FIELD TRIP GUIDEBOOK FOR PRECAMBRIAN MIGMATITIC TERRANE OF THE MINNESOTA RIVER VALLEY

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FIELD TRIP GUIDE BOOK FOR

PRECAMBRIAN MIGMATITIC TERRANE OF THE MINNESOTA RIVER VALLEY

Leaders

J.A. Grant, Glen R. Himmelberg, and S.S. Goldich

Special Papers

PRECAMBRIAN GEOLOGY OF THE MINNESOTA RIVER VALLEY BETWEEN MORTON AND MONTEVIDEO

Part 1 - Geology and Structure, J.A. Grant

Part II - Geochronology and Geochemistry, S.S. Goldich

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PART 1 - GEOLOGY AND STRUCTURE

James A. Grant[1]

INTRODUCTION

This summary of the Precambrian geology of the Minnesota River Valley is largely condensed from Grant (1972) to which the reader may turn for further details and interpretations.

The Minnesota River Valley provides a tantalizing window onto the Canadian Shield on the eastern margin of the Great Plains, tantalizing because of the high grade of the metamorphism, and especially because of the antiquity of the rocks there exposed. Essentially, this is a migmatitic terrane of granitic gneisses with lesser amphibolitic gneisses, commonly with pyroxene, and biotite-rich gneisses, which may contain garnet, cordierite, sillimanite, anthophyllite, or hypersthene. Some of the rocks are greater than 3.0 b.y. in age, and they have been involved in metamorphism and deformation at least 2.6 b.y. ago. These events left rocks with a metamorphic grade in the upper amphibolite or granulite facies, and with a major structure that is similar throughout most of the exposed area. Later minor intrusions, dominantly mafic, cut the older rocks, and conglomerate and quartzite of the Sioux Formation of Late Precambrian age locally overlie them.

Deep weathering of the gneisses formed a regolith about 100 feet thick, a part of which was reworked in the formation of Cretaceous deposits of sand and clay. Over this came the glacial deposits of the Pleistocene. With the formation of Lake Agassiz, drainage via Glacial River Warren scoured out the precursor of the present valley leaving an underfit present-day Minnesota River and the glimpse of the Precambrian described in the following pages.

Lund(1956) divided the Precambrian rocks of the valley into three groups, (a) an older, basic complex of gabbroic and quartz dioritic gneisses, (b) a "Minnesota Valley Granite Series" of younger granites and granitic gneisses and (c) post-granite intrusions. He provided some structural data, especially in the vicinity of Granite Falls, and delineated most of the areas of outcrop. This yielded a most valuable base for later work in the valley, for example, the geochronological study by Goldich and others (1961). This work is now superseded by Goldich and others (1970), which is the major source of geochronological data in the valley. Himmelberg (1968) gave a detailed account of the

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geology of the Montevideo-Granite Falls area, which is the basis for the description in this report. Finally, published and unpublished work of the writer provides most of the geological detail on the Sacred Heart-Morton area (Grant, 1972).

The portion of the valley described here contains the two best exposed and most informative areas in the valley, from Morton to Sacred Heart, and Granite Falls to Montevideo. Although the geology of the two areas is more remarkable for similarities than for differences, correlation of mapped units between the two is speculative.

MORTON-SACRED HEART AREA

This area extends from the village of Morton northwest to the outcrops south of Sacred Heart, a distance of about 22 miles. In this area, it has been possible to demonstrate gross stratiformity in the migmatitic terrane, and four units, each a few thousand feet thick, have been mapped on the basis of lithologic similarity. In ascending order, the first three units are quartzofeldspathic gneisses, respectively with abundant, common, and rare rafts of amphibolite; the uppermost unit consists of biotite-rich gneisses and lesser amphibolite. Distinguished from these rocks is quartz monzonite, which forms concordant and discordant bodies in the gneisses. Except for some of the discordant quartz monzonite bodies, these rocks occur in major folds, with wave lengths on the order of a few miles, and shallow easterly-plunging axes. From north to south, the main folds are a synclinorium and anticlinorium north of Delhi, and a synclinorium and anticlinorium in the vicinity of Morton. The grade of metamorphism is probably upper amphibolite facies throughout, and no mineralogical isograds have been drawn here. Late mafic dikes are much less common than in the Granite Falls area.

The lowermost unit (A) consists of interlayered amphibolite and quartzofeldspathic gneiss. It is best exposed in the core of the Delhi anticlinorium (Stop 4), and has been traced northwestward on the south side of the valley to the vicinity of the Sacred Heart quartz monzonite. Where best exposed, two layers of amphibolite about 100 feet thick are bounded by quartzofeldspathic gneiss with or without amphibolite rafts. The amphibolite bodies rarely extend for more than a few tens of feet; and quartzofeldspathic veins parallel and cross the layers, yielding a network-breccia which grades into quartzofeldspathic gneiss with amphibolite rafts.

The next higher unit (B), consisting of quartzofeldspathic gneiss with amphibolite rafts, is about 1,500 feet thick on the south side of the Delhi synclinorium; but to the northwest it is correlated with a lithologically and stratigraphically similar unit twice as thick, and this is tentatively correlated with the gneiss on the north side of the Sacred Heart pluton. To the south, this unit again appears in the core of the Morton anticlinorium, the correlation being based on (a) the abundance of amphibolite rafts in the gneiss and (b) the stratiform position below a unit lacking

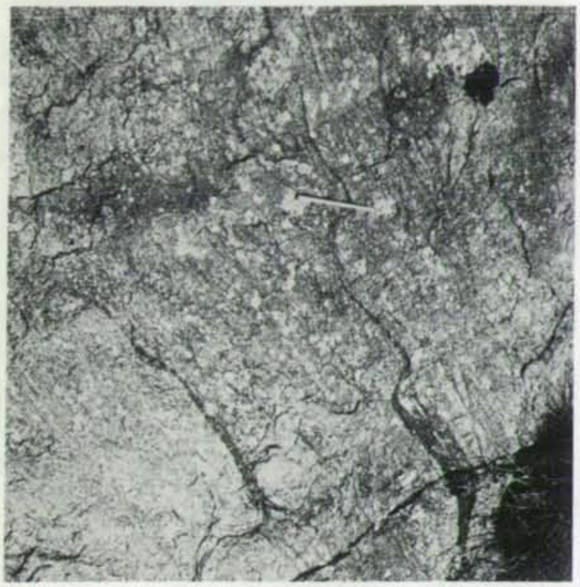

Figure 1. Schlieren in quartzofeldspathic gneiss, SE1/4 sec. 32, T. 114 N., R. 36 W.

Figure 3. Discrete granitic veining in quartzofeldspathic gneiss.

Figure 2. Compositional banding in quartzofeldspathic gneiss.

Figure 4. Nebulitic granitic veining in quartzofeldspathic gneiss.

such inclusions. This is the type locality of the Morton Gneiss (Stops 1 and 2); and it should be emphasized that although this rock has many similarities with "Morton Gneiss" as mapped elsewhere in the valley (Lund, 1956) it is but one variant within one unit in a sequence of related migmatitic gneisses.

The third unit (C) is best developed around the Delhi synclinorium. It is a quartzofeldspathic gneiss, 1,500-3,000 feet thick, which contains sparse amphibolitic rafts. To the southeast, as mentioned above, this is correlated with the rocks above unit B, in the core of the Morton synclinorium.

The quartzofeldspathic gneiss, where it is monolithologic, is a gray to pale pink, medium- to coarse-grained biotite-quartz-plagioclase gneiss, locally containing minor green hornblende or potassium feldspar. Not uncommonly, plagioclase forms megacrysts and mafic schlieren are present (fig. 1). Compositional banding, reflecting differences in the proportions of the major minerals, is locally well developed (fig. 2). Especially in the vicinity of the Sacred Heart pluton and from Delhi south to Morton, permeation by granitic material ranges from discrete veins (fig. 3) to a nebulitic structure (fig. 4), and masses of gneissic quartz monzonite may be found. Where permeation was most intense, as near North Redwood, it is difficult to delineate the quartzofeldspathic gneiss from gneissic quartz monzonite. Clinopyroxene is not uncommon, but occurs only where biotite, quartz, or both are scarce or absent. Orthopyroxene was found in only one thin section, from Morton. Commonly, the amphibolite is gneissic and layered; black amphibolitic layers alternate with gray quartzofeldspathic gneiss (fig. 5) and veinlets of similar material may cross the amphibolite, yielding a network-breccia (fig. 6). (An even more clear-cut breccia occurs where amphibolite is in contact with, and veined by, quartz monzonite.) There is gradation from this type of interlayering to separation of the amphibolite into rafts in a matrix of quartzofeldspathic gneiss, apparently due to the relative competence of the amphibolite. Where both lithologies are major components of the rock, dilatation structure may be found, the less competent gneiss having flowed between blocks of amphibolite. Where the less competent lithology is dominant, the amphibolitic rafts tend to be lensoid. Some amphibolite rafts are fine grained, and have angular projections into the surrounding gneiss (e.g., at Morton); these may represent fragmented mafic dikes in the gneiss.

The most complex migmatites, which have three major lithologies -- as for example at Morton -- consist of schlieren of amphibolite or of quartzofeldspathic gneiss, commonly with the former appearing as a core to the latter, in a matrix of granitic gneiss (fig. 7). One gets the impression of a sequence of different competency in a flowing medium, with amphibolite being more competent than the gray quartzofeldspathic gneiss, which is more competent than the granitic component.

The uppermost unit (D) is confined to the core of the Delhi synclinorium (Stop 5). It lies conformably above and intertongues with unit C. There is a complexly folded association of biotite-rich gneisses and am-

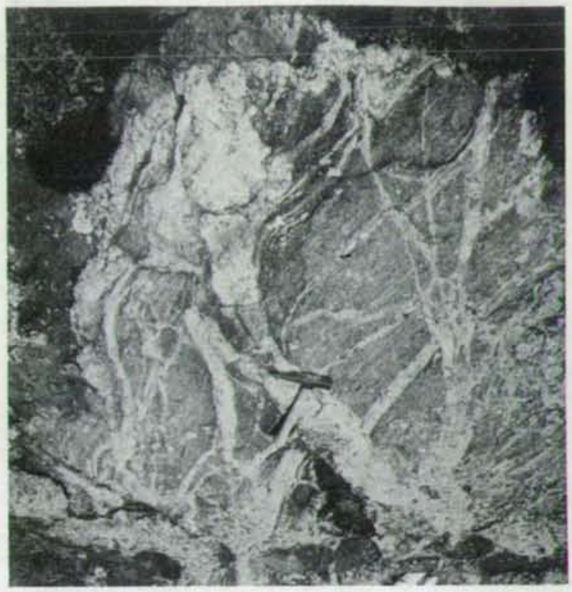

Figure 5. Interlayered amphibolite and quartzofeldspathic gneiss.

Figure 6. Network breccia of amphibolite with veinlets of gray quartzofeldspathic gneiss.

Figure 7. Schlieritic rafts of amphibolite and gray quartzofeldspathic gneiss in a matrix of pink and gray granitic gneiss.

phibolite, in which discontinuous amphibolite layers and disharmonic folds are common, again considered to have resulted from differences in the competency of the rocks involved. The amphibolite occurs as discontinuous layers, lenses and boudins, and is a black, medium-grained, granular, well foliated rock, consisting mainly of plagioclase and green hornblende, which is commonly associated, even in the same grains, with cummingtonite. On the margins of such bodies, rodded quartz-cummingtonite gneiss is common, and quartz-rich gneisses are abundant near the base of the unit.

The biotite-rich gneisses are principally of two kinds. The dominant one is a gray-black, thinly layered gneiss commonly containing the assemblage biotite-cordierite-garnet-anthophyllite as well as quartz and plagioclase. The second type is a heterogeneous, gray, banded gneiss, containing quartz, plagioclase, and biotite (fig. 8), with common sillimanite knots and potassium feldspar-rich patches, and rare garnet or cordierite. Muscovite generally is developed around the sillimanite knots.

A few small masses of coarse quartzofeldspathic gneiss are present in the area of unit D, and these may contain biotite, garnet, or anthophyllite. Also, a pink granitic dike, now albitized (?), traverses the extreme northeastern edge of the outcrop, and is at least spatially related to areas in which the gneisses show extreme low-grade hydrothermal alteration.

The last major rock type to be described is quartz monzonite, which occurs principally as the Sacred Heart pluton, but also as major bodies northeast of Delhi and near North Redwood. Minor dikes of similar composition are found throughout, and the migmatites, as noted above, are locally permeated by granitic material.

The Sacred Heart pluton (Stops 6 and 7) apparently intrudes the surrounding gneisses, the principal evidence for this being the dilation implied by the correlation of the two amphibolite layers of unit A with amphibolite-rich zones near the northern and southern limits of exposure of the pluton, and the demonstrable discordance of several adjacent subconcordant dikes which closely resemble the Sacred Heart pluton in lithology, and are in part mapped as merging with it at its eastern end (fig. 9). The presence of rotated inclusions is not considered to be as good evidence as the above; this simply implies relative movement of the inclusions in a flowing matrix. The main body is typically a pink, medium-grained, homogeneous to faintly foliated and compositionally layered quartz monzonite, with as much as five percent biotite and two percent each of chlorite and muscovite, both of which may be secondary.

On the north side of the pluton (6) there is a distinctive salmon-pink, medium-grained clinopyroxene granite that has abundant, rather nebulitic basic inclusions. The inclusions are commonly zoned, and dominantly composed of two feldspars, hornblende and clinopyroxene; apparently the major reaction here depended on the incompatibility of quartz-biotite-clinopyroxene, yielding hornblende and potassium feldspar. Immediately

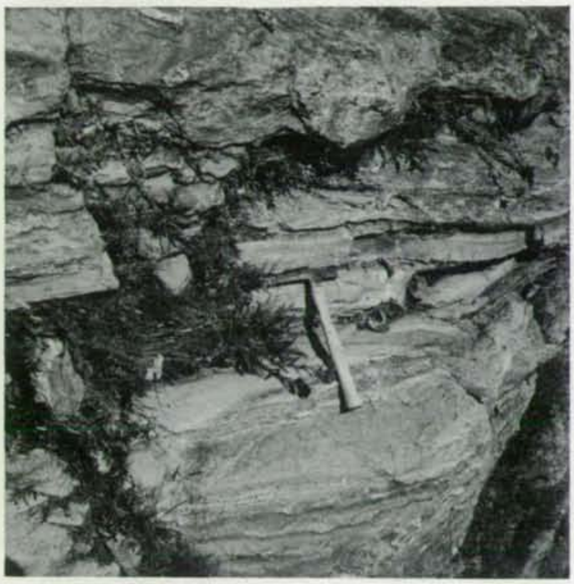

Figure 8. Banded biotite-quartz-plagioclase gneiss contianing sillimanite or garnet.

