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CHARACTERIZATION OF CRYSTALLINE ROCKS IN THE LAKE SUPERIOR REGION, USA: IMPLICATIONS FOR NUCLEAR WASTE ISOLATION

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ABSTRACT

The Lake Superior region (Wisconsin, the Upper Peninsula of Michigan, and Minnesota) contains 41 Precambrian crystalline (medium- to coarse-grained igneous and high-grade metamorphic) rock complexes comprising 64 individual but related rock bodies with known surface exposures. Each complex has a map area greater than 78 km^2. About 54% of the rock complexes have areas of up to 500 km^2, 15% fall between 500 km^2 and 1000 km^2, 19% lie between 1000 km^2 and 2500 km^2, and 12% are over 2500 km.^{2} Crystalline rocks of the region vary widely in composition, but they are predominantly granitic. Repeated thermo-tectonic events have produced early Archean gneisses, migmatites, and amphibolites with highly tectonized fabrics that impart a heterogeneous and anisotropic character to the rocks. Late Archean rocks are usually but not invariably gneissose and migmatitic. Proterozoic rocks of the region include synorogenic (foliated) granitic rocks, anorogenic (non-foliated) granites, and the layered gabbro-anorthosite-troctolite intrusives of the rift-related Keweenawan igneous activity. Compared with the Archean rocks of the region, the Proterozoic bodies generally lack highly tectonized fabrics and have more definable contacts where visible. Anorogenic intrusions are relatively homogeneous and isotropic. On the basis of observed geologic characteristics, postorogenic and anorogenic crystalline rock bodies located away from recognized tectonic systems have attributes that make them relatively more desirable as a possible site for a nuclear waste repository in the region. This study was conducted at Argonne National Laboratory under the sponsorship of the U.S. Department of Energy through the Office of Crystalline Repository Development at Battelle Memorial Institute, Columbus, Ohio.

INTRODUCTION

The Lake Superior region (also referred to as the north-central region in National Waste Terminal Storage Program documents) is defined here to include Wisconsin, the Upper Peninsula of Michigan, and Minnesota. This paper presents summary descriptions of the characteristics of crystalline rocks of the region for the purpose of assessing their relative suitability for nuclear waste isolation. The data are summarized from more comprehensive geologic studies of the region.[1,2]

Sponsored by the U.S. Department of Energy's Crystalline Repository Project Office, this study identified 41 crystalline rock complexes comprising 64 individual but related rock bodies (see Table I) and was conducted within the following framework. Crystalline rocks, as defined by the Office of Crystalline Repository Development at Battelle Memorial Institute, Columbus, Ohio, are medium- to coarse-grained igneous and high-grade metamorphic rocks. All rock bodies or complexes included in the study have intermittent exposures over a mapped area of at least 78 km^2, except when they are part of a larger complex of geologically related units. Information on geometry, age, origin, petrography (mineral composition, and the degree and type of alteration), structural features, and geophysics was considered most relevant for defining the geologic characteristics of the rock bodies.

Geological details, in many cases, are obscured by onlapping Paleozoic sedimentary rocks and a discontinuous but pervasive cover of glacial drift. Therefore, geologic field control is inadequate in some areas.

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TABLE I

Distribution of Described Crystalline Rock Complexes/Bodies in the Lake Superior Region

State	Rock Complexes	Rock Bodies*
Wisconsin	17	40
Michigan	9	9
Minnesota	15	15
Total	41	64

*Bodies that cross state lines are included in the state containing the larger portion.

For this reason, the available geological information varies greatly in level of detail. Although geophysical studies have been helpful in regional evaluations, further geologic control through field and laboratory work is essential in developing a coherent picture of the crystalline rocks of the region.

In addition to the geologic characteristics of crystalline rocks summarized here, information on seismicity, tectonics, surficial deposits, hydrology, and mineral resources of the Lake Superior region was published in Ref. 3. Similar data bases have been prepared for the northeastern[4,5] and southeastern[6] regions of the U.S. Such comprehensive data bases will provide a reliable geologic basis for identifying areas for detailed geologic characterization. Such in-depth studies may lead to selection of a rock body that would be suitable for a nuclear waste repository.

This paper describes the time and space relations, geologic setting, lithologic and structural characteristics, and relative homogeneity of the crystalline rock bodies of the Lake Superior region.

TIME AND SPACE RELATIONS

Radiometric age data (see Appendix) are available for most of the crystalline rocks of the Lake Superior region. Therefore, individual or related rock bodies were grouped into the following chronologic groups proposed by the U.S. Geological Survey:

Proterozoic	
Late	600-1000 m.y.
Middle	1000-1600 m.y.
Early	1600-2500 m.y.
Archean	
Late	2500-2800 m.y.
Middle	2800-3400 m.y.
Early	3400 m.y. and older

Crystalline rocks of the region range in age from ~3600 m.y. (Early Archean) to ~1000 m.y. (Middle Proterozoic). Tables II and III, which summarize the time and space relations of the 41 rock complexes of this study, yield the following observations.

1. About half of the rock complexes are less than 500 km^2 in map area. About one third fall between 500 km^2 and 2500 km^2 (see Table II).
2. Rock complexes greater than 2500 km^2 are present in Minnesota and Wisconsin.
3. Archean and Proterozoic complexes are roughly equal in abundance, but the former account for about 60% of the total area.
4. Archean rocks predominate in Minnesota and the Upper Peninsula of Michigan, whereas Proterozoic rocks are more abundant in Wisconsin.
5. The area occupied by Archean crystalline rocks in Minnesota is roughly twice the total area occupied by the crystalline rocks in Wisconsin.

