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Paleoproterozoic basin development and sedimentation in the Lake Superior region, North America

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Abstract

The peneplaned Archean craton in the Lake Superior region was the platform upon which a continental margin assemblage was deposited. Extension resulted in localized rifts that received thicker accumulations of sediments and volcanic rocks than did adjacent parts of the platform. Seas transgressed onto the continent several times and an ocean basin opened south of the present-day Lake Superior. Island arcs that formed during subduction collided with the craton margin as the ocean basin closed; oceanic crust is poorly preserved as a dismembered ophiolite sequence. The arc volcanics are preserved as the Wisconsin magmatic terranes. The collision resulted in a fold-and-thrust belt known as the Penokean orogen. To the north of the fold-and-thrust belt, a northward-migrating foreland basin — the Animikie basin — developed. Thick turbidite successions were deposited along the basin axis, and terrigenous clastics and Lake Superior-type iron-formation were deposited on the shelf along the northern margin of the basin.

The primary paleoclimatic indicators are: (1) glaciogenic rocks at the base of the Paleoproterozoic succession in Michigan indicating ice-house conditions; (2) remnants of a paleosol on the glaciogenic rocks indicative of deep weathering, probably under subtropical conditions and therefore of greenhouse conditions; and (3) carbonate minerals after gypsum, halite, and anhydrite in stromatolitic dolomite, indicative of aridity.

Three second-order depositional sequences are bounded by major unconformities, and can be correlated throughout the Lake Superior region.

Keywords: Paleoproterozoic; Paleoclimates; Magmatism; Correlation; Penokean orogeny; Foreland basin

1. Introduction

This paper summarizes the history of Paleoproterozoic supracrustal rocks of the Lake Superior region deposited between ≈2200 and ≈1730 Ma. The region has long been of interest, largely because of more than a century of mining of Lake Superior-type iron-formations.

Much of the following introduction is from Morey (1996). Supracrustal sequences of Paleoproterozoic age in the Lake Superior and Lake Huron regions constitute a discontinuous linear foldbelt 1300 km long which extends from central Minnesota to eastern Ontario along the south margin of the Superior province of the Canadian Shield (Figs. 1 and 2). The foldbelt is referred to here as the Penokean orogen. The orogen is transected at both ends of Lake Superior by Mesoproterozoic rocks of the Midcontinent Rift System, and in eastern Ontario by Mesoproterozoic rocks of the Grenville Front tectonic zone.

From west to east, the supracrustal sequences are

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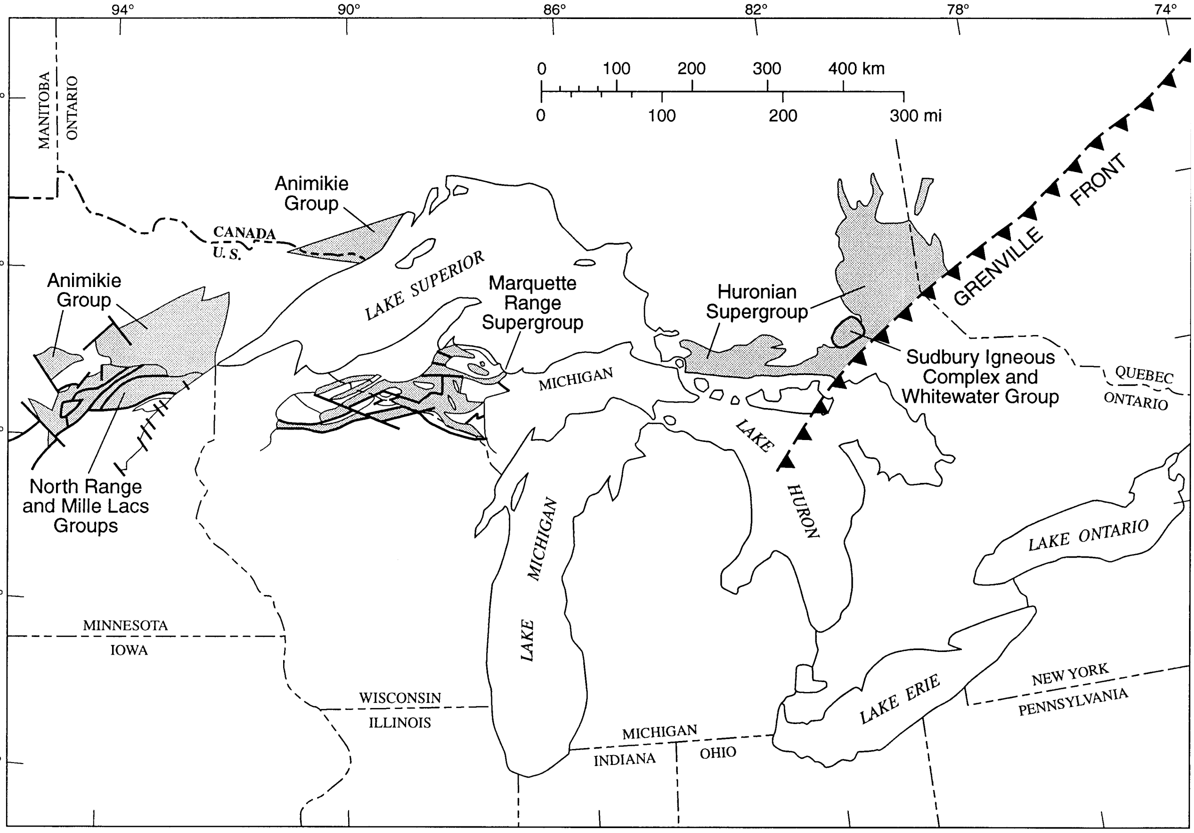


Fig. 1. Generalized distribution of Paleoproterozoic rocks in the Great Lakes region. Stippled pattern denotes the stratified rocks, both sedimentary and volcanic. Modified from Morey (1996) and references included therein.

the Mille Lacs, North Range, and Animikie Groups in Minnesota, the Marquette Range Supergroup in northern Michigan and Wisconsin, and the Huronian Supergroup and Whitewater Group in Ontario. All are composed dominantly of epiclastic rocks, but subordinate volcanic and hypabyssal intrusive rocks are present locally. The Lake Superior region also contains appreciable chemical sedimentary rocks, chiefly iron-formation, whereas the Lake Huron region lacks iron-formation.

The iron-formations that are present in several parts of the Lake Superior region were formerly believed to represent a unique temporal event that could be used to correlate isolated sequences (e.g. Van Hise and Leith, 1911). The idea of a principle episode of iron-rich deposition persisted into the 1980s (e.g. Morey, 1983; Morey and Van Schmus, 1988; Morey, 1993). It was first challenged by the structural studies of Southwick et al. (1988) in Minnesota, who showed that the Penokean orogen consists of two major components, an allochthonous fold-and-thrust belt on the southeast and one or more tectonic foredeeps on the northwest. The fold-and-thrust belt consists of several discrete panels bounded by discontinuities that have small-scale features consistent with large-scale northwest-verging nappes (Southwick and Morey, 1991). The fold-and-thrust belt flanks a tectonic foredeep that extended to the Mesabi range in northern Minnesota and the Gunflint range in Minnesota and adjacent Ontario, the type locality for the Animikie Group. Because the foredeep is filled with strata assigned to the Animikie Group, Southwick et al. (1988) have referred to it as the 'Animikie basin'. This usage of Animikie basin is considerably more restricted than that used in earlier literature (Morey, 1983; Morey and Van Schmus, 1988).

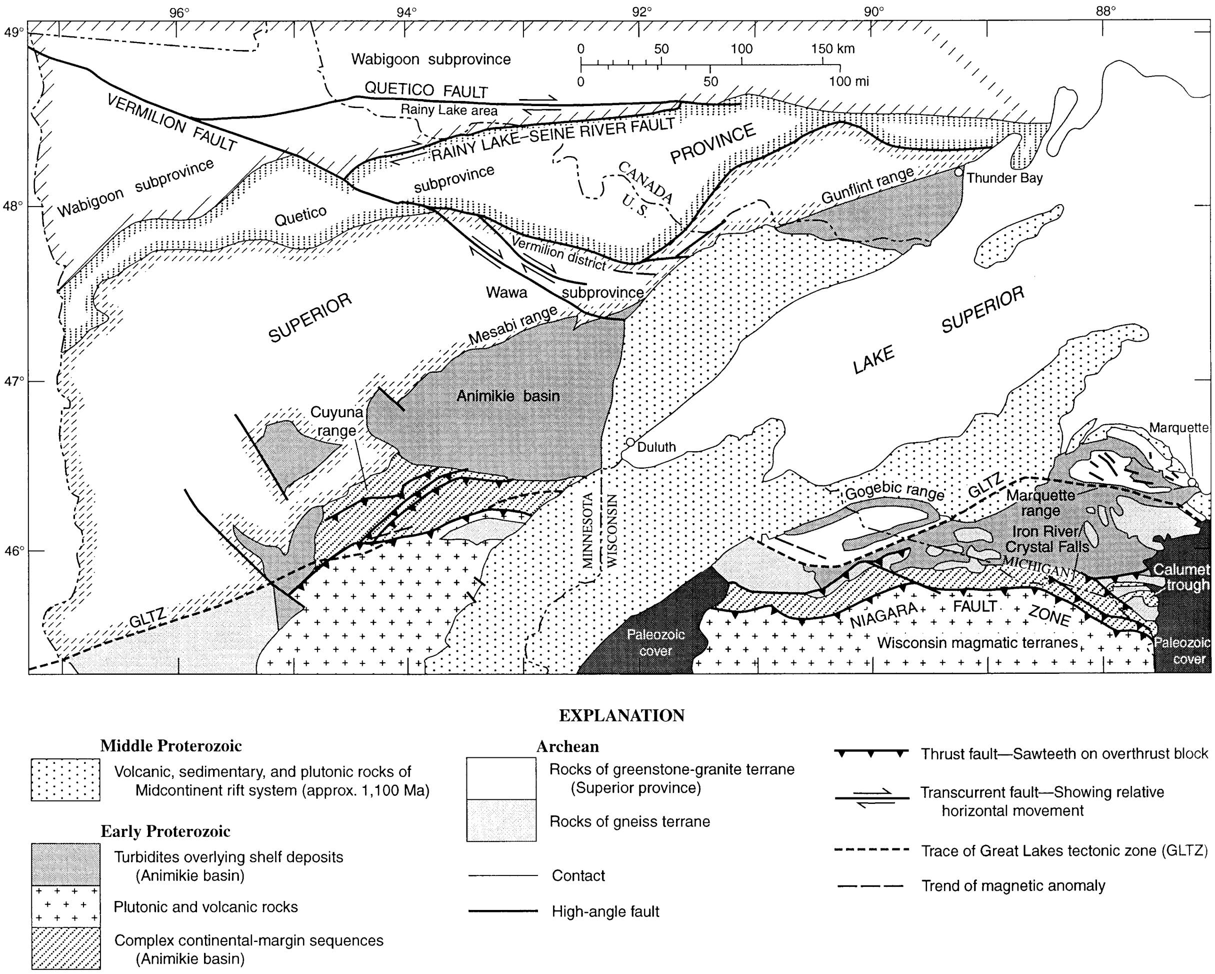


Fig. 2. Generalized geologic-tectonic map showing the distribution of Precambrian rocks and structural elements of the Lake Superior region. Modified from Ojakangas (1994) and references included therein.

