FIELD TRIP GUIDEBOOK FOR THE PRECAMBRIAN ROCKS OF THE MINNESOTA RIVER VALLEY

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

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INTRODUCTION

The gently rolling farmland of southwestern Minnesota is a deceptive blanket over a rich record of the evolution of the earth's crust. The effects of Pleistocene glaciation dominate the area, and the landscape is characterized by a wide variety of glacial deposits which cover most of the bedrock geology (Fig. 1). However, many outcrops are a product of glacial erosion and all the Precambrian outcrops in the Minnesota River Valley (MRV) were exposed by steambed erosion in the Glacial River Warren. This river drained Glacial Lake Agassiz prior to the disappearance of the ice sheet which prevented northward drainage to Hudson Bay.

As can be seen in Figure 2, the Precambrian rocks of Minnesota occupy a central position in the North American continent. This position is reflected in the present day drainage pattern of the continent. Despite the low topographic relief (600-2,000 ft), there are three major drainage divides in Minnesota (Fig. 1). The gentle relief and low elevation are also deceptive indicators of the crustal thickness of the North American continent in the region, which is on the order of 40 km (Halls, 1982).

Despite its thickness and antiquity, the crust in Minnesota has remained geologically active. This is attested to in part by the fact that the Mesozoic north-south hinge line of the sedimentary basins involved in the formation of the Rocky Mountains crossed Minnesota (Fig. 3). During the Paleozoic the region was involved in a number of oscillations of epicontinental seas (Fig. 3). The distribution of the thin veneer of Phanerozoic rocks (maximum thickness less than 600 m), which were produced in these two episodes of crustal evolution, is shown in Figure 3 and in the geologic map of Minnesota on the frontispiece of the guidebook. The geologic record is briefly outlined on the back cover. The thick, "stable" crust in the region is currently involved in the isostatic rebound associated with the disappearance of the Pleistocene ice sheets over North America. The locations of 12 recorded earthquakes in Minnesota are shown on Figure 3. The distribution of the earthquakes appears to be related to Precambrian tectonic features (Mooney and Morey, 1981), and may be related to reactivation of old fault systems in the course of isostatic rebound (Dutch, 1981).

The Precambrian rocks in Minnesota define five distinct geologic terranes. The geology of these terranes is briefly outlined on the last page of the guidebook, and further details may be found in Sims and Morey (1972) and in more recent papers listed in Morey and others (1981). The outcrops in the MRV are part of the oldest terrane (I). They contain a reord of a broad spectrum of igneous and metamorphic rocks which span a time interval from at least 3,500 to 1,800 m.y. (Figs. 4 and 5, Table 1). Terrane I extends into central Minnesota where it is separated from the greenstone-granite terrane (II) to the north by a complex tectonic zone (Sims, 1976; Southwick, 1980) (Fig. 3).

The structural record and the crosscutting relationships of the different rock units exposed in the MRV indicated a complex geologic history to early workers (Lund, 1956; Himmelberg and Phinney, 1967). The geochronological definition of the geologic history of the MRV, a major contribution to Precambrian geology, was made by S.S. Goldich as he moved from geochemical studies of rock weathering (Goldich, 1938) to pioneering work in the field of isotope geochemistry (Goldich and others, 1980a). The first hint of the extended record of early earth history came with the U-Pb data on zircons from MRV granitic gneisses by T. Stern of the U.S. Geological Survey in the early sixties (Goldich, 1972). This led to further work by Catanzaro (1963), which could be interpreted to reflect a 3,550-m.y. age for the gneisses and a thermal resetting at 1,800 m.y. Subsequent research has substantiated this interpretation and has led to the current recognition of four major episodes of crustal evolution in the MRV rocks: (1) Emplacement of the protoliths for the quartzofeldspathic gneisses and associated amphibolites prior to 3,550 m.y. (2) Development of a supracrustal sequence on the old protolith, metamorphism, and emplacement of granite in the old gneisses at 3,000 m.y. (3) Emplacement of a quartz monzonite batholith at 2,700 m.y. (4) Intrusion of granitic stocks and basaltic dikes at 1,800 m.y. The succession of rock types and the geographic distribution on which the geochronology is based are illustrated schematically in Figure 4 and compared with the greenstone-granite terrane in northern Minnesota in Figure 5. Bauer (1980) has identified four different periods of deformation in the Montevideo-Granite falls area. These are illustrated schematically in Figure 6 and the overall timing of the rock-forming events as now understood is summarized in Table 1.

The "old gneiss" terrane and the greenstone-granite terrane in northern Minnesota (terranes I and II, Fig. 3) are representative of two distinct geologic terranes found in the Precambrian shield areas of all the continents: high-metamorphic-grade gneisses and low-grade greenstone-granite belts, respectively (Windley, 1977). The high-grade gneiss terranes consist of metamorphic quartzofeldspathic gneisses derived from sedimentary, volcanic, and/or granitic rocks and complexly interlayered with amphibolites. In some areas, such as western Greenland, quartzites, iron-formation, and anorthositic rocks are additional components (Bridgwater and others, 1978). The characteristic features of the high-grade terranes are the complexity of the structural relationships of the constituent rock types and the high-grade metamorphism. Mineral-assemblage stabilities indicate that these rocks have been subjected to temperatures approaching 1,000°C and pressures of up to 10 kilobars (Windley, 1977, p. 15). The structural complexities record the deformation involved in the transformation of water-rich rocks formed in the surface and near-surface environment to water-poor rocks at depths of 10 to 30 km. The actual depth of equilibration of the high-grade gneisses is a matter of debate. First of all, it is clear that the heat budget of the earth requires higher geothermal gradients in the Archean, but the change in gradient with time is uncertain. Fyfe (1974) estimates a gradient as high as 100°C/km in the early radioactive crust. Secondly, the crust has thickened with time, but at an unknown rate (Fyfe, 1974; Fyfe and Leonardos, 1973; O'Hara, 1975).

The greenstone-granite terranes are deformed into isoclinally folded linear belts, but these successions of submarine to subaerial volcanic rocks, associated sedimentary sequences, and intrusive granites retain their stratigraphic integrity and were metamorphosed only to low-grade, water-rich metamorphic rocks. Because the greenstone-granite terranes contain the essential precursor lithologies of the high-metamorphic-grade gneiss terranes, a common view has been that the latter are merely deeper crustal equivalents of the former (Bowes and Hopgood, 1975). However, the growing body of geochemical and isotopic data indicates that the high-grade terranes are generally older (>2,700 m.y.) than, and lithologically and chemically distinct from, the greenstone-granite terranes (Lambert and others, 1976). This is clearly the case in North America (Fig. 2) where the boundary between the two terranes is a tectonic zone (Sims, 1976, 1980), in which a major addition of metasedimentary and igneous rocks was made to the crust during the early Proterozoic (Morey, 1978; Fig. 5).

Closure of a modern-day island arc system provides a possible analog for the type of general geologic environment which could have produced the Archean and lower Proterozoic geology of North America. In a model favored by Windley (1977, p. 63) the high-metamorphic-grade gneiss terrane could have formed in the main part of an island arc system, and the greenstone-granite terrane in a back-arc basin. A later separation and closing of the two terranes would be required to produce the lower Proterozoic additions to the crust (Burke and Dewey, 1973). It has been proposed that the early impact history of the earth may have localized the evolution of the Archean terranes (Weiblen and Schulz, 1978; Grieve, 1980). These interpretations remain matters of conjecture. Subsurface studies and drilling in the Great Lakes tectonic zone (Southwick, 1980) should significantly advance our understanding of the evolution of the North American continent.

GLOSSARY

To facilitate discussion of the geology on the outcrops, brief definitions of the principal rock types in the Minnesota River Valley are provided below. Rock types are listed in order of increasing presumed age. Minerals are listed in order of decreasing abundance. Detailed descriptions may be found in Grant (1972), Himmelberg (1968), and Goldich and others (1980a, b) and references therein.

Hornblende andesite—a fine-grained, massive, black dike rock containing plagioclase, hornblende, biotite, and minor iron-titanium oxides, apatite, quartz, and potassium feldspar.

Olivine tholeiite—a fine-grained, massive, black dike rock containing plagioclase, olivine, Ca-pyroxene, and minor iron-titanium oxides.

Adamellite—a medium-grained, granular, pink granite containing plagioclase (35%), K-feldspar (30%), quartz (25%), and biotite (10%).

Tholeiitic diabase—a fine- to medium-grained, black dike rock containing plagioclase, Ca-pyroxene, hornblende, iron-titanium oxide, and biotite.

Quartz monzonite—a medium-grained, pink, massive granite containing Na-plagioclase (40%), K-feldspar (30%), quartz (28%), and biotite (2%).