TABLE II

Distribution of Crystalline Rock Complexes by Map Area* in the Lake Superior Region

State	<500 km^2	500-1000 km^2	1000-2500 km^2	>2500 km^2	Total
Wisconsin	10	4	2	1	17
Michigan	7	-	2	-	9
Minnesota	5	2	4	4	15
Total	22	6	8	5	41
% of total	53.7	14.6	19.5	12.2	100.0

*Areas measured from Figs. 2-4.

GEOLOGIC SETTING

Geological relationships indicate that Precambrian orogenic and igneous episodes in the Lake Superior region were very active though generally of short duration. There is considerable evidence of repeated vertical and horizontal movements, regional and thermal metamorphism, deformation, and intrusion. The rift systems and intracratonic basins that developed on the Archean basement provided depositional sites for supracrustal sedimentary and volcanic rocks.

Major Orogenic and Igneous Episodes

Based on radiometric ages, three major episodes of orogenic/igneous activity are recognized in the Lake Superior region: Algoman orogeny (~2650 m.y.),[7,8] Penokean orogeny (~1850 m.y.),[8,9,10] and Keweenawan igneous activity related to the Midcontinent rift system (1200-900 m.y.).[11,12] Anorogenic magmatism approximately 1500-1760 m.y. ago also played an important role in the region's geologic history, particularly in Wisconsin.[10,13] A 1630-m.y. thermal event may have affected the rocks of the region.[7,10,14] The prevalence of anorogenic magmatic events in the region since 1760 m.y. indicates that vertical movements have prevailed over horizontal tectonism.[12]

The Algoman orogeny was marked by emplacement of granitic magmas and by welding of the Archean gneiss terrane to the south to the Archean greenstone-granite terrane to the north. The boundary zone, or suture, between these Archean terranes is defined by the Great Lakes tectonic zone, which is approximately 50 km wide and extends discontinuously across the region (see Fig. 1) in a roughly northeasterly direction for about 1200 km.[15] This zone displays a distinctive tectonism that affected both Archean and Proterozoic rocks. It also defines, but in places straddles, the northern margin of the Penokean fold belt.[15] The zone was characterized by active compression during the Algoman orogeny (~2650 m.y.), extensional tectonics before the Penokean orogeny (2500-2000 m.y.), compression during the Penokean orogeny (1900-1850 m.y.), extension during Middle Proterozoic time, and minor reactivation during Phanerozoic time. The Proterozoic events in this zone are probably related to changes in the mobile high-grade gneiss basement coupled to the stable greenstone-granite terrane. On the basis of

TABLE III

Age and Map Area Relationships of Crystalline Rocks of the Lake Superior Region

Wisconsin Rock Complexes	Wisconsin Area (km^2)	Michigan Rock Complexes	Michigan Area (km^2)	Minnesota Rock Complexes	Minnesota Area (km^2)	Total Complexes / Total Area	%** of Complexes / % of Total Area
Early Archean							
1		1		2		4	10
	396		308		8882	9586	20
Late Archean							
3		8		7		18	44
	2351		3186		13479	19016	39
Archean Total							
4		9		9		22	54
	2747		3494		22361	28602	59
Early Proterozoic							
10		2*		5		15	36
	5441		15*		3409	8850	18
Middle Proterozoic							
3		-		1		4	10
	5050		-		5902	10952	23
Proterozoic Total							
13		-		6		19	46
	10491		-		9311	19802	41
Grand Total							
17		9		15		41	100
	13238		3494		31672	48404	100

*Included with Wisconsin.
**Figures rounded to whole numbers.

recent geophysical data and test drilling, the tectonic role of the Great Lakes tectonic zone in the Proterozoic is subject to different interpretations. However, the evidence at hand does not support the idea that the zone defined a Proterozoic continental margin in Minnesota.[16]

Evidence of the Penokean orogenic event is prominently developed in the Upper Peninsula of Michigan and in Wisconsin. The event was marked by large-scale igneous activity, high-grade metamorphism, faulting, and folding.[17] Penokean folding and metamorphism of the Archean rocks increased in intensity to the south and southeast, causing remobilization of basement gneisses into gneiss domes in the western part of the Upper Peninsula of Michigan and northern Wisconsin.[18,19] Passive deformation accompanying block faulting in basement rocks may have caused formation of structural basins in overlying sedimentary formations.

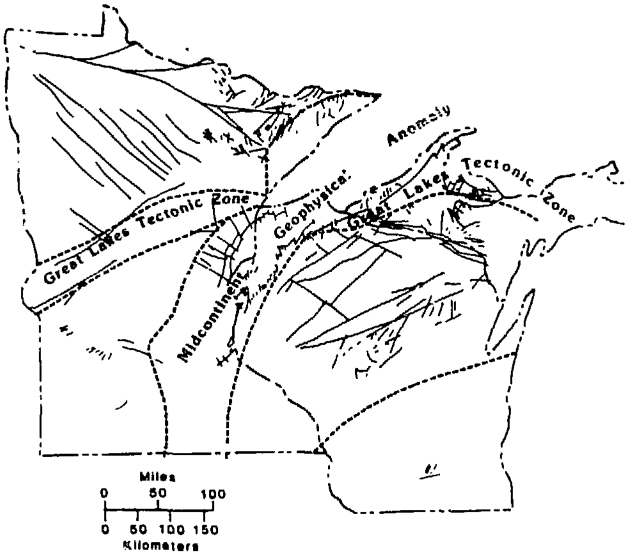

Fig. 1. Major Fault Trends in the Lake Superior Region (Midcontinent geophysical anomaly is also referred to as the Midcontinent rift system) (Source: Refs. 2,3).

