RB-SR WHOLE-ROCK ISOTOPIC GEOCHEMISTRY AND PETROLOGY OF THE TONALITIC-TRONDHJEMITIC PHASE OF THE ARCHEAN QUARTZO-FELDSPATHIC GNEISS, SACRED HEART-NORTH REDWOOD AREA, MINNESOTA RIVER VALLEY

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ABSTRACT

Quartzo-feldspathic gneisses of Archean age crop out in southwestern Minnesota, within the Sacred Heart-North Redwood area of the Minnesota River Valley. In this area, three units of migmatitic quartzo-feldspathic gneiss exist in a grossly layered sequence with the uppermost unit being an interlayered unit of biotite-rich gneiss and amphibolite. Contained within the quartzo-feldspathic gneisses are layers and rafts of amphibolite. The units are several hundreds of meters thick, and have been folded into an easterly trending, open-fold system with a wave length of a little more than a kilometer. The gneisses are in the upper amphibolite facies, having been involved in a period of high-grade metamorphism prior to 2650 m.y., when they were intruded by quartz monzonite bodies.

The composition of the quartzo-feldspathic gneiss varies from tonalitic to quartz monzonitic. Eleven whole-rock samples of the tonalitic phase, or gray gneiss, were sampled. The medium- to coarse-grained, granular samples of gray gneiss range in texture from homogeneous to banded and are composed primarily of plagioclases, with major amounts of quartz and biotite, and occasionally hornblende. Each sample has less than three percent of K-feldspar.

The major element chemistry of the samples is similar to other Archean intrusive and gneissic rocks of tonalitic composition and K is less than 2.21 percent in each sample. In detail, the regular chemical variations of these samples allows them to be placed into two chemical groups, suggesting that the gneisses are not all cogenetic.

Rb in the whole-rock samples varies from 15-88 ppm, and averages 58, while Sr varies from 191-944 ppm and averages 584. The abundance of Sr can be used to further subdivide the chemical groups.

The eleven samples do not form an isochron. Model ages were calculated, assuming an initial ^{87}Sr/^{86}Sr ratio of 0.700, and show much variation. Three samples have model ages greater than 3400 m.y., while the bulk of the others are clustered at 2970 m.y. and also 2700-2770 m.y. and may reflect metamorphic events. It is not clear from the limited amount of data to what degree metamorphic events have affected the istopic systems and model ages, hence the age or ages of the gray gneiss in this area cannot be uniquely resolved.

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INTRODUCTION

Statement of the Thesis Problem

Exposures of amphibolite to granulite facies, Archean gneisses have been detected in scattered areas world-wide. Many of these occurrences have been found to be very old, exceeding 3000 m.y. (Moorbath, 1976). The most intensely studied Archean gneiss, in terms of geochronology, is the Amitsôq Gneiss of western Greenland, which has yielded concordant Rb-Sr and Pb/Pb whole-rock ages which average about 3750 m.y. (Black et al., 1971; Moorbath et al., 1972; Baadsgaard, 1973; Moorbath et al., 1975). Other areas where similarly old gneisses exist are eastern Labrador--3622 ± 72 m.y. (Rb-Sr whole-rock isochron age; Hurst, 1975), northern Norway--3460 ± 70 m.y. (Pb/Pb whole-rock age; Taylor, 1975), Rhodesia--3500-3600 m.y. (Rb-Sr whole-rock isochron age; Hickman, 1974), and Montana, U.S.A.--3400 m.y. (Rb-Sr whole-rock isochron age (Mueller, 1976).

Many of the problems of continental growth depend upon the age and isotopic measurements of major sialic rock units. The gneissic rocks in the Minnesota River Valley bear lithologic similarities to those found in other ancient gneiss terranes, and some of these are known to have similarly old ages also.

It is the purpose of this study to investigate the Rb-Sr whole-rock isotopic systems of the gray, tonalitic-trondhjemitic phase of the quartzo-feldspathic gneiss in the Sacred Heart-North Redwood area, to test whether the gneisses in this area are cogenetic and to determine if possible, how old they are.

Regional Precambrian Geology

Archean, high-grade metamorphic rocks are exposed in southwestern Minnesota within the Minnesota River Valley (Figure 1). This polymetamorphic crystalline segment of the earth's crust is located on the southern edge of the Canadian Shield and has mineral assemblages characteristic of the upper amphibolite and granulite facies (Grant, 1972; Himmelberg and Phinney, 1967). The rocks consist of openly folded sequences of migmatitic granitic and amphibolitic gneisses, and have been intruded by an abundance of quartz monzonite. Geochronologic studies have shown the existence of at least some of the gneisses prior to the major metamorphic event which occurred in the approximate time span from 3000 m.y. to 2600 m.y. (Goldich et al., 1970; Wilson and Murthy, 1976).

Gravity and magnetic anomalies from southwestern to Minnesota (Zietz and Kirby, 1970; Craddock and

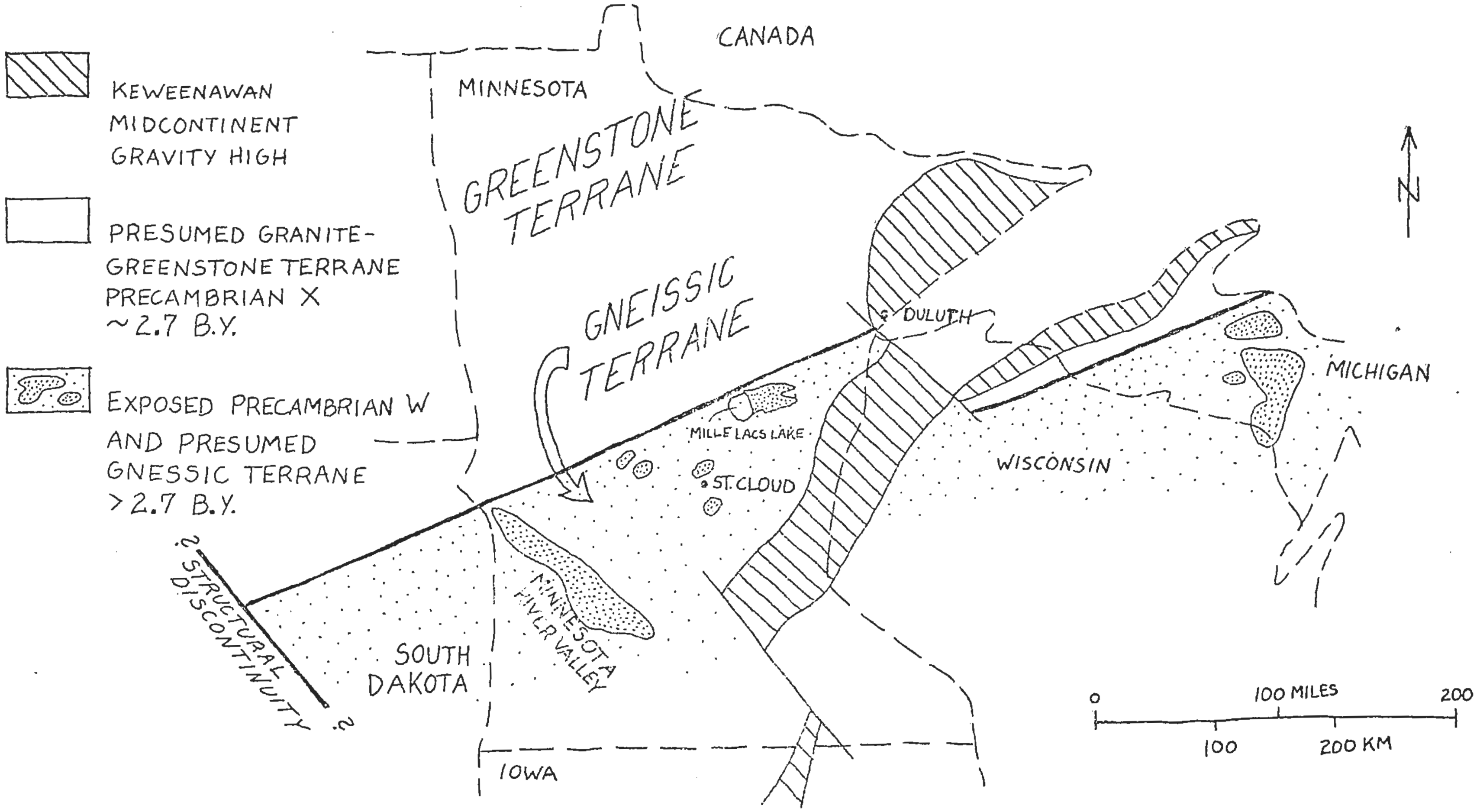

Figure 1--LOCATION AND BOUNDARIES OF PRECAMBRIAN TERRANES. (after: Morey, G. B. and Sims, P. K., 1976, p. 150)

others, 1970) indicate that rocks similar to those found in the Minnesota River Valley underlie this area as well. There are isolated exposures of Archean rocks in central Minnesota (Figure 1) which exhibit similarities in structural style and metamorphic grade to the migmatitic rocks of the Minnesota River Valley (Morey and Sims, 1976). The McGrath Gneiss, near Mille Lacs Lake, is of granitic composition and has a minimum age of 2700 m.y. (Struckless and Goldich, 1972). Other Archean rocks in central Minnesota near St. Cloud and Melrose include hornblende-pyroxene gneiss and garnet-cordierite gneiss (Morey and Sims, 1976). Even though geochronologic evidence does not indicate positively that the Archean rocks in central Minnesota are as old as those exposed in the Minnesota River Valley, the lithologic and structural similarities between the two makes the correlation feasible (Morey and Sims, 1976).

To the north of the high-grade exposure in central Minnesota is the Archean granite-greenstone terrane of northeastern Minnesota, typical of the Superior Provine (Goodwin, 1967). Here, isoclinally-folded volcanic-sedimentary sequences appear in curvilinear belts with northeasterly trends. Between the "greenstone belts" are a variety of migmatic and granitic rocks. The intrusive granitic rocks are thought to have deformed the supracrustal rocks and metamorphosed them to greenschist facies (Anhauesser and others, 1969). The pattern of rock types permits the detection of this terrane beneath Mesozoic and Cenozoic cover across northern Minnesota by geophysical methods (Zietz and Kirby, 1970; Craddock and others, 1970). Radiometric dating of both the intrusive rocks and supracrustal rocks indicates that their formation or deformation was nearly time synchronous at about 2700 m.y. (Goldich, 1972).

The lack of contact exposure between the granite-greenstone terrane and the high-grade rocks to the south makes their geologic relations uncertain. Morey and Sims (1976) have used outcrop patterns and geophysical data to delineate the boundary of these two terranes. In Minnesota, the boundary runs northeasterly across the central portion of the state from a point near Duluth in the east to a point near Ortonville in the west (Figure 1). The epicenters of many Minnesota earthquakes are documented to lie near this boundary line (Walton, 1977). The western extension of this line stretches 210 kilometers into South Dakota where it may be terminated by a northwesterly-trending basement structure (Morey and Sims, 1976). The eastern truncation lies between two segments of Keweenawan intrusive, extrusive, and sedimentary rocks (Morey and Sims, 1976).

Gneissic rocks also appear across the Late Precambrian gravity high in central and northern Wisconsin and northern Michigan (Morey and Sims, 1976). These rocks are mainly quartzo-feldspathic gneisses and are also similar in nature to those found in the Minnesota River Valley, but attempts to determine their age have been inconclusive because of a long, complex tectonic history (Sims and Peterman, 1976; Van Schmus, 1977).

Geology of the Minnesota River Valley

The Minnesota River runs southeastward diagonally across southwestern Minnesota, following a valley created by the glacial river Warren (Matsch and Wright, 1967). The valley segment from Ortonville to New Ulm is about 200 kilometers long with a width that does not often exceed three to four kilometers. The river is now sluggish, but as the late Pleistocene ice sheets melted, the high-energy discharge dissected blankets of glacial sediments, Cretaceous strata and in places the Late Precambrian Sioux Quartzite to expose knobs of Archean basement rock.

Lund (1956) provided the first detailed study of the rocks of the Minnesota River Valley. He located the outcrops, and described and delineated three groups of rocks. The detailed mapping of Himmelberg (1968) in the Granite Falls-Montevideo area and Grant (1972) in the remainder of the valley both clarified the work of Lund and determined the regional structure (Figure 2).

The Archean migmatitic rocks exposed in the Minnesota River Valley consist of amphibolitic and quartzo-feldspathic gneisses. These rocks along with the abundant granitic material represent the product of repeated episodes of metamorphism and intrusion, and the complex series of thermal events have made it difficult to determine the original age and protolith of these rocks.

Although the structure is not well defined in some areas, it appears to be quite similar throughout the valley region. Where the rocks can be differentiated into a stratiform sequence, they reveal an open fold system with an east-northeasterly, gently plunging axis. The wave length of these folds is of a few kilometers. Minor fold systems and other structural aspects are discussed by Bauer (1976), who has suggested four periods of folding occurred throughout the region during Archean time.

