STATE MAP SERIES S-21
Bedrock Geology

GEOLOGIC MAP OF MINNESOTA
BEDROCK GEOLOGY

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INTRODUCTION

This map is a new construct that incorporates existing geologic maps where prior mappers had adequate ground control, and new interpretations based on drill hole, geophysical, and unpublished data where they did not. The interpretation differs significantly from previous maps to reflect new data and accommodate scale. It portrays our current geologic understanding of the temporal and geographic distribution of units within major Precambrian terranes (Fig. 1), and of the Phanerozoic strata. The western part of the map is inferred largely from geophysical maps, anchored locally by drilling. In many places, contacts are drawn between units of the same or similar apparent rock type (and same unit label); these are recognized as geometrically distinct, though geophysically or lithologically similar. Digital files corresponding to this map allow removal of Cretaceous, Paleozoic, and some parts of Mesoproterozoic strata to reveal an interpretation of the underlying Precambrian bedrock.

DESCRIPTION OF MAP UNITS

PHANEROZOIC ROCKS

MESOZOIC

Cretaceous

Ku **Undifferentiate**d—Conglomerate, sandstone, mudstone, shale, marlstone, siltstone, and minor lignite, deposited in marine and non-marine settings; likely Cenomanian to Campanian age. Unit outline is the product of contouring the stratigraphic top and base, from which an isopach grid was created. Because the distribution is patchy, unit boundaries were drawn from the gridded data to represent locations where more than 25 feet (8 meters) of thickness occurs. As a result, many areas outside of the unit boundaries may be overlain by thin Cretaceous strata and the unit is depicted without a contact line.

Kc **Coleraine Formation**—Conglomerate, lignite, sandstone, and shale; shallow marine and non-marine. Late Cenomanian age is inferred. Despite exposures in mines on the Mesabi Iron Range, the position of much of the unit contact is highly speculative.

Ka **Claystone, siltstone, and sandstone**—An Albian age is tentatively inferred from a single analysis of pollen.

Jurassic

Ju **"Hallock Red Beds"**—Shale, limestone, dolomite, siltstone, and sandstone.

PALEOZOIC

Dmu **Middle and Upper Devonian**—Dolostone, limestone, and shale; includes the Lithograph City Formation, Coralville Formation, and Hinkle and Eagle Center Members of the Little Cedar Formation.

Dm **Middle Devonian**—Dolostone, sandy dolostone, limestone, and shale; includes the Chickasaw Shale and Bassett Member of the Little Cedar Formation, and Pinicon Ridge and Spillville Formations.

Ou **Upper Ordovician**—Limestone, shaley limestone, and dolostone; includes the Maquoketa Formation, and the Stewartville, Prosser, and Cummingsville Formations of the Galena Group. Also includes limestone and dolostone of the Red River Formation, and sandstone and shale of the Winnipeg Formation in northwest Minnesota.

Omu **Middle and Upper Ordovician**—Shale, dolomitic limestone, and sandstone; includes the Decorah Shale of the Galena Group, the Platteville and Glenwood Formations, and the St. Peter Sandstone.

Ol **Lower Ordovician**—Dolostone, sandy to silty dolostone, and sandstone; includes the Shakopee Formation and Oneota Dolomite of the Prairie du Chien Group.

Cu **Upper Cambrian**—Sandstone, siltstone, shale, and dolostone; includes the Jordan Sandstone and St. Lawrence Formation, and the Mazomanie, Lone Rock, and Davis Formations of the Tunnel City Group.

Cmu **Middle and Upper Cambrian**—Sandstone, siltstone, and shale; includes the Wonewoc Sandstone, Eau Claire Formation, and Mt. Simon Sandstone.

