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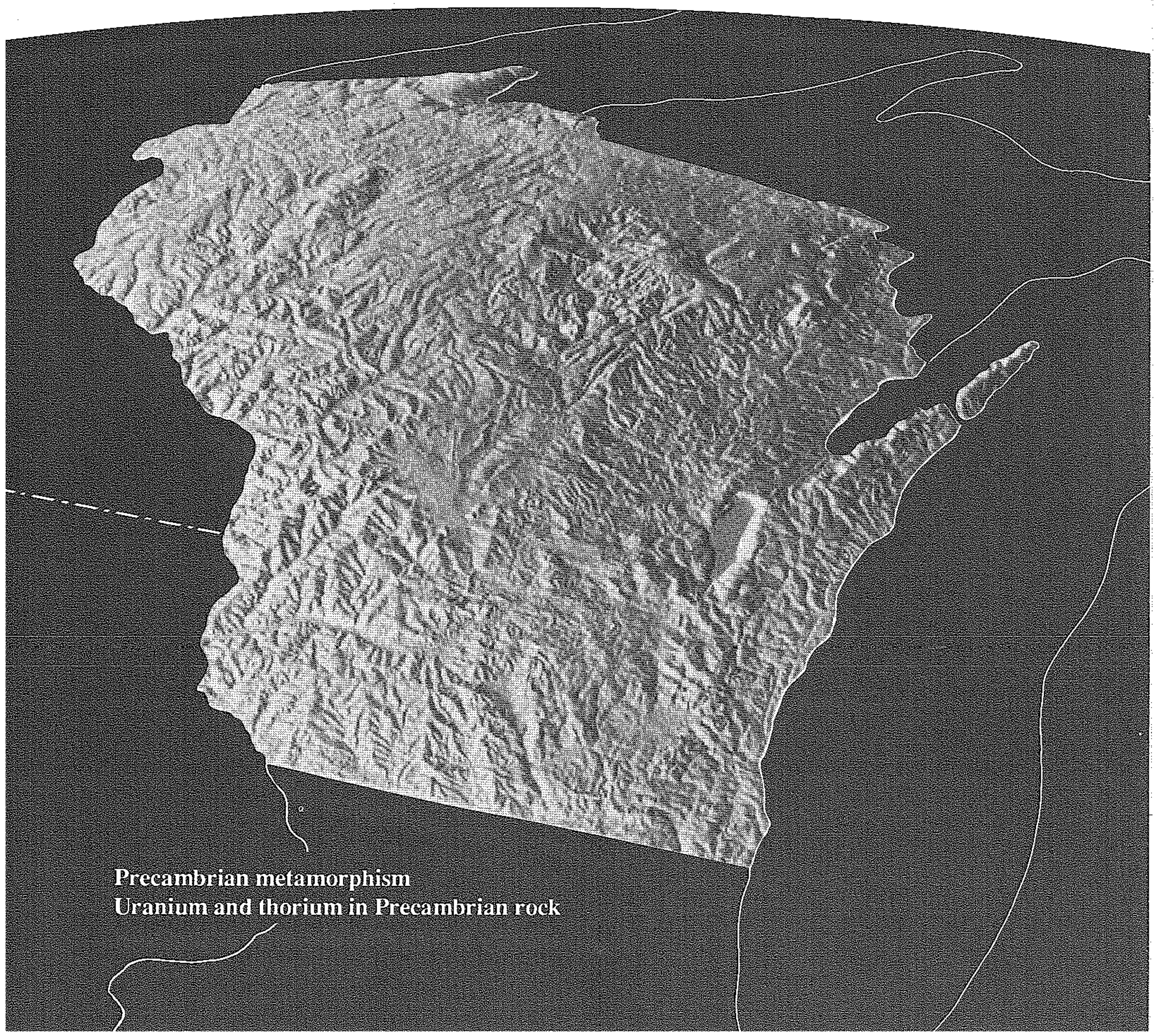

Precambrian metamorphism
Uranium and thorium in Precambrian rock

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Precambrian metamorphism in the southern Lake Superior region and its bearing on crustal evolution

C.A. Geiger and C.V. Guidotti

Uranium and thorium in selected Precambrian rock units in Wisconsin

Gregory Mursky, James W. Anderson,
Timothy R. Cook, and William S. Meddaugh

U.S. Department of Energy publications on uranium and radiometric surveys of Wisconsin

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PREFACE

"Geoscience Wisconsin" is a serial that addresses itself to the geology of Wisconsin -- geology in the broadest sense to include rock and rock as related to soil, water, climate, environment, and so forth. It is intended to present timely information from knowledgeable sources and make it accessible with minimal time in review and production to the benefit of private citizens, government, scientists, and industry.

Manuscripts are invited from scientists in academic, government, and industrial fields. Once a manuscript has been reviewed and accepted, the authors will submit a revised copy of the paper, and the Geological and Natural History Survey will publish the paper as funds permit, distribute copies at nominal cost, and maintain the publication as a part of the Survey list of publications. This will help to insure that results of research are not lost in the archival systems of large libraries, or lost in the musty drawers of an open-file.

The papers in this volume deal principally with Precambrian rock. Chuck Geiger and Chuck Guidotti present a comprehensive summary and analysis of the metamorphic history of the Lake Superior region. Greg Mursky, Jim Anderson, Tim Cook, and Scott Meddaugh present the results of several thesis investigations on the distribution of uranium and thorium in selected granitic rock units.

We greatly acknowledge the use of the following illustrations that have been previously published:

Figure 1 from A.M. Goodwin, Archean basin-craton complexes and the growth of Precambrian shields: Canadian Journal of Earth Sciences, v. 14, p. 2737-2759 (1977).

Figure 2-2 from G.B. Morey, Animikee Basin, Lake Superior region, U.S.A., _in_ Trendall, A.F., and Morris, R.C., ed., Iron-formation: Facts and Problems: Amsterdam, Elseviers Science Publishers, p. 13-67 (1983).

Plate 1 from H.L. James, Zones of regional metamorphism in the Precambrian of northern Michigan: Geological Society of America Bulletin, v. 66, p. 1455-1488 (1955).

We encourage submission of manuscripts relating to Wisconsin Geology. Special consideration will be given to papers which deal with timely topics, present new ideas, and have regional or statewide implications.

M.G. Mudrey, Jr.
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PRECAMBRIAN METAMORPHISM IN THE SOUTHERN LAKE SUPERIOR REGION AND ITS BEARING ON CRUSTAL EVOLUTION

C.A. Geiger[1] and C.V. Guidotti[2]

ABSTRACT

The Precambrian terrane of the southern Lake Superior region records a long and complex geologic history. The oldest rock in the region was formed around 3.8 to 3.6 Ga and repeated tectonic, igneous, and metamorphic activity continued throughout the Precambrian until about 1.1 Ga.

Two contrasting Archean-aged geologic terranes are present. The first is an older southern gneiss terrane, parts of which were produced at least 3.8 to 3.6 Ga. This terrane experienced regional metamorphic activity at approximately 3.1, 2.6, 1.8, and 1.6 Ga. To the north, a granite-greenstone terrane which constitutes the second and younger group of Archean rock was formed 2.75 to 2.6 Ga. Archean metamorphism(s) in the gneiss terrane was relatively high-grade (P = 5-6 Kb, T = 650-800 °C), with some localized areas reaching the granulite facies. In contrast, regional metamorphism in the greenstone belts of the granite-greenstone terrane was low grade ($P \leq 3$ Kb, $T < 450$ °C). Late Archean metamorphism in the southern gneiss terrane may be related to a collision event with the more northern granite-greenstone terrane.

Early Proterozoic sedimentation, volcanism, and plutonism were extensive throughout much of the southern Lake Superior region, especially in Wisconsin. Metamorphism associated with the Penokean orogeny of 1.90 - 1.80 Ga was widespread and occurred mainly in the low-pressure to intermediate- to low- pressure ($P < 4$ Kb) facies series, except for a possible belt of intermediate-pressure facies series ($P \sim 7.5$ Kb) kyanite schist in northern Wisconsin. The highest grade attained was the lower sillimanite zone, but much of the metamorphism reached only into the greenschist facies. Metamorphism at this time was concurrent with or preceded slightly the major deformational activity. At least two major phases of deformation can be recognized throughout the Lake Superior area. It is proposed that the metamorphism accompanying the Penokean orogeny can be interpreted in a plate-tectonic context. Medium-pressure kyanite schist in northern Wisconsin may represent a suture or mark the site of crustal collision.

Post-Penokean metamorphism around 1.63 Ga also appears to be widespread, but is of low grade. Interpretation of the 1.63 Ga metamorphism is complicated by the intrusion of the Wolf River Batholith and related rock (1.5 - 1.45 Ga), which possibly produced widespread contact-like metamorphism in central and southern Wisconsin. The tectonic interpretation of the 1.63 Ga event is uncertain and widely debated at the present time.

A possible, but presently unconfirmed pre-Penokean metamorphism around 2.4 - 2.1 Ga is also obscured and complicated by younger tectonic and metamorphic events.

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INTRODUCTION

The Precambrian terrane of the southern Lake Superior region of Minnesota, Wisconsin, and Upper Michigan has experienced a protracted geologic history. The crust in this region contains some of the few truly ancient rock presently exposed at the Earth's surface. Multiple orogenic and anorogenic events have formed and shaped the present crustal structure and have formed the various types of basement rock found in the region. As in all ancient terranes, determining the effects of metamorphism is especially important for understanding the geologic history.

A regional geothermometric and geobarometric study of metamorphic rock in the southern Lake Superior area will aid in constructing, as well as constraining, tectonic models for the Precambrian Era in this area. Rock to the east in Canada that has experienced many of the same geologic events as those in the Lake Superior region will be excluded. Finally, tectonic models that are consistent with the petrologic and geologic data are discussed. This P-T synthesis is the first attempt at constructing a rigorous, regional P and T overview, and our geologic conclusions should be considered as working models. Published data on the chemistry of minerals are sparse to nonexistent, so most pressure and temperature estimates will be based on metapelitic index-minerals, along with consideration of well known discontinuous mineral-reaction and stability curves. Published P and T estimates are also incorporated. Although intermediate-facies-series amphibolite and greenschist are ubiquitous throughout this area, it is more difficult to quantitatively estimate P and T of metamorphism for such bulk compositions and they will largely be excluded in this paper.

REGIONAL SETTING

The Precambrian basement of the southern Lake Superior region consists of both Archean and Proterozoic rock. Much of it, termed the Southern Province (fig. 1), is actually the southernmost extension of the vast Precambrian area to the north that makes up the North American Shield. This province is bounded on the north by the large Superior province and covered in the west and south by Paleozoic and Mesozoic rock. Geochronologic studies allow qualitative correlation of some rock of the Southern Province with Archean rock in Wyoming and Montana. Much of the early radiometric geochronologic work in North America was done by geochemists working in the Lake Superior region (Goldich, 1972). Because of the lack of good exposure, Precambrian rock is found only as inliers surrounded and partially covered by Phanerozoic rock and thick deposits of Pleistocene glacial material. Hence, direct geologic mapping is difficult and subject to considerable differences in interpretation. Geologic reviews regarding the Archean and Early Proterozoic of the Great Lakes region have been collated by Morey and Hanson (1980) and Medaris (1983), respectively. The papers, therein, form the basic historic framework within which the metamorphism will be interpreted. Review and synthesis of these papers suggests that the following geologic events appear to (or possibly could) involve major region-wide metamorphism in the Lake Superior Region.

(1) 3.8-3.5 Ga Mortonian orogeny related to the early formation of sialic and now largely gneissic crust. Any possible metamorphism associated with this event cannot be recognized at the present time because of younger, strong overprinting events.

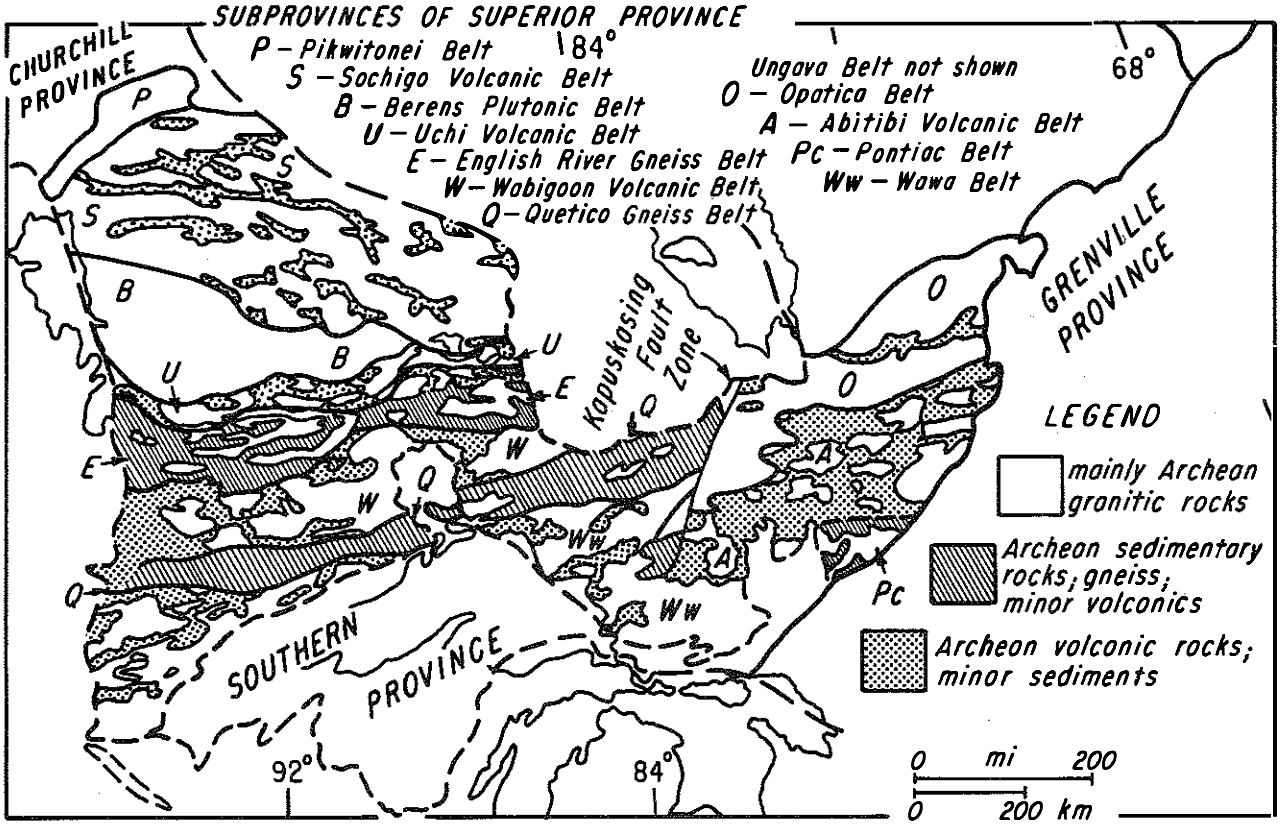

Figure 1. Location of the Southern Province relative to the distribution of Archean subprovinces of the Superior Province. The Southern Province is contiguous but separated from the Superior province. The area in Canada is not described in detail in the text (from Goodwin, 1977).

(2) 3.0–2.6 Ga a late Archean event termed the Kenoran or Algoman orogeny (2.75–2.6 Ga). This interval may be marked by two metamorphisms, at least in Minnesota.

(3) 2.4–2.1 Ga unnamed, poorly understood early Proterozoic event. Any metamorphism(s) associated with this period has yet to be geologically or petrologically demonstrated.

(4) 1.90–1.8 Ga the Penokean orogeny. The most significant Proterozoic tectonic event.

(5) 1.63 Ga—an unnamed event; part of the Baraboo interval.

(6) 1.5-1.45 Ga--an anorogenic event producing the Wolf River Batholith and related rock.

(7) 1.1 Ga--Keweenawan rifting event. Metamorphism at this time was not regionally extensive as only the Keweenawan basin and immediate rock were affected.

DATA AND RESULTS

Archean Metamorphism

Much of the granite-greenstone terrane (Sims, 1976) of the North American shield and the Lake Superior region (figs. 1 and 2) formed 2.75-2.60 Ga, thereby producing a relatively thick, stable, areally extensive and permanent continental crust. The metamorphism within the U.S. part of this granite-greenstone terrane has received relatively little study and few P and T data are available. The sedimentary and volcanic rock of the greenstone belts are relatively low grade (greenschist facies), except where they border on the associated gneissic or granitic units; there the grade locally increases up to the amphibolite facies (Morey, 1978). At best, metamorphic analogies can be drawn from studies in the Superior Province. Jolly's (1974) examination of the metamorphic zonation of a part of the Abitibi greenstone belt of the eastern Superior Province (fig. 1) identified an initial region-wide prehnite-pumpellyite facies metamorphism. Jolly suggested a model of simple burial metamorphism to account for the metamorphism of these volcanic piles. Therefore, pressure of metamorphism was probably relatively low, with $P < 4$ Kb. Although compressional features can be observed, the preservation of original volcanic textures suggests that penetrative deformation and recrystallization were not intense. Tectonically late intrusives of associated granitic or gneissic rock produced albite-epidote-actinolite and hornblende-almandine aureoles in the supracrustal rock.

Studemeister (1983) estimated T = 325-450 °C and P = 2-3 Kb for a regional metamorphic event which affected both supracrustal sedimentary and volcanic rock, along with a previously intruded stock for a small part of the Wawa greenstone belt (fig. 1). These estimates were based on the mineral assemblage chlorite-actinolite-epidote-albite in mafic metavolcanics and the FeS contents of sphalerite where buffered by pyrite and pyrrhotite. These conditions are also likely to be similar for the greenstone belts of the southern Lake Superior area. For the most part it appears that this terrane was not strongly affected by younger tectonic, metamorphic, or deformational events (Sims, 1976).

Rock of the gneissic subprovinces or granite-migmatite massifs within Sim's (1976) granite-greenstone terrane (Southwick, 1972) display higher grades of metamorphism. The only data available for this rock in the U.S. are for the Vermilion granite-migmatite massif of northeast Minnesota (fig. 1), where Southwick (1976 and in Morey, 1978) has described sillimanite, cordierite, staurolite, garnet and sapphirine. He estimated T = 600-700 °C and P = 3-5 Kb for this rock.

