Geoscience Wisconsin
Volume 13, July 1989

URANIUM AND THORIUM IN SELECTED PRECAMBRIAN ROCK UNITS IN WISCONSIN

Gregory Mursky[1], James W. Anderson[1],
Timothy R. Cook[1], and William S. Meddaugh[1]

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

---

[1]Department of Geosciences, University of Wisconsin-Milwaukee, Milwaukee, Wisconsin, 53201

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 1×10^{-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.

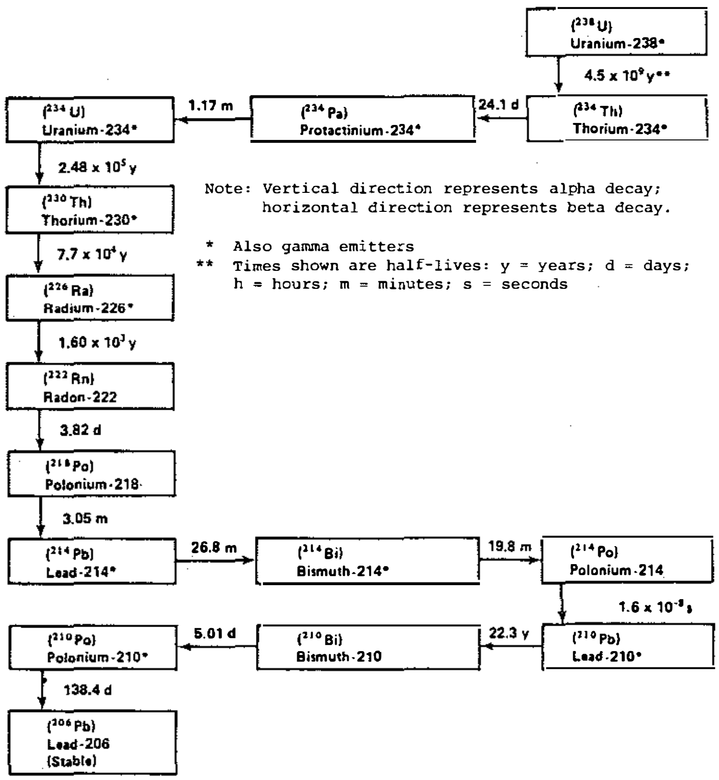

Figure 1. The radioactive decay series for uranium-238.

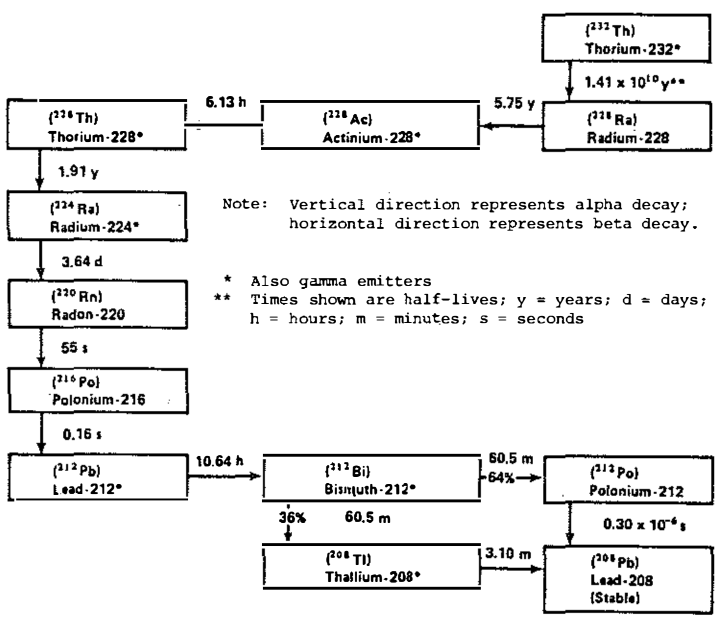

Figure 2. The radioactive decay series of thorium-232.

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

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.

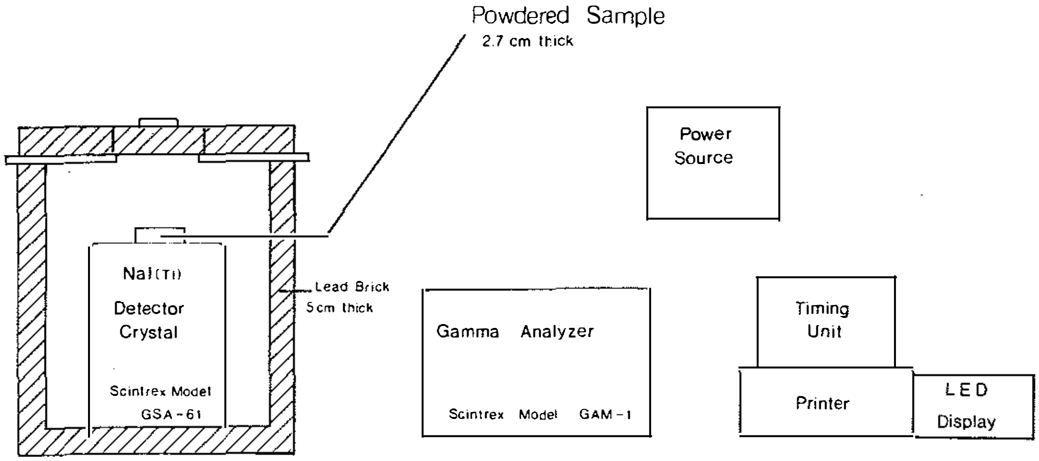

Figure 3. Schematic diagram of the gamma-ray spectrometer facility used to analyze rock samples for uranium and thorium.