PROTEROZOIC ROCKS

The Proterozoic rocks in Minnesota are the remnants of four orogenic and rifting events. The Paleoproterozoic rocks contain evidence for a classic Wilson cycle of rifting and continental collision during the Geon 18 Penokean orogeny. The resulting crust was deformed, metamorphosed, and plutonized to varying degrees by the Geon 17 Yavapai and Geon 16 Mazatzal orogenies. The Yavapai Province in southeastern Minnesota contains older continental crust deformed during Geon 17 and is intruded by granitic rocks. Some strata assigned to the Animikie basin likely were deposited during the Yavapai event. Mesoproterozoic rocks are the product of Geon 11 continental rifting, producing volcanic and sedimentary rocks of the Keweenawan Supergroup, and intrusions of the Midcontinent Rift Intrusive Supersuite.

For brevity, approximate age dates are expressed below using the "~" symbol, and specific references to those dates are omitted. Refer to regional maps, publications, and digital files associated with this map for details. Most ages represent analyses of zircons using U-Pb methods. Somewhat less reliable ages acquired by Ar-Ar analyses of magmatic biotite or hornblende are marked with an asterisk (*).

MESOPROTEROZOIC

Keweenawan Supergroup and Midcontinent Rift Intrusive Supersuite

Mss **Sandstone, siltstone, and local conglomerate**—Includes the Hinckley Sandstone and Fond du Lac (youngest detrital zircons ~1,000 Ma) and Solar Church Formations; deposition in eolian, fluvial, and lacustrine environments.

Beaver Bay Complex and other hypabyssal intrusions

Mbd **Diabase and ferrodiorite**—Includes the Beaver River diabase, Silver Bay (~1,096 Ma), Milepost 7, Leveaux, Shoepack Lake, Cabin Creek, and Monker Lake intrusions.

Mbg **Gabbro, ferrogabbro, and gabbronorite**—Includes the Lax Lake and Cloquet Lake gabbros, Sonju Lake (~1,096 Ma), Dam Five, Wilson Lake (~1,096 Ma), Fourmile Lake, and Upper Manitou intrusions (~1,096 Ma).

Mbf **Granophyre and granite**—Includes the Blesner Lake, Finland (~1,098 Ma), and Cloquet Lake granophyres (~1,095 Ma).

Mbt **Troctolite, augite troctolite, and troctolitic gabbro of the Houghtaling Creek troctolite (~1,099 Ma).**

Duluth Complex—layered series

Mlf **Ferromonzodiorite forming the upper contact zone.**

Mlg **Gabbro**—Includes the Western Margin, Greenwood Lake, Bald Eagle (~1,098), Lake One, Lake Three, Wilder Lake, and Osier Lake intrusions.

Mlt **Troctolite**—Includes the Boulder Lake, Tuscarora (~1,099 Ma), Partridge River (~1,098 Ma), South Kawishiwi, and part of the Western Margin intrusions.

Mlc **Cyclic zone**—Gabbro to troctolite (~1,099 Ma).

Duluth Complex—anorthositic series

Mau **Anorthositic intrusions and inclusions, undifferentiated (~1,099 Ma).**

Duluth Complex—early gabbro series

Mge **Gabbroic cumulates**—Includes the Poplar Lake (formerly Nathan's layered series) and Crocodile Lake intrusions (~1,107 Ma).

Duluth Complex—felsic series

Mfg **Granophyre, ferromonzodiorite, and leucogabbro**—Includes the Mt. Weber (~1,106 Ma), Whitefish Lake (~1,109 Ma), Beth Lake, Misquah Hills (~1,106 Ma), and Cucumber Lake (~1,106 Ma) granophyres, and Wine Lake monzodiorite.

Miscellaneous intrusions

Mmd **Diabase, gabbro, and ferromonzodiorite**—Primarily sills including the Endion, Lester River, Silver Cliff, Stony Point, Split Rock, Lafayette Bluff, Lake Clara–Lichen Lake, Pigeon River, and Reservation River intrusions.

Mmg **Gabbroic intrusions**—Including the Sawmill, London, Brule River, Hovland, and Pigeon Point intrusions.

Mmf **Felsic intrusive rocks, granophyre**—Includes parts of the Eagle Mountain (~1,098 Ma) and Pine Mountain (~1,095 to 1,098 Ma) intrusions.

