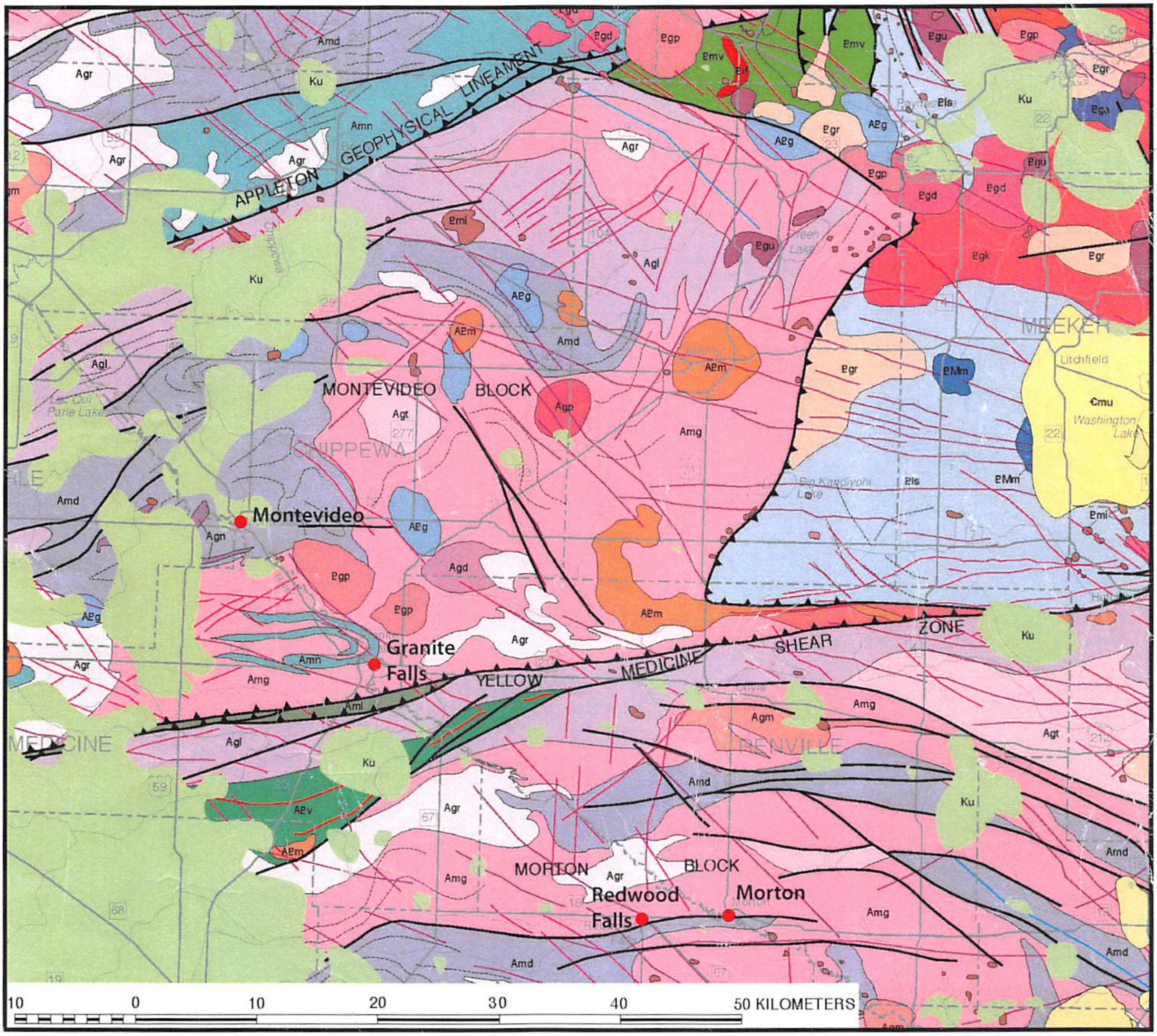
Geologic Map of the East-Central Minnesota River Valley Subprovince



MESOARCHEAN to PALEOARCHEAN

Includes the Montevideo, Morton, and related gneisses in the Minnesota River Valley subprovince of west-central and southwestern Minnesota. The subprovince is divided into distinct blocks (the Benson, Montevideo, and Morton) separated by faults and structural discontinuities defined largely by geophysical maps. The gneissic rocks, dated at ~3,524 to 3,485 Ma, were cut by tonalite at ~3,422 Ma, granodiorite at ~3,385 to 3,370 Ma, and granite at ~2,604 Ma (including the Sacred Heart Granite—unit Agr). Significant metamorphic events are recorded at ~3,300, ~3,140, and ~2,600 Ma.

Amg **Granitic orthogneiss and migmatite**—Geophysical map patterns imply this unit intruded other gneisses.

Amt **Foliated to gneissic tonalite and granodiorite.**

Amd **Granitoid gneiss with dioritic to amphibolitic enclaves**—Produces moderately high and varied gravity and magnetic signatures.

Amn **Amphibolitic to dioritic gneiss.**

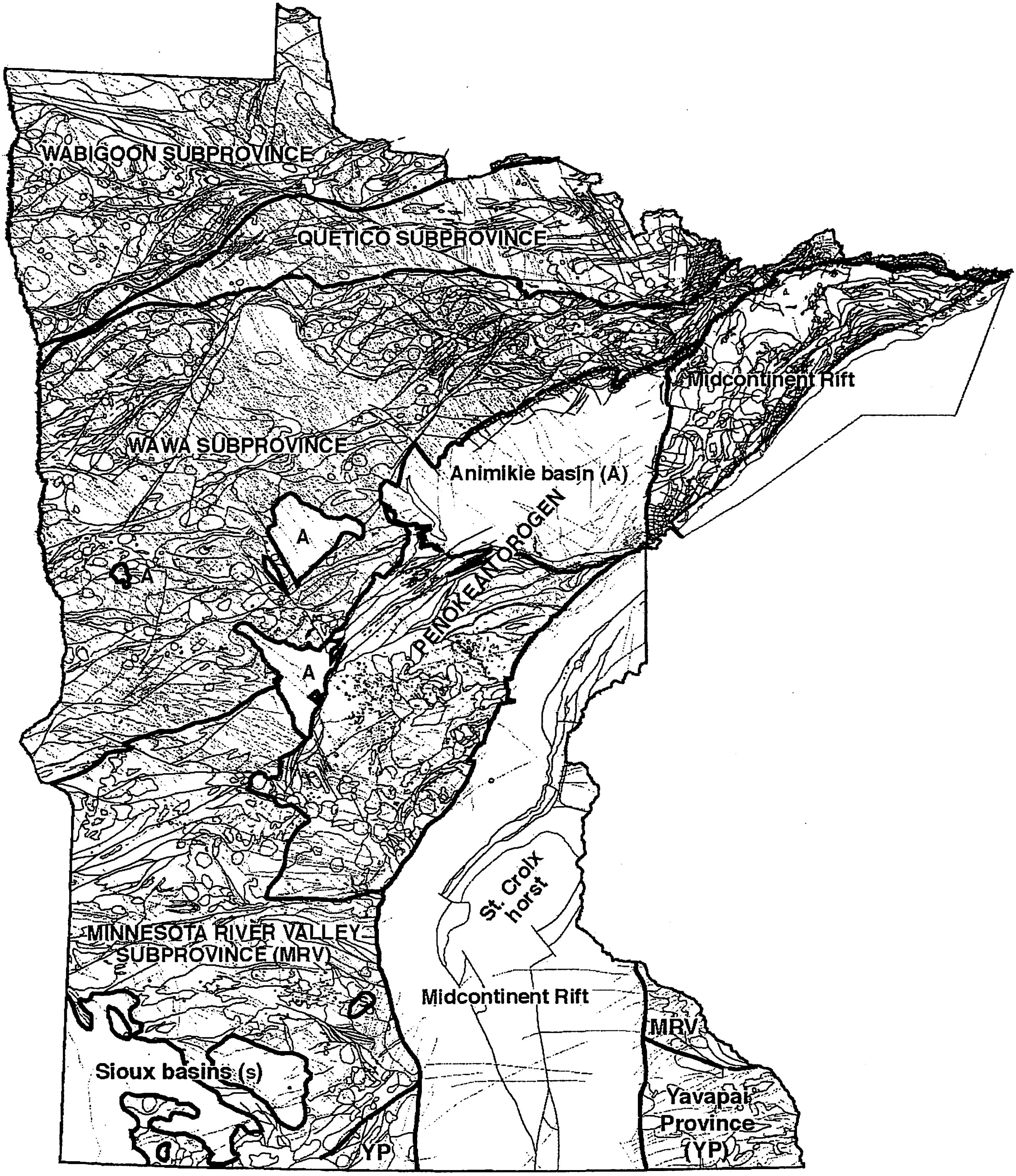
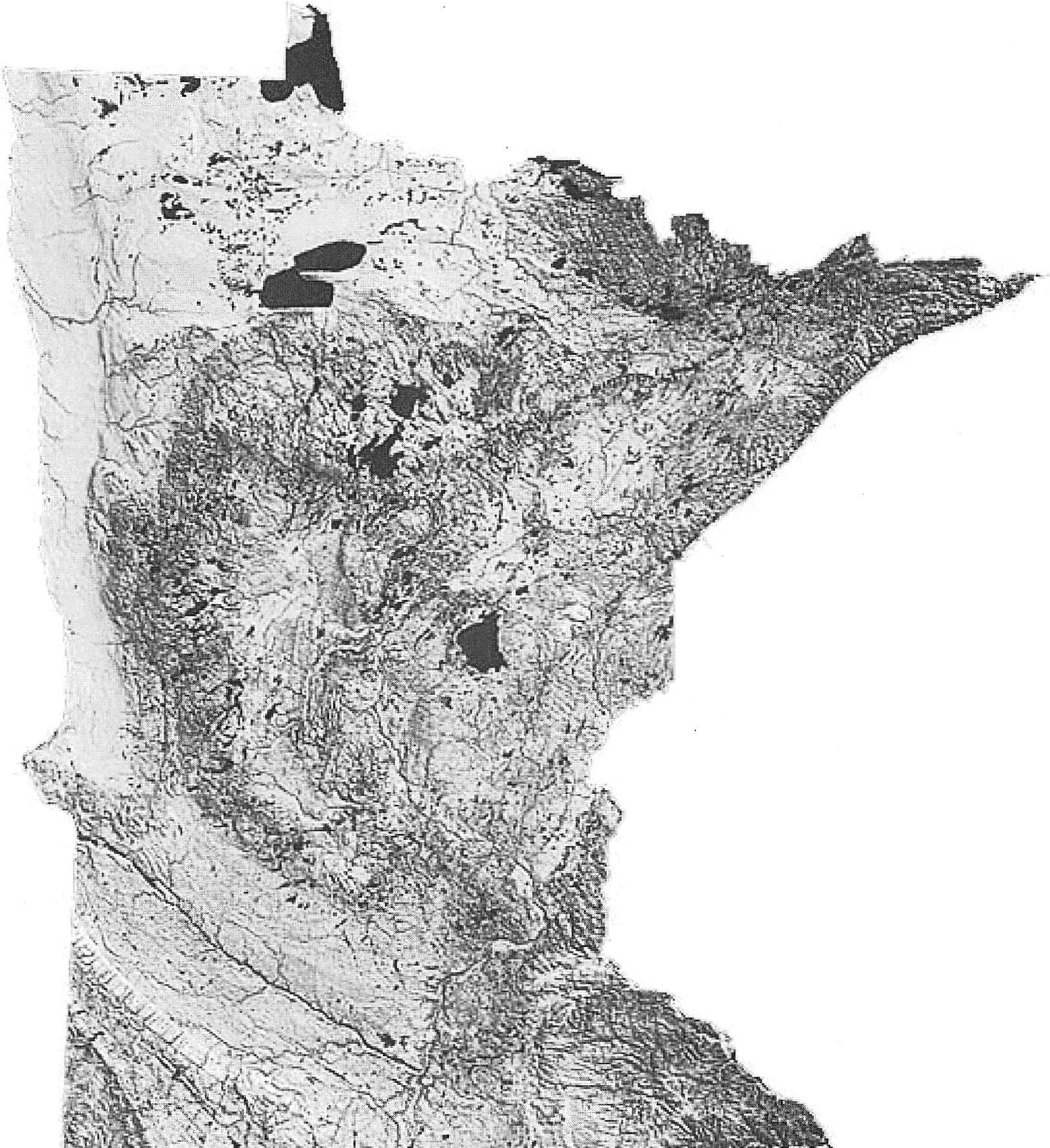


Figure 1. Terrane map of Precambrian bedrock showing subprovinces of the Archean Superior Province (iron-formation shown in red), significant elements of Paleoproterozoic bedrock, the Mesoproterozoic Midcontinent Rift, and mafic dikes (gray) of Paleoproterozoic and Mesoproterozoic age.