Aplite—a fine- to medium-grained, pink to red dike rock containing plagioclase, K-feldspar, quartz, and mica. Found as crosscutting dikes in quartzofeldspathic gneisses.

Garnet biotite gneiss—a coarse-grained gray, foliated gneiss containing plagioclase (43%), biotite (23%), quartz (21%), orthopyroxene (8%), garnet (5%), and minor K-feldspar.

Hornblende pyroxene gneiss—a coarse-grained, gray, foliated gneiss containing plagioclase (60%), orthopyroxene (21%), Ca-pyroxene (10%), biotite (7%), and hornblende (2%).

Quartzofeldspathic gneiss—a coarse-grained, gray to red, foliated gneiss containing plagioclase/K-feldspar, quartz, biotite, and hornblende. The foliation is defined by the modal layering of biotite, quartz, and feldspar. It is the principal rock type in the MRV. Different varieties are recognized along the exposures in the MRV, depending on crosscutting relations and classification schemes (Fig. 7; Grant, 1972; Goldich and others, 1980a, b).

Unraveling the complexity of the quartzofeldspathic gneisses has been the crux of the effort to recognize the oldest component in the MRV and in fact in all Archean terranes. Two principal varieties have been recognized by crosscutting relations and isotopic data (Goldich and others, 1980a, b): (1) an older, Na-rich variety (tonalite), and (2) a younger K-rich variety (granite, adamellite, granodiorite).

Amphibolite—fine- to medium-grained, black, foliated, mafic rock containing plagioclase, hornblende, biotite, and iron-titanium oxides. The major-element data indicate that the whole spectrum of compositional types of Archean mafic igneous rocks is represented in the amphibolites in the MRV (Goldich and others, 1980a, b). Field relations indicate that some amphibolites are probably mafic inclusions in the quartzofeldspathic gneisses, whereas others are interlayered with the gneisses, and still others were probably intruded (Goldich and others, 1980b; Neilsen and Weiblen, 1980).

Just what the original protolith was for the quartzofeldspathic gneisses and interlayered amphibolites remains a matter of conjecture. The present consensus appears to be that clastic rocks of volcanogenic or sedimentary origin were subjected to a number of episodes of metamorphism, intrusion, and deformation. The tonalitic gneiss and associated amphibolites appear to be the oldest rock units. The amphibolites may include material that was included or interlayered or intruded in the protolith of the tonalitic gneiss prior to the deformation (Goldich and others, 1980b). Granitic gneiss and pegmatitic gneiss may have originated as partial melts during metamorphism and deformation of the tonalitic gneiss and amphibolite. The interlayered rocks of contrasting composition formed by these processes are referred to as migmatites.

GUIDE TO FIELD TRIP STOPS

An index to field trip stops and the general distribution of geologic units and structural relations as currently known are shown on Figure 8. Stop descriptions are modified from Grant and Goldich (1972).

STOP #1. Hornblende-pyroxene gneiss and garnet-biotite gneiss: Municipal Park, Granite Falls, NE¼ sec. 3, T. 115 N., R. 39 W. (Fig. 9).

Hornblende-pyroxene gneiss and garnet biotite-gneiss are exposed on either side of Highway 67 near the entrance to the Municipal Park. These supracrustal rocks were probably derived from graywacke sediments. They preserve a record of burial to sufficient depth to have transformed hydrous minerals in the original sedimentary rocks to pyroxene-garnet mineral assemblages (Himmelberg and Phinney, 1967).

The layered mafic gneisses form the southern limb of the antiform at Granite Falls. Just south of the entrance to the park, a northeast-trending tholeiitic dike cuts the gneisses. Along Highway 212 on the north side of the river and along Highway 67 into the park, there are exposures of a metagabbro (Fig. 9).

On the basis of rock type and orientation, the tholeiitic dike is no doubt of the same generation as the 1,800-m.y.-old dikes at Stop #2. The metagabbro has been dated at 2,620 $\pm$ 20 m.y. (Wilson and Murthy, 1976), and the layered mafic gneisses have a recrystallization age of 3,460 $\pm$ 150 m.y. (Wilson and Murthy, 1976).

STOP #2. Quartzofeldspathic gneiss and later intrusions at Granite Falls, NE¼ sec. 28, T. 116 N., R. 39 W.

Typical pink to red, foliated, quartzofeldspathic gneiss of the granitic variety is exposed along the rail cut on the north limb of the Granite Falls antiform (Fig. 9). Early folding of pegmatitic veins as shown schematically in Figure 6 can be found here.

Northeast-trending hornblende andesite dikes cut the quartzofeldspathic gneiss. Rounded inclusions of dike rock with biotite rims occur in the contact zone of an adamellite intrusion exposed along the rail cut. A small exposure of the adamellite stock is exposed on the east side of the county road. K-Ar (Hanson and Himmelberg, 1967), U-Pb (Catanzaro, 1963), and Rb-Sr (Goldich and others, 1970) all indicate emplacement of the hornblende andesite and the adamellite at about 1,800 m.y.

STOP #3. Quartzofeldspathic gneiss, amphibolite, and adamellite at Montevideo, SE¼ sec. 20, T. 117 N., R. 40 W. (Fig. 10).

The outcrops southeast of Montevideo (Fig. 10) are the type locality for Lund's (1956) Montevideo granite gneiss. The general range of compositions of these and similar rocks in the Granite Falls area is shown in Figure 7. The foliation in these rocks is defined by biotite-rich layers which alternate with quartzofeldspathic layers as much as 50 feet thick.

Between U.S. Highway 212 and the adjacent rail cut, a conformable lens of amphibolite is exposed. On the east side of the rail cut at the north end of the outcrops, a complex contact between granodioritic gneiss and a more massive red adamellite is exposed on a south-facing weathered outcrop surface.

The succession of deformational events is illustrated in Figure 6, and a possible correlation with metamorphic events is outlined in Table 2. U-Pb and Rb-Sr data (Wooden and others, 1980 and references therein) are consistent with the interpretation that (1) the quartzofeldspathic gneisses record an age of at least 3,550 m.y., and (2) the gneisses were intruded by adamellite between 3,300 and 3,000 m.y. This magmatic episode was followed by disturbances of the isotopic systems at 2,700 and 1,800 m.y., dates which correspond with the ages of the Sacred Heart pluton (Stop #4) and the adamellite and hornblende andesite (Stop #2). This succession of events is similar to that deduced for the Morton area (Stop #7).

STOP #4. Contact zone between the Sacred Heart quartz monzonite and quartzofeldspathic gneiss and amphibolite enclaves south of Sacred Heart, W½ secs. 8 and 17, T. 114 N., R. 37 W and NE¼SW¼ sec. 21, T. 114., R. 37 W. (Fig. 11).

A migmatite contact zone between quartzofeldspathic gneiss and the Sacred Heart quartz monzonite pluton is exposed along Redwood County Highway 7, 7 miles south of Sacred Heart. The quartz monzonite is similar to that in the main exposed part of the pluton to the southwest. Migmatitic structures exposed along the highway and in outcrops in the SW¼ sec. 7, T. 114 N., R. 37 W. include raft, vein, dilation, folded, augen, and schlieren structures involving gray quartzofeldspathic gneiss, amphibolite, and quartz monzonite. The complexity of the interlayering and crosscutting relationships of the intrusive, 2,700-m.y.-old quartz monzonite in the older quartzofeldspathic gneisses and amphibolite can serve to indicate processes that produced the complexity of the older gneiss terrane.

The massive black amphibolite exposures in sec. 21 and occurrence of diopside-garnet quartz veining may be construed to define vesiges of pillow lava structures. The bulk composition of these amphibolites is komatiitic. These rocks are prime candidates for further age dating in the MRV to establish whether they are older than, contemporaneous with, or younger than the quartzofeldspathic gneisses.

STOP #5. Supracrustal rocks and amphibolite enclaves north of Delhi, SW¼ sec. 28, T. 114 N., R. 36 W. (Fig. 12).

The outcrops in this area are complex in structure and in lithogolic variations over short distances. They lie on the south side of an easterly plunging synclinorium (Fig. 8), 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 (Fig. 6).

Amphibolite rafts, up to 1,000 feet in strike-length, form about half of the exposures, and behave 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.

The lower units of the interlayered gneisses are dominantly rodded quartz-cummingtonite gneiss. Upper units consist of quartz-plagioclase-biotite gneiss containing K-feldspar, muscovite, sillimanite, and garnet and a thinly layered quartz-plagioclase gneiss containing biotite, anthophyllite-garnet, and cordierite. Textures and mineral compositional zoning are interpreted to be related to retrogression across the second sillimanite isograd (Grant and Weiblen, 1970).