Barovich et al. (1989) used Sm–Nd techniques to show that the lower part of the Marquette Range Supergroup in Michigan had a northern Archean cratonic provenance, whereas the upper part had a southern Paleoproterozoic volcanic provenance. Although the structural details are complicated, the combined studies of Southwick et al. (1988) and Barovich et al. (1989) show that the Penokean orogen can be generally divided into an early extensional phase, when sedimentary rocks including iron-formation were deposited on an evolving continental margin, and a subsequent compressional phase, when these continental margin deposits were folded and metamorphosed and partly buried under sediments in one or more northward-migrating foredeep basins partly filled with iron-formation as well as detritus from a newly formed island arc — the Wisconsin magmatic terranes to the south. Finally, the island arc and the continental margin were sutured together at about 1850 Ma.

Correlations within the region are somewhat complicated by the presence of the 1.1 Ga Midcontinent Rift System (60–100 km wide) that separates the region into a southeastern segment (Michigan–Wisconsin) and a northwestern segment (Minnesota–Ontario). Also, different stratigraphic names have been applied to similar stratigraphic entities over the past century of geological investigations.

Further complications include a paucity of exposures (particularly in the northwestern segment) because of a thick mantle of Pleistocene glacial materials, the general lack of dateable rock units, and the results of several deformational events that occurred during the Penokean orogeny. Fortunately, most of the rocks have been only slightly metamorphosed under greenschist facies conditions, and therefore have retained primary sedimentary attributes. The rocks of the southeastern segment have been correlated with those of the northwestern segment in a variety of ways (e.g. LaRue, 1981a,b; Morey and Van Schmus, 1988). Recent correlations are summarized in Fig. 3, along with a summary of geochronometric ages where established.

As this paper is limited in length, we are unable to refer to the countless papers that have contributed to the present understanding of the geology of the Lake Superior region. Stratigraphic nomenclature in the Lake Superior region is encumbered by literally hundreds of named units, many of which contribute little to an understanding of the geology. Herein we keep such nomenclature to a minimum and present a broad synthesis that depicts with a broad brush the major aspects of the Paleoproterozoic history of the region.

2. Regional geology, southeastern segment

The southeastern segment in Wisconsin and Michigan includes, from oldest to youngest, the Chocolay, Menominee, and Baraga Groups (Fig. 3). A fourth lithostratigraphic entity, the Paint River Group, was once believed to conformably overlie the Baraga Group (e.g. Cannon, 1986). However, Cambray (1978) used geophysical data to suggest that the two groups were separated by a major discontinuity. Subsequently, Sims (1990) mapped the discontinuity as a thrust fault and suggested that the Paint River Group is stratigraphically equivalent to the upper part of the Baraga Group.

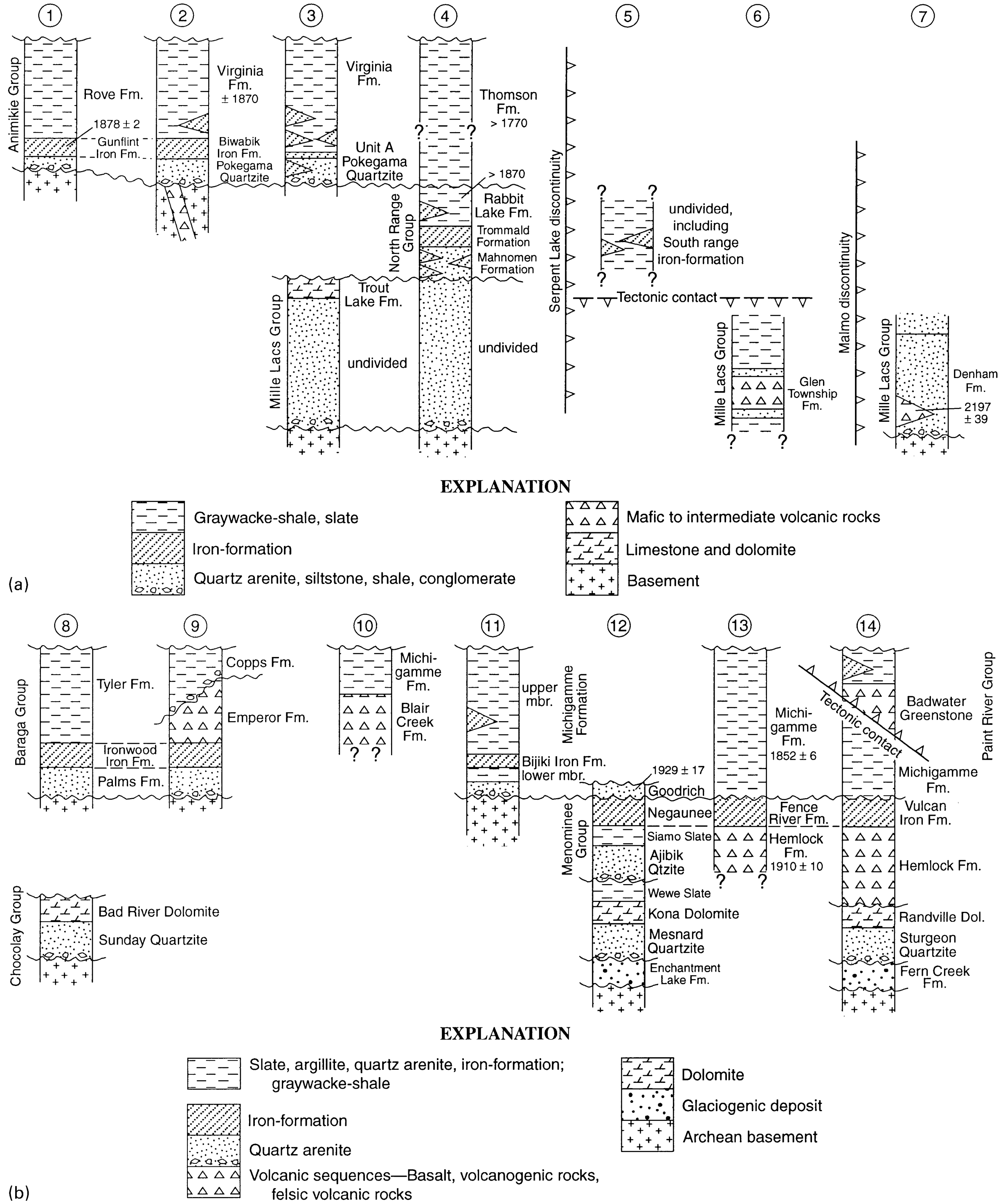
The stratified rocks in the southeastern segment generally increase in thickness from north to south. The succession is about 2 km thick in northwestern Wisconsin and as much as 9 km thick along the Michigan–Wisconsin border in the southeastern part of northern Michigan. For more details, see Morey (1993, 1996).

2.1. Chocolay Group

The lowest units of the Chocolay Group — the Fern Creek, Enchantment Lake, and Reany Creek Formations — unconformably overlie Archean granitic and mafic volcanic rocks. These three formations have been interpreted as glaciogenic (Pettijohn, 1943; Gair, 1981; Puffett, 1969), although that idea has been challenged by LaRue (1981b) and Mattson and Cambray (1983). Ojakangas (1984) re-emphasized a glacial origin for all three formations, for in his view each contains diamictites and dropstone units that are typical of ancient glacial deposits (Ojakangas, 1985). Low chemical index of alteration (CIA) values, as proposed by Nesbitt and Young (1982) are consistent with a glacial origin. More recently, Sims (1991) suggested, with little supporting evidence, that the Reany Creek Formation was deposited in an Archean strike–slip basin.

The glacial units are separated from overlying strata by unconformities marked by remnants of a paleosol that now consists of sericite and quartz (i.e. sericite schist). CIA values are high, consistent with the removal of cations during weathering. Unconformably overlying strata include thick units of orthoquartzite (now quarzite), referred to as the Sturgeon and Mesnard Quartzites. The orthoquartzite is inferred to have been derived from the weathering profile on the craton and deposited during a marine transgression onto a continental margin (Ojakangas, 1997). The two quartzite formations are overlain by stromatolitic dolomite units, the Randville and Kona Dolomites, respectively. On the Gogebic range, the Sunday Quartzite overlies Archean basement rocks

Fig. 3. (a) Lithostratigraphic correlations of Paleoproterozoic stratified rocks of the northwestern segment of the Lake Superior region (Minnesota and Ontario). The locations of the numbered stratigraphic sections are shown in Fig. 5. Wavy line, unconformity; question marks denote uncertain extent of unit. Modified from Morey (1996) and references included therein. (b) Lithostratigraphic correlations of Paleoproterozoic stratified rocks of the southeastern segment of the Lake Superior region (Michigan and Wisconsin). The locations of the numbered stratigraphic sections are shown in Fig. 5. Wavy line, unconformity; question marks denote uncertain extent of unit. Modified from Morey (1996) and references included therein.