Figure 9. Discordant contact between hornblende-biotite-plagioclase gneiss (on left) and quartz monzonite (on right).

north of this, except on the northeast side of the pluton, is a zone characterized by coarse, dark-green amphibolitic blocks separated by pink potassium feldspar-rich pegmatite and lesser gray plagioclase-rich pegmatite, and there is gradation between this zone and that described immediately above. Similar rocks are exposed near the southern margin of the outcrop here, and it is these two zones that are tentatively correlated with the two amphibolite layers of unit A. To the north, three mappable subcondordant dikes of quartz monzonite are found, two of which are traceable for more than two miles. The dikes are slightly finer grained than the main body, and their margins are foliated. Locally, even these dikes have a faint compositional banding. In their vicinity, the gneisses tend to be migmatites with a wide range of structural forms, with the exception of the more nebulitic varieties; raft and veinitic types are very common (Stop 7).

To the southeast, in the valley east of Delhi (Stop 4), there is a pink, medium-grained quartz monzonite, which also is massive to gneissic. In detail, this rock crosscuts the gneisses, but its foliation is essentially concordant with that in the gneisses. Many apophyses from this body transgress the country rocks (especially in the core of the Delhi anticlinorium). Almost certainly this mass is continuous with the similar-appearing rock in the valley east of North Redwood, but here especially, the rock is more commonly inequigranular and very highly weathered. Locally, it is very difficult to separate it from the associated gneisses.

It may be noted that pegmatitic dikes are especially common both on the north side of the Delhi synclinorium and near North Redwood, and aplitic dikes are less common.

Only three small diabase dikes have been found to cut the gneisses in this region, but one isolated exposure in the core of the Delhi synclinorium is a granular rock having the assemblage colorless clinoamphibole-olivine-spinel, partly serpentinized. Whether this is related to the late mafic intrusions or part of the metamorphic ensemble is unknown at present.

Structure

The major structures are defined not only in terms of the gross stratiformity described above -- which depends substantially on lithologic correlations that are impressionistic over long distances in such a terrane -- but also in terms of analysis of the foliations and lineations measured in the region.

With respect to the foliations -- schistosity, gneissosity, and compositional layering -- in these gneisses, including the quartz monzonite, the structure is grossly consistent from area to area. The overall compilation for the region yields a broad girdle with two rather subdued maxima, and hence at least monoclinic and possibly orthorhombic symmetry.

On the basis of this last assumption an axial plane is defined, approximately N. 84° E., 82° N., and the B-axis N. 83° E., 12°.

Elongate mineral grains and mineral aggregates yield a maximum about N. 84° E., 16°, interpreted as B-lineations (linear elements parallel to the major fold axis) congruent with the data from foliation planes. However, there is a spread in the data, and a very subsidiary maximum at about N. 53° E., 20°. In contrast, the strong maximum in minor fold axis is coincident with this subsidiary maximum in the mineral lineation data, and a spread of fold axis measurements extends to coincide with the maximum in the mineral lineation data. This is interpreted as resulting from the development of relatively common mineral elongation (L_1) and less common minor folds (F_1) congruent with the major fold system (although some of the F_1 folds have axial planes parallel to the local compositional layering), and the development of relatively common minor folds (F_2) and rare mineral elongations (L_2) after this. That this is basically correct can be demonstrated in the field; in particular, warping of mineral elongations (L_1) in the minor folds (F_2) is not uncommon (Stop 5).

A later deformation (L_2 and F_2) is indicated by lineations and more commonly, by warping or kinking of older structures along nearly vertical planes. The trends of such planes box the compass overall, but there is a very strong maximum about N. 60° E., and a tendency for the apparent movement to be right-lateral where discernible (figs. 1 and 3). (The warping of foliations in the main quarry at Morton is of this nature.) Faulting is rare in the region, but an observed fault surface and the only two mapped faults trend northeast.

Two major shear zones trend northwestward; one can be traced from near North Redwood for more than 10 miles, and the other crosses the axis of the Morton synclinorium. No major displacement has been determined for either.

Post L_1 deformation runs the gamut from ductile to brittle deformation. Such deformation not only partly controlled the development of granitic material in the gneiss (plate 3) but also gave rise to folding, shearing, fracturing, and faulting.

Metamorphism

The most instructive outcrops are those in unit D, in the core of the Delhi synclinorium. From these, the following maximum-phase equilibrium assemblages are inferred, omitting accessory phases:

1. quartz-plagioclase-hornblende-garnet

2. plagioclase-hornblende-clinopyroxene-sphene

3. quartz-plagioclase-biotite-cordierite-garnet-anthophyllite-

ilmenite

4. quartz-potassium feldspar-plagioclase-biotite-cordierite-sillimanite

5. quartz-potassium feldspar-plagioclase-biotite-garnet

Cummingtonite is common in assemblage 1, either as discrete grains or homoaxially grown with hornblende, and was not considered part of the equilibrium assemblage: this may be in error, and a detailed study of the amphibole-bearing assemblages is being started with J. H. Stout. In the one thin section in which assemblage 4 was found, andalusite is also present (the similar assemblage lacking both andalusite and cordierite is common). Assemblage 5 with sillimanite as an additional phase occurs in hand specimen, but has not been found in a single thin section.

Additional assemblages from elsewhere in the region are:

6. potassium feldspar-plagioclase-biotite-hornblende-clinopyroxene-sphene

7. plagioclase-hornblende-clinopyroxene-orthopyroxene

8. quartz-potassium feldspar-plagioclase-biotite-hornblende-sphene

In these assemblages, biotite and clinopyroxene do not appear together with more than one percent quartz, and the three minerals are probably not stable with respect to hornblende-potassium feldspar, involving a reaction such as:

$$4\ SiO_2 + K(Fe,Mg)_3AlSi_3O_{10}(OH)_2 + 2\ Ca(Fe,Mg)Si_2O_6 \rightarrow KAlSi_3O_8 + Ca_2(Fe,Mg)_5Si_8O_{22}(OH)_2.$$

This reaction has also been invoked to explain the zoned inclusions in the granite of the Sacred Heart pluton.

Assemblage 7 has been found only in one thin section -- from an amphibolitic inclusion in the gneiss at Morton. With this exception, the above assemblages (and of course the more common assemblages with lesser numbers of phases) are diagnostic of the upper amphibolite facies at pressure-temperature conditions where quartz-muscovite is unstable but quartz-biotite-sillimanite and quartz-cordierite-garnet are stable (Grant, 1968, p. 925).

Retrogressive metamorphism is evident. In particular, rocks containing potassium feldspar and sillimanite show development of muscovite around the sillimanite knots and, in part intergrown with myrmekite, around and within the potassium feldspar, implying retrogression across the second sillimanite isograd, as discussed by Evans and Guidotti (1966). Zoning in garnet in assemblage 3, showing low Mn and high Mg/Mg+Fe in core relative to margin, suggest cryptic retrogression in this assemblage

(Grant and Weiblen, 1971). As noted above, the development of cummingtonite may be due to retrogression, as it is at Granite Falls. As would be expected, chloritization and sericitization are not uncommon, and extreme alteration to chloritic or albite-epidote bearing assemblages was found locally in unit D, and along the major shear zones.

GRANITE FALLS-MONTEVIDEO AREA

Between the Granite Falls-Montevideo area and the Sacred Heart-Morton area there is an interval of 8 miles without exposure, and an inferred major fault zone. The following description is largely from Himmelberg (1968). The area is underlain by granitic gneiss, hornblende-pyroxene gneiss, and garnet-biotite gneiss, which generally constitute units 1,000 to 5,000 feet thick, although smaller scale interlayering is common. Possibly a syncline exists between Montevideo and Granite Falls, but the major exposed structure is an easterly-plunging anticline (Lund, 1956) at Granite Falls. Southeast of Granite Falls, the exposures end near the inferred major fault zone.

The granitic gneiss is a pink to red, medium-grained, equigranular, leucocratic rock, which commonly has compositional layering resulting from alternations of biotite-rich and quartzofeldspathic beds. This layering is commonly paralleled by biotite plates and locally by flat quartz lenses. Relatively massive granite (Stop 9), granitic pegmatites, and bluish quartz lenses parallel and crosscut the foliation of the gneiss. Minor folding, warping and incipient boudinage are common. Numerous hornblende-pyroxene gneiss layers and lenses of variable thickness are present, but none of garnet-biotite gneiss is known. The granitic gneiss consists dominantly of quartz, microcline microperthite, antiperthitic plagioclase, and brown biotite, with sparse, local garnet. The feldspars are clouded by opaque iron oxides and in some of the red outcrops at Montevideo, by hematite.

The hornblende-pyroxene gneiss is a gray-black, medium-grained, equigranular rock, which varies from a uniform amphibolite to a banded gneiss. The amphibolite occurs most commonly as layers or lenses in the granitic gneiss (the dominant mode of occurrence near Montevideo) and as discrete layers within the hornblende-pyroxene gneiss. Sharp conformable contacts with adjacent rocks are the rule, and the long axes of lenses parallel the foliation.

The extensive hornblende-pyroxene gneiss immediately south of Granite Falls is a gray gneiss that has a compositional layering resulting from different proportions of minerals. However, around the nose of the anticline northwest of Granite Falls, the unit consists of a heterogeneous interlayered series of mafic layers rich in hornblende and pyroxene but poor in quartz, quartzofeldspathic layers with subordinate hornblende and pyroxene, and layers of pegmatitic granitic gneiss. Quartz lenses and veins parallel and crosscut the foliation. Structures such as minor folding, warping, and boudinage are rare in these rocks, but hornblende-pyroxene rodding is found locally. The principal minerals in most of this gneiss are antiperthitic plagioclase, greenish-brown hornblende, orthopyroxene, pale green clinopyroxene, brown biotite, and opaque oxides. Replacement of the amphibole and pyroxenes by cummingtonite, blue-green amphibole, and serpentine is common.

The garnet-biotite gneiss is a dark-gray, medium-grained, equigranular, well foliated gneiss that has layers of light-gray, coarse-grained, granular gneiss and a preferred orientation of biotite and prismatic orthopyroxene. The northern contact between these rocks and the hornblende-pyroxene gneiss is concordant and essentially marked by the first appearance of garnet (Stop 8). The southern contact probably is a fault. Quartz, antiperthitic plagioclase, reddish-brown biotite, and garnet are the major minerals, and orthopyroxene is common in the well foliated gneiss. There is a conspicuous lack of either clinopyroxene or hornblende.

A heterogeneous series of interlayered gneisses -- leucogranitic gneiss, hornblende-pyroxene gneiss or amphibolite, hornblende-biotite-quartz-plagioclase gneiss, and hornblende-bearing granitic gneiss -- crop out in the southeasternmost part of the area.

Post-metamorphic mafic dikes as much as 75 feet across cut the gneisses. Most are dark-gray, medium-grained tholeiitic diabase having fine-grained margins. Replacement of augite by green hornblende is common. Hornblende andesite forms abundant narrower dikes that are grayish black and porphyritic-aphanitic and have phenocrysts of plagioclase or quartz. Black, aphanitic olivine diabase dikes are rare, and their relationships to the other mafic dikes are not known. At one locality, a pink, medium-grained biotite adamellite ("granite of Section 28" in Goldich and others, 1961) intrudes a hornblende andesite dike, yielding a spectacular net-veined structure (Stop 10), first described by Lund (1956).

Structure

The rocks described above have foliations defined by compositional banding, preferred orientation of planar or prismatic minerals, flat quartz lenses, and hornblende segregations. Although no differences in the attitudes of the several foliations have been found, some of the compositional banding may be pre-metamorphic in origin. Poles to the foliations define a great-circle girdle with a B-axis N. 85° E., 15°.

Lineations consist of parallel minerals and mineral aggregates, axes of minor folds, and boudins. No significant difference was found in compilations of lineations from three arbitrary subdivisions of the area. The range in bearing of B-maxima is N. 70° E. to S. 82° E., with a plunge of approximately 15°. A-lineations, with bearings essentially normal to this area are present locally (boudins and minor folds).

These structural data suggest a structure homogeneous with respect to all measured elements; a gently-plunging, inclined, cylindrical fold system, having at least monoclinic symmetry. The B-axis from foliation data (N. 85° E., 15°) and the B-axis from lineation data (N. 88° E., 15°) are considered equivalent.

Steeply-dipping shear zones generally less than a foot wide are common, and may be marked by mylonite or veins of granitic pegmatite. Most trend N. 35°-60° W., although a few trend northeast. Evidence for left-lateral displacement was noted on some of the northwest-trending shear zones.

A major, easterly-trending fault zone near the southeastern limit of outcrops is inferred from aeromagnetic and gravity data (Zietz and Kirby, 1970; Craddock and others, 1970) and from the tightly appressed compositional layering and cataclastic structures present in the adjacent outcrops.

All the mafic dikes cut the foliation of the metamorphic rocks, and dominantly occupy a nearly vertical fracture system trending approximately N. 55° E. The small shear zones mentioned above post-date the tholeiitic diabase, but pre-date the hornblende andesite dikes.

