclase (An₁₀₋₂₀) and perhaps Mg-rich biotite and/or hornblende along with some of the original magma. The Silvermine Granite has considerable variation in Al, Ca/Na, and Fe/Mg ratios (Fig. 8) and probably also has wider variation in mineralogy than shown by the one modal analysis in Table 1.

The Knoblick Granite contains high Ca/Na and Al content and low Fe/Mg ratios compared to the other Bevos Group, parts of which overlap with the Silvermine Granite (Fig. 8). The modal analysis available for the Knoblick Granite indicates that it contains relatively higher amounts of plagioclase, K-feldspar, biotite, and hornblende than the other Bevos Group units and probably formed by accumulation of Mg-rich biotite and/or hornblende, plagioclase (An₁₅₋₂₅), and K-feldspar.

Analyses of the major elements reported in this paper agree with analyses by other authors (e.g. Kisvarsanyi, 1972) and indicate that the Bevos Group apparently differentiated in place to form parts of the Slabtown and Silvermine granites, and the Knoblick Granite as cumulates, and the Graniteville and Breadtray Granites from residual magmas. The Butler Hill Granite, and

perhaps to some extent, parts of the Slabtown, Silvermine, and Breadtray granites are intermediate to the Bevos Group in mineralogy, chemistry, and geographical location, and probably represent the parent magma.

Trace Elements

Trace elements may be used to modify and elaborate on the relationships predicted using the major elements concerning the differentiation of the Bevos Group. Trace element behavior in silicate magmas has been experimentally related to distribution coefficients (D) for the trace element partitioning between the solid and liquid phases (Gast, 1968; Ewart and Taylor, 1969; Philpotts and Schnetzler, 1970; and Drake and Weill, 1975). A distribution coefficient is defined as the concentration of the trace element in the solid phase divided by the concentration of the trace element in the melt ($D = c^s/c^l$). Minerals with a D greater than one for an element will tend to be enriched in that element, and minerals with a D less than one will tend to enrich the melt in that element, during crystallization from a magma. Distribution coefficients, for rhyolitic rocks, from Arth and Hanson (1975), are used for both qualitative and quantitative purposes in this paper, and are summarized in Appendix VI.

The minerals which tend to incorporate Ba, Sr, and Eu, and reject Rb and all other REE relative to the melt, as observed in the Bevos Group cumulates (Fig. 9), are the feldspar minerals. Qualitatively, fractional crystallization of plagioclase and K-feldspar from a parent magma tends to concentrate Ba (K-feldspar), Sr (K-feldspar and plagioclase), and Eu (K-feldspar and plagioclase) in the cumulate minerals, while Rb and all other REE

are rejected from the feldspar and are enriched in the residual magma. This mineral fractionation, as previously mentioned concerning major elements, is compatible with the model in generating the trace element variations observed in the Bevos Group (Figs. 9, 10), assuming that the parent magma was similar in composition to the Butler Hill Granite. This assumption is believed to be valid, as discussed previously, because the Butler Hill Granite is intermediate to the other Bevos Group units in field relationships, mineralogy, major and trace element composition, and is a relatively large pluton as would be expected of a parent magma (Figs. 3, 8, 9; Tables 1, 5).

The Bevos Group cumulates, the Knoblick, and parts of the Silvermine and Slabtown granites, contain some biotite and hornblende (Table 1) which tend to concentrate Rb and REE respectively. The amount of hornblende present is compatible with the proposed fractionation model, but biotite alone would generate increasing, rather than the observed decreasing, Rb contents in the cumulates (Fig. 9). Qualitatively, these minerals could cause the lower Fe/Mg ratios in the cumulates (Fig. 8), but they probably are not present in large enough quantities, compared to the feldspars, to appreciably affect the Rb contents of the cumulate portions.

One trace element trend not yet explained by the proposed fractionation model for the Bevos Group is the La/Lu ratio variation, and the anomalously low La obtained for some of the Breadtray Granite samples (Table 5, Fig. 10). Although distribution coefficients for La are not available, extrapolation of the known REE distribution coefficients can be of assistance (Appendix VI). The feldspar minerals have distribution coefficients about ten

times higher for the light REE relative to the heavy REE and probably create the variation in the La/Lu ratios, in agreement with the proposed fractionation model. Biotite shows little preference for any of the REE, and hornblende has higher affinities for the heavy REE relative to the light REE, but, again, these minerals are probably not in sufficient abundance to create a trend in the trace element contents. Of special interest is the very high affinity allanite has for the light REE relative to the heavy REE (Appendix VI). Qualitatively, if small amounts of allanite fractionated from the magma which later formed the Breadtray Granite, the observed REE distributions could be generated in the residual magma. Complete petrographic and mineralogic data on the Breadtray and Butler Hill granites concerning the presence of allanite are unavailable at this time. However, allanite has been observed in granites of similar age and composition from Wisconsin (Anderson, 1975).

The Musco Group contains higher Al, plagioclase, ferromagnesium minerals, Fe/Mg, Ba, Eu/Sm, lower K-feldspar, and similar Rb, Sr, and Ca/Na as the Butler Hill Granite. The high Ba, Eu/Sm and plagioclase is similar to the cumulate portions of the Bevos Group, but Rb, Sr, Fe/Mg, and Ca/Na ratios are not like the cumulate portions of the Bevos Group. For this reason, different models for the formation of the granites of the Musco Group must be considered, and further analyses of the data are necessary to approximate the origin of these granites, and this will be discussed later.

Approximation of Source Material

The origin of granites and their relationships with metamorphic and other more basic igneous rocks has been controversial for years (Gilluly, 1953; Read, 1957; Raguin, 1965). Recent studies in experimental petrology in granitic systems at high temperature and pressure have helped solve these controversies. For example, large volumes of granitic melts cannot be formed by fractionation from basaltic magmas (Carmichael, et al, 1974), although Kushiro (1972) and Bailey and Schairer (1966) believed that calc-alkaline and alkaline silicic rocks can form by fractionation from basic melts. Bailey and Schairer (1966) found that granitic melts formed by fractionation tend to plot away from the low temperature eutectics on Qz-Ab-Or plots, unlike the St. Francois Mountain granites which cluster near the appropriate cotectic lines (Figs. 15, 16). Recently, it has been reported that large volumes of granitic melts can be produced by melting of sedimentary rocks metamorphosed in the amphibolite to granulite facies of regional metamorphism (e. g. Winkler, 1976). For these reasons, it may be assumed that the large volumes of granite of the St. Francois Mountains probably formed by partial melting of crustal rocks, and therefore, this type of rock will be used to approximate the source.

The $\text{Sr}^{87}/\text{Sr}^{86}$ initial ratios (Table 2) of the St. Francois Mountains generally range from 0.702 to 0.707. The Graniteville Granite has a higher $\text{Sr}^{87}/\text{Sr}^{86}$ initial ratio of 0.7254. The higher Graniteville Granite value is caused by high $\text{Rb}^{87}/\text{Sr}^{86}$ ratios, as much as 2.5 (Bickford and Mose, 1975), which leads to a great uncertainty in the value of the intercept in a Rb-Sr isochron.

Discounting the high value for the Graniteville Granite, the initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratios for the granites of this complex may be assumed to be generally low. The initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratios are low enough to preclude salic crustal rocks from being the source material, although a source intermediate in composition would have appropriate Rb/Sr ratios (0.10-0.30) to generate 1500 million year old rocks with the observed $\text{Sr}^{87}/\text{Sr}^{86}$ ratios of 0.7048 (Van Schmus, et al, 1975), and Anderson and Cullers (1978) concluded that a tonalitic crustal source could have been the parent material which formed that batholith.

The source rock mineralogy (Table 6) was approximated from data on Precambrian sedimentary rocks, mostly shales and graywackes, analyzed by Condie (1967), and Condie, et al (1970), and from postulated sources by Anderson and Cullers (1978). Possible trace element contents of the source for the St. Francois Mountains were approximated from data on Precambrian sedimentary rocks by Wildeman and Condie (1973), Wildeman and Haskin (1973), and McCarthy (1976) and are in Figure 11 and Appendix VI. Figure 11 shows the ranges of the chondrite-normalized REE data of the possible sources and the average Precambrian shale and formation distributions which are later used in the theoretical modeling for the formation of the St. Francois Mountain plutons. The proposed REE values of the source are assumed to be consistent with source rocks of intermediate composition.

Table 6 also shows the ranges of source rocks used by Anderson and Cullers for modeling Precambrian granite formation. Their modeling required the source to contain quartz, plagioclase, biotite, hornblende, zircon, and apatite, and possibly K-feldspar,

Table 6. Possible source material compositions
(volume percent)

Minerals	Precambrian Sedimentary Rocks ^a	Tonalitic Source ^b	Approximated Source for St. Francois Mountains
Quartz	0-33	10-25	10-35
Plagioclase (An ₃₀)	0-15	35-65	10-35
K-feldspar	0-25	0-5	0-20
Biotite	3-53	10-25	10-50
Muscovite	0-5	-----	-----
Hornblende	-----	3-15	0-5
Orthopyroxene	-----	0-15	0-5
Clinopyroxene	-----	0-5	0-5
Olivine	-----	0-10	-----
Zircon	-----	0.1-0.3	Trace?
Apatite	-----	0.1-0.3	Trace?
Garnet	-----	0-1	0-1

a. From Condie (1967), and Condie, et al (1970).

b. From Anderson and Cullers (1978).

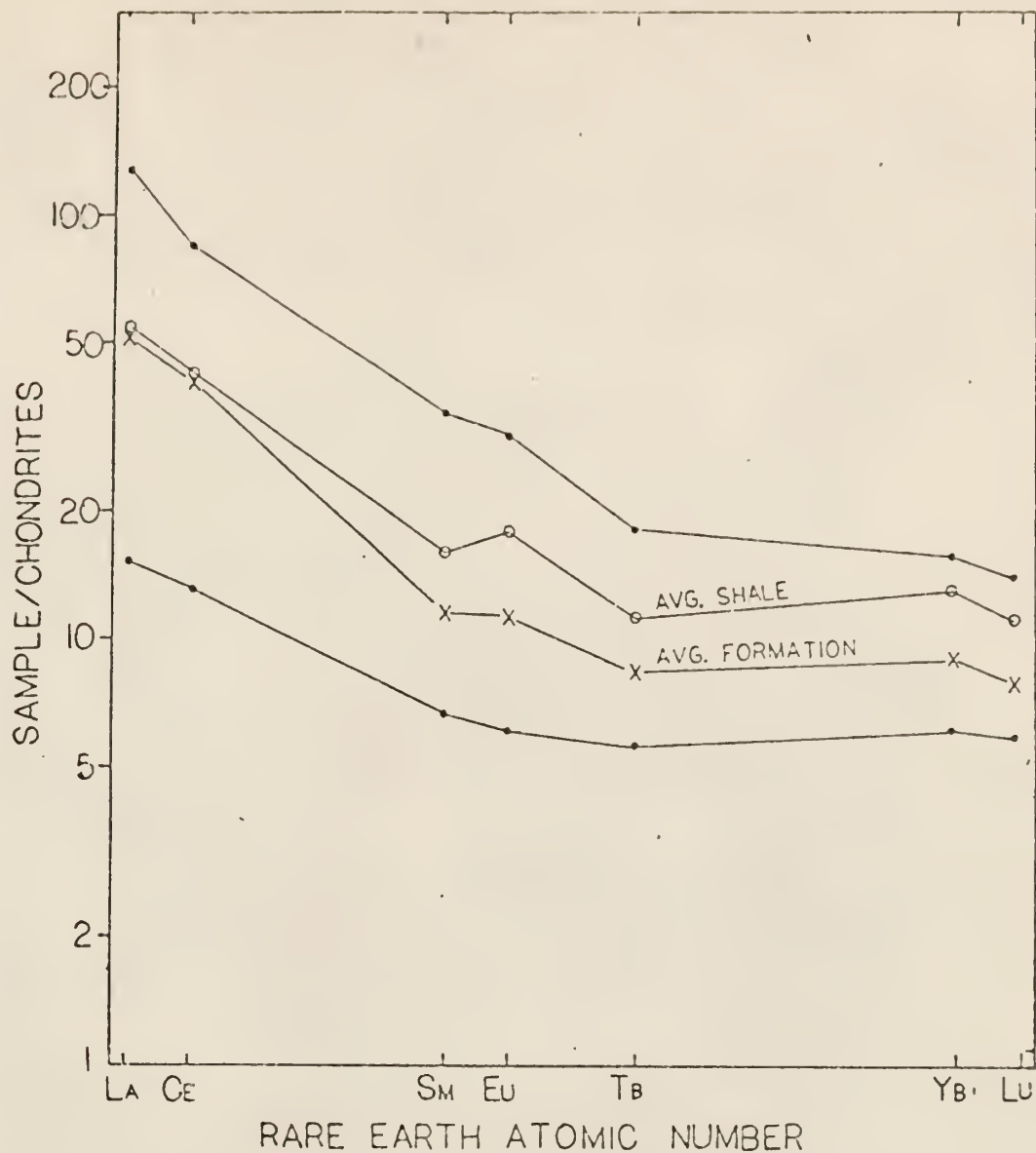
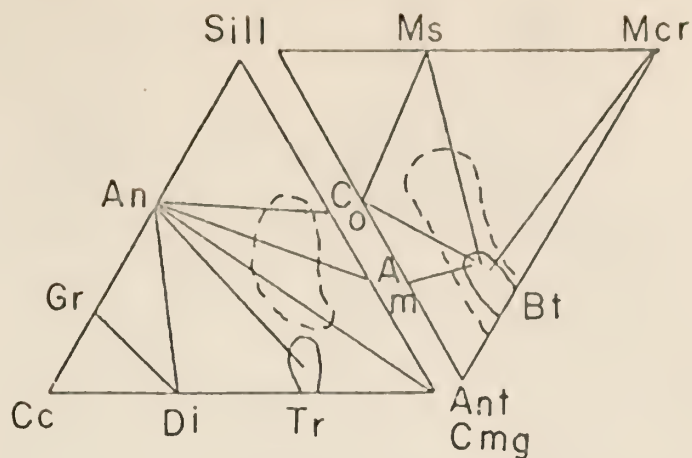


Figure 11. Chondrite normalized REE plots of Precambrian sedimentary rocks, after Wildeman and Haskin (1973), and Wildeman and Condie (1973). The plot shows the upper and lower ranges of Precambrian sedimentary rocks (•), the average Precambrian shale (o), and the average Precambrian formation (x).