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Geology and geochronology of Paleoarchean gneisses in the Minnesota River Valley

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ABSTRACT

Outcrops within the broad expanse of the Minnesota River Valley in southwestern Minnesota mark the southernmost exposures of the Archean Superior Province of the Canadian Shield. Despite their relatively restricted exposure, the Meso- to Paleoarchean gneisses in the Minnesota River Valley have received considerable attention due to both their antiquity and their complexity. The rocks exposed include the migmatitic Morton and Montevideo granitic gneisses, schistose to gneissic amphibolite, metagabbro, and paragneiss. The units have undergone upper amphibolite to granulite facies metamorphism, multiple periods of folding, and intrusion by a weakly foliated Neoarchean granitic unit (the Sacred Heart Granite) and Paleoproterozoic mafic dikes and adamellite granite. Classic geochronologic studies of the Minnesota River Valley gneiss terrane from the 1960s through the 1970s used K-Ar, Rb-Sr, and U-Pb zircon isotopic techniques to establish the antiquity of the gneisses and general aspects of the geologic history of the terrane. However, more recent U-Pb SHRIMP (sensitive high-resolution ion microprobe) zircon geochronology has considerably refined our understanding of the complex history of the gneiss terrane. These studies indicate that the oldest units in the Minnesota River Valley terrane crystallized ca. 3500 Ma, but the rocks subsequently saw new zircon growth associated with events at ca. 3440, 3385, 3140, and locally 3080 Ma. The Archean history of the terrane culminated with high-grade metamorphism ca. 2619 Ma and intrusion of the Sacred Heart Granite at 2604 Ma.

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In addition to visiting classic outcrops of the Morton and Montevideo Gneiss, this field trip includes stops at each of the major gneissic rock units in the Minnesota River Valley. We will examine field relationships that are the basis for both our general understanding of the deformation and metamorphic history of the gneiss terrane and the sampling strategies for our recent geochronologic and ongoing isotopic studies.

INTRODUCTION

Rocks from the Archean Eon hold a fascination for both scientists and the general public for the glimpse they offer into the early history of Earth. For geologists, they provide clues to the secular changes in the evolving Earth, from stages following early Earth accretion to a differentiated Earth containing a rigid outer shell dominated by plate tectonic processes. However, the certainty of these changes belies the uncertainty of their rates, their relationships to one another, and to the thermal history of the cooling Earth. Opinions vary markedly, for instance, regarding the stages in the progressive growth of continents, and the timing and progressive development of plate tectonic processes (cf. Rollinson, 2006; and papers compiled in Reimold and Gibson, 2006; Van Kranendonk et al., 2007; and Condie and Pease, 2008).

Although Neoarchean terranes are widely distributed among the world's Precambrian shields, Mesoarchean, and particularly Paleoarchean and Eoarchean rocks, are much less common. The gneiss terrane exposed in the Minnesota River Valley is one of 25–30 sites, distributed among Precambrian shields on all the continents and Greenland, which are known to contain Paleoarchean and older rocks (Condie, 2007). Despite their sparse occurrence and wide distribution, most Paleoarchean gneiss belts have several features in common, including: (1) gneissic igneous rock over a wide range of compositions, (2) relatively large components of tonalite, trondhjemite and granodiorite (TTG), (3) minor supracrustal components of sedimentary and volcanic origin, (4) layered mafic to ultramafic igneous intrusions and mafic dikes, (5) intense deformation that commonly includes multiple periods of folding and ductile shear zones ranging from centimeters to kilometers across, (6) metamorphic mineral assemblages in the upper amphibolite to granulite faces, and (7) modest size blocks (typically <500 km across) that are bounded by younger Archean terranes.

This field trip will visit outcrops that exemplify most of these characteristics.

Notes on the Origin of Precambrian Exposures in the Minnesota River Valley

Although the Precambrian outcrops considered during this trip are quite limited and restricted to the floor of the river valley, we owe their very exposure to the Cretaceous and Late Pleistocene postglacial history of the area. So before examining the very old, we want to provide brief background on the relatively young geologic history that makes this trip possible.

Glacial River Warren, a major outflow drainageway from Glacial Lake Agassiz, excavated the broad valley of the present-day Minnesota River. Lake Agassiz was a huge ice-margin impoundment that formed on the southwest flank of the retreating Laurentian ice cap ~12,000 years ago and persisted for several hundred years; at its maximum it covered large parts of Manitoba, Ontario, North Dakota, and Minnesota. The high discharge, low gradient Glacial River Warren flowed southeast from the southern tip of the lake and initially cut a series of anastomosing channels across a till plain of generally low relief. Later the flow was focused into one main spillway that became more deeply incised and eventually reached solid Precambrian bedrock.

In excavating its channel to bedrock, Glacial River Warren removed ~50–100 m of glacially deposited sediment, from less than 10 to ~30 m of Late Cretaceous mudstone and shale, and a variable thickness of weathered material that had developed on the Precambrian rock surface during a long period of subaerial exposure prior to Late Cretaceous marine inundation. The weathering profile is as thick as 150 m where it is preserved beneath Upper Cretaceous strata in upland areas on either side of the Minnesota River Valley. The bottom of the weathering profile, i.e., the top of sound Precambrian rock, is an irregular surface on which the local relief ranges from less than 10 to more than 100 m.

The natural outcrops in the Minnesota River Valley are products of the pre–Late Cretaceous weathering and vigorous river erosion in the Quaternary. The primary valley-bottom microtopography of bedrock knobs and intervening swales reflects the morphology of the base of the weathering profile as etched out and somewhat modified by fluvial processes. The topographic knobs were former pinnacles of relatively unweathered rock; the topographic lows were the loci of deeper weathering facilitated by more susceptible rock compositions or zones of fracture permeability. Once uncovered and flushed by Glacial River Warren, the more deeply weathered zones became river channels characterized by chutes and rapids, and the taller of the pinnacles became intra-channel islands. Later changes in river dynamics led to the construction of tributary-mouth deltas and terraces of different kinds along the sides of the large valley that had been cut during earlier periods of high river discharge.

REGIONAL ARCHEAN SETTING

The Minnesota River Valley terrane is recognized as the southernmost terrane of the Superior Province of the Canadian Shield. However, its extent and relationship to the Superior Province are primarily inferred from geophysical and sparse drill-hole data. On the basis of their analysis of aeromagnetic and gravity anomalies, Morey and Sims (1976) recognized that the boundary between the Minnesota River Valley terrane and the granite-greenstone terrane in northern Minnesota (Vermilion District–Wawa terrane) roughly coincides with the Morris fault (Fig. 1). Subsequently, Sims (1980) and Sims et al. (1980) extended this boundary from Minnesota into Wisconsin and the Upper Peninsula of Michigan (Fig. 1) and named it the Great Lakes Tectonic Zone. Seismic reflection data across the Morris fault segment of the Great Lakes Tectonic Zone in Minnesota indicate that the fault dips 30–40° toward the north (Gibbs et al., 1984; Smithson et al., 1985).

Aeromagnetic maps of southwestern Minnesota (Chandler, 1987, 1989, 1991) and detailed gravity and magnetic modeling within the Minnesota River Valley (Schaap, 1989; Southwick and Chandler, 1996) delineated four crustal blocks within the Minnesota River Valley terrane (Fig. 1) that are bounded by three east-northeast–trending geophysical anomalies, which roughly parallel the Morris fault. Most of the previous work in the Minnesota River Valley, including the stops during this field trip, has concentrated on exposures in the Morton block and the Montevideo block, which are separated by the Yellow Medicine shear zone (Fig. 1). Southwick and Chandler (1996) and Southwick (2002) recognized a belt of moderately to weakly metamorphosed mafic and ultramafic rocks, the Taunton belt, which is parallel to and partly within the Yellow Medicine shear zone. They suggested that the Taunton belt may represent either allochthonous greenstone belt rocks that were infolded with older cratonic gneisses, or a remnant of Neoarchean oceanic crust along a suture between the Montevideo and Morton blocks.

ROCK TYPES

Rocks exposed in the Minnesota River Valley between the towns of Morton and Montevideo (Fig. 1) include a complex of granitic migmatites, schistose to gneissic amphibolite, metagabbro, and paragneisses. The best-known units are the Morton Gneiss (Stops 1, 2, and 5a), which is well exposed locally within the Morton block (Fig. 1) and the Montevideo Gneiss (Stops 8, 9, and 10) that occurs within the Montevideo block. Himmelberg (1968) provided more detailed descriptions of the rock units in the Granite Falls area, and Grant (1972) provided detailed descriptions of the rock units in the Morton block, including an inferred layered sequence for the units. The Morton Gneiss is a tonalitic to granodioritic migmatite with younger veins and interlayers of granitic pegmatite and locally abundant amphibolitic enclaves—interpreted to have crystallized from tholeiitic basalt magmas (Nielsen and Weiblen, 1980; Weiblen, 1982) (Fig. 3). The Montevideo Gneiss is a banded, medium- to coarse-grained, granitic gneiss with sparse amphibolitic enclaves (Fig. 4). In the Montevideo area, it also contains local diffuse veins and layers of a finer grained, weakly foliated, massive granitic phase that locally cuts the gneissic banding (red massive phase of Bauer, 1980) (Stops 9 and 10; Fig. 4H). Paragneiss, derived mostly from a greywacke protolith, occurs southeast of Granite Falls (Stop 7) and northeast of Delhi (Stop 4). Layers of mafic gneisses, including metagabbro, hornblende-pyroxene gneiss, and amphibolite occur near Granite Falls (Stops 6 and 7). The Morton Gneiss is also intruded by a younger, weakly deformed granitoid, the 2600 Ma Sacred Heart Granite (Doe and Delevaux, 1980; Schmitz et al., 2006) (Stop 5b). This unit does not intrude the Montevideo Gneiss, and no equivalent intrusive body has been recognized in the Montevideo block (cf. Table 1). Rocks in the Ortonville-Odessa area in the Benson block (Fig. 2; not visited during this trip) include little-studied granitic gneiss and paragneiss, which have recently been dated by Schmitz et al. (2006) at 2603 Ma. Proterozoic intrusive units in the Granite Falls area, most of which are not visited during this trip, include a series of northeast-trending tholeiitic diabase dikes (2080 Ma; Stop 6) and hornblende andesite dikes (1670–1730 Ma K/Ar hornblende ages; Hanson and Himmelberg, 1967; Himmelberg, 1968), and an anorogenic granite (section 28 granite, 1840 ± 20 Ma Pb/Pb age, Doe and Delevaux, 1980; Catanzaro, 1963).