Metamorphism

Twenty-two assemblages considered to represent a close approach to equilibrium are listed by Himmelberg and Phinney (1967, p. 329-330), and the following are the maximum-phase assemblages from that list:

1. quartz-potassium feldspar-plagioclase-biotite-hornblende-clinopyroxene-orthopyroxene-magnetite-ilmenite

2. quartz-potassium feldspar-plagioclase-garnet-hornblende-clinopyroxene-magnetite-ilmenite

3. quartz-plagioclase-hornblende-sphene-hematite

4. quartz-plagioclase-garnet-hornblende-clinopyroxene-orthopyroxene-magnetite-ilmenite

5. plagioclase-biotite-hornblende-clinopyroxene-orthopyroxene-hematite

6. quartz-potassium feldspar-plagioclase-biotite-garnet-orthopyroxene-magnetite-ilmenite

7. quartz-potassium feldspar-plagioclase-biotite-garnet-rutile-hematite

The first five are from hornblende-pyroxene gneiss, 6 is from garnet-biotite gneiss, and 7 is from the granitic gneiss. The common assemblages from these three units are respectively 1, without potassium feldspar and with or without quartz, 6, with or without orthopyroxene, and 7, without rutile. Himmelberg and Phinney found no empirically incompatible phases in these assemblages, regular distribution of Fe and Mg between coexisting hornblende-clinopyroxene-orthopyroxene, and only minor compositional variation in mineral grains for a given mineral in a given specimen. The occurrence of pyroxene or hornblende at any locality appears to be chemically controlled, rather than due to fluctuations in temperature or pressure. Thus, these assemblages are considered to be isofacial, and yet cannot be assigned to a hornblende-granulite, or pyroxene-granulite facies (see Turner, 1968, p. 186 and p. 320-336). They are simply assigned to the granulite facies, on the bases of the presence of orthopyroxene rather than Ca-free orthoamphibole and the common occurrence of the typical assemblage plagioclase-hornblende-clinopyroxene-orthopyroxene (Turner, 1968, p. 320).

The retrograde metamorphism is discussed by Himmelberg and Phinney (1967, p. 341-347), and they suggest that this may be related in part to a discrete, later event.

SYNTHESIS

Lithologic Correlation

Throughout the Morton-Montevideo region there are significant similarities in gross lithologies. Stratiform units on the order of 1,000 feet are mappable, and consist of quartzofeldspathic gneisses, amphibolites and pyroxene granulites, and apparently uppermost in each area, biotite-rich gneisses. Quartz monzonite is widespread in the south and present in the north, with the reverse being true of late mafic dikes.

Despite these similarities, however, exact correlation of map units between the two areas is not possible at present.

Structure

The major structure from Morton to Montevideo relates to open folding about an axis approximately N. 85° E., 15°, with congruent mineral lineations and less abundant minor fold axes. Later deformation involving minor folding, warping, shearing and faulting is in evidence throughout, although most evident in the southern area.

Metamorphism

Mineral assemblages from the northern area are typical of the granulite facies, whereas those to the south (based largely on the evidence from unit D) are referred to the upper amphibolite facies. However, with one probable exception, the mineral associations from the region as a whole are not necessarily incompatible, and could be explained by differences in bulk composition. This is by no means necessarily the only reason for the different assemblages. The one exception is the presence of orthopyroxene and absence of orthoamphibole in the north with the reverse being true in the south (apart from the one known example of orthopyroxene at Morton).

Retrograde metamorphism is evident in both areas, but the detailed timing of metamorphic events in the two areas has not been resolved as yet.

Origins of the Gneisses: Speculation

The biotite-rich gneisses of unit D near Delhi and the garnet-biotite gneisses at Granite Falls are compatible with derivation from sedimentary rocks in the graywacke range and the quartz-rich gneisses of unit D may represent original chert.

The amphibolites and hornblende-pyroxene gneisses occur as layers or rafts in quartzofeldspathic gneisses or the gneisses of unit D, suggesting that they may have been layered rocks originally. Thus a mafic igneous origin, as sheet-like intrusives, or as volcanic (or volcanogenic) rocks is postulated for these.

The quartzofeldspathic gneisses are more difficult to interpret. One cannot be certain to what extent the present compositions are similar to those of the original rocks. Now, the compositions range from tonalitic to granitic, and are compatible with derivation from igneous origins. However, two problems arise; is the tonalitic material essentially primary or a residuum from partial melting of a more potassic protolith, and to what extent was the granitic material of local derivation during the metamorphism or 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.

SUMMARY

The Precambrian geology of this part of the Minnesota River Valley is summarized in the following working hypothesis.

Prior to 3.0 b.y. and probably as early as 3.6 b.y., a layered series was formed composed of granitic rocks overlain by graywacke-like sediments with basaltic rocks locally abundant in both. Whether the igneous rocks were extrusive, intrusive, or both is not known.

By about 2.65 b.y., these rocks had been deformed into a fold system on a shallow east-northeasterly-plunging axis, and metamorphosed to the upper amphibolite or granulite facies. Possibly, partial melting of appropriate compositions, accompanying deformation, gave rise to the common migmatitic structures. In the later stages of these events, large bodies, dominantly of quartz monzonite, were emplaced in the southern area in particular.

Minor deformation continued after this, overlapping the times of emplacement of mafic dikes until 1.8 b.y., when small intrusions such as the adamellite at Granite Falls were formed. Possibly, mild metamorphism occurred at this time, especially in the upper valley.

We have a coherent geology throughout this elongate window onto the oldest known rocks in North America. And these rocks differ little in kind from other early Precambrian rocks known across the Canadian Shield.

PART 2 - GEOCHRONOLOGY AND GEOCHEMISTRY

Samuel S. Goldich

INTRODUCTION

The granitic gneisses in the vicinities of Morton, Granite Falls, and Montevideo are among the oldest known crustal rocks. Like very ancient rocks in other parts of the world the gneisses have had a complicated history, and metamorphic changes have masked their original characters and obscured their age. Conservatively the age may be given as 3200 or 3300 m. y. Goldich and others (1970) have attempted to probe the metamorphic history and concluded that the gneisses date back to 3550 m.y. ago. Similarly old, or older gneisses (3600 to 4000 m.y.) have been reported from the Godthaab district, West Greenland (Black and others, 1971). Field and more detailed geochronological and geochemical investigations are being continued, and the nature of this work is briefly indicated in following sections.

GEOCHRONOLOGY

General Statement

On the basis of K-Ar and Rb-Sr mica ages Goldich and others (1961) suggested two periods of orogeny accompanied by magmatic activity in southwestern Minnesota. A major orogenic event, approximately 2500 m.y. ago, was postulated for the Morton area in which granite near Sacred Heart was considered to be a late- or postkinematic intrusion. A younger event, approximately 1800 m.y. ago, was suggested in the Granite Falls area. This interpretation was soon found to be untenable when Rb-Sr determinations on K-feldspar samples from both areas gave similar ages of approximately 2500 m.y. (Goldich and Hedge, 1962).

The Rb-Sr ages on K-feldspar, like the mica ages, failed to give any indication that the gneisses actually were much older than 2600 m.y., and this was first revealed in zircon lead-alpha determinations by T. W. Stern in the U. S. Geological Survey Laboratory, Washington, D. C. The startling lead-alpha ages of 2800 and 3000 m.y. led to the isotopic U-Pb analyses by Catanzaro (1963). Catanzaro analyzed two zircon concentrates from the Morton Gneiss; one from the granite gneiss near Granite Falls, the Montevideo granite gneiss of Lund (1956); and one from the granitic intrusion

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in the Montevideo gneiss, the "granite of section 28" (Goldich and others, 1961, p. 140). All the zircon U-Pb ages are discordant, but the Pb^{207}/Pb^{206} ages for the zircon from the gneisses range from 3100 to 3280 m.y., and the age for the zircon from the younger intrusion is 1825 m.y. (Catanzaro, 1963, p. 2046). Further work was then undertaken, and some preliminary results were reported in an abstract by Stern (1964). In this work zircon from the residual clay developed by weathering of the Morton Gneiss was also analyzed, and it was shown (Stern and others, 1966) that a large proportion of the lead was removed from zircon during weathering. Marked discordance in the Pb^{206}/U^{238} and Pb^{207}/U^{235} ages resulted from the leaching of the lead by ground water, but the Pb^{207}/Pb^{206} ages apparently were not greatly affected. Goldich and Gast (1966) sampled partially weathered biotite in the residual clay and found that weathering seriously affected the K-Ar age and even more so the Rb-Sr age.

K-Ar ages determined on hornblende concentrates (Thomas, 1963; Hanson and Himmelberg, 1967; Hanson, 1968) are considerably older than corresponding K-Ar ages on biotite. Mineral ages from the Minnesota River Valley are summarized in Figure 10.

Morton and Montevideo Gneisses

U-Pb Ages

The U-Pb zircon ages by Catanzaro (1963) demonstrated beyond any doubt that the K-Ar and Rb-Sr ages on biotite and K-feldspar reflect metamorphic events. They do not date the time of crystallization of igneous rocks, nor are they necessarily reliable indicators of the time of major metamorphic events. A new attack on the problem was then initiated with the more refined Rb-Sr whole-rock technique and with additional U-Pb isotopic analyses of zircon. The results are given in the paper by Goldich and others (1970) from which Figure 10 is taken. In this diagram, mineral ages, and Rb-Sr isochron age, and U-Pb concordia age interpretations reveal three major events. The oldest, the Mortonian event, at approximately 3550 m.y. ago is subject to some interpretation because both the Rb-Sr and the U-Pb ages are discordant as a result of a high-grade metamorphic event that occurred 2650 m.y. ago and a lower-grade metamorphism at approximately 1850 m.y. ago.

The original three zircon analyses of Catanzaro (1963, p. 2047) when plotted on a concordia diagram (Wetherill, 1956) defined a line intersecting the concordia curve at 3550 and 1850 m.y. The discordance in the U-Pb ages of the zircon can be attributed to loss of lead from zircon, 3550 m.y. old, as a result of a thermal event 1850 m.y. ago. The mineral ages in the range from 1700 to 1900 m.y. (fig. 10) may be cited as support for this interpretation. Catanzaro (1963), however, noted: (1) that in this episodic lead-loss interpretation the 2500-m.y. metamorphic event, although the stronger of the two events, apparently did not affect the zircon; and (2) that the zircon from the younger granite of section 28 also gave discordant ages, which, to his mind, complicated the simple episodic lead-loss interpretation.

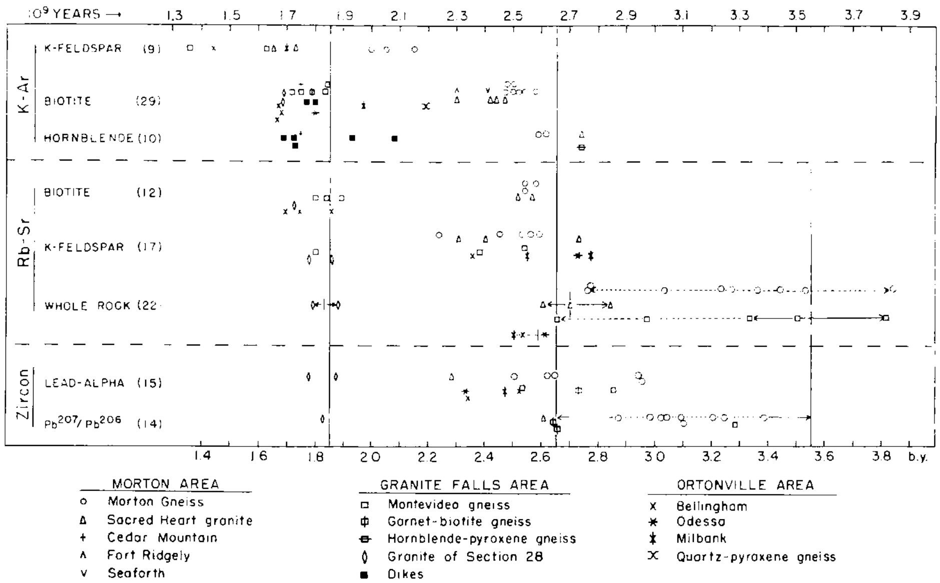

Figure 10. *Plot of radiometric ages of rocks and minerals from the Minnesota River Valley showing principal events (from Goldich and others, 1970, fig. 2).*

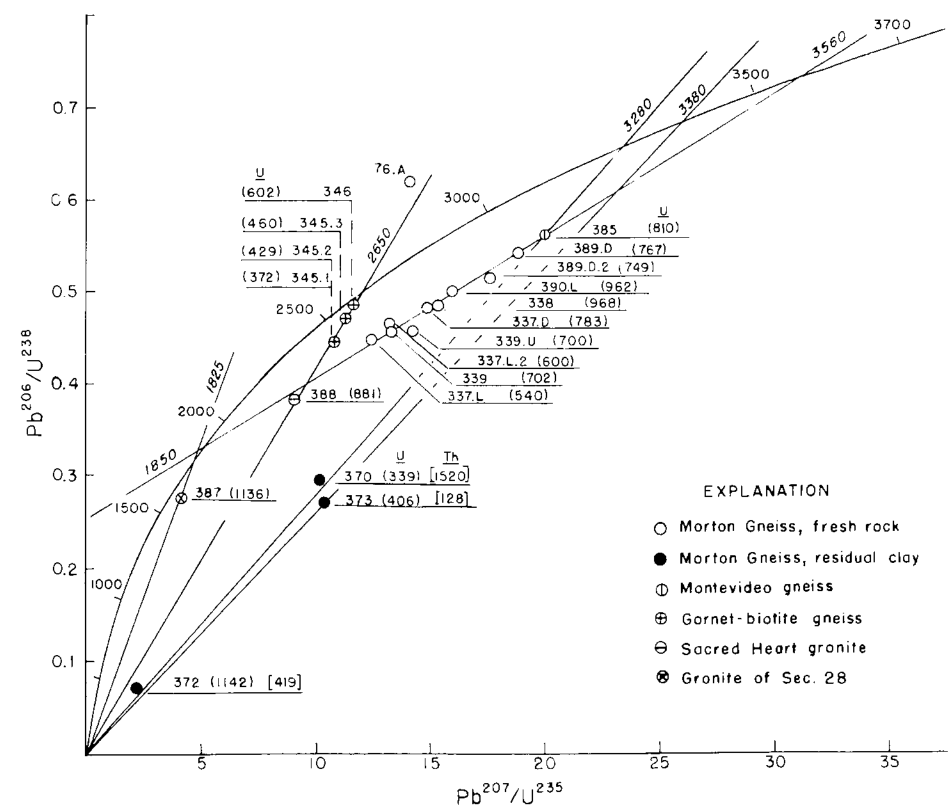

Figure 11. *Concordia diagram of zircon and allanite (76.A) samples. Contents of U and Th in ppm in brackets. The 1850-3650-m.y. chord is a linear regression of the zircon samples from the gneisses (from Goldich and others, 1970, fig. 6).*

Figure 11, from Goldich and others (1970, p. 3680), is a plot of zircon samples and an allanite from the gneisses and from other rocks in the Minnesota River Valley. The chord, which represents a linear regression of the zircon samples from the gneisses, gives upper and lower intercept ages of 3560 and 1850 m.y., respectively, similar to those of Catanzaro (1963) and Stern and others (1966). Three zircon samples from the residual clay on the Morton Gneiss (Stern and others, 1966) also are included. A line drawn from the origin through the sample point intersects the concordia curve to give the Pb^{207}/Pb^{206} age of the sample. Sample 385 from the Montevideo gneiss is 3280 m.y. old, but if it is assumed that there has been no fractionation during the ground-water leaching of lead from sample 373 from the residual clay, a minimum age of 3380 m.y. is indicated for the Morton Gneiss.