STOP #6. Cretaceous weathering profile on Morton quartzofeldspathic gneiss, SW¼SW¼ sec. 29, T. 112 N., R. 35 W.

Along an abandoned road off county Road 101 in north Redwood county is a succession of soil horizons developed on a terrace of the glacial River Warren. The terrace was developed on a Cretaceous weathering profile on the Morton quartzofeldspathic gneiss. Ghost structures of the hornblende, biotite, and feldspar can still be seen in the deeply weathered gneiss. The Cretaceous weathering was interpreted by Goldich in his classic study (Goldich, 1938). No subsurface samples have been analyzed in the isotopic studies to date, and so the effect of this weathering event on the isotopic systems has not really been assessed.

STOP #7. Quartzofeldspathic gneiss and amphibolite at Morton, NE¼ sec. 31, T. 113 N., R. 34 W. (Fig. 13).

The quarry walls, surface outcrops, and waste-rock piles at Morton provide excellent opportunities to observe the complex lithologic and structural relationships of quartzofeldspathic gneiss and amphibolite. On the east wall of Quarry #3 (Fig. 13), a block of tonalitic gneiss is included in granodioritic gneiss. Some amphibolite occurs as inclusions in the tonalitic gneiss. At the same quarry, the alignment of large, meter-sized blocks of amphibolite in the foliation of the quartzofeldspathic gneisses suggests that the precursors of these amphibolite occurrences were intruded into the gneisses as dikes. Structural evidence such as this suggests that some of the amphibolite and the tonalitic gneiss are the oldest components of the quartzofeldspathic gneisses. On the other hand, some of the amphibolite may be younger than the grandioritic gneiss (Nielsen and Weiblen, 1980).

Several generations of granitic magmatism have been recorded in the exposures at Morton, including emplacement of pegmatite and at least two episodes of emplacement of adamellite, granodiorite, and aplite. This record and probable age relationships are summarized in Table 1. Differences between the Morton and Granite Falls areas have been summarized by Goldich and others (1980a). In view of the absence of stable garnet clinopyroxene assemblages at Morton, either a higher stratigraphic section or a faulted section having less vertical uplift is exposed at Morton than at Montevideo and Granite Falls (Figs. 4 and 8).

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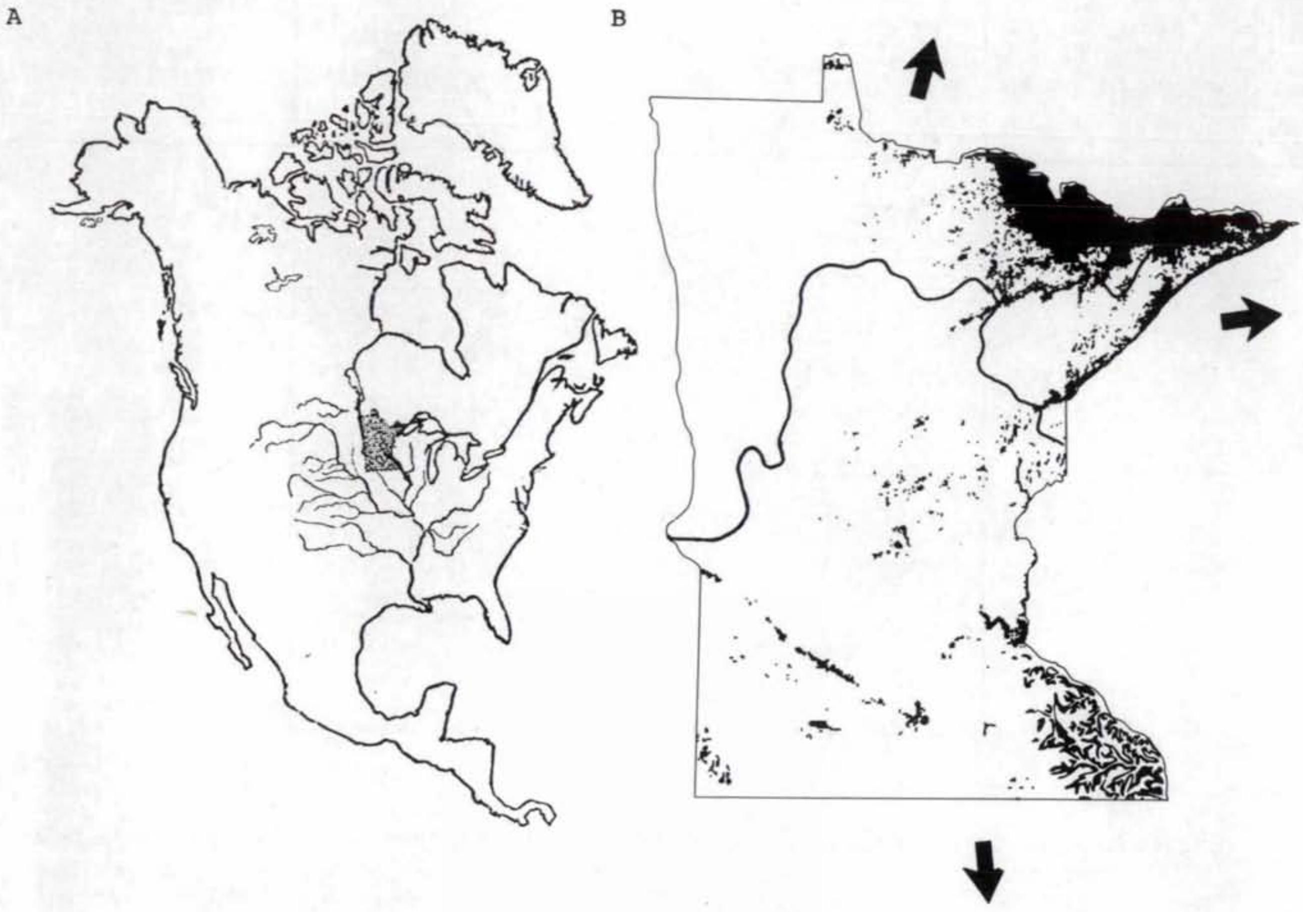


Figure 1. Index, bedrock, and drainage maps.

A, location of Minnesota relative to the drainage pattern of central North America (modified from Bray, 1977). Small arrows indicate the three drainage systems.

B, generalized bedrock outcrop map of Minnesota (modified from Morey, 1981). Black areas indicate areas of sporadic abundant exposures of bedrock; the remainder of the state is blanketed with a cover of soils, lakes and streams, glacial drift, peat, and alluvium (Kanivetsky, 1979; Goegel and Walton, 1979). Arrows indicate general directions of drainage from the three major divides (Schwartz and Thiel, 1963) into Hudson Bay and the St. Lawrence and Mississippi river systems.

The extrapolations from the bedrock exposures required to define the geology on the frontispiece and Figure 3 are constrained by geophysical data (Chandler, 1981a, b; Chandler and Walton, 1980) and by subsurface data (Olsen and Mossler, 1982).