1
2
3
4
5
6
7
Animikie Group
Rove Fm.
1878 ± 2
Gunflint Iron Fm.
Virginia Fm.
± 1870
Biwabik Iron Fm.
Pokegama Quartzite
Virginia Fm.
Unit A
Pokegama Quartzite
Thomson Fm.
> 1770
> 1870
North Range Group
Rabbit Lake Fm.
Trommald Formation
Mahnomen Formation
Mille Lacs Group
Trout Lake Fm.
undivided
undivided
Serpent Lake discontinuity
undivided, including South range iron-formation
Tectonic contact
Mille Lacs Group
Glen Township Fm.
Malmo discontinuity
Mille Lacs Group
Denham Fm.
2197 ± 39
EXPLANATION
Graywacke-shale, slate
Iron-formation
Quartz arenite, siltstone, shale, conglomerate
Mafic to intermediate volcanic rocks
Limestone and dolomite
Basement
(a)
8
9
10
11
12
13
14
Baraga Group
Tyler Fm.
Copps Fm.
Emperor Fm.
Ironwood Iron Fm.
Palms Fm.
Michigamme Fm.
Blair Creek Fm.
Michigamme Formation
upper mbr.
Bijiki Iron Fm.
lower mbr.
1929 ± 17
Goodrich
Menominee Group
Negaunee
Siamo Slate
Ajibik Qtzite
Wewe Slate
Kona Dolomite
Mesnard Quartzite
Enchantment Lake Fm.
Michigamme Fm.
1852 ± 6
Fence River Fm.
Hemlock Fm.
1910 ± 10
Tectonic contact
Badwater Greenstone
Paint River Group
Michigamme Fm.
Vulcan Iron Fm.
Hemlock Fm.
Randville Dol.
Sturgeon Quartzite
Fern Creek Fm.
Chocolay Group
Bad River Dolomite
Sunday Quartzite
EXPLANATION
Slate, argillite, quartz arenite, iron-formation; graywacke-shale
Iron-formation
Quartz arenite
Volcanic sequences—Basalt, volcanogenic rocks, felsic volcanic rocks
Dolomite
Glaciogenic deposit
Archean basement
(b)

rather than glaciogenic rocks, and is overlain by the Bad River Dolomite.

The Fern Creek–Reany Creek–Enchantment Lake package has been correlated with the Gowganda Formation, a glaciogenic unit at the base of the Cobalt Group in the uppermost Huronian Supergroup exposed some 200 km to the east in Ontario (e.g. Young, 1970, 1983; Puffett, 1969; Ojakangas, 1982, 1985). The Gowganda is the uppermost of three glaciogenic units in the Huronian Supergroup. Similarly, the Sunday–Mesnard–Sturgeon and the Bad River–Kona–Randville packages have been correlated with the Lorrain Quartzite and the Gordon Lake Formation, respectively, in the Cobalt Group of Ontario. Thus the Chocolay Group strongly resembles the Cobalt Group, implying that the two could well be equivalent. The age of the Gowganda on the basis of a Rb/Sr isochron is 2240 ± 87 Ma (Fairbairn et al., 1969). The entire Huronian Supergroup is cut by the Nipissing Diabase with a U–Pb baddeleyite age of 2219 ± 4 Ma (Corfu and Andrews, 1986). Thus, the glacial units in Michigan could have been deposited before 2200 m.y. and perhaps as early as 2300 m.y.

2.2. Menominee Group

Rocks of the Menominee Group unconformably overlie the Chocolay Group, or where it was removed by erosion, rocks of Archean age. Sedimentation began in the Marquette trough (an east-trending graben) with deposition of the Ajibik Quartzite. The quartzite is overlain by the Siamo Slate, a unit of argillite and graywacke, with Bouma sequences indicative of turbidity currents that flowed in a westerly direction parallel to the trough axis (LaRue, 1981a).

The major Negaunee Iron Formation of the Marquette range, dominantly oxide and carbonate iron-formation, was the next formation to be deposited. Correlative iron-formations such as the Vulcan Iron Formation of the Menominee range to the south (just east of the Iron River/Crystal Falls district in Fig. 2) were deposited in other fault-bounded troughs. The Negaunee contains a few intercalated terrigenous clastic beds derived from the south side of the Marquette trough via turbidity currents, as well as a large volume of mafic sills and dikes. In the Calumet trough, south of the Marquette trough, the Vulcan Iron Formation overlies a volcanic sequence of generally basaltic composition, the Hemlock Formation, which was emplaced at 1910 ± 10 Ma (Van Schmus and Bickford, 1981). The Badwater Greenstone in Michigan and the Emperor Volcanics along the Wisconsin–Michigan border are thought to have similar ages.

2.3. Baraga Group

The Baraga Group on the western Gogebic range in northern Wisconsin (Fig. 2) consists of three formations (Fig. 3). The lowest is the Palms Quartzite (argillite and quartzite) that unconformably overlies the Chocolay Group, the Palms is conformably overlain by the Ironwood Iron Formation, and the Tyler Formation (slate and metagraywacke) conformably overlies the Ironwood. On the eastern Gogebic range, volcanic rocks are intercalated with the Ironwood Iron Formation. This bimodal basalt and rhyolite sequence, the Emperor Volcanic Complex (Licht and Flood, 1992), was deposited in a half-graben (LaBerge, 1992). To the south of the Gogebic range, the rocks of the Baraga Group are found in fault-bounded basins in the subsurface (G.L. LaBerge, personal communication, 1999). Therefore, it seems that the sedimentary rocks of the main part of the Gogebic range were deposited on a stable shelf, with less stable conditions to the east and the south. However, the Baraga Group rocks to the south likely were deposited on a stable shelf, and then *preserved* in grabens that formed later.

Farther east in Michigan, the Baraga Group unconformably overlies either Archean basement or the eroded remnants of the Menominee Group. The group consists of the Goodrich Quartzite, a basal unit thought to be a shallow marine, tidally influenced deposit. It passes upward into the Michigamme Formation (Ojakangas, 1994). The Michigamme is divided into a lower slate member also inferred to have been deposited in a tidally influenced environment, a middle iron-formation member (Bijiki) inferred to have been deposited below wave base in somewhat deeper water, and an upper slate member inferred to have been deposited in still deeper water with turbidity currents being a major depositional mechanism (Ojakangas, 1994). Limited paleocurrent data indicate that the currents in the southern part of the Michigamme outcrop area flowed toward the north, whereas those in the northern part flowed toward the south.

Phosphorite clasts enclosed in iron-formation from the basal part of the lower slate member have yielded an essentially concordant Pb–Pb date of 1929 ± 17 Ma (Zartman, 1987, quoted in Klasner et al., 1989). A sample of Michigamme Formation metamorphosed to biotite-grade has yielded a U–Pb zircon age of 1852 ± 6 Ma (Sims et al., 1989), which has been interpreted as the metamorphic age associated with the collision of the Wisconsin magmatic terranes (i.e. the Penokean orogeny). Although a detailed description of the zircon grain is unavailable, the zircon could well be detrital, providing a maximum age for sedimentation of the Michigamme Formation.

3. Regional geology, northwestern segment

The Paleoproterozoic supracrustal rocks in the northwestern segment, including east-central and northeastern Minnesota and the adjoining part of Ontario, are for the most part poorly exposed. However, mining of iron ore on the Mesabi and Cuyuna ranges and continued mining of taconite on the Mesabi range have resulted in excellent artificial exposures and an abundance of drillhole information. Geophysical surveys and stratigraphic test drilling by the Minnesota Geological Survey, especially in areas of little economic interest, also have been major sources of information (e.g. Southwick et al., 1988).

Stratigraphic interpretations in Minnesota were long based on the premise that all iron-formations were correlative and that all the supracrustal rocks belonged to the Animikie Group (e.g. Morey, 1978). New data have shown that at least two older supracrustal successions — the Mille Lacs and the North Range Groups — are present beneath the Animikie rocks in east-central Minnesota and that both contain substantial amounts of iron-formation (Southwick et al., 1988). The complex configuration exhibited by these older supracrustal successions is illustrated in Fig. 4.

3.1. Mille Lacs Group

Rocks now assigned to the Mille Lacs Group were first recognized many years ago, but their stratigraphic significance was not appreciated until the work of Marsden (1972). Subsequently, Morey (1978) formally named the unit and subdivided it into several formations. More recent interpretations show that the Mille Lacs Group comprises an important part of the Penokean fold-and-thrust belt and therefore no longer constitutes the ordered cohesive succession envisioned by Morey (1978). Nevertheless, the group in general is comprised of various rock types including orthoquartzite, limestone, dolomite, sulfide-rich carbonaceous slate, iron-formation, and mafic pillowed volcanic rocks. Sparse outcrops indicate that these rocks have been subjected to at least two periods of deformation. Volcanic rocks near the base of the group have provided a Sm–Nd isochron age of 2197 ± 39 Ma and a Rb–Sr whole-rock isochron of 1738 ± 16 Ma (Beck, 1988).

3.2. North Range Group

The North Range Group forms a coherent stratigraphic package geographically located between twice-folded rocks of the Mille Lacs Group and once-folded rocks of the Animikie Group. This group consists of three conformable formations. The Mahnomen Formation is a siltstone–shale sequence with interbedded iron-formation, the Trommald Formation is primarily an iron-formation, and the overlying Rabbit Lake Formation is a graywacke–shale sequence with thin lenses of iron-formation. A Rb–Sr whole rock isochron age implies that the group was metamorphosed ≈ 1870 Ma (Peterman, 1966).

Little is known about the depositional history of the poorly exposed North Range Group. Preliminary studies imply that detritus in the Mahnomen was derived from low-rank metasedimentary rocks much like those that occur in the Mille Lacs Group (Morey et al., 2001). Iron-formation sedimentation occurred in an east-trending half-graben-like structure that deepened to the south and involved considerable hydrothermal activity (McSwiggen et al., 1995; Melcher et al., 1996). The Rabbit Lake Formation was deposited under euxinic conditions, possibly in part as the graben continued to evolve.