In addition to the zircon samples from the gneisses, four samples from the garnet-biotite gneiss in Granite Falls and one sample from the Sacred Heart granite are plotted in Figure 11. The results have a significant bearing on the interpretation of the data from the gneisses. Sample 346 from the garnet-biotite gneiss, with nearly concordant ages, plots just below the concordia curve, but the three sized fractions of sample 345 are discordant and plot along a line indicating relatively recent lead loss. Sample 388 from the Sacred Heart granite is more sharply discordant but also plots near the 2650-m.y. chord. These discordant ages, as well as those of sample 387, could be explained using Tilton's (1960) model for loss of lead by continuous diffusion. The age discordance in the zircon from the gneisses, then, might be explained as the result of continuous diffusion combined with episodic lead loss. This possibility has been considered by Catanzaro (1963) and by Stern and others (1966).

Returning to the simple model of lead-loss from the zircon as a result of a thermal event 1850 m.y. ago, it is obvious that the zircon from the garnet-biotite gneiss and from the Sacred Heart granite do not show this effect, but these samples as well as sample 387 do show an age discordance indicating a relatively recent loss of lead. A similar relatively recent lead loss should then be expected in the zircon from the Morton and Montevideo gneisses. If the apparent linearity of the points is explained by episodic loss of lead from 3550-m.y. zircon as a result of a thermal event 1850 m.y. ago, it must follow that the zircon in the gneisses was a closed system since the 1850-m.y. event. This is not an acceptable conclusion.

The two-stage model (Goldich and others, 1970, p. 3681) combines episodic lead loss at 2650 m.y. ago as a result of a high-grade metamorphic event with a relatively recent loss of lead resulting from the dilatancy effects of uplift and erosion. The lack of evidence for a younger thermal event in many areas where discordant U-Pb ages have been found, in part, prompted Tilton (1960) to develop a model for lead loss by continuous diffusion. Goldich and Mudrey (1969), however, rejected the continuous diffusion model, and suggested that a principal cause of discordant U-Pb ages is lead loss from zircon that occurs relatively late in the rock's history; hence the Pb^{207}/Pb^{206} ages approach the true age, and the discordance closely resembles that produced by recent lead loss. As can be seen in

Figure 11, this is precisely the case in the zircons from the garnet-biotite gneiss (345 and 346), the Sacred Heart granite (388), and the granite of section 28 (387).

The dilatancy model relates the loss of radiogenic lead to the loss of water from metamict zircon when quartz-bearing rocks are brought close to the surface through uplift and erosion. The radioactive decay of uranium and thorium produces radiation damage in the crystal structure of zircon with the development of crystallites and amorphous compounds. As has been well demonstrated by Silvèr (1962) the extent of the radiation damage depends on the original uranium and thorium contents and on the age of the zircon. It has long been known that water enters the microcapillary openings in metamict zircon, and Mumpton and Roy (1961) concluded that the water is largely molecular water that is strongly adsorbed on the metamict phases. Grünenfelder (1963) suggested that there is a positive correlation between the age discordance and the water content of zircon. Obviously a thermal event, even at low temperature, would be effective in driving out water with loss of some radiogenic lead, producing age discordance. Goldich and Mudrey (1969), however, extended this concept to include the loss of water from metamict zircon as a result of uncovering by erosion. Crystalline rocks, especially those containing large amounts of quartz (R. H. Jahn, letter, 1970) undergo fracturing and rifting near the surface. With relief of pressure some of the water with dissolved radiogenic lead escapes from the zircon.

The dilatancy model explains the age discordance of the zircon from the garnet-biotite gneiss, the Sacred Heart granite, and the granite of section 28. We should expect the zircon in the ancient gneisses to show a similar effect; hence a two-stage model is required. The apparent linearity of the points (fig. 11) is explained as the result of the severe metamorphism at 2650 m.y. ago; the intercept giving 1850 m.y. is a coincidence. The heavy dashed chord in Figure 12 is a reconstruction of the age discordance developed in the zircon of the granitic gneisses during the 2650-m.y. event. The zircon in the garnet-biotite gneiss which was involved in the event was completely recrystallized and reset; whereas the zircon in the granitic gneisses was only partially affected. The difference may be related to the relatively high water content of the garnet-biotite gneiss compared to the relatively dry granitic gneisses. The essentially concordant zircon (345 and 346) fixes the lower intercept, but the upper intercept cannot be rigorously demonstrated (Goldich and others, 1970, p. 3682). It represents an interpretation of the data with samples 385 and 372 (fig. 11) setting minimum values.

In the interpretation in Figure 12, all the points for the zircon samples from the gneisses originally were on or near the heavy dashed chord, and their present position is attributed to loss of lead in Cretaceous time when the Morton Gneiss was brought close to the surface and subjected to deep weathering. At the same time some radiogenic lead was lost from the zircon of other rocks producing some age discordance in each.

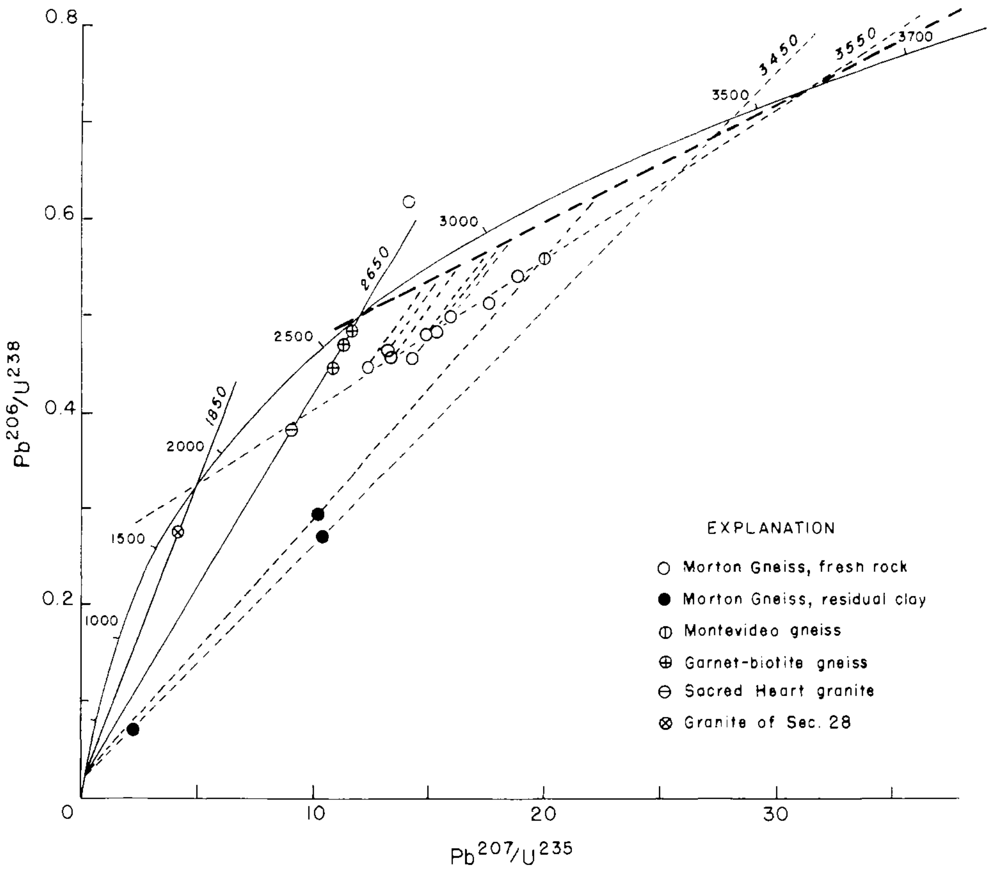

Figure 12. Concordia diagram illustrating two-stage model. A primary age discordance (heavy chord) was produced in the zircon in the gneisses during the 2650-m.y. metamorphism. secondary discordance in the gneisses and in the granites was developed through the dilatancy effects of uplift and erosion appro i-mately 100 m.y. ago. Zircon from the residual clay shows additional loss of lead from ground water leaching. The dilatancy-model age for the gneisses is a minumum value of 3450 m.y.; for the Sacred Heart granite, it is 2650 m.y.; and for the granite of section 28, it is approximately 1850 m.y. (Goldich and others, 1970, fig. 7).

Rb-Sr Ages

The Rb-Sr whole-rock and rock-mineral ages, like the U-Pb zircon ages, are discordant and are subject to interpretation. Whole-rock, plagioclase, and K-feldspar samples from the Morton Gneiss are plotted in Figure 13 (Goldich and others, 1970, p. 3685). A linear regression of all samples gives the 2550-m.y. isochron which is also the average Rb-Sr age of three biotite samples plotted in Figure 10. The whole-rock points (208, 338) in Figure 13, however, lie above the isochron, and the dotted line drawn through the whole-rock and plagioclase points corresponds to an age of 2650 m.y. The initial ratio, Sr^{87}/Sr^{86}, for both isochrons is 0.710, and it is clear that redistribution of radiogenic Sr^{87} among the mineral phases occurred during the 2650-m.y. metamorphic event which is dated by the U-Pb zircon age. It is also clear that the isotopic system in the minerals has not been closed since the 2650-m.y. event.

Figure 14 shows all the whole-rock data for the Morton and Montevideo gneisses. The line through the points for samples 339 and KA-209 gives an age of 3800 m.y. which is not highly significant, but the indicated initial Sr^{87}/Sr^{86} ratio of 0.700 is considered reasonable for rocks with a minimum age of 3200-3300 m.y. The 3550-m.y. isochron was computed for the Montevideo gneiss samples (385, 369, and KA-209) using 0.700 for the initial Sr^{87}/Sr^{86} ratio. Samples of the dark-colored, tonalitic phase of the Morton Gneiss (339, 389.D, and 337.D) fit the isochron; 3550 m.y. is considered the best original age for the ancient gneisses. The subsequent history is complex and speculative, but the present data are a solid basis for more detailed studies which are continuing.

2600-2700-m.y. Granites

The age of the Sacred Heart granite is limited by the Pb^{207}/Pb^{206} zircon age of 2605 m.y., with a model age of 2650 m.y. (fig. 12), a K-Ar hornblende age of 2740±140 m.y. (Thomas, 1963), and a Rb-Sr isochron age of 2700 m.y. (Goldich and others, 1970, p. 3687). Some additional work is planned because the mineral ages clearly indicate disturbance of both the Rb-Sr and K-Ar isotopic systems (fig. 10).

In the upper part of the Minnesota River Valley in the vicinity of Odessa and Ortonville and in the Milbank area of South Dakota numerous small outcrops of granite have been sampled. The preliminary data suggest that these granites probably are contemporaneous with the Sacred Heart granite. More detailed studies are planned.

The Fort Ridgely granite of Lund (1956) forms small outcrops along the Minnesota River approximately 2.5 miles northwest of Fort Ridgely State Park and 12 miles southeast of Morton. This granite is currently being studied at Northern Illinois University. Rb-Sr and U-Pb determinations indicate an age of 2600-2700 m.y.