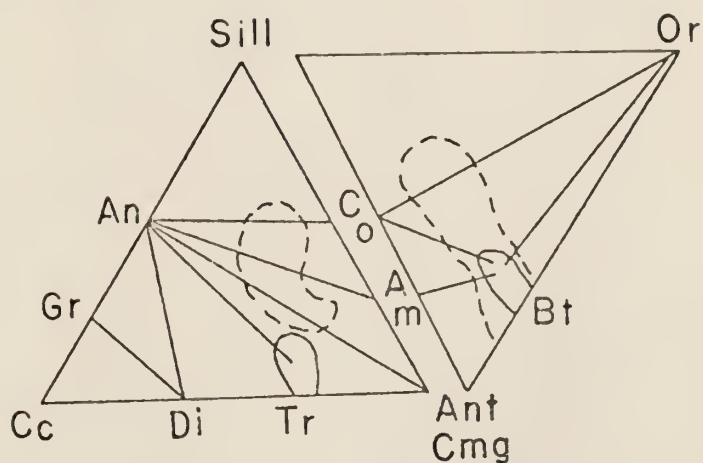
pyroxene, olivine, and garnet. The source approximated for the St. Francis Mountains (Table 6) is intermediate in composition, consistent with the Sr isotopic data, and consistent with observed Precambrian crustal mineralogy and trace element contents.

The metamorphic rock facies corresponding to this type of mineralogy is in Figure 12, after Winkler (1965). This figure shows two subfacies of the cordierite-amphibolite regional metamorphic facies, and the stability regions within the subfacies. Figure 12a contains muscovite, which, with increasing temperature reacts with quartz and biotite to form orthoclase, cordierite, and sillimanite, and produces the subfacies shown in Figure 12b. Figure 12b represents the highest grade of regional metamorphism at moderate pressures, which may contain pegmatites, according to Winkler (1965), and probably represents the metamorphic rocks which exist prior to crustal fusion.

Also in Figure 12 are the regions where graywackes plot within the subfacies, suggesting possible source mineralogy which could form a granitic melt upon fusion. The minerals which are apparently stable in these regions are sillimanite, orthoclase, biotite, hornblende, garnet, cordierite, and anorthite, in similar ratios shown in Table 6. As will be discussed later, the presence and approximate amount of each mineral in the source can be better estimated from analyses of the REE data.



A. Sillimanite-Cordierite-Muscovite-Almadine Subfacies



B. Sillimanite-Cordierite-Orthoclase-Almadine Subfacies

Figure 12. Regional Cordierite-Amphibolite metamorphic subfacies, after Winkler (1965). Am=almadine, An=anorthite, Ant=anthophyllite, Bt=biotite, Cc=calcite (wolastonite), Cmg=cumingtonite, Di=diopside, Gr=grossularite, Mcr=microcline, Ms=muscovite, Or=orthoclase, Sill=sillimanite, Tr=tremolite, ----- =field of graywackes.

Estimation of Intensive Parameters

The quartz, albite, orthoclase, and anorthite norms were recalculated to 100 percent for plotting on the Qz-Ab-Or and An-Ab-Or ternary diagrams. The Qz-Ab-Or-An-H₂O system approximates the SiO₂-NaAlSi₃O₈-CaAl₂Si₂O₈-H₂O system which has been studied extensively in the past twenty years by Tuttle and Bowen (1958), Winkler, et al, (1960, 1961, 1972, 1973, 1975), Shaw (1963), von Platen (1965), von Platen and Holler (1966), Luth, et al (1964), Luth and Tuttle (1969), Luth (1969), James and Hamilton (1969), Piwinsky and Wyllie (1970), Brown and Fyfe (1970), Presnall and Bateman (1973), Winkler (1976), and others.

As a result of these experimental studies, this system may be used to estimate intensive parameters associated with the formation of granitic rocks. Most experimental systems were conducted under water-saturated conditions, so estimates of temperatures during fusion assume that the natural systems are at or near water saturation. The melting relationships of granitic systems under different water saturation conditions is in Figure 13. Curve number one is the solidus of a water-saturated granite and, as a result of the water saturation, has the lowest melting temperatures. Curve two is of a dry biotite granite, and curve three is of a granite with four percent water available. Biotite is an important contributor to lowering melting temperatures of granitic systems due to the presence of OH in the structure. Metamorphic terrains usually do not exceed temperatures of about 800 degrees Centigrade (Winkler, 1976), so there must be at least four percent H₂O available, or biotite present in order for granites to be formed by melting (Fig. 13).

Figure 13. Temperature versus pressure diagram showing various solidus and liquidus relations in granitic rocks, from Winkler (1974). (1) = solidus in system Qz-Ab-Or if water present; (2) = solidus of dry biotite granite; (3) = liquidus if 4% H₂O available; (4) = liquidus if 2% H₂O available; (5) = solidus of dry Qz-Ab-Or system, no OH minerals available.

Figure 14. Isobaric tetrahedral Qz-Ab-Or-An-H₂O system at 5 kb H₂O pressure, perspective view, from Winkler, et al (1975). The shaded areas represent cotectic surfaces separating fields within the tetrahedron: (A) = liquid + plagioclase + quartz + vapor; (B) = liquid + plagioclase + alkali feldspar + vapor; (C) = liquid + alkali feldspar + quartz + vapor. P represents the intersection of the ternary eutectics with the cotectic surfaces, and the line P-E₅ is where all five phases are in equilibrium at any given temperature.

FIGURE 13

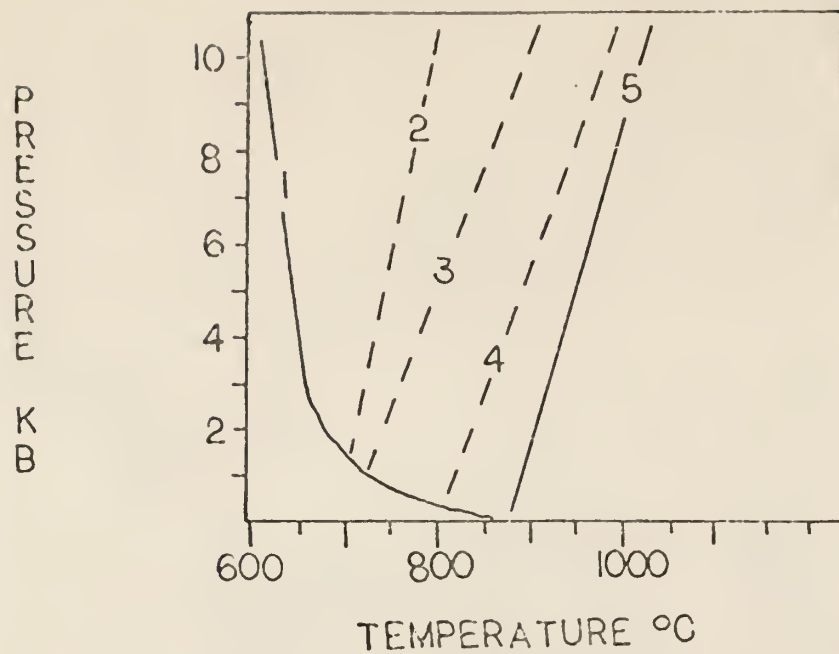
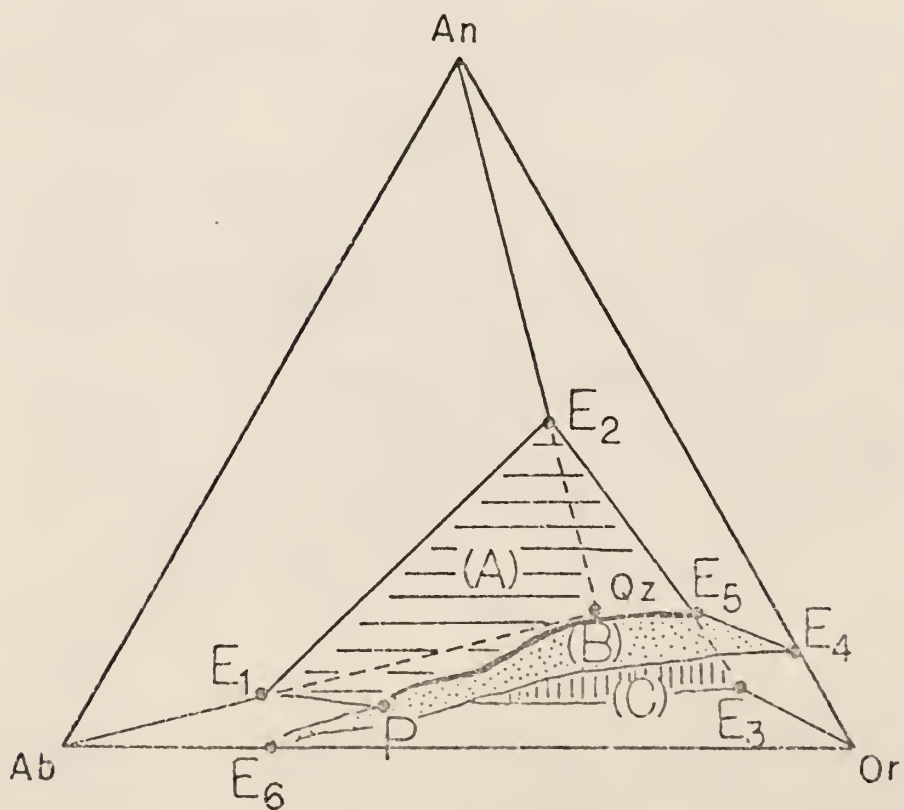


FIGURE 14



The Qz-Ab-Or-An-H₂O tetrahedron is in Figure 14. This diagram was drawn from data from the four ternary systems at saturated-water pressure of 5 kilobars (kb). Experiments have shown that in the Qz-Ab-Or system, the base of the tetrahedron, the first melt will form at the composition of point P. If higher pressures are experienced, the point P in the three component system, and the P-E₅ line in the four component system, moves toward the Ab end of the diagram, and vice versa. A water-saturated Qz-Ab-Or system at 5 kb will form a melt first at about 650°C at a composition close to point P (Figs. 13, 14). A rise in temperature will cause increased melting in the four component system, and the melt composition will move along the cotectic line P-E₅ until one of the phases in the source disappears. At that time, the melt composition will leave the P-E₅ line and enter one of the three cotectic surfaces and proceed in a direction away from the component which is not present in the source.

The norms for the Musco Group, and the Butler Hill Granite, which is assumed to represent the Bevos Group parent magma, are plotted in Figure 15. This diagram is superimposed with data on total pressure and Ab-An ratios of the source, as summarized by Anderson and Cullers (1978) from data taken from James and Hamilton (1969), von Platen (1965), Winkler and von Platen (1958, 1959, 1961), von Platen and Holler (1966), and Brown and Fyfe (1970). This simplified plot illustrates two principles derived from the experimental work. One, as the anorthite component of the source increases, the minimum melt composition moves away from the albite end of the diagram; and two, as the pressure of the melting increases, the composition of the minimum melt

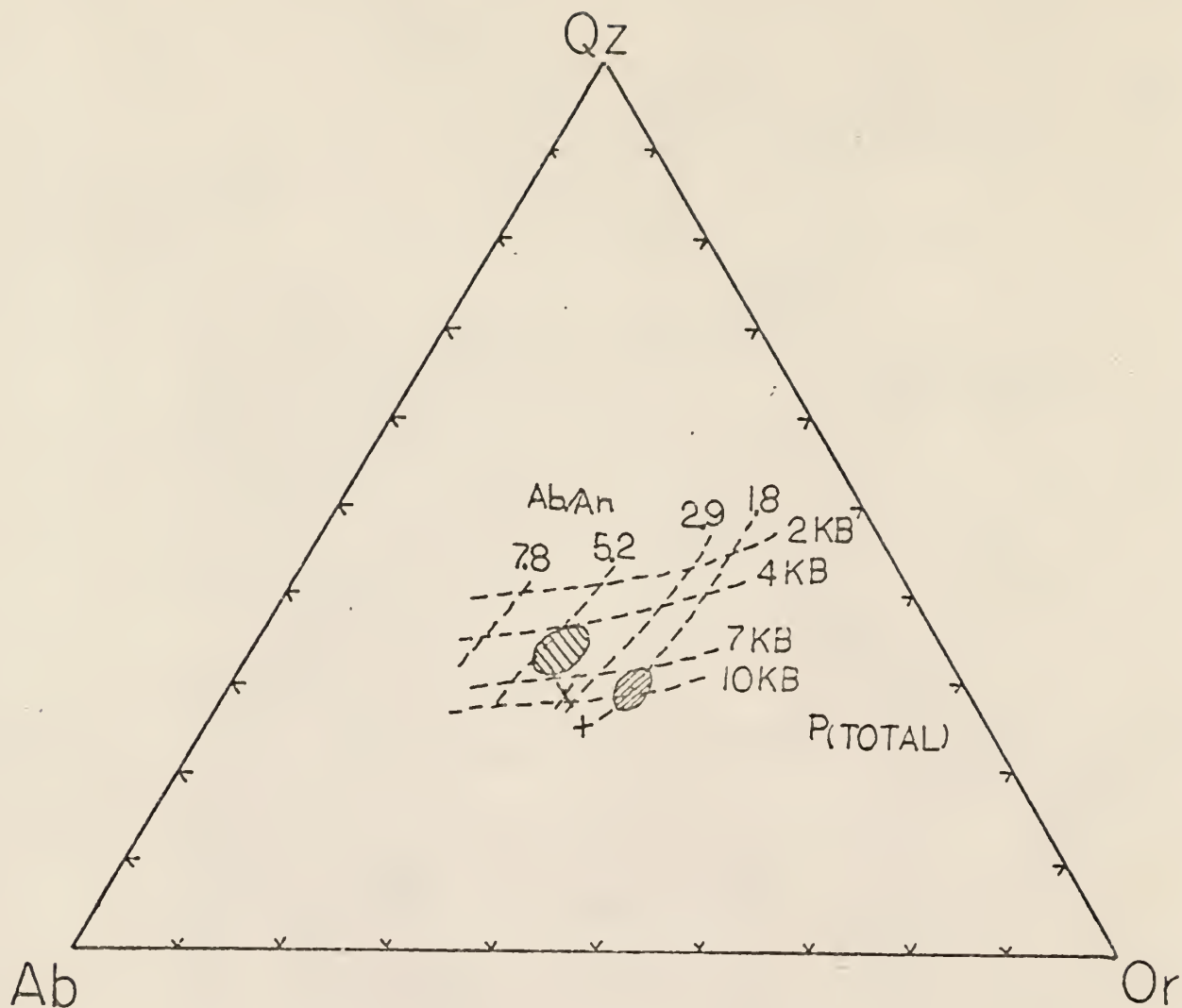


Figure 15. Qz-Ab-Or ternary diagram showing comparison of the St. Francois Mountain granites with experimental work in the granite system. The source rock albite/anorthite ratio data and the total pressure data are from Anderson (1975). The Butler Hill Granite (hatched circle) represents the Bevos Group; and the Munger Granite (hatched circle), Carver Creek Granite (X), and Buford Granite (+) represent the Musco Group.

moves toward the albite and orthoclase end of the diagram. The data from the St. Francois Mountain granites suggest that the Bevos Group was formed from a source containing an Ab/An ratio of about 4 to 5, and between 4 to 7 kb total pressure. The Musco Group clusters in the region shown experimentally to form at 7 to 10 kb total pressure, and from a source with an Ab/An ratio of about 2. This means that the Musco Group apparently formed at slightly higher pressure, and from a slightly more mafic source than did the Bevos Group.

