# FINAL REPORT
# DIAMOND-DRILLING FOR GEOLOGIC INFORMATION IN THE MIDDLE PRECAMBRIAN BASINS IN THE WESTERN PORTION OF NORTHERN MICHIGAN.

By

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1979

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# INTRODUCTION

## Drilling Conceived and Completed

In April, 1977, Robert C. Reed and David W. Snider of the Geological Survey Division of the Michigan Department of Natural Resources submitted a preliminary unsolicited proposal to Merle E. Crew of ERDA concerning the diamond drilling of mainly Precambrian X Michigamme Formation in four separate structural basins in Marquette and Iron Counties. The two major justifications for this proposal were the need for probing new unexplored geologic environments considered favorable for uranium deposition, and the need for basic geologic information, in the traditional function of governmental agencies. Previous work by the AEC (in the 1950's), by Cannon and Klasner (1976), by Kalliokoski and Johnson (1976), by Mancuso, Lougheed, and Shaw (1975), and by Vickers (1956) had indicated a potential for uranium and phosphate in these strata, even though they are not well exposed in the four basins. The proposal was accepted and implemented with funding by ERDA (now by the U. S. Department of Energy), contracted by the Bendix Field Engineering Corporation, and subcontracted by the Michigan Geological Survey Division of the DNR, with the result that between September 26, 1977, and May 11, 1978, six initially vertical holes probed a total of 9896 feet (1109 feet or 11.2% in overburden, 155 feet or 1.6% in Precambrian Y mafic dikes, 8386 feet or 84.7% in Precambrian X Goodrich Quartzite and Michigamme Formation, and 246 feet or 2.5% in Precambrian W basement lithologies). In addition to normal examination of core, logging, and storing of core, the holes were extensively logged geophysically, acidized core was tested for phosphate content by ammonium molybdate, splits from five out of every thirty feet of core were subjected to chemical scrutiny, thin sections of all lithologies were examined, and radiometric determinations of geologic age were made for confirmation of Precambrian W basement which was encountered in each of the three basins in Marquette County.

## Locations of Drill Sites

Figures 1 and 2 illustrate the drill locations in Marquette and Iron Counties, Michigan. Proceeding generally from north to south:

The East Baraga Basin was probed by three holes: Initially vertical DL-1 in the NW¼, SW¼ section 5, T.50N., R.28W., Marquette County, terminated at 2148 feet, deviating from the vertical by 56¼°, N.14°E. Initially vertical DL-3 in the NW¼, NW¼ section 14, T.50N., R.29W., terminated at 1634 feet, deviating from the vertical by 44°, N.18°E. DL-1 and DL-3 failed to penetrate to the Precambrian W basement as a consequence of overburden-concealed structural complexities, and as a consequence of deviation of the holes from the intended vertical as the bits attempted to penetrate the pervasive slaty cleavage perpendicularly. Therefore, an originally unplanned hole, DL-7 in the SW¼, NE¼ section 4, T.50N., R.28W., was drilled 1½ miles east of DL-1 to overlap lower strata encountered in DL-1. The hole encountered the Precambrian W basement at 659 feet, before terminating at 679 feet deviating 14½° from the vertical. An inclined hole, DL-2 planned between DL-1 and DL-3, was never drilled because of budgetary considerations, and will not be further discussed.

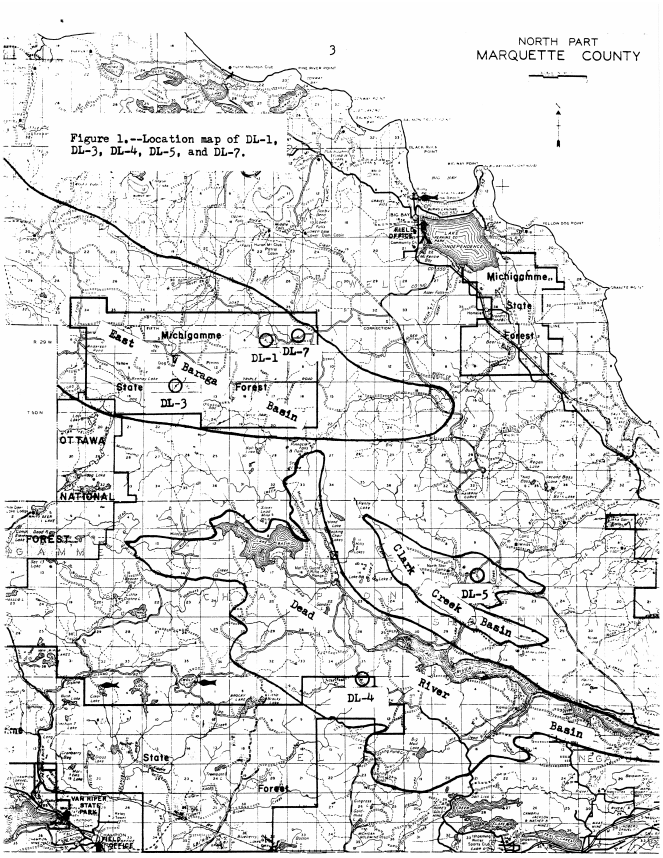
The Clark Creek Basin was tested by DL-5 in the NW¼, SE¼ section 16, T.49N., R27W., Marquette County, where the hole was terminated at 1148 feet with a deviation from the vertical of 3°, S. 10°W., after penetrating the Precambrian W basement at 997 feet.

The Dead River Basin was cored at DL-4 in the NW¼, NE¼ section 2, T.48N., R.28W., Marquette County, where the hole was terminated at 3176 feet with a deviation from the vertical of 12 , S. 30°W., after encountering the Precambrian W basement at 3119 feet.

Field Engineering Corporation subcontract details and financial matters were handled by J. A. Papania, Director or Procurement, and by D. C. Grove, Subcontract Administrator. Frequent telephone and written communication was maintained with T. J. Price, BFEC Drilling Superintendent. Charles F. Hajek and Jack McCaslin of BFEC observed the drilling for extended periods. BFEC geophysical logging was originally planned by Mike Callihan, and was implemented by Kirk Hayer and Wayne D. Gisler.

For the Geological Survey Division of the Michigan Department of Natural Resources the manager of the project was Robert C. Reed, Chief, Mining and Environmental Geology Section. Day-to-day administration and complete planning for chemical analyses were carried out by the assistant manager, David W. Snider, Research Staff Unit Coordinator, who also completed well sitting at DL-4 and submission of samples for chemical studies. Jack Van Alstine, Regional Geologist, supervised all environmental considerations, local public relations, coordination with area foresters, and geophysical logging. The cores currently are under his jurisdiction at Marquette, at DNR

Region 1 Headquarters. Placing and surveying monuments near drill sites was accomplished by David B. Babbitt and Arthur O. Enger. Financial matters were administered by Raymond D. Schofield, Erna E. Dennison, and Marian Speerbrecker.




[Figure 1. Location map of DL-1, DL-3, DL-4, DL-5, and DL-7.]

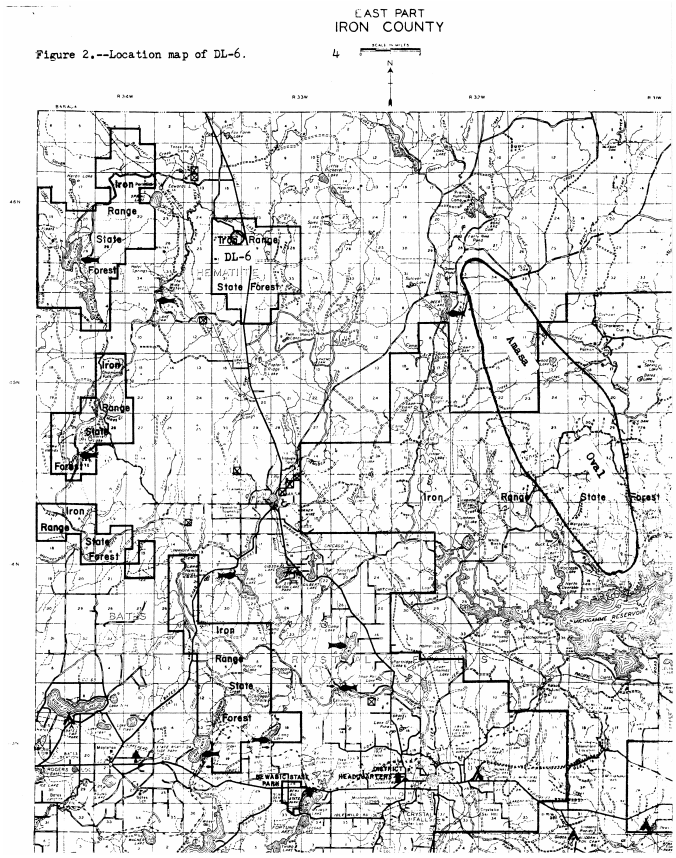
The Longyear Company was represented by Walter Newbauer. During the drilling J. E. Stubblefield and J. W. Kivela were foremen.

The Bird well Division of S. S. C. geophysical logging at DL-1 and DL-3 was carried out by G. Rigdon, the logging at DL-5 was carried out by Mike Stefanov, and the logging at DL-4 and DL-6 was carried out by J. Morehead.

The Barringer Magenta Ltd. chemical analyses were supervised by Romana B. Cruz.

The northwest flank of the Amasa Oval was drilled at DL-6 in the NE¼, NE¼ section 30, T.46N., R.33W., Iron County, where the hole was terminated at 1093 feet deviating from the vertical by 4½°, N.55 E. Fractured ground caused binding of the rods and abandonment of the hole before the base of the Michigamme Formation was attained.

