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Early and Middle Proterozoic history of the Great Lakes area, North America

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Two major supracrustal sequences, the Huronian Supergroup in Ontario and the Marquette Range Supergroup and Animikie Group of Michigan and Minnesota, overlie an Archean basement. These sequences are about 2200–2300 Ma and 1900–2000 Ma old respectively. The major Early Proterozoic tectonic event is the 'Penokean Orogeny', which occurred about 1850–1900 Ma ago and included deformation, high-grade regional metamorphism, and extrusive and intrusive igneous activity. This was followed by formation of rhyolitic, ignimbritic volcanic rocks and emplacement of associated granites about 1790 Ma ago. The entire region was subsequently subjected to low-grade regional metamorphism 1650–1700 Ma ago, followed by emplacement of anorogenic quartz-monzonite, in part rapakivi, plutons 1500 Ma ago. Late Proterozoic Grenville and Keweenawan events represent the youngest major Precambrian activity in the region.

The rocks involved in the Penokean Orogeny lie along the southern margin of the Archean craton of the Superior Province and are interpreted as representing Early Proterozoic cratonic-margin orogenic activity. The distribution of rocks types and structures associated with the Penokean Orogeny and with similar orogenic belts along the margin of the Archean craton of North America suggest that these orogenic belts may have formed as a result of processes similar to modern plate tectonics, although the data are far from conclusive at present.

Introduction

The area of interest in this paper comprises the exposed or near-surface Precambrian rocks of Early and Middle Proterozoic age which are present along the southern margin of the Superior Province of the Canadian shield. This is a region of considerable importance in the development of Precambrian geology in North America, due in large part to the occurrences of major economic deposits of iron, copper, nickel, silver, and uranium and to the fact that it includes the classic Huronian and Animikian supracrustal successions. More importantly, however, the region includes the transition from the stable Archean craton of the Canadian shield into younger Precambrian rocks and orogenic complexes which form the basement of the southern portion of the North American continent. Furthermore, it is one of only a few regions in North America where orogenic belts along the margin of the original Archean craton are exposed (figure 1). The other main areas are the Ketilidian belt in southern Greenland (Bridgwater, Escher & Watterson 1973*a*; Bridgwater, Watson & Windley 1973*b*), the Rocky Mountains in southern Wyoming and northern Colorado in the United States (Hills, Gast, Houston & Swainbank 1968; Peterman & Hedge 1968; Hills & Armstrong 1974), and in the region of the Coronation geosyncline in northwestern Canada (Hoffman 1973).

Until the past few years most detailed studies in the Great Lakes region were concerned with the geologic history of individual areas, due in part to the lack of continuity between many of the areas and the difficulty of correlating from one region to another. With the advent of radiometric dating and its application over the past two decades and with continued field studies, however, it is now becoming possible to examine the geological relations of this region in total and to work out models for its geological evolution during the Early Proterozoic.

In this paper I will review the Precambrian geology of the Great Lakes area as it is currently understood in general and as I interpret it in certain respects based on recent work and work in progress. I will then attempt to relate the geology of this region to the larger problems concerning the evolution of the North American continental mass during the Early and Middle Proterozoic.

As any geologist working with Precambrian rocks is well aware, time or time-stratigraphic

Figure 1. Map showing the inferred size of the Archean craton of North America and Greenland (pre-drift positions) at the beginning of Proterozoic time. The horizontally ruled area was affected by Early Proterozoic intracratonic remobilization; the diagonal ruled belt in the east represents area remobilized during the Grenville Orogeny in Late Proterozoic time. Numbers in the central and western United States refer to the approximate ages (Ma) of Precambrian basement rocks and show the general distribution of various age rocks. Areas C, CW, GL, and K represent areas of Early Proterozoic continental margin activity which are still preserved and are exposed. See text for further discussion.

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nomenclature for the Precambrian does not exist in any coherent, widely accepted form. In this paper I follow a traditional Archean–Proterozoic convention with absolute age assignments as follows: Archean, ⩾ 2400 Ma; Early Proterozoic, 1800–2400 Ma; Middle Proterozoic, 1200–1800 Ma; and Late Proterozoic, 600(±)–1200 Ma ago. In addition, I informally subdivide Early Proterozoic time into Huronian (2100–2400 Ma) and Penokean (1800–2100 Ma) periods. As will be seen below, these time subdivisions are quite workable in the Great Lakes area in particular and for much of North America in general, but they should not necessarily be considered applicable on a world-wide basis.

Absolute ages used in this paper, whether from my own work or that of others, are based on the traditionally used decay constants for uranium ($\lambda(^{238}U) = 1.54 \times 10^{-10}\,a^{-1}$ and $\lambda(^{235}U) = 9.72 \times 10^{-10}\,a^{-1}$) and the corresponding, geologically determined decay constant for rubidium ($\lambda(^{87}Rb) = 1.39 \times 10^{-11}\,a^{-1}$; Aldrich, Wetherill, Tilton & Davis 1956). Use of a recent redetermination of the decay constants of uranium (Jaffey *et al.* 1971) and a correspondingly adjusted decay constant for ^{87}Rb would result in the quoted ages being reduced by $1\frac{1}{2}$–2 %, an adjustment that may be made uniformly by geochronologists in the next few years.

Table 1. Major Proterozoic events in the Great Lakes area

approximate age/Ma	events
	I. *Late Proterozoic* (600–1200 Ma)
900–1200	formation of Grenville Province
1100	Kewenawan volcanism, sedimentation, plutonism
	II. *Middle Proterozoic* (1200–1800 Ma)
1500	anorogenic plutons in Wisconsin, Ontario; associated thermal metamorphism
1650–1700	wide spread low-grade metamorphism; (associated with deformation?)
> 1500, < 1800	quartzose sedimentation in Wisconsin, Minnesota, South Dakota
1780–1800	rhyolite and granite in southern Wisconsin
⩾ 1750	plutonic rocks in Ontario (Cutler Batholith)
	III. *Early Proterozoic* (1800–2400 Ma)
	(*a*) Penokean period (1800–2100 Ma)
1850–1900	plutonic rocks in Wisconsin, Michigan, Minnesota } Penokean Orogeny
1850–1950	deformation in Wisconsin, Michigan, Minnesota, Ontario } Penokean Orogeny
1900–2000	sedimentation and volcanism in Minnesota, Michigan, Wisconsin
	(*b*) Huronian period (2100–2400 Ma)
2100 ± 50	Deformation and metamorphism in Michigan, Ontario
2160	intrusion of Nipissing Diabase
	deformation (may be included in 2100 Ma event above)
2150–2400	deposition of Huronian Supergroup rocks
	IV. *Archean* (> 2400 Ma)
2400–2500?	uplift and erosion
2500–??	formation of Archean basement complex

Regional geology

The generalized geology of the western Great Lakes area is shown in figure 2, and the sequence of major events is given in table 1. An Archean basement complex is unconformably overlain by Early Proterozoic rocks which were deformed, intruded by plutonic rocks, and metamorphosed to varying degrees during the Penokean Orogeny toward the end of Early Proterozoic time. Post-Penokean rocks of Middle Proterozoic age occur throughout the area, particularly in the southern portions. The latest major Precambrian events were the formation of the Grenville Province to the east and the Keweenawan rift(?) and its associated rocks in the Lake Superior region.