The exposures of Precambrian bedrock are concentrated in four geographic areas along the river valley. The northern-most section is the Ortonville-Odessa area (Figure 2), and consists of granitic rocks, dominantly a foliated quartz monzonite. There are other granitic phases present, some of which contain deformed remnants of more mafic material. The

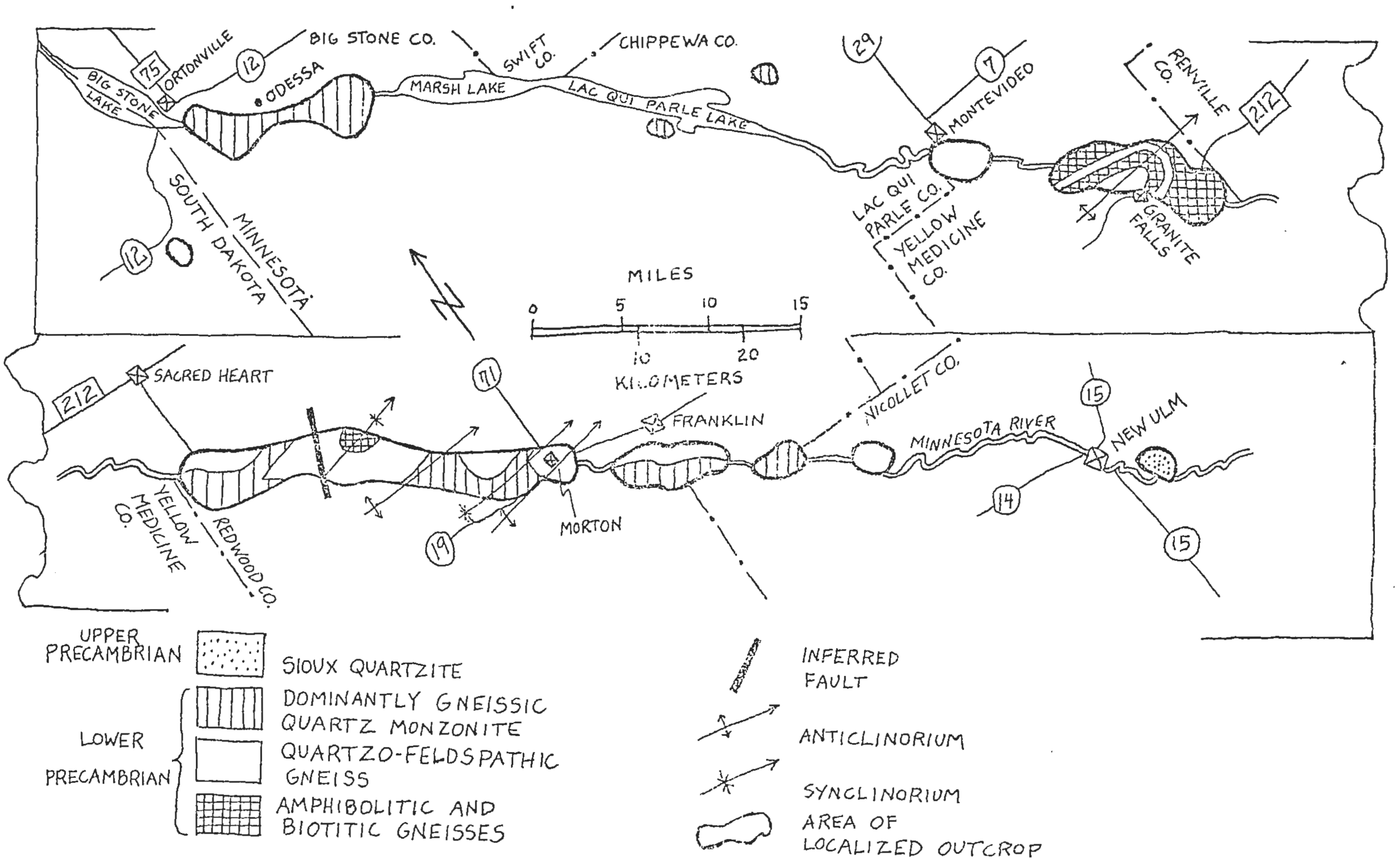

Figure 2--AREAS OF OUTCROP AND GEOLOGY OF MAIN PRECAMBRIAN ROCK TYPES. (after Grant, J. A., 1972, p. 178)

orientation of the minor fold axes and lineations are quite similar to other structures found in the other areas to the southeast (Grant, 1972).

The Granite Falls-Montevideo area is southeast of Ortonville and has been studied by Himmelberg (1968). The geology of the area consists of a layered sequence of gneisses. Units of granitic gneiss (the Montevideo Gneiss), hornblende-pyroxene gneiss, and garnet-biotite gneiss are 300-1500 meters thick and involved in an easterly-plunging anticline. The mineral assemblages here are indicative of the granulite facies (Himmelberg and Phinney, 1967). The gneissic rocks were intruded by a set of tholeiitic diabase dikes, which were in turn cut by a set of hornblende-andesite dikes. Another intrusion is a pink, medium-grained biotite adamellite, known as the "granite of section 28" (Goldich et al., 1961) which locally intrudes a hornblende-andesite dike.

Southeast of the Granite Falls-Montevideo area, and probably separated by a fault zone, is the Sacred Heart-Morton area described by Grant (1972). Relatively good exposure in the area reveals a grossly-layered, folded sequence of three lower units of quartzo-feldspathic gneiss, divided by Grant according to the relative abundance of amphibolite contained within the gneiss. In ascending order are units A (quartzo-feldspathic gneiss interlayered with amphibolite), B (quartzo-feldspathic gneiss containing common amphibolite rafts), and C (quarto-feldspathic gneiss rarely associated with amphibolite). The uppermost unit in the layered sequence (D) is of interlayered biotite-rich gneiss and amphibolite. Younger granitic material pervades the area and appears in a spectrum of sizes and forms. The grade of metamorphism is in the upper amphibolite facies (Grant, 1972).

The quartzo-feldspathic gneiss in the Sacred Heart-North Redwood area is often migmatitic and appears in a variety of pink to gray hues and many textural forms. They are medium- to coarse-grained rocks composed primarily of plagioclase, quartz, and biotite, plus occasional and variable amounts of hornblende and K-feldspar. The rocks vary from quartz monzonite to tonalitic in composition, with much being trondhjemitic (Goldich, 1972). Compositional banding of the light and dark minerals is often evident.

The inclusions of amphibolite within the quartzo-feldspathic gneisses are granular rocks of hornblende and plagioclase, containing a small amount of quartz. The amphibolite layers in unit A of the quartzo-feldspathic gneiss are about 100 meters thick (Grant, 1972) while the rafts occur in lensoid shaped bodies, most often parallel to the foliation of the surrounding gneiss, and are found to be up to a few tens of meters long.

Unit D consists of metasedimentary rocks, some orthogneiss, and orthoamphibolite.

These units (A,B,C,D) occur on a scale of a few hundred meters thick and are involved in major folds, with a pair of synformal and antiformal structures near Delhi and again near North Redwood.

Major quartz monzonite bodies intrude the gneisses south of Sacred Heart, and also northeast of Delhi, near North Redwood. These rocks are medium-grained and pink, and vary texturally from homogeneous to compositionally layered. Narrow dikes of similar composition appear throughout the area, and on a smaller scale, the permeation of veinlets of granitic material into the gneisses is evident.

The southern-most segment of the exposed Precambrian rocks is the Franklin-New Ulm area. As a whole, the area is poorly exposed and has been subjected to a greater degree of weathering than the other areas. Here, quartzo-feldspathic gneiss containing rafts of amphibolite, and gneissic quartz monzonite is exposed. Intruding these rocks is the Cedar Mountain Complex (a small gabbro-granophyre body (Grant, 1972)) and other similar intrusions. Overlying these older rocks is the Sioux Quartzite which crops out near New Ulm, and is known elsewhere in southwestern Minnesota. It is dominantly a red, tightly cemented quartzite, with minor mudstone and conglomerate (Austin, 1972).

Cretaceous rocks are found to overlie the Precambrian rocks in many parts of the valley. These include a basal clay-rich residuum derived from the gneisses, along with subsequent overlying shales, clays and lignites (Parham, 1970).

Finally, the area has been covered by an extensive series of superposed Pleistocene tills and outwash (Matsch, 1972).

Previous Geochemical Studies

Geochronological studies in the Minnesota River Valley have not only given an indication of the old ages of the rocks occurring there, but have also helped separate and clarify the complicated sequence and plutonic events. At present, several events have been defined on the basis of geochronological work as summarized by Grant (1972); (1) the age of the old gneisses, (2) the age of the major metaphoric imprint and the development of the major structure, (3) the age of the major quartz monzonite emplacement, (4) the ages of post-metamorphic intrusives and age of a possible low-grade metamorphism, and (5) the age of the Sioux Quartzite.

1. The Age of the Old Gneisses

The first proof of the antiquity of the rocks in the Minnesota River Valley came from Catanzaro (1963). His studies on the uranium-lead systems of zircons from the quartzo-feldspathic gneisses near Morton and Granite Falls gave discordant ages from 2800 m.y. to 3200 m.y. indicating that the gneisses were older than the ages of the granite-greenstone terrane to the north.

In determining the age of the quartzo-feldspathic gneisses from the Morton and Montevideo areas, Goldich and others (1970) analyzed the U-Pb systems of zircon concentrates along with the Rb-Sr whole-rock isotopic systems. They believed that the best age for these gneisses was approximately 3550 m.y., but their interpretation was complicated because both isotopic systems were discordant, and apparently disturbed by a major metamorphic event at about 2650 m.y.

Goldich and Hedge (1974) presented further results from Rb-Sr whole-rock studies of the quartzo-feldspathic gneisses near Montevideo. Six additional whole-rock samples from the fine-grained foliated phase were analyzed and used in conjunction with some of the samples selected for the 1970 study. Assuming an initial $^{87}Sr/^{86}Sr$ ratio of 0.700, the data indicated an isochron of 3800 m.y.

Wooden, Goldich and Ankenbauer (1975) selected samples of tonalitic gneiss south and east of Delhi. Using the Rb-Sr whole-rock method, the data defined an isochron age of 3650 ± 50 m.y. and an initial $^{87}Sr/^{86}Sr$ ratio of 0.6993.

Wilson and Murthy (1976) selected samples from the layered amphibolic gneisses near Granite Falls. The samples included the inner and outer units of hornblende-pyroxene gneiss and the unit of garnet-biotite gneiss. Whole-rock isochron ages from the Rb-Sr data indicated that this section of hornblende-garnet-pyroxene granulite facies rocks at Granite Falls has a minimum age of 3550 m.y.

2. The Age of the Major Metamorphic Imprint and Development of the Major Structure

Many mineral geochronological studies show that a period of high-grade metamorphism caused the recrystallization and development of biotite, K-feldspar, and hornblende in the gneissic units of the Minnesota River Valley. The Rb-Sr systems of micas and K-feldspar from the quartzo-feldspathic gneisses in the Granite Falls-Montevideo and Sacred Heart-Morton areas give model mineral ages which are about 2500 m.y. (Goldich, 1961; Goldich and Hedge, 1963; Goldich et al., 1970). K-Ar ages of hornblende from the quartzo-feldspathic gneisses in the Morton area give a slightly higher age of formation, being near to 2600 m.y. (Thomas, 1963; Hanson, 1968). K-Ar studies of hornblende in the hornblende-pyroxene gneisses in the Granite Falls vicinity yield radiometric ages of 2740 m.y. (Hanson and Himmelberg, 1967) and 2590-2760 m.y. (Hanson, 1968).

Because the mineral lineations of the high-grade metamorphic assembleges are congruent to the major structure, the last major metamorphism is believed to be time synchronous with the development of the major structure (Grant, 1972). Bauer (1976) has done a detailed structural analysis of the rocks exposed in the Montevideo-Granite Falls area and has concluded that the major structure, as well as three other minor fold systems developed during the time span from 3000 m.y. to 2600 m.y.

3. The Age of the Major Quartz Monzonite Emplacement

A major granitic intrusion, the Sacred Heart pluton, occurs south of Sacred Heart. Rb-Sr whole-rock and K-feldspar data (Goldich et al., 1970), U-Pb data from zircons (Goldich et al., 1970), and K-Ar hornblende data (Hanson, 1968; Thomas, 1963) each give an age of approximately 2650 m.y. Rb-Sr data of Goldich and Wooden (personal communication) shows that the granitic components of the quarto-feldspathic gneiss (adamellites, granites) are all younger than the gray gneiss.

The study of Rb-Sr whole-rock samples and K-feldspar, plus four lead-alpha determinations from a quartz monzonite in the Ortonville-Odessa area suggests that some of the granitic material present may be of the same age as the granitic body at Sacred Heart (Goldich et al., 1970).