3.3. Animikie Group

The Animikie Group unconformably overlies the Mille Lacs and North Range Groups to the south and the Archean basement to the north (Southwick and Morey, 1991). Although the unconformity is not exposed, magnetic data show North Range structures

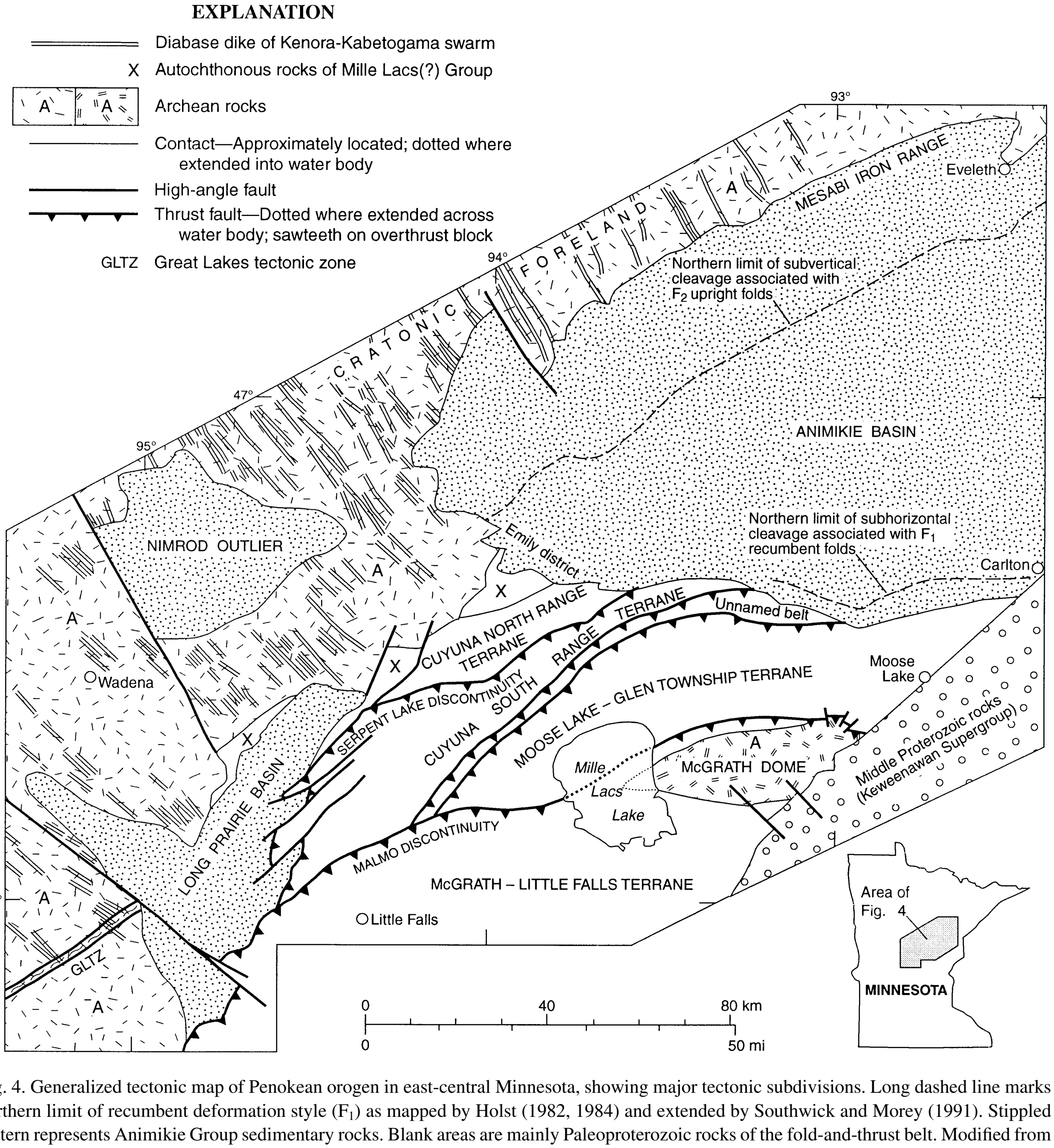


Fig. 4. Generalized tectonic map of Penokean orogen in east-central Minnesota, showing major tectonic subdivisions. Long dashed line marks northern limit of recumbent deformation style (F_1) as mapped by Holst (1982, 1984) and extended by Southwick and Morey (1991). Stippled pattern represents Animikie Group sedimentary rocks. Blank areas are mainly Paleoproterozoic rocks of the fold-and-thrust belt. Modified from Sims (1996c) and references included therein.

beneath Animikie strata to the east of the exposed North Range Group (Chandler, 1993). See Fig. 4.

The group consists of three conformable major formations on both the Mesabi and Gunflint ranges. The respective units on the two ranges are the Pokegama and Kakabeka Quartzites (the lowest formations), the Biwabik and Gunflint Iron Formations (the middle formations), and the Virginia and Rove Formations (the upper formations, composed of graywacke and shale). The Thomson Formation in the northern part of east-central Minnesota is correlative with the Virginia and Rove Formations. The two iron-formations are on strike with each other and were probably continuous, but were subsequently isolated by the intrusion of the mafic Duluth Complex at ≈ 1100 Ma.

The environments of deposition of these units have been studied by Ojakangas (1983), as follows. The Pokegama (<50 m thick) is interpreted to have been deposited in a tidally influenced environment near the shoreline, having received clastics from the Archean basement to the north. The lowermost Pokegama contains a sequence of alternating thicker and thinner laminae that provide evidence of the diurnal inequality that is being investigated for possible clues to the Paleoproterozoic lunar orbit (Ojakangas, 1996). The Biwabik (as thick as 225 m) is interpreted to have been deposited seaward of the Pokegama, on a shallow marine, tidally influenced shelf. Two sand-textured members (dominantly iron oxides and chert) were deposited in shallow water, as indicated by stromatolites, cross-bedding, and rounded (locally oolitic) grains of iron minerals and chert. Two mud-textured members (dominantly iron-silicates, iron-carbonates, and chert) were deposited in deeper waters on the outer shelf in a low-energy setting, likely related to upwelling waters from the deeper part of the basin. Tidal currents may have disrupted the mud-textured sediment and transported sand-grain-sized aggregates into shallower water where they were altered by seafloor processes and early diagenetic processes. The Virginia, Rove and Thomson Formations (thousands of meters thick) were deposited in deep water where turbidity currents were particularly active (Morey and Ojakangas, 1970; Morey, 1967; Lucente and Morey, 1983).

Various ages have been reported for the Animikie Group, but the most significant ages are U–Pb dates on zircons in volcanic ash layers. Euhedral zircons from a reworked tuff in the upper Gunflint Iron-formation are dated at 1878 ± 2 Ma (Fralick et al., 1998), and a zircon age from an ash layer near the base of the Virginia Formation is 1850 Ma (Hemming et al., 1996).

4. Tectonic framework

The generalized tectonic framework of the western Lake Superior region is presented in the map of Fig. 5. The Archean craton in the Lake Superior region developed in Archean time by the accretion of volcanic–sedimentary–plutonic arcs about 2700 Ma, culminating in the Algoman (Kenoran) orogeny. Erosion of the Archean rocks continued for the next 500–600 m.y., interrupted by a mafic dike swarm (and presumably accompanying lava flows that have since been removed by erosion?) emplaced at $2077 + 4/-3$ Ma (Wirth et al., 1995). This long period of erosion produced a gently undulating plain upon which the Paleoproterozoic supracrustal units were deposited.

Schulz et al. (1993) visualized three tectonic stages in the origin of the continental margin assemblage — an intracratonic or intrarift stage, a rift stage, and a post-breakup stage — beginning with a passive margin. LaRue and Sloss (1980) and LaRue (1981a,b) suggested that Chocolay deposition occurred in shallow basins that were precursors to later structural troughs (i.e. grabens or half-grabens). The Chocolay and Mille Lacs Groups were most likely deposited during a marine transgression. Both were probably once more widespread than today, and are now present in these extensional structures where they were preserved from subsequent uplift and erosion. The angular unconformity between these groups and the overlying Menominee and North Range Groups is interpreted as a 'rift-onset unconformity' (after Falvey, 1974). This unconformity need not necessarily be correlative (as to age) with the rift-onset unconformity beneath the Huronian Supergroup, as recognized by Fralick and Miall (1989).

The Menominee and North Range Groups were deposited during another marine transgression onto the shelf. Thicker sedimentary packages accumulated and were preserved in shelf-parallel grabens that dissected the continental shelf at several localities. Thick sections occur in the Marquette (LaRue and Sloss, 1980) and Calumet troughs where particularly thick units of iron-formation accumulated along with packages of basalt and associated volcanogenic rocks of continental affinity (Ueng et al., 1988; Beck and Murthy, 1991).

