Correlation of Precambrian Rocks of the Lake Superior Region, United States

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By G.B. MOREY *and* W.R. VAN SCHMUS

CORRELATION OF PRECAMBRIAN ROCKS OF THE
UNITED STATES AND MEXICO

Edited by JACK E. HARRISON *and* ZELL E. PETERMAN

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Lithology, distribution, correlation, and isotope ages of exposed Precambrian rocks in the Lake Superior region of the north-central United States

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CORRELATION OF PRECAMBRIAN ROCKS OF THE LAKE SUPERIOR REGION, UNITED STATES

By G.B. MOREY[1] and W.R. VAN SCHMUS[2]

ABSTRACT

Precambrian rocks in the Lake Superior region underlie parts of Minnesota, Wisconsin, and Michigan, very near the geographic center of the North American continent. The region contains two contrasting basement terranes of Archean age—a gneiss terrane and a greenstone-granite terrane. The more southerly gneiss terrane records one of the earliest identifiable events in Earth history, for the protoliths of some of the gneisses are about 3,600 million years old. The gneiss terrane remained tectonically active throughout much of Precambrian history, as indicated by a succession of events that have been dated at 3,000-2,900 m.y., 2,600 m.y., 2,400-2,300 m.y., 2,100-2,000 m.y., 1,900-1,800 m.y., about 1,760 m.y., about 1,630 m.y., and 1,500-1,450 m.y. ago. In contrast, the second Archean terrane—the greenstone-granite terrane—formed within an interval of only a few hundred million years approximately 2,700 million years ago, and has remained essentially stable since about that time.

Two distinctly different sequences of stratified rocks were formed during Early Proterozoic time. The older sequence, deposited between 2,100 m.y. and 1,900 m.y. ago, consists predominantly of clastic rocks of geosynclinal affinity and includes the great iron-formations of the region. These rocks are bounded on the south, in Wisconsin, by a somewhat younger sequence of dominantly mafic volcanic rocks. Sedimentation and volcanism were either terminated or closely followed by several tectonic, metamorphic, and igneous events that span the interval from 1,890 m.y. to 1,770 m.y. ago and that collectively are referred to as the Penokean orogeny. Post-Penokean, Early Proterozoic rocks include felsic volcanic and epizonal granitic rocks, approximately 1,760 m.y. old, which are overlain by quartzitic red beds of fluvial to shallow-water marine origin. These rocks were locally deformed and metamorphosed at approximately 1,630 m.y. ago and were intruded by Middle Proterozoic alkalic and alkaline igneous rocks approximately 1,500 m.y. ago.

In late Middle Proterozoic time, during the interval 1,200-1,000 m.y. ago, a sequence of dominantly mafic volcanic, hypabyssal, and plutonic igneous rocks and derivative red beds was formed as part of the Midcontinent rift system. This major tectonic feature extends from the Lake Superior region to near the Kansas-Oklahoma border in Central United States.

Although some rocks in the interval 1,000-900 m.y. ago may be present, no rocks of definite Late Proterozoic age have been recognized in the Lake Superior region.

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INTRODUCTION

Precambrian rocks in the Lake Superior region underlie parts of Minnesota, northern Wisconsin, and northern Michigan, very near the geographic center of the North American continent. With respect to surface exposures, the region lies at the southern extremity of the Canadian Shield, but if the subsurface geology is considered, the region is located near the center of the Precambrian basement of the North American craton (pl. 1, index; fig. 1). Because of their position at the edge of the Canadian Shield, the Precambrian rocks are buried to the east, south, and west by increasing thicknesses of Phanerozoic strata. However, Precambrian rocks also are exposed as inliers in Phanerozoic strata in southwestern Minnesota and south-central Wisconsin. Additionally, much of the bedrock is covered by a considerable thickness of Quaternary glacial and postglacial materials.

GEOLOGIC AND CHRONOMETRIC RELATIONS

The geologic map of the Lake Superior region (fig. 2) and the correlation chart (pl. 1) emphasize a wide diversity of superposed rock types and events, ranging in age from about 3,600 m.y. to 1,000 m.y. The rationale for dividing this long span of time into the Archean and Proterozoic Eons, with a boundary at 2,500 m.y. ago, is discussed by the International Union of Geological Sciences Working Group on the Precambrian for the United States and Mexico (Harrison and Peterman, 1982). The Archean is subdivided into Early, Middle, and Late Archean Eras by time boundaries at 3,400 and 3,000 m.y., and the Proterozoic into Early, Middle, and Late Proterozoic Eras by time boundaries at 1,600 and 900 m.y.

FIGURE 1.—Location of the Lake Superior region as related to the Canadian Shield and to known or inferred Precambrian basement rocks of the North American craton (Morey, 1978b).

The chronometric aspects of the correlation chart were constructed using procedures and conventions given in the introductory chapter of this series (Harrison and Peterman, 1984). The correlations are based on geologic relations and radiometric data published through early 1984. These data indicate that the Archean rocks in the Lake Superior region can be divided into two distinct suites—a gneiss terrane and a greenstone-granite terrane—that differ in age, rock assemblage, structural style, and metamorphic grade (Morey and Sims, 1976; Sims, 1980). The Late Archean (2,750-2,600 m.y.) greenstone-granite complexes that occur in the northern part of the region are typical of much of the Superior structural province (Stockwell and others, 1970); the southern part of the region is underlain by a complex assemblage of gneiss, amphibolite, and granite that is in part 3,600 m.y. old. Because these terranes have had profoundly different geologic histories and significant effects on the Early Proterozoic geology, they have been used to subdivide the correlation chart (pl. 1) into two discrete geographic entities, a northern segment underlain by greenstone-granite and a southern segment underlain by gneiss.

ARCHEAN ROCKS

The gneiss terrane and the greenstone-granite terrane are juxtaposed along a boundary named the Great Lakes tectonic zone (Sims and others, 1980). Although the location of the zone is fairly well defined (fig. 2), the manner in which the rocks of the two terranes are interrelated along and within the zone is not well understood. Seismic reflection profiling in east-central Minnesota (Gibbs and others, 1984) has defined a concentration of north-dipping seismic planes that project to the surface near the trace of the Morris fault, which Sims and others (1980) used to define the south edge of the tectonic zone. The moderate dip of these planes (about 30°), their continuity over tens of kilometers, and their persistence throughout the crust in this region led Gibbs and others (1984) and Pierson and Smithson (1984) to suggest that the seismic planes correspond to thrust-fault zones that originated in Late Archean time and along which rocks of the greenstone-granite terrane were thrust over rocks of the gneiss terrane.

Modeling of aeromagnetic and gravimetric data across the zone (Southwick and Chandler, 1983) also has delineated two layers separated by a northward-dipping boundary that is truncated on the north by a high-angle fault. This high-angle fault corresponds to the northern edge of the Great Lakes tectonic zone in Minnesota. The upper layer appears, from limited shallow drilling in the area, to consist largely of folded low-grade metavolcanic and metasedimentary rocks of Late Archean and (or) Early Proterozoic age. The lower layer has geophysical attributes similar to those associated with rocks in the gneiss terrane, but these rocks have not yet been drilled.

Geologic relations in and around the Great Lakes tectonic zone are further complicated in Minnesota (Morey, 1983a,b), and in Wisconsin and Michigan (Sims and Peterman, 1981, 1983; Sims and others, 1984), by Late Archean and Early Proterozoic tectonic events that produced structures oriented subparallel to the boundary between greenstone-granite and gneiss terranes. Therefore, the Great Lakes tectonic zone is a fundamental crustal feature that was tectonically reactivated a number of times in the Precambrian and Phanerozoic.

GNEISS TERRANE

The gneiss terrane, as defined in the Lake Superior region, is that segment of Archean crust composed of basement gneisses that are in part Early and Middle Archean (or older than 3,000 m.y.) in age, have ubiquitous amphibolite to granulite metamorphic grade, and a distinctive structural style that is characterized in many areas by moderately dipping foliations and low

EXPLANATION

- Phanerozoic rocks, undivided
- Middle Proterozoic
  - Ym — Midcontinent rift system (Age, ≈1,200–1,000 m.y.)
  - Yg — Wolf River batholith and Wausau Syenite Complex (Age, ≈1,500 m.y.)
- Early Proterozoic
  - Xq — Quartzite, rhyolite, and epizonal granite (Age, ≈1,760–1,630 m.y.)
  - Xg — Granitoid rocks (Age, 1,890–1,770 m.y.)
  - Xv — Granitoid and volcanic rocks of the Wisconsin magmatic terrane (Age, ≈ 1,890–1,825 m.y.)
  - Xs — Stratified rocks of the Animikie basin—Includes the major iron-formations of the region (Age, ≈ 2,100–1,860 m.y.)
- Wgm — Late Archean greenstone-granite terrane (Age, 2,750–2,650 m.y.)
- Agn — Archean gneiss terrane (Age, ≈3,600–2,600 m.y.)
- Contact
- Fault
- Location of Great Lakes tectonic zone

FIGURE 2.—Generalized bedrock geologic map of all Precambrian rocks of the Lake Superior region (modified from Morey and others, 1982, and Mudrey and others, 1982).

to moderately plunging fold axes. The terrane also contains some apparently younger (2,800–3,000 m.y.) migmatitic gneisses (Van Schmus and Anderson, 1977). In places, such as in east-central Minnesota (Southwick and Chandler, 1983), at Watersmeet, Mich. (Sims, 1980; Sims and others, 1984), and in Dickinson County, northern Michigan (James and others, 1961), older gneisses are unconformably overlain by Late Archean supracrustal rocks and intruded by Late Archean plutonic rocks.

Exposures of Early and Middle Archean rocks in the gneiss terrane are limited by an extensive cover of Proterozoic and Phanerozoic rocks and very young glacial debris, and accordingly, the geographic extent of the gneiss terrane is poorly known. The terrane is inferred, however, to continue eastward into the Lake Huron region of Ontario (Sims and others, 1981) and westward an unknown distance beneath Phanerozoic cover in South Dakota. The southern extent of the terrane into Iowa also is obscured by a thick Proterozoic and Phanerozoic cover (Anderson and Black, 1983).

STRATIGRAPHY AND GEOCHRONOLOGY

The gneiss terrane is best known from the Minnesota River Valley (fig. 3) where a grossly conformable sequence of interlayered migmatitic gneisses, apparently a few thousand meters thick (Grant, 1972), is intruded by younger granitic and pegmatitic rocks. The gneisses are folded on east-trending, gently plunging axes, and have mineral assemblages characteristic of upper amphibolite- and granulite-facies metamorphism (Bauer, 1980; Himmelberg and Phinney, 1967). The best exposures are in the Granite Falls–Montevideo (Himmelberg, 1968; Goldich, Hedge, and others, 1980) and Sacred Heart–Morton areas (Grant, 1972; Goldich, Wooden, and others, 1980; Wooden and others, 1980; Goldich and Wooden, 1980).

In the Granite Falls–Montevideo area, the gneisses are metamorphosed to granulite grade and consist dominantly of a quartzofeldspathic gneiss called the Montevideo Gneiss (Goldich and others, 1970). The Montevideo Gneiss is a medium-grained, equigranular, leucocratic rock consisting of alternating layers of a gray, foliated, granodioritic paleosome and a red granitic neosome. The red granitic neosome occurs both concordantly and discordantly and as veins in the granodiorite. The gray granodioritic phase yields Rb-Sr whole-rock ages of about 3,680±70 m.y., whereas the red granite phase yields an age of 3,045±32 m.y. (Goldich, Hedge, and others, 1980). The terrane also contains layers and lenses of garnet-biotite gneiss, amphibolite, and metagabbro. These rocks record a high-grade metamorphic event at about 2,600 m.y. (Wilson and Murthy, 1976), but presumably all these units are about 3,500 m.y. old. Postmetamorphic mafic dikes and a small pluton called the granite of section 28 emplaced at 1,840±50 m.y. ago (Doe and Delevaux, 1980) intrude gneisses near Granite Falls.

In the Morton–Sacred Heart area, Grant (1972) has delineated four rock units. The three lower units are quartzofeldspathic gneisses individually characterized by abundant, common, and rare rafts of amphibolite. The middle unit in this succession is the Morton Gneiss (Goldich and others, 1970). Where not migmatized, the quartzofeldspathic gneisses are tonalitic or granodioritic in composition and generally are compositionally layered. The uppermost stratigraphic unit in the area is composed of two kinds of biotite gneiss and amphibolite. One of the biotite gneisses contains the mineral association biotite-cordierite-garnet-anthophyllite in addition to quartz and plagioclase, and the other contains sillimanite and potassium feldspar and, locally, garnet and cordierite. Amphibolite also occurs in the biotite gneisses as discontinuous layers, lenses, and boudins. Rubidium-strontium and U-Pb data suggest that the tonalitic and granodioritic gneisses and the associated amphibolite lenses in the Morton–Sacred Heart area are 3,500 m.y. or more old (Goldich and Wooden, 1980). Also, zircon dating by ion microprobe methods indicates that the paleosome is 3,535±45 m.y. old (Williams and others, 1984), an age consistent with a Sm-Nd model age of 3,580±30 m.y. from a saprolitic clay developed from the Morton Gneiss (McCulloch and Wasserburg, 1978). Where migmatized, the neosome is granite and, locally, pegmatite, which formed during two later episodes. An older deformed granite was emplaced about 3,043±26 m.y., and a younger, largely undeformed granite was emplaced 2,555±55 m.y. ago (Goldich and Wooden, 1980).

The gneissic rocks are intruded by the Sacred Heart Granite of Lund (1956), a medium-grained, generally homogeneous to weakly foliated rock that yields a Pb-Pb age of 2,605±6 m.y., which Doe and Delevaux (1980) interpreted as the time of emplacement. The Sacred Heart Granite is late-tectonic or possibly posttectonic.