St. Croix horst volcanic sequences

Mcv **Chengwatana volcanic rocks; primarily mafic flows.**

Mbv **North Branch mafic volcanic sequence.**

Mmv **Minong volcanic sequence (~1,095 Ma).**

Mfv **Clam Falls volcanic sequence (~1,102 Ma).**

North Shore Volcanic Group—upper sequence, normal polarity

Msl **Schroeder-Lutsen basalts**—Unconformably overlies units described below.

Mns **Interflow sandstone, siltstone, and conglomerate.**

Mnu **Undifferentiated mafic to felsic lava flows**—Includes the Lakeside, Lakewood, and Cross River lavas.

Mnr **Rhyolite and icelandite**—Includes the Cross River, Palisade Head (~1,096 Ma), Devil Track, Maple Hill, Grand Marais, and Kimball Creek lavas.

Mnb **Basalt and basaltic andesite**—Includes the Leif Erickson, Lakeside (~1,098 Ma), Sucker River, Larsmont, Two Harbors, Crow Creek, Gooseberry River, Gustafson Hill, Baptism River, Good Harbor Bay, Cascade River, Croftville, Red Cliff, and Marr Island lavas.

North Shore Volcanic Group—lower sequence, reversed and unknown polarity

Mnl **Lower sequence, primarily basalt**—Includes the Ely's Peak and Grand Portage basalts and Hovland lavas (~1,108 Ma).

Mms **Puckwunge and Nopeming Sandstones.**

Mvu **Undifferentiated volcanic rocks and volcanic hornfels.**

Reversely polarized intrusions

Mld **Logan intrusions**—Diabase and gabbro sills and dikes; locally porphyritic (~1,108, 1,115 Ma).

Mmi **Small mafic intrusive stocks**—Diabase, diorite, pyroxenite, and gabbro; reversed magnetic polarity; includes the Esko and Tamarack intrusions emplaced into unit Pas.

PALEOPROTEROZOIC or MESOPROTEROZOIC

PMm **Mafic intrusions (gabbro, diabase) of unknown age**—Includes the LL, BKV, and Lake Washington intrusions in Meeker County.

Diabasic to lamprophyric dikes—Trajectories are largely inferred from aeromagnetic maps; includes the Kenora–Kabetogama swarm (~2,076 Ma), Franklin dike (~2,067 Ma), and dikes of likely Mesoproterozoic age. Exposed thicknesses range from a few meters to more than 100 meters.

PMr **Reversely polarized**—Dashed where concealed by younger bedrock strata.

PMn **Normally polarized**—Dashed where concealed by younger bedrock strata.

PMu **Dikes having unknown polarity or very speculative distribution**—Short segments represent outcrop exposures of mafic dikes.

PALEOPROTEROZOIC

Psq **Sioux Quartzite**—Quartzite, mudstone, and local conglomerate of fluvial and marine origin (~1,760 to 1,630 Ma; 1,902 ± 55 Ma rhyolite pebble in basal conglomerate).

Geon 17 post-tectonic (post-Penokean orogeny) intrusions related to the Yavapai orogeny

Pmi **Mafic intrusions including pyroxenite, peridotite, gabbro, and lamprophyre**—Defined largely by magnetic signature. One intrusion in Morrison County is ~1,791 Ma*, and lithologically similar intrusions cut the Foley Granite (~1,774 Ma).

East-central Minnesota batholith

Pmy **Mylonitic, gneissic, and schistose rocks of plutonic and volcanic protolith.**

Pgu **Granitic rocks, undifferentiated**—Largely inferred from geophysical maps.

Pgr **Granite**—Reddish, variably porphyritic, massive; includes the St. Cloud Red (~1,779 Ma), Foley (~1,774, 1,779 Ma), Pierz (~1,779 Ma), and Pease granites, and Richmond charnockitic granite (~1,772 Ma). An unnamed granite in south-central Minnesota is slightly older at ~1,792 Ma.

Pgk **Rockville Granite and rocks inferred to be related**—Coarse-grained and pink to white (~1,780 Ma).

Pgd **Gray granodiorite to granite intrusions**—Includes the Reformatory (~1,783 Ma), Freedhem (~1,775, 1,776 Ma), Isle (~1,779 Ma), and Warman (~1,787 Ma) intrusions.