The Great Lakes Tectonic Zone (GLTZ) as defined by Morey and Sims (1976), Sims et al. (1980), and Sims (1991, 1996a), is an Archean crustal boundary as wide as 30–40 km, that separates gneisses as old as 3550 Ma (the Minnesota River Valley subprovince of

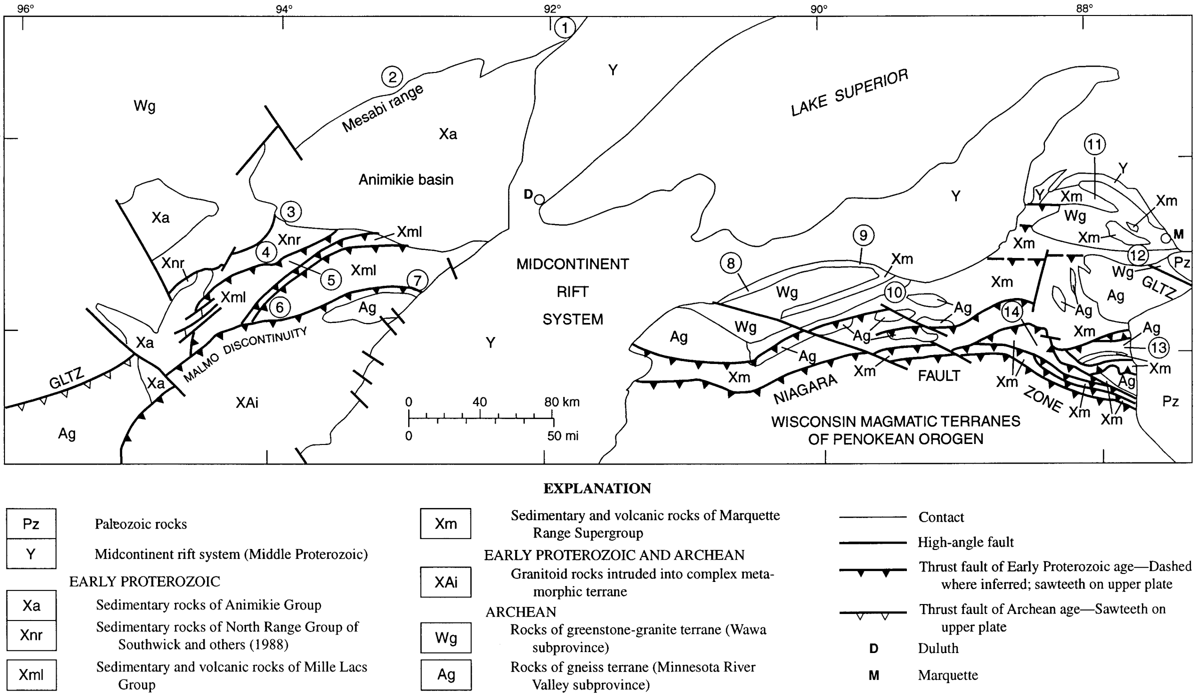


Fig. 5. Generalized geology of the major part of the Paleoproterozoic Penokean orogen, Lake Superior region. GLTZ, Great Lakes tectonic zone. Modified from Sims (1991, 1996b).

southern Minnesota) from the 2700 Ma greenstone–granite terrane of the Wawa subprovince to the north (Fig. 2). Based on geophysical data, the zone has been interpreted as a north-dipping paleosuture (thrust zone) that resulted from a continent–continent collision in late Archean time (Gibbs et al., 1984; Smithson et al., 1986). Subsequently the zone became the focus of crustal instability and was reactivated, possibly several times, during Paleoproterozoic time. The zone appears to have been a hinge across which the stratified rocks abruptly thickened to the south and where volcanic rocks became considerably more abundant (Schulz et al., 1993). The hingeline appears to have been a major factor in the location of the Animikie basin and in the location of Penokean deformation, even causing local gneiss domes by reactivation of Archean basement.

Actual crustal separation and sea-floor spreading terminated the rift stage. The Baraga and Animikie Groups were subsequently deposited upon a regional erosional surface developed on both Archean and Paleoproterozoic rock units (Schulz et al., 1993; Morey, 1996). Northward subduction and the formation of an island arc have been modeled as the initial steps in the closing of the ocean, followed by southward subduction and additional volcanism (LaBerge et al., 1984). With the onset of southward subduction, the northward movement of the Wisconsin magmatic terranes (i.e. volcanic arcs) and the initiation of the Penokean fold-and-thrust belt ($\approx$200 km wide and $\approx$1300 km long), the Animikie foredeep basin developed (Hoffman, 1987; Southwick and Morey, 1991). A different model, based primarily on geochemical data, involves a back-arc setting that may have evolved into a foreland basin as the back-arc basin closed (Hemming et al., 1995). That is, of course plausible as an initial stage, especially in the southern part of the basin; however, our model is primarily concerned with the turbiditic basin fill that makes up the bulk of the sediment in the Animikie basin.

We believe that the Animikie Group of Minnesota–Ontario and the Baraga Group of Michigan–Wisconsin were deposited in this foreland basin. The basal units, comprised of siliciclastic sediment largely derived from the Archean terrane to the north, and the widespread overlying iron-formation, appear to have been deposited in a shallow marine, tidally influenced environment on the northern edge (i.e. peripheral bulge) of the northward-migrating Animikie basin (Ojakangas, 1994). Penokean folding and metamorphism of the North Range Group occurred by 1870 Ma (Peterman, 1966), and geologic evidence suggests that the Mille Lacs Group was folded and metamorphosed before that time (Southwick et al., 1988). Therefore, it seems that Penokean deformation was underway earlier than the oft-quoted collision date of about 1850 Ma, but a precise beginning date is lacking. See Sims (1996c).

The siliciclastic and iron-formation units are exposed in the Gogebic range of Michigan and Wisconsin (Palms Quartzite and Ironwood Iron Formation), in the Mesabi range of Minnesota (the Pokegama Quartzite and Biwabik Iron Formation), and in the Gunflint range of Minnesota and Ontario (the Kakabeka Quartzite and the Gunflint Iron Formation). They probably were continuous from south to north prior to the development of the Midcontinent Rift System in Mesoproterozoic time. A consequence of this model is that they are diachronous, with the units in Michigan–Wisconsin (located ≈ 100 km to the south of the Mesabi range during deposition) thus somewhat older than those in Minnesota–Ontario. The thickest and uppermost units in the basin, essentially lithostratigraphic correlatives but probably differing somewhat in age, are the Michigamme, Tyler, Copps (in the southeastern segment), and the Thomson, Virginia and Rove Formations (in the northwestern segment). These are typical turbidite–mudstone (flysch) sequences. Proving the diachroneity, however, may well be impossible.

Several lines of evidence, including neodymium isotopes (Barovich et al., 1989), paleocurrents, and paleogeographic setting, indicate that graywacke of the southern part of the outcrop area was derived from the fold-and-thrust belt to the south, which is comprised of Paleoproterozoic Wisconsin magmatic terranes, Archean miniplates, and older Paleoproterozoic sedimentary units formed on the continental margin (Ojakangas, 1994). In contrast, the graywacke in the northern part of the basin was derived from Archean terranes to the north (Figs. 6 and 7). However, muddy rocks of the Virginia Formation on the north side of the basin also bear a geochemical imprint of a young differentiated volcanic arc as a source (Hemming et al., 1995); this arc was probably situated to the south and was part of the Wisconsin magmatic terranes. Volcanic ash is the likely source of at least part of the muddy fraction. However, resedimented lapilli tuff beds in the Gunflint Iron Formation of Ontario were probably derived from local volcanic sources that also produced minor basaltic flows.

Later stages of the Penokean orogeny in Michigan and east-central Minnesota resulted in thrusting and segmentation of some previously deposited turbidite–mudstone sequences, notably those in the southern part of the Animikie basin. The Michigamme Formation was folded, faulted, and metamorphosed (see, e.g. Cannon, 1973; Klasner, 1978; Klasner et al., 1991). The rocks are dominantly metamorphosed to the greenschist facies, but several nodes of high-grade rocks occur in Michigan (e.g. James, 1955), as do gneiss domes of reactivated Archean basement (e.g. Attoh and Klasner, 1989). There is evidence for both thin-skinned and thick-skinned styles of deformation in Michigan (Gregg, 1993; Klasner and Sims, 1993). Details of the Penokean orogeny can be found in, for example, Sims et al. (1989) and Sims (1996).

In east-central Minnesota, attributes of the Penokean orogen have been reasonably well-documented, especially given the sparse outcrop data (e.g. Holst, l982, 1984; Holm et al., 1988; Southwick et al., 1988; Southwick and Morey, 1991; Morey and Southwick, 1995). As summarized by Southwick et al. (1988) and Sims (1996c), the orogen there consists of a fold-and-thrust belt, consisting of four structural terranes presumably separated by major north-verging thrust faults (Fig. 4). The southernmost terrane contains volcanic components analogous to those found in the Wisconsin magmatic terranes, but consists mostly of high-grade gneiss, migmatite having both volcanic and metasedimentary paleosomes, and several varieties of granites. The middle two terranes are comprised of multiply deformed rocks of the Mille Lacs Group, whereas the northernmost sedimentary terrane is less metamorphosed and less deformed (Boerboom and Southwick, 1999a,b). These terranes are interpreted to be partially overlapped by younger Paleoproterozoic rocks of the Animikie basin (Fig. 4). The boundary between the Animikie basin and the