The distinct petro-tectonic zones in early Proterozoic rocks of the Lake Superior region, particularly in Wisconsin, may represent active *continental margin processes.*[20] *Alternatively,* sedimentation may have taken place in rifted basins during breakup and spreading along the southern margin of the Archean craton.[21]

The Penokean (~1850-m.y.) magmatism in Wisconsin is considered to represent margin-type igneous activity terminated by collision.[22,23] Some of the Penokean granitic rocks show iron enrichment similar to the "magnetite series" rather than the low oxygen fugacity of the "ilmenite series."[24] The intrusive complexes of northeastern and northern Wisconsin, and some of those in east-central Minnesota, are probably representative of the main eugeosynclinal orogenic belt, whereas the 1760-1500-m.y. magmatism was predominantly anorogenic and alkaline.[23,25,26]

The Midcontinent rift system formed 900-1200 m.y. ago and was probably the last major thermal-tectonic event in the region. Associated igneous activity occurred over a relatively short period of time. It probably initiated ~ 1200 m.y. ago and reached maximum development about 1100 m.y. ago.[12]

Fault Trends

Major fault trends[2,3] in the Precambrian terranes of the Lake Superior region (see Fig. 1) have the following generalized features:[2,3,27]

1. A northwest-striking fault pattern in the greenstone-granite terrane of northwestern Minnesota. This pattern is particularly well developed north of the Great Lakes tectonic zone.

2. East-northeast- to east-trending faults in the gneissic rocks south of the Great Lakes tectonic zone

in Minnesota, in the Upper Peninsula of Michigan, and south of the Midcontinent rift system in Wisconsin. These faults were probably affected by the Penokean orogeny.

3. A coherent fault pattern in the Minnesota portion of the Great Lakes tectonic zone.

4. Complex fault patterns within the Midcontinent rift system.

Metamorphism

The pattern of discontinuous outcrops, the limited availability of drill core samples, and the local focus of many metamorphic studies have resulted in information on metamorphism in the region that varies greatly in detail. Moreover, repeated metamorphism has caused overprinting of metamorphic events. Therefore, correlation of mineral assemblages with specific metamorphic or tectonic events in the region becomes complex and difficult, particularly for the Archean rocks. Interpretations of the metamorphic history of the area have led to its division into five metamorphic terranes, or broad geographic areas, characterized by common metamorphic grade, rock assemblage, and tectonic style.[28] Archean crystalline rocks are an essential component of the high-grade gneiss terrane, where metamorphism reached lower granulite facies, but the greenstone-granite terrane has been affected by greenschist and, locally, upper amphibolite facies metamorphism.

Even though the regional metamorphic grade is generally low, Penokean-age rocks in the Upper Peninsula of Michigan and northern Wisconsin contain areas of low-pressure, low- to high-temperature metamorphism expressed as distinct thermal nodes.[29,30,31] Thermal effects are marked by the progressive appearance of biotite to sillimanite zones, which possibly caused textural and compositional inhomogeneities in the crystalline rocks. Post-Penokean rocks do not display significant metamorphic modifications.

OVERALL CHARACTERISTICS OF THE CRYSTALLINE ROCKS OF THE REGION

The 41 crystalline rock complexes considered in this study occupy a total inferred map area of 48,404 km^2, with several individual units exceeding 2500 km^2. Represented are batholiths of elongate, irregular oval shapes; domes with gneissic cores of remobilized basement rocks; circular and zoned intrusions; and elongate rock bodies. They range from ultramafic to felsic in composition, but granitic lithologies predominate.

CHARACTERISTICS OF ARCHEAN ROCKS

There are a total of 22 rock complexes of Archean age (see Appendix), 18 of which are of Late Archean age (see Figs. 2-4). They occupy a total area of 28,602 km^2, of which 22,361 km^2 (75%) is underlain by nine bodies in Minnesota (see Table III). In the Upper Peninsula of Michigan, the crystalline rock bodies are predominantly of Archean age, with a total area of 3494 km^2, whereas in Wisconsin the four Archean rock complexes have an inferred map area of 2747 km^2.

Early Archean Rocks (3400 m.y. and older)

Recent radiometric age data indicate that there are four crystalline rock complexes of definite Early Archean age in the Lake Superior region (see Appendix and Figs. 2-4). Two of these, the Montevideo[32] and Morton Gneiss[33,34] complexes, occur in a window along the Minnesota River valley in southwestern Minnesota. Several mantled gneiss domes occur near Watersmeet[35,36] in Michigan and in northernmost Wisconsin. Early Archean rock complexes account for roughly 10% of those described in this study and occupy 20% (9586 km^2) of the total area of crystalline rocks. They are most prominent in Minnesota, where they underlie 8882 km^2.

As inferred from geological and geophysical data, Early Archean rocks generally form elongate and domal or subcircular bodies that are probably several kilometers thick. Their mutual contact relations and those with country rocks are complex and often diffuse. Late-stage dikes and sills of diabase, aplite, and pegmatite are common.

Lithologically these rocks are represented by mixed gneisses (both paragneiss and orthogneiss), migmatites, and amphibolites that recrystallized from igneous or volcanoclastic protoliths or as remobilized basement rocks.[19,32,33,35] In terms of the quartz-alkali-feldspar-plagioclase-feldspar (Q-AF-PL) diagram,[37] their modal mineralogy, though variable, corresponds to the diorite, tonalite, granodiorite, granite, and adamellite (monzonite) fields.

In Minnesota, Early Archean rocks constitute the high-grade gneiss terrane that was tectonically active throughout much of the Archean. Such repeated metamorphism and deformation caused extensive recrystallization, intense foliation, shear zones, and folding, resulting in a highly tectonized fabric and lithological heterogeneity. Evidence exists for at least eight thermo-tectonic events and four phases of folding. Earlier folding is marked by small, isoclinal, recumbent folds that are coaxial with major folds on east-trending, low-plunging axes.[28,38] Younger parasitic, disharmonic folds have orientations consistent with major folds. Still younger minor folds trend northwesterly.