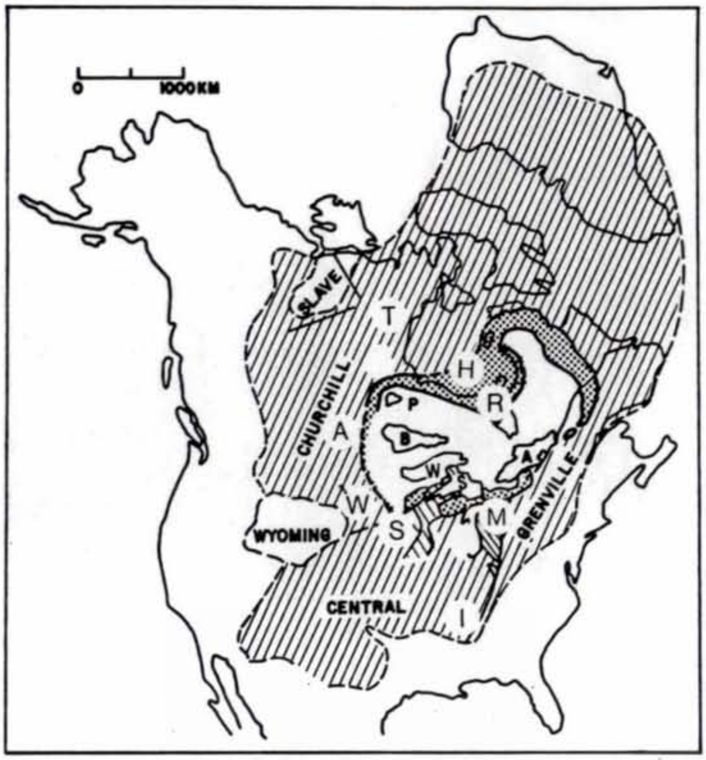


Figure 2. Generalized geologic map of the North American craton (modified from Weiblen and Schulz, 1978). Outer dashed line, approximate locus of Paleozoic troughs (adapted from Stewart, 1976). Right diagonal pattern, speculative extent of contiguous Archean crust in North America. Only three of the many post-Archean geologic features that are known in this terrane are indicated: the Proterozoic fault-bounded aulacogens (thick straight lines) which separate the Slave and Churchill Provinces (Windley, 1977); the Late Precambrian Midcontinent Rift (left diagonal pattern) (Morey, 1978); and the continental plate collision boundary (thick line) which separates the Grenville Province from the Central, Superior, and Churchill Provinces. S, Lake Superior. Dotted pattern, Proterozoic troughs. These troughs define a discontinuous annulus around the Superior Province: on the north by the Labrador Trough (Dimroth, 1972), on the southeast by extension of the Labrador Trough in the Grenville Province (Windley, 1977) and the Huronian Supergroup (Windley, 1977), on the south by the Animikie Group in Wisconsin and Minnesota (Sims, 1976), and on the west by geophysical anomalies (Lidiak, 1971; Douglas, 1973). The Wyoming, Slave, and Superior Provinces are Archean (>2,500 m.y.) greenstone-granite terranes. The Central and Churchill Provinces together and Grenville Province have been thought to represent Proterozoic (<2,500 m.y.) and Late Precambrian (<1,500 m.y.) additions to the North American craton, respectively (Hurley and others, 1962; Condie, 1976a, b). The northeast boundary of the Churchill Province is not shown.

Goodwin (1977) has defined a number of elliptical basins within the Superior Province: A, Abitibi Basin; W, Wabigoon Basin; B, Berens Craton; and P, Pikwitonei region. These basins are developed in gneissic terrane within the Superior Province, and the basins consist of increasing amounts of gneiss of increasing metamorphic grade in the order listed. Goodwin (1977) suggests that this reflects deeper intersections of the basins from southeast to northeast across the Superior Province.

The general positions of the intracratonic basins of North America are also indicated: A, Athabasca; H, Hudson Bay; I, Illinois; M, Michigan; MR, Moose River; S, Sioux; T, Thelon; W, Williston.

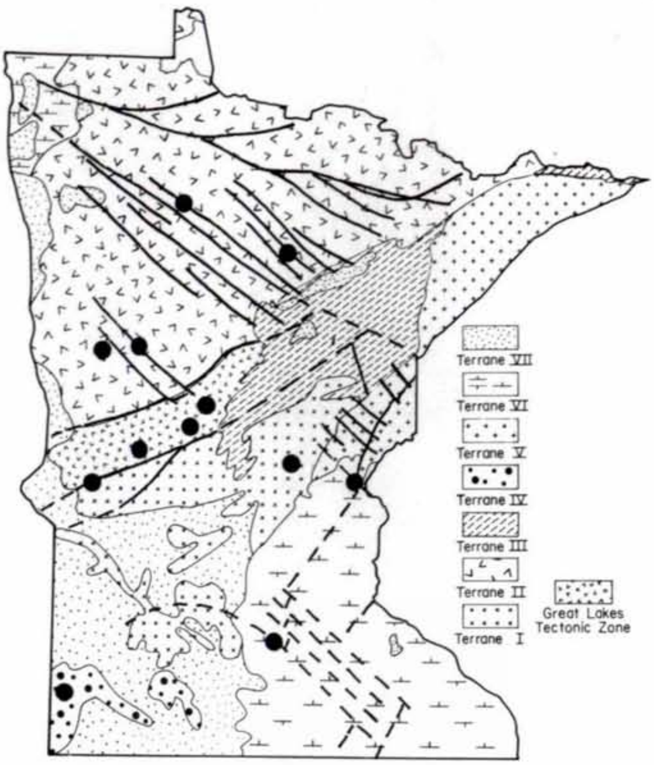


Figure 3. Generalized geologic map of Minneosta (modified from Morey, 1982, and Southwick, 1980). Geologic units are indicated in more detail on the frontispiece, and the five terranes are described on the back cover. The Great lakes tectonic zone (Sims and others, 1980) may be part of a more or less complete annulus around the Superior Province greenstone-granite terrane (Fig. 2). Solid dots indicate locations of 12 recorded earthquakes in Minnesota (Mooney and Morey, 1981). Heavy lines indicate fault systems or shear zones, largely inferred from geophysical data.

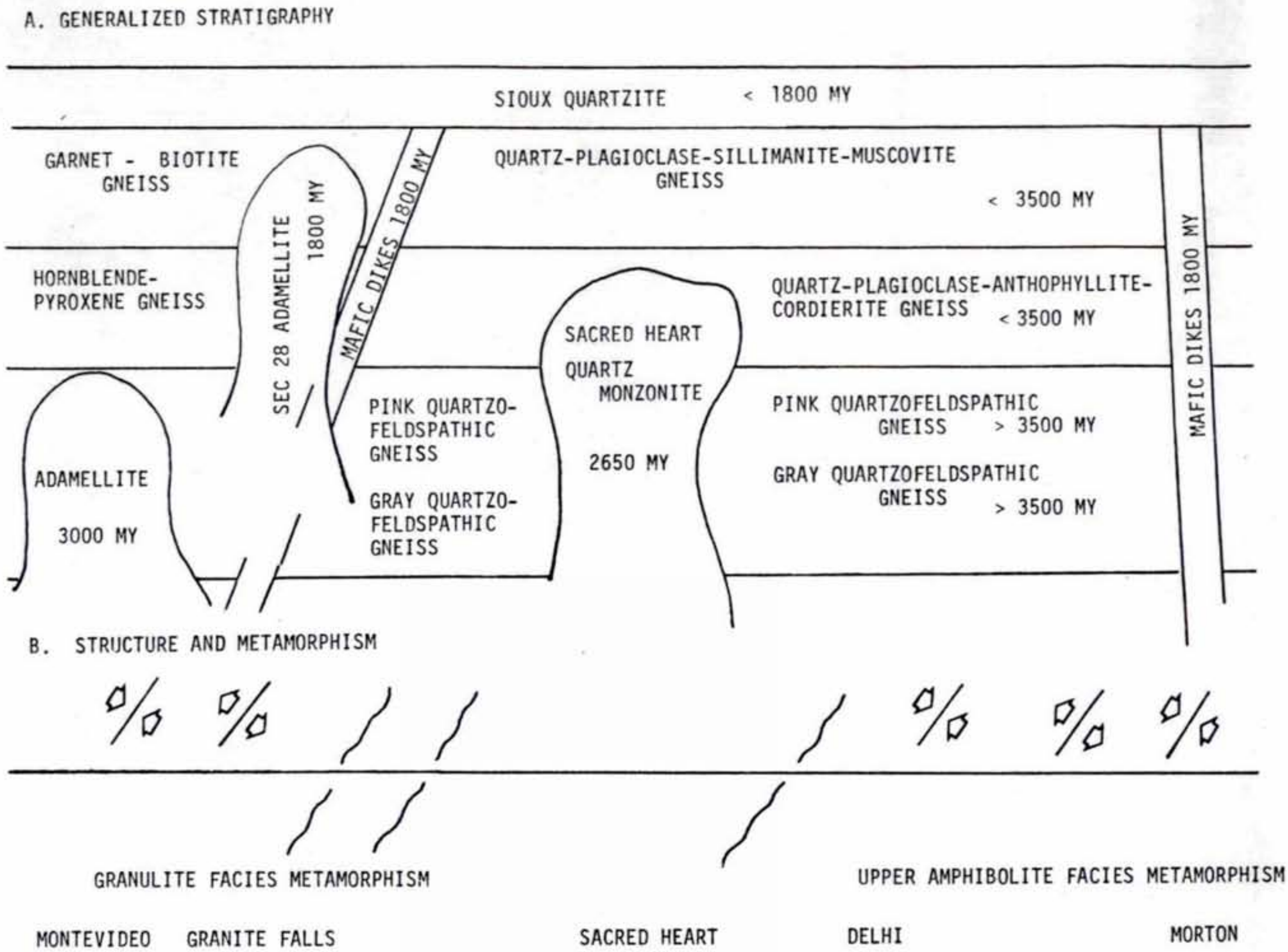


Figure 4. Schematic summary of the geographic, lithologic, stratigraphic, metamorphic, and structural relations of the Precambrian rocks in the Minnesota River Valley. A, general geographic and stratigraphic distribution of rock units described in the text. B, metamorphic and structural relations.