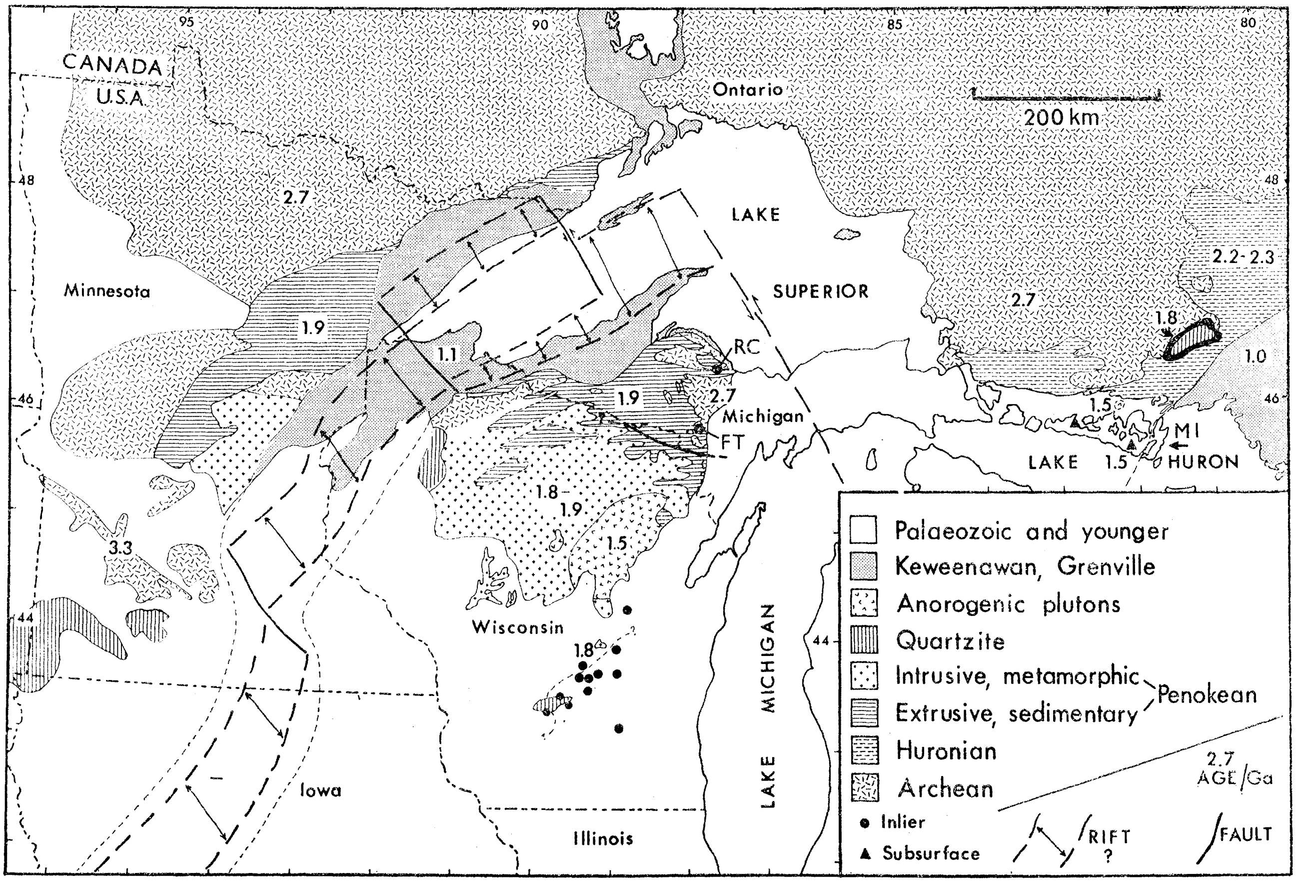

Figure 2. Generalized geologic map of the Great Lakes area showing the distribution of rocks of the Precambrian basement. Ages are given approximately in billions of years (Ga). The inferred Keweenawan rift is from Chase & Gilmer (1973) and represents only one version of the structure. Compiled from various sources including my own published and unpublished work.

Archean

The Archean rocks of prime concern in this paper are those involved in the transition from the greater-than-2700 Ma old Superior craton southward into younger, Early to Middle Proterozoic terrain (figure 2). These include the Archean basement rocks of southern Minnesota, northwestern Wisconsin, northern Michigan, and along the north shore of Lake Huron in Ontario. Few detailed age or petrologic studies have been carried out on these rocks, although they are generally well covered by regional mapping. The data that are available (e.g. Aldrich, Davis & James 1965; Van Schmus 1965; Goldich 1972) show that these basement rocks are generally extensions of the Superior Province to the north. There is one, and possibly another, exception to this generalization: the rocks of the Minnesota River Valley in southwestern Minnesota which are in part greater than 3300 Ma old (Goldich, Hedge & Stern 1970;

Goldich & Hedge 1974; Farhat & Wetherill 1974) and possibly some of the presumed Archean rocks in the Felch Trough area in northern Michigan ('FT', figure 2) which may be Early Proterozoic as discussed later.

For the most part the Archean basement in the Great Lakes area consists of the more granitic phases of the Superior Province (Goodwin 1974) with major remnants of greenstone belts occurring only in the western part of the region. Recent reports discussing these rocks include those of Card *et al.* (1972) in Ontario, of Cannon & Simmons (1973), Gair & Thadden (1968), Bayley, Dutton, Lamey & Treves (1966), and James, Clark, Lamey & Pettijohn (1961) in Michigan, and of Arth & Hanson (1975), Goldich, Hanson, Hallford & Mudrey (1972), Hanson, Goldich, Arth & Yardley (1971), Peterman, Goldich, Hedge & Yardley (1972), and Sims & Morey (1972) in Minnesota and adjacent parts of Ontario. The most recent report covering the Archean rocks in northwestern Wisconsin is that of Aldrich (1929).

One of the major unresolved problems concerning the Archean basement in relation to the Proterozoic history of the region is that of determining how far south it extended during Early Proterozoic sedimentation, volcanism, and subsequent orogenic activity. In other words, were all the Proterozoic rocks deposited on or emplaced into and through a continental type crust, or are some of the Proterozoic rocks the result of processes taking place at or beyond a former continental margin? Archean rocks are known to underlie Early Proterozoic rocks in the Lake Huron region of Ontario, in northern Michigan, in northwestern Wisconsin, and in most, if not all, of Minnesota. However, a recent study of the buried basement rocks of Manitoulin Island ('MI', figure 2) in northern Lake Huron, Ontario, did not yield any evidence that the Archean basement extends much farther south than the north shore of Lake Huron; if it does, it has been extensively re-worked during younger orogeny (Van Schmus, Card & Harrower 1975*a*).

Rocks of proven Archean age have not yet been found in central, eastern, or southern Wisconsin. In northeastern Wisconsin the Quinnesec Formation (metavolcanic rocks) has often been referred to as Archean or Lower Precambrian (Bayley *et al.* 1966; Dutton 1971), but Banks & Rebello (1969) obtained U-Pb analyses on zircons yielding an age of about 1905 Ma for these rocks, indicating that they are Early Proterozoic in age. The oldest known rocks in the area are those of the Carney Lake Gneiss in Michigan, to the north of a major fault system (Bayley *et al.* 1966; south of 'FT' in figure 2). Gneissic, migmatitic, and amphibolitic rocks of possible Archean age do crop out in central Wisconsin (Weidman 1907). However, U-Pb analyses on zircons from quartz diorite intrusive into these rocks yield an age of about 1850–1900 Ma, and Rb-Sr studies on the older rocks are so far indeterminate (Van Schmus 1974; Van Schmus, Thurman & Peterman 1975*c*).

In summary, available data show that much of the basement in the Great Lakes area during the Early Proterozoic consisted of continental rocks of the Superior Province craton, but there are no indications that this continental basement extended farther south than presently known outcrop limits. Furthermore, Archean rocks in the area south of Lake Superior eastward to the north shore of Lake Huron have been extensively involved in later orogenic events. Thus, since studies of exposed and buried basement rocks farther to the south have yielded no indications of Archean ages (Goldich, Lidiak, Hedge & Walthall 1966; Muehlberger, Hedge, Denison & Marvin 1966; Bickford & Mose 1972; Van Schmus *et al.* 1975*c*), it is likely that the southern limit of the Superior craton currently lies generally in the area shown in figure 1. However, the nature or origin of that margin is not yet known.

Early Proterozoic: Huronian period

Ontario (Lake Huron region)

Within the Great Lakes region, the area along the north shore of Lake Huron is probably one of the best studied in terms of the regional geology (see, for example, Card *et al.* 1972, and many of the papers from the Symposium on Huronian Stratigraphy and Sedimentation held in 1971 – cf. Young 1973; Robertson 1973).

Table 2. The Huronian Supergroup

stratigraphic unit	rock types
Cobalt Group	
Bar River Formation	quartzite, red siltstone
Gordon Lake Formation	varicoloured siltstone
Lorrain Formation	conglomerate, quartzite, arkose
Gowganda Formation	conglomerate (tillite), arkose, argillite
major unconformity	
Quirke Lake Group	
Serpent Formation	arkose, sub-greywacke
Espanola Formation	dolomite, siltstone, greywacke, limestone
Bruce Formation	conglomerate (tillite)
Hough Lake Group	
Mississagi Formation	subarkose
Pecors Formation	argillite, siltstone
Ramsay Lake Formation	conglomerate (tillite)
Elliot Lake Group	
McKim Formation	argillite, sub-greywacke
Matinenda Formation	subarkose, uraniferous conglomerate
(various local names)	mafic to felsic volcanic rocks
major unconformity	
Archean Basement Complex	

Stratigraphy and ages. Supracrustal rocks of known Huronian Supergroup (table 2) affinity are limited to the portion of Ontario north of Lake Huron, east of Lake Superior, and west of the Grenville Province (figure 2). The geology and stratigraphy of the Huronian Supergroup are generally well understood and will not be reviewed in detail here. With the exception of a minor amount of extrusive rock near the base of the section, the rocks of the Huronian Supergroup are all characteristic of deposition in a shallow-water shelf environment or a fluvial-deltaic environment that was periodically subjected to glacial conditions. Sediment thicknesses generally increase to the south and paleocurrent studies indicate that source regions were to the north or northwest. It is commonly assumed that the margin of the Archean craton was to the south during Huronian times, although it is also possible that the deposition took place in a large, shallow intracratonic sea and only the northern part of it is preserved. There are a number of local instances of mild tectonic activity during sedimentation, but in general the region was stable (Card *et al.* 1972).