Details on drilling practice are covered in six 7 - 16 page engineering reports on the six holes, obtainable from Bendix Field Engineering Corporation Technical Library, P.O. Box 1569, Grand Junction, Colorado 81501. G3BX-50 (79). Such details will not be reported here. In five of the-holes, core recovery was almost 100%, whereas at DL-6, core recovery averaged 96%.




[Figure 2. Location map of DL-6.]

The drill sites were selected by the Michigan Geological Survey on the dual criteria determined by a gravity survey of the region by John Klasner of the U. S. Geological Survey, and by the location of State land or land open to the State for drilling, and by proximity to available roads. These criteria, which will not be repeated here in detail, are completely covered in the April, 1977 33-page preliminary unsolicited proposal to ERDA, “Drilling for Geologic Information in Middle Precambrian Basins in the Western Portion of Northern Michigan,” by Robert C. Reed and David W. Snider of the Geological Survey Division of the Michigan Department of Natural Resources. Emphatically, it should be re-emphasized that this project was not designed as mineral exploratory drilling guided by geological, geophysical, or geochemical anomalies, but rather this project was designed to provide fundamental geological information in areas where a thick cover of Pleistocene sediments prevents adequate coverage by normal governmental areal geologic mapping. The drill sites were selected so as to yield a maximum stratigraphic section of the Precambrian X strata in each of the four basins.

## Personnel Involved

Overseeing the entire project on behalf of DOE at Grand Junction was John R. Ellis, Subsurface Project Officer of the NURE Project Office. For the Bendix Radiometric age dates of Precambrian W rocks from DL-4, DL-5, and DL-7 were accomplished by Dr. W. R. Van Schmus and Roger D. Hammond of the Department of Geology, University of Kansas.

Originally, when the author was retained as geologist-in-charge of the project by the Michigan Geological Survey, it was assumed that the drilling would be accomplished during summer months and would not occur during winter teaching responsibilities at Michigan State University. When Grand Junction approved the project for an autumn 1977 start, Jack W. Avery was retained to monitor drilling at the rigs. Mr. Avery therefore logged most of the holes and dealt with the drillers daily. Much of the author's time was utilized in coordinating various efforts, communicating, obtaining core boxes, chemicals, sample bags, and other supplies, and in coping with numerous agencies. To pick up the core at the drill rigs, to slab it on a diamond saw for thin sections and chemical samples, to split core, to test it with ammonium molybdate for phosphate content, and to clean and store the core methodically, William T. Swenor was hired as a technician. The six engineering reports and the six preliminary geologic data reports were prepared by the author in addition to the present report.

## Purpose of the Present Report

This report does not repeat the details presented in the six engineering reports with microfiche copies of geophysical logs, obtainable from Grand Junction; this report does not repeat the details presented in the six preliminary geologic data reports with on-site logging of the core by Jack W. Avery and David W. Snider, and the author's observations, interpretations, and exploration recommendations, obtainable from Greg Wilson, Michigan Geological Survey Division of the DNR, Stevens T. Mason Building, Box 30028, Lansing, Michigan 48909. Instead, this report covers 1) chemical and age-dating data not yet presented, 2) correlation among all holes, and 3) a summary of the significant aspects of regional geology learned from drilling data. The serious reader interested in the region should obtain the six engineering and the six preliminary geologic data reports to augment topics covered here. Undoubtedly, industry, government, and academia can and will extract many more meaningful bits of information from the cores, so that eventually further publications may ensue.

# CHEMICAL ANALYSES

## Program Design

David W. Snider designed a statistically unbiased program of sampling the core by arranging for 2 pounds of "walnut"-sized pieces of split core every 3 to 6 inches in a 5-feet-iong segment from every 30-feet-long segment of footage. If the core was taken from DL-1 between 734-739 feet, the sample was labeled i-734-739; the next sample, 30 feet deeper, was labeled 1-764-769. Because only nine digits or dashes could appear on computer print out, the drill location number was dropped for footage beyond 999 feet, so that for DL-1 between 1004-1009 feet the computer print-out would indicate 1004-1009, but at least it would appear in the same vertical column below location-specified footage less than 1000 feet deep. Therefore, in the accompanying appendix of tabular chemical data, to find the hole number for depths more than 999 feet where dashes appear in the read-out, the reader should look higher in the same vertical column to find the hole number specified as a prefix to the span of footage for depths in that hole less than 1000 feet. In some instances no dashes appear, as in 4B16091614 which means that the analysis refers to DL-4 in the B sequence, drilled after a major wedging, between 1609-1614 feet. The prefix S refers to special samples collected for economic interest between routinely sampled intervals: S5-713-714 refers to a special sample at DL-5 between 713-714 feet. The prefix EX refers to Exxon core, not discussed here, which is in the possession of the State.

## Analytical Procedure

The samples were submitted to Romana B. Cruz of Barringer Magenta Ltd., Rexdale, Ontario, where they were prepared and subjected to hydrofluoric/nitric/perchloric acid digestion, and then submitted to multi-element radio frequency argon plasma emission analysis for 1) whole-rock determinations of rock-forming oxides consisting of $Al_2O_3$, CaO, $Fe_2O_3$, $K_2O$, MgO, MnO, $Na_2O$, $P_2O_5$ and $TiO_2$ ($SiO_2$ was determined in a separate atomic absorption analysis), and 2) trace elements consisting of Ag, Ba, Be, Cd, Co, Cr, Cu, Ni, Pb, Sr, V, Zn, and Zr. Colorimetric analysis of As and Mo, analysis of organic carbon, and analysis of U and Th were conducted separately after only nitric/perchloric acid digestion (to exclude such constituents in silicates which would have dissolved in the hydrofluoric acid digestion, above) were separately determined. The relatively low Mo analyses reported indicate that technician William T. Swenor carefully cleaned the cores after testing them for phosphate content with ammonium moiybdate before submitting lumps from splits for chemical analysis. Twelve special samples from possibly economically interesting core from DL-4B, DL-5, and DL-7 and not systematically sampled were subjected to the same type of analysis, except a determination for gold was

substituted for the determination of organic carbon in some samples.

## Data Presentation

The chemical data in the appendix appear in two forms: 1) in graphic profiles printed as horizontal sequences of asterisks (to simplify comparison with geophysical logs in microfiche which accompany each engineering report for each hole, available from Grand Junction), and 2) in digitized vertical columns. In both profiled and digitized statements of data, depth appears on the y-axis and magnitude of constituents appears on the x-axis. It is suggested that the reader should grasp the significant trends by perusing the profiled plots first, and after that the reader should confirm specific values of interest on the digitized columns. Both whole-rock and trace element analyses are shown in both profiled and digitized form. For the benefit of economic geologists, a special combination of analyses has been designated the trace element indicator group for potential mineralization (As, Cu, Ni, $P_2O_5$, Pb, Th, U, V, and Zn). These data are plotted in the profile form as the sum of unit values of adjusted and normalized analyses of the above-mentioned constituents, based upon the maximum occurrence of each in this project.

## Some Interesting Examples of Chemical Values

The analyses reveal some general and specific observations:

Organic carbon of the slates and argillites of the Michigamme Formation commonly ranges between ½%-3%. Higher carbon content in some instances correlates with maxima of other elements, presumably precipitated in a reducing environment. For example, the highest organic carbon content noted in the project, 8.01%, occurs in a special sample from a 2-inches-thick conglomerate within cherty carbonates (presumably the Bijiki Iron-Formation Member) of the Michigamme Formation at a depth of 3011 feet at DL-4B, where uranium content, 130 ppm, is the highest observed in any metasediments in this project. A duplicate determination after hydrofluoric/nitric/perchloric acid digestion yielded 260 ppm uranium, thereby suggesting that half of the total uranium was available in readily leached compounds whereas the other half was not easily leached, but possibly was bound within silicates. This core causes a scintillometer to register almost five times background count. In the same special sample vanadium attained a peak of 862 ppm, and $P_2O_5$ attained 2.79%. In the same hole, a regular sample of massive carbonaceous argillite of the Upper (Slate or Argillite) Member of the Michigamme Formation between 2899-2904 feet contains 6.02% organic carbon and 612 ppm copper. At DL-6 the maximum organic carbon content of 3.56% at 848-853 feet, again within slaty and cherty iron-formation of the Michigamme Formation, correlates with the maximum copper content in that hole of 971 ppm. The first instance probably was syngenetic sedimentary reduction whereas the second and third probably involved some epigenetic remobilization, according to textural and structural evidence. As indicated in the section on base metals, page 33, even in bedding planes where sulfides appear to be syngenetic, maximum mineralization is adjacent to Keweenawan Precambrian Y faults and breccia zones which transect bedding planes and Penokean slaty cleavage. Further, the sheets of sulfides within slaty cleavage clearly formed after sedimentation. Such slaty cleavage-related stringers of sulfides are most abundant adjacent to Keweenawan faults and breccias. An exception to the occurrence of organic carbon with other elements appears at DL-5 in a special sample of basal Bijiki carbonate-rich conglomerate at 713-714 feet, where organic carbon is reported to be 4.05%, but uranium content is only 0.8 ppm. However, carbon-seamed stylolites at the base and two inches above (confirmed by Jack Van Alstine) imply considerable removal of soluble materials, possibly including once-present uranium. Jack W. Avery determined that the core registers approximately 2½ times background count on a scintillometer.

The highest uranium content noted in five-feet routine samples from this project occurs at DL-5 between 1024-1029 feet with 76 ppm, and between 1054-1059 feet with 72 ppm in a Precambrian W green porphyritic metarhyolite tuff. These values exceed those from more commonly celebrated Precambrian W source rocks for Precambrian X strata, such as granite, and they suggest that perhaps some of the uranium in the Precambrian X strata was originally derived from the weathering of Lower Precambrian rhyolites. It is of interest to compare the 76 and 72 ppm chemical determinations to Bendix KUT geophysical probing for the same footage, averaging 57 and 24 ppm respectively (see DL-5 engineering report, available from Grand Junction). In general, the uranium content of Precambrian X strata is much lower, mainly between 0.2 - 5.4 ppm after nitric/perchloric acid digestion. Presumably, hydrofluoric/nitric/perchloric acid digestion would yield values twice as high, as at DL-4B at 3011 feet. As detailed in the DL-5 preliminary geologic data report, available from the Michigan Geological Survey, the most interesting potentially economic possibility determined by drilling relates to presumably volcanogenic strata-bound sulfide mineralization in Precambrian W metabasalt from 1059-1148 feet, with copper ranging between 124-2010 ppm and gold ranging between 20-50 ppb. While this is definitely not ore, it may be the pyrite-rich and pyrrhotite-rich fringe characteristic of strata-bound massive sulfide ore bodies. Recommendations for exploration are stated in the preliminary geologic data report for DL-5, pages 4-6.

# AGE DATING AND CORRELATION OF PRECAMBRIAN W ROCKS

In an August 20, 1978, report on age dating, W. R. Van Schmus stated that U-Pb ages from zircons separated from Precambrian W rocks are as stated in the following observations:

## Dead River Basin

DL-4B gneissic tonalite or quartz diorite (without much potassium feldspar) composite sample from 3166-3174 feet yielded an age of 2700 + 15 m.y. Deeper portions of fresh rock (as sampled for age dating) megascopically resemble numerous surface samples of the Compeau Creek Gneiss. Upper portions, up to the apparently unfaulted unconformity with the Goodrich Quartzite at 3119 feet, appear to grade into the Goodrich through a chloritic metaregolith zone. This transition is reminiscent of the transition between the Precambrian W granite gneiss and the overlying Ajibik Quartzite west of the Republic Trough, described by Villar (1965, p. 17 - 18). That transition misled Lamey (1937) to the interpretation that the base of the Ajibik Quartzite was locally granitized by an intrusive granite, presumably of late Precambrian X age. Fortunately, at DL-4B tapioca-like grains of clastic quartz, presumably derived from quartz phenocrysts of Precambrian W porphyritic metarhyolite, occur in the basal Goodrich Quartzite to a depth of 3119 feet, so that upon careful examination the major unconformity can be located. This transition zone and metaregolith at DL-4B imply deep pre-Goodrich weathering, and imply that abundant feldspar grains in the Goodrich Quartzite are more the result of rapid erosion, transportation, and deposition than a result of desert or glacial climate.

## Clark Creek Basin

The DL-5 composite sample of Precambrian W porphyritic metarhyolite tuff from 1000-1059 feet yielded an age of 2700 + 15 m.y. The determination was based upon one-tenth the minimum abundance of zircons previously used at the University of Kansas, as a consequence of the paucity of zircons in this rock. This sample is a green slightly sheared unit presumed to correlate with the Sheared Ryholite Tuff Member of the Mona Schist, or with felsic rocks in the Lighthouse Point Member of the Mona Schist (Puffett, 1974, p. 14 - 15, p. 19 - 20). The underlying metabasalt with massive sulfide mineralization is presumed to correlate with more typical units of the Mona Schist. The contact between these two units is almost perpendicular to the base of the Precambrian X basal Goodrich Quartzite. The 2700 m. y. metarhyolite tuff directly beneath the Goodrich Quartzite does not appear to be a deeply weathered metaregolith, as is the 2700 m. y. tonalite directly beneath the Goodrich at DL-4B. The basal Goodrich at DL-5 is a ¼-inch-thick black carbonaceous seam (unslickensided and presumably unfaulted) at the bottom of the basal conglomerate of the Goodrich (996-997 feet). Perhaps this indicates local reduction rather than oxidative weathering immediately preceding Goodrich Deposition.

The 2700 m.y. ages of Precambrian W basement at DL-4B and DL-5 are consistent with those which Dr. Van Schmus has obtained from surface exposures of Precambrian W rocks nearby in Marquette County.

## East Baraga Basin

The DL-7 granite from a split section from 687-697 feet yielded an apparent age of 2600 + 15 m. y., which is similar to some ages which Dr. Van Schmus has obtained in Dickinson County. Megascopically the DL-7 granites resemble granites exposed farther south in Marquette County. The DL-7 microcline-rich granites could be the source of the abundant clastic microciine found in the Goodrich Quartzite and in the Lower (Slate or Argillite) Member of the Michigamme Formation. The uppermost granite with supergene veins of chert and carbonate uncomformably underlies conglomerates and cherty carbonate of the Bijiki Iron-Formation Member of the Michigamme Formation. This is similar to veined granite underlying iron-formation northwestward along strike at Big Eric's Crossing, NW¼, NW¼ section 35, T.52N., R.30W., Baraga County as shown by Johnson (1976, p. 100). Ms. Johnson correlates the iron-formation with the Greenwood, following the usage of Mancuso, Lougheed, Seavoy, and Shaw, 1975, p. 25. As at DL-4 and as at exposures at Big Eric's Crossing, the core at DL-7 indicates that the Precambrian W rocks immediately below the unconformity constitute a metaregolith, weathered prior to Precambrian X deposition and mildly metamorphosed after Precambrian X sedimentation. The unconformity at DL-7 occurs at a depth of 659 feet.

## Inexactness from Rb-Sr Determinations

Dr. Van Schmus reported that Rb-Sr determinations on rocks from these cores were inexact as a consequence of either insufficient Rb relative to Sr, or it may be a consequence of apparently younger ages caused by open chemical systems which must have operated during various geologic events.

# CORRELATION WITHIN PRECAMBRIAN X BARAGA GROUP

## Basis for Correlation Among Holes

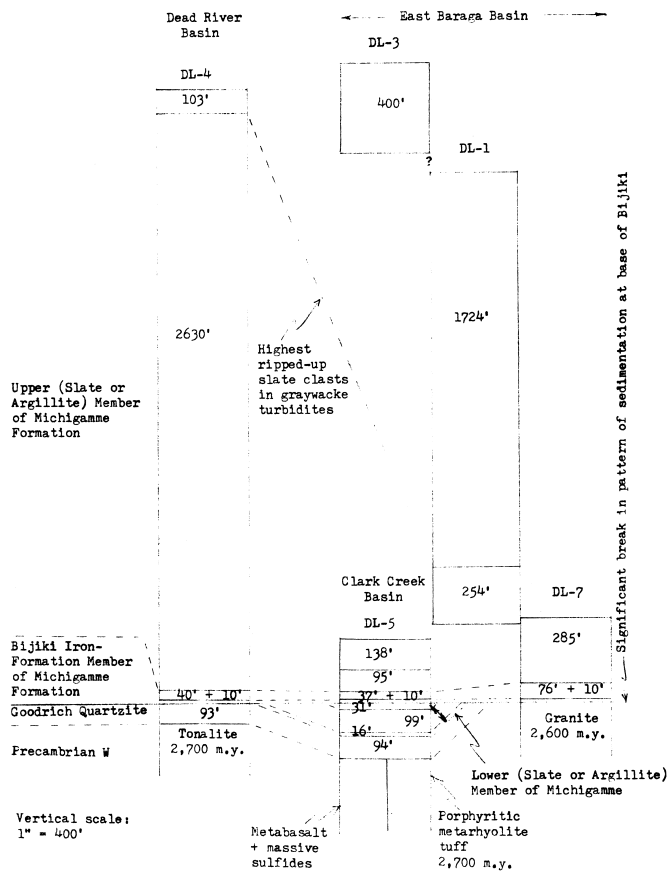
In the Dead River, Clark Creek, and East Baraga Basins of Marquette County, strata of the Baraga Group rest directly upon Precambrian W rocks with profound unconformity. In the following stratigraphic correlation among the five holes in Marquette County, depth intersections have been converted trigonometrically to stratigraphic thicknesses, the numbers stated without parentheses. In contrast, numbers in parentheses are

depth intersections in feet, as actually logged. The main basis for correlation is the presence in all three basins of two stratigraphic units: 1) Ten feet of cherty carbonate, graywacke and conglomerates (3008-3019 feet) at DL-4B, 10 feet of gray-green carbonate-rich conglomerate and agglomerate (702-714 feet) at DL-5, and 10 feet of carbonate-rich conglomerate (648-659 feet) at DL-7 are overlain by 2) phosphatic cherty carbonates and elastics as 40 feet of sulfide-bearing light gray cherty carbonate and carbonate-rich argillite, graywacke, and thin conglomerates at DL-4B (2966-3008 feet), as 37 feet of white cherty carbonate with algal stromatolites, chert, and light gray carbonate-rich argillite at DL-5 (660-702 feet), and as 76 feet of sulfide-bearing light gray cherty carbonate with algal stromatolites, and several thin conglomerates at DL-7 (569-648 feet). The latter occurrence, at DL-7 appears to be continuous westward into Baraga County along the northern margin of the Baraga Basin into phosphatic cherty iron-formation tentatively correlated by Mancuso, Lougheed, and Shaw (1975, p. 586) with the Negaunee Iron-Formation. This was later correlated by Mancuso, Lougheed, Seavoy, and Shaw (1975, p. 25) with the Greenwood Iron-Formation Member of the Michigamme Formation, and correlated by Tyler and Twenhofel (1952, p. 148) with the Bijiki Iron-Formation Member of the Michigamme Formation. The current drilling tentatively favors the latter correlation because 1) no stratigraphically higher phosphatic-cherty correlatives of iron-formation were encountered in these drill holes in the overlying half-mile-plus thickness of Michigamme Formation, and 2) because abundant (Clarksburg) volcanics were not found above the cherty beds in these drill holes, only obscure 5-inches to 2-feet thick pyritic and chloritic beds (possibly propylitized andesite tuffs) at DL-1 (1718 feet) and at DL-3 (315, 317, 418, 909, 1119, and 1123 feet) were intersected. The most conspicuous marker of possibly partial volcanic origin is the 10-feet-thick agglomerate and conglomerate at DL-5 (702-714 feet) below the cherty beds. On the south limb of the Marquette Synclinorium the Clarksburg Volcanics overlie the Greenwood Iron-Formation Member of the Michigamme Formation. If the cherty carbonate beds in the drill holes are correlatives of the Bijiki Iron-Formation Member of the Michigamme Formation, the following stratigraphic nomenclature applies to these holes, whose critical stratigraphic relationships are summarized in figure 3.

## Dead River Basin

DL-4 contains 93 feet of Goodrich Quartzite (3019-3119 feet), 10 feet of possibly Bijiki cherty carbonate, graywacke, and conglomerate (3008-3119 feet), 40 feet of Bijiki cherty carbonate and carbonate-rich argillites, graywackes, and conglomerates (2966-3008 feet), and 2630 feet of argillites and graded-bedded turbidite graywackes of the Upper (Slate or Argillite) Member of the Michigamme Formation (76-2966 feet). It is here suggested that at the phosphorite locality in the NE¼ section 15, T.49N., R.28W., described by Cannon and Klasner (1976, p. 3 - 5), 3½ miles northnorthwest from DL-4, that their unit #2, rusty-weathering dolomitic quartzite, is correlated with the Goodrich Quartzite. Further, their cherty phosphate-bearing unit #3 probably is the Bijiki Iron-Formation Member of the Michigamme Formation, and their thinly laminated gray-green argillite unit #4 probably is part of the Upper (Slate or Argillite) Member of the Michigamme Formation.

Figure 3.--Stratigraphic sections of Marquette County holes:




## Clark Creek Basin

DL-5 contains 94 feet of Goodrich Quartzite (884-997 feet), 146 feet of argillite and graywacke of the Lower (Slate or Argillite) Member of the Michigamme Formation (714-884 feet), 10 feet of possibly Bijiki green-gray carbonate- and chlorite-rich conglomerate and agglomerate (702-714 feet), 37 feet of Bijiki chert, cherty carbonate, and carbonate-rich argillite (660-702 feet), and 233 feet of argillites and graywackes (339-660) feet of the Upper (Slate or Argillite) member of the Michigamme Formation.

## East Baraga Basin

DL-1 and DL-7 contain neither the Goodrich Quartzite nor the Lower (Slate or Argillite) Member, but start with 10 feet of possibly Bijiki carbonate-rich conglomerate (648-659 feet), followed by 76 feet of Bijiki cherty carbonate with thin conglomerates (569-648 feet), and 2203 feet of graded-bedded graywackes, argillites, and

slates of the Upper (Slate or Argillite) Member of the Michigamme Formation (243-569 feet at DL-7 and 71-2148 feet at DL-1). The 400 feet stratigraphic section of slates at DL-3 (163-1634 feet of low-angle intersection plus duplication) cannot precisely be correlated with units in the other holes. Probably the finely-grained slate units at DL-3 are higher in the Upper (Slate or Argillite) Member of the Michigamme Formation than any units observed in the other holes: Concentric-circle Busk structural projections, based upon dips observed in outcrops and upon the unexpectedly high dips at DL-3, imply that the Michigamme Formation may be more than five thousand feet thick in the East Baraga Basin. Of course, Busk constructions are more appropriate for parallel folding than they are for similar folding such as occurs in the Lake Superior region, but they are the best that can be utilized with the scarce data available, and they do give us an order of magnitude for depth to Precambrian W basement. By any standards, the Michigamme Formation is thick.

## Northwest Flank of Amasa Oval, Iron County

The 286 feet of Michigamme argillites and slates alternating with thin iron-formations (236-1093 feet) at DL-6 cannot safely be correlated with stratigraphic units observed in the Marquette County holes. However, the presence of thin iron-formations favors a correlation with Bijiki or older strata, so that probably the Iron County cores correlate with Bijiki or the Lower (Slate or Argillite) Member of the Michigamme Formation.

## A Major Unconformity in the Michigamme Formation?

While no angular discordance was noted at the base of the Bijiki cherty carbonates and elastics in the three Marquette County basins probed, a major break in pattern of sedimentation and paleogeography was indicated at that horizon: Figure 3 implies that during Goodrich and Lower Slate or Argillite "time" the three basins experienced independent histories, with deposition of the Goodrich Quartzite in the center of the Dead River Basin, with deposition of the Goodrich Quartzite and the Lower (Slate or Argillite) Member in the Clark Creek Basin, and with erosion on the north fringe of the East Baraga Basin. Apparently just before Bijiki "time" the entire area was covered by a common sea, so that hitherto isolated sedimentary basins were then interconnected, and all three thereafter received Bijiki and Upper (Slate or Argillite) Member sediments. Subsequent Penokean and later deformations apparently re-isolated the three into the present structural basins. The configurations of the pre-Bijiki sedimentary basins may have been quite different from the configurations of the present structural basins as suggested by the following correlation: Instead of resembling the section at DL-4, in the central Dead River Basin, Puffett's (1974, p. 35) section for the eastern Dead River Basin more closely resembles the sequence at DL-5, in the Clark Creek Basin, thereby suggesting a possible connection between the latter two. Figure 4 applies the names used in the present report to the strata described by Puffett. Presumably, during the Lower (Slate or Argillite) "time" the eastern end of the Dead River Basin (with DL-5-type stratigraphy) was not connected to the central part of the Dead River Basin, at DL-4.

The discrepancies among sections of Goodrich and Lower (Slate or Argillite) Member strata in the various areas contrast with the relative universality of Bijiki and Upper (Slate or Argillite) Member strata throughout the region. This implies a major tectonic and sedimentary break at the base of the Bijiki Member, with a disconformity between the Goodrich Quartzite and the Bijiki at DL-4B, and a nonconformity between the Precambrian W granite and the Bijiki at DL-7. The break at the base of the Bijiki at DL-5 (714 feet) represents less erosion than the two above-mentioned examples, however, even at DL-5, the lowest foot or so of the Bijiki is a basal conglomerate, the lowest two-inches-thick portion of which contains carbon-seamed stylolites which presumably indicate a considerable post-depositional and pre-metamorphic removal of material by solution. Such stylolites should not be confused with the disconformity.

A major break in the middle of a formation such as the Michigamme appears to violate the principles of classical stratigraphy. Perhaps new stratigraphic names are in order. However, to avoid confusion, traditional names are used and attention is called to the significant tectonic and sedimentary changes which occurred just before Bijiki sedimentation in areas north of the Marquette Synclinorium. Such changes may not have occurred in the Marquette Trough which may have experienced uninterrupted sedimentation throughout Michigamme "time".

With regard to the release and movement of uranium, this major change in sedimentary pattern in the middle of the Michigamme Formation mainly resulted in a decrease in the available source areas which could have provided uranium, and which hereafter were locally completely inundated. Therefore, the Bijiki Iron-Formation Member, deposited immediately after such universal inundation, probably is the latest (the youngest) Precambrian X unit that might contain significant syngenetic uranium derived from those source areas. This sedimentary break is not a typical unconformity and has no relevance to unconformity-related uranium deposits, such as those in the Northern Territory of Australia, in Saskatchewan, in Ontario, and in the Rand. In Michigan this change in sedimentary pattern diminished, rather than increased, opportunities for uranium ores.

It should be pointed out that in the five holes in the three basins in Marquette County, the shallowest bedrock encountered in all holes is here correlated with the Upper (Slate or Argillite) Member of the Michigamme

Formation. This interpretation is at variance with the interpretation depicted on Cannon's (1977) preliminary blue-line Map Showing Precambrian Geology in Parts of the Baraga, Dead River, and Clark Creek Basins, Marquette and Baraga Counties, Michigan. This map suggests that the shallowest bedrocks at the drill sites are portions of the Lower (Slate or Argillite) Member of the Michigamme Formation. The drill sites are located on sandy plains with few outcrops. If continuous surface exposure, comparable to the almost 100% core recovery in the holes, had been available to Cannon, he might have inferred the same stratigraphic interpretations proposed in this report.

| Name of Unit | Depth (feet) | Thickness (feet) | Name of Unit | Thickness (feet) |
|---|---|---|---|---|
| Upper (Slate or Argillite) Member (carbonaceous and pyritic argillite and graywacke) | 339-523* 602-660 | >233 | Metasiltite and slate (carbonaceous and pyritic) | >500 |
| Bijiki Iron-Formation Member (cherty carbonate and clastics) | 660-714 | 47 | Chert conglomerate and Iron-formation | 320-450 |
| Lower (Slate or Argillite) Member | | | | |
| Thin-bedded graywacke and argillite | 714-750 | 31 | Thin-bedded graywacke (chloritic, carbonaceous, and pyritic) | 300-500 |
| Thin-bedded argillite (upper 73 feet very chloritic, and possibly correlate with Clarksburg Volcanics?) (pyritic) | 750-866 | 99 | | |
| Absent (possibly Greenwood or unnamed Iron-Formation Member) | | | Magnetite-rich argillite | <100 |
| Thin-bedded argillite, graywacke, and quartzite | 866-884 | 16 | Thin-bedded graywacke (chloritic and sericitic) | 300-500 |
| Goodrich Quartzite with argillite layers (feldspathic and conglomeratic) | 884-997 | 94 | Basal quartzite (sericitic, feldspathic, conglomeratic) | 100-250 |

Figure 4
Comparison of Baraga Group strata at DL-5, Clark Creek Basin, and approximately nine miles southeastward in the eastern Dead River Basin, as measured by Puffett (1974, p. 35). Note significant thickening of each unit to the southeast.

*At DL-5, a Precambrian Y mafic dike occurs between depths of 523-602 feet.

# SIGNIFICANT MICROSCOPIC AND MEGASCOPIC OBSERVATIONS RELEVANT TO PRECAMBRIAN X SEDIMENTATION

## Goodrich Quartzite

Thin sections from the two holes penetrating this unit, DL-4B (3019-3119 feet) and DL-5 (884-997 feet), contain clastic quartz, chert, microcline, plagioclase, altered orthoclase, minor leucoxene, and considerable quantities of interstitial carbonate. Clastic quartz near the base of the formation in DL-4B contains very well-rounded "tapioca-like" sand grains which are presumed to be derived from quartz phenocrysts of Precambrian W porphyritic metarhyolites and tuffs, similar to such rocks encountered at DL-5 (997-1059 feet). The presence of clastic microcline at both DL-4B and DL-5 is significant, inasmuch as that mineral is missing from the Bijiki and Upper (Slate or Argillite) Members of the Michigamme Formation with only two exceptions: 1) In the lowest foot of the Bijiki at DL-7, clastic microcline unconformably overlies microcline-rich Precambrian W granite, 2600 m.y. old; 2) In the lowest 12 feet of what is here called the Upper (Slate or Argillite) Member, Burns (1975, Unit A, p. 22) reports the presence of clastic microcline in northeastern Baraga County. Precambrian W granites, such as at DL-7, may have been a site of erosion and a source for clastic microcline found at DL-4B and DL-5. The disappearance of microcline at higher stratigraphic levels than cited, and the persistence of plagioclase, generally a less stable mineral, throughout essentially a half-mile thick sequence of Upper (Slate or Argillite) strata at DL-4, implies that the source of the microcline may have been inundated by early Upper (Slate or Argillite) "time", whereas the source of the plagioclase was not covered until much later.

At DL-4B minor scattered phosphate occurs in the Goodrich Quartzite. The base of the formation is there a highly chloritic reworked regolith which appears to grade into the unreworked regolith developed on the 2700 m. y. old tonalite and gneiss. Metamorphism of the regolith apparently occurred during the Penokean orogeny, hence it is called a metaregolith. The actual unconformity at 3119 feet is selected on the basis that the deepest clearly clastic sand grains of "tapioca" quartz occur at that level.

At DL-5 a ¼-inch-thick bed of carbon and sulfides occurs (900 feet), and another ¼-inch-thick carbon seam is found at the base of the formation (997 feet), at the base of a one-foot-thick basal conglomerate with a gray-green matrix surrounding chert, quartz, and black phosphate pebbles, mostly ¼-inch in diameter. Perhaps this carbon seam, lying directly upon a major angular unconformity with the underlying 2700 m. y. old green porphyritic metarhyolite tuff, suggests locally reducing conditions and explains the relatively slight degree of weathering and oxidation displayed by the metarhyolite which possesses no deep fossil regolith comparable to the one developed on the tonalite at DL-4B (+3119 feet).

With regard to uranium, at DL-4 the metaregolith developed on tonalite, unconformably below the Goodrich, is significantly lacking in uranium as a consequence of pre-Goodrich oxidation and weathering. In contrast, at DL-5 the porphyritic green metarhyolite tuff unconformably below the Goodrich contains from 72 - 76 ppm uranium, and was not oxidized or depleted as a consequence of the local reducing nature of the basal Goodrich. Elsewhere, such green metarhyolite tuffs must have been oxidized, depleted, and eroded as suggested by the tapioca-like quartz grains (from porphyry phenocrysts) which occur as clasts in the basal Goodrich at DL-4. The erosion of such clasts implies oxidation of uraniferous matrix metarhyolite, and implies that such volcanics served as sources of uranium, although not at DL-5. Significant clastic microcline and orthoclase in the Goodrich show that generally favorable granitic source areas were exposed to erosion and could have served as sources of uranium during Goodrich deposition.

## Lower (Slate or Argillite) Member of the Michigamme Formation

In the Marquette County holes this stratigraphic unit apparently is present only at DL-5 (714-884 feet) where it is stratigraphically 146 feet thick as shown in figures 3 and 4. It consists of three parts, from bottom to top, as follows: 1) 16 feet (866-884 feet) of quartzite and graywacke alternate upward with increasing amounts of straight thin bedded argillite with tan 1-2 mm grains which appear in thin section (868 feet) to be rhombs of iron carbonates replacing feldspars; 2) 99 feet (750-866 feet) of gray-green straight bedded argillite, the upper 73 feet of which are strongly chloritic (perhaps a volcanic admixture). (A routine chemical sample (844-849 feet) shows that this unit contains some phosphates which were missed by the ammonium molybdate tests, presumably as a consequence of neutralization of the acid used.); 3) 31 feet (714-750 feet) of light gray thin straight bedded hard siliceous argillite and graywacke are vuggy and brecciated, perhaps as an indirect indication of pre-Bijiki erosion and slumping. Thin sections of all three lithologic types contain clasts of quartz, chert, microcline, and plagioclase. Carbonaceous matter is present, and carbonates are abundant. Chlorite and sericite have recrystallized probably from clayey and other original constituents obliterated by mild metamorphism. Sulfides, mainly pyrite, are present.

With regard to uranium possibilities, the presence of clastic microcline grains suggests that granitic generally favorable source areas were still exposed to erosion during the deposition of the Lower (Slate or Argillite) Member.

DL-6, in Iron County, contains a true stratigraphic thickness of 286 feet (236-1093 feet) of alternating carbon-rich and carbonate-rich chloritic graywackes and argillites alternating with cherty and slaty iron-formation layers. At DL-6 the graywackes and argillites are non-phosphatic, whereas the iron-formation layers are conspicuously phosphatic.

## Bijiki Iron-Formation Member of the Michigamme Formation

This formation appears to be the lowest stratigraphic unit common to all three, the Dead River, Clark Creek, and East Baraga Basins. In all three, the base of the formation shows ten feet of sediments with significantly coarse elastics, above which are from 37 - 76 feet of cherty carbonates with stromatolites and additional elastics. Some of the chert is bedded and is presumably of chemical or biological origin, whereas some chert occurs in clasts.

At DL-4, 10 feet (3008-3019 feet) of cherty carbonate alternate with sulfide-rich graywacke and two 2-inch-thick radioactive conglomerates (3008 and 3011 feet) with quartz, chert, black phosphatic (apatite), and broken phosphatic (collophane) algal stromatolites. These are overlain by 40 feet (2966-3008 feet) of cherty carbonate, conglomerates, and argillites which display carbonate clasts as well as interstitial carbonate. Conglomerates contain carbonaceous black phosphatic pebbles and chert pebbles.

At DL-5, the lowest foot of 10 feet (702-714 feet) of slightly radioactive gray-green conglomerate contains chloritic argillite, chert, and black phosphate pebbles in a chlorite-carbonate matrix with stylolites at the base and slightly above. This grades upward into a carbonate- and chlorite-rich agglomerate or reconstituted water-laid volcaniclastic bed. This unit is pyritic and is overlain by 37 feet (660-702 feet) of cherty carbonates with algal stromatolites and carbonate-rich chloritic or sericitic argillites. The top of the cherty carbonates (660 feet) is slightly chloritic and slightly radioactive.

At DL-7, 10 feet (648-659 feet) of carbonate-rich finely grained conglomerates and grits are arkosic and contain microcline and plagioclase in the lowest foot, where the Bijiki rests with major unconformity directly upon Precambrian W microcline-rich granite. The clastic microcline in this basal Bijiki is stratigraphically the highest clastic microcline observed in this drilling, although clastic plagioclase continues upwards throughout the overlying half-mile thickness drilled of the Michigamme Formation, at DL-4, and in shorter segments at DL-1, DL-3, and DL-5. The upper portion of the Bijiki consists of 76 feet (569-648 feet) of cherty carbonates with algal stromatolites alternating with conglomerates with black phosphatic pebbles, clastic chert and clastic carbonate in a marble matrix. In addition to the typical 1-inch by 6-inch algal stromatolites, ¼-inch spheroidal organic features (at 569 feet) occur at the top of the formation.

With regard to uranium deposition, this phosphatic unit is the first to represent complete inundation of the entire local region, including the inundation of the preexisting granitic microcline-bearing source areas. The Bijiki therefore represents essentially the last opportunity for the incorporation of debris from those good source areas into syngenetic sedimentary uranium concentrations in the Michigamme Formation. While this drilling project revealed no encouragement for commercial uranium mineralization in any of the units probed, it did reveal that the Bijiki Member appears to be the most favorable Precambrian X stratigraphic unit of ail those drilled.

## Upper (Slate or Argillite) Member of the Michigamme Formation

Like the Lower Member, the Upper Member consists mainly of slates, argillites, metasiltites, and graywackes with conspicuous organic carbon and sulfides, and with large amounts of carbonates as chemical and clastic constituents, and with clastic quartz, chert, and plagioclase, and with sericite and chlorite derived from the mild metamorphism of clastic clay minerals. However, unlike the Lower Member, the Upper Member contains 1) thin (less than one foot thick) marble beds

with algal stromatolites, 2) numerous carbon-seamed stylolites in such carbonates revealing considerable dissolving of apparently plastic carbonates, 3) graded-bedded turbidites as graywackes with ripped-up clasts of argillite or slate, characteristic of Bouma's or Stanley's lowest units of geosynclinal flysch cycles, rapidly deposited in deep water, 4) phosphates restricted to the lowest portion of the Upper Member (stratigraphically the lowest 140 feet at DL-4, the lowest 130 feet at DL-5, and the lowest 72 feet at DL-7), and 5) no clastic microcline in these cores. However, as noted on page 21 of this report, Burns (1975) observed clastic microcline in the basal 12 feet (his Unit A) of what is presumed to be the Upper Member in Baraga County, in the western portion of the Baraga Basin. This difference suggests a slightly later continuation of exposure and erosion of the microcline-rich source rocks in Baraga County than is recorded in Marquette County. Another distinction between the rocks of Baraga County and Marquette County relates to Burns' observation on his pages 91 and 92 that plagioclase does not occur in the uppermost 265 feet thickness (his Units E and F) of his 847-feet-thick sequence in the Baraga County cores which he studied. In contrast, in Marquette County clastic plagioclase occurs in a half-mile thickness of this member at DL-4 (from 226-2966 feet), and at still higher stratigraphic levels at DL-3 (at 416 and 429 feet).

The Upper Member constitutes a generally upward-fining sedimentary sequence. Further, this member appears to be more coarsely grained in the southernmost hole, DL-4, than in any of the others. A metamorphic corollary of this sedimentary observation is the most intensive development of slaty cleavage (which significantly deflected drilling) in the northernmost holes, DL-1, DL-3, and DL-7, which contain the highest proportion of fine elastics. All the holes in this project penetrated rocks of relatively low metamorphic rank. The northward fining of clastic sizes suggests a source to the south, in harmony with the observation of Burns (1975, p. 84 - 86) for Baraga County that such strata thicken southward. Note in the above paragraph that the thickness of basal phosphates likewise increases to the south.

At DL-4 coarsely grained "salt and pepper" graded-bedded graywackes from 2 inches to 7 feet in thickness occur (142-2966 feet) as do such graywackes with ripped-up fragments of interbedded black slates or argillite (187-2966 feet). Soft-sediment deformation and penecontemporaneous fragmentation and brecciation are abundant in these turbidites, which extend throughout most of this member from its base (2966 feet) almost to ledge (at a depth of 76 feet). A singular upward-narrowing wedge-shaped veinlet of chamosite with a maximum thickness of 3/4 inch extends obliquely across 8 inches of core (at 2829 feet). This slightly limonitic aggregate of spherulitic masses is less isotropic than greenalite, and it causes a blue reaction with cobalt nitrate to confirm the presence of combined aluminum. Other chlorites are present in the surrounding rock. Dark carbonaceous marbles with algal stromatolites and stylolites are from 3-5 inches thick (at 2761, 2769, 2774, 2856, 2861, and 2907 feet). Presumably, these correlate with marbles in Burns' (1975) Units C, c, and d in Baraga County. The youngest massive quartzite-graywacke bed at DL-4 (2358-2375 feet) occurs relatively near the base of the member; the youngest conglomerate is a 6-inches thick zone with pyrite and chalcopyrite at even greater depth (2832 feet).

At DL-5 (320-660 feet) penecontemporaneously deformed argillites predominate over graywackes, in the reverse of their proportions at DL-4. Clastic plagioclose is present throughout. Carbonate veinlets rather than marble beds occur in the expected footage for marble, perhaps as a consequence of the intrusion of a Precambrian Y mafic dike (523-602 feet) which apparently has rendered the argillites hornfelsic and has concentrated considerable pyrite in adjacent strata.

At DL-7 (243-569 feet) oxidation has modified originally black or gray carbonaceous and pyritic argillites and slates into green and red strata, at shallow depths (less than 313 feet). Such rocks are devoid of pyrite, whose oxidation presumably produced sulfuric acid. Such acid may have dissolved the carbonates of marbles and related algal stromatolites rendering such criteria inappropriate for correlating with marbles and stromatolites observed at DL-1. Below the level of obvious oxidation, 2-inches thick marbles with stromatolites occur (483 and 536 feet). Loose correlation between these two holes was based upon the occurrence of light gray argillite with ripped-up clasts of black slate (315-332 feet at DL-7 and 2100-2104 feet at DL-1). Post-metamorphic conformable clay seams, 1-inch thick, occur within the zone of oxidation (276 and 286 feet). Interesting feathery and crenulated carbon streaks are found in light gray argillite below the oxidized zone (518-519 and 563 feet). Elsewhere, the carbon is more evenly dispersed, below the oxidized zone.

At DL-1 black and gray slates and argillites including black and gray "poker chip" slates are most common in the upper portions of the hole. In such strata plagioclase is rare or absent. Slate is the most common rock at the top, and argillite and metasiltite become more common with depth, as does clastic plagioclase. Graded-bedded graywackes occur at intermediate to maximum depths (665-2148 feet). Ripped-up clasts of black slate or argillite in coarse turbidites occur at maximum depths (1894-2148 feet). Clearly, clastic grain size increases from top to bottom. Dark gray marbles with algal stromatolites and stylolites occur as minor 6-inches thick (1992 feet) and 1-inch thick (2039 feet) beds. A particularly interesting band (2137 feet) of welded very well rounded carbonate intraclasts approximately 2 mm in diameter suggests that weakly consolidated carbonates behaved plastically as they were eroded from unlithified slightly older lime muds, and redeposited a short distance from their source. Another very interesting bed occurs a short distance (83-86 feet) below ledge (71 feet), where a black carbonaceous bed has developed 30% porosity apparently at the expense of original pyrite and carbonates which have been

oxidized and leached. The remaining major constituents are approximately equal amounts of quartz and carbon. The impermeable underlying gray to black slate (86-89 feet) registers radioactivity twice background count, to suggest that the porous zone transmitted uranyl solutions downdip, and that some were reduced at the footwall of the porous zone, in contact with pyritiferous slates. Review of evidence in all the holes impels the author to withdraw the suggestion made in item #13 on page 2 of the report on preliminary geologic data for DL-1 that the 6-inches of pyritiferous chlorite and calcite at 1718 feet are possibly correlative with the Clarksburg Volcanics: Subsequent holes have indicated that these are much higher strata, portions of the Upper (Slate or Argillite) Member of the Michigamme Formation.

At DL-3 the most abundant lithology is black slate with some gray argillite. Very little graywacke is present. Fresh clastic plagioclase occurs (416 and 429 feet). Presumably, these strata represent higher stratigraphic levels than cored elsewhere during this project. Again, review of evidence gathered in the drilling of subsequent holes suggests abandonment of the suggestion made in item #13 on page 2 of the report on preliminary geologic data for DL-3 that thin pyritiferous chlorite layers may correlate with the Clarksburg Volcanics: Instead, these beds probably are relatively high in the Upper (Slate or Argillite) Member of the Michigamme Formation.

The southward thickening of sedimentary units and the southward coarsening of clastic sizes implies that the highly uraniferous Precambrian W Republic area granitic rocks, to the south, should have provided an excellent source of uranium for these sediments. Unfortunately, the maximum 5.4 ppm uranium and average 2.5 ppm uranium from the 5-feet-long chemical samples suggest that such was not the case. The preponderance of clastic plagioclase and the almost universal absence of clastic microcline and orthoclase in the Upper (Slate and Argillite) Member suggest that the favorable granitic source areas may have been inundated and hence were no longer sources of debris.

## METAMORPHISM

With chlorite and sericite, the Precambrian X strata drilled during this project belong to the chlorite zone of metamorphism according to the classification of James (1955), and in the muscovite-chlorite subfacies of the greenschist facies (Hietanen, 1967), in agreement with the observations of Burns (1975, p. 94) for Baraga County. This low metamorphic rank is reflected in the presence of chamosite at DL-4B (2829 feet). Talcous pyrophyllite (confirmed by blue cobalt nitrate tests for aluminum) as gouge and as fracture fillings in the upper portions of some holes, DL-1 (129-134 feet), DL-3 (236-240, 255 feet), and DL-4 (84-116 feet), is thought to have formed after the Penokean orogeny. (See paragraphs on structural style.)

There is no evidence of significant remobilization of uranium during Penokean metamorphism. With the exception of 130 ppm uranium in one 2-inches-thick conglomerate of the Bijiki Member, the highest uranium chemical analysis from Baraga Group strata was 5.4 ppm, and the average value was 2.5 ppm.

## PRECAMBRIAN Y DIABASE AND GABBRO

Magnetically negative unmetamorphosed mafic dikes with chilled borders occupy two orientations: 1) essentially east-west with vertical dip, as at DL-3 (1545-1551 feet), and parallel to N.70°-80°W., 45°-60°SW. slaty cleavage in the Michigamme Formation, as at DL-4B (2286-2358, 2825-2827 feet) and as at DL-5 (523-602 feet). The presence of pyrite and other sulfides in association with the magnetically easily located dikes may be relevant to reduction and precipitation of down-dip-migrating uranyl solutions in very rare permeable beds of Precambrian X age.

The close spatial relation between sulfide mineralization and Precambrian Y Keweenawan faults parallel to both sets of Keweenawan dikes suggests that this gineous activity may have provided heat to energize convection cells of available brines and waters. Drilling suggested that sulfides have been remobilized in this way. Uranium also may have moved during these events, but proof of this is lacking in the drill cores.

## STRUCTURAL STYLE AND TIMING

Much structural infomation appears in the six preliminary geologic data reports, and such data will not be repeated here. However, comparison of these data reveals late Precambrian X Penokean and Precambrian Y Keweenawan regional tectonic styles. In Marquette County, all three basins apparently were subjected to NNE-SSW compression during the Penokean orogeny, resulting in the development of these gently-plunging synclines with originally rather uniformly oriented axial-plane slaty cleavage, N.70°-80°W., 50°-55°SW. Minor Keweenawan faulting encountered during the drilling in Marquette County consists of two orientations of gravity faults which are parallel to the two orientations of Precambrian Y mafic dikes: 1) East-west vertical faults with north blocks downthrown occur at DL-1 (129-134, 592-622, 999-1000, 1775-1784, 1895-1897, and 2085-2088 feet) and these faults drag both bedding and slaty cleavage. 2) N.70°-80°W., 15°-90°SW. faults parallel to slaty cleavage and with downthrown southwestern blocks occur at DL-3 (236-240, 647, 803-805, and 1252 feet), DL-4B (1053-1056, 1316-1318, 1394-1402, 1540-1545, 1685-1706, and 2098 feet) DL-5 (462-463, 477-498, 729, 743, 744, 792, 796, and 1056 feet), and DL-7 (500-502 feet). The latter observation, at DL-7, is based upon a re-examination of the cores and differs from the vertical fault pictured on figure 1, page 4, of the preliminary geologic data report; instead the fault apparently dips almost 40°SW. The slickensided graphite, pyrophyllite and clayey gouges of these faults

are unmetamorphosed, implying post-Penokean movement. Randomly oriented slay cleavage in fragments in fault breccias likewise indicates some post-Penokean movement. Both orientations of faults are consistent with Keweenawan north-south horizontal tension suggested by Cannon (1978). If major faults of these two sets are also present in this region, then Keweenawan horst and graben structures may exist in these basins of Baraga Group strata. The present lower (20°-40°SW.) than average (35°-65°SW.) dip of Penokean axial-plane slaty cleavage in the Clark Creek Basin (DL-5) suggests rotation of that block during Keweenawan tensional events.

In Iron County, at DL-6, the highly fractured nature of the ground confirms the presence of nearby faults. Prophyllite and clayey gouges suggest that some of the movement is post-Penokean, with again, an east-west strike for the faults.

# POSSIBILITIES FOR ORE IN PRECAMBRIAN W STRATA

## Gold and Copper

The most promising opportunity for finding ore implied by this drilling occurs in the vicinity of DL-5, as described on pages 4 - 6 of the preliminary geologic data report for that hole. As discussed in those recommendations, metabasalt (1059-1148 feet), presumably of the Mona Schist, contains massive and stringer pyrite and pyrrhotite with 20 - 50 ppb Au and 124 - 2010 ppm Cu. Such materials appear to be strata-bound volcanogenic mineralization of Precambrian W age rather than epigenetic Precambrian X or Y impregnations, inasmuch as the immediately overlying Precambrian W porphyritic metarhyolite tuff (997-1059 feet) is devoid of any mineralization. It is suggested that the traces of gold and copper in the massive pyrrhotite and pyrite may be part of the iron-rich fringe of a possible gold and copper ore body. Specific recommendations for exploration are presented in the preliminary geologic data report.

# POSSIBILITIES FOR ORE IN PRECAMBRIAN X STRATA

## Base Metals

The universal absence of silver in sulfide mineralization in Precambrian X Baraga Group carbonaceous and pyritic strata diminishes the possibility that such concentrations are solely of Keweenawan hydrothermal origin. However, the presence of such mineralization in sheets along Penokean slaty cleavage as well as along bedding planes adjacent to faults and dikes of Keweenawan age, and in breccia zones parallel to such faults and dikes as well as parallel to bedding indicates that the present location of mineralized patches is related to Keweneenawan events. Therefore, the most likely origin involves a combination of 1) precipitation of dispersed iron, copper, lead, and zinc sulfides in the reducing environment of Baraga Group carbonaceous sediments during Precambrian X “time”, followed by 2) remobilization and reconcentration of such sulfides during Keweenawan igneous and tectonic events during Precambrian Y “time”. Much mineralization is accompanied by quartz and carbonate veinlets.

Jack W. Avery has reported megascopically discernible base metal sulfides at the following depths: at DL-3 in the Upper (Slate or Argillite) Member (343, 805, 965-1123 feet), and DL-4 in the Upper (Slate or Argillite) Member (1388-1506, 1685-1706, 2827-2947 with a 6-inches thick conglomerate at 2832 and a 5-feet chemical sample at 2899-2904 with 612 ppm Cu), at DL-5 in the basal Bijiki Member (713-714 feet) and in the Lower (Slate or Argillite) Member (at 792 feet), and at DL-7 in the Bijiki Member (573-575 feet). In Iron County, at DL-6, base metal sulfides occur in the slates and argillites (266-376 feet) and in the cherty iron-formation layers (the 848-853 feet chemical sample contains 971 ppm Cu, and 965-977 feet core contains visible base metal sulfides). The 612 ppm Cu at DL-4 and the 971 ppm Cu at DL-6 appear to be the best base metal traces routinely collected in five-feet samples from the Baraga Group strata drilled in this project. Recommendations for exploration near each hole appear in each preliminary geologic data report.

## Phosphates

Ammonium molybdate tests of acidized core and routine chemical analyses of five-feet samples reveal that minor quantities of phosphate occur in rocks ranging in age from Precambrian W tonalite and granite at DL-4 and DL-7 up through all Baraga Group stratigraphic units. However, the uppermost phosphates occur in the lowermost portion of the Upper (Slate or Argillite) Member of the Michigamme Formation: the lowest 140 feet at DL-4, the lowest 130 feet at DL-5, and the lowest 72 feet at DL-7. Phosphates are not reported from younger strata. The four greatest amounts of phosphate are reported from correlatives of iron-formation: The greatest abundance reported from this study is for 2.79% $P_2O_5$) from a 2-inches-thick conglomerate near the base of the Bijiki Iron-Formation Member at DL-4B (3011 feet), 3½ miles southsoutheast from the section 15 phosphate occurrence (with more than 15% $P_2O_5$ described by Cannon and Klasner (1976, p. 3 - 5). At DL-5 the maximum phosphate analysis from a 5-feet-long sample (664-669 feet) of 0.43% $P_2O_5$ also is obtained from the Bijiki. The maximum analysis from DL-7 (575-580 feet) of 0.28% $P_2O_5$ also is in the Bijiki. In Iron County, at DL-6 $P_2O_5$ ranges between 0.32% - 0.69% with an average of 0.50% in the iron-formation layers of the Michigamme Formation. No commercial encouragement was encountered in these drill holes except for the scientific observation of stratigraphic continuity of slightly phosphatic rocks which may grade

laterally into phosphate deposits elsewhere in the region, presumably to the northwest of the Marquette County holes. However, the presence of phosphate within these strata is relevant to the ready dissolving and redistribution of oxidized uranium as uranyl phosphate complex ions, as implied by the chemistry of Langmuir (1978).

## Uranium

In the 5-feet-long routine chemical samples, collected from every 30 feet of core, the highest uranium content in Baraga Group strata was 5.4 ppm, and the average value was approximately 2.5 ppm uranium, both values obtained from readily soluble uranium dissolved by nitric/perchloric acid digestion (not including hydrofluoric acid). By the same technique, the highest value obtained from the cores was 130 ppm uranium from a 2-inches thick conglomerate in the Bijiki Iron-Formation Member at DL-4 (3011 feet). When digested in nitric/perchloric/ hydrofluoric acids, the total uranium in the latter sample was 260 ppm, suggesting that 50% of the total uranium was present as readily dissolved species. This is the same order of magnitude determined by Vickers (1956, p. 40 - 41) who demonstrated that 31% - 42% of the Michigamme Formation total uranium could be easily dissolved from crushed rock by distilled water. However, discounting the following figures of Vickers and Mancuso to 31%, to 42%, or to 50% of their stated total uranium content yields soluble uranium values far in excess of those exhibited in the cores: Vickers reported 13-90 ppm total uranium in unaltered Michigamme slates, and Mancuso (1977) reported a maximum of 435 ppm total uranium in Baraga County radioactive phosphatic occurrences in what is here considered Bijiki Iron-Formation Member. The low values in the cores, with an average of 2.5 ppm relatively soluble uranium, do not augur well for down-dip supergene enrichments derived solely from these drilled strata.

The geologic data report for DL-7 (Trow, 1978, p. 2 - 4) illustrates the possible development of roll fronts in pyritic-carbonaceous strata with an initial wave of oxidation which changes black rocks to green by oxidizing the sulfur of pyrite without oxidizing the iron, followed by a second wave of oxidation which changes green rocks to red by oxidizing the iron. Through such oxidation tetravalent uranium could be oxidized to mobile uranyl species, to be precipitated through reduction down dip. To yield a uraniferous roll front with a cross section of 100 square feet in a permeable bed 10 feet thick, deriving all uranium from the 2.5 ppm average in the bed, solutions would have to migrate 5,000 feet down dip to form an “ore body” with 1250 ppm uranium, if not blocked and reduced with resulting lower tenor at higher levels by a vertical east-west sulfide-rich Keweenawan diabase dike. In the latter instance, such leaner concentrations might be detected at the surface by alpha-radon or helium detectors on the up-dip (with respect to Baraga Group strata) side of Precambrian Y diabase dikes located by their negative magnetic signatures. Sufficient down-dip migration to insure sufficient tenor for roll fronts yields unattractively deep targets, if all such uranium is derived solely from the slates themselves.

Suitably permeable strata were conspicuously absent from the Marquette County cores. Experience at DL-7 indicates that green-red oxidized strata are very permeable and are characterized during drilling by a complete loss of circulation which fails to respond to usual mudding and grouting remedies. Such strata require casing and reduction to smaller tools for continued drilling. If someone encounters such a zone at great depth, then one might seek a roll front down dip from such a hole, as the longer (and deeper) the migration of uranyl solutions in such lean strata, the greater the opportunity for finding sufficient concentrations of reduced uranium species. The only other conspicuously permeable bed in the Marquette County holes occurred at DL-1 (83-86 feet) where a black sooty carbonaceous cherty porcellanite developed 30% porosity presumably through dissolving of carbonates, above a footwall of black impermeable slate in which radioactivity increased to two times background. These observations suggest that some uranyl solutions moving down dip in the porous zone were reduced and fixed as tetravalent uranium by the underlying carbonaceous and pyritic slate. Fault-induced permeability at DL-6, in Iron County, was not accompanied by obvious uranium enrichment. The general paucity of permeable beds in the mildly metamorphosed Michigamme Formation and the commonly low uranium content of such strata drilled are not overwhelmingly favorable for the formation of rich dike-intersection or roll-front supergene uranium ore bodies. Perhaps the most important function that Baraga Group carbonaceous strata may have accomplished is to have served as the electrically conductive carbon source for the electrochemical evolution of methane to reduce and precipitate uranium in overlying oxidized rocks, as indicated in the following paragraphs, whether those oxidized rocks are oxidized iron-formation, the Jacobsville Sandstone, or Pleistocene drift (time permitting).

# A NEW MODEL FOR SASKATCHEWAN'S UNCONFORMITY-RELATED ORE BODIES IS RELEVANT TO MICHIGAN

## General Principles

Hoeve and Sibbald (1978) suggest that ore bodies of reduced uranium species, at and above the unconformity at the base of the mainly oxidized Athabasca Formation, were precipitated by rising fugitive reducing agents such as methane. Carbon dioxide and methane occur in the ores, and some underlying graphite appears to have been decomposed. Hoeve and Sibbald ascribe the evolution of these gases to thermally activated reactions involving the carbon-hydrogen-oxygen system within the carbonaceous strata below the unconformity. Rather than calling upon thermal events related to deep-burial diagenesis or to metamorphism to provide the energy for these near-equilibrium reactions, it is here suggested that the alternative may be that electrochemical cells energized the methane-producing reactions. This proposal is somewhat similar to that of Tilsley (1978, and to Robertson, Tilsley, and Hogg, 1978) who suggested electroplating directly adjacent to conductors rather than evolution of fugitive reducing gases migrating upward from conductors. The presence of considerable ore tonnages at higher levels than the graphitic conductors in Saskatchewan implies the correctness of the Hoeve-Sibbald appeal to rising gases which have developed ore and bleached zones in otherwise unaltered hematitic sandstones.

Sato and Mooney (1960) demonstrate that a negative electrical self-potential geophysical anomaly exists above a carbonaceous conductor exposed to shallow oxidizing solutions and to deep reducing solutions. Figure 5 illustrates an application of such an electrical cell to Saskatchewan unconformity-type ores:

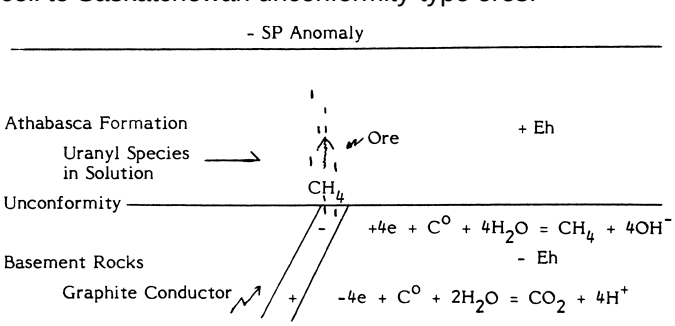



Figure 5
Schematic cross section of methane generation and resulting pitchblende ore above graphite conductor with a negative self-potential geophysical anomaly (at the time of ore deposition) in the Athabasca Basin.

The advantage of this model is that it does not require either deep burial or metamorphism to provide the energy to drive the methane-producing reaction to the right. A natural electric current does the job.

Thermodynamically, methane should reduce soluble uranyl species to pitchblende. Rumors that laboratory experiments show kinetically that methane will not reduce uranyl species in oxygenated waters are not in this case convincing because 1) such experiments have resulted in acidic waters from the oxidation of methane. However, in its simplest statement, such a reaction,

$$O_2 + CH_4 + 2UO_2^{++} + 4OH^- = 2UO_2 + 4H_2O + CO_2$$

consists of two rate-determining steps,

$$\text{a) } O_2 + CH_4 + UO_2^{++} + 2OH^- = UO_2 + 3H_2O + CO,$$

$$\text{and b) } CO + UO_2^{++} + 20H^- = UO_2 + H_2O + CO_2,$$

both of which require an excess of hydroxide ions. These would be expected in oxygenated ground waters through hematitic porous media. 2) Such experiments have not included the presence of finely divided hematite, which is present in unaltered Athabasca Formation and which may be relevant:

$$\tfrac{1}{2}O_2 + CH_4 + 2UO_2^{++} + Fe_2O_3 = 2UO_2 + 2Fe^{++} + 2H_2O + CO_2.$$

3) Such experiments have not involved negative electrical fields consistent with low-voltage high-capacitance negative self-potential geophysical anomalies. Such experiments apparently have not duplicated the geological conditions in Saskatchewan, and hence should not be cited as evidence against the postulated effectiveness of methane as a reductant in Saskatchewan. To condense the presentation, each of the above reactions is a combination of two half-cell reactions, and for the sake of simplicity, the uranyl soluble species $UO_2^{++}$ is used, even though phosphate and carbonate complex ions are more likely in the pH range expected.

It should be noted that presently, concealed methane-producing graphite conductors are being located by geophysical methods other than self-potential surveys, for example by various ground or airborne EM methods. Self-potential anomalies would be expected to persist only as long as high Eh oxygenated waters percolated through the Athabasca Formation, thereby driving the electrochemical reactions. Likewise, methane production would be expected to persist only as long as such solutions migrated and provided a contrast to basement rock connate water.

Essentials for this model include the folowing: 1) An oxidized permeable medium transporting an abundant flow of relatively oxygenated uranyl solutions of relatively high Eh, above and in contact with 2) more reduced rocks with lower Eh connate waters penetrated by or including 3) a graphitic conductor with sufficient adjacent permeability (ground preparation) to permit migration of ions to close the electric circuit related to the current (flow of electrons) in the conductor itself. The following paragraphs illustrate some examples in which Precambrian X carbonaceous strata in Michigan may be

responsible for uranium concentrations in geometrically overlying oxidized rocks.

## Michigan Oxidized Iron-Formations/Soft Iron Ores and Graphitic Slates of Precambrian X Age

Two-thirds of the supergene uranium occurrences in Michigan's metasedimentary rocks cited by Johnson (1976, p. 108 - 127) occur where oxidized iron-formation or soft iron ore is in contact with graphitic slate. A classic example is well illustrated (James, Dutton, Pettijohn, and Wier, 1968, p. 114 - 118) from the Sherwood mine, near Iron River, where in 1951 Robert C. Reed and John M. Ohlson discovered uraninite with equivalent $U_3O_8$ as high as 0.513% in small pockets in overturned oxidized cherty iron-formation where it geometrically lies above a graphitic-pyritic slate. Where the beds are not overturned and the graphitic slate lies geometrically and stratigraphically above the oxidized iron-formation, no uranium occurs. This geometry fits the model here presented, and suggests that the graphite generated methane which rose into the oxidizing solutions to precipitate sulfides and uraninite. The great depth of oxidation of iron-formations to a depth of 5000 - 6000 feet in the Marquette district (Boyum, 1975) suggests that in post-Precambrian X time appropriate oxidizing solutions penetrated to very deep levels in the Lake Superior region. Some of the most favorable sites for supergene uranium possibilities in Michigan lie in oxidized iron-formations or soft ores above graphitic beds.

## Michigan's Precambrian 2 Jacobsville Sandstone over Precambrian X Graphitic Slates

Jorma Kalliokoski (1977) has well stated the favorability of such a combination, in considerable detail.

## Pleistocene Drift over Precambrian X Graphitic Slates

Enough time may not have elapsed since the end of the Pleistocene for the formation of ores in glacial drift. However, the presence of excellent sources of uranium in Precambrian W granitic and metarhyolitic rocks, the permeability and state of oxidation of some drift, and the presence of reduced carbonaceous strata in underlying Precambrian X sequences suggest the geometric favorability for the eventual formation of pitchblende in the Pleistocene sediments. Such potential ores may be growing at present, associated with self-potential anomalies and the evolution of methane.

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