

TRACE ELEMENT GEOCHEMISTRY AND  
GEOCHRONOLOGY OF EARLY PRECAMBRIAN  
GRANULITE FACIES METAMORPHIC ROCKS  
NEAR GRANITE FALLS IN THE  
MINNESOTA RIVER VALLEY

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ABSTRACT OF THE DISSERTATION

Trace Element Geochemistry and  
Geochronology of Early Precambrian  
Granulite Facies Metamorphic Rocks  
Near Granite Falls, in the  
Minnesota River Valley

by

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The Sr isotopic composition and the trace element contents of K, Rb, Sr and Ba have been measured for 27 whole-rock samples and 18 mineral separates taken from four rock units in the Minnesota River Valley near Granite Falls, Minnesota. In addition, 4 whole-rock samples and 1 mineral separate were analyzed from samples of amphibolite xenoliths from the Morton-Sacred Heart area southeast of Granite Falls. The isochron ages obtained from the Rb-Sr data are given below in AE (billions of years); ages determined for metamorphic events are given in brackets. The initial ratios ( $R_i$ )

given refer to the whole-rock isochrons.

Garnet-Biotite Gneiss:

$$3.54 \pm .14 [1.81], R_i = .7008 \pm .0009$$

Hornblende-Pyroxene Gneiss (Outer Unit):

$$3.31 \pm .26 [1.78], R_i = .7011 \pm .0012$$

Hornblende-Pyroxene Gneiss (Inner Unit):

Geochemical disequilibrium precludes dating

but suggests an age greater than 3.8.

Metagabbro of Himmelberg:

$$2.68 \pm .20 [1.80, 2.41], R_i = .7037 \pm .0001$$

Amphibolite xenoliths:

$$3.52 \pm .15, R_i = .7094 \pm .0013$$

The trace element distribution patterns suggest the following interpretations. The hornblende-pyroxene gneiss (inner unit) is older than the Montevideo gneiss (which has been previously dated at 3.7 AE); the closest analog is probably a metamorphosed island arc basalt. The hornblende-pyroxene gneiss (outer unit) is probably analogous to a metamorphosed oceanic alkali basalt. The metagabbro is probably analogous to a metamorphosed ocean floor basalt or low-K tholeiite and the age of 2.68 AE is only a minimum. The garnet-biotite gneiss is probably analogous to a metamorphosed graywacke and the age of 3.54 AE is only a minimum. The amphibolite inclusions analyzed are probably analogous to metamorphosed graywackes

and are older than the Morton gneiss, which has been previously dated as being 3.55 AE old.

The rocks at Granite Falls therefore probably represent a very old (3.7 AE) layered sequence of basaltic rocks and graywackes which was intruded by the Montevideo gneiss 3.7 AE ago. The rock types are analogous to those of the less metamorphosed Archean greenstone-granite complexes, and are compatible with formation in an ancient island arc tectonic environment. They are probably the remnants of the original continental nucleus of the North American Craton.

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The Minnesota River Valley follows a straight course through glacial till plains for 180 miles from its head in the Browns Valley to the big bend at Mankato. It is along this section that crystalline bedrock exposures occur. The present river is grossly underfit, for it meanders within a sharply defined one to four mile wide valley formed by the much larger Glacial River Warren. This glacial river drained Glacial Lake Agassiz and , in so doing, was able to cut down through 150 to 250 feet of glacial till covering the bedrock. The resulting outcrops expose a central portion of the North American Craton.

The crystalline rocks of the area comprise a grossly layered sequence consisting of migmatitic granitic gneisses, amphibolite gneisses, and granulite gneisses of several varieties. The gneisses are inter-layered on a fine scale in places, and are cut by younger dikes and small intrusions. Previous isotopic age dating of the Montevideo and Morton gneisses has shown that these rocks are probably among the oldest on earth, with ages approaching four billion years. Consequently the Minnesota River Valley provides a rare and valuable window into the Early Precambrian history of the earth.

The rocks of the Granite Falls area have not been

dated by Rb-Sr methods, except for the Montevideo Gneiss. The objectives of this study are to further the understanding of the age and early history of these rocks through analyses of K, Rb, Sr, Ba, and the isotopic composition of Sr, and also to provide a better understanding of the behavior of Sr in these rocks during metamorphism.

## PREVIOUS INVESTIGATIONS

The Minnesota River Valley was visited by explorers as early as 1700, when the first accredited exploration was made by Le Sueur (Winchell and Upham, 1884). In 1823 the explorer Keating, a member of Major Long's expedition, noted "primitive rocks in situ" in the valley and observed:

"These (granite) masses bear very evident signs of crystalline origin, but the process must have been a confused one."

Keating's observation regarding the complexity of the history of Minnesota River Valley rocks has been substantiated by almost every subsequent investigator, although, strictly speaking, it is the investigators who have been confused, rather than the rocks.

Winchell and Peckham (1874) also wrote of the rocks in this area. They noted most of the major rock units and also provided a description of the terrane:

The valley all the way between Minnesota Falls and Granite Falls is about two miles wide and presents a singular billowy prospect of granite knobs, rising and falling on all sides, the river worming its way among them and having frequent rapids and waterfalls useful for mill privileges. At Granite Falls, as at Minnesota Falls, and all the way in between, the rock in the valley is a schistose granite that resembles that at St. Cloud both in color and composition. This, however, forms but a small part, the greater portion being schistose or laminated. It also varies to a red granite, i.e. one in which there are evident flesh-colored crystals of feldspar. These two variations do not seem to lie with any ascertainable fixed relation or superposition to the schistose or bedded

granite. This granite shows occasionally a knob of hornblende schist... The trap dykes... occur in the river bottoms about a mile above Granite Falls."

Other descriptions published prior to 1900 include Warren (1878), who first surveyed the valley in 1866, J. Hall (1869), Winchell and Upham (1888), and C.W.Hall (1899). Several specimens of rock from the Granite Falls area were included in an early U.S. Geological Survey educational series of specimens (Bayley, in Diller 1898). Structural and ornamental stone quarried in the Minnesota River Valley have been described by Bowles (1918) and Theil and Dutton (1935).

The first detailed map of the geology was published by Lund (1956). Lund dated some of the rocks as Huronian or pre-Huronian by the zircon-habit method of Tyler, et al., (1940), and also published some modal analyses and rock descriptions for various rock units.

Goldich, et al., (1961) dated rocks in the Granite Falls area (and elsewhere) but because of the dating technique used (K-Ar on biotite) they obtained an age of 1.8 AE (AE = billion years). This age was erroneously interpreted as a major emplacement event. Subsequent work showed that a delineation of the geological sequence of events and their ages was premature in 1961. Goldich and Hedge (1962) found evidence for an age of 2.4 AE on K-feldspars, and concluded that the 1.7-1.8 AE age was the result of a metamorphic event at that date,

rather than widespread igneous emplacement.

The first indication of an exceptionally old age for rocks in the Minnesota River Valley came with the publication of a U-Pb concordia plot by Catanzaro (1963). The data obtained by Catanzaro on zircon from two samples of the Morton gneiss and one of the Montevideo gneiss indicated an age of 3.55 AE with a metamorphic event at 1.8 AE. A sample of zircon from a small granite body in Sec.28 near Granite Falls gave an age of formation of 1.85 AE.

The 3.55 AE age determination of Catanzaro was duplicated by Stern (1964) using five zircon samples and one allanite sample from the Morton gneiss near Morton. An age of 2.65 AE was obtained on three zircon size fractions from the garnet-biotite gneiss near Granite Falls.

Hanson and Himmelberg (1967) studied dikes in the Granite Falls area and found that one type, the tholeiitic diabase dikes, were intruded into the older gneisses a minimum of 2.0 billion years ago, whereas a second type, the hornblende andesite dikes, were intruded about 1.8 billion years ago. One sample of hornblende from the hornblende-pyroxene gneiss (country rock) yielded a K-Ar age of 2.74 AE.

Himmelberg and Phinney (1967) studied mineral assemblages in the Montevideo gneiss, the garnet-biotite gneiss, and the hornblende-pyroxene gneiss (all in the

Granite Falls - Montevideo area). They concluded that the rocks had been subjected to regional, granulite facies metamorphism; mineral assemblages characteristic of both subfacies of the granulite facies as well as of the amphibolite facies were attributed solely to compositional variations rather than differences in metamorphic grade. It was also concluded that a close approach to chemical equilibrium was attained during this metamorphism.

Himmelberg (1968) reported a revision of some of the geology of the Granite Falls - Montevideo area determined by Lund (1956), and also reported thin section studies on the rocks.

The most comprehensive study of the ages of Minnesota River Valley rocks is that of Goldich, Hedge and Stern (1970). They presented Rb-Sr and U-Pb data which supported an age of 3.55 AE for the Morton and Montevideo gneisses, and also metamorphic events at 1.8 and 2.6 billion years.

Hanson and Arth (1972) reported theoretical trace element calculations and analytical data suggesting that a rock such as the Montevideo Gneiss could be generated by the partial melting at mantle depths of an amphibolite or eclogite of Archean basalt composition.

Goldich and Stern (1974) published additional Rb-Sr analyses on samples from the Montevideo gneiss and revised their estimate of the age of formation up



to 3.8 billion years.

Goldich and Hedge (1974, 1975) published analyses indicating that the red, massive phase of the Montevideo Gneiss was emplaced in the older (3.8 AE) gray phase about 3.0 billion years ago.

Farhat (1975) and Farhat and Wetherill (1974, 1975) presented additional analyses on the Montevideo Gneiss and the Hornblende-pyroxene Gneiss which suggested to them an uncertain age in the 3.1 - 3.3 AE range, with a metamorphism at 2.5 AE.

## EXPERIMENTAL PROCEDURES

A. Powder sample preparation

1. Whole-rock samples weighing 4-5 kg were selected in the field for analysis and were cobbled to remove previously exposed surfaces, leaving a fresh core.
2. The samples were removed to a sample preparation room and were broken down into pieces less than 3 cm in size using a sledge hammer and iron plate.
3. The pieces were examined and those having soiled or weathered surfaces were discarded.
4. The remaining pieces were washed several times in distilled water in a large Pyrex beaker and then dried in a dessicating oven at 110° C.
5. The pieces were removed, one at a time, with clean tongs, and crushed to less than 5 mm using a hard tool steel mortar and pestle.
6. The rough-crushed sample was rolled and coned for 15 minutes, and then coned and quartered to obtain a representative 500 gram fraction.
7. The 500 gram fraction was crushed in the mortar to less than 2 mm.
8. The 500 gram fraction was rolled and coned for 15 minutes and then coned and quartered to obtain two 100 gram fractions, one for whole-rock analysis and one for mineral separation.

9. The 100 gram fractions were returned to the mortar and crushed to a fine powder (smaller than 100-mesh).
10. The fraction for mineral separation was sieved to yield a fraction between 100 and 200 mesh in size.
11. Both fractions were stored in labeled glass vials for later chemical and mineral separation.

B. Mineral separation

1. A 10-cm Pyrex funnel burette was partially filled with a heavy liquid; the following were used:
  - (a) BROMOFORM (BF), density = 2.89
  - (b) TETRABROMOETHANE (TBE), density = 2.96
  - (c) METHYLENE IODIDE (MI), density = 3.30
  - (d) THALIIUM MALONATE FORMATE (TMF), d. = 4.25
2. A few grams of powdered sample were sprinkled onto the heavy liquid and stirred in with a glass stirring rod.
3. The sample was allowed to stand a separate.
4. Heavy (bottom) fraction was drawn off into one beaker; the light (top) fraction was drawn off into another beaker.
5. The heavy liquid was washed away with acetone; the sample was washed in acetone and decanted six times, and dried.
6. Steps 2-5 were repeated until several hundred milligrams of each mineral were obtained. Samples

were processed according to the heavy liquids flow chart on table 1.

7. Mineral fractions were washed in acetone and dried in a dessicating oven.
8. Mineral separates were microscopically examined to verify completeness of separation exceeding 99%. Samples which were inadequately separated were re-run through steps 2-8.
9. Mineral separates were stored in labeled glass vials.

C. Chemical separation

1. 0.2 to 0.3 grams of sample were weighed on an analytical balance and placed in labeled Teflon beakers.
2. One drop of  $\text{HClO}_4$  was added.
3. 2 ml of ultrapure HF solution (manufactured in the laboratory from ultrapure gaseous HF and triple-distilled water) were added.
4. The mixture was allowed to stand and react for several hours.
5. The mixture was evaporated to dryness.
6. Ten ml of ultrapure 10-Normal HCL (manufactured in the laboratory from ultrapure gaseous HCl and triple-distilled water) were added.
7. The mixture was heated to boiling and slowly diluted with triple distilled water to a 2N solution.

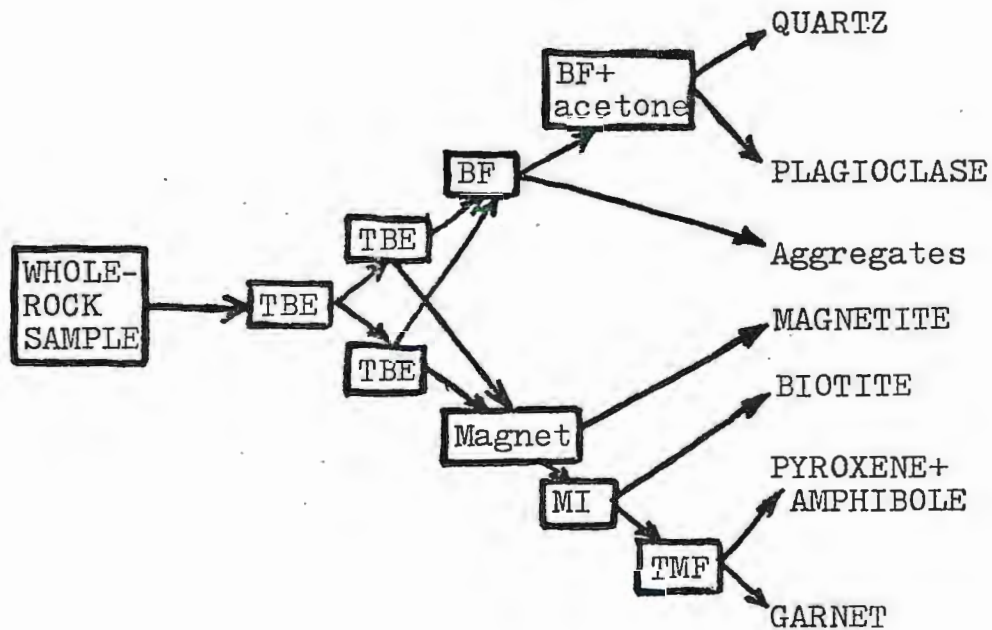


Table I. Mineral separation flow chart. Heavy liquids (described in text) and a hand magnet are used. Arrows pointing up indicate fractions which float in the heavy liquid (or are picked up by the magnet); arrows pointing down indicate fractions which sink in the heavy liquid.

8. The resulting solution was poured into a 100-ml volumetric flask and diluted to exactly 100 ml with triple-distilled water.
9. 50 ml were stored in a plastic bottle and labeled for possible future use.
10. 45 ml were used for the isotope composition (IC) analysis.
  - (a) evaporated down to 1 ml of solution (acidity of about 6 N).
  - (b) diluted to 3 ml (2N) with triple-distilled water.
  - (c) processed through ion-exchange column, Sr concentrate collected.
  - (d) Sr concentrate evaporated to dryness in 5-ml quartz microbeaker.
  - (e) One drop of  $\text{HClO}_4$  and one drop of  $\text{HNO}_3$  added and evaporated to dryness.
  - (f) microbeaker is cooled, covered with Parafilm, labeled and stored for future mass spectrometer analysis.
11. 5 ml used for isotope dilution (ID) analysis:
  - (a) K, Rb, Sr, and Ba spikes added.
  - (b) processed according to steps 10-a through 10-f above. K and Rb concentrates were

collected in the same microbeaker; Sr and Ba were collected in a different microbeaker.

All of the above-described chemical digestion was done only in Teflon beakers under dry nitrogen atmosphere and clean room conditions.

The ion exchange procedure utilizes columns manufactured on campus of pure quartz, having the following dimensions: inside diameter = 1.9 cm; resin bed height = 19 cm; total quartz column height = 33 cm. The resin used was Bio-Red analytical grade AG 50W-X8 Cation Exchange Resin, 200-400 mesh, hydrogen form. Columns were calibrated by Michael Coscio using radioactive tracer isotopes supplied by Oak Ridge National Laboratories.

#### D. Mass spectrometer analysis

All isotope analyses were performed on a 30-cm radius, single-focussing mass spectrometer with a programmable magnetic field and a digital, on-line data collection system. Detailed specifications of this instrument and supporting equipment are given on table 2 and figure 1.

Table 2. Mass spectrometer specifications

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Type:	- 30-cm radius, $60^\circ$ single-focussing, with programmable magnetic field and on-line data collection system
Filaments:	- Rhenium (H.Cross Co.) 0.002 inch thickness 0.030 inch width
Ion production:	- Surface thermal ionization
Accelerating voltage:	- 7500 volts
Ion detection:	- Electron multiplier, gain of 1400, plus a vibrating reed electrometer (VRE)
Ion signal conversion:	- Analog signals from VRE are measured by a digital voltmeter consisting of a voltage-to-frequency converter (Vidar 240) and counter (Dana 8104)
Magnetic field control:	- Varian FR-40 control-gaussmeter modified to accept programmed commands
Operating pressure:	- Source = $3 \times 10^{-7}$ torr Analyzer = $6 \times 10^{-8}$ torr
Vacuum pump system:	- 1 mechanical pump (Edwards Speedivac ED 500); 2 diffusion pumps (Edwards Speedivac EO 4); 2 ion pumps (Ultek)
Data collection system:	- Varian on-line computer interfaced with magnetic field control
Spikes (internal standards):	- Solutions of $K^{41}$ , $Rb^{87}$ , $Sr^{86}$ , and Ba 135 calibrated against gravimetric solutions of Johnson-Matheson Spec-pure reagents

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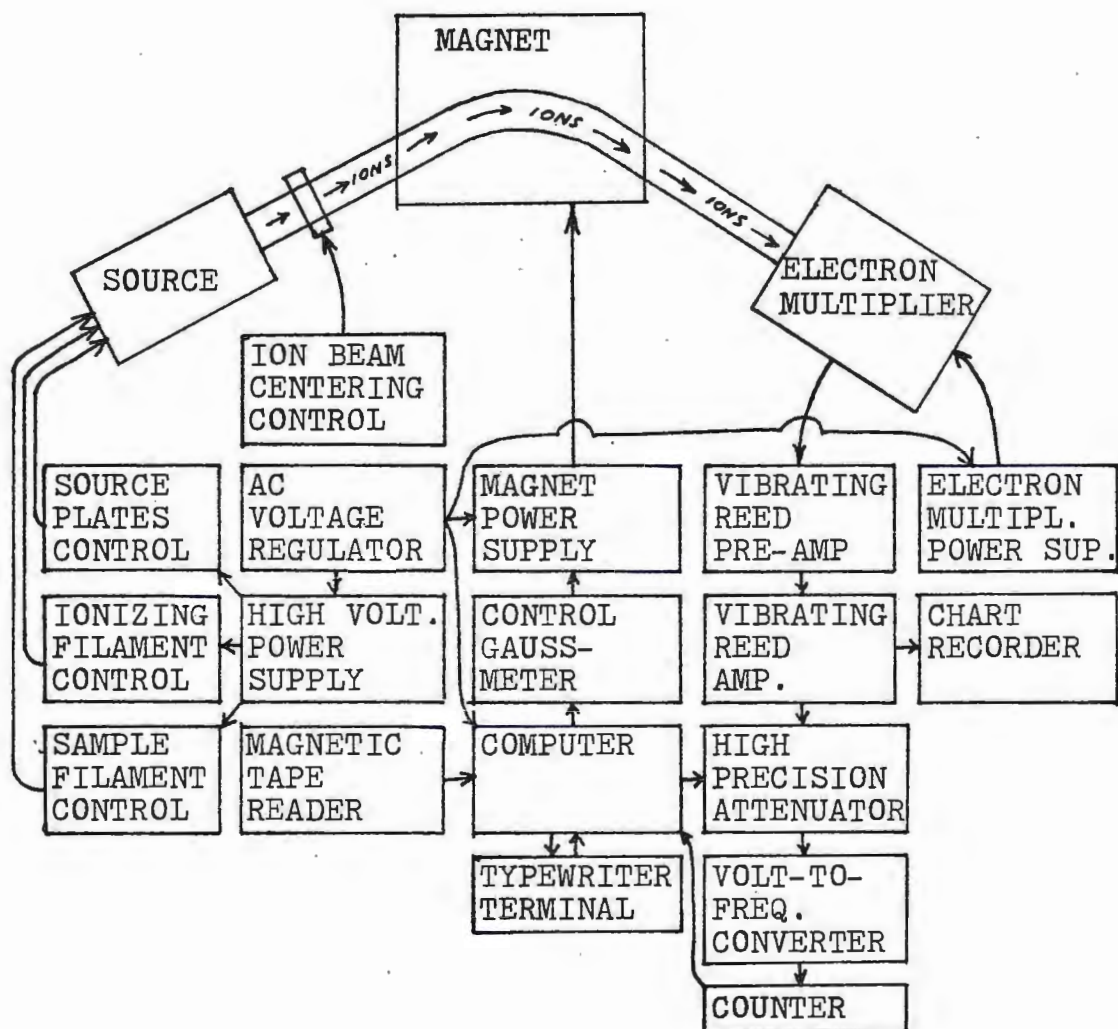


Figure 1. Modular configuration of mass spectrometer and on-line data gathering system.

Operational procedures were as follows: the source assembly was kept clean by frequent disassembly and bathing in boiling 50% nitric acid. Filaments were purged of possible contaminants by heating in a vacuum for 1-8 hours at twice the current used in the analysis. Samples were loaded onto the Re filament using ultrapure 0.1 N nitric acid; filaments were discarded after one use.

Once the system was sealed and pumped down to operating vacuum, the Re sample filament was heated by a current of 1.5 to 2.5 amps. Current to the source plates was tuned manually to achieve optimum intensity at the lowest filament current possible, and to achieve peak shapes of maximum width and horizontal tops. Fine adjustment was made on the magnet control-gaussmeter manually. From this point onward the analysis of either IC or ID samples was carried out under the commands given by the on-board computer, and the possibility of operator biasing of the data collection was thereby eliminated.

The computer program (written by Norman Evenson) controlled the switching of the magnetic field for the detection of various isotopes, retained the data in memory until the conclusion of the run, and after the run was completed, made statistical calculations. These calculations culminated in the determination of

the concentration (in ppm) of the element being analyzed in an ID analysis, plus the 2 sigma error, or in the case of an IC analysis, determination of the  $\text{Sr}^{87}/\text{Sr}^{86}$  ratio and corresponding 2 sigma error. Each run consisted of a series of symmetrical up-down scans of the mass spectrum, with background measurements made at 0.5 mass unit on either side of the peaks. A linear interpolation of peak intensities yielded the relevant isotopic ratios. Measurements of peak intensities were made allowing a settling time of two seconds between the magnetic field change and the start of integration to allow for stabilization of the VRE, the magnetic field, and the other electronics. Integration time was one second. Data were not collected for Sr IC analyses until the  $\text{Rb}^{87}$  level was ascertained to be less than  $3 \times 10^{-5}$  of the  $\text{Sr}^{87}$  intensity; no Rb spike was present in the Sr IC samples. Further details of this system are given in Murthy, et al., (1971).

#### E. Statistical considerations

##### Isotope dilution equation:

$$W_x = (W_t) \frac{(R_t - R_m)(R_s M_1 + M_2)}{(R_m - R_s)(R_t M_1 + M_2)}$$

Where:  $W_x$  = weight of an element in the sample (unknown)

$W_t$  = weight of element in the spike (known)

$R_s$  = (Isotope #1 / Isotope #2) of the element

in the spike (natural abundance)

$R_m$  = (Isotope #1 / Isotope #2) of the element  
in sample + spike (measured)

$M_1$  = atomic weight of isotope #1

$M_2$  = atomic weight of isotope #2

Linear regression computation:

Linear regressions were computed according to the method of York (1969) in which errors in both X and Y are considered.

Decay constant of Rb<sup>87</sup> used:  $1.39 \times 10^{-11}$  per year.

Errors:

Errors in isotope dilution data arise principally from uncertainty in measuring the amounts of the individual spikes and from isotopic fractionation during the mass spectrometer analysis. These may each show maximum deviations of about  $\pm 1\%$ . Therefore errors of  $\pm 2\%$  are assigned to elemental abundance measurements, and to the Rb<sup>87</sup>/Sr<sup>86</sup> ratios, and are considered conservative.

Blank levels for total analytical procedures have been repeatedly measured over the last ten years by various operators, and are currently determined to be: K = 20 ng; Rb = 0.1 ng; Sr = 1.0 ng; Ba = 6.0 ng. These are negligible at the levels of concentration and precision reported here but are still used in the

final calculations.

in no case are  $2\sigma$  errors on the IC analysis assigned at less than 0.00005, as this is considered the practical limit of precision and long term reproducibility of the system, as determined by periodic measurement of isotopic standards over ten years by various operators.

$\text{Sr}^{87}/\text{Sr}^{86}$  ratios taken during isotope composition analyses were corrected on a proportional basis relative to the measured  $\text{Sr}^{86}/\text{Sr}^{88}$  ratio which, unfractionated, was presumed to be 0.1194.

For each IC analysis 400 scans of the mass spectrum were taken, divided into up-down scan pairs, ten pairs each, in twenty sets. For isotope dilution analyses ten pairs for each of 3 to 8 sets were taken. Backgrounds were measured before every pair.

Further discussion of errors produced in various separate portions of the system can be found in Murthy, et al., (1971).