STRUCTURAL GEOLOGY

Geologic mapping and structural analysis by Lund (1956), Himmelberg (1968), Grant (1972), Grant et al. (1972), and Bauer (1980) (compiled and summarized by Bauer and Himmelberg, 1993) identified and characterized several periods of ductile deformation within both the Montevideo and Morton blocks. Grant (1972) (see also Grant et al., 1972) mapped and described several upright easterly trending, moderately plunging folds in the Morton block, and Lund (1956) and Himmelberg (1968) mapped a similarly oriented fold in the Granite Falls area (Fig. 2) of the F_2 generation described here. The earliest deformation affecting the gneisses, D_1, produced a well-defined gneissic banding and a banding-parallel foliation (S_1) in all of the granitic gneisses (Figs. 3 and 4). F_1 folds in granitic veins in the gneisses are folded about S_1 (Figs. 3D and 4E). The gneissic banding was subsequently folded by the series of upright F_2 folds that plunge moderately to gently to the east-northeast (Fig. 2). Both the Morton and the Montevideo gneisses locally contain an S_2 foliation sub-parallel to the axial traces of minor F_2 folds (Fig. 3H) and rarely display F_1–F_2 type-3 fold interference patterns (Fig. 4C). The Morton Gneiss also contains numerous small steeply dipping zones of ductile shear that may also have formed during the F_2 folding (Stops 1, 2, and 5a; Figs. 3F and 3G), but these zones have not been studied in detail. Bauer (1980) recognized two younger folding events in the Granite Falls and Montevideo areas, including an F_3 fold event with steep to moderate southeast dipping, northeast striking axial planes. The north-to-northwest–directed shortening associated with the F_2 and the F_3 folding events are consistent with Neoarchean north-northwest–directed shortening associated with the accretion of the Minnesota River Valley terrane to the southern margin of the Superior Province.

Proterozoic shear zones and fracture systems are locally well developed in the Montevideo block. Numerous ductile, mylonitic

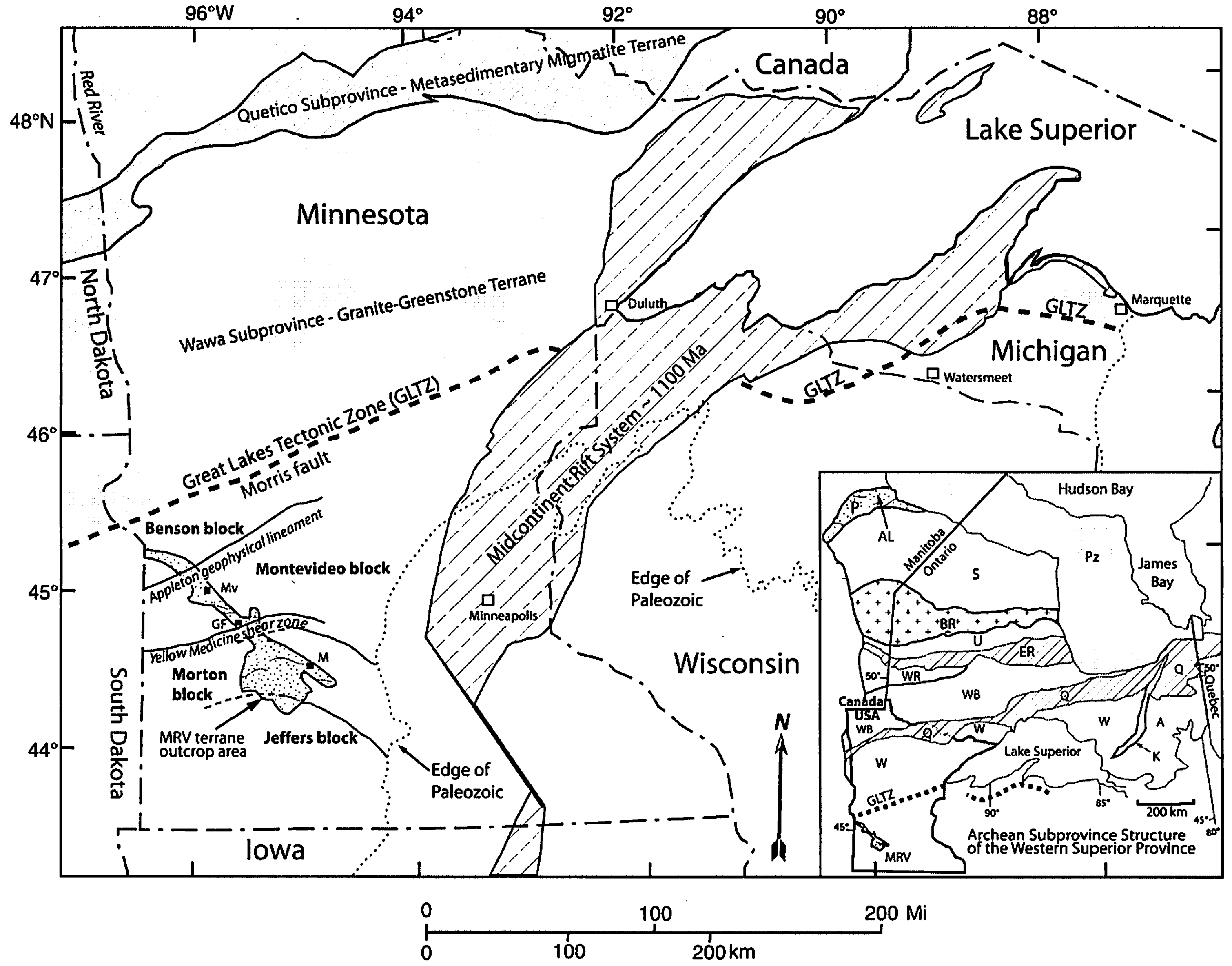


Figure 1. Maps showing the regional Archean geologic context for rocks exposed in the Minnesota River Valley terrane. Areas of Proterozoic outcrops, other than rocks of the Midcontinent rift system (MCR), are not shown (MCR beneath Paleozoic cover is based on the Midcontinent gravity anomaly). Town locations shown in the Minnesota River Valley terrane are: MV—Montevideo, GF—Granite Falls, M—Morton. Subprovince locations shown on the inset map of the western Superior Province are, from south to north: MRV—Minnesota River Valley, W—Wawa, K—Kapuskasing structural zone, A—Abitibi, Q—Quetico, WB—Wabigoon, WR—Winnipeg River, ER—English River, U—Uchi, BR—Berens River, S—Sachigo, P—Pikwitonei. AL indicates the location of the Assean Lake area; Pz indicates Paleozoic cover west and southwest of Hudson Bay and James Bay. Map sources include: Sims (1991), Southwick and Chandler (1996), and Ontario Geological Survey (1992).

TABLE 1. SUMMARY OF U-Pb SHRIMP AGES FROM ARCHEAN UNITS FROM THE MONTEVIDEO AND MORTON BLOCKS (FROM BICKFORD ET AL., 2006) AND AGES OF PROTEROZOIC INTRUSIVE ROCKS IN THE MONTEVIDEO BLOCK

Age (Ma)	Montevideo Block	Morton Block
3500	Primary crystallization of Montevideo Gneiss	Primary crystallization of Morton Gneiss
3440–3420	Zircon-forming event	Zircon-forming event
3385	Granodiorite intrusion and growth of zircon rims in Montevideo Gneiss	Local intrusion of granodiorite into the Morton Gneiss
3140	Mafic Intrusion in Montevideo Gneiss in Granite Falls	Growth of rims on older zircons in Morton Gneiss
3080	Growth of zircons in Montevideo Gneiss	
2619	Granite Falls area: high-grade metamorphism of garnet-biotite gneiss; growth of rims on older zircons in Montevideo Gneiss	Variable growth of rims on older zircons in Morton Gneiss
2604		Emplacement of Sacred Heart Granite
2080	Tholeiitic diabase dikes—K/Ar hornblende ages	
1804 ± 20	Anorogenic section 28 granite—Pb/Pb	
1670–1730	Hornblende andesite dikes—K/Ar hornblende ages	

shear zones, as much as two meters wide, deformed the Montevideo Gneiss in both the Montevideo and the Granite Falls areas (Himmelberg, 1968; Bauer, 1980; Young, 1987). Most of the zones display left-lateral displacement and trend between N 35° and 60° W (with an average of N 47° W), but a few of the zones trend ~N 45° E. The shear zones locally deform the tholeiitic diabase dikes (2080 Ma), but they are cut by the younger hornblende andesite dikes (ca. 1670–1730 Ma). The local ductile shear zones noted above in the Morton Gneiss contain minerals that have recovered their internal deformation—showing no evidence of their previous shear-induced strains—and are clearly much older than the Proterozoic shear zones near Granite Falls. Late, northeast-trending fractures zones in the Granite Falls area are locally intruded by the Proterozoic mafic dikes. More easterly trending, dextral fractures zones (Stop 6), which are approximately parallel to the Yellow Medicine shear zone, contain associated pseudotachylyte, and have been attributed to younger tectonic and isostatic adjustments along the Yellow Medicine shear zone during the Penokean Orogeny (ca. 1800 Ma) (Craddock and Magloughlin, 2005).

METAMORPHISM

Rocks of the Granite Falls and Montevideo areas have received the most extensive metamorphic studies in the Minnesota River Valley due to their granulite facies mineral assemblages. Garnet and hypersthene occur in both the mafic and granitic gneisses and in biotite-garnet-cordierite paragneiss (Stop 7) (Himmelberg and Phinney, 1967; Himmelberg, 1968). The hypersthene-bearing Montevideo Gneiss in the Granite Falls area commonly displays the dark green color typical of charnockites on fresh surfaces (Figs. 4A and 4B), whereas similar charnockite in the Montevideo area has been oxidized to a deep red color on fresh surfaces (Figs. 4F and 4H), and hypersthene is commonly replaced or partially replaced by a yellow to reddish chloritic phase (cf. Oliver and Schultz, 1968).

Outcrops near Morton, Redwood Falls, and Delhi include upper amphibolite facies assemblages (Grant, 1972). Metasedimentary units north of Delhi (Stop 4) include porphyroblasts of garnet, sillimanite, and cordierite, and local biotite-cordierite-garnet-anthophyllite assemblages that were extensively studied by Grant and Weiblen (1971). Moecher et al. (1986) completed a comparative geothermobarometric study of rocks from both the Granite Falls and Morton areas and found temperature ranges of 650–750 °C and pressures of 4.5–7.5 kbar (0.45–0.75 GPa), using a variety of thermobarometers. They attributed the observed temperature variations to varying degrees of re-equilibration of the mineral assemblages during cooling, but allowed for possible real temperature and pressure variations between the granulite and amphibolite facies regions. Himmelberg and Phinney (1967) and Himmelberg (1968) also recognized retrograde metamorphic recrystallization in rocks of the Granite Falls area, and they attributed some of the retrograde reactions to re-equilibration during cooling following the granulite facies metamorphism. However, they also attributed some of the retrogression to Paleoproterozoic events (Goldich et al., 1961; Hanson and Himmelberg, 1967; Doe and Delevaux, 1980) that are not recognized in the Morton block (Table 1).