In east-central Minnesota gneisses of possible Early or Middle Archean age include the Richmond and Sartell Gneisses of Morey (1978a), the Hillman Migmatite of Morey (1978a) and the McGrath Gneiss of Woyski (1949). The first three units form a basement that lies to the west of an extensive Early Proterozoic cover. These gneisses have not been dated radiometrically, but they resemble those in the Minnesota River Valley in having been metamorphosed to the upper amphibolite or granulite facies and folded into generally open, moderately plunging antiforms and

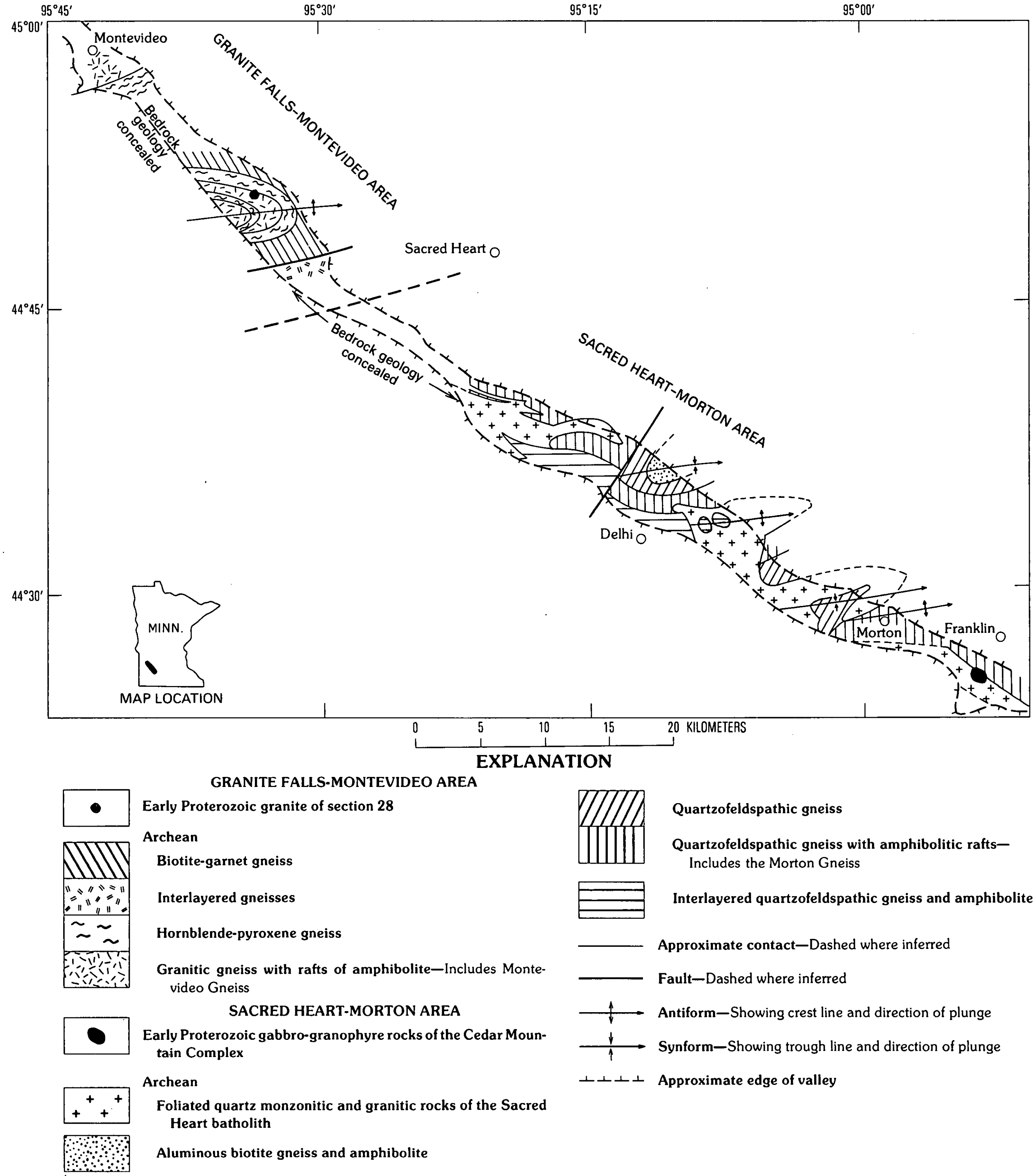


FIGURE 3.—Geologic map of Minnesota River Valley, southwestern Minnesota, showing major rock units and structural attributes as mapped by Grant (1972).

synforms (Dacre and others, 1984). The McGrath Gneiss forms several gneiss domes surrounded by superjacent metasedimentary and metavolcanic strata of Early Proterozoic age (Morey, 1978b). It is a coarse-grained, locally migmatitic, augen gneiss of quartz monzonitic composition. It yields a minimum Rb-Sr whole-rock isochron age of 2,700 m.y. (Stuckless and Goldich, 1972). The original age of the McGrath, however, is obscured by a pervasive metamorphic and cataclastic event at about 1,770 m.y. ago (Keighin and others, 1972).

In the western part of northern Michigan, near the Michigan-Wisconsin boundary, Archean gneiss forms several domes. Although not all the domes have been studied in detail, the rocks in one dome—informally called the gneiss at Watersmeet (Sims and Peterman, 1976)—are an augen gneiss of tonalitic to granodioritic composition, which is intruded by younger granitic rocks. Radiometric studies of the gneisses indicate an Early Archean age. $^{207}Pb/^{206}Pb$ ages on several fractions of zircon range from 3,199 to 3,411 m.y., and a primary age of 3,562±39 m.y. is indicated by a concordia plot (Peterman and others, 1986). Zircon dating by the ion microprobe has yielded a somewhat older age of approximately 3,650 m.y. (Williams and others, 1984), which is consistent with a Sm-Nd age of about 3,620±30 m.y. (McCulloch and Wasserburg, 1980). In contrast, whole-rock Rb-Sr systems in the dome are highly disturbed and define secondary isochrons of about 1,750 m.y., recording reactivation during Early Proterozoic time (Sims and others, 1984). At Watersmeet, the gneiss is unconformably overlain by amphibolite and biotite gneiss which yields a U-Th-Pb age of approximately 2,640 m.y. The amphibolite and gneiss are cut by a 2,590-m.y. leucogranite (Sims and others, 1984).

As in the Watersmeet area, the geology in southern Marquette and Dickinson Counties, in upper Michigan (fig. 2), consists of islandlike masses of Archean gneiss surrounded by tightly folded supracrustal strata of Late Archean or Early Proterozoic age. Gneissic rocks are exposed over a broad area south of the Marquette district in the informally designated Southern complex of Van Hise and Bayley (1895), in the Amasa uplift (Gair and Wier, 1956), a large northwest-trending gneiss dome located about 15 km west of the Southern complex, and in several other unnamed, fault-bounded antiformal blocks in Dickinson County (James and others, 1961). The Southern complex consists dominantly of the Bell Creek Gneiss (Cannon and Simmons, 1973), whereas the core of the Amasa uplift is composed of the Margeson Creek Gneiss of Gair and Wier (1956). These similar and possibly equivalent gneisses are very coarse grained megacrystic rocks of granitic to granodioritic composition. The Bell Creek Gneiss is intruded by parts of the Compeau Creek Gneiss of Gair and Thaden (1968) along the north edge of the Southern complex. The latter is dominantly tonalitic to granodioritic in composition and contains lenses and layers of amphibolite.

Rubidium-strontium data indicate that the Bell Creek and Compeau Creek Gneisses are at least 2,550 m.y. old, and more likely are about 2,750 m.y. old (Van Schmus and Woolsey, 1975; Hammond and Van Schmus, 1978). The gneisses have been affected by several later events as indicated by Rb-Sr ages on biotite of 1,630±40 m.y. (Van Schmus and Woolsey, 1975), whole-rock Rb-Sr ages of about 1,850 m.y., and local anatexis in the Compeau Creek Gneiss at about 2,350 m.y. ago (Hammond and Van Schmus, 1978).

Strongly deformed and cataclastic gneissic rocks in Dickinson County, Mich., include the granite gneiss of the Norway Lake area of James and others (1961) and the Carney Lake Gneiss of Bayley and others (1966). The former is a porphyroclastic augen granitic gneiss containing inclusions of mafic metavolcanic material, schist, and quartzite, whereas the latter consists dominantly of granitic gneiss with lesser interlayered amounts of hornblende-biotite gneiss and biotite-rich gneiss. The granite gneiss of the Norway Lake area is unconformably overlain by metamorphosed strata assigned to the Dickinson Group (James, 1958). The uppermost units of this group, which consist dominantly of arkose, metagraywacke, schist, and amphibolite, grade laterally and vertically into a belt of granitic gneiss, which in turn apparently grades into the gneiss at Granite Bluffs of Aldrich and others (1965) as well as into several other masses of unnamed granitic gneiss. Thus, at least two gneiss-forming events may have taken place in Dickinson County.

Attempts to date the granite gneiss of the Norway Lake area have been only partially successful, mainly because of multiple later events. Banks and Van Schmus (1971, 1972) reported that zircons from the gneiss yield an age of about 2,400 m.y; Rb-Sr data, however, indicated an older parentage. More recent zircon analyses for the granite gneiss at Norway Lake (Van Schmus, unpub. data, 1986) confirm that it is about 2,600 to 2,800 m.y. old, but indicated also that it has been altered by subsequent events. Post-Dickinson granitic gneisses yield zircons with ages of 2,600 m.y., but Rb-Sr data for these rocks indicate a major event causing redistribution of Rb and Sr about 1,965±65 m.y. ago (Van Schmus and others, 1978). Detrital zircons from the East Branch Arkose of the Dickinson Group yield Pb-Pb ages of about 2,900 m.y. (Banks and Van Schmus, 1972) which, together with the presence of inclusions of schist and quartzite in the granite gneiss at Norway Lake, imply the existence of a terrane older than 2,900 m.y. in the region.

Zircons from the Carney Lake Gneiss in Dickinson County, the southernmost exposed Archean unit in Michigan, indicate an age of about 2,750 m.y. (Aldrich and others, 1965; Van Schmus and others, 1978). These data are difficult to interpret in terms of specific events; they clearly show that the Archean rocks of this region were extensively reworked during Proterozoic time.

Gneissic rocks in central Wisconsin are separated from those in northern Michigan by a belt of Early Proterozoic volcanic and plutonic rocks, named the Wisconsin magmatic terrane (fig. 2). The gneissic terrane consists dominantly of amphibolite, garnetiferous hornblende gneiss, and schist, all intruded by mafic rocks, quartz diorite, and several kinds of granitic rocks and their cogenetic pegmatites (Myers, 1974; Cummings, 1984). Their age has not been determined. Zircons from migmatitic gneisses in the Pittsville area and along the Black River define a concordia-intercept age of approximately 2,800 m.y. (Van Schmus and Anderson, 1977; DuBois and Van Schmus, 1978). Although the Rb-Sr systematics observed for whole-rock samples from the Pittsville area clearly reflect the event at 2,800 m.y., they also can be interpreted as indicating a protolith age in the range of 3,000 m.y. to 3,200 m.y. for the gneisses (Van Schmus and Anderson, 1977). Recent U-Pb results on zircons from a small remnant of Archean gneiss near Marshfield, Wis., indicate that the protolith to the gneiss is about 3,000 m.y. old (Van Schmus, unpub. data, 1986). Van Schmus and Anderson (1977), Maass and others (1980), and Van Schmus (1980) have shown that the gneisses were intruded by several kinds of tonalitic and granodioritic rocks as young as 1,830±15 m.y.; some of these younger rocks have a secondary foliation similar to that in the gneisses, which implies that the terrane was extensively deformed during Early Proterozoic time. Consequently, it is difficult to determine whether the Precambrian rocks in central Wisconsin are an Archean gneissic basement with many Early Proterozoic plutons or a plutonic complex with many remnants of an Archean gneissic crust.

GREENSTONE–GRANITE TERRANE

Late Archean rocks of the greenstone–granite terrane constitute nearly all the bedrock in northern Minnesota (fig. 2); but these rocks are well exposed only in the Vermilion district of northeastern Minnesota (Sims, 1976a), along the International Boundary in the Rainy Lake district (Goldich and Peterman, 1980), and in the Birchdale–Indus area (Ojakangas and others, 1977). Rocks of the greenstone–granite terrane also are exposed locally south of Lake Superior along the Wisconsin–Michigan border and in northern Michigan just south of Lake Superior. In these areas, the Archean rocks occur as inliers surrounded and partly overlain by strata of Early Proterozoic age.

The greenstone–granite terrane forms the southern part of the Superior province of the Canadian Shield. In Canada the terrane has been divided into several large, east-northeast-trending volcanic-plutonic belts or subprovinces that alternate with belts of migmatite and gneiss (Goodwin, 1978). Three of these belts extend westward into Minnesota; from north to south they are the Wabigoon volcanic-plutonic belt, represented by exposures in the Birchdale–Indus and Rainy Lake districts; the Quetico gneiss belt, represented by exposures in the Vermilion Granitic Complex; and the Shebandowon or Wawa volcanic-plutonic belt, represented by exposures in the Vermilion district proper. The Late Archean rocks that crop out south of Lake Superior are most likely part of the Wawa volcanic-plutonic belt, although those in central Wisconsin could be part of yet another migmatite-gneiss belt.