The rocks show the effects of amphibolite-lower granulite facies metamorphism[28] (2600-3000 m.y.). Retrogressive metamorphism is apparent in the alteration of the clinopyroxene, garnet, and feldspar phases. Such alteration may reflect low-temperature equilibration (cooling) after the main, relatively high temperature stage of granulite facies metamorphism.[28] However, retrogression and recrystallization may also be related to Late Archean granite magmatism and later periods of thermal metamorphism. High-grade gneisses were subjected to cataclasis and regional metamorphism between 1800 m.y. and 2000 m.y. ago. Remobilization of Archean basement during the Penokean orogeny produced isolated mantled gneiss domes in the Upper Peninsula of Michigan and northern Wisconsin.[19]

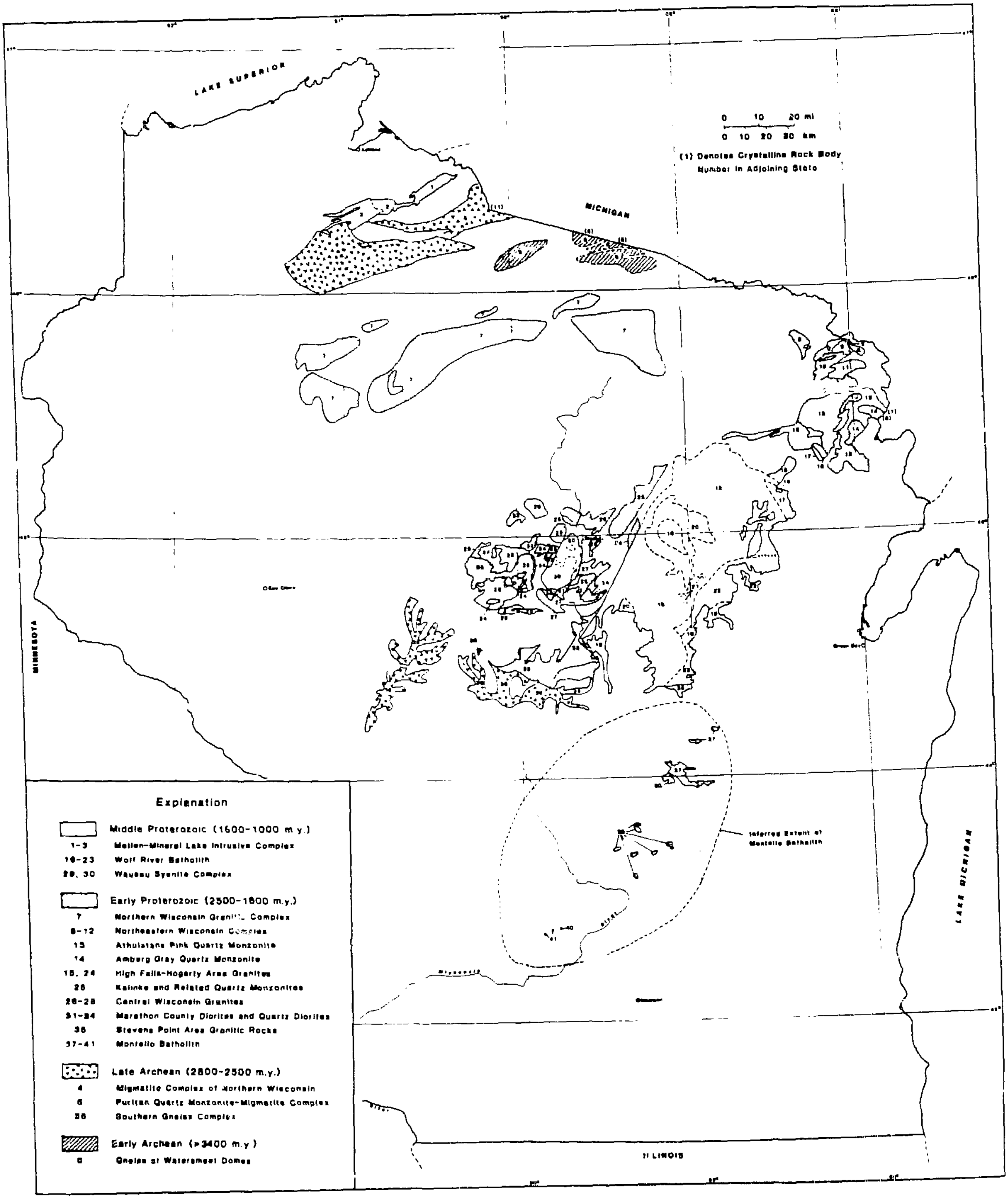

Fig. 2. Distribution of Exposed Crystalline Rocks of Wisconsin.