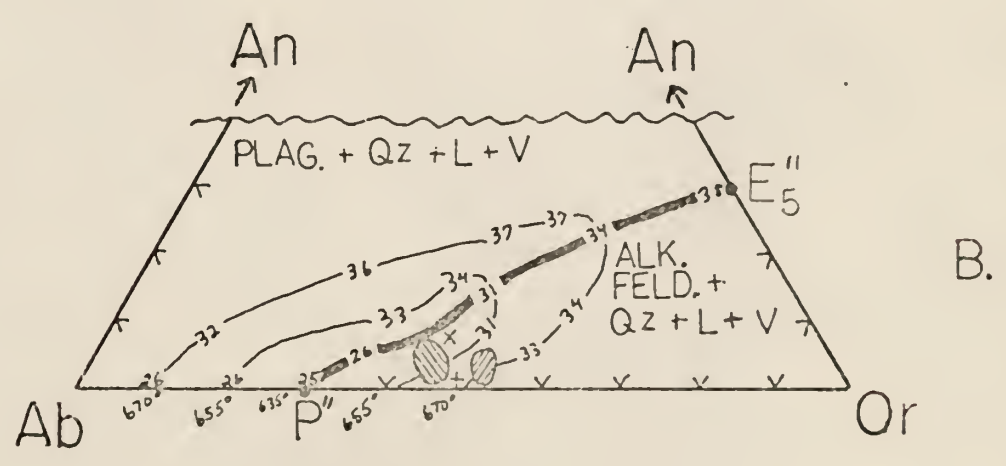
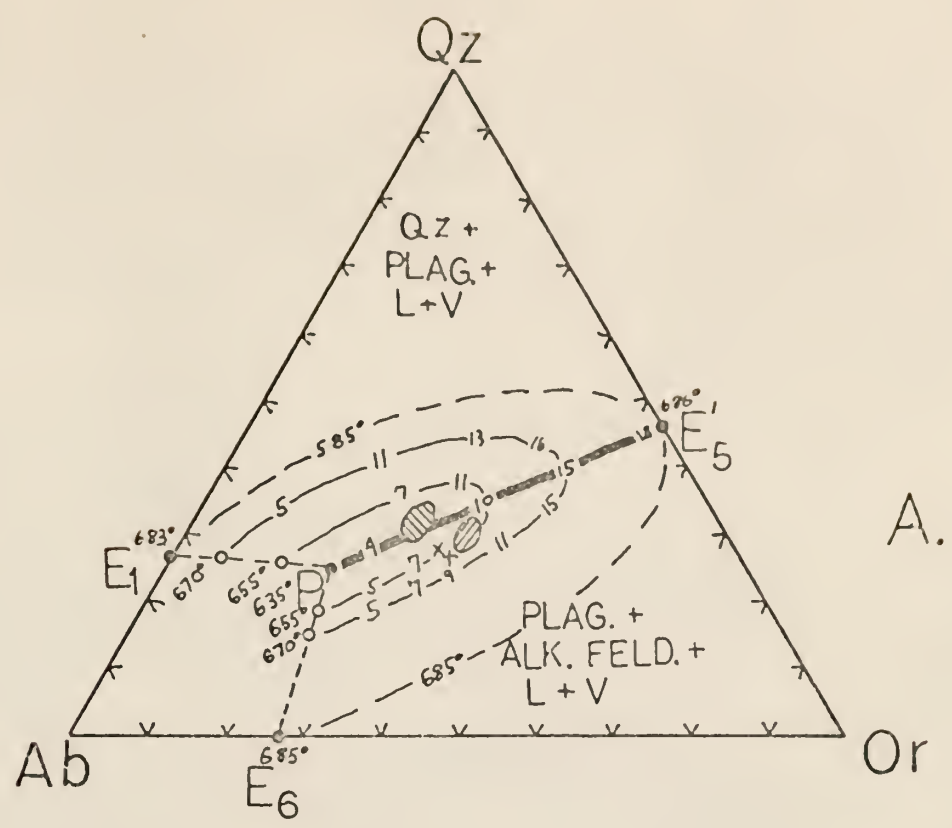
Furthermore, the norms for the Butler Hill Granite and the Musco Group were plotted on Qz-Ab-Or and An-Ab-Or ternary diagrams (Fig. 16). These diagrams were taken from Winkler (1976, p. 299) and are two-dimensional projections of the Qz-Ab-Or-An tetrahedron (Fig. 14) onto a given face. The perspective for Figure 16a is looking downward onto the tetrahedron and shows the projection of the experimentally determined isotherms on the cotectic planes which separate the fields within the tetrahedron as dashed lines. The numbers between the dashed lines represent the anorthite value at that point on the three-dimensional planes within the tetrahedron.

The perspective for Figure 16b is from the front of the tetrahedron and shows projections of the cotectic surface isotherms onto the front surface. The numbers between the dashed lines represent the quartz value at that point on the three-dimensional surface within the tetrahedron, as before with the anorthite values. Using the two diagrams, one can represent and visualize any point within the tetrahedron.

The isotherms drawn on these cotectic surfaces are the result

Figure 16A. Projection of cotectic line P-E₅ and of the two cotectic surfaces plagioclase + alkali feldspar + liquid + vapor, and quartz + plagioclase + liquid + vapor from the An apex onto the side Qz-Ab-Or. The numbers on the projected isotherms indicate anorthite content of a specific melt. The diagram, from Winkler, et al (1975, p. 254) is for water saturated systems at 7 kb. The Butler Hill Granite (⊗) represents the Bevos Group; and the Munger Granite (⊙), Carver Creek Granite (X), and Buford Granite (+) represent the Musco Group.

Figure 16B. Projection of cotectic line P-E₅ and of the two cotectic surfaces alkali feldspar + quartz + liquid + vapor, and plagioclase + quartz + liquid + vapor from the Qz apex onto the side An-Ab-Or. The numbers indicate quartz content of a melt composition. The diagram, from Winkler, et al (1975, p. 255) is for water saturated systems at 7 kb. The symbols are the same as in Figure 16A.



$P(H_2O) = 7KB$

of many years of research dealing with melting of experimental systems of different compositions and under different pressures. The diagrams are for water-saturated systems at 7 kb pressure, which most closely approximates the St. Francois Mountain system, as derived from Figure 15. The P-E₅ line is the path that melt compositions follow during progressive melting when in equilibrium with all components. For example, a system containing quartz, plagioclase, and feldspar, but no anorthite, will first melt at 635°C with the composition of point P (Fig. 16), unlike the same system at 5 kb pressure previously mentioned which melts first at about 650°C. A system with 10 percent anorthite will melt first at 655°C and have a composition on the line between P and E₅. Similarly, a heterogenous system may melt first at 635°C and have a first melt composition at P, but with progressive melting of the more refractory minerals (anorthite), the melt composition will move along the P-E₅ line toward E₅.

Similarly, melts can be analyzed and their normative composition calculated and plotted on these experimental diagrams to determine conditions of melting (Winkler and Lindemann, 1972; Winkler, et al, 1975). This has been done successfully with granitic systems (Anderson, 1975) to determine possible temperatures of magma formation, assuming at least near water-saturation. The St. Francois Mountain normative minerals for the different groups are plotted in Figure 16. The Bevos Group, represented by the Butler Hill Granite, melted from about 640 to 660°C; whereas the granites of the Musco Group melted from about 650 to 670°C. If the natural system which formed the St. Francois Mountains granite was not at complete water saturation, one may infer

slightly higher temperatures of formation, probably 20 to 50°C higher. But still, the intensive parameters suggest that the Bevos Group formed at lower temperatures and pressures, and from a more felsic source than the Musco Group.

Formation of the Parent Magma of the Bevos Group

The possible source rock mineralogy and the temperatures and pressures which prevailed during the formation of the primary magmas have been estimated based on the Sr isotopic data and evaluation of the major element chemistry (normative minerals). In conjunction with these estimates, further evaluation of the Ba and REE data can be used to qualitatively derive fusion models for the formation of the granitic magmas. The model obtained here suggests that the parent magma of the Bevos Group could have formed by 10 to 20 percent melting in the lower crust of a source containing quartz, plagioclase, K-feldspar, biotite, and hornblende.

Melting models derived by Gast (1968) and refined by Shaw (1970) were used for modeling. Shaw's aggregate melt model which assumes that each new portion of liquid formed is constantly mixed with preceding liquids was used for the modeling. The basic aggregate model equation is in (1).

$$\frac{\bar{c}^1}{c_0} = \frac{1 - (1 - F)^{1/D_0}}{F} \quad (1)$$

where \bar{c}^1 = concentration of the trace element in the melt
 c_0 = concentration of the trace element in the source
 F = fraction (percent) melted
 D_0 = bulk distribution coefficient
 = $\sum D \cdot X$, where
 D = percentage of each mineral in the source
 X = distribution coefficient (Appendix VI)

This basic aggregate equation assumes modal melting of the source, that is, that the minerals in the source melt in propor-

tions equal to their modal abundances. Because experimental work has shown that this is not always true, a variation of the aggregate model, that of non-modal melting was used (2).

$$\frac{\bar{c}_1}{c_0} = \frac{1 - (1 - P \cdot F / D_0)^{1/F}}{F} \quad (2)$$

where \bar{c}_1 , c_0 , D_0 , F , and D are the same as in (1)
 P = bulk distribution coefficient based in the percentages of the minerals melting
 $= \sum D \cdot X_I$, where
 X_I = the percentages of each mineral melting.

The major difference in the non-modal melting model relative to the modal model is, for example, in the melting of biotite. Biotite may constitute 40 percent of the source rock, but only about 5 percent of the minerals melting at a given temperature may be biotite, so this is taken into account with the non-modal melting model.

The Butler Hill Granite was assumed to represent the parent magma type of the Bevos Group. The source mineralogy and trace element contents used in the modeling were consistent with the Sr isotopes and the data in Table 6, Figure 11, and Appendix VI. The distribution coefficients (Appendix VI) indicate that quartz rejects all REE and Ba, plagioclase concentrates Eu, K-feldspar concentrates Eu and Ba, biotite concentrates only Ba, and hornblende concentrates the intermediate and heavy REE. By adjusting the source material mineral percentages and the melting percentages in the models, with the trial and error method, theoretical melting models were obtained which were compared to the observed REE and Ba values in the rocks.

The model which best fits the trace element distributions of the Butler Hill Granite was obtained by using a source con-

taining about 20 percent quartz, 34 percent plagioclase, 20 percent K-feldspar, 25 percent biotite, and 1 percent hornblende. The percentages of mineral melting were approximated from the Qz-Ab-Or ternary plot for the Butler Hill Granite (Fig. 16), based on the estimated intensive parameters, and were about 30 percent quartz, 35 percent plagioclase, 30 percent K-feldspar, and 5 percent biotite. Varying the melting ratios of the source had a lesser effect on the trace element compositions of the liquid than did varying the mineral ratios of the source.

The theoretical melt models that produced trace element compositions which closely matched those of the Butler Hill Granite are in Figure 17. These models assume 10, 15, and 20 percent melting of the proposed source material with a REE composition similar to the average Precambrian sedimentary formation (Figs. 11, 17; Appendix VI). The chondrite normalized REE compositions of the different theoretical melts are in Figure 17 and are compared to the range of values obtained for the Butler Hill Granite (dashed lines). Ba was also modeled based on source rock compositions ranging from 800 to 1200 ppm, after McCarthy (1976).