The Huronian Supergroup was deposited unconformably on the 2500–2700 Ma old Archean basement and was intruded by sills and dykes of the Nipissing diabase about 2160 Ma ago (Van Schmus 1965; Fairbairn, Hurley, Card & Knight 1969). Fairbairn *et al.* also reported a Rb-Sr isochron age of about 2290 Ma for the Gowganda Formation. Roscoe (1973) estimated

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the age of the Huronian deposition as 2250–2450 Ma ago, but I consider an interval of 2150–2400 Ma more reasonable, with the actual duration of sedimentation and position within that interval unknown.

Tectonic history. The structural and metamorphic history of the Huronian region is complex. Many of the events occurred in post-Huronian time as defined here (more recently than 2100 Ma ago), but field and structural studies indicate that some folding and faulting occurred during and before emplacement of the Nipissing Diabase. Deformation is generally more intense in the southeastern part of the outcrop area, where the Huronian strata are tightly folded about generally east–west trending fold axes. There is disagreement as to whether much of the deformation occurred prior to the emplacement of the Nipissing Diabase (Card *et al.* 1972) or whether most of the deformation occurred in post-Huronian time (Brocoum & Dalziel 1974). This uncertainty bears on the problem of the Penokean Orogeny, as will be discussed below.

There are numerous faults in the region, one of the major ones being the east–west trending Murray Fault system in the southern part of the outcrop area. Faults of this system were active for many hundreds of millions of years and were active during Huronian sedimentation. Movement on the faults in the area has often been complex. For the Murray Fault system, there is evidence for down-faulting of the southern blocks during Huronian sedimentation, followed by uplift of the southern blocks in post-Huronian time (Card *et al.* 1972). Metamorphic effects due to the possible late-Huronian deformation have not been recognized, due either to their absence or to overprinting by younger events.

Michigan and Minnesota

One of the major problems concerning Huronian rocks and events in the Great Lakes area has been that of correlations between the Lake Huron area and that to the west in Michigan and Minnesota. In particular, there has been a tendency to refer to the Early Proterozoic supracrustal sequences in Michigan and Minnesota as 'Huronian' and to relate all the deformation of these rocks to the 'Penokean Orogeny'.

James (1958) argued against using the term 'Huronian' in Michigan and Minnesota and proposed that 'Animikie' be used for these strata. Cannon & Gair (1970) proposed that 'Marquette Range Supergroup' be used in Michigan, with 'Animikie Group' being retained in Minnesota. Some recent papers (e.g. Young 1973) continue to argue in favour of at least a partial correlation, but recent geochronologic studies and much of the stratigraphic data argue against such a correlation in my opinion (see Morey 1973, as well as discussion in later sections).

One important question is whether there are any rocks in Michigan or Minnesota which are approximately or exactly the same age as the Huronian Supergroup or related rocks in the Lake Huron region. One possibility is the Reany Creek Formation in northern Michigan ('RC', figure 2) which rests unconformably on Archean basement rocks and is very similar to parts of the Gowganda Formation in Ontario (Puffet 1969). Unfortunately, however, there is no stratigraphic or structural evidence that it unconformably underlies the rocks of the Marquette Range Supergroup, a necessary prerequisite to the suggested correlation, and no geochronologic data bearing on its age are available.

Hanson & Malhotra (1971) obtained minimum ages of about 2000 Ma on a series of mafic dykes in Minnesota, and these dykes may be about the same age as those of the Nipissing

Diabase in Ontario, and along with the Nipissing Diabase be related to other suites of 2100–2200 Ma old mafic dykes in the Canadian shield (Gates & Hurley 1973).

In the Felch Trough area in northern Michigan ('FT', figure 2), work by myself and Dr P. O. Banks (Banks & Van Schmus 1971, 1972, and in preparation) shows that rocks assigned to the Archean or Lower Precambrian by James *et al.* (1961) and Aldrich *et al.* (1965) yield very complex age patterns. We have not fully resolved the original ages of all these rocks, some of which may be approximately the same age as those of the Huronian Supergroup. In any case, the data (figure 3) clearly show that these rocks were strongly deformed, metamorphosed to high grade (amphibolite) and intruded by granitic rocks about 2100 Ma ago, prior to deposition of the Marquette Range Supergroup. Thus, there is evidence of a definite orogenic pulse toward the end of Huronian time, but its extent is still not yet fully known.

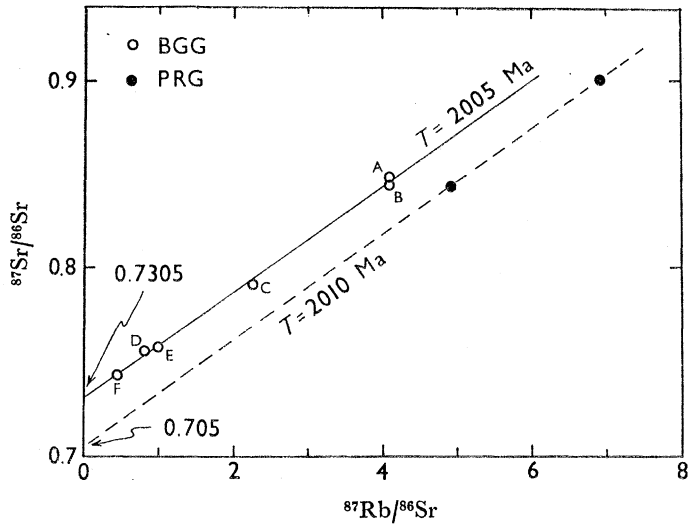

FIGURE 3. Plot of Rb-Sr data for samples of pre-Marquette Range Supergroup basement rocks of the Felch Trough area ('FT', figure 2), Michigan. Data from work in progress by myself in collaboration with Dr P. O. Banks. BGG samples represent individual layers from a single block of banded gray gneiss and are interpreted as representing Sr isotopic homogenization during high-grade metamorphism 2000–2100 Ma ago. PRG samples are from a 'porphyritic red granite' that intrude the metamorphic complex and indicate an age of about 2000 Ma; U-Pb analyses on zircons from this unit define an age of about 2100 Ma (Banks & Van Schmus 1972). The data on these units set an older limit of about 2000 Ma for the overlying Marquette Range Supergroup.

Early Proterozoic: Penokean period

The term 'Penokean Orogeny' as recognized by Goldich *et al.* (1961) referred to the post-Animikie tectonic, plutonic, and metamorphic activity in Minnesota, Wisconsin, and Michigan and was extended at that time to include folding of Huronian strata to the east in Ontario. Goldich *et al.* placed the time of the Penokean Orogeny about 1600–1800 Ma ago, but it has subsequently been revised to 1800–2000 Ma ago (Goldich 1968, 1972; Van Schmus 1972). Recent studies now indicate that the main peak of the orogeny can be placed approximately 1850–1900 Ma ago (Van Schmus 1974) as discussed below. In this paper my informal use of 'Penokean period' for the latter half of the Early Proterozoic includes the deposition or extrusion of Animikie Group rocks in Minnesota, Marquette Range Supergroup rocks in Michigan, and related rocks in Wisconsin as well as plutonic and metamorphic rocks associated with the Penokean Orogeny.

Minnesota and Michigan

The stratigraphy and structure of Penokean age rocks are best known from studies in Minnesota and Michigan, where they include the major iron ore deposits of the Lake Superior region (Bayley & James 1973). Table 3 summarizes the stratigraphy of Early Proterozoic rocks of the area; because of the number of geographically separate areas which contain these strata, there is a multiplicity of formational names for equivalent strata that cannot be shown in table 3. More detailed discussions may be found in James (1954, 1958), Cannon & Gair (1970), Sims & Morey (1972), and Morey (1973).