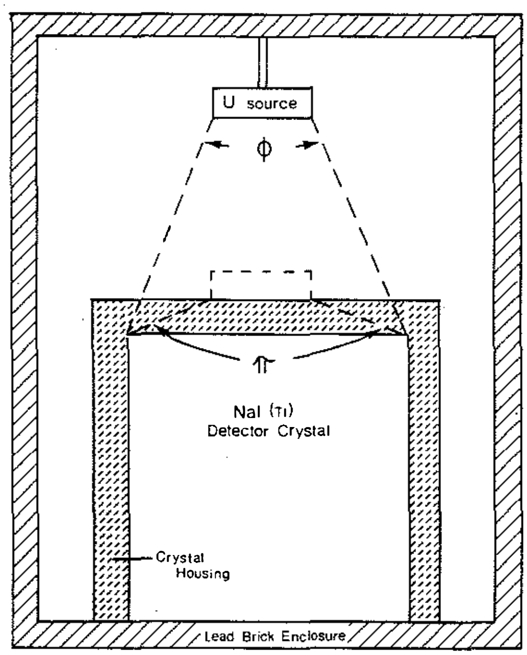

Figure 4. Source-detector configuration for the determination of the stripping ratio (s), thorium and uranium concentration factors (Q_{Th}, Q_U, and height correction factor (h).

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):

$$QTh, U = (cps/ppm)/kg$$

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 T1208 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

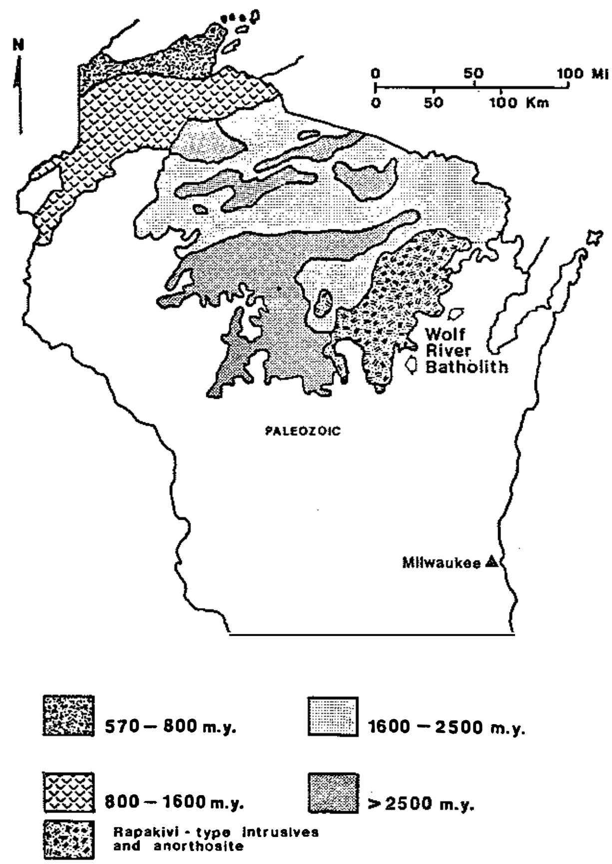

Figure 5. Generalized geologic map of Wisconsin showing the location of the Wolf River batholith.

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).

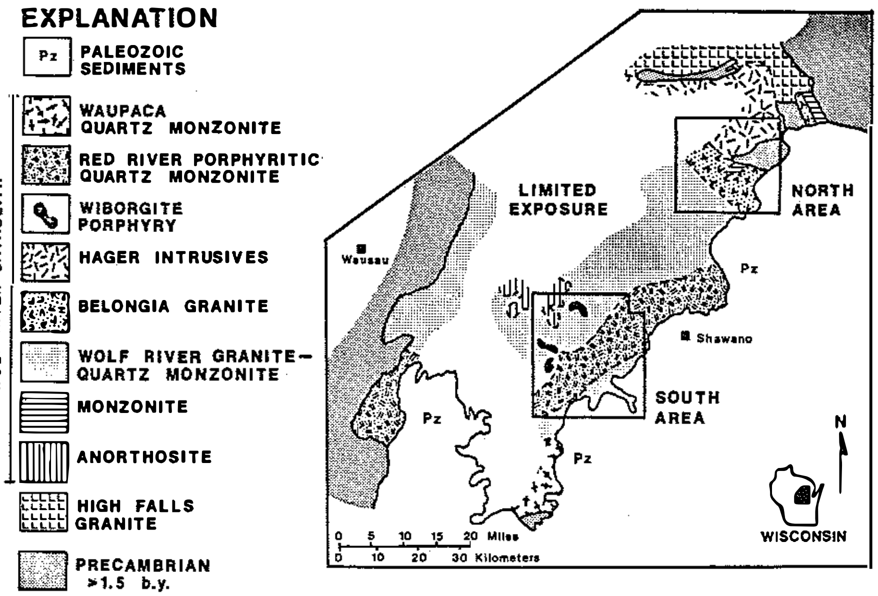

Figure 6. Geologic map of the Wolf River batholith (modified from Anderson, 1975). North and south areas correspond to regions of the batholith for which detailed radiometric distribution maps are given in figure 8 and 9 (after Meddaugh, 1978).