The 10, 15, and 20 percent melt models closely approximate the trace element composition of the Butler Hill Granite, but do not preclude slight variations in the modeling. For example, if the average REE compositions of Precambrian shales (Fig. 11, Appendix VI) are used in conjunction with slightly more hornblende (about 2 percent) in the source rock, and similar melting percentages, a fairly good fit with the trace element compositions of the Butler Hill Granite is obtained. Also, up to about 10

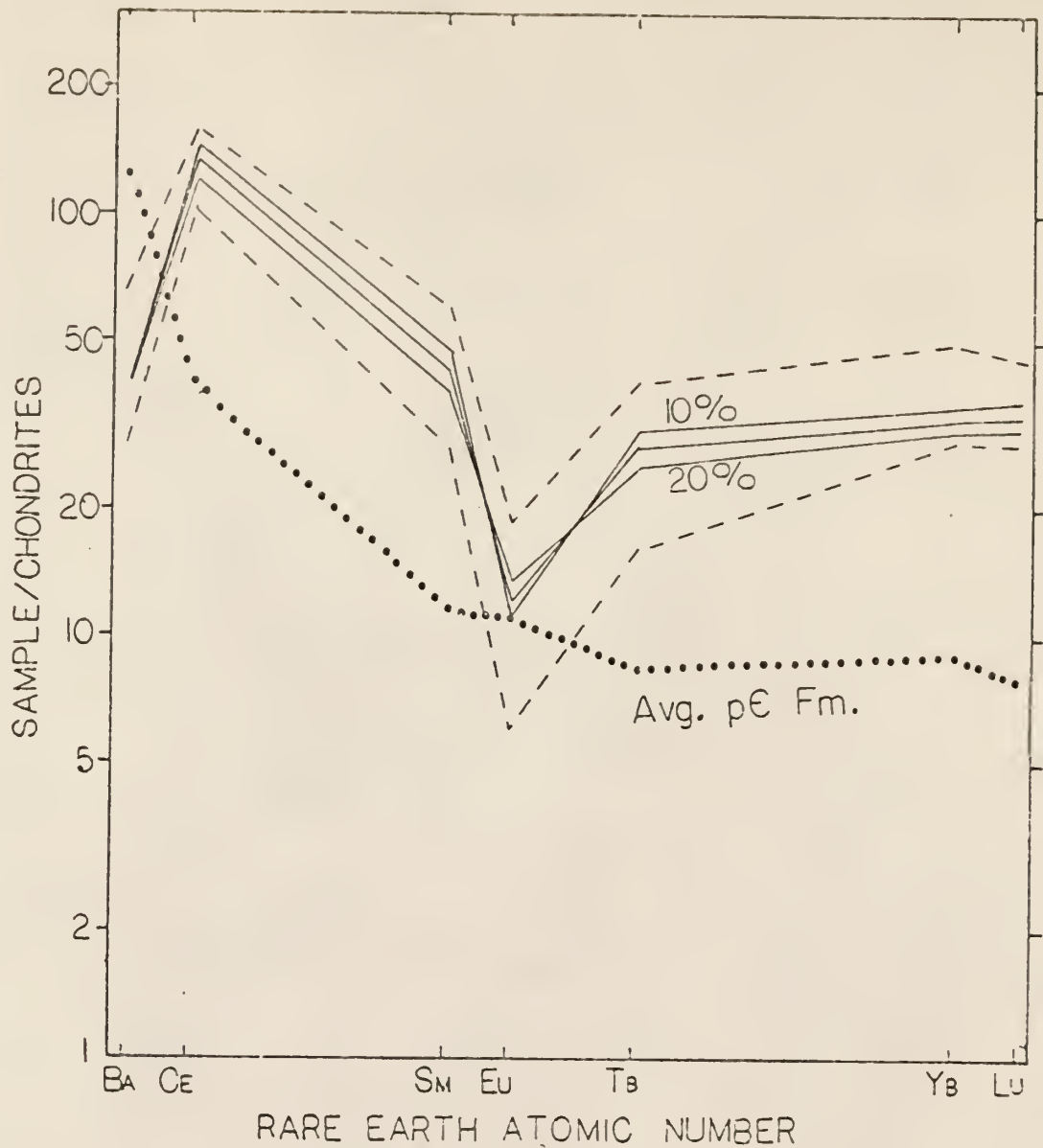


Figure 17. Theoretical Ba and REE distributions compared to the observed ranges in the Butler Hill Granite. The plotted Ba values are one-tenth of actual values. Dashed lines represent the upper and lower limits of the Ba and REE values of the Butler Hill Granite, from Figure 10 and Appendix V. Solid lines represent the Ba and REE values obtained with 10, 15, and 20 percent fusion of a source with REE values of the average Precambrian Formation (dotted line), from Figure 11 and Appendix VI. The models assumed source mineralogy of 20 percent quartz, 34 percent plagioclase, 20 percent K-feldspar, 25 percent biotite, and 1 percent hornblende; and the mineral melting ratios were 30 percent quartz, 35 percent plagioclase, 30 percent K-feldspar, and 5 percent biotite. See text for discussion.

percent pyroxene could be present in the source without appreciably changing the model results. It must be assumed that these variations surely occur in nature and only approximations for the formation of the granitic melts can be postulated based on the available data.

The trial and error method showed that garnet could not have been present in the source, as it lowered the heavy REE contents in the theoretical melts too much. This is important when estimating the composition of the source rock (Fig. 12). Evidently, the source rock cannot plot in the stability field of garnet, although the source is still compatible with the other metamorphic fields. Distribution coefficients for cordierite are not available, so that mineral could not be considered in the quantitative modeling, although it could theoretically still be present in the metamorphic source rock.

The major element characteristics of the parent magma of the Bevos Group cannot be fully analyzed in respect to the proposed fusion model at this time. Experimental petrology has shown, though, that granites similar in composition to those observed can be produced by melting of metamorphic rocks, as discussed previously. Further analyses of major element behavior during fusion will be discussed in the next section.

In summary, the model concerning the formation of the parent magma of the Bevos Group suggests that the magma apparently formed about 1500 million years ago and at about 640 to 660°C, and from 4 to 7 kb pressure. These pressures and temperatures correspond to depths of 15 to 25 Km within the earth, which would be in the lower crust (Kyllie, 1971). The source rock was intermediate

in composition and probably in the sillimanite-cordierite-orthoclase-biotite subfacies (excluding garnet) of the regionally metamorphic cordierite-amphibolite facies. The trace element data, based on theoretical melt models, suggest that the magma could have been formed by 10 to 20 percent melting of a heterogeneous source.

Formation of the Parent Magmas of the Musco Group

The chemical data suggest that the Musco Group cannot be associated with the differentiation of the Bevos Group. The data show that the Musco Group is higher in plagioclase and the ferromagnesian minerals, Al, Ba, Eu/Sm, and Fe/Mg; lower in K-feldspar, and similar in Ca/Na, Rb, and Sr contents than the Butler Hill Granite. Also, estimates of intensive parameters have shown the Musco Group formed from a source of lower Al/An ratios, and higher temperatures and pressures than did the Bevos Group. The U-Pb age dates indicate that the Musco Group formed about 1400 million years ago, about 100 million years later than the Bevos Group. Not only do these data suggest that the Musco Group doesn't fit into the Bevos Group differentiation series, but that the Musco Group apparently formed after the Bevos Group and at different depths in the crust and from a slightly different source composition.

Two possibilities exist for the formation of the Musco Group in relation to the Bevos Group. One, that the Musco Group formed as a product of progressive fusion of the source that formed the Bevos Group; or two, that the Musco Group formed independently from the Bevos Group and from a similar, but different source.

These possibilities can be analyzed further in the light of experimental data in respect to progressive fusion presented by Gast (1968), Anderson (1975), and McCarthy (1976). Theoretically, progressive fusion of a plagioclase-biotite bearing amphibolite (the proposed source of the Bevos Group) causes progressively increasing concentration in the melt of Al, Ca, Mg, Ba, Rb, Sr, and Eu because the bulk distribution coefficients for these elements in this source is greater than one (Anderson, 1975). Of these elements, only Ba and Eu, and to a certain extent, Al are higher in the Musco Group than in the Bevos Group (Figs. 8, 10), whereas the other elements mentioned show no significant differences between the groups. The observed trends tend to refute the progressive fusion possibility, and, along with the age and intensive parameter estimates, suggest that a separate fusion event is the most likely possibility.

This possibility was tested using the melt model equations (2) on the Ba and REE data similar to the method previously described. The mineralogy of the source selected was slightly more mafic (i.e. more biotite, less quartz and K-feldspar) than the mineralogy used in the Bevos Group modeling, in order to be consistent with the estimates of the Ab/An ratios (Fig. 15). A major problem arose when trying to produce Ba and Eu contents in the theoretical melts similar to those observed in the Musco Group. Different mineralogy and melting ratios of the source were tested in equation (2), but by staying within the limits of the source composition set by the Sr isotopes (Table 6), the high Ba and Eu contents observed in the Musco Group were initially impossible to derive in the theoretical melts.

Further investigation showed that K-feldspar is the only mineral in the source which concentrates both Ba and Eu (Appendix VI). Theoretically, if during fusion, the source melted to such an extent that all K-feldspar melted, then both Ba and Eu, which had previously been retained in the K-feldspar would be released into the melt; or there was no K-feldspar in the source to begin with.

In order to best include these possibilities in the theoretical modeling, new equations derived by Hertogen and Gijbels (1976) were implemented. They refined Shaw's (1970) aggregate melt model by taking into account the disappearance of one or more of the components from the source due to complete melting. Equation (3) is the formula derived by Hertogen and Gijbels for this type of melting.

$$\frac{\bar{c}_1}{c_0} = \frac{1 - M_A \left(\frac{1 - F}{1 - F_A} \right)^{1/P_{II}}}{F} \quad (3)$$

where \bar{c}_1 , c_0 , F , and D are the same as in Equation (1)

F_A = the degree melted at the time of the disappearance of the first component due to the melting

P_{II} = the bulk distribution coefficient based on the melting percentages during the second stage of melting

= $\Sigma D \cdot X_{II}$, where X_{II} is the percentages of the minerals melting during the second stage of melting

$M_A = 1 - (\bar{c}_1/c_0) \cdot F_A$ (from Equation 2).

Equation (2) is also used in this calculation for determination of the variable M_A (3) because the trace element concentrations of the melt are assumed to be the same for both models until the degree of melting (F_A) is reached when one of the components in the source is gone. Infinite melting model variations are possible with this modeling as the source mineralogy must be

selected, as well as the ratios of minerals melting during the first stage of fusion, and also the melting ratios during the second stage of fusion (i.e. after the component has all melted).

K-feldspar was selected as the mineral to melt completely because of the high Ba and Eu distributions in the Musco Group, and also because of the low K-feldspar content in the group (Table 1). This is also consistent with experimental melting of various sedimentary rocks reported by Winkler (1976) which indicated that K-feldspar was usually the first mineral to disappear from the source due to melting. The point when K-feldspar disappeared from the source (F_A) was arbitrarily selected to be 15 percent of melting, and the first stage mineral melting ratios were assumed to be similar to the position of the Musco Group samples on the Qz-Ab-Or plot (Fig. 16), which are 28 percent quartz, 32 percent plagioclase, 35 percent K-feldspar, and 5 percent biotite. The modelling for the formation of the parent magma of the Musco Group using Equation 3 improved the results obtained for the Ba and Eu contents in the theoretical melts. Slightly different models were obtained which fit the different trace element compositions of the Musco Group granite, and the model variations are described below.

The Carver Creek and Buford granites contain higher Eu and heavy REE contents than the Munger Granite, and the trace element distributions of these units were most closely approximated when using a source containing about 20 percent quartz, 10 percent plagioclase, 10 percent K-feldspar, and up to 45 percent biotite. Up to 15 percent pyroxene can also fit into the source rock mineralogy without changing the trace element distributions of

the melts appreciably. A source of this type is consistent with the Sr isotopes, and prior to melting could be in the cordierite-biotite-amphibolite facies of regional metamorphism (Fig. 12). The melting ratios of the second stage used in the modeling were arbitrarily selected as 49 percent quartz, 49 percent plagioclase, and 2 percent biotite. Again, some of the pyroxenes could substitute for either quartz or biotite as they have similar distribution coefficients (Arth and Hanson, 1975).

Figure 18 shows the comparison of the observed REE values for the Carver Creek and Buford granites with the theoretical models produced by 20 and 30 percent fusion. The average REE distribution of Precambrian shales was approximated for the source rock and was found to produce melts which most nearly fit the actual REE distributions of the Carver Creek and Buford granites. The models produced Ba contents ranging from 1200 ppm for 20 percent fusion to 1800 ppm for 30 percent fusion based on source rock values ranging from 800 to 1200 ppm Ba, after McCarthy (1976). The obtained values are comparable with Ba concentrations contained in the Carver Creek Granite, but are slightly low for the Buford Granite (Appendix VI).

The Munger Granite contains lower intermediate and heavy REE contents than the Carver Creek and Buford granites which suggests minerals that concentrate these elements, like hornblende or garnet in the residual source material. This unit was modeled similar to the rest of the Musco Group, and required the complete melting of K-feldspar at the arbitrarily selected point of 15 percent fusion, and the initial mineral melting proportions used in the modeling were the same.