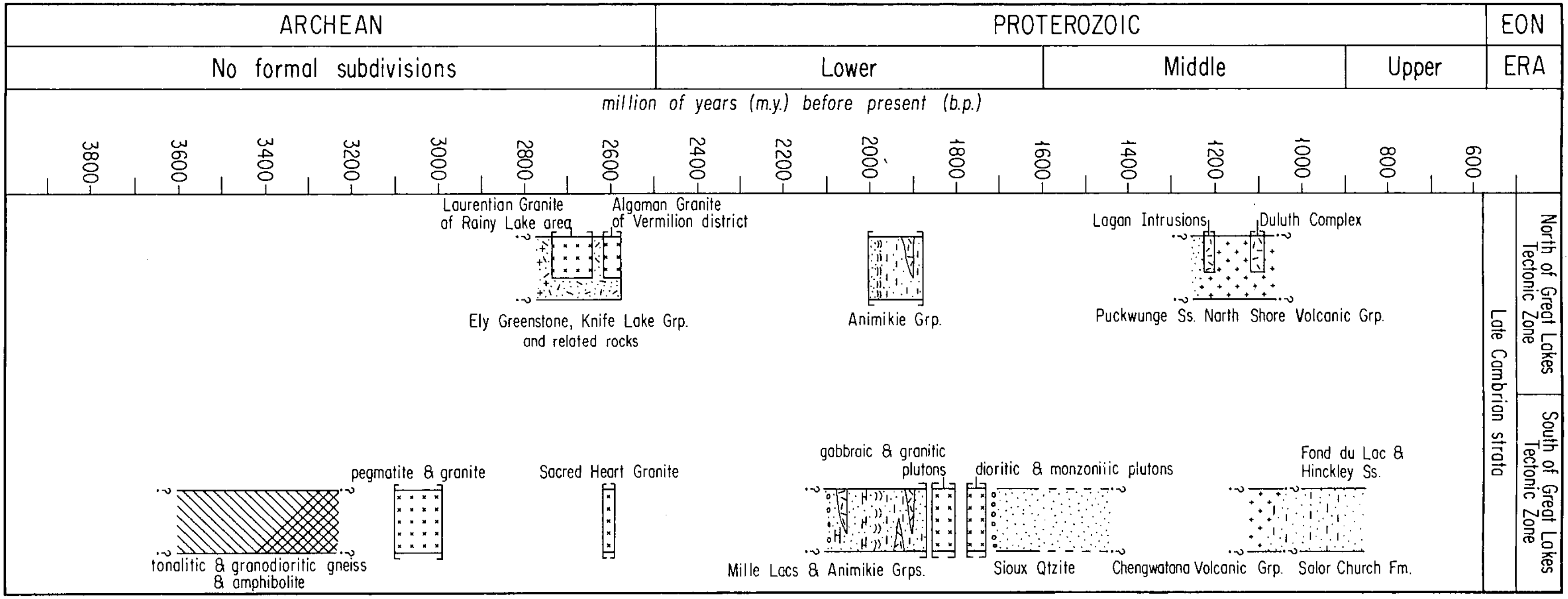


Figure 5. Comparison of the stratigraphy of the Minnesota River Valley rocks and the greenstone-granite of northern Minnesota (from Morey, 1982). A more complex record of crustal evolution is preserved in the Minnesota River Valley rocks (right-hand column) than in the greenstone-granite terrane (left-hand column).

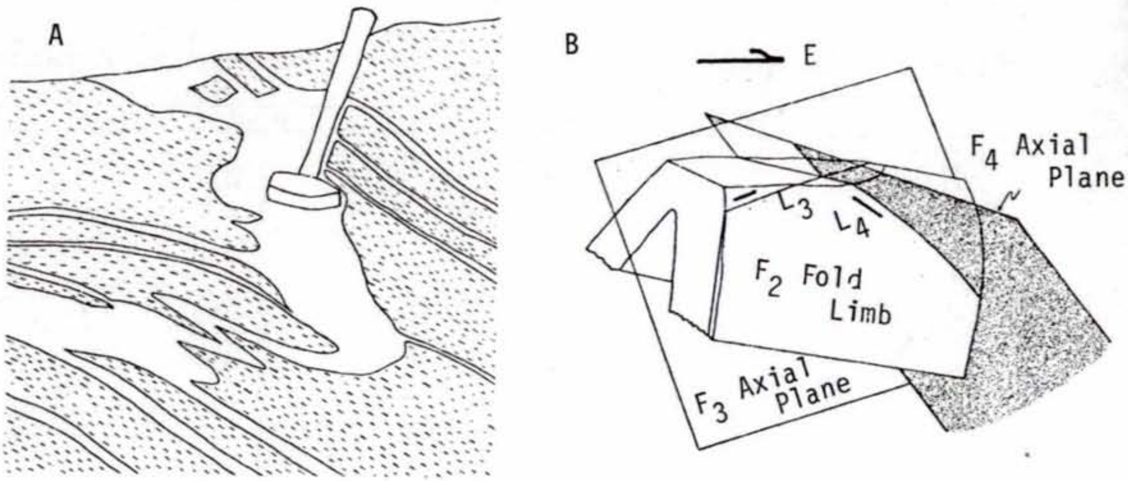


Figure 6. Synoptic illustration F_1–F_4 phases of folding of quartzofeldspathic gneisses in the Minnesota River Valley (modified from Bauer, 1980). A, schematic illustration of early folding of vein material which crosscuts the primary foliation of quartzofeldspathic gneisses. B, relative orientation of the axial planes of F_2–F_4 folds. The F_2 fold represents the major structures, such as the Granite Falls antiform (Fig. 8) and the synform between Granite Falls and Montevideo (Bauer, 1980). Lineations (L_3 and L_4) are produced by intersection of the F_3 and F_4 axial plains with the F_2 folds.

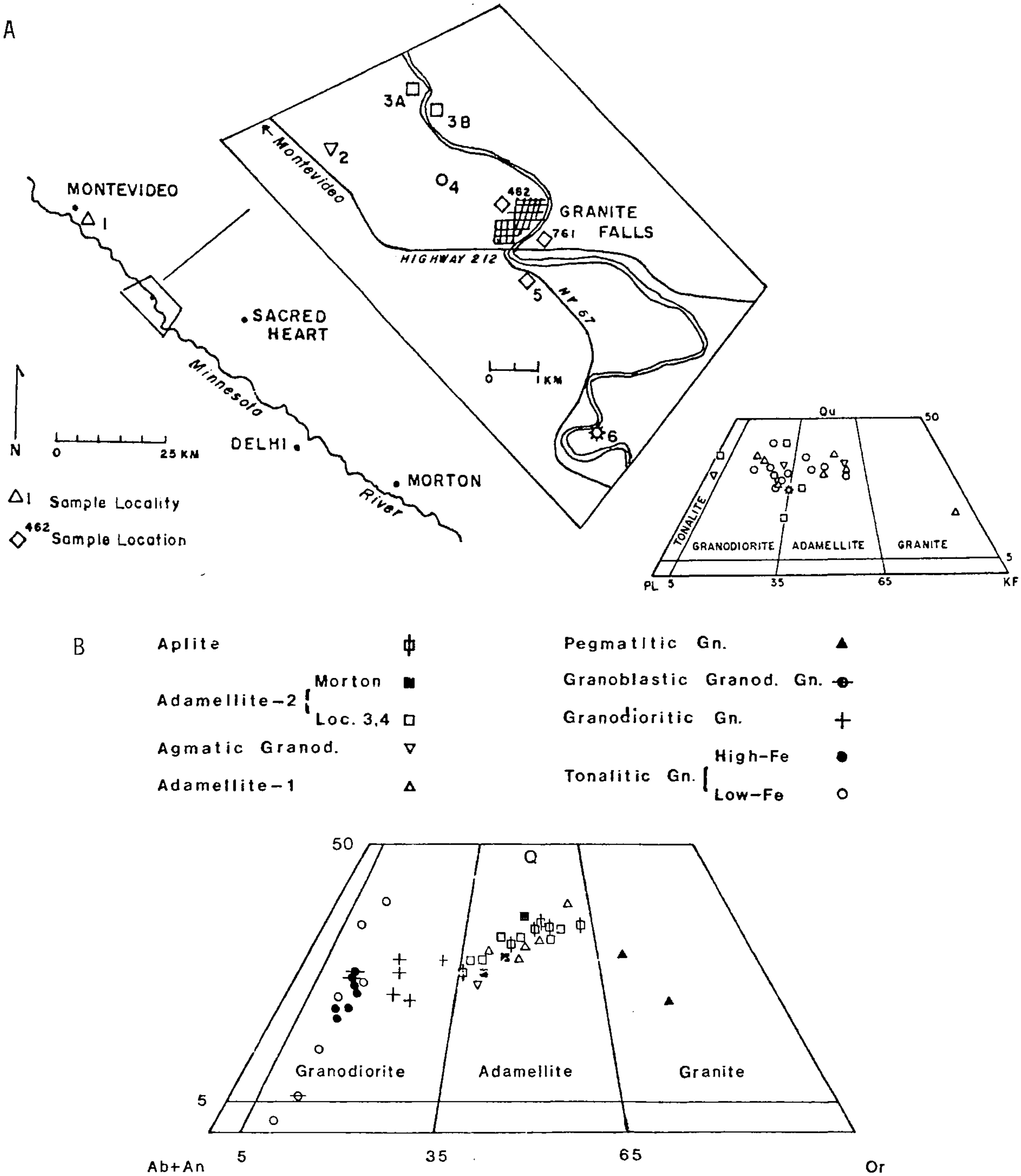


Figure 7. Modal classification of quartzofeldspathic gneisses. A, classification of quartzofeldspathic gneisses in the Granite Falls area (Goldich and others, 1980a). Rock names are based on Johannsen's (1939) system. B, classification of quartzofeldpathic gneisses in the Morton area (Wooden and others, 1980).