4. The Age of Post-Metamorphic Intrusives and the Age of a Possible Low-Grade Metamorphism

Post-metamorphic intrusions have also been studied. Near Granite Falls, a small adamellite pluton, the granite of section 28, yields an Rb-Sr whole-rock and K-feldspar isochron age of approximately 1850 m.y. (Goldich, 1961; Goldich and Hedge, 1962; Goldich et al., 1970). Also, Catanzaro (1963) obtained an age of 1800 m.y. for this body using the U-Pb method on a zircon concentrate.

Another intrusion, the Cedar Mountain Complex near Franklin, yields a K-Ar hornblende age of about 1.7-1.8 b.y. (Hanson, 1968).

Hanson and Himmelberg (1967) obtained an age of 2080 m.y. for the tholeiitic diabase dikes near Granite Falls, using the K-Ar technique on hornblende. Crosscutting the dike set are hornblende-andesite dikes which yield K-Ar hornblende and biotite ages of 1.7-1.8 b.y.

The K-Ar and Rb-Sr biotite ages from the gneisses in the Granite Falls-Montevideo area, as well as those from the granitic gneisses in the Ortonville-Odessa area suggest a low-grade metamorphic event at approximately 1850 m.y. (Goldich et al., 1970), and this is supported by the Rb-Sr mineral ages for the amphibolitic gneisses in the Granite Falls vicinity (Wilson and Murthy, 1976).

5. The Age of the Sioux Quartzite

The youngest of the Precambrian rocks found in the Minnesota River Valley is the Sioux Quartzite, which crops out near New Ulm and is known elsewhere in southwestern Minnesota. In Iowa, a rhyolite recovered from drill core is thought to intrude and postdate the quartzite, and has yielded a Rb-Sr whole-rock age of 1470 m.y. (Lidiak, 1971).

PETROLOGY AND MAJOR ELEMENT CHEMISTRY OF THE GRAY TONALITIC GNEISS WHOLE-ROCK SAMPLES, SACRED HEART-NORTH REDWOOD AREA

Sampling

The units of quartzo-feldspathic gneiss in the Sacred Heart-Morton area of the Minnesota Valley consist of rocks of varied composition, color, grain size, and texture, but similar mineralogy. The rocks are sometimes migmatitic, and an example of this nebulosity is nicely represented by the famous building stone from the Morton quarry where amphibolitic, tonalitic, and granitic phases are involved in intricate patterns. Other mixtures of phases show the gneissic gray phase locally permeated by granitic material. When alone, the gray phase may be homogeneous to compositionally banded in texture, or perhaps have wispy concentrations of biotite and hornblende engulfed in a coarse-grained matrix of primarily plagioclase and quartz. The gray gneisses most often have a low percentage of K-feldspar and are tonalitic to trondhjemitic in composition (Lund, 1956; Goldich et al., 1970), and were sampled for use in this study.

There are many possible origins for this type of tonalitic rock. The regular, centimeter-wide, light and dark compositional banding is reminiscent of sedimentary bedding, and perhaps some of the patches and veins of the pinkish, granitic material are the product of the partial melting of the original rock, but if the gneisses of tonalitic composition are representative of the original rock, it is probable that they are igneous in origin.

If all of the gray gneisses originated by the intrusion of a tonalitic magma, it follows that much of the quartz monzonite in the area, which is often complexly intertwined with the gray phase in the migmatitic rocks, must have been introduced into the gray gneiss by magmatic or metasomatic means and may not be cogenetic. The intrusive nature of the Sacred Heart body at 2650 m.y. is well documented, and is not thought to be derived from a partial melting of the gneisses (Grant, 1972). Rare earth analyses of granitic veins which cut the Montevideo Gneiss suggest that they too are not attributable to the partial melting of the parental gneiss (Hanson, 1975). Also, in an area south of Sacred Heart, near the contact of quartzo-feldspathic gneiss unit B (Grant, 1972) with the Sacred Heart pluton, Welsh (1976) has concluded that the origin of the pink, microcline-rich bands within the quartzo-feldspathic gneiss are a result of the injection of a K-rich magma. Hence, the likelihood that the pinkish granitic material is not cogenetic or coeval with the gray tonalitic geiss seems to be great, and should be avoided in sampling.

To obtain an Rb-Sr whole-rock isochron age from the quartzo-feldspathic gneiss in the Sacred Heart-North Redwood area, it is necessary that the set of whole-rock samples be cogenetic and coeval, with the individual samples as a closed system through time. The gray, tonalitic portions of the quartzo-feldspathic gneiss units in the Sacred Heart-North Redwood area were sampled for this age determination study under the assumptions that the whole-rock samples satisfy the theoretical requirements. If the tonalitic gneiss is of igneous origin, it is possible to test whether or not the samples are cogenetic by the study of the major element chemistry and strontium isotopes.

Each whole-rock sample must be a closed system from the time of the origin of the rock in order for the isotopic systems to be a reflection of the original nature of the rock. Intrusion and metasomatism by a granitic magma, partial melting of the gneisses, and weathering are some of the processes by which the isotopic systems may be opened. In this area, it is known that much of the granitic material present involves the emplacement of younger quartz monzonite into the quartzo-feldspathic gneisses, and this would tend to result in the addition of Rb to the isotopic system of the gneiss. It is possible that, in some cases, the pink granitic material is the product of local melting of the gneisses. In either case, if the detection of a mixture of granitic and tonalitic phases is possible, it would indicate that the isotopic systems have not remained closed since the origin of the gneiss.

The metasomatic influences of the quartz monzonite intrusions are difficult to determine. For this reason, hand samples were taken from 3-10 meter wide quartz monzonite dikes intruding the gneissic country rock at the Schmidt farm location near North Redwood. The dikes exhibited sharp-walled parallel contacts and definitely cross-cut the foliation of the surrounding gneisses. The samples of the dikes, along with those taken into the gneisses were slabbed and stained for the detection of K-feldspar. They generally indicated that the metasomatic influence of these particular intrusions was confined to less than a meter from the contact. Thus, it would seem that in this area at least, one should sample more than a few meters from the contact to obtain a sample that has not been obviously influenced by the dike. However, there are diverse modes of occurrence of the quartz monzonite phase within the quartzo-feldspathic gneiss in the Sacred Heart-North Redwood area, and these may have had a greater metasomatic influence on the country rock than at the Schimdt farm location. So, in order to decrease the possible metasomatic effects, samples of the gray gneiss were taken a maximum distance away from any quartz monzonite which appeared on an outcrop scale.

The textures of the gray gneiss were also utilized in the selection of whole-rock samples, because it was assumed that the most simple, regular textures reflected the least complicated responses to metamorphic events and hence were more likely to represent a closed system.

Because weathering can also be responsible for opening the isotopic system of the rock, fresh samples were preferred. Petrographic examination of each sample collected in the field was used to determine whether the amount of alteration of the whole-rock sample was significant, and whether it should be processed further.

Eleven samples of the gray tonalitic gneiss were considered worthy of Rb-Sr isotopic investigation. The petrography and major element chemistry of these samples is discussed further in this chapter. The sample locations and whole-rock descriptions are to be found in Appendix I, with the procedure of sample preparation and analytical technique in Appendix II.

Petrography

The first objective in viewing thin sections of the whole-rock samples was to determine the freshness of each sample. All of the rocks showed alteration to some degree. The degree of alteration exhibited by plagioclase, hornblende, and biotite was the basis upon which a final, arbitrary choice was made. Because these minerals compose a large percentage of the rock (usually greater than 65%) and are subject to the greatest amount of alteration, weathering of these minerals may critically affect the isotopic systems. If less than five percent of the thin section area of plagioclase, hornblende, and biotite showed marked alteration, the whole-rock sample was considered for further processing.

Generally the rocks vary little in thin section. Petrographic examination revealed a medium- to coarse-grained interlocking mosaic of minerals. The major minerals are plagioclase, quartz, and biotite which are abundant in every rock. Hornblende is occasionally present and may be quite abundant. K-feldspar is found in nearly every rock, but never in large amounts. Zircon, apatite, sphene, and opaque oxides are very common accessory minerals, with allanite appearing in a few rock samples. Alteration products of the minerals include chlorite, epidote, muscovite, opaque oxides, and sericite.

Modal analyses of the eleven whole-rock samples of quartzo-feldspathic gneiss from the Sacred Heart-North Redwood area are given in Table 1. Based on modal analyses, the rocks are classified as being tonalitic to trondhjemitic in composition (Strekesian, 1967). Statistical difficulties in determining accurate modal analyses stem from the coarse-grain size and contorted compositional banding of the gneiss so that the whole-rock sample may not be adequately represented by thin section. Slabbed sections stained for feldspars were useful corroboration for the microscopic determination of the K-feldspar modal percentage.

Plagioclase occurs both as porphyroblasts and also as a "matrix-former" in the gneisses. Porphyroblastic plagioclase is usually a single grain, a centimeter in length and width. These grains are randomly spaced and are consistently larger than the rest of the matrix plagioclase. In some samples they are absent altogether (RSG-4,8), present to only a few percent (RSG-1,2,3,6,7,9,11), or compose a few tens of percent of the whole-rock (RSG-5,11). The porphyroblasts are well twinned, but unzoned and free of inclusions.

The matrix plagioclase is usually one to two millimeters, subhedral, and equidimensional. A few rocks show euhedral plagioclase in the matrix

TABLE 1--PETROGRAPHIC MODAL ANALYSES OF QUARTZO-FELDSPATHIC GNEISS WHOLE-ROCK SAMPLES, SACRED HEART-NORTH REDWOOD AREA

(based on 500 counts/section)

	RSG 1	RSG 2	RSG 3	RSG 4	RSG 5	RSG 6	RSG 7	RSG 8	RSG 9	RSG 10	RSG 11
plag	53.7	46.6	76.9	59.0	57.5	83.3	51.2	54.4	68.6	63.4	53.3
qtz	29.4	20.7	15.2	18.9	36.3	4.6	43.6	37.2	11.8	19.4	38.7
biot	12.1	5.7	5.1	16.3	1.0	9.3	4.1	6.7	13.4	7.7	4.0
K-spar	3.2	0.6	1.9	2.7	2.4	2.0	0.3	1.3	2.1	0.5	2.0
hbl	tr	25.0	-	2.1	-	tr	-	tr	-	6.1	-
chlor	tr	-	0.1	tr	1.2	tr	tr	tr	0.4	1.5	0.8
epid	tr	tr	tr	tr	0.4	tr	tr	0.2	tr	0.5	0.5
musc	0.4	tr	0.7	-	1.2	tr	0.8	tr	tr	tr	tr
mgnt	0.2	1.1	tr	0.2	tr	0.2	tr	0.3	tr	tr	0.6
sph	0.4	-	tr	tr	-	0.5	tr	tr	0.5	0.7	tr
zirc	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr
alan	-	-	tr	tr	-	-	tr	-	-	tr	tr

(RSG-6,7,11), with inclusion-free, slightly-zoned albite twins, one to two millimeters long. More often, plagioclase occurs as poorly twinned, anhedral grains containing small inclusions of round quartz blebs, subhedral biotite, and euhedral zircon and apatite.

Quartz was greater than ten percent in all but one of the slides (RSG-6). The grains are anhedral and form an interlocking mosaic with the surrounding minerals. In the lighter colored compositional bands the quartz is generally coarse-grained (2 mms or more) whereas in the darker portions of the rock it is usually only 1/2-1 mm. Oftentimes, small round blebs of quartz are contained within the larger grains of plagioclase.

In the slide (RSG-6) which showed only four percent quartz, the plagioclase content of the rock was very high, with many of the grains being euhedral. This gave quartz (and also sphene) an interstitial habit.

Anhedral to subhedral biotite is present in the samples, averages about eight percent and is about one millimeter long. Euhedral apatite and zircon are often enclosed by the biotite grains. When biotite and hornblende are together in a rock they are most often intergrown. Usually the biotite is an olive-green to tan-brown color, but in the sample RSG-7, it is a reddish color, indicative of a high titanium content. In this rock, biotite is associated with, and often encloses a major amount of the zircon that is present. Alteration of biotite to chlorite and epidote is sometimes complete. Needles of opaque oxides, in triangular configuration, are found within some of the more severely altered biotite grains.

Only a few samples of the gneiss contain large, discreet grains of hornblende. These large grains are usually associated with, and sometimes intergrown biotite, and often sphene if present. Porphyroblastic hornblende appears in RSG-2, and these are green subhedral grains about a centimeter long, and are confined to the coarser-grained, plagioclase-quartz-rich, light-colored compositional bands. The remainder of the hornblende in this rock is within the darker bands and appears as anhedral, one millimeter-sized grains in the mosaic. The large amount of hornblende in this rock (about 25%) and other characteristics to be discussed later, makes it unrepresentative of the gray gneiss.

In RSG-10, euhedral, coarse-grained, blue-green hornblende is set within a coarse-grained, granular quartz-plagioclase setting. Here, the long axes of the hornblende grains parallel foliation defined by the preferred orientation of biotite. In other samples, nonporphyroblastic hornblende is found in the matrix (RSG-1,4,6,8) and is green, subhedral, about one millimeter in diameter, and often intergrown with biotite.