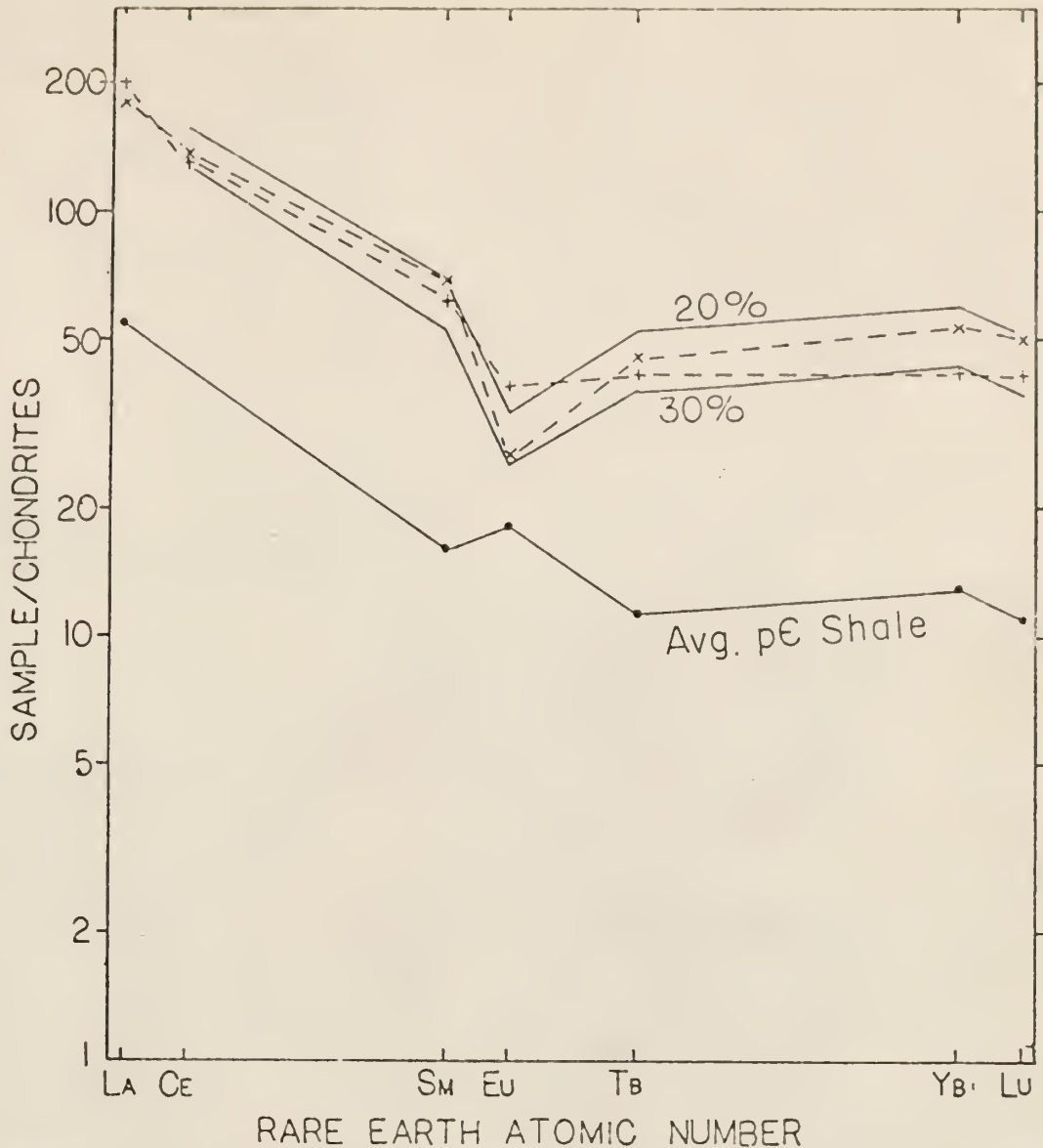


Figure 18. Comparison of REE distributions of the theoretical melt models to the observed REE distributions of the Carver Creek and Buford Granites. Lower solid line (•) represents the average REE distribution of Precambrian shales. Dashed lines represent the REE distributions of the Carver Creek (x) and Buford (+) granites. Other solid lines represent 20 and 30 percent fusion of a source with mineralogy of 20 percent quartz, 10 percent plagioclase, 10 percent K-feldspar, and up to 45 percent biotite. The first stage melting proportions were 28 percent quartz, 32 percent plagioclase, 36 percent K-feldspar, and 5 percent biotite. The second stage melting proportions were 49 percent quartz, 49 percent plagioclase, and 2 percent biotite. See text for discussion.

The source rock which was used to model the Munger Granite was also similar to the source considered for the other Musco Group granites, but required 2 to 4 percent hornblende and possibly up to 1 percent garnet to lower the heavy REE content in the melts. The melting proportions of the second stage were changed to include these minerals and were arbitrarily selected as 49 percent quartz, 49 percent plagioclase, 1 percent biotite, and 1 percent garnet and/or hornblende. Figure 19 compares results of the two different melting models with the observed ranges in the Munger Granite. One model considered 35 percent fusion of a source containing 2 percent hornblende, and the other model represents 30 and 40 percent fusion of a source containing 1 percent garnet. These two models are in Figure 19 and illustrate the differences obtained in the melts when different mineralogy and melting proportions are used for the modeling. When these two models are combined, assuming that the source contains both hornblende and garnet, nearly the same REE distributions as contained in the Munger Granite are produced, when using the average REE distributions of Precambrian shales to approximate the source rock values. Barium values were also calculated and produced melts containing from 1300 to 1800 ppm Ba, exactly within the range contained in the Munger Granite.

As before, these models can include variations in melting proportions and trace element distributions of the source rock and mineral contents, but still provide a good approximation for the formation of the granitic melts which formed these granites. The source material which formed the Munger Granite is the only one found so far in the St. Francois Mountains which could include

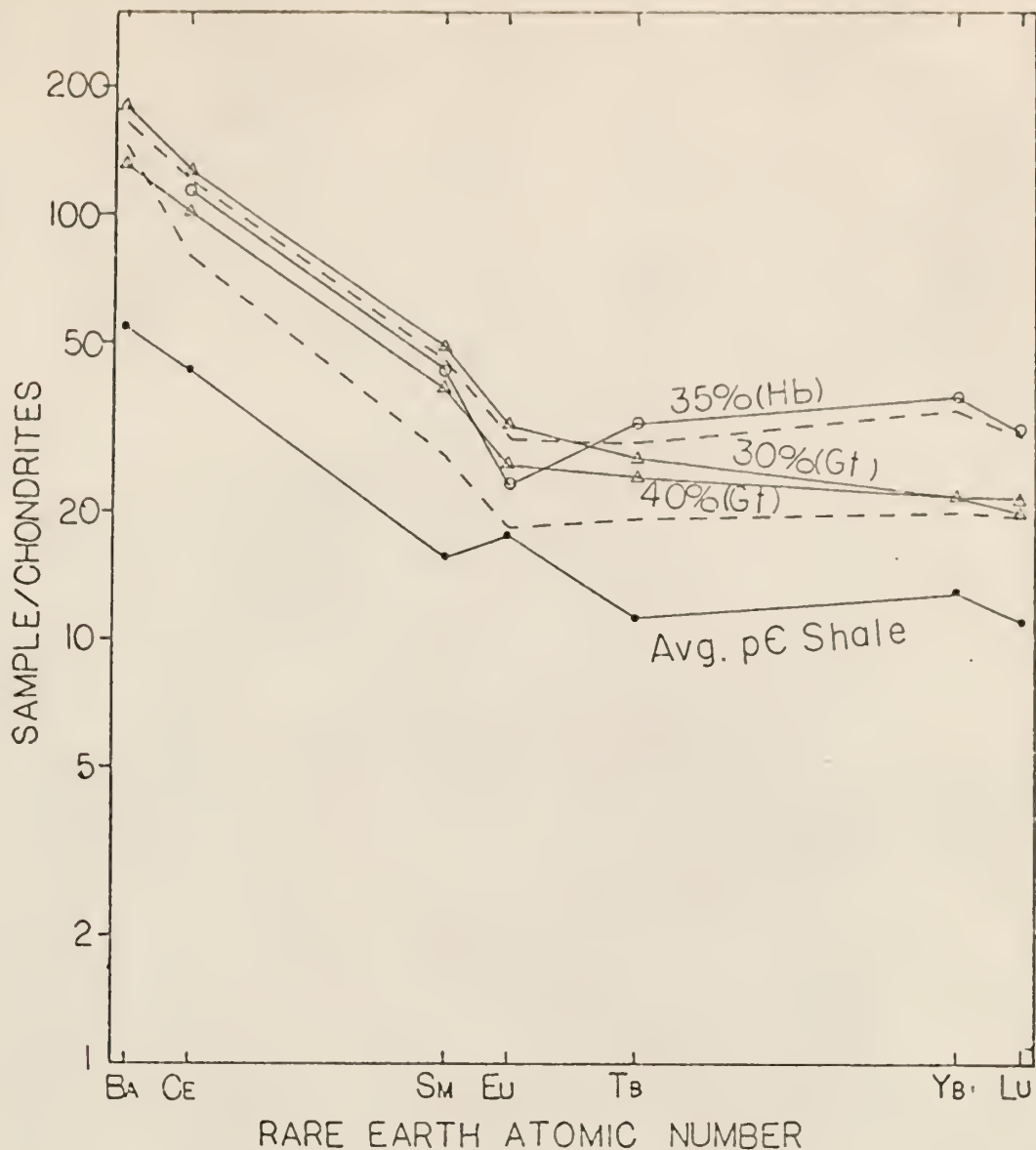


Figure 19. Comparison of Ba and REE distributions of the theoretical melt models to the observed ranges in the Munger Granite. Barium values are one-tenth of actual values. The lowest solid line (•) represents the REE distribution of Precambrian shales. Dashed lines represent the upper and lower ranges of the Munger Granite REE distributions. The two theoretical distributions (Δ) represent 30 and 40 percent fusion of a source containing 1 percent garnet (Gt). The best fit model for the Munger Granite includes both hornblende and garnet in the residual source rock. The initial source mineralogy was 20 percent quartz, 10 percent plagioclase, 10 percent K-feldspar, and up to 45 percent biotite, with 2 to 4 percent hornblende and up to 1 percent garnet. The melting ratios of the first stage were 28 percent quartz, 32 percent plagioclase, 36 percent K-feldspar, and 5 percent biotite. See text for discussion.

some garnet, and therefore being in or near the stability region of garnet in Figure 12. This further helps to place limits on the possible compositions of the source rock. Garnet is stable only at higher pressures, consistent with depth and pressure estimates for the Musco Group, previously discussed.

In summarizing the theoretical models derived for the formation of the Musco Group, the Carver Creek and Buford granites apparently formed by 20 to 30 percent melting of a metamorphic source containing residual quartz, plagioclase, biotite, and possibly some pyroxene, but no K-feldspar. The Munger Granite suggests 30 to 40 percent fusion of a similar source but including some residual hornblende and garnet. Possibly the Musco Group represents progressive fusion of the same source, with the greater amount of melting involving the more refractory minerals (hornblende and garnet) and producing the Munger Granite.

The Musco Group formed at about 650 to 670°C (assuming near water saturation) and at pressures of 7 to 10 kb. These pressures are present at depths of 20 to 30 Km, suggesting that melting occurred in the lower crust (Wyllie, 1971). Also, the Musco Group apparently formed after the Bevos Group and from a slightly more mafic source which could have been the cause of the higher melting temperatures.

CONCLUSIONS AND TECTONIC IMPLICATIONS

The chemical, petrographic, and isotopic data obtained in this and other studies reveal the petrogenetic history of the St. Francois Mountains. The data show two groups of granites with different modes of formation. The Bevos Group was formed first, about 1500 million years ago, by 10 to 20 percent melting in the lower crust of a regionally metamorphic source in the cordierite to amphibolite facies. The magma apparently rose toward the surface and subsequently cooled to produce differentiated magmas through fractional crystallization of the ferromagnesium minerals, plagioclase, and K-feldspar to form the different units of the Bevos Group. The Knoblick and parts of the Slabtown and Silvermine granites are cumulates, containing higher plagioclase and ferromagnesium contents than other Bevos Group units, whereas the Graniteville and Breadtray granites formed as residual liquids. The Butler Hill Granite is intermediate in mineralogy and composition to the other units of the Bevos Group, and because of this, its large volume, and location to the other units, is proposed to most nearly represent the characteristics of the parent magma. The cooling and extrusion of some magma as volcanic ejecta could have caused collapse and formed one or more proposed calderas in the vicinity.

The Musco Group formed at a later time, about 1400 million years ago, slightly deeper in the lower crust, by 20 to 40 percent melting of a different and more mafic source in the amphibolite-granulite facies of regional metamorphism. This group represents different degrees of melting of the source with the Munger Granite

representing the highest degree of melting. These granites apparently injected almost to the surface, and perhaps intruded the volcanic rocks as ring fracture dikes, caused by the collapse of the previous igneous activity.

Granites of similar age and composition occur in Wisconsin, Oklahoma, and Texas and could represent an arc of related igneous activity associated with a similar tectonic regime. Anderson and Cullers (1978) proposed modes of formation for the Wolf River Batholith in Wisconsin similar to that derived for the St. Francois Mountains; and the two complexes could be closely related. Any type of crustal upwarping would relieve load pressure at depth and could cause the metamorphic rocks to intersect their melting curves and produce granitic melts. Anderson and Cullers (1978) proposed that initial stages of crustal rifting, similar to the neogene rifting in Africa, could have been responsible for the formation of the granitic rocks. The similarities of these two complexes seems to support this theory, in that some sort of crustal tectonism may have occurred to produce a very large arc of granitic rocks. Further investigations into the Precambrian basement of the midcontinent will greatly improve the understanding of the evolution of the continent during Precambrian time.

APPENDIX I

Preparation of Rock Samples

Rock samples collected in the field for chemical analyses ranged from 5 to 24 pounds, depending on the degree of weathering and how much of the weathered surface could easily be chipped away in the field. The rock samples were chipped and cleaned of all weathered material by using Ward's large Rock Trimmer fitted with a chisel point. A few of the freshest fragments were retained for making thin sections and the rest of the fresh fragments were crushed for chemical use as described below.

The rock samples were sent to Rudolf von Huene labs, 1555 East Walnut Street, Pasadena, California, where standard uncovered thin sections were prepared.

One to two pounds of the freshest part of the rock samples were crushed with a large Sturtevant Laboratory Roll Jaw Crusher, model 1C1. This crusher reduced the rock fragments to about pebble size. The samples were then fed into a BICO circular pulverizer, type UA, which reduced the samples to about sand size. Each sample was crushed and ground separately, and the equipment was cleaned after each use by brushing with a wire brush and blowing with compressed air. An air exhaust fan was used to keep dust and contamination to a minimum during the crushing process.

The samples were then split to reduce volume, and the largest portion was stored in a sealed glass container. The smaller portion, about 100 grams, was placed in a Spex mixer/mil., catalogue number 8000, milled for 20 to 30 minutes, and then stored in air-tight glass vials. The samples would pass through a 200 mesh sieve after this milling.

APPENDIX II

Petrographic Descriptions

The following are petrographic descriptions of thin sections of samples of the Munger Granite which were analyzed geochemically for this report. The samples were similar mineralogically and texturally as all but two samples are hypidiomorphic-granular granites. The two exceptions (6-18-10 and 6-15-9) were granophyres. A full length petrographic report was done on one sample representing each textural variety (6-28-7, granular; 6-28-10, granophyre). Because the rest of the samples were similar to the representative samples analyzed, only brief petrographic and modal analyses are reported for these additional samples, noting only the most important similarities and differences. At the end of the descriptions is a table which summarizes the petrography for each sample.