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 SiO2 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

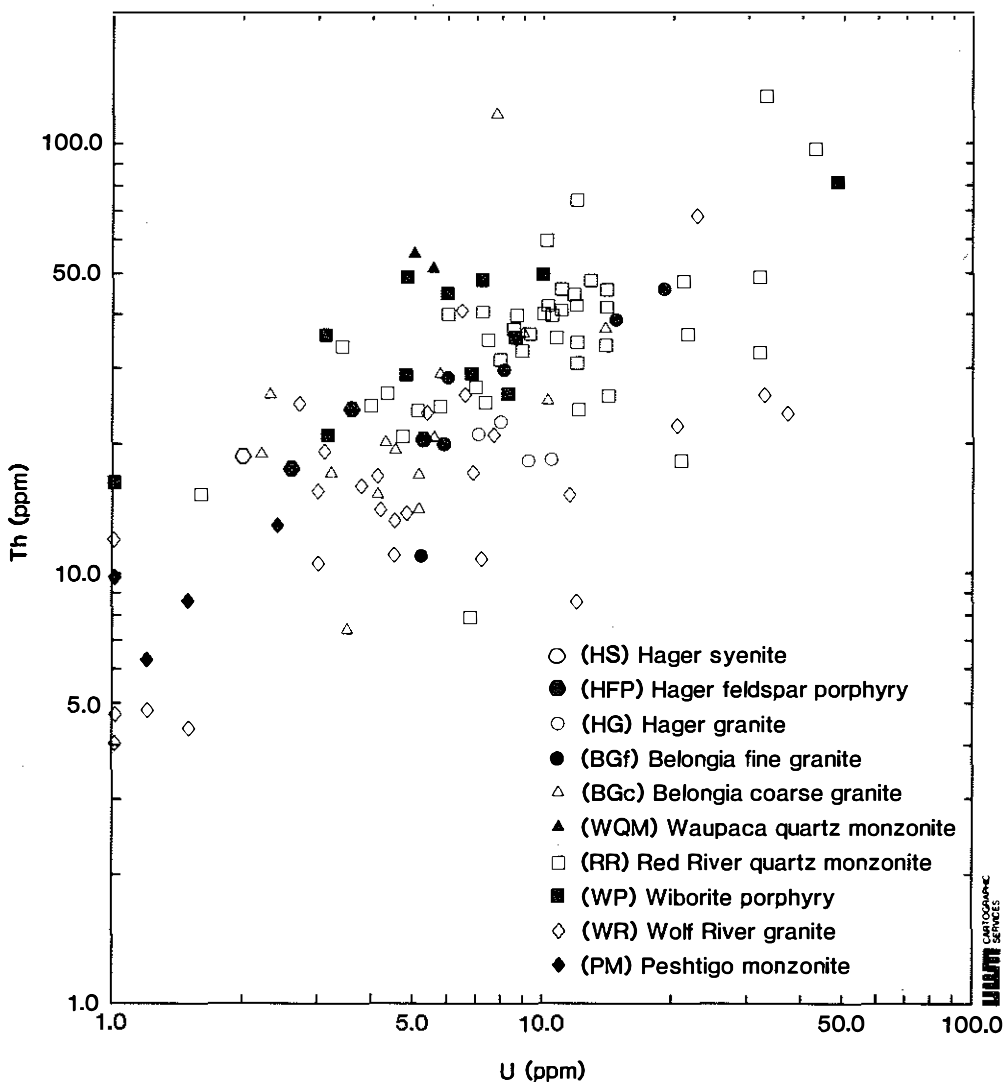

Figure 7. Distribution of uranium and thorium in Wolf River batholith, Wisconsin.