In Minnesota an older Archean gneiss terrane to the south of the granite-greenstone terrane (Sims 1976) has received more detailed study. The type rock of this terrane is located in the Minnesota River Valley, where true

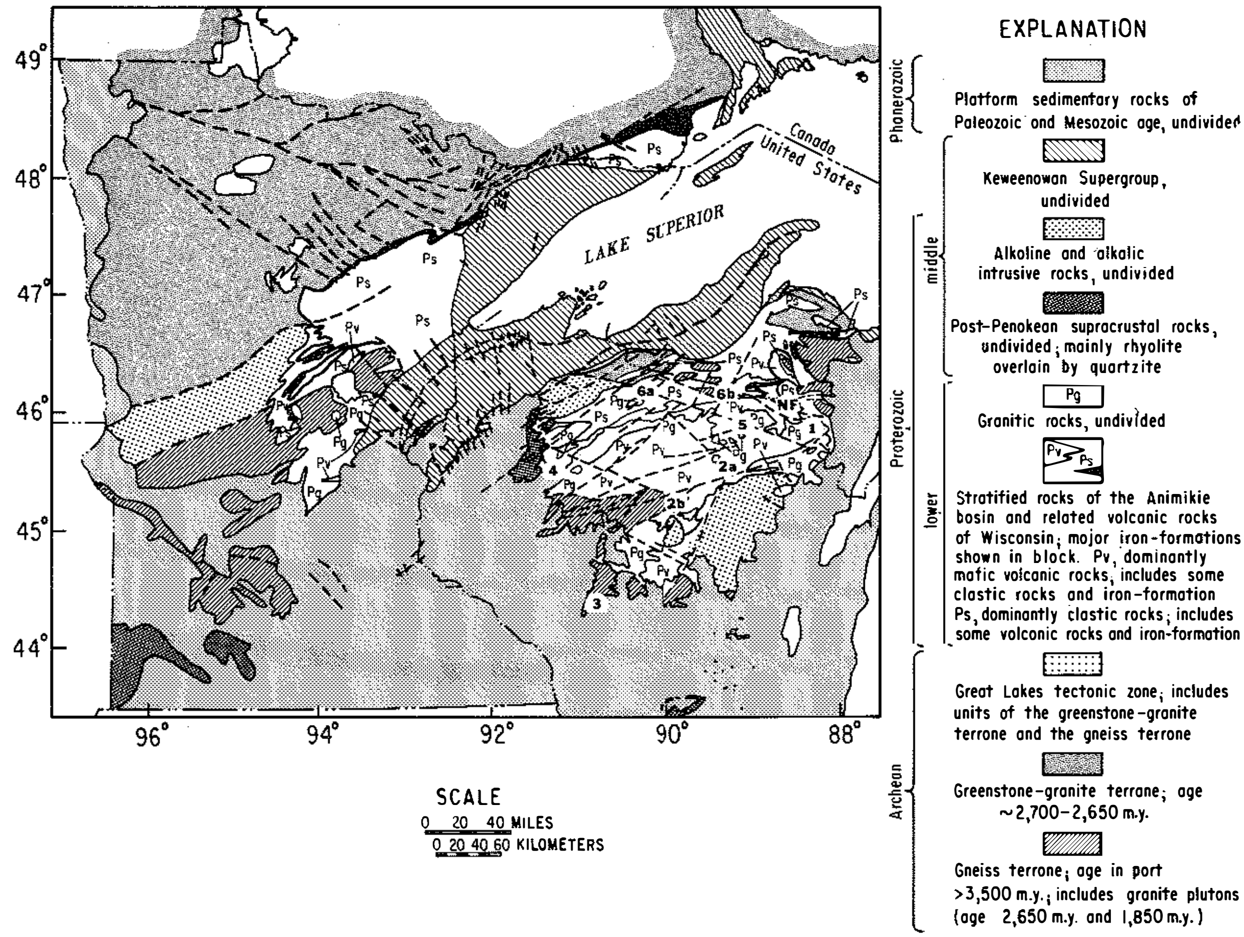

Figure 2. Detailed Geologic map of the Southern Province of the Lake Superior region. Compare with figure 1. Numbers refer to metamorphic localities described in text. NF stands for the Niagara Fault (from Morey, 1983)

orthopyroxene granulites, hornblende amphibolite, and migmatite are present (Himmelberg, 1968). Here the exact timing of metamorphism is not agreed upon. Bauer (1980) concluded from a structural study that metamorphism occurred over a long interval between 3.05 Ga and 2.65 Ga; the mineral textures suggest no discernible hiatus. Goldich and Wooden (1980), however, have interpreted the geochronologic data as indicating that two district high-grade metamorphic events occurred, at least in the Morton area, at 3.05 Ga and 2.6 Ga. Thus, there is some uncertainty regarding the exact timing of metamorphism. The possibility of Archean polymetamorphism should be considered. Later Penokean igneous intrusions around 1.8 Ga probably imprinted some metamorphic signature on the Archean metamorphic rock (Himmelberg, 1968). Himmelberg and Phinney (1967) and Himmelberg (1968), in the most complete metamorphic study of the Minnesota River Valley, could find no large-scale metamorphic zonation nor did they map any isograds. Presumably, all the different lithologies formed under similar P and T conditions, with differences in the degree of hydration of mineral assemblages controlled by differences in the activity of H_2O. A wide variety of mineral assemblages (see Morey, 1978) which can provide estimates of P and T are present. Grant and Weiblen (1971) present a garnet-biotite K_D of 0.22-0.23 taken from the central region near Dehli. Garnet-biotite thermometry (Thompson, 1976; Holdaway and Lee, 1977; Ferry and Spear, 1978) gives a range of T = 635-680 °C, assuming P = 6.0 Kb. We also calculated a maximum pressure from the same area using the cordierite-garnet-quartz- Al_2SiO_5 barometer of Newton and Wood (1979). The mineralogic assemblage reported by Grant and Weiblen lacked an Al_2SiO_5 phase, so estimated pressures of P_{dry} = 4.8 Kb or P_{H_2O} = 6.0 Kb are maxima. The latter is probably a better estimate for these hydrous metapelites.

The presence of sillimanite, muscovite and quartz indicates that the Minnesota River Valley is not a high-P granulite terrane. P must be less than 7.0 Kb at T < 650 °C (fig. 3).

Leier and Perkins (1982) have presented P and T estimates for much of the Minnesota River Valley. Garnet-biotite temperatures from a variety of localities fall within a narrow range of 640-670 °C. Two-feldspar temperatures show considerable scatter ranging from 730-720 °C down to 450 °C. The latter was attributed to resetting during the 1.8 Ga Penokean event. Pressure estimates are relatively uniform ranging from 5 to 7 Kb and averaging about 6 Kb, and they show no depth progression along the valley. Previously, Goldich and others (1980) speculated that rock in the northwest part of the Minnesota River Valley were buried to greater depths than those to the southeast. Moecher and Medaris (1984) have also presented P and T estimates for granulite at Granite Falls. Their P estimates of 4.7 to 5.3 Kb are a little lower than those of Leier and Perkins (1982). T was estimated at 665 °C using garnet-clinopyroxene (Ellis and Green, 1979) and magnetite-ilmenite (Spencer and Lindsley, 1981) thermometry. Orthopyroxene-clinopyroxene thermometry (Lindsley, 1983), using clinopyroxene compositions, gave 675 °C.

Temperature estimates by Dacre and others (1984) for the Sartell Gneiss of east-central Minnesota, where garnet-cordierite gneiss is found, were based on Fe-Mg partitioning between garnet and biotite and garnet and cordierite (Thompson, 1976; Hensen and Green, 1973). Some inconsistencies were noted, such as between the garnet-biotite thermometers, with 805 °C being the best overall estimate. Pressure was estimated at 5.1 Kb using Hensen and Green's (1973) garnet-cordierite-orthopyroxene-quartz barometer. This is consistent with the rather iron-rich nature of the cordierite (Mg/Mg+Fe = .58) found in the gneiss.

Rigorous temperature and pressure estimates for the 3.0-2.6 Ga event(s) in Wisconsin and Michigan are lacking. Migmatite from Linwood Township, Wood County, Wisconsin, were estimated to have formed at 5 to 6 Kb water pressure using melt compositions projected onto the granite ternary Or-Ab-Qtz (Van Schmus and Anderson, 1977). The Granitic melts were thought to be injected from a local source. Reasonable inferred temperatures for melting of these compositions at P_{H_2O} = 6 Kb, are T = 700 °C $\pm$ 50 °C. Although diagnostic index-mineral assemblages and pelitic lithologies, specifically, are lacking, Morey (1978) grouped the Archean gneiss terrane of central Wisconsin into the upper amphibolite-granulite facies. However, there has been little to no orthopyroxene reported from either Michigan or Wisconsin. Garnet-bearing gneiss is also relatively uncommon. We prefer to regard this rock as belonging to the upper amphibolite facies.

Retrograde metamorphic features or younger overprinting of additional as-

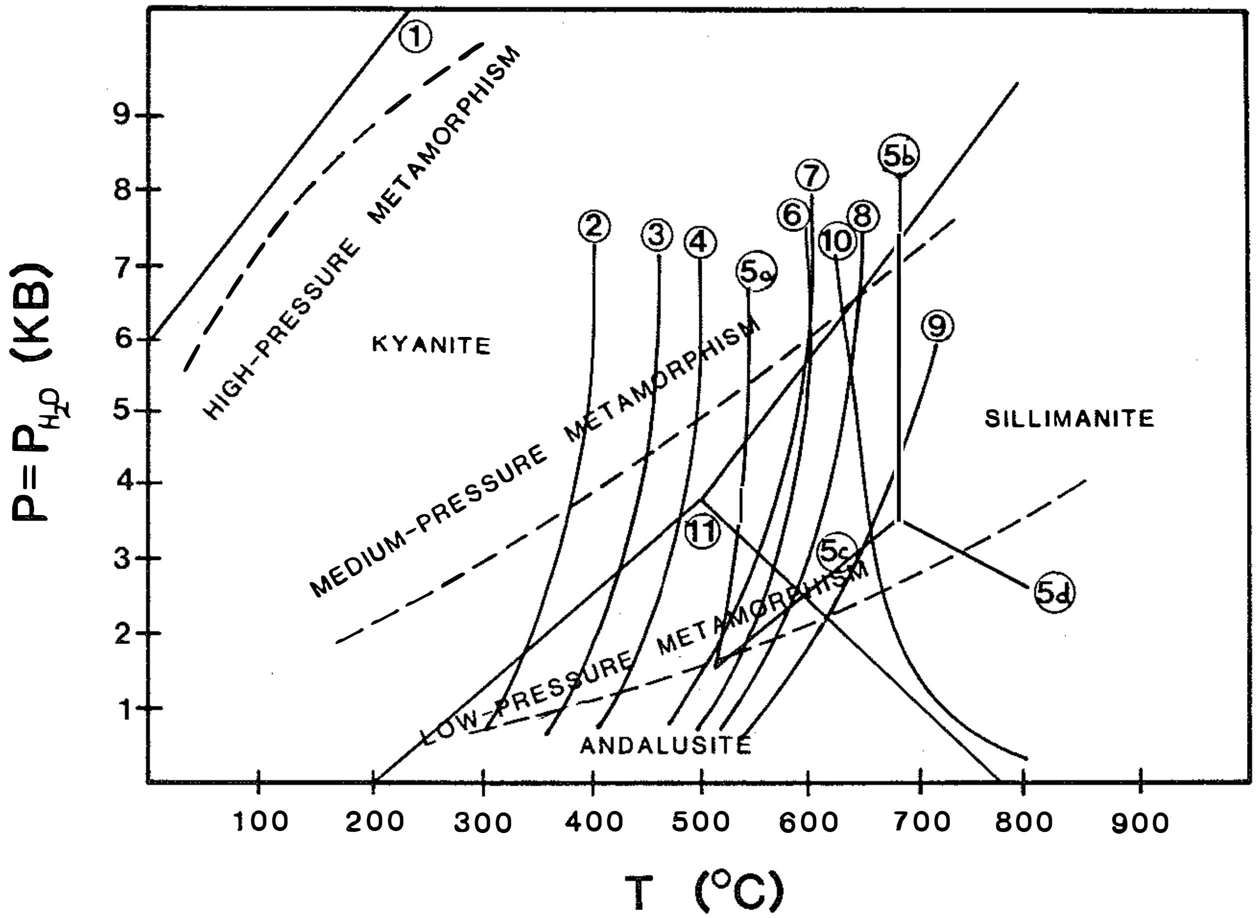

Figure 3. Petrogenetic grid showing relevant mineral equilibria and reaction curves of interest. See text for details. The three metamorphic facies series depicted are from Miyashiro (1973) and the reaction curves are: (1) Albite = jadeite + quartz (Holland, 1980); (2) Kaolinite + quartz = pyrophyllite + H_2O (Thompson, 1970); (3) Pyrophyllite = Al_2SiO_5 + quartz + H_2O (Kerrick, 1968); (4) Garnet + chlorite + muscovite = biotite + staurolite + H_2O (Guidotti, 1974); (5a) Fe-chloritoid + Al_2SiO_5 = staurolite + quartz + H_2O; (5b) Staurolite + quartz = almandine + sillimanite + H_2O; (5c) Staurolite + quartz = cordierite + H_2O; (d) Cordierite = almandine + sillimanite + quartz + H_2O (Richardson, 1968–5a–5d); (6) Paragonite + quartz = Al_2SiO_5 + albite + H_2O (Chatterjee, 1972); (7) Staurolite + chlorite + muscovite = Al_2SiO_5 + biotite + quartz + H_2O (Guidotti, 1974); (8) Staurolite + muscovite = Al_2SiO_5 + biotite + garnet + H_2O (Hoschek, 1969); (9) Muscovite + quartz = sanidine + Al_2SiO_5 + H_2O (Chatterjee and Johannes, 1974); (10) Albite + orthoclase + quartz + H_2O = melt (Luth and others, 1964); (11) Al_2SiO_5 phase diagram of Holdaway (1971).

semblages are found in many of the Archean units discussed above, but the exact timing and grade of the retrograde effects or polymetamorphism is not known.

Early Proterozoic Metamorphism

Morey (1978), Van Schmus (1976) and LaBerge and Myers (1984) have argued for a period of metamorphism at restricted localities between 2.4 - 2.1 Ga. These proposals were based on age determinations and field relationships; however, they have only been advanced in areas where the effect of the younger Penokean orogeny have obliterated many older geologic features and thus complicated the metamorphic aspect of the rock. Because conclusive petrologic evidence does not, as yet, exist, any possible metamorphism around 2.4 - 2.1 Ga will not be discussed here.

Much of the metamorphism and deformation now observed in the Southern Province is due to the Penokean orogeny, a period of major regional metamorphism in the Proterozoic (1.90-1.80 Ga; Van Schmus, 1976). Some workers have concluded that the metamorphism was rather uniformly low grade, but data presented below show this is not the case. Generally, this regional metamorphism appears to range from greenschist to upper-amphibolite facies conditions. The intensity or grade does tend to decrease to the north (Morey, 1978), where weakly metamorphosed Animikean strata rest upon the Archean granite-greenstone terrane. The Gunflint Iron-formation of Animikean age in extreme northeast Minnesota and Canada is hardly metamorphosed (Morey, 1978); the Gogebic Range, located in Wisconsin about 40 km north of locality 6a (fig. 2), displays low-grade assemblages and shows little Penokean deformation.

Although much of the Penokean metamorphism in northern Michigan and northernmost Wisconsin is low to medium grade on a regional basis, James (1955) defined certain areas of higher grade nodes (fig. 4). In the two northeastern most nodes (Republic and Peavy), the metamorphic grade progresses from the chlorite zone up into the sillimanite zone (fig. 4). Recent metamorphic studies both in the Republic and Peavy Node by Haase (1982), Attoh (1976), Attoh and Vander Meulen (1984) have confirmed James' original isograds. The Watersmeet node as originally mapped by James only reached the garnet zone; however, Black (1977) found staurolite, kyanite and some sillimanite in the central core.

The mineral assemblages and compositions given by James (1955) and Haase (1982) for the Republic Node restrict T to 500-525 °C for the staurolite zone and 550-615 °C for the sillimanite zone at P~2.0-3.8 Kb (table 2). The high-grade silicate mineral assemblages, when combined with the oxygen isotope data of James and Clayton (1962), give a reasonable metamorphic temperature profile starting with T~325 °C in the chlorite zone and increasing up to 615 °C in the sillimanite zone (table 1).

The second major Penokean metamorphic node in Michigan is to the south near Peavy Pond (fig. 4) and is similar to that at Republic with respect to the grades of metamorphism, except the thermal gradient is steeper on the west side of the node (fig. 4). At Peavy Pond the sillimanite zone is centered around a gabbroic-diorite intrusion of early Penokean age--1.90 Ga (Bayley, 1959; Banks and Van Schmus, 1971). Attoh and Vander Meulen (1984) used a geobarometer based on the assemblage sillimanite-garnet-plagioclase-quartz to calculate P = 4.6 Kb for the sillimanite zone, and used garnet-biotite thermometry to calculate T = 592 °C. They estimated 545-582 °C for the staurolite zone and 485-557 °C for garnet zone metapelitic rock. Heat flow calculations indicate that the diorite intrusion, alone, could not account for these elevated temperatures and proposed that an external temperature gradient was required. Bayley (1959) has shown that the mafic igneous intrusions are themselves metamorphosed (that is predated metamorphism).

Table 1. Estimate of temperatures from metamorphic zones around the Republic node, Michigan.

Zone	Chlorite		Biotite	Garnet		Staurolite			Sillimanite	
sample no.	3	4	5	7	8	10	11	12	16	18
$\delta^{18}O$ qtz	16.5	18.0	15.9	15.2	13.3	11.5	11.2	13.8	10.4	8.7
$\delta^{18}O$ mag	-1.4	3.9	3.9	4.3	2.5	-0.9	-0.1	2.4	-0.1	-0.5
Δqtz-mag	17.9	14.1	12.0	10.9	10.8	12.4	11.3	11.4	10.5	9.2
T°C[1]	150	205	245	270	270	235	260	260	280	320
T°C[2]	255	325	385	425	430	380	410	410	435	495
T°C[3]						500	-	525	550	615

[1] James and Clayton (1962)

[2] recalculated using fractionation curve of Becker and Clayton (1976) precision $\pm$ 10-15 °C

[3] Haase (1982)

Relatively low-pressure metamorphism also characterizes most of the Penokean igneous belt in Wisconsin. Andalusite is the dominant Al_2SiO_5 polymorph. Cummings (1978) made a regional geologic study in northeast Wisconsin with emphasis on the metamorphism and mineralization effecting the volcanic Quinnesec formation, locality 1, figure 2. This formation consists predominantly of intermediate to mafic volcanic flows and tuffs with interspersed and localized felsic domes. Banks and Rebello (1969) obtained U-Pb ages of 1905 $\pm$ 30 Ma on zircon taken from a felsic unit. Throughout the area several large Penokean intrusives crosscut the volcanics and these have been dated in the general range 1.88 to 1.81 Ga. Cummings reports T = 500-540 °C and P = 1.5-3.5 Kb based upon the assemblage andalusite (partially pseudomorphed)-muscovite-chlorite- quartz taken from a tuffaceous unit and garnet- biotite K_D data obtained in other units.

We have undertaken a reconnaissance petrographic study of metapelitic schists sampled just west of the town of Merrill and near Kempster (fig 2., locs 2a, b). Table 2 lists the relevant assemblages. At location 2a there is

Table 2. Critical mineral assemblages in the metamorphic nodes.