6-28-7

Textures: Holocrystalline, porphyritic, hypidiomorphic-granular, myrmekitic. Megaphenocrysts of subhedral anorthoclase(?) perthite to 5mm (10.8 percent), a few rimmed with myrmekitic quartz; and anhedral rounded quartz to 3.6mm (6.3 percent). Fine-grained (0.3mm) granular groundmass of anhedral quartz (23.2 percent), subhedral, twinned plagioclase of An₁₀₋₂₀ (43.5 percent), anhedral biotite (11.3 percent), subhedral anorthoclase(?) (2.1 percent), and subhedral magnetite (2.1 percent). The accessory minerals (1.8 percent) are sphene, fluorite, zircon, and apatite.

Rock Name: Biotite Granite Porphyry

Sequence of Mineral Formation: 1) Perthite, 2) Quartz,

3) Biotite, 4) Magnetite, 5) Plagioclase, 6) Accessories.

Mineral Descriptions:

Quartz Low relief, low birefringence (white-steel blue-yellow), uniaxial (+). Granular, anhedral in groundmass averaging 0.3mm (23.2 percent). Anhedral, rounded as phenocrysts to 3.6mm with undulating extinction. A few grains occur as tiny (0.02mm) myrmekitic intergrowths surrounding feldspar phenocrysts. Also poikilitically enclosed in feldspar phenocrysts. Contains inclusions of zircon and fluorite.

Perthite Low relief, low birefringence, biaxial (-), 2V approximately 50°, perpendicular cleavage of the (010) and (001) planes. Subhedral phenocrysts to 5mm (10.8 percent) show a few myrmekitic textures on the rim with quartz; carlsbad twinning, patched, string, and zoned perthitic textures, and occasional shatter cracks. The phenocrysts contain zonally arranged poikilitic inclusions of quartz, twinned plagioclase (An₁₀₋₂₀), hornblende, fluorite, magnetite, and biotite. Also contained in the groundmass (2.1 percent) as much smaller (0.3mm) subhedral to euhedral perthitic laths with inclusions of hornblende, magnetite, and biotite.

Moderately to heavily weathered to sericite which is often in zonally arranged patterns. This mineral could either be anorthoclase perthite or orthoclase perthite.

Plagioclase Low relief, low birefringence, biaxial (+) and (-), albite twinning with extinction of the twins about 5 to 8 degrees. Subhedral in the groundmass from 0.1 to 2mm (43.5 percent) with inclusions of biotite, sphene, fluorite, and magnetite. Weathered to sericite.

Biotite Moderate relief, moderate birefringence, uniaxial (-)

with 2V about 4 degrees, pleochroic red, green, and brown. Anhedral to 0.4mm scattered throughout the rock (11.3 percent).

Contains inclusions of sphene, and associated with zircon.

Magnetite Opaque, subhedral to cubical to 0.6mm. Throughout the groundmass in quartz, plagioclase and biotite, and in the myrmekite surrounding the feldspar phenocrysts (2.1 percent).

Closely associated with biotite and sphene. Contains inclusions of sphene.

Fluorite Isotropic, negative relief, subhedral to cubical with (111) cleavage, ranges from 0.04 to 0.12mm. Contained in quartz and associated with biotite. Trace mineral.

Sphene High relief, high birefringence, biaxial (+), prismatic. Ranges from 0.02 to 0.16mm and is associated with quartz, magnetite, biotite, and plagioclase. Trace mineral.

Zircon High relief, high birefringence, tiny laths about 0.025mm, in quartz and the groundmass, associated with biotite and magnetite. Trace mineral.

Apatite Clear, moderate relief, anisotropic, low birefringence, hexagonal and tabular 0.02mm in length. Trace mineral.

Sericite High relief, high birefringence, occurs as weathered product of feldspars and plagioclase as tiny microlites (0.01mm).

6-28-10

Textures: Holocrystalline, porphyritic, rapakivi, granophyric, with a few myrmekite. Megaphenocrysts of euhedral to rounded orthoclase to 3.24mm (1.1 percent), subhedral perthite to 2.9 mm (1 percent) with myrmekitic quartz and rapakivi plagioclase, and anhedral quartz to 3.6mm (3.2 percent). Fine granophyric, micro-

graphic, and rare granular groundmass from 0.005 to 0.2mm of anhedral quartz (about 34 percent), subhedral, twinned plagioclase of An₁₀₋₂₀ (41 percent), granular biotite (14.5 percent), and subhedral magnetite (3.3 percent). The accessory minerals (2 percent) are sphene, hornblende, apatite, fluorite, and iron oxides. The feldspars are weathered to sericite.

Rock Name: Rapakivi Biotite Granite Granophyre

Sequence of Mineral Formation: 1) Orthoclase, 2) Perthite, 3) Quartz, (quench) 4) Magnetite, 5) Biotite, 6) Plagioclase, 7) Accessories.

Mineral Descriptions:

Quartz Low relief, low birefringence, uniaxial (+), undulatory extinction, Anhedral, rounded, shattered phenocrysts from 0.2 to 3.6mm (3.2 percent) with inclusions of biotite, magnetite, and sphene. Granophyric to granular in the groundmass from 0.005 to 0.2mm (about 34 percent) showing micrographic intergrowths with plagioclase and within quartz grains. Myrmekitic to 0.01mm surrounding feldspar phenocrysts.

Perthite Low relief, low birefringence, biaxial (-), 2V about 50 degrees, perpendicular cleavage. Subhedral micro-perthitic phenocrysts to 2.9mm (1 percent) with myrmekitic quartz and highly weathered, twinned rapakivi plagioclase 0.2mm thick which surrounds the phenocrysts. A few occurrences of subhedral perthite to 0.01mm in the groundmass. Weathered to sericite. This mineral is either anorthoclase or orthoclase perthite.

Orthoclase Low relief, low birefringence, biaxial (-), perpendicular cleavage, 2V about 70 degrees. Fresh euhedral to rounded phenocrysts to 3.24mm (1.1 percent).

Plagioclase(albite-oligoclase) Low relief, low birefringence, biaxial (+), (-), albite twinning with extinction of the twins about 5 to 8 degrees. Subhedral, granophyric, micrographic to granular laths in the groundmass from 0.005 to 0.2mm (about 41 percent). Weathered to sericite.

Biotite Moderate relief, moderate birefringence, uniaxial (-), 2V to about 4 degrees, anhedral, granular, pleochroic green, red, and brown, scattered throughout the groundmass from 0.01 to 0.43mm (14.5 percent). Tends to form unconnected elongations to about 1mm. Contains inclusions of magnetite, sphene, apatite, and fluorite. Rounded miarolitic cavities are contained within biotite which are filled with iron oxides and perhaps fluorite as secondary minerals.

Hornblende High relief, moderate birefringence, biaxial (-), pleochroic green and brown, prismatic, with about 120 degree cleavage on the (001), to 0.8mm. Trace mineral.

Magnetite Opaque, anhedral to cubic. Throughout groundmass to 0.64mm and associated with biotite and containing inclusions of sphene (3.3 percent).

Sphene High relief, high birefringence, biaxial (+), cubical, prismatic to 0.06mm in groundmass and as inclusions in quartz, magnetite, and biotite. Trace mineral.

Apatite Moderate relief, low birefringence, 0.02mm to 0.12mm tabs associated with biotite and magnetite. Trace mineral.

Fluorite Isotropic, negative relief, anhedral to cubical from 0.02 to 0.07mm, associated with biotite perhaps as miarolitic cavity filling. Trace mineral.

Iron Oxide Translucent yellow brown, anhedral, rounded, forms

center of several biotite miarolitic cavities and is probably a secondary mineral. Trace.

Sericite High relief, high birefringence, occurs as tiny microlites about 0.01mm. Weathering product of the feldspars and plagioclase.

6-28-1

Holocrystalline, porphyritic, myrmekitic, hypidiomorphic-granular granite with 7 percent rounded anhedral quartz (2-3mm), and 12 percent subhedral perthitic K-feldspar (3mm) as phenocrysts. The granular matrix (0.2mm average) is composed of 32 percent anhedral quartz, 41 percent twinned subhedral plagioclase (An_{10-20}), 6 percent pleochroic anhedral biotite, and 1 percent magnetite with accessory (1 percent) fluorite, apatite, and sphene. The feldspars are altered to sericite and the biotite is altered to iron oxides.

6-28-3

Holocrystalline, porphyritic, myrmekitic, hypidiomorphic-granular granite with 0.4 percent anhedral quartz (3mm) and 11 percent subhedral perthitic K-feldspar (4mm) as phenocrysts. The granular matrix (0.4mm average) is made of 27 percent anhedral quartz, 49 percent twinned subhedral plagioclase (An_{10-20}), 8 percent anhedral, pleochroic biotite, 2 percent subhedral pleochroic hornblende, and 2 percent subhedral magnetite. The accessory minerals (1 percent) are fluorite, apatite, zircon, and sphene. The feldspars are altered to sericite and biotite to iron oxides.

6-28-6

Holocrystalline, porphyritic, myrmekitic, slightly granophytic, hypidiomorphic-granular granite with 3 percent anhedral quartz (3mm) and 13 percent altered, subhedral perthitic K-feldspar as phenocrysts. The granular matrix (0.5mm average) is composed of 28 percent anhedral quartz, 45 percent twinned subhedral plagioclase (An_{10-20}), 6 percent anhedral pleochroic biotite, 3 percent subhedral pleochroic hornblende, and 2 percent subhedral magnetite. The accessory minerals (1 percent) include sphene, zircon, apatite, and fluorite. The feldspar are altered to sericite and biotite to iron oxides.

6-28-8

Holocrystalline, porphyritic, slightly myrmekitic, hypidiomorphic-granular granite with 3 percent anhedral quartz (1mm) and 12 percent euhedral to subhedral altered perthitic K-feldspar (2.5 to 4.0mm) as phenocrysts. The granular matrix (0.2mm average) consists of 30 percent anhedral quartz, 45 percent subhedral twinned plagioclase (An_{10-20}), 6 percent anhedral pleochroic biotite, 1 percent subhedral pleochroic hornblende, and 2 percent subhedral magnetite. The accessory minerals (1 percent) include sphene, apatite, and fluorite. The feldspars are altered to sericite.

6-28-14

Holocrystalline, porphyritic, rapakivi, myrmekitic, hypidiomorphic-granular granite with 6 percent anhedral quartz (2mm) and 15 percent subhedral to euhedral altered perthitic K-feldspar (4mm), which is rimmed with rapakivi plagioclase, as pheno-

crysts. The granular matrix (0.5 to 0.6mm average) consists of 45 percent subhedral plagioclase (An_{10-20}), 25 percent anhedral quartz, 5 percent anhedral pleochroic biotite, 3 percent subhedral magnetite, and 1 percent subhedral pleochroic hornblende. Accessory minerals include zircon, apatite, fluorite, and sphene. The feldspars are altered to sericite and biotite to iron oxides.

6-15-9

Holocrystalline, porphyritic, myrmekitic, granophyric granite with about 5 percent anhedral quartz (2.5mm) and 10 percent subhedral to euhedral altered perthitic K-feldspar (3.5mm) phenocrysts which are rimmed with quartz and plagioclase myrmekite. The granophyric matrix (0.4mm average) is made of interlocking subhedral plagioclase (about 45 percent), anhedral quartz (about 25 percent), radiating biotite (about 10 percent), subhedral magnetite (about 3 percent), and subhedral hornblende (about 2 percent). The accessory minerals include sphene, apatite, and fluorite. The feldspars are altered to sericite.

Table 7. Petrographic Summary of the Munger Granite

Sample, Texture	Pheno- cryst Minerals	Per- cent	Size (mm)	Matrix Minerals	Per- cent	Size (mm)
6-28-1 hypidio- morphic- granular	Quartz	7	2-3	Quartz	32	0.3 avg.
	K-feld.	12	3	Plagioclase	41	"
				Biotite	6	"
				Magnetite	1	"
				Accessory	1	"
6-28-3 hypidio- morphic- granular	Quartz	0.4	3	Quartz	27	0.5 avg.
	K-feld.	11	4	Plagioclase	49	"
				Biotite	8	"
				Hornblende	2	"
				Magnetite	2	"
			Accessory	1	"	
6-28-6 hypidio- morphic- granular	Quartz	3	3	Quartz	28	0.5 avg.
	K-feld.	13	3	Plagioclase	45	"
				Biotite	6	"
				Hornblende	3	"
				Magnetite	2	"
			Accessory	1	"	
6-28-7 hypidio- morphic- granular	Quartz	6	3-4	Quartz	23	0.3 avg.
	K-feld.	11	4-5	Plagioclase	44	"
				Biotite	11	"
				K-feld.	2	"
				Magnetite	2	"
			Accessory	2	"	
6-28-8 hypidio- morphic- granular	Quartz	3	1	Quartz	30	0.2 avg.
	K-feld.	12	2.5-4	Plagioclase	45	"
				Biotite	6	"
				Magnetite	2	"
				Hornblende	1	"
			Accessory	1	"	
6-28-10 grano- phyric	Quartz	3	3-4	Quartz	34	0.005-2
	K-feld.	2	3-4	Plagioclase	41	"
				Biotite	15	"
				Magnetite	3	"
				Accessory	2	"
6-28-14 hypidio- morphic- granular	Quartz	6	2	Quartz	25	0.5-0.6
	K-feld.	15	4	Plagioclase	45	"
				Biotite	5	"
				Magnetite	3	"
				Hornblende	1	"
6-15-9 grano- phyric	Quartz	5	2-3	Quartz	25	0.4 avg.
	K-feld.	10	3-4	Plagioclase	45	"
				Biotite	10	"
				Magnetite	3	"
				Hornblende	2	"
			Accessory	1	"	

APPENDIX III

Spectrophotometry Procedure

Major element analyses were obtained by atomic absorption and emission spectrophotometry similar to the method described by Buckley and Cranston (1971). A Perkin-Elmer model 305b spectrophotometer was used for the analyses.

Five granitic rock samples and three U.S.G.S. standard rocks were included in each run. The three standard rocks were used as reference standards for silica analyses, and for measurement of precision and accuracy for the other elements. The rock samples were prepared for analyses by weighing 0.1000 gram ± 0.0005 gram of the powdered rock samples into a 25 ml teflon lined Parr Acid Digestion Bomb containing 6 ml of HF acid, and 1 ml of aqua regia.