Table 3. Early Proterozoic strata in Michigan and Minnesota

Minnesota	Michigan
Animikie Group	Marquette Range Supergroup
(upper): greywacke, siltstone	Paint River Group: siltstone, greywacke
	Baraga Group: siltstone, greywacke, basalt
	unconformity
(middle): iron-formation	Menominee Group: iron-formation, siltstone, quartzite
(lower): quartzite, conglomerate	
unconformity	*unconformity*
(unnamed) dolomite	Chocolay Group: dolomite, quartzite, conglomerate
major unconformity	*major unconformity*
Archean Basement Complex	Archean Basement Complex

Depositional history. In general, four stages in the depositional history of these strata can be recognized, with the most complete record preserved in Michigan. These stages are relevant to the tectonic history of the region and are briefly summarized below.

The first stage was shallow-water deposition on a stable shelf and is represented primarily by the quartzite and dolomite of the Chocolay Group in Michigan, although isolated remnants of similar rocks are also found to the west. These strata represent typical miogeoclinal type facies and were deposited unconformably on crystalline basement. They thicken to the south-southeast and were apparently derived from uplifted Archean basement to the north and northwest. These strata probably represent deposition on an inactive continental margin or the northern part of a large, shallow intracratonic basin. So far, no 'off-shelf' equivalents have been recognized. These strata were mildly deformed and partly eroded prior to deposition of the next stage.

Sediments of the second stage were deposited unconformably on those of the first stage or, to the north and west, directly on crystalline basement. This stage was also shallow-water type deposition and is represented by the lower part of the Animikie Group in Minnesota and the lower part of the Menominee Group in Michigan. There is evidence for mild tectonic disturbance during sedimentation, particularly in Michigan, and indications that uplift was taking place to the south, creating a shallow basin or series of shallow basins along the (presently) northern edge of the Early Proterozoic sea (James 1954; Cannon 1973). The southern rims of these basins may or may not have been emergent; there is little evidence for northward transport of detritus (Morey 1973).

At the close of the second stage, detrital sedimentation effectively ceased over much of the area and was followed by the third stage, formation of major, chemically precipitated iron-formations comprising the central portion of the Animikie Group in Minnesota and the upper part of the Menominee Group in Michigan. This deposition was conformable with that of the second stage, although in many cases the transition is abrupt (Morey 1973). In Michigan, tectonic disturbance during this stage of deposition (James 1954) is regarded as the beginning of the Penokean Orogeny by Cannon (1973). As a result of this activity, Menominee Group rocks in Michigan were uplifted and partly eroded prior to the next stage of deposition. In Minnesota, however, the second and third stage rocks remained submerged and sediments of the next stage were deposited conformably on the earlier units (Morey 1973).

The fourth stage of deposition resulted from rapid subsidence of the depositional basins. As a result, a deep-water, eugeosynclinal environment was created, with the deposition of siltstone, shale, and greywacke of the upper part of the Animikie Group in Minnesota and of the Baraga and Paint River groups in Michigan. The character and sedimentary structures of these rocks indicate continued derivation from the north and northwest from uplifted continental basement (Morey 1973; Nilsen 1965). In the southern portions of the Michigan section and in northeastern Wisconsin, the Baraga Group contains thick accumulations of mafic, in part submarine, volcanic rocks (James, Dutton, Pettijohn & Wier 1968; Dutton 1971). Total thicknesses of the deep-water and volcanic succession exceed several thousands of metres in Michigan, indicating drastic subsidence of the continental basement. None the less, all indications are that the entire preserved stratigraphic section was deposited on continental basement and does not represent an oceanic type back-arc basin (Cannon 1974).

Ages and correlation. Following deposition of the above strata, tectonic activity increased, culminating in the major peak of the Penokean Orogeny (see below). Igneous rocks associated with this event cut formations of the Marquette Range Supergroup in several places, particularly in Iron and Dickinson counties, Michigan (Bayley 1959; James *et al.* 1961, 1968). These rocks have been well dated at about 1900 Ma (Aldrich *et al.* 1965; Banks & Van Schmus 1971, 1972), setting a younger limit to the age of the strata. As mentioned earlier, these strata rest unconformably on a basement complex which underwent deformation, plutonic intrusion, and metamorphism about 2100 Ma ago, setting a corresponding older limit for the age of the strata. Banks & Van Schmus (1972 and in preparation) have also obtained a U-Pb age of about 1950 Ma for zircon from rhyolite of the Hemlock Formation in the Baraga Group, consistent with the above age bracket. In Minnesota, Peterman (1966) obtained an age of metamorphism of about 1850 Ma for Animikie Group metasediments and Hanson & Malhotra (1971) interpret the 2000–2100 Ma old mafic dikes of Minnesota as pre-Animikie. Thus, presently available data strongly indicate an age of 1900–2000 Ma for the Early Proterozoic suprecrustal rocks in Michigan and Minnesota, precluding their correlation with the Huronian Supergroup to the east.

Orogenic history. In general, Penokean orogenic activity in Minnesota and Michigan increased to the south and southeast. This orogenic activity is represented by varying degrees of deformation, metamorphism, and intrusion of plutonic rocks and is well summarized by Morey (1973) for Minnesota and by Cannon (1973) and Cannon & Klasner (1972) for Michigan. The studies in Michigan indicate that deformation began with an episode of gravity sliding and soft-sediment deformation due to regional tilting or instability on palaeoslopes. This was followed by block faulting of the basement rocks, which produced the major large fold structures of the region. The folds were apparently produced as a result of the Proterozoic rocks being passively draped over and between uplifted fault blocks, rather than by major compressional tectonics, and caused refolding of the structures produced during the first phase of deformation.

The folding of the first phase has primarily east–west trending axes, whereas the trends of the major domes and synclines produced by the block faulting are quite divergent (Cannon 1973). In Minnesota, post-depositional folding due to the Penokean Orogeny is confined primarily to east-central Minnesota and consists of major folding along east–west to northeast–southwest trending axes. In general, however, outcrop control is insufficient to determine the major causes of deformation (Morey 1973).

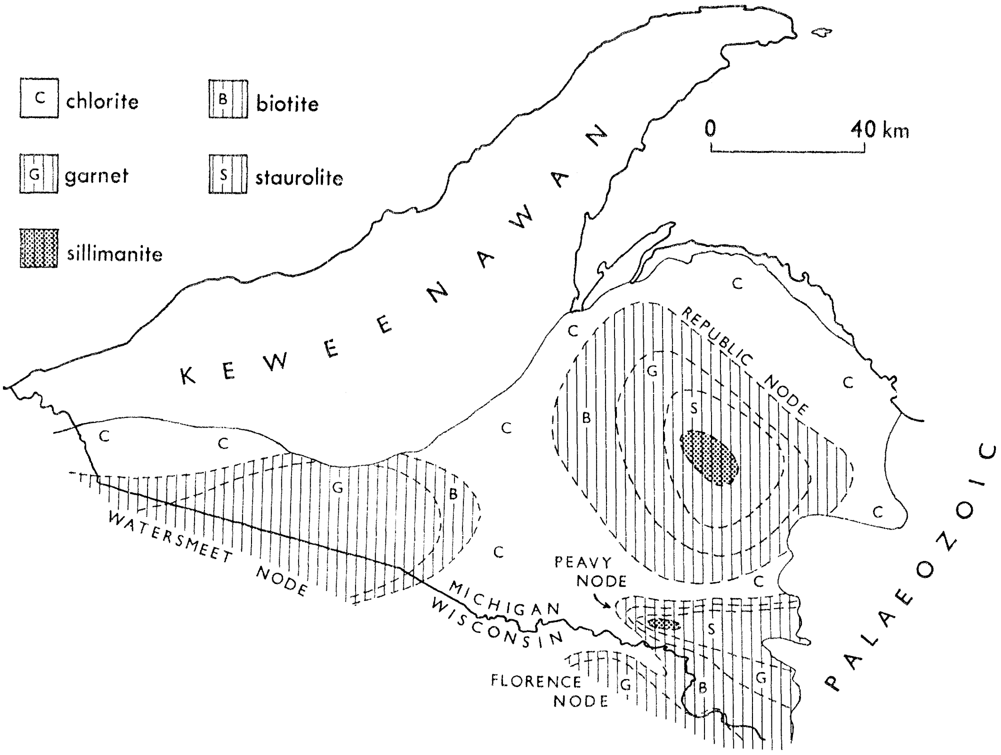

FIGURE 4. Map of northern Michigan showing the four nodes of Early Proterozoic metamorphism delineated by James (1955).