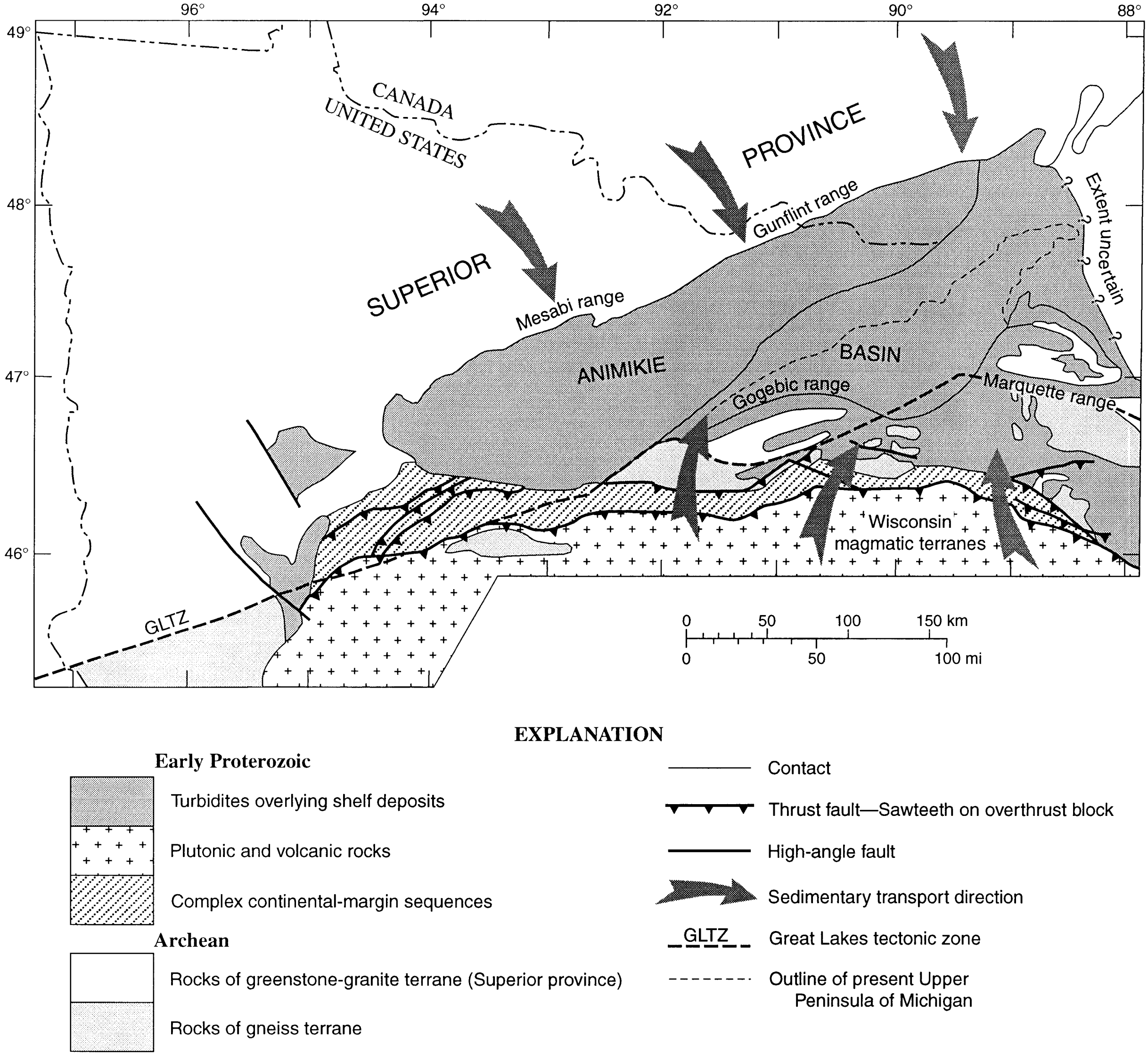


Fig. 6. Schematic hypothesized paleogeography at the time of sedimentation of the Animikie Group turbidites that overlie shelf deposits in the Animikie basin. The rocks of the 1.1 Ga Midcontinent Rift System have been removed from the map, and Michigan and Wisconsin are thus positioned 100 km closer to Minnesota–Ontario than they were after the formation of the Midcontinent Rift System. Arrows denote generalized transportation directions of sediment from major source areas. Compare with Figs. 2, 5 and 7. Modified from Ojakangas (1994) and references included therein.

fold-and-thrust belt in east-central Minnesota is taken to be an unconformity that separates once-folded rocks on the north (i.e. the Thomson Formation) from twice-folded rocks on the south (Holst, 1982, 1984, 1991).

A generalized model of this complex tectonic history from Morey and Southwick (1995) is reproduced here as Fig. 8.

5. Magmatism

The Archean craton began to undergo extension at 2.45 Ga, as indicated by mafic igneous rocks at the base of the Huronian Supergroup in Ontario (e.g. Heaman, 1997; Cheney, 1998; Halls, 1998). A second extensional pulse occurred at 2.21–2.1 Ga with

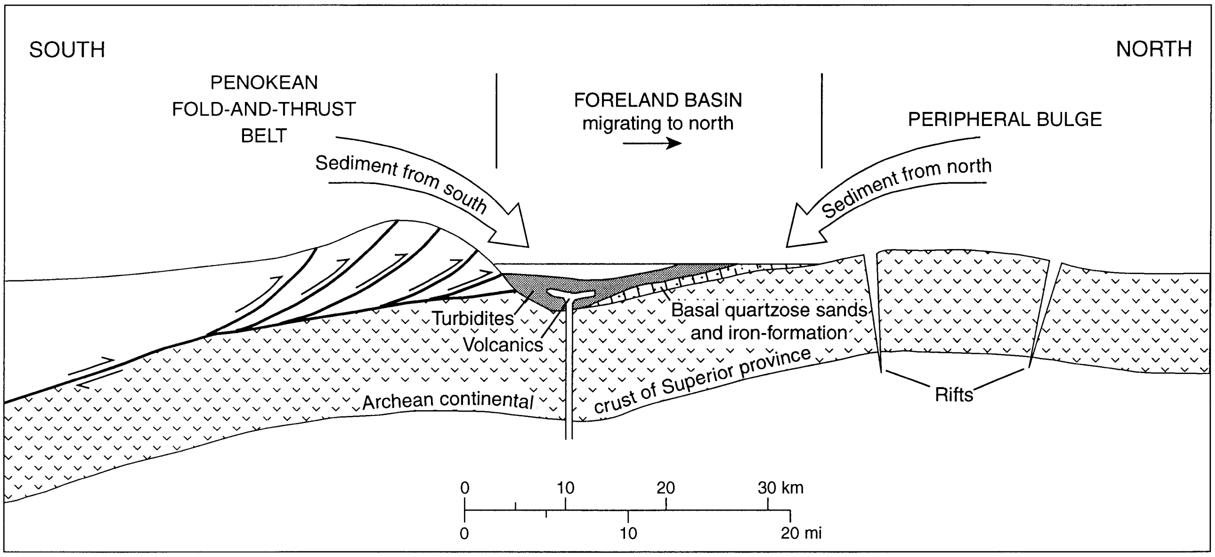


Fig. 7. Schematic cross-section depicting deposition of the Animikie Group turbidites that overlie shelf deposits in the Animikie basin, with sediment derived from both the north and the south. The southern area, the fold-and-thrust belt, comprises a complex assemblage including (1) accreted Paleoproterozoic volcanic and plutonic rocks of the Wisconsin magmatic terranes, (2) accreted Archean miniplate terranes, (3) older Paleoproterozoic passive-margin sedimentary rocks and volcanic rocks produced during initial rifting of the continental margin, both scraped off the southward-subducting Archean Superior craton, and (4) recycled initial foredeep deposits, possibly including basal shallow water sandstones deposited in the transgressing sea of the northward-migrating foreland basin. The peripheral bulge comprises a source-rock assemblage of Archean granitic rocks and Archean volcanic–sedimentary (greenstone) belts. Scale is approximate. Compare with Fig. 6. Modified from Ojakangas (1994) and references included therein.

emplacement of the Nipissing Diabase sills and major dike swarms in the Huronian Supergroup (e.g. Buchan et al., 1988; Roscoe and Card, 1993) and at 2077 + 4/−3 Ma with the emplacement of the Kenora-Kabetogama dike swarm in northern Minnesota (Southwick and Day, 1983; Wirth et al., 1995).

Unlike the tholeiitic basaltic rocks of continental affinity in the Marquette Range Supergroup, the volcanic rocks of the younger Wisconsin magmatic terranes (a bimodal suite of basaltic and rhyolitic rocks) are characteristic of tholeiitic and calc-alkaline volcanic rocks of oceanic island arcs (Sims et al., 1989).

The geology of the Wisconsin magmatic terranes along the southern side of the Penokean orogen has been summarized by Sims et al. (1993) and Sims (1996c). The magmatic terrane in Wisconsin consists of two volcano-plutonic sequences. A northern terrane having two components ranging in age from 1889 to 1760 m.y. is separated from a southern terrane having components ranging in age from 1860 to 1835 m.y. by a south-verging paleosuture. The two terranes were amalgamated at about 1840 Ma and intruded by stitching plutons of granitic composition at about 1835 Ma. The terranes are interpreted to be the product of both southward subduction and younger northward subduction, with accumulation on oceanic crust as indicated by a dismembered ophiolite (Schulz, 1987). Back-arc basin and island arc settings are suggested.

The magmatic terrane in east-central Minnesota is composed largely of granitoid plutons of several ages and only minor quantities of mafic volcanic rocks (Jirsa et al., 1995). This 'east-central Minnesota batholith' has yielded U–Pb zircon ages from plutons that range from 1787 ± 3 to 1772 ± 1 Ma (Van Schmus et al., 2000). Cooling continued until 1760 Ma, based on $^{40}A/^{39}A$ step-heating mineral ages (Holm et al., 1998). The Wisconsin magmatic terranes collided with the continent at about 1850 Ma (Sims, 1996b). The Niagara fault zone (Fig. 2) in Wisconsin (a 10 km-wide zone of ductile shears, steeply dipping rocks, and down-dip stretching lineations), and the Malmo discontinuity in Minnesota (Fig. 4), mark the north-verging collisional suture (Sims, 1996b). In summary, the Penokean orogen contains volcanic rocks ranging in age from 1880 to 1840 Ma and plutonic rocks ranging in age from ≈1980 Ma (the age of an intrusive that reportedly cuts the McGrath Gneiss) to ≈1770 Ma, the age of granites in east-central Minnesota (Southwick and Morey, 1991; Sims et al., 1993).

Rocks of the Wisconsin magmatic terranes contain major copper-zinc massive volcanogenic sulfide deposits, but only one small deposit has been mined to date (e.g. De Matties, 1994; Morey and Sims, 1996).

Younger Paleoproterozoic anorogenic magmatic rocks — rhyolite and granite — are present in south-central Wisconsin to the south of the fold-and-thrust belt (Smith, 1983). They are dated at ≈1760 Ma. A peraluminous suite includes ash-flow tuff and two-mica granite, and a metaluminous suite contains rhyolite and granite. These magmatic rocks and the overlying "Baraboo Interval" quartzites (Dott, 1983) were folded at ≈ 1630 Ma.

6. Paleoclimate

A glaciogenic origin for the basal Chocolay formations has been documented by several workers, as described above, and thus ice-house (i.e. cold) conditions presumably prevailed. The correlation of these Michigan glaciogenic units with the Gowganda Formation of the Huronian Group to the east in Ontario was also referenced above. Further correlations with Paleoproterozoic glaciogenic rocks in Wyoming, USA (e.g. Roscoe and Card, 1993) and in Finland and adjacent Karelia, Russia, are warranted and suggest widespread continental-scale glaciations on these two continents and perhaps on a single supercontinent (Ojakangas, 1988; Ojakangas et al., 2001). A relatively high-latitude location would seem likely, but Williams and Schmidt (1997) on paleomagnetic evidence have suggested that Huronian glaciation occurred within 11° and possibly within 4° of the paleoequator. This finding would be equally applicable to the nearby Lake Superior region.