GEOCHRONOLOGY AND ISOTOPE GEOCHEMISTRY

Geochronology

The geochronology of the gneisses exposed in the Minnesota River Valley was extensively studied during the 1960s through the 1970s (e.g., Catanzaro, 1963; Hanson and Himmelberg, 1967; Himmelberg, 1968; Goldich et al.,1970; Goldich and Hedge, 1974; Farhat and Wetherill, 1975; Wilson and Murthy, 1976; Goldich et al., 1980; Goldich and Wooden, 1980; and Wooden et al., 1980). These studies used K-Ar, Rb-Sr, and U-Pb zircon isotopic techniques to establish the antiquity of the gneisses and general aspects of the geologic history of the

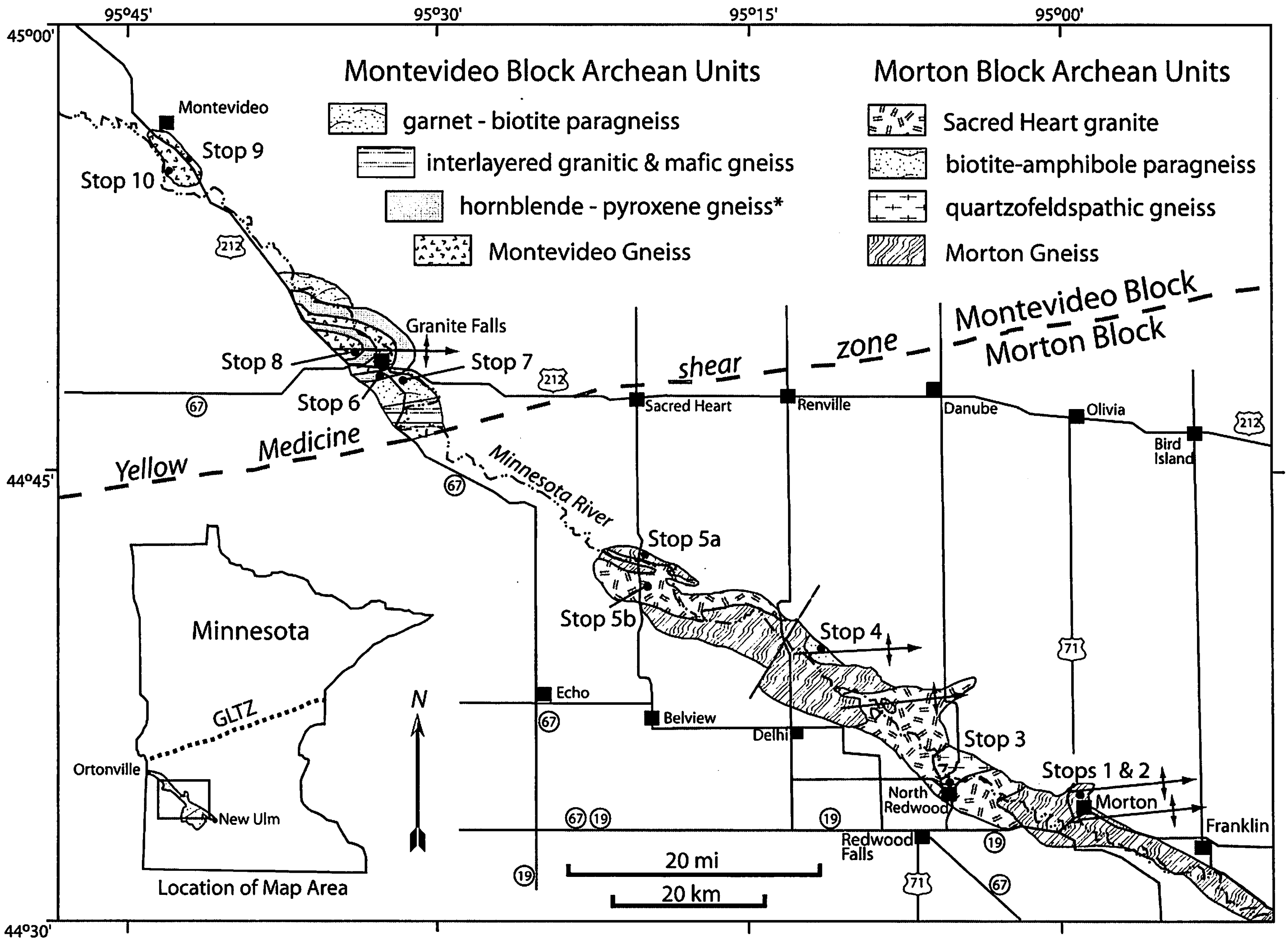


Figure 2. Simplified geologic map showing the distribution of major rocks units exposed in the Minnesota River Valley and the locations of the trip stops. The distribution of rock units is simplified from Himmelberg (1968), Grant (1972), and Southwick (2002). *The hornblende-pyroxene gneiss unit includes the metagabbro unit referred to in the text along the southeastern margin of Granite Falls. GLTZ—Great Lakes Tectonic Zone.

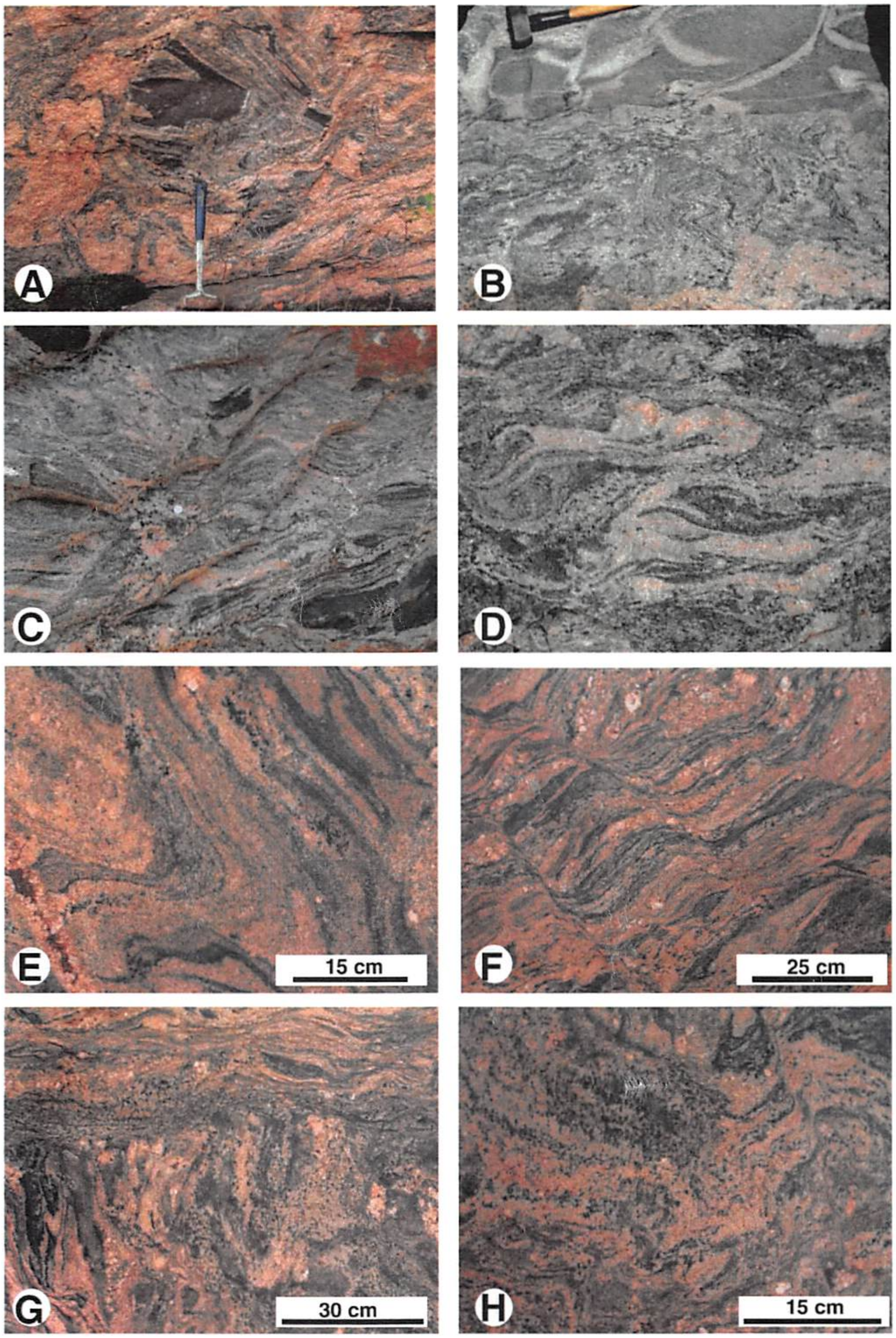


Figure 3. Morton Gneiss from Stop 1 (outcrop images A and B) and Stop 2 (polished slab images E–H), and Stop 5a (outcrop images C and D). (A) Gray tonalite gneiss with enclaves of amphibolite, intruded by pink granite pegmatite and folded by F_2 folds. (B) F_2 folding in gray tonalite cut by pink pegmatite and weakly foliated agmatitic granodiorite in the upper third of the photo. (C) Banded gray tonalite gneiss with dismembered amphibolite enclaves, intruded by pink granite pegmatite locally containing idioblastic hornblende, folded by F_2 folds and ductile shears with local fleck structure. The coin used as a scale in this and the next photograph is ~2.4 cm in diameter. (D) Granitic veins in gray tonalite gneiss aligned in S_1 gneissic banding and folded by an F_1 isoclinal fold. (E) F_2 folding of interlayered gray tonalite gneiss and pink granite pegmatite. (F) Strongly foliated interlayered gray tonalite gneiss and pink granite deformed into thin ductile shear zones. (G) Migmatitic gneiss cut by a zone of ductile shear in the upper third of the photo. (H) Interlayered gray tonalite gneiss and pink granite pegmatite folded by F_2 folds. In some zones of spotted hornblende-plagioclase layers, the hornblende and biotite clots are aligned in an S_2 foliation parallel to the axial traces of the F_2 folds.