K-feldspar is present in small percentages in all but one of the rocks (RSG-2). It usually appears interstitially, often with a slight amount of myrmekitic development or near hornblende-biotite clots. In rare cases, small irregular patches of K-feldspar are located within the grains of plagioclase, as in sample RSG-11. Much of the K-feldspar shows gridiron twinning characteristic of microcline. It does not appear to be altered to a significant degree.

Apatite and zircon are ubiquitous and occur as small isolated euhedral grains which are sometimes contained within plagioclase, but more often as euhedral grains in the proximity of biotite and are often concentrated within the biotite itself. The high percentage of accessory minerals associated with the biotite-hornblende intergrowths gives the mafic minerals a clotty-spongy type of appearance.

Allanite is found in a few thin sections as small to euhedral, brownish grains within or near to biotite, sphene and plagioclase (RSG-3,4,8,9,10,11). In RSG-10, the allanite grains are euhedral and greatly altered. Alteration products of allanite include highly birefringent epidote and muscovite. Many euhedral grains of zircons are contained within these grains, which are both contained by biotite.

Major Element Chemistry

The major element chemistry for the eleven whole-rock samples of tonalitic quartzo-feldspathic gneiss is incomplete. However, the average values for those elements analyzed are similar to other quartzo-feldspathic gneisses from the Morton-Sacred Heart area (Goldich et al., 1970), the average of Archean dacitic, tonalitic and trondhjemitic rocks from north-eastern Minnesota (Arth, 1976), and those of other Archean gray gneiss complexes elsewhere (Table 2). The K_20 contents are lower than other gneissic terranes.

The chemical data also indicates a chemical heterogeneity of the whole-rock samples, with the variability reflected by the plots of %$Si0_2$ vs. %Al_20_3 and %$Si0_2$ vs. %Feo total (Figures 3, 4). The additional chemical data comes from the unpublished analyses of Goldich and Wooden and shows the existence of separate populations, or chemical groups of gneiss in the Morton-Sacred Heart area. From Figures 3 and 4, it appears that the samples may be divided into two groups. One group contains samples RSG-1,2,4, and 7, while the other chemical group contains samples RSG-3,5,6,8,9,10, and 11. Sample RSG-8 is chemically ambiguous and may fit in either group. It is noted

TABLE 2--MAJOR ELEMENT CHEMISTRY OF RSG-SERIES AND VARIOUS ARCHEAN TONALITIC ROCKS

	1	2	3	4	5	6	7
$Si0_2$	67.4	69.1	72.0	71.57	69.45	68.60	66.7
Al_20_3	16.7	15.6	15.4	15.30	15.18	15.90	17.1
$Ti0_2$	0.4	0.39	0.21	0.226	0.31	0.04	0.3
Fe_20_3	3.28*	4.32*	1.82*	2.04*	2.51*	2.53*	0.9
Fe0	-	-	-	-	-	-	1.5
Mn0	0.04	0.04	0.02	0.028	0.04	0.03	0.04
Mg0	1.04	0.86	0.64	0.69	0.81	0.94	1.4
Ca0	3.46	3.14	2.22	2.45	2.80	2.60	3.8
Na_20	**	5.17	5.80	5.06	4.50	5.28	5.8
K_20	1.44	1.38	1.71	2.53	2.47	2.47	1.2
P_20_5	0.09	0.09	0.01	0.09	0.12	0.13	-

*represents analysis for total Fe

**Na_20 chemical data not available

1 average of 11 samples, RSG-series, Sacred Heart-North Redwood area (Seeling and Wooden, unpublished analyses)

2 sample 389-D, dark phase from Morton Gneiss (Goldich et al., 1970)

3 sample 339, roadout south of Renville (Goldich et al., 1970)

4 average of 8 samples, Hebron Gneiss, East Labrador (Barton, 1975)

5 average of 12 samples, Amitsoq Gneiss, West Greenland (Hurst et al., 1975)

6 average of 10 samples, Uivak Gneiss, East Labrador (Bridgewater and Collerson, 1976)

7 average of Precambrian dacites, tonalites, and trondhjemites of northeastern Minnesota (Arth, 1976)

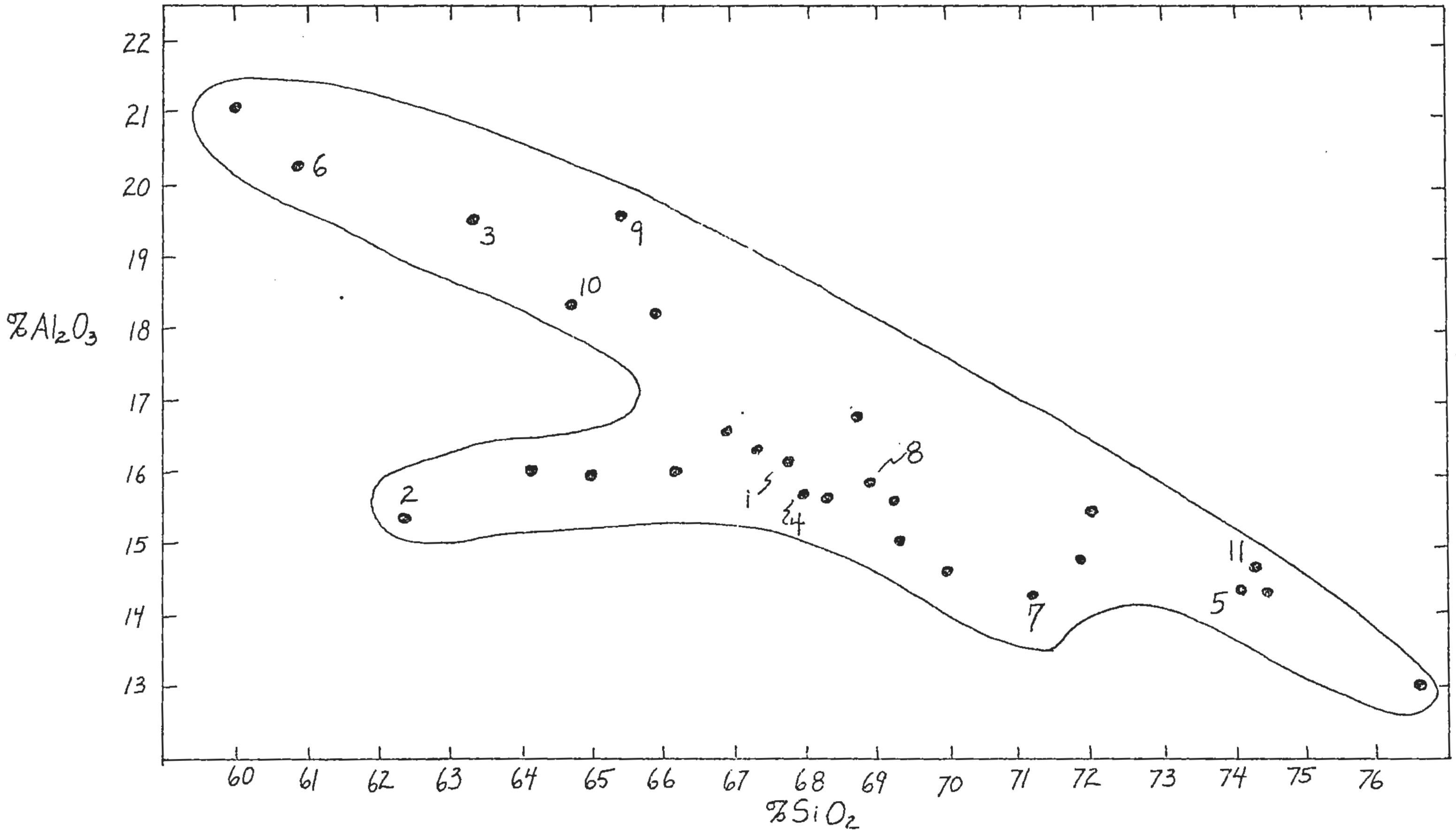

Figure 3--%SiO$_2$ VS. %Al$_2$O$_3$, QUARTZO-FELDSPATHIC GNEISS WHOLE-ROCKS, MORTON-SACRED HEART AREA. (after: Goldich and Wooden, Seeling and Wooden, unpublished analyses)

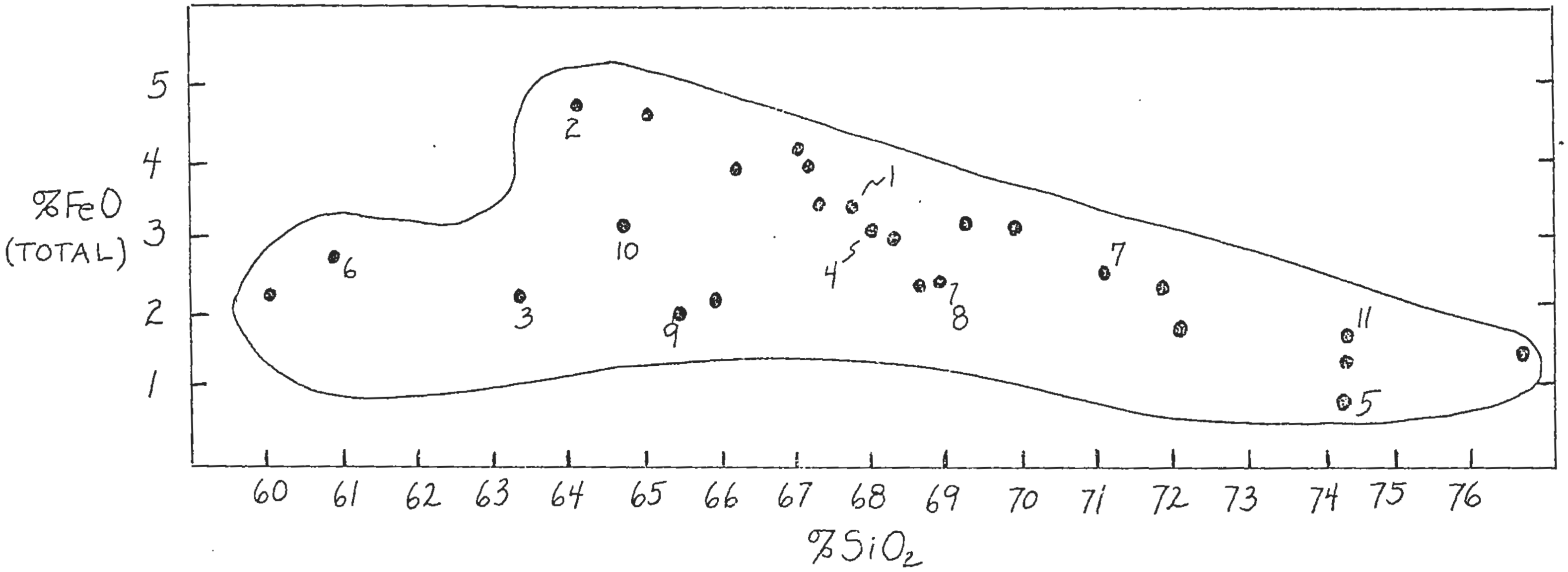

Figure 4--%SiO$_2$ VS. %FeO (TOTAL), QUARTZO-FELDSPATHIC GNEISS WHOLE-ROCKS, MORTON-SACRED HEART AREA. (after: Goldich and Wooden, Seeling and Wooden, unpublished analyses)

from the chemical data that sample RSG-2 is unusual chemically, in that it has a much higher FeO total, MnO, MgO and CaO than the other samples.

Simple fractionation of plagioclase, hornblende, biotite and quartz from a magma of the gray gneiss composition would tend to produce a continuum on a SiO_2 vs. another oxide diagram because the most likely phases to fractionate are plagioclase (moderate SiO_2), and hornblende and biotite (low SiO_2). In Figures 3 and 4 there appear to be two linear arrays or trends for samples with similar SiO_2 contents, which isn't expected from simple fractionation processes. The ppm abundances of Sr will be used to further clarify the chemical groups.

The appearance of two linear trends for these rocks suggests that separate chemical groups of gray gneiss are present and that these are not related by a simple fractionation process (Wooden, written communication). While it is possible that the gneisses may have come from different sources, they may have come from the same source, but melted under different conditions. If two or more different sources were involved, it is doubtful that these sources had significant differences in the isotopic $^{87}Sr/^{86}Sr$ ratios, for the earth at this time was of relatively young age, and had not accumulated a great deal of radiogenic ^{87}Sr. The uncertainty resulting from chemical heterogeneity of the gneiss complicates the age determination process, but if the gneiss were generated from sources of the same general composition, the initial ratios perhaps differed only slightly, and thus maintain the validity of the use of Sr isotopes for isochron work.

Conclusion

Petrographic examination of the eleven whole-rock samples taken from the Sacred Heart-North Redwood area showed that the rocks are similar in texture and mineralogy, with RSG-2 being most aberrant. The high amounts of plagioclase and quartz, and the low amounts of K-feldspar in the samples are characteristic of rocks of trondhjemitic composition. The eleven samples chosen showed limited effects of weathering and no obvious signs of chemical contamination by later K-rich intrusions.