Analytical statistical errors for the IC analyses are given in the last figures in the data tables as  $\pm 2\sigma_m$  where  $\sigma_m$  is calculated as follows:

$$\sigma_m = \frac{\sum_{i=1}^n (\bar{X}_i - m)^2}{n(n-1)}$$

where  $n$  = number of sets of scans, and  $(\bar{X}_i - m)$  is the

difference between the mean value of the i-th set and the mean of all sets.

The  $\text{Rb}^{87}/\text{Sr}^{86}$  ratio is calculated from the ID analysis as follows:

$$\frac{\text{Rb}^{87}}{\text{Sr}^{86}} = \frac{\text{Rb}_w}{\text{Sr}_w} \underbrace{\hspace{10em}}_{\text{correction coefficient}} \frac{\text{Rb}_{\text{ID}}}{\text{Sr}_{\text{ID}}}$$

The most recent determination for the value of the correction coefficient is 2.89102.

Ages were calculated from the linear regression according to the standard age equation:

$$t = \frac{1}{\lambda} \ln [1 + \tan a]$$

where  $t$  = age,  $\lambda$  = the  $\text{Rb}^{87}$  decay constant, and  $a$  = the slope angle of the isochron.

## SAMPLE LOCATIONS

The general geology of the Minnesota River Valley is shown in Figure 2. Rock units in the Granite Falls area are shown in more detail in Figure 3, along with approximate sample locations. The Hornblende-pyroxene Gneiss of Himmelberg (1968), which was the Gabbro Gneiss of Lund (1956), has been subdivided here into three units: the Hornblende-pyroxene Gneiss (Inner Unit), the Hornblende-pyroxene Gneiss (Outer Unit), and the Hornblende-pyroxene Granulite or "Metagabbro". The Metagabbro unit was first recognized as distinct from the rest of the hornblende-pyroxene gneiss by Himmelberg (personal communication). Himmelberg recognized the unit by its relative lack of banding and the presence of two pyroxenes plus hornblende. His only criterion for considering the inner and outer units as separate bodies is that they are not in contact at the surface. The possibility that these two units are actually parts of a single unit which was split by an intrusion of the Montevideo Gneiss will be discussed in the next section.

Sample locations are given on Figures 4 for the Hornblende-pyroxene Gneiss (Inner Unit), Figure 5 for the Metagabbro, Garnet-biotite Gneiss, and Hornblende-pyroxene Gneiss, Figure 6 for the amphibolite xenolith from the Sacred Heart area, Figure 7 for the amphib-

olite inclusions from the Schmidt Farm, and Figure 8 for the amphibolite xenolith from the Morton quarry.














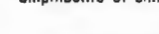
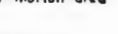

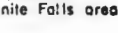
All samples were chosen for their apparent freshness and lack of alteration. Samples GF-21 and GF-22 were located less than a meter from the top of the roadcut whereas the other samples were located at least two meters below the top of the roadcut. As will be shown in the next section, these two samples plot below the isochron determined by the other samples and may do so because of incipient weathering attributable to the sample locations relative to the weathering surface. On the opposite side of the road there is a remnant of a large pot-hole. Samples GF-21 and GF-22 may have been located adjacent to a Cretaceous weathered zone that was gouged out in the Pleistocene.

Samples of amphibolite xenoliths were taken from three different areas and appear to represent two different types of occurrences: large "rafts" up to several tens of meters in length, and much smaller inclusions in the 10 to 50 cm size range. Samples MORT-1 and SH-1 are from small inclusions and sample AM-1 is from a large raft. SH-1 was the only amphibolite sample which appeared obviously contaminated by lighter felsic material from its host.



Figure 2. General geology of the Minnesota River Valley compiled by Grant in Sims and Morey (1972).

# EXPLANATION

-  Sioux Quartzite
-  Gabbro to granodiorite  
(Similar to rocks of Cedar Mountain complex)
-  Adamellite
-  Granite  
(Dominantly gneissic quartz monzonite; stippled where rafts of amphibolite or gneiss are common)
-  Biotite gneiss  
(Garnet-biotite gneiss of Granite Falls area and biotite gneiss and amphibolite of unit D near Dehn)
-  Hornblende-pyroxene gneiss
-  Migmatitic gneiss
-  Undivided quartzfeldspathic gneiss, commonly with rafts of amphibolite
-  Quartzfeldspathic gneiss of unit C, Sacred Heart-Morton area
-  Quartzfeldspathic gneiss with amphibolitic rafts of unit B, Sacred Heart-Morton area
-  Interlayered quartzfeldspathic gneiss and amphibolite of unit A, Sacred Heart-Morton area
-  Granitic gneiss with rafts of amphibolite (Montevideo gneiss), Montevideo-Granite Falls area
-  Interlayered gneisses, south of Granite Falls
-  Inferred fault
-  Synclinalorium
-  Contact, approximate and assumed
-  Anticlinorium

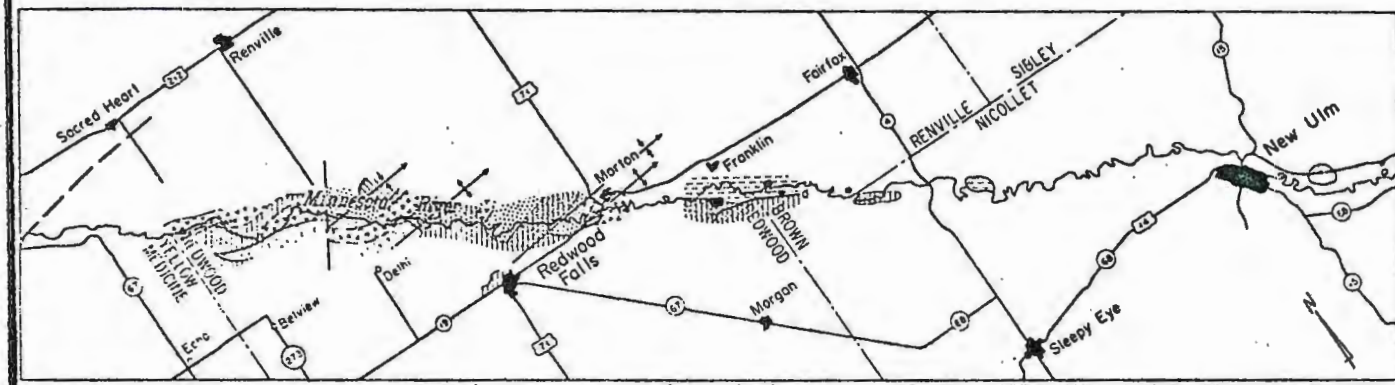
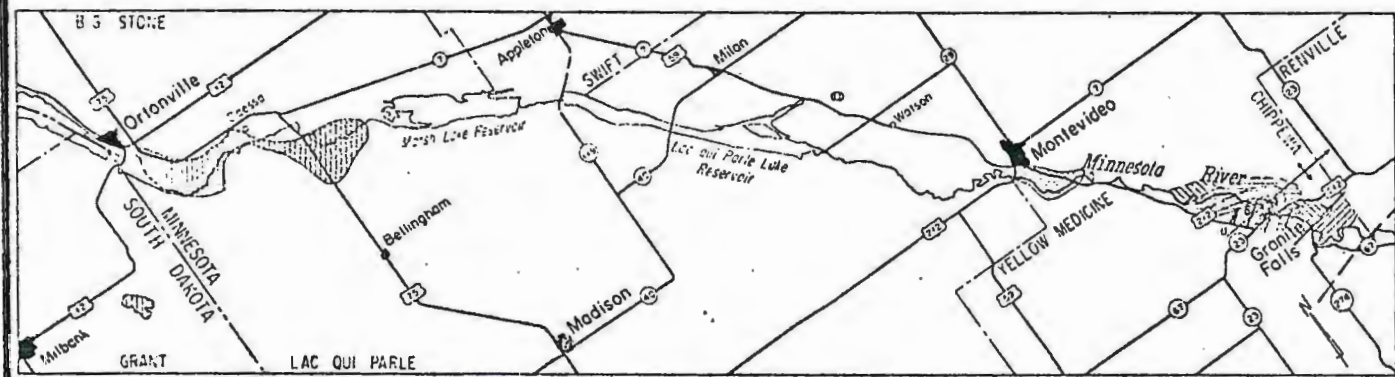


Figure 3. General geology (as determined by Lund, 1954, and Himmelberg, 1968) and approximate sample locations in the Granite Falls area.

Rock units:

- A: Montevideo Gneiss (Inner Unit)
  - B: Hornblende-pyroxene Gneiss (Inner Unit)
  - C: Montevideo Gneiss (Outer Unit)
  - D: Hornblende-pyroxene Granulite (Metagabbro of Himmelberg)
  - E: Hornblende-pyroxene Gneiss (Outer Unit)
  - F: Garnet-biotite Gneiss
- Gabbro gneiss inclusions not shown.

See figures 4 and 5 for more precise locations.

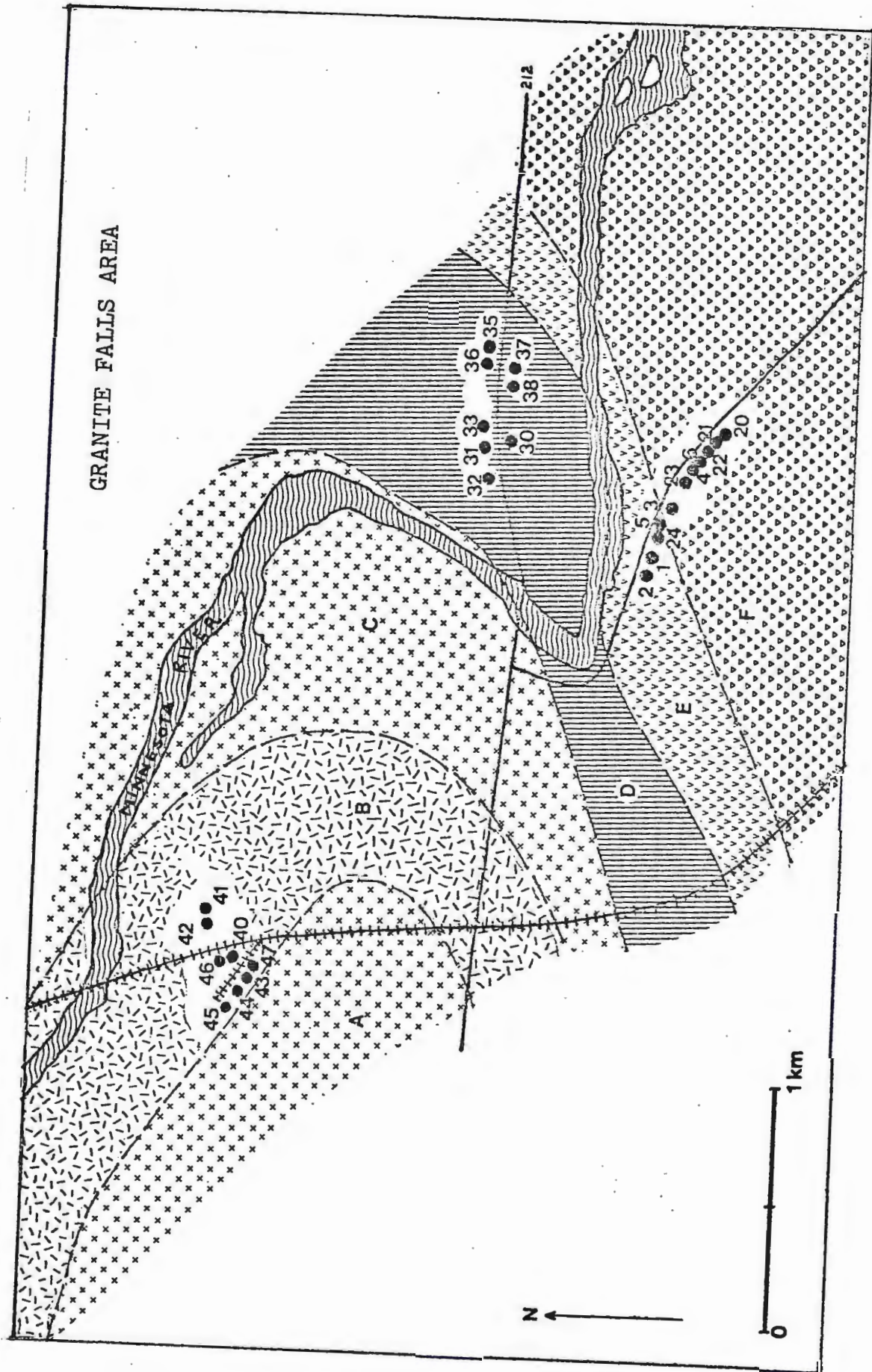


Figure 4. Sample locations for samples of the Hornblende-pyroxene Gneiss (Inner Unit). Sample numbers on the map have the "GF" prefix omitted. The map area is located in T. 116 N., R. 39 W., and was mapped by Himmelberg (1968). Rock units shown include the Montevideo Gneiss (Inner Unit) (A), the Hornblende-pyroxene Gneiss (Inner Unit) (B), the Montevideo Gneiss (Outer Unit) (C), and late dikes which cut across the map area in a northeast-southwest direction.

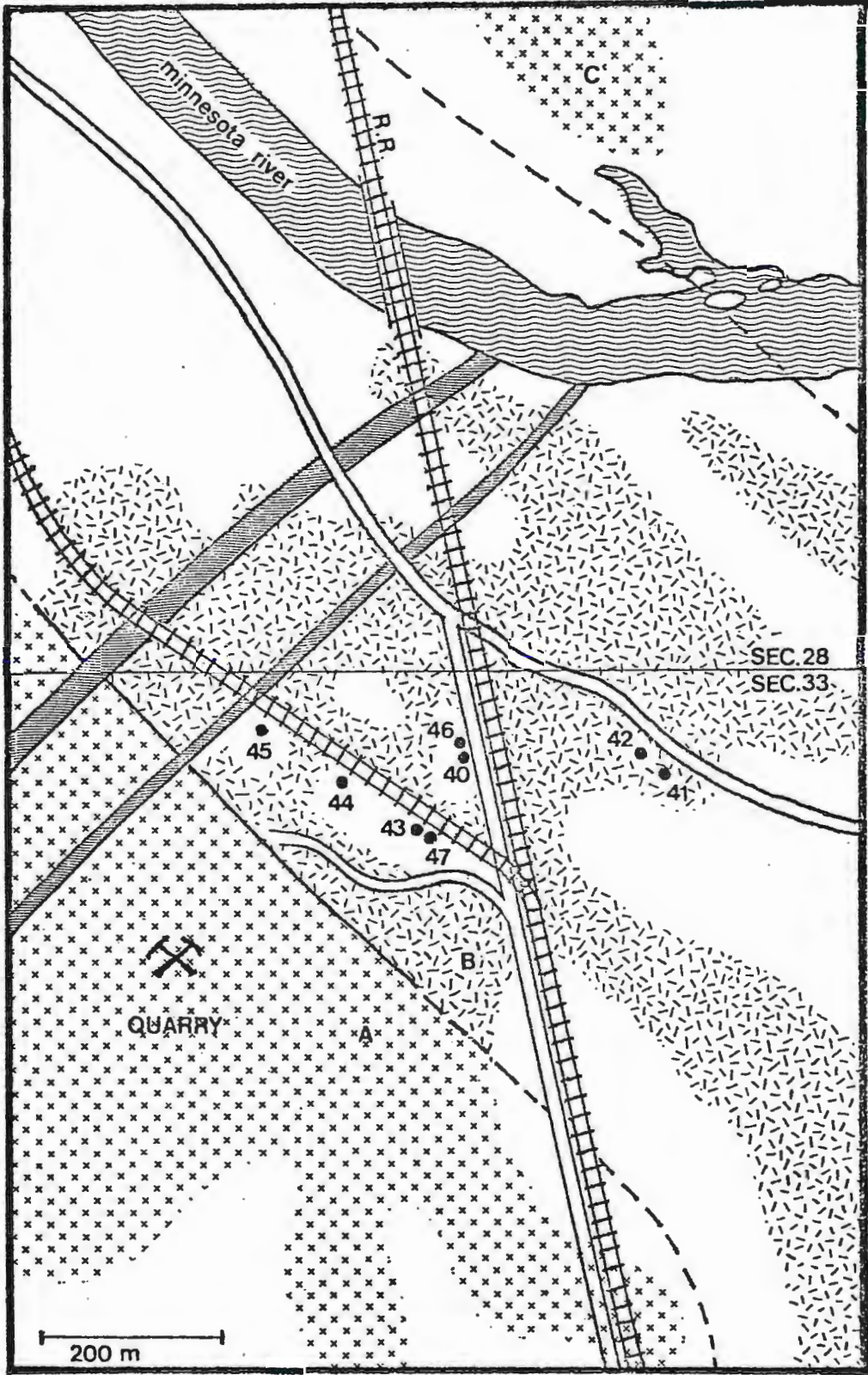


Figure 5. Sample locations for samples of the Hornblende-pyroxene Granulite (Metagabbro), 30,31,32,33,35,36,37,38; for samples for the Hornblende-pyroxene gneiss (Outer Unit), 1,2,5,24; for samples of the Garnet-biotite Gneiss, 3,4,6,20,21,22,23. (latter two shown on b.)

Dashed lines represent approximate rock unit contacts (see Figure 3).

Heavy line is a late (1.8 Ae) dike.

b. shows the southwest side of the roadcut on Highway 67, and indicates the location of each sample. Horizontal view looking southwest.

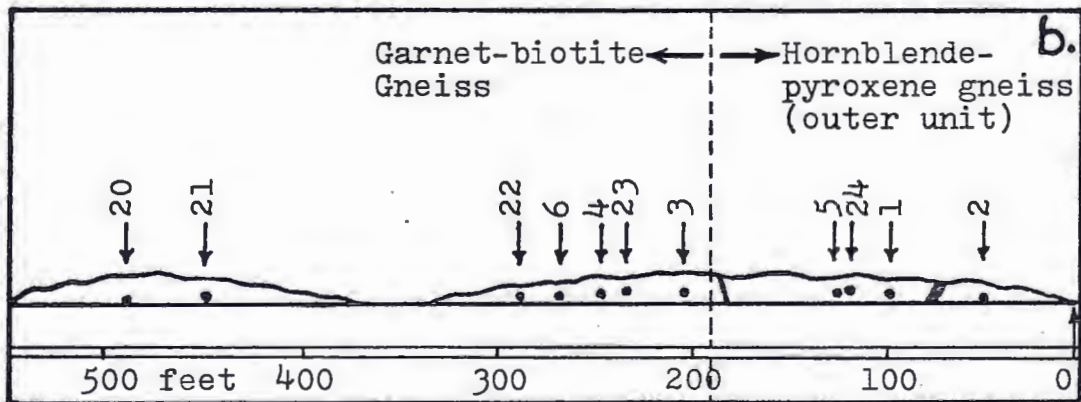
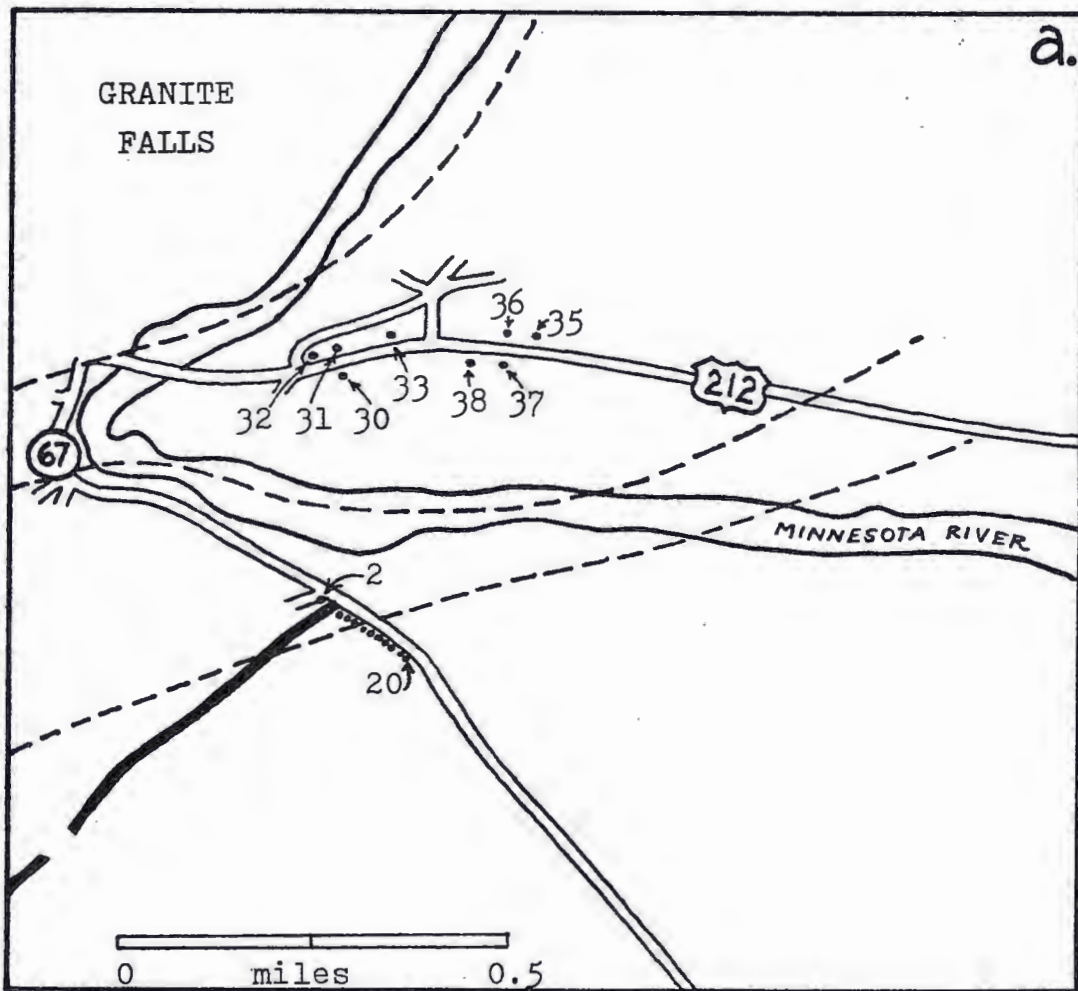




Figure 6. Sample location for sample SH-1 is indicated by an "X" in the center of the map area. The sample was removed from an amphibolite inclusion approximately 1 foot in diameter suspended in Sacred Heart Granite. The map is from Grant (1972b), and shows the geology of the Sacred Heart area, T. 114 N., R. 37 and 38 W.