Metamorphic zone or locality	Critical P-T phases or assemblages	T	p
Sillimanite Zone at Republic	Andalusite Sillimanite andalusite-fibrolite	---	<3.8 Kb
	Garnet-biotite K_D's	550-615 °C	---
	Quartz-muscovite-andalusite-sillimanite-plagioclase-biotite-magnetite	550-610 °C	2.2-3.8 Kb
Staurolite Zone at Republic	Staurolite-quartz	500-525 °C	>1.5-2.0 Kb
	Chloritoid-quartz	<550	---
	Andalusite-quartz-chloritoid	<550	<3.8 Kb
	Andalusite-muscovite-quartz ± paragonite	<500	<3.8 Kb
2a + 2b - WI	Quartz-andalusite-biotite-staurolite-muscovite-plagioclase-chlorite	525-575 °C	1.5-3.8 Kb
2a - WI	Quartz-staurolite-garnet-biotite-chlorite-plagioclase-muscovite	525-575 °C	1.5-3.8 Kb
2b - WI	Quartz-andalusite-chlorite-plagioclase-biotite-muscovite-± garnet	---	<3.8 Kb
3 - WI	Quartz-chlorite-muscovite-andalusite	---	<3.8 Kb
	Quartz-biotite-chlorite-staurolite-garnet-andalusite-muscovite	500-575 °C	1.5-3.8 Kb
	Quartz-biotite-plagioclase-muscovite	---	---

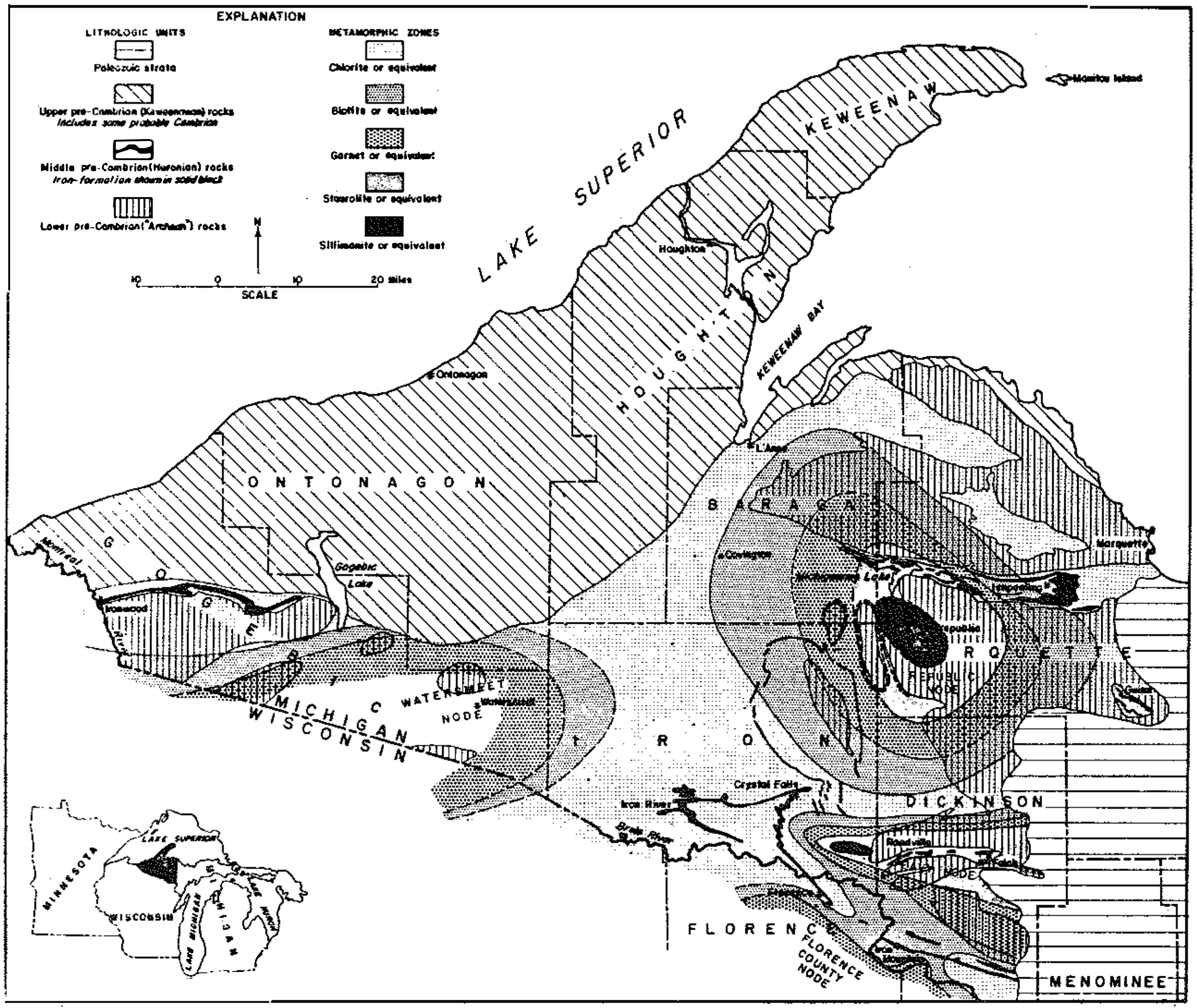

Figure 4. Generalized geologic and metamorphic zonation map of northern Michigan. Note the 4 metamorphic nodes. The Watersmeet node can be extended westward into Wisconsin with inner staurolite and kyanite ($\pm$ sillimanite) zones, but they are not depicted here (James, 1955).

petrographic evidence of chlorite overprinting the major foliation and also partially replacing staurolite. Nonetheless, assuming chlorite is an equilibrium phase, then use of various stability curves restricts P = 1.5-3.8 Kb and T = 525-575 °C (table 2 and fig. 3). This is a slightly higher temperature than that at locality 1, and is consistent with the presence of staurolite. In the Quinnesec area the garnet-chlorite tie-line probably was not broken, thereby precluding the reaction garnet + chlorite + muscovite = staurolite + biotite + quartz + H_2O. According to Guidotti (1974) this occurs around 500 °C at P = 3 Kb (fig. 3).

Assemblages at 2a and 2b may involve 4-phase AFM fields and one may question whether garnet is stabilized by CaO or MnO or both, and whether chlorite is in equilibrium with the other phases. Nevertheless, the P-T estimates for both localities are similar and it is quite probable that they represent the same lithology which was subjected to similar metamorphic conditions (table 2). The hand samples from both localities are remarkably similar. Weidman

(1907) mapped a graywacke schist, containing andalusite, in the Merrill area which he termed the Hamburg slate. The metapelites at 2a and 2b are probably from this unit. Direct dating of the Hamburg slate by Rb-Sr mineral isochrons (biotite and muscovite) has given ages of 1.80, 1.60, 1.51 Ga and a couple of anomalous younger ages (Aldrich and others, 1959; in Dutton and Bradley, 1970). We interpret the 1.80 Ga date to represent Penokean regional metamorphism. The 1.60 Ga date may represent regional low-grade metamorphism around 1.63 Ga to be discussed later, and the 1.51 Ga age may represent partial resetting by the Wolf River Complex which is nearby to the east (fig. 2). Greenberg and Brown (1983) have proposed, alternatively, that these assemblages are not Penokean metamorphics, but contact related phenomenon formed by intrusion of the Wolf River Batholith.

Locality 3 is located just east of Black River Falls, within the Jackson County iron mine. The iron mine is situated within the central Archean province of Wisconsin (fig. 2). However, this area has been intruded with Penokean-age plutons (Maass, 1983), and we conclude that the major metamorphism of this area may be Penokean in age. Table 2 lists the metapelitic assemblages from rock surrounding the iron-formation, which based on petrographic evidence, underwent two discrete metamorphisms (Jones, 1978). The first involved isoclinal folding and produced the assemblages listed in table 2 above and corresponded to the amphibolite facies, with T = 500-575 °C and P $\leq$ 3.0 Kb. The second metamorphism was not accompanied by any penetrative deformation. It was a separate event and not merely a retrogression of the first and strongest metamorphism. During this second metamorphism, andalusite was unstable as petrographic features indicated that the retrograde reaction biotite + andalusite + H_2O = chlorite + staurolite occurred, and Jones (1978) suggested that equilibrium was attained in this second metamorphism at conditions of the medium to upper greenschist facies. Garnet-biotite thermometry gives temperatures in the range 360-425 °C, with one pair giving an anomalously low T of 260 °C. Therefore garnet and biotite reequilibrated to the last metamorphic event.

May (1976) has described various stratigraphic units sampled from diamond-drill cores taken in an investigation of massive sulfide mineralization in Ladysmith area, locality 4, figure 2. Nearly all the stratigraphic units are steeply dipping and are described as various kinds of metavolcanic tuff. Several mineral assemblages in more Al-rich bulk compositions permit estimates of P and T. The two most diagnostic assemblages are quartz-biotite-chlorite- garnet and andalusite-biotite-chlorite $\pm$ quartz and sericite. Andalusite displays extensive alteration, but its presence restricts P to $\leq$ 3.8 Kb. T was less than 600 °C and it is probable that for these pelitic compositions the garnet-chlorite tie-line was broken, forming andalusite + biotite at T $\geq$ 500 °C (Guidotti, 1974). Penokean intrusives are located just south of Ladysmith and we infer the metamorphism in this area also to be Penokean in age.

The Pelican River deposit of age 1.83 Ga (Wiggins and Brett, 1977) is another early Proterozoic massive sulfide ore-body similar to that at Ladysmith, locality 5, figure 2. Wiggins and Brett (1977) estimated P = 4.6 Kb using the sphalerite geobarometer of Scott (1976), and T = 550-600 °C based upon the assemblage anthophyllite-quartz-Mg chlorite-muscovite. Anthophyllite was originally identified as sillimanite, but this identification was corrected when the abstract was presented.

In summary, it appears that the P of metamorphism of localities 1 through 5 is bracketed between 4.6 and 1.5 Kb (the lower limit is arbitrarily chosen based on the general appearance of this regionally metamorphosed rock) and averaging somewhere around 3 Kb. T is restricted between 500-600 °C. This metamorphism can be classified as andalusite-sillimanite type (Miyashiro, 1973 - fig. 3). Metamorphism appears to be Penokean in age, and all these localities are found within the Penokean igneous fold-belt.

The last Penokean-aged localities to be described in Wisconsin are labeled 6a and 6b (fig. 2). They represent the highest-grade metapelitic rock in the Lake Superior region and are contained within the Animikean basin (fig. 2). Rb-Sr whole-rock dates on this metasedimentary rock give a Penokean age of 1.82 Ga (Sims and others, 1984). Locality 6a near Lac du Flambeau has been described by Black (1977) and is the central part of James' Watersmeet node, if the original metamorphic zones are extended westward from Michigan (fig. 4).

Black described two different lithologic sequences at locality 6a of steeply dipping metamorphic rock that are separated by a large west northwest - east southeast striking fault. Rock to the south of this fault constitutes a southern gneiss sequence and are characterized by biotite gneiss, amphibolite, and kyanite-staurolite metapelite. Rock north of the fault is termed the northern greenstone sequence and consists of pillowed greenstone, mafic metavolcanic, slate, and iron- formation.

Near Lac du Flambeau (6a), the assemblages in the high-grade southern sequence include gedrite-plagioclase-quartz-biotite-staurolite in amphibolites, and plagioclase-quartz-biotite-kyanite-garnet-staurolite-muscovite-graphite-pyrrotite $\pm$ sillimanite in high-grade metapelites. Migmatite is associated with the sillimanite-bearing metapelite localities. The co-existence of kyanite and sillimanite in some metapelites and several relevant mineral stability curves gives P = 7.5 Kb and T = 685 °C, Black (1977). Black's compositional data for co-existing garnet, biotite, and plagioclase allow P and T to be calculated using various geothermobarometers. Garnet-biotite temperatures range from 630-680 °C using garnet core compositions and the calibrations of Ferry and Spear (1978) and Thompson (1976). Using the garnet = plagioclase + Al_2SiO_5 + quartz barometer of Perchuck and others (1981), two different pressures were obtained. At one locality the staurolite-kyanite schist gave P = 8.3 $\pm$1 Kb (T = 675 °C) to P = 7.8 (T = 650 °C), and at the other locality they gave P = 6.85 $\pm$1 Kb (T = 675 °C) to P = 6.45 Kb (T = 650 °C). As two different outcrops are involved, there is a possibility that they may have equilibrated at slightly different pressures. But considering the uncertainties, the preferred average value is P = 7.5 Kb and this compares well with that obtained from relevant P-T curves (fig. 3).

On the north side of the fault, the sequence displays a much lower grade of metamorphism, for example, original sedimentary and volcanogenic structures are still present, thereby attesting to the lesser degree of deformation and recrystallization that affected this rock. Here rigorous P and T estimates are not possible, but based upon the mineralogic assemblages, Black (1977) concluded that metamorphism took place in the lower amphibolite facies at low to moderate pressures.

Kyanite-staurolite schist has also been reported in drill core (Allen and Barrett, 1915) 80 km east of Flambeau near Lac Vieux Desert (locality 6b). Hence, the southern lithologic sequence may delineate a 100 km long belt of high-grade metamorphism stretching from Lac du Flambeau (6a) to Lac Vieux Desert (6b). This belt appears narrow, as similar high-grade rock is not found far north or south of this east-west trending sequence. Lack of good exposure in the middle section of this belt precludes a confirmation of this hypothesis. Nonetheless, one can at least consider the possibility of a kyanite-sillimanite type of metamorphism (fig. 3) extending from 6a to 6b.

The effects of Penokean metamorphism are poorly understood in Minnesota. A large area west of Duluth has exposures of Animikean metasedimentary rock that was deformed in the Penokean orogeny (fig. 2). Morey (1978) has listed various mineral assemblages from this area and none contain an Al_2SiO_5 polymorph. This may be a bulk-composition effect (not aluminous enough), but it is more probably related to the grade of metamorphism. The absence of Al_2SiO_5 phases suggests that the chlorite-garnet pair remained stable for average pelitic bulk-compositions. This reaction curve is located at T = 500 °C at P = 4.5 Kb (Guidotti, 1974, fig. 3). Indeed, Morey (1978) has mapped much of this area as belonging to the subgreenschist (mainly in the north) and greenschist facies. The metamorphic grade does increase towards the south near the first appearance of Penokean granitic rock. Here biotite, garnet, and staurolite isograds occur as concentric rings around a Penokean intrusive complex (Morey, 1978). The presence of staurolite restricts T to about 550 ± 50 °C and P > 2 Kb (fig. 3). Labotka and others (1980) have suggested T = 450 °C to 485 °C and P = 6.0 ± 0.3 Kb (garnet + biotite + muscovite + plagioclase) for an unspecified part of the Animikean Thompson formation. If their P estimate is correct, rock in Minnesota may have been metamorphosed to higher pressures than the majority of those in Wisconsin and Michigan, which contain andalusite and sillimanite.

Despite the limitation of data in some areas, the following statements can be made about Penokean metamorphism.

(a) Except for the kyanite schist belt between (6a) and (6b), and possibly the area considered in Labotka and others (1980), all of it occurred in the general P range of 3 ± 1 Kb, that is, andalusite-sillimanite type. Between (6a) and (6b) the P was higher (7.5 ± Kb, kyanite-sillimanite type).

(b) In no cases does it seem that the metamorphic conditions exceeded the upper stability limit of staurolite. The highest grade attained was the lower sillimanite zone as defined in Guidotti (1974).

(c) The overall metamorphic grade in the Penokean magmatic belt is of the amphibolite facies, but greenschist facies rock is typically observed in Animikean metasedimentary rock in Michigan and Minnesota.

(d) From (a) and (b) it is clear that the general metamorphic style of the Penokean event is similar to that formed during the Acadian metamorphism of New England (Thompson and Norton, 1968). This would include being associated with fairly extensive plutonism and some kind of plate tectonic activity.

Penokean Deformation - Thermal-Time Relations

Penokean structural-deformational studies have been undertaken in a number of localized areas, but no synthesis has been attempted for the entire Lake Superior region. From the available data there does appear to be fairly good agreement in recognizing the relationships between the regional deformational events and metamorphism. In general, as discussed below for specific areas, it appears that metamorphism during the Penokean orogeny occurred concurrently or preceded slightly the major structural deformation(s).

Several structural studies have been undertaken on Animikean strata and Archean basement in northern Michigan that were deformed during the Penokean orogeny (Klasner, 1978; Powell, 1972; James, 1955; Kappmeyer and Wiltschko, 1984). The earlier studies (Powell, 1972 and James, 1955) suggested that Penokean metamorphism almost completely postdated deformation, but Klasner (1978) and Kappmeyer and Wiltschko (1984) have argued against this. Klasner recognized four phases of structural deformation (F_1, F_1', F_2, F_3), but with F_1 and F_1' related to a single long lived deformational event, where F_1 represented an initial phase and F_1' a renewed or continued pulse of F_1 deformation. Thermal activity started before F_1 and peaked around F_2. Hence, mineral growth was concurrent with the major deformation. F_1 produced a strong, regional foliation, S_1. F_2 and F_3 were thought to be related to late uplift of large underlying blocks of Archean basement. Some deformation did postdate metamorphic recrystallization (Klasner, 1978; Kappmeyer and Wiltschko, 1984).

In north-central Wisconsin detailed deformational-time studies have been made by Maass and others (1980) and Maass (1983). The former study documented two ages of Penokean intrusive granitic rock in central Wisconsin (about 80 km east of locality 3)--1.84 Ga foliated tonalite and 1.82 Ga lineated tonalite. Three folding events were recognized in this area (F_1, F_2, F_3). The latter study concentrated on Penokean rock located in the same area and others farther north and west of the previous study area. Here three folding events (F_1, F_2, F_3) were again recognized. F_1 was characterized by steeply dipping isoclinal folds, thus attesting to "substantial horizontal compression" (Maass, 1983). Metamorphism was generally concurrent with the major structural deformation and both metamorphosed synkinematic and undeformed post-kinematic Penokean granitic rock was recognized. Synkinematic plutons were generally emplaced late during F_1.

In northeastern Wisconsin the areally extensive Dunbar Gneiss has been well studied structurally (Sims and others, 1985). This felsic, but lithologically diverse, domal body has been suggested to be a large-scale fold-interference structure formed through polydeformation and diapirism (Sims and others, 1985). Four deformations have been recognized. D_1 produced the major S_1, foliation formed during an early amphibolite facies metamorphism, and then superimposed $F_2(D_2)$ and $F_3(D_3)$ folding produced the large-scale fold-interference structure. D_4 occurred during late diapiric uprise, which was thought to be related to collision of two crustal blocks.

North of this area in the vicinity of the Niagara Fault (fig. 2), the geologic and structural features are complicated. Larue (1983) and Ueng and others (1984) have described a number of discrete early Proterozoic terranes. The structural relationships among these small terranes or packets are complex, as is their relationship to the Penokean igneous belt in Wisconsin and metasedimentary rock in northern Michigan. In the area just north of the Niagara Fault five phases of deformation have been recognized (Ueng and others, 1984). This area is miogeoclinal with no Penokean plutonic rock yet recognized. Only the first two episodes of deformation, yielding F_1 and F_2, produced regional structural features. F_1 produced extreme shortening in the north-northeast -- south-southwest orientation.

In east-central Minnesota, Connolly (1981) studied a small area of Animikean-age strata that were deformed during the Penokean orogeny, and noted evidence for three deformations (D_1, D_2, D_3). Connolly's D_1 was marked by south dipping, overturned or recumbent isoclinal folds. Although no quantitative estimate of shortening was given, this would imply significant horizontal shortening. Holst (1984) has presented quantitative strain analysis data demonstrating that recumbent folding up to nappe scale occurred in east-central Minnesota during this time. Connolly (1981) concluded that the culmination of metamorphism was initiated prior to D_1, which continued during, after, and into D_2 and D_3. D_1 was marked by upper-greenschist to lower-amphibolite facies conditions (no P or T estimates given). Regional metamorphism continued during the weaker D_2 and D_3 deformations at greenschist facies conditions.

Middle Proterozoic Metamorphism

It became apparent during the course of various geochronologic studies in the Lake Superior region in the 1960s and 1970s that certain isotopic systems recorded an event that postdated the Penokean orogeny. U-Pb, Rb-Sr, and K-Ar studies on both whole-rock and mineral separates commonly recorded an age around 1.63 Ga (Goldich and others 1961; Peterman and others, 1985), although no igneous rock having similar crystallization ages could be found. Moreover, various metasedimentary rock unconformably overlying older Proterozoic rock was recognized as being deformed and metamorphosed (Dalziel and Dott, 1970), but the exact significance and age of their metamorphism remained unclear.