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

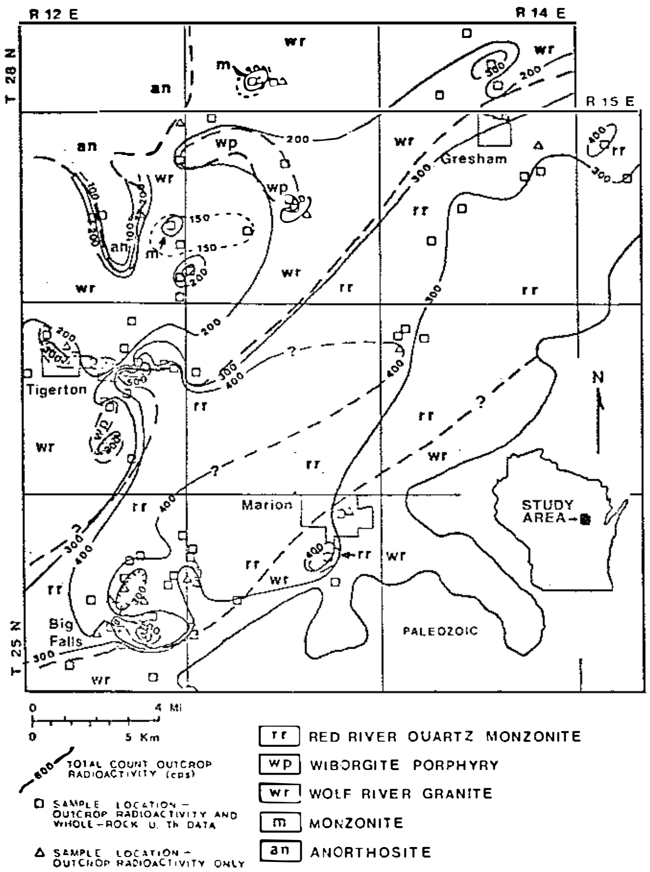

Figure 8. Outcrop radioactivity map, south area of Wolf River batholith.

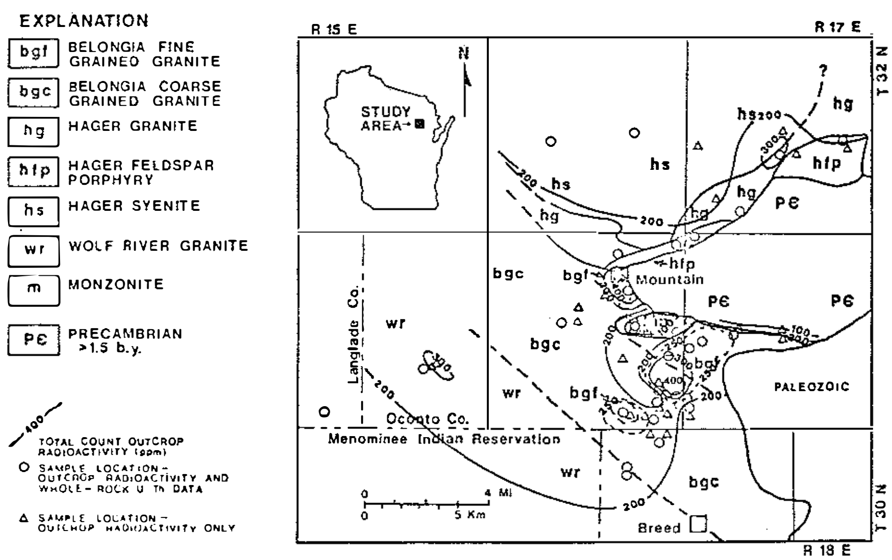

Figure 9. Outcrop radioactivity map, north area, Wolf River batholith.

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.

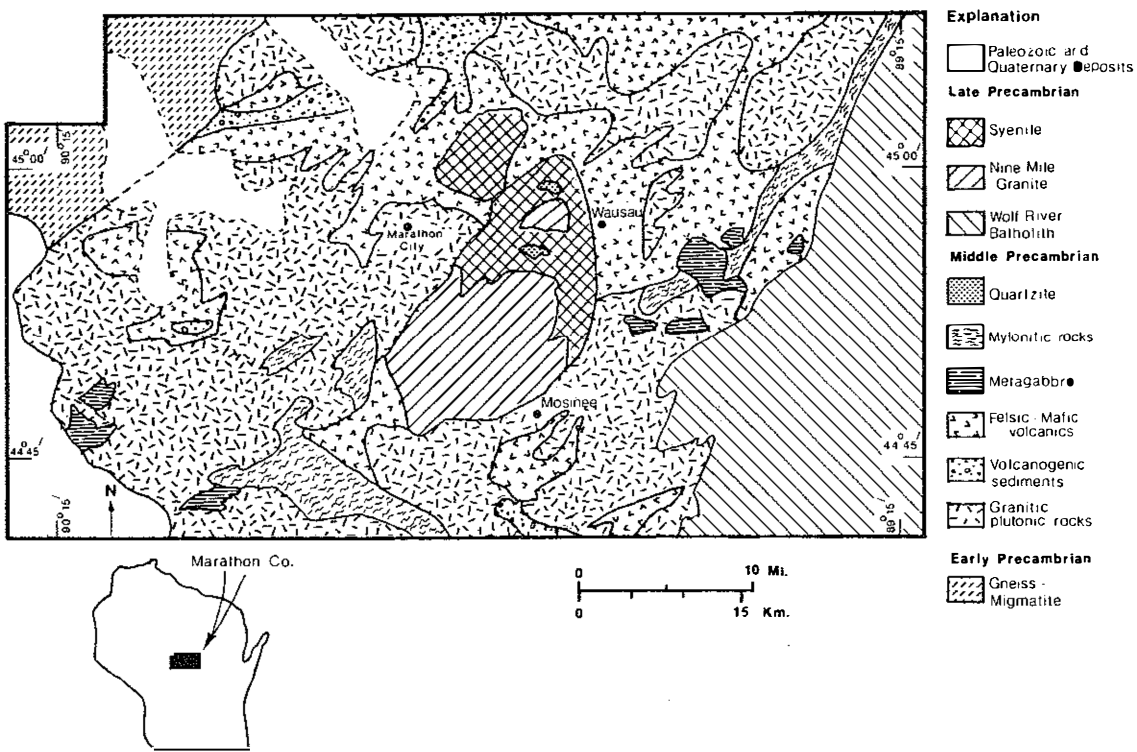

Figure 10. Generalized geologic map of Marathon County, Wisconsin (modified from LaBerge and Myers, 1983).