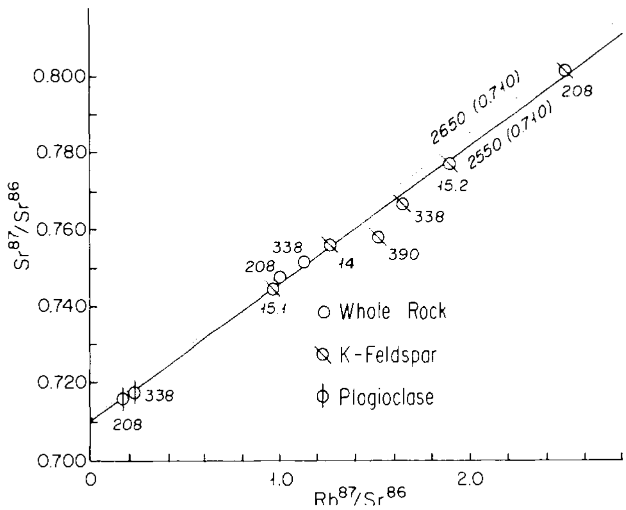

Figure 13. *Rb-Sr diagram of whole-rock, plagioclase, and K-feldspar samples from the Morton Gneiss. The 2550-m.y. isochron is a linear regression of all samples. The 2650-m.y. isochron was constructed for whole-rock and plagioclase samples (Goldich and others, 1970, fig. 8).*

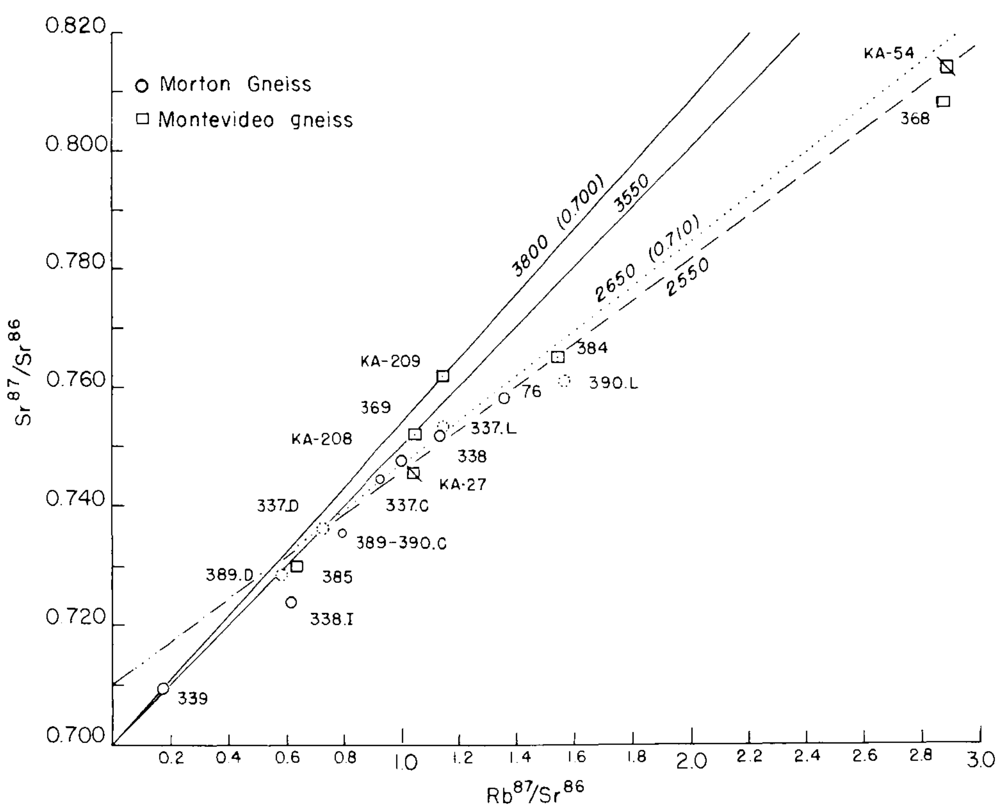

Figure 14. *Rb-Sr isochron diagram of whole-roch and feldspar samples from the Montevideo gneiss and whole-roch samples from the Morton Gneiss. Sample 337.C is a composite calculated from 337.D (dark-colored phase) and 337.L (light-colored), and 389-390.C is a composite of 389.D and 390.L. The 3550-m.y. isochron was constructed from the weighted average of the data for samples 385, 369, and KA-209. The 2550-m.y. and 2650-m.y. isochrons are from figure 13.*

1800-m.y. Plutons

Several relatively small plutons in the Minnesota River Valley were emplaced approximately 1800 m.y. ago. The best dated of these is the granite of section 28 which cuts the Montevideo gneiss and a hornblende andesite dike northwest of Granite Falls. The Pb^{207}/Pb^{206} age for zircon is 1825 m.y. (Catanzaro, 1963), and the model age is 1850 m.y. (fig. 12). Mineral ages range from 1690 m.y. (K-Ar on biotite) to 1870 m.y. (lead-alpha on zircon). A small gabbro-granophyre intrusive complex in the Morton Gneiss south of Franklin probably is of similar age as is suggested by K-Ar determinations on biotite (Goldich and others, 1961, p. 135) and on hornblende (Hanson, 1968, p. 5). Both determinations gave 1750 m.y. (see fig. 10).

Dike Rocks

Basaltic dikes in the Granite Falls area have been dated by Hanson and Himmelberg (1967). Three types were recognized: tholeiitic diabase, hornblende andesite, and olivine diabase. All the mafic dikes cut the structure of the gneissic country rock; hence are younger than the regional deformation dated at 2650 m.y. ago. The hornblende andesite in a few localities cuts the tholeiitic diabase dikes, and Hanson and Himmelberg (1967, p. 1430) found that the tholeiitic diabase dikes are cut by shear zones that did not affect the hornblende andesite dikes. The relative age of the olivine diabase dike could not be determined in the field, and samples were not dated. Two tholeiitic dikes were dated by K-Ar; a hornblende concentrate gave 2080 m.y. and a whole-rock sample 1800 m.y. If it can be assumed that the dikes are contemporaneous, the whole-rock age is definitely low, and 2080 m.y. may be accepted as a minimum age.

Four hornblende andesite dikes were dated, and the biotite and hornblende ages range from 1690 to 1930 m.y. Both biotite and hornblende from two of the dikes were dated, and in both cases the biotite gave an older age than the hornblende. The hornblende andesite dike intruded by the granite of section 28 was not dated, but if we assume the hornblende andesite dikes were contemporaneous, the age of 1850±50 m.y. determined for the granitic pluton sets a minimum age. The age of 1930 m.y. determined on hornblende from one of the dikes may approach the correct age, but because of the small potassium content this value may have a large analytical error.

Aplitic dikes are fairly common in the Morton Gneiss and cut the foliation. These rocks have not been studied, and the problem of dating them is under consideration. Sill-like masses of leucocratic composition and aplitic texture are a special problem in the Montevideo gneiss, and illustrate the close interrelationship between field and laboratory investigations. Himmelberg (1968) divided the granitic gneiss in the Granite Falls area into two types: (1) leucocratic, pink to red, medium-grained biotitic gneiss and (2) "quartzo-feldspathic" massive layers. Samples of the two types were included in the Rb-Sr study. Sample 369 of the gneissic phase plots close to the 3550-m.y. isochron, but sample 368 of the massive phase is much younger. The radiometric data disagreed with the field work, and re-examination of the locality showed that the "quartzofeldspathic" phase cross cuts the foliated phase. The precise age remains to be determined, and samples will be included in the study of the aplitic rocks. Present information indicates that the sill-like masses and dikes are older and are not related to the 1850-m.y. event.

Epeirogeny

The dilatancy model to explain discordant U-Pb ages of zircon is a relatively recent suggestion, but the possible effects of epeirogeny and cooling history on K-Ar mineral ages have been explored and discussed for some years. Harper (1967) has reviewed the contributions by a number of investigators to the development of the concept that mica ages reflect the time of uncovering and of stabilization of the K-Ar and Rb-Sr isotopic systems in micas. In this interpretation mica ages do not date the time of original crystallization nor of subsequent metamorphic events.

Goldich and others (1970, p. 3691) suggested that the biotite ages from the Minnesota River Valley are in a gross manner related to uplift and erosion of large blocks of the basement. The K-Ar and Rb-Sr systems were stabilized in biotite in the Morton Gneiss, the Sacred Heart granite, and in the granite near Fort Ridgely approximately 2500 m.y. ago, but final stabilization in the gneisses in the Granite Falls-Montevideo area and in the granites of the Odessa-Ortonville area was not achieved until approximately 1800 m.y. ago.

The interpretation that the mica ages are fundamentally uncovering or cooling ages is attractive, because there is little evidence for a widespread 1850-m.y. thermal event. There are some aspects of the mica ages, however, that are not easily reconciled with the simple interpretation of cooling ages related to epeirogeny. The Rb-Sr age on biotite from the granite of Section 28 is 1725 m.y. or roughly 100 m.y. less than the age of the granite, but the K-Ar biotite age is 1690 m.y., nearly 150 m.y. younger. Similarly in the Sacred Heart granite the Rb-Sr biotite ages are approximately 100 m.y. less than the age of the granite, and the K-Ar ages are approximately 200 m.y. less.

GEOCHEMISTRY

General Statement

The Morton Gneiss is a hybrid rock. The contorted dark-gray and red layers make it unusually attractive, and it has been widely used as architectural and monumental stone. Lund(1956, p. 1482) suggested that the gneiss and its complex structure probably were formed through a combination of processes. He described the rock as a hybrid "formed by the strewing out of basic inclusions in a granitic magma." Gneisses of this type commonly have been called "migmatite," a fine-sounding term that unfortunately gives the impression that the rock once so classified presents no problems.

Lund's suggestion that the gray phase of the Morton Gneiss represents a product formed by the reaction between mafic inclusions and granitic magma was considered in sampling. Large samples (20 to 65 kg) of the tonalitic gray phase and the red granitic phase were collected. This material was crushed and ground so that zircon could be concentrated. At an appropriate stage in the procedure, representative cuts of the samples were taken for chemical analysis. The analyses are given in Table 1, and the locations of the samples are in the Appendix.

Chemical Analyses

Morton Gneiss

Sampling of a rock as complicated as the Morton Gneiss is a difficult, if not impossible, task. This was recognized in the early work (Goldich, 1938, p. 37):

> Certain discrepancies or irregularities, both in chemical and in mineralogical data obtained in the study of the fresh granite gneiss and of its residual weathering products, are undoubtedly the result of differences in parent-material.

The new average chemical composition (table 2, No. 2) calculated for the Morton Gneiss by Goldich and others (1970) on the whole compares favorably with the original bulk analyses (table 1, No. 76), but there are significant differences in the values for Na_2O and K_2O and in the Na/K ratios. The composite sample 338 from Morton more nearly resembles the calculated average which is based on samples 76, 338, 339 (table 1) and on a computed average of samples 389.D and 390.L (table 2).

The chemical analyses of the gray- and red-colored phases of the Morton Gneiss revealed some unusual features which, in part, were recognized by Lund (1956) from his modal analyses, yet could not be fully appreciated without the chemical data. These are as follows:

1. The gray phase could not have been formed by reaction between a mafic rock of gabbroic composition and a granitic liquid.

2. The coarse-grained gray phase is a tonalite with the potassium largely in the biotite. It is a trondhjemite of magmatic origin, locally heavily contaminated by reaction with mafic inclusions.

Table 1 -- Chemical analyses, in weight percent, of rocks from the Minnesota River Valley

	Sacred Heart Granite		Granite Section 28	Granite Ortonville Area	
	KA-24	388	387	55	109
SiO_2	76.6	71.8	68.3	74.13	72.59
Al_2O_3	12.6	13.6	15.2	13.72	15.10
TiO_2	0.08	0.18	0.46	0.14	0.15
Fe_2O_3	0.67	1.84	0.98	0.48	0.71
FeO	0.47	1.51	2.76	0.94	0.56
MnO	0.01	0.02	0.05	0.03	0.01
MgO	0.15	0.31	1.25	0.31	0.43
CaO	0.64	1.55	2.80	1.03	2.06
SrO	0.011	0.076	0.052	0.015	0.043
Na_2O	3.00	3.51	3.86	3.23	4.58
K_2O	5.42	4.35	3.05	5.28	3.20
BaO	0.05	0.24	0.18	n.d.	n.d.
Rb_2O	0.019	0.012	0.008	0.027	0.009
P_2O_5	0.00	0.10	0.12	0.06	0.06
H_2O +	0.38	0.39	0.63	0.26	0.12
H_2O -	0.03	0.02	0.06	0.00	0.03
Total	100.1	99.5	99.8	99.65	99.65

Analysts: 76, S.S. Goldich (1938); 338-387, C.O. Ingamels, N.H. Suhr, and S.S. Goldich (SiO_2; and H_2O); 55 and 109, Eileen H. Oslund (Goldich and others, 1961, p. 129)

Table 1 -- Chemical analyses, in weight percent, of rocks from the Minnesota River Valley

	Morton Gneiss					Montevideo Gneiss		
	76	338	339	389.D	390.L	KA-209	384	385
SiO_2	71.54	70.8	72.0	69.1	71.2	73.6	71.6	74.1
Al_2O_3	14.62	14.2	15.4	15.6	14.5	14.1	14.1	14.5
TiO_2	0.26	0.25	0.21	0.39	0.03	0.21	0.26	0.04
Fe_2O_3	0.69	0.74	0.38	0.90	0.82	0.82	0.85	0.38
FeO	1.64	2.03	1.44	3.42	1.07	1.63	1.65	0.30
MnO	0.04	0.04	0.02	0.04	0.01	0.03	0.03	0.00
MgO	0.77	0.74	0.64	0.86	0.10	0.43	0.50	0.09
CaO	2.08	2.32	2.22	3.14	0.42	1.82	1.73	1.18
SrO	0.034	0.034	0.070	0.044	0.048	0.024	0.030	0.045
Na_2O	3.84	4.07	5.80	5.17	1.70	4.38	4.60	3.86
K_2O	3.92	3.40	1.71	1.38	9.78	2.50	3.27	5.03
BaO	0.09	0.08	0.06	0.03	0.41	0.06	0.09	0.26
Rb_2O	0.014	0.012	0.004	0.008	0.024	0.009	0.015	0.009
P_2O_5	0.10	0.08	0.01	0.09	n.d.	0.07	0.08	0.00
H_2O +	0.30	0.26	0.32	0.27	0.13	0.33	0.28	0.11
H_2O -	0.02	0.05	0.05	0.04	0.03	0.08	0.05	0.04
Total	100.12*	99.1	100.3	100.5	100.3	100.1	99.1	99.9

*Includes 0.14 CO_2 and 0.02S

Table 2 -- Calculated composite and average chemical compositions, in weight percent.

	1	2	3
SiO_2	69.5	71.0	73.9
Al_2O_3	15.4	14.9	14.3
TiO_2	0.32	0.26	0.13
Fe_2O_3	0.88	0.67	0.60
FeO	2.95	2.02	0.97
MnO	0.03	0.03	0.02
MgO	0.71	0.72	0.22
CaO	2.60	2.30	1.50
SrO	0.045	0.045	0.035
Na_2O	4.48	4.45	4.12
K_2O	3.06	3.02	3.77
BaO	0.11	0.09	0.16
Rb_2O	0.011	0.010	0.009
P_2O_5	0.07	0.07	0.04
H_2O +	0.23	0.28	0.22
Total	100.3	99.9	100.0

1. Morton Gneiss, composite of 389.D and 390.L

2. Morton Gneiss, average of 389-390.C, 76, 338, and 339

3. Montevideo gneiss, average of KA-209 and 385

3. The leucocratic, red-colored phase is coarse-grained and locally pegmatitic in texture. Its composition is highly potassic (K_2O, 9.78 percent) and is that of a potash pegmatite. Similar chemical analyses of pegmatite are tabulated by Johannsen (1932, p. 75, table 4).