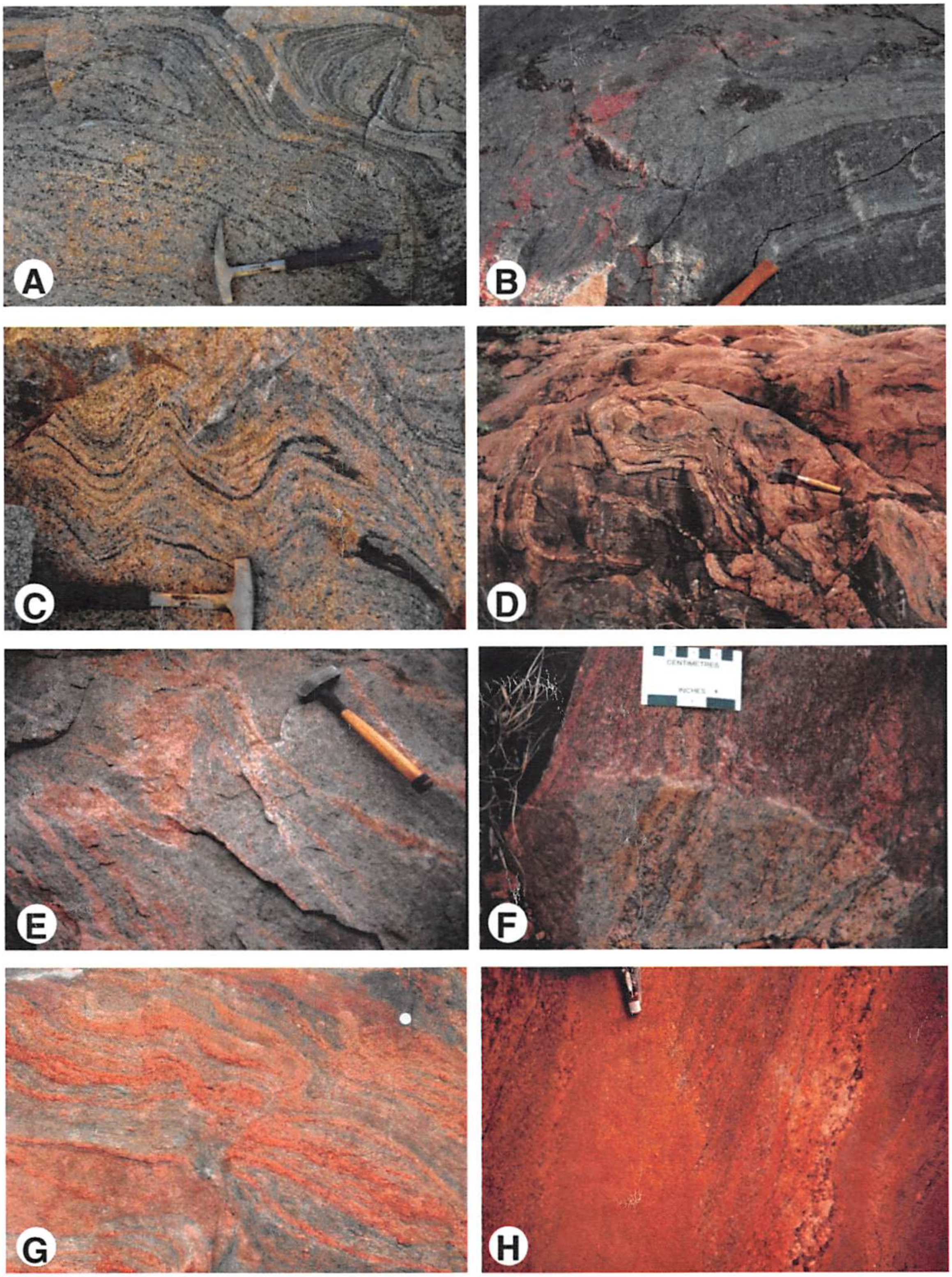
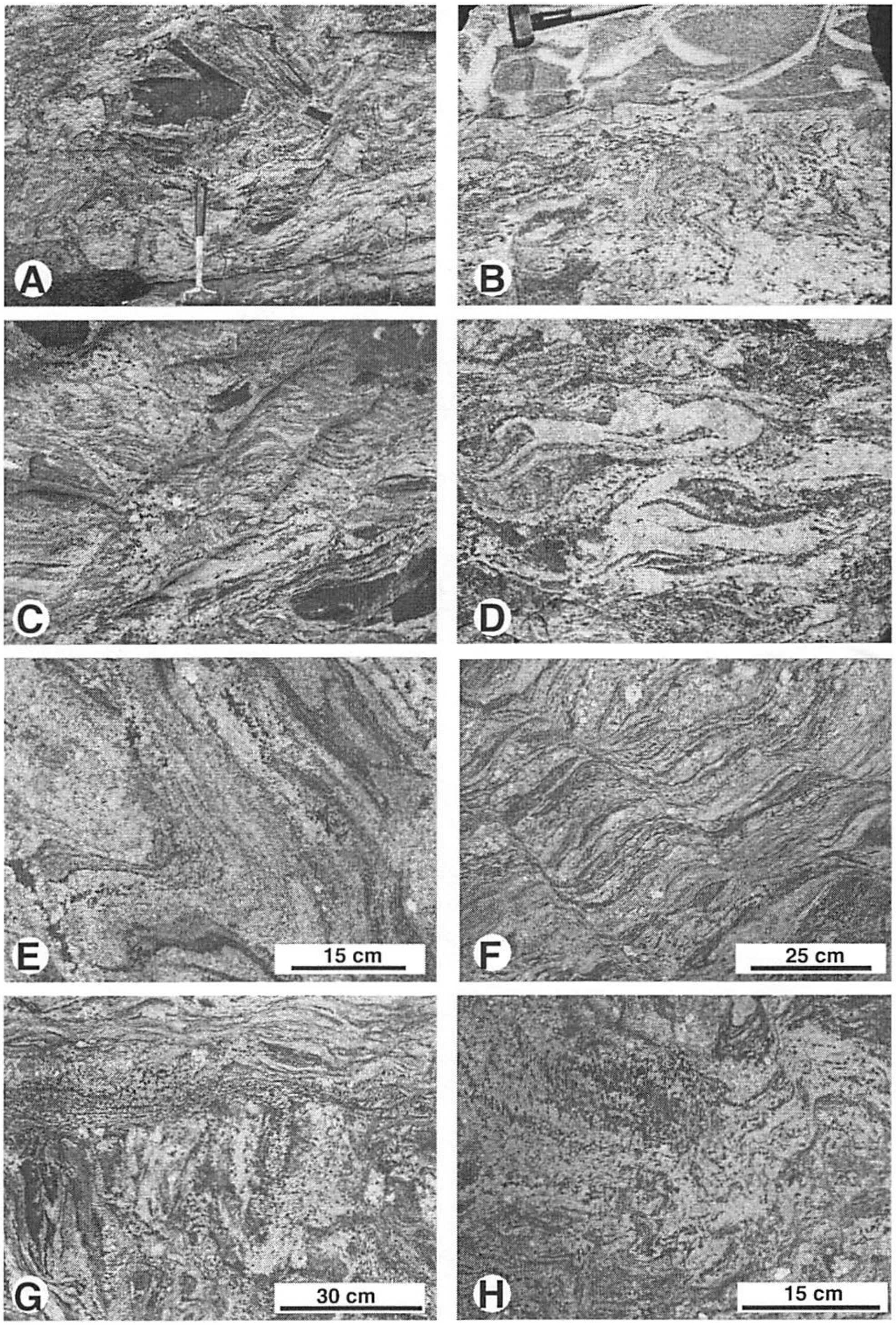


Figure 4. Montevideo Gneiss from Stops 8 (images A, B, and C), 9 (images D, E, and F), and 10 (images G and H). (A) Yellow-green charnockite gneiss folded by tight F_2 folds and younger open F_3 folds. (B) Foliated mafic unit, similar to sample MRV-8, intruded into green charnockitic gneiss with red granitic bands. (C) Granitic gneiss folded by F_1 fold (closing to the right) and refolded by upright F_2 folds. (D) Migmatite gneiss composed of foliated granodiorite intruded by pink granite. The gneissic banding is folded by an upright s-symmetry F_2 fold. (E) Pink granitic veins intruding foliated gray granodiorite and folded by F_1 folds. (F) Oxidized charnockite gneiss with brick red color on fresh surfaces. (G) Typical weathered surface appearance of the gneiss near Montevideo with folded granitic layers in gray granodiorite (coin scale diameter is 2.4 cm). (H) Polished slab of gneiss with gneissic banding cut by weakly foliated red massive granite.



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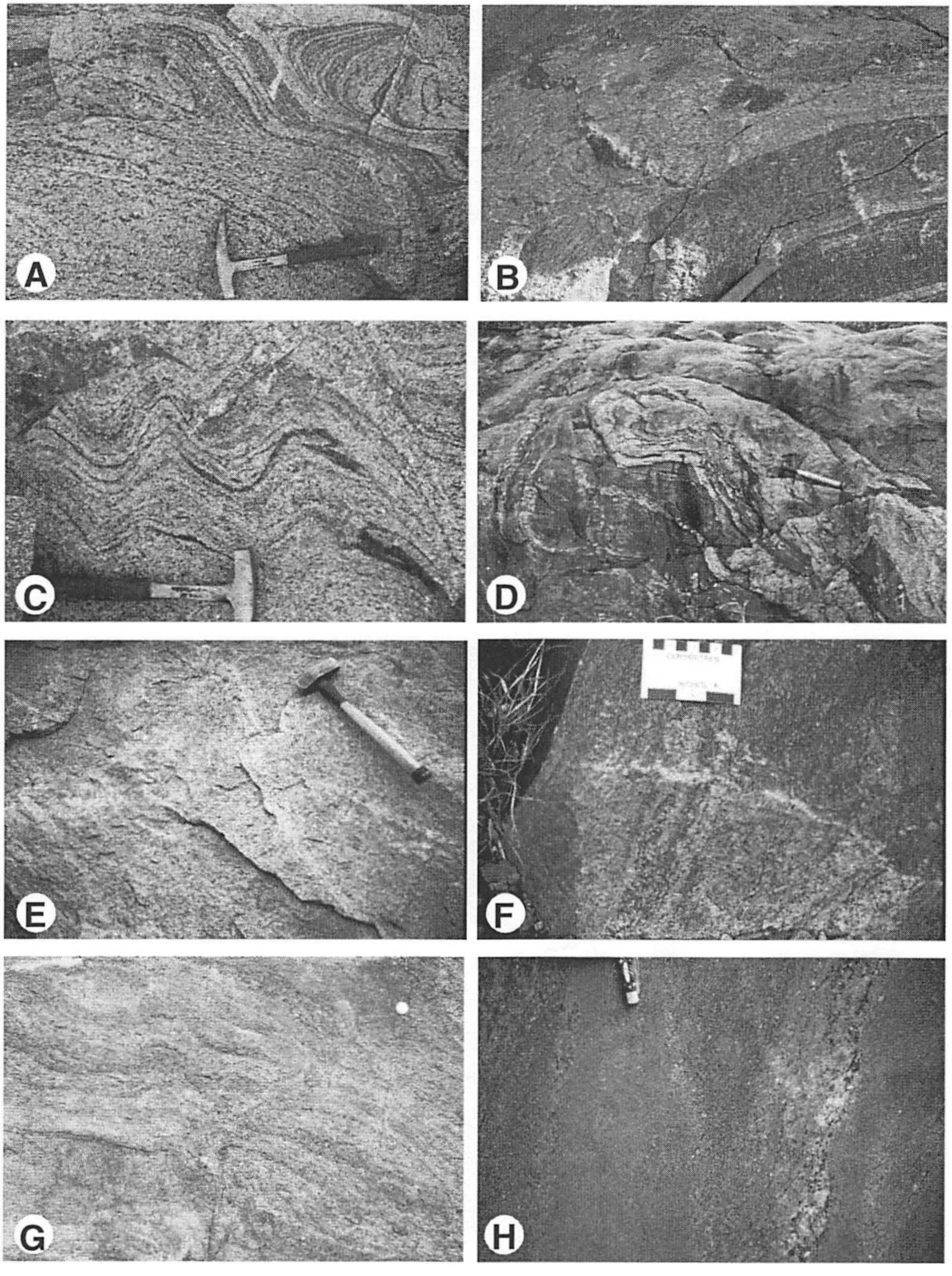

Figure 4. Montevideo Gneiss from Stops 8 (images A, B, and C), 9 (images D, E, and F), and 10 (images G and H). (A) Yellow-green charnockite gneiss folded by tight F_2 folds and younger open F_3 folds. (B) Foliated mafic unit, similar to sample MRV-8, intruded into green charnockitic gneiss with red granitic bands. (C) Granitic gneiss folded by F_1 fold (closing to the right) and refolded by upright F_2 folds. (D) Migmatite gneiss composed of foliated granodiorite intruded by pink granite. The gneissic banding is folded by an upright s-symmetry F_2 fold. (E) Pink granitic veins intruding foliated gray granodiorite and folded by F_1 folds. (F) Oxidized charnockite gneiss with brick red color on fresh surfaces. (G) Typical weathered surface appearance of the gneiss near Montevideo with folded granitic layers in gray granodiorite (coin scale diameter is 2.4 cm). (H) Polished slab of gneiss with gneissic banding cut by weakly foliated red massive granite.

terrane. However, more recent U-Pb SHRIMP zircon geochronology studies by Bickford et al. (2006) and high-precision thermal ionization mass spectrometry (TIMS) measurements by Schmitz et al. (2006) have considerably refined understanding of the complex history of the Minnesota River Valley gneiss terrane. The ages and associated interpretations presented here are based mostly upon the geochronology of Bickford et al. (2006), which was done on the SHRIMP-RG (sensitive high-resolution ion microprobe reverse geometry) instrument at the Stanford–U.S. Geological Survey Laboratory at Stanford University, with additional reference to the studies of Schmitz et al. (2006) for data on the Sacred Heart Granite.