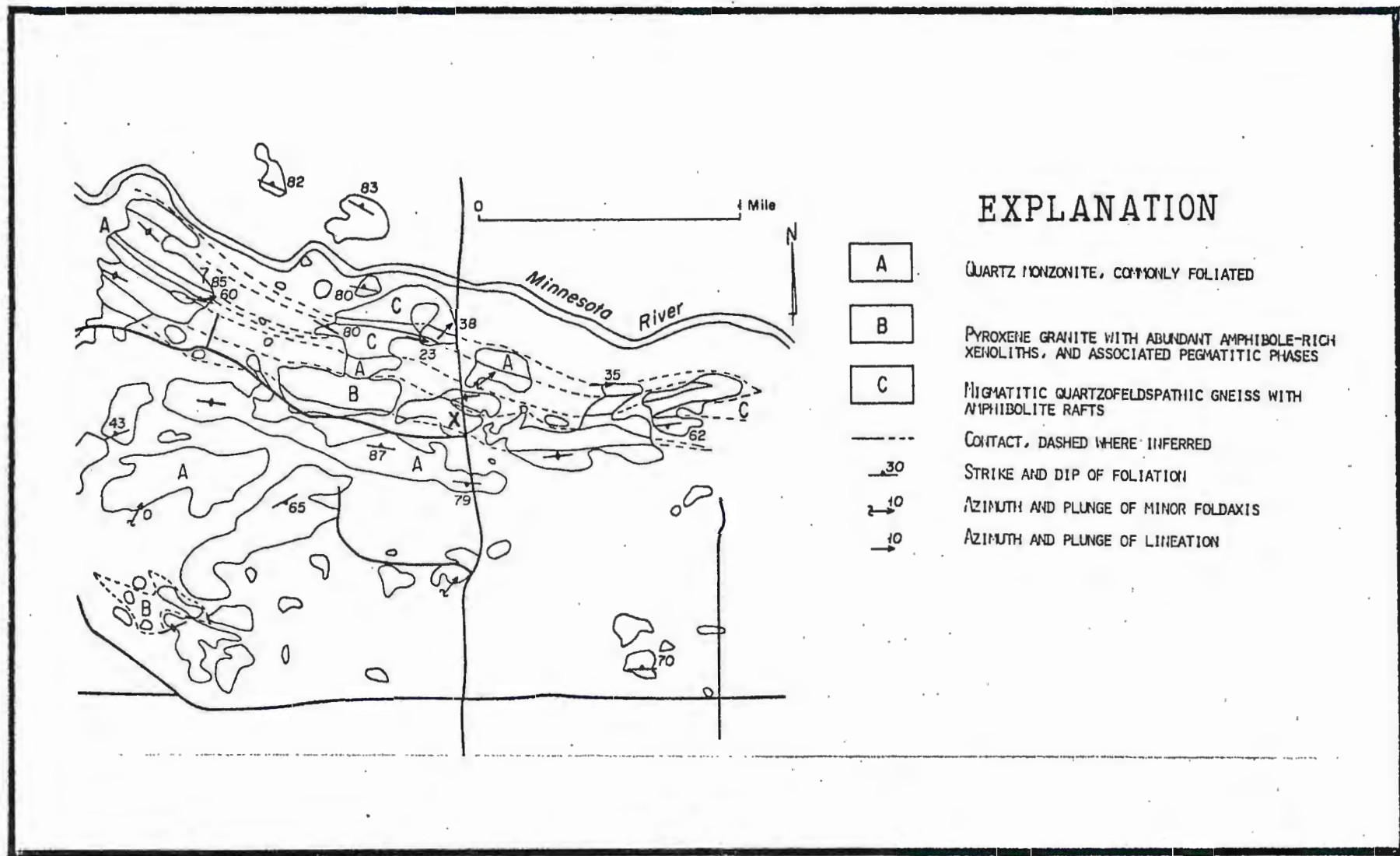
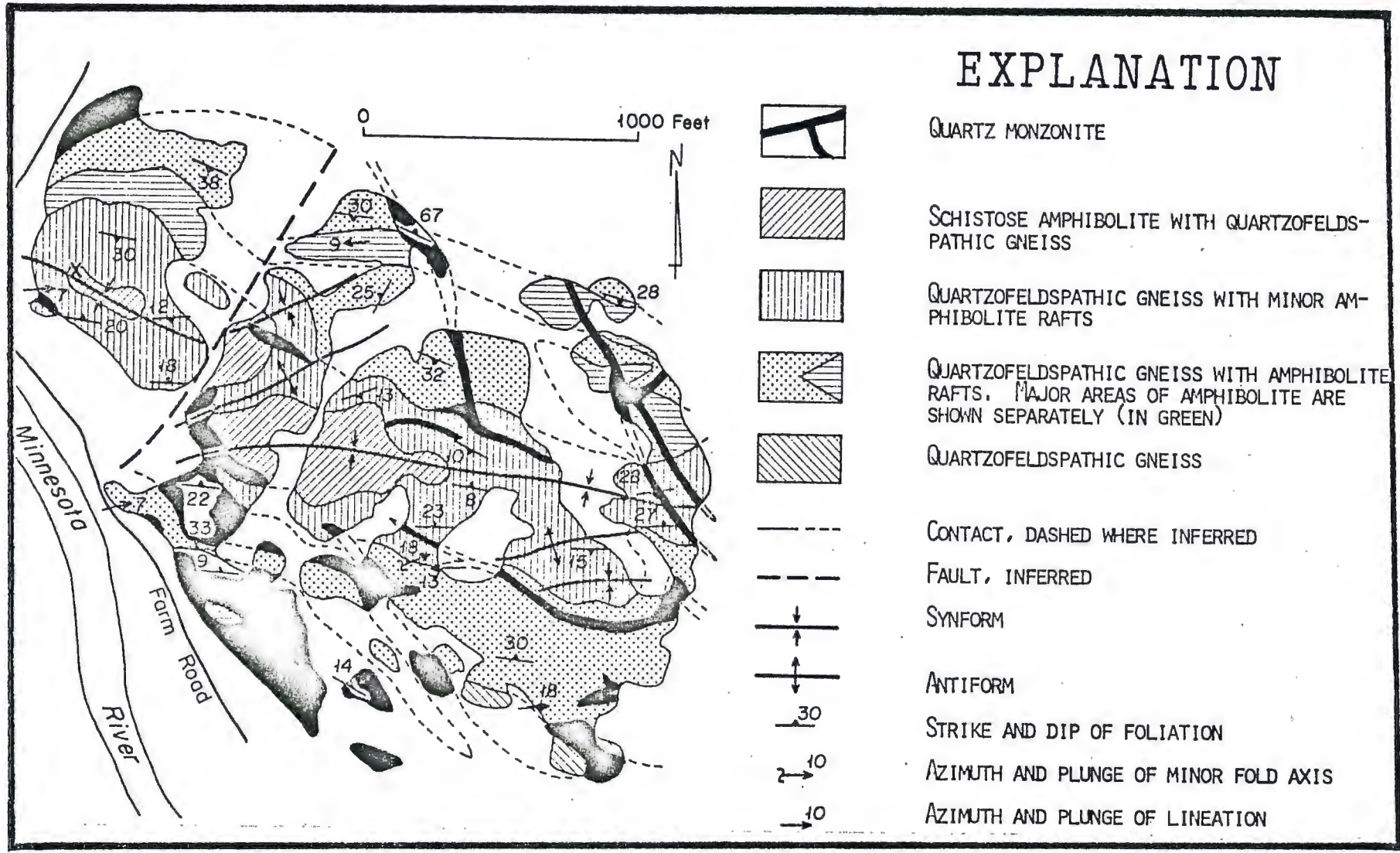


Figure 7 . Sample location for sample AM-1 is indicated by an "X" in the upper left portion on the map area. The sample was removed from a large (300 feet) amphibolite "raft". The map shows the generalized geology in the area of Secs. 2 and 11, T. 113 N., R. 36 W., and is from Grant (1972b). (Schmidt farm)

# EXPLANATION



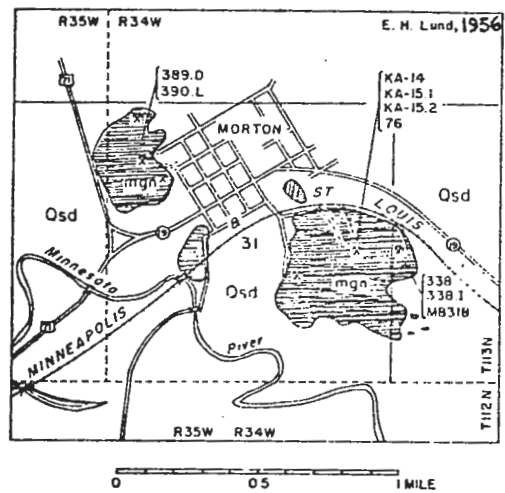


Figure 8. The location of sample Mort-1 was in the Cold Spring Granite Company quarry, near the locations of Goldich samples KA-14, KA-15.

## RESULTS

Isotopic composition of Sr, and the abundances of K, Rb, Sr and Ba, have been measured for 27 whole-rock samples and 18 mineral separates from the Granite Falls area, and 4 whole-rock samples and 1 mineral separate from the Morton-Sacred Heart area. Analytical results are presented on tables 3, 4 and 5. The results have been used to construct Rb-Sr evolution diagrams (Figures 9 through 15). A general summary of the age determinations is presented on tables 6 and 7. A summary of all age determinations ever made on rocks from the Granite Falls area, including those determinations made here, is presented on Figure 16.

Table 3. Whole-rock analyses of samples from the Granite Falls area

Sample Number		K (ppm)	Rb (ppm)	Sr (ppm)	Ba (ppm)	K/Rb	Rb/Sr	Sr/Ba	Rb/ Sr	Sr/ Sr
<b>a. Hornblende-pyroxene Gneiss (Outer Unit)</b>										
GF-1	WR	12,586	30.51	180.68	363.21	413	0.169	0.497	.48818	.72412±9
GF-2	WR	11,099	31.67	436.72	657.33	401	0.073	0.664	.20965	.71115±7
GF-5	WR	9,926	16.67	174.75	296.90	596	0.095	0.589	.27547	.71430±15
GF-24	WR	11,646	42.17	478.51	614.91	276	0.088	0.778	.25476	.71244±12
AVE.	WR	11,314	30.25	317.67	483.09	374	0.095	0.795	.27465	

Table 3. continued

Sample Number	K (ppm)	Rb (ppm)	Sr (ppm)	Ba (ppm)	K/Rb	Rb/Sr	Sr/Ba	<sup>87</sup> Rb/ <sup>86</sup> Sr	<sup>87</sup> Sr/ <sup>86</sup> Sr
<b>b. Garnet-biotite Gneiss</b>									
GF-3 WR	11,816	27.05	407.09	573.30	437	0.066	0.710	.19210	.71110±8
GF-4 WR	18,872	56.33	465.56	635.67	335	0.014	0.732	.34979	.71833±13
GF-6 WR	19,121	59.28	510.52	1042.3	323	0.116	0.490	.33569	.71741±10
GF-20 WR	15,771	56.21	429.28	191.05	281	0.131	2.247	.37857	.71953±9
GF-21 WR	15,764	53.19	463.20	64.68	296	0.115	7.170	.33195	.71495±5
GF-22 WR	15,940	57.14	375.23	604.48	279	0.152	0.621	.44024	.71919±9
GF-23 WR	27,193	105.02	354.96	998.19	259	0.296	0.356	.85532	.74419±8
AVE. WR	17,782	59.17	429.41	587.10	300	0.138	0.731	.39896	



Figure 14. Rb-Sr evolution diagram showing analyses of five mineral separates and the whole-rock analysis from sample GF-4 (Garnet-biotite Gneiss). Least squares regression indicates an age of metamorphism of  $1.78 \pm .04$  Ae (2 sigma). The garnet analysis was not used in the regression.

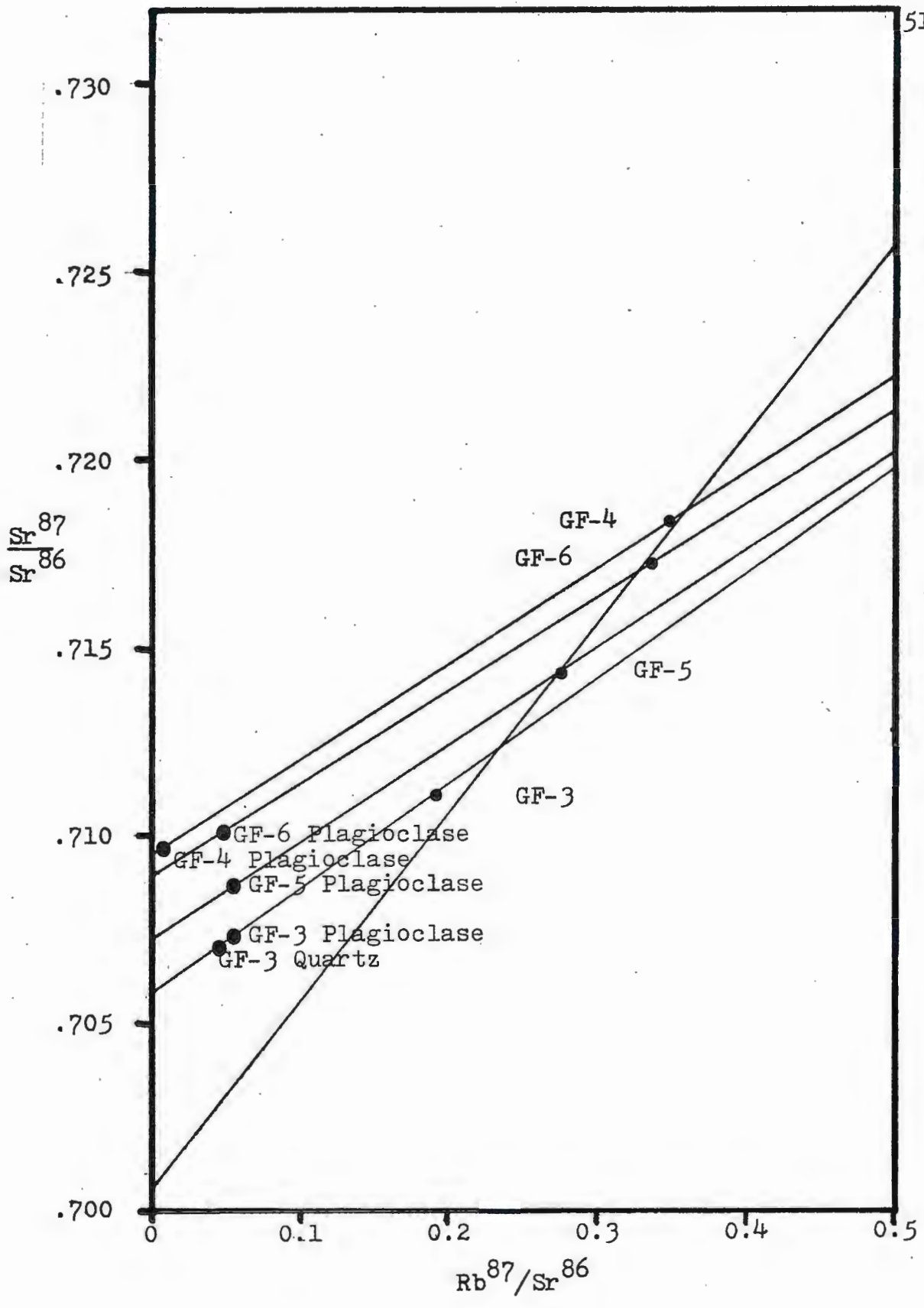


Figure 13. Hornblende-pyroxene Gneiss (Outer Unit ) (GF-5), and Garnet-biotite Gneiss Rb-Sr evolution diagram. Metamorphic isochrons indicated by the analyses of plagioclase and a quartz fraction yield ages of 1.91 Ae (GF-3), 1.79 Ae (GF-4), 1.78 Ae (GF-5), and 1.81 Ae (GF-6). Small points are whole-rock analyses; large points are analyses of mineral separates.

Table 5. Mineral analyses for samples from the Granite Falls area

Sample Number	K (ppm)	Rb (ppm)	Sr (ppm)	Ba (ppm)	K/Rb	Rb/Sr	Sr/Ba	Rb/ Sr	Sr/ Sr
<b>a. Hornblende-pyroxene Gneiss (Outer Unit)</b>									
GF-5 Plag.	6,244	8.84	481.07	419.97	-	-	-	.05317	.70873 $\pm$ 34
GF-5 Biot.	44,854	242.47	64.04	2484.90	-	-	-	10.946	.98134 $\pm$ 33
<b>b. Garnet-biotite Gneiss</b>									
GF-3 Qtz.	5,940	6.04	401.25	382.30	-	-	-	.04352	.70705 $\pm$ 7
GF-3 Plag.	6,383	9.98	548.07	312.97	-	-	-	.05264	.70735 $\pm$ 12
GF-3 Biot.	65,048	282.60	33.10	2074.9	-	-	-	24.683	1.29160 $\pm$ 8
GF-4 Plag.	12,098	19.70	7296.80	596.00	-	-	-	.00781	.70970 $\pm$ 32
GF-4 Magnet.	1,652	6.79	23.45	57.01	-	-	-	.83710	.73324 $\pm$ 22
GF-4 Pyrox.	781	3.51	8.38	24.60	-	-	-	1.2109	.73938 $\pm$ 14
GF-4 Garnet	953	4.12	3.82	36.30	-	-	-	3.1180	.79339 $\pm$ 173
GF-4 Biot.	44,286	218.9	112.10	1165.7	-	-	-	5.6453	.85124 $\pm$ 8
GF-6 Biot.	56,489	256.33	78.53	1887.5	-	-	-	9.4365	.96090 $\pm$ 30
GF-6 Plag.	6,686	12.76	777.92	363.29	-	-	-	.04742	.71008 $\pm$ 84

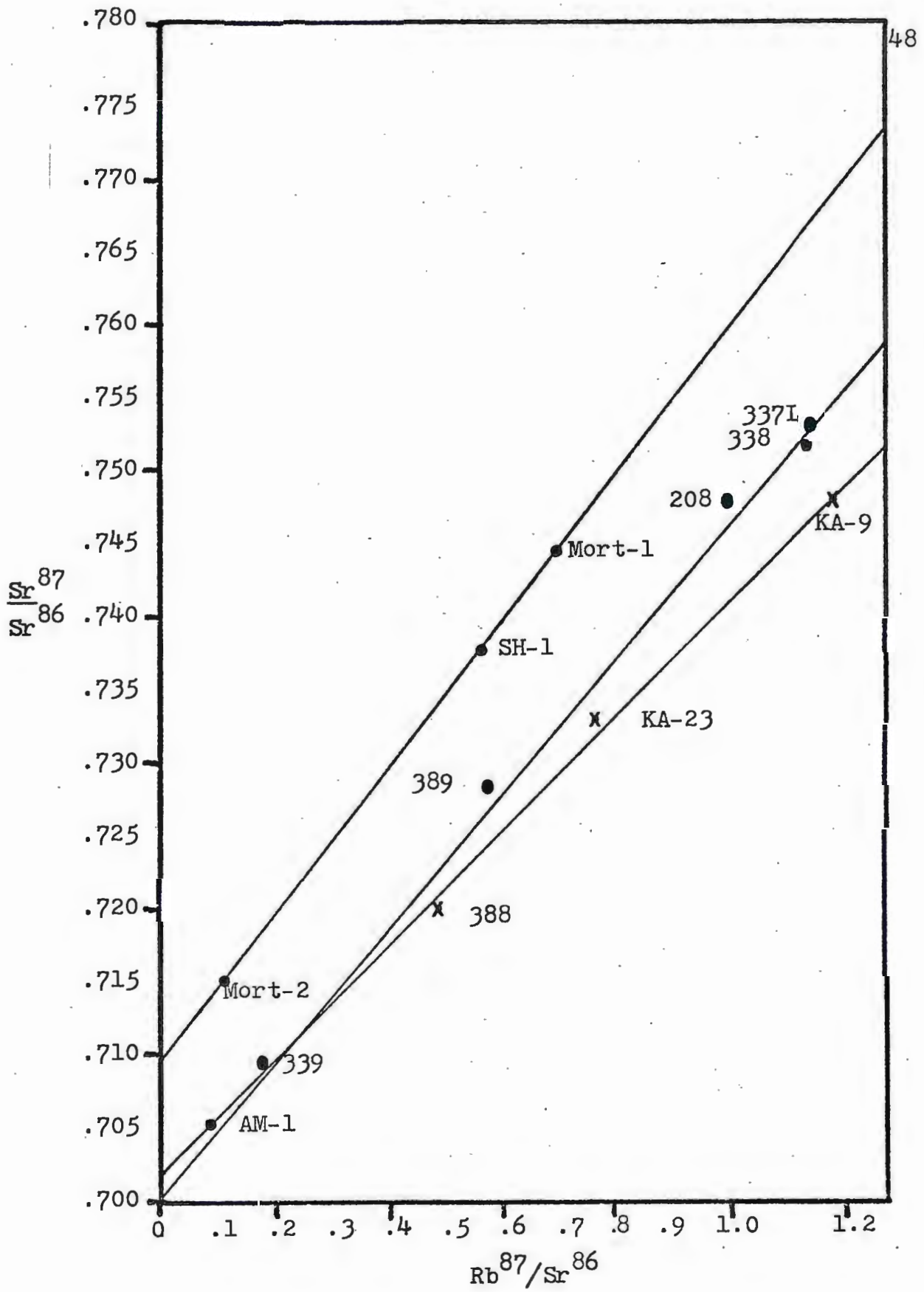


Figure 12. Rb-Sr evolution diagram showing analyses of samples of amphibolite inclusions. Samples Mort-1 and Mort-2 are from black inclusions in the Morton Gneiss; sample SH-1 is from an inclusion in the Sacred Heart Granite; sample AM-1 is from a large "raft" of black amphibolite in the Morton Gneiss. Other analyses shown are samples of the Morton Gneiss and Sacred Heart Granite analyzed by Goldich et al, (1971), and the corresponding isochrons. Sample AM-11 falls very close to the isochron of its host rock unit, the Morton Gneiss, whereas the other analyses seem to indicate a different isochron. With only three data points the new isochron may be an accidental alignment; nevertheless it is suggestive of the great age of the inclusions. Large dots are Morton Gneiss, X's are Sacred Heart Granite, small dots are new analyses.

The three-point isochron yields an apparent age of  $3.52 \pm .15$  AE (2 sigma), with an initial Sr ratio of .709.

Table 4. Amphibolite inclusions from the Morton--Sacred Heart area

Sample Number	K (ppm)	Rb (ppm)	Sr (ppm)	Ba (ppm)	K/Rb	Rb/Sr	Sr/Ba	<sup>87</sup> Rb/ <sup>86</sup> Sr	<sup>87</sup> Sr/ <sup>86</sup> Sr
MORT-1 WR	16,039	63.969	265.07	n.a.	251	0.241	-	.69769	.74441±10
MORT-2 WR	7,837	2.910	75.070	40.78	2695	0.039	1.841	.11207	.71504±27
MORT-2 Hb1	10,341	11.276	18.172	27.07	-	-	-	1.7939	.76474±35
SH-1 WR	42,180	197.80	998.19	982.9	213	0.198	1.016	.57288	.73758±21
AM-1 WR	7,227	11.552	393.16	n.a.	626	0.029	-	.08495	.70524±8
AVE. WR	18,321	69.058	432.87	511.84	265	0.160	0.846	.46122	

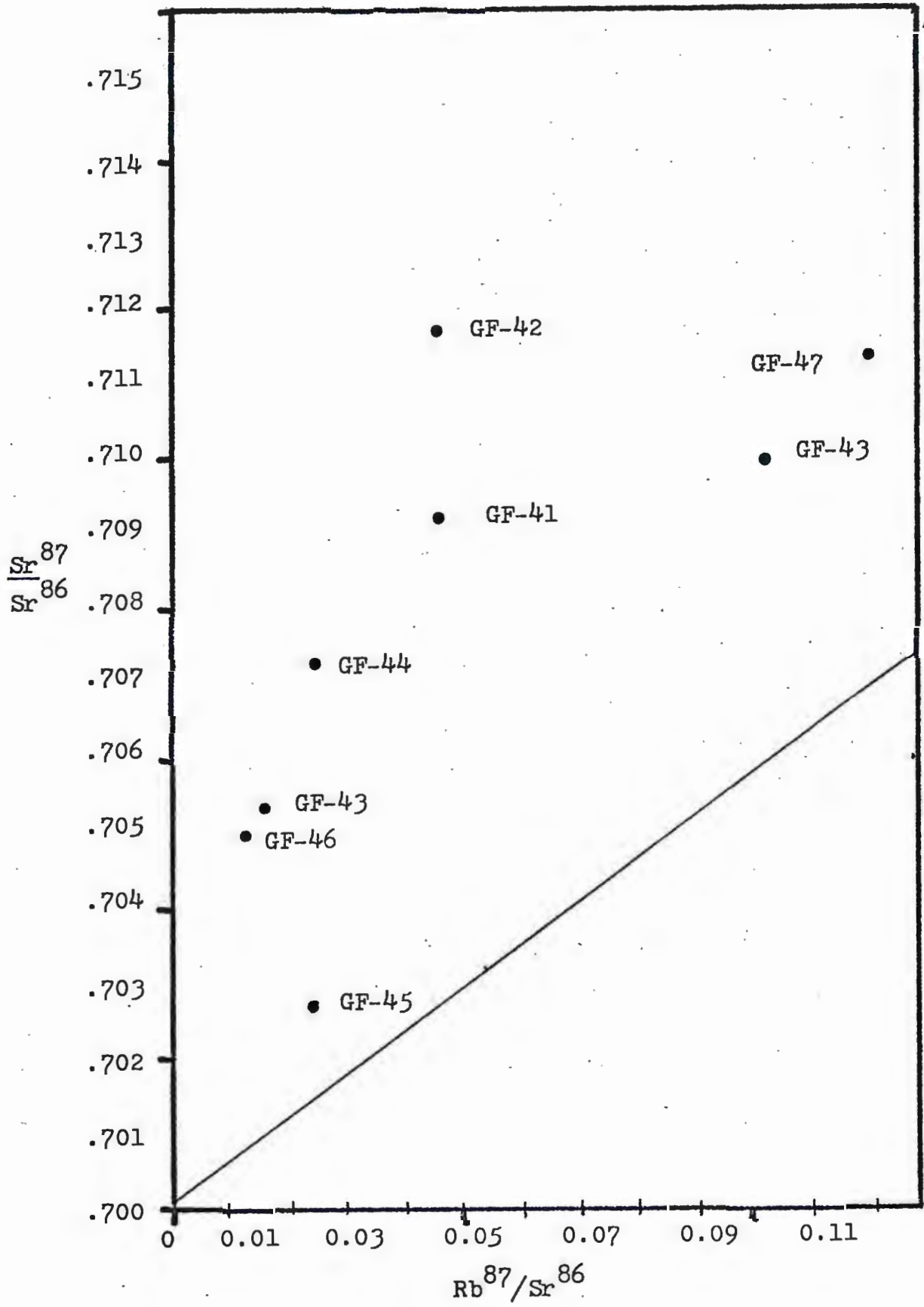




Figure 11. Rb-Sr analyses of whole-rock samples of the Hornblende-pyroxene Gneiss (Inner Unit). The reference isochron is the 3.54 Ae isochron determined by samples from the Garnet-biotite Gneiss and Hornblende-pyroxene Gneiss (Outer Unit).

