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PRELIMINARY REVIEW
OF PRECAMBRIAN SHIELD ROCKS
FOR POTENTIAL WASTE REPOSITORY

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INTRODUCTION

This short report is intended to give an overview of the Canadian Shield and is primarily concerned with the part that is seismically the least active of the North American continent. The metamorphic and igneous rocks of the more stable elements of the shield provide what we consider excellent possibilities for dry excavations suitable for the long-term storage of radioactive waste materials. Structurally and compositionally these rocks are suitable for such excavations.

THE CANADIAN SHIELD

General Statement

Each of the continental masses of the earth is characterized by a nucleus of very old Precambrian rocks which are exposed at the surface and known as shields. The name Precambrian simply indicates that these rocks are older than the fossiliferous Cambrian strata. Radiometric age measurements place the time boundary between the Cambrian and older series at approximately 570 m. y. (10^6 yrs.) ago. The oldest dated Precambrian rocks are 3600 to 3800 m. y. old, and in Greenland, Labrador, and Minnesota considerable work has been done to establish their age and to decipher the complicated geologic history.

The principal areal exposure of Precambrian rocks in North America is in Canada and measures many thousands of square kilometers; hence the shield in North America is referred to as the Canadian Shield. Figure 1 is an old but useful illustration showing how some of the larger concepts relating to the development of the Canadian Shield evolved. The principal geologic province and the approximate age or range in age of the rocks are shown. The Canadian Shield is roughly an annular exposure around Hudson Bay. As shown in Figure 1 in the vicinity of Hudson Bay and on the outer perimeter the Precambrian rocks of the Shield are covered with relatively thin layers of Paleozoic and younger sedimentary rocks. Thus drill holes through the younger rocks encounter the Precambrian rocks at depths roughly proportional to the distance away from the Shield. The greater part of the North American continent

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is underlain by Precambrian rocks, but only in areas adjacent to the Shield is it common to refer to the Precambrian basement as the subsurface extension of the Shield.

The Canadian Shield (Fig. 1) extends into the northern parts of Minnesota, Wisconsin, and Michigan, and in New York in the Adirondack Mountains. Because of similarities in lithology, structure, and the common factor introduced by the large Precambrian cherty iron formations and the derived iron ores the region including Minnesota, Wisconsin, and Michigan has commonly been referred to as the Lake Superior district.

Subdivisions of the Canadian Shield

Physiographic

The international boundary commonly becomes a geographic limit in discussions pertaining to the Canadian Shield. The physiographic regions of Canada are shown in Figure 2. Similarly, physiographic regions are recognized in the United States, and there are significant differences in the physiographic development of Canada and the United States; however the discussion here is concerned largely with the gross features. Most of Canada and a large part of the northern United States were glaciated during the Pleistocene (Fig. 3). The glaciers did considerable work in eroding and transporting materials and in levelling the region so that today it is characterized by relatively low relief, for the most part rarely exceeding 100 m. Elevations rising 200-300 m. above the general level are prominent features, locally named mountains. The topography on the Canadian Shield, however, was largely the result of stream erosion and was developed in late Precambrian or early Paleozoic time. Glaciation has modified the ancient surface, reducing some of the highlands and filling in some of the lowlands.

Structural

Although the structure in the Precambrian rocks is complex, it has been intensively studied because of its close relationship and control of mineralization. Figure 4 is a generalized map showing the structural trends in the Canadian Shield. On the basis of physiographic, structural, and also lithologic characters the

Canadian Shield was divided into structural provinces and sub-provinces (Fig. 5).

Geologic Provinces

Radiometric age measurements on mineral and rock samples from the Canadian shield developed age patterns that further characterize the structural provinces, and on the basis of the various features mentioned above the Canadian Shield has been divided into geologic provinces which are essentially the same as the structural provinces (Fig. 5). For example the large Superior Province that extends south into the United States is characterized by east-west structural trends of greenstone-granitic gneiss belts. These rocks were first formed 2600 m. y. or more ago. They were involved in the Kenoran (Algonian) orogeny and locally show the effects of metamorphism resulting from younger igneous activity, folding, shearing, and so forth.