4. Both the gray tonalitic phase and the red pegmatitic phase are magmatic; they do not represent interlayered sedimentary materials.

Chemically the gray tonalitic phase resembles the trondhjemitic Northern Light Gneiss of the Saganaga Lake-Northern Light Lake area on the Minnesota-Ontario boundary (Goldich and others, 1972). Preliminary results for the gray tonalitic phase of the Morton Gneiss show a rare-earth pattern similar to that of the Northern Light Gneiss and the closely associated Saganaga Tonalite (J. G. Arth, letter, March 3, 1972). The trondhjemitic Northern Light Gneiss is relatively depleted in the rare earths and has a positive europium anomaly. The rare-earth pattern together with trace-element and bulk chemical composition suggests a derivation of trondhjemitic magma by partial melting of eclogite or garnet-rich amphibolite of basaltic composition at mantle depth (Hanson and Goldich, 1972; Hanson and Arth, 1972). A similar origin is suggested for the tonalitic gray phase of the Morton Gneiss.

Montevideo Gneiss

The informal name Montevideo gneiss as used here represents the granitic phase designated by Himmelberg (1968) as granitic gneiss. The gray tonalitic and red pegmatitic phases of the Morton rock are lacking. The Montevideo gneiss is pink to red in color; medium grained, but locally also coarse to pegmatitic in texture; and leucoadamellite to leucogranite in composition. As mentioned earlier the radiometric dating led to the recognition of a difference in age of two prominent textural phases; hence the Montevideo gneiss also appears to be a hybrid rock. Of the three analyzed samples (table 1) KA-209 and 385 represent the gneissic phase, and sample 384 is a mixture of the biotitic gneissic and of the massive quartz-feldspar phases.

The average composition of the gneissic phase (KA-209 and 385) is given in Table 2. The leucocratic composition of the Montevideo gneiss is well shown in the chemical analyses. The average composition differs from the average for the Morton Gneiss in relatively lower contents of Fe, MgO, and CaO. These are offset by the relatively higher content of SiO_2 in the Montevideo gneiss compared with the Morton Gneiss average. The Montevideo gneiss also has the composition of an igneous rock. It may possibly represent rhyolitic extrusive rocks (Goldich and others, 1970, p. 3693), but it is most improbable that it was originally an arkosic sediment.

Sacred Heart Granite

Two analyses of Sacred Heart granite (table 1) show considerable differences. Sample KA-24 is from the Larsen quarry which was opened on an isolated knob approximately 15 miles southwest of the main outcrop of the granite south of Sacred Heart. The correlation is based on lithology (Goldich and others, 1961, p. 130), and if the rocks are genetically related, the granite of sample 388 may possibly represent a slightly contaminated magma. Inclusions of amphibolite are abundant in the granite of the type locality.

An average of the Sacred Heart granite analyses would approach the average composition of the Montevideo gneiss; however, it appears unlikely that the granite was derived by melting of the gneiss. An initial Sr^{87}/Sr^{86} ratio of about 0.710 (see fig. 14) would be expected, but the determined ratio for the granite is approximately 0.702 (Goldich and others, 1970, p. 3687).

Granite of Section 28

The granite of section 28 is considerably contaminated with small to large inclusions of the hornblende-andesite dike which it intruded; hence the chemical analysis (No. 387, table 1) is difficult to interpret. The contents of Fe, MgO and CaO are considerably greater than that of the Sacred Heart granite or the analyzed granites of the Ortonville area. The Rb-Sr isochron (Goldich and others, 1970, p. 3689) was constructed for two whole-rock samples and respective K-feldspar concentrates. The Rb/Sr ratios for the two whole-rock samples are similar, and the difference could be explained by the degree of contamination of the granite. As explained in the section on the radiometric dating, it appears likely that there is little difference in age of the hornblende-andesite dike and that of the granitic pluton, and the isochron age of 1830 m.y. agrees with the U-Pb zircon age.

IMPLICATIONS OF ISOTOPIC AND CHEMICAL DATA

Three events are shown in the grouping of the radiometric ages in Figure 10. The younger events were resolved by the K-Ar and Rb-Sr ages of the earlier work. The whole-rock Rb-Sr determinations, but especially the U-Pb zircon data, permit dating of these events at 1850 $\pm$ 50 and 2650 $\pm$ 50 m.y. The older event, or, more likely, events, have been obscured by the younger ones, and the record between 3600 and 2650 m.y. ago is fragmentary. It may be summarized briefly as follows:

(1) The dark-gray tonalitic phase of the Morton Gneiss dates back to 3550 m.y. ago. It was followed by intrusion of the red pegmatitic phase. The two phases are intimately mixed, and the texture and structure of the Morton Gneiss is best explained in terms of magmatic intrusion as first suggested by Lund (1956). The Morton Gneiss, then, is a synkinematic intrusion of trondhjemite and potash pegmatitic granite closely related in time 3550 m.y. ago. Goldich and others (1970, p. 3693) suggested the name Mortonian for this event.

(2) The possibility of the granitic phase having been generated during the 2650-m.y. event has been considered and dismissed on the following grounds:

(A) None of the zircon from the red granitic phase has a Pb^{207}/Pb^{206} age of 2650 m.y. or less; the lowest value is 2870 m.y. for sample 337.L.

(B) Zircon from both dark- and light-colored phases form a linear pattern (figs. 11 and 12). The point representing zircon from 390.L is bracketed (fig. 11) by points for 390.D and 339, both dark-colored tonalitic samples which fit the 3550-m.y. Rb-Sr isochron (fig. 14), whereas sample 390.L gives a much younger Rb-Sr age which is explained as a result of loss of radiogenic Sr^{87} during and following the 2650-m.y. event.

(3) The Montevideo granitic gneiss also dates back to 3550 m.y. ago, but the recent work shows that there is a considerable component that crosscuts the structure but is definitely older than the 1850-m.y. granite of Section 28. If one accepts Himmelberg's (1968) conclusion that all the structure in the Granite Falls area was developed during the 2650-m.y. metamorphism, the massive quartz-feldspar, sill-like intrusions are 2650 m.y. or slightly younger. If the structure is much older as has been suggested for the Morton Gneiss, the quartz-feldspar rock may also be considerably older than 2650 m.y. Precise dating is needed.

(4) By analogy with the Montevideo gneiss it also is possible that some of the granitic rock in the Morton Gneiss was introduced around 2650 m.y. ago, and we are dealing with three or four mixed rocks of different ages.

(5) It is not unusual in view of the age of the ancient gneisses that they should be referred to as protocrust, but this probably is erroneous. The data at hand, although fragmentary, suggest, rather, that the rocks were evolved through processes similar to those recognized in many other Precambrian terranes. Throughout the river valley there are numerous inclusions in the gneisses. Lund (1956) suggested that the mafic inclusions represented the basement. Some of the mafic inclusions may actually be dikes that were fragmented and deformed, but some may represent oceanic crust older than 3550 m.y.

(6) On the assumption that the rocks in the Minnesota River Valley are a layered sequence all deformed in one major orogeny 2650 m.y. ago, the nature of the pile can be conjectured to have consisted of basaltic lavas and sedimentary rocks, probably with dikes and some sill-like masses of diabase and gabbro. To my mind this is a highly oversimplified hypothesis. Remnants of metasedimentary rocks are known in various localities in the valley. In the upper reaches there are inclusions of metasedimentary rocks in the granites, but none has been definitely recognized in the inclusions or clasts in the ancient gneisses. These metasedimentary rocks could have been deposited at some time during the interval from 3550 to 2650 m.y. ago and predate the major deformation which has affected them as well as the gneisses.

In conclusion, an obvious statement is that much work remains to be done. The work accomplished to date, however, affords a useful base, and some of the objectives are now more clearly defined. The one thing that is clear is that we must face up to complexity of the geologic history. The lesson we have learned is summed up in a statement by Carl Hedge (Goldich and others, 1970, p. 3672):

> The various radiometric techniques, as they were developed, have been applied, and each additional type of information has forced more complex interpretations of the geologic history.

WEATHERING

During the Cretaceous, probably Late Cretaceous, a thick regolith was developed in southwestern Minnesota under a humid tropical or subtropical climate. In the vicinity of Morton the weathered profile attained 100 feet or more in depth, and locally the residual materials were reworked into layers of sand and kaolinitic clay. These deposits have been described in some detail by Parham (1970) who distinguished three units:

Unit 1 is a residuum in which kaolinite is the principal clay mineral. Some tubular halloysite was identified and occurs in minor amounts, particularly in the lower part of the profile.

Unit 2 is an Upper Cretaceous deposit of kaolinite and quartz derived from the residual clay. Halloysite was found in trace amounts. The top of the unit is an indurated three- to five-foot layer of pisolitic clay, generally iron-rich, and containing small amounts of gibbsite and boehmite.

Unit 3 disconformably overlies unit 2 and consists of gray to black, organic-rich clays, thin layers of lignite and a thin bed of bentonite. Kaolinite is abundant in the lower part of unit 3, but gives way to montmorillonite and illite which become progressively more abundant from bottom to top. Parham concluded that the change in clay minerals probably was the result of a change from a humid tropical climate to a more temperate climate.

The residual clay is well displayed in the bluffs of Redwood River, a tributary of the Minnesota River. The parent rock is far from homogeneous as has been noted in the discussion of the problem of arriving at an original composition, and as a result the weathered profile is not uniformly developed. There are considerable lateral as well as vertical variations in the degree of decomposition. In places, pegmatitic zones have been more durable than the finer grained phases and now protrude as ridges in the banks of weathered material. In most outcrops some evidence of the nature of the original rock can be found in texture, structure, color banding, or in the shattered and broken remnants of quartz veins.

Since their publication some 34 years ago (Goldich , 1938), the chemical and mineralogical data for the residual clay derived by weathering of the Morton Gneiss have been quoted and presented in many different forms. Some ingenious calculations and diagrams have been used, but probably none depicts the data more simply and honestly than the original diagram reproduced in Figure 15.

The order of rates of loss of the major constituents of the Morton Gneiss is Na>Ca>Mg>K>Si>Al. Relative to aluminum, iron, on the average, shows a gain and of course, a very large amount of water and small amounts of carbon dioxide have been added. The latter requires some explanation. Calcite was found only in the fresh gneiss and is a good criterion for the freshness of the rock as calcite is easily removed by leaching in early stages of weathering. The carbon dioxide in the residual clay is in the mineral siderite. Iron, especially in the presence of organic matter, is readily reduced and becomes mobile in the weathering profile. The iron is carried down and is precipitated as siderite. Thus iron may be lost from the upper part of a weathering profile and gained in the lower part.

In lateritic profiles aluminum also may become mobile and form concretions and sheets of gibbsite along fractures or joints in the laterite. The assumption that aluminum has remained constant, therefore, is open to question. Both aluminum and iron, however, probably are essentially constant if the entire profile is considered, and future studies might well be directed to testing this proposition.

Chemical data reveal some interesting details concerning the behavior of biotite and zircon under weathering conditions. K-Ar determinations on four samples of altered biotite separated from the residual clay derived from the Morton Gneiss gave surprisingly similar ages of 1940, 1860, 1830, and 1840 m.y. (Goldich and Gast, 1966, p. 373). The average of these is 1870 m.y., by coincidence the approximate age of the granite of section 28. The Rb-Sr ages, however, for the first three samples are 610, 490, and 570 m.y., respectively, averaging 550 m.y. More significant is the fact that the loss of Ar^{40} is substantially greater than the loss of K, reducing the age. The rate of oxidation or loss of ferrous iron exceeds that for the removal of potassium from the biotite, and the loss of total iron was somewhat less than for potassium.

The drastic reduction in the Rb-Sr ages results from the loss of radiogenic Sr^{87}. The rate of loss of rubidium is considerably less than for potassium. The K/Rb ratios for three samples of partially altered biotite range from 44 to 64, compared to a range from 92 to 121 for three samples of biotite from fresh Morton Gneiss.

The zircon in the residual clay was described (Goldich, 1938, p. 37) as follows:

> Even the zircon, however, shows signs of attack in its dusty, granular appearance. The altered mineral is brown, has a lower birefringence than fresh zircon, and tends to become opaque.

This is reasonably good for a description of metamict zircon, but not for origin which was not widely appreciated in the early 1930's. The U-Pb analyses of three samples of zircon concentrated from the residual clay show appreciable leaching of lead by ground water; the loss of uranium-derived lead ranges from 45 to 85 percent (Stern and others, 1966, p. 371).

In conclusion I quote Cliff Ollier (1969, p. 286):

> The study of weathering is still in the stage where new techniques can play a large part in research, and there is a stimulating need for ingenuity and novelty in weathering investigations.

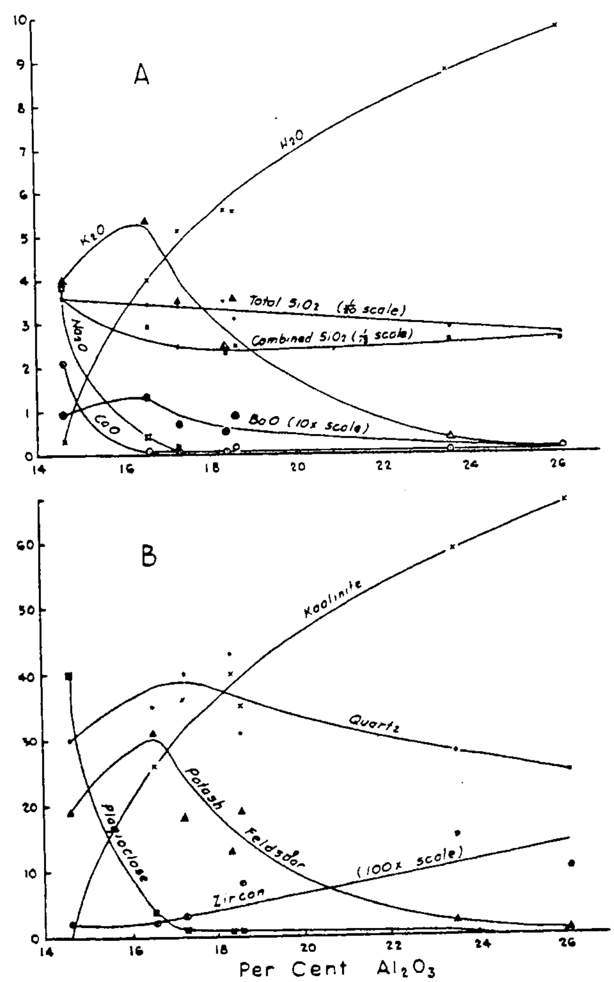

Figure 15. Variation diagrams of the series of fresh and decomposed granite gneiss samples from the Morton-Redwood Falls area.