The major element chemistry of the whole-rock samples shows that while the whole-rock samples are generally similar in composition to other gneissic and intrusive rocks of tonalitic composition, they may be divided into two chemical groups, defined by the linearity of the trends of %SiO_2 vs. %FeO total, and also %SiO_2 vs. %Al_2O_3. Even though the groups may not be related by a simple fractionation process, they still yield information about the age of the rocks, because the initial $^{87}Sr/^{86}Sr$ ratios for the groups probably did not differ by much.

The association of amphibolite (of tholeiitic composition) and quartzo-feldspathic gneiss of tonalitic-trondhjemitic composition is common in the high-grade metamorphic, Early Precambrian rocks (> 2.7 b.y.) and composes a large amount of the continental basement. Barker and Peterman (1974) postulate that the bimodal suite of tholeiite and high-silica low-potash dacite are largely of volcanic origin, with the intrusive equivalents injected into the lower parts of the volcanic piles. Noting the andesite gap in composition of the Early Precambrian gneiss terranes, and the relative abundance of such volcanic rocks in the supracrustal rocks of the granite-greenstone terranes, and assuming more hydrous conditions and higher heat flow in the Early Precambrian, they propose a model for the generation of the bimodal tholeiitic-dacitic magmatism in the Early Precambrian. The model suggests an early basaltic crust and pyrolitic upper mantle which contain much amphibole and other hydrous minerals. If a slab of this material were to be subducted the dehydration of the hydrous minerals and release of water would prohibit the formation of an andesitic liquid by partial melting and rather would produce a dacitic liquid with a residuum of amphibole and other silica-poor phases. As the slab proceeded downward, total melting would ensue, creating a melt of tholeiitic composition.

The previous model is based upon the theoretical results of many current workers and is attractive for the petrogenesis of the gray gneiss in the Minnesota River Valley.

Rb-Sr ISOTOPIC GEOCHEMISTRY AND AGE DETERMINATION

Rb-Sr Whole-Rock Isotopic Geochemistry

The amounts of Rb, Sr and K for the eleven whole-rock samples of tonalitic, gray gneiss from the Sacred Heart-North Redwood area can be found in Table 3. Also listed are the pertinent Rb-Sr isotopic ratios. The Rb-Sr isotopic data was determined by mass spectrometry, with the analytical technique for this procedure reported in Appendix II. The K data was determined by XRF on fused glass disks, and represents an average of separate determinations on two disks per sample (Seeling and Wooden, unpublished analyses).

The amounts of Rb range from 15 to 88 ppm, and averages 58, while K varies from 0.80% to 2.21%, averaging 1.2%. The average values for Rb and K are slightly lower than analyses of the gneisses reported by Goldich et al. (1970), and those of other gray gneiss complexes of the North Atlantic craton (Table 4).

The Rb^+ ion, because it is similar in size and charge to the K^+ ion (1.45 Å vs. 1.33 Å), tends to be incorporated into K-bearing silicates with an average crustal ratio for K/Rb of about 250 (Hamilton, 1965).

TABLE 3--%K, K/Rb AND Rb-Sr ISOTOPIC DATA

Sample No.	%K	Rb (ppm)	Sr (ppm)	Rb/Sr	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr	K/Rb
RSG-1	1.26	76	326	.233	.674	.7265	166
RSG-2	0.97	66	387	.171	.493	.7170	146
RSG-3	1.08	61	906	.067	.195	.7075	177
RSG-4	2.21	66	420	.157	.454	.7198	334
RSG-5	0.80	15	546	.028	.079	.7048	533
RSG-6	1.29	88	944	.093	.269	.7103	146
RSG-7	1.19	75	191	.393	1.135	.7488	158
RSG-8	1.08	51	708	.072	.208	.7087	211
RSG-9	1.24	49	760	.065	.186	.7101	253
RSG-10	1.22	63	628	.100	.290	.7118	194
RSG-11	0.86	29	617	.047	.136	.7066	297

(Rb-Sr data done by mass spectrometry, K data done by XRF on fused glass disks, average of separate determinations on 2 disks per sample, Seeling and Wooden, unpublished analyses)

TABLE 4--A COMPARISON OF THE AMOUNTS OF K, Rb, Sr AND K/Rb WITH OTHER ARCHEAN GRAY GNEISS COMPLEXES

	%K	Rb(ppm)	Rb/Sr	Sr(ppm)	K/Rb
1	1.2	58	.099	584	237
2	1.15	73.9	.200	369	156
3	1.42	35.5	.060	587	400
4	2.09	86.0	.245	351.0	243.3
5	2.05	100.0	.366	273.0	205.0
6	2.09	100.0	.175	570.0	209.0

1 average of 11 samples (Rb-Sr, this study; K, Seeling and Wooden, unpublished analyses)

2 sample 389-D, dark phase from Morton Gneiss (Goldich et al., 1970)

3 sample 339, roadcut south of Minnesota River, south of Renville (Goldich et al., 1970)

4 average of 8 samples, Hebron Gneiss, East Labrador (Barton, 1975)

5 average of 12 samples, Amitsoq Gneiss, West Greenland (Hurst et al., 1975)

6 average of 10 samples, Uivak Gneiss, East Labrador (Bridgewater and Collerson, 1976)

In the rocks analyzed in this study, K is primarily confined to K-feldspar and biotite. The majority of the eleven whole-rock samples have K/Rb ratios below or near the crustal average (Table 3), and falls within the range of the K/Rb ratios for other gray gneiss complexes (Table 4).

Sr tends to be incorporated within the structure of plagioclase, substituting for Ca, which has a similar ionic charge (+2) and ionic radius (1.22 Å for Sr, 0.99 Å for Ca). There is a wide range in Sr concentrations in the samples (191-944 ppm), and the average is again similar to the amounts reported for other gray gneiss complexes (Table 3).

The relationship of Rb to K, and Sr, and that of Sr to SiO_2 can be used to further establish the presence of several chemical groups of gneiss in this area (Figures 5,6,7) and show the chemical and isotopic similarities of these groups RSG-5,11; RSG-3, 6,8,9,10; and RSG-1,2,4,7. The relationship of the groups of chemically similar rocks to geographic location, mineralogy or texture is not evident.

Age Determination

While it is possible that the samples of gneiss are not all cogenetic and possibly should not be placed on the same isochron, the Rb-Sr whole-rock isotopic data, if placed on a strontium evolution diagram, proves informative (Figure 8). A computer

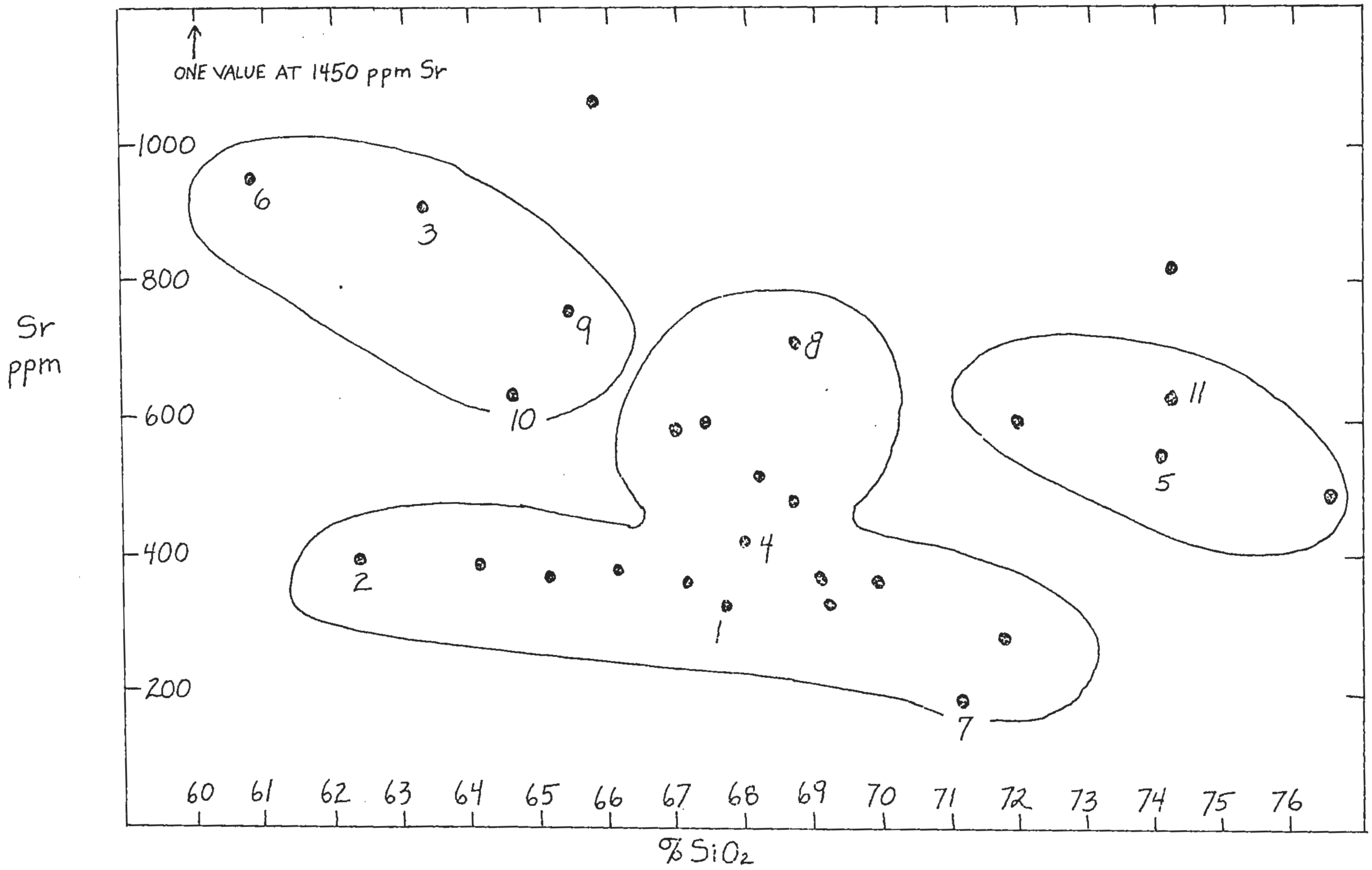

Figure 5--Sr (ppm) VS. %SiO_2, QUARTZO-FELDSPATHIC GNEISS, WHOLE-ROCK SAMPLES, SACRED HEART-MORTON AREA, MINNESOTA RIVER VALLEY. (after: Goldich and Wooden, Seeling and Wooden, unpublished analyses)

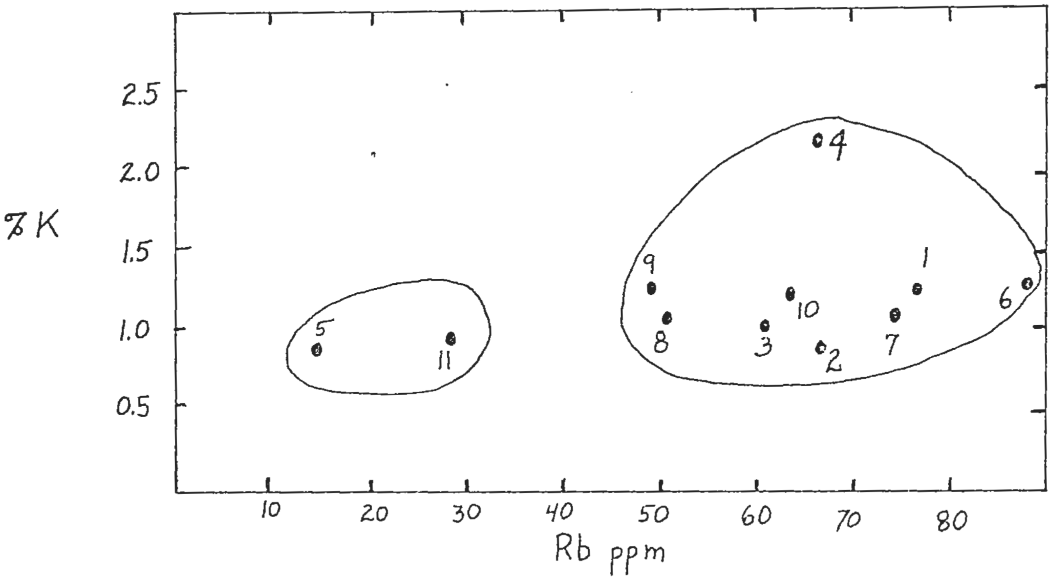

Figure 6--%K VS. Rb (ppm), QUARTZO-FELDSPATHIC GNEISS, WHOLE-ROCK SAMPLES, SACRED HEART-NORTH REDWOOD AREA, MINNESOTA RIVER VALLEY. (after: Seeling and Wooden, unpublished analyses)