Table 3. continued

Sample Number	K (ppm)	Rb (ppm)	Sr (ppm)	Ba (ppm)	K/Rb	Rb/Sr	Sr/Ba	<sup>87</sup> Rb/ <sup>86</sup> Sr	<sup>87</sup> Sr/ <sup>86</sup> Sr
<b>d. Hornblende-pyroxene Gneiss (Inner Unit)</b>									
GF-40 WR	4,110	1.288	236.60	112.43	3192	0.005	2.104	.01574	.70533±7
GF-41 WR	5,607	4.153	263.94	181.30	1350	0.016	1.456	.04549	.70924±6
GF-42 WR	7,090	4.995	315.83	272.63	1419	0.016	1.158	.04573	.71175±6
GF-43 WR	5,861	9.852	278.03	429.57	595	0.035	0.647	.10244	.71004±11
GF-44 WR	4,106	2.583	311.67	223.71	1590	0.008	1.393	.02396	.70726±10
GF-45 WR	4,389	2.775	347.85	195.14	1582	0.008	1.783	.02306	.70275±8
GF-46 WR	4,152	1.168	259.50	141.23	3555	0.005	1.837	.01301	.70497±10
GF-47 WR	5,777	13.778	332.48	604.94	419	0.041	0.550	.11980	.71138±8
AVE. WR	5,137	5.074	293.24	270.12	1012	0.017	1.086	.05002	

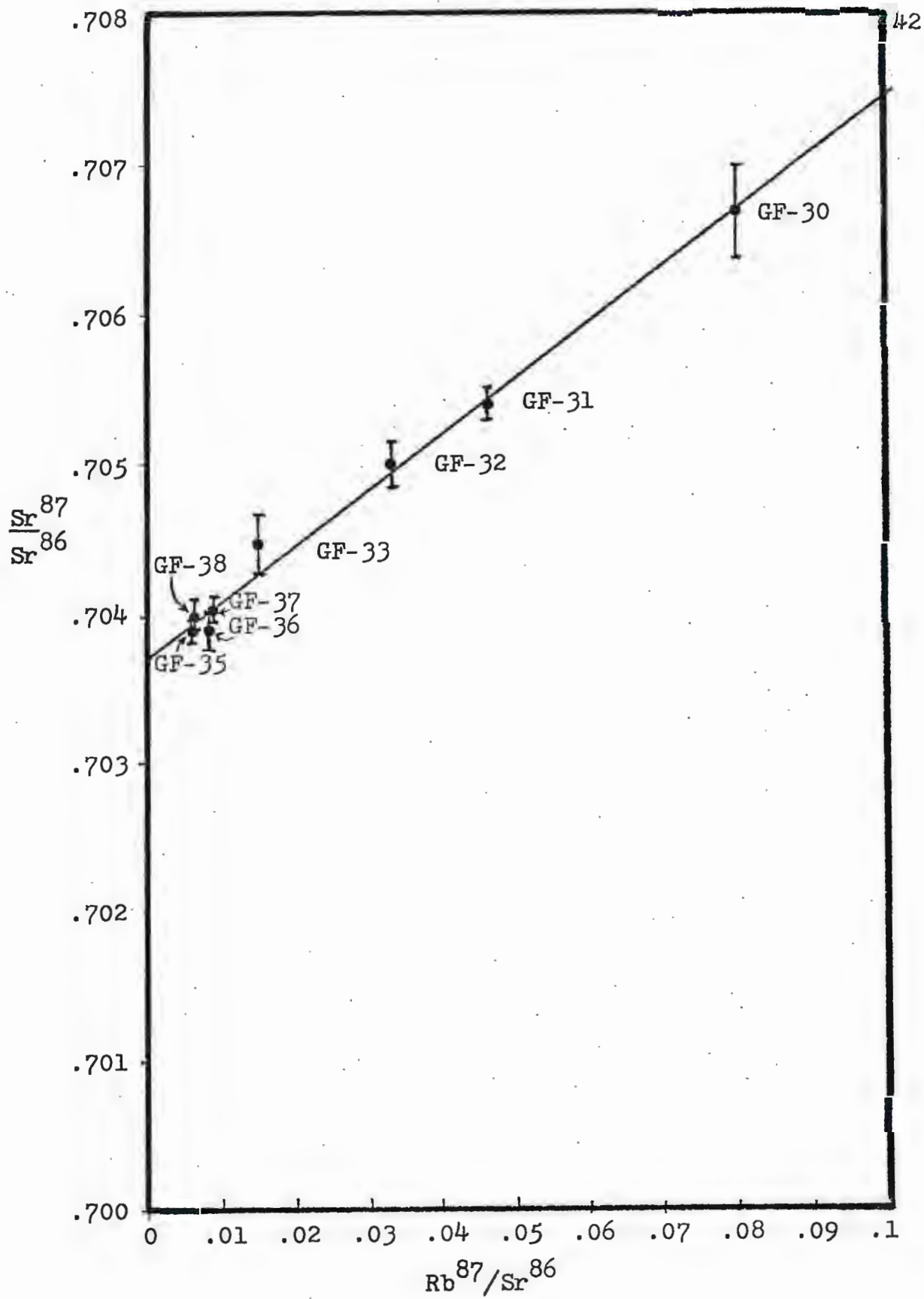


Figure 10. Rb-Sr evolution diagram showing analyses of samples from the Hornblende-pyroxene Granulite (Metagabbro of Himmelberg). Error brackets are shown for the I.C. analyses. Because of the very small spread of points the indicated isochron is not a reliable indicator of age. The isochron gives an apparent age of  $2.60 \pm .20$  AE (2 sigma).

Table 3. continued

Sample Number	K (ppm)	Rb (ppm)	Sr (ppm)	Ba (ppm)	K/Rb	Rb/Sr	Sr/Ba	<sup>87</sup> Rb/ <sup>86</sup> Sr	<sup>87</sup> Sr/ <sup>86</sup> Sr
<b>C. Hornblende-pyroxene Granulite (Metagabbro)</b>									
GF-30 WR	4,941	7.30	264.76	184.69	677	0.028	1.434	.07972	.70672±33
GF-31 WR	4,302	4.43	279.99	233.58	972	0.016	1.199	.04570	.70543±12
GF-32 WR	3,173	2.97	269.24	170.92	1067	0.011	1.575	.03193	.70500±16
GF-33 WR	3,470	1.55	302.56	304.49	2234	0.005	0.994	.01484	.70446±20
GF-35 WR	1,106	0.52	266.91	85.10	2111	0.002	3.136	.00567	.70393±10
GF-36 WR	1,153	0.83	287.08	97.73	1389	0.003	2.937	.00836	.70392±15
GF-37 WR	1,291	0.81	257.06	95.86	1593	0.003	2.682	.00912	.70405±8
GF-38 WR	948	0.63	281.59	77.22	1511	0.002	3.647	.00644	.70400±10
AVE. WR	2,548	2.38	276.15	156.20	1071	0.009	1.768	.02602	

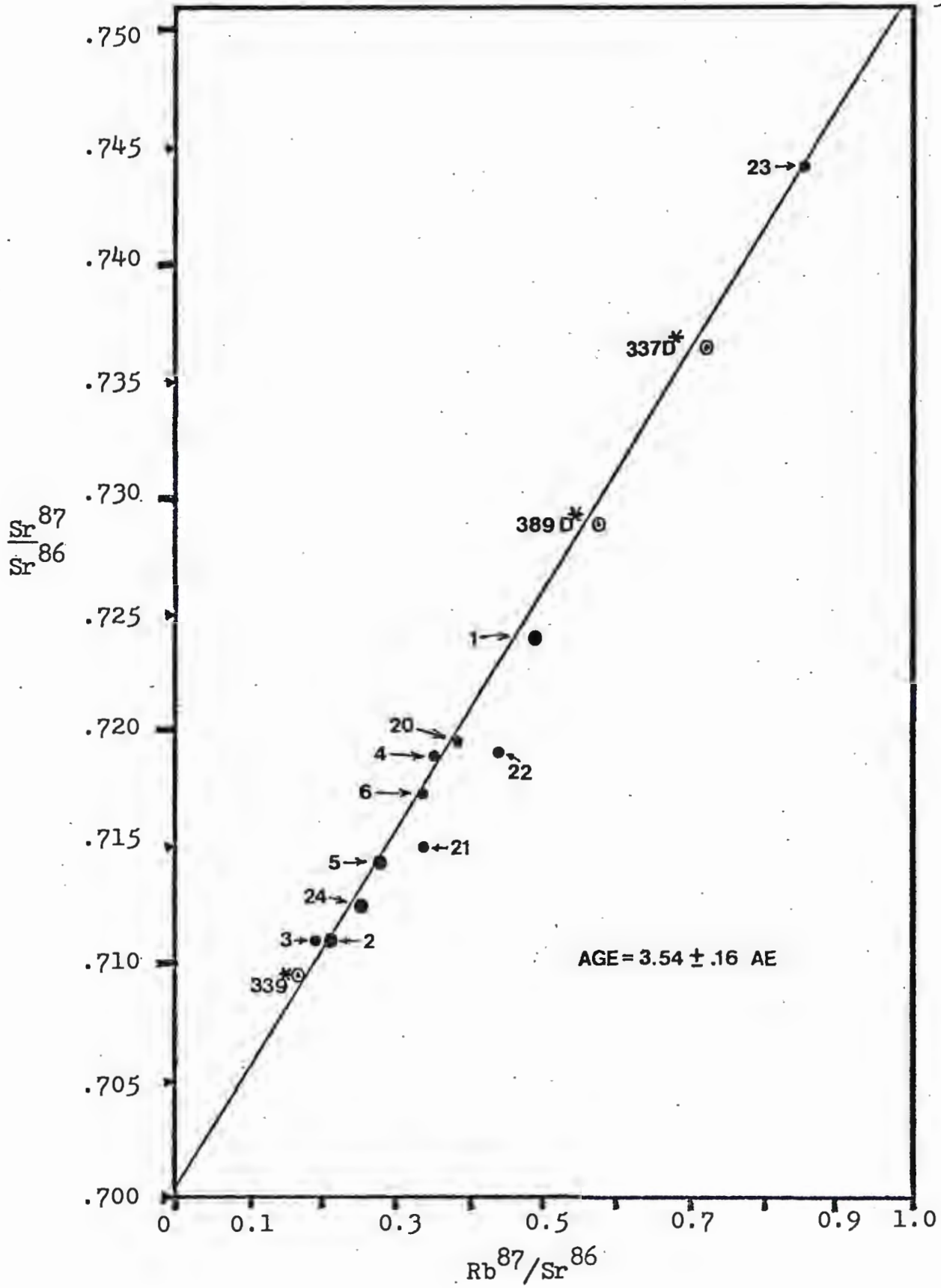


Figure 9. Rb-Sr evolution diagram for analyses of samples of the Hornblende-pyroxene Gneiss (Outer Unit)(large dots) and the Garnet-biotite Gneiss (small dots). Analyses by Goldich (1971) are also shown.\* The regression for age determination was made without the Goldich points and samples 21 and 22. All samples are from the Granite Falls area.

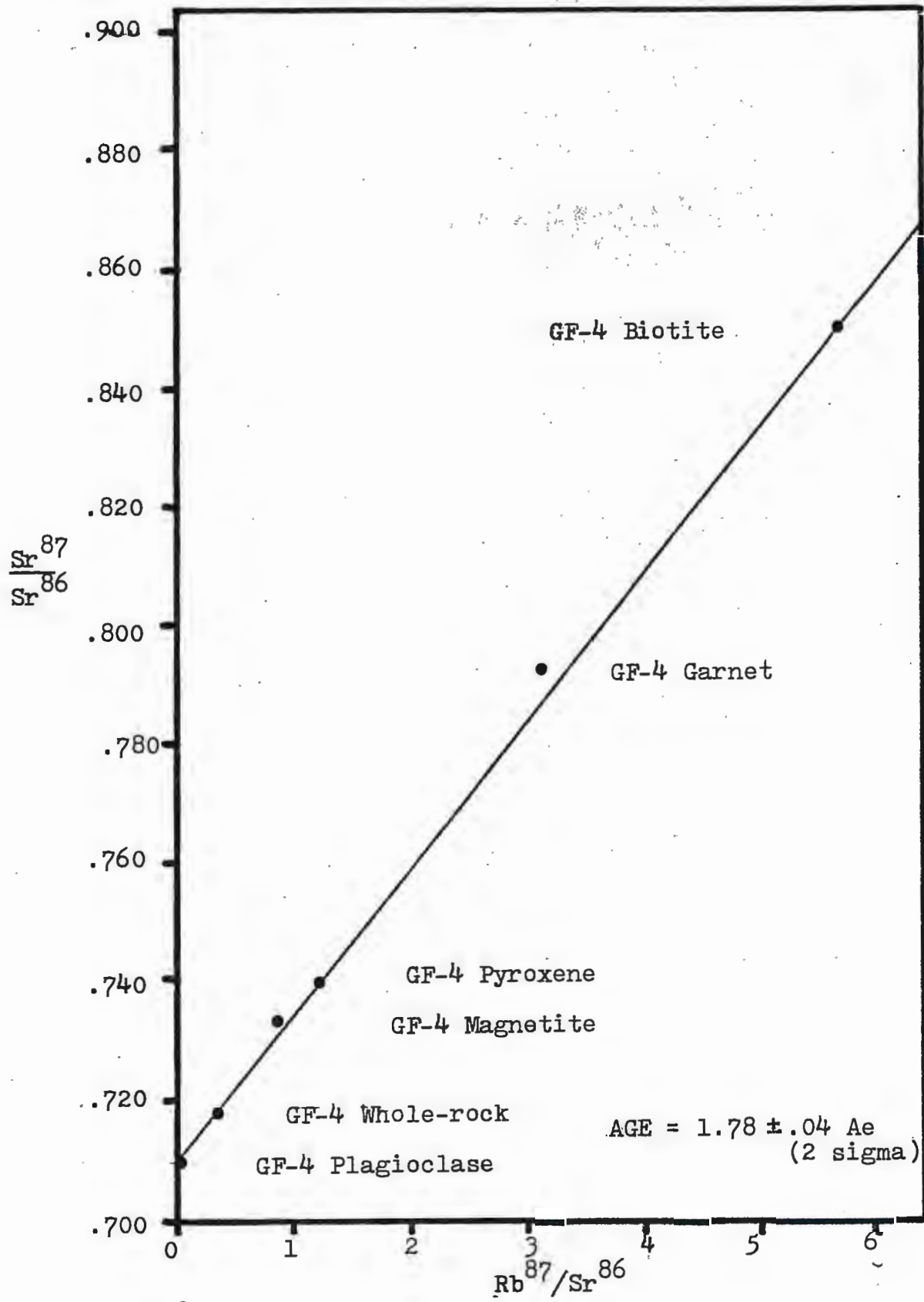




Figure 15. Rb-Sr evolution diagram showing biotite-whole rock tie lines for samples from the Hornblende-pyroxene Gneiss (GF-5), and Garnet-biotite Gneiss.

Ages indicated are:

GF-3: 1.69 Ae

GF-4: 1.68 Ae

GF-5: 1.78 Ae

GF-6: 1.90 Ae

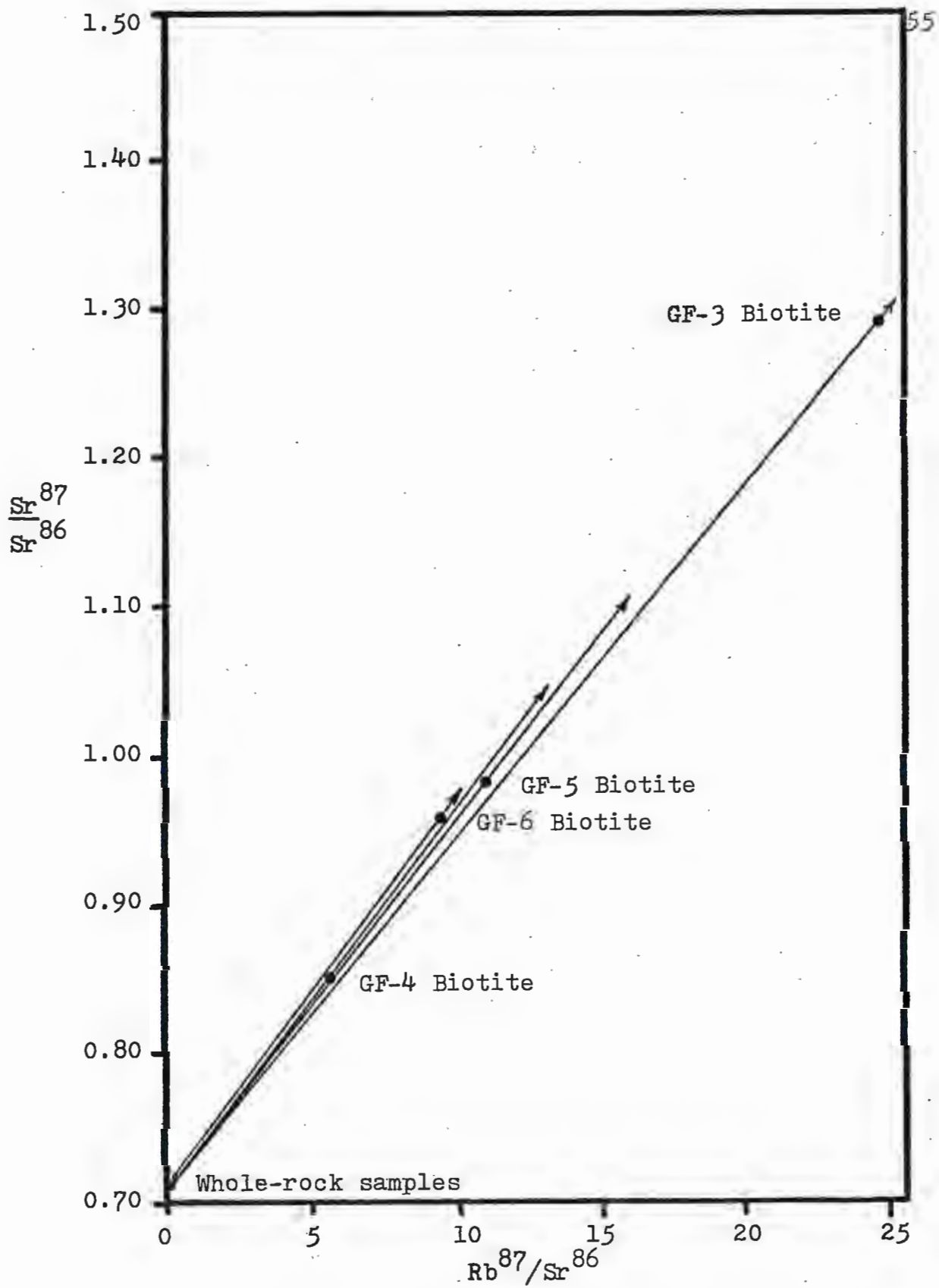


Table 5. continued

Sample Number	K (ppm)	Rb (ppm)	Sr (ppm)	Ba (ppm)	K/Rb	Rb/Sr	Sr/Ba	<sup>87</sup> Rb/ <sup>86</sup> Sr	<sup>87</sup> Sr/ <sup>86</sup> Sr
<b>C. Hornblende-pyroxene Granulite (Metagabbro)</b>									
GF-31 Plag.	3,490	5.03	354.45	245.67	-	-	-	.04104	.70520±13
GF-31 Hbl-Px	5,498	1.72	47.11	171.35	-	-	-	.10584	.70748±31
GF-32 Plag.	2,533	2.74	421.55	133.01	-	-	-	.01881	.70467±16
GF-32 Hbl-Px	3,535	2.12	48.00	175.02	-	-	-	.12794	.70725±8
GF-33 Plag.	2,248	1.20	400.96	185.82	-	-	-	.00863	.70430±26
GF-33 Hbl-Px	5,422	1.55	35.02	111.09	-	-	-	.12813	.70751±10

Table 6. Summary of whole-rock age determinations 57

Rock unit	no. pts.	AGE m.y.	$2\sigma$	Inter- cept	$2\sigma$
Hornblende-pyroxene Gneiss (Outer Unit)	4	3,313	$\pm 256$	.7011	$\pm .0009$
Garnet-biotite Gneiss	5	3,537 <sup>1</sup>	$\pm 140$	.7008	$\pm .0009$
COMPOSITE of Hornblende-pyroxene Gneiss (Outer Unit) and Garnet-Biotite Gneiss	9	3,537 <sup>1</sup>	$\pm 156$	.7005	$\pm .0009$
Hornblende-pyroxene Granulite (Metagabbro)	8	2,680	$\pm 202$	.7037	$\pm .0001$
Amphibolite inclusions Morton-Sacred Heart	3	3,517 <sup>2</sup>	$\pm 150$	.7093	$\pm .0013$

<sup>1</sup>Samples 21 and 22 omitted from the regression.

<sup>2</sup>Sample AM-1 omitted from the regression.

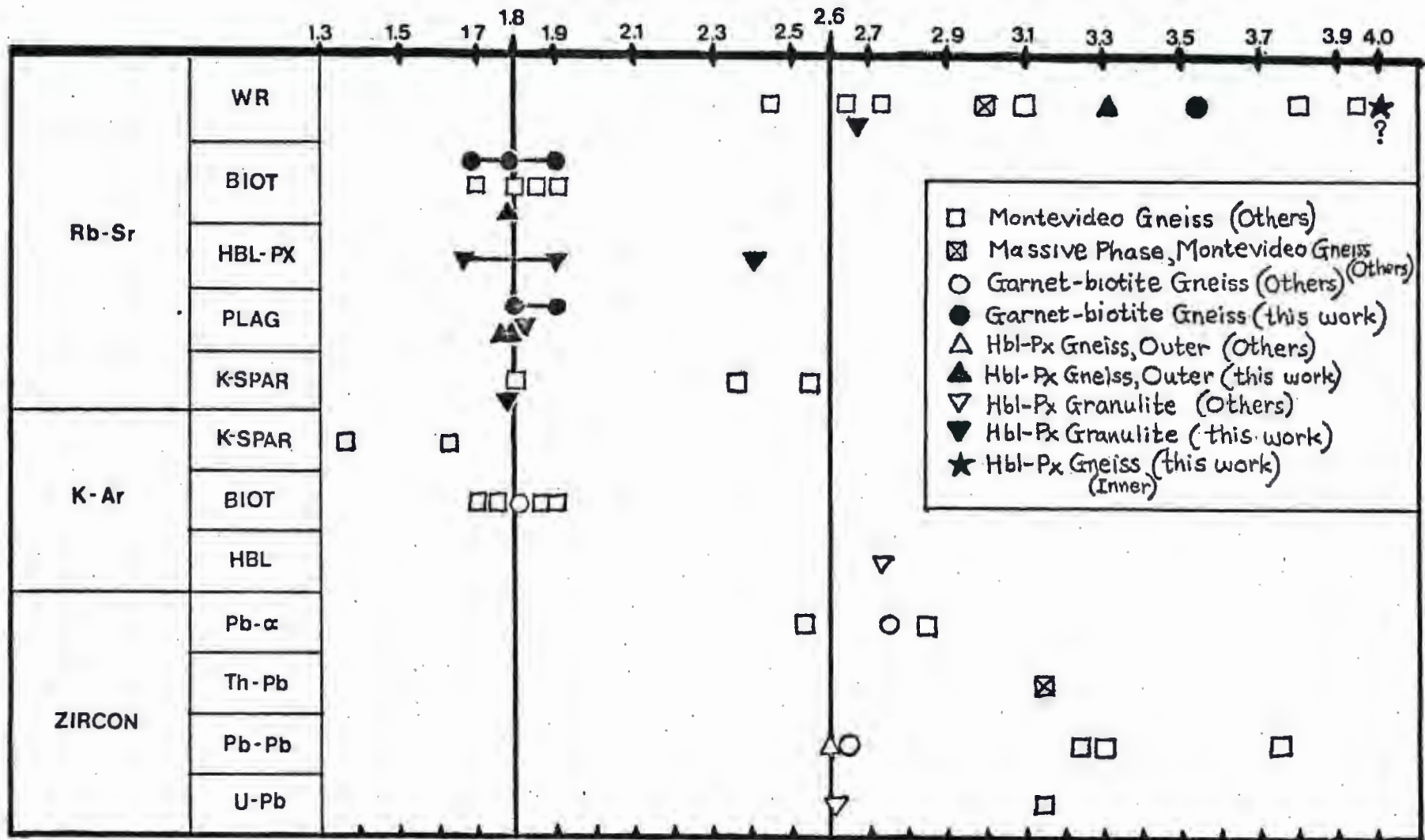
Table 7. Summary of mineral age determinations

58

Rock unit, minerals	no. pts.	AGE m.y.	2 $\sigma$
Hornblende-pyroxene Gneiss (Outer Unit)			
Plag.-WR (GF-5)	2	1,780	
Biot.-WR (GF-5)	2	1,778	
Garnet-biotite Gneiss			
Plag-WR (GF-3)	2	1,908	
Biot-WR (GF-3)	2	1,685	
Plag-WR (GF-4)	2	1,792	
Biot-WR (GF-4)	2	1,783	
5 mineral-WR (GF-4)	6	1,779	<u>+40</u>
Plag-WR (GF-6)	2	1,806	
Biot-WR (GF-6)	2	1,899	
Hornblende-pyroxene Granulite (Metagabbro)			
Hbl,Px-WR (GF-31)	2	2,410	
Plag-WR (GF-32)	2	1,783	
Hbl,Px-WR (GF-32)	2	1,666	
Plag-Px-WR(GF-32)	3	1,674	
Plag-WR (GF-33)	2	1,830	
Hbl,Px-WR (GF-32)	2	1,910	
Plag-Px-WR(GF-33)	3	1,909	

Figure 16. Summary of all isotopic age determinations made on samples from the Granite Falls area. Filled symbols are analyses reported in this study; open symbols are analyses reported by other researchers.

Figure 16. SUMMARY OF ALL AGE DETERMINATIONS IN THE GRANITE FALLS AREA



A. Age of the Montevideo Gneiss and the effect of metamorphism on Rb-Sr isochrons

The Montevideo Gneiss is the only unit in the Granite Falls area not sampled in this study because it has been sampled extensively by other workers (Goldich, et al, 1970, Goldich and Hedge, 1974, 1975, Farhat, 1975, Farhat and Wetherill, 1975). The age of the Montevideo Gneiss is nevertheless a critical factor in the interpretation of the history of all rocks in the Granite Falls area, and the interpretation of the available data is in dispute; for these reasons a discussion of the interpretation of the published data on the Montevideo Gneiss is included here with some remarks on the bases of Rb-Sr age interpretations in general as related to sampling procedures.

Before discussing the data, I wish to discuss some geochronological terms in use and introduce some new terms.

The term isochron currently has at least three applications in geology; the meaning relative to isotope geochronology is given very briefly below.

Isochron: (Iso = equal; chron = time or age)

A straight line determined by plotting two isotopic ratios (radioactive isotope A over a stable reference isotope C, and the daughter product of A over C) for several samples; the slope of the line is a function of age.