In northern Minnesota, the volcanic-plutonic belts are characterized by overlapping piles of mafic volcanic rocks and related synvolcanic intrusions (Schulz, 1980, 1982). Lenses of banded iron-formation occur throughout and are common in the upper parts of the dominantly mafic successions (Morey, 1980). The mafic rocks pass abruptly upward and laterally into dacitic to rhyodacitic volcaniclastic rocks, which in turn grade upward and laterally into dominantly volcanogenic graywacke–shale sequences derived from the volcanic centers (Ojakangas, 1972). Beds of chert, carbonaceous shale, and rare siliceous marble also are present in parts of the graywacke–shale sequences (Morey and others, 1970; Green, 1970). The complexly interlayered volcanic and sedimentary rocks have been folded several times (Hooper and Ojakangas, 1971; Hudleston, 1976) and metamorphosed to the greenschist facies contemporaneously with diapiric rise of granitic bodies of batholithic dimensions. Because of the characteristic greenschist-facies metamorphism, the volcanic-sedimentary successions are commonly called greenstone belts.

Most of the plutonic igneous rocks that bound the several greenstone belts in northern Minnesota are younger than the volcanism and sedimentation, although one pluton—the Saganaga batholith in the Vermilion district—was emplaced and unroofed more or less contemporaneously with sedimentation. The Giants Range batholith along the south side of the Vermilion district is divided into several older syntectonic units of tonalitic to granitic composition and younger posttectonic rocks of monzonitic to quartz monzonitic composition (Sims, 1976a). Posttectonic rocks also form several small plutons scattered widely along the lengths of the greenstone belts.

Late Archean migmatitic gneiss belts are represented in northern Minnesota (fig. 4) by the Vermilion Granitic Complex (Southwick and Sims, 1979). The interior portions of this fault-bounded structural entity consist entirely of granite—previously named the Vermilion Granite (Grout, 1925), but now called the Lac La Croix Granite (Southwick and Sims, 1979). Most of the complex, however, consists of biotite schist and amphibolite, metamorphosed generally to the upper greenschist facies (garnet grade) and in places (particularly near larger bodies of igneous rock) to the upper amphibolite facies (sillimanite grade). The gneisses also have had a complex history of injection, anatexis, metasomatism, and deformation. The Lac La Croix Granite was more or less passively emplaced into previously folded stratified rocks, most likely at depths somewhat greater than plutonic activity in adjoining volcanic-plutonic belts (Southwick, 1972, 1976; Day, 1983).

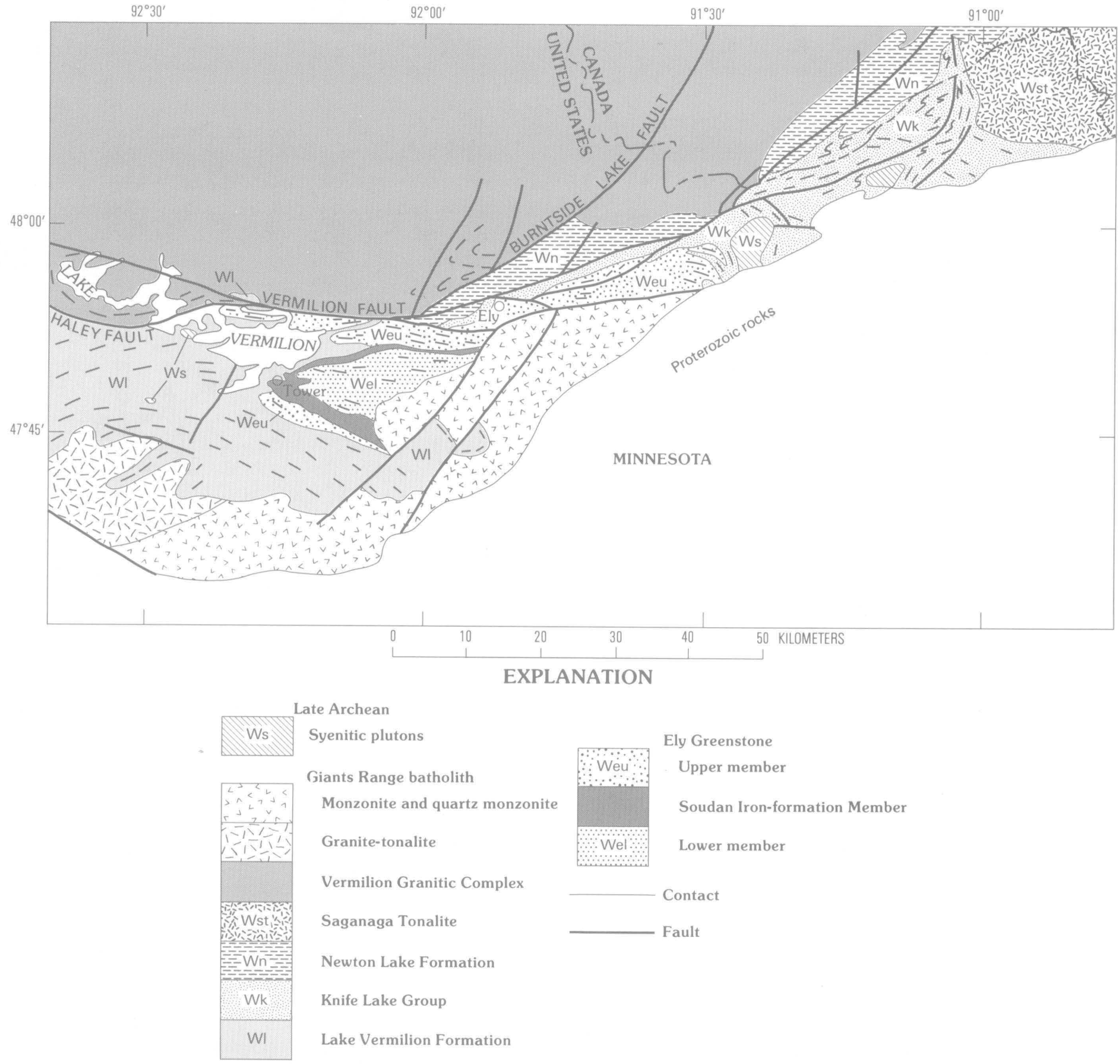


FIGURE 4.—Geologic map of a part of the Vermilion district (modified from Sims, 1976a) and the Vermilion Granitic Complex (modified from Southwick and Sims, 1979). The Vermilion fault separates the Vermilion district to the south from the Vermilion Granitic Complex to the north. This break also corresponds with the boundary between the Wawa volcanic-plutonic belt to the south and the Quetico gneiss belt to the north.

STRATIGRAPHY AND GEOCHRONOLOGY

The stratigraphic succession of Late Archean rocks astride the International Boundary between Minnesota and Ontario contains many stratigraphic units prominently mentioned in the geologic literature (fig. 5). Lawson (1888, 1913) distinguished two periods of deformation and magmatic activity which he called the Laurentian and the Algoman. In his view, the Laurentian rocks were intruded into a dominantly metasedimentary sequence (called the Coutchiching Series), which in turn was overlain by a dominantly metavolcanic sequence (called the Keewatin Series). After a period of erosion, a second metasedimentary sequence (called the Seine Series) was deposited, and this second sequence and also the older rocks were deformed a second time when the Algoman intrusions were emplaced.

The concept of a two-fold subdivision separated by a post-Laurentian unconformity persisted well into the

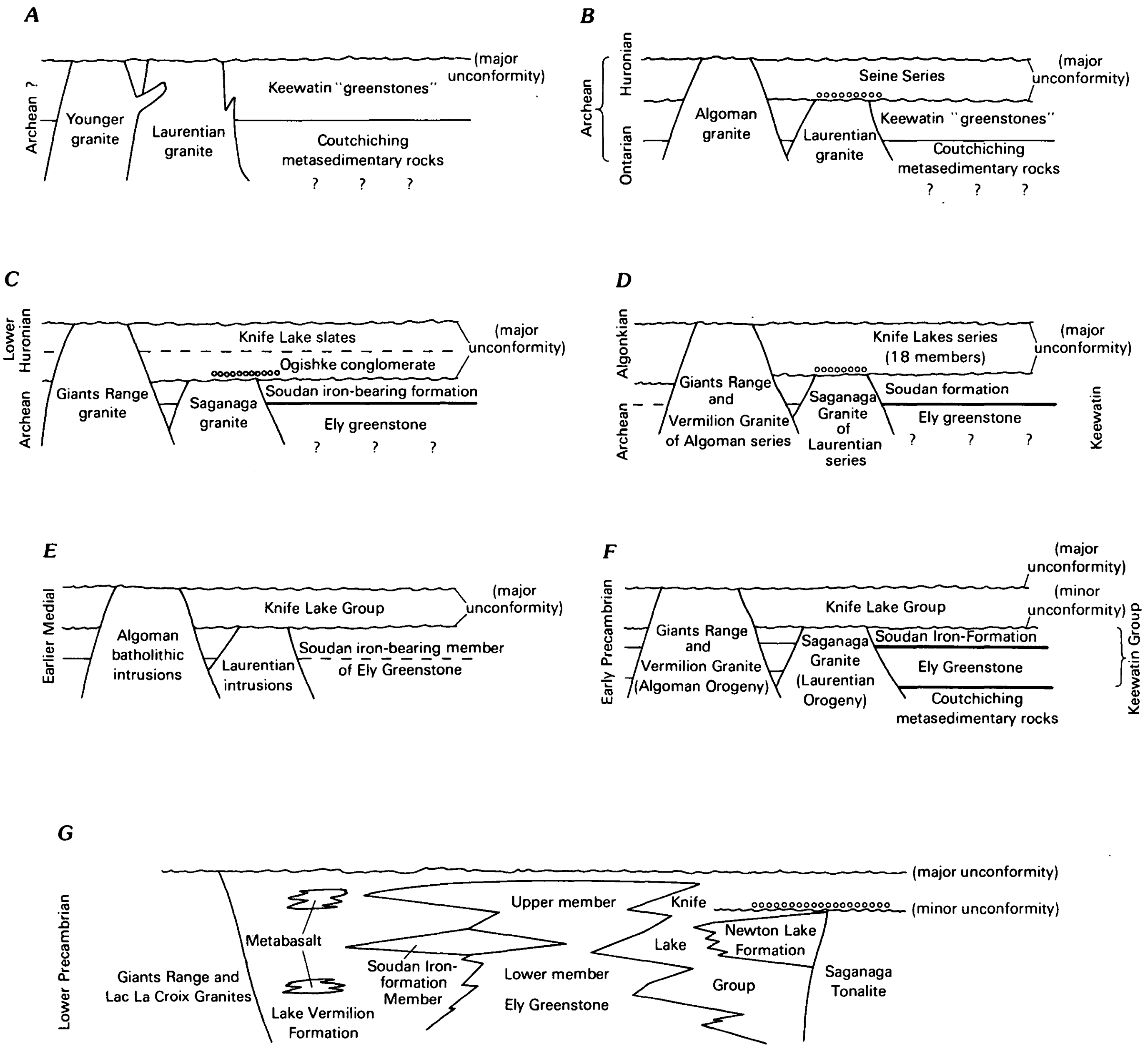


FIGURE 5.—Idealized sections showing evolution of stratigraphic nomenclature in the Archean greenstone–granite terrane of northern Minnesota and adjoining Ontario. *A*, Rainy Lake district (Lawson, 1885, 1888); *B*, Rainy Lake district (Adams and others, 1905; Lawson, 1913); *C*, Vermilion district (Clements, 1903); *D*, Eastern Vermilion district (Gruner, 1941); *E*, Northern Minnesota (Grout and others, 1951); *F*, Northern Minnesota (Goldich and others, 1961); *G*, Vermilion district (Morey and others, 1970; Sims, 1976a).

middle of the 20th century (for example, Grout and others, 1951). However, as pointed out first by Goodwin (1968) and since then by many others, any volcanic-sedimentary assemblage in the Superior province may consist of a single mafic-to-felsic-to-sedimentary sequence, or it may consist of several of these sequences that are repeated in space and time. The resulting stratigraphic succession can be complex, particularly near the fringes of individual volcanic centers where any stratigraphic interpretation is complicated by the interfingering of diverse volcanic and sedimentary rock types.

All the major rock-forming events in the Rainy Lake area occurred between approximately 2,700 and 2,600 m.y. ago (Tilton and Grunenfelder, 1968; Hart and Davis, 1969; Peterman and others, 1972; Goldich and Peterman, 1980). Hart and Davis (1969) obtained several whole-rock Rb-Sr isochron ages in the interval 2,700–2,500 m.y. ago that were numerically consistent with the stratigraphic succession, as described by Lawson. However, zircon samples from all the units collectively define a U-Pb age of about 2,710±30 m.y.; Peterman and others (1972) also obtained a Rb-Sr age for the so-called Algoman granites of 2,485±90 m.y., which is approximately 185 m.y. younger than a corresponding U-Pb zircon age of 2,670 m.y. Such discrepancies between older U-Pb, and apparently younger Rb-Sr whole-rock, potassium-argon, and Rb-Sr mineral ages (Hanson and others, 1971) are common in the greenstone–granite terrane of northern Minnesota. Peterman and others (1972) have suggested that the rocks behaved as partially open systems during one or more periods of subsequent low-grade metamorphism, hydrothermal alteration, or cataclasis.

An interlayered sequence of metavolcanic and metasedimentary rocks also occurs in the Vermilion district of northern Minnesota (fig. 5*G*), where the Ely Greenstone interfingers with and is overlain by the Lake Vermilion Formation or the Knife Lake Group (Morey and others, 1970). A second volcanic unit, the Newton Lake Formation, which also contains several tabular, ultramafic intrusions, overlies the Knife Lake Group (Green, 1970). This simple stratigraphic succession is complicated at the east end of the district by the Saganaga batholith, a classic example of a "Laurentian batholith." (See Grout and others, 1951.) This pluton intrudes mafic volcanic rocks apparently equivalent to the Newton Lake Formation, whereas adjacent Knife Lake strata lie on its eroded surface. Therefore, part of the Knife Lake Group is older and part of it is younger than the Saganaga batholith. Igneous rocks of the Giants Range batholith intrude all the stratified rocks and appear to represent the last major rock-forming event in the greenstone–granite terrane.