APPENDIX A - LOCATION OF CHEMICALLY ANALYZED SAMPLES

Morton Gneiss

76 Composite from main quarry, collected in 1934 (Goldich, 1938).

338 Composite from dump of old quarry just east of main operating quarry, Morton (6/22/62).

339 Blasted road cut along road from Delhi to Renville, 0.5 mile southeast of bridge on Minnesota River, SE1/4 sec. 30, T. 65 N., R. 36 W. (6/23/62).

389.D Dark-colored phase, small quarries northwest of Morton and just north of school (6/22/62).

390.L Light-colored (red) phase, locality of 389.D (6/22/62).

Montevideo Gneiss

KA-209 Outcrop in bank of Minnesota River, approximately 2 miles southeast of Granite Falls (5/17/58; see Minn. Geol. Survey Bull. 41).

384 Cut along U. S. Highway 212, 1.6 miles southeast of Montevideo (6/23/62).

385 Cut along Great Northern Railroad track, north of Granite Falls, NW1/4 sec. 28, T. 116 N., R. 39 W. (6/23/62).

Sacred Heart Granite

KA-24 Larsen quarry, 8 miles west and 3 miles south of Echo (5/28/56; see Minn. Geol. Survey Bull. 41).

338 Quarry south of Sacred Heart, SW1/4 sec. 7, T. 114 N., R. 37 W. (6/23/62).

Granite of Section 28

387 Outcrops north of road, NW1/4 sec. 28, T. 116 N., R. 39 W. (6/23/62).

Granites in Odessa-Ortonville Area

55 Quarry, west of U. S. Highway 75, approximately 4.5 miles southeast of Odessa in SW1/4 sec. 16, T. 120 N., R. 45 W. (8/11/56; see Minn. Geol. Survey Bull. 41).

109 Quarry, southeast of Ortonville, Cold Spring Granite Co. (Minn. Geol. Survey Bull. 41, p. 129).

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ROAD LOG

James A. Grant, Glen R. Himmelberg[1] and Samuel S. Goldich

First Day

Mileage		
0.0	0.0	Tri-Court Motel, Morton (Junction Minn. Hwy. 19 and U. S. 71). Go east on Minn. Hwy. 19.
0.2	0.2	Turn left, go past the school.
0.1	0.3	STOP 1. Turn left, park at rear of school. Return to Hwy. 19.

Morton Gneiss; Morton. The vicinity of Morton is the type locality for the Morton Gneiss. The particular variant seen here is that of unit B (see Part 1) - a migmatitic quartzofeldspathic gneiss with amphibolite rafts. Three major lithologies are involved in the migmatite: schlieric rafts of black pyroxene or biotite amphibolite, or of gray quartz-plagioclase gneiss, often with the former as a core to the latter, lie in a matrix of pink (and gray) granitic gneiss. One has the impression of differential competency in a flowing medium, with amphibolite being more competent than gray quartz-plagioclase gneiss, which was more competent than the granitic component. The outcrops lie on the crest of the Morton anticlinorium (F_1), and the overall dip of the compositional layering is 20° E. However, this is warped on steep northerly trending planes, with apparent movement east side down (F_2). From Rb-Sr analyses, the compositional banding is at least 2.65 ± 0.15 b.y. old; U-Pb analyses of zircon from the gray and pink gneisses are interpreted as yielding minimum ages of about 3.2 ± 0.1 b.y. (see Part 2, figs. 11, 12 and 14). Chemical analyses of the gray and pink phases are given in Part 2, Table 1.

0.1	0.4	Hwy. 19, turn left.
0.2	0.6	Four-way stop, turn right.
0.2	0.8	Railroad - cross and turn left.
0.4	1.2	STOP 2. Cold Spring Quarry, Morton. Main quarry of the Cold Spring Granite Company.

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This is the only operating quarry in the Morton Gneiss; the interesting quarrying methods were developed largely by the Cold Spring Granite Company. The geology is similar to that at the previous stop, seen here in spectacular three dimension.

Turn around and leave quarry; return to four-way stop on Hwy. 19.

0.6	1.8	Four-way stop, turn left onto Minn. Hwy. 19.
0.6	2.4	Junction Minn. 19 and U. S. 71. Go south on U. S. 71.
0.2	2.6	Minnesota River.
0.2	2.8	Cretaceous clay on south side of road.
3.0	5.8	Turn right onto Redwood Co. 101.
1.6	7.4	STOP 3. Keep left and park.

Weathered Morton Gneiss, North Redwood. Goldich's (1938, p. 21) localities 3 and 5 are in this vicinity. Sample 3 is near the base of the hill on the west side of the road and south of the railroad in North Redwood. Sample 5 is near the crest of the hill on the east side of the road. Sample 5 has been called aberrant; actually it is a perfectly valid sample, but the original material apparently contained a large amount of pegmatite, and illustrates the variability in the parent material.

Structures similar to those seen at Morton can still be detected in the deeply weathered gneiss, which is less homogeneous than the dominant foliated quartz monzonite of the vicinity.

Turn right to Hwy. 101 again.

0.1	7.5	Railroad; cross into North Redwood and keep left on Hwy. 101.
0.9	8.4	Minnesota River.
0.7	9.1	Pink and gray quartzofeldspathic gneisses.
0.3	9.4	Turn left onto gravel road, Renville Co. 15.
4.3	13.7	STOP 4. Schmidt farm. Lithologies and structures in the migmatitic terrane, four miles northwest of North Redwood; SE 1/4 sec. 2 and NE1/4 sec. 11, T. 113 N.,

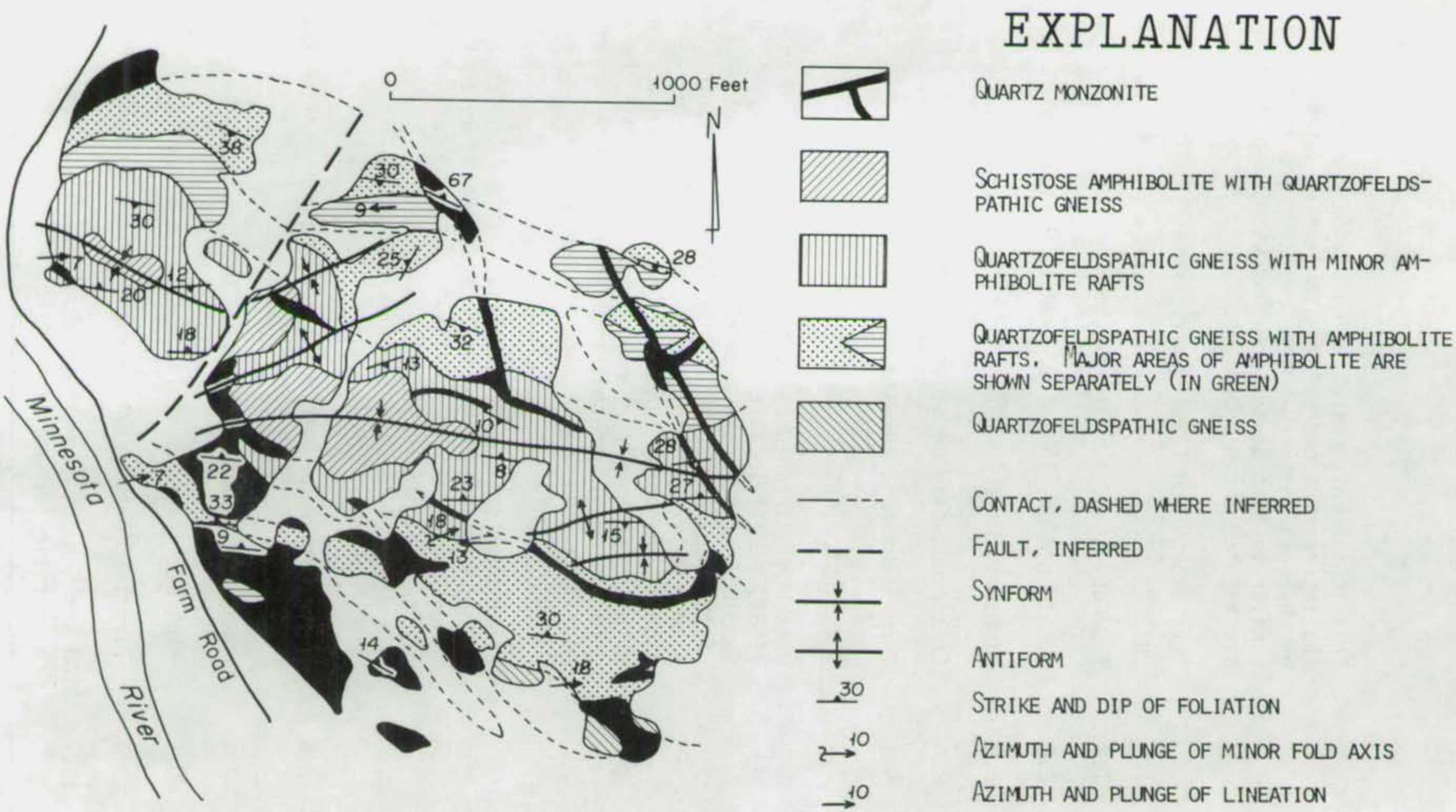

Figure 1. Generalized geological map of the vicinity of stop 4 (Secs. 2 and 11, T. 113 N., R. 36 W.).

R. 36 W.

These outcrops (fig. 1) are typical of unit A, interlayered quartzo-feldspathic gneiss and amphibolite, but most of the lithologies common in units A, B and C can be seen here, as well as quartz monzonite. Moreover, it is possible to demonstrate the possibility and problems of mapping stratiform lithologic units in this migmatitic terrane.

These outcrops lie in the core of the Delhi anticlinorium -- despite the fact that the major structure here is synclinal, for anticlines flank the exposures to both north and south. The rocks here are displaced from the adjacent country rock by the emplacement of subconcordant gneissic quartz monzonite, which surrounds the exposed migmatittes, and is interpreted to underlie them. The units mapped in the migmatites are:

1. pink to gray quartzofeldspathic gneiss (SE only).

2. Gray quartzofeldspathic gneiss with rafts of amphibolite. Agmatic amphibolite forms a reasonably continuous layer on the north side of the syncline, whereas only some rafts are found on the south side, where the "amphibolite" is more leucocratic and biotitic.

3. Gray quartzofeldspathic gneiss, with rare amphibolite rafts.

4. Schistose amphibolite, commonly agmatic, with quartzofeldspathic gneiss.

The correlation of these units is best on the north side of the syncline, and local subdivision is possible, as in unit 2 in the northwest corner, but such subdivisions cannot be carried for any great distance.

Subconcordant to discordant quartz monzonite is well exposed on the south side, and dikes and sills are abundant in the eastern two-thirds of this hill. The major mass is subconcordant, and apparently was emplaced late in the F_1 deformation, but prior to the end of F_2 deformation, since minor faults correlated with this cut the quartz monzonite.

1.8	15.5	Intersection with Renville Co. 21, continue on Renville Co. 15.
0.1	15.6	Keep left on Renville Co. 15.

0.5	16.1	Foliated quartz monzonite dike in creek bed.
0.8	16.9	STOP 5. Breitkreutz farm. Structure and mineralogy of unit D; sec. 28, 29, 32, 33, T. 114 N., R. 36 W.

Unit D, composed of metasedimentary gneisses and amphibolite, is uppermost in the Sacred Heart-Morton area, and the most informative in terms of metamorphism. The outcrops in this pasture (fig. 2) are complex in structure and in lithologic variations over short distances. They lie on the south side of an easterly plunging synclinorium, with individual folds on the order of a few hundred feet in wavelength. Abrupt changes in attitude and disharmonic deformation are common, but the major folding is correlated with F_1 deformation, and lineations (L_1) are warped on minor folds of F_2.

Amphibolite rafts, up to 1,000 feet in strike-length, form about half of the exposures, and behaved as rigid masses relative to the more easily deformed gneisses surrounding them. The amphibolite is typically a medium-grained lineated cummingtonite-bearing amphibolite, with or without garnet, and without pyroxene. At the base of the unit, the surrounding gneisses are dominantly rodded quartz-cummingtonite gneiss. Above this the gneiss is typically a thinly layered biotite-cordierite-garnet-anthophyllite gneiss (Grant and Weiblen, 1971) and uppermost is a heterogeneous biotite-quartz-plagioclase gneiss with or without microcline, muscovite, garnet, cordierite, and sillimanite, with textures interpreted as due to retrogression across the second sillimanite isograd.

Continue northwest on Renville Co. 15.

1.5	18.4	Gray quartzofeldspathic gneiss to left - north limb of Delhi synclinorium.
0.9	19.3	Intersection Renville Co. 15 and Renville Co. 6. Turn left on Renville Co. 6.
0.7	20.0	Minnesota River; road becomes Redwood Co. 6.
0.5	20.5	Pink and gray quartzofeldspathic gneiss.
7.4	27.9	Intersection of Redwood Co. 6 with Minn. 19 and 67. End of first part of field trip, and start of second part. (To return to Redwood Falls and Morton turn left (east) on Minn. 19.
5.0	32.9	Redwood Falls, junction with U. S. 71.