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

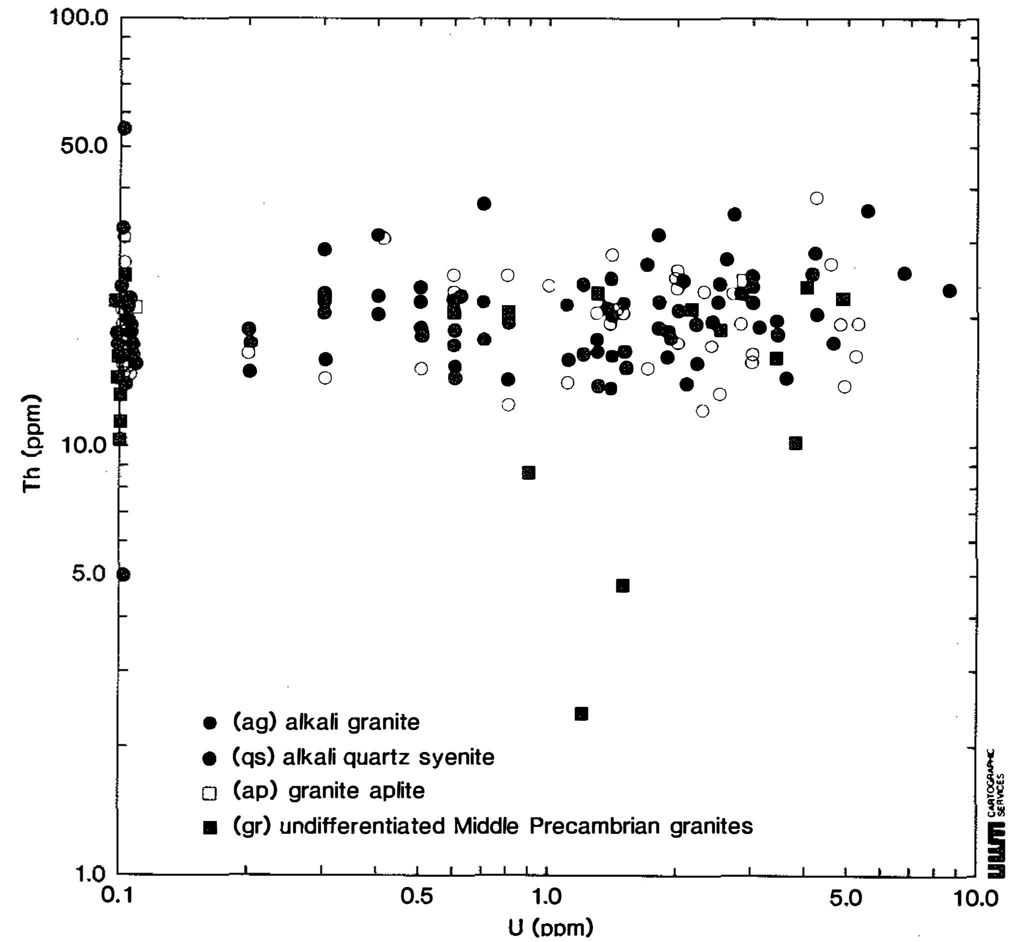

Figure 11. Distribution of uranium and thorium in Ninemile Pluton and syenite, Marathon County, Wisconsin.

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

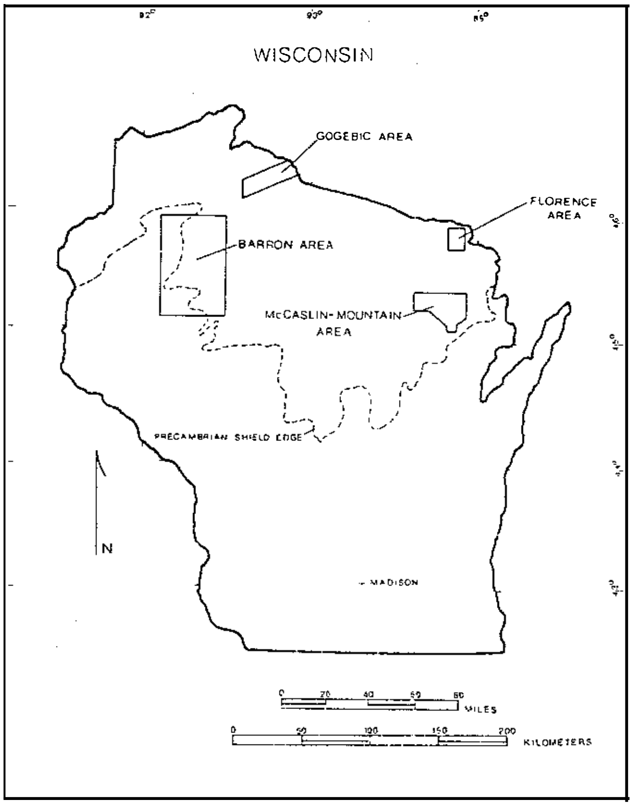

Figure 12. Location map of the selected Proterozoic quartzite-conglomerate rock units in Wisconsin.