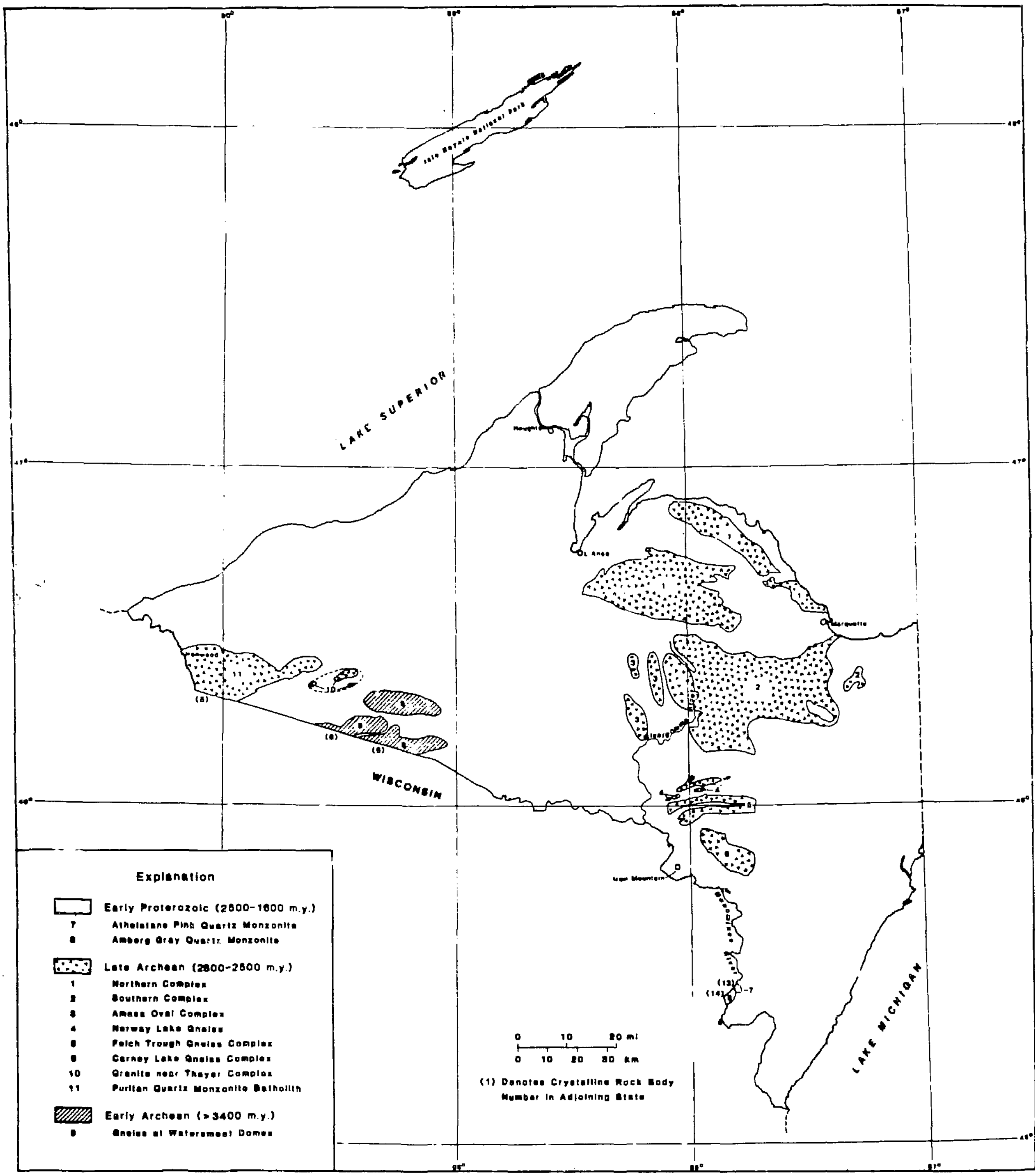

Fig. 3. Distribution of Exposed Crystalline Rocks of the Upper Peninsula of Michigan.