The term "scatterchron" has been in use in recent literature to indicate an isochron determined by a plot of points that do not all lie on the isochron within the limits of experimental error. The same definition has recently been applied to the new term "errorchron", introduced by Brooks, et al., (1972). It is clear from the term "scatterchron" that the meaning is related to an isochron defined by a scatter of data points. There is no implication regarding the accuracy of the individual analyses or of the age indicated. However, the term "errorchron" carries with it a judgment that an error is somehow involved which bears significantly on the interpretation of the isochron, and that this error is a function of scatter. As will be shown in subsequent discussions, this is not necessarily the case. Considering that error of any kind and scatter are not necessarily directly related, it is recommended that the term "errorchron" be dropped from the literature or reserved for the case where an unusually serious analytical error of some kind is involved.

The following new terms proposed do not represent new concepts, but rather supplant sometimes lengthy or inaccurate phrases in current use; condensation of the phrases and ideas into single words will facilitate discussion and help avoid ambiguity.

Primachron: (Prima = first or original; chron = age)

An isochron which represents the time of crystallization or emplacement of a body of rock. In the past, "whole-rock isochrons" have been presumed to be primachrons.

Metachron: (Meta = change, metamorphism; chron = age) An isochron which represents an age of metamorphism of a rock unit. ("mineral isochrons" are usually metachrons, but in the absense of any metamorphic event they are usually primachrons)

Pseudochron: (Pseudo = false, fallacious; chron = age) An isochron which indicates a geologically meaningless age because of sampling accidents, geologic complexity or disequilibrium — the "Fallacious Isochron" of Goldich (1972).

Goldich (1972) pointed out that low temperature metamorphism, faulting and shearing can lead to pseudochrons. Farhat (1975) and Farhat and Wetherill (1974, 1975) discussed the possibility of pseudochrons being generated by linear but incomplete, uniform re-equilibration of the Sr isotopes during a metamorphic event. The principle is related to the difference between primachrons and metachrons.

According to accepted theory (Lanphere, et al., 1963) homogenization of Sr isotopic ratios during a metamorphic event can be achieved over a distance of

a few millimeters or possibly centimeters, which is sufficient for the different minerals within a certain volume of rock to attain approximately identical  $\text{Sr}^{87}/\text{Sr}^{86}$  ratios (and thus plot on a horizontal isochron at the time of metamorphism). Useful terms in a discussion of diffusion and re-equilibration are defined below.

Diffusion coefficient (D): the factor describing the ease with which one substance can diffuse through another substance; a function of temperature and the nature of the substances. (The effect of pressure has not been experimentally investigated for rocks)

Diffusion factor (Dt): the diffusion coefficient multiplied by the duration of the metamorphosing conditions (t). This measure has been used by Farhat (1975) as a measure of metamorphic intensity.

Diffusion distance ( $\sqrt{Dt}$ ): defined by Hoffmann (1974); in the case of diffusion from a constant concentration  $C_1$  into a semi-infinite medium  $C_2$ ,  $\sqrt{Dt}$  gives the approximate distance at which the concentration equals the mean of  $C_1$  and  $C_2$ .

Equilibration distance (E): Defined here as the distance over which concentration gradients are negligible. It is a function of the diffusion distance and an arbitrary value, Z, which is the maximum concentration difference (over any distance) that is to be considered "negligible". K, the "error function" (Schewmon, 1963)

is a function of Z. Current convention in the deriva-<sup>65</sup>  
tion of K results in the definition of  $E = 4K\sqrt{Dt}$ .  
(see Fig.17)

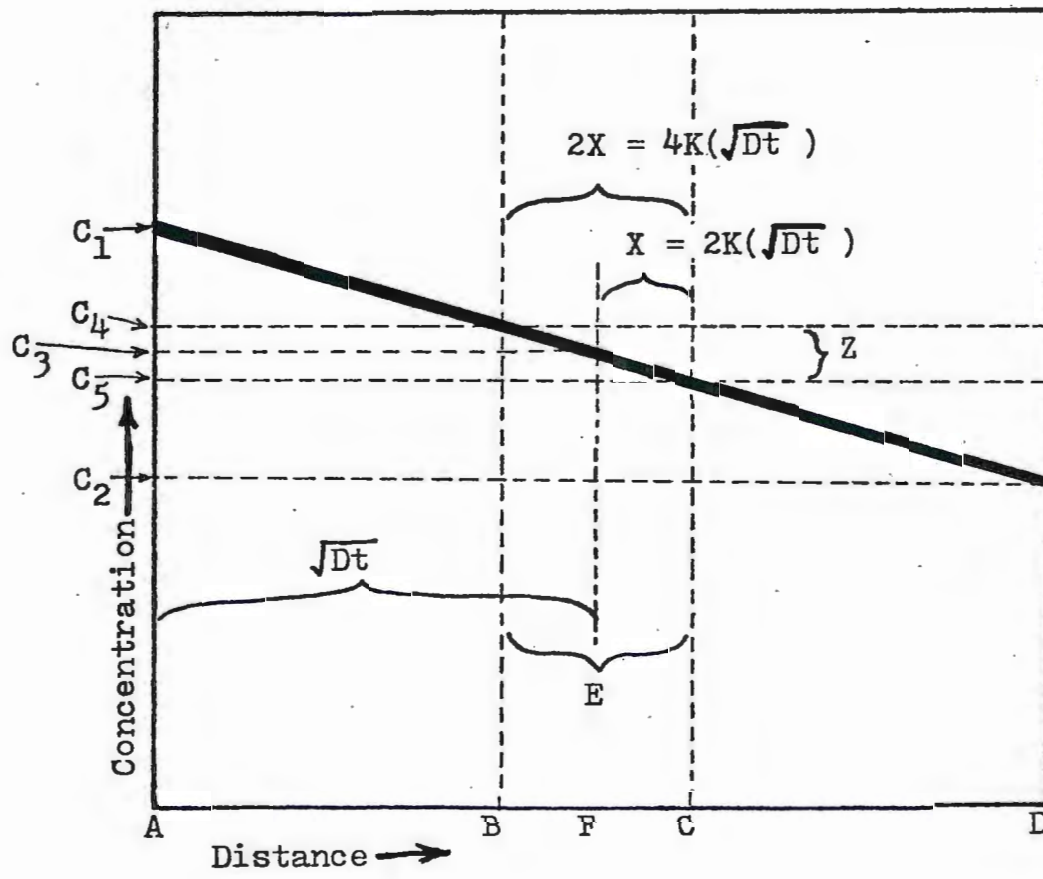
Equilibration volume (V): Defined here as the volume generated in three dimensions by E; the smallest volume of rock in which the rock as a whole retains its pre-metamorphic  $Sr^{87}/Sr^{86}$  ratio, i.e. was a closed system. In rocks in which D is isotropic, V will be a sphere of diameter E. In anisotropic rocks D will be different in different directions, E will therefore be different in different directions, and V will not be a sphere.

The model of Rb-Sr behavior under metamorphic conditions which is generated by these definitions will be referred to as the "Equilibrated Volume Model". Under this model a non-linear distribution can no longer be attributed simply to disequilibrium induced at the time of metamorphism, but will be explained strictly on the basis of sampling. Disequilibrium on some scale must exist from the moment of metamorphism until the unlikely event that the metamorphism completely homogenizes the  $Sr^{87}/Sr^{86}$  ratio over the entire rock formation, thereby wiping out all evidence of the age of crystallization of the original rock. Such a case, where the equilibration volume encompasses the entire rock unit, is probably only attained in reality

Figure 17. Concentration distribution after metamorphism in a hypothetical case. The concentration  $C_1$  at point A decreases to concentration  $C_2$  at point D, and is indicated by the heavy line. The "diffusion distance"  $\sqrt{Dt}$  (as defined by Hoffmann, 1974) represents the distance from the border of the outward-diffusing source (A) to the point which is midway between A and the original concentration level of the lower concentration member which is at D: in this case, the distance A-F. Farhat (1975) made use of the term "diffusion factor",  $Dt$ , as a measure of metamorphic intensity.

In this study the "Equilibration distance",  $E$ , is the preferred measure. This distance is defined in the text as the distance over which concentration gradients are negligible. It is a function of the diffusion distance  $\sqrt{Dt}$  and the arbitrary value  $Z$  which is the maximum concentration difference over any distance that is to be considered "negligible". The constant  $K$  (the "error function") is a function of  $Z$ . Current convention (e.g. Schewmon, 1963) in the derivation of  $K$  results in the definition of  $E$  as  $4K\sqrt{Dt}$ .

Because  $E$  is a function of  $Z$ , and  $\sqrt{Dt}$  is not, the relation between  $E$  and  $Dt$  is dependent upon the choice of  $Z$ , and a general statement about the relationship of the size of  $E$  to  $\sqrt{Dt}$  cannot be made.



by partial or total melting.

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The model of Farhat (1975) is instructive and useful for generating theoretical test situations. It is unrealistic in that the onset and waning of metamorphism are probably gradual processes lasting possibly as long as several million years. But it will most likely never be possible to experimentally delineate this cycle, so the term (Dt) is the best approximation for some purposes. Although the equilibration volume will be a function of (Dt), (Dt) can only be determined experimentally by first determining E, so the term (Dt) is not very useful for practical field applications.

It must be remembered that once metamorphism begins there is no volume of rock of any size which precisely retains its pre-metamorphic  $\text{Sr}^{87}/\text{Sr}^{86}$  ratio. Therefore the determination of E and V are dependent upon the limit of variance (Z) arbitrarily established and considered tolerable for the purposes of geochronology but which will nevertheless allow a slight scatter of data points about the isochron.

Now we will review the results of sampling procedures and the resulting data distributions in the light of the Equilibrated Volume Model. There are several possibilities that may occur when a geochronologist takes rock samples from a metamorphic terrane for analysis. The primary source of difficulty lies in the

fact that E and V are unknown at the time of sampling. 68

The possibilities and their results are as follows.

Case #1: The whole-rock samples taken are larger than V. Result: the data points will define a primachron with accuracy of fit approaching the experimental error.

Case #2: The rock samples taken are as large as V. Result: the data points will define a primachron with scatter dependent upon the magnitude of Z.

Case #3: Whole-rock samples taken are smaller than V but were separated by distances larger than E at the outcrop. Result: the data points will define a scatter-chron which will approximate the primachron if the number of samples is large enough, and the variation within adjacent equilibrated volumes is small compared to the variation of  $\text{Sr}^{87}/\text{Sr}^{86}$  between adjacent equilibrated volumes. The data points will define a scatter-chron which is a pseudochron of age intermediate between formation and metamorphism if the variation of  $\text{Sr}^{87}/\text{Sr}^{86}$  within adjacent equilibrated volumes is high relative to the variation between adjacent equilibrated volumes. In the first subcase a pseudochron can still be generated by accidental alignment.

Case #4: The whole-rock samples taken are smaller than V, and the maximum separation of any two samples does not exceed E, i.e. all samples in situ could be enclosed

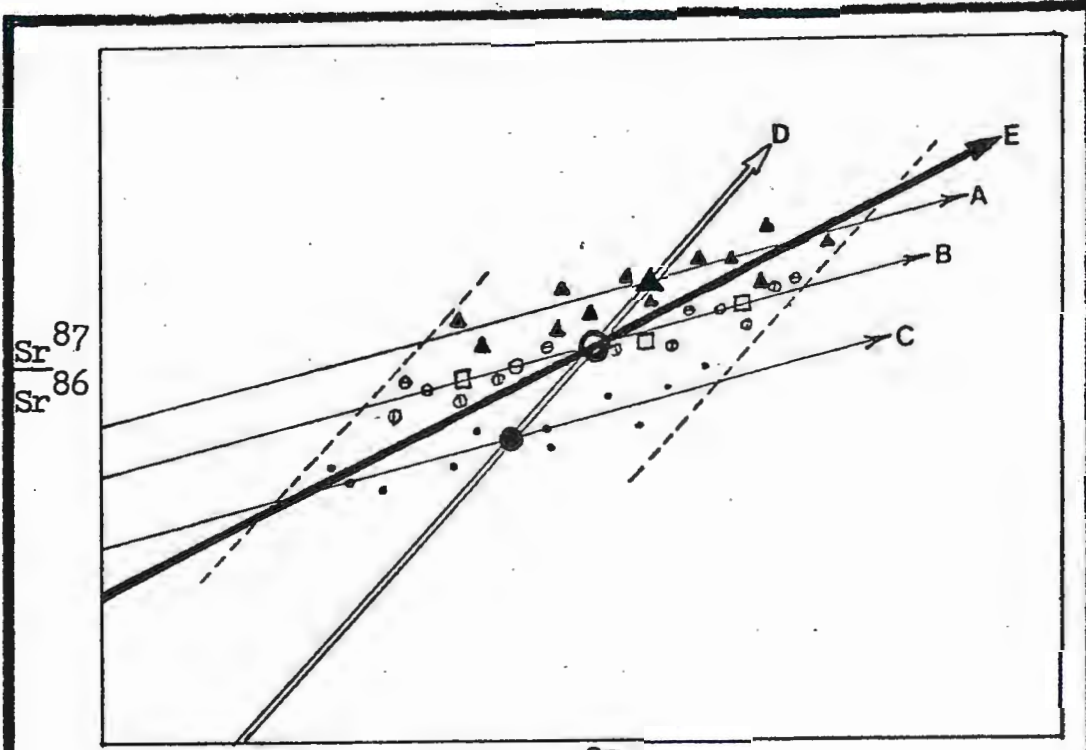


within a single V. Result: the data points will yield a scatterchron which will define a metachron. The scatter will be dependent upon Z.

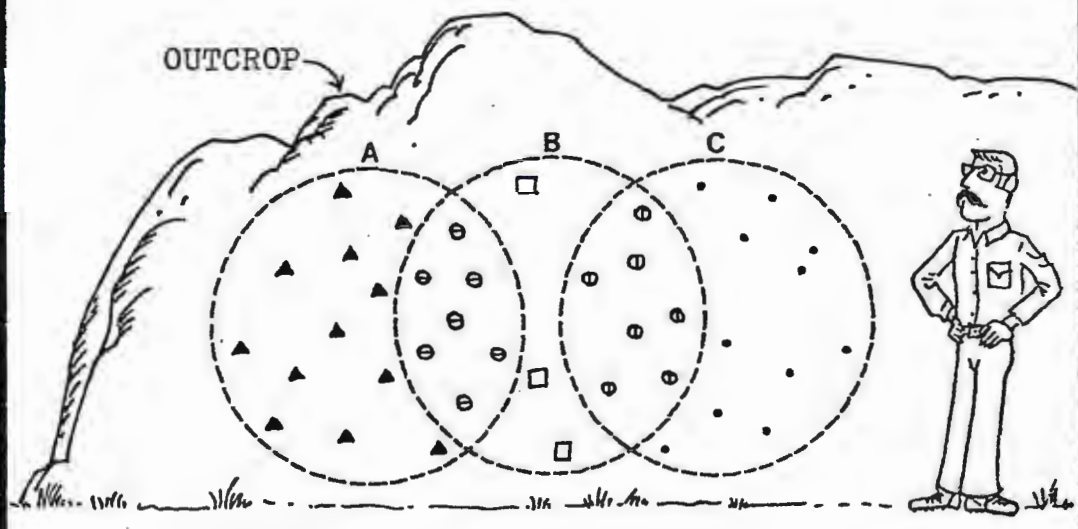
In case #3 the width of the scatter envelope will be a function of (a) sample volume, (b) V, and (c) compositional variability of the rock within V. The scatter will become apparent when (b) becomes large enough to be in the same order of magnitude as (a), or (a) becomes small enough in comparison to (b). The researcher has control only over (a), so in order to reduce the scatter, and the potential for generating a pseudochron, it would be necessary to do one of two things: (1) increase sample size so that (a) and (b) are no longer in the same order of magnitude, or (2) increase the number of samples within a V until together they represent the average composition of all the rock within the V, then average or mix those samples together into a composite sample. Method (1) has the advantage of yielding a much closer approximation to linearity, but the required sample size could become impractical for the geochemist to process and analyze. Method (2) is the method devised by Farhat (1975), and is the most practical.

Figure 18 illustrates a result obtained from a hypothetical field situation. Samples taken within zone A (the volume of which equals V), for example, would conform with case #4 above, and yield a scatterchron approximating metachron A in the figure. Similarly,

Figure 18. The effect of sampling procedures in a high-grade metamorphic area. The large triangle ( $\blacktriangle$ ) represents the mean of all samples taken within zone A at the outcrop. (Zones A, B, and C all have diameters equal to the Diffusion Length). Similarly the large circle ( $\bigcirc$ ) is the mean of all samples taken within zone B, and the large dot is the mean of all samples taken within zone C. Note that some samples are within two overlapping zones, and are therefore represented in the means for both zones. A probable distribution of all of these data points is shown on the Rb-Sr evolution diagram. In this illustration, isochron D yields the original age of formation of the rock, and isochrons A, B, and C yield the date of metamorphism (metachrons). The dashed lines delineate the approximate boundaries of the field in which data points are likely to lie. Isochron E is the regression of all data points individually (without first averaging groups together as was done for isochron D) and gives a false, meaningless age (pseudochron) which is less than the age of formation.



$\frac{Rb^{87}}{Sr^{86}}$



DIFFUSION LENGTH

samples from zone B will approximate metachron B and samples from zone C will approximate metachron C.

If the samples taken within zone A are sufficiently numerous and representative their average will plot on primachron D. If samples are taken from an area as large as zone A+B+C they will scatter around both a metachron and the primachron. A regression of such samples taken individually and not averaged in any way will yield a pseudochron indicating an age intermediate between the formation age and the metamorphic age (pseudochron E), as described in case #3 above, and as produced theoretically by Farhat, (1975).

If the entire volume of rock enclosed within zone A were to be removed and processed the resulting data point would plot on the primachron according to case #2 (above).

Any set of samples taken within a zone smaller than the critical volume will scatter along a metachron as in case #4. Considering that E is a maximum diameter for re-homogenization, as defined by Z, it follows that a smaller volume will have a closer approximation to perfect homogenization at the time of metamorphism because a smaller value of Z could be used without the sample exceeding V in size.

Consequently if samples for a metachron determination are taken from a smaller total volume they will yield a metachron with less scatter, but probably also less

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spread. The total average will also be less representative of the whole critical volume. That is, a group of samples from progressively smaller areas will yield less scatter along a metachron, but their averages will have a greater scatter along the primachron. The standard solution to the problem of small spread along the metachron is to choose one sample which is presumably much smaller than the equilibration volume  $V$ , crush it, separate it into its component minerals, and analyze the minerals separately to obtain a "mineral age". This is the practical ultimate in obtaining a metachron, but it can be seen from this model that crushing and separating a small rock sample is preferable to using a large rock sample because a small sample almost certainly came closer to perfect homogenization at the time of metamorphism. Therefore the block method of Farhat (1975) is not the best for determining a metamorphic age.

The implications of the Equilibrated Volume Model are interesting, because the model demonstrates the transition, in the field, between samples which will yield a metachron, samples which will yield a primachron, and all cases in between. Furthermore the degree of scatter along isochrons is systematically predicted for the first time, and is seen to not always indicate an inaccurate age except in certain circumstances.

The statement made by Farhat and Wetherill (1975): "Evidence that a Rb-Sr age has been inadequately measured is provided by the failure of some of the samples to lie on an isochron (within experimental error)." is therefore not necessarily correct.

A principle cause of scatter in Rb-Sr age dating is probably the collecting of samples smaller than the equilibration volume. It is possible that a body of previously determined data on an area other than the Minnesota River Valley could be advantageously re-evaluated in the light of this model. Suppose, for example, the following situation: A researcher has taken samples carefully, one every foot or so, along a line running the length of a straight, 100-foot road-cut. The plotted analyses yield a distressingly severe scatter, and the regression yields an age younger than expected from previous research on other units in the same area. The approach suggested here would be to begin averaging the samples in consecutive groups. The first test would be a regression of the averages of groups of two. If the samples are numbered consecutively from one end of the outcrop to the other, the averages would be computed on the following sets of two:

1+2, 2+3, 3+4, 4+5, 5+6, etc.

The second test would involve sets of three as follows:

1+2+3, 2+3+4, 3+4+5, 4+5+6, etc.

The third test would involve sets of four as follows:

1+2+3+4, 2+3+4+5, 3+4+5+6, etc.

The tests would continue up to two final sets of 99 samples each. The average of all 100 points could be used as a control point which must surely be on the primachron. The scatter (2) should decrease as the spread of samples approaches E, and level off thereafter. The age indicated by the regression should increase up to that same point and level off, although it might eventually decrease again because of random factors as the sets become very large. The maximum age at the leveling-off point is therefore the best determination. In this way the primachron can be more accurately determined and, incidentally, E can be established for the area.

Once E has been determined experimentally in an area, other implications of this model become operative. They are applicable to the dispute between Farhat and Wetherill (1975) and Goldich and Hedge (1975) regarding the genesis of the two phases of the Montevideo Gneiss. These phases are the so-called red or massive phase and the gray or dark phase. Analyses by Goldich and Hedge, even when including Farhat's data, indicate an age for the red phase of  $3,000 \pm 90$  m.y. with an initial ratio of .7065. Other

analyses by Goldich and Hedge (1974) indicate an age of 3,800 m.y. ( $\pm$ ?) to 3,950 $\pm$ 70 m.y., with an initial  $\text{Sr}^{87}/\text{Sr}^{86}$  ratio of .7000 to .698. Analyses by Farhat on apparently similar samples taken from three 2-3 meter "blocks" (blocks KA-209, MV-100, Mv-102) failed to show any difference between the two phases. The method of Farhat is based on the assumption that E in a sampled area is greater than the block diameters of 2-3 meters, and that the samples from each block will therefore plot on metachrons. This assumption proved justified for the Montevideo Gneiss; each block gave an apparent metachron approximating an age in the neighborhood of 2,600 m.y., a time of established, major, regional metamorphism in the Minnesota River Valley.

However, Farhat and Wetherill did not follow up this discovery with the logical conclusions. Goldich, et al., (1970), while discussing interpretation problems regarding data from the Morton Gneiss (the apparent counterpart of the Montevideo Gneiss farther south in the Minnesota River Valley) made the following comment:

"There are...some troubling aspects, not the least of which is accepting diffusion of Sr measured not in millimeters but in tens of centimeters or more."

Goldich obviously noticed the tendency of whole rock samples to sometimes indicate metamorphic ages, but was unwilling to accept without more proof the concept of Sr re-equilibration on a scale of meters. Farhat

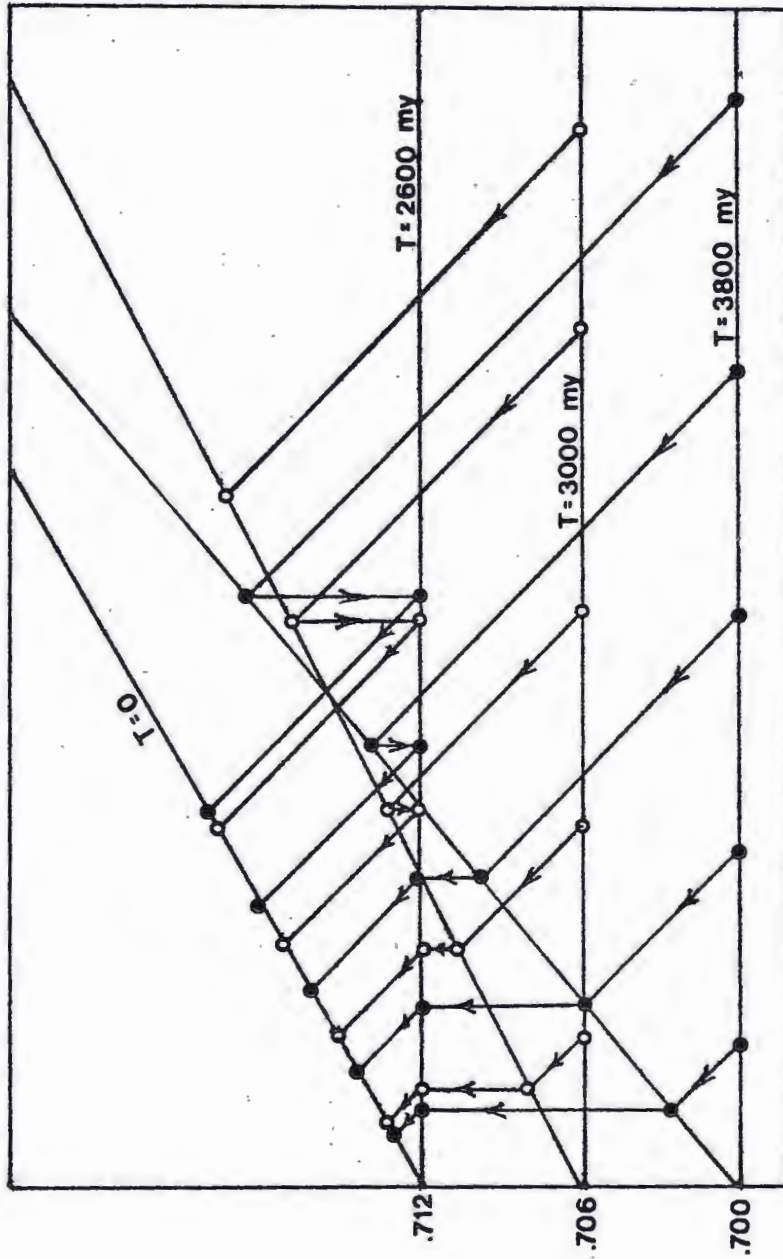


(1975) has provided that proof. Farhat and Wetherill observed that both phases of the Montevideo Gneiss within a given block plot on the same metachron (with an initial ratio of 0.711 to 0.712), and seem to view this as evidence that the two phases had the same pre-metamorphic initial ratios, and by inference, the same age. However when one considers that the two phases are intermixed on a scale of less than a meter, and that E is in excess of three meters, it becomes a certainty that samples of both phases taken from within one block of size V or less will plot on the same metachron because they will both have had their Sr homogenized together to the same ratio at the time of metamorphism. Figure 19 illustrates the evolution of a single metachron, as seen by Farhat, from the two intermixed units of different ages as seen by Goldich and Hedge (1975). Therefore Farhat's block data give the expected result and furnish no evidence one way or the other for a difference in the ages of the two phases.