Radiometric dating has delineated only one major period of plutonic igneous activity and metamorphism in the Vermilion district. Rocks of the Saganaga batholith have yielded a U-Pb age of 2,650±50 m.y. (Anderson, 1965) and two Rb-Sr whole-rock isochron ages of 2,650 m.y. and 2,630 m.y. (Hanson and others, 1971). The batholithic rocks are cut by the posttectonic Icarus pluton, which has yielded a similar Rb-Sr isochron age of approximately 2,630 m.y. (Hanson and others, 1971).

The Giants Range batholith, along the south side of the Vermilion district, and the Lac La Croix Granite along the north side have yielded Rb-Sr isochron ages of 2,610±65 m.y. (Prince and Hanson, 1972), and 2,620±95 m.y. (Peterman and others, 1972), respectively. Supracrustal rocks in the district have Rb-Sr isochron ages of 2,590±110 to 2,630±180 m.y. (Jahn and Murthy, 1975). Posttectonic rocks dated by U-Pb methods include the Snowbank Lake pluton, emplaced at approximately 2,700 m.y. ago (Catanzaro and Hanson, 1971). Thus a significant igneous–tectonic event occurred in the greenstone–granite terrane of northern Minnesota at about 2,700 m.y. ago.

Stratigraphic relations in the greenstone–granite terrane south of Lake Superior have not been studied in detail. However, in northwestern Wisconsin and adjoining parts of Michigan, pillowed mafic lavas and mafic to felsic pyroclastic rocks assigned to the Ramsay Formation are intruded by the Puritan Quartz Monzonite (Schmidt, 1976), a plutonic body of batholithic dimensions that has yielded a Rb-Sr whole-rock isochron age of 2,650±140 m.y. (Sims and others, 1977). However, zircons from a nearby, related granite in the Great Lakes tectonic zone gave a concordia intercept age of 2,745±65 m.y., which probably also is the best estimate of the age of the Puritan Quartz Monzonite (Peterman and others, 1980).

Similar rocks also assignable to the greenstone–granite terrane constitute the Northern complex of the Marquette district in northern Michigan (Van Hise and Bayley, 1895). The oldest rock unit, called the Kitchi Schist (Gair and Thaden, 1968; Morgan and DeCristoforo, 1980) consists of mafic flows and tuffs which grade upward into a coarse volcanic breccia of felsic composition. The lower part of the Kitchi contains a large serpentinized ultramafic body, the Deer Lake Peridotite of Morgan and DeCristoforo (1980). The Kitchi Schist is overlain in turn by the Mona Schist, a sequence of mafic flows with iron-formation near the top. The metavolcanic rocks have been intruded and metamorphosed by granitic rocks assigned to the Compeau Creek Gneiss (Gair and Thaden, 1968) and by other unnamed tonalitic to granodioritic plutons. These units, as well as the volcanic rocks, yield U-Pb ages of 2,750 to 2,700 m.y. (Peterman and others, 1980; Hammond and Van Schmus, 1978). Thus, when all the radiometric data are considered collectively, the greenstone–granite terrane in the Lake Superior region formed in a remarkably short span of time about 2,700 m.y. ago.

PROTEROZOIC ROCKS

Rocks of Early and Middle Proterozoic age are extensive in the southern part of the Lake Superior region (fig. 2). The Early Proterozoic rock record consists of two sedimentary-volcanic supracrustal sequences separated in time by a number of discrete tectonic-thermal events that occurred during the interval of 1,850±30 m.y. ago (Van Schmus and Bickford, 1981), except in Michigan, where events possibly as young as 1,750 m.y. have been recognized (Sims and others, 1984). These events have been referred to collectively as the Penokean orogeny (Goldich and others, 1961; Cannon, 1973).

The pre-Penokean rocks of Early Proterozoic age are a "geosynclinal sequence," composed mainly of clastic sedimentary rocks, with lesser but significant amounts of mafic volcanic rocks, and subordinate chemical sediments, chiefly iron-formation. The post-Penokean sequence consists dominantly of subaerial rhyolite and coeval granitic rocks overlain by quartz-rich sedimentary rocks of fluvial origin. The upper part of the post-Penokean sequence also contains units of black shale and iron-formation-bearing dolomite of possibly marine origin. The post-Penokean rocks were affected by a tectonic-thermal event at about 1,630 m.y. ago that also disturbed the isotopic systems of many of the older rocks in the Lake Superior region.

Rock-forming events in Middle Proterozoic time included the intrusion of the Wolf River batholith and several syenitic complexes in south-central Wisconsin and the formation of the Midcontinent rift system, a major structure that extends southward from the Lake Superior region to at least the southern part of Kansas.

PRE-PENOKEAN, EARLY PROTEROZOIC ROCKS

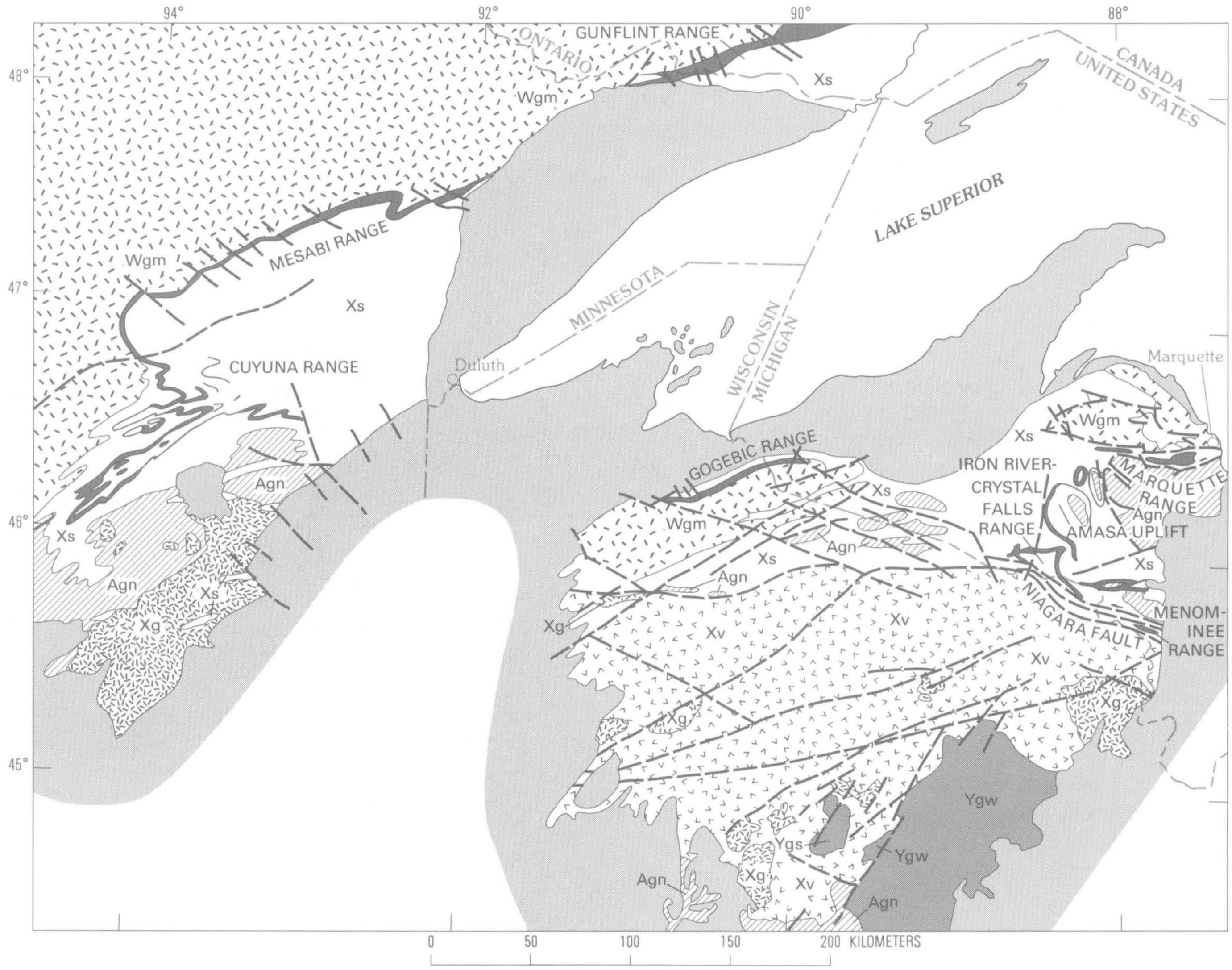
Pre-Penokean, Early Proterozoic rocks constitute a discontinuous linear foldbelt some 1,300 km long extending from northern and east-central Minnesota, through northern Wisconsin, and across much of the southern part of northern Michigan. These rocks compose the major part of the Southern province (Stockwell and others, 1970) or the Hudsonian fold belt along the United States–Canada border on the tectonic map of North America (King, 1969). In addition to abundant clastic rocks, this sequence contains nearly all the commercially exploited iron-formations in the region (fig. 6). A second and possibly younger sequence of dominantly volcanic rocks forms a separate east-trending belt that extends across northern Wisconsin.

The pre-Penokean stratified rocks of the Lake Superior region were deposited in the Animikie basin (Morey, 1983a), one of several basins that formed over and approximately parallel to the Great Lakes tectonic zone (Sims and others, 1981). The strata form a generally southward-thickening wedge that can be divided into two facies on the basis of pronounced differences in rock type and thickness: (1) a relatively thin succession (1.5–2.0 km) of predominantly sedimentary rocks deposited on greenstone–granite terrane north of the Great Lakes tectonic zone; and (2) a much thicker succession of intercalated sedimentary and bimodal basaltic and rhyolitic volcanic rocks to the south (Sims and others, 1981).

The rocks of the Animikie basin in Michigan are fault bounded on the south against a thick, stratigraphically complex sequence of volcanic rocks, including basalt, andesite and rhyolite, and lesser amounts of sedimentary rocks of clastic and chemical origin. This dominantly volcanic sequence forms the Wisconsin magmatic zone (or terrane), which occurs as an east-trending belt extending across much of northern Wisconsin (Greenberg and Brown, 1983; May and Schmidt, 1982). Although extensively developed in Wisconsin, correlative volcanic rocks have not been recognized along the south side of the Animikie basin in east-central Minnesota. Because of this and because a fault (Niagara fault) separates volcanic rocks from the rocks in the eastern segment of the Animikie basin, the stratigraphic relations of the volcanic sequence to the better known dominantly sedimentary succession are not clearly understood.

The stratified rocks of the Animikie basin were extensively deformed and metamorphosed during the Penokean orogeny (Cannon, 1973; Klasner, 1978; Morey, 1978b). The degree of deformation varies considerably from north to south and appears related at least in part to contrasting kinds of Archean basement rocks. Thus, the stratified rocks can be divided into two broad zones on the basis of contrasting styles of deformation and grades of metamorphism—a northern stable cratonic zone and a southern deformed zone termed the Penokean fold belt (Sims and others, 1980; Sims and Peterman, 1983). The tectonic front separating the two zones coincides approximately with the inferred northern edge of the Great Lakes tectonic zone.

North of the tectonic front, the Proterozoic supracrustal rocks unconformably overlie the Archean greenstone–granite basement and are virtually undeformed and unmetamorphosed (Morey, 1983a). South of the tectonic front, supracrustal rocks within the



EXPLANATION

Rocks younger than Early Proterozoic in age—Undivided except for Ygs, Wausau Syenite Complex, and Ygw, Wolf River batholith

Early Proterozoic

Xg **Granitoid rocks of tonalitic to granitic composition**—Age, 1,770–1,890 m.y

Xv **Volcanic and granitoid rocks of the Wisconsin magmatic terrane**—Includes metavolcanic rocks, older granitic gneiss, and younger granodioritic and granitic rocks

Xs **Stratified rocks of the Animikie basin**—Includes major iron-formations shown as screened

Wgm **Late Archean rocks of the greenstone-granite terrane, undivided**

Agn **Archean rocks of the gneiss terrane, undivided**

Contact

Fault

FIGURE 6.—Generalized geology of Lake Superior region showing distribution of Early Proterozoic rocks referred to in text (modified from Morey and others, 1982).

foldbelt display two contrasting tectonic styles. The rocks in Minnesota and in a broad subzone 60–70 km wide between the tectonic front and the Niagara fault zone in Wisconsin and Michigan are intensely deformed (for example, Cannon, 1973; Klasner, 1978) and are characterized by a nodal distribution of metamorphic zones (James, 1955). The volcanic rocks south of the Niagara fault zone in Wisconsin also are intensely deformed, but the metamorphic patterns have a linear rather than a nodal geometry (Sims and Peterman, 1983). The volcanic rocks south of the fault zone also contain numerous mesozonal granitic plutons of Early Proterozoic age (Sims and Peterman, 1980; Van Schmus, 1980). All supracrustal rocks within the Animikie basin are presumed to lie unconformably on Archean rocks, and Early or Middle Archean gneisses are exposed in the cores of several gneiss domes or upraised fault blocks. The volcanic rocks also lie on Archean gneisses in places, but in other places the basement gneisses are of Early Proterozoic age (Sims and others, 1982).