The three glaciogenic units in Michigan are each overlain by thin units of sericite schist that were interpreted by Ojakangas (1997) to be remnants of a paleosol; additional work is in progress. A paleosol more than 100 m thick and containing aluminous minerals also has been found in Ontario within the Lorrain Formation at the top of a lower arkosic member and below an orthoquartzite (quartzite) member that overlies the Gowganda Formation (Ojakangas, 1997; Ojakangas et al., 1998). The CIA values (CIA of Nesbitt and Young, 1982) increase upward from the 50s to the high 80s, reflecting the gradual upward loss in K_2O, Na_2O, and CaO. The lower (arkosic) Lorrain Formation is interpreted to be a fluvial (glacial) outwash deposit. The paleosol may indicate a period of chemical weathering in a subtropical to tropical climate, presumably under wet conditions, as is occurring on the present-day Earth. However, a higher partial pressure of CO_2 in the Paleoproterozoic atmosphere, and therefore higher H_2CO_3 levels, could have also accelerated chemical weathering, perhaps without such a climate.

Each of the glaciogenic formations and their overlying paleosol remnants in Michigan is overlain by a thick orthoquartzite unit, interpreted to be the product of the erosion and reworking of a deeply weathered cover (i.e. paleosol) on glaciogenic material and Archean basement. The thick paleosol in Ontario is overlain by the upper orthoquartzite member of the Lorrain Formation. Presumably the quartz sands accumulated under the same climatic conditions that formed the paleosols.

The orthoquartzite units are in turn overlain by units of dolomite, the best-exposed and best-known of which is the Kona Dolomite of the Marquette district, Michigan. The presence of stromatolites, pseudomorphs of dolomite after halite and gypsum crystals, and anhydrite nodules, tepee structures, and dessication cracks in the Kona imply warm, arid paleoclimatic conditions and a sabkha-like environment of deposition.

Weathering of rock and biogeochemical cycling of carbon may have played a major role in these climatic changes (e.g. Bekker et al., 1998a; Bekker et al., 1998b).

Interestingly, the carbon isotopes provide evidence at odds with traditional lithostratigraphic correlation of the carbonate units (Bekker, 1998). The Kona is ^{13}C-enriched, as is the Gordon Lake Formation of the Huronian Supergroup, and on this basis they could well be correlative units, supporting the lithostratigraphic correlations (Bekker and Karhu, 1997; Bekker

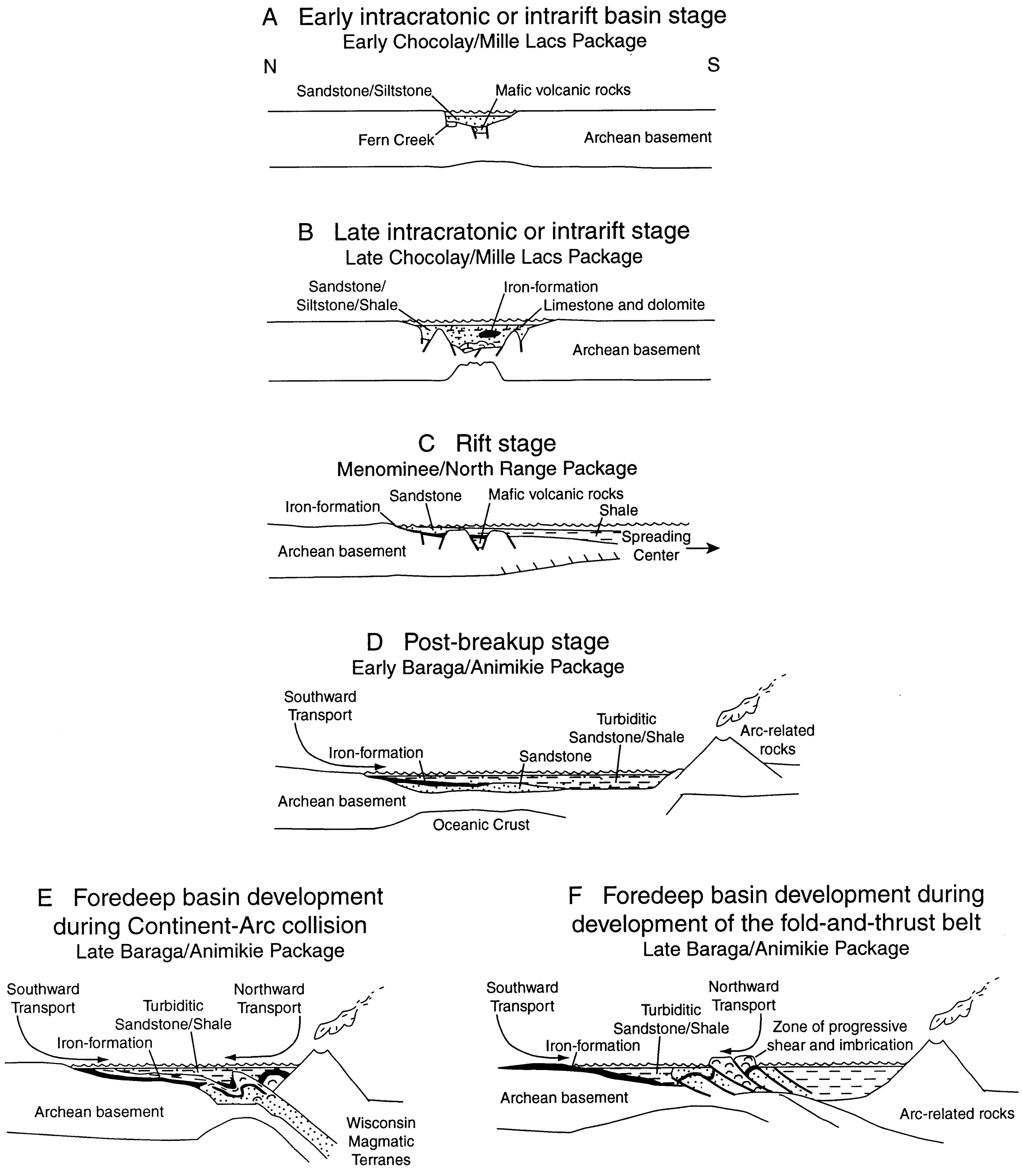


Fig. 8. Tectonic evolution of the Penokean orogen. Modified from Southwick and Morey (1991) and references included therein.

et al., 1997). However, the other dolomite formations in the Lake Superior region, long correlated with the Kona (Bad River, Trout Lake, Randville, Saunders and Denham), have normal to slightly enriched ^{13}C isotope signatures and are, on this basis, either older or younger than the Kona Dolomite (Bekker et al., 1996; Bekker and Karhu, 1997; Bekker, 1998). Resolution of this correlation problem will have to wait until more abundant data become available and the behavior of carbon isotopes is better understood. Assuming that the high ^{13}C excursion is a world-wide event, it is dated on the basis of evidence from the Fennoscandian Shield as lasting from $\approx 2.22-\approx 2.06$ Ga (Karhu, 1993).

7. Correlations and sequence stratigraphy

Correlations in the Lake Superior region over much of the past century were based on the premise that major iron-formations were the result of a single depositional event and were the same age (e.g. Morey and Van Schmus, 1988; Morey, 1996). Recent studies have shown that there are at least three periods of deposition of iron-formation in Minnesota (Southwick et al., 1988; Southwick and Morey, 1991; Morey and Southwick, 1995), with the youngest and most important being the Biwabik Iron Formation of the Mesabi range and its correlatives, the Gunflint Iron Formation and possibly Unit A of the Emily district (location 3 in Fig. 5). There are two major episodes of deposition in Michigan–Wisconsin: (1) the Negaunee Iron Formation of the Marquette range and the correlative Vulcan and Fence River Iron Formations of the Menominee range and the Iron River-Crystal Falls area; and (2) the Ironwood Iron Formation of the Gogebic range and the equivalent Bijiki Member of the Michigamme Formation (e.g. Ojakangas, 1994; Morey, 1996).

Sequence stratigraphic (allostratigraphic) methodology has been applied to the Paleoproterozoic rocks of the Lake Superior region on a broad scale (Morey and Southwick, 1995; Morey, 1996). Major unconformities in the Lake Superior region have long been the boundaries that divide the sedimentary section into groups. Thus the groups are unconformity-bound depositional sequences as defined by Sloss (1963). When coupled with lithostratigraphy and radiometric dates, sequence stratigraphy becomes a useful tool (Christie-Blick et al., 1988). The unconformities are used in the correlation of the sedimentary columns of the northwest and southeast segments of the Lake Superior region, as well as correlations with the Huronian Supergroup in Ontario where unconformities separate the four groups. Because the underlying basis of allostratigraphy is presumed to be eustatic (world-wide) sea-level changes, it also allows for the strengthening of intercontinental correlations.

There are four major unconformities in the Marquette Range Supergroup in Michigan–Wisconsin, including the unconformity with the underlying Archean basement rocks. The second is above the paleosol that formed on the glaciogenic units of the Chocolay Group. The third is the ‘rift-onset’ unconformity between the Chocolay and the Menominee Groups. The fourth is the ‘post-breakup’ unconformity between the Menominee and Baraga Groups.

Glaciogenic units have not been identified in Minnesota, although a paleosol has been tentatively recognized at the base of the Mille Lacs Group in east-central Minnesota. An unconformity between the dolomite of the Mille Lacs Group and the overlying North Range Group is likely correlative with the rift-onset unconformity between the Chocolay and Menominee Groups in Michigan The unconformity between the North Range and the Animikie Groups has been documented in the subsurface (Chandler, 1993) by geophysical methods, whereas the same unconformity is well-exposed at the surface where the Animikie Group overlies Archean basement.

Lithostratigraphic correlations of the Marquette Range and Huronian Supergroups have been established for a long time, with the first such proposal being by Irving (1888).