The possibility of a rather long diffusion distance can be illustrated in an example. During high-grade metamorphism the following values for D and t may well have existed:

$D_{\text{Sr}} = 10^{-9} \text{ cm}^2/\text{sec}$ . At 1 atm, on the extrapolated Arrhenius plot of Hoffmann (1974), for an olivine tholeiite, this value would correspond to a

Figure 19. Hypothetical Rb-Sr evolution diagram illustrating how the metamorphic isochrons of two rock units of differing ages can be congruent. The rock unit that crystallized at 3800 my (solid points) is intermixed with the unit which intruded it and crystallized at 3000 my. When these intermixed units were metamorphosed at 2600 my their Sr isotopic ratios were equilibrated together to an identical value (0.712). Subsequent aging will produce a single metamorphic isochron, as measured at the present (T=0).



$\frac{Sr^{87}}{Sr^{86}}$

$\frac{Rb^{87}}{Sr^{86}}$

temperature of about  $1100^{\circ}$  C.

$t = 10^7$  years. (duration of metamorphic conditions)

$\sqrt{Dt} = 5.6$  meters.

A value of 5.6 meters is clearly sufficient to account for observations in the Minnesota River Valley, although it must be remembered this is for the diffusion distance and not E, and that a direct relation between the two cannot be described without first specifying Z and therefore K. But it is likely that the two are in the same order of magnitude for most situations.

Farhat (1975) also disputes the 3,800 m.y. age for the Montevideo Gneiss obtained by Goldich (1974). To resolve this dispute a closer examination of the data of both researchers in the light of the model proposed here is required. Farhat suggests ten samples be taken from each block and averaged together to yield a primachron data point. From the viewpoint of the model described here, and considering that Farhat has already established a minimum equilibration distance for the area of about three meters, this method seems reasonable. A significantly large number of samples from each block is critical; unfortunately Farhat did not take ten samples each, as he suggested, from blocks MV-100, MV-102 and KA-209, so it is not particularly surprising that the block averages did not fall on Goldich's 3,800 m.y. primachron.

And yet Farhat and Wetherill use the results from these blocks to dispute Goldich's 3,800 My isochron.

One of the fundamental predictions of the Equilibrated Volume Model is that the highest accuracy for the primachron is obtained when the highest number of samples is analyzed, and when each sample is as large as possible. Consequently all samples analyzed by Goldich, Farhat, and others, should be considered for use in the regression; the method of selecting and omitting points is critical, and subject to bias. An effort is made in the following paragraphs to arrive at an unbiased analysis of the existing data.

All of the published analyses on the Montevideo gneiss are given on Table 8. Sample 384 can be logically excluded from the regression because the authors state that the sample is definitely a mixture of the dark and red phases of the gneiss. These phases have been shown (Goldich and Hedge, 1975) to be different in age. The remaining samples are either strictly from the dark (older) phase, or are of indeterminate composition relative to the two phases.

One point, sample MV-20 (block composite), appears to be unusually deviant relative to the trend of the other points. In the past it has been customary to discard any points which are intuitively believed to be overly deviant, but this is not a statistically prudent

Table 8. All published Rb-Sr Montevideo Gneiss data.

R = Red phase; D = Dark phase; E = 2 sigma error.

<sup>1</sup>Data on individual samples from Farhat (1975), recalculated into composites on table 10 of this study.

<sup>2</sup>Data from Farhat (1975).

<sup>3</sup>Data from Goldich, et al (1970).

<sup>4</sup>Data from Goldich and Hedge (1974).

<sup>87</sup>Rb/<sup>86</sup>Sr E for <sup>1</sup> and <sup>2</sup> was not given and is assumed here for the purposes of calculation to be a reasonable value.

Calculation of the composites is shown on table 9.

SAMPLE	R	D	$\frac{R}{D}$	$\frac{^{87}\text{Rb}}{^{86}\text{Sr}}$	E (%)	$\frac{^{87}\text{Sr}}{^{86}\text{Sr}}$	E
KA-209 block <sup>1</sup> (4-sample composite)		X		1.1030	2	.75617	.0001
MV-100 block <sup>1</sup> (3-sample composite)		X		1.0093	2	.74950	.0001
MV-102 block <sup>1</sup> (3-sample composite)		X		0.9441	2	.74504	.0001
MV-20 block <sup>1</sup> (6-sample composite)			X	1.8070	2	.77468	.0001
MV-70 block <sup>2</sup> (10-sample composite)			X	1.1637	2	.75967	.0001
MV-72 block <sup>2</sup> (10-sample composite)			X	0.7795	2	.74305	.0001
MV-73 block <sup>2</sup> (10-sample composite)			X	0.7759	2	.74326	.0001
MV-74 block <sup>2</sup> (10-sample composite)			X	0.8344	2	.74509	.0001
KA-209 <sup>3</sup>		X		1.142	3	.762	.001
385 <sup>3</sup>		X		0.633	3	.730	.001
369 <sup>3</sup>		X		1.045	3	.7521	.001
384 <sup>3</sup>			X	1.546	3	.7651	.001
KA-54 <sup>4</sup>		X		0.8066	1	.7455	.0002
605 <sup>4</sup>		X		0.8076	1	.7434	.0002
606 <sup>4</sup>		X		1.009	1	.7544	.0002
607 <sup>4</sup>		X		0.3183	1	.7206	.0002
608 <sup>4</sup>		X		0.8769	1	.7472	.0002
609 <sup>4</sup>		X		0.6136	1	.7324	.0002
339 (Morton Gneiss) <sup>3</sup>				0.175	3	.7096	.001

Table 9. Calculation of composites from the Montevideo Gneiss data reported by Farhat (1975). The content of dark and red phases for block MV-20 is unknown, so all samples reported are used. However for samples MV-102, MV-100, and KA-209 Farhat did distinguish between the dark and red phases, and only his samples labeled D, for Dark, are used to calculate these composites. The  $Rb^{87}/Sr^{86}$  sample ratios were apparently calculated by Farhat using a correction factor (times the ppm ratio) of 2.87678. They were recalculated here using the better figure of 2.89102. The composites given are the ratios of the means (as opposed to the mean of the ratios given above each composite value). The  $Sr^{86}$  and  $Sr^{87}$  compositions were calculated from Farhat's data according to the following equations:

$$Sr^{86} = \frac{(Sr\ ID)(P^{87} + P^{86})}{(1 + Sr^{87}/Sr^{86})} \quad \text{and}$$

$$Sr^{87} = [(Sr\ ID)(P^{87} + P^{86})] - (Sr^{86})$$

Where Sr ID = the total Sr determined in ppm by ID analysis,  $P^{87}$  = the natural abundance of  $Sr^{87}$  (i.e. 7.02%),  $P^{86}$  = the natural abundance of  $Sr^{86}$  (i.e. 9.86%).

Composite values thus obtained are believed to yield the same results as would be obtained by Farhat's method of mixing equal portions of the powdered samples together and doing a single analysis on the mixture.



SAMPLE	Rb (ppm)	Sr (ppm)	Rb <sup>87</sup> / <sup>86</sup> Sr	Sr <sup>87</sup> (ppm)	Sr <sup>87</sup> (ppm)	Sr <sup>87</sup> / <sup>86</sup> Sr
MV-20-1	129.14	197.79	1.8876	14.6363	18.7507	.78057
MV-20-2	150.94	227.10	1.9215	16.7860	21.5485	.77899
MV-20-3	132.73	243.36	1.5768	17.8249	23.2543	.76652
MV-20-6	186.39	223.95	2.4127	16.7505	21.0523	.79566
MV-20-8	86.38	271.93	0.9183	19.5726	26.3292	.74338
MV-20-9	147.72	169.04	2.5264	12.6632	15.8707	.79790
MV-20 MEAN	138.88	222.20	1.8739	16.3723	21.1343	.77717
MV-20 COMPOSITE			1.80695			.77468
MV-102-4D	84.35	258.31	0.9441	18.6169	24.9858	.74510
MV-102-5D	103.20	256.47	1.1633	18.5972	24.6949	.75308
MV-102-3D	71.37	278.12	0.7419	19.9292	27.0175	.73764
MV-102 MEAN	86.31	264.30	0.9498	19.0478	25.5661	.74527
MV-102 COMPOSITE			0.94406			.74504
MV-100-3D	115.5	314.9	1.0604	22.8068	30.3483	.75150
MV-100-5D	112.0	331.8	0.9759	23.9731	32.0347	.74835
MV-100-6D	115.5	335.8	0.9944	24.2697	32.4133	.74876
MV-100 MEAN	114.3	327.5	1.0102	23.6832	31.5988	.74954
MV-100 COMPOSITE			1.0093			.74950
(KA-209 locality of Goldich)						
MV-9-5D	92.29	204.3	1.3060	14.9093	19.5765	.76159
MV-104-4D	86.05	211.6	1.1757	15.4374	20.2807	.76119
MV-104-9D	88.59	197.2	1.2988	14.4010	18.8864	.76250
MV-107-4D	62.54	250.5	0.7218	18.0201	24.2643	.74266
KA-209 MEAN	82.37	215.9	1.1256	15.6920	20.7520	.75699
KA-209 COMPOSITE			1.10295			.75617

practice. The deviant point may simply be part of a random, normal distribution of data which together will delineate an isochron. If so, the point should be included in the regression even though seemingly deviant. The question is whether the deviant point (outlier) is sufficiently deviant to suggest that it is not a member of the same population as the other data points. If sufficiently deviant, some geological explanation is required, and the point may be omitted from the regression. A statistical test of the outlier should be made; a confidence level of 95% is considered by most statisticians to be a reasonable cut-off for the identification of outliers. Such a test will allow the omission of a point from the regression if it is shown that there is less than a 5% chance that the point is a part of the same population as the other samples. Specifically, a T-test should be applied in the following manner. The regression is re-computed without the possible outlier, and the Y-value ( $\text{Sr}^{87}/\text{Sr}^{86}$ ) on the isochron at the X-value ( $\text{Rb}^{87}/\text{Sr}^{86}$ ) of the outlier represents the predicted value of Y for the outlier. This value is subtracted from the actual value and the result is divided by the standard error of the predicted value. For sample MV-20 the calculation is:

$$T = \frac{(.77468 - .7905)}{(.0037)} = 4.2757$$

Tables are available (see for example, Snedecor and Cochran, 1967) to which this value may be compared, and it is found that sample MV-20 is significant only at the 98% level, i.e. there is only a 2% chance that MV-20 belongs in the regression with the other samples. This is sufficient statistical cause to omit the point from the regression. Rather than rely on intuition, geochronologists should delete samples from consideration only when they fail the T-test, or when there is clear geological evidence for doing so. To do otherwise is to bias the analysis and to make the error calculation unreliably low.

Goldich, et al., (1970) published five analyses, but attributed two of these (368 and 384) to the red phase, and therefore excluded them from the regression for the presumably older gray phase which we are discussing here. Goldich and Hedge (1974) presented new data but omitted without explanation samples 385 and 369 from consideration. Until it is satisfactorily explained why these samples should be omitted, they must be retained in the regression.

Goldich's practice of including "sample 339 from the Morton gneiss as a guide to the initial ratio of 0.700 and an age of 3,800 My" is clearly indefensible. If one wishes to specify a minimum initial ratio on the basis of BABI (Basaltic Achondrite Best Initial)

there is no need to include a point from a possibly unrelated intrusion 54 km away. It is probably wise to establish a minimum initial ratio of 0.700, but not by addition of an extraneous point, and the use of 0.700 as a maximum on purely theoretical considerations would be an a priori assumption. As shown below, there is no need to use a minimum value for the initial ratio.

On the basis of the previous discussion, there are only two acceptable approaches to the data. The first approach is to consider all points not omitted for some specific reason, such as known red phase content. There are 16 such points, and they indicate an age (Fig. 20) of 3,360 My with an initial ratio of 0.7042. The second approach is to also eliminate all samples in which there is a possible but unknown content of the red phase. This leaves 12 points which indicate an age of 3,390 My with an initial ratio of 0.7034. The ages are not significantly different, but the second approach yields an initial ratio which is lower and therefore more reasonable for rocks of this age. The value of 0.7034 is nevertheless still uncomfortably high for rocks of this age, and should instead be within the range of 0.700 to 0.701 (see, for example, Hurley and Rand, 1969).

Clearly the problem with the Montevideo gneiss is one of data scatter and range, and only a larger number of samples can improve the age determination.

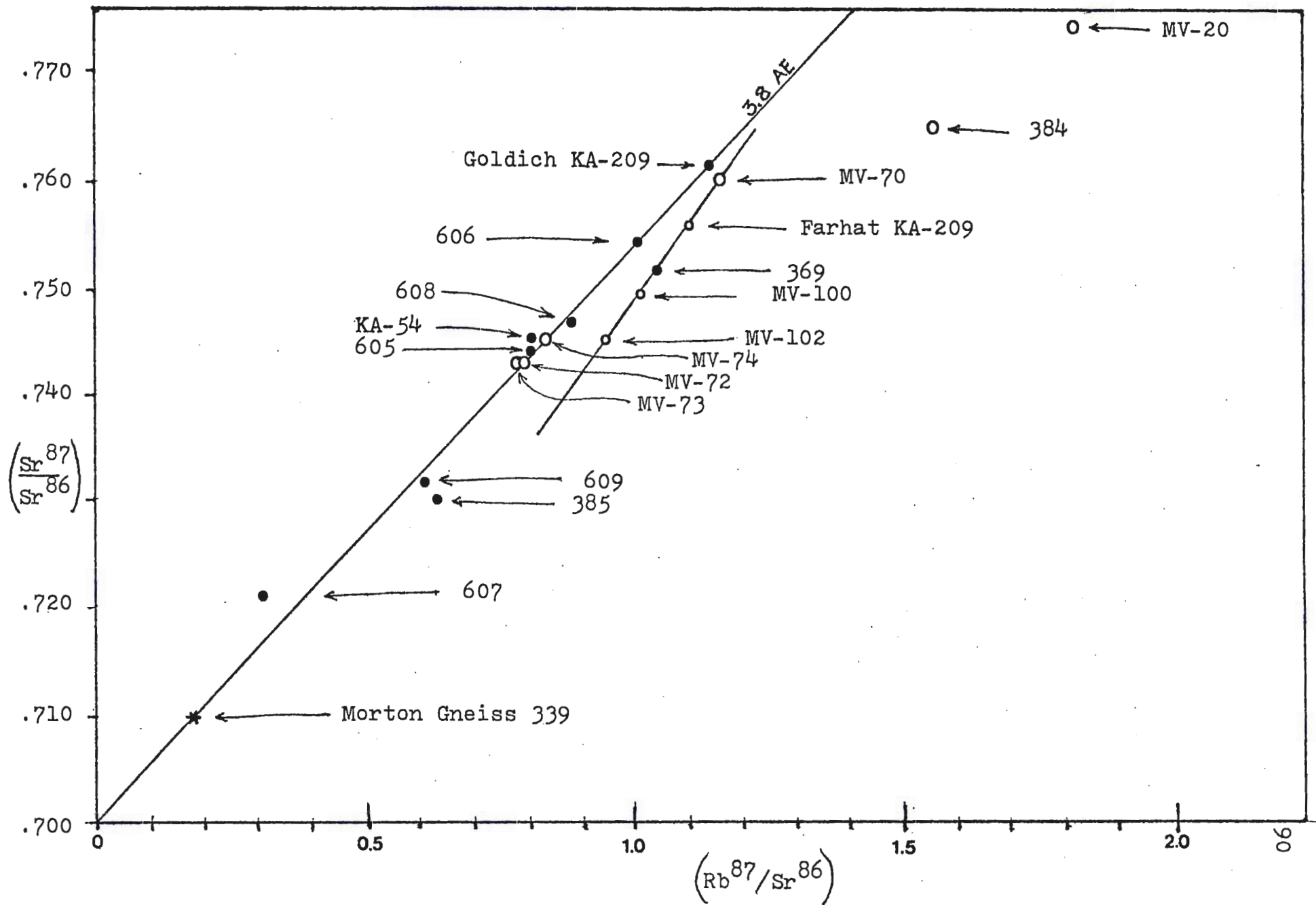
Figure 20. Rb-Sr evolution diagram showing all analyses of Montevideo Gneiss samples. Large open circles are samples which may contain contamination by the red, or light-colored component, which is probably younger than the Montevideo Gneiss. All are Farhat samples except 384 which is a Goldich, et al, sample. Small open circles are Farhat analyses recalculated for this study. Closed circles are analyses by Goldich, et al.

The 3.8 Ae isochron is preferred by Goldich although to obtain it many analyses must be rejected and an extraneous point (339) from another rock unit must be introduced.

Sample MV-20 meets the requirements for a statistical outlier.

The danger inherent in selecting or rejecting points for a regression on the basis of linearity is well-illustrated by the case of the points MV-70, Farhat KA-209, 369, MV-100, and MV-102. These five points are remarkably colinear, as indicated by the reference line through them, however together they produce an isochron indicating an apparent age of  $4.70 \pm .20$  Ae, with an initial Sr ratio of 0.681. Neither of these figures can have any meaning in view of the current understanding of the limits of the age of terrestrial rocks and initial ratios. However in another case the error may not be as obvious.

The only conclusion indicated by these analyses is that the Montevideo Gneiss MAY be as old as 3.8 Ae, but it may also be somewhat younger. The scatter of the data points as well as the lack of points for control at the lower end of the isochron prohibit further conclusions.



In particular, samples are needed which have low Rb/Sr ratios, similar perhaps to that of the Morton sample 339, in order to give better control to the lower end of the isochron. Adequate data at the lower end, as Goldich and Hedge wish to indicate, will most likely lower the initial Sr ratio into the above-mentioned 0.700 to 0.701 range, in which case the age indicated would be in the 3,600 to 3,700 My range. It is definitely possible that more data will substantiate the claim of Goldich and Hedge for an age of 3,800 My.

It is instructive to note the surprisingly linear accidental alignment of five Montevideo gneiss samples (MV-70, Farhat KA-209, 369, MV-100 and MV-102) to form a pseudochron of low statistical error: 4,700 My  $\pm$ 200 (2 $\sigma$ ), with an initial ratio of 0.681. This demonstrates the interpretive hazards of (1) selecting data points solely on the basis of linearity while discarding seemingly deviant points, and (2) taking too few samples in an area which has undergone major metamorphic re-equilibration.

There is one other area of disagreement not yet discussed which can be resolved. Two different metamorphic ages have been reported for the Montevideo Gneiss, by the Rb-Sr method. Goldich, et al, (1970) obtained ages on biotite separates from four rock samples which cluster around 1.8 billion years. Farhat

and Wetherill (1974, 1975) obtained ages on three large blocks, by their block sampling technique, which cluster around 2.6 billion years. Considering that the best estimate (discussed earlier) for the age of formation of the Montevideo Gneiss is about 3.7 billion years, it seems possible that the block method of Farhat and Wetherill has yielded an accidental isochron intermediate between 1.8 and 3.7 billion years. However 2.6 AE is a well-established time of major metamorphism in the Minnesota River Valley. An examination of the diffusion process suggests that it is indeed possible to obtain two meaningful metamorphic ages (in addition to an age of formation) via Rb-Sr analysis of a single rock unit; the intermediate age is not necessarily an accident.

Two assumptions are required, if two meaningful metamorphic ages are to be obtained: (1) the equilibration distance during the 2.6 AE metamorphism was greater than three meters, and (2) the equilibration distance during the 1.8 AE event was only a few centimeters. These assumptions are reasonable in the case of the Minnesota River Valley; previous investigators generally agree that the 2.6 AE event was a high-grade, regional, granulite facies metamorphism whereas the 1.8 AE event was very weak in comparison. If the samples from which the biotite separates were extracted were not much larger in diameter than the 1.8 AE equilibration distance the biotite Sr will have been



well-homogenized within those samples during the 1.8 AE event and yield a 1.8 AE metachron. If the rock samples taken by Farhat and Wetherill for their block method analysis were each at least as large in diameter as the 1.8 AE equilibration distance they will each represent a closed system and will not yield a 1.8 AE metachron, but rather a 2.6 AE metachron. Figure 21 illustrates an idealized set of data from such a situation.

The following conclusions regarding the Montevideo gneiss are therefore offered:

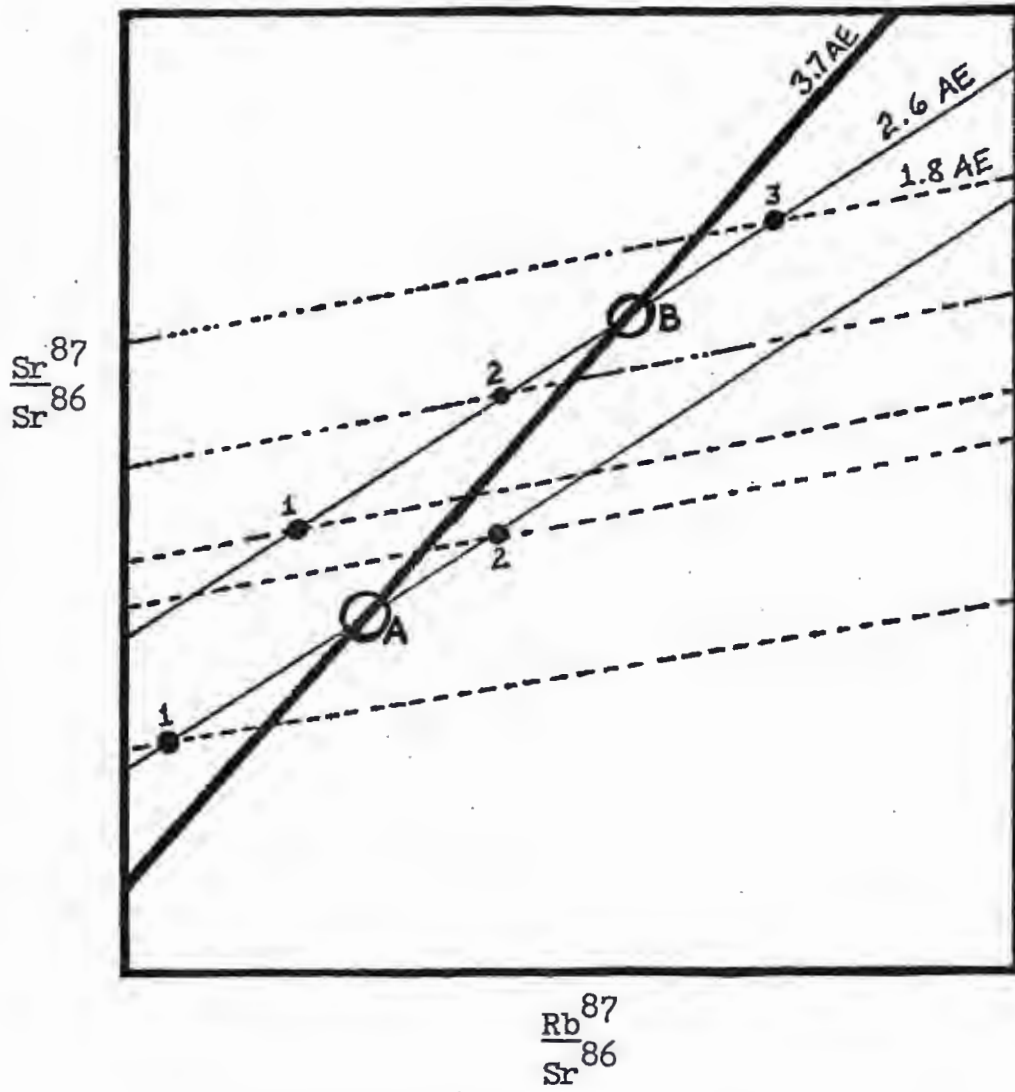
(1) The best age for the Montevideo gneiss obtainable from the currently available data is 3,400 My, although this age will probably eventually be shown to be within the 3,600 to 3,700 My range.

(2) There is no evidence to dispute a different age for the red massive phase, and this age has been best calculated by Goldich and Hedge (1975) as 3,000 My  $\pm$  90 ( $R_i = 0.7065$ ).

(3) All of the Farhat analyses obtained from mixtures of these two phases may be of little value.

(4) The equilibration distance achieved in the Montevideo gneiss during the 2,600 My metamorphism exceeds three meters, therefore the block sampling technique (ten samples per block, homogenized) proposed by Farhat (1975) for the determination of a primachron

Figure 21. Idealized set of data from a rock unit (like the Montevideo Gneiss) which has undergone high-grade and low-grade metamorphic events. Circles A and B represent averages of many rock samples from within blocks A and B; the heavy isochron obtained is the original age of formation. The dots are rock samples from each block which define the high-grade metachrons. Mineral separates from each rock sample produce the dotted isochrons which are low-grade metachrons. Two metamorphic events are revealed as well as the age of formation.



is advisable, and large samples are essential for accurate original age determination.

(5) The block sampling technique may yield a metamorphic age but is inferior to the analysis of mineral fractions in determining a metamorphic age. On the other hand, the block sampling technique can be the best method of determining a primachron in an area of high-grade regional metamorphism.

Goldich (1972) commented on the problem posed by isochrons derived from metasedimentary rocks:

"Whole-rock Rb-Sr isochron studies of metasedimentary rocks yield valuable geological information, but the metasedimentary rocks may be derived from a number of different terranes; hence, the isochrons may be especially difficult to assess. Development of reliable criteria for their interpretation will be useful."

It is possible to predict many of the potential results when whole-rock analyses of metasediments are attempted. An examination of the limits produced in theoretical situations, combined with some geologically reasonable assumptions, can serve to place tentative limits on the interpretation of experimental results.