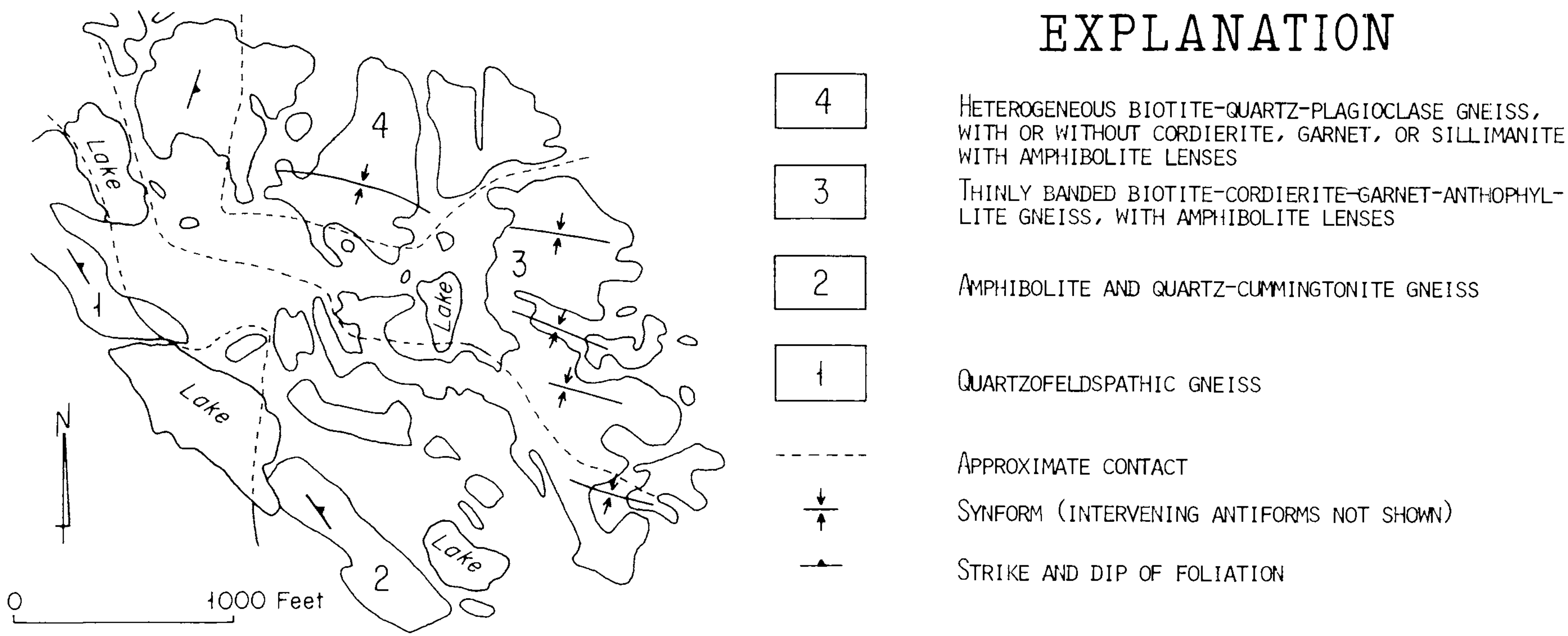

Figure 2. Generalized geological map of the vicinity of stop 5 (Secs. 28, 29, 32, and 33, T. 114 N., R. 36 W.).

5.8 38.7 Tri-Court Motel, Morton.

Second Day

0.0 38.7 Intersection Redwood Co. 6 and Minn. 19 - continue west on Minn. 19.

5.6 44.3 Minn. 273; turn right.

4.5 48.8 Belview.

4.7 53.5 Sacred Heart quartz monzonite.

0.9 54.4 Note compositional banding in cut on west side of road.

1.6 56.0 STOP 6. Turn left on gravel road and park. Margin of the Sacred Heart pluton; SW1/4 sec. 8, T. 114 N., R. 37 W.

The Sacred Heart pluton is composed dominantly of pink, medium-grained quartz monzonite, massive to faintly banded, alternate bands being slightly different in texture and mineralogy, but still quartz monzonite. This banding is folded in accordance with F_2 deformation.

At the T-junction (fig. 3) quartz monzonite similar to that in the main exposed part of the pluton crops out, but passes abruptly northward into a salmon-pink pyroxene granite with diffuse green-black amphibole-rich xenoliths, some of which show zoning suggesting instability of quartz-biotite-clinopyroxene, in favor of hornblende-potassium feldspar. Pink potassium feldspar and gray plagioclase pegmatite is associated with this, but the major pegmatitic development is at the crest of the rise, where coarse amphibolitic blocks lie in a pegmatitic matrix. This zone can be traced for two miles along strike, and is similar to another on the south side of the valley here. In looking for a source for the amphibolite, correlation of these two zones with the two amphibolite layers of unit A is suggested, implying dilation of unit A to accommodate the Sacred Heart pluton. If so, what has happened to the quartzofeldspathic gneiss of unit A, as seen at STOP 4?

This zone is in contact (not exposed here) with a subconcordant dike of quartz monzonite, similar in lithology and structures to the main pluton, which appar-

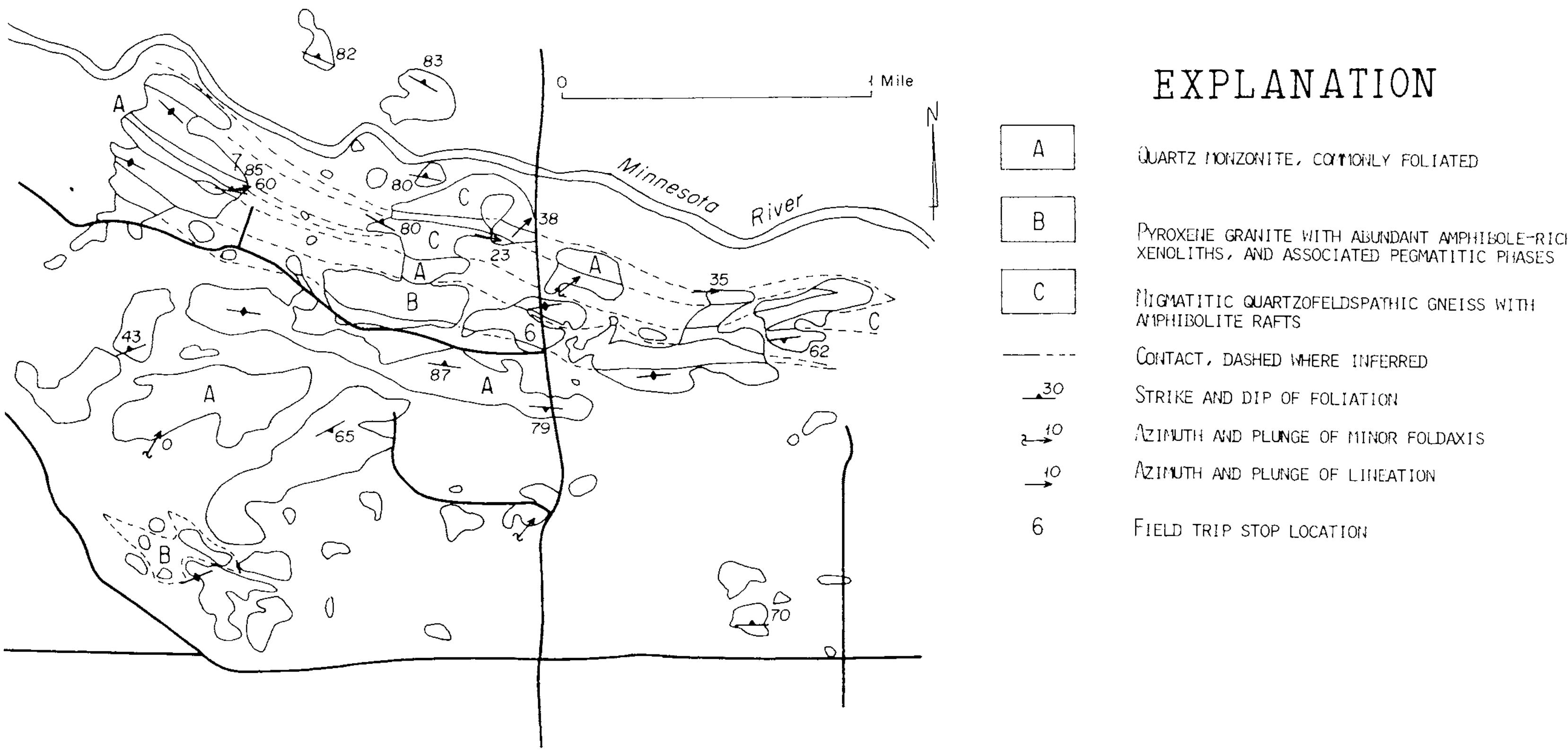

Figure 3. Geological map of the Sacred Heart area, stops 6 and 7 (T. 114 N., R. 37 and 38 W.).

ently cuts out the pegmatitic zone to the east. At the northern end of the roadcut, one finds the northern contact with the migmatitic country rock, which will be better seen at STOP 7.

Continue west on gravel road.

1.1 57.1 Turn right on farm road.

0.2 57.3 STOP 7. Wurscher farm. Migmatitite and quartz monzonite dikes on the north side of the Sacred Heart pluton; Leo's Wurscher's farm. SW1/4 sec. 7, T. 114 N., R. 37 W.

This continues the traverse started at the previous stop: the continuation of the quartz monzonite dike seen there is found southwest of the barn (see fig. 3).

A variety of migmatitic structures are well displayed here: raft, vein, dilatation, folded, augen and schlieric structures involving gray quartz-plagioclase gneiss and amphibolite, and permeation by quartz monzonite. To the north, a dike of quartz monzonite forms the crest of the ridge, and on the rather indefinite north side of this is an excellent example of "layer-cake" vein structure, with F_2 deformation. This is similar, including sporadic garnet, to some of the Montevideo granitic gneiss to be seen at STOPS 9 and 10.

Turn around and leave farm.

0.2 57.5 Turn right on gravel road.

1.2 58.7 Intersection with gravel road, turn right.

3.0 61.7 Intersection with Minn. 67, turn right onto Minn. 67.

12.0 73.7 Yellow Medicine River.

8.0 81.7 STOP 8. Hornblende-pyroxene gneiss and garnet-biotite gneiss; Municipal Park, Granite Falls.

These exposures of granulite facies rocks lie on the southern limb of the Granite Falls antiform. Within the park, the hornblende pyroxene gneiss has the assemblage quartz-plagioclase-hornblende-clinopyroxene-orthopyroxene-garnet whereas at the north end of the road cut, biotite appears rather than garnet. At this last locality mafic dikes cut the gneisses.

To the south, there is a concordant contact with garnet-biotite gneiss (essentially marked by the first appearance of garnet) and this gneiss has the assemblage quartz-plagioclase-garnet-biotite-orthopyroxene.

Go north on Minn. 67 into Granite Falls, driving through hornblende-pyroxene gneiss.

0.7	82.4	Intersection with U. S. 212, turn left (west), onto U. S. 212 passing outcrops of Montevideo gneiss.
1.2	83.8	Intersection, Minn. 67 and Minn. 23; continue on U. S. 212.
9.1	92.9	Minnesota River.
1.6	94.5	STOP 9. Roadcuts on U. S. 212. Montevideo granite gneiss; Hwy. 212. SE1/4 sec. 20, T. 117 N., R. 40 W.

The outcrops southeast of Montevideo are the type locality for Lund's (1956) Montevideo granite gneiss. This locality is on the northern limb of the inferred synform between Montevideo and Granite Falls. The foliation is relatively straight and steeply-dipping although warping and boudinage are present.

The outcrops show the general nature of the Montevideo gneiss -- a leucocratic pink to red granitic gneiss with the assemblage quartz-microcline-plagioclase-biotite, with or without garnet. Biotite-rich bands alternate with quartzofeldspathic layers up to 50 feet in thickness.

In this area crosscutting relations may be found, between the typical banded gneiss and a more massive phase, as is seen in the western road cut. It is from this locality that Goldich and others (1970) obtained two different ages for the granitic rocks (see Part 2, fig. 14, samples 369 and 368; sample contained both rock types).

Also exposed here is a unit of hornblende-pyroxene gneiss (amphibolite) with the assemblage plagioclase-hornblende-clinopyroxene-orthopyroxene. The contact of this with the granitic gneiss is conformable and the occurrence is typical of numerous lenses and layers in the granitic gneiss throughout the Granite Falls-Montevideo area.

Turn around; go east on U. S. 212.

12.0	106.5	Intersection with Minn. 67 in Granite Falls. Turn left onto Granite Street.
0.3	106.8	Turn right onto 10th Avenue.
0.3	107.1	Turn left onto Prentice Street.
0.3	107.4	Turn left onto Oak Street.
0.1	107.5	Minnesota River.
0.2	107.7	Turn left across railroad.
1.0	108.7	Turn left onto gravel road.
1.4	110.1	STOP 10. Later intrusions: hornblende and site and adamellite. SE1/4 sec. 20, T. 116 N., R. 39 W.

In these exposures typical straight-banded Montevideo granitic gneiss (Part 2, sample 385, Fig. 11 and 14, and Table 1) with hornblende-pyroxene gneiss inclusions is cut by two dikes of hornblende andesite. One of these in turn is in contact with a small adamellite body ("granite of Section 28" -- see Part 2, p. 9).

In this contact zone, round to cauliflower-like masses of the dike-rock appear in the marginal phase of the adamellite. The inclusions commonly have biotite rims, obvious on the weathered surface. Such structures may be explained by penecontemporaneous intrusion (e.g. Windley, 1965) and indeed the radiometric data on the two units are compatible with this.

Return to paved road to return to Minneapolis.

1.4	111.5	Turn right on paved road.
1.0	112.5	Turn right across railroad, onto Oak Street.
0.2	112.7	Minnesota River.
0.1	112.8	Turn left onto Prentice Street.
0.3	113.1	Turn right onto 10th Avenue.
0.3	113.4	Turn left onto Granite Street.
0.3	113.7	Intersection with U. S. 212. Turn left to return to Minneapolis.