Igneous activity associated with the Penokean Orogeny in Minnesota and northern Michigan is limited to southern areas of exposure. In east-central Minnesota there are several plutonic bodies ranging in composition from tonalite to granite which apparently post-date rocks of the Animikie Group. K-Ar and Rb-Sr data from these rocks (mostly on micas) yield minimum ages of about 1750–1800 Ma (Goldich *et al.* 1961; Keighin, Morey & Goldich 1972), consistent with ages of other intrusive rocks associated with the Penokean Orogeny. Igneous rocks 1800–1900 Ma old have also been reported from parts of the Minnesota River Valley, where they intrude the Archean complex (Goldich *et al.* 1970).

In Michigan there was minor plutonic activity associated with the Peavy metamorphic node (figure 4, see below). Basement rocks and Early Proterozoic metasedimentary rocks have been cut by a number of granitic and pegmatitic dykes, and a small differentiated, syn-orogenic plutonic complex is present in the sillimanite grade portion of the node (Bayley 1959; James *et al.* 1961). Age studies on these intrusive rocks indicate that they are about 1900 Ma old (Aldrich *et al.* 1965; Banks & Van Schmus 1971, 1972).

Metamorphic effects associated with the Penokean Orogeny are widespread in northern Michigan, but in Minnesota they are primarily confined to the east-central portion where a metamorphic halo exists in the area of plutonism (Morey 1973) and to a lesser degree in the Minnesota River Valley, where Penokean activity has affected mineral systems in some of the older rocks (Goldich *et al.* 1970; Farhat & Wetherill 1974).

In northern Michigan, James (1955) delineated the metamorphism into four distinct nodes (figure 4), two of which extend southward into Wisconsin. The metamorphic nodes were formed more or less contemporaneously with the Penokean deformation in the Republic area (Cannon & Klasner 1972; Cannon 1973) and reached peak temperatures prior to intrusion of the igneous rocks in the Peavy node (Bayley 1959; James *et al.* 1961). Thus, on structural and petrologic grounds the metamorphism is also about 1900 Ma old and an integral part of the Penokean Orogeny. This conclusion is supported by the fact that the Florence node in the Michigan–Wisconsin border area is developed marginally to 1850–1900 Ma old plutonic rocks of northeastern Wisconsin (Banks & Cain 1969). Attempts to confirm the age of primary metamorphism in Michigan by radiometric dating of the metamorphic minerals have so far proved unsuccessful due to the presence of younger thermal overprints (Aldrich *et al.* 1965; Van Schmus & Woolsey 1975).

In summary, the Penokean Orogeny is represented in Minnesota and northern Michigan by deformation, metamorphism, and plutonic rocks. These events occurred about 1850–1900 Ma ago and are most prevalent in southern portions of the region. The deformation appears not to have involved much compression of the underlying Archean continental basement in this region, which was largely deformed by vertical block faulting. The metamorphism is typically of a low-pressure, low- to high-temperature variety, with andalusite and sillimanite being the common stable polymorphs of aluminosilicate (Cannon 1973; Morey 1973).

Wisconsin

One of the major problems relating to Precambrian geology in the Great Lakes region has been the lack of a comprehensive understanding of Precambrian rocks in much of Wisconsin. As a result, the most recent published geologic map for Precambrian rocks in Wisconsin (Dutton & Bradley 1970) has only lithologic designations. Much of this problem has been due to the scarcity of definitive age measurements. The only such work until recently was that of Banks & Cain (1969), Banks & Rebello (1969), Dott & Dalziel (1972), and some of the mineral ages reported by Bass (1959) and Goldich *et al.* (1961, 1966). Over the past several years my own research efforts have been largely concerned with the geology and ages of Precambrian rocks in Wisconsin. As a result of this work and that of several colleagues, much of it still in progress, it is now possible to establish a good picture of the regional Precambrian geology in Wisconsin and to relate it to that of the Great Lakes area in general (Van Schmus 1974; Van Schmus, Medaris & Banks 1975*b*; Van Schmus *et al.* 1975*c*). However, we have found that Rb-Sr isochrons for Precambrian rocks in Wisconsin often record some metamorphic event (Van Schmus *et al.* 1975*c*), so that it is necessary to rely on U-Pb ages from separated zircons for primary age control where possible.

For the most part the Precambrian basement of Wisconsin consists of metavolcanic and plutonic rocks with local infolded or included remnants of metasedimentary rocks. No coherent analysis can be attempted yet from the metasedimentary rocks. Results to date from U-Pb analyses of zircons (figures 5 and 6) show that Early to Middle Proterozoic igneous rocks in

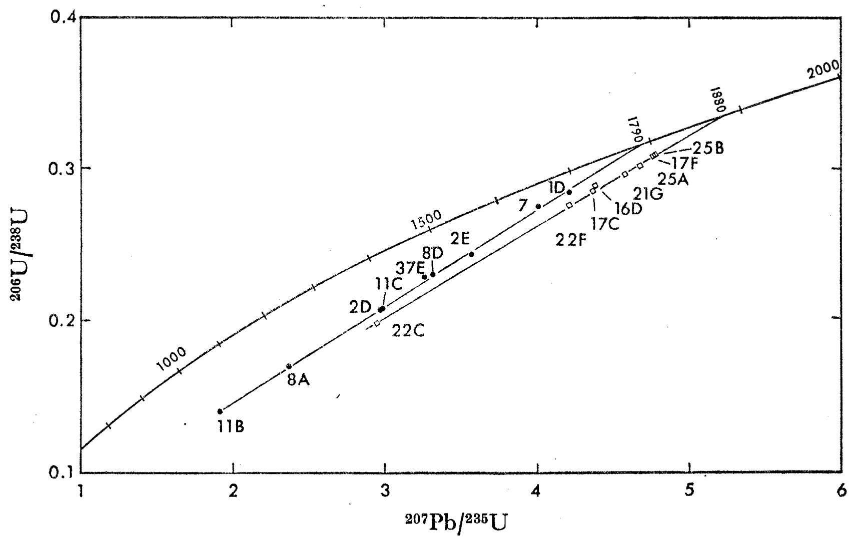

FIGURE 5. Plot of U-Pb data for zircon fractions from a variety of igneous rocks of the Wisconsin basement complex. Sample locations are shown in figure 6. These data clearly show that there are two distinct age suites present in addition to the 1500 Ma old Wolf River Batholith (data not shown). The older suite is about 1880 ± 30 Ma old and represents orogenic rocks of the Penokean Orogeny. The younger suite is about 1790 ± 25 Ma old and represents post-orogenic rhyolite and granite. Data from unpublished work of mine in progress.

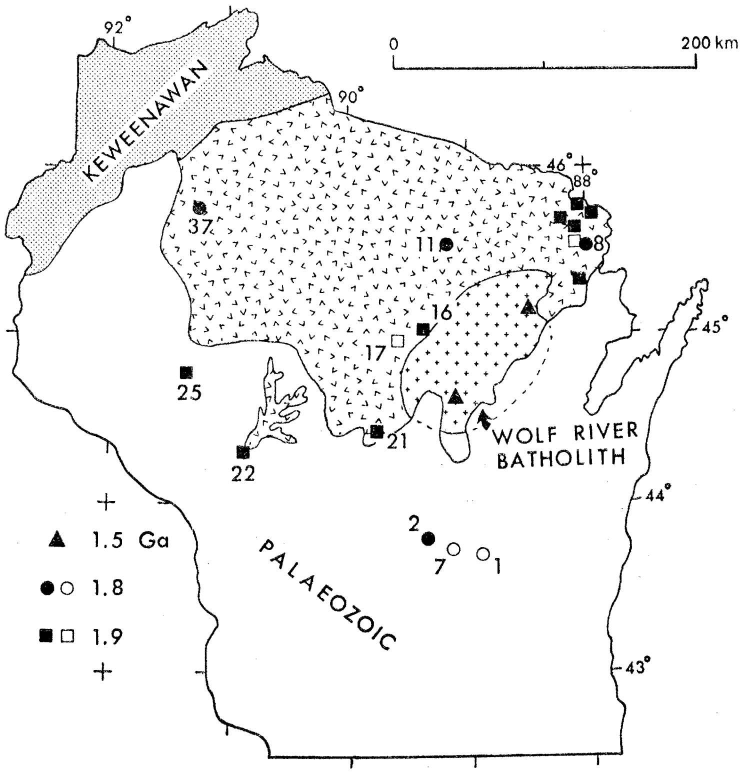

FIGURE 6. Map of Wisconsin Precambrian basement showing distribution of ages determined from U-Pb analyses on separated zircons. Numbered localities are from unpublished work of mine (figure 5). Un-numbered localities are from Banks & Cain (1969), Banks & Rebello (1969), and Van Schmus *et al.* (1975*b*). Open symbols represent extrusive rocks, closed symbols represent intrusive rocks. Ages in billions of years (Ga).