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

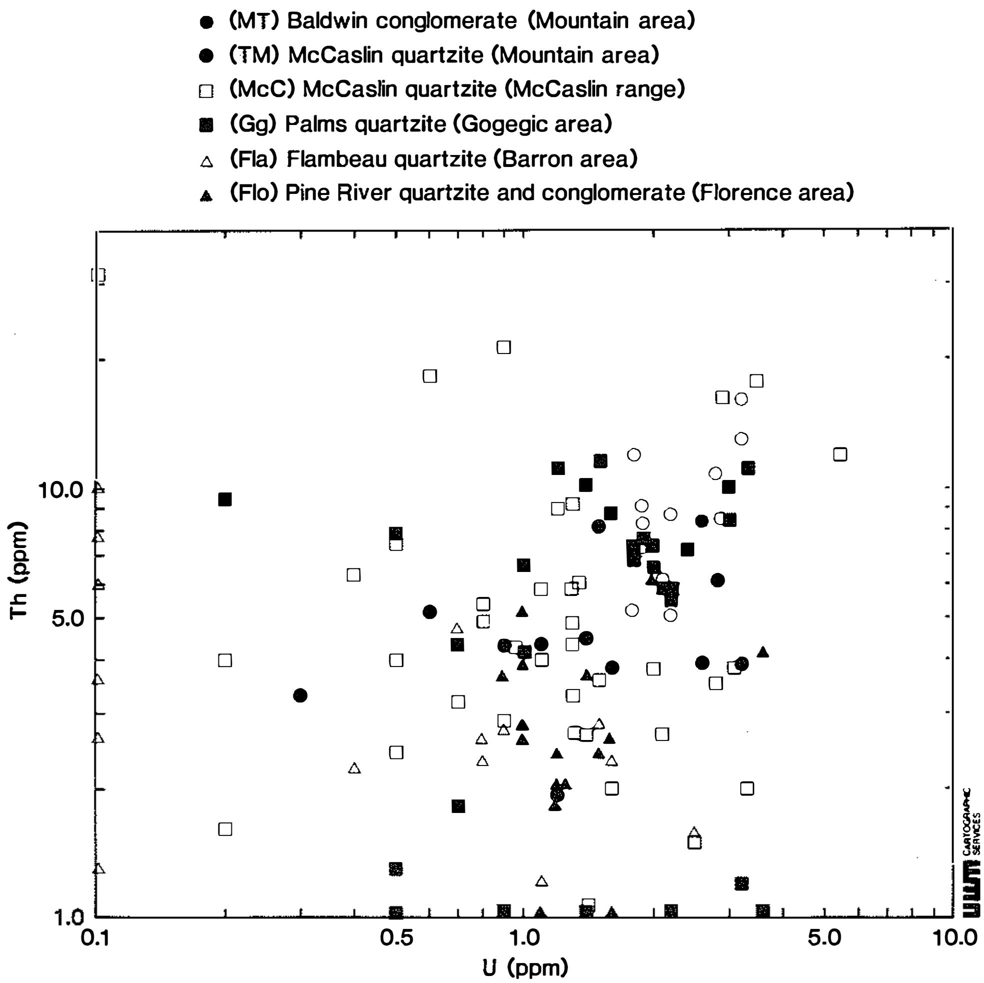

Figure 13. Distribution of uranium and thorium in Proterozoic quartzite-metaconglomerate, Wisconsin

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.

ACKNOWLEDGMENTS

The authors wish to acknowledge helpful suggestions and assistance of Robert W. Taylor in the de-bugging of the gamma-ray spectrometer. M.G. Mudrey, Jr., of the Wisconsin State Geological and Natural History Survey, provided the many topographic maps and arranged for the preparation of thin sections. Donna Schenstrom prepared the illustrations and Mark Long typed the manuscript. To all of them we offer sincere thanks.

REFERENCES CITED

Adams, J.A.S., Osmond, J.K., Rogers, J.J.W., 1959, The geochemistry of thorium and uranium, in Ahrens, L.H., and others, eds., Physics and Chemistry of the Earth, v. 3: New York, Pergamon Press, p. 298-348,

Adams, J.A.S., 1963, Laboratory gamma-ray spectrometer for geochemical studies, in Adams, J.A.S., and Lowder, W.M., eds., The natural radiation environment, Chicago, The University of Chicago Press, p. 485-499,

Adams, J.A.S., and Gasparini, P., 1970, Gamma-Ray Spectrometry of rocks: Amsterdam, Elsevier Publishing Company, 295 p.