Stratigraphy and Crustal Thickness

With the introduction of radiometric age determinations, correlation of formations in the Precambrian received great attention, and very considerable progress has been made in defining the Precambrian stratigraphic succession. This subject for all of the Canadian Shield is too large for review, and some attention is given to the Precambrian stratigraphy in the discussion of the Lake Superior region in a later section of this report. Canadian geologists have long used a two-fold classification of Precambrian rocks. The oldest rocks are the Archean and were first formed 2600 m. y. ago or prior to that time. These are the rocks of the greenstone-granitic gneiss belts mentioned above. The younger Proterozoic rocks are more platform-type of sediments deposited on the more or less stabilized Archean craton.

The east-west structural trend of the Archean rocks is shown in Figure 6. Estimates of the thickness by Moorhouse (1965) are shown, but because of the complexity of the structure these figures should not be taken too literally.

Very little is known about the crustal thickness of the Shield, and our information at present is based on rather limited seismic studies. In general the crustal thickness is of the order of 40 km. (range 35-40 km.). The thickness apparently increases beneath Lake Superior (50 km.) and decreases beneath the Hudson platform at Hudson Bay (25 km.).

Fig. 2 Physiographic regions of Canada (Douglas, 1968).
 Note: The relationships between the physiographic subdivisions and the geologic provinces (Fig. 1)

Fig. 3 Extent of continental Pleistocene glaciation in northern North America (Geological Survey of Canada, 1957).

Fig. 4 Generalized structural trends in the Canadian Shield (Douglas, 1968)

Fig. 5 Structural provinces and subprovinces of the Canadian Shield (Douglas, 1968)

Fig. 6 East-west trend of Archean structural belts and estimated thicknesses of Archean sequences.

LAKE SUPERIOR REGION

General Statement

The Lake Superior region as used here includes adjoining Ontario as well as Minnesota, Wisconsin and Michigan. It is convenient to divide the Precambrian rocks into three major divisions used by the Minnesota Geological: Early, Middle and Late Precambrian with time boundaries of 2600 and 1800 m.y. ago as shown in Table 1. A similar three-fold division with somewhat different time boundaries was used by the Ontario Department of Mines in compiling the most recent geological map of the Province. The Geological Survey of Canada uses a two-fold division of Archean and Proterozoic with a time boundary of 2560 m.y. The Proterozoic is divided, from oldest to youngest, into the Aphebian, Helikian, and Hadrynian. The time boundary between the Aphebian and the Helikian is 1800 m.y., corresponding to the time boundary between the Middle and Late Precambrian. In the usage of the Geological Survey of Canada the terms Kenoran and Hudsonian orogenies correspond to the Algoman and Penokean orogenies of Table 1.

Early Precambrian or Archean Rocks

In general the same stratigraphic elements listed in Table 1 are found throughout the Lake Superior region, but the formal terminology differs in different areas. The Archean sequence is largely composed of basaltic and andesitic lavas; pyroclastic material ranging from rhyodacitic to rhyolitic in composition; graywacke-shale sequences altered to metagraywacke-slate; banded iron formation with minor carbonate and related sedimentary rocks. These rocks were folded and intruded by numerous dikes and large masses or plutons of tonalitic to granodioritic magma in an early phase of the Algoman (Kenoran) orogeny. The section in northeastern Minnesota, for ex-

ample from oldest to youngest, includes the Ely Greenstone and Soudan iron-formation that were folded and intruded by numerous dikes of rhyodacitic composition, the Northern Light of Gneiss of trondhjemitic composition, and the Saganaga Tonalite. In the Rainy Lake district the Keewatin lavas that correspond to the Ely Greenstone are underlain by an older metasedimentary group, the Coutchiching Series of Lawson (1913). In the Rice Bay area of the Rainy Lake area the Coutchiching is 2000 m or more in thickness.

In northeastern Minnesota and also in the Rainy Lake district in Ontario the early Archean volcanic and pyroclastic rocks were folded and intruded by numerous dikes and plutons of tonalitic composition. These masses started their ascent as magma but continued to rise as diapirs so that they were uncovered and provided coarse detritus to adjacent basins forming conglomeratic wedges in the Knife Lake sediments of northeastern Minnesota and in the Seine sediments in Ontario. The erosion surface or unconformity was recognized by Lawson in Ontario and by early workers of the Minnesota Geological Survey, and on the basis of geological relationships, the Laurentian orogeny was defined. The unconformity is well exposed in Cache Bay of western Saganaga Lake, and in the country to the south, and also on Shoal Lake and along Highway 11 in the Rainy Lake district. The conglomerates are wedges in the thick graywacke-shale sequences of the Knife Lake group in Minnesota and the Seine Series of Ontario.