Pgp **Gabbro, pyroxenite, diorite, and lamprophyre**—Includes the Watab quartz diorite (~1,780 Ma), St. Wendell quartz gabbro, and an unnamed diorite (~1,786 Ma).

Pga **Gabbroic, noritic, and anorthositic intrusions.**

Pgm **Granitoid intrusions, variably magnetic**—Includes the Ann Lake granite (~1,784 Ma) and Glendorado pluton (~1,788 Ma).

Hillman tonalite

Pdt **Tonalite to leucodiorite (~1,792, 1,793, 1,800 Ma).**

Pgt **Tonalite**—Locally migmatitic, variably magnetic; contains abundant biotite schist paleosome of graywacke protolith (presumably derived from the Little Falls Formation, unit Pls).

Geon 18 intrusions and supracrustal rocks (syn- to late Penokean orogenesis)

Pdg **Granodiorite, variably foliated**—Includes the Bradbury Creek (~1,877 to 1,857 Ma) and Philbrook (~1,854 Ma*) intrusions.

Animikie Group

Pas **Slate and graywacke**—Includes the Rove (~1,836 to 1,777 Ma), Virginia (~1,832 Ma near base), and Thompson Formations (youngest zircons in the Thompson Formation ~1,790 Ma).

Pac **Virginia Formation**—Slate and graywacke with thin carbonate layers.

Pai **Gunflint (~1,878 Ma), Biwabik, and Emily Iron Formations**—Locally includes thin basal sandstone and conglomerate. Capped by an irregular layer of brecciated iron-formation and ejecta derived from the 1,850 Ma Sudbury meteorite impact.

Paq **Pokegama Quartzite**—Includes conglomerate and siliceous mudstone.

Twice-deformed metasedimentary rocks at the apparent base of the Animikie basin

Pag **Graywacke and slate.**

Psi **Sulfidic iron-formation.**

Pgs **Graywacke and slate with graphitic and sulfidic zones.**

Pml **Penokean intrusion**—Mille Lacs granite (~2,009 Ma).

Pls **Little Falls Formation**—Schist and slate of graywacke-mudstone protolith.

Mille Lacs and North Range Groups in the fold-and-thrust belt of the Penokean orogen (twice-deformed)

Pm **Mille Lacs and North Range Groups and equivalent sedimentary rocks**—Includes the Mahnomen and Rabbit Lake Formations and Trout Lake marble.

Pif **Iron-formation in the Cuyuna North and South Ranges and Mille Lacs Group**—Includes the Trommald Formation.

Pvs **Interlayered volcanic and sedimentary rocks.**

Pmv **Interlayered volcanic, volcaniclastic, sedimentary, and hypabyssal intrusive rocks**—Includes parts of the Mille Lacs Group, North and South Range Groups, and Glen Township Formation.

Pmq **Dam Lake quartzite.**

Pmd **Denham Formation**—Lithic sandstone (reworked saprolite), marble, and mica schist (youngest detrital zircons greater than 2,000 Ma).

Pgn **Sartell Gneiss**—Quartzofeldspathic orthogneiss and schist; local metaconglomerate; age unknown.

ARCHEAN or PALEOPROTEROZOIC

Aml **Mylonite, varied protolith**—Age of shearing unknown and likely protracted.

Ami **Magnetic intrusions, undifferentiated**—Typically too small to ascertain gravity expression.

APg **Granitic intrusion of unknown age**—Low gravity and magnetic expression.

APd **Dioritic to granodioritic intrusion of uncertain age**—Moderate gravity and magnetic expression.

APm **Gabbroic to dioritic intrusion**—High to moderate gravity and magnetic signature. Includes Providence and Cottonwood intrusions in southwestern Minnesota.

APv **Mafic volcanic and hypabyssal intrusive rocks of uncertain age**—Adjacent to and within the Yellow Medicine shear zone.