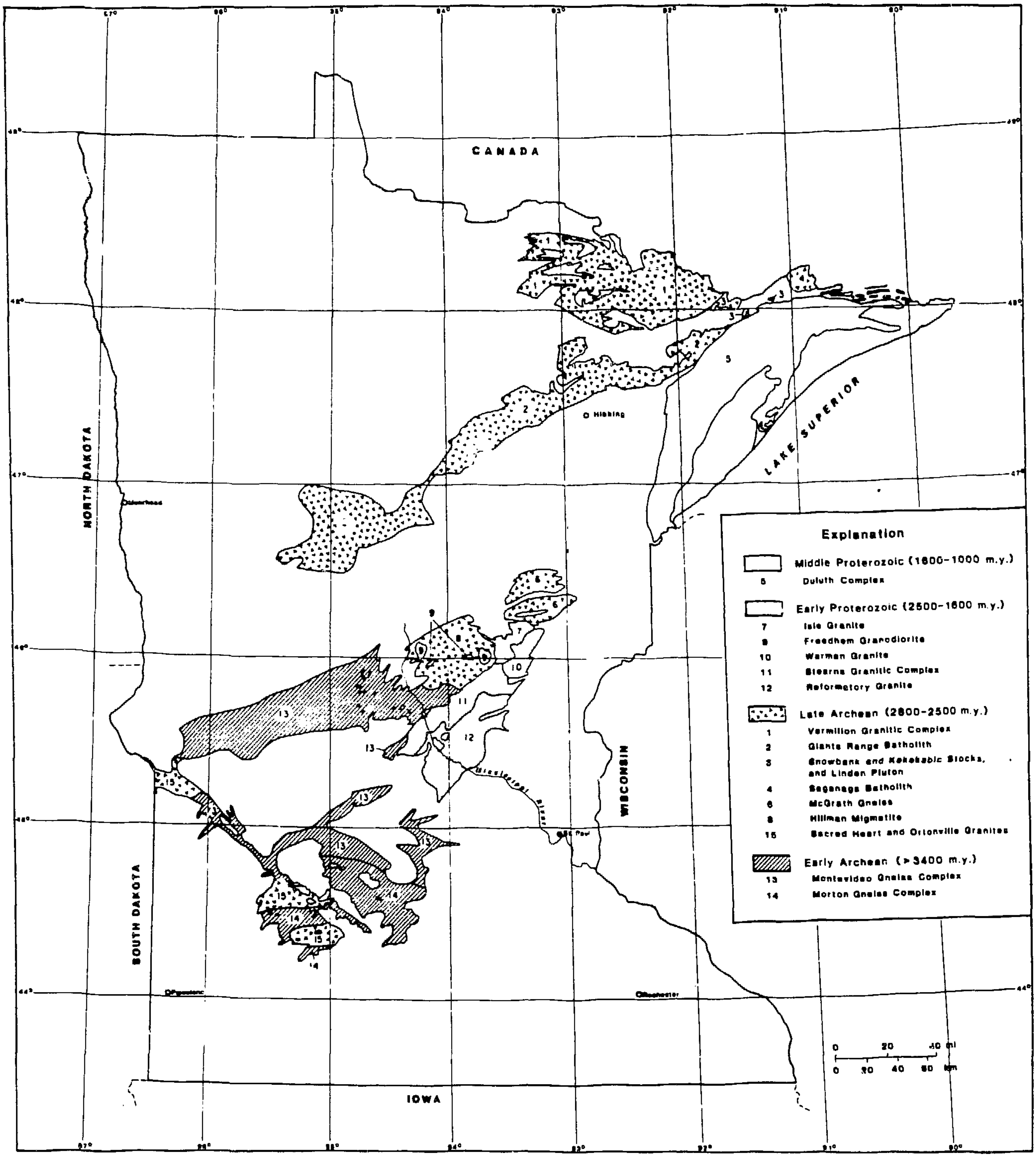

Fig. 4. Distribution of Exposed Crystalline Rocks of Minnesota.

Late Archean Rocks (2500-2800 m.y.)

Late Archean complexes comprise 44% of those described in the present study and occupy 39% (19,016 km^2) of the area of crystalline rocks. They are prominent in Minnesota and the Upper Peninsula of Michigan. Those in Minnesota occupy about 70% (13,479 km^2) of the area of Late Archean rocks described herein (see Table III).

Late Archean rock bodies exhibit elongate, circular, and irregular shapes. They form a roughly north-south belt lying in the middle of the Upper Peninsula of Michigan, a belt that extends to the Michigan-Wisconsin border. Most of the crystalline rock bodies of Late Archean age in the region are part of the greenstone-granite terrane of northern Minnesota, the western part of the Upper Peninsula of Michigan, and northwestern Wisconsin (see Figs. 2-4). Such terranes may be (1) relics of an early thin crust, (2) Archean continental and oceanic crust, or (3) components of protocontinents. Analogies for the greenstone belts based on plate tectonics range from midocean ridge,[39] to subduction zones as postulated in contemporary island arcs,[40,41] to "back arc" marginal basins behind island arcs.[42]

Lithologies of the Late Archean rocks are usually, but not invariably, gneissose and migmatitic. Their mineralogical characteristics on the Q-AF-PL diagram conform to the granite, granodiorite, monzonite, tonalite, and gabbro fields. Recrystallization and several phases of deformation have resulted in tectonized fabrics and mixed lithologies in many of the complexes. Penokean thermo-tectonic effects are perhaps strongest in the Michigan and Wisconsin rocks. Late-tectonic intrusions are relatively less deformed and compositionally more uniform. Syntectonic units are granitic, while posttectonic units are syenitic to monzonitic to quartz monzonitic in composition.[28]

The syntectonic Giants Range batholith is foliated and has a wide contact-metamorphic aureole of amphibolite facies.[43,44] The Vermilion Grantic Complex, a product of migmatization of intrusive pulses of variable composition and late-stage dikes and apophyses, has been intensely deformed.[45] Strong foliation and cataclastic structures are evident, and contacts with country rock are less diffuse than those of Early Archean crystalline rocks.[46] The Sacred Heart and Ortonville granitic bodies that occur along portions of the Minnesota River valley are relatively unfractured and only faintly foliated, and possibly represent passive intrusions into folded metasedimentary rocks. These granitic rocks exhibit late-stage veining.

Late Archean lithologies in the Upper Peninsula of Michigan and northwestern Wisconsin are similar and consist of gneisses and migmatites. The prominent Northern and Southern complexes of the Upper Peninsula of Michigan are highly migmatized and intensely foliated, with the intensity of foliation increasing towards margins.[47,48] The western part of the Southern Complex shows complex phases of folding and foliation.[49,50,51] Cataclastic zones are highly brecciated and are similar to those along the edge of the McGrath Gneiss in Minnesota. The Puritan Quartz Monzonite batholith has a randomly textured, relatively homogeneous interior, with a rim zone of migmatite.[52,53]

Though younger, the Southern Gneiss Complex in central Wisconsin has certain lithologic and fabric similarities to the rocks of the high-grade gneiss terranes to the west in Minnesota.[54,55] It seems to have been more severely affected by the Penokean orogeny and is riddled with Early Proterozoic crystalline rocks.[56]

Late Archean rocks of the granite-greenstone terrane have been largely affected by greenschist facies regional metamorphism. Posttectonic intrusives have narrow upper amphibolite facies contact metamorphic aureoles.

CHARACTERISTICS OF PROTEROZOIC ROCKS

A total of 19 rock complexes of Proterozoic age were identified and described for the region (see Figs. 2-4 and the Appendix), 15 of which are of Early Proterozoic age. They have a total map area of 27,456 km^2, of which 18,145 km^2 (66%) lies in Wisconsin, with the remainder found in Minnesota (see Table III). Extremely small portions of two bodies in northeastern Wisconsin extend into the Upper Peninsula of Michigan.

Early Proterozic Rocks (1600-2500 m.y.)