The unconformities described above delineate what we interpret as possible second-order stratigraphic cycles, i.e. the super cycles or the original sequences of Sloss (1963) as refined by Vail et al. (1977). Second-order cycles in Phanerozoic strata have durations of 10–100 m.y., and if compared to modern plate movements, may have been caused by eustatic sea-level changes induced by volume changes in global mid-ocean spreading ridge systems. Subsidence due to rifting, thermal decay, and loading might also account for the marine transgressions above the unconformities. The glaciogenic units of Michigan, with the Archean unconformity as the lower-bounding unconformity and the top of the weathered zone representing the upper-bounding unconformity, may represent a third-order cycle of a shorter duration, on the order of 1–10 m.y.

Theoretically, the melting of continental-scale glaciers should be followed by a eustatic sea level rise related to this deglaciation. Whereas this could be the cause of the marine transgression that followed, leading to the deposition of the orthoquartzite and carbonate successions, such an explanation poses some temporal problems on both the North American and Fennoscandian shields. The aforementioned paleosols are interpreted to have developed on the glaciogenic units. The weathering profiles are 75 m thick in Finland (Marmo, 1992) and 50 m thick in Ontario; the thin profiles in Michigan are most likely erosional remnants. Such thicknesses are indicative of an intense interval of deep weathering. If the succeeding transgression was related to deglaciation, it was long-delayed. Regional post-glacial rebound may have been a contributing factor.

Large iron-formations world-wide are apparently linked to major marine transgressions onto the cratons (e.g. Simonson and Hasler, 1996), and this certainly appears to be the case in the Lake Superior region. Third-order cycles of 1–10 m.y. or fourth-order cycles of 0.2–0.5 m.y. duration may be contained within the iron-formations of the Animikie and Baraga Groups. Wolff (1917) divided the $\approx$ 200 m-thick Biwabik Iron Formation of the Mesabi Range into four members (i.e. third-order cycles?) that are, from the bottom up, the Lower Cherty, Lower Slaty, Upper Cherty, and Upper Slaty. These were based on bedding thickness and grain size. The thin-bedded 'slaty' units (they are not slates) are fine-grained, whereas the thick-bedded 'cherty' units have a dominant granular texture. These have long been interpreted as the products of an initial transgression, a regression, and a second transgression (e.g. White, 1954). However, the lower slaty member is absent in the western Mesabi and in the Emily district off the west end of the Mesabi (White, 1954; Morey and Southwick, 1993). One of us (Morey) suggests that the present western rock units are more likely the result of a sea-level stillstand and accompanying prograding deposition of coarser grained iron-formation sediments in deeper water.

Similar slaty and cherty members are present in the Gunflint Iron Formation (Broderick, 1920; Goodwin, 1956). Goodwin called upon vertical regional tectonic processes as the main control on sedimentation. Most recently, Pufahl et al. (2000) interpreted basal transgressive, middle regressive, and upper transgressive depositional cycles, presumably of third-order or fourth-order type. They also suggested that coarsening-upward grainstone successions $\approx$ 10 m thick may represent parasequences bounded by marine flooding surfaces that were the product of a series of periodic sea level rises, each followed by stillstands and shoaling.

On the Gogebic range, even more members (i.e. slaty and cherty members) were delineated by Hotchkiss (1919); in Aldrich (1929). These can also be interpreted as third- or fourth-order cycles related to eustatic changes in sea level. Studies to date in the Lake Superior region have not delineated minor (fifth-order) cycles.

8. Summary of Paleoproterozoic history

1. The Paleoproterozoic rocks of the Lake Superior region formed on the continental margin of a peneplaned craton comprised of Archean volcanic, plutonic, and metamorphic rocks about 2.7 b.y. old. This was the ancient supercontinent of Kenorland.

2. The oldest supracrustal rocks in Michigan are three glaciogenic units — the Fern Creek, Enchantment Lake, and Reany Creek Formations of the Chocolay Group — all probably deposited $\approx$ 2,300 Ma. They record ice-house conditions. The diamictite–dropstone unit association that makes up these three formations indicates either a glaciolacustrine environment or a glaciomarine environment. The glaciomarine interpretation would require an initial marine transgression onto the craton, perhaps related to the early stages of deglaciation.

3. A climatic change to warm and moist (subtropical to tropical?) greenhouse conditions resulted in weathering of the upper portions of the glaciogenic units; remnants of a paleosol are present as units of sericite schist. Abundant sand-sized quartz probably blanketed the region at that time, as the fine-clay fraction was washed or blown away.

4. A marine transgression (the second?) onto the continental margin reworked the quartz sand and deposited the Mesnard, Sturgeon, and Sunday Quartzites. These are conformably overlain by dolomitic units, most notably the Kona Dolomite of the Marquette area. The Kona contains features characteristic of a sabkha environment. These units comprise the upper two formations of the Chocolay Group, and are an ancient example of the orthoquartzite–carbonate association that is common in rocks of Phanerozoic age.

5. Rifting near the continental margin, the product of an extensional tectonic regime, formed graben/half-graben basins in which the Chocolay Group was preserved when erosion removed much of the orthoquartzite- carbonate association from the craton margin. The rifting likely began before Chocolay deposition began, and continued long after Chocolay deposition had ceased. The resultant unconformity above the Chocolay Group in this area is equated to the 'rift-onset unconformity' of Phanerozoic rock sequences.

6. Another major marine transgression (the third?) onto the craton margin resulted in the deposition of orthoquartzite, argillite, and iron-formation of the Menominee Group. These rock types were probably deposited over a broad shelf but were best developed in graben structures that continued to subside during sedimentation and which exerted local controls on siliciclastic deposition. Continental-type mafic extrusive and intrusive rock units occur in the Menominee Group, products of the extensional tectonic regime, and indicate that sedimentation was well underway by 1910 $\pm$ 10 Ma.

7. Uplift and erosion followed and the Menominee Group rocks were removed from much of the shelf. These units are best preserved in the grabens.

8. The rift stage ended with actual crustal separation and development of new sea-floor. Subduction probably ensued shortly thereafter and the volcanic arcs that are now preserved as the Wisconsin magmatic terranes moved northward and collided with the continent at about 1850 Ma, with the development of a collisional suture represented by the Niagara fault zone in Wisconsin and the Malmo discontinuity in Minnesota. This collisional event and on-going compression produced the fold-and-thrust belt of the Penokean orogen, and on its northern side, the Animikie (foreland) basin.

9. The Baraga and Animikie Groups were deposited in the Animikie basin during a fourth marine invasion. Siliciclastic units and iron-formation, both diachronous, were deposited on the peripheral bulge along the northern edge of the northward-migrating basin from $\approx$ 1900– $\approx$ 1870 Ma. A contemporaneous thick sequence of mudstone and graywacke, a classic turbidite 'flysch' sequence, was deposited in the basin, with sources situated both to the north (foreland) and to the south (fold-and-thrust belt).

10. The initiation of the Penokean orogeny is not well constrained, but it started some time before $\approx$ 1870 and continued to $\approx$ 1850 Ma (?). It involved both thick-skinned and thin-skinned thrusting of virtually all supracrustal units, including the deposits of the Animikie basin. Deformation and metamorphism are strongest to the south; the northernmost deposits of the Animikie basin are essentially undeformed and unmetamorphosed. Numerous plutons were intruded during the orogeny.

11. A rhyolite–granite terrane in Wisconsin documents post-orogenic magmatic activity at $\approx$ 1760 Ma.

12. Weathering and erosion of the fold-and-thrust belt and adjacent rock units resulted in the deposition of thick orthoquartzites to the south of the belt, over a period of >100 m.y. ($\approx$ 1850– $\approx$ 1730 Ma) after the culmination of the orogeny. These are now the quartzites of the Baraboo Interval; the units apparently differ in age. A thermal front separating quartzite units with differing amounts of deformation and dated at 1630 Ma is apparently the last Paleoproterozoic event in the region.

9. Speculations

Supercontinent Kenorland (Williams et al., 1991), which formed during Late Archean time, apparently started breaking up at 2450 Ma in Ontario in the region of the Huronian Supergroup deposition, but finally broke apart at about $\approx$ 2.1 Ga, with the Wyoming craton moving westward and the Fennoscandian (Baltic) craton moving eastward, leaving the larger North American craton behind (Roscoe and Card, 1993). The Penokean orogeny was part of the reassembly of a new supercontinent (Hoffman, 1988) that Williams et al. (1991) named Hudsonland. This supercontinent also included the Fennoscandian

Shield, as did Kenorland. There are many similarities in the geology of the Canadian and Fennoscandian Shields, and the Svecofennian orogeny of the Fennoscandian Shield is comparable to the Penokean orogeny in many respects. See Ojakangas et al. (2001) and Aspler and Chiarenzelli (1998) for discussions on possible North American–Fennoscandian connections.

Allostratigraphic data, when coupled with lithostratigraphic and radiometric data, support the correlation of the northwestern and southeastern segments of the Lake Superior region. Although correlations can be made with the Huronian Supergroup, exposed only a few hundred kilometers to the east of the Lake Superior region, they are at best somewhat tenuous. Even more tenuous are intercontinental correlations.

Nonetheless, some of the major Paleoproterozoic unconformities and second-order depositional sequences on the Canadian Shield described here may be correlative with those described on the Fennoscandian Shield (Ojakangas et al., 2001). For example, eroded mafic rocks at the base of the Huronian Supergroup and at the base of the Sumian Group on the Fennoscandian Shield both yield ages of $\approx$ 2500–2450 Ma. The unconformities at the base of the Animikie and Baraga Groups, and at the base of the Kalevian Group on the Fennoscandian Shield, date at about 1900 Ma. Whether these unconformities are due to eustatic sea-level changes or regional tectonics is as yet an unanswered question. Interestingly, numerous similarities in lithostratigraphy, magmatism, deformation, age dates, climatic changes, and erosional surfaces on the two cratons imply the existence of a supercontinent in Paleoproterozoic time (e.g. Ojakangas, 1988; Ojakangas et al., 1998, 2001; Aspler and Chiarenzelli, 1998). Obviously, very detailed comparative studies and a greater number of precise radiometric dates will be necessary before intercontinental correlations can be more than speculation.

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