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GEOLOGIC TERRANES OF MINNESOTA AND THEIR URANIUM POTENTIAL

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GEOLOGIC TERRANES OF MINNESOTA AND THEIR URANIUM POTENTIAL

By

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INTRODUCTION

The geology of Minnesota is exceedingly complex (fig. 1). It is characterized by a wide diversity of superposed rock types ranging in age from about 3,600 million years (m.y.) before present to less than 10,000 years before present. Although complex, the rock record can be subdivided into seven bedrock units, or terranes, each having characteristic lithic and structural attributes (fig. 2). One additional terrane, consisting of unconsolidated glacial deposits of Pleistocene age, that overlies all of the bedrock terranes also is recognized.

Five of the terranes consist of Precambrian rocks or rocks older than approximately 570 m.y. Of these, Terranes I and II are fundamental crustal segments of Archean age, i.e., older than 2,500 m.y. Terrane I underlies much of southern Minnesota and consists of quartzofeldspathic and amphibolitic gneiss metamorphosed to the upper amphibolite or lower granulite grade. Formed in part about 3,600 m.y. ago, this terrane has been metamorphosed and intruded by igneous rocks a number of times including 3,000 m.y., 2,600 m.y., 1,850-1,800 m.y. and 1,725 m.y. Terrane II, in northern Minnesota, is a typical greenstone-granite terrane characterized by a variety of supracrustal and plutonic rocks and formed around 2,700 m.y. ago. Stratified sedimentary rocks deposited in early Proterozoic time 2,100 m.y. to 1,870 m.y. ago in an intracratonic basin centered approximately over the boundary between Terranes I and II in east-central Minnesota comprise Terrane III. Terrane IV, deposited in a basin on the gneissic basement of southwestern Minnesota in early Proterozoic time 1,725 m.y. to 1,600 m.y. ago consists predominantly of quartz-rich sedimentary rocks. Mafic plutonic and volcanic rocks and derivative red beds that formed in middle Proterozoic time in an incipient rift system about 1,200 m.y. to 1,100 m.y. ago comprise Terrane V. Space for this terrane was made by the rifting of the terranes formed earlier in northeastern, east-central and southeastern Minnesota.

The Precambrian terranes in turn are overlain in southeastern and northwestern Minnesota by Terrane VI, a generally flat-lying sequence of interlayered sandstone, shale, limestone and dolomite, all of Cambrian (570 m.y. to 500 m.y.), Ordovician (500 m.y. to 435 m.y.) or Devonian (410 m.y. to 360 m.y.) ages. These rocks, as well as the various Precambrian terranes in northwestern and western Minnesota, are overlain by a sequence of Jurassic(?) red beds and Cretaceous (96 m.y. to 63 m.y.) sandstone, shale and conglomerate assigned to Terrane VII. Lastly, all of the bedrock is overlain by thin to thick glacial and postglacial deposits of Quaternary (less than 2.0 m.y.) age assigned here to Terrane VIII.

Uranium occurs in relatively small quantities, widely disseminated in each of the geologic terranes in Minnesota. However, the formation of an ore deposit from which uranium can be profitably extracted requires a unique combination of geological conditions that occur at only a very few places in the world. Although exploration interest in a region may stem from the more or less random discovery of traces of mineralization, it more commonly begins with the knowledge that the geology of an area is comparable to the geology of areas where mineral deposits are known to occur. Evaluation of a region's mineral potential always starts with an evaluation of whatever information is available about the geology of the region.

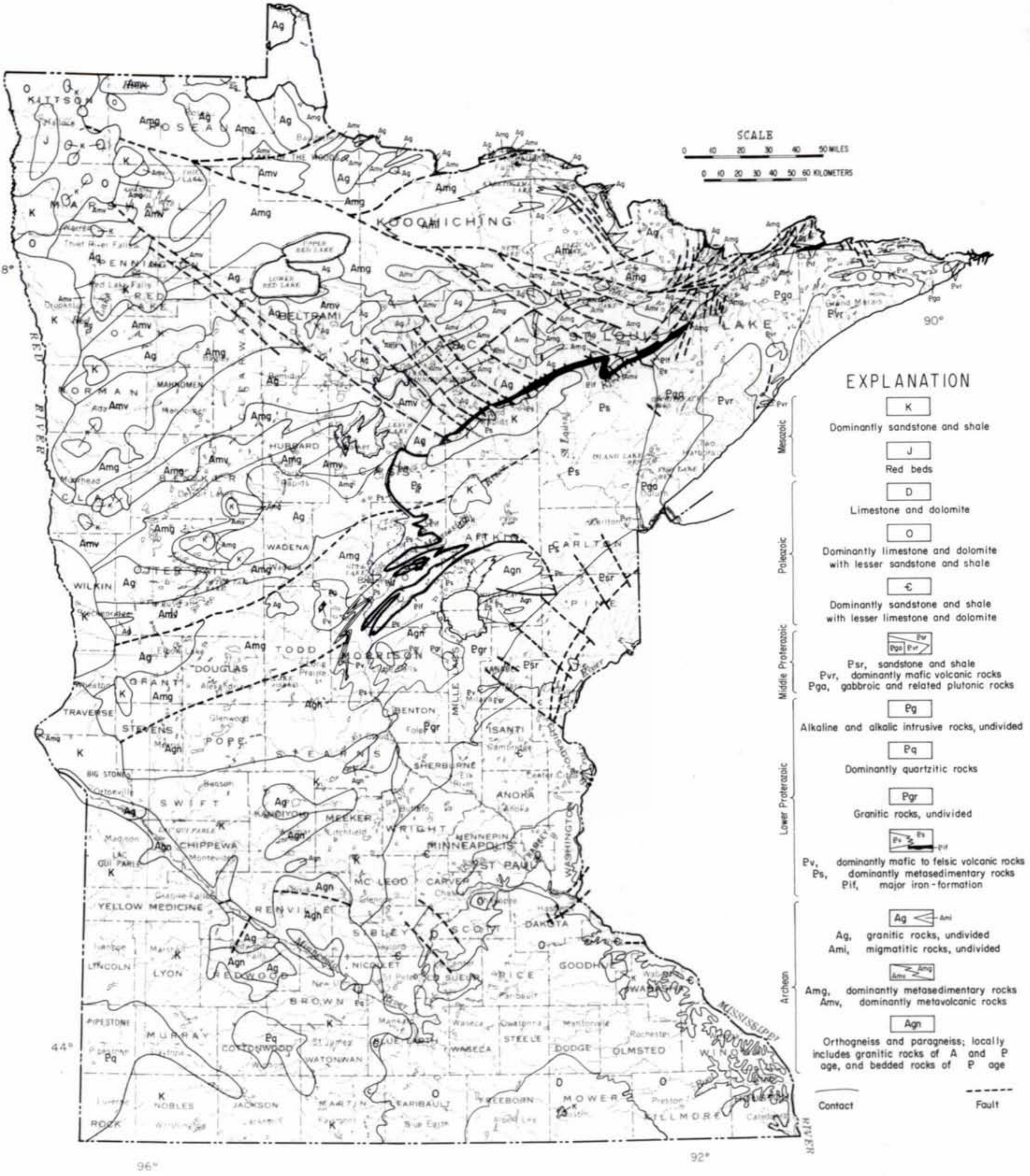

Figure 1. Generalized bedrock geologic map of Minnesota (modified from Morey, 1976).

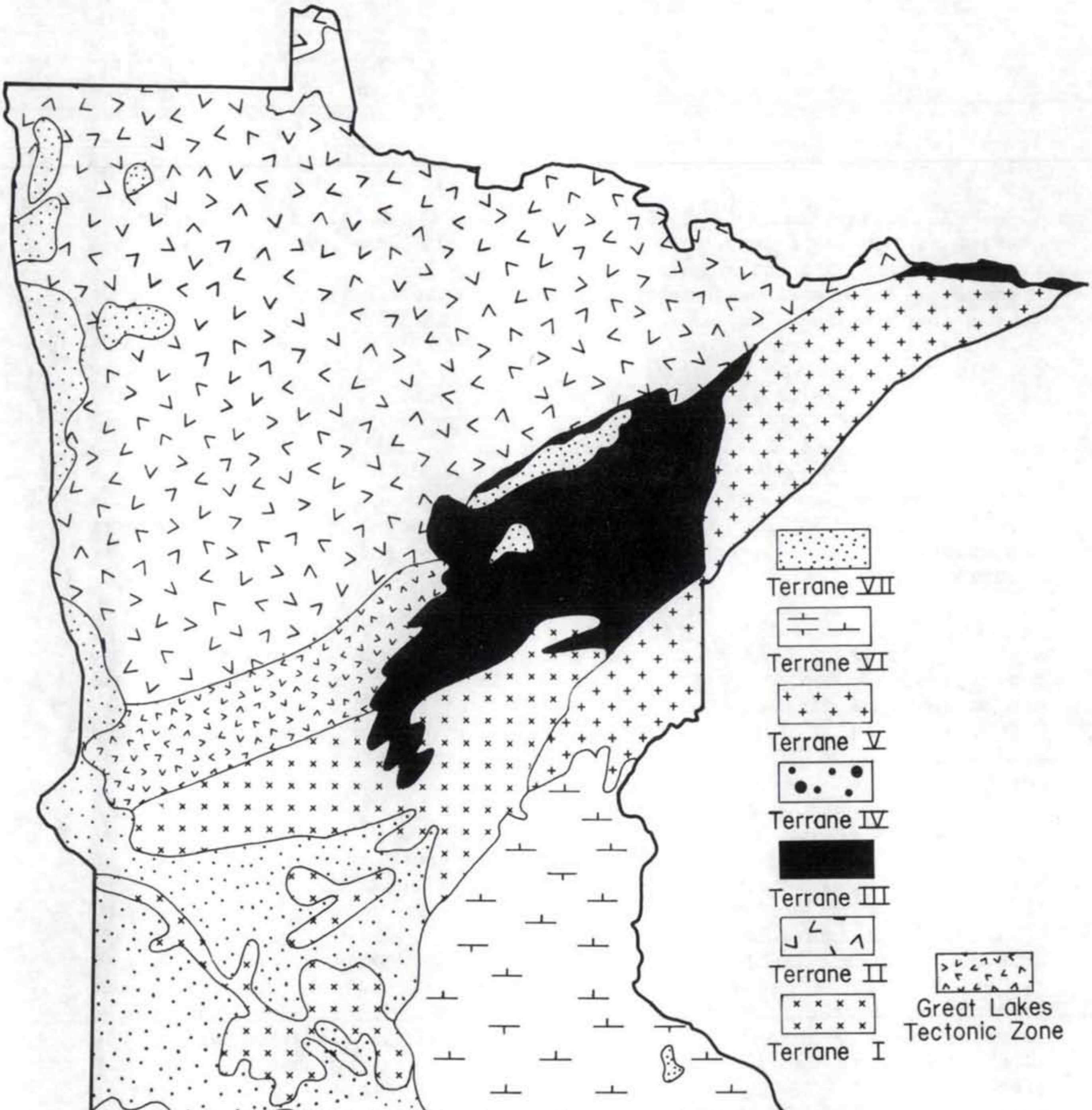

Figure 2. Generalized geologic map showing the inferred distribution of bedrock terranes in Minnesota (see text for discussion). Terrane I, gneiss terrane; Terrane II, greenstone-granite; Terrane III, intracratonic stratified rocks; Terrane IV, platform-type supracrustal rocks; Terrane V, rocks of the Midcontinent rift system; Terrane VI, Paleozoic rocks; Terrane VII, Mesozoic rocks.

GEOLOGY OF URANIUM

Uranium is not a rare element. It generally occurs in measurable quantities in all rocks, soils, and waters. However, the formation of an ore deposit requires a geological environment where geochemical processes have led to an exceptional concentration of uranium hundreds of times greater than the average abundance in common rocks.

Even though uranium ore deposits require a special set of geological conditions for their formation, they occur widely throughout the world in a variety of geologic settings. At first glance, each known deposit has what appears to be a bewildering set of geological attributes that are more or less unique to that locality. Despite these local differences, there are only two main circumstances that can lead to the formation of an ore deposit. One involves the upward migration of hot fluids (called hydrothermal solutions) and molten rock (called magma), which commonly leads to the concentration and precipitation of uranium, as well as other metals, in mineral veins or in bodies of mineralized igneous rock. The other involves the processes of weathering, erosion and sedimentation which take place at or near the surface. These processes may lead to the leaching of uranium from ordinary rocks, its transportation in solution by ground water, and its reprecipitation in concentrated deposits where the solubility of uranium is reduced by residues of organic material in the rock.

Deposits originating from the rise of heated fluids through the crust are called primary or hydrothermal deposits. Deposits formed by leaching and reprecipitation of uranium during weathering and ground-water movement are called secondary or sedimentary deposits. If the latter class of ore deposits formed at the time the enclosing rocks were deposited, they are syngenetic in origin, whereas if they formed sometime later, they are epigenetic in origin.

The distinction between primary and secondary ore deposits is not always clearly defined, for both sets of processes may have contributed to the creation of a uranium deposit. Primary processes may concentrate more than average amounts of uranium in large bodies of rock throughout a region. If these rocks are later uplifted and exposed to weathering, they provide abundant uranium to be further concentrated by secondary processes. Several cycles of solution and enrichment may occur before mineable ore deposits of uranium are formed. Moreover, there is increasing evidence that ground water or seawater in geologically active zones may circulate to considerable depth, be heated and mineralized by reactions with surrounding rocks, and then move upward as a hydrothermal solution. The minerals thus transported to higher levels in the crust create deposits in which the distinction between primary and secondary processes is somewhat blurred. The situation is further complicated by the fact that some uranium deposits in very old rocks appear to have formed at a time when the lack of free oxygen in the earth's atmosphere made the chemistry of rock weathering and secondary deposition of uranium quite different from that of later geologic periods.

Because the distinction between the kinds of ore-forming processes is somewhat blurred, it is convenient to consider uranium occurrences in terms of the type of host rock (igneous vs sedimentary) and the type of mineralization (syngenetic vs epigenetic). Classification schemes using these parameters abound in the geological literature, and most of them recognize a variety of subclasses within each major group. For example, the scheme of Jones (1978a), which is widely used by the U.S. Department of Energy (DOE) in their National Uranium Resource Evaluation (NURE) program, recognizes five subclasses of syngenetic deposits and six subclasses of epigenetic deposits associated with sedimentary rocks (table 1). As part of the same scheme, Mathews (1978a) recognizes three subclasses of deposits associated with the crystallization of a magma and four subclasses of deposits associated with hydrothermal activity in and around a solidifying magma. The NURE scheme also recognizes a third major class of uranium deposits referred to as unconformity-related, vein-breccia deposits, which cannot be related satisfactorily to either sedimentary or to igneous/hydrothermal processes (Mathews, 1978b). Of the various classes of uranium deposits summarized in Table 1, only five are applicable to Minnesota. These include three classes related to plutonic igneous processes (fig. 3)--classes (310), (320) and (380)--one class related to syngenetic processes--class (120)--and one class of uncertain origin--class (710).

Although the classification schemes arbitrarily subdivide what is essentially a continuum, they provide a useful means of enumerating so-called recognition criteria for specific kinds of deposits. These recognition criteria not only summarize the common attributes of a particular class of deposit, but they also form the basis for the identification of environments that are potentially favorable for uranium mineralization.

In this report, each of the geologic terranes in Minnesota will be briefly described and evaluated for its uranium potential in terms of recognition criteria developed by the U.S. Department of Energy. These criteria will be used systematically to identify, describe and evaluate geological environments in the various terranes that may be favorable for the deposition and concentration of uranium.

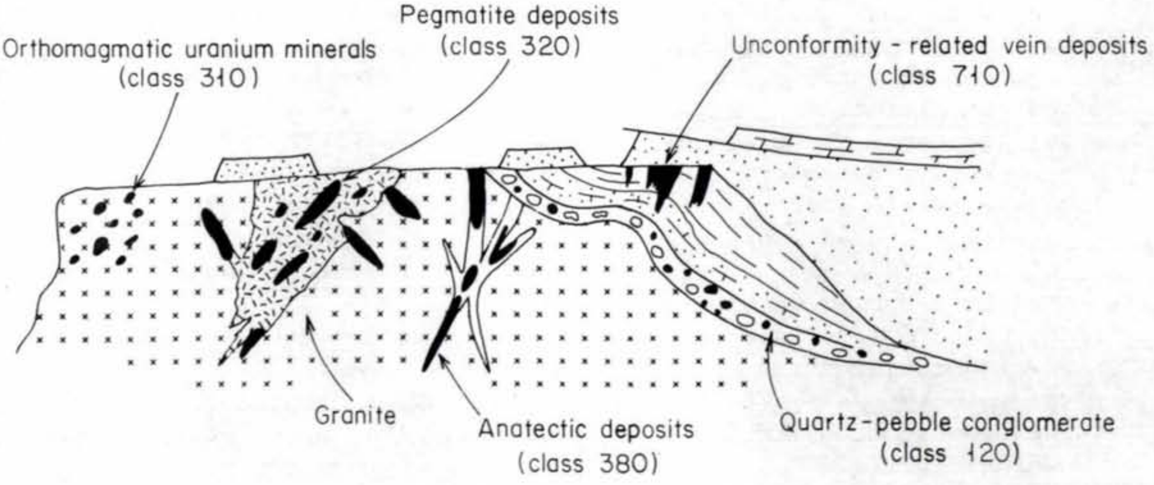

Figure 3. Diagrammatic cross section showing important geologic settings for mineral occurrences (in black) in Minnesota.

Table 1. Uranium deposits classification scheme used by the U.S. Department of Energy NURE program (modified from Jones, 1978a; Mathews, 1978a,b) [class numbers in parentheses]

I. DEPOSITS THAT OCCUR IN SEDIMENTARY ROCKS
  A. Syngenetic deposits
    (110) Placer - mechanical concentrations of resistant uranium minerals such as monazite and zircon in river and beach sands.
    *(120) Quartz-pebble conglomerate - specified kind of placer characterized by pyrite and the uranium minerals, uraninite and brannerite.
    (130) Marine black shale - muds with uranium absorbed from seawater by clay particles and organic material.
    (140) Phosphorite - marine deposits in which uranium substitutes for calcium in phosphate minerals of the apatite group.
    (150) Water - waters such as brine, seawater, mine and mill waters with appreciable quantities of dissolved uranium.
  B. Epigenetic deposits
    (210) Lignite, coal and carbonaceous shale - uranium in oxidized ground water reduced and precipitated by the organic material.
    (220) Evaporative precipitates - secondary uranium concentrations that precipitate in outcrops or in pore spaces, solution cavities and fractures by the evaporation of oxidized ground water.
    (230) and (240) Limestones and sandstones - uranium deposits formed along boundaries between rock types where chemical conditions change from oxidizing to reducing.
II. DEPOSITS IN AND RELATED TO PLUTONIC IGNEOUS ROCKS (ROCKS FORMED FROM SLOWLY COOLING MAGMA AT DEPTH)
    *(310) Orthomagmatic - uranium deposits formed during crystallization of the magma.
    *(320) Pegmatitic - uranium deposits formed in veins and fractures from volatile materials during late-stage crystallization.
    (330) Magmatic hydrothermal - uranium deposits formed in veins from hydrothermal solutions derived from a magma.
    (340) Contact metasomatic - uranium deposits formed by the interaction of hydrothermal solutions derived from a magma with the country rock in which the magma was emplaced.
    (350) Autometasomatic - uranium deposits formed by the interaction of hydrothermal solutions and crystallized material in a magma.
    (360) Authigenic - occurrences formed by postmagmatic redistribution and concentration of uranium in veins and along fracture zones in the parent pluton.
    (370) Allogenic - occurrences formed by postmagmatic redistribution and concentration in fractures away from the source pluton in nearby rocks.
    *(380) Anatectic - uranium occurrences formed by partial melting of a source rock and subsequent reconcentration of uranium in fractures, etc., both in the parent pluton and in the surrounding country rock.
III. URANIUM DEPOSITS OF UNCERTAIN GENESIS
    *(710) Unconformity-related deposits - uranium deposits formed at or near unconformities between diverse rock types.
    (720) Vein-type deposits in metamorphic rocks - uranium occurrences as epigenetic deposits in veins that follow fractures, etc., in metamorphic rocks.
    (730) Vein-type deposits in sedimentary rocks - uranium occurrences as epigenetic deposits in veins that follow fractures in sedimentary rocks.

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*Classes of uranium deposits applicable to the geology of Minnesota.

Terrane I - Gneiss Terrane

Rocks assigned to the gneiss terrane are inferred to underlie much of southern and west-central Minnesota. The gneiss terrane is separated from the younger greenstone-granite terrane to the north by a major structural discontinuity some 48 km wide that trends diagonally across the central part of Minnesota from approximately 45°30'N. to near the western end of Lake Superior. This structural zone, termed the Great Lakes tectonic zone (Sims and others, 1980), appears to consist of gneissic rocks of Terrane I overlain locally by metasedimentary and metavolcanic rocks of Terrane II. Additionally the zone contains isolated remnants of Terrane III.

The gneiss terrane is exposed in the Minnesota River Valley of southwestern Minnesota (Grant, 1972), in east-central Minnesota (Morey, 1978), and at a few scattered localities in west-central Minnesota (Morey, in prep.). In the Minnesota River Valley, where the terrane is best known, several types of migmatitic gneiss--including hornblende-pyroxene gneiss, garnet-biotite gneiss, tonalitic and granodioritic gneiss, and biotite gneiss--and related hybrid rocks have been recognized. In general, all of these rocks have been metamorphosed to the upper amphibolite or lower granulite facies. Because of the pervasive metamorphic overprint, the original nature of the principal gneissic units is conjectural. The garnet-biotite and biotite gneiss are probably derived from a sedimentary protolith, the hornblende-pyroxene gneiss from a mafic igneous protolith, and the tonalitic and granodioritic gneiss from some felsic protolith.

All gneissic rocks in the Minnesota River Valley have been subjected to several periods of folding (Bauer, 1980) and metamorphism (Himmelberg and Phinney, 1967; Grant, 1972) that have led to the formation of a completely tectonized fabric characterized by various kinds of mineralogic layering. Thus although a number of lithic units have been recognized (Grant, 1972), they do not necessarily imply a stratigraphic succession, but may merely reflect a repetition of rock types due to structural processes. Mapping of the various lithic units has led to the recognition of a number of moderately open antiforms and synforms that plunge gently east and have axial planes dipping steeply south. However, Bauer (1980) has delineated two sets of folds that are younger than the major antiformal structures and one set that may be older. The oldest folds are small, isoclinal, recumbent folds that are coaxial with the major antiforms and synforms. These folds may be remnants of a very early period of folding, or they may have formed during the early development of the major structures. Folds younger than the major antiforms and synforms include small to large parasitic folds; their orientations are generally consistent with those of the major antiforms. Still younger minor folds, whose axial planes trend in a northwesterly direction and are inclined to the northeast, also are present. The latter folds may have formed well after the main period of folding.

Some of the gneiss in the Minnesota River Valley has been dated by Rb-Sr and U-Pb methods at approximately 3,600 m.y. (Goldich and others, 1980; Goldich and Wooden, 1980). Granitic magma was intruded in the form of small irregular masses, sheets, and lit-par-lit injections approximately 3,000 m.y. ago. Upper amphibolite to lower granulite facies metamorphism affected both the older gneissic and the granitic phases at approximately 3,000 m.y., or during the interval from 3,000 m.y. to 2,600 m.y. (Goldich and others, 1980). Subsequently the gneiss was invaded by large granitic plutons having ages of about 2,600 m.y. (Doe and Delevaux, 1980). Some retrograde metamorphism of the gneiss terrane appears to have accompanied this period of igneous activity (Wilson, 1976). The gneiss terrane in the Minnesota River Valley also was invaded by granite stocks at around 1,850 m.y. and by several small granite-dioritic complexes at around 1,725 m.y. These stocklike bodies are too small to show on Figure 1.

The origin and history of the gneissic rocks in east-central Minnesota is complex and only partly understood, mainly because exposures are sparse and scattered. The bulk of the gneiss is of quartzofeldspathic composition, including tonalitic and granodioritic variants, and may represent a complex assemblage of greatly deformed, highly metamorphosed, plutonic and volcanic igneous rocks. Lesser quantities of hornblende-pyroxene gneiss, amphibolite, and cordierite-garnet-biotite schist occur as lenses, layers and blocks within the quartzofeldspathic gneiss. The amphibolites and the hornblende-pyroxene gneiss probably represent highly disrupted discordant intrusions, whereas concordant layers of mica-rich schist have been interpreted as metamorphosed sedimentary rocks that were caught during plutonism. Thus some of the mafic enclaves are older and some are younger than the enclosing quartzofeldspathic gneiss. Regardless, all the gneissic rocks underwent several episodes of deformation and high-grade metamorphism (Morey, 1978) to the upper amphibolite or granulite grade.

Igneous activity at around 1,850 to 1,800 m.y. (Goldich and others, 1961), a major rock-forming event in east-central Minnesota, started with the emplacement of dikelike bodies of gabbro and diorite, passed through a phase of granodioritic and sodic granitic plutonism, and ended with the emplacement of a potassic granitic batholith characterized by a rapakivi-like porphyritic border phase of sodic composition. Most of these Middle Precambrian plutonic rocks were emplaced passively as indicated by their crosscutting relationships with structures in the gneissic rocks and by their relatively homogeneous and undeformed nature. However, some of the earlier sodic rocks were emplaced under syntectonic conditions inasmuch as incipient cataclastic zones coincide with cataclastic zones in the gneissic rocks.

Uranium Potential

As a group the ancient gneissic rocks of the Minnesota River Valley and east-central Minnesota (Southwick and others, 1981; Morey and others, 1981) contain only background quantities of uranium (on the order of 1 ppm to 10 ppm). Highest uranium values are found in granitic pegmatites of various styles and ages that traverse the gneiss (on the order of 5 ppm to 10 ppm) and in biotite schist enclaves (on the order of 5 ppm to 12 ppm). Although the occurrence of vein-type deposits [class (320) of Mathews, 1978a] cannot be ruled out, no positive indications have been found as yet, and the prospects are not encouraging in these rocks. It is likely that uranium indigenous to the ancient gneisses has been progressively mobilized and removed during repeated episodes of metamorphism and anatexis. Furthermore, results of an extensive hydrogeochemical sampling program over much of the gneiss terrane (ORGDP, 1979a, 1979b; Morey and Lively, 1980) show no anomalies that can be ascribed unequivocally to uranium concentrations in the gneiss terrane. In northwestern Pine County near Denham, for example, in an area where radioactivity readings are 7 to 10 times background (Ojakangas, 1976), anomalously high concentrations of uranium and radon occur in several water wells (Morey and Lively, 1980). Although the bedrock here is mapped as part of the gneiss terrane, these water wells could equally well penetrate scattered erosional remnants of lower Proterozoic rocks of Terrane III which form a more or less continuous cover over the gneiss terrane just to the north. The hydrogeochemical anomalies could therefore be related either to the unconformity between the gneiss and the overlying lower Proterozoic stratified rocks of Terrane III, or to metamorphic segregations in the gneiss terrane. The significance of the hydrogeochemical anomalies will be discussed more completely below.

The 2,600-m.y.-old granitic plutons associated with the gneiss terrane in the Minnesota River Valley may have some uranium potential. Of the several granitic bodies shown on Figure 1, the Sacred Heart Granite in Redwood, Renville and Yellow Medicine Counties is somewhat more radioactive than other Minnesota granites and is notably more radioactive than its gneissic wall rocks (Ojakangas, 1976). The Sacred Heart Granite has been classified as an unfavorable environment (Southwick and others, 1981) because the probability of finding 100 tons or more of U_3O_8 at a grade of 100 ppm or better is low. However the rock may contain marginal to subeconomic orthomagmatic concentrations [class (310) of Mathews, 1978c], and therefore is described here in some detail.

The Sacred Heart Granite is chiefly a grayish-pink to brick-red, medium-grained granite that contains subequal amounts of quartz, K-feldspar and plagioclase, together with about 6 percent biotite and characteristic trace amounts of sphene. The biotite content varies somewhat in and near the contact zone where the rock is faintly banded.

Two structurally distinct but mineralogically similar types of pegmatite are associated with the Sacred Heart Granite. One class of pegmatite forms gradationally bounded, generally irregular small masses within the granite proper; these appear to be segregation pods, probably volatile controlled, that developed late in the cooling history of the magma. The second type of pegmatite forms sharply bounded straight dikes that commonly cut across the contacts of the granite and continue into the country rock. The dikes locally cut the irregular pegmatite pods, and therefore are somewhat younger; they are fracture fillings formed from late-stage magmatic fluids after the main mass was cool enough for brittle fractures to develop. Both kinds of pegmatite are simple quartz-feldspar-mica rocks without notable zoning. No rare pegmatite minerals were observed, nor have any been reported by others (Southwick and others, 1981).

These geologic characteristics fit many of the criteria associated with uranium deposits of the orthomagmatic and pegmatitic classes (Mathews, 1978c). The pluton is late to posttectonic, located in a region of extensive crustal reworking, and is probably of crustal derivation. Although the chemical composition of the granite is not peralkaline, the ratio of alkalies to calcium is toward the high end of the normal calc-alkaline spectrum. Moreover, the uranium content (on the order of 10 ppm to 20 ppm) in the Sacred Heart Granite is somewhat above average for granitic rocks in general. The magma system apparently was weakly enriched in uranium, and therefore it is possible that late magmatic processes may have produced marginal to submarginal uranium deposits, as yet undiscovered, in association with aplite and pegmatite. Evidence for the late magmatic concentration of uranium is found in one pegmatite dike that contains 95 ppm U_3O_8. No uranium minerals have been recognized petrographically; most likely the uranium occurs in the crystal structures of zircon and sphene, and perhaps to a lesser degree in biotite.

As judged from data now available, the 1,850-m.y. to 1,800-m.y.-old plutonic rocks associated with the gneiss terrane in east-central Minnesota have little potential for uranium deposits (Morey and others, 1981). As a whole, they average less than 15 ppm uranium. In general they exhibit a progressive increase in uranium content with increasing silica content. The gabbroic to granodioritic rocks contain only 1 ppm to 3 ppm uranium. Their generally mafic composition precludes any likelihood for orthomagmatic or other types of primary mineral deposits, and no structural environments particularly favorable as sites for secondary mineralization were identified in these rocks. The sodic and potassic granites exhibit larger but more variable amounts of uranium. Of the sodic bodies, the Pierz and Warman Granites of Morey (1978) contain less than 3 ppm uranium, whereas the Isle and Reformatory Granites contain approximately 10 ppm to 15 ppm uranium. The somewhat higher values in the latter plutons are most likely due to the presence of sphene as a widespread accessory mineral (Morey, 1978). The Stearns Igneous Complex of Morey (1978), particularly the potassic St. Cloud Granite, contains on the average around 5 ppm uranium with a maximum value of about 12 ppm. Again the somewhat higher values are due to the presence of sphene and zircon as widespread accessory minerals (Morey, 1978). Correlative rocks in the Minnesota River Valley also contain only background quantities of uranium. Thus these 1,850-m.y. to 1,800-m.y-old intrusive rocks contain uranium concentrations not significantly above those for average granites of any age or geographic location (Clark and others, 1966; Burwash and Cumming, 1976). Although the occurrence in the more felsic intrusions of orthomagmatic [class (310)] or pegmatitic [class (320)] deposits as described by Mathews (1978c) cannot be entirely discounted, no positive indications were found.

Small plugs of gabbro, diorite, quartz diorite and granitic rocks emplaced in the gneiss terrane and exposed along the Minnesota River Valley also contain only background amounts (about 1 ppm to 5 ppm) of uranium. On the whole, these rocks are too mafic in composition to be likely hosts for orthomagmatic or other types of primary uranium mineralization, and no structural environments particularly favorable as sites for secondary mineralization were identified.

Terrane II - Greenstone-Granite Terrane

Rocks characteristic of the greenstone-granite terrane are exposed over a wide area in northern Minnesota. In general this terrane, which is typical of the Superior province of the Canadian Shield, consists of a thick succession of subaqueous volcanic rocks, derivative sedimentary rocks, and intrusive granitic rocks (Morey, 1980). The volcanic-sedimentary successions constitute complexly folded and faulted, east-trending belts between flanking granitic batholiths. Several periods of folding, accompanied my metamorphism, occurred contemporaneously with the emplacement of the oldest plutonic rocks recognized, which range in composition from tonalite to granite (Sims, 1976). Anorogenic bodies of monzonite, quartz monzonite and syenite were later emplaced in the supracrustal rocks, apparently as diapirs. Extensive faulting accompanied and followed emplacement of the igneous rocks.

Radiometric data from numerous localities indicate that the evolution of this terrane, at least in the Lake Superior region, occurred during a short-lived volcanic-plutonic event about 2,750 m.y. to 2,700 m.y. ago (Jahn and others, 1974). These data indicate that once formed, most of the terrane has remained essentially stable and unaffected by later events except for cataclasis and several periods of dike emplacement, and the effects on parts of the terrane of rifting and emplacement of Terrane V rocks.

Inasmuch as sedimentation, deformation, metamorphism and plutonism were closely related in time, Terrane II is arbitrarily subdivided into three lithotectonic elements: (1) supracrustal units of so-called "greenstone belts"; (2) batholithic units; and (3) fault-bounded "granite-migmatite massifs."

The supracrustal units throughout northern Minnesota are characterized by interfingering and repetitive rock types, which more or less define east-northeast-trending "greenstone" belts separated by batholithic rocks or by fault-bounded granite-migmatite massifs. Each greenstone belt in turn consists of several mafic to felsic volcanic sequences complexly intercalated with chemically precipitated chert or iron-formation or with clastic sedimentary rocks derived from the volcanic rocks. The volcanic sequences are predominantly composed of subaqueous basalt and synvolcanic diabase, but include dacitic to rhyodacitic volcanogenic and volcaniclastic rocks (Schulz, 1980). The sedimentary rocks are mainly graywacke and shale, but beds of banded iron-formation, chert, carbonaceous shale, and rare siliceous marble also are present (Ojakangas, 1972; Green, 1970).

Typically the supracrustal rocks have been folded several times and each greenstone belt generally constitutes an eastward-trending upright anticlinorium. Folding was approximately contemporaneous with the emplacement of the oldest batholithic rocks and is attributable to compression resulting from the diapiric rise of the granitic bodies (Sims, 1976). Metamorphism of the supracrustal rocks to greenschist and locally to middle amphibolite facies accompanied the folding.

In general, the metamorphic grade within the greenschist facies increases in intensity toward bounding granite masses or major faults so that in some places it is possible to define a biotite isograd (e.g., Sims, 1976). Retrograde metamorphism of the supracrustal rocks also is widespread as indicated by mineralogic transformations such as: (1) the alteration of biotite to chlorite and/or pumpellyite, (2) alteration of plagioclase to epidote, and (3) sericitization of metamorphic plagioclase. Whether these transformations represent re-equilibration in response to declining temperatures during late stages of metamorphism at 2,700 m.y., or whether they formed in response to some subsequent period of cataclasis or very low grade metamorphism has not been established (Hart and Davis, 1969; Hanson and Malhotra, 1971).

Batholithic rocks that have intruded the supracrustal rocks form a second lithotectonic segment in the greenstone-granite terrane. In northern Minnesota where they have been well studied, many of the batholithic units are composite structural entities consisting of a number of smaller plutons.

In general these plutons are of variable size and may be divided into older syntectonic units of tonalitic to granitic composition and younger posttectonic rocks of monzonitic to quartz-monzonitic composition.

The syntectonic igneous rocks are characterized by foliated textures, contacts that are conformable with the internal structure of the adjacent supracrustal rocks, abundant inclusions, and wide metamorphic aureoles ranging from the greenschist facies to the upper amphibolite facies; the inner parts of some of the aureoles are migmatized. The metamorphic grade increases toward the batholithic rocks and is characterized by: (1) the progressive loss of relict volcanic and clastic textures, (2) the progressive disruption of layering, and (3) a progressive increase in the degree of metasomatism. The inner parts of some of the contact metamorphic aureoles are characterized by the addition of K_2O leading to the formation of antiperthites and to the alteration of hornblende to biotite and epidote.

In contrast to the syntectonic granitoid rocks, the posttectonic rocks of generally quartz-monzonitic composition truncate the regional structures and have steep primary foliations that are discordant with the regional structure, but tend to be concordant with the structures in immediately adjacent wall rocks. In addition to the major batholithic units, posttectonic rocks of generally syenitic composition form small plutons that are widely scattered along the supracrustal belts. Regardless of their composition or stratigraphic setting, these posttectonic rocks have narrow metamorphic aureoles that lack primary textures except for layering. The maximum grade obtained is generally of the lower amphibolite facies; felsic rocks typically are characterized by mineral assemblages that contain garnet, hornblende, plagioclase and sphene, whereas mafic rocks contain diopside, epidote, zoisite and actinolite.

Fault-bounded, linear blocks of biotite schist and amphibolite intercalated with igneous rocks of dioritic to granitic composition comprise a third discrete lithotectonic segment in Terrane II. In general, these rocks have been metamorphosed to the upper amphibolite facies, have had a complex history of injection, anatexis and metasomatism, and are associated with syntectonic igneous rocks. Therefore they are analogous in many ways to the contact-metamorphosed supracrustal rocks associated with the batholithic units. However, the fact that these fault-bounded blocks are areally extensive and contain much more migmatitic material than do the other batholithic units in northern Minnesota led Southwick (1972) to refer to the blocks as "granite-migmatite massifs."

The Vermilion Granitic Complex of Southwick and Sims (1980) is the best studied granite-migmatite massif in northern Minnesota. Supracrustal rocks along the outer fringes of this complex have metamorphic mineral assemblages similar to those in adjacent supracrustal rocks. However, primary textures within the complex have been totally obliterated except for layering, and the fabric is entirely metamorphic in origin. Moreover primary layering is recognizable only by contrasting grain sizes and differing modal proportions of plagioclase, quartz, biotite, and muscovite. Sill-like bodies of igneous material, ranging in thickness from a few centimeters to tens or hundreds of meters, become more abundant in the interior portions of the massif. In places the supracrustal rocks contain garnet, staurolite, hornblende and epidote. These rocks in turn pass into a stromatoform migmatite characterized by roughly equal proportions of schist and granite; much of the schist contains so many quartzofeldspathic stringers that the combined rock appears gneissic. The core of the massif consists of granite containing numerous biotite-rich inclusions that show all stages of transformation to rocks having the texture and composition of the enclosing granite. These inclusion-rich zones grade transitionally into areas consisting almost entirely of monotonous granite whose uniformity is interrupted only by scattered zones of nebulitic inclusions.

Supracrustal rocks within several hundred meters of granite bodies in the core of the Vermilion Granitic Complex contain mineral assemblages suggesting temperatures and pressures in the neighborhood of 600-700°C and 3-5 kilobars (Southwick, 1976), a metamorphic environment compatible with inferred temperatures and pressures at the time of crystallization of the granitic phases in the massif (Southwick, 1972).

Uranium Potential

None of the supracrustal units of the greenstone-granite terrane exhibits particularly large scintillometer readings (Ojakangas, 1976). In general, most of the volcanic rocks are too mafic to contain appreciable concentrations of uranium. Although chemical data are sparse (Rogers and others, 1970), uranium contents of 26 samples of argillaceous and sandy rocks range from 0.3 ppm to 2.1 ppm (average 1 ppm). Corresponding thorium concentrations range from 1 ppm to 9 ppm and average about 4 ppm. Thus the uranium and thorium contents of these rocks are lower than those in other Precambrian rocks, but the thorium-to-uranium ratios are higher (Malan and Sterling, 1970). This may be a primary feature, or the high thorium-to-uranium ratio may indicate the preferential leaching of uranium during some subsequent event. Regardless, sedimentary rocks in the sequence do not appear to represent favorable environments for syngenetic uranium deposits, and their geologic setting is not favorable for the formation of epigenetic deposits.

Most of the batholithic units in the greenstone-granite terrane also exhibit generally low scintillometer readings (Ojakangas, 1976). Furthermore many of the syntectonic rocks were derived by the partial melting at mantle depths of either eclogite or amphibolite of basaltic composition (Hanson and Goldich, 1972; Arth and Hanson, 1975), and the concentration of uranium in such melts does not seem to be a likely process. Reported thorium and uranium contents of several posttectonic granitic plutons are generally low. Uranium ranges from less than 1 ppm to 7 ppm, whereas thorium ranges from less than 1 ppm to 37 ppm (Rye and Roy, 1978). It may be of significance, however, that Rye and Roy (1978) noted an increase in both thorium and uranium with increasing potassium content. Therefore many of the late-phase granitic melts could be possible sources of primary uranium mineralization, either as orthomagmatic deposits [class (310) as described by Mathews (1978c)], or more probably as late-stage pegmatite deposits [class (320) as described by Mathews (1978c)].

Late-stage pegmatite deposits may occur in the Northwest Angle where K-feldspar, muscovite, quartz, albite, garnet and beryl occur in very coarse grained pegmatite veins. This area has many geologic attributes similar to those associated with the class (320) pegmatite deposits described by Mathews (1978c). Moreover the area is characterized by above-average scintillometer readings (Ojakangas, 1976). Ojakangas (1976) also reports, albeit secondhand from a newspaper article, an assay of one pegmatite having 1.31 percent equivalent uranium. Thus late-stage igneous phases in selected parts of the Terrane II batholithic units may be environments favorable for uranium deposits.

Although the main granitic core of the Vermilion Granitic Complex is characterized by low radioactivity readings and small uranium values (1 ppm to 2 ppm), the migmatitic parts of the complex have somewhat higher than average levels of radioactivity (Ojakangas, 1976). These elevated values may be related in part to the presence of thorium, particularly in the metasedimentary phases where 3 ppm to 29 ppm have been reported (Rye and Roy, 1978). However, some of the metasedimentary phases also contain as much as 9 ppm uranium, although most analyzed samples have values ranging from 1 ppm to 6 ppm. Rye and Roy (1978) have speculated that many of the igneous phases in the massif may have formed by the partial melting of the metasedimentary phases which were already somewhat enriched in uranium. Thus late-stage granitic dikes, sills and veins with elevated uranium and thorium contents may be present in the massif. More importantly, however, the granite-migmatite massifs themselves have many geologic attributes similar to those that characterize anatectic uranium deposits--class (380) of Mathews (1978c)--in mixed igneous/metamorphic terranes elsewhere in the world.

Terrane III - Intracratonic Stratified Rocks

Rocks assignable to Terrane III comprise a thick succession of metasedimentary and metavolcanic rocks of early Proterozoic age that formed between 2,000 m.y. and 1,870 m.y. ago. They were deposited in an intracontinental basin centered over and approximately parallel with the Great Lakes tectonic zone. In general these rocks record a complete transition from shallow-water deposition on a stable shelf to deep-water deposition in a eugeosynclinal environment (Morey, 1979; in prep.). The stratified rocks in the southern part of the basin were subsequently deformed and metamorphosed, mainly by the vertical reactivation of underlying gneissic rocks. North of a sharp tectonic front, which coincides with the north edge of the Great Lakes tectonic zone, the stratified rocks are undisturbed except for regional tilting and local faulting along reactivated Archean faults.

The sedimentary and volcanic rocks of Terrane III are divisible into two sequences separated by an unconformity. Each sequence is estimated to attain a maximum thickness of approximately 1 km in the area north and east of Mille Lacs Lake. However, extensive deformation, combined with the lack of well-exposed stratigraphic marker beds, makes any estimate of thickness debatable.

The distribution and extent of the older sequence, the Mille Lacs Group of Morey (1978), has been recognized only recently, whereas the younger sequence is correlative with the well-known Animikie Group of northern Minnesota and Ontario. The basal part of the Mille Lacs Group--the Denham Formation of Morey (1978)--consists predominantly of quartzite, quartzose siltstone, and quartz-rich argillite with lesser amounts of limestone, dolomite, and quartz-pebble conglomerate. Significant bodies of pillowed metabasalt and associated volcanogenic and hypabyssal rocks are interlayered with the quartzitic rocks near the base of the Mille Lacs Group. These dominantly volcanic sequences form mappable units of appreciable size, both to the northeast of Mille Lacs Lake--Glen Township Formation of Morey (1978), and southwest of the Cuyuna district--Randall Formation of Morey (1978). Diabase sills and thin layers of mafic tuff also occur throughout the Mille Lacs Group, but most are too small to be shown at the scale of Figure 1. Thin, lenticular beds of oxide- to carbonate-facies iron-formation and thin to thick beds of pyrite-rich carbonaceous argillite are intercalated with the volcanic rocks of the Glen Township and Randall Formations, but do not appear to be present in the upper part of the Mille Lacs Group.

An unconformity separates the Mille Lacs Group from the overlying Animikie Group. The basal part of the Animikie Group--Mahnomen Formation of Schmidt (1963)--consists predominantly of feldspathic siltstone and lesser amounts of quartzite and limestone. Oxide- and silicate-facies iron-formation--Trommald Formation of Schmidt (1963)--composes the middle part of the group, whereas predominantly clastic rocks compose the upper part--Rabbit Lake Formation of Schmidt (1963). The Rabbit Lake Formation is divisible into three members. The so-called "lower member" consists of carbonaceous mudstone, feldspathic siltstone, and mafic tuffs or flows. This in turn is overlain by a persistent layer of iron-formation--Emily Iron Formation Member of Marsden (1972). The Emily Member is overlain by the so-called "upper member" which consists predominantly of carbonaceous mudstone, feldspathic siltstone, and scattered beds of fine- to medium-grained feldspathic graywacke. Lenses of iron-formation as much as several tens of meters thick and at least several kilometers long also are present in the "upper member" of the Rabbit Lake Formation. Although definitive details are lacking, it is inferred that the Rabbit Lake Formation is correlative with the Thomson Formation of Carlton and Pine Counties. The Thomson Formation contains appreciable quantities of carbonaceous mudstone, but it is typified by abundant beds of fine- to medium-grained, feldspathic to quartzose graywacke, by locally abundant units of carbonaceous slate, and by the presence of tuffaceous beds and coeval hypabyssal sills or dikes.

Regionally, the Terrane III rocks comprise a broad, eastward-plunging synclinorium bounded on the north, west and southeast by Archean rocks. In general, the entire section is complexly folded into a number of large anticlines and synclines having many coaxial second- and third-order folds on their limbs (Morey, 1978). The style of deformation changes from open folds with near-vertical axial planes in the north to isoclinally overturned folds with steeply dipping (60° to the southeast) axial planes in the south.

The Terrane III rocks also reflect an increase in metamorphic grade from north to south. To the north the argillaceous rocks of the Animikie Group lack slaty cleavage and are only slightly, if at all, metamorphosed. However, south of the tectonic front, they are characterized by a slaty cleavage and by mineral assemblages indicative of lower greenschist-facies metamorphism. Farther south the same rocks have been metamorphosed to the upper greenschist facies; mineral assemblages contain biotite, muscovite, plagioclase (oligoclase to andesine), quartz, and calcite. Still farther south and particularly in the southern part of Carlton County, the argillaceous rocks have been metamorphosed to the garnet grade of the lower amphibolite facies.

The Thomson Formation is juxtaposed against rocks of the Mille Lacs Group across a major fault that trends northwest from northwestern Pine County. On the west side of the fault, the Denham Formation has been metamorphosed to the lower amphibolite grade. Garnet is common in the more quartzose beds, hornblende is abundant in calcareous and volcanic units, and staurolite occurs in proximity to the McGrath Gneiss.

The areas of most intense deformation also are the areas of most intense metamorphism. The biotite, garnet, and staurolite isograds conform in a general way to the fold geometry and define metamorphic highs around mantled gneiss domes cored by Terrane I rocks. In detail, the metamorphic isograds transect major fold axes, and it therefore appears that the deformation and metamorphism were discrete events.

Uranium Potential

Several stratigraphic units within the Terrane III sequence are believed to have some potential for syngenetic uranium deposits. These include: (1) the basal Mille Lacs Group from the general vicinity of Denham in northwestern Pine County to Little Falls in Morrison County, and (2) phosphate-rich beds in certain parts of the Thomson Formation. Additionally, the Thomson Formation has a considerable potential for epigenetic vein-breccia uranium deposits, particularly near unconformably overlying rocks of Terrane V. This class of deposits will be discussed more completely in a following section.

Rocks of the Denham Formation immediately above the basal unconformity of the Mille Lacs Group are considered favorable on stratigraphic and hydrogeochemical grounds (Morey and others, 1981) for uranium deposits of either the quartz-pebble conglomerate class [class (120) deposits as described by Jones, 1978b] or of the unconformity-related vein-breccia class [class (710) as described by Mathews, 1978d].

The Denham Formation forms a heterogeneous sequence that consists dominantly of arenitic quartz-rich rocks ranging in grain size from conglomerate to coarse siltstone. Minor quantities of pillow basalt, mafic to intermediate agglomerate, iron-formation, and limestone or dolomite are intercalated locally with the quartz-rich sedimentary rocks.

Conglomeratic units near the base of the Denham Formation occur as lens-like sedimentation units as much as 9 m thick. In general, they are massive to very poorly bedded. Conglomeratic clasts include clear, gray or blue quartz, microcline, "granitic" rock fragments consisting of either quartz and microcline or quartz and plagioclase, and recrystallized chert. The sand-size grains consist dominantly of granoblastic quartz, strongly sericitized microcline, sodic plagioclase, and lesser amounts of "granitic" rock fragments. Silt- and clay-size material in the matrix is extensively recrystallized, and consists dominantly of quartz and muscovite and lesser amounts of biotite and chloritoid; garnet and staurolite also are present as additional phases at higher metamorphic grades.

Quartzitic units intercalated with and overlying the conglomeratic units vary in color from white or light reddish gray to dark reddish gray. The light-colored varieties consist almost entirely of sand- and silt-size quartz, microcline, and lesser amounts of plagioclase, whereas the reddish-gray varieties contain minor amounts of hematite and ankerite in addition to the above-mentioned clastic minerals. Some of the red-colored rocks may be extensively recrystallized cherty iron-formation. Interbedded argillaceous units are light colored and consist of intercalated laminae or very thin beds of argillite and argillaceous siltstone. The argillaceous siltstone layers in turn are laminated; layers rich in quartz alternate with layers rich in muscovite and chlorite, and at higher metamorphic grades, muscovite, biotite and garnet.

Volcanic rocks in the Denham Formation are dominantly mafic in composition and are characterized by pillow structures having rinds several centimeters thick. In places they are as much as 20 m thick, characterized by light-gray, angular, vaguely porphyritic fragments as much as 10 cm in diameter set in a dark-colored, markedly porphyritic groundmass.

A pervasive metamorphic overprint, coupled with locally extreme tectonic recrystallization has destroyed most primary sedimentary structures other than layering in the Denham Formation. Nevertheless, the presence of lenticular beds of quartz-pebble conglomerate, intercalated with mineralogically mature arenites near the base of the group, implies that sedimentation started in a shallow, fairly high energy depositional regime, possibly under fluvial to marginal marine conditions. Subsequently, the depositional basin underwent rapid subsidence and the epiclastic rocks were abruptly replaced by increasing quantities of extrusive and pyroclastic rocks which accumulated under subaqueous conditions. Volcanism was accompanied locally by the precipitation of chert and iron-bearing minerals, perhaps by fumarolic activity under generally reducing conditions. As volcanism waned, gradual clastic sedimentation began and continued in an environment where sedimentation more or less kept pace with subsidence (Morey, 1979).

Regionally, the geologic characteristics of the Denham Formation (table 2) fit many of the criteria associated with quartz-pebble conglomerate-related uranium deposits [class (120) as described by Jones (1978b)]. Moreover, the ground-water samples (Morey and Lively, 1980) show anomalous patterns in the concentrations of uranium and radon that may be interpreted as being related to the subcrop distribution of the formation, particularly where it is in contact with gneissic basement rocks. Anomalously high concentrations of uranium and radon also occur in several wells in areas where the first bedrock has been mapped as Archean gneiss. Although these wells have been assigned to the gneiss terrane, they could equally well penetrate scattered erosional remnants of quartzite, conglomerate, and iron-formation of the Denham Formation which occur on top of the gneiss.

The Denham Formation has many geologic attributes similar to those associated with the Huronian Supergroup where detrital uranium deposits appear to be the end product of a rather specific sedimentological regime characterized by anoxygenic atmospheric conditions. However, the Denham Formation is some 200 million years younger than the Huronian Supergroup and thus may have formed under an oxygenic environment. The importance of an anoxygenic atmosphere to the formation of uranium deposits of the quartz-pebble conglomerate class has been debated, inasmuch as sedimentological and diagenetic conditions may be of greater importance (e.g., Dimroth and Kimberley, 1976).

The hydrochemical anomalies associated with the Denham Formation could also be related to epigenetic processes leading to the formation of unconformity-related vein-breccia deposits as described below for the Thomson Formation. In particular, the hydrogeochemical anomalies in the Denham Formation occur near the present erosional edge of the overlying Terrane V sedimentary rocks, and along a major northwest-trending fault zone that juxtaposes the Denham Formation against the Thomson Formation. Therefore it is conceivable that areas of epigenetic mineralization may be localized along either side of this fault zone as implied by the presence of uranium pathfinder elements such as potassium, sodium, lithium, and magnesium (Morey and Lively, 1980). Unfortunately, the hydrogeochemical and geological data are inadequate to discriminate between the possible occurrence of either class of deposit at this time. Nonetheless, the data summarized in Morey and Lively (1980) do indicate a large anomalous area which should be evaluated more completely.

Syngenetic phosphate-rich units in the Thomson Formation have been discussed by geologists associated with the Rocky Mountain Energy Company (Skillings Mining Review, February 16, 1980). They describe two phosphate-rich, pebble-conglomerate beds (7.5 cm and 25.4 cm thick) that average 200 ppm and 15 to 25 percent P_2O_5 over a strike length of 242 m. In general the average uranium grade increases in proportion to the percentage of phosphate.

Table 2. Comparison of geologic characteristics of the Denham Formation with characteristics of class (120) deposits

Characteristic	Model class (120) deposits (Jones, 1978b)	Denham Formation
1. Tectonic setting	On Archean shield; source rocks of granitic composition.	On Archean shield; source rocks of granitic composition.
2. Host rock: Age	Early Proterozoic; 2,200 to 2,700 million years.	Early Proterozoic; 2,100 to 1,900 m.y.
Lithology	Oligomictic, pyritic quartz-pebble conglomerate; clasts of quartz, chert or quartzite in a matrix of quartz, feldspar, pyrite, heavy minerals, and sericite or chlorite; typically cross-bedded.	Oligomictic quartz-pebble conglomerate; clasts of quartz, chert, feldspar, and granitic rock fragments in a matrix of quartz feldspar, granitic rock fragments, muscovite, and chloritoid.
3. Depositional environment	Chiefly braided stream; lacustrine, marginal marine environments also may be represented; anoxygenic atmosphere.	Fluvial to marginal marine environment; atmosphere transitional between anoxygenic and oxygenic (?).
4. Associated rocks	Quartzite, arkose, siltstone, argillite, and subaerial volcanic rocks of basaltic composition.	Quartzite, feldspathic quartzite, siltstone, argillite, iron-formation, and subaqueous volcanic rocks of basaltic composition.
5. Metamorphic grade	Greenschist facies.	Greenschist to amphibolite facies.
6. Geometry	Stratiform; thin and lenticular beds, often coalesced into thin sheets.	Stratiform; thin and lenticular.
7. Mineralization	Uraninite and/or brannerite, locally uranothorite, coffinite, gummite and thucholite.	No uranium mineralization known; possibly thorium-rich (Kalliokoski and others, 1978).

A second phosphate-rich uranium occurrence in the Thomson Formation has been recently described by Morey and Lively (1980). Unlike the conglomerate samples, this sample, which contains approximately 400 ppm uranium and 57,000 ppm phosphorous, was collected from a finely laminated bed approximately 10 cm thick that was intercalated with thicker beds of carbonaceous slate. The marked correlation between uranium and phosphorous in this sample, in light of what appears to be a generally positive correlation between uranium and phosphorous in many analyzed Thomson samples (see Morey and Lively, 1980 for discussion), implies that uranium-bearing phosphate beds of syngenetic origin may be fairly abundant in the Thomson Formation.

The location of the Rocky Mountain discovery has not been precisely defined, but the location of Morey and Lively's sample occurs on a generally east-northeast-trending hydrogeochemical uranium anomaly that is about 12 km long. This coincidence suggests that Morey and Lively's uranium-rich phosphate sample may be part of a stratigraphic unit that has considerable lateral continuity.

Phosphate-rich rocks also have been found in northern Michigan in the Marquette Range Supergroup which is correlative with both the Mille Lacs and Animikie Groups of Minnesota (Mancuso and others, 1975; Cannon and Klasner, 1976; Trow, 1979). Some of the phosphatic rocks in Michigan contain concentrations of U_3O_8 averaging 100 ppm with maximum values of 400 ppm (Trow, 1979). Thus, they are not unlike those found in the Thomson Formation.

As far as the author is aware, no economic uranium-rich phosphate deposits have been recognized in the Precambrian geologic settings represented by the Thomson Formation and the occurrences so far recognized in the Marquette Range Supergroup. However, the presence of uranium-rich phosphate beds within the Thomson Formation is relevant to the ready dissolution of oxidized uranium as uranyl-phosphate complexes--constituents necessary for the formation of epigenetic vein-breccia deposits as discussed below.

Terrane IV - Platform-Type Supracrustal Rocks

Locally deformed and slightly metamorphosed quartzite and lesser amounts of aluminum-rich mudstone, all assigned to the Sioux Quartzite, compose Terrane IV. So far as is known, this terrane, which may be several thousands of meters thick, lies entirely on the gneissic rocks of Terrane I in southwestern Minnesota.

The Sioux Quartzite was deposited between 1,725 m.y. and 1,600 m.y. ago and therefore is early Proterozoic in age. It forms a thick sequence of dominantly orthoquartzitic sandstone that has not been formally subdivided. The basal part of the formation contains scattered beds of texturally and compositionally mature polymict conglomerate (Miller, 1961) as well as beds of red siltstone and mudstone (catlinite). Catlinite units also occur fairly commonly in the upper third of the formation. Weber (1977) estimates that the Sioux Quartzite as a whole consists of 90 percent orthoquartzite, 8 percent conglomerate, and 2 percent mudstone. This estimate is based on outcrop measurements, however, and may not accurately reflect the composition of deeper parts of the formation. A deep well at Hull, Iowa, about

60 km south of the Minnesota border, cuts alternating layers of quartzite and rhyolite in the Sioux at a depth of 231 m (Beyer, 1893; Norton, 1897), and probable tuff beds have been encountered in three other wells elsewhere in northwestern Iowa (Yoho, 1967). Moreover, interbeds of arkose a few meters thick have been noted at a depth of about 133 m in a section also containing tuffaceous horizons, in the Tiezen No. 1 Gisolf well in Lyon County, Iowa (Yoho, 1967, p. 13). It therefore appears that rhyolite, felsic tuff, and feldspathic detrital rocks which may be volcanogenic in part, all increase southward (basinward) in the Sioux Quartzite.

Estimates of the thickness of the Sioux range from 1,600 m to 2,400 m (Baldwin, 1951; Austin, 1972). However, because neither the base nor the top of the Sioux is exposed and structural control is poor, this thickness estimate is inexact although probably of the correct order of magnitude. The coarse basal conglomerate exposed near New Ulm is about 18 m thick (Miller, 1961). Because the upper surface of the Sioux is an unconformity and the prevailing regional dip in southwestern Minnesota is to the south, the depth from the surface to the basal unconformity increases from north to south.

Highly mature orthoquartzitic sandstone is the dominant rock in the Sioux Quartzite. More than 90 percent of the clastic grains in the orthoquartzite are unit-grains of quartz; the remainder are chiefly polycrystalline quartz and chert. Each rounded sand grain is coated with hematite and the aggregate is totally cemented by secondary quartz overgrowths. Sorting is good to excellent. Most of the orthoquartzite was medium to coarse sand originally, with lesser amounts of fine sand and coarse silt; overall, the grain size of the sand decreases upward in the section.

The basal conglomerate exposed near New Ulm contains a poorly sorted assemblage of chemically and mechanically resistant clasts in a matrix of medium to coarse quartz sand. The largest clasts are about 35 cm in diameter and are composed of granular ferruginous chert, gray chert, and earlier cycle quartzite. The quantity of vein quartz clasts increases with diminishing grain size in the conglomerate. Pebbles of rhyolite and other fine-grained felsic volcanic rocks are minor constituents of the basal conglomerate, and clasts of granite and gneiss are totally lacking.

Thin beds and shallow channel fills of conglomerate and pebbly quartzite occur in the dominantly orthoquartzitic section above the basal conglomerate. These beds contain fundamentally the same kinds of pebbles as the basal conglomerate, but the pebbles are finer and much better sorted. They grade into coarse quartzite both vertically and horizontally.

The mudstones in the Sioux occur in beds that have gradational basal contacts and erosional tops. The base of the overlying quartzite bed typically is marked by a thin mud-chip conglomerate. Mudstone beds range in thickness from a few centimeters to 4 m, and range in composition from virtually pure claystone to silty mudstone.

Primary structures indicative of shallow-water deposition in a braided fluvial environment abound in the lower parts of the Sioux Quartzite. Trough cross-bedding, symmetrical ripple marks, current ripple marks, and mud cracks are the most common structures observed; sand waves, planar cross-bedding, load casts, mud clasts, parting lineations and climbing ripple laminations are less abundant. Herringbone cross-bedding and reactivation surfaces, possibly indicative of tidal sedimentation, are found only in the upper third of the section (Weber, 1977).

Large-scale trough cross-bedding and, less commonly, planar cross-bedding, are the dominant primary structures in sections of coarse orthoquartzite and conglomerate. Originally horizontal master bedding surfaces are indistinct and commonly several meters apart stratigraphically. In general, medium-grained orthoquartzite sections display smaller troughs and typically have ripple-marked horizontal bedding as well, indicating a less energetic depositional environment. Thin-bedded, fine orthoquartzite, siltstone and mudstone commonly have ripple-marked and mud-cracked bedding surfaces only a few centimeters apart stratigraphically, indicating deposition on mud flats that were alternately flooded and exposed to desiccation.

The numerous current structures in the Sioux Quartzite clearly indicate deposition from a southeast-flowing current regime. Although a shallow-water depositional environment is clearly indicated by the primary structures in the Sioux Quartzite, the exact nature of the shallow-water environment is considerably less certain. Weber (1977) concluded that the lower two-thirds of the formation was deposited either in a plexus of braided alluvial channels or in a shallow, high-energy marine environment, whereas the upper third was deposited in a shallow marine environment affected by tidal currents. Earlier, Miller (1961) made the interesting suggestion that the Sioux may represent a pediment-fan assemblage of fluvial sediments that was slowly inundated and reworked by a transgressing sea. Miller further concluded that intense weathering of the basement must have preceded alluvial-fan sedimentation in order to account for the absence of locally derived granite and gneiss cobbles in the basal conglomerate.

Uranium Potential

The unconformity beneath the Sioux has many of the geologic criteria (table 3) associated with unconformity-related uranium deposits (Mathews, 1978d). The principal factor along the Sioux unconformity that is lacking but seemingly required for concentrating uranium near unconformities is a geologic reducing agent. However, reductant rocks may occur in the underlying gneiss terrane beneath the unconformity. Therefore, even though no uranium mineralization has been identified to date, there is potential for future discovery of mineralization in the subsurface. This potential is supported in part by the existence of several areas where water wells that are spatially related to the Sioux unconformity contain ground water having anomalous concentrations of uranium, helium and radon. In one of these areas, waters circulating in the vicinity of the unconformity are enriched in uranium and helium, but are depleted in radon, relative to waters within the Sioux itself. These relationships imply that dissolved radium, which is the emitter of radon, may be captured in iron-oxide-coated fracture surfaces and grain boundaries within the Sioux, whereas dissolved uranium and helium are not detained and thus are able to migrate down the modern hydrologic gradient beyond the subcrop of the unconformity. Although the observed anomalies are not considered to be directly indicative of significant uranium mineralization, they are compatible with possible uranium concentrations near the unconformity surface (Southwick and others, 1981).

Terrane V - Rocks of the Midcontinent Rift System

The final event in the formation of the Precambrian crust in Minnesota was the development of the so-called "Midcontinent Rift system." Rifting during middle Proterozoic time was accompanied by the massive upwelling of mantle-derived magmas with the solidification of mafic plutonic rocks at depth and widespread volcanism and clastic sedimentation at the surface. Rocks associated with this period of rifting at about 1,100 m.y. compose Terrane V.

Terrane V is particularly well developed in northeastern Minnesota where a variety of mafic plutonic rocks--Duluth Complex--and their volcanic roof rocks--North Shore Volcanic Group--are exposed for 250 km along the North Shore of Lake Superior (fig. 1). In east-central Minnesota, correlative volcanic rocks disappear beneath the Paleozoic strata of the Midcontinent region 160 km south of the western end of Lake Superior, but they continue southward in the subsurface for more than 1,000 km as a belt of basaltic volcanic rocks 40 to 85 km wide. These rocks yield the so-called "Midcontinent Gravity High" characterized by one of the largest positive gravity anomalies in the United States. Terrane V rocks also continue east-northeastward from the western end of Lake Superior in a broad belt extending across northern Wisconsin and Michigan (White, 1966) before turning southward and disappearing again beneath Paleozoic strata of the Michigan basin (Oray and others, 1973).

Table 3. Comparison of geologic characteristics of the Sioux unconformity with characteristics of class (710) deposits

Characteristic	Model class (710) deposit (Mathews, 1976d)	Sioux unconformity
1. Tectonic setting	Stable craton.	Stable craton.
2. Kind of unconformity	Erosion surfaces where terrestrial sediments overlie metamorphic complexes.	Sioux Quartzite may be in part terrestrial although the upper part appears to be marine. Subjacent Archean rocks are metamorphic.
3. Lithology	*Upper sequence*: Typically orthoquartzitic to feldspathic fluvial sandstones marked by high degree of textural and mineralogical maturity. Commonly less well sorted, less mature near base, which may be conglomeratic.	*Sioux*: Possesses all criteria of model upper sequence.
	Older metamorphic complex: Lithologic details are not significant except presence of reductants. Graphitic, chloritic, sulfide-bearing schists associated with larger U deposits.	*Archean gneiss*: Chloritic rocks known locally; extensive graphite- or sulfide-bearing zones not known.
4. Age	Major deposits associated with Proterozoic unconformities.	Proterozoic (probable age of Sioux in 1,650-1,700 m.y. range).
5. Structure	Very mild deformation of upper sequence; reactivated basement faults occur near U deposits.	Sioux is gently deformed. Faulting in Sioux appears to be of reactivation type.

Rocks within the rift system can be arbitrarily divided into three lithotectonic assemblages which partially overlap in space and age. The oldest assemblage, which crops out in northeastern Minnesota, consists predominantly of sedimentary rocks--Puckwunge and Nopeming Sandstones--and possibly coeval, low-alumina, tholeiitic sills called the Logan intrusions. The next assemblage is predominantly igneous and consists of at least two separate suites of lava flows and associated plutonic rocks that were emplaced over a relatively short span of time, about 1,100 to 1,000 m.y. ago. Pyroxene-phyric lava flows, pyroxene diabase sills and minor dikes, and gravity-segregated plutonic units--peridotite, anorthositic gabbro, and granophyre--compose the older suite. The younger suite consists of plagioclase-phyric lava flows, olivine diabase dikes and minor sills, and troctolitic-gabbroic plutonic rocks. Emplacement of these contrasting igneous rock suites appears to have been related to the progressive development of surface and subsurface void spaces produced by extensive faulting, which increased in frequency and intensity with time (Weiblen and Morey, 1980). The uppermost lithotectonic assemblage consists of two suites of clastic sedimentary rocks of alluvial to fluvial origin. The older suite--the Solor Church Formation--locally is intercalated with lava flows; it consists of lithic sandstone and shale that were deposited in a number of fault-bounded basins along the axis of the rift. The younger suite consists of arkosic and quartzose sandstone--Fond du Lac Formation and Hinckley Sandstone respectively--deposited in large, half-grabenlike basins along the flanks of the rift. This predominantly sedimentary suite marks the gradual cessation of crustal separation and magmatism. However, dominantly vertical faulting continued intermittently throughout the time of active sedimentation and into the Paleozoic Era.

Uranium Potential

The mafic volcanic and plutonic rocks, because of their generally mafic compositions, do not represent generally favorable environments for uranium mineralization. However Ojakangas (1976) suggests that some rhyolitic flows in the North Shore Volcanic Group and granophyric bodies in the Duluth Complex are considerably more radioactive than their mafic associates. These felsic units appear to be late-stage differentiates from a generally mafic source. As such they contain relatively large amounts of potassium, and thus theoretically could contain larger amounts of uranium and thorium. However, to my knowledge, this possibility has not been confirmed by analytical data.

The Terrane V sedimentary rocks also appear to have little potential for syngenetic uranium deposits. The Solor Church Formation was derived dominantly from the mafic volcanic rocks, which had little uranium to start with, whereas the Puckwunge, Nopeming, Fond du Lac and Hinckley formations are texturally and mineralogically mature entities. Any syngenetic uranium concentrations in these rocks would have been leached by oxidizing ground waters. This conclusion is substantiated in part by analytical data (Morey and Lively, 1980) which indicate that the Fond du Lac and Hinckley formations contain on the average only 3 ppm to 4 ppm uranium. However, even with these small uranium concentrations, the sedimentary rocks of Terrane V may have served as source rocks for possible epigenetic uranium occurrences in the Thomson Formation in Carlton County and near Mora in Kanabec County in the Hinckley Sandstone itself.

Rocks of the Thomson Formation of Terrane III along and near the angular unconformity between it and the overlying Fond du Lac Formation of Terrane V are considered favorable on stratigraphic and hydrogeochemical grounds for unconformity-related uranium deposits of the vein-breccia class [class (710) deposits as described by Mathews (1978d)].

In general, the Fond du Lac Formation in Carlton and Pine Counties dips 5 to 12 degrees to the southeast and thickens from an erosional feather edge to more than 2,000 m (Mooney and others, 1970) near a major fault in the Midcontinent Rift system. This abrupt thickening over a relatively short distance implies that the Fond du Lac detritus was deposited in a half-grabenlike basin characterized by an extensive set of northeast-trending growth faults, downthrown to the southeast (Morey, 1972a).

The Fond du Lac Formation forms a heterogeneous sequence consisting dominantly of subarkosic to arkosic sandstone, siltstone, and silty shale; intercalated thin to thick beds of intraformational shale-pebble conglomerate, interformational basalt-pebble conglomerate, and a basal quartz-pebble conglomerate are minor lithologies (Morey, 1967).

The basal quartz-pebble conglomerate is exposed in only one place west of Duluth where it is about 3 m thick. However, Winchell (in Morey, 1967) reported thicknesses of as much as 23 m apparently in paleochannels cut into the underlying Thomson Formation. Vein quartz is the predominant pebble lithology, but clasts of iron-formation, chert, and slate are locally abundant. Pyrite and marcasite are ubiquitous and occur in the conglomerate as patches and blebs several centimeters in diameter, and as finer disseminated grains; much of the sulfide has been oxidized to limonite.

The sandstone of the Fond du Lac Formation is of arkosic or subarkosic composition. It consists of 36 to 68 percent quartz, 5 to 29 percent feldspar (dominantly orthoclase with lesser albitic plagioclase and microcline), 1 to 10 percent rock fragments (dominantly chert and quartzite with lesser basalt, felsite, iron-formation and schist), 1 to 15 percent matrix material composed of quartz, illite, chlorite and rare kaolinite, and 1 to 20 percent cement of hematite, calcite, quartz and dolomite. Heavy minerals include leucoxene, apatite, tourmaline, zircon, magnetite-ilmenite, and garnet. The siltstone and shale, although fine grained, are mineralogically equivalent to the sandstone.

The Fond du Lac Formation was deposited by a series of meandering streams that had their headwaters in a mixed granitic igneous and metamorphic source area and flowed eastward and southeastward across a broad alluvial plain (Morey, 1967). Various sedimentary structures, including fining-upward sequences of beds and the lensoid nature of all rock types, imply a fluvial-deltaic setting with numerous channels and broad interchannel areas.

The widespread occurrence of iron oxides implies that the Fond du Lac Formation is now in a highly oxidized state. However the original sediments were not oxidized at the time of deposition. The iron-oxide staining now so prevalent is attributed to postdepositional diagenetic changes involving the oxidation of mafic minerals such as hornblende, biotite, and possibly magnetite (Morey, 1967).

The underlying Thomson Formation consists predominantly of graywacke, siltstone and slate, but appreciable thicknesses of carbonaceous and pyritic slate and lesser thin to thick units of mafic tuff, mafic lava, and coeval hypabyssal sills and dikes are present locally. Abundant carbonate concretions, particularly in the argillaceous units, also characterize the formation.

The Thomson Formation is intensively folded; the folds vary from broad, open, symmetrical folds in graywacke to tight, asymmetrical, overturned folds in the less competent slate units. The larger folds trend about N. 85° E., appear to plunge gently to moderately in that direction, and can be traced for distances of several kilometers.

Both normal and reverse faults are common in the Thomson Formation, but most of them have displacements of a few meters or less. The normal faults commonly strike N. 30° E. whereas the reverse faults strike approximately N. 85° E., a direction approximately parallel to a well-developed slaty cleavage. The Thomson Formation also is characterized by a well-developed joint system; one set strikes approximately N. 30° E., whereas the conjugate set strikes N. 30° W. This system probably formed in response to a north-south compressional stress at the time of folding. The northeast-trending joint set is occupied at least locally by diabasic gabbro dikes of Keweenawan age, whereas the northwest-trending set is commonly brecciated and filled with quartz and calcite, much impregnated with pyrite.

The relative proportions of graywacke, siltstone and slate vary without regard to stratigraphic position. Typically, the coarser grained units tend to occur in packages separated by fairly thick intervals of slate. Because the thick slate sections weather and erode more rapidly than either of the coarse-grained rocks, they form surfaces of low relief. Consequently most exposures occur in graywacke- and siltstone-abundant parts of the formation. However, exploration drilling has delineated several thick layers of carbonaceous slate, and these layers can be traced for distances of several kilometers by available geophysical data. Therefore, carbonaceous slate may be a fairly abundant constituent of the Thomson Formation.

The carbonaceous slates are very fine grained and contain as much as 20 percent carbonaceous material, generally in the form of disordered graphite. All the carbonaceous units contain minor to abundant amounts of quartz and feldspar; in some units, the detrital minerals occur as discrete beds or laminae, whereas in others they are dispersed throughout.

All of the available evidence indicates that the Thomson Formation records a period of deep-water sedimentation characterized by hemipelagic sedimentation periodically interrupted by southward-flowing turbidity currents which deposited thin to thick beds of feldspathic graywacke and siltstone (Morey and Ojakangas, 1970).

Rocks of both sides of the unconformity between the Fond du Lac and Thomson Formations have all of the geologic criteria associated with the unconformity-related vein-breccia deposits [class (710) deposits described by Mathews, 1978d] summarized in Table 4. Furthermore, hydrogeochemical sampling in the area (Morey and Lively, 1980) has defined a number of anomalous areas that occur in the Thomson Formation along a broad band about 8 km wide that more or less parallels the inferred Thomson-Fond du Lac unconformity.

Several of the hydrogeochemical anomalies parallel the direction of bedding in the Thomson Formation and at least one corresponds to the syngenetic, uranium-rich phosphate layers described previously. Other hydrogeochemical anomalies trend in a northwesterly direction, and again at least one of these anomalies is coincident with a fracture zone that has above-average radioactivity readings and uranium values of around 18 ppm U_3O_8 (Ojakangas, 1976). It is the potential for deposits of the vein-breccia type in the northwest-trending fractures that has stimulated much of the exploration activity in the area.

The coincidence of hydrogeochemical anomalies (Morey and Lively, 1980) with several anomalous aeroradioactivity values previously recognized by Neuschel (1969) implies that the Hinckley Sandstone north and east of Mora in Kanabec County also may be a favorable site for unconformity-related uranium deposits of the vein-breccia class. In this area the Fond du Lac and Hinckley formations unconformably overlie granitic rocks, dip 10 degrees or so east, and thicken from a feather edge near Mora to more than 1,700 m along the Douglas fault 35 km southeast of Mora. The area is broken by at least two northwest-trending faults that were active as recently as St. Croixan time. At least one of these faults is a major rift structure with at least 1,000 m of pre-Fond du Lac-Hinckley displacement.

The Hinckley Sandstone consists almost entirely of thick-bedded to very thick bedded, quartzose sandstone. Nonetheless, gritty and conglomeratic beds with clasts as large as 8 cm in diameter of quartzite, vein quartz, chert, felsite and granite occur locally--as in outcrops about 3 km north of Mora--as do thin beds of quartz-rich mudstone.

The Hinckley detritus is predominantly medium to coarse grained. The grains are generally moderately to well rounded, and sorting varies from poor to moderate. The average framework composition is about 96 percent quartz, 2 percent feldspar, and 2 percent felsic volcanic rock fragments, metamorphic rock fragments and chert (Tryhorn and Ojakangas, 1972). Quartz cement is ubiquitous, but a carbonate cement occurs locally, as does a sparse clay fraction composed of illite and kaolinite. Outcrops are stained by iron oxides which were deposited both before and after deposition of quartz cement. Accessory minerals include well-rounded grains of zircon, tourmaline, rutile, and garnet (Tryhorn and Ojakangas, 1972), as well as locally abundant amounts of leucoxene, ilmenite, and pyrite (Tyler and others, 1940).

The mineralogic maturity of the rock, the rounding of the grains, and the presence of some reworked quartz grains having abraded overgrowths (Tryhorn and Ojakangas, 1972) imply that older sandstones provided much of

Table 4. Comparison of geologic characteristics of the Thomson-Fond du Lac unconformity with characteristics of class (710) deposits

Characteristic	Model class (710) deposits (Mathews, 1978)	Thomson-Fond du Lac unconformity
1. Tectonic setting	Stable craton.	Stable craton.
2. Kind of unconformity	Erosion surface where terrestrial sediments overlie metamorphic complexes.	Fond du Lac fluvial in origin. Subjacent Thomson Formation metamorphosed from the greenschist to the amphibolite grade.
3. Lithology	Upper sequence: Typically orthoquartzitic to feldspathic fluvial sandstones marked by high degree of textural and mineralogical maturity. Commonly less well sorted, less mature near base which may be conglomeratic.	Fond du Lac: Possesses all criteria of model upper sequence.
	Older metamorphic complex: Lithologic details are not significant except presence of reductants. Graphitic, chloritic, sulfide-bearing schists associated with larger uranium deposits.	Thomson: Extensive areas where carbonaceous, sulfide-bearing beds are present.
4. Age	Major deposits associated with Proterozoic unconformities.	Proterozoic (probable age of Fond du Lac in 1,100 to 900 m.y. range).
5. Structure	Very mild deformation of upper sequence; reactivated basement faults occur near uranium deposits.	Fond du Lac is undeformed. Faulting in Fond du Lac appears to be of reactivation type.
6. Apparent requirements for U deposition (epigenetic model)	A. Moderately uraniferous source rocks in basement or within sedimentary section.	A. Thomson and Fond du Lac Formations are adequate source rocks.
	B. Circulation of oxidizing ground water to dissolve uranium from source rocks.	B. Fond du Lac is a red-bed sequence indicating oxidizing conditions.
	C. Channelways and appropriate barriers to concentrate ground-water flow typically just below unconformity.	C. Minor faults known above unconformity; suitable channelways well developed in Thomson Formation.
	D. Local reducing environments to cause precipitation of uranium from oxidizing solutions.	D. Reducing environments abundant in Thomson Formation.
7. Mineralization	Pitchblende in veins, breccias, fracture fillings.	Low-grade uranium mineralization in fracture zones.

the detritus now found in the Hinckley Sandstone. Because medium-scale cross-bedding is common and current ripple marks are present, Tryhorn and Ojakangas (1972) inferred that the Hinckley was formed by the reworking of the feldspathic Fond du Lac Formation in a stable, shallow-water lacustrine environment.

The hydrogeochemical radioactivity anomalies in the Hinckley Sandstone near Mora are somewhat surprising