Middle Precambrian or Aphebian Rocks

The general nature of the Middle Precambrian rocks is indicated in Table 1. In the Lake Superior district these rocks are best known for

the extensively developed banded iron-formations. A correlation of formations in the district is given in Table 2. In Ontario, the type locality of the Huronian rocks, the sequence is dominantly elastic sediments with little or no iron formations. This fundamental difference in lithology is largely the basis for objection to the use of Huronian as a time-stratigraphic term. Radiometric dating of the Nipissing diabase (Van Schmus, 1965) in the Blind River-Bruce mines area, Ontario, places a minimum age of 2100 m.y. on the Huronian Group. Radiometric age determinations on argillites and rocks related to the iron-formations in the Labrador trough and in the Lake Superior district are considerably younger (1600-1850 m.y.), but these ages may simply reflect folding and low-grade metamorphism. Thus the Huronian Group of the type locality in Ontario may be older than the Animikie Group of the Mesabi and Gunflint districts, or it may simply be a coarse clastic facies and of similar age. For the present this problem remains unresolved.

Late Precambrian or Helikian and Hadrynian Rocks

The Late Precambrian rocks in the Lake Superior region are referred to the Keweenawan. The best known rocks are the Middle Keweenawan volcanic rocks, the North Shore Volcanic Group and the Duluth Gabbro or the Duluth igneous complex. A correlation chart for the Late Precambrian rocks in the Lake Superior region is given in Table 3.

Igneous and Metamorphic Rocks

Three major periods of folding and igneous activity have been recognized in the Lake Superior region as follows:

Keweenawan igneous activity (ca. 1100 m.y.)

Penokean orogeny (ca. 1850 m.y.)

Algoman orogeny (ca. 2700 m.y.)

During these periods the rocks described above were folded and intruded by magmas with the result that their primary features were changed in varying degree ranging from low-grade (greenschist facies) to high-grade (granulite facies) metamorphism.

The crystalline metamorphic rocks and associated igneous rocks are naturally extremely well developed in the Canadian Shield, and these present excellent prospects for excavations which should be well suited for the long-term storage of radioactive waste materials.

Structure

Introductory Statement

The structure of the Lake Superior region is complicated because of the three major periods of orogeny and igneous activity, but the major structural elements are fairly well known. Mountain building or orogeny accompanied by metamorphism and igneous activity develops crystalline metamorphic and igneous rocks that are more or less amenable to radiometric age measurement; therefore, it appeared logical to attempt to apply some of the principles developed in the study of geologically young mountains to the Precambrian (Goldich and others, 1961). Since this early work the concepts of plate tectonics have undergone rapid development. Present-day tectonic concepts are closely related to the movement of large plates with the major earth structures developing at plate junctions. It is not uncommon to see a statement to the effect that the plate-tectonics concept has revolutionized geology and completely displaced the geosyn-

clinal hypothesis of mountain building.

The plate tectonic concept, however, is not easily applied to the ancient rocks of the Precambrian, and some sort of compromise is useful. Most geologists will accept the hypothesis of mobile zones common to both the geosynclinal and the plate-tectonic concepts. Thick wedges of immature and rapidly accumulated sediments and volcanic rocks typical of the eugeosyncline or of the active plate margins are an essential feature. The piles accumulate to thicknesses of the order of 30,000 to 50,000 feet. Possibly in early Precambrian time, because of greater heat flow, the crust may have been thin and more flexible or mobile; nevertheless, the cycle worked out for more recent mountains applies to Precambrian belts, and the wedges or piles of conglomerate, graywacke-shale, and volcanic rocks were strongly deformed and depressed to depths in the mantle where partial melting generates tonalitic to granodioritic magma. These then moved upward invading the supracrustal cover rocks.