Because previous studies had suggested that rocks in the Minnesota River Valley might be as old as 3800 Ma (Rb/Sr study of Goldich and Hedge, 1974), Bickford et al. collected samples primarily in a search for very old components. However, their results showed that the oldest rocks are 3500 Ma, and that—as could have been predicted—these rocks had a long and complex history. That history was beautifully recorded in "zircon growth" events that presumably entailed elevated temperatures and the presence of fluids. Examples of zircons with multiple overgrowths are shown in Figure 5, and the contexts for the ages represented are discussed below in association with specific trip stops.

As shown in Table 1 (modified from Bickford et al., 2006), the primary age of both the Montevideo and Morton gneisses is 3500 Ma; however, there was also a 3440–3420 Ma zircon-forming event. In the Montevideo block, this event is recorded in the age of a zircon core in a late, 3140 Ma foliated mafic intrusion (noted below) into the Montevideo gneiss (Figs. 4B and 5C); in the Morton block, 3440 Ma ages have also been reported from the Morton gneiss by Schmitz et al. (2006) and I.S. Williams (2005, personal commun.). There was a widespread event at ca. 3380 Ma that is represented by granodiorite intrusions into both the Montevideo and Morton gneisses, and this event is also recorded by overgrowths on older zircon cores in both the Montevideo and Morton gneisses.

Bickford et al. (2006) collected the mafic intrusive rock (noted above) (MRV-8, Fig. 4B) in the classic "Green Quarry" of previous studies (currently operated by Martin Marietta Aggregates; Stop 8), hoping that it would be an early phase of the Montevideo gneiss. However, it turned out to be a considerably younger mafic intrusion, with an age of 3140 Ma. Rims of this age are found on older zircons in the Morton gneiss, indicating that this was a widespread zircon-forming event. Zircons in the Montevideo gneiss also display overgrowths that yield ages of 3080 Ma, although no zircons or overgrowths of this age were found in the Morton gneiss. This age may be a thermal response to intrusion of the red, massive granitic phase described by Bauer (1980) (Fig. 4H), which cuts the banding in the Montevideo Gneiss near Montevideo (Stops 9 and 10), but has not been found in the Morton Block.

Finally, the Sacred Heart Granite, dated by Bickford et al. (2006), yielded an age of 2604 Ma, an age confirmed by the

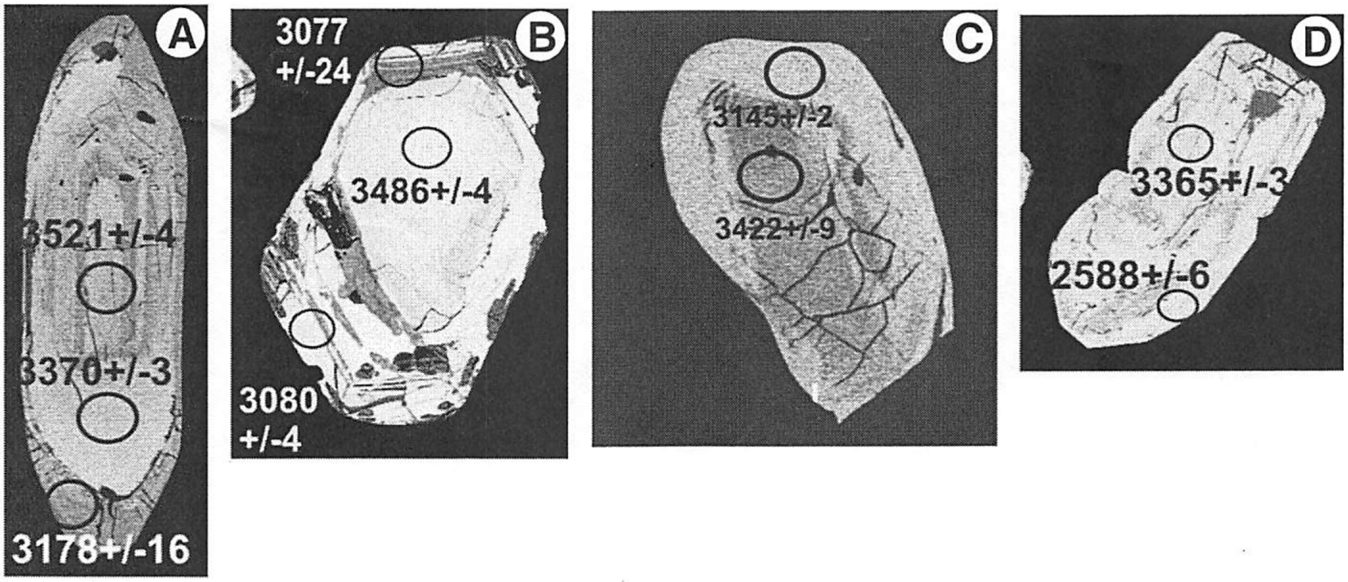

Figure 5. Back-scattered electron scanning electron microscope images of zircons analyzed and discussed by Bickford et al. (2006) showing core-overgrowth relations. (A) Zircon image from sample MRV-6 (Morton gneiss, Stop 5a) that shows 3521 ± 4 Ma core with a 3370 ± 3 Ma overgrowth, in turn overgrown by 3178 ± 16 Ma zircon. (B) Zircon image from sample MRV-1 (Montevideo gneiss, Stop 9) showing 3486 ± 4 Ma core overgrown by 3080 ± 4 Ma rim. (C) Zircon image from sample MRV-8 (mafic unit from Stop 8) showing a 3422 Ma core, presumed to have been inherited from Montevideo Gneiss country rock, and a rim with an age of 3145 Ma interpreted as the age of the mafic intrusion into the gneiss. (D) Zircon image is from Sample MRV-4 (Morton gneiss, Stop 1) and shows a 3365 ± 3 Ma core overgrown by a 2588 ± 6 Ma zircon rim.

TIMS analyses of Schmitz et al. (2006). The emplacement of the Sacred Heart Granite coincided with widespread high-grade metamorphism, based on the fact that only ca. 2600 Ma zircons have been found in the garnet-biotite gneiss in the Granite Falls area (Stop 7), and distinctive 2600 Ma overgrowths have been found on older zircon cores in both the Montevideo and Morton gneisses.

The major tectonothermal events recognized in the zircon geochronology occurred in both the Morton and the Montevideo blocks, indicating that both blocks have had a common history since ca. 3500 Ma.

Isotopic Chemistry

Until recently, the only isotope geochemistry available for Minnesota River Valley rocks was Sr isotopic data reported by Goldich et al. (1980) and Goldich and Wooden (1980); Goldich and Wooden also reported preliminary Sm-Nd ages, ranging from 3600 to 3200 Ma, for rocks in the Morton area that were measured by M.T. McCulloch and G.J. Wasserburg. McCulloch and Wasserburg (1980) also reported a Nd model age of 3580 ± 30 Ma for residual clay developed on Morton gneiss. In fall 2008, Bickford and Syracuse University graduate student Aaron Satkoski traveled to the University of Florida to obtain Hf isotopic data from the zircons in the Bickford et al. (2006) SHRIMP mount. Because the data proved intensely interesting (see below), in 2009 Bickford, with colleagues Scott Samson, Aaron Satkoski, and field guide Bob Bauer, collected new samples from the Minnesota River Valley exposures to be used, in addition to the samples of Bickford et al., for Sm-Nd analyses.

The Hf isotopic data are shown in Figure 6, an initial ε_{Hf} versus age plot. Shown on the plot are isotopic evolution lines based on ^{176}Lu/^{176}Hf = 0.005. Although this ratio is lower than published values, it was calculated from whole-rock trace-element data. The most interesting observation is that Hf isotopic compositions from zircons in essentially all of the rocks studied, including the 3380 Ma granodioritic intrusions into both the Montevideo and Morton gneisses, plot along the Hf evolution trajectory of the Morton and Montevideo gneiss. This indicates that the gneiss complex has remained essentially a closed system, melting and re-melting for ~900 Ma, with little to no new juvenile or evolved crustal input. Exceptions are the Sacred Heart Granite and the 3140 Ma mafic intrusion, whose ε_{Hf} values are significantly more positive, indicating that the granite and the mafic intrusion are mixtures of juvenile components with much older, presumably 3500 Ma, crust. This observation is consistent with the finding of a 3420 Ma core in a zircon from the mafic intrusion.

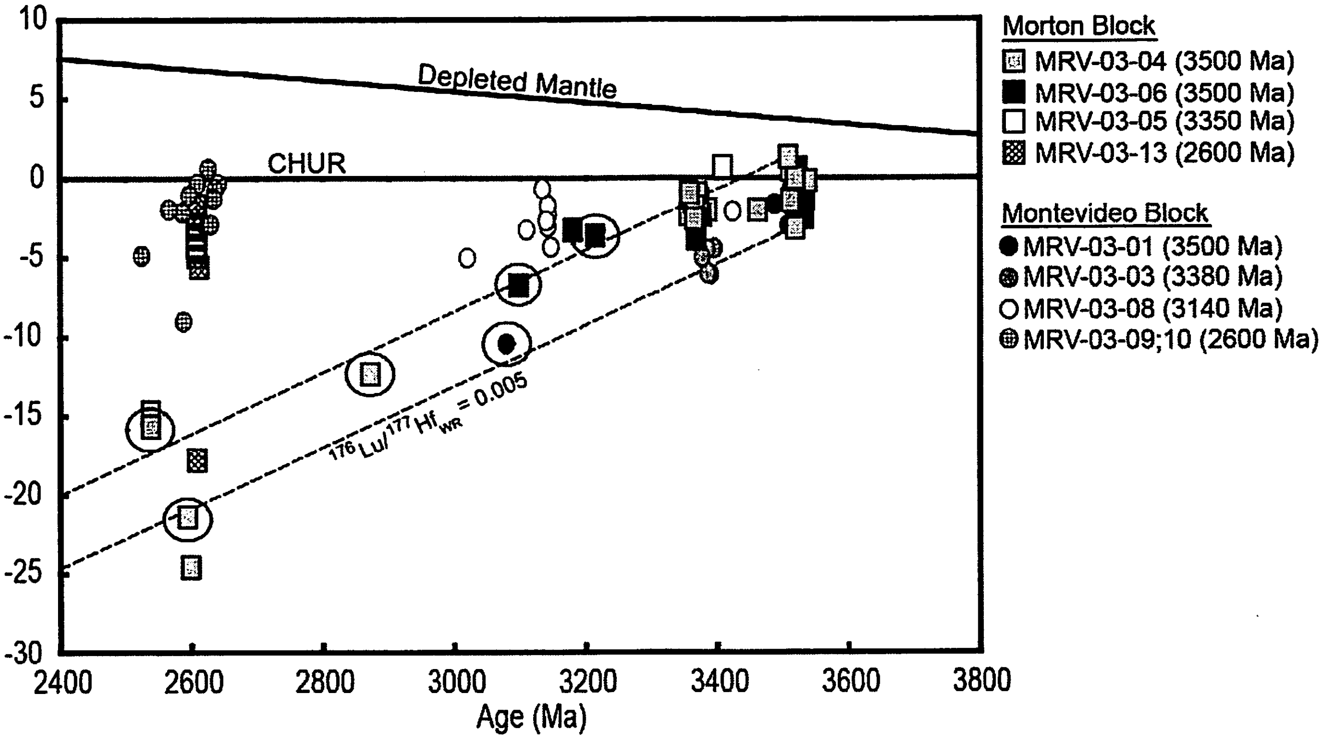

Figure 6. Age versus initial ε_{Hf} diagram for zircon from the Minnesota River Valley (MRV). Ages are from the ^{207}Pb/^{206}Pb data of Bickford et al. (2006). Dashed lines are the whole-rock evolution paths calculated from 176Lu/177HfWR = 0.005; this ratio was calculated from the average Lu/Hf ratio of the 3500 Ma samples. Circled data points are data collected from younger zircon rims on older cores. Values for CHUR (chrondritic uniform reservoir) are after Blichert-Toft and Albarède (1997). Depleted-mantle values of ε_{Hf} = 0 at 4.65 Ga and 16 at 0 Ga are after Nowell at al. (1998).