For example, in southern Wisconsin red quartzite like the Baraboo and Waterloo rests unconformably on 1.76 Ga rhyolites (Dalziel and Dott, 1970; Van Schmus, 1976). In northwest Wisconsin the Barron Quartzite overlies Penokean-aged rock. In southwest Minnesota the Sioux Quartzite rests on rock that was last metamorphosed around 1.85-1.7 Ga, as well as intruded by Penokean plutons (Goldich and others, 1970).

Greenberg and Brown (1984) have suggested, that there is a close relationship between the metamorphism of the quartzite and related metasedimentary rock in central and southern Wisconsin, and anorogenic intrusions which are thought to be 1.5 to 1.45 Ga in age. Guidotti and others (unpub.) have determined a probable ^{39}Ar-^{40}Ar metamorphic date of 1.43 Ga on an amphibolite associated with the quartzite at Waterloo. These two studies, plus the proposal of Hoppe and others (1983) suggesting buried 1.5-1.45 Ga plutons in southern Wisconsin, indicate that the southern Wisconsin quartzite may have been contact metamorphosed at 1.5 Ga and not regionally metamorphosed at 1.63 Ga. In contrast, no 1.5 Ga age dates are known from northernmost Wisconsin or Michigan, but 1.63 Ga dates are common.

The metamorphic grade of the Middle Proterozoic quartzite is variable. Based upon a petrographic study of aluminous, pelitic interbeds at Waterloo, Geiger and others (1982) documented two periods of metamorphism (M_1 and M_2), which postdated two deformations (D_1 and D_2). Using the assemblage chlorite-chloritoid-andalusite-muscovite-quartz-hematite $\pm$ plagioclase, they concluded that for M_1, T = 350-550 °C and $P_{H_2O} = P_{TOT}$ = 1.0-3.8 Kb (fig. 3). The presence of M_1 pseudomorphs with a staurolite-like habit indicate that T was closer to 550 °C. M_2 was a separate, lower grade event, possibly unrelated to M_1 directly, and occurring at $P < 3.8$ Kb and $T < 500$ °C.

Metamorphism at Baraboo was lower in grade, although deformation was intense. There phyllitic units contain the assemblage quartz-muscovite- pyrophyllite-hematite; this restricts T to less than 430 °C (fig. 3). Andalusite was reported from the Seely Slate which overlies the Baraboo Quartzite (Wiedman, 1904). However, petrographically this slate appears low grade (chlorite-quartz-plagioclase-hematite) and examination of several thin-sections indicates Wiedman's andalusite was probably a misidentification. P of metamorphism was still probably similar to that at Waterloo (P = 1-4 Kb; Geiger, 1986). The difference in metamorphic grade between these two lithologically similar quartzites is demonstrated by the presence of pyrophyllite in aluminous interbeds at Baraboo and not at Waterloo. At Waterloo, pyrophyllite has been consumed by either of two possible reactions: Pyrophyllite = andalusite + quartz + H_2O and/or pyrophyllite + chlorite = chloritoid + quartz + H_2O.

The present data do not suggest polymetamorphism at Baraboo. The structural history has been determined in detail by Dalziel and Dott (1970), who have observed S_1 and S_2 cleavages within the more phyllitic units. Although the detailed structure is more complicated, the gross structural features appear similar to those at Waterloo. There are late breccia zones within the quartzite that contain hydrothermal quartz crystals and the aluminous mineral, dickite. Fluid inclusion filling temperatures give 105- 107 °C for quartz crystals sampled from this breccia zone (Bailey, in Dalziel and Dott, 1970). These zones are late geologic fractures that postdate the major structures in the Baraboo Quartzite. They formed after the main metamorphism, possibly at 1.5 Ga.

The Barron Quartzite of northwest Wisconsin has aluminous beds containing diaspore-quartz-kaolinite-illite (Morey, 1978). The Sioux Quartzite in Minnesota is similar and contains muscovite-diaspore-quartz-hematite and pyrophyllite-quartz-muscovite-kaolinite-illite assemblages (Morey, 1978). The presence of quartz + kaolinite at both localities restricts $T < 350$ °C and it was probably lower (fig. 3). It is clear that these two quartzites are not as intensely metamorphosed or folded as the Baraboo and Waterloo in southern Wisconsin.

In addition to affecting post Penokean-aged sedimentary rock, the 1.63 Ga and 1.5 Ga events apparently imprinted metamorphic feature(s) on older Penokean or Archean rock. Earlier discussion on Penokean metamorphic rock showed that mineral retrogression was in most cases ubiquitous. In some instances polymetamorphism also appeared likely. In Wisconsin this is sometimes characterized as a discrete overprinting by a new mineral assemblage (for example, Jackson County, Iron Mine). Other localities from northern Wisconsin show evidence of pseudomorphic minerals (for example, Quinnesec, Ladysmith, possibly Merrill). The pseudomorphic minerals grew at a lower grade than the main Penokean metamorphism, corresponding to the greenschist facies. Garnet is often surrounded by chlorite and in the Dunbar dome Nielsen (1984) noted that cordierite was replaced by pinite.

In metasedimentary rock from the thick Animikean basin of east-central Minnesota, Morey (1978) reports the occurrence of secondary muscovite grains that overprint an earlier Penokean metamorphic fabric and give K-Ar dates of about 1.63-1.61 Ga. Farther to the east near Marquette, Michigan, Rb-Sr model ages on minerals (biotite and muscovite) separated from Archean gneissic basement rock and early Proterozoic metasedimentary rock give an age of around 1.665 Ga (Van Schmus and Woolsey, 1975).

DISCUSSION

Archean

The Archean interval of metamorphism(s), which falls between 3.0-2.6 Ga, was characterized in the southern gneiss terrane by upper-amphibolite to granulite facies metamorphism. We favor the proposal that two periods of Archean metamorphism affected the Minnesota River Valley (Goldich and Wooden, 1980) and that the younger 2.6 Ga event produced most of the metamorphic mineral assemblages seen today. For example, an age of 2.65 Ga was obtained from U-Pb dating of zircons taken from a garnet-biotite gneiss (Goldich and others, 1970). This metamorphic gneiss of probable sedimentary origin records a high-grade metamorphic recrystallization event that is probably not an older igneous or detrital zircon age. This suggests that the 2.65 Ga-event was sufficiently intense to recrystallize most silicate assemblages.

No data have yet been presented to justify more than one episode of Archean metamorphism in Wisconsin and Michigan. However, the Archean rock there has not received as much intensive geochronologic study as those in the Minnesota River Valley. If a 2.8 Ga age is accepted as the metamorphic age of Archean rock in central Wisconsin (Van Schmus and Anderson, 1977) and in Upper Michigan, then two simple, end-member tectonic scenarios relating metamorphic events in all southern gneissic rock are possible, if they were all part of a large, single crustal block or unit (Sims, 1976; Morey, 1978). The first is that the rock in Minnesota has experienced an entirely different metamorphic and tectonic history than those in Wisconsin and Michigan, because rock in Minnesota gives ages of metamorphism at 3.05 Ga and 2.6 Ga versus 2.8 Ga in central Wisconsin. The second scenario would link all of these areas in one grand metamorphic episode (but polymetamorphic in Minnesota) starting at 3.05 Ga and ending at 2.6 Ga. The differences in ages could then be attributed to differences in times of thermal equilibration and uplift, resulting in contrasting times of isotopic closure. If there was a large, single block of Archean crust extending from Minnesota to central Wisconsin and Michigan (Sims, 1976; Morey, 1978), it would seem that the simplest assumption for such a high-grade regional terrane is that all areas experienced a similar tectonic history--(scenario two).

Contrary to the Sims-Morey proposal is the idea that the various pieces of southern gneissic Archean crust (Minnesota River Valley, Watersmeet, central Wisconsin) may have formed in different geographic areas, and may never have been linked in an early, contiguous pre-2.75 Ga southern Lake Superior Archean gneissic terrane. Unfortunately, incomplete isotopic data for Archean rock in central Wisconsin and Michigan preclude a definite choice of any of the possible scenarios presented above.

The Minnesota River Valley has been considered the type area for the southern gneissic terrane, and the rock there can be best classified as belonging to a transitional facies between the amphibolite and granulite facies.

Pressure and temperature never reached those characteristic of the higher grade massif-type granulite terranes, such as those found in South India or the Adirondacks (Raith and others, 1982; Bohlen and Essene, 1980). The widespread presence of migmatite and abundant hydrous amphibolite demonstrate that temperature or water partial pressure were lower and higher respectively, when compared to other Precambrian granulite terranes. This non-granulitic signature could also simply be a result of a depth zone arrangement where deeper levels of the Archean gneissic crust are not exposed. Newton and Hansen (1983) have reviewed the P and T regimes of many Precambrian granulite terranes. One characteristic of the true granulite terranes is a metamorphic pressure signature between 6 and 10 Kb with most clustering around 8 Kb, and temperatures ranging from 750-900 °C. P and T estimates in the Minnesota River Valley fall toward the lower end of more transitional granulite terranes.

The only granulite of the southern Lake Superior region may be the Archean metamorphic rock of east-central Minnesota. Pressures of metamorphism here are similar to those in the Minnesota River Valley, being roughly 5 Kb, but temperatures appear to be 125 to 150 °C higher (805 °C versus 650-675 °C). This area might be equivalent with rock in the Minnesota River Valley, but age-dates are required to confirm this. The simplest hypothesis would link this rock with the 2.6 Ga old transitional granulite facies metamorphism of the Minnesota River Valley.

Rock of similar age in Wisconsin and Michigan, which may have experienced the same metamorphism, display equivalent or slightly lower grades of metamorphism than those in the Minnesota. This metamorphic rock generally lacks orthopyroxene and garnet in either felsic or mafic gneiss. Orthopyroxene marks the incoming of the granulite facies and the absence of garnet suggests that metamorphic pressure was not very high (that is less than 7 Kb around 700 °C). Therefore, the relatively low pressures and temperatures observed across the entire gneiss terrane and the large regional similarities in metamorphic grade for the Algoman orogeny, argue against a simple depth zone explanation. Instead, this indicates that Archean metamorphism in the southern Lake Superior region did not progress to the higher grades seen in Precambrian areas elsewhere throughout the world.

It is clear that Archean metamorphism in the southern gneiss terrane was more intense than in the greenstone belts of the more northern granite-greenstone terrane. Rock in the former were buried to depths of roughly 20 km and those of the latter to no more than 10 km. We tentatively propose that the 2.6 Ga metamorphism in the Minnesota River Valley and east central Minnesota, was caused by a collision between the southern gneiss terrane and the more northern granite-greenstone terrane. Gibbs and others (1984) identified large thrust faults in central Minnesota from COCORP seismic reflection data. They proposed that they formed as a result of a collision between the 2.7 Ga Superior Province and the older 3.5 Ga southern gneiss terrane. Depths of burial between 15 and 20 km and metamorphism in the gneiss terrane could be explained by crustal underthrusting beneath greenstones, as has been postulated in other granulite terranes. Crustal overlapping by a greenstone terrane of normal thickness (35 km) as a mechanism for producing the metamorphism seems to be ruled out by the relatively low paleopressures of 5 - 6 Kb observed, versus 8 Kb as in many true granulite terranes. It is interesting, however, that pressure of metamorphism may have been similar between the Minnesota River Valley and east-central Minnesota. Higher pressure should be expected nearer the collision zone; instead it appears that pressure was roughly equivalent and only temperature was higher nearer this junction.

Early Proterozoic

Most of the detailed work on Penokean metamorphism has concentrated on Michigan and Wisconsin. From a close examination, it appears that the pattern of metamorphism is somewhat different in these two states. Penokean metamorphism in Michigan is nodal (James, 1955), whereas in Wisconsin it appears that much of the Penokean orogenic foldbelt is of a relatively uniform upper greenschist to amphibolite grade. To the extent that any variation in grade can be detected in Wisconsin, it appears that it is partly linear in pattern (localities 2a-2b and 6a-6b, figure 2). Furthermore, in Wisconsin, sillimanite- grade rock is generally absent, whereas in Michigan sillimanite is found in the inner part of the Republic and Peavy Nodes where, of course, pelitic lithologies are more abundant. Nonetheless, (excluding localities 6a and 6b) the temperature of Penokean metamorphism in the center of the nodes may have attained slightly higher values in Michigan. The present erosional depth in both states seems to be roughly similar (depths corresponding to 2-4 Kb, excluding localities 6a and 6b). Thus large differences in the depth during metamorphism cannot be invoked to explain the difference in maximum temperature attained. Outside of the nodes the metamorphic grade in Michigan seems to be slightly lower than the overall grade in Wisconsin.

James (1955) proposed the existence of a buried pluton beneath the Republic Node to account for the bullseye pattern of metamorphism. If such an hypothesis is advanced further to explain the patterns of all Penokean metamorphic nodes, then there should be synorogenic plutons beneath Peavy Pond or the central Watersmeet area. However, no large Penokean-age plutonic bodies crop out anywhere in the western Upper Peninsula of Michigan (fig. 2). In the high-grade part of the Watersmeet node only few Penokean intrusive igneous rock is found. This area is, instead, dominated by older Archean rock and Animikean-aged metasedimentary rock (fig. 2). Where early Penokean (1.90 Ga) mafic igneous rock does crop out, as at the Peavy Node, it is metamorphosed (Bayley, 1959).

Small pegmatites do occur near Republic (Van Schmus and Woolsey, 1975) and in the center of the Peavy Node, and migmatite is present near locality 6a in the Watersmeet Node. This rock may be related to some buried granitic source, but they could just as well represent the products of ultrametamorphism occurring at deeper crustal levels. Such an interpretation is supported by the fact that the magmatic pegmatites at Republic are located within the sillimanite zone where partial melting would most likely occur. The same is generally true for the Peavy and Watersmeet Nodes, where the igneous rock is restricted to the highest grade zone. Hence, we interpret the pegmatite and migmatite as partial melts resulting from ultrametamorphism, and not as high-level representatives of hypothetical, more deeply buried crustal plutons that solely caused Penokean regional metamorphism. We are of the opinion that a more fundamental and region wide heat-flux is required to promote metamorphism in not only the nodes, but also in the more widespread low-grade areas not contained within any tectonic hot-spot.

In Wisconsin south of the metamorphic nodes there are numerous Penokean intrusive and extrusive igneous rock (fig. 2). Here the volcanic rock, which appears to be the first expression of any kind of Penokean igneous activity, is metamorphosed. Younger, Penokean granitic plutons are synmetamorphic; a substantial fraction are postmetamorphic (Maass, 1983). The large volume of igneous rock present in Wisconsin can probably account for the higher overall metamorphic grade of rock observed in the Penokean magmatic belt. Lux and others (1986) recognized that low-pressure/high-temperature (that is andalusite-sillimanite) metamorphic terranes might originate during orogenesis from deep-level contact metamorphism near granitoid batholiths. In northern New England they propose that the higher grade Acadian metamorphism observed at the present erosional surface is a consequence of granitic plutonism. This general model is applicable to Penokean metamorphic rock in Wisconsin. It follows the observations that higher grade assemblages are found close to and associated with Penokean intrusives (Greenberg and Brown, 1983; Sims and others, 1985). However, the primary heat source is still unknown. Melting must be caused by either transient high mantle heat fluxes or conductive heating subsequent to crustal thickening (Lux and others, 1986). Regional metamorphic geotherms could be partly a result of mantle related magma (basalts) fluxing through or ponding at the base of the crust. The Penokean orogeny did experience early and pervasive basaltic volcanism.

Similar low-pressure metamorphic field geotherms or facies series have been recognized many places worldwide, the northeastern Appalachians (Thompson and Norton, 1968) being a classic example. Metamorphism in the northern Appalachians has been successfully related to early Paleozoic continental collision between North America and Europe (Bird and Dewey, 1970). Cambray (1978) proposed a plate-tectonic model to account for the geology of the early Proterozoic in the Lake Superior region. He proposed that deposition of sediment (Animikean) began around 2.0 Ga upon a rifted Archean basement. Younger Animikean-aged sediment was then deposited upon a passive continental margin along an east-west trending basin that overlies the Great Lakes Tectonic zone (fig. 2). This may have been a zone of crustal weakness or instability. Later the sedimentary rock was deformed and metamorphosed in a collision with a plate or arc moving from the south during the Penokean orogeny. Cambray suggested that the granite and rhyolite in Wisconsin represented a Cordilleran-type margin of the southern plate. His proposed plate suture lies in the area of the Quinnesec Formation in northeast Wisconsin. This general model has been extended and modified by other workers (for example, Larue, 1983). Greenberg and Brown (1983) and Van Schmus (1976) have also presented possible plate-tectonic- like models, but with northward dipping subduction zones. Greenberg and Brown (1983) proposed that the Penokean volcanic belt in Wisconsin may once have been an island arc, although analogies with modern island arcs may be somewhat different. Greenberg and Brown (1983) and Larue (1983) consider that the east-west trending Niagara Fault of northern Wisconsin (fig. 2) marks a major structural break between the Penokean volcanic-plutonic (magmatic) complex of Wisconsin and the Animikean-aged sedimental-volcanic (miogeoclinal) terrane of northern Michigan. This tectonic model is consistent with the type of low-pressure metamorphism found within the Penokean igneous belt. Moreover, the belt of kyanite or medium-pressure facies series rock of localities 6a-6b (fig. 2) can be modeled as forming slightly north of and roughly parallel to a suture zone during collision of two plates along a westward extension of the Niagara Fault. The actual case is probably more complicated because "sutures and suture zones ... are rarely simple well defined easily recognizable lineaments" (Dewey, 1977). In fact, in northern Wisconsin a large number of large east-west trending faults have been recognized by many workers (Sims, 1976; Sims and others, 1980).

In the sense of forming along a suture, the belt of kyanite-bearing rock might be roughly analogous to the blueschist of Mesozoic and Cenozoic Orogens. The pressure of metamorphism for the kyanite schist is about 7.5 Kb, and this is similar to some younger blueschists. Ernst (1971) suggests 5 to more than 8 Kb for subduction related rock of the Californian Franciscan. However, metamorphic temperatures of 650 °C for the kyanite schist, are much higher than those of geologically more recent blueschists, where T = 150-300 °C (Ernst, 1971). On the other hand, some recent high-pressure subduction related terranes, such as at New Caledonia and Sanbagawa, Japan, have metamorphic zones that may have formed at temperatures approaching 600 °C at 7-14 Kb (Brothers and Yokoyama, 1982). Low temperatures are not always intrinsic to all subduction zones.

Much has been written about the possible differences in tectonic style and heat-flow between Precambrian and Phanerozoic time. Thus, if plate-tectonics was operative during the Archean or Early Proterozoic, it may have had a different style. Miyashiro (1973) has discussed the requirements for low- temperature, high-pressure metamorphism to occur during subduction. The rate of plate descent should be rapid and the initial temperature of the descending slab low. The slope and thickness of the subducted plate also controls the pressure and temperatures of metamorphism. If subduction took place at a shallower angle or level, or the initial plate temperature was higher in Penokean time than today, then the resulting metamorphic field geotherm during subduction may have produced the medium-pressure series shown in figure 3. This scenario is speculative, but it is consistent with the present data. It is also possible that the medium-pressure series recorded by these schists was a function of the uplift and cooling rate (England and Thompson, 1984). The important point is that the kyanite schists, which were originally pelitic sediment, were buried to depths around 25 km, and thus, 10-15 km deeper than the low-pressure andalusite-sillimanite series rock surrounding them to the north and south. This has important tectonic implications. Crustal thickening during plate collision could be invoked to explain the different depths of burial. But such thickening would have to occur in a narrow band (6a-6b) or in a localized and restricted area such as 6a. This seems unlikely. Understanding fault movement may be critical in explaining the distribution of this metamorphic rock and their relationship to the tectonic processes that occurred about 1.9 Ga.