STRATIGRAPHY AND GEOCHRONOLOGY

The Animikie basin is separated into two distinct segments by Middle Proterozoic and younger rocks (fig. 6). Rocks of the northwest segment contain the sequences of the Mesabi and Cuyuna iron ranges of northern and east-central Minnesota and of the Gunflint range of Ontario; and the southeast segment contains those of the Gogebic, Marquette, Menominee, and Iron River–Crystal Falls ranges of northern Wisconsin and Michigan (fig. 7). Because they are physically separated, the rocks in the northwest segment have been assigned to the Mille Lacs and Animikie Groups (Morey, 1978a) and those in the southeast segment to the Marquette Range Supergroup (Cannon and Gair, 1970). The Marquette Range Supergroup is much thicker and more diverse than the Mille Lacs and Animikie Groups and is interrupted by unconformities that serve to divide it into the Chocolay, Menominee, Baraga, and Paint River Groups (James, 1958).

A major stratigraphic problem concerning the stratified rocks of the Animikie basin has been their correlation with the partly glaciogenic Huronian Supergroup (Robertson and others, 1969), on the north shore of Lake Huron in Ontario. (See Young, 1966; Church and Young, 1970; and Young, 1983, for a discussion.) The basal part of the Early Proterozoic succession at places in Michigan contains coarse clastic deposits, named the Reany Creek and Fern Creek Formations, that may be partly glacial in origin (Pettijohn, 1943; Puffett, 1969; Gair, 1975, 1982; Ojakangas, 1984; for a contrary view see Larue, 1981a, or Mattson and Cambray, 1983). Since the work of James (1958), most correlations place the Reany Creek and Fern Creek Formations in the Chocolay Group. However, Pettijohn (1943), Tyler and Twenhofel (1952), and Dutton and Bradley (1970) have suggested that they are separated from overlying Chocolay strata by an unconformity. Regardless of whether the unconformity exists, the Reany Creek–Fern Creek strata could be correlative with glacial units in the upper part of the Huronian Supergroup in Canada. Young (1983) further extended the correlation of Marquette Range and Huronian Supergroup strata by correlating the entire Chocolay Group with the upper part of the Huronian Supergroup.

The present chronometric data seem to indicate that at least parts of the Marquette Range Supergroup are younger than the Huronian Supergroup. In the Felch trough area of Michigan, the basement rocks were affected by a metamorphic episode about 2,000 m.y. ago that did not affect the unconformably overlying Marquette Range rocks (Van Schmus and others, 1978). Similarly, the Mille Lacs Group in east-central Minnesota unconformably overlies a migmatitic terrane yielding an apparent Rb-Sr age of 2,100 to 2,000 m.y. (Goldich, 1973). In northern Minnesota, the somewhat younger Animikie Group unconformably overlies dike rocks 2,120±67 m.y. old (Beck and Murthy, 1982). These events correspond to the approximate age of the Nipissing Diabase dikes which intrude Huronian strata in Canada (Van Schmus, 1965, 1976; Fairbairn and others, 1969; Gibbons and McNutt, 1975), thus making the Huronian older than 2,100 m.y. These relationships imply that the Mille Lacs and Animikie Groups and at least most of the Marquette Range Supergroup are distinctly younger than the Huronian Supergroup. Although the actual depositional age is unknown, Banks and Van Schmus (1971, 1972) have reported a U-Pb age of 1,910±10 m.y. for zircon from a rhyolite in the Marquette Range Supergroup. The rhyolite unit is part of the Hemlock Formation, which traditionally has been placed in the Baraga Group (James, 1958). However, Prinz (1976) suggested that the Hemlock Formation correlates with the Negaunee Iron-formation of the Menominee Group, a correlation diagrammed in figure 7.

Lithostratigraphic correlations within and between the individual iron-mining districts within the Animikie basin are well established, and the Marquette Range Supergroup generally is interpreted as recording a complete transition from a "stable craton" to a "eugeosynclinal" environment (James, 1954; Bayley and James, 1973; Larue and Sloss, 1980; Morey, 1983a). Evidence for such a transition is especially clear in the northwest segment of the Animikie basin, where the sedimentary record can be divided into five depositional phases

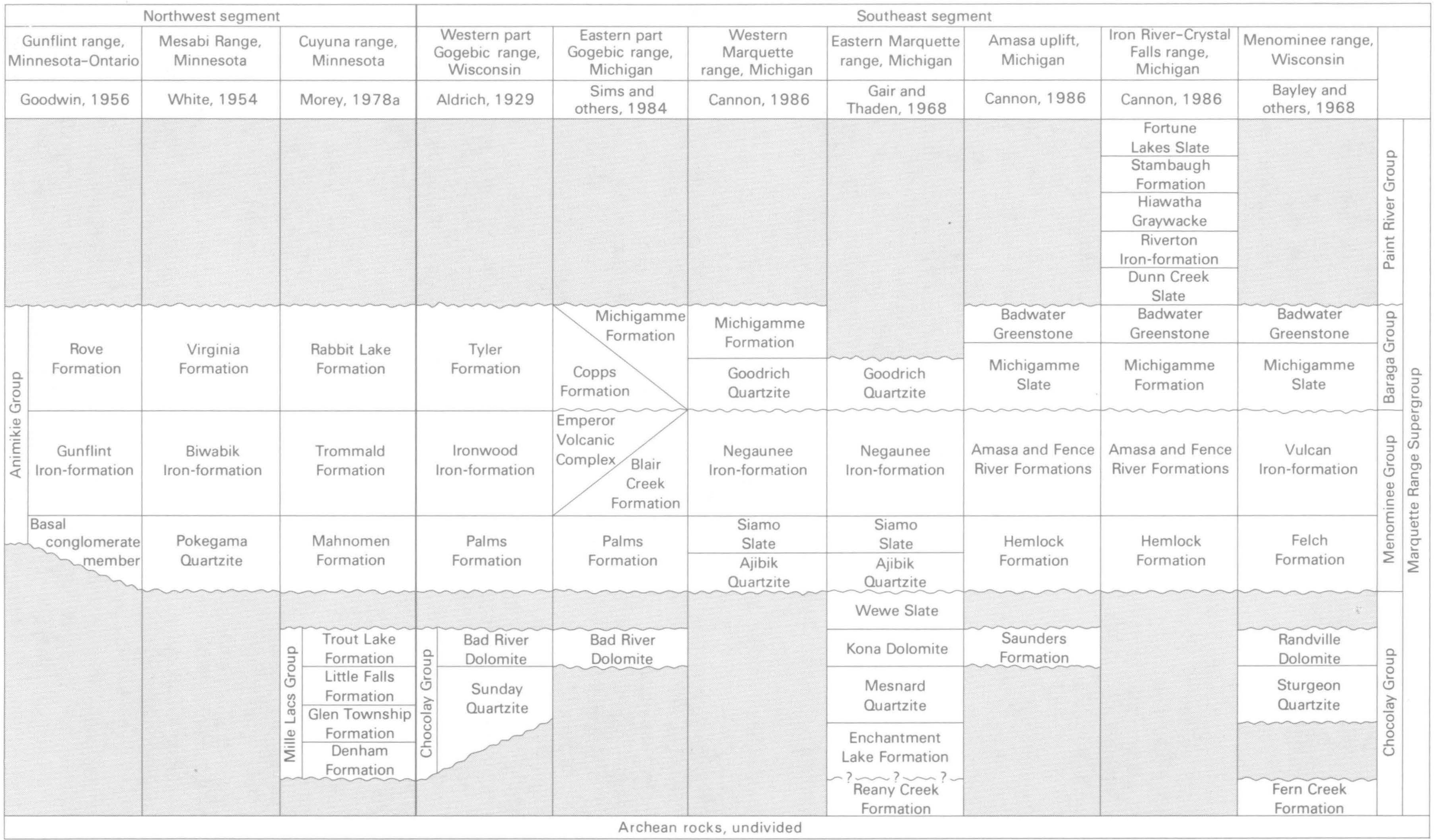


FIGURE 7.—Correlation chart for Early Proterozoic strata in the Animikie basin (modified from Morey, 1983b).

(Morey, 1983b). The first two phases constitute a miogeosynclinal sequence during which sediments were derived from both north and south of the basin (see also Ojakangas, 1983). The third phase represents a shelf upon which iron-rich strata were precipitated, whereas the fourth phase forms a transitional sequence marked by rapid subsidence of the shelf and concurrent deposition of black, carbonaceous mud. The fifth phase is a southward-thickening flysch deposited by southward-flowing turbidity currents associated with submarine fan complexes.

Stratified rocks over the greenstone–granite basement in the southeast segment of the Animikie basin are similar to those in the northwest segment. For example, the Chocolay and Menominee Groups along the Gogebic Range in Michigan are strikingly similar to the Mille Lacs and Animikie Groups in Minnesota. Traditionally such lithologic similarities provide much of the evidence for correlation of strata between the northwest and southeast segments of the basin.

The stratigraphic succession is much more diverse and complex elsewhere in the southeast segment where the basement is Archean gneiss. The Marquette Range Supergroup can be divided into three, generally fining upward depositional cycles (Sims and others, 1981). The first cycle consists mostly of shallow-water sediments, stromatolitic dolomite, and locally, slate, which collectively constitute the Chocolay Group (Larue, 1981a). The second cycle consists of the Menominee Group and contains the major iron-formations of the region (Larue, 1981b). Although the iron-formations over the greenstone–granite terrane record nearly contemporaneous transgressive sedimentation over large parts of the Archean craton, those over the gneiss terrane differ greatly in thickness, stratigraphic detail, and depositional facies. Moreover, the Menominee Group contains appreciable quantities of bimodal mafic and felsic volcanic rocks.

The third cycle, starting at the base of the Baraga Group, was a period of pronounced crustal disturbance characterized by differential subsidence that culminated with deposition of a thick graywacke–slate sequence. Volcanic rock units in the southern part of the basin are lenticular and locally as much as 3 km thick. Gabbroic dikes and sills were emplaced at this time as subvolcanic equivalents of the basaltic lavas (Cannon, 1973). A similar, unstable tectonic regime persisted through deposition of the Paint River Group in the southern part of the basin.

Inasmuch as depositional patterns in the southeast segment are very similar to those in the northwest segment, it seems certain that both segments are part of the same intracontinental basin. This basin formed by rifting processes akin to those associated with protoceanic rift systems of Phanerozoic age (Cambray, 1978).

The Niagara fault system along the southern edge of the Animikie basin, in northeastern Wisconsin, juxtaposes dominantly sedimentary rocks of the basin against a nearly 200-km-wide sequence of dominantly volcanic rocks to the south (May and Schmidt, 1982; Greenberg and Brown, 1983). The volcanic rocks are truncated to the west by Middle Proterozoic rocks of the Midcontinent rift system, for correlative rocks have not been recognized west of the Middle Proterozoic Midcontinent rift system in central Minnesota. However, Early Proterozoic plutonic rocks are extensive in east-central Minnesota.

The volcanic belt in Wisconsin is intruded by a variety of plutonic rocks of Early Proterozoic age, and has been called the Penokean volcano-plutonic belt (Van Schmus, 1976) or the Wisconsin magmatic zone (Sims and Peterman, 1984). Although inferred to underlie a large area, the volcanic rocks of the zone have been studied at only a few places (Greenberg and Brown, 1983). In northeastern Wisconsin, the volcanic rocks are assigned to a number of units including the Quinnesec Formation, a mainly basaltic unit with intercalated andesite, rhyolite, and iron-formation (Cummings, 1978; Dutton, 1971; Schulz and Sims, 1982; Schulz, 1983). In the Rhinelander–Crandon area to the west, a mixed unit of mafic flows and felsic to intermediate tuffs and breccias is overlain by a sequence of dominantly mafic flows (Schmidt and others, 1978). An even more felsic succession occurs near Ladysmith at the western end of the volcanic belt, where a sequence of dacitic to rhyolitic crystal tuffs and massive andesitic, dacitic, and rhyolitic flows has been studied in some detail (May, 1977). Similar volcanic rocks also have been mapped in central Wisconsin, where an older succession of volcanic rocks metamorphosed to the amphibolite facies is unconformably overlain by a younger basalt-rhyolite sequence metamorphosed to the greenschist facies (LaBerge and Myers, 1984).

The felsic parts of the volcanic sequence at Ladysmith, Crandon, and several other places contain massive copper- and zinc-bearing sulfide deposits similar to those observed in stratabound, volcanogenic massive sulfide deposits in greenstone belts of Archean age in Canada (May, 1977; Schmidt and others, 1978). After Van Schmus (1976) established that the volcanic rocks were Early Proterozoic in age, it was suggested that they were correlative with the upper part of the Marquette Range Supergroup. However, a felsic unit from the Quinnesec Formation has yielded a zircon U-Pb age of about 1,869±25 m.y. (Banks and Rebello, 1969, recalculated). Mafic rocks from the same formation have yielded a Sm-Nd age of 1,871±57 m.y. (Beck and Murthy, 1984). Model lead ages from two of the massive sulfide deposits in the volcanic sequence also are about 1,830±150 m.y. old (Stacey and others, 1977; Afifi and others, 1984). The model lead age has been interpreted as a primary age, mainly because the contained sulfide deposits are believed to be synvolcanic in origin (Sims, 1976b). Thus, the chronometric data indicate the presence of two distinct sequences of volcanic rocks in the eastern segment of the Lake Superior region, with those in Wisconsin perhaps being as much as 50 m.y. younger than those in the Marquette Range Supergroup. This distinction has been further substantiated by Schulz (1983), who has shown that the volcanic rocks of the Marquette Range Supergroup have trace-element patterns characteristic of continental tholeiites, whereas the volcanic rocks of the Wisconsin magmatic zone have a more oceanic chemical affinity.