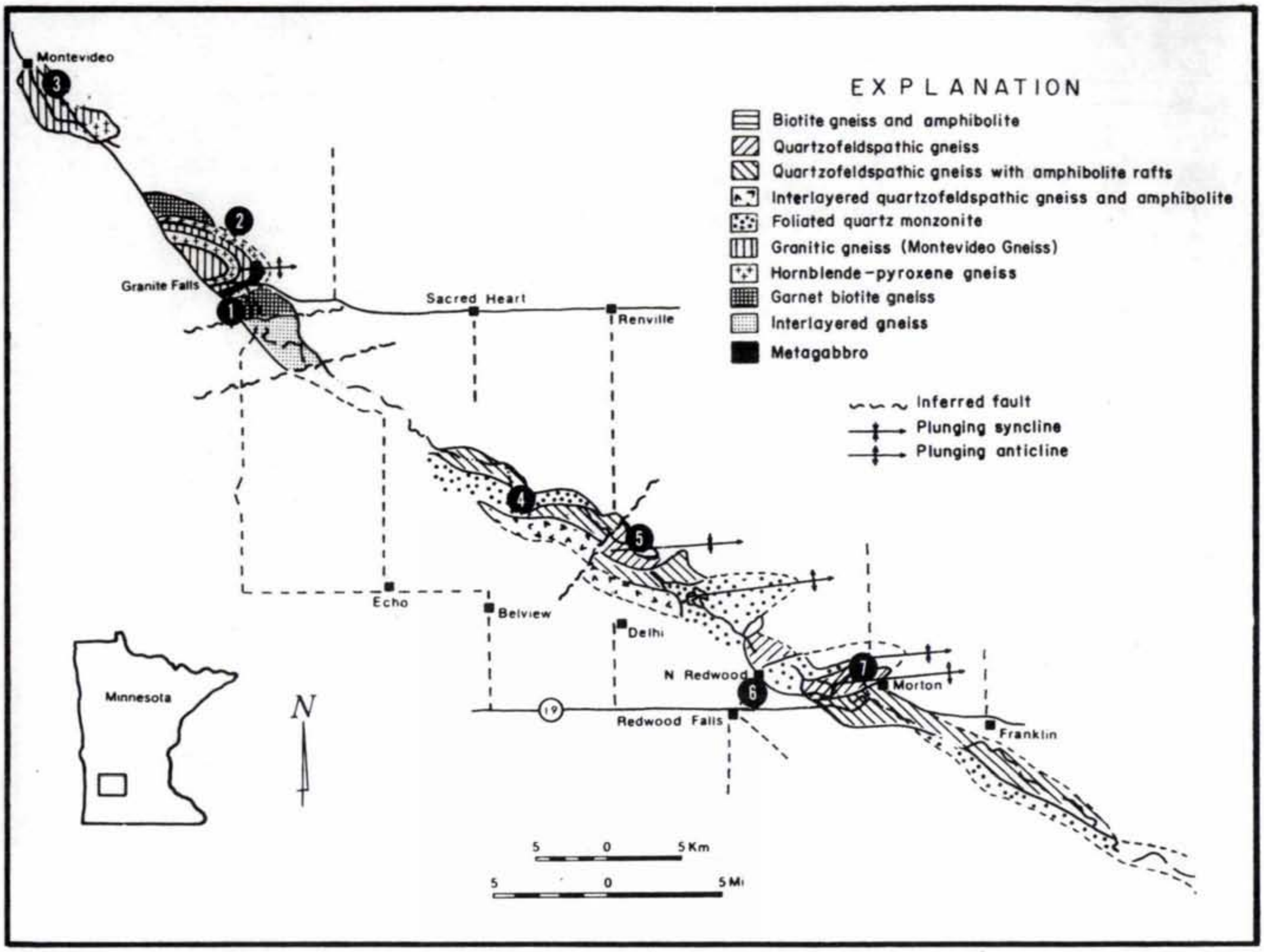


Figure 8. General lithologic, structural, and index map of field trip stops in the Minnesota River Valley (modified from Bauer, 1980).

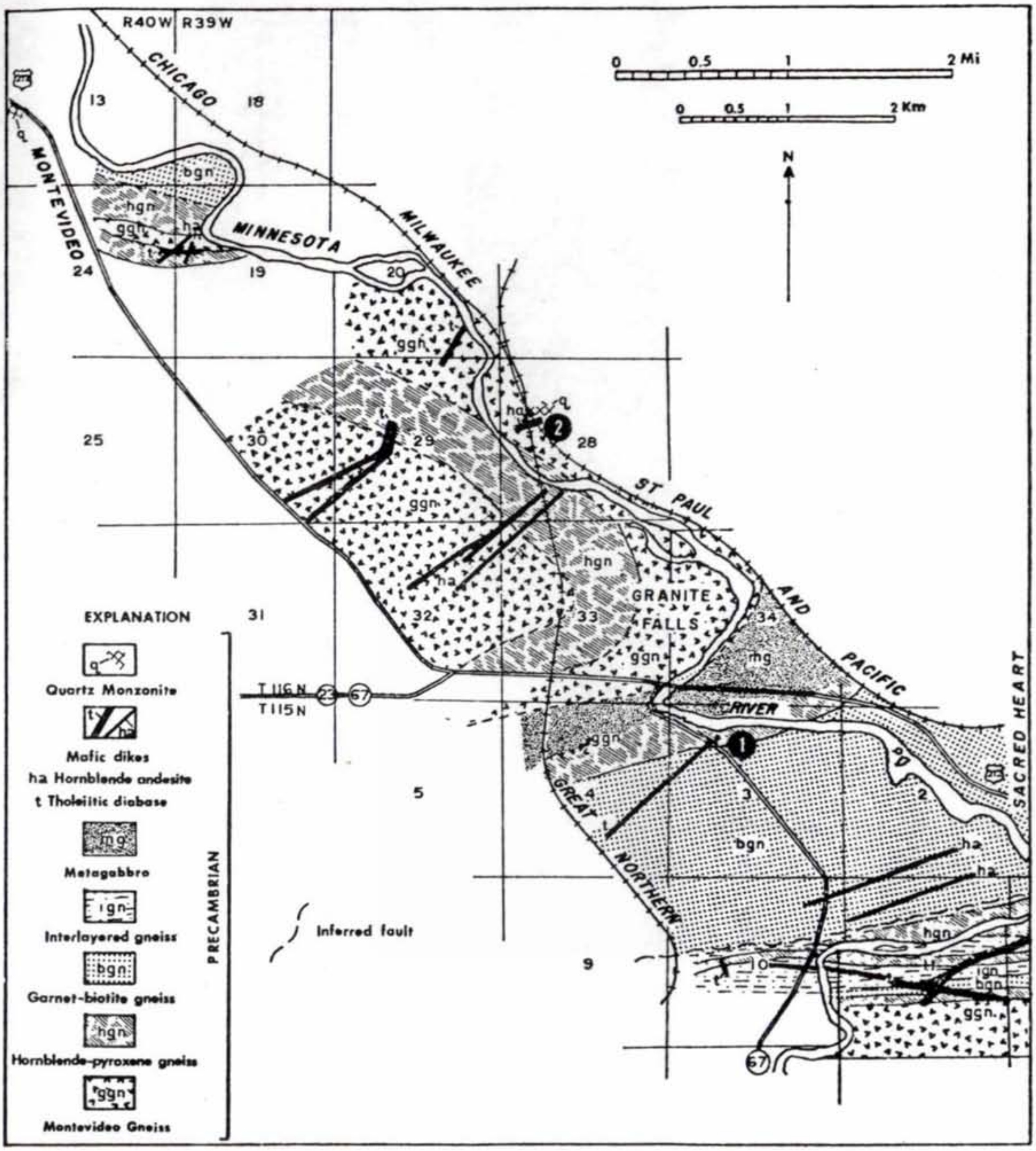


Figure 9. Geologic map of the Granite Falls area (from Bauer, 1980). Stop #1 at Granite Falls Municipal Park along the south bank of the Minnesota River in the NE¼ sec. 3, T. 115 N., R. 39 W. Stop #2 along the Milwaukee, St. Paul, and Pacific rail cut in the NE¼ sec. 28, T. 116 N., R. 39 W.