We have attempted to relate the large region-wide Penokean deformational history to the metamorphism using the thesis that the best approach is a combination of regional geologic mapping and geologic synthesis together with detailed structural studies in key areas. As in all multiply deformed terranes, the deformational events could well be relative and localized sequences and their absolute relationships probably vary both in time and space (Williams, 1985) across the Penokean orogen. It appears that two and possibly three major and regionally significant Penokean deformations can be found in rock of widely separated areas. The first and second deformation appear to be penetrative and the most significant, both locally and on a regional scale. Intense horizontal compression has been argued for in part of Wisconsin and Minnesota (Maass, 1983; Holst, 1984), but not as yet in Upper Michigan, away from the Niagara Fault. Most importantly, it would seem that Penokean metamorphism and deformation are largely contemporaneous.

Contrary to previous ideas that suggested vertical tectonic styles (Greenberg and Brown, 1983; Sims, 1976), structural studies point to horizontal compression in Wisconsin and Minnesota during the Penokean (Maass, 1983; Connolly, 1981; Holst, 1984). In contrast, more vertical-type tectonic activity has been proposed in northern Michigan (Cannon, 1973). The studies indicating intense horizontal compression are consistent with a plate-tectonic model involving colliding plates or arcs. In addition, it may be more than a coincidence that both the deformation and style of metamorphism appear to be different in Michigan than that in Wisconsin and Minnesota.

Middle Proterozoic

Regional metamorphism in the southern Lake Superior region occurred after the Penokean orogeny; however, it is difficult to separate the effects of 1.63 Ga and 1.5-1.45 Ga metamorphism in central and southern Wisconsin. Other younger Proterozoic ages have also been detected (Peterman and others, 1985).

We propose that the 1.63 Ga event produced a regional low-grade metamorphism. The fact that radiometric dates give ages of 1.63 Ga at great distances from the 1.5 Ga Wolf River batholith and related plutons does suggest that some thermal activity occurred at 1.63 Ga. Recent Th-U-Pb dating on whole-rock and mineral separates from a variety of localities in northern Wisconsin give 1.63 Ga ages; they reflect shearing and retrogressive metamorphism (Afifi and others, 1984) and not simple crustal uplift (Greenberg and Brown, 1984).

An alternative explanation for the ubiquitous pseudomorphing and polymetamorphic mineral assemblages is late-state metamorphic retrogression or multiple thermal episodes occurring during the Penokean orogeny, or both. Late-stage metamorphic mineral retrogression occurs in most metamorphic terranes during cooling and uplift, but it is not as pervasive as that seen in many of the Penokean-aged rock. Cummings (1984) has described polymetamorphic Penokean rock in the Eau Claire complex of western Wisconsin. He interpreted the earliest metamorphism as amphibolite facies and a second thermal event as epidote-amphibolite. However, because no age data are given by Cummings, the final metamorphism could also be interpreted as being post-Penokean (1.63 Ga).

In southern Wisconsin the Baraboo and Waterloo quartzite may have experienced either or both of the 1.63 and 1.5-1.45 Ga aged events. Traditional views placed their metamorphism at 1.63 Ga (Van Schmus, 1980; Geiger and others, 1982). However, recent work suggests that the main metamorphism is related to the Wolf River event at 1.5 Ga (Greenberg and Brown, 1984).

The grade of metamorphism is distinctly higher at Waterloo (for M_1) than at Baraboo, which is located 65 Km to the northwest of the former. This difference could be as much as 120 °C. Both units are strongly deformed. Polymetamorphism is observed at Waterloo. Although metamorphic-based petrographic studies from Baraboo are meagre, there does not seem to be any existing evidence supporting more than one episode of metamorphism (Dalziel and Dott, 1970). This is puzzling, because the quartzite at both localities are part of the same stratigraphic unit. One would expect similar tectonic histories for both localities.

Despite the above problems of interpretation, it appears that none of the Baraboo interval quartzite has been deeply buried. Van Schmus and Bickford (1981) have suggested that the 1.63 Ga metamorphism is a foreland manifestation of an event that produced similar aged igneous rock (Mazatal Belt) that extend from Arizona and New Mexico to possibly as far north as Illinois. This would have been a tectonic event of large continental proportions. Dott (1983) suggested that the southern Baraboo interval quartzite were deformed and metamorphosed at 1.63 Ga in a continental collision occurring to the south in Iowa and Illinois.

Small areas of metamorphism in the Lake Superior region can be related to Keweenawan rifting (1.1 Ga). This event was also of continental dimensions, but any associated metamorphism appears to be restricted quite closely to igneous or rifting activity. Keweenawan dikes do intrude rock located outside the rift valley, but they are usually small and did not alter their host rock to any significant extent.

CONCLUSIONS

We have reviewed the metamorphism of the Precambrian terrane of the southern Lake Superior region. The Earth's crust in this area has experienced a long and complex orogenic and anorogenic history starting around 3.6 Ga and ending 1.1 Ga ago. Relatively small and localized, but possibly thick sialic continental nuclei formed the first crust as at Watersmeet and the Minnesota River Valley by 3.6 Ga. Since then and occurring over a 2,500 m.y. interval at least three major regional metamorphic periods have been recognized. These periods are around or between 3.1 and 2.6 Ga, 1.9-1.8 Ga, and 1.63 Ga. Metamorphism may also have occurred regionally or semiregionally around 2.4-2.1 Ga and 1.5-1.45 Ga, but the present data are inadequate to confirm this suggestion. No metamorphism older than 3.1 Ga has yet been recognized. In Minnesota two periods of metamorphism seem to have taken place between 3.1 and 2.6 Ga. The younger event appears to be related to the Kenoran or Algoman Orogeny. It was characterized by upper-amphibolite to lower-granulite facies metamorphism in the southernmost Lake Superior area.

Some workers have called for a hot, thin Archean crust (Collerson and Fryer, 1978). However, this does not seem to be the case for the Lake Superior region where geobarometry estimates give about 6 Kb for the Minnesota River Valley. Using an average of 6 Kb and 675 °C, an inferred metamorphic field geothermal gradient would be 35 °C/km. This metamorphic gradient is similar to that suggested by Boak and Dymek (1982) for Archean metamorphic assemblages in Greenland.

Of course, metamorphic field geotherms or facies do not represent the actual P-T path experienced by rock undergoing burial metamorphism and subsequent excavation and uplift during a complete tectonic cycle. Quantitative P-T-t path studies need to be undertaken on both the Archean and Penokean units to enable more quantitative tectonic models to be formulated. Yet, the P and T data presented from the Archean metamorphic period in the Lake Superior region shows, that as in other areas of the world, by the end of the Archean (2.5 Ga) a relatively thick, largely sialic, stable crust had developed. Since then, parts of the southern gneiss terrane may have remained at approximately the same crustal level after being buried earlier to 20 km depth. The greenstone belts in the more northern granite-greenstone terrane were probably never buried to depths greater than roughly 10 km.

The Penokean orogeny reworked and metamorphosed rock in the southern gneiss terrane, especially in Wisconsin. New crustal material was also produced. Here the suggestion was made that the orogeny and associated metamorphism could be described in terms of a plate-tectonic model involving plate or arc collision. It is not clear how the Watersmeet gneiss (3.6 Ga) and the Puritan Quartz monzonite (2.6 Ga) were affected by the Penokean orogeny. These two units are located close to the kyanite-schist of the Watersmeet node, yet they appear relatively unaffected. Moreover, low-grade metasedimentary rock and volcanic rock are located just to the north and east of the kyanite-schist at locality 6a. They are separated from the kyanite schist by a large fault (Black, 1977). Fault movement may have played a critical role in juxtaposing rock with such different metamorphic grades and ages. Sims and others (1981) have proposed northeast-trending faulting in this same area to account for the close spatial association of Archean and Proterozoic rock. The possible presence of thrust sheets must also be considered, especially in the context of the recent study of Holst (1984).

Post-Penokean metamorphism is just beginning to be unraveled. A variety of age data suggest a low-grade metamorphic event around 1.63 Ga. This could account for the ubiquitous retrograde effects seen in Penokean aged rock. However, 1.63 Ga effects are obscured by possible 1.5 Ga regional contact metamorphism, especially in southern Wisconsin. Structural geology studies at Baraboo have had a long history, but until recently little has been done with regards to interrelating the metamorphism and large-scale tectonics. Only recently have several tectonic models been put forth (Dott, 1983; Van Schmus and Bickford, 1981; Greenberg and Brown, 1984), but agreement among these models is poor and reflects a critical lack of understanding of the tectonic processes operating between 1.76 and 1.45 Ga.

NOTE ADDED IN PROOF

Peterson and Geiger (1987, 1988) have described high pressure and temperature Archean granulites from the Harwood gneiss of Dickinson County, Michigan. Petrographic relationships indicate at least two period of metamorphism. Quantitative geothermometry and geobarometry involving two generations of garnet indicate 850-950 °C and 8-10 Kb for the first event and 650 °C and 7-8 Kb for the second event. The Harwood gneiss represents the highest grade metamorphic rock in the Southern Province yet described and are evidence for deep burial of supracrustal rock to at least 25 km.

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URANIUM AND THORIUM IN SELECTED PRECAMBRIAN ROCK UNITS IN WISCONSIN

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ABSTRACT

The article summarizes the results of uranium and thorium investigations, by gamma-ray spectrometry, of several Precambrian rock units in Wisconsin.

The highest values were encountered in the Wolf River batholith where uranium values range from less than 1 ppm to more than 30 ppm; thorium values range from less than 5 ppm to more than 50 ppm. The mean value for uranium is 6 ppm and for thorium 24 ppm with a Th/U ratio of 4.2. The highest uranium and thorium values are found in the younger, more differentiated units of the batholith.

The Ninemile Pluton in Marathon County contains uranium concentrations between less than 1 ppm and 15.6 ppm with a mean value of 1.6 ppm; the range for thorium was between 12.1 ppm and 56.4 ppm and a mean of 21.2 ppm. The high Th/U ratio, with an averagge value of 12 indicates that uranium may have been preferentially leached during weathering.

Middle Proterozoic quartzite- metaconglomerate units in northeastern and northwestern parts of Wisconsin show a range of uranium concentrations from less than 1 ppm to 5 ppm and a mean value of 1.5 ppm. The thorium concentrations range from less than 1 ppm to 32 ppm with a mean value of 5.4 ppm. The mean Th/U ratio is nearly 4. These ranges and averages are well within the normal values for similar rock types found in the literature.

INTRODUCTION

Uranium and thorium are present in trace amounts in almost all geological materials as minor constituents in the lithosphere. Taylor (1964) calculates that the average concentration of uranium in the earth crust amounts to 1.8 ppm (parts per million) and that of thorium 7.2 ppm. Uranium and thorium may occur in several ways in rock: in radioactive accessory minerals such as uraninite, thorite, monazite, zircon, and allanite; as isomorphic substitutions in the crystal lattice of such minerals as sphene, apatite, niobates, tantalates, and titanates; as molecular or ionic disseminations in, or associated with, the major rock-forming minerals; and as entrapments in lattice imperfections, along fractures and cleavage planes, along grain boundaries, or as fluid inclusions.

Each atom of uranium and thorium decays through discrete transformations and characteristic half-lives by the emission of several alpha and beta particles and gamma rays to form daughter products which are different than the parent element (figs. 1 and 2). Among the products of radioactive decay of uranium and thorium are radium and radon, which are considered to be health hazards. Radium-226, which is a product of decay of uranium-238, is of special concern because if has a relatively long half life (1620 years) and high

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specific activity. The human body metabolizes radium in much the same way as calcium whereby radium-226 becomes concentrated in bones. The United States Environmental Protection Agency (EPA) recommends that the amount of radium in drinking water not exceed 5 pCi/L (picocuries per liter-- one picocurie of radium equals 1 x 10^{-12} grams).

This article summarizes the results of three separate studies on the concentration of uranium and thorium in several different regions of Wisconsin, including granitic rock of Wolf River batholith, granitic rock, near Wausau, in Marathon County, and quartzite and metaconglomerate units in northeastern and northwestern parts of Wisconsin.

The appendix containing the laboratory data is published separately by the Wisconsin Geological and Natural History Survey Open-file Report WOFR 88-3 (Mursky and others, 1988).

PREVIOUS INVESTIGATIONS

Publications dealing with the concentration of uranium and thorium in the Precambrian rock of Wisconsin are fairly limited. Turner (1948) and Vickers (1956) studied the radioactivity associated with rock of the Wausau Syenite Complex, in particular the radioactivity of zircon and the occurrence of thorogummite nodules in residual soil. More recently Kalliokoski (1976) conducted a reconnaissance study of known uranium and thorium occurrences in Wisconsin and Upper Michigan which includes a review of all known radioactive exposures in Wisconsin. The majority of the occurrences are found in the Red River quartz monzonite of the Wolf River batholith where they are limited to narrow pegmatites, fractures, joints, and veinlets in small exposures.

The U.S. Department of Energy as part of the National Uranium Resources Evaluation Program (NURE) released several reports on the radioactivity in northern Wisconsin. Two groups of reports are pertinent to this study: aero-radioactivity reports (Geometrix, 1978) and hydrogeochemistry reports (Arendt and others, 1978a,b,c).

The gamma ray and magnetic surveys covered 44,800 km^2 of the area between longitudes 92° and 88° and between latitudes 46° and 44°. The gamma ray survey utilized a 7803 cm^3 NaI detector crystal whereby thorium, uranium, and potassium count rates were sampled and recorded digitally over one-second intervals.

The hydrogeochemical and stream sediment survey covered 34,800 km^2 of the area between longitudes 92° and 88° and latitudes 46° and 45°. A total of 990 groundwater, 922 stream water, and 909 sediment samples were collected and analyzed for 28 elements. Kinneman and Illsley (1962) completed another hydrogeochemical study for uranium in northeastern Wisconsin and the adjacent Upper Peninsula of Michigan. The study was carried out with an average sampling density of two samples per township over an area of 9600 km^2.

Other NURE reports on Wisconsin are listed at the back of this Geoscience Wisconsin volume.

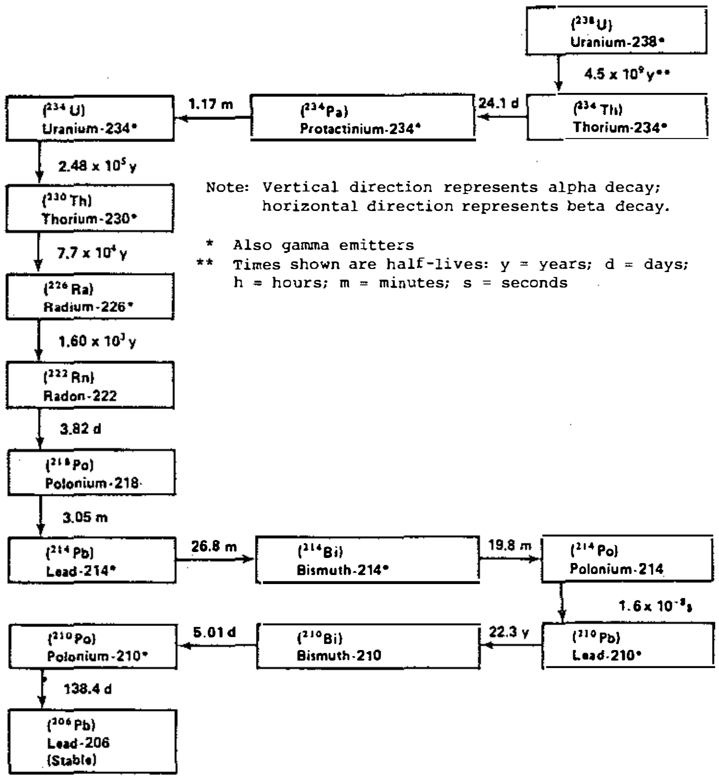

Figure 1. The radioactive decay series for uranium-238.

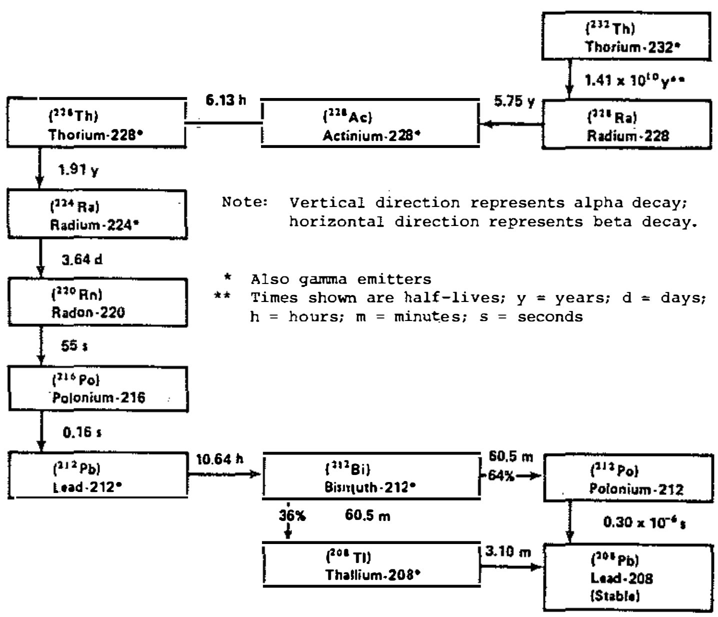

Figure 2. The radioactive decay series of thorium-232.

ANALYTICAL TECHNIQUES

Whole Rock Uranium and Thorium Analysis

Whole-rock uranium and thorium concentrations in parts- per-million (ppm) were determined by the gamma spectrographic technique utilizing the method given by Adams and Gasparini (1970), and used by Meddaugh (1978), Anderson (1979), and Cook (1980) for this study.

The laboratory facility consists of a testing chamber, gamma-ray sensor, gamma analyzer, timing unit, and digital printer and display unit (fig. 3). The gamma-ray sensor, and 1852 cm3 (15.2 by 10.2 cm) NaI crystal detector with an attached photomultiplier tube assembly (Scintrex Model GSA-61), was enclosed in a testing chamber constructed of 5-cm thick lead bricks. Two bricks on the top of the chamber are removable to allow insertion of samples into the chamber. The gamma sensor is connected to the electronics of the gamma analyzer - a differential, four channel, pulse- height discriminator (Scintrex Model GAM-1). A timing unit, LED digital display, and printer unit are connected to the gamma analyzer in such a way that the number of counts accumulated in a single channel is printed after a preselected time interval.

The channels viewed by the pulse-height discriminator are centered on 2.6 MeV, ^{208}Tl photopeak of the Th-232 decay series, with a window width of approximately 0.26 MeV (Th channel), and 1.76 MeV, ^{214}Bi photopeak of the U-238 decay series, with a window width of approximately 0.19 MeV (U channel).