The samples were then sealed in the teflon-lined bombs and heated to 110 degrees Centigrade for 45 minutes in an oven. During heating, 4.0 grams of boric acid were dissolved in warm, distilled-deionized water in teflon beakers for each sample, stirring occasionally with teflon stirring rods. After heating, the bombs were opened, visually inspected for complete dissolution, and quantitatively transferred to the warm boric acid solutions and stirred. The solutions were then brought to 200 ml volume with distilled-deionized water and transferred to polyethelene containers for storage, and labeled as (I) solutions for dilution purposes.

A flow diagram of the spectrophotometry procedure is in Figure 20 to assist the reader in the following the descriptions which follow.

Figure 20. Spectrophotometry Procedure Flow Diagram

1. $\left\{ \begin{array}{l} 0.1000 \pm 0.0005 \text{ gram powdered rock sample} \\ + 6 \text{ ml HF} \\ + 1 \text{ ml Aqua Regia} \end{array} \right\}$ in bomb
 110°C for
 45 mins.
- +
 4.0 grams Boric Acid dissolved in warm distilled-deionized water and dilute to 200 ml.

Result: Solution (I), in the linear concentration range for analyses of Al, Ca, Mg, Ba, Sr, and Rb.

2. Dilute approximately 20 ml of Solution (I) 1:2 with Blank

Result: Solution (II), in the linear concentration range for analyses of Fe, Na, and Si.

3. Dilute approximately 2 ml of Solution (I) 1:9 with Blank

Result: Solution (III), in the linear concentration range for analyses of K.

Allow all solutions to equilibrate at least one day after mixing.

4. Order of analyses: III

1. Si, Fe, Na from (II) solutions
2. K from (III) solutions
3. Al from (I) solutions

Add 1000 ppm K to about 40 ml of the remaining (I) solution

4. Ba, Sr, Rb analyses from (I) solutions after the addition of K.

Add 1000 ppm Sr to the remaining (I) solution

5. Ca, Mg analyses after addition of Sr.

The (I) solutions were in the linear concentration range, for these granitic samples, for proper analyses of Al, Ca, Mg, Ba, Sr, and Rb. But, for analyses of Fe, Na, and Si, a portion of the (I) solutions (about 20 ml) was diluted with the blank solution in the ratio of 1 to 2, and the new solutions were called (II) solutions. The preparation of the blank solutions are summarized in the next paragraph. For analyses of K, 1 to 5 ml of the (I) solutions was diluted with blank in the ratio of 1 to 9, and called (III) solutions. These dilutions were made about one day after preparation of the original (I) solutions to insure proper equilibration of the original solutions. After allowing all solutions to equilibrate another day, the rock sample solutions were ready for analyses of Si, Fe, Na, Al, and K.

Blank solutions were prepared in one liter volumes by weighing 20.0 grams of boric acid into 30 ml of HF acid and 5 ml of aqua regia, and bringing the volume to about 100 ml over a warm hot plate until all of the boric acid was dissolved. The volume was then brought to one liter in a volumetric flask and transferred to a polyethelene container for storage.

For preliminary trial runs, 0.5 percent lanthanum as $\text{LaCl}_3 \cdot 6\text{H}_2\text{O}$ (5000 ppm La) was added to both blank and sample solutions to supposedly help eliminate flame interferences for some elements. This solution, even in concentrations as low as 100 ppm was cloudy, indicating a precipitate, and hindered analyses, as a build up of matter collected on the burner head, preventing good results. Because of this, nothing was added to the respective solutions for analyses of Si, Fe, Na, K, and Al, as good results were obtained for the U.S.G.S. standard rocks for these

elements with no additions. For analyses of Ba, Rb, and Sr, 1000 ppm of reagent grade K was added to all solutions, standards, blank, and samples, to prevent flame interferences. For analyses of Ca and Mg, 1000 ppm of reagent grade Sr was added to all solutions for the same reason. With this in mind, a certain order of analyses of the elements was adopted to insure that no contamination of the samples could occur from the additions. Si, Fe, and Na were analyzed first from the (II) solutions, then K from the (III) solutions, followed by Al from the (I) solutions. Then, K was safely added to a portion of the (I) solutions for analyses of Ba, Sr, and Rb. Rb was analyzed last in this sequence because it requires a different flame and burner configuration (Table 9). Finally, Sr was added to some of the remaining (I) solutions for analyses of Ca and Mg.

Several standards were prepared from stock standard solutions in the appropriate amounts to approximate the concentrations of the granitic rock samples. A high and low standard solutions was prepared in such a way as to bracket the rock sample concentrations of each element (Table 8). Analytic grade stock standard solutions of Al, Ba, Rb, and Sr were prepared by dissolving appropriate amounts of Al wire, $\text{BaCl}_2 \cdot \text{H}_2\text{O}$, RbCl, and $\text{Sr}(\text{NO}_3)_2$ in distilled deionized water to make 1000 ug/ml (ppm).

Standard solutions of Si were not used for determination of the SiO_2 contents of the samples. It was found to be more accurate to use the published values of the three U.S.G.S. standard rocks plotted against their respective absorption values given by spectrophotometry in each run to define a straight line plot. The granite sample absorption values, for each run, plotted on

Table 8. Standard Solution Concentrations (ppm)

Element	Reagent Used	Low Standard	High Standard
Al	Al wire	40	50
Fe	Stock Std.	2	6
Ca	Stock Std.	8	18
Mg	Stock Std.	2	6
Na	Stock Std.	4	10
K	Stock Std.	1	2
Ba	BaCl ₂ ·H ₂ O	0.5	1
Rb	RbCl	0.1	0.2
Sr	Sr(NO ₃) ₂	0.1	0.4

Table 9. Instrument Settings for Atomic Absorption Spectrophotometer

Element	Wavelength Setting	Slit	Burner Orientation ⁺	Burner height position	C ₂ H ₂	air	N ₂ O	Range	Function
Si	251.8	3	parallel	6.0	5.25		4.75	UV	Abs.
Al	309.2	4	parallel	7.0	5.0		5.0	UV	Abs.
Fe	248.5	3	parallel	7.0	5.0	5.0		UV	Abs.
Mg	285.3	4	perpendicular	4.5	4.75	5.25		UV	Abs.
Ca	211.4	4	parallel	6.2	4.5	5.5		Vis	Abs.
Na	294.4	4	perpendicular	6.2	5.0	5.0		Vis	Abs.
K*	382.9	4	perpendicular	4-7	4.75	5.25		Vis	Emiss.
Ba	276.8	2	parallel	6.0	4.75		5.25	Vis	Emiss.
Rb	389.6	5	4" parallel	5.0	9.0	9.0		Vis	Emiss.
Sr	230.2	4	parallel	7.0	4.75		5.25	Vis	Emiss.

* With red filter
 + Two inch burner

this graph gave a graphic answer for the unknown silica concentrations. This method proved itself in repeated analyses, and avoided many problems involved with using synthesized standard solutions.

Ignition was performed to obtain the volatile content of the samples. About 0.5 gram of sample was weighed to the nearest 0.0001 gram, placed into a pre-weighed platinum crucible, and heated to 1000°C in a muffle furnace for thirty minutes. The crucibles were allowed to cool to room temperature in a desiccator before reweighing for determination of sample loss, and the weight percent loss was calculated.

APPENDIX IV

INAA Procedure

Approximately 0.2 gram of the powdered rock samples was weighed to the nearest 0.005 gram and placed into clean polyethylene irradiation vials. Iron wire flux monitors (about 50 mg) were wrapped around the portion of the vial containing the sample. The vials were then sealed with a warm soldering gun to insure that the vials were both air and water tight. Five samples and one standard (usually BCR-1) were irradiated at a time in the central thimble of the Kansas State Triga Mark II reactor at full power (about 1×10^{13} neutrons per square cm-sec.).

After irradiation, the samples were allowed to cool in the reactor bay until they were safe to be handled (less than one Roentgen per hour at contact). The samples were then transferred to plastic bags (about one cm across) and mounted onto cards (8x8.5 cm) for radioassay. The iron wires were removed from the vials and mounted on similar cards for radioassay about two weeks after irradiation. The variation in the iron activity was used as a monitor for the reactor flux which can vary from sample to sample.

Two different types of INAA were used for element analyses in this report. For analyses of Mn and Na which have relatively short half lives (Table 10) the samples were irradiated at full power in the central thimble of the reactor for about ten minutes. After allowing the samples to cool for about six hours, they were repackaged, and each sample radioassayed for about fifteen minutes.

For analyses of the REE, Fe, Na, and Ba, the samples were

Table 10. Summary of Nuclide Properties used in INAA
(adapted from Gorden, et al, 1968)

Element (Nuclide)	Half Life ($T_{\frac{1}{2}}$)	Best gamma energy (keV)	Best time after irrad. for ctg.	Interfering Peaks
Na ²⁴	15.0 hr.	1369 1732	few hours to 7 days	
Fe ⁵⁸	45 day	191 1098 1291	10, 40 days	
Mn ⁵⁶	2.58 hr.	847 1811	few hours	Eu ^{152m}
Ba ¹³¹	12 day	496	10 days	
La ¹⁴⁰	40.2 hr.	329 487	4, 10 days	
Ce ¹⁴¹	33 day	145	40 days	Fe ⁵⁹
Sm ¹⁵³	47 hr.	103	4 days	
Eu ¹⁵²	12 years	122 245	40 days	Hf ¹³¹ , Pa ²³³
Tb ¹⁶⁰	72.1 day	299	10, 40 days	Pa ²³³
Yb ¹⁷⁵	4.21 day	396	10 days	Pa ²³³
Yb ¹⁶⁹	32 day	177	40 days	Ta ¹⁸²
Lu ¹⁷⁷	6.7 day	208	10 days	

irradiated at full power in the central thimble of the reactor for about four hours. The samples were allowed to cool for about four days before repackaging and radioassay. Four days after irradiation the samples were assayed for one hour each, and ten and forty days after irradiation, the samples were assayed for five hours each.

Table 10 is a summary of the elements analyzed using INAA, their half lives ($T_{\frac{1}{2}}$), their gamma energies, the best time after irradiation for counting, and the interfering peaks to watch for during radioanalyses.

APPENDIX V

Analytical Data for the St. Francois Mountains

The major and trace element data and C.I.P.W. norms are in Table 11. The major and trace element data for the Munger, Carver Creek, and Buford granites (Musco Group) were obtained in this study by the author. Major element and Ba, Rb, and Sr data for all other rock units were obtained from Bickford (1977, personal communication). For most of the samples, additional Ba, Rb, Fe, and Na data was obtained with INAA during analyses of the REE, and when duplicate analyses were available, the values between analysts were averaged together for use in this report.

Table 11. Analytical Data for the St. Francois Mountains

Samples Elements	Musco Group Munger Granite							
	6- 28-1 ^a	6- 28-3 ^a	6- 28-6 ^a	6- 28-7 ^a	6- 28-8 ^a	6- 28-10 ^a	6- 28-14 ^a	6- 15-9 ^a
Oxides (weight percent)								
SiO ₂	71.3	71.5	70.1	72.1	71.1	70.9	72.4	73.0
Al ₂ O ₃	13.30	13.04	13.01	13.57	13.08	12.81	13.49	13.38
Fe as Fe ₂ O ₃	2.91	3.25	3.20	2.78	3.34	3.58	3.43	3.35
CaO	0.39	0.63	0.69	0.41	0.97	0.74	0.30	0.25
MgO	0.13	0.22	0.12	0.18	0.13	0.15	0.18	0.17
MnO	0.06	0.08	0.08	----	----	0.09	----	0.06
K ₂ O	5.78	5.81	6.14	5.52	6.02	5.66	5.92	5.94
Na ₂ O	3.27	3.39	3.35	3.23	3.44	3.30	3.45	3.31
Ignition	0.010	0.009	0.009	0.005	0.009	0.002	0.003	0.012
Total	97.15	97.93	96.70	97.80	98.09	97.23	99.17	99.47
Norms (percent)								
Q	28.06	26.62	24.90	29.82	25.15	27.39	27.25	28.61
ab	29.50	31.45	31.45	30.00	31.85	30.90	31.60	30.35
or	35.50	35.55	38.05	33.80	36.75	34.95	35.75	35.90
an	2.00	3.25	2.38	2.10	2.50	3.53	1.50	1.25
c	1.32	0.00	0.00	1.73	0.00	0.00	0.95	1.16
wo	0.00	0.00	0.49	0.00	0.98	0.13	0.00	0.00
hm	2.10	2.33	2.33	2.00	2.40	2.60	2.44	2.38
en(di)	1.18	0.76	0.46	0.52	0.38	0.58	0.52	0.58
Total	99.66	99.96	100.06	99.97	100.01	100.08	100.01	100.23
Trace elements (ppm)								
Ba	1460	1460	1490	1610	1525	1550	----	1510
Rb	170	195	300	130	320	146	182	261
Sr	50	115	36	58	50	90	----	----
La	41.0	43.3	55.4	31.4	48.9	43.7	42.7	40.6
Ce	78.5	75.5	100.0	51.4	80.7	76.3	77.5	75.3
Sm	7.5	7.5	9.7	5.8	7.9	8.3	8.7	7.4
Eu	1.65	1.37	2.21	1.47	1.81	1.89	1.50	1.56
Tb	1.06	1.28	1.39	1.12	1.15	1.21	1.20	1.10
Yb	4.1	4.58	5.97	3.7	4.2	4.36	4.51	4.6
Lu	0.75	0.76	0.98	0.66	0.75	0.74	0.87	0.84
Eu/Sm	0.220	0.183	0.228	0.253	0.229	0.228	0.172	0.211
Eu/Eu*	0.745	0.581	0.769	0.792	0.766	0.764	0.580	0.695
La/Lu	54.7	56.9	56.5	47.5	65.2	59.1	49.1	48.3
ΣREE*	199.9	203.8	256.3	144.9	212.1	204.1	205.3	195.2

Analysts (a) this report
 (b) from Bickford (1977, personal communication)
 (c) from Bickford (1977, personal communication), except
 for Fe, Na, Ba, Rb, and REE, this report, NAA.

* REE not analyzed were estimated from chondrite normalized curves, less Y.