The Hf data also demonstrate that the oldest rocks, the Montevideo and Morton gneisses, do not have crustal residence ages greater than ca. 3600 to possibly 3700 Ma, and thus were not formed by melting of much older crustal rocks. New Sm-Nd data, although still preliminary at this time, are consistent with the Hf isotopic data. The TTG compositions of the gneisses are consistent with derivation by partial melting of amphibolitic rocks that were not older than ca. 3700 Ma.

DAY 1.

Entering the town of Morton from the west on Minnesota Highway 19 (W. 2nd Street), turn left on Centennial Drive. Park behind the school on the immediate left and walk NW on N. Centennial to paths accessing the abandoned quarries to the west.

Stop 1. Morton Gneiss Abandoned Quarries
(15T 341730 E, 4935238 N)

The Morton area is the type locality for the Morton Gneiss, and the quarries at this stop display the best available exposures of the gneiss. The pit walls and the adjacent waste piles provide fresh rock exposures that have been sampled by all of the geochronologic studies of the Morton gneiss. The unit is a complex migmatitic gneiss (Figs. 3A–3H) that includes: (1) an early gray foliated biotite tonalite gneiss; (2) local bands of spotted hornblende-plagioclase layers with idioblastic hornblende (granoblastic hornblende granodiorite of Goldich et al., 1980; stictolithic or fleck structure of Mehnert, 1971); (3) layers of pink granite to leucogranite pegmatite; and (4) rafts and schlieren of amphibolite. Sparse exposures of a fine-grained reddish gray-brown granodiorite (upper part of Fig. 3B), with a weak biotite foliation, occur in the southernmost quarry pit. This unit includes irregular blocks of the granodiorite surrounded by diffuse pink-to-tan veins of fine-grained granite. Goldich et al. (1980) described and referred to this unit as agmatitic granodiorite. It is similar to, and probably an equivalent of the foliated granodiorite at Stop 3.

The quarries of this stop lie near the culmination of an F_2 antiform (Fig. 2) mapped by Grant (1972), and all of the units are locally folded by F_2 folds (in the fold sequence nomenclature of Bauer, 1980, noted above). Small-scale F_2 folds fold the strong gneissic banding and locally have sheared limbs that appear to have formed during the late stages of the folding (cf. Fig. 3C). These shears commonly contain small pockets of the granoblastic hornblende granodiorite (fleck structure).

Sample MRV-4 from this location, dated by Bickford et al. (2006), yielded two groups of zircon ages: 3516 ± 17 Ma and 3360 ± 9, with rims yielding ages of 3145 ± 2 and 2595 ± 4.

Return to Highway 19 (W. 2nd Street) and turn left. Continue six blocks to the NE on W. 2nd Street, turn right on N. Main Street continuing past W 1st Street to the Cold Spring Granite–Morton Quarry entrance. This is a private operating quarry that is not available to the general public.

Stop 2. Morton Gneiss Operating Quarry
(15T 343045 E, 4934600 N)

The Morton Quarry, operated by the Cold Spring Granite Company of Cold Spring, Minnesota, produces dimension stone from the Morton Gneiss (trade name Rainbow Granite) and sells it as building facing stone and counter tops throughout the country. For instance, Figures 3E, 3F, 3G, and 3H are photographs from both the exterior and interior walls of the Adler Planetarium in Chicago. Several of the buildings on Hennepin Avenue in downtown Minneapolis have ground-level facing stone from this quarry. The walls of the Morton Quarry, which are flat from the quarrying process, have exposures of the Morton Gneiss and the features described for Stop 1. The actual exposed features and proportion of the various gneiss components (e.g., gray gneiss versus red granite) vary with time in response to the quarrying process. The quarry operates on a demand basis and may not be active at the time of our trip. However, we will be met by a Cold Spring Granite representative who will provide a tour of the facilities and describe the dimension stone processing at the quarry.

Return to Highway 19 and turn left (southwest). Proceed to the T-intersection of Highway 19 and Minnesota Highway 71/ Highway 19 and turn left. Proceed west to Redwood Falls (~7.3 mi). At 15T, 333501 E, 4934139 N turn right (north) onto Redwood County Road 101. Pass through the town of North Redwood on Road 101 and cross the Minnesota River Bridge where Highway 101 becomes Renville County Road 1. At 15T, 334169 E, 4937779 N (~0.5 mi past the bridge) turn right onto a gravel quarry road.

Stop 3 (Optional Stop). Granodiorite Intrusion into Morton Gneiss
(15T 334134 E, 4937693 N)

Outcrops in this quarry contain exposures of the weakly foliated granodiorite, which was discussed for Stop 1 (agmatitic granodiorite of Goldich et al., 1980). This unit intrudes the Morton Gneiss (Fig. 3B). Sample MRV-5 of the granodiorite, dated by Bickford et al. (2006) from this location, yielded consistent zircon U-Pb data giving an age of 3377 ± 19 Ma.

Return to Renville County Road 1 and turn right (north). Travel ~0.5 mi to 15T 334437 E, 4938636 N and turn left (northwest) onto Renville County Road 15. This road runs parallel to the Minnesota River. Travel ~8 mi to the farm road at 15T 326065 E, 4945885 N. This is the entrance to private property containing Stop 4.

Stop 4. Feldspar Biotite Schist (Paragneiss) and Amphibolite
(15T 325685 E, 4945745 N)

Scattered low-lying outcrops at this stop contain paragneiss and amphibolite in a series of east-southeast–trending synforms mapped by J.A. Grant, which are illustrated in Grant et al. (1972).

Grant recognized a lower unit of quartzo-feldspathic gneiss, overlain successively by an amphibolite-quartz-cummingtonite gneiss and two paragneiss units—a thinly banded biotite-cordierite-anthophyllite gneiss (Grant and Weiblen, 1971) and an overlying biotite-quartz-plagioclase gneiss with or without microcline, muscovite, cordierite, garnet, or sillimanite.

Grant interpreted the paragneiss units as the uppermost units in the Morton block, and this interpretation is supported by detrital zircon studies of Bickford et al. (2006). Sample MRV-11 from Grant's uppermost unit, yielded a suite of detrital zircons with ages of 3520, 3480, 3380, 3140, and 2600 Ma (Fig. 7). This detrital age spectrum displays all of the "zircon forming" events recognized in studies of other rocks in the Minnesota River Valley (Table 1). The 2600 Ma ages were only determined from rims on older grains, indicating that the feldspar-biotite gneiss protolith accumulated after 3140 Ma but prior to the 2600 Ma event.

Return to Renville County Road 15 and continue northwest ~2.5 mi to the intersection with Renville County Road 6. Turn right onto County Road 6, and travel ~0.2 mi to a left turn back onto Road 15. Continue northwest on County Road 15 ~7.0 mi to Renville County Road 9 and turn left (south) and continue ~0.4 mi to a road cut in the Morton Gneiss (Stop 5a).

Stop 5. Overview

The contact zone between the Morton Gneiss, and associated amphibolite, with the Sacred Heart Granite occurs adjacent to the stretch of Renville County Road 9 and its continuation south of the Minnesota River as Redwood County Road 7. Grant (1972) and Welsh (1976) described interlayering of the gneiss and the granite across this zone, which includes a clinopyroxene syenite interpreted to be a result of partial assimilation of amphibolite by the intruding granite (Welsh, 1976). Stop 5a, at the northern extent of the outcrops includes exposures of the Morton Gneiss. Stop 5b, at the southern outcrop, includes uncontaminated exposures of the Sacred Heart Granite that grade into the contaminated contact zone.

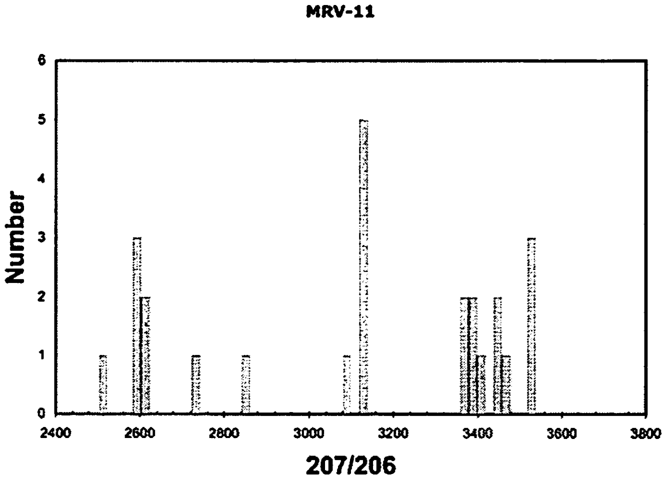

Figure 7. Histogram showing the distribution of detrital zircon ages from sample MRV-11 of feldspar-biotite schist from Stop 4.

Stop 5a. Morton Gneiss Road Cut
(15T 314600 E, 4951896 N)

This relatively new road cut provides good exposures of the Morton Gneiss. All of the features described for Stop 1 are also evident at this stop, including amphibolite rafts in the S_1-foliated gray tonalite gneiss (Fig. 3C), granitic veins in the gneiss that are locally folded about S_1 (Fig. 3D), zones of ductile shear in the gneiss, and local bands of spotted hornblende-plagioclase layers. Sample MRV-6 of Bickford et al., (2006), collected from this stop, yielded two zircon populations: 3529 ± 3 Ma and 3356 ± 10 Ma, essentially the same as MRV-4 from Stop 1. Interestingly, zircon rims gave ages of 3178 ± 18 Ma, whereas ca. 2600 Ma rims, which might have been expected from the proximity of this site to the Sacred Heart Granite contact, were not recognized

Stop 5b. Sacred Heart Granite Road Cut
(15T 314605 E, 4950835 N)

The granite at the southern end of this site is uncontaminated and similar to the main part of the Sacred Heart pluton. It is typically a pink, medium-grained massive to weakly foliated unit that locally has a faint banding folded by open F_2 folds. To the north, this unit grades abruptly into the pyroxene syenite contact zone, which contains partially resorbed inclusions of amphibolite.

Sample MRV-13 comes from uncontaminated Sacred Heart Granite ~250 m south of this stop (15T 3146356 E, 4952557 N). This sample yielded a concordia upper intercept age of 2604 ± 5 Ma, consistent with the 2605 ± 6 Ma Pb-Pb age of Doe and Delevaux (1980). Schmitz et al. (2006) reported a TIMS age of 2603 ± 1 for both the Sacred Heart Granite and the Ortonville Granite.