The 15 Early Proterozoic rock complexes account for 37% of the total number of complexes and 8850 km^2 (18%) of the total area, of which 5441 km^2 (61%) lies in Wisconsin. The 1850-m.y. magmatism related to the main phase of the Penokean orogeny is represented by the Northern, Northeastern, and Central Wisconsin complexes, and the Stearns and Freedhem complexes of east-central Minnesota, which straddle or lie to the south of the Great Lakes tectonic zone.

These bodies have elongate, circular, or oval shapes and intrude Archean granitic, metasedimentary, and metavolcanic rocks. They appear to intrude each other as well. Contacts with country rocks are well defined to somewhat diffuse. Internal facies changes may be gradational.

Lithologically, the 1850-m.y. crystalline rocks have diorite, tonalite, granodiorite, granite and monzonite[57,58] affinities on the Q-AF-PL diagram. Metagabbro is a subordinate lithology. The rocks are either (1) massive, relatively homogeneous, and isotropic; (2) massive, with primary flow textures or weak foliation; or (3) well foliated, with the foliation increasing in intensity toward the margins of the intrusives. The Northeastern Wisconsin Complex shows domal penetration, with a wide migmatite contact zone.[67] The amount of xenolith material and the degree of alteration are variable.

The 1760-m.y. crystalline rocks, which have alkalic (monzonite and granite) affinities, are relatively less metamorphosed and are massive and uniform in composition.[26,59] The Reformatory, Isle, and Warman granites[7,14] in Minnesota are similar to those near Wausau and to the inliers thought to define the Montello batholith[26] in southern Wisconsin. These rocks have relatively low mafic content; some are essentially quartz-feldspar granites. There is some evidence for cataclasis, and a 1630-m.y. thermotectonic event may have affected the area.[26,10,14]

The regional metamorphic grade in the 1850-m.y. rocks is generally low, but distinctive zones of high metamorphic intensity are present, particularly in the Upper Peninsula of Michigan and northeastern Wisconsin. Variations in the extent of these metamorphic highs may be a function of the plasticity of the basement during Penokean metamorphism and tectonism.[28] Although the size and shape of the zones vary, the zones are mostly related to uplifted blocks or domes of Archean gneisses, except in northern Wisconsin. Vertical tectonic processes during the Penokean orogeny may have caused reactivation of older gneisses. Post-Penokean metamorphism was low grade, and post-Penokean granites have narrow contact metamorphic aureoles reaching pyroxene hornfels facies.

Middle Proterozoic Rocks (1000-1600 m.y.)

Middle Proterozoic rocks are represented by four complexes (see Figs. 2-4) with a map area of 10,952 km^2 (23%) that is almost equally distributed between Wisconsin and Minnesota (see Table III).

The 1500-m.y.-old oval-shaped Wolf River batholith and the subcircular and zoned Wausau Syenite Complex form the eastern margin of the exposed Precambrian basement in Wisconsin. These crystalline units have well-defined contacts with the country rocks and probably extend to considerable depth. Compositionally, they lie in the granite, syenite, monzonite, and anorthosite fields of the Q-AF-PL diagram. The anorogenically emplaced Wolf River batholith consists of several phases of alkalic granite with rapakivi affinities.[60] In overall character, the major phase of the batholith is quite uniform in composition and has not been much affected by faulting, alteration, and metamorphism. The Wausau Syenite Complex shows petrological zoning and may have been forcefully emplaced, as evidenced by abundant xenoliths.[59,61]

The layered complexes of the Mellen[62,63] and Duluth[64,65,66] areas attain thicknesses of almost 3000 m and were intruded some 900-1200 m.y. ago during an episode of protracted crustal extension along the Keweenawan rift zone. Gabbros and related rocks, including anorthosite and peridotite, are the predominant phases, but minor granite is also present. The intrusives are inhomogeneous as a result of igneous layering. They have well-developed, narrow contact metamorphic aureoles. Alteration of mafic minerals by magmatic fluids is pervasive.

CONCLUSIONS

The Archean and Proterozoic rock bodies and complexes of the present study are almost equally abundant and underlie roughly comparable areas (Archean = 60%; Proterozoic = 40%) in the Lake Superior region. Archean rocks are generally strongly deformed, highly recrystallized, and intensely foliated. They exhibit highly tectonized fabrics and highly variable lithologies. Their structural anisotropy and lithologic heterogeneity make them relatively less desirable for a mined repository, partly due to the difficulty in predicting changes in their physical properties. Synorogenic Penokean rock bodies share certain structural characteristics with deformed Archean rocks, but they lack highly tectonized fabrics and are relatively more homogeneous. Several of these bodies have uniform interiors.

Postorogenic and anorogenic rocks of the Archean and Proterozoic complexes are more cohesive and possess a high degree of structural isotropy and lithologic homogeneity. Therefore, based on observed geologic characteristics, postorogenic and anorogenic crystalline rock bodies located away from recognized tectonic systems have attributes that make them relatively more desirable as a possible site for a nuclear waste repository in the region.