ARCHEAN ROCKS

The Archean bedrock of Minnesota represents the southern exposed extent of the Superior Province, which is divided into four major tectonomagmatic terranes known as the Wabigoon, Quetico, Wawa, and Minnesota River Valley subprovinces (Fig. 1). Each is a discrete fragment of oceanic and continental crust that was assembled by accretion into the Superior craton, largely completed by approximately 2.6 Ga.

NEOARCHEAN

Intrusions in all subprovinces of the Superior Province

Generally discrete, unfoliated to weakly magmatically foliated or lineated plutons

Agr **Granitic intrusion**—Includes the Sacred Heart (~2592, 2,603 Ma) and Ortonville granites, the Shannon Lake Granite (~2,674), and other intrusions having low gravity and magnetic signatures.

Agu **Granitoid intrusion**—Constrained solely by low gravity and magnetic signatures.

Asd **Syenite, monzodiorite, granodiorite, and diorite**—Commonly hornblende- or pyroxene-bearing; includes the Coon Lake, Side Lake, and Linden (~2,666 Ma*) plutons of north-central Minnesota.

Agm **Granite to granodiorite**—Variably magnetic.

Agp **Gabbro, peridotite, pyroxenite, lamprophyre, and metamorphic equivalents**—Includes the Oaks intrusion (~2,671 Ma) in the Wabigoon subprovince, and a ~2,639 Ma lamprophyre in the western Wawa subprovince; locally defined by variably high gravity and magnetic signatures.

Aqm **Monzonite, quartz monzonite, and granodiorite**—Includes the Farm Lake phase of the Giants Range batholith.

Agd **Granodiorite to hornblende diorite, locally magmatically foliated**—Includes the Britt Granodiorite (~2,685 Ma) and other intrusions having moderate gravity and magnetic signatures.

Ast **Saganaga Tonalite (~2,690 Ma)**—Tonalite to granodiorite; typically contains large quartz phenocrysts and granodioritic to dioritic autoliths.

Adt **Tonalite-leucodiorite plutons**—Includes the Grygla, Red Lake Falls, and other plutons having low magnetic and gravity signatures.

Aqp **Porphyritic quartzofeldspathic dikes**—Typically hypabyssal intrusions associated with felsic volcanic sequences.

Foliated to gneissic intrusive complexes and components of batholiths

Agl **Leucogranite**—Occurs along the Yellow Medicine Shear Zone and elsewhere, primarily in batholithic settings.

Agt **Foliated to gneissic tonalite, granodiorite, and diorite**—Includes the Lookout Mountain tonalite (~2,718 Ma) of the Giants Range batholith and other intrusions within batholithic complexes defined by a low-to-moderate gravity signature with magnetic foliation apparent from aeromagnetic maps.

Agn **Granitic to granodioritic orthogneiss**—Includes the McGrath Gneiss (~2,752 ± 15, 2,557 Ma) and unnamed units.

Ags **Schist and tonalitic to granodioritic paragneiss**—Typically adjacent to large batholithic complexes.

Metamorphic and intrusive rocks of the Quetico subprovince—Composed of biotite-plagioclase schist, granitoid intrusions, and migmatite. The schist was derived from graywacke deposited ~2,698 to 2,692 Ma in an accretionary prism during collision of the Wawa subprovince island arc to the south, with the Superior craton (superterrane) to the north (Shebandowanian orogeny). This was followed by multiple episodes of intrusion, migmatization, metamorphism, and deformation. Metamorphic grade is symmetrical along the axis of the subprovince, with greenschist grade at the margins and amphibolite to granulite facies near the center.

Aql **Lac La Croix Granite**—Pink biotite granite that is variably magnetic and locally pegmatitic (~2,665 to 2,667 Ma).

Aqg **Granite-rich migmatite**—Contains neosome of variably magnetic biotite granite similar to the Lac La Croix Granite, and paleosome of tonalite to granodiorite gneiss and schist.

Aqt **Migmatite dominated by tonalitic to granodioritic neosome.**

Aqs **Biotite schist of graywacke protolith, and schist-rich migmatite.**

Aqa **Amphibolitic schist and gneiss**—Both extrusive and intrusive protoliths are likely.