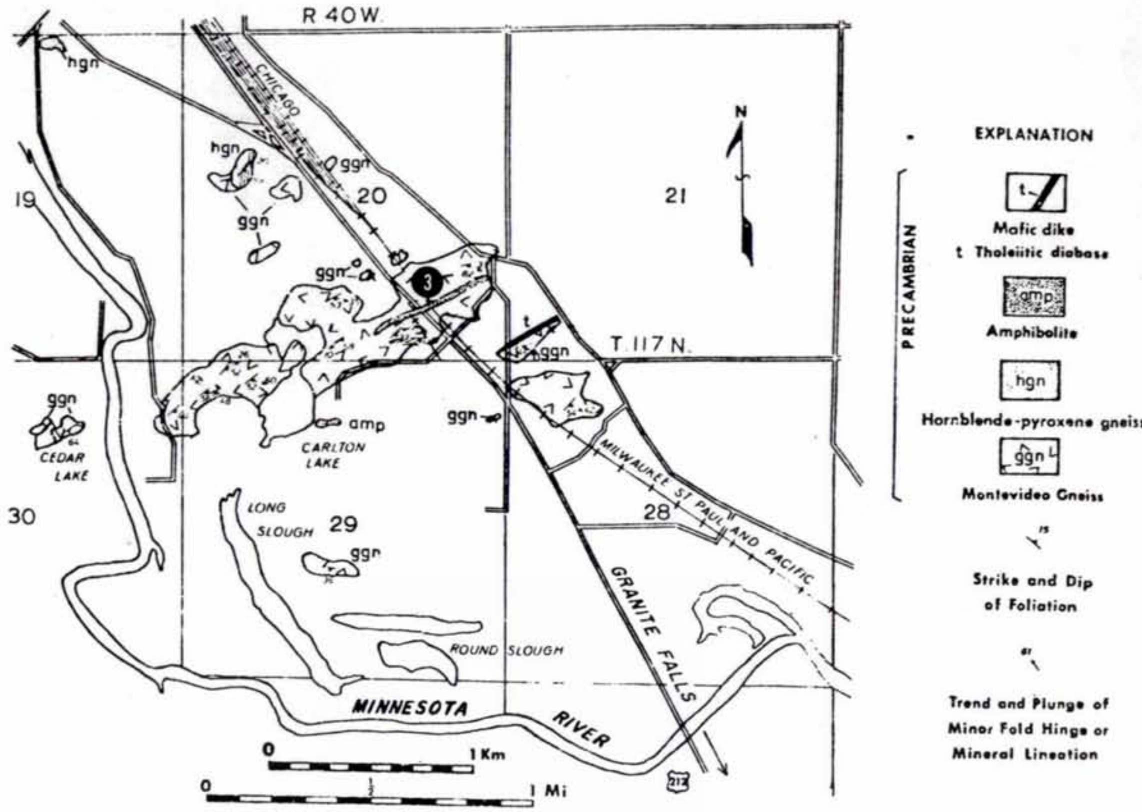
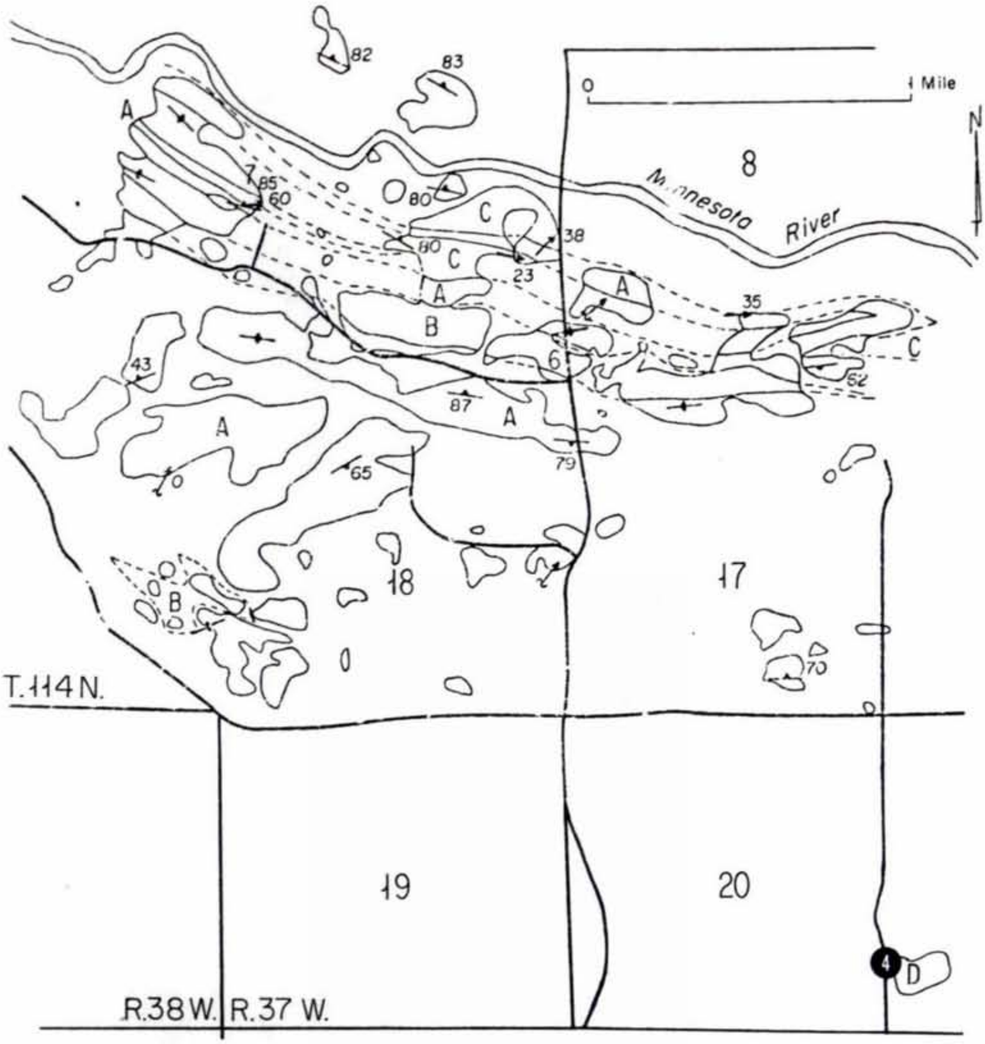


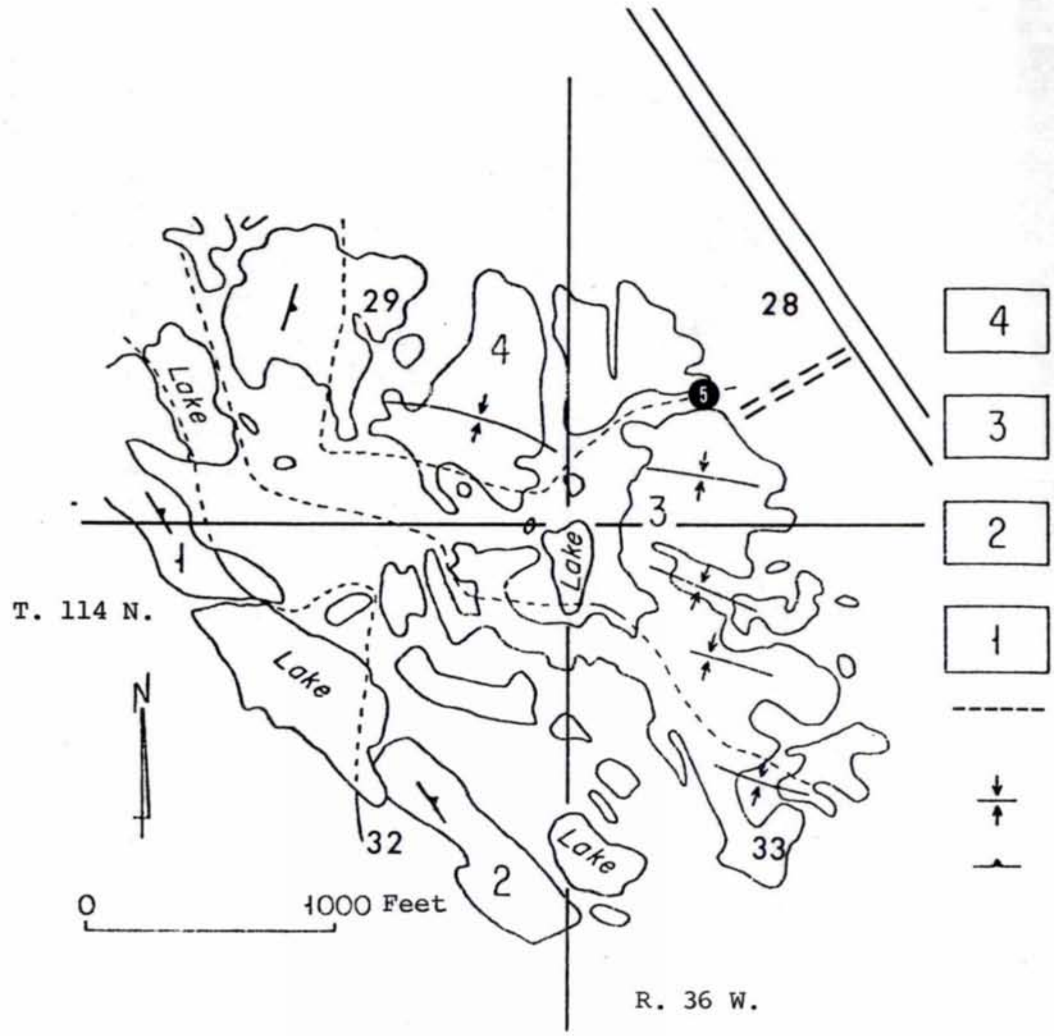
Figure 10. Location map for Stop #3 (modified from Bauer, 1980).