APPENDIX

Geochronology of Crystalline Rock Bodies of The Lake Superior Region

Name/ Fig. 1 No.	Age (m.y.)	Dating Method	Ref.
Wisconsin			
Early Archean			
Gneiss at Watersmeet Domes/6	3410 ± 80	U-Th-Pb zircon	35
	3600 ± 40	Sm-Nd whole rock	36
Late Archean			
Migmatite Complex of Northern Wisconsin/4	2600-2750	Lithostratigraphic correlation	2,27
	2700	U-Pb, zircon	84
Puritan Quartz Monzonite-Migmatite Complex/5	2610 ± 50	Rb-Sr whole rock	67
	2710 ± 140	Rb-Sr whole rock	68
Southern Gneiss Complex/36*	$\geq$2800	U-Pb, zircon	54
Early Proterozoic			
Amberg Gray Quartz Monzonite/14	1630 ± 20	Rb-Sr whole rock	69
	1760 ± 10	U-Pb, zircon	10
Athelstane Pink Quartz Monzonite/13	1860 ± 15	U-Pb, zircon	70
	1810 ± 50	Rb-Sr whole rock	69

Wisconsin (Cont'd)

Name/ Fig. 1 No.	Age (m.y.)	Dating Method	Ref.
Early Proterozoic (Cont'd)			
Central Wisconsin Granites/26-28	1615 ± 23	Rb-Sr whole rock	13
	1850-1950	Lithostratigraphic correlation	27
High Falls-Hogarty Area Granites/15,24	~1850	Lithostratigraphic correlation	27
Kalinke and Related Quartz Monzonites/25	1825 ± 20	U-Pb, zircon	10
Marathon County Diorites and Quartz Diorites/31-34	1850-1950	Lithostratigraphic correlation	10
	1840 ± 20	U-Pb, zircon	
Montello Batholith/37-41	1760 ± 10	Pb-Pb, zircon	10,71
	1800 ± 30	U-Pb, zircon	
Northeastern Wisconsin Complex/8-12	1890 ± 15	U-Pb, zircon	70
	1810 ± 50	Rb-Sr whole rock	13
Northern Wisconsin Granitic Complex/7	1885 ± 65	Rb-Sr whole rock	58
Stevens Point Area Granitic Rocks/35	1824 ± 25	Rb-Sr whole rock	10
	1842 ± 10	Rb-Sr whole rock	10
Middle Proterozoic			
Mellen-Mineral Lake Intrusive Complex/1-3	1115 ± 15	U-Pb, zircon	72
	1037 ± 30	Rb-Sr, biotite	73
Wausau Syenite Complex/29,30	1520 ± 25	Rb-Sr whole rock	13,74
Wolf River Batholith/16-23	1468 ± 34	Rb-Sr whole rock	74
	1510 ± 15	U-Pb, zircon	

*Riddled with small Early Proterozoic bodies.
**Contains small Late Archean gneiss units.

Upper Peninsula of Michigan

Name/ Fig. 3 No.	Age (m.y.)	Dating Method	Ref.
Early Archean			
Gneiss at Watersmeet Domes/9	3410 ± 80	U-Pb, zircon	35
	3600 ± 40	Sm-Nd whole rock model age	36

Upper Peninsula of Michigan (Cont'd)

Name/ Fig. 3 No.	Age (m.y.)	Dating Method	Ref.
Late Archean			
Amasa Oval Complex/3	2480 ± 200	U-Pb, diffusion, zircon	75
	2900 ± 200	Rb-Sr, potassium feldspar model age	
Carney Lake Complex/6	2790	U-Pb, diffusion, zircon	75
Felch Trough Gneiss Complex/5	≥2700	U-Pb, zircon	75
	1730	K-Ar, hornblende	
		Lithostratigraphic relations	84
Granite near Thayer Complex/10	2600	Rb-Sr whole rock	35
	2745 ± 65	U-Pb, zircon	
Northern Complex/1	2600 ± 200	Rb-Sr whole rock	76
		Correlation	
Norway Lake Gneiss/4	2390	Rb-Sr, potassium feldspar model age	75
	≥2700	Correlation	84
Puritan Quartz Monzonite Batholith/11	2610 ± 50	Rb-Sr whole rock	67
	2710 ± 140	Rb-Sr whole rock	68
Southern Complex/2	2500-2800	Rb-Sr whole rock correlation	76

Minnesota

Name/ Fig. 4 No.	Age (m.y.)	Dating Method	Ref.
Early Archean			
Montevideo Gneiss Complex/13	3600	Rb-Sr whole rock	32
Morton Gneiss Complex/14	3600	Rb-Sr whole rock	33
	3100	U-Pb, zircon	34
Late Archean			
Giants Range Batholith/2	2670 ± 65	Rb-Sr whole rock, muscovite	77
	2300-2600	K-Ar, biotite	7
	2700	U-Pb, sphene	78

Minnesota (Cont'd)

Name/ Fig. 4 No.	Age (m.y.)	Dating Method	Ref.
Late Archean (Cont'd)			
Hillman Migmatite/ 8	1700-1770	K-Ar, biotite	14
	1600-1690	Rb-Sr whole rock	7
	~2700	Stratigraphic correlation	2
McGrath Gneiss/6	2700	Rb-Sr whole rock	14
	1730-1740	K-Ar, biotite Rb-Sr, biotite	7
Sacred Heart and Ortonville Granites/15	2700	Rb-Sr whole rock	9
	2600 ± 60	U-Th-Pb, feldspars/ whole rock	79
Snowbank and Kekekabic Stocks, and Linden Pluton/3	~2700	U-Pb, sphene	80
	~2700	Lithostratigraphic correlation	81,2
Vermilion Granitic Complex/1	2700 ± 50	Rb-Sr whole rock	82
	2550	K-Ar, biotite	7
Early Proterozoic			
Freedhem Granodiorite/9	1630-1710	K-Ar, biotite	7,14
Isle Granite/7	1680	K-Ar, biotite	7,14
Reformatory Granite/12	1780	K-Ar, biotite	7
Stearns Granitic Complex/11	1770	K-Ar, biotite	14
	1820	Rb-Sr whole rock	14
	1730	Rb-Sr whole rock	14
Warman Granite/10	1760	K-Ar, biotite	7
Middle Proterozoic			
Duluth Complex/5	1090	K-Ar, biotite	7
	1115 ± 14	Rb-Sr whole rock	83
	1120-1140	U-Pb, zircon	72

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