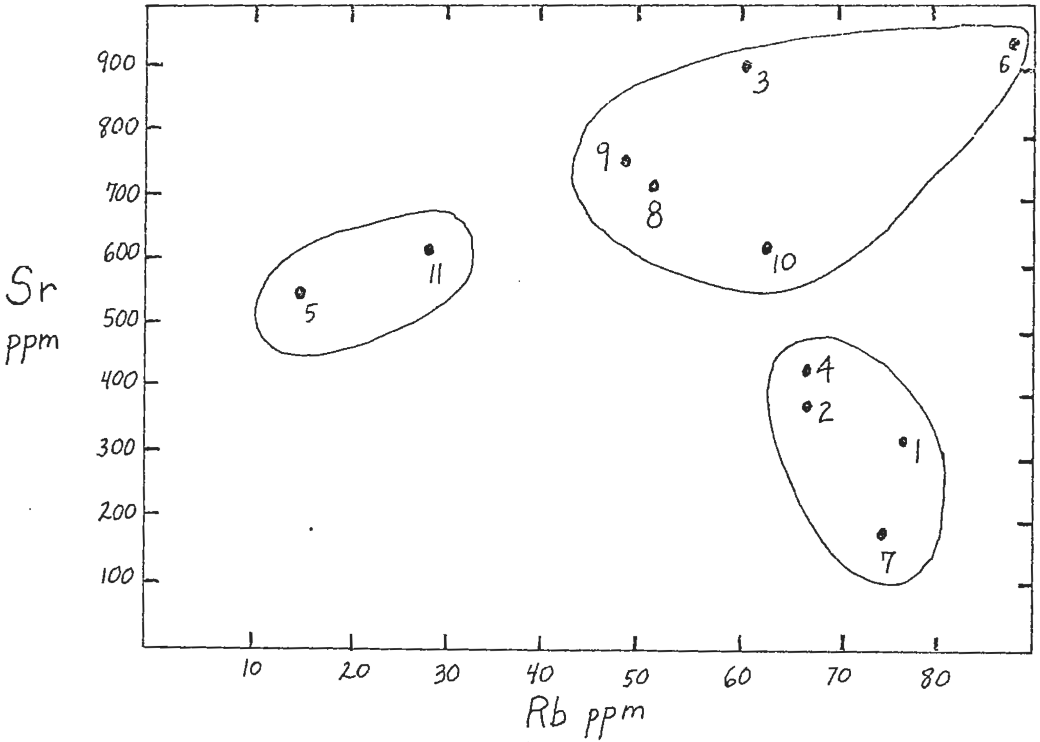

Figure 7--Rb (ppm) VS. Sr (ppm), QUARTZO-FELDSPATHIC GNEISS, SACRED HEART-NORTH REDWOOD AREA, MINNESOTA RIVER VALLEY

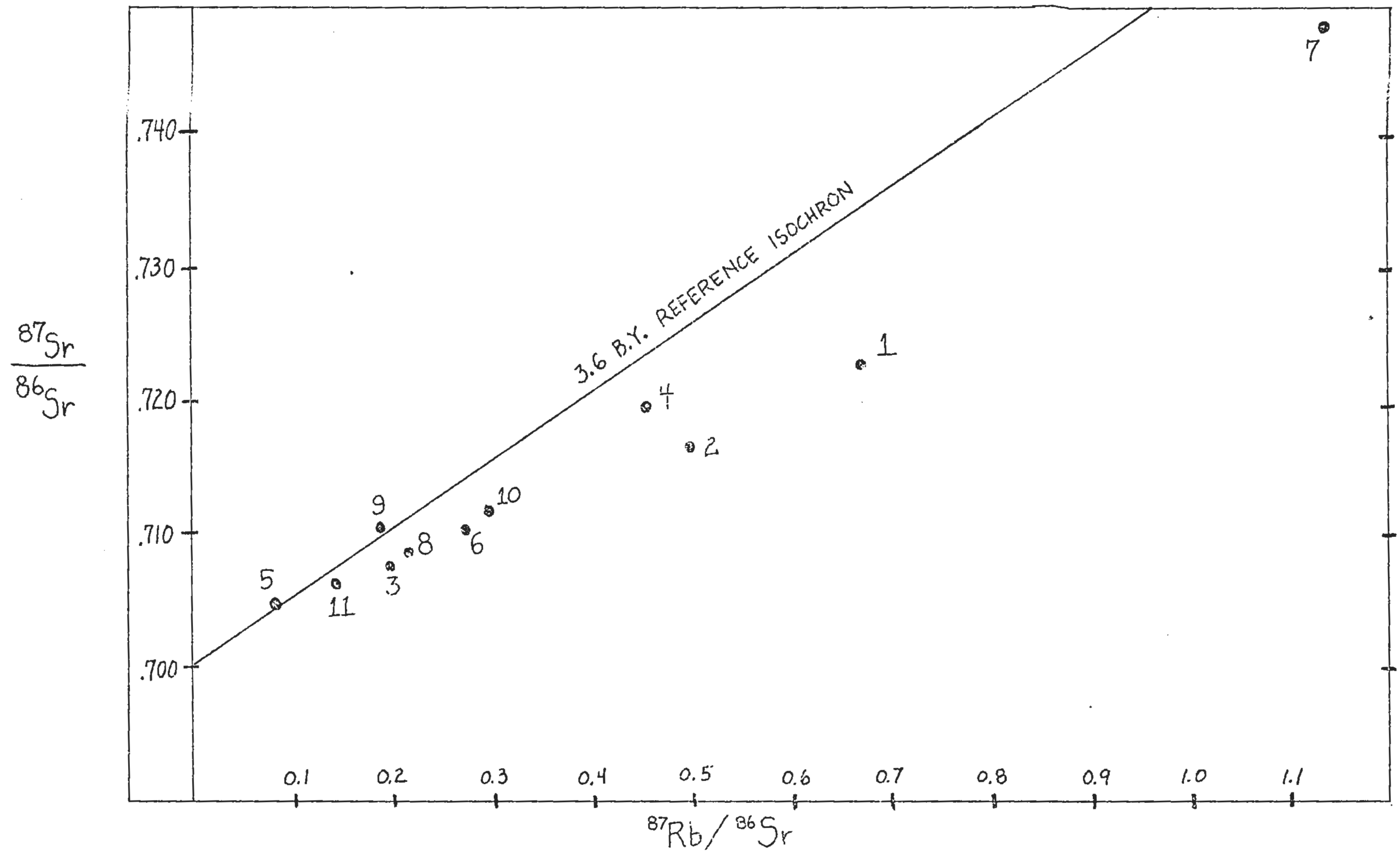

Figure 8--STRONTIUM EVOLUTION DIAGRAM, TONALITIC QUARTZO-FELDSPATHIC GNEISS, SACRED HEART-NORTH REDWOOD AREA, MINNESOTA RIVER VALLEY

program was used to calculate the least squares fit of a line through the data points. It is evident that the points are not all colinear, and the data from ten of the eleven samples (RSG-2 was not used in this determination) gives an isochron age of 2.91 b.y. with a high standard error of ± 200 m.y., and defines an initial $^{87}Sr/^{86}Sr$ ratio of 0.7005.

Sample RSG-2 was not used in the previous calculation because the sample is unlike the others in major element chemistry, mineralogy and texture. The sample has much higher total FeO, MnO, MgO and CaO than the others. The whole-rock sample itself is composed of a medium-grained, granular matrix of plagioclase, quartz, and biotite, with a large amount of hornblende (up to 25%), separated by a network of coarse-grained plagioclase-quartz-rich veins containing large hornblende porphyroblasts. The veins are a few centimeters wide and some of them cross-cut others. This sample was taken from quartzo-feldspathic gneiss unit A, where the gneiss is interlayered with amphibolite, and it is believed that some of the amphibolite may have been included in the whole-rock sample. It is doubtful that this sample has remained a closed system in any case.

The isochron age for the ten points is controlled by the samples with relatively higher Rb/Sr ratios, in particular RSG-1,4 and 7, which have similar major element chemistry and isotopic characteristics. Because the samples at the upper end of the isochron may not be cogenetic with those points at the lower end, the isochron may have no real meaning.

The initial $^{87}Sr/^{86}Sr$ ratio is primarily a reflection of the Sr isotopic composition for those samples with high amounts of Sr, and low Rb/Sr ratios. This includes the two chemical groups RSG-3,6,8,9,10 and RSG-5,11. The initial $^{87}Sr,^{86}Sr$ ratio defined by the isochron (0.7005) is similar to other rocks of quartz diorite composition (Arth and Hanson, 1972), but slightly higher than the 0.700 $^{87}Sr/^{86}Sr$ used in the age determinations by Goldich et al. (1970) of the Morton Gneiss, and that determined by Wooden et al. (1976), in the study of the tonalitic gneiss from the Delhi area, where a whole-rock isochron defined an initial $^{87}Sr/^{86}Sr$ ratio of 0.6993.

Another method of evaluating the age significance of the isotopic data is to assume an initial $^{87}Sr/^{86}Sr$ ratio which appears to be reasonable, and calculate the model age for each sample using the formula:

$$\frac{\ln_e \dfrac{(^{87}Sr/^{86}Sr)_p - (^{87}Sr/^{86}Sr)_o}{(^{87}Rb/^{86}Sr)_p} + 1}{\lambda} = t$$

t = millions of years since origin of system
$\lambda = 1.39 \times 10^{-11}$/year
p = measured, present ratio
o = original, initial ratio

Assuming an initial ratio of 0.700 for $^{87}Sr/^{86}Sr$, the model ages were calculated, and the resulting ages appear in Table 5.

TABLE 5--MODEL AGES FOR THE WHOLE-ROCK SAMPLES

Sample No.	Model Age (m.y.)
RSG-1	2770
RSG-2	2440
RSG-3	2730
RSG-4	3070
RSG-5	4220
RSG-6	2770
RSG-7	3030
RSG-8	2950
RSG-9	3790
RSG-10	2870
RSG-11	3410

The set of model ages shows considerable spread in values. The model ages of RSG-5,9,11 are much older than the rest, whereas samples RSG-4,7,8,10 cluster at 2970 m.y. and RSG-1,3,6 range from 2700-2770 m.y. The lowest age is that of RSG-2 at 2440 m.y.

The groupings of model ages indicated above do not altogether coincide with the established chemical and isotopic groups (Figures 5,6,7). Samples RSG-5 and 11 are isotopically and chemically similar and both have relatively old ages, but these are 800 m.y. apart. The other old model age comes from sample RSG-9. The model ages have more uncertainty as the Rb/Sr ratio becomes lower, for small changes in Rb concentration at lower Rb/Sr levels gives large model age changes. The great range in the older model ages may result from the chemical differences of the samples, but most probably represents the response of the samples to metamorphic processes. Sample RSG-5 for example has an unreasonably old age and most certainly has not acted as a closed system.

The lowest model age, from sample RSG-2 is 2440 m.y., is suspect for it is younger than the Sacred Heart pluton, which intrudes it. This sample is not considered to be representative of the quartzo-feldspathic gneiss.

The samples which have model ages clustering at 2970 ± 100 m.y., and 2700-2770 m.y. are from different chemical groups. It is possible that the clustering of ages is a response of the rocks to metamorphic processes, where the Rb-Sr isotopic systems have been reset to reflect a metamorphic age.

Metamorphic and igneous processes commonplace in migmatitic terranes of complicated geological history may have been responsible for the disturbance of the

Rb-Sr isotopic systems. Some of these processes are:

1. The isochemical re-equilibrium or closed system rehomogenization of the isotopic system during regional metamorphism, if on a scale greater than the volume represented by the whole-rock sample, would tend to redistribute the Rb-Sr isotopes. This would tend to equilibrate the $^{87}Sr/^{86}Sr$ system, increase the new $(^{87}Sr/^{86}Sr)_o$, and create a lower, metamorphic age for the rock. This is the process that could have affected the samples which have apparent ages from 2700-3030 m.y.

2. Rb loss or gain during metamorphism could occur during mineral transformations. Wooden et al. (1976) have cited the mineralogical transformation:

Quartz-plagioclase-biotite gneiss ------>
Quartz-plagioclase-hornblende-microcline gneiss

where the hornblende and microcline retained only part of the Rb.

Rb loss or gain could also occur if partial melting of the gneiss had occurred. Rb and K would tend to be concentrated in the melt, and if separated from the residuum, would tend to lower the Rb/Sr ratio of the rock and increase its age. Because it is not entirely certain that the tonalitic composition is that of the protolith, it is difficult to determine to what extent K and Rb may have moved during metamorphic events.

3. Sr gain or loss is less likely to occur in these rocks during a metamorphic event, because of the high Sr concentration of the gneiss, and also because plagioclase is the major mineral.

4. Rb and K may have entered the gneisses during the intrusion of granitic magmas and accompanying metasomatism at about 2650 m.y. (Sacred Heart pluton) and this would tend to lower the apparent age of the sample. Field evidence indicates that sample RSG-1 may have been affected by the Sacred Heart pluton, which is only about 0.9 kilometers from the sample location, but there is no chemical or isotopic evidence to support this.

5. The gain or loss of radiogenic Sr during metamorphism may take place because radiogenic Sr may no longer act as a compatible replacement for K, as the parent Rb was, in the mineral structures of K-feldspar, biotite and hornblende.