Wisconsin can be divided into three distinct suites: (*a*) 1850–1900 Ma old volcanic and plutonic rocks which make up most of the basement complex of northern and northeastern Wisconsin (Banks & Cain 1969; Banks & Rebello 1969) and extend into central and western Wisconsin (Van Schmus 1974); (*b*) 1780–1800 Ma old granitic and rhyolitic rocks which apparently underlie most of southern Wisconsin (Van Schmus 1974); and (*c*) 1500 Ma old anorogenic plutonic rocks, particularly the Wolf River batholith of rapakivi affinity in east-central Wisconsin (Van Schmus *et al.* 1975*b*).

The 1850–1900 Ma old suite consists of dioritic to granitic plutonic rocks which are intrusive into a complex of essentially contemporaneous volcanic rocks (see, for example, Van Schmus *et al.* 1975*c*). The ages and distribution of these rocks suggest that they are directly related to the Penokean Orogeny and may represent a volcanic-plutonic arc to the south of the sedimentary basins of Michigan and Minnesota. However, the complex in Wisconsin is separated from the section in Michigan by a major fault system (Bayley *et al.* 1966; Dutton 1971) and so far the basement to the volcanic succession in Wisconsin has not been found.

The 1780–1800 Ma old suite of rocks consists principally of rhyolitic (ignimbritic) extrusive rocks and granitic intrusive rocks (granophyric granite to porphyritic quartz monzonite). The extrusive rocks only occur in southern Wisconsin, principally as inliers in the Paleozoic rocks (Asquith 1964). The intrusive rocks extend into central and northern Wisconsin, with the epizonal, granophyric rocks concentrated to the south (Weidman 1898) and the transition to coarser-grained varieties occurring northward to northwestward. At present it is not known how these rocks relate to the slightly older ones assigned to the Penokean Orogeny. The base of the volcanic rocks has not been found in outcrop, but it is presumed that they overlie the 1850–1900 Ma old rocks. The younger rocks could represent a late stage igneous event associated with the causes of the Penokean Orogeny, or they could be related to a separate younger event acting on the pre-existing Penokean orogenic complex (see, for example, Bridgwater & Windley 1973).

The 1780–1800 Ma old rocks have also been subjected to deformation and low grade geochemical alteration, so it is clear that the Penokean Orogeny was not the last major tectonic event in the region (Van Schmus *et al.* 1975*c*).

Ontario

In the Lake Huron region of Ontario, a major feature is the Sudbury structure of probable impact origin and rocks associated with it (see Bray 1972 for papers dealing with this feature). The actual formation of the structure is not important in terms of normal Proterozoic tectonic models, but its age is. Various estimates of the age of the Sudbury structure range from 1700 to 2000 Ma (Faure, Fairbairn, Hurley & Pinson 1964; Gibbons, Adams & McNutt 1972; Hurst & Wetherill 1974), but recent work by Krogh & Davis (1974) and Gibbons & McNutt (1975) indicates that the age of the norite phase of the irruptive is most likely about 1870 Ma. The structure has been subjected to considerable compression in a NW–SE direction since its formation, but because of the age uncertainties it has not been possible to say for sure whether this was post-Penokean deformation (Card *et al.* 1972), or whether it was part of a single period of deformation which occurred as part of the Penokean Orogeny (Brocoum & Dalziel 1974). The recent result of 1870 Ma for the age of the irruptive suggests that the deformation of this structure is post-Penokean, in line with the multiple deformational history outlined by Card *et al.* (1972). However, this does not settle the question of whether the main deformation of the Huronian strata in the southeast part of the area is pre-Penokean (i.e. Huronian) as suggested by Card *et al.* (1972) or whether most or all the major deformation occurred in a single event as part of the Penokean Orogeny (Brocoum & Dalziel 1974).

Although the age of deformation is not well known, geochronological studies by Fairbairn *et al.* (1969) indicate that post-deformational high-grade metamorphism in the southeastern part of the area probably occurred about 1950 Ma ago. Like the Penokean metamorphism in Michigan and Minnesota, that in Ontario was also dominantly of a low-pressure, low- to high-temperature variety.

Igneous rocks of Penokean age are scarce or absent; the unit most likely of Penokean age is the Cutler batholith, which has a minimum age of 1750–1800 Ma (Wetherill, Davis & Tilton 1960). To the east, in the Grenville Province, Krogh & Davis (1969) have reported Rb-Sr isochron ages of about 1800 Ma for some of the gneissic and plutonic rocks, indicating that Penokean age rocks may have been present there as well.

Middle Proterozoic

Depositional history

The principal sedimentary rocks of Middle Proterozoic age in the Great Lakes area are the widespread quartzites of Wisconsin, Minnesota, and South Dakota (Dott & Dalziel 1972). These quartzites were deposited sometime after extrusion of the 1780–1800 Ma old rhyolite of southern Wisconsin (Van Schmus *et al.* 1975*c*), and there are indications that the quartzite was deposited on a major erosion surface developed on the rhyolite and associated intrusive rocks. In any case, the quartzites are no younger than 1500 Ma, the age of plutonic rocks intruded into them (Dott & Dalziel 1972; Van Schmus *et al.* 1975*b*).

The Whitewater Group sediments within the Sudbury basin may also be Middle Proterozoic in age (Card *et al.* 1972), but they do not appear to be closely related to any rocks outside the Sudbury basin.

Deformation and metamorphism

The quartzite and rhyolite in Wisconsin were all folded and faulted during Middle Proterozoic time, probably prior to intrusion of the 1500 Ma old Wolf River batholith, which cuts the older rocks but appears to be much less faulted (Van Schmus *et al.* 1975*b*). Exact dating of the deformation is uncertain, however.

There is considerable evidence for wide-spread, generally low grade metamorphism (specifically, resetting the Rb-Sr rock and mineral 'ages') throughout the Great Lakes region about 1650 to 1700 Ma ago (Van Schmus *et al.* 1975*c*). The cause for this event has not yet been found. No igneous rocks of this age are known to exist in the region, but it is possible that Middle Proterozoic deformation mentioned above was responsible for, or related to, this low-grade metamorphism.

There were also apparently significant thermal effects throughout the southern portion of the area shown in figure 2 due to widespread anorogenic igneous activity about 1500 Ma ago (below).

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Igneous activity

There are several occurrences of 1500 Ma old plutonic rocks in the Great Lakes region (Van Schmus 1965; Van Schmus *et al.* 1975*a, b*). The largest of these is the Wolf River batholith in east-central Wisconsin, a large anorogenic complex of general quartz monzonitic composition. This complex is notable because the rock types present are strikingly similar to those of typical rapakivi massifs in Finland. In addition, there is anorthosite associated with the batholith, apparently as large included masses or roof pendants. The 1500 Ma old rocks in the great Lakes region are part of a major suite of such rocks that extend from Labrador southwestward across North America to the southwestern United States (Silver 1968; Bickford & Mose 1972; Frith & Doig 1973; Bridgwater & Windley 1973; Van Schmus *et al.* 1975*a, b*) and represent an important phase in the evolution of the North American Precambrian basement during the Middle Proterozoic. As yet, however, insufficient data exist to interpret the exact nature and origin of that event and similar events (Bridgwater & Windley 1973).

Late Proterozoic

Two major events in the Late Proterozoic affect interpretation of older events. One was the Keweenawan event in the Lake Superior region about 1100 Ma ago (e.g. Craddock 1972), for if the Keweenawan event was related to partial rifting as shown on figure 2 (King & Zeitz 1971; Chase & Gilmer 1973), then any reconstruction of pre-Keweenawan events must take into account any lateral displacements that may have resulted. The other event was the formation of the Grenville Province, also about 1100 Ma ago. It is now well known that many of the rocks in the Grenville Province are re-worked Proterozoic and Archean rocks (e.g. Wynne-Edwards 1972), and any reconstruction of the eastern portion of North America during Archean and Middle to Early Proterozoic times will have to take that into account.

Discussion and interpretations

Great Lakes area

Based on our current knowledge of the geology and age relations of Early Proterozoic rocks in the Great Lakes area, the following stages of development can be recognized.