Table 11 (continued). Analytical Data for the St. Francois Mountains

Samples Elements	Musco Group		Bevos Group					
	Carver		Graniteville		Breadtray Granite			
	Creek ^a	Buford ^a	Granite	BSF-242 ^c	BSF-246 ^c	12- 5-5a	12- 5-6 ^c	12- 5-7 ^c
Oxides (weight percent)								
SiO ₂	70.0	70.9	72.9	72.8	----	77.1	77.3	
Al ₂ O ₃	13.16	12.94	12.20	12.38	----	12.34	12.11	
Fe as Fe ₂ O ₃	4.71	3.34	1.39	0.96	1.91	1.39	1.15	
CaO	1.09	0.68	0.49	0.83	----	0.24	0.10	
MgO	0.33	0.17	0.03	0.04	----	----	----	
MnO	0.09	----	----	0.003	0.038	0.040	0.014	
K ₂ O	4.79	5.58	4.57	5.30	----	5.00	5.16	
Na ₂ O	3.89	4.15	3.89	4.01	3.56	3.70	3.01	
Ignition	0.88	0.34	1.63	1.23	----	0.80	0.88	
Total	98.94	98.10	97.10	97.55	-----	100.61	99.72	
Norms (percent)								
Q	25.33	23.77	30.70	27.33	-----	33.73	37.90	
ab	36.05	37.55	36.40	37.50	-----	33.65	27.75	
or	29.30	34.05	28.20	32.50	-----	30.00	31.50	
an	4.40	0.58	2.55	0.15	-----	1.20	0.50	
c	0.00	0.00	1.06	0.00	-----	0.39	1.55	
wo	0.48	1.17	0.00	1.66	-----	0.00	0.00	
hm	3.38	2.39	1.00	0.70	-----	0.98	0.82	
en(di)	1.04	0.48	0.04	0.12	-----	0.00	0.00	
Total	99.98	99.99	99.95	99.96	-----	99.95	100.02	
Trace elements (ppm)								
Ba	1140	2050	140	263	430	----	390	
Rb	157	230	380	320	250	----	190	
Sr	82	75	17	23	----	----	----	
La	54.0	60.0	52.4	58.3	42.5	85.2	16.8	
Ce	116.0	111.0	114.0	107.0	148.5	140.0	86.2	
Sm	14.2	13.2	15.1	11.4	7.8	12.6	3.8	
Eu	1.90	2.85	0.29	0.20	0.45	0.63	0.41	
Tb	2.30	2.04	2.66	2.10	0.99	2.07	1.02	
Yb	9.17	7.20	19.15	14.30	7.32	8.40	8.75	
Lu	1.55	1.28	2.90	2.70	1.29	1.34	1.38	
Eu/Sm	0.134	0.216	0.019	0.018	0.058	0.050	0.108	
Eu/Eu*	0.428	0.700	0.059	0.054	0.203	0.158	0.292	
La/Lu	34.8	46.9	18.1	21.6	32.9	6.36	12.2	
ΣREE*	310.5	303.3	327.7	287.9	290.3	357.7	173.8	

Analysts (a) this report
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 (c) from Bickford (1977, personal communication), except
 for Fe, Na, Ba, Rb, and REE, this report, NAA.

* REE not analyzed were estimated from chondrite normalized curves, less Y.

Table 11 (continued). Analytical Data for the St. Francois Mountains

Samples Elements	Bevos Group Breadtray Granite (contd.)				Butler Hill Granite		
	12- 5-3 ^a	5- 5-13 ^a	12- 5-17 ^c	N- 1775g ^c	12- 5-9 ^c	M0- 22 ^c	M0- 23 ^c
Oxides (weight percent)							
SiO ₂			77.1	75.4	76.1	72.4	75.1
Al ₂ O ₃			12.38	12.90	12.88	12.85	12.70
Fe as Fe ₂ O ₃			0.94	0.85	2.11	2.47	2.63
CaO			0.09	0.04	0.74	1.02	0.98
MgO			-----	0.05	-----	0.22	0.33
MnO			0.017	-----	0.036	-----	0.094
K ₂ O			5.44	5.21	4.66	4.14	4.17
Na ₂ O			3.36	3.27	4.07	3.64	3.85
Ignition			0.85	1.44	0.88	-----	-----
Total			100.18	99.16	101.40	96.74	99.85
Norms (percent)							
Q			34.50	34.83	30.90	32.06	33.32
ab			30.70	30.35	36.70	35.00	33.50
or			32.75	31.85	27.70	25.00	29.65
an			0.50	0.20	3.05	5.00	2.17
c			0.86	1.98	0.00	0.00	0.00
wo			0.00	0.00	0.26	0.00	0.39
hm			0.67	0.14	1.30	1.85	0.96
en(di)			0.04	0.14	0.06	1.08	0.00
Total			100.02	99.95	99.97	99.99	99.99
Trace elements (ppm)							
Ba			-----	560	-----	730	-----
Rb			-----	190	-----	-----	-----
Sr			-----	14	-----	86	-----
La	66.5	51.3	17.6	8.0	69.9	64.4	57.7
Ce	123.2	105.0	84.3	67.6	135.5	136.0	116.0
Sm	10.4	10.9	5.08	3.3	11.0	12.6	11.4
Eu	0.57	0.68	0.30	0.10	0.91	0.80	0.96
Tb	1.48	1.58	1.30	2.79	3.36	1.96	1.72
Yb	8.28	8.07	9.52	9.8	7.82	7.95	6.42
Lu	1.36	1.25	1.48	1.16	1.23	1.47	1.19
Eu/Sm	0.055	0.062	0.059	0.030	0.083	0.063	0.084
Eu/Eu*	0.188	0.211	0.162	0.056	0.261	0.208	0.273
La/Lu	48.9	41.0	11.9	6.9	56.8	43.8	48.5
ΣREE	301.3	268.7	178.7	159.3	328.6	330.1	288.3

Analysts (a) this report
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 (c) from Bickford (1977, personal communication), except
 for Fe, Na, Ba, Rb, and REE, this report, NAA.

* REE not analyzed were estimated from chondrite normalized curves, less Y.

Table 11 (continued). Analytical Data for the St. Francois Mountains

	Bevos Group				Slabtown Granite	
	BSF- 155 ^b	BSF- 42 ^c	ANS- 20 ^c	5- 5-17 ^c	BSF- 259 ^c	BSF- 258 ^a
Oxides (weight percent)						
SiO ₂	74.2	73.1	76.8	77.7	70.9	----
Al ₂ O ₃	13.10	12.50	12.19	12.48	13.15	----
Fe as Fe ₂ O ₃	2.28	2.03	1.36	0.58	3.63	5.44
CaO	0.96	0.83	0.62	0.20	1.18	----
MgO	0.26	0.30	----	----	0.45	----
MnO	0.039	0.062	0.025	0.006	----	----
K ₂ O	4.78	4.30	4.93	4.89	3.47	----
Na ₂ O	3.54	3.53	3.67	3.59	4.54	5.55
Ignition	2.17	1.89	0.61	1.08	0.83	----
Total	101.33	98.54	100.21	100.53	98.15	----
Norms (percent)						
Q	29.80	33.10	33.32	35.52	27.05	
ab	33.00	33.00	33.50	32.70	42.15	
or	29.50	26.50	29.65	29.35	21.25	
an	5.00	4.50	2.17	1.00	5.40	
c	0.30	0.60	0.00	1.01	0.00	
wo	0.00	0.00	0.39	0.00	0.26	
hm	1.60	1.50	0.96	0.41	2.61	
en(di)	0.80	0.80	0.00	0.00	1.28	
Total	100.00	100.00	99.99	99.92	100.00	
Trace elements (ppm)						
Ba	403	460	----	----	810	1600
Rb	260	202	----	----	104	134
Sr	71	90	----	----	112	----
La	54.9	54.8	65.9	44.2	42.2	44.9
Ce	117.0	102.0	129.0	87.0	75.1	98.1
Sm	9.4	10.1	9.0	5.7	9.3	11.1
Eu	0.59	0.64	0.48	0.47	2.11	2.50
Tb	1.34	1.42	1.56	0.75	1.27	1.50
Yb	6.22	6.47	8.87	5.92	----	6.50
Lu	1.18	1.22	1.44	0.92	0.74	1.15
Eu/Sm	0.063	0.063	0.053	0.082	0.227	0.225
Eu/Eu*	0.210	0.211	0.168	0.276	0.771	0.751
La/Lu	46.5	44.9	45.8	48.0	57.0	39.0
ΣREE*	273.0	258.4	305.3	201.2	207.6	255.5

Analysts (a) this report
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 (c) from Bickford (1977, personal communication), except
 for Fe, Na, Ba, Rb, and REE, this report, NAA.

* REE not analyzed were estimated from chondrite normalized curves, less Y.

Table 11 (continued). Analytical Data for the St. Francois Mountains

Samples Elements	Bevos Group Silvermine Granite		
	BSF- 268 ^c	BSF- 255 ^c	BSF- 233 ^c
Oxides (weight percent)			
SiO ₂	68.0	71.0	74.4
Al ₂ O ₃	14.93	13.18	12.67
Fe as Fe ₂ O ₃	3.38	2.16	1.57
CaO	2.14	0.75	0.64
MgO	0.60	0.39	0.21
MnO	0.086	0.040	0.023
K ₂ O	3.45	4.50	4.55
Na ₂ O	4.95	3.94	3.79
Ignition	0.48	1.51	1.62
Total	98.02	96.47	99.47
Norms (percent)			
Q	19.90	27.85	31.81
an	45.50	37.05	35.05
or	20.90	27.90	27.75
an	8.50	3.90	3.25
c	0.00	0.52	0.38
wo	0.96	0.00	0.00
hm	2.41	1.57	1.11
en(di)	1.84	1.20	0.64
Total	100.01	99.99	99.99
Trace elements (ppm)			
Ba	950	1165	700
Rb	133	167	114
Sr	208	153	95
La	27.7	36.4	33.5
Ce	56.0	65.0	65.0
Sm	6.0	4.6	4.63
Eu	1.44	0.91	0.70
Tb	1.26	0.62	1.20
Yb	5.0	2.63	4.14
Lu	0.64	0.51	0.55
Eu/Sm	0.240	0.198	0.151
Eu/Eu*	0.778	0.676	0.411
La/Lu	43.3	71.4	60.9
REE	154.5	153.8	160.3

Analysts (a) this report
 (b) from Bickford (1977, personal communication)
 (c) from Bickford (1977, personal communication), except
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APPENDIX VI

Element	Quartz#	Plagioclase	K-feld.	Biotite	Hornblende	Garnet	Allanite#	Avg. #m.	Avg. Sp. #
Ce	0.001	0.27	0.044	0.32	1.52	0.35	1400	34.0	41.3
Sm	0.001	0.13	0.18	0.26	7.77	2.66	220	2.66	3.36
Eu	0.001	2.15	1.13	0.24	5.14	1.5	50	0.91	1.32
Tb	0.001	0.06	0.009	0.29	12.5	20.	low	0.41	0.57
Yb	0.001	0.049	0.012	0.44	8.38	40.	low	1.54	2.24
Lu	0.001	0.046	0.006	0.33	5.5	30.	low	0.24	0.34
Ea	0.001	0.308	6.12	9.7	0.044	0.017	----	800-1200	800-1200
Rb	0.001	0.041	0.366	2.24	0.014	0.0085	----	----	----
Sr	0.001	4.4	3.87	0.672#	0.022	0.015	----	----	----

* Values reported by Arth and Hanson (1975).
 # Values estimated by Anderson and Cullers (1978).
 + Values from Wileman and Haskin (1973).
 ++ Values averaged from Wildeman and Haskin (1973), and Wildeman and Condie (1973).

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PETROGENESIS OF THE PRECAMBRIAN BEVOS AND MUSCO GROUPS,
ST. FRANCOIS MOUNTAINS IGNEOUS COMPLEX, MISSOURI

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ABSTRACT

Thirty samples of the St. Francois Mountains igneous complex, southeastern Missouri, representing the major plutons of the Bevos and Musco groups, have been analyzed for major elements, Ba, Rb, Sr, and the rare earth elements (REE). Absolute REE contents are similar to other granitic rocks ($\Sigma\text{REE} = 154\text{-}358$ ppm), and negative Eu anomalies and Ba contents are quite variable ($\text{Eu}/\text{Sm} = 0.018\text{-}0.24$; $\text{Ba} = 140\text{-}2050$ ppm). Data obtained here and from other sources suggest that the two groups of granite apparently formed by two episodes of melting of a regionally metamorphic source in the amphibolite to granulite facies containing varied amounts of quartz, plagioclase, potassium feldspar, biotite, and possibly hornblende and garnet.

Variation in major and trace element contents ($\text{Ba}=140\text{-}1600$ ppm; $\text{Eu}/\text{Sm} = 0.018\text{-}0.227$) of the Bevos Group suggest that differentiation, caused by fractional crystallization of the feldspar and ferromagnesium minerals, could have formed the different granites of this group. The Knoblick Granite, and parts of the Slabtown and Silvermine granites apparently formed from cumulate minerals mixed with some of the parent magma; whereas the Graniteville and Breadtray granites probably formed from the residual liquids.

The Butler Hill Granite, and parts of the Slabtown, Silvermine and Breadtray granites are intermediate in composition and mineralogy to the Bevos Group and most closely represent the parent magma type. Therefore, the major and trace elements of the Butler Hill Granite were used to derive the petrogenesis of the

Bevos Group. The parent magma apparently formed about 1500 million years ago (Bickford and Mose, 1975) by 10 to 20 percent melting in the lower crust (640-660°C, and 4 to 7 kb) from a source containing residual quartz, plagioclase, potassium feldspar, and biotite.

The Munger, Buford, and Carver Creek granites of the Musco Group contain generally larger quantities of Ba (1140-2050 ppm) and Eu (Eu/Sm = 0.13-0.25) as well as greater quantities of plagioclase and ferromagnesium minerals than the Bevos Group. The Musco Group formed about 1400 million years ago (Bickford and Mose, 1975) by 20 to 40 percent melting (650-670°C, and 7 to 10 kb) of a similar but more mafic source, than the one for the Bevos Group, but contained no potassium feldspar in the residuum. Small amounts of hornblende and garnet could also have been present in the source which formed this group.