Supracrustal and hypabyssal intrusive rocks of the Wawa and Wabigoon subprovinces—Strata are subdivided approximately by their apparent temporal relationship to three major periods of deformation: the first (D_1), at about 2,695 Ma, which may

be equated with the Shebandowanian orogeny in adjacent Ontario; the second (D_2), at about 2,680 Ma, occurred during the Minnesotan orogeny and produced regional fabrics, folds, and prograde metamorphism to greenschist-amphibolite grade. The former may represent collision of the Wawa subprovince with the composite Superior superterrane to the north. The latter can be attributed to collision of the Minnesota River Valley subprovince with the Superior superterrane along a suture known as the Great Lakes Tectonic Zone. A D_3 event is manifest in the Quetico subprovince as broad folds involving D_2 fabrics, and elsewhere by faulting.

Post-D_1/pre-D_2 alkalic volcanic and successor-basin deposits

Asc **Conglomerate, lithic sandstone, and graywacke, undifferentiated**—Includes the Midway sequence, Seine Group, and a part of the Knife Lake Group known as the Ogishkemuncie conglomerate that contains clasts of ~2,690 Ma Saganaga Tonalite (unit Ast). Deposition of alluvial fan and fluvial sediments occurred in fault-bounded basins.

Aks **Knife Lake Group volcanogenic lithic sandstone, conglomerate, siltstone, graywacke, and slate.**

Akc **Knife Lake Group conglomerate**—Clasts consist largely of hornblende-bearing volcanic rocks.

Akv **Knife Lake Group, hornblende-phyric volcanic flows, breccia, and tuff.**

Pre-D_1 metavolcanic, metasedimentary, and hypabyssal intrusive rocks

Ams **Schist of sedimentary protolith**—Metamorphosed to upper greenschist to amphibolite facies.

Aif **Iron-formation**—Includes the Soudan Iron Formation and many unnamed units.

Asg **Volcanogenic graywacke and mudstone**—Includes the Lake Vermilion Formation.

Avs **Volcaniclastic rocks of felsic to intermediate composition.**

Acv **Calc-alkalic volcanic and volcaniclastic rocks.**

Aag **Mafic to ultramafic hypabyssal intrusive complexes composed of gabbro, pyroxenite, diorite, and anorthosite**—Includes the Mentor and Deer Lake complexes, intrusions of the Newton Lake Formation, all within the Wawa subprovince; and the UBD intrusion (~2,685 to 2,695 Ma*) in the Wabigoon subprovince.

Amv **Mafic metavolcanic rocks**—Includes minor volcaniclastic and hypabyssal intrusive rocks metamorphosed to lower greenschist to lower amphibolite facies; includes the Ely Greenstone (~2,722 Ma).

Auv **Mafic to ultramafic (komatiitic) volcanic rocks**—Includes the Newton Lake Formation and Deer Lake sequence.

Amm **Interlayered metavolcanic, volcaniclastic, and hypabyssal intrusive rocks**—Metamorphosed to amphibolite facies.

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.

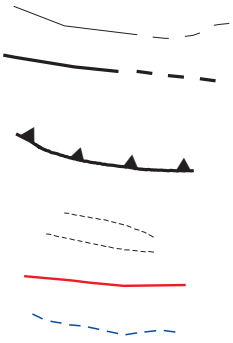
Amg **Granitic orthogneiss and migmatite**—Geophysical map patterns imply this unit intruded other gneisses.

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.**

MAP SYMBOLS



Geologic contact—Dashed where concealed by younger bedrock strata.

Fault—Strike or dip-slip kinematic sense; steeply dipping. Dashed where concealed by younger bedrock strata.

Thrust fault, or structural or geophysical discontinuity interpreted to have involved thrust displacement—Teeth on inferred upper plate.

Foliation—Inferred from aeromagnetic data.

Iron-formation.

Dike—Concealed by younger bedrock strata.