Travel south on County Road 7 ~1.0 mi to the crossing intersection with County Road 27 and turn right (west). Continue ~1.0 mi to the Y intersection and continue west (left road) on Yellow Medicine County Road 2 for ~3.0 mi to the intersection with Minnesota Highway 67. Turn right (north) on Highway 67 and continue north and northwest ~13.3 mi to the intersection of Highway 67 and Minnesota Highway 23, just south of the town of Granite Falls. Cross the intersection to examine road-cut outcrops at Stop 6 on the northwest corner of the intersection.

Overview of the Granite Falls Area

The Granite Falls antiform (Fig. 2), originally mapped by Lund (1956) and Himmelberg (1968), includes the Montevideo Gneiss, two mafic units that Himmelberg characterized as hornblende-pyroxene gneiss, and an outer metasedimentary unit that he referred to as garnet-biotite gneiss (referred to here as a paragneiss). All of the units contain granulite facies mineral assemblages (Himmelberg and Phinney, 1967; Himmelberg, 1968). Although the hornblende-pyroxene gneiss is mapped as two layers of a single unit, it includes both a mafic migmatite containing granitic layers and a more massive metagabbro unit that contains little or no granitic layering, which is located only on the southern limb of the fold.

Stop 6. Metagabbro Road Cut
(15T 298519 E, 4964203 N)

Metagabbro at this stop intruded the Montevideo Gneiss along the southern limb of the Granite Falls antiform, and includes exposures in sections 3 and 4 of T. 115 N., R 39 W. and section 34 of T. 116 N., R 39 W. (see the geologic map of Himmelberg, 1968). The unit comprises uniformly gray medium-grained rock with a weak compositional banding and a typical mineral assemblage of plagioclase-hornblende-clinopyroxene-orthopyroxene. Wilson and Murthy (1976) report a low-K tholeiitic composition for the unit and a Rb-Sr age of 2680 ± 200 Ma. This poorly constrained age, nevertheless, suggests that the metagabbro may have been intruded during high-grade metamorphism at ca. 2619 Ma (Table 1). As such, intrusion of this unit could have helped to produce the granulite facies conditions experienced by the units in the Granite Falls–Montevideo area relative to the amphibolite facies conditions displayed by units in the Morton block.

Steeply dipping Proterozoic fractures and narrow shear zones in this outcrop trend ca. N.80° E., approximately parallel to the Yellow Medicine shear zone (Fig. 2), and contain variably oriented pseudotachylite seams (as much as 2 cm wide) and associated calcite veins (Craddock and Magloughlin, 2005). The pseudotachylite formed in a number of phases, and kinematic reconstruction is complex. Winged porphyroclasts in the country rock preserve dextral and sinistral kinematic displacement, primarily opposite the sinistral sense of S-C structures in the country rock and of sinistral fault drag indicators along the strike-slip zones that contain the pseudotachylite seams. Craddock and Magloughlin interpret the fractures and pseudotachylite to have formed during phases of tectonic and isostatic adjustments along the Yellow Medicine shear zone during the Penokean orogeny (ca. 1.8 Ga).

DAY 2.

Return to the intersection of Minnesota Highways 23 and 67, and turn east onto Highway 67. Continue ~0.65 mi to the Granite Falls Municipal Park. There are turn offs on both the left and the right into the park. Take the right (west) turn and park to the left side of the park road.

Stop 7. Hornblende-Pyroxene Gneiss and Garnet-Biotite Paragneiss, Granite Falls Municipal Park
(15T 299157 E, 4963972 N)

This stop includes units on the southern limb of the Granite Falls antiform (Fig. 2) that dip steeply to the south-southeast. Outcrops of hornblende-pyroxene gneiss occur along both park roads extending to the east and west of Highway 67, and along the extensive road cut to the southeast along Highway 67. *Beware of road traffic; the shoulder is narrow along the road cut.* Outcrops of the garnet-biotite paragneiss occur along the southeastern extension of the Highway 67 road cut and to the east and west of the highway. A Proterozoic mafic dike cuts the hornblende-pyroxene gneiss in the northwestern part of the road cut, nearest the park roads.

The hornblende-pyroxene gneiss is a gray to black, medium-grained rock with a typical mineral assemblage of plagioclase-hornblende-clinopyroxene-orthopyroxene-quartz, ±garnet, ±biotite. The concordant contact with the garnet-biotite paragneiss in the road cut is marked by the first appearance of significant garnet. The typical assemblage in this unit is quartz-plagioclase-biotite-garnet-hypersthene ± cordierite. The freshest samples of this unit occur along a power line cut to the east of this stop near the Minnesota River, where samples analyzed by Bickford et al. (2006) were collected. Zircons analyzed from this unit gave an upper-intercept age of 2619 ± 20 Ma. Only one older zircon was found in their study, presumably a detrital grain, which yielded an age of 2994 ± 10 Ma.

Turn left (northwest) onto Highway 67 and return to the intersection with Highway 23. Turn right (north) onto Highway 23 and continue ~0.35 mi to the intersection with U.S. Highway 212. Continue north across Highway 212 into the central part of Granite Falls on Granite Street. Four blocks north of the intersection, turn left (west) at the T-intersection onto 9th Avenue (County Highway 22). Continue west ~1.0 mi to 14th Street (just past the railroad tracks) and turn right. Continue north on 14th Street to the entrance of the Martin Marietta Aggregate quarry entrance. Entrance to the quarry must be arranged in advance and may not be available depending on blasting schedules.

Hard hats are required. Quarry walls may be unstable, particularly near recently blasted areas. Avoid steep and highly fractured quarry walls.

Stop 8. Montevideo Gneiss, Martin Marietta Aggregates—Granite Falls Quarry
(15T 297693 E, 4965789 N)

This location, the "Green Quarry" mentioned in previous literature, is the site for many of the dated samples of the Montevideo Gneiss from Granite Falls. The granite gneiss is strongly banded with alternating layers containing variable amounts of plagioclase, microcline, and biotite. The typical mineral assemblage of the gneiss is quartz-plagioclase-microcline-biotite, ±hypersthene, ±garnet. The hypersthene-bearing rocks have the typical greenish color of charnockite on fresh surfaces (Figs. 4A and 4B).

The quarry walls have provided some of the best evidence for and exposures of the multiple fold events that deformed the gneiss. The quarry lies along the axial trace of the Granite Falls antiform (Fig. 2), and the gneissic banding and S_1 foliation are commonly folded by upright symmetric F_2 folds with easterly striking axial planes (Fig. 4C). Tight to isoclinal recumbent F_1 folds are present, which can also be recognized in F_1-F_2 interference patterns (Fig. 4C). Open F_3 folds, described by Bauer (1980), locally deform the limbs of F_2 folds (Fig. 4A).

Dismembered rafts of mafic intrusive rocks occur within the gneiss, but they tend to be larger and less numerous that those in the Morton Gneiss. A steep, northeast-striking Proterozoic dike cuts through the central part of the quarry.

Dated rocks from this site include the Montevideo Gneiss and a dismembered mafic unit in the gneiss. Sample MRV-7 of the Montevideo gneiss yielded an age of 3496 ± 9 Ma, but a number of grains yielded ages in the 3350–3300 Ma range and many grains have 2600 Ma overgrowths. Sample MRV-8, which was collected in the hope of finding an older phase of the Montevideo gneiss, nevertheless yielded an age of 3141 ± 2 Ma, and thus could be a disrupted late mafic intrusion into the Montevideo gneiss. This unit, a foliated plagioclase-pyroxene rock, is similar to the mafic layer in the gneiss shown in Figure 4B. This unit also contained a zoned zircon with a core, presumed to have been inherited from Montevideo Gneiss country rock, with a 3422 Ma age (Fig. 5C).

Return to 14th Street and continue south, crossing 9th Avenue to 11th Avenue. Turn right (west) and continue ~0.75 mi on 11th Avenue to the intersection with U.S. Highway 212. Turn right (north) onto 212 and continue ~10.3 mi toward the town of Montevideo. Stop 9 is southeast of Montevideo. Park vehicles just beyond the road cut or on a short side road to the railroad tracks (to the northeast), which is just beyond the road cut.

Stop 9. Montevideo Gneiss, Road Cut on U.S. Highway 212 and an Adjacent Railroad Cut

(15T 286918 E, 4977694 N)

This outcrop was designated the type locality for Montevideo Gneiss of Lund (1956), and it has provided samples for most of the geochronologic studies of the gneiss (Goldich et al., 1961; Goldich, et al., 1970, Goldich and Hedge, 1974; Farhat and Wetherill, 1975, Goldich and Wooden, 1980; and Bickford et al., 2006). Sample MRV-1 of the gray granodiorite gneiss from this location, analyzed by Bickford et al. (2006), yielded an age of 3485 ± 10 Ma. However, zircon rims with ages of 3380 Ma and 3080 Ma were also observed (e.g., Fig. 5B).

The gneiss at this location includes an early phase of medium-grained, S_1-foliated, gray biotite granodiorite that is cut by layers of courser grained pink granite (Figs. 4D, 4E, and 4F). The granite layers are locally folded about the S_1 foliation (Fig. 4E), and tightly folded granitic layers aligned in S_1 define the gneissic banding in the unit. Locally, a finer grained, weakly foliated, massive granitic phase cuts both components of the gneiss and the S_1 foliation (Fig. 4H). All of the granitic units contain mineral assemblages of quartz-plagioclase-microcline, ±garnet, ±hypersthene (rare). The plagioclase is commonly antiperthitic, and the microcline is commonly mesoperthitic. The rare hypersthene is generally partially replaced by a yellow-gold chloritic phase that also appears as a probable complete replacement of hypersthene in some rocks. On fresh surfaces, all of the components of the gneiss have a brick-red color (Figs. 4F and 4H), which is common to oxidized variants of green charnockite such as the charnockite at Stop 8 (Figs. 3A and 3B).

The banding of the interlayered gneiss units throughout the Montevideo area dips moderately to the southeast and is folded by easterly plunging upright F_2 folds. The invariable s-symmetry of the F_2 folds in the gneiss is consistent with the occurrence of the Montevideo outcrops on the northern limb of a major, unexposed F_2 synform in the covered region between this stop and the northern limb of the Granite Falls antiform.

Continue northeast on Highway 212 ~1.8 mi. Turn left (southwest) on U.S. Highway 59 and turn left (southeast) again within ~50 m onto a gravel road. Continue ~0.15 mi to a Y intersection and take the left fork south onto River Road SW. Continue south ~1.25 mi to a dirt road on the left at 15T 285448 E, 4977453 N. Park on the side of the road and walk northeast ~200 m up the road to abandoned quarry pits and waste piles in the Montevideo Gneiss. Stop 10 lies along the southern edge of a large wetlands slough and ~400 m west-northwest of Carlton Lake.

Stop 10 (Optional). Montevideo Gneiss at Carlton Lake Quarry

(15T 285611 E, 4977569 N)

The gneiss at this outcrop (Figs. 4G and 4H) has the same characteristics found at Stop 9. The red massive phase of the gneiss is more common as lit-par-lit injections parallel to the gneissic banding as well as layers crossing the banding (Fig. 4H). The quarry waste piles afford excellent samples of the various phases of the gneiss and good candidates for photographs of the gneiss features.

Sample MRV-3 collected by Bickford et al. from this location yielded an age of 3385 ± 8, and is thus a later intrusion into the Montevideo gneiss. One xenocryst with an age of 3500 ± 3 Ma was found.

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