EXPLANATION

A	Quartz Monsonite, commonly foliated	----	Inferred contacts
B	Pyroxene granite with abundant amphibole-rich xenoliths, and associated phases	30	Strike and dip of foliation
		10	Azimuth and plunge of minor foldaxis
C	Migmatitic quartzofeldspathic gneiss with amphibolite enclaves	10	Azimuth and plunge of lineation
D	amphibolite enclaves	4	Field Stop location

Figure 11. Location map for Stop #4 (modified from Grant and Goldich, 1972).



EXPLANATION

HETEROGENEOUS BIOTITE-QUARTZ-PLAGIOCLASE GNEISS WITH OR WITHOUT CORDIERITE, GARNET, OR SILLIMANITE WITH AMPHIBOLE LENSES

QUARTZOFELDSPATHIC GNEISS

THINLY BANDED BIOTITE-CORDIERITE-GARNET-ANTHOPHYLLITE GNEISS WITH AMPHIBOLE LENSES

APPROXIMATE CONTACT

SYNFORM (INTERVENING ANTIFORMS NOT SHOWN)

AMPHIBOLITE AND QUARTZ-CUMMINGTONITE GNEISS

STRIKE AND DIP OF FOLIATION

Figure 12. Location map for Stop #5 (modified from Grant and Goldich 1972). T. 114 N., R. 36 W.

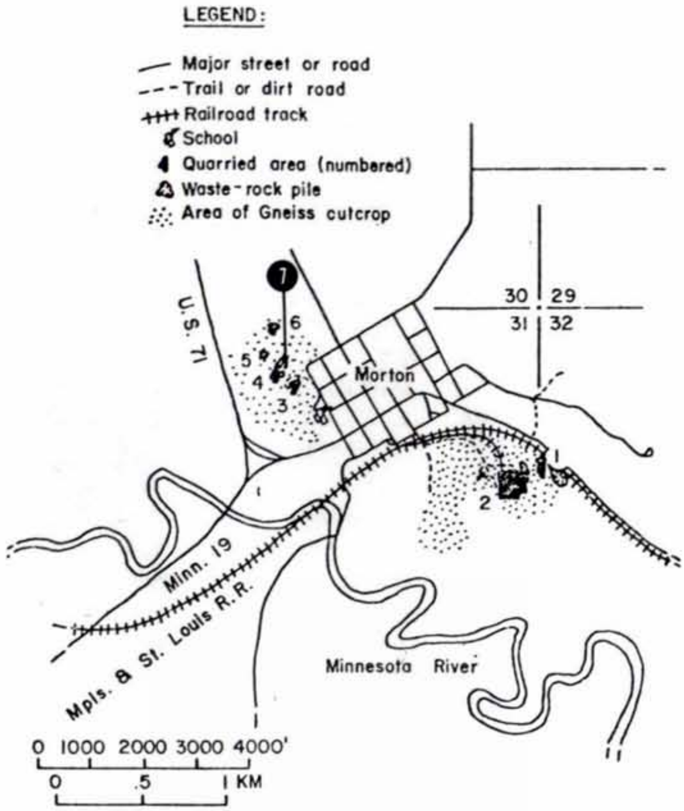


Figure 13. Location map for Stop #7 (modified from Nielsen and Weiblen, 1980). 1–6 location of quarries in Morton.

Table 1. Summary of Geologic Events in the Morton Area, Minnesota River Valley (modified from Goldich and Wooden, 1980)

Time (m.y.)			Description
			Sioux Formation, conglomerate and quartzite, New Ulm (Goldich and others, 1961, 1970).
			Uplift and erosion
1,800	●	•	Thermal event accompanied by emplacement of small igneous masses, i.e., gabbro-granophyre and basaltic dikes southeast of Franklin (Goldich and others, 1961; Hanson, 1968).
		★	Epidote veinlets in Morton Gneiss by hydrothermal activity.
		•	Uplift and erosion; stabilization of area 2,400–2,500 m.y. ago (K-Ar and Rb-Sr mineral ages, Goldich and others, 1970).
Proterozoic			
Archean			
		•	Aplite, pegmatite, and aplite-pegmatite dikes; post-kinematic and traversing structure of the Morton Gneiss (Rb-Sr, 2,590 ± 40 m.y.).
		•	Adamellite-2, late-kinematic (Rb-Sr, 2,555 ± 55 m.y.).
2,600	●	•	High-grade metamorphism producing final structure of the Morton Gneiss (Rb-Sr rock-mineral, K-Ar mineral ages). Emplacement of Sacred Heart Granite (Pb-Pb, Doe and Delevaux, this volume; U-Pb, Rb-Sr, Goldich and others, 1970).
	●	• ★	Emplacement of pegmatitic granite and adamellite-1 (U-Pb minimum age, 3,043 ± 26 m.y.).
3,050	●	•	High-grade metamorphism of tonalitic gneiss-amphibolite complex (Rb-Sr secondary isochrons resulting from Rb gain in amphibolites and tonalitic gneisses; U-Pb age of 3,070 m.y. on zircon from amphibolite (Farhat, 1975).
		★	Emplacement of pegmatitic granite and adamellite-1.
			Regional folding forming the tonalitic gneiss-amphibolite complex. Intrusion of basaltic dikes and sills.
3,500	●	•	Intrusion of coarse-grained tonalites in a volcanic pile of andesitic to dacitic flows and/or pyroclastic material with possible intercalations of basaltic flows, surmised from field relationships. (Rb-Sr, 3,475 ± 110 m.y. for tonalitic and related gneisses; U-Pb minimum age, 3,300 m.y.).

● Major event; • based on age determinations; ★ position uncertain.

Table 2. Summary of Precambrian Geologic Events in the Montevideo-Granite Falls Area of the Minnesota River Valley (modified from Bauer, 1980).

	Structural Events	Metamorphic Events and Igneous Intrusions
		Low-grade regional metamorphism
		Quartz monzonite pluton Hornblende andesite dikes Olivine tholeiite dikes
F_4	Formation of ESE-plunging folds near Montevideo and N to NW-plunging folds in the Granite Falls area. Formation of WNW to NE-striking shear zones	Tholeiite dikes
	Local generation of S_3 foliation	Fixing of mineral ages in the gneisses and metagabbro Local reorientation of quartz, biotite, hornblende, and garnet in the S_3 foliation plane
F_3	Formation of the NE-trending folds on the N-dipping limbs of major F_2 structures and SW to SE to NE-trending folds on the S-dipping limbs of the major F_2 structures	
F_2	Formation of major eastward-plunging antiforms and synforms	Formation of L_2 mineral lineations parallel to F_2 fold hinges Intrusion of adamellite in the Montevideo Gneiss
F_1	Development of F_1 folds in pegmatite veins	
		Intrusion of pegmatite veins
	Formation of S_1 foliation	Recrystallization producing high-grade mineral assemblages oriented by S_1 foliation
	Formation of gneissic layering	
		Intrusion of amphibolite precursor dikes Intrusion of gabbro Formation of precursors for: Hornblende-pyroxene gneiss Garnet-biotite gneiss Layered Montevideo gneiss