Even though the gneisses do show some chemical heterogeneity, it is evident that the Rb-Sr isotopes have been disturbed by the complicated series of events that have postdated the formation of the original rock, and that any, a combination or all of the previously listed processes could have been operative.

What then can be said about the age of the tonalitic quartzo-feldspathic gneiss in this area?

Zircons from the iron-poor and iron-rich gneisses in the Morton-Sacred Heart area give $^{207}Pb/^{206}Pb$ ages of at least 3220 m.y. This is a minimum age because the Pb/Pb data is discordant. The data from the iron-rich gneisses are from Goldich et al. (1970) and the data from the iron-poor set of gneisses comes from new work of Goldich and Wooden (personal communication).

Rb-Sr studies by Goldich and Wooden have been done on a regional sampling basis and the 30 samples indicate an age of 3500-3600 m.y. The individual areas have been reset to an age of about 3000 m.y. (personal communication).

Only a few of the model ages from this study show ages of 3200 m.y. or older, but this in itself may be taken as an indication that at least some of the gneisses are at least 3200 m.y. The complicated geologic history of the area has disturbed the Rb-Sr systematics, and it seems increasingly probable that a metamorphic event at approximately 3000 m.y. has been one of the complicating factors. Not only do four of the model ages from this study cluster near this age, but also the Rb-Sr data from individual areas sampled by Goldich and Wooden. The foliated, dark-colored phase of the Montevideo Gneiss was also affected at this time for the U-Th-Pb systems were reset by a thermal event (Doe and Delevaux, 1976).

That the model ages of some of the whole-rock samples studied here cluster about 2740 m.y. is not totally unexpected. Zircons from the gneisses in the Sacred Heart-Morton area have been partially or totally recrystallized at this time (Goldich et al., 1970). Also, the influence of the Sacred Heart and other similar intrusions at about 2650 m.y. may have contributed significantly toward resetting the age of the gneiss in this area.

Conclusion

The quartzo-feldspathic gneiss in the Sacred Heart-North Redwood area of the Minnesota River Valley of southwestern Minnesota was sampled in order to obtain a set of cogenetic, coeval whole-rock samples, that had maintained as a closed system throughout their geologic history. The more simple textures of the gray, tonalitic portions of the gneiss were desired for this study, and it was hoped that the samples were out of the influence of the younger granitic phases present.

In thin section the samples appeared quite similar, but chemically, the major element percentages allowed the samples to be placed into several chemical groups, all of which are not related by a simple fractionation process, and may possibly be from different sources, or perhaps differences in pressure, temperature and P_{H_2O} during melting of the source area (Wooden, personal communication).

Because the samples may not be cogenetic, and because the effects of the complicated geologic history have most certainly altered the Rb-Sr isotopic systems, creating much scatter on a strontium evolution diagram, their isochron age of 2.91 b.y. may be meaningless. Some of the calculated model ages (assuming 0.700 for $^{87}Sr/^{86}Sr$) give indications of age older than 3200 m.y. and other cluster near 3000 m.y. and 2740 m.y. and may reflect metamorphic events.

In summary, very little can be said about the primary age of the gneiss, except that it is older than 3200 m.y. The lack of potentially cogenetic samples is a handicap, but more uncertainty has been created in the Rb-Sr isotopic systems by the response of the rocks to metamorphic processes.

Future studies concentrating on determining the age of the quartzo-feldspathic gneiss in the Sacred Heart-Morton area will all face the possibility that disturbances of the Rb-Sr isotopic systems have resulted from the metamorphic events. To sample from a restricted and local area, one may be more assured of getting samples of one compositional type and may show a more complete isotopic equilibrium reflecting a metamorphic age of perhaps 3000 m.y. or 2600-2700 m.y. If the locality had been insulated from the effects of metamorphism, a set of samples may produce an Rb-Sr isochron age which may yield the original age of the gneiss. The complicated Rb-Sr systematics require that a large amount of data is necessary to define the trends of these rocks.

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APPENDIX I

LOCATION AND DESCRIPTION OF SAMPLES

Sample RSG-1 was taken from an outcrop south of Sacred Heart on the north side of the Minnesota River about 1.1 kilometers (0.7 miles) west of the intersection of Renville county roads 9 and 15. The knob-like outcrop is within the quartzo-feldspathic gneiss Unit B, and represents the northwesternmost exposure of the Sacred Heart-Morton area. The gneiss has very well developed composition banding, with individual bands being each a few centimeters wide and folded on a small scale. There are few veins of granitic material present, but they occasionally appear, and are often parallel to the banding of the gneisses. The sample is coarse-grained and granular with the arrangement reminiscient of salt and pepper. There is a sparse, random occurrence of porphyroblastic plagioclase.

RSG-2 was obtained from an outcrop within Unit A near the south bank of the Minnesota River, between Redwood County roads 19 and 6. The rocks in this outcrop are adjacent to large layers of amphibolite. RSG-2 is a rock of bimodal grain size. The darker, medium-grained matrix makes up most of the rock and has a high amount of hornblende. The matrix is separated by thin, irregular and non-planar, centimeter-wide bands or veins of coarse-grained plagioclase and quartz, with an occasional hornblende porphyroblast. The lighter colored bands appear to cross cut others.

RSG-3 is from an outcrop in Unit B, about one mile south of the Minnesota River between Renville County roads 17 and 6. Three other samples were taken from this vicinity, and these are RSG-9,10 and 11. RSG-3 is a yellowish with leopard skin-like splotches created by the linear roads and clots of biotite. The rock is coarse-grained and granular, with a few, random plagioclase porphyroblasts.

The other samples from this vicinity are from nearby ridges that parallel the river here. RSG-9 is a well banded gneiss, much like RSG-1, and is also folded on a small scale. It is proximal to RSG-10, a sample from an adjacent portion of a discontinuous ridge. RSG-10 is light colored, coarse-grained and equigranular. Compositional banding is not well defined, for the rock is quite homogeneous. Field relations show that this type of gneiss is intrusive into the rocks similar to RSG-9, for a xenolith of a banded gneiss is contained in the granular gneiss from which RSG-10 was sampled.

The last sample taken from this locale is RSG-11, which is located on another ridge nearer the river. The rock has an orangish hue and exhibits a nebulous foliation, this created by wispy, semi-continuous concentrations of medium-grained biotite in a very coarse-grained mass of plagioclase and quartz. The sample has a large amount of porphyroblastic plagioclase, with 25% of the total plagioclase being about 2-3 centimeters.

RSG-4 and 8 were taken from Unit A, a locale known as the Schmidt farm. This is just north of the river and near the intersection of Renville County roads 21 and 15. The samples are similar in appearance. RSG-4 is a very homogeneous, gray and granular, medium-grained rock. No obvious compositional banding or porphyroblastic development exists. The rock fabric is only the parallelism of the biotite flakes, which are evenly distributed in the quartz-plagioclase setting.

RSG-8 shows a slight composition banding. It is a coarse-grained rock and has a brownish cast to it. There are poorly defined parallel bands of coarser grained plagioclase and quartz separated by bands slightly enriched in biotite.

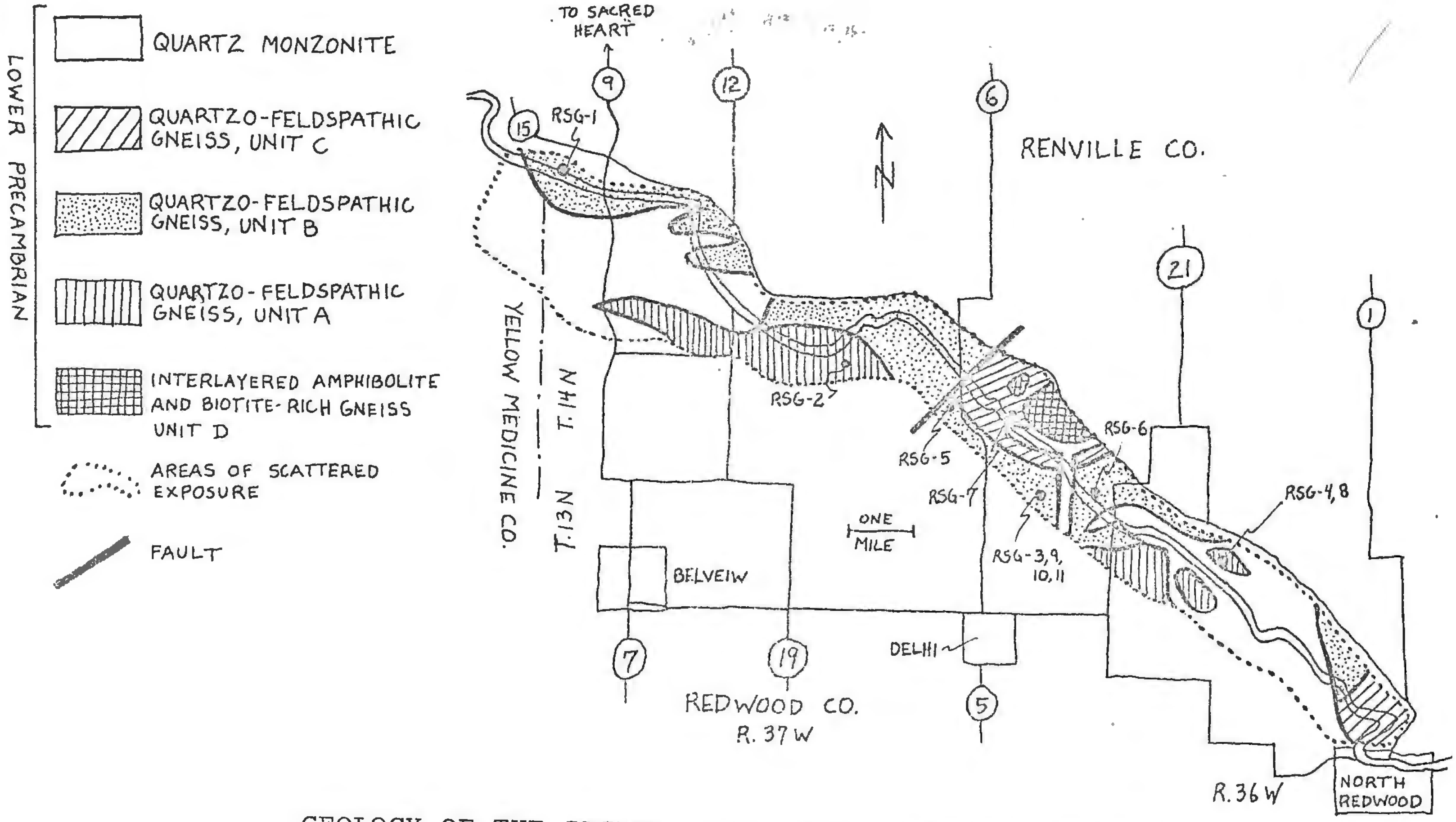
RSG-5 is within Unit B, a roadcut about one mile south of the river, and south of Renville on Redwood County road 6. This sample is from an outcrop near a presumed fault zone which lies to the west. The sample is a yellowish-white blend and is a coarse-grained to pegmatitic rock. Plagioclase and quartz separate irregularly-shaped clots of concentrated biotite, and the foliation is rather wild and discontinuous.

RSG-6 is also within Unit B, and is from the north side of the river about 1.5 miles west of the intersection of Renville County roads 21 and 15. The rock is light-colored, granular and coarse-grained. It exhibits a somewhat nebulous development of compositional segregation. The concentration of biotite in the plagioclase-quartz rich rock creates the ill-defined, discontinuous, dark-colored compositional bands.

The only sample from Unit C is RSG-7. The sample is light-colored, coarse-grained and looks much like RSG-6 in general appearance. At times the plagioclase appears to be quite euhedral in hand specimen and forms an interlocking mosaic with biotite and quartz. The compositional segregation is again nebulous, discontinuous and folded. There is a general lack of granitic and amphibolitic material in this area. The sample location is north of the river about 2.5 miles east of the intersection of Renville County roads 6 and 15. The sample is just south of the exposure of Unit D, in the "pasture of Delhi."