If the samples to be analyzed are in secular equilibrium (a not unreasonable assumption for this study) and the contribution to the Th channel from the U-238 decay series is negligible (except when U>>Th), then the following equations, modified from Adams and Gasparini (1970), can be used to calculate the equivalent Th and U values for a given sample:

$$eTh(ppm) = \frac{RTh - BGTh}{m\ (QTh)\ h}$$

and

$$eU(ppm) = \frac{RU - BGU - (S(RTh - BGTh))}{m\ (QU)\ h}$$

where

eTh(ppm)	=	equivalent thorium in parts per million;
eU(ppm)	=	equivalent uranium in parts per million;
RTh	=	observed count rate (cps) in the Th channel;
RU	=	observed count rate (cps) in the U channel;
BGTh	=	background count rate (cps) in the Th channel;
BGU	=	background count rate (cps) in the U channel;
QTh	=	concentration factor for Th (cps/ppm)/kg;
QU	=	concentration factor for U (cps/ppm)/kg;
S	=	stripping ratio;
m	=	mass of sample (kg); and
h	=	height correction factor.

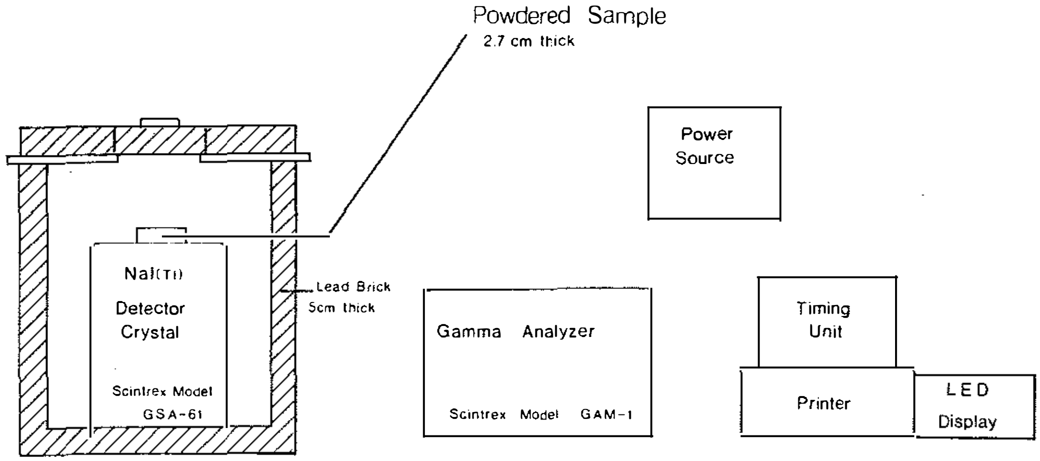

Figure 3. Schematic diagram of the gamma-ray spectrometer facility used to analyze rock samples for uranium and thorium.

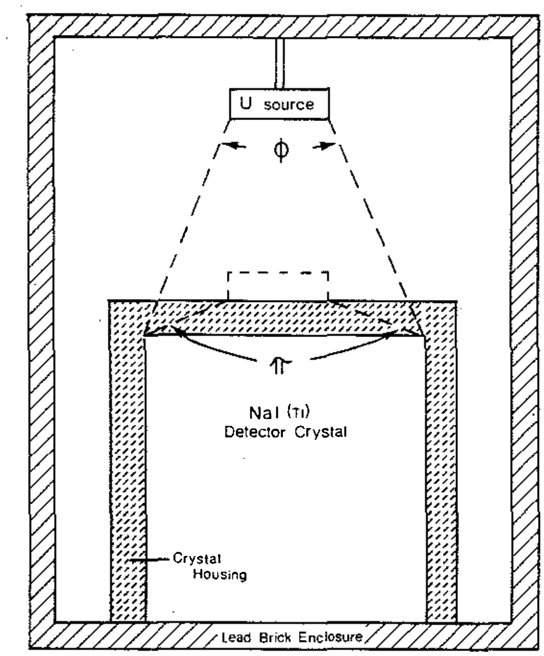

Figure 4. Source-detector configuration for the determination of the stripping ratio (s), thorium and uranium concentration factors (Q_{Th}, Q_U, and height correction factor (h).

All of the variables in the above equation except RTh, RU, and m are constants and must be evaluated for a particular laboratory before analysis of samples commences.

Background count rates in the Th and U channels were measured inside the testing chamber several times daily for a period of four weeks prior to testing, and checked periodically throughout the study. Instrument stability was obtained when the source was suspended 14.7 cm above the center of the detector housing, and this configuration (fig. 4) was used for determination of S, QTh, and QU.

The uranium and thorium concentration factors QU and QTh equate samples with known mass and concentration in ppm to unknown samples and are determined using the following equation (modified from Adams and Gasparini, 1970):

$$\text{QTh, U} = (\text{cps}/\text{ppm})/\text{kg}$$

The concentration factors were evaluated using the Canadian Radioactive Ore Standard DH-1. A sample container was filled with 0.114 kg of the powdered standard and sealed. The standard was then suspended above the detector housing and tested in the same manner as the unknown samples.

All of the rock samples analyzed were placed directly on the detector housing; thus, a height correction factor, h, was needed to maintain the source-detector geometry when the S, QTh, and QU values were calculated. The value of h is simply the ratio of the solid angles seen by the detector crystal when the samples are suspended and when they are directly on the detector housing (fig. 4). The value of h was then calculated from h = pi/psi. The accuracy of the h value was checked by analyzing 0.106 kg of powdered Canadian Radioactive Ore Standard DL-1 (83 ppm Th, 41 ppm U) in the same manner as the unknown samples. Values for eU and eTh were determined to be 41 5.6 ppm and 73 5.7 ppm respectively. Both of the above values are within the statistical accuracy obtained at the lower concentrations of U and Th encountered in the unknown samples; thus, the value of h is considered to be accurate.

In order to be able to compare U and Th concentrations for the various samples a uniform testing procedure must be followed. Source - detector geometry and separation, sample thickness and diameter must be kept constant. Large samples provide more gamma-ray emitters and improve statistical accuracy of the concentrations in ppm; thus, sample containers were chosen that were as large as practical.

A large number of accumulated counts is necessary to keep statistical errors due to fluctuations in sample and background decay rates to a minimum. Counting statistics and associated errors are discussed by Adams and Gasparini (1970) and Loevinger and Berman (1951). Reduced source- detector separation increases the number of gamma-rays interacting with the detector crystal; therefore, samples were placed directly on the gamma-ray sensor housing.

Sample Preparation and Testing

All rock samples were crushed, seived to a size of less than 2mm, and placed into 8.0 cm diameter by 2.7 cm deep tin containers. Containers of this size were chosen because they are large enough in diameter and shallow enough in depth to accommodate a fairly large sample (0.187 to 0.250 kg) without introducing a serious problem of self-absorption of gamma-rays. The containers were then made air-tight by sealing the joint between the can and the top with plastic tape.

Samples were stored for a minimum of 45 days prior to testing to re--establish secular equilibrium of the gaseous daughter product (radon) of the ^{238}U and ^{232}Th decay series that was probably released during crushing. Sealing of the containers assured a buildup of the gaseous daughters in the container and a more uniform equilibrium state after the 45-day storage period.

Before analysis of the samples the gamma analyzer had to be energy calibrated in order to accurately locate the 2.62 MeV Tl208 photopeak. Calibration was accomplished by placing a pure thorium source (sample TS-3 provided by Scintrex Inc.) into the testing chamber 14.7 cm inches) above the detector housing and then following the procedure described in the Scintrex GAM-1 Instruction Manual (1974). The energy calibration did not drift significantly in a 10-hour period, so re-calibration was performed once daily. Samples were analyzed during the day hours; however, the scintillation counter remained on continuously throughout the study to avoid warm-up stability problems.

After calibration the samples were placed into the testing chamber in direct contact with the gamma sensor housing and allowed to accumulate counts for a minimum of 70 minutes (>7000 counts). The exact number of counts accumulated during a precise amount of time was recorded and used to determine the count rate for the sample. Analysis of a single sample in both the U and Th channels typically required 140 minutes to complete.

WOLF RIVER BATHOLITH

Geology and Petrology

The Wolf River batholith underlies over 9000 km^2 of northeastern Wisconsin (fig. 5) including parts of Waupaca, Portage, Shawano, Marathon, Oconto, Menominee, Marinette, and Langlade counties. It also underlies the Menominee and Stockbridge Indian Reservations. The batholith is a large anorogenic epizonal composite pluton that consists mainly of granite and quartz monzonite with much lesser amounts of syenite, monzonite, and anorthosite (Anderson, 1975). It is similar in many respects to the classic rapakivi massifs of Finland, and is believed to be part of a major Middle Proterozoic continental event (Silver and others, 1977; VanSchmus and others, 1975; and Anderson, 1975). It was dated by VanSchmus and others (1975) at 1.5 G.a.

A geologic map of the batholith, divided into eight rock units by Anderson (1975), is given in figure 6. Detailed descriptions of the various rock units are given by Anderson (1975) and summaries provided by VanSchmus and others (1975) and Medaris and others (1973). Additional geologic studies of parts of the batholith that include useful geologic maps are Borst (1958) and Lahr (1972). Other studies of the batholith include Mancuso (1957, 1960), Prucha (1946), Weidman (1907), and Weis (1965).

The rock units of the batholith are characteristically porphyritic. Rapakivi texture is fairly common and is particularly well developed in the

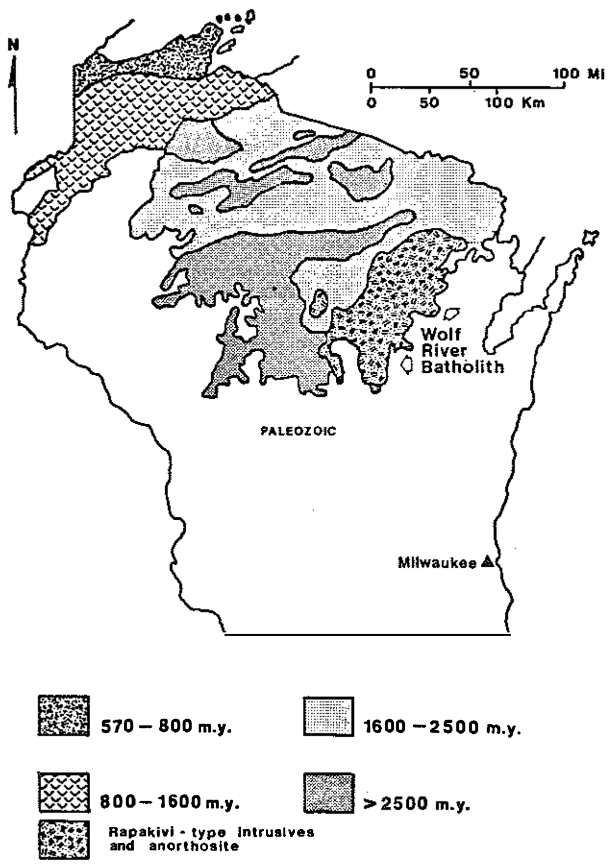

Figure 5. Generalized geologic map of Wisconsin showing the location of the Wolf River batholith.

Waupaca quartz monzonite and small dike-like bodies of Wiborgite porphyry (Anderson, 1975). The units share a chemistry that is high in alkalies (notably potassium), silicon, and Fe/Mg, and low in calcium, magnesium, and aluminum (Anderson and Cullers, 1978).

Because of the sparsity of exposures throughout most of the area, the internal age relations of the various units of the batholith are imperfectly known. On the basis of chemical, mineralogical, and field studies, Anderson (1975) suggested that the Belongia fine granite and the Belongia coarse granite differentiated from the Wolf River granite whereas the Red River quartz monzonite (probably the youngest unit of the batholith), Wiborgite porphyry, and the Wolf River granite are undifferentiated and represent the products of progressive fusion. According to Anderson and others (1980), the source material would have been compositionally similar to tonalite, granodiorite, or andesite. Among the oldest units of the batholith are the bodies of monzonite and anorthosite (Anderson, 1975). The anorthosite, which occurs as isolated masses, may not be genetically related to the batholith and may instead represent large xenoliths or roof pendants (VanSchmus and others, 1975).

The Wolf River batholith intrudes a variety of metasedimentary, metavolcanic, and calc-alkaline plutonic rock most of which are part of the 1.85 Ga central and northeastern Wisconsin complexes (VanSchmus and others, 1975b).

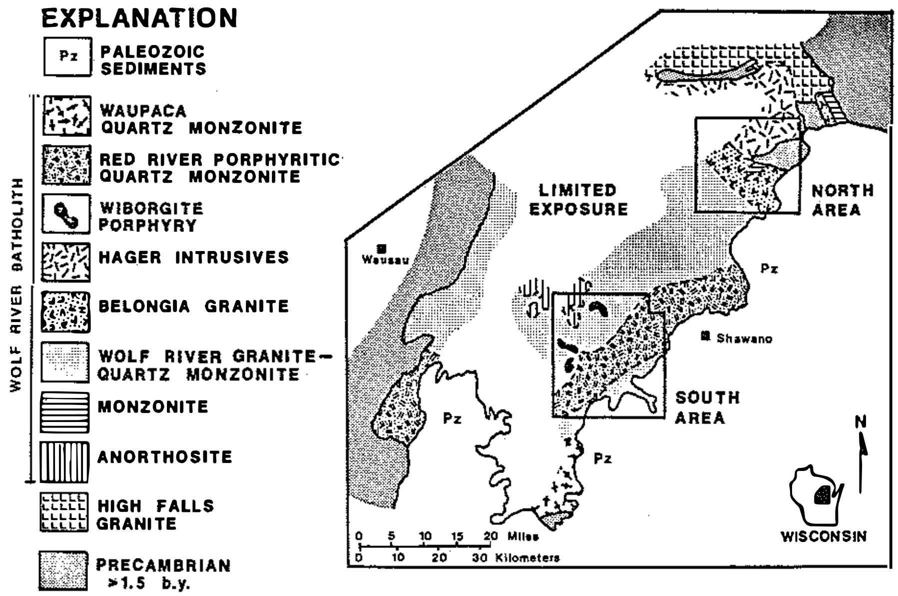

Figure 6. Geologic map of the Wolf River batholith (modified from Anderson, 1975). North and south areas correspond to regions of the batholith for which detailed radiometric distribution maps are given in figure 8 and 9 (after Meddaugh, 1978).

Uranium and Thorium Concentrations

Uranium and thorium values for the whole-rock samples from Wolf River batholith are summarized in figure 7 and table 1 and reported in detail in Mursky and others (1988). The average values, based on exposed surface area for the Wolf River batholith as a whole, are:

$$Th = 24.4 \text{ ppm}$$
$$U = 6.02 \text{ ppm}$$
$$Th/U = 4.16$$

These values are higher than average values given by Adams and others (1959) for silicic intrusive rock which ranges between 3 and 4 ppm uranium and 10 and 15 ppm thorium. The average Th/U ratio for the batholith is comparable to the average Th/U ratio for silicic intrusives of 3 to 4. Individual units of the batholith show considerable variation in uranium and thorium values, but tend to plot in fairly distinct fields (fig. 7). Uranium values range from less than 1 ppm in Wolf River granite to more than 30 ppm in the Red River quartz monzonite. Thorium values range from less than 5 ppm in Wolf River granite to more than 50 ppm in the Red River quartz monzonite and Waupaca quartz monzonite.

A few samples obtained from small aplite and pegmatite veins, and from zones rich in mafic minerals of some exposures contain values up to 183 ppm uranium and 153 ppm thorium.

Table 1. Average thorium, uranium, and Th/U values for the individual units of the Wolf River batholith.

Unit[1]	Th (ppm)	U (ppm)	Th/U[2]
Red River Quartz Monzonite (43)	36.4	10.9	3.4
Wiborgite porphyry (9)	31.2	6.2	6.2
Wolf River Granite (22)	15.1	4.1	3.7
Belongia Coarse Granite (17)	21.7	6.0	3.6
Belongia Fine Granite (6)	30.8	10.3	3.0
Hager Granite (3)	17.1	8.0	2.2
Hager Feldspar Porphyry (4)	15.5	2.9	5.8
Hager Syenite (2)	19.0	1.9	9.7
Monzonite (4)	9.5	1.5	6.8
Anorthosite (1)	4.3	nd[3]	---
Waupaca Quartz Monzonite (3)	53.5	5.4	9.5

[1]Numbers in parentheses are the number of samples analyzed for each unit.

[2]Calculated from individual Th/U values.

[3]Not detected.

The trends shown by the uranium and thorium data appear to show an increase in uranium and thorium in the younger more differentiated units, whereas the extremely low uranium and thorium samples correspond to those lower in SiO_2 content. Such an increase in uranium and thorium during differentiation is consistent with trends observed by Larsen and others (1956), Larsen and Gottfried (1960), Rogers and Ragland (1961), and Tilling and Gottfried (1969) for a number of differentiated series.

Areal Distribution of Uranium and Thorium

Contoured outcrop radiometric maps for uranium plus thorium and potassium for two regions of the Wolf River batholith are shown in figures 8 and 9. The location of these two regions, referred to as the south area and the north area, is given in figure 6. These two areas account for over 90 percent of the exposures visited.

In the south area (fig. 8) outcrop radioactivity of the Red River quartz monzonite, the most radioactive unit of the entire batholith, increases from

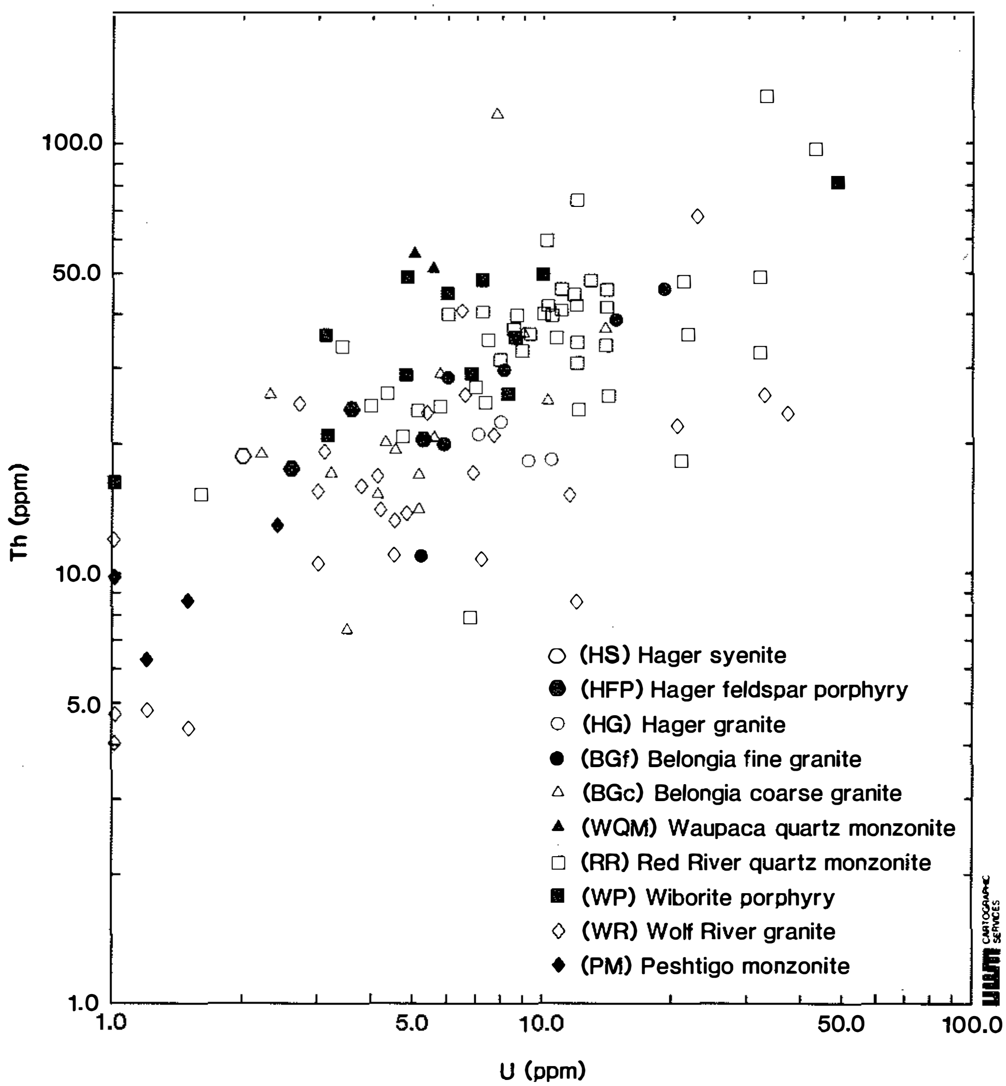

Figure 7. Distribution of uranium and thorium in Wolf River batholith, Wisconsin.