The volcanic rocks of the Wisconsin magmatic zone are intruded by a variety of plutonic rocks ranging in composition from quartz diorite to granite. Granitic units at the west end of the zone have yielded a composite Rb-Sr isochron age of 1,885±65 m.y. (Sims and Peterman, 1980). Uranium-lead zircon ages on several plutons from the east end of the zone range from 1,890 m.y. to 1,820 m.y. (Banks and Cain, 1969; Van Schmus, unpub. data, 1980); the younger rocks tend to be less deformed than the older plutons (Maass and others, 1980). Thus, it appears that igneous activity culminated in Wisconsin about 1,850±30 m.y. ago. This age is similar to: (1) the metamorphic age of approximately 1,820 m.y. (Aldrich and others, 1965) for the Peavy Pond Complex in northern Michigan; (2) the ages of a number of small granite and pegmatite bodies in northern Michigan (Sims and Peterman, 1984; Sims and others, 1977); (3) the probable age (1,800 m.y.–1,700 m.y.) of plutonic rocks in east-central Minnesota (Spencer and Hanson, 1984); and (4) the age (1,840±50 m.y.) of an Early Proterozoic granite stock that cuts the Archean gneiss terrane in the Minnesota River Valley (Doe and Delevaux, 1980).

POST-PENOKEAN, EARLY PROTEROZOIC ROCKS

Events of post-Penokean, Early Proterozoic age in the Lake Superior region include: (1) extrusion and intrusion of rhyolitic and granitic rocks of the "Fox River valley type" at 1,760±10 m.y. followed by (2) deposition of texturally mature quartz-rich red beds of the "Baraboo–Sioux type," and (3) subsequent low-grade, regional metamorphism at about 1,630 m.y.

RHYOLITES AND GRANITES OF THE FOX RIVER VALLEY TYPE

Volcanic and granitic rocks of dominantly felsic composition crop out as small, scattered inliers in south-central Wisconsin (fig. 2), mainly as mounds or topographic highs surrounded by Phanerozoic strata (Mudrey and others, 1982). Most of the known exposures occur along the valley of the Fox River (Asquith, 1964; Smith, 1978a) and around the margins of the Baraboo district (Dalziel and Dott, 1970). However, the rhyolitic rocks were once more widely distributed, because several outliers of flat-lying, felsic extrusive rocks unconformably overlie folded Early Proterozoic strata in east-central Minnesota (Van Hise and Leith, 1911; Morey and others, 1981), and large rhyolite clasts are present near the inferred base of the Sioux Quartzite in southwestern Minnesota (Weber, 1981).

The rhyolitic rocks along the Fox River appear to be subaerial in origin and include various proportions of intercalated porphyritic and nonporphyritic flow units, ash-fall tuff and breccia, ignimbrite, and mud-flow breccia, exposed in a series of open, north-northeast-trending antiforms and synforms (Smith, 1978b). Flow directions imply that the eruptive centers were to the northwest and that flow was predominantly to the southeast (Smith and Hartlaub, 1974). Chemical data (Smith, 1978b; 1983) indicate that the rhyolites and the associated granites are coeval and of both peraluminous and meta-aluminous affinity. The granites of the Fox River valley are epizonal in character and apparently were intruded into their own volcanic roof rocks. However, several synchronous quartz monzonitic plutons of mesozonal character have been identified to the north in the Wisconsin magmatic zone (Van Schmus, Thurman, and Peterman, 1975; Van Schmus, 1980), including the Amberg Quartz Monzonite of Medaris and Anderson (1973), the granite near Monico, and the porphyritic granite at Radisson. Judged from limited chemical data (Anderson and others, 1980), the plutons in northern Wisconsin appear to be the deep-seated equivalents of the granitic rocks in the Fox River valley.

The rhyolitic and granophyric rocks along the Fox River valley yield U-Pb concordia ages of about 1,760±10 m.y. (Van Schmus, Thurman, and Peterman, 1975; Van Schmus, 1978, 1980). Similar U-Pb concordia ages of 1,760±10 m.y. have been obtained from the mesozonal plutons that crop out in northern Wisconsin. A small, epizonal, gabbroic-granophyric stock, the Cedar Mountain Complex of Lund (1956), which cuts the Archean gneisses in the Minnesota River Valley, has a similar age of 1,750 m.y. (Goldich and others, 1961; Hanson, 1968). Although no substantive evidence indicates that the epizonal rocks of the Minnesota River Valley or the mesozonal rocks of northeastern and central Wisconsin are related petrogenetically to the rhyolitic and granitic rocks of the Fox River valley type, the radiometric data imply that igneous activity was widespread in the Lake Superior region about 1,760 m.y. ago.

SEDIMENTARY ROCKS OF THE BARABOO-SIOUX TYPE

Sedimentary rocks of the Baraboo-Sioux type are exposed in only a few areas (fig. 2) but are widely distributed in the subsurface over much of the southern part of the Lake Superior region (Dott, 1983). In addition to the Baraboo Quartzite in southern Wisconsin and the Sioux Quartzite in southwestern Minnesota and adjoining States, the sequence includes the Waterloo Quartzite in southern Wisconsin (Dott and Dalziel, 1972), and the Barron and Flambeau Quartzites in northwestern Wisconsin (Dott, 1983; Campbell, 1981).

As the names imply, the sequence, which has been inferred to be as much as 2,000 m thick in places, is dominated by red beds of braided fluvial origin, derived dominantly from the north and northwest (Weber, 1981; Morey, 1983c; Southwick and Mossler, 1984). The quartzite in the Baraboo area is overlain by 100 m of black argillaceous strata called the Seeley Slate, which in turn is overlain by 300 m of dolomite and iron-formation called the Freedom Formation (Weidman, 1904; Leith, 1935; Schmidt, 1951). Dott (1983) has suggested that the Seeley Slate and Freedom Formation were deposited by shallow marine processes. Erosion subsequently removed an unknown amount of the Freedom Formation before additional quartzite and shale—the Dake Quartzite and Rowley Creek Slate—were deposited.

The sedimentary rocks of the Baraboo-Sioux type have been variably deformed and metamorphosed. The northernmost Barron Quartzite is only broadly warped and contains kaolinite. The Sioux Quartzite also is broadly folded and contains kaolinite and diaspore. However, the bottom part of the formation, at least locally, contains pyrophyllite, which implies a burial metamorphic event (Vander Horck, 1984). In contrast, both the Baraboo and Waterloo Quartzites have been complexly folded; the former contains pyrophyllite and minor muscovite, and the latter contains andalusite and abundant muscovite (Geiger and others, 1982).

In southwestern Minnesota, the Sioux Quartzite rests on Archean gneiss that was affected by a thermal event around 1,800 m.y. ago (Goldich and others, 1970): interbedded argillaceous rocks yield a K-Ar mineral age of approximately 1,200 m.y. (Goldich and others, 1961). Therefore, the age of the Sioux Quartzite is not well constrained. In contrast, the Baraboo Quartzite overlies 1,760±10 m.y.-old rhyolitic rocks, and some geologic evidence implies that the two may be locally contemporaneous (Greenberg and Brown, 1984). The quartzitic rocks at Waterloo are in turn intruded by pegmatite which has yielded mineral ages of about 1,400 m.y. (Bass, 1959; Goldich and others, 1966). These pegmatites are probably closer to 1,470–1,500 m.y. in age, corresponding to times of other major igneous activity in the region (Van Schmus, Thurman, and Peterman, 1975). The volcanic rocks near Baraboo have yielded a Rb-Sr whole-rock isochron age of about 1,630±40 m.y. (Van Schmus, Thurman, and Peterman, 1975), an age that may reflect a period of folding and shearing (Smith, 1978a; Van Schmus, 1976). Because folding and shearing in the rhyolitic rocks probably were contemporaneous with folding of the quartzitic rocks, Van Schmus (1980) has suggested that the Baraboo Quartzite was deposited in the interval 1,760±10 m.y. to 1,630±40 m.y.

THE 1,630 M.Y. METAMORPHIC EVENT

Although a metamorphic event that reset the Rb-Sr systematics of the volcanic and quartzitic rocks at about 1,630 m.y. ago is well defined in southern Wisconsin, it is not geographically limited to that area. Van Schmus and Woolsey (1975) have shown that the Archean and Early Proterozoic rocks over a large area of northern Michigan underwent a major period of Rb-Sr reequilibration at 1,630±40 m.y. ago. Early Proterozoic rocks of the Animikie Group in northern Minnesota have yielded Rb-Sr whole-rock isochron ages of 1,624 m.y. (Keighin and others, 1972). A similar Rb-Sr age of 1,600±24 m.y. has been obtained from the correlative Gunflint Iron-formation in Canada (Faure and Kovach, 1969).

Igneous rocks having primary ages of about 1,630 m.y. have not been found in the Lake Superior region. Therefore, the widespread resetting of the Rb-Sr systems of a variety of rocks at that time must have been accomplished primarily by a low-grade metamorphic event, possibly accompanied by folding and shearing. Most likely these processes were the northern manifestation of a more extensive orogenic event that occurred to the south (Van Schmus and Bickford, 1981).

MIDDLE PROTEROZOIC ROCKS

Middle Proterozoic events in the Lake Superior region include the emplacement of the Wolf River batholith and the syenitic complexes of the Wausau type in Wisconsin, and the development of the Midcontinent rift system, a narrow belt of dominantly mafic rocks flanked by half-graben wedges of derivative sedimentary rocks, which extends from the Lake Superior region southward at least to Kansas.

WOLF RIVER BATHOLITH AND WAUSAU SYENITE COMPLEX

Rocks assigned to the Wausau Syenite Complex and to the Wolf River batholith underlie parts of south-central Wisconsin (figs. 2, 6). These rocks are representative of a large number of anorogenic, calcalkaline to alkaline plutons that invaded a broad zone of preexisting continental crust extending from Labrador to California and Wyoming to Mexico about 1,450 m.y. ago (Silver and others, 1977).

In Wisconsin, the syenitic complexes form two small calderalike plutons that are generally circular in plan view, and whose structures are accentuated by the concordant distribution of numerous large, vertically dipping xenoliths. The larger, Wausau pluton (LaBerge and Myers, 1973; Myers, 1976) consists of two partially overlapping segments. The older segment contains pyroxene- and amphibole-bearing syenite and the younger segment is differentiated inward from a pyroxene-bearing syenite to a core of biotite-bearing granite. The smaller Stettin pluton (Myers, 1973a, b) is more alkalic and is differentiated inward from a rim of biotite-bearing syenite, nepheline-syenite gneiss, or syenite, through intermediate zones of amphibole- and pyroxene-bearing syenite and magnetite-rich, nepheline-hedenbergite-fayalite-bearing syenite, to a core of pyroxene-bearing syenite (Myers, 1976).

The Wolf River batholith is an epizonal, composite unit of alkaline affinity. It consists of at least 10 separate plutons that are mostly of quartz monzonitic to granitic composition, but units of monzonite, syenite, quartz porphyry, feldspar porphyry, and anorthosite also have been mapped (Medaris and others, 1973). Individual plutons within the batholith formed by differentiation from early granite to late quartz monzonite, most likely by the progressive fusion of a crustal source (Anderson and Cullers, 1978). The anorthosite units appear to represent large xenolithic blocks or roof pendants of an older unit caught up during emplacement of the batholithic rocks.

Zircons from the Wausau pluton yield a U-Pb concordia intercept age of 1,520±15 m.y. (Van Schmus, 1980), and zircons from several plutons of the Wolf River batholith yield an age of 1,485±15 m.y. (Van Schmus, Medaris, and Banks, 1975). Both yield apparent Rb-Sr isochron ages of approximately 1,435±34 m.y. (Van Schmus, Medaris, and Banks, 1975), and apparently were affected by the same post-crystallization event. A pegmatite dike that cuts the Waterloo Quartzite yields a similar Rb-Sr age of approximately 1,410 m.y. (Bass, 1959), and muscovite from a phyllite in the Waterloo Quartzite yields a minimum K-Ar age of 1,410 m.y. (Goldich and others, 1966). These ages probably represent slight degradation of systems somewhere near 1,480 m.y., rather than discrete younger events.

MIDCONTINENT RIFT SYSTEM

The final event in the formation of the Precambrian crust in the Lake Superior region was the Midcontinent rift system (King and Zietz, 1971). Rifting was accompanied by massive upwelling of magma, solidification of mafic plutonic rocks at depth, and widespread volcanism and clastic sedimentation at the surface. Rocks associated with this period of rifting contain large stratabound deposits of native copper and copper sulfides and comprise a classical sequence of rocks called the Keweenawan system (Goldich and others, 1961), Keweenawan series (White, 1972), or Keweenawan supergroup (King, 1976). Unfortunately none of these stratigraphic names has been formally defined (Morey and Green, 1982).

Rocks of the Midcontinent rift system crop out along the shores of Lake Superior and extend from near the western end of Lake Superior to the south-southwest for a distance of about 160 km, to a place where they pass beneath overlapping Paleozoic strata (fig. 8). Geophysical evidence indicates that this arm of the rift system—generally referred to as the Midcontinent geophysical anomaly—extends southward beneath the Paleozoic strata for another 1,600 km to central Kansas (King and Zietz, 1971) and possibly to the Kansas–Oklahoma border (Yarger, 1983). A second arm of the rift system extends southeastward from the eastern end of Lake Superior (Hinze and others, 1975; Catacosinos, 1981) beneath the Paleozoic strata of the Michigan basin to approximately the buried continuation of the Grenville Front. At least two locations in Canada have been suggested for the third possible arm of this rift system. One extends from north of Isle Royale to the general vicinity of Lake Nipigon. This half-graben-like structure is filled by sedimentary rocks of the Sibley Group. The other proposed third arm, the Kapuskasing structural zone, extends from very near the eastern end of Lake Superior north-northeastward into Canada (Percival and Card, 1983). Rocks of undisputed Keweenawan affinity have not been defined in the Isle Royale–Lake Nipigon structure and occur only to a very limited extent in the Kapuskasing structural zone (Percival and Krogh, 1983), and thus there may be no well-defined third arm.