Aldrich, H.R., 1929, Geology of the Gogebic Iron Range of Wisconsin: Wisconsin Geological and Natural History Survey Bulletin 71, 279 p.

Anderson, J.L., 1975, Petrology and geochemistry of the Wolf River batholith: Madison, University of Wisconsin, Ph.D. dissertation, 297 p.

Anderson, J.L., Cullers, R.L., and VanSchmus, W.R., 1980, Anorogenic metaluminous and peraluminous granite plutonism in the Mid-Proterozoic of Wisconsin, U.S.A.: Contributions to Mineralogy and Petrology, v. 74, p. 311-323

Anderson, J.W., 1979, Radiometric study, of selected Middle Precambrian quartzite-metaconglomerate units in northern Wisconsin: Milwaukee, University of Wisconsin-Milwaukee, M. S. thesis, 103 p.

Andrews, R.D., 1976, The geology and geochemistry of plutonic bodies in Central Marathon County, Wisconsin: Milwaukee, University of Wisconsin-Milwaukee, M.S. thesis, 137 p.

Anonymous, 1974, GAM-1 Differential single channel gamma analyzer instruction manual: Salt Lake City, Utah, Scintrex Incorporated, 31 p.

Arendt, J.W., and others, 1978a, Hydrogeochemical and stream sediment reconnaissance basic data for Green Bay NTMS Quadrangle, Wisconsin: Department of Energy (ERDA) Report GJBX-93(78).

Arendt, J.W., and others, 1978b, Hydrogeochemical and stream sediment reconnaissance basic data for Rice Lake NTMS Quadrangle, Wisconsin, Minnesota: Department of Energy (ERDA) Report GJBX-95(78).

Arendt, J.W., and others, 1978c, Hydrogeochemical and stream sediment reconnaissance basic data for Iron Mountain NTMS Quadrangle, Michigan, Wisconsin: Department of Energy (ERDA) Report GJBX-97(78).

Borst, R.I., 1958, The granites of Big Falls, Wisconsin; Madison, University of Wisconsin, M. S. thesis, 61 p.

Clark, S.P., Peterman, Z.E., and Heier, K.S., 1966, Abundances of uranium, thorium, and potassium, in Handbook of Physical Constants: Geological Society of America Memoir 97, p. 521-541.

Cook, T.R., 1980, The dispersion of uranium and thorium during weathering of a rapakivi granite near Wausau, Wisconsin: Milwaukee, University of Wisconsin-Milwaukee, M. S. thesis, 104 p.

Dutton, C.E., 1971, Geology of the Florence area, Wisconsin and Michigan: United States Geological Survey Professional Paper 633, 54 p.

Dutton, C.E., and Bradley, R.E., 1970, Lithologic, geophysical, and mineral commodity maps of Precambrian rocks in Wisconsin: United States Geological Survey Investigation Map I-631, 6 sheets.

Erickson, R.L. and Blade, L.V., 1963, Geochemistry and petrology of the Alkalic Igneous Complex at Magnet Cove, Arkansas: United States Geological Survey Professional Paper 425, 95 p.

Geometrix, 1978, Aerial gamma ray and magnetic survey, Rice Lake Quadrangle, Wisconsin; Iron Mountain Quadrangle, Wisconsin/Michigan; Eau Claire Quadrangle, Wisconsin/Minnesota; Green Bay Quadrangle, Wisconsin: Department of Energy (ERDA) Report GJBX26(78), two volumes.

Heinrich, E.Wm., 1958, Mineralogy and geology of radioactive raw materials: New York, McGraw-Hill Book Company, Inc., 654 p.

Hotchkiss, W.O., 1915, Mineral land classification . . .: Wisconsin Geological and Natural History Survey Bulletin 44, 378 p.

Hotchkiss, W.O., Bean, E.F., and Aldrich, H.R., 1929, Mineral lands of a part of northern Wisconsin: Wisconsin Geological and Natural History Survey, Bulletin 46, 176 p.

Ingram, W.N., and Keevil, N.B., 1951, Radioactivity of the Bourlagaque, Elzevir, and Cheddar batholiths, Canada: Geological Society America Bulletin, v. 62, p. 131-148.

Kalliokoski, J., 1976, Uranium and thorium occurrences in Precambrian rocks, Upper Peninsula of Michigan and northern Wisconsin, with thoughts on other possible settings: Department of Energy (ERDA) Report GJBX-48(76), 257 p.

Kinnaman, R.L., and Illsley, C.T. 1962, Geochemical and geophysical reconnaissance in Northern Peninsula, Michigan and Northeastern Wisconsin: United States Atomic Energy Commission (Department of Energy), Production Evaluation Division, RME 1099, 101 p.

LaBerge, G.L. and Myers, P.E., 1983, Precambrian geology of Marathon County, Wisconsin: Wisconsin Geological and Natural History Survey Information Circular 45, 88 p.

LaBerge, G.L., 1980, The Precambrian geology and tectonics of Marathon County, Wisconsin: Fieldtrip Guidebook for the 26th Annual Institute on Lake Superior Geology, 50 p.