00 - 400 cps in the central part to 600 -800 cps at its contact with the older Wolf River granite. Increased radioactivity in marginal zones of plutons is common (Slack, 1949; Slack and Whitman, 1951; Ingram and Keevil, 1951; and Heinrich, 1958) and has been ascribed primarily to the outward movement of late stage fluids (deuteric or hydrothermal) enriched in uranium and thorium (Heinrich, 1958; and Adams and others, 1959).

The more radioactive margins of the Red River quartz monzonite correspond to areas of high uranium and thorium values. Thus values of 8 - 10 ppm uranium and 30 - 40 ppm thorium are typical of interior zones, and values of 20 - 30 ppm uranium and 50 - 60 ppm thorium are common for exposures near the contact between the Red River quartz monzonite and Wolf River granite. It is interesting that the known uranium and thorium prospects described by Kalliokoski (1976) are all located in the more radioactive peripheral zone of the Red River

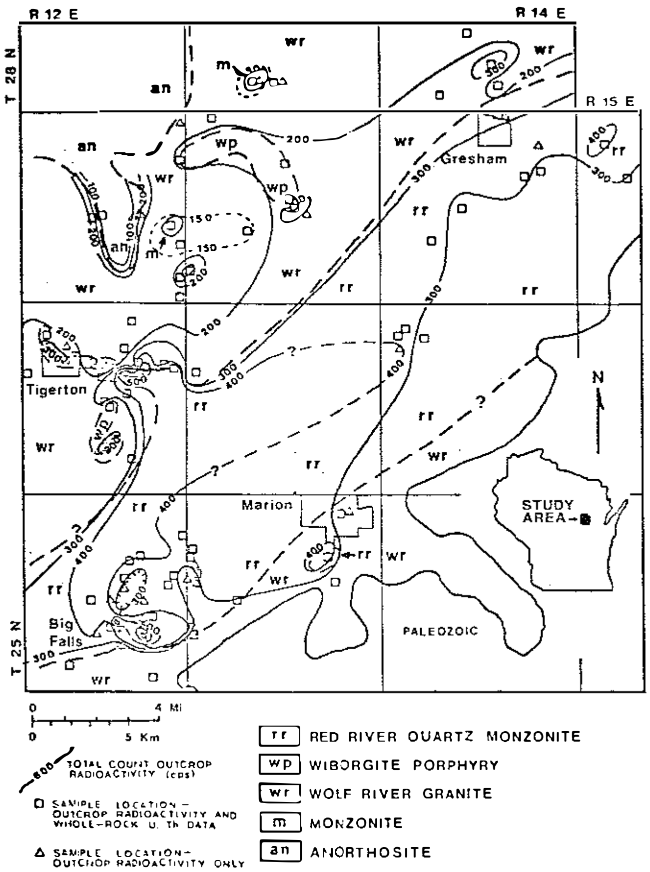

Figure 8. Outcrop radioactivity map, south area of Wolf River batholith.

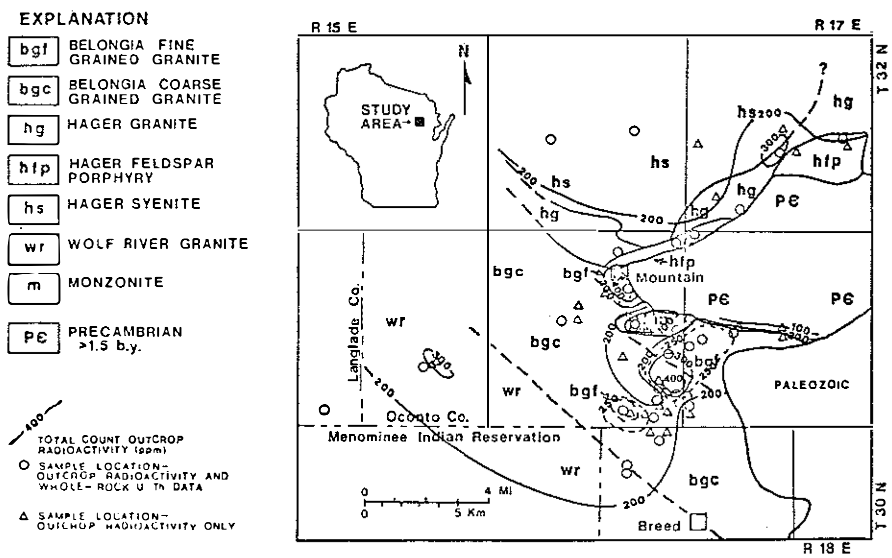

Figure 9. Outcrop radioactivity map, north area, Wolf River batholith.

quartz monzonite. The generally low Th/U ratios for the peripheral zone may indicate a preferential movement of uranium relative to thorium.

There is also a zone of increased radioactivity at the Wolf River granite-anorthosite contact related to the abundant pegmatitic and aplitic dikes that separate the two units. One sample of aplite yielded values of 37 ppm uranium and 23 ppm thorium.

In the north area of the batholith (fig. 9) a general increase in outcrop radioactivities as the contact with older Precambrian units (mainly Waupee metavolcanic and metasedimentary rock) is approached is reflected by generally increasing uranium and thorium values and decreasing Th/U ratio.

There is a small scale (15 m, not shown on the maps) zone of sharply increased radioactivity in the Belongia fine granite at its contact with the older Waupee metavolcanic and metasedimentary rock. Radioactivities increase from about 300 cps to 450 - 500 cps at the contact. Values decline rapidly over a distance of 0.5 m to less than 70 cps in the older Waupee metavolcanic and metasedimentary rock.

A similar, small scale (10 m, not shown on the maps) zone of higher radioactivity occurs in the marginal zone of the Belongia coarse granite and its contact with the older monzonite pluton (referred to as the Peshtigo monzonite by Medaris and others, 1973). Values increase from 200 - 225 cps to 350 - 400 cps at the contact. Outcrop radioactivity of the monzonite is about 110 cps.

An area of high radioactivity (450 cps) in the Belongia coarse granite (SE corner of T. 31 N., R. 16 E.) corresponds to the location of one of the few pegmatites that occur in the Wolf Rivewr batholith. The location is coincident with a peak in thorium values (40 ppm) but not uranium values. One sample from the pegmatite yielded values of 116 ppm thorium and 8 ppm uranium.

NINEMILE PLUTON, MARATHON COUNTY

Geology and Petrology

The Ninemile Pluton is located in central Marathon County, Wisconsin (fig. 10). It is aroximately 220 km^2 in extent and appearsto represent a broad dome- shaped Middle Proterozoic intrusion that was epigenetically emplaced subsequent to all major plutonic events in the area. The pluton has a peripheral zone 2 - 3 km wide of grus, crumbly rapakivi granite which constitutes the focal point of this study. The Ninemile Pluton is contemporaneous in age with the Wolf River batholith (VanSchmus, 1976) or about 1.5 Ga. It is dominated by two lithologies -- alkali granite and alkali syenite. The samples range in their state of disaggregation from slightly weathered to coarse gravel sized material. Most samples have coarse-grained, hypidiomorphic granular texture due to large crystals of perthitic microcline. Fractures and cleavage planes in microcline have been filled with hematite which imparts a deep red color to the rock. Quartz and plagioclase (An_{5-14}) occur as interstitial grains to microcline.

Biotite is the most abundant accessory mineral; however, hornblende, magnetite, hematite, epidote, and apatite are present in most samples.

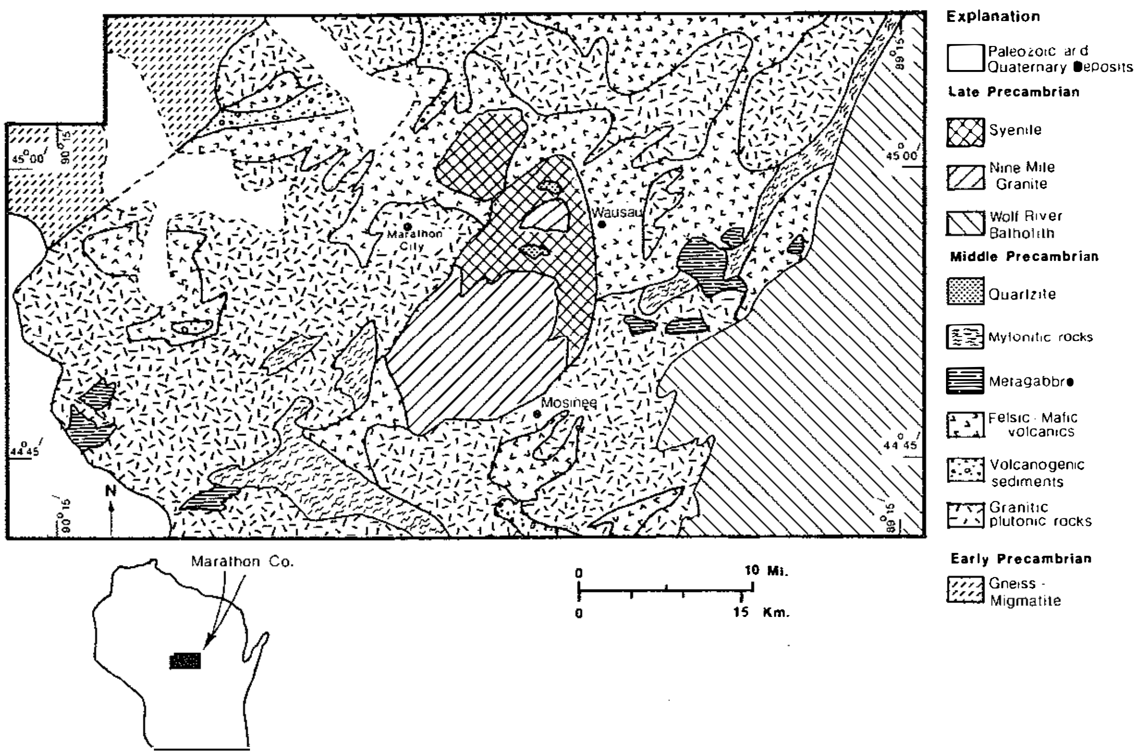

Figure 10. Generalized geologic map of Marathon County, Wisconsin (modified from LaBerge and Myers, 1983).

Chlorite is present as an alteration product of both biotite and hornblende. Radioactive accessory minerals include allanite and zircon with zircon being the most prevalent. Allanite is highly altered and exhibits metamict zones. Zircon is predominantly found in biotite masses although concentrations of zircon can be found along feldspar or quartz grain boundaries as well. Andrews (1976) provides a more complete petrographic description including modal analyses and a discussion of the genetic and tectonic aspects of the Ninemile Pluton, whereas LaBerge and Myers (1983) discuss its relationship to other rock units in Marathon County.

Uranium and Thorium Concentrations

Whole-rock uranium and thorium data for the Ninemile Pluton is summarized in figure 11. The mean and range of the uranium values are 1.6 ppm and trace to 15.6 ppm, respectively; whereas the mean and range of the thorium values are 21.2 ppm and 12.1 to 56.4 ppm, respectively.

The average value of the Th/U ratio is 13 which is much higher than the average of 3 to 4 for silicic intrusive rock as reported by Adams and others (1959). Average uranium and thorium for silicic intrusive rock are 3 to 5 ppm and 13 to 20 ppm (Adams and others, 1959; Clark and others 1966) respectively. When compared to other alkaline granitic rock, the Ninemile Pluton appears to be depleted of thorium and uranium. The large value of the Th/U ratio indicates that uranium has been preferentially leached relative to thorium.

An estimate of the amount of leachable uranium and thorium is provided by comparing the uranium and thorium content of highly weathered, gravelly

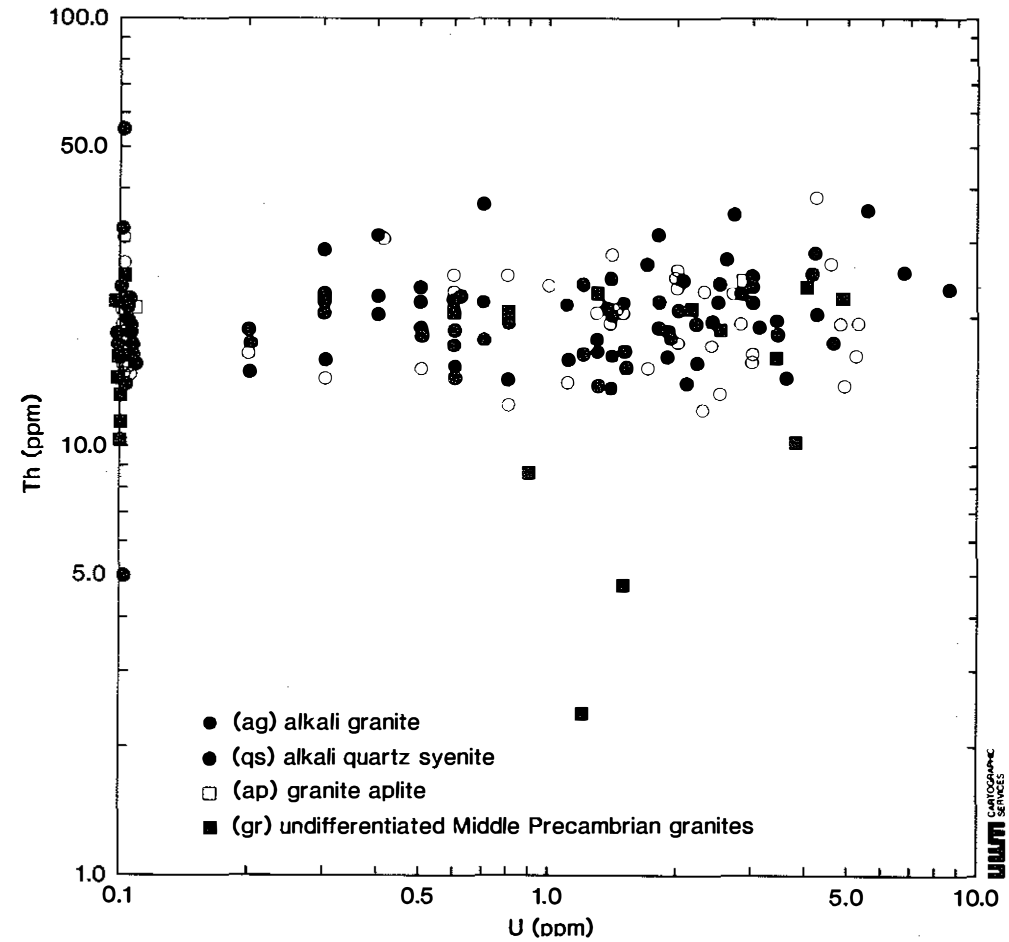

Figure 11. Distribution of uranium and thorium in Ninemile Pluton and syenite, Marathon County, Wisconsin.

samples to adjacent slightly weathered rock samples (table 2). An average of 28 percent of the thorium and 76 percent of the uranium appears to have been leached between the two stages of disaggreation of the rock. If one assumes that the rock samples have not lost thorium and an initial Th/U ratio of 4, then minimum values of the uranium and thorium content for fresh unweathered rock would be 6.8 ppm and 27.3 ppm respectively. In all probability, the slightly weathered rock samples also have lost a part of their initial thorium content during transformation from fresh unweathered rock to their present state. Again assuming an initial Th/U ratio of 4 and a constant percentage of thorium loss, the initial concentration of uranium and thorium in fresh unweathered rock would be 9.5 ppm and 38 ppm, respectively.

Samples of alkali quartz syenite have an 11 percent greater thorium content than do samples of alkali granite. In a study of the zoned Magnet Cove alkaline igneous complex in Arkansas, Erickson and Blade (1963) found that thorium concentrations were higher in the early formed marginal rock as compared to the late-formed core rock. A similar genetic relationship exists in the Wausau Syenite Pluton between the peripheral alkali quartz syenite which was intruded by the alkali granite (Ninemile Pluton) core. Upon weathering, the alkali granite rock samples have lost only 4 percent more thorium than the alkali

Table 2. Comparison of thorium, uranium, and Th/U ratio values between rock samples and "gravel" samples.

Sample	Th (ppm)	U (ppm)	Th/U
17-1-30+ G	24.0	1.2	20
17-1-30-Rs	35.1	2.7	13
17-2-25 G	22.1	2.5	9
17-2-25-Rs	28.0	2.6	11
17-3-10 G	22.1	0.5	44
17-3-15-Rs	22.9	0.6	38
16-1-20 G	18.7	0.0	--
16-2-30 G	16.0	1.1	15
16-1-25-Rs	26.3	6.7	4
16-1-30-Rs	31.0	1.8	17
16-2-20 G	14.7	3.6	4
16-2-20-Rs	36.3	5.6	6
15-3-5 G	16.6	1.2	14
15-3-15 G	19.9	1.4	14
15-3-10-Rs	18.9	3.4	6
13-2-0 G	20.8	1.5	14
13-2-5-Rs	27.1	4.6	6
13-2-10 G	27.7	0.0	--
13-2-20 G	17.9	0.0	--
13-2-15-Rs	23.4	2.3	10
13-4-45 G	16.1	0.3	54
13-4-45-Rg	26.1	2.0	13
19-1-5 G	15.7	0.1	157
19-1-10-Rg	13.5	2.5	5
18-1-20 G	14.9	0.2	75
18-1-30 G	23.8	3.0	8
18-1-25-Rs	24.6	8.8	3
6-1-5 G	22.7	1.3	17
6-1-5-Rg	30.2	15.6	2
7-1-5 G	19.8	0.0	--
7-1-10-Rg	38.6	4.2	9
Average values			
Rock samples (14)	27.3	4.5	6
Gravel samples (17)	19.6	1.1	18

R - indicates competent rock sample
G - indicates decomposed rock sample (gravel)
s - alkali quartz syenite sample
g - alkali granite sample
\+ - indicates depth below surface (feet)

quartz syenite samples. Thus, it appears that the greater thorium content of the alkali quartz syenite is partly a reflection of the primary distribution of thorium in the pluton. Increased thorium (and uranium) in the marginal zones of plutons is common (Heinrich, 1958; Ingram and Keevil, 1951) and has been ascribed to the outward movement of late stage fluids (deuteric or hydrothermal) enriched in these elements (Heinrich, 1958; Adams, and others, 1959).