Because the possibilities have, to my knowledge, never been discussed in the literature, a presentation of them is given here. The constraints predicted will be applied to the interpretation of Minnesota River Valley rocks, and may be applied to other Archean gneisses of possibly metasedimentary origin.

This discussion need not consider the case of a metasedimentary metachron; the metachron will indicate an age as accurate as those obtained on metamorphosed igneous rocks because the metamorphic homogenization of  $\text{Sr}^{87}/\text{Sr}^{86}$  takes place regardless of the premetamorphic nature of the rock. Considered here will be what have, in the past, been referred to as whole-rock isochrons. Whether the whole-rock isochron will be some type of

pseudochron or primachron is the principle question.<sup>98</sup>

In all cases except the case where there is only one source rock for the sedimentary rock, the meta-sedimentary isochron will represent some type of composite of the isochrons of the source rocks. The first consideration must be the variables associated with the source rocks.

These variables determine the different cases which must be considered in predicting possible composite isochrons; they are listed below:

(1) Number of source rock units represented in the sedimentary rock. If only one is represented the isochron can be interpreted under the same criteria used for igneous rocks.

(2) Predeposition extent of weathering. The effect of weathering on Rb-Sr whole-rock ages has been investigated and discussed by Fullagar and Ragland (1975), and their findings indicate that weathered samples will have ages ranging from essentially the same as fresh samples to no more than 20% younger than the age obtained from fresh samples. Ages are lowered only where biotite and K-feldspar have undergone considerable alteration, and are effected little by the weathering of plagioclase.

(3) Predepositional occurrence of metamorphism in the source rocks.

(4) Age of the source rocks.

(5) Initial  $\text{Sr}^{87}/\text{Sr}^{86}$  ratio of the source rocks.

(6) The nature of the mixing of the source rock particles to form the sedimentary rock.

(7) The variation in the average Rb content between the source rocks.

(8) The variation of the range of Rb content (spread on the isochron) within source rocks, relative to each other.

It would be possible to divide these variables into almost an infinite number of levels. It is only required for this discussion to divide them into topologically distinct categories; levels within a continuously varying range can be ignored. The possibilities within each variable are given below:

- (1) Number of source rocks: Two, or More than two.  
(the case of one is unique)
- (2) Predepositional weathering: Significant or Insignificant.
- (3) Predepositional metamorphism: Yes or No.
- (4) Age of source rocks: Identical or Different.
- (5) Initial Sr ratio: Identical or Different
- (6) Nature of mixing: Homogeneous constant ratio, or Homogeneous random ratio, or Systematically variable ratio (Higher Sr-87 with lower Rb), or Systematically variable ratio (Higher Sr-87 with higher Rb)
- (7) Average Rb content of source rocks: Identical or Different.

(8) Rb range (spread) of source rocks:

100

Identical and small, or  
Identical and large, or  
Different (one large and  
one small).

Even with these extremely simplified divisions there are >700 possible combinations of circumstances. There are more topological possibilities than noted above; for example, under variable #8-c, where the ages of the source rocks are different, the unit having the smaller spread could be the older or the younger unit. Another example: where the ages and initial ratios are different, the oldest unit could have the higher or lower initial ratio. If it has the lower ratio the source rock isochrons will cross; if it has the higher ratio they will not cross. With those additional possibilities, the maximum number of combinations of these variables that could conceivably occur in nature rises to >1000. This incredibly high degree of potential variability in circumstances has no doubt been intuitively recognized by many geochronologists and accounts for the absence of literature on the subject.

The chances of any meaningful interpretation of data from a metasedimentary rock are clearly hopeless unless some assumptions and constraints are used to eliminate all the possible combinations in which a relatively random apparent age, i.e. an age older than



the oldest source rock or younger than the youngest source rock, can be generated. In the case in which both the age and initial ratios of the source rocks are identical the isochrons are congruent; any other mixing or abundance variables cannot alter the composite isochron. Weathering could alter the composite isochron as previously described, so the age of any source rock isochron must be considered a minimum. In the Minnesota River Valley the most likely premetamorphic sedimentary rock type is graywacke, a rock composed of relatively unweathered rock and mineral grains. Consequently the isochron(s) of the source unit(s) has probably changed relatively little. Unfortunately this cannot be confirmed because metamorphic recrystallization destroys the evidence; microscopic examination of metasedimentary rocks will not reveal much about the extent of premetamorphic weathering, so the possibility of a lowered apparent age due to weathering can never be completely discounted.

Predepositional metamorphism can be ignored as a factor because it will not alter the source rock primachrons.

The above assumptions are well-founded, but the number of possible combinations remaining for consideration is still around 500, many of them yielding random ages. Some more speculative assumptions are

required if an interpretation is to be possible.

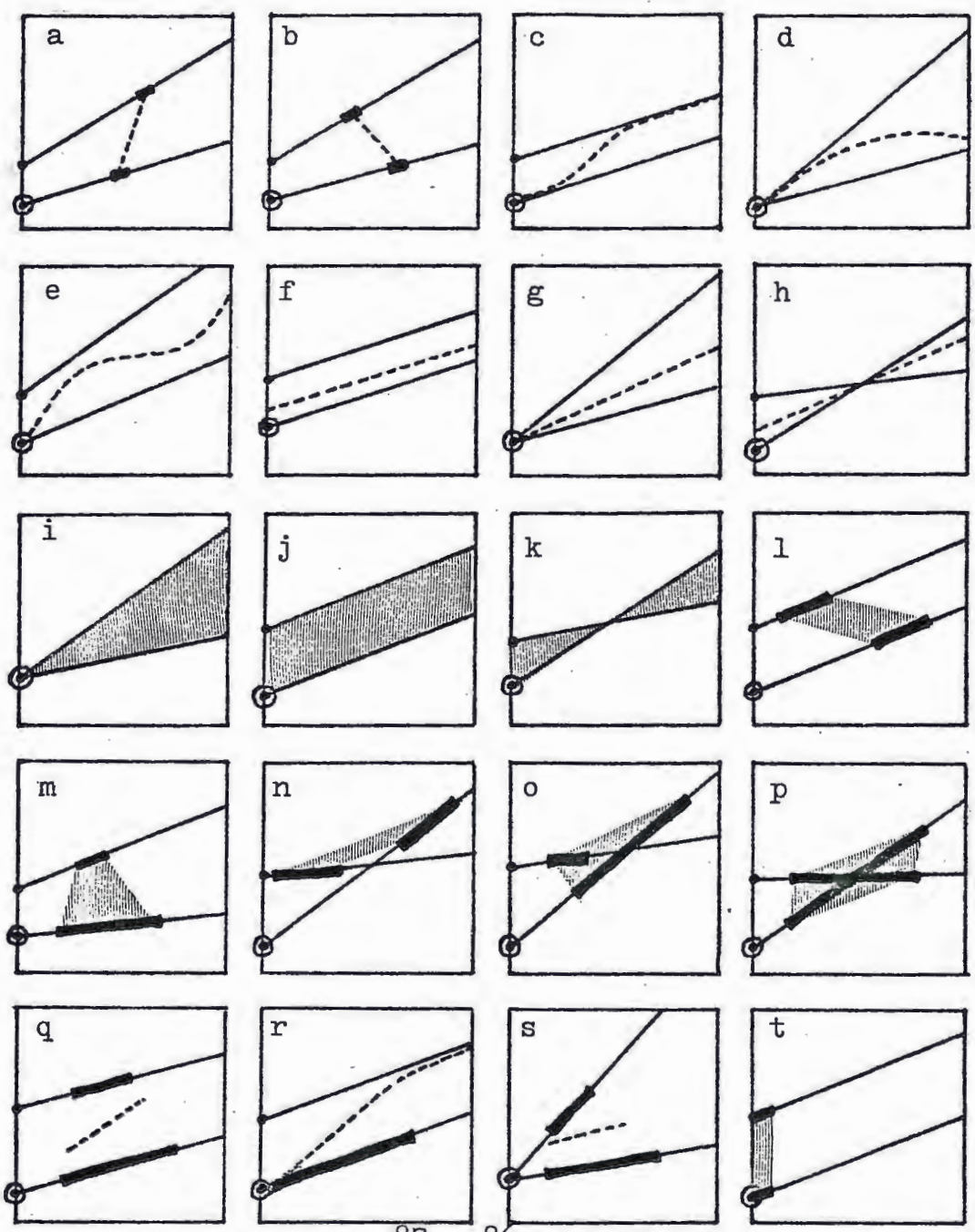
Combinations involving different average Rb contents and very small ranges with homogeneously random or systematic mixing ratios (as in Figure 22-a) could potentially yield pseudochrons of almost any age, including negative ages (as in Figure 22-b). There is no statistical reason why negative ages would be any less likely than positive ages in such a case, and in as much as a negative apparent age has never, to my knowledge, been observed (or at least never published), we will tentatively assume this type of pseudochron never occurs in nature. If the mixing ratio in the above case is homogeneous and constant the result would be essentially a point rather than an apparent isochron, and would, at least, not be susceptible to erroneous interpretation.

Systematically variable mixing (varying vertically and/or laterally at the outcrop) could potentially yield pseudochrons of random ages (Figures 22-q,r,s). However a common result would be curved isochrons (Figure 22-c,d,e) and because such isochrons have not, to my knowledge, been observed, we will assume that this type of pseudochron does not occur in nature.

A pseudochron with a high degree of scatter could still result from a homogeneous, random mix between two isochrons of differing average Rb content

Figure 22. Topologically possible composite isochrons and analysis distribution zones for a system consisting of two different source rocks in a metasedimentary unit. Only cases f, g, and h are concluded (in the text) to actually occur in nature.

$\frac{Sr^{87}}{Sr^{85}}$



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

	two source rock isochrons
	source rock isochron with Rb range limit indicated
	composite metasedimentary isochron
	zone in which a random scatter of points will occur

(as in Figure 22-1,n) or of similar average Rb content (as in Figure 22-i,j,k,m,o,p). If we refrain from attempting to interpret all data which lacks a reasonably close approximation to linearity, these and other misleading combinations can be eliminated.

With the above additional assumptions and stipulations, 45 possibilities remain (e.g. Figure 22-f,g,h). In none of these cases can the apparent age be greater than the age of the oldest source unit. Given these assumptions, a metasedimentary isochron is therefore a minimum age for the source rocks.

In all cases where the geochronologist does not feel justified in making the necessary assumptions, a metasedimentary isochron must be considered impossible to unambiguously interpret. If constraints can be imposed by field relations or other types of experimental data, some of these assumptions may be proven correct (or incorrect) for a given situation. In view of the potential complexity involved in a metasedimentary Rb-Sr system it is critical to make reasonable assumptions and to obtain as much supplemental data as possible by other means, which can be applied to the geologic situation to eliminate possible combinations of circumstances. Only in this way can a reliable interpretation of a metasedimentary isochron be achieved.

Archean terranes around the world generally are characterized by metavolcanic and metasedimentary gneisses and schists of various types, and commonly by mafic to felsic intrusions. Dynamothermal metamorphism of high grade (granulite or amphibolite facies) is common and, due to the extreme age of the rocks, polymetamorphism is to be expected. Metasomatic alteration, anatectic magma generation, and complex, orogenically-associated faulting have affected most Archean areas. These factors obscure earlier events to varying degrees and make the interpretation of geologic history a difficult if not impossible task. The more an Archean series of rocks is subjected to such events, the more inscrutable its origin and early history become. The principle interpretation problems are discussed here as a preface to the interpretation of the Granite Falls rocks.

Problem #1: The intrusion/inclusion problem.

In many cases of intense metamorphic recrystallization and tectonism no igneous textures remain to distinguish intruding from intruded units. The presence of apparent inclusions of host rock in the apparent intrusion are of no interpretive value because they may instead be remnants of (younger) apophyses or disrupted dikes rather than (older) inclusions.

Apparent flow textures are more commonly the product of metamorphically induced plastic flow or foliation rather than primary igneous textures. Only by showing that one of the units is of sedimentary origin (and therefore not an intrusion), or by obtaining significantly different isotopic dates can the time relationship of the units be proven.

Problem #2: The metasedimentary/metaigneous problem.

Apparently one of the most common and widespread sedimentary rock types in Archean times was graywacke (Pettijohn, 1943). Most of the Archean sections of Temiskaming age in the Canadian Shield, for example, are composed of rocks of the graywacke suite; the metamorphic counterpart of graywacke, as will be shown in the next section, is also found in the Minnesota River Valley. The composition of graywacke, because of the mineralogical immaturity of the sediment, is very similar to many igneous rock types from which it may be derived. The interpretation problem is the result of this fact. To cite some examples, Edwards (1947) described a graywacke resembling andesite in composition, and Taliaferro (1943) noted graywackes approaching the composition of granodiorite (the most common composition worldwide (Pettijohn, 1975)). Graywackes of basaltic composition are not uncommon (Pettijohn, 1957).

Once such rocks have undergone high-grade tectonism/metamorphism it becomes very difficult to distinguish them from their metamorphosed igneous equivalents. All sedimentary textures and structures have been destroyed by recrystallization, and chemical differences in bedding can be homogenized over a considerable distance under certain circumstances. A moderate enrichment in Rb is sometimes a clue to a sedimentary past. Bulk composition and trace element contents must be carefully compared and evaluated if evidence of a sedimentary history is to be found. These comparisons are not infallable, and the various lines of evidence can only suggest the probability of one origin or the other.

Problem #3: The correlation problem (of rock units).

Rock units in Archean terrane of sporadic exposure or in areas of extensive intrusion are usually extremely difficult to correlate. Metamorphism commonly has destroyed all textures and mineralogical peculiarities of the various units leaving only bulk composition and trace elements as a guide. In many cases metamorphism has altered even these characteristics. Consequently two similar but different units may become almost indistinguishable from each other, and be erroneously interpreted as a single unit. Or metamorphism may act upon a unit to yield different compositions in different parts of the unit which



are entirely a function of metamorphic re-equilibration. Especially in the case of similar rock units with appreciable internal chemical variability, the reliability of a determination of their identity by chemical means alone is suspect. No assumptions can therefore be made regarding the identity of two units without a body of data of statistically significant size.

The above three problems are the principle difficulties posed by a metamorphic terrane. There are a variety of other problems of more limited scope which are described below.

Problem #4: The up/down problem.

The question of which side of a rock layer was on top at the time of deposition is usually answered through an examination of textures normally destroyed by high-grade tectonic metamorphism. Overturning of a sequence is a distinct possibility in the history of an Archean rock, and thus the direction of accumulation with time is commonly unknown. A series of layered volcanic rocks varying systematically in composition may be compared with similar trends for more recent rocks to form an interpretation, but where no

such major trend is discernable the question generally cannot be resolved.

Problem #5: The magma genesis problem.

Grant (1972), in discussing the origin of the Montevideo gneiss, comments:

"...two problems arise; (1) is the tonalitic material essentially primary or a residuum from partial melting of a more potassic protolith, and (2) to what extent was the granitic material of (a) local derivation during the metamorphism, or (b) introduced late in these events in conjunction with such bodies as the Sacred Heart pluton?

The crux of the problem is that in such a high grade plutonic environment introduction of magma, partial melting, and metasomatism are all possible processes which could occur in concert with one another."

Even on a scale of less than a meter this ambiguity poses a difficult problem. In migmatitic areas such as the Wurscher farm (Grant, 1972b) where blocks and fragments of schistose material are interlaced with a magmatic phase it is often not possible to distinguish lit-par-lit injection from partial melting. The fluid phase, frozen in the process of movement, could have been on its way into, or on its way out of the schistose phase. In the first case there may be no genetic relationship but in the second case there is.

Problem #6: Limitations of isotope geochronology.

It is possible that a complex sequence of events, involving great thicknesses of deposits intrusions and metamorphism, could take place during a time span shorter than the 2 $\sigma$  error bracket of the resulting isochrons. In such a case isotope geochronology is

incapable of delineating the sequence of events.

Fifteen or twenty years ago the term "absolute age" was attached to isochron determinations, but since that time it has been shown that many such determinations yield only a minimum age. Goldich (1972) pointed out that systematic analytical errors lead to good linearity of points but fallacious isochrons which may not only give a wrong age but also a wrong initial  $\text{Sr}^{87}/\text{Sr}^{86}$  ratio. Consequently the interpretation of all geochemical dating must be more judicious and less absolute in its conclusions. The limitations of the technique must be taken into consideration.

Problem #7: The metasedimentary source rocks problem.

The problems inherent in the interpretation of metasedimentary isochrons were discussed in section B of this chapter, and it was concluded that the indicated age can only be interpreted as a minimum age for the oldest source rock represented. Unfortunately there is as yet no way to extract information on the source rocks separately, or even to discern how many of them are represented.

Problem #8. The correlation problem (of events).

The question of the association of various intrusions with various periods of deformation, and of either of these types of events with regional or local thermal metamorphism poses great difficulty. Intrusive and metamorphic events can be dated by isotopic means

to obtain a general framework for discussion, but in the case of a polymetamorphic history it is commonly difficult to ascertain which metamorphic event produced which metamorphic textures and structures. An intrusion which pre-dates or post-dates a metamorphism by a short period of time can be metamorphosed by a second event, and the relationship becomes obscure. Intrusions can insinuate themselves along zones of weakness in a folded terrane and give the appearance of having themselves been folded by the deformational metamorphic event. Deformational, thermal, and intrusive features may be created independently of each other and are not necessarily related.

Problem #9: Fault obliteration.

In a high-grade metamorphic area, contacts between formational units often become diffuse and gradational. If these contacts are the result of conformable faults the sequence may be disrupted or discontinuous without there being any visible evidence of this fact. The inference of a fault must therefore be made strictly on the basis of general and regional geology unless large structures are clearly cut and displaced.

Problem #10: Non-uniformitarianism.

There is no guarantee that geologic processes operated in the Archean precisely as they have in recent times. If unfamiliar processes have been at work their results may be difficult and misleading to interpret.

D. Interpretation of rocks in the Granite Falls area

Montevideo Gneiss

In a previous section of this chapter it was concluded from the data of others that the best age for the gray (oldest) phase is about 3.7 AE.

Goldich, et al, (1970) and Grant (1972), among others, have discussed the derivation of the Montevideo gneiss and have come to no positive conclusions regarding its origin. They do agree that the Montevideo gneiss was a relatively deep-seated intrusion. The data and interpretations of other workers on this unit will not be re-worked here. It is agreed, however, that the Montevideo Gneiss is most likely a metamorphosed igneous intrusion, which was probably created by the partial melting at depth of igneous rocks or their sedimentary equivalents. The results of all research to date, however, are still insufficient to positively identify the protolith origin.

Hornblende-pyroxene Gneiss (Inner Unit)

The data from this unit do not plot on an isochron; therefore nothing positive can be said about its age from an isotope dating standpoint. Nevertheless this distribution is not entirely devoid of indications. Because all points plot above the Montevideo gneiss isochron (of Goldich and Hedge, 1974) we can infer that the chemical equilibrium of this rock unit was disturbed

by a loss of Rubidium, a gain of radiogenic Strontium, or both. For the following discussion it must be remembered that there has never been any evidence to show that simple weathering can have such an effect. In the case of weathering, points tend to move below the isochron rather than above it (Fullagar and Ragland, 1975, Goldich and Gast, 1966).

If isotopic dating is not possible from the data the next logical consideration is the possible correlation of rock units. It is possible that only a loss of Rb was involved. The average Rb content seen today would have to be increased by a factor of about 3 for the data to potentially plot on an isochron in the 3.6 to 3.8 AE range with an initial Sr ratio of .700. In order to match the average Rb content of the outer unit of the hornblende-pyroxene gneiss the content of the inner unit would have to be increased by a factor of about 6; to match the metagabbro it would have to be decreased by a factor of about 2. There is nothing suggestive in these comparisons. If, on the contrary, the average Rb content of the inner unit, when adjusted to that of the outer unit or metagabbro, could produce a reasonably similar isochron it would suggest the possibility of a correlation between the units, and a lack of Sr contamination. But this did not prove to be the case, so we are left with two possibilities: (1) Sr contamination, with or without Rb depletion, took place, or

(2) no Sr contamination took place, and the inner unit does not correlate with the outer unit or the metagabbro. If Sr contamination took place there will be no isochron evidence useful for correlation. There is currently no way to distinguish by direct means whether or not Sr contamination took place, so this line of reasoning is inconclusive.

Lanphere, et al (1963) showed that in the case of Sr contamination the points on the original isochron will move toward the point on the Sr ratio ordinate which represents the average Sr isotopic ratio of the contaminant. It can be seen from the plot of the data for the inner unit (Figure 11) that the average contaminant ratio could not be much less than 0.709 (because of the geometrical relationship between the position of point GF-42 and the oldest possible isochron), but could conceivably be much greater. Contamination by the Montevideo gneiss is compatible with this interpretation; the average Sr isotopic ratio of the seven samples reported by Goldich and Hedge (1974) is 0.744.

There are two possible interpretations of the relationship between the Montevideo gneiss and the inner unit of the hornblende-pyroxene gneiss. One is that the inner unit was intruded as a sill into the Montevideo gneiss and is therefore the younger of the two. Under this interpretation the apparent inclusions within the Montevideo gneiss are either unrelated to

the inner unit or are disrupted dikes and apophyses. Considering the scale and severity of the chemical disturbance it is difficult to understand how any event could so seriously disrupt the equilibrium of the inner unit while not seriously disrupting the equilibrium of the supposedly older Montevideo gneiss on both sides of the inner unit; it will be remembered that Goldich's data on the Montevideo gneiss is believably colinear, and many of his samples were collected from a quarry just a few hundred meters from the sample locations for this study on the inner unit.

The other possibility is that the Montevideo gneiss intruded around the inner unit of the hornblende-pyroxene gneiss on both sides, and that the inner unit is therefore the older of the two. This interpretation fits the observed data much better; the Montevideo magma was the source of Sr contamination which impregnated the inner unit. Consequently this interpretation is preferable. Incidental to this conclusion is the speculation that depletion of Rb in the inner unit probably did not take place, since the contaminating agent (the Montevideo gneiss) is much higher in Rb than the hornblende-pyroxene gneiss, and could not reasonably be expected to widen this difference by leaching Rb out of the inner unit. There is still no evidence useful for correlation but at least an age relationship between the Montevideo gneiss and the inner unit has



been tentatively established.

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It may be noticed from the plot of the data that 4 of the 8 data points roughly define a 4.0 AE isochron. This is mildly suggestive in view of the above interpretation that the inner unit is probably older than the 3.7 AE Montevideo gneiss. However the initial Sr ratio of 0.704 is considerably higher than the 0.700 ratio expected for rocks of this age. There is a very small possibility that the 4.0 AE isochron is a metamorphic isochron roughly approximating the intrusion date of the Montevideo gneiss, and that the initial Sr ratio is too high for this reason. However the scatter of the other points strongly suggests that this is an accidental alignment.

Trace element trends can suggest probable premetamorphic rock types. A plot of trace element contents of the inner unit is given on Figure 23, and the trend for the same elements in a variety of other rock types is shown for comparison. The trend is clearly within the basalt zone (even allowing for some depletion in Rb), and is most similar to that of an island arc basalt, except for the higher Ba content. Barium metasomatism is fairly common so this discrepancy is not too significant. A plot of the average content of K vs. Rb (Figure 24) shows that the samples follow the oceanic basalt trend: further evidence for the premetamorphic rock type. A third indication is

Figure 23. Trace element compositions of Minnesota River Valley rocks relative to ocean floor basalts, and relative to other varieties of volcanic rocks. Rock units analyzed in this study are shown by dotted lines. Other analyses compiled by Jahn (1972).

- (A) Oceanic alkali basalt
- (B) Hornblende-pyroxene Gneiss (Outer Unit)
- (C) Archean felsic and intermediate rocks
- (D) Hornblende-pyroxene Gneiss (Inner Unit)
- (E) Calc-alkaline andesite
- (F) Average basalt
- (G) Hornblende-pyroxene granulite (Metagabbro)
- (H) Low-K tholeiite
- (I) Archean basalts
- (J) Island arc basalts
- (K) Ocean floor basalts

ROCK / OCEAN FLOOR BASALT

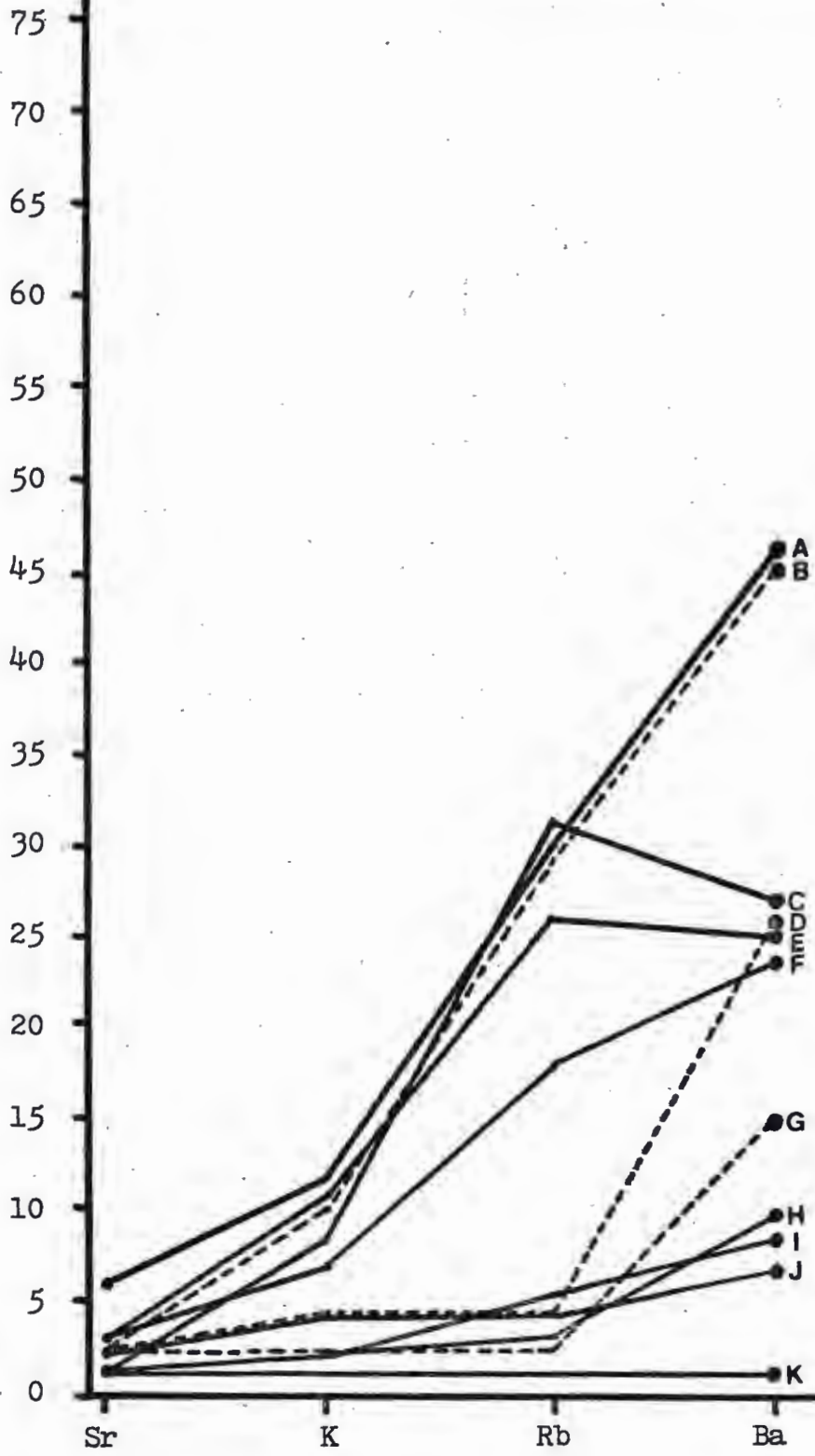


Figure 24. Plot of K vs. Rb for rocks analyzed in this study, with the general trends of oceanic and continental basalts shown for comparison.