In early reports on Keweenawan geology (summarized in Morey and Green, 1982) it was noted that igneous activity—represented by lava flows and mafic intrusions—was preceded and followed by deposition of dominantly clastic strata. Therefore, the Keweenawan succession was divided into a lower, a middle, and an upper part (Van Hise and Leith, 1911). More recent geologic and paleomagnetic data, however, indicate that igneous activity and sedimentation were partly contemporaneous and that boundaries separating volcanic and sedimentary rocks are not everywhere synchronous (for example, White, 1972). Thus, a recent trend has been towards subdividing the Keweenawan in terms of magnetopolarity units. At least two reversals of magnetic polarity (DuBois, 1962; Books, 1968, 1972) occur within the Keweenawan sequence (fig. 9). An older normal-to-reverse magnetic reversal has been identified in volcanic sequences that crop out only in northern Wisconsin and Michigan. Evidence for a younger reverse-to-normal magnetic reversal is much more widespread, but unfortunately the reversal took place during a depositional hiatus represented by an unconformity. Although both reversals have limited chronostratigraphic value, they provide a means of broadly correlating rock units of diverse distribution in the region.

Quartz-rich sandstone, siltstone, and conglomerate of the Bessemer Quartzite, Puckwunge Sandstone, and Nopeming Formation (fig. 9) are the oldest unequivocal Keweenawan rocks in the region (Ojakangas and Morey, 1982). Although these formations have similar lithotopes and occupy a stratigraphic position beneath lava flows, they are not correlative. The Bessemer Quartzite is unconformably overlain by normally polarized volcanic rocks, whereas those over the Nopeming Formation and Puckwunge Sandstone are reversely polarized (Books, 1972; Green and Books, 1972).

The chronometric ages of the basal Keweenawan clastic units are poorly constrained. However, the Puckwunge Sandstone of northern Minnesota has been traditionally correlated with the Sibley Group in Canada (Robertson, 1973; DuBois, 1962), which has yielded a Rb-Sr isochron age of 1,340±33 m.y. (Wanless and Loveridge, 1978). This age is considerably greater than those typically associated with the Midcontinent rift system. However, the data are highly scattered and the behavior of the Rb-Sr system in such sedimentary rocks is uncertain. Therefore the age may be of uncertain value. Because of the problematic value of the reported age and because the Sibley Group lacks any evidence of a volcanic component, Green (1983) and Halls and Pesonen (1982), among others, have suggested that the Sibley Group formed at some time prior to the onset of sedimentation and volcanism related to the Midcontinent rift.

The earliest unequivocal Keweenawan eruptive rocks occur in northern Michigan and Wisconsin, where thay are assigned to the Siemens Creek Formation of the Powder Mill Group (Hubbard, 1975a). The lowermost one or two flows are pillowed, but most of the formation, which is as much as 1,300 m thick, formed under subaerial conditions. Subaqueous and subaerial flows in the lowermost 100 m or so of the formation are normally polarized, whereas the remainder is reversely polarized (Books, 1968, 1972).

The Kallander Creek Formation overlies the Siemens Creek Formation in the Powder Mill Group. This formation formed under subaerial conditions, is as much as 4,500 m thick (Green, 1977), and is reversely polarized (Books, 1972). Other reversely polarized volcanic rocks (Green and Books, 1972) include the Grand Portage and Hovland Lavas in the basal part of the North Shore Volcanic Group in northeastern Minnesota (Green, 1972) and the Elys Peak Basalts near Duluth (Kilbury, 1972). Hypabyssal intrusions emplaced during this interval of reversed magnetic polarity include the dikes from Marquette and Baraga Counties in northern Michigan (Pesonen and Halls, 1979) and the intrusions near Logan (Jones, 1984; Weiblen and others, 1972; DuBois, 1962) in northern Minnesota. The plutonic-gabbroic rocks of Nathan's (1969) so-called "layered series of the Gunflint prong" of the Duluth Complex also were emplaced at this time.

The chronometric age of the reversely polarized volcanic rocks in the Powder Mill Group has not been established, but Silver and Green (1972), using U-Pb zircon ages, have suggested that the magnetically normal units from the group and from throughout the region formed in the 1,110±10 m.y. range. However, Hanson (1975) reported $^{40}Ar/^{39}Ar$ ages of 1,147 to 1,172 m.y. for plagioclase separates from the Logan intrusions. York and Halls (1969) have reported a K-Ar age of approximately 1,210 m.y. from a Logan-type intrusion, and Hanson and Malhotra (1971) have reported an even older K-Ar age of 1,305±65 m.y. for a chilled margin of a Logan-type intrusion. Although these ages are imprecise, as is a Rb-Sr isochron age of 1,242±200 m.y. (Wanless and Loveridge, 1978) from sedimentary rocks metamorphosed by a Logan-type intrusion, they collectively suggest that Keweenawan igneous activity began considerably before 1,110±10 m.y. ago.

Contact relationships between reversely polarized and overlying normally polarized parts of the North Shore Volcanic Group are covered or obscured by intrusive rocks. Regional geologic map patterns (Green, 1982) and detailed aeromagnetic data (Chandler, 1983) imply that the contact is a low-angle unconformity. The normally polarized parts of the North Shore Volcanic Group consist dominantly of basalt, but also contain intermediate and felsic lavas (Green, 1977, 1982, 1983; Basaltic Volcanism Study Project, 1981) and minor quantities of interlayered sedimentary rocks (Merk and Jirsa, 1982; Jirsa, 1984). The volcanic rocks overlie and were the roof for mafic plutonic rocks of the Duluth and Beaver Bay Complexes (Weiblen and Morey, 1980; Weiblen, 1982). Cogenetic zircons from felsic rocks in the volcanic sequence and the Duluth Complex yield U-Pb ages of 1,110±10 m.y. (Silver and Green, 1963, 1972). This age agrees closely with a Rb-Sr isochron age of 1,090±30 m.y. for the Duluth Complex (Faure and

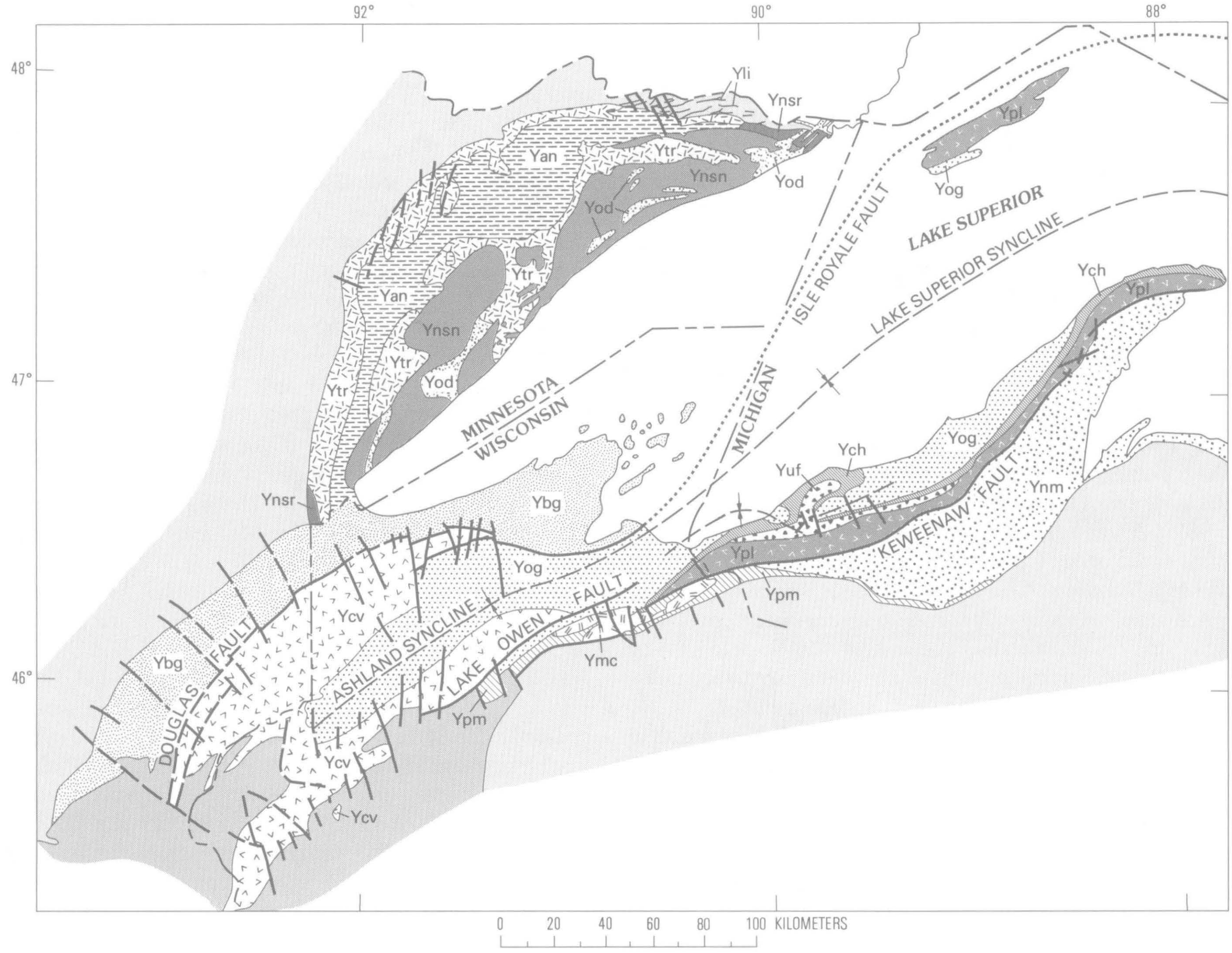


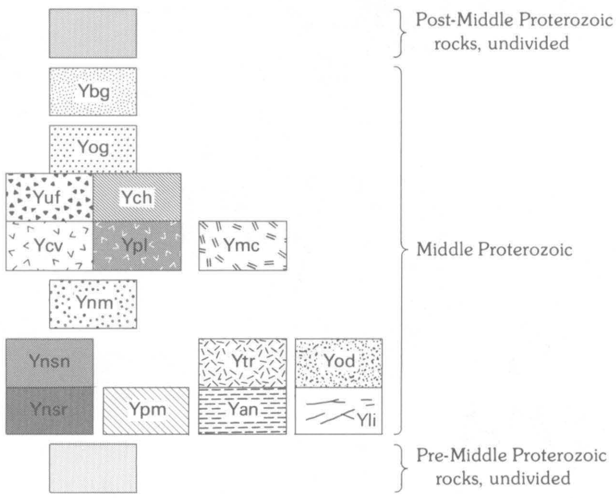
FIGURE 8 (above and facing page).—Generalized geology of western Lake Superior region showing distribution of Middle Proterozoic rocks associated with the Midcontinent rift system (Morey and Green, 1982).

others, 1969). The volcanic rocks also are intruded by a number of hypabyssal intrusions that are comagmatic with parts of the Duluth Complex (Weiblen and Morey, 1980). These include rocks in northeastern Minnesota that are correlative with the intrusions near Pigeon River of Geul (1970) in Canada (Mudrey, 1976, 1977). The intrusions near Pigeon River have yielded a K-Ar age of approximately 1,150 m.y. (York and Halls, 1969) and a $^{40}Ar/^{39}Ar$ age of 1,145±10 m.y. (Hanson, 1975). Still younger dikes and sills also occur in northeastern Minnesota. These include the Endion sill at Duluth, which has produced a Rb-Sr isochron age of 1,068±30 m.y. (Faure and others, 1969).

Two other normally polarized eruptive units (Books and Green, 1972; Books, 1972) crop out to the south of Lake Superior. These are the Portage Lake Volcanics along the Keweenaw Peninsula (White, 1960, 1966) and on Isle Royale in the northern part of Lake Superior (Huber, 1973), and the Chengwatana Volcanic Group in east-central Minnesota (Morey and Mudrey, 1972) and adjoining parts of Wisconsin (White, 1978). Of the two, the Portage Lake Volcanics are much better known, mainly because of their contained native copper deposits (White, 1968). Although neither continuous nor entirely correlative (for example, White, 1978), both consist predominantly of basalt and both lack rocks of intermediate chemical composition (Cornwall, 1951; Jolly and Smith, 1972; Morey and Mudrey, 1972; Green, 1977, 1982).

Both units also occupy uncertain stratigraphic positions within the normally polarized epoch, mainly because their contacts are either faulted or covered by younger materials. However, near Mellen, Wis., the Chengwatana Volcanic Group overlies the Powder Mill

CORRELATION OF MAP UNITS



LIST OF MAP UNITS

- Ybg — Bayfield Group, undivided, and Hinckley Sandstone and Fond du Lac Formation in Minnesota
- Yog — Oronto Group, undivided
- Yuf — Unnamed formation of White (1972)
- Ych — Copper Harbor Conglomerate
- Ycv — Chengwatana Volcanic Group and related rocks
- Ypl — Portage Lake Volcanics
- Ymc — Mellen Intrusive Complex
- Ynm — Nonmagnetic rocks of Hubbard (1975a) and Jacobsville Sandstone

North Shore Volcanic Group

- Ynsn — Volcanic rocks of generally mafic composition having normal paleomagnetic polarity
- Ynsr — Volcanic rocks of generally mafic composition having reverse paleomagnetic polarity and the Nopeming Sandstone and the Puckwunge Sandstone

Duluth and Beaver Bay Complexes

- Ytr — Troctolitic and gabbroic series and related felsic rocks
- Yan — Anorthositic series and related ultramafic and felsic rocks
- Ypm — Powder Mill Group, undivided, and Bessemer Quartzite
- Yod — Olivine diabase intrusions
- Yli — Intrusions near Logan, northern Minnesota

Contact

Fault—Dashed where approximate; dotted where concealed by water

Axis of syncline

Group (White, 1978) and is separated from it by sedimentary rocks that Aldrich (1929) called the conglomerate of Davis Hill. The correlation of that conglomerate with other units of the region is unknown. To the east, Portage Lake rocks in Michigan are similarly juxtaposed against a sequence of "nonmagnetic rocks" that appear to be sedimentary in origin (King, 1975) and that overlie the Powder Mill Group. Hubbard (1975a) suggested that the sedimentary rocks may be a western facies of the Jacobsville Sandstone and that they are unconformably overlain by the Portage Lake Volcanics. Most interpretations, however, infer that the Portage Lake and sedimentary rocks are juxtaposed in this area by the Keweenaw fault (Kalliokoski, 1982).