Huronian

Rocks of the Huronian Supergroup were deposited or extruded in Ontario on a southward sloping Archean basement and in a shallow-water to fluvial (at times glacial) environment 2150–2400 Ma ago; there is considerable uncertainty as to whether there are Huronian age supracrustal rocks in Michigan or Minnesota. A definite orogenic pulse can be recognized throughout the region toward the end of Huronian time as defined in this paper. This orogenic pulse appears to be most intense in the southernmost areas of exposed Huronian cover or Archean basement. It is represented by at least some deformation of Huronian strata and emplacement of the Nipissing Diabase in the Lake Huron region of Ontario, by metamorphism, granitic plutonism, and deformation in Michigan, and by emplacement of mafic dykes in Minnesota. This orogenic pulse is distinct from and older than that involving Early Proterozoic strata in Michigan, Minnesota, and Wisconsin for which the term ‘Penokean Orogeny’ is more properly applied.

Because of general lack of information about what kinds of rocks existed or were being formed to the south at this time, and because of the apparent lack (or lack of recognition) of orogenic events of this age elsewhere in North America, I will not attempt to interpret the Huronian events except to note that they are indicative of crustal instability during the first part of the Early Proterozoic and as such an indication of later events.

Penokean

The Penokean period began with the deposition of miogeoclinal sediments (Chocolay Group) on a southward facing slope. This was followed unconformably by deposition of additional miogeoclinal sediments and by sedimentary iron-formation of the Menominee Group in Michigan and the lower and middle Animikie Group in Minnesota. By this time, mild deformation and uplift had apparently created a submarine barrier to the south, forming the shallow basins in which the iron-formations were deposited. This was followed by relatively rapid subsidence of the crust and the deposition of a thick accumulation of deep-water, eugeosynclinal type sediments of the Baraga and Paint River groups in Michigan and the upper Animikie Group in Minnesota. In Michigan at this time there were also locally significant periods of basaltic volcanism, and extensive basaltic volcanism was occurring throughout northern and central Wisconsin approximately contemporaneously with the latter stages of sedimentation in Michigan and Minnesota. The accumulation of supracrustal rocks occurred roughly in the interval 1900–2000 Ma ago.

Following sedimentation and volcanism, and in part contemporaneous with it, the supracrustal rocks were strongly deformed, intruded by plutonic rocks, and metamorphosed during the Penokean Orogeny 1850 to 1900 Ma ago. The plutonic activity was primarily confined to the volcanic terrain in northern and central Wisconsin, although the deformation and metamorphism occurred throughout northern Michigan and east-central Minnesota and eastward into Ontario.

Rocks involved in the main activity of the Penokean Orogeny can be divided into two suites. The first is a northern belt of dominantly sedimentary rocks of the Animikie Group and the Marquette Range Supergroup. The second is a volcanic-plutonic complex in northern and central Wisconsin, lying to the south of the first suite and, at least in places, separated from it by a major east–west trending fault system. This association of rock suites is suggestive of an active collisional plate margin with a volcanic-plutonic arc and back-arc basins (figures 7 and 8). However, if this were the case, the arc may not have been emergent for major periods of time; the preserved eugeosynclinal sediments of the northern belt show very little evidence of derivation from the south, and they contain very little volcanic detritus. Alternatively, post-Penokean uplift and erosion could have removed all traces of a phase or phases of sedimentation in which material was derived from a southern highland source. In addition, it is not yet known whether the volcanic-plutonic complex was built on subsided continental crust or on oceanic floor off the edge of the craton.

Late(?) and post-Penokean

In Wisconsin a third suite of rocks possibly related to the Penokean Orogeny can be recognized: the 1780–1800 Ma old granite and rhyolite of southern Wisconsin (figure 7). The full extent of these rocks is not yet known, but related plutons extend into northern

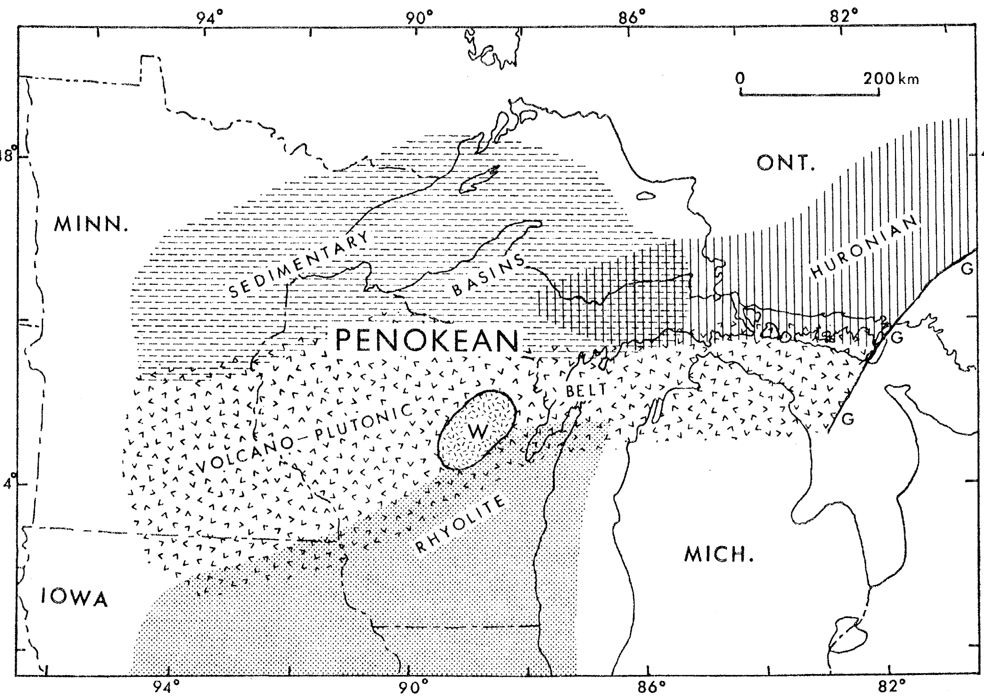

FIGURE 7. Paleogeologic map showing possible distributions of (*a*) pre-Penokean Huronian depositional basins or platform, (*b*) Penokean depositional basins in Minnesota and Michigan, (*c*) Penokean volcanic-plutonic orogenic belt, and (*d*) post-Penokean rhyolite terrane of southern Wisconsin. Also shown are the later Wolf River batholith ('W') and the Grenville Front ('G').

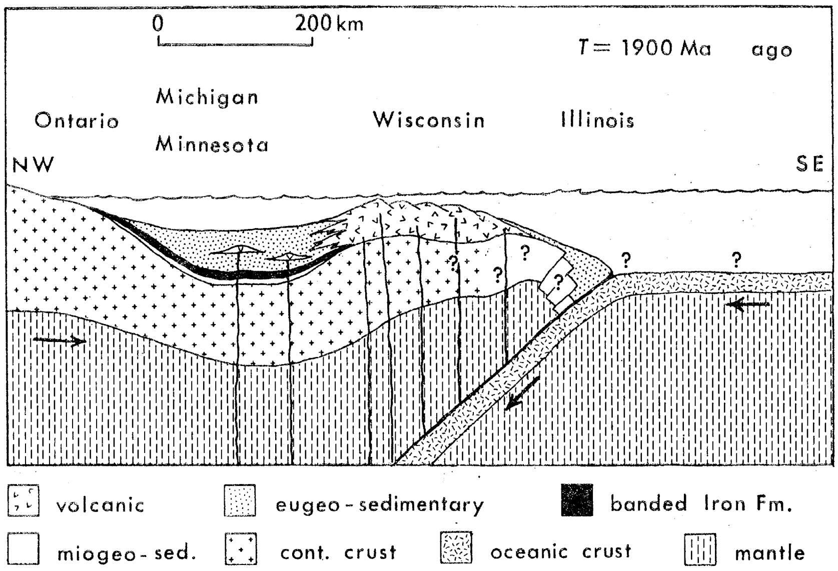

FIGURE 8. A possible reconstruction of the margin of the Archean craton about 1900 Ma ago during the early stages of the Penokean Orogeny (before intrusion of plutonic rocks in the volcanic arc and associated metamorphism and deformation). Modified after figure 6 of James (1954), but the presence of the subduction zone is still purely hypothetical, and other models are quite possible.

Wisconsin and subsurface data (Dutton & Bradley 1970) indicate that the extrusive rocks extend southward beneath the Paleozoic and younger cover. At present it is not known whether these rocks represent a distinct period of continental evolution in the Great Lakes area or are due to some late-stage event related to the main Penokean Orogeny. In any case, a major problem will be to account for the large amount of dominately felsic rock produced during this event.