One feature of the folded mountain chains that is accepted by structural geologists is uplift and subsequent erosion exposing plutonic igneous rocks and metamorphic rock of amphibolite to granulite facies. Uplift or vertical translation was by blocks uplifted along faults. There is much evidence in the Precambrian rocks to support this model.

The development and application of radiometric dating techniques to Precambrian rocks have an interesting history. Once it was thought that concordant mineral ages by two or more techniques were definitely the age of crystallization or origin. Later it was discovered that both K-Ar and Rb-Sr mineral ages commonly date a metamorphic event subsequent to initial formation. Now it is widely accepted that K-Ar and Rb-Sr mica ages may date the time of uncovering, that is, the time of uplift and erosion that

by movements of blocks and shearing in the granite is an obvious feature. In eastern Minnesota in the Denham area large fault zones have been found in the field following extensive age measurements in the laboratory. A well-recrystallized cataclastic zone in the McGrath Gneiss (2700 m.y. or older) has been dated at 1770 m.y. ago.

Late Precambrian

The structure of Lake Superior is a basin or syncline formed by downwarping. The Middle Precambrian North Shore Volcanic Group (Table 3) was intruded by the gabbroic magma (Duluth Gabbro), and it first was postulated that with release of the pressure responsible for the intrusion, the whole region sagged forming a lopolith (Grout, 1918). Taylor (1964), however, ascribed the origin of the Duluth syncline to structural evolution independent of the Duluth Gabbro. More recently Chase and Gilmer (1973) have attempted to relate the Keweenaw igneous activity to a plate tectonic model in which the Midcontinent gravity high marks a continental rift system.

Figure 8 is a generalized geologic map of the Lake Superior region in which Craddock (1972) has shown the known and inferred distribution of Upper Precambrian rocks. Craddock describes the rocks briefly and discusses the probable thickness in some detail. The cumulative thickness of the Middle Precambrian plateau basalts is about 40,000 feet. Major faults in Craddock's compilation (Fig. 8) are the Douglas fault and the Hastings-Lake Owen fault. The area between the faults is now structurally high, and Craddock named it the St. Croix horst. A major cross fault, the Belle Plaine fault, is shown in Figure 8. Actually, there are numerous strike faults and also cross faults

uncovered the presently exposed rocks to a depth at which the radioactive decay systems were stabilized in the minerals.

Early Precambrian

A large volume of radiometric age determinations on minerals and rocks in the Lake Superior region indicate that the interval of time for uplift and erosion required to stabilize the decay systems in minerals ranges from 50 to 150 million years. In the Early Precambrian rocks of the Lake Superior region, for example, whole-rock Pb-Sr isochron ages and U-Pb zircon concordia ages indicate that the complete cycle from sedimentation to collapse of the depositional trough with subsequent folding, intrusion, and metamorphism probably took 20-50 m.y. The major orogeny is dated at approximately 2700 m.y. ago. Mineral ages, as well as disturbed Rb-Sr isochrons, indicate that the area was uplifted and eroded to depth at which stabilization of the decay systems was achieved 2550 m.y. ago. During this period faulting was an important process. Horizontal displacements of considerable magnitude are known in the Archean rocks, but of particular interest to us are the large vertical translations that were achieved. These vertical movements were accomplished along major fault zones that permitted block movements. The fault pattern in northeastern Minnesota is shown in Figure 7.

Middle Precambrian

In east-central Minnesota the Penokean granites have been dated by a number of techniques. The post-kinematic granites in the Saint Cloud area were emplaced approximately 1820 m.y. ago. Mineral ages indicate that uplift with erosion stabilized the isotopic systems in biotite approximately 1770 m.y. ago. During the 50-million year interval uplift was accomplished

beyond those shown in Fig. 8 (Morey and Mudrey, 1972). Some of the faults displace Cambrian and Ordovician strata, and some of the faults, first formed in Late Precambrian time were activated in Paleozoic time.