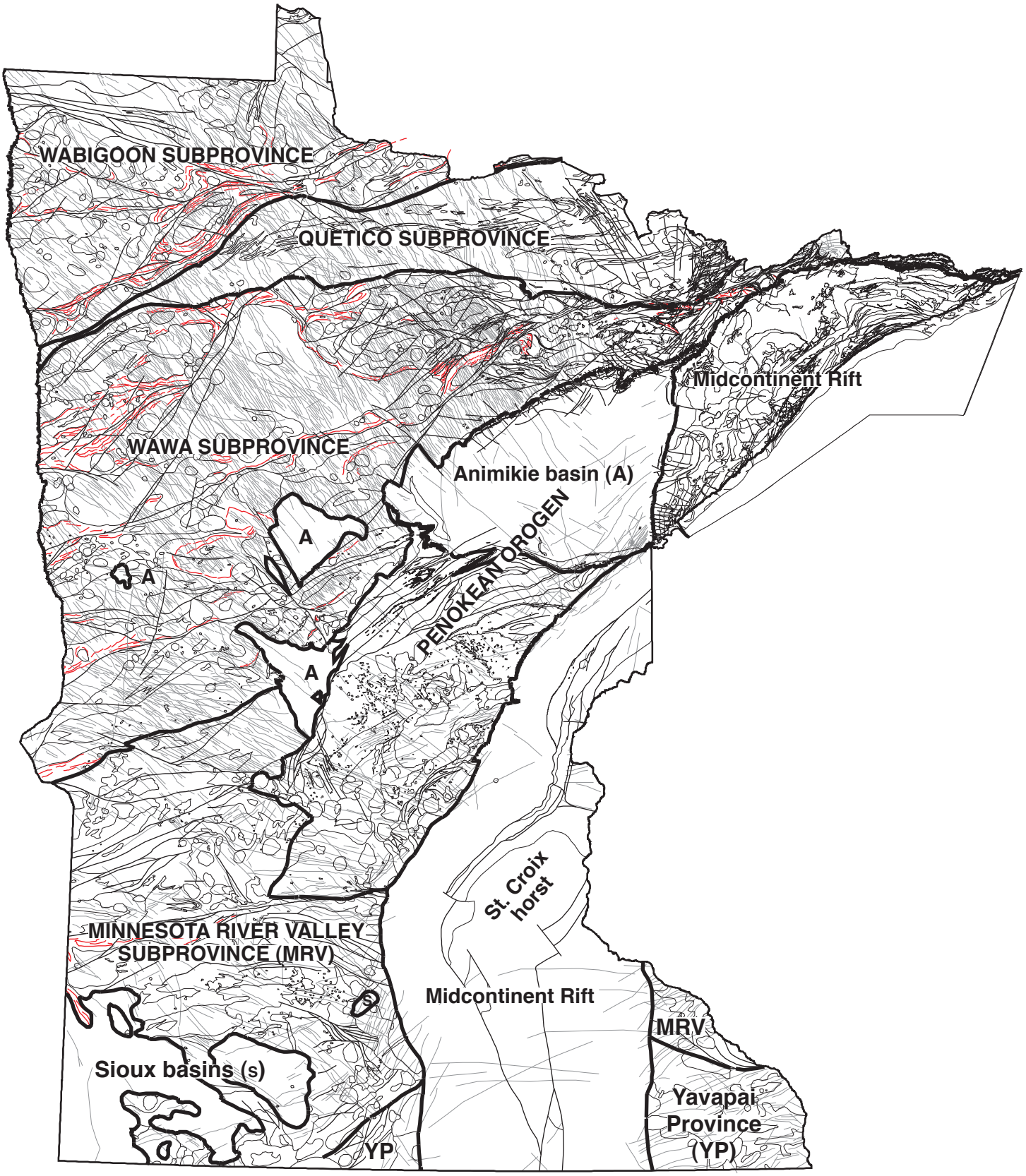


Figure 1. Terrane map of Precambrian bedrock showing subprovinces of the Archean Superior Province (iron-formation shown in red), significant elements of Paleoproterozoic bedrock, the Mesoproterozoic Midcontinent Rift, and mafic dikes (gray) of Paleoproterozoic and Mesoproterozoic age.

CORRELATION OF MAP UNITS

Significant unconformities are indicated by dashed lines.
Approximate ages are shown in million years (Ma).