MIDDLE PROTEROZOIC QUARTZITE AND METACONGLOMERATE

Wisconsin contains several Middle Proterozoic quartzite-metaconglomerate rock units which, in terms of their age and lithology, have many similarities to the uranium-producing quartz-pebble conglomerate of Canada, South Africa, and Brazil. The formations studied here were the Baldwin conglomerate and the McCaslin quartzite in the McCaslin - Mountain area; the Pine River quartzite - conglomerate in the Florence area; the Palms quartzite in the Gogebic area; and the Flambeau quartzite in the Barron area (fig. 12).

A total of 121 representative whole-rock samples were analyzed for uranium and thorium content. The average uranium and thorium concentrations in these 121 samples are 1.5 ppm and 5.4 ppm respectively whereas the range for uranium was trace to 5 ppm and for thorium trace to 32 ppm. These averages and ranges are well within the normal values for similar rock types found elsewhere.

THE McCASLIN-MOUNTAIN AREA

Geology and Petrology

The McCaslin-Mountain area is located in the northeastern part of Wisconsin and includes parts of Oconto, Forest, Langlade, and Marinette counties. The study area is contained within longitudes 88°45' and 88°15' and between latitudes 45°7'30" and 45°27'30".

The McCaslin-Mountain area is one of diverse gelogic history in that it includes metavolcanic, metasedimentary, and plutonic rock. Parts of the area have been mapped by Mancuso (1960, 1957), Motten (1972), and Lahr (1972). The geologic units that were tested for their radioactivity were the Baldwin conglomerate and the McCaslin quartzite. The Baldwin conglomerate occurs as a thin belt up to 90 m wide and 3.2 km long, which appears to pinch out at both ends.

The Baldwin Formation is a medium-gray metaconglomerate that consists of elongate pebbles in a matrix of rock fragments, quartz, and microcline, with varying amounts of biotite and muscovite. The pebbles are poorly sorted and well-rounded to sub-rounded; consisting mainly of quartz, Waupee volcanics, foliated Macauley granite, and potash feldspar. Most of the potash feldspar is relatively unaltered microcline which suggests that the sediments were transported a short distance. The pebbles generally range from 2 mm to 7 cm in diameter.

The McCaslin quartzite is considered by Dutton (1971) to be time equivalent to the Baldwin conglomerate and crops out along the McCaslin Range, at

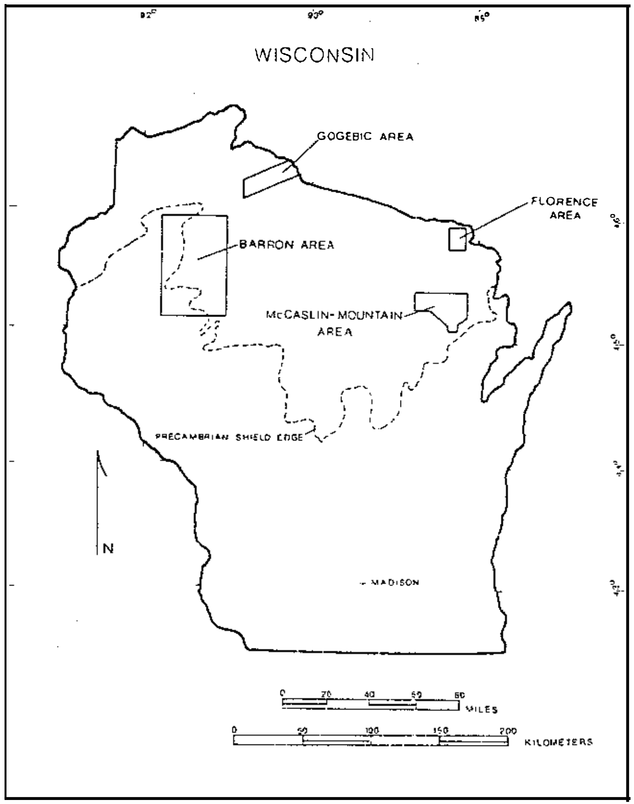

Figure 12. Location map of the selected Proterozoic quartzite-conglomerate rock units in Wisconsin.

Thunder Mountain, and at Deer Lookout Tower Hill. The McCaslin quartzite consists of a basal metaconglomerate and quartzite with the quartzite comprising the bulk of the formation.

The quartzite of the McCaslin Formation is a hard, brittle, vitreous rock which varies in color from white to shades of purple, and locally brick red. The quartzite is generally more than 85 percent quartz with varying amounts of muscovite, hematite, specularite, and rarely biotite and chlorite. Occasionally the quartz grains have rutile or zircon inclusions. The texture varies from a mosaic of interlocking quartz grains to medium-sized rounded grains. Bedding is present in some exposures and is usually recognized by changes in grain size or contrasting colors within beds. Crossbedding and ripple marks are also apparent at some exposures.

The basal metaconglomerate of the McCaslin Range consists of well-rounded to sub-rounded pebbles and cobbles in a matrix of light-gray to brick-red quartzite. The pebbles are primarily composed of vein quartz with dark gray (hematitic) or white quartzite pebbles which are locally abundant. Occasionally jasper, hematite or iron formation pebbles are present and are usually smaller and more angular than the quartz or quartzite pebbles. The pebbles are generally poorly sorted with an average diameter of 2 to 4 cm and a maximum diameter of 10 to 17 cm. The matrix is composed mostly of quartz grains with varying amounts of hematite, muscovite, and rarely andalusite, chlorite, tremolite, and biotite.

The basal metaconglomerate at Thunder Mountain is similar to that of the McCaslin Range except that the pebbles are generally much smaller. Most pebbles at Thunder Mountain are either quartz or hematitic quartzite and are generally 0.5 cm in diameter with a maximum of 1.5 to 2 cm in diameter. The matrix of the metaconglomerate at Thunder Mountain is composed mostly of well-rounded quartz grains, with poikiloblastic andalusite common in many samples. Other minerals of the matrix include sillimanite, hematite, specularite, muscovite, chlorite, and zircon.

Uranium and Thorium Concentrations

The distribution of uranium and thorium in the Middle Proterozoic quartzite and metaconglomerate units of the McCaslin-Mountain area is shown in figure 13. Locally, the distribution of radioisotopes is random; however, regionally, there are three distinct areas with differing levels of radioactivity. The areas include the McCaslin quartzite in McCaslin Range area, the McCaslin quartzite in Mountain area, and the Baldwin-conglomerate in Mountain area.

In the McCaslin Range the mean and range of thorium is 6.8 ppm and 1 to 32 ppm respectively; whereas the mean and range of uranium is 1.5 ppm and from trace to 5 ppm respectively. In the McCaslin quartzite in Mountain area, the range of thorium and uranium is from 2 to 8 ppm and trace to 3 ppm, respectively. The mean is 4.5 ppm for thorium and 1.5 ppm for uranium. The majority of McCaslin quartzite samples from the McCaslin Range contain between 2 and 9 ppm thorium, with several samples containing between 10 and 32 ppm thorium. Comparatively, most samples of McCaslin quartzite from the Mountain area contain between 2 and 6 ppm thorium, with no samples being greater than 8 ppm thorium. Therefore, there is a general decrease of thorium from north to south within the McCaslin quartzite.

The range of thorium and uranium in the Baldwin conglomerate from the Mountain area is 5 to 16 ppm and 2 to 3 ppm respectively. The Baldwin conglomerate samples are fairly evenly distributed between 5 and 16 ppm thorium, and from 2 to 3 ppm uranium. The mean thorium and uranium concentrations in the Baldwin Formation are 9.3 ppm and 2.4 ppm, respectively; whereas the mean thorium and uranium concentrations in the McCaslin Formation are 5.6 ppm and 1.5 ppm, respectively. Therefore, the Baldwin conglomerate has a somewhat higher average concentration of thorium and uranium than the McCaslin quartzite.

THE FLORENCE AREA

Geology and Petrology

The Florence area is located in northeastern Wisconsin in Florence County. The study area is contained within longitudes 88°15' and 88°22' and between latitudes 45°49' and 45°56'.

The Florence area has both Archean and Proterozoic rock which have been described by Nilsen (1964), Dutton (1971), and others. The Archean is represented by the Quinnesec Formation. The Early Proterozoic includes the Baraga Group (Michigamme Slate and Badwater Greenstone Formations), the Paint River Group (consisting of the Dunn Creek Slate, Riverton Iron Formation, and Early Proterozoic metagabbro, metadiabase, and granite. In the Florence area only

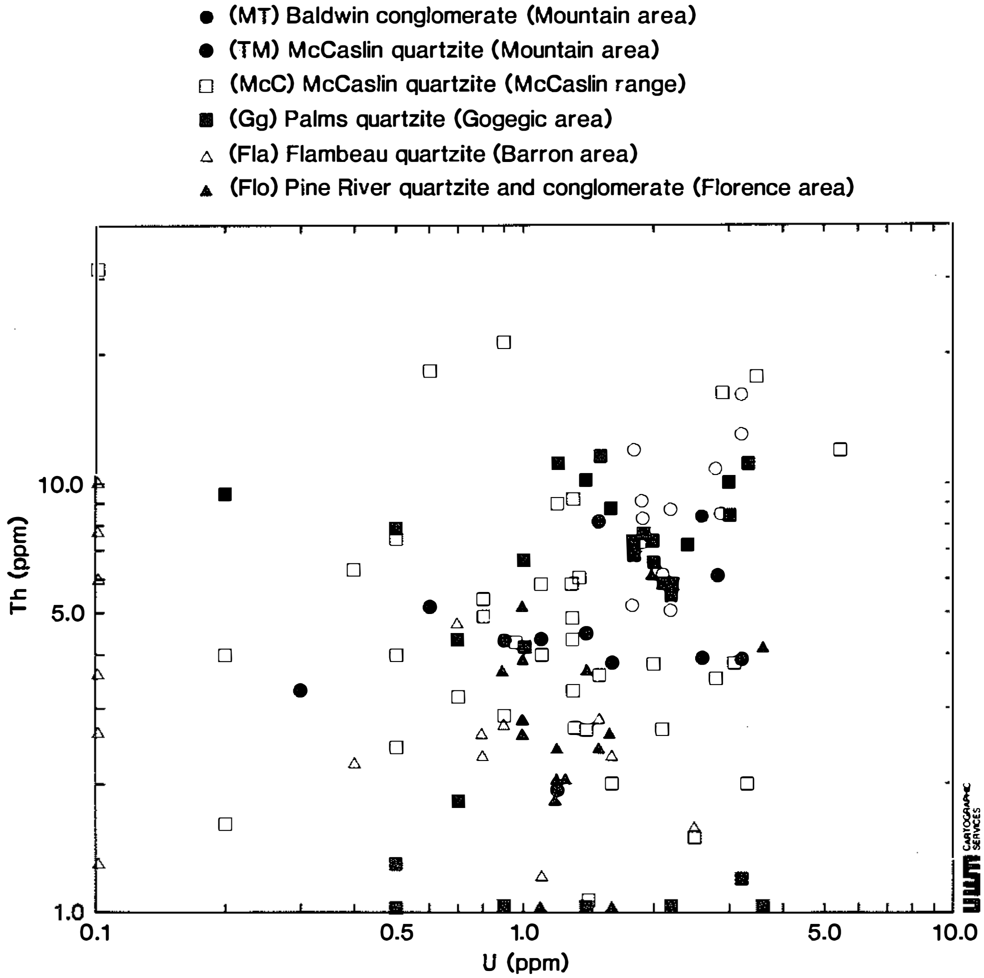

Figure 13. Distribution of uranium and thorium in Proterozoic quartzite-metaconglomerate, Wisconsin

the Pine River quartzite-conglomerate, a member of the Michigamme Slate, was analyzed for its radioactivity.

The Pine River quartzite-conglomerate member of the Michigamme Slate has been studied in detail by Nilsen (1964) and consists of a lower metaconglomerate, a middle pebbly quartzite and an upper metaconglomerate. The Pine River member is represented by a ridge that extends for about three miles from the center of sec. 28, T. 39 N., R. 18 E., to the northeast corner of sec. 24, T. 39 N., R. 17 E. Exposures are common throughout the length of the ridge, which is up to 210 m wide.

The upper and lower metaconglomerate units are composed mainly of pebbles and rarely cobbles of fine-grained quartz (recrystallized chert or quartzite) with varying amounts of vein quartz, jasper, iron formation, and, rarely, hematite. In addition to distinct pebbles and cobbles, there are very abundant lenticular shaped, fine-grained quartz forms thought by Nilsen (1964) to represent stretched pebbles. The stretched pebbles range in size from 1.25 to 23 cm in diameter. The matrix of the metaconglomerate is composed primarily of gray quartzite with varying amounts of sericite, muscovite, hematite, specularite, biotite, chlorite, and grunerite.

The middle pebbly quartzite unit is a light-gray to reddish-gray, or white, fine-grained quartzite with occasional pebbly layers. It is composed mostly of quartz with some hematite, muscovite, and sericite, and rarely kyanite.

Uranium and Thorium Concentrations

In the Pine River quartzite-conglomerate the range of thorium and uranium is from 1 to 6 ppm and from 1 to 4 ppm respectively, and the mean is 2.9 ppm for thorium and 1.4 ppm for uranium. The distribution of uranium and thorium appears to be completely random within the Pine River quartzite-conglomerate (fig. 13).

THE GOGEBIC AREA

Geology and Petrology

The Gogebic area lies in the northwestern part of Wisconsin and includes parts of Iron, Ashland, and Bayfield counties. The study area is defined by the northeasterly trending Gogebic Range and is contained within latitudes 90°10' and 90°45', and between longitudes 45°7'30" and 45°27'30".

The Gogebic area in Wisconsin has been most extensively described by Aldrich (1929) and includes Archean, Early, and Middle Proterozoic units. The Early Proterozoic Gogebic area includes the Chocolay Group (Bad River Dolomite Formation in Wisconsin), the Menominee Group (Palms Quartzite and Ironwood Iron Formation), and the Tyler Slate. In the Gogebic area the Palms quartzite was the only one selected for the uranium and thorium analyses.

The Palms quartzite unconformably overlies the Bad River dolomite and occurs as a prominent ridge (along with the Ironwood Iron Formation) across the entire Gogebic area. The Palms quartzite is an average of 135 m thick and is divided into a lowermost metaconglomerate, a middle metasiltstone, and an upper quartzite.

The metaconglomerate consists of well-rounded, poorly sorted pebbles of granite with some vein quartz and graywacke in a matrix of grayish-green quartzite with potash feldspar and chlorite. The pebbles are generally 5 cm in diameter, but may be as large as 20 cm in diameter (Aldrich, 1929).

Near Mount Whittlesey, is an excellent exposure of metaconglomerate. Here the Bad River dolomite underlies the Palms quartzite, and the pebbles are almost exclusively recrystallized chert. The pebbles are poorly sorted, angular to sub-rounded, and range from 2 mm to 10 cm in diameter. The matrix of the metaconglomerate is composed of gray, fine-grained quartzite with minor amounts of muscovite.

Metaconglomerate is also exposed along the Potato River in the NW corner, SW1/4 sec 20, T. 45 N., R. 1 E. At this location the underlying rock type is greenstone which is reflected as pebbles within the metaconglomerate. However, evidence that the Bad River dolomite was at one time present can be seen in the abundant chert and cherty dolomite clasts in the rock. The matrix of the metaconglomerate is composed of green, fine-grained quartzite with chlorite, feldspar, and minor carbonate.

The upper unit of the Palms quartzite is composed of massive, vitreous, pure quartzite. The color of the quartzite is white, green to brown, or red. The upper quartzite consists of medium-grained, well-rounded quartz with varying amounts of mica, magnetite, and rarely amphibole. The upper quartzite ends abruptly but appears to be conformable with the overlying Ironwood Iron-Formation.

Uranium and Thorium Concentrations

The distribution of uranium and thorium in the Palms quartzite of the Gogebic area is illustrated in figure 13. The range and mean of thorium in the Palms quartzite is trace to 11 ppm and 5.7 ppm respectively; whereas the range and mean of uranium is from trace to 4 ppm and 1.7 ppm respectively. The majority of the Palms formation samples contain trace to 3 ppm uranium and are relatively uniformly distributed between 0 and 11 ppm thorium. Throughout the Palms quartzite there appears to be no relationship between radioactivity and vertical or lateral position within the formation.

THE BARRON AREA

Geology and Petrology

The Barron area is located in the northwestern part of Wisconsin and includes parts of Washburn, Barron, Rusk, and Sawyer counties. The study area is contained within longitudes 89°53' and 91°49' and between latitudes 45°45' and 46°.

The Barron area has been described by Hotchkiss (1915, 1929) and Dutton (1971). The Barron area includes rock of Paleozoic and Middle Proterozoic age. The Middle Proterozoic includes the Barron quartzite, the Flambeau quartzite and several unnamed units of metavolcanic and metasedimentary rock, and granite. The relative stratigraphic positions of the Middle Proterozoic units are largely unknown due to a lack of exposures and radiometric age dates. It is generally believed, however, that the Barron quartzite is younger than the Flambeau quartzite and the rock covering the eastern part of the area. In the Barron area only the Flambeau quartzite was tested radiometrically.

The quartzite of the Flambeau Formation is reddish- brown or purple, to yellowish-gray, and is composed of well- cemented, medium-to fine-grained quartz with minor amounts of feldspar and hematite. The quartzite occasionally is cross-bedded and ripple marks were noted at the SW corner, NW1/4SW1/4 sec 6, T. 32 N., R. 6 W.

Uranium and Thorium Concentrations

The distribution of thorium and uranium in the Flambeau quartzite of the Barron area is shown in figure 13. As in most of the other areas studied the radioisotope distribution of the Flambeau quartzite appears to be completely random. The range of thorium and uranium concentration is 1 to 10 ppm and trace to 2 ppm respectively. The mean thorium and uranium concentrations are 3.6 ppm and 0.8 ppm respectively. Most of the samples contain from 1 to 3 ppm thorium, whereas all samples contain between trace and 2 ppm uranium.

CONCLUSIONS

The major control over the distribution of uranium and thorium in the Wolf River batholith is believed to be due to primary magmatic processes. The high uranium and thorium values and low Th/U ratios characteristic of the more radioactive marginal zones of the Red River quartz monzonite indicate that some late-stage enrichment of uranium and thorium may have occurred. Due to the relatively high uranium and thorium content of the batholith a considerable amount of uranium and thorium could be released during weathering.

Within the Ninemile Pluton it appears that uranium has been preferentially leached from the rock relative to thorium and alkali granite appears to be slightly more susceptible to leaching of uranium and thorium than alkali quartz syenite. Vertically uranium and thorium tend to increase with depth suggesting a fine control over the vertical distribution.

The average concentration of uranium and thorium within the Middle Proterozoic metasedimentary rock units are somewhat higher than the average concentration for similar rock types reported in the literature.

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In 1984 the U.S. Geological Survey assumed from the Department of Energy, the responsibility for archiving and sale of NURE data. Copies of NURE data tapes, whether dealing with the analyses of rock, stream sediment, or water can be purchased from the EROS Data Center, User Services, Mundt Federal Building, Sioux Falls, South Dakota 57198 (Telephone 605-594-6151). Paper or microfiche copies of NURE written reports or maps are available as open-file reports from the U.S. Geological Survey Open-file Services Section, Denver Federal Center, Box 25425, Denver, Colorado 80225 (Telephone 303-236-7476).

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After the manuscript has been reviewed by an associate editor and reviewers (specialist in the field addressed by the paper) a final decision on acceptance or rejection will be made by the editor. The manuscript, if accepted, will be returned to the author for modification, based on the recommendations of the associate editor and reviews, and for preparation of the final copy. The final manuscript will then be submitted to the editor who will see the manuscript through its publication stages.

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