- Hornblende-pyroxene granulite (Metagabbro)
- Garnet-biotite Gneiss
- Hornblende-pyroxene Gneiss (Inner Unit)
- ⊖ Hornblende-pyroxene Gneiss (Outer Unit)
- ▼ Average of Archean basalts (Jahn, 1972)

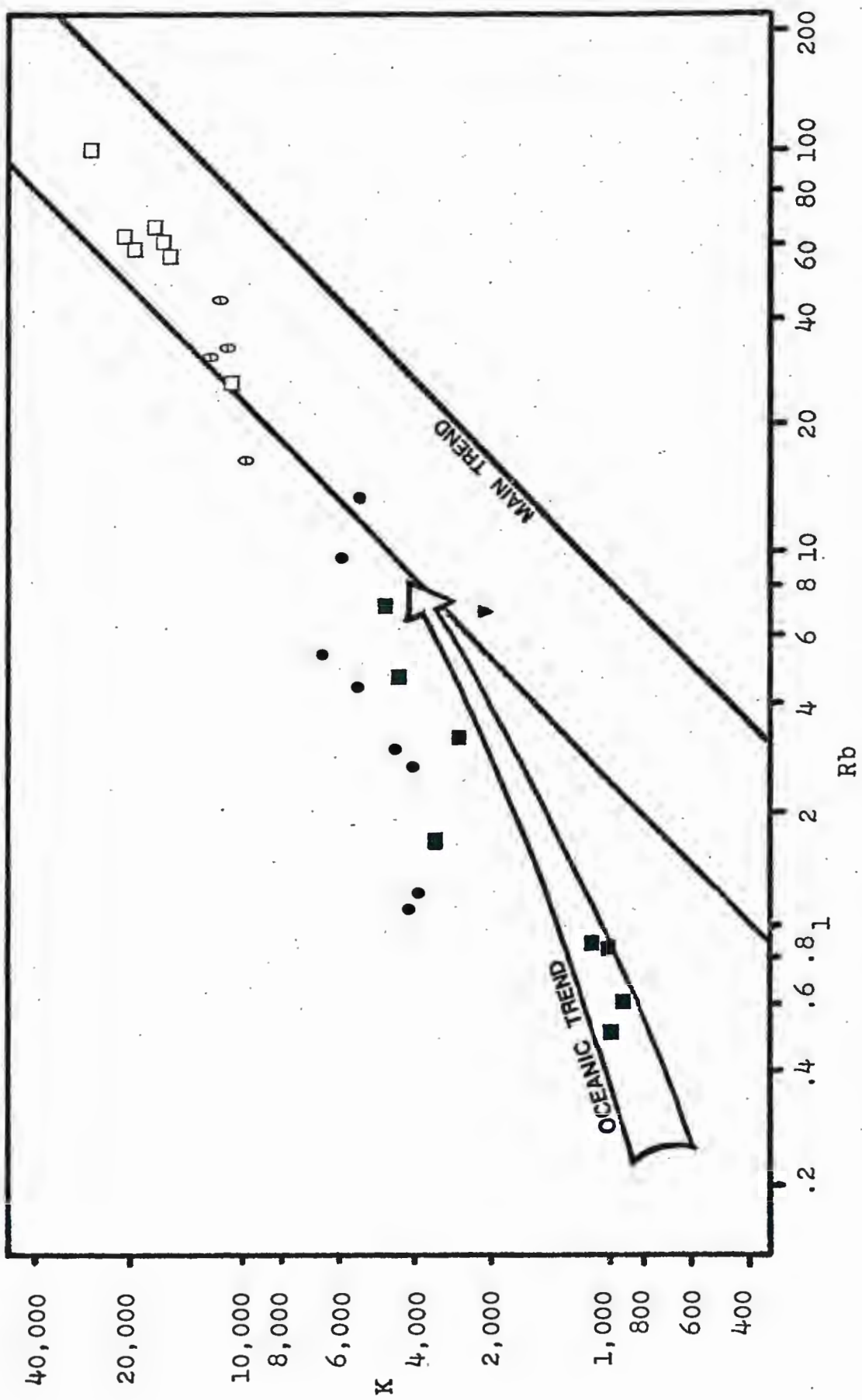
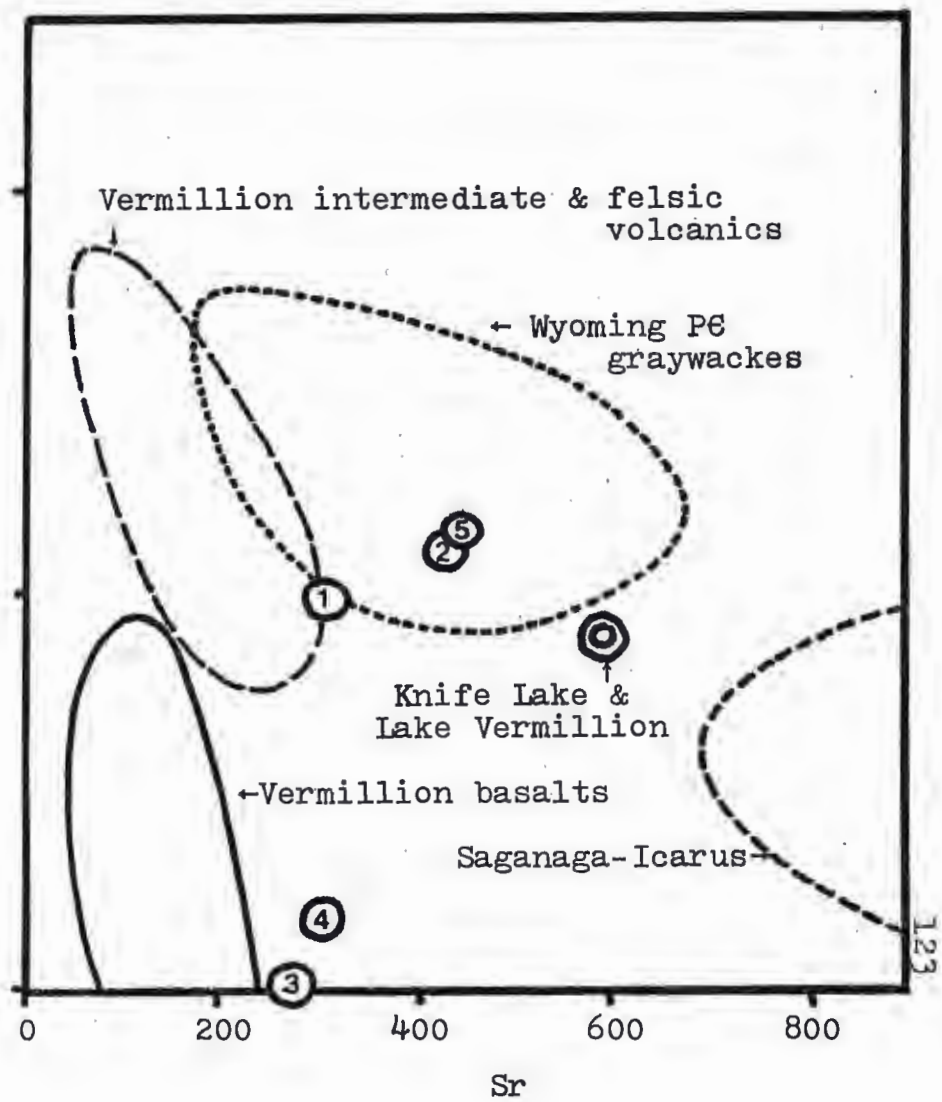
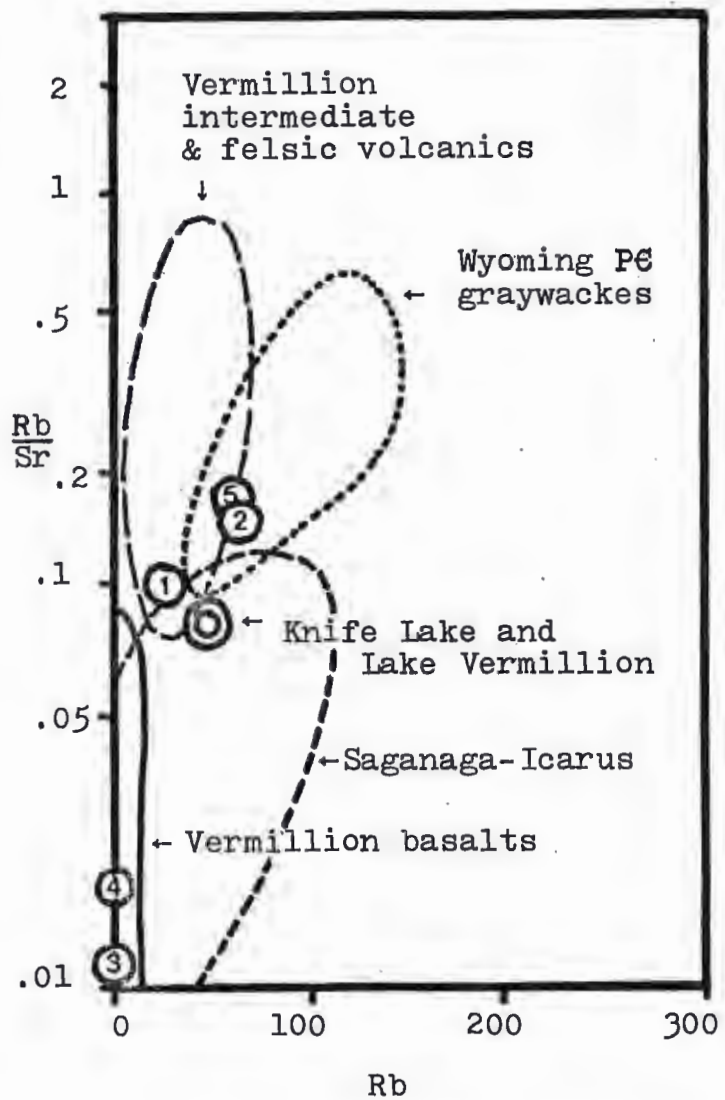


Figure 25. Average ratios of analyses of Rb and Sr for rock units in this study compared to the distribution zones for analyses of other rock groups of possibly similar lithology.

- (1) Hornblende-pyroxene Gneiss (Outer Unit)
- (2) Garnet-biotite Gneiss
- (3) Hornblende-pyroxene Granulite (Metagabbro)
- (4) Hornblende-pyroxene Gneiss (Inner Unit)
- (5) Amphibolite inclusions

Distribution zones for the other rock units are from Jahn (1972).



provided by a plot of Rb/Sr against Rb and against Sr, which demonstrates that the average content is within or very close to the zone defined by Archean Vermilion basalts from northern Minnesota (Figure 25).

#### Metagabbro of Himmelberg

Himmelberg (1975, personal communication) has designated this unit as a metagabbro, although he has seen no textural or mineralogical evidence to suggest whether this unit was originally a gabbro intrusion or a basalt flow. His conclusion (1968) that the unit may be an intrusive sill was based solely on the fact that the unit is not continuous to the northwestern arm of the Granite Falls antiform, and therefore appears to be a lens of local extent. Acceptance of this interpretation is conditional on acceptance of the idea that a layered sequence cannot contain lenses of extrusive basalt: a tenuous assumption at best.

Isochron data indicate an age of 2.68 AE with an initial Sr ratio of 0.704. This result is somewhat ambiguous. The isochron could be a whole-rock metachron (similar to those obtained by Farhat on the Montevideo gneiss) and not represent the original age of the rock. Furthermore the spread of the points on the isochron is extremely small, and is approaching the lower limit of reliability of the analytical system. Consequently this age must be considered a minimum. Pb/Pb zircon



dating of this unit by Farhat (1975) yielded an age of 2.69 Ae, confirming that date as a minimum age of formation.

The Rb-Sr mineral ages obtained on hornblende-pyroxene and plagioclase from this unit indicate incomplete resetting during the 1.8 AE event; two rock samples give ages around 1.8 AE and one gives an age of 2.4 AE.

Trace element plots (Figures 23, 24 and 25 imply that the metagabbro is of basaltic composition, and possibly something very similar to an ocean floor basalt or a low-K tholeiite. The four eastern-most samples come the closest to ocean floor basaltic composition (for K, Rb and Sr), but appear to have experienced the same type of Barium metasomatism that has effected the inner unit of the hornblende-pyroxene gneiss. This comparable enrichment in Ba is the only feature which suggests a correlation between the metagabbro and the inner unit. But metasomatism could have affected both units at some indeterminate time after their emplacement, and probably bears no genetic significance.

The metagabbro series of outcrops sampled, which are roadcuts along Highway 212, appear to be zoned with respect to Rb content. Four samples from the eastern-most cut average 0.7 ppm Rb, one sample from the center cut contains 1.5 ppm Rb, and three samples

from the western-most cut average 4.9 ppm Rb. This distribution of Rb may be a relict feature produced in the original rock during crystallization from a magma, and supports the theory of its intrusive origin.

#### Hornblende-pyroxene Gneiss (Outer Unit)

A minimum age for this unit has been established by Farhat (1975). He obtained a Pb/Pb age on zircon of 2.6 AE.

Four whole-rock samples from this unit give a Rb-Sr age of 3.31 AE  $\pm$  0.26 AE, with an initial ratio of 0.701  $\pm$  0.001. The error bracket is large because only four points are involved, but additional data could reasonably be expected to define an isochron of at least 3.5 AE and an initial ratio of 0.700. This isochron would be congruent with the isochron for the garnet-biotite gneiss (discussed next) with which the outer unit is in contact. A plagioclase-biotite mineral isochron gives an age of 1.78 AE.

The trace element distribution shown on Figure 18 demonstrates a very close similarity in the contents of K, Rb, Sr and Ba to that of an oceanic alkali basalt. Figure 25 shows that the composition falls not far from the range for basaltic rocks in the Vermilion District, Northeastern Minnesota. This is consistent with

opinions of Grant (1972) who suggested that the hornblende-pyroxene gneisses were either originally mafic volcanic rocks or "volcanic" sills.

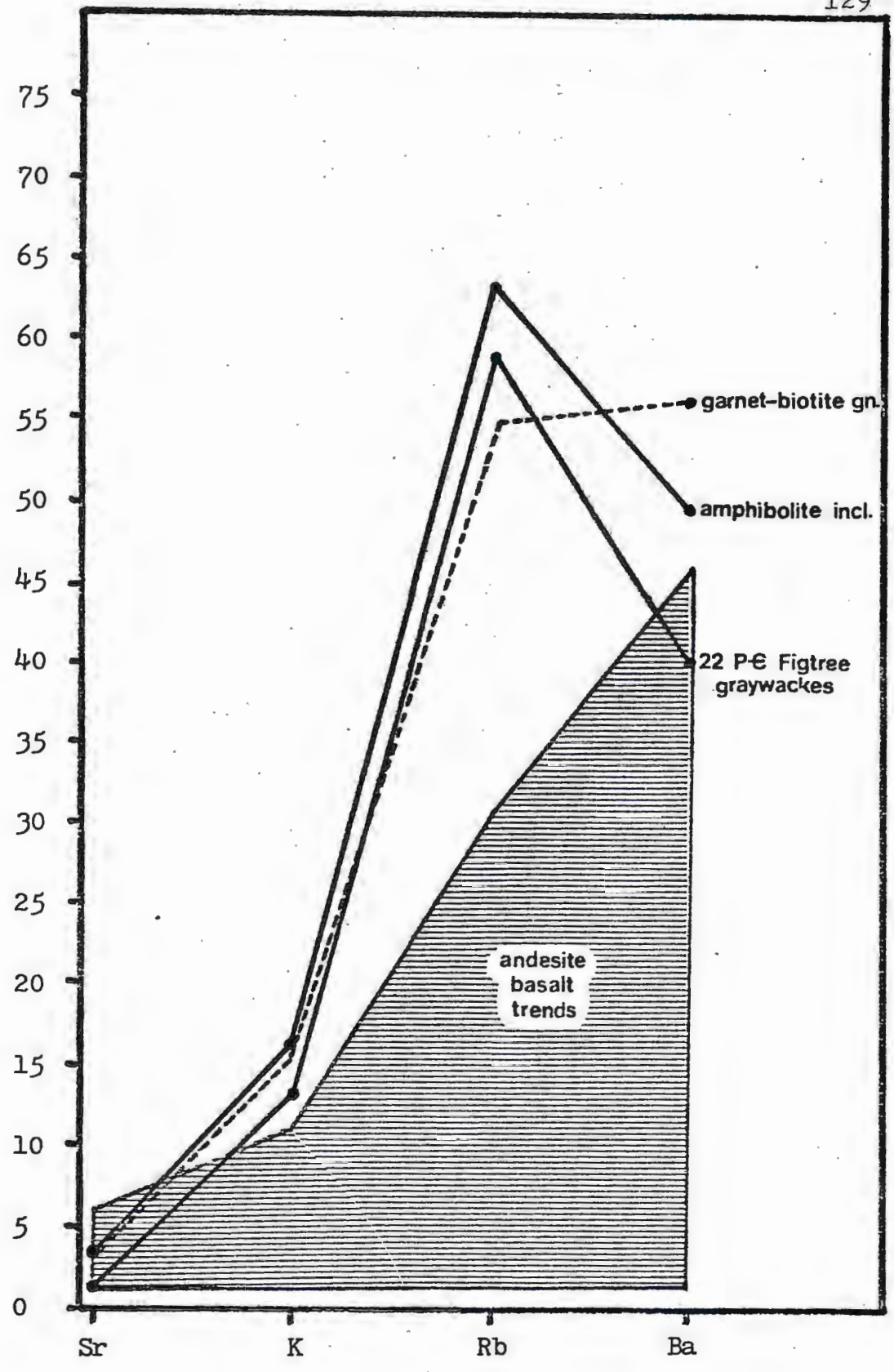
#### Garnet-biotite Gneiss

A whole-rock age of  $3.54 \pm 0.14$  AE with an initial strontium ratio of  $.7008 \pm 0.0009$  has been determined for this unit. Biotite and plagioclase metamorphic ages determined on two rock samples, and a mineral isochron including plagioclase, magnetite, pyroxene, garnet, and biotite for a third sample all cluster around 1.8 AE. The initial whole-rock Sr ratio is acceptably low for a rock of this age. It has been concluded earlier in this chapter that a Rb-Sr whole-rock isochron for a metasedimentary rock yields only a minimum age. Therefore this unit could be older than the Montevideo gneiss (3.7 AE), and could be a part of the original layered sequence intruded by the Montevideo gneiss.

A plot of K, Rb, Sr and Ba (Figure 26) suggests that this rock was probably derived from a graywacke. These data support an identical conclusion reached by Grant (1972) on the basis of bulk composition and structure. A plot of Rb/Sr against Rb and Sr (Figure 25) falls within the zone for Precambrian Wyoming graywackes, further substantiating a sedimentary origin.

Figure 26. Trace element compositions of the Garnet-biotite Gneiss and the Amphibolite inclusions plotted relative to ocean floor basalt. The zone of andesite basalt trends as determined by Jahn (1972) is shown for comparison, as well as the average trend for 22 analyses of Precambrian Figtree graywackes.

ROCK / OCEAN FLOOR BASALT



The identification of graywacke as the original rock type carries several implications. Pettijohn (1943) regarded graywackes as the earmark of tectonically unstable regions, especially eugeosynclinal belts where sediments and volcanic rocks are interbedded. In a recent review of the literature on graywacke, Pettijohn (1975) concluded that graywackes are not to be found in undeformed sequences deposited on stable cratonic shield areas, but rather are the product of geosynclinal sedimentation. Pettijohn further concludes that graywackes consist of the waste products of a high land mass, and frequently occur interbedded with volcanic rocks. This description agrees with the observation that the Garnet-biotite Gneiss (nee graywacke) in the Granite Falls area was originally interbedded with volcanic rock types common to marine basins. The data is still fragmentary and incomplete, but the most appealing interpretation is that at the time of deposition the area now known as the Minnesota River Valley was somewhat off-shore from the continental margin, and that the area was in an active volcanic zone possibly similar to continental plate margins today which are volcanically active by association with a downthrusting oceanic plate.

Zircon Pb/Pb ages obtained on this unit by Stern (1964) and Goldich, et al., (1970) indicate a metamorphic age of 2.65 AE. Clearly the minerals have

been reset by the 1.8 AE event with respect to the Rb-Sr system, but the Pb/Pb system retains the evidence of the earlier, stronger event at 2.6 AE. This is not unusual in dry, Precambrian, granulite facies rocks (P. Hurley, personal communication).

E. Interpretation of amphibolite inclusions from the Morton - Sacred Heart area

Four samples of amphibolite inclusions were analyzed. Three of these samples were colinear, yielding a 3.5 AE Rb-Sr isochron with an initial Sr ratio of 0.709. The fourth sample, from a large raft in the Morton Gneiss, plotted on the Morton Gneiss isochron. The three colinear amphibolites are more radiogenic than was expected. Their isochron has an unusually high initial Sr ratio for rocks of that age, suggesting that the 3.5 AE age may be a reflection of a metamorphic event at that time, such as the Mortonian Event.

The possibility cannot be denied that the three-point isochron may be fortuitous. However it is still highly suggestive that these amphibolites may come from at least two (and probably more) distinct populations, and that one or all are older than the Morton Gneiss.

Figure 26 shows a plot of the trace element data for the average of the four amphibolite samples. Their

trend is strikingly similar to that for the Figtree graywackes, and is in fact more similar to a graywacke than the garnet-biotite gneiss at Granite Falls. This evidence mitigates against the suggestion by Goldich, et al. (1970) and Grant (1972b) that the amphibolites are largely of igneous origin. If a sedimentary origin for the amphibolite inclusions, as suggested by the results of this study, can be positively established it would prove that the inclusions are older than the Morton Gneiss, and are remnants of older Archean sedimentary rocks dredged up by the intrusion of the Morton Gneiss, and again by the Sacred Heart Granite.



## CONCLUSIONS

The interpretation most compatible with the results of this study is that all of the gneisses in the Granite Falls area (except the Montevideo Gneiss) formed a layered sequence over 3.7 AE ago, in a geologic setting analogous to modern-day island arcs. In this view the garnet-biotite gneiss represents a subaqueously deposited graywacke, as previously discussed; the hornblende-pyroxene gneiss (inner unit) represents an island arc basalt; the hornblende-pyroxene gneiss (outer unit) represents an oceanic alkali basalt; the metagabbro represents an ocean floor basalt or low-K tholeiite. This sequence subsided to a great depth where melting or partial melting of rocks lower in the sequence produced the Montevideo Gneiss intrusion about 3.7 AE ago.

Evidence primarily from other researchers has indicated a major period of regional, high-grade metamorphism 2.6 AE ago. In this study ample evidence has been found for the 1.8 AE metamorphic event, and the incomplete resetting of mineral ages in the metagabbro at 1.8 AE is compatible with this being a very weak event.

Results of this study tend to confirm the interpretation of Grant (1972b) that these rocks are older,

higher-grade metamorphic analogs of the rock assemblages characteristic of greenstone-granite complexes. Also confirmed is the observation of Goldich, et al. (1970), and others, that the country rock intruded by the Montevideo Gneiss is older and appears to have been a layered series of basaltic lavas and sedimentary rocks.

Results of this study suggest that the source rocks for some of the amphibolite inclusions in the Morton Gneiss and Sacred Heart Granite are of gray-wacke origin, and are therefore older than the gneiss. This evidence contradicts the suggestions of Goldich, et al. (1970) and Grant (1972b) that the amphibolites are largely of igneous origin.

The following environment at the time of deposition of the rocks at Granite Falls is compatible with the results of this study: an environment off-shore from a continental margin, near an area of active volcanism such as an island arc.

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