Stratigraphic relations between the Portage Lake Volcanics and the North Shore Volcanic Group are equally uncertain. However, the nearly linear northwest shoreline of Lake Superior may represent an exhumed erosion surface formed on rocks of the North Shore Volcanic Group before the Portage Lake Volcanics were erupted (White, 1966). This unconformity, however, may represent a relatively short hiatus inasmuch as U-Pb ages from the two units appear to be indistinguishable (Silver and Green, 1972). Many of the reported Rb-Sr results from felsic units in the Portage Lake Volcanics also are concordant, within stated uncertainty limits, with the U-Pb ages of Silver and Green (1972), but other Rb-Sr ages are significantly discrepant (Van Schmus and others, 1982). Reported Rb-Sr ages range from 1,075±25 m.y. to 1,016±30 m.y. (Chaudhuri, 1973, 1975; Chaudhuri and Brookins, 1969; Chaudhuri and Faure, 1967). The slightly younger Rb-Sr ages are consistent with the stratigraphic succession, but the more discrepant ages may reflect disturbed Rb-Sr isotopic systems. As with data from the volcanic rocks, Rb-Sr results from the intrusive rocks must be interpreted with caution.

Intrusive rocks that were emplaced more or less contemporaneously with the Portage Lake Volcanics include the Mellen Intrusive Complex of Hubbard (1975a), the Mineral Lake intrusion of Olmsted (1968), and the Rearing Pond intrusion of Olmsted (1979), all in the general vicinity of Mellen, Wis. Gabbro from the Mellen Complex yields a Rb-Sr isochron age of 1,075±25 m.y. (Chaudhuri and others, 1969), whereas granite from the Mineral Lake intrusion gives an age of 1,042±30 m.y. (Chaudhuri and Brookins, 1969).

The Chengwatana Volcanic Group is conformably overlain by sedimentary rocks of the Oronto Group in Wisconsin and the Solor Church Formation in Minnesota (Morey and Ojakangas, 1982). The Oronto Group also overlies the Portage Lake Volcanics in parts of Michigan, but in other places, the two are separated by yet another normally polarized volcanic unit of generally felsic composition, the unnamed formation of White (1972). The unnamed formation is interlayered with the Copper Harbor Conglomerate, formerly considered to be the lowermost unit of the Oronto Group. Therefore,

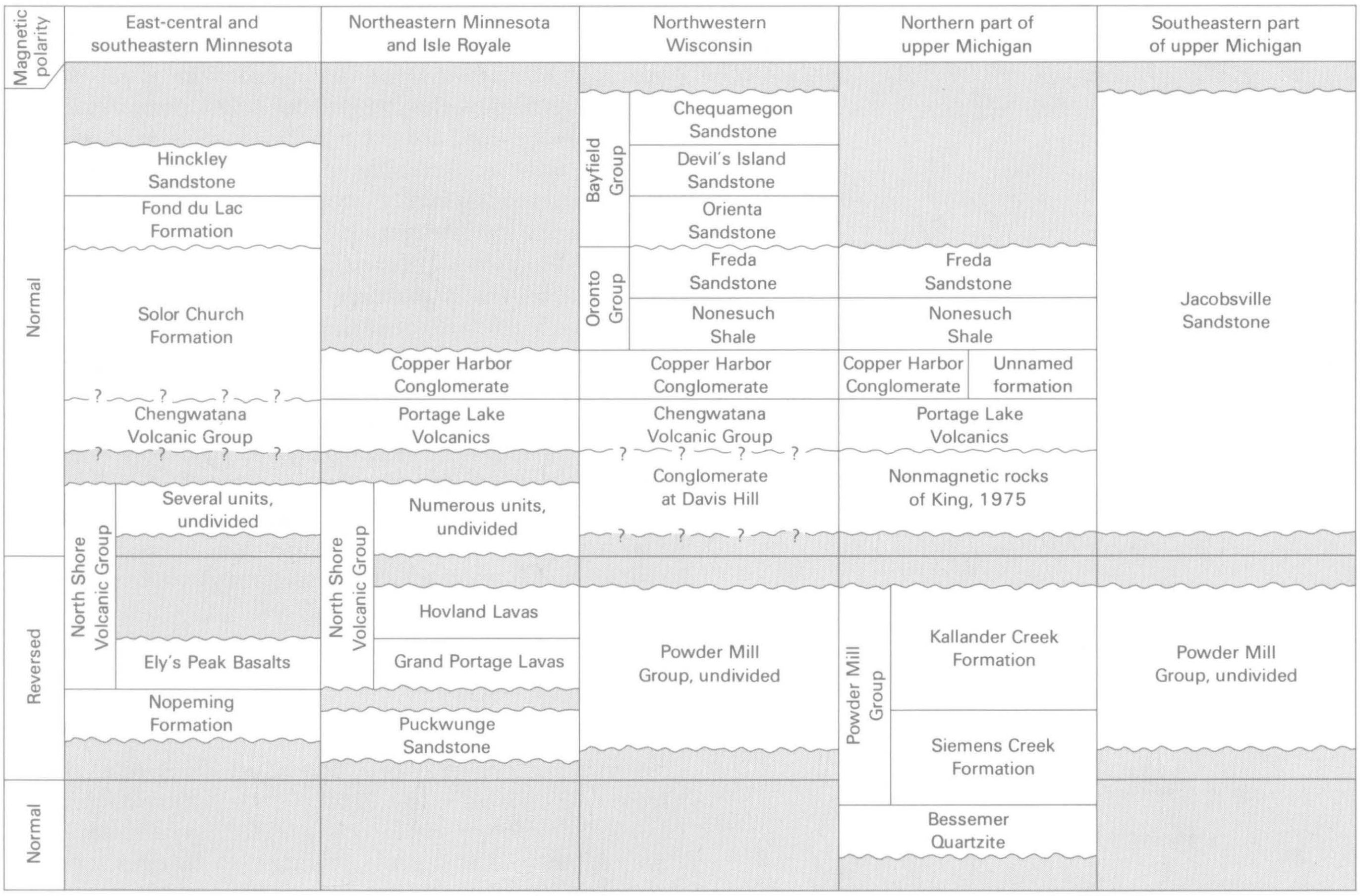


FIGURE 9.—Correlation chart for Middle Proterozoic rocks associated with the Midcontinent rift system in the Lake Superior region (modified from Green, 1977).

a Rb-Sr age of 1,072±25 m.y. (Chaudhuri, 1972) from a rhyolite flow approximates both the time volcanism ended and the time clastic sedimentation started in this part of Michigan.

The Oronto Group, as redefined by White (1972), consists of the Nonesuch Shale and the overlying Freda Sandstone. The Copper Harbor Conglomerate as well as the rocks of the Oronto Group all exhibit normal magnetic polarity (Books, 1972; Henry and others, 1977; Halls and Pesonen, 1982). The Copper Harbor Conglomerate and Freda Sandstone are dominantly red colored clastic units of lithic sandstone, shale, and conglomerate deposited by alluvial and fluvial processes (Daniels, 1982; Elmore, 1984), whereas the Nonesuch Shale is an unoxidized sequence of dark-gray to black siltstone, shale, and mudstone deposited by lacustrine processes. The Nonesuch is mineralized with copper sulfides over a wide area; the only economic concentrations occur near White Pine, Mich. (Ensign and others, 1968).

The Solor Church Formation in southern Minnesota physically resembles the Copper Harbor Conglomerate and Freda Sandstone, consisting of lithic sandstone, siltstone, and shale deposited by fluvial processes (Morey, 1974). Although the Solor Church Formation and the Oronto Group were never continuous units, Morey and Ojakangas (1982) have suggested on the basis of lithologic similarity that both are part of the same depositional episode. The time of this depositional episode in Michigan is bracketed by the 1,072±25 m.y. age from the unnamed formation and a Rb-Sr isochron age of 1,052±50 m.y. from the Nonesuch Shale (Chaudhuri and Faure, 1967). The signifance of the latter age has been questioned (Van Schmus and others, 1982) mainly because the Nonesuch was derived from a volcanic source of that age. However, Ruiz and others (1984) have reported a Rb-Sr age of 1,047±35 m.y. from calcite veins associated with the copper mineralization in the Nonesuch. Therefore it seems likely that the Oronto Group was deposited between approximately 1,100 and 1,000 m.y. ago, an age further substantiated by a K-Ar age of 1,062±34 m.y. (M.A. Lanphere as quoted in White, 1968) from a biotite-bearing rhyolite stock near Bear Lake, Mich., that intrudes the Freda Sandstone.

A number of felsic intrusions whose ages cluster around 930±35 m.y. (such as a granite stock just north of Mellen) also have been recognized in Wisconsin and Michigan (Chaudhuri, 1972, 1976). Compared with the felsic extrusive rocks, these intrusions have significantly higher initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, implying a previous crustal history (Chaudhuri and others, 1969). If the Rb-Sr isotopic systems are undisturbed in these rocks, the reported ages define the end of igneous activity in the Lake Superior region. However, the biotite-bearing rhyolite stock near Bear Lake that was dated by M.A. Lanphere at 1,062±34 m.y. also yielded an apparent Rb-Sr isochron age of 985±25 m.y. (Chaudhuri, 1975). This suggests that the Rb-Sr isotopic system, at least in this one rock, has been disturbed. Thus all the very young felsic intrusions may be much older than their apparent Rb-Sr ages. In that regard, the paleomagnetic pole positions of these rocks are not significantly different from those associated with other normally polarized extrusive rocks (Van Schmus and others, 1982). Therefore, although it has been suggested that igneous rocks as young as 980–900 m.y. may exist in the Lake Superior region, their presence has not been firmly established.

The youngest Precambrian sedimentary rocks in the Lake Superior region are assigned to the Bayfield Group (Thwaites, 1912). In Wisconsin, the group consists of three formations, from oldest to youngest the Orienta, Devils Island, and Chequamegon Sandstones (Morey and Ojakangas, 1982; Ostrom, 1967). Correlative rocks in Minnesota include the Fond du Lac Formation (Morey, 1967) and the overlying Hinckley Sandstone (Tryhorn and Ojakangas, 1972). The Bayfield Group and its Minnesota equivalents are typical red-bed sequences of fluvial and lacustrine origin (Morey and Ojakangas, 1982). They differ from the older Oronto Group in that they lack primary igneous material, are less well lithified, and are more arkosic or quartz rich in composition.

The age of the Bayfield Group is uncertain: it has been assigned to the Late Proterozoic (for example, King, 1976) or to the Early–Middle Cambrian (for example, Ostrom, 1967). However, the Fond du Lac Formation has a paleomagnetic pole position akin to those associated with other Middle Proterozoic rocks in the rift system (Watts, 1981).

A third alluvial-fluvial red-bed sequence—the Jacobsville Sandstone of Lane and Seaman (1907)—crops out over a wide area in the southeastern part of northern Michigan (Hamblin, 1958; Kalliokoski, 1982). This sequence consists of lithic to arkosic sandstone, conglomerate, and some shale. It forms a wedge that dips and thickens toward the northwest and unconformably overlies magnetically reversed volcanic rocks of the Powder Mill Group or still older pre-Keweenawan basement rocks (Bacon, 1966; Hubbard, 1975a). Because much of its northern limit coincides with the Keweenaw fault, the stratigraphic position of the Jacobsville Sandstone is uncertain. On the basis of regional considerations, it has been correlated with the Bayfield Group (White, 1966), the Oronto Group (Ostrom, 1967), rocks of the Cambrian System (Hamblin, 1958), and with a sequence possibly older than the Portage Lake Volcanics (Babcock, 1975, 1976; Hubbard, 1975a). However, paleomagnetic data suggest that the Jacobsville is only slightly younger than the Freda Sandstone of the Oronto Group (Roy and Robertson, 1978).

SUMMARY

Several conclusions regarding the geologic history of the Lake Superior region can be made from the stratigraphic and chronometric data summarized on the geochronometric correlation chart (pl. 1). The Archean gneiss terrane records a long span of geologic history extending back to about 3,600 m.y. ago, which is nearly a billion years before any major datable geologic event in the Late Archean greenstone–granite terrane. Additional major geologic events took place in the gneiss terrane almost a billion years after formation of the greenstone–granitic terrane. The gneiss terrane was tectonically mobile throughout much of Precambrian history as indicated by a succession of events that have been dated at about 3,600 m.y., 3,000–2,900 m.y., 2,600 m.y., 2,400–2,300 m.y., 2,100–2,000 m.y., 1,900–1,800 m.y., 1,760 m.y., 1,650 m.y., and 1,500–1,450 m.y. In contrast, the greenstone–granite terrane formed within a narrow range of a few hundred million years approximately 2,700 m.y. ago and has remained essentially stable since that time, except for several periods of low-grade metamorphism and dike emplacement. Lastly, both crustal segments were transected and affected when the Midcontinent rift system formed 1,200–1,000 m.y. ago.

Although some rocks in the 1,000–900 m.y. interval may be present, no rocks of definite Late Proterozoic age have been recognized in the Lake Superior region.

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