Era	Lithology	Event (Approximate age)	Intrusive Rocks
Paleozoic 600 m.y.	-----Unconformity----- Clastic rocks having dominantly fluvial attributes		
	-----disconformity-----		Duluth Complex and small mafic intrusions in northeastern Minnesota
Late Precambrian	Mafic lava flows, tuffs, and interbedded sedimentary rocks		
	-----Unconformity----- Clastic rocks having shallow-water attributes	Deformation and metamorphism (?) (ca. 1,200 m.y.)	Diabasic gabbro dikes in northern and east-central Minnesota
		Unnamed period of mild deformation and metamorphism in NE. Minn. about 1,600-1,700 m.y.	
1,800 m.y.	-----Unconformity----- Clastic rocks and iron-formation having shallow-water to deep-water, or miogeosynclinal, attributes	Penokean orogeny (ca. 1,850 m.y.)	Granitic plutons in east-central Minnesota and small plutons of granitic and mafic rocks in Minnesota River Valley
Middle Precambrian	-----disconformity----- Clastic and carbonate sedimentary rocks having shelf-like attributes		Dikes of diabasic gabbro and diorite in northern Minnesota (stratigraphic position relative to the shelf-like strata unknown)
2,600 m.y.	-----Unconformity----- Lava flows, pyroclastic deposits, and graywacke-type sandstones having deep-water attributes	Algonian orogeny (ca. 2,700 m.y.)	Small syenitic plutons in northern Minnesota; Granitic rocks of Vermilion, Giants Range, and Saganaga batholiths in northern Minnesota; McGrath gneiss in east-central Minnesota; and Soudan, Red Heart and Otterville plutons in southwestern Minnesota
Early Precambrian	-----Unconformity?----- Gneisses of igneous and sedimentary derivation	Mortonian event (ca. 3,550 m.y.)	Morton Gneiss and Montevideo gneiss, at least in part, in southwestern Minnesota

Table 1 Time-stratigraphic framework of Precambrian rocks in Minnesota.

MESABI RANGE CUYUNA RANGE GOGEBIC RANGE DICKINSON COUNTY MARQUETTE RANGE

UPPER PRECAMBRIAN SEDIMENTARY AND IGNEOUS ROCKS

(younger than 1.6 b.y.)

unconformity				
Animikie Group	Virginia Formation	Rabbit Lake Formation	Tyler Slate	Badwater Greenstone
				Michigamme Slate
				Hemlock Formation
				Baraga Group { Michigamme Slate
				Goodrich Quartzite
disconformity				
Animikie Group	Biwabik Iron-formation	Trommald Formation	Ironwood Iron-formation	Vulcan Iron-formation
				Leclerq Formation
	Pokegama Quartzite	Mahnomen Formation	Palms Quartzite	Menominee Group { Nagaunee Iron-formation
				Simo Slate
				Apibik Quartzite
				Marquette Range Supergroup
unconformity				
	Trout Lake formation quartzite and slate?	Bad River Dolomite	Sunday Quartzite	Randville Dolomite
				Sturgeon Quartzite
				Iron Creek Formation
				Wewe Slate
				Kona Dolomite
				Mesnard Quartzite
				Enchantment Lake Formation

unconformity

LOWER PRECAMBRIAN IGNEOUS AND METAMORPHIC ROCKS

(older than 2.6 b.y.)

Table 2. Correlation chart of Middle Precambrian rocks in the Lake Superior region (Sims and Morey, 1972, p. 202).

			Southern Minnesota	N. Wisconsin- W Michigan	Isle Royale, Michigan	Northeastern Minnesota	Thunder Bay, Ontario	Eastern End, Lake Superior
UPPER PRECAMBRIAN	KEWEENAWAN	Upper	Hinckley Sandstone	Chequamegon Sandstone	Jacobsville Sat	Hinckley Sandstone		Jacobsville Sandstone
			Fond du Lac Formation	Devils Island Sandstone		Orienta Sandstone		Fond du Lac Formation
			Solar Church Formation	Freda Sandstone		Konesuch Formation		Copper Harbor Conglomerate
		Middle	Chengwatona volcanic group	Portage Lake lava series	Portage Lake lava series	North Shore Volcanic Group	Michigan Island volcanic rocks
			?—?—?	?—?—? South Range volcanic rocks	? ?	North Shore Volcanic Group	Gres Co., Marquette Point, Along Bay, Cape Gargantua volcanic rocks	
Lower	?—?—?	Bessemer Quartzite	? ?	Puckwunge Formation	Osler Group
	Sioux Quartzite	Berron Quartzite	? ?	Sibley Group
MIDDLE PRECAMBRIAN		Igneous and metamorphic rocks	Igneous and metamorphic rocks	? ?	Metasedimentary rocks	Metasedimentary rocks	Metasedimentary rocks	

Table 3 Correlation chart of Late Precambrian rocks in the Lake Superior region (Sims and Morey, 1972, p. 282).

Fig. 7 Fault pattern in Lower Precambrian rocks in the region of Ely, Minnesota (Sims and Morey, 1972, p. 47).

Fig. 8 Generalized map of the Lake Superior region (Craddock, 1972) showing the known and inferred distribution of Keweenaw volcanic and sedimentary rocks and some of the major faults. Also shown is the general distribution of the Late Precambrian Sioux Quartzite in southwestern Minnesota and adjacent parts of South Dakota and Iowa.

GLACIAL REBOUND

A noteworthy feature of the Canadian Shield as well as some of the platform-type sedimentary sequences which overlap it, is that a heavy load of ice covered most of it in recent geologic time. Melting of the extensive ice sheets has unloaded these rocks and various amounts of rebound have taken place and are still continuing, although at a lessening rate. For example Frost and Lilly (1966) measured vertical uplift in feet per century in an area north of Quebec City P.Q. where relative movements between +0.60 feet and 0.50 feet per century were reported. The area of negative movements overlapped a seismic zone northeast of Quebec City.

Crustal movement in the Great Lakes region has been known for more than a century. Clark and Persoage (1970) present a table (attached) of relative crustal movement on the Great Lakes. Thus, Thunder Bay Ont. (formerly Port Arthur) is rising about 1 foot per century relative to Duluth Minn. even though Duluth itself is rising at a rate of about 0.5 feet per century. A map showing the relative crustal movement rates of the Great Lakes region is attached.

Recent measurements (Lewis 1970) at Manitoulin Island, Ontario suggest a constant uplift of 2.2 mm. per year over the past 5000 years, relative to the Lake Huron outlet area at Sarnia Ont.

Average rates of post glacial uplift for northern and eastern North America are shown on an attached map by Andrews (1970).

Walcott (1970) infers from the amplitude of gravity anomalies, that a substantial amount of further uplift will occur and that the relaxation time is of the order of 10,000 to 20,000 years. Rebound uplifts of several hundred feet have been reported from Sweden since deglaciation there.

This type of rebound is regional in nature and should not have a significant effect on large stable structural blocks. Its significance lies more in its bearing on lake drainage, ship canals and things of similar engineering interest.

Fig. 9 Rates of relative crustal movements in feet per century.

Fig. 10 Average rates of post-glacial uplift for northern and eastern North America in meters per 100 years (after Andrews, 1970).

SEISMICITY

The Canadian Shield is generally considered to be a stable area but this is not true in the strict sense. There is a history of earthquakes that resulted in major damage in a zone that extends northeasterly from Lake Ontario along the St. Lawrence river. This zone is shown on various seismic risk maps.

The important question that arises is - how does one evaluate the probability that an earthquake will cause damage in a certain area or at a particular place? Various forms of seismic risk maps have been developed in attempts to answer this question. Such maps are based upon the seismic history of the region mapped. Usually this consists of some record of epicenter location, intensities and damage that resulted. Their use as risk maps is based on the assumption that future earthquakes will occur where they have occurred in the past. A problem that arises is that records in one area may be much more complete, and encompass a longer time, than in another.

The first general seismic risk map by the U. S. Coast and Geodetic Survey 1945 (Ulrich), was later superseded by a seismic risk map prepared by Richter in 1958. The Coast and Geodetic Survey published its most recent risk map in 1969. (Algermissen)

In all of the above maps, as well as those of Woollard (Fig. 11) there is a remarkable scarcity of recorded earthquakes in or near the shield rocks of the Lake Superior region. A recent earthquake,

not shown on these maps, occurred on July 9, 1975 in west-central Minnesota near the "Goldich" line which marks the southern boundary of the Lake Superior province. This recent earthquake had a magnitude of 4.6 and an intensity between V and VI. Its location was 96° west longitude, 45° 35' north latitude. The center was 65 kilometers southwest of the last previous event in 1950, and about 100 kilometers southwest of a documented earthquake that occurred over 100 years ago.

An earthquake of some what greater magnitude is recorded on the various seismic maps, in the upper peninsula of Michigan, prior to 1938. The only earthquakes shown for Wisconsin were in the most southerly part of the state near the Illinois border. None are shown for the Wisconsin Precambrian areas. No earthquakes have been recorded in the areas north and west of Lake Superior nor in any part of Minnesota except along the important discontinuity referred to as the "Goldich" line.

All the seismic risk maps that have come to our attention classify the Lake Superior region among the seismically most stable of the continent. It seems clear that selection of an in-rock storage site in these regions, well away from major fault zones should provide minimum risk of seismic instability.

Fig. 11 Relation of earthquake epicenters to tectonic structures in the U.S.
(after Woollard 1958)

HYDROGEOLOGY

The major part of the shield region is underlain by crystalline rocks. Only minor areas are covered by relatively unmetamorphosed and by undisturbed sedimentary rocks. Most of these rocks are covered by a thin discontinuous mantle of surficial material which is commonly thicker in the valley areas than on the uplands. Although the topography is locally rugged, relief is usually no more than a few hundred feet. Annual precipitation varies from near 22 inches at the western edges of the shield to 44 inches near the St. Lawrence river, one third to one half of it as snow.

In general, groundwater in the crystalline rocks occurs only in fractures so that the potential amounts depend directly on the number, size and permeability of such fractures.

During the summer of 1975 a number of deep mines were visited to study the ways in which water enters these deep mine penetrations in Precambrian rocks. At depths exceeding 3000 feet no water was observed, and none was reported by the mine staffs. Water has been reported at one mine at Elliot Lake Ontario at that depth, in a thrust fault zone. At an adjoining mine where the working area is a thousand feet or so below the thrust fault no water was found. The mines visited included workings in, or partly in, gneisses, iron formation, quartz-pebble conglomerate, basic volcanics, shale, norite and siderite.

It is worth noting that in the active mining areas there are numerous primary fractures such as shear zones, faults and joints but these are dry, despite the fact that extensive mining has

disturbed the rock equilibrium and created secondary permeability in the wall rocks. The implication is that in areas where such extensive disturbance has not occurred, the fractured rock should be impermeable. At depths between 2000 and 3000 feet, some water occurs in some mines, at depths less than 2000 feet water commonly occurs in fractures and should be expected.

The Creighton mine near Sudbury Ont. at 7000 feet, was the deepest mine visited. It is dry at that depth and is dry to above 3000 feet from surface. It seems clear that at depths exceeding 3000 feet there is very little probability of encountering water-bearing fractures. At depths beyond 5 or 6000 feet the rock pressures are such that the probability of water entering an underground opening, through the rock is exceedingly small. At such depths the particular rock type probably will have little bearing on permeability. Experience in deep mines confirms this general statement.

Whether the above would be true for major crustal flows is not known. However a storage site should not be selected along or very near a linear feature of that kind.

There seems to be little data readily available on the chemistry of groundwaters in Precambrian rocks. Brown (1968 p.781) notes in general that groundwater in the Canadian Shield is similar to the acid surface waters and has a similar low pH. He suggests that the groundwater flow systems are comparatively short and shallow. In some mines the groundwater is affected by the minerals of the ore deposits and may be very acidic and corrosive. This is however a rather local condition that would be unlikely except in or near sulfide mineralization.

It should be pointed out that the chemical nature of the water in near-surface fractures should bear some relation to the overlying surficial deposits. For example, if a high carbonate glacial drift overlies an area, the pH of the cleft water ought to be higher than in areas where the drift is derived from crystalline rocks of non-carbonate type.

At depths, any waters encountered which are stagnant should be expected to reflect the chemistry of the enclosing rocks rather than the nature of the surficial cover. There is also the possibility of minor amounts of original water trapped within the rocks and not introduced later through fractures.

A careful review of the geologic and mining publications of a particular area may locate some data on the chemistry of waters encountered at depth at one or more points within the area. There is information that can be assembled.

CONCLUSIONS AND GENERAL EVALUATION

Storage space for radioactive waste can be excavated in crystalline Precambrian rocks. Some advantages are listed below:

1. Future access to stored materials can be assured.
2. Precambrian terranes have been stable geologically for hundreds of millions of years.
3. Precambrian areas such as the Lake Superior region are among the least seismically active areas in the North American continent.
4. Such seismic activity (earthquakes) as have been reported are related to fault zones which can be avoided in site selection.
5. The crystalline metamorphic and igneous rocks are chemically stable and structurally sound. Self-supporting excavations can be made to afford suitable storage for radioactive waste; however the level and quantity of the radioactive materials will be important factors in site selection, depth of excavations, and engineering design.
6. Groundwater is not considered to be a problem as the rocks at depth are dry. Introduction of surface water in the excavation, however, must be considered and proper safeguards established.
7. No particular difficulty should be encountered in selecting suitable sites well away from mines and mineral deposits, and in areas where the potential for such deposits is very low.
8. Selection of the most suitable rock types within a stable block or terrane will require considerable investigation, and the nature of such studies will depend on the specific parameters envisaged for the repository.

9. Erosion rates for the Precambrian Shield rocks are very slow so that possible effects on a repository complex are expected to be insignificant.
10. A repository at suitable depth in the crystalline rocks should have the minimum chance of contaminating near-surface groundwaters.
11. The possible onset of a new glacial stage in the Lake Superior region in 10,000, or several tens of thousands of years, should be considered, and possibility might be considered in the overall model for a repository.

REFERENCES CITED

- Andrews, J. T., 1970, Present and post-glacial rates of uplift for glaciated northern and eastern North America derived from post-glacial uplift curves: Symposium on recent crustal movements, Nat. Res. Council Canada, 703-715.
- Chase, C. G., and Gilmer, T. H., 1973, Precambrian plate tectonics: the mid-continent gravity high: *Earth Planetary Sci. Letters*, 21, 70-78.
- Clark, R. H., and Persoage, N. P., 1970, Some implications of crustal movement in engineering planning, Symposium on recent crustal movements, Nat. Res. Council Canada, 629-633.
- Craddock, C., 1972, Late Precambrian; Regional geologic setting, in *Geology of Minnesota*, p. 281-291.
- Douglas, R. J. W. (Editor) 1970, *Geology and economic minerals of Canada: Geol. Survey of Canada*, Ottawa, 838 p.
- Frost, N. H., and Lilly, J. E., 1966, Crustal movements in the Lake St. John area of Quebec: *Geol. Survey Canada* 20, No. 4, 292-299.
- Goldich, S. S., Nier, A. O., Baadsgaard, H., Hoffman, J. H., and Krueger, H. W., 1961, The Precambrian geology and geochronology of Minnesota: *Minn. Geol. Survey Bull.* 41, 193 p.
- Grout, F. F., 1918, The lopolith, and igneous form exemplified by the Duluth Gabbro: *Am. Jour. Sci.*, ser. 4, 46, 516-522.
- Lawson, A. C., 1913, The Archean geology of Rainy Lake re-studied: *Geol. Survey Canada*, Mem 40, 115 p.
- Lewis, C. F. M., 1970, Recent uplift of Manitoulin Island, Ontario, Symposium on recent crustal movements: Nat. Res. Council Canada, 665-675.
- Morey, G. B., and Mudrey, M. G., Jr., 1972, Keweenawan volcanic rocks in east-central Minnesota in *Geology of Minnesota: Minn. Geol. Survey*, 425-430.
- Sims, P. K., and Morey, G. B. (Editors) 1972, *Geology of Minnesota: A centennial volume: Minn. Geol. Survey, Univ. Minn.* 632 p.
- Taylor, R. B., 1964, *Geology of the Duluth Gabbro complex near Duluth, Minnesota: Minn. Geol. Survey Bull.* 44, 63 p.
- Van Schmus, R., 1965, The geochronology of the Blind River-Bruce mines area, Ontario, Canada: *Jour. Geology*, 73, 755-780.
- Walcott, R. I., 1970, Isostatic response to loading of the crust in Canada, Symposium on recent crustal movements: Nat. Res. Council Canada, 716-725.
- Woollard, G. P., 1958, Areas of tectonic activity in the United States as indicated by