Following formation of the southern Wisconsin granite-rhyolite complex, the area was probably uplifted and partly eroded, after which extensive beds of quartzose sandstone were deposited. The entire area was then further deformed and subjected to widespread low-grade metamorphism 1650–1700 Ma ago. The next well dated event was the intrusion of the Wolf River batholith in Wisconsin and other quartz-monzonitic plutons in the northern Lake Huron region about 1500 Ma ago. There is apparently a major gap in the Precambrian record of the Great Lakes area until about 1100–1200 Ma ago, when the Keweenawan and Grenville events began. Since these events, the region has been tectonically relatively stable, except for broad regional uplift or subsidence and Palaeozoic and younger sedimentation.

Similar areas in North America

The bulk of the Precambrian basement of North America and Greenland consists of rocks which either formed in Proterozoic time or are Archean rocks which were re-mobilized in Proterozoic time. Figure 1 shows the general age distribution of rocks in the Precambrian basement and is based on my interpretation of numerous literature sources. I have presented the Archean craton as a former single mass. Rocks yielding Proterozoic ages within the mass are interpreted as being due to intracratonic mobilization with locally developed areas of Proterozoic sedimentation, volcanism, and plutonism. Major examples would be the Churchill Province and the Hudsonian Orogeny of the Canadian shield (Davidson 1972) and the Nagssugtoqidian mobile belt of south-central Greenland (Bridgwater *et al.* 1973*a*). In addition, I have provisionally accepted the view of Dimroth (1970, 1972) that the Labrador geosyncline (figure 1) was developed as an intracratonic structure rather than a continental margin structure.

Petro-tectonic assemblages that probably represent continental margin processes during the Early Proterozoic in North America are well preserved and well exposed in only four regions known to me at present. These are shown in figure 1 and are the Great Lakes area ('GL'), the Coronation geosyncline in northwestern Canada ('C') (Hoffman 1973; Hoffman, Dewey & Burke 1974; Baadsgaard, Morton & Olade 1973), the Rocky Mountains of southern Wyoming and northern Colorado ('CW') (Hills *et al.* 1968; Peterman & Hedge 1968; Hills & Armstrong 1974), and the Ketilidian mobile belt ('K') of southern Greenland (Bridgwater *et al.* 1973*a*; Van Breemen, Aftalion & Allaart 1974; Gulson & Krogh 1975). The rest of the Archean continental margin(?) has either been destroyed by younger events such as the Grenville Orogeny or is buried under younger sedimentary cover. Continued sequential development of North America during the Proterozoic is apparently best recorded in the basement rocks of south-central and southwestern United States (figure 1). For these rocks, however, delineation of the full extents of and the boundaries between the various age suites has only been accomplished in the southwest United States (Silver 1968); elsewhere the pattern shown in figure 1 is largely diagrammatic and shows the general trend to younger suites of rock southward.

Comparison of the geology and chronology of the cratonic-margin areas in figure 1 indicates distinct similarities which, taken as a whole, may be indicative of the general nature of active continental margin processes during the Early Proterozoic. In particular, four distinct petrotectonic zones can be recognized: (1) stable interior, (2) marginal mobile zone, (3) main orogenic belt, and (4) post-orogenic felsic volcanic and/or plutonic rocks.

In all four areas mentioned above, the stable interior consists of Archean continental rocks. Early Proterozoic sedimentary rocks may be absent due to erosion or non-deposition; those that are present are generally flat-lying or very gently deformed. Some Early Proterozoic faulting and mafic dykes may be present. Mild metamorphic effects, such as re-setting of K-Ar and Rb-Sr ages on micas, may extend into the stable interior from the orogenic areas farther out.

The marginal mobile zone consists of Early Proterozoic depositional slopes or basins underlain by Archean sialic crust. Early Proterozoic sedimentary rocks began largely as miogeoclinal shelf deposits derived from the stable interior and may grade upward into deeper water, eugeosynclinal or flysch type deposits, and then further upward into molasse type deposits derived from a 'seaward' highland. The most complete record of this type is that of the Coronation geosyncline (Hoffman 1973). Both the basement rocks and the sedimentary cover have undergone varying degrees of deformation and metamorphism and may have been intruded by a few small bodies of granite. In general, the intensity of deformation and metamorphism increases toward the outer limit of the older sialic basement, and structural trends are roughly parallel to the margin. Deformation of the sialic basement in this zone was largely by vertical tectonics and block faulting and probably did not involve much crustal shortening. However, gravity sliding or overthrusting from more outer regions may have caused considerable shortening of the Proterozoic strata overlying the older basement.

Rocks of the main orogenic belt may be separated from those of the marginal mobile belt by a major tectonic feature such as a shear zone or a fault system, or the transition may be narrow and continuous. Rocks of the orogenic belt consist primarily of eugeosynclinal type sediments and/or basaltic extrusive rocks which have been strongly deformed, metamorphosed, and intruded by syn-orogenic plutons ranging in composition from tonalite to granite. Within the main orogenic belt there is little to no evidence of sialic basement, or for that matter, any basement at all. The rocks of this belt I consider possibly analagous to modern arc type assemblages, although insufficient data exist at present to permit detailed comparison.

The three zones mentioned above are related to the actual orogeny which occurred along the cratonic margin and, as pointed out by Hills & Armstrong (1974), are similar in many ways to the structures of more modern orogenic belts such as the southern Appalachians in the eastern United States. Therefore, it is quite possible that Early Proterozoic cratonic-margin orogenic belts were formed as a result of processes acting along convergent plate boundaries. Clearly, however, much more data is needed before detailed interpretations can be made. For example, insufficient geophysical data exist to determine whether there are any characteristic types of anomalies.

In the Great Lakes area and the Coronation geosyncline region, the 'outermost' portions of the orogenic belts are composed of thick accumulations of felsic extrusive rocks and associated epizonal granitic plutons. In southernmost Greenland there are numerous post-orogenic felsic rapakivi type plutons. In the western United States, abundant post-orogenic rocks similar in age to the main orogeny are not present near the tectonic front as in other areas. However, the main orogenic complex itself is very wide, extending southward from Wyoming through Colorado and into northern Arizona. In central Arizona there is a transition from the northern

1720–1800 Ma old complex into a southern terrain of extensive felsic volcanism and plutonism (Livingston & Damon 1968; Silver 1968). Allowing for the larger distances involved, the felsic igneous rocks of southern Arizona could represent the felsic igneous zones found closer to the fronts in the other areas.

In all four areas, the younger felsic igneous rocks are apparently 50–100 Ma younger than the main orogenic events, although the timing of respective events is not the same from area to area (for example, the orogenic plutons in Colorado are about 1750 Ma old whereas they orogenic plutons in the Great Lakes area are about 1880 Ma old). A possible exception is the felsic rocks of the Coronation geosyncline area (i.e. the Great Bear batholith) for which good ages are not yet available; existing data (Hoffman 1973) suggest that they are younger than the orogenic complex (the Hepburn batholith). It is uncertain at this time whether the felsic rocks in these areas were formed as a direct consequence of the processes responsible for the main orogenies, or whether they were formed by some distinct, younger event acting on the pre-existing Early Proterozoic continental margin orogenic assemblages. It is worth noting, however, that this Early Proterozoic orogenic assemblage was the site for further anorogenic igneous activity 200–300 Ma later (the 1450–1500 Ma old suite of rocks mentioned previously).

Conclusions

In conclusion, I interpret the Early Proterozoic geology of the Great Lakes area provisionally as representing orogenic processes along the margin of an Archean cratonic mass. It is cautiously concluded that processes similar to modern plate tectonics may have been generally operational at such margins, but to date a direct, detailed comparison is not possible. If plate tectonic processes were operational, they probably differed in detail as to mechanisms and resulting petrologic assemblages, and these differences will have to be sorted out with future work. Finally, it is recognized that quite different styles of *intra*-cratonic orogenic activity were also operational (see, for example, Sutton & Watson 1974), leading to a complex total picture of tectonic processes during the Early Proterozoic.

This review was prepared while I was a visitor at the Department of Geology, Imperial College, London, and I wish to thank Professor J. Sutton, F.R.S., and the staff for their hospitality. Dr J. Watson read an early version of the paper and provided many helpful suggestions. I have benefited considerably in this overall study from conversations and field trips with numerous geologists working in the Great Lakes area and wish to acknowledge their cooperation, without which much of my work could not have been accomplished. Continuing financial support has been provided in part by the National Science Foundation (Grants GA-1362, GA-15951, GA-43426) and by research funds of the University of Kansas.

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