LOCATIONS OF WHOLE-ROCK SAMPLES, SACRED HEART-NORTH REDWOOD AREA

Sample No.	Sec.	T.N.	R.W.
RSG-1	S$\frac{1}{2}$6, N$\frac{1}{2}$7	114	36
RSG-2	NE$\frac{1}{4}$26	114	36
RSG-3	SE$\frac{1}{4}$32, NE$\frac{1}{4}$5	114	36
RSG-4	S$\frac{1}{2}$2, N$\frac{1}{2}$11	113	35
RSG-5	30	114	36
RSG-6	SE$\frac{1}{4}$33	113	36
RSG-7	S$\frac{1}{2}$29	114	36
RSG-8	S$\frac{1}{2}$2, N$\frac{1}{2}$11	113	35
RSG-9	SE$\frac{1}{4}$32, NE$\frac{1}{4}$5	114	36
RSG-10	SE$\frac{1}{4}$32, NE$\frac{1}{4}$5	114	36
RSG-11	SE$\frac{1}{4}$32, NE$\frac{1}{2}$5	114	36

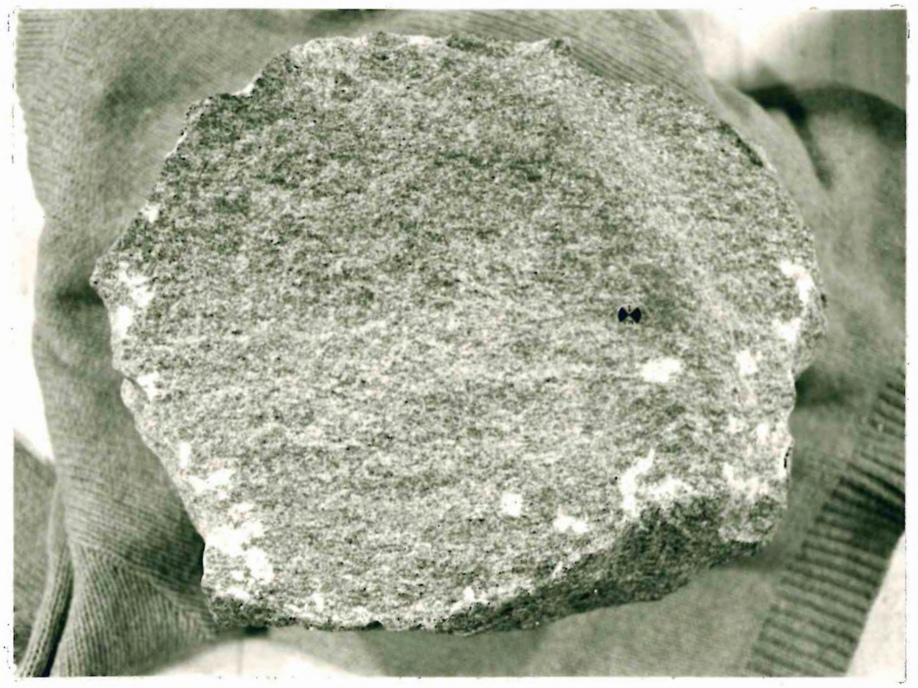


GEOLOGY OF THE SACRED HEART-NORTH REDWOOD AREA AND LOCATION OF WHOLE-ROCK SAMPLES

RSG-1, WHOLE-ROCK SAMPLE

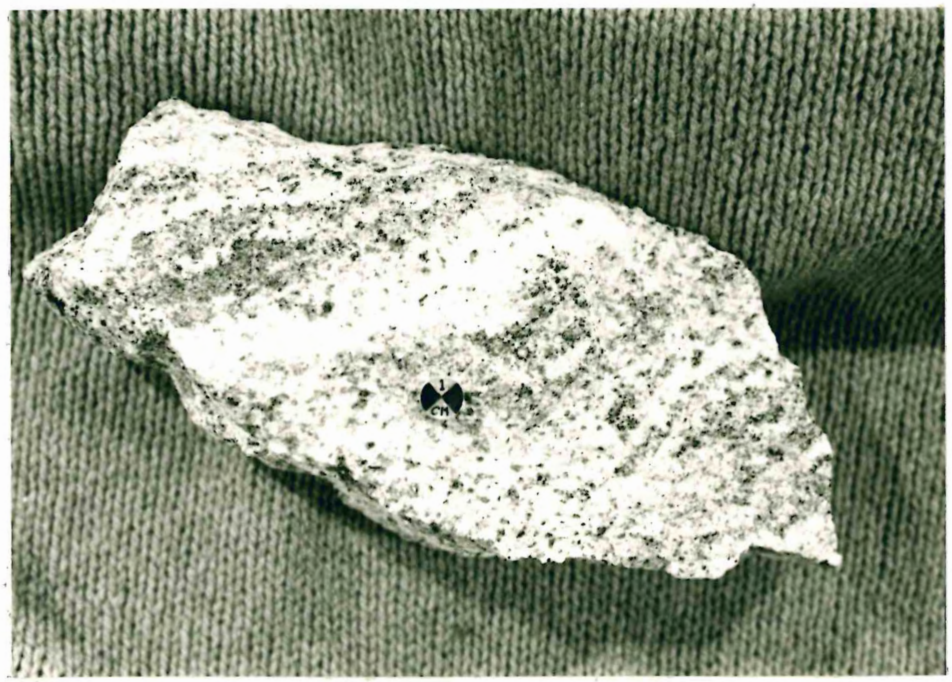
RSG-2, WHOLE-ROCK SAMPLE

RSG-3, WHOLE-ROCK SAMPLE



RSG-4, WHOLE-ROCK SAMPLE

RSG-5, WHOLE-ROCK SAMPLE



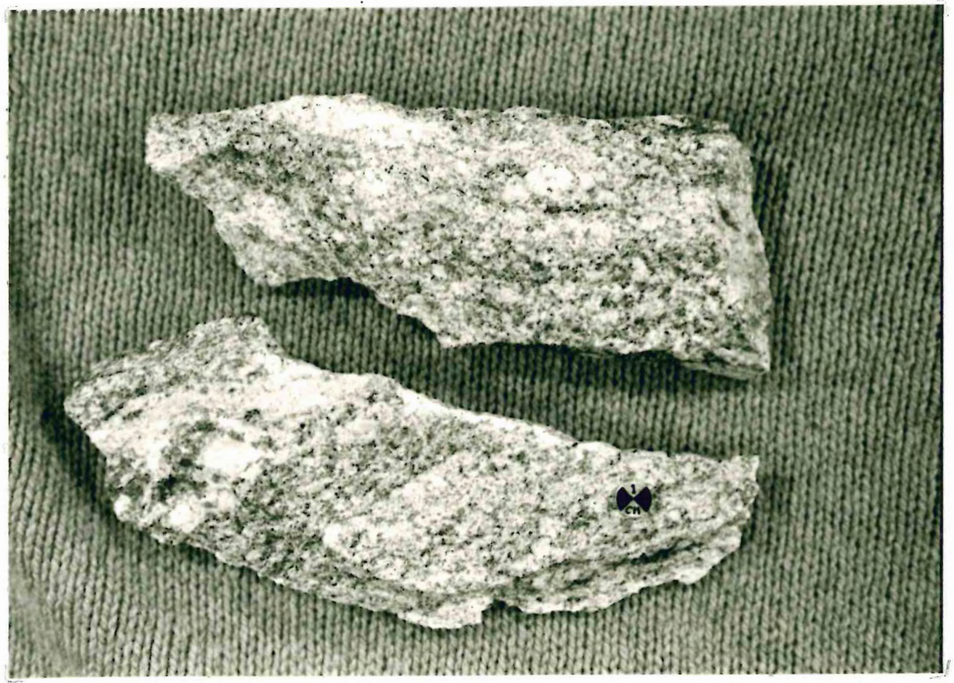
RSG-6, WHOLE-ROCK SAMPLE

RSG-7, WHOLE-ROCK SAMPLE

RSG-8, WHOLE-ROCK SAMPLE

RSG-9, WHOLE-ROCK SAMPLE

RSG-10, WHOLE-ROCK SAMPLE



RSG-11, WHOLE-ROCK SAMPLE

APPENDIX II

ANALYTICAL TECHNIQUE

The amounts and ratios of the naturally occurring isotopes of Rb and Sr (see below) are measurable by the mass spectrometer, for the isotopes have charge and mass differences.

PROPORTIONS OF NATURALLY OCCURRING
Rb AND Sr ISOTOPES (Harper, 1973)

Sr	88	82.56%	Rb 87	72.15%
	87	7.02	85	27.85
	86	9.86		
	84	0.56		

All of the isotopes of Rb and Sr are stable with the exception of Rb 87, which decays to Sr 87 (radiogenic strontium) via the emission of a low energy beta particle. The rate of radioactive decay is difficult to measure, and remains uncertain, but currently is taken to have a decay constant (λ) of 1.39×10^{-11}/year by most geochronologists (Goldich, 1972). The half-life of this decay is the time taken for one-half of an original amount of parental Rb 87 to decay to its daughter product Sr 87. This value is 50×10^{9} years, and is the inverse of the decay constant.

To utilize the radioactive decay as a timepiece, isotopic measurements of the whole-rock samples must be made. Relatively unweathered, 10-30 kilogram samples were obtained in the field, where they were cleaned of weathered surfaces. The samples were reduced to centimeter-sized chips in the laboratory, by means of a jaw-crusher. Not all of the chips were to be used in the analysis, and the total was reduced to a handful-sized pile by coning and quartering. The selected chips were washed in triple-distilled water, undergoing ultrasonic vibrations to remove surface dust. The washed chips were ground to a coarse powder in a steel mortar and pestle, and then to a fine powder in an agate bowl.

Approximately 0.200 grams of sample powder were randomly selected and precisely measured into a teflon beaker where the sample was dissolved upon the addition of hydrofluoric, hydrochloric, and perchloric acids. The resulting solution was transferred into a 100-ml volumetric flask and diluted to volume. For the determination of the amounts of Rb and Sr, a one-ml aliquot of the sample solution was spiked with known amounts of Rb 87 and Sr 86. For the determination of the isotopic composition of Sr, a much larger, unmeasured and unspiked portion of the sample solution was used. The selected sample solutions were processed through an ion exchange column. When the concentrated solutions of Rb and Sr were collected, they were then purified of organic debris, and evaporated to dryness. The samples were then ready for analysis by the mass spectrometer.

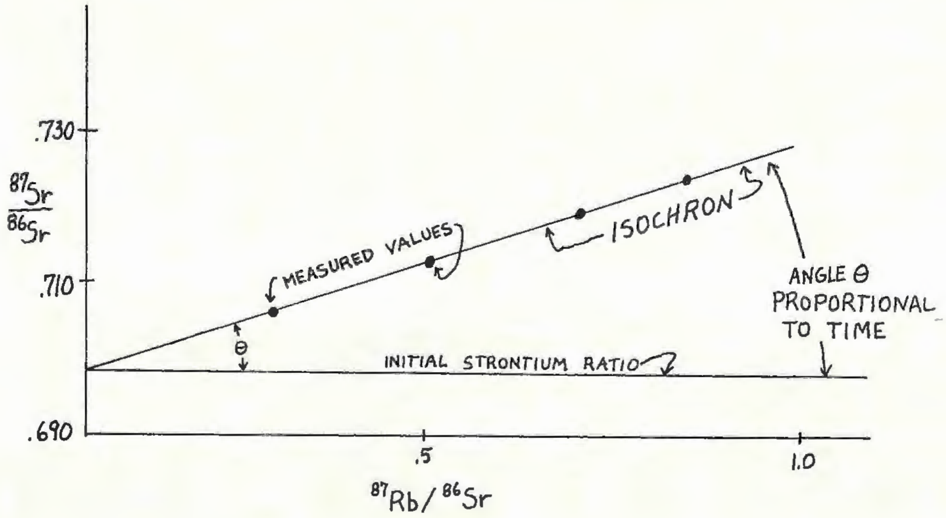
The mass spectrometer at the University of Minnesota is a 60 degree, single focusing instrument with a 30-cm radius, a programmable magnetic field, and an on-line data collection system. For the detection of the different isotopes, a series of up-down scans is made across the mass spectrum. Background radiation measurements are made at 0.5 mass units on either side of the peaks. Numerous sets, of ten readings per set, are recorded to form a strong statistical basis for the final data. All of the strontium isotopic data were normalized to the ratio of Sr 86/Sr 88 = 0.1194. Also, duplicate splits and runs were occasionally analyzed to check the precision of the previous determinations.

After the abundances of Rb and Sr are determined from a geological sample, the ^{87}Rb/^{86}Sr ratio is calculated. For a system closed to Rb and Sr, one may relate the measured ratios of ^{87}Rb/^{86}Sr and ^{87}Sr/^{86}Sr to the age of the system by the equation:

$$(^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_t = (^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_o + (^{87}\mathrm{Rb}/^{86}\mathrm{Sr})_t\ (e^{\lambda t} - 1).$$

The subscript (t) refers to the time that has passed since the origin of the system (o).

A coeval, cogenetic set of samples, having the same initial $^{87}Sr/^{86}Sr$ ratios and differing $^{87}Rb/^{86}Sr$ ratios at t = 0, will have these ratios altered with the passage of time, resulting from the decay of Rb and the generation of radiogenic Sr. If the present, measured ratios of $(^{87}Sr/^{86}Sr)_t$ and $(^{87}Rb/^{86}Sr)_t$ from a set of cogenetic, coeval whole-rock samples are plotted on a strontium evolution diagram (Nicolaysen, 1961), the points will define a line or isochron, with the slope of the isochron from the initial $(^{87}Sr/^{86}Sr)_o$ ratio being a function of time (t), since the samples had the same $(^{87}Sr/^{86}Sr)$ ratio. The intercept of the isochron at $(^{87}Rb/^{86}Sr) = 0$ will define the initial $(^{87}Sr/^{86}Sr)_o$ ratio. An example of a strontium evolution diagram is displayed in Figure 8.



STRONTIUM EVOLUTION DIAGRAM