Lahr, M.M., 1972, Precambrian geology of a greenstone belt in Oconto County, Wisconsin and geochemistry of the Waupee Volcanics: Madison, University of Wisconsin-Madison, M. S. thesis, 62 p.

Larsen, E.S., Jr., Phair, G., Gottfried, D., and Smith, W.L., 1956, Uranium in magmatic differentiation: United States Geological Survey Professional Paper 300, p. 65-74.

Larsen, E.S., 3d and Gottfried David, 1960, Uranium and thorium in selected suites of igneous rocks: American Journal of Science (Bradley Volume), v. 258-a, p. 151-169.

Loevinger, R., and Berman, M., 1951, Efficiency criteria in radioactivity counting: Nucleonics, v. 9, p. 26-39.

Mancuso, J.J., 1957, Geology and mineralization of the Mountain area, Wisconsin: Madison, University of Wisconsin, M. S. thesis, 32 p.

Mancuso, J.J., 1960, Stratigraphy and structure of the McCaslin district, Wisconsin: East Lansing, Michigan State University, Ph.D. dissertation, 101 p.

Medaris, L.G., Jr., Anderson, J.L., and Myles, J.R., 1973, The Wolf River batholith - A Late Precambrian rapakivi massif in northeastern Wisconsin, in Guidebook to the Precambrian geology of northeastern and northcentral Wisconsin: Wisconsin Geological and Natural History Survey, Madison, p. 9-29.

Meddaugh, W.S., 1978, The distribution of uranium and thorium in the Wolf River batholith, northeastern Wisconsin: Milwaukee, University of Wisconsin-Milwaukee, M. S. thesis, 117 p.

Motten, R.H., 1972, The bedrock geology of the Thunder Mountain area, Wisconsin: Bowling Green, Ohio, Bowling Green University, M.S. thesis, 59 p.

Mursky, Gregory, Anderson, J.W., Cook, T.R., and Meddaugh, W.S., 1988, Uranium and thorium data for selected Precambrian rock units in northern Wisconsin: Wisconsin Geological and Natural History Survey Open-file Report WOFR 88-3, 41 p.

Nilsen, T.H., 1964, Geology of the Animikean Pine River (Breakwater) quartzite-conglomerate and Keyes Lake quartzite, Florence County, Wisconsin: Madison, University of Wisconsin, M.S. thesis, 100 p.

Prucha, J.J., 1946, The rapakivi granite of Waupaca, Wisconsin: Madison, University of Wisconsin, M. S. thesis, 18 p.

Rogers, J.J.W. and Ragland, P.C., 1961, Variation of thorium and uranium in selected granitic rocks: Geochimica et Cosmochimica Acta, v. 25, p. 99-109.

Silver, L., Bickford, M.E., VanSchmus, W.R., Anderson J.L., Anderson, T.H., and Medaris, L.G., Jr., 1977, The 1.4 - 1.5 transcontinental anorogenic plutonic perforation of North America (abs): Geological Society of America, Abstracts with Programs, v. 9, p. 1176-1177.

Slack, H.A., 1949, Radioactivity measurements in the Kirkland Lake area, northern Ontario: Transactions American Geophysical Union, v. 30, p. 867-874.

Slack, H.A. and Whitman, K., 1951, A further investigation of the radioactivity of the Round Lake and Elzevir batholith: Transactions American Geophysical Union, v. 32, p. 44-48.

Taylor, S.R., 1964, Abundance of chemical elements in the continental crust: a new table: Geochimica et Cosmochimica Acta, v. 28, p. 1273-1285

Tilling, R.I. Gottfried, D., 1969, Distribution of thorium, uranium, and potassium in igneous rocks of the Boulder batholith region, Montana, and its bearing on radiogenic heat production and heat flow: United States Geological Survey Professional Paper 614-E, 21p.

Turner, D.S. 1948. Heavy accessory mineral and radioactivity studies of the igneous rocks in the Wausau area: Madison, University of Wisconsin, Ph.D. dissertation, 107 p.

VanSchmus, W.R., Medaris, L.G., Jr., and Banks, P.O., 1975, Geology and age of the Wolf River batholith, Wisconsin: Geological Society of America Bulletin, v. 86, p. 907-914.

VanSchmus, W.R., Thurman, E.M. and Peterman, Z.E., 1975b., Geology and Rb-Sr. chronology of Middle Precambrian rocks in eastern and central Wisconsin: Geological Society of America Bulletin, v. 86, p. 1255-1265.

VanSchmus, W.R., 1976, Early and Middle Proterozoic history of the Great Lakes Area: Philosophical Transactions of the Royal Society of London, v. 280, p. 605-628.

Vickers, R.C., 1956, Airborne and ground reconnaissance of part of the Syenite Complex near Wausau, Wisconsin: United States Geological Society Bulletin 1042-D, 44 p.

Weidman, S., 1907, Geology of north-central Wisconsin: Wisconsin Geological and Natural History Survey Bulletin 16, 697 p.

Weis, L.W., 1965, Origin of the Tigerton anorthosite: Madison, University of Wisconsin, Ph.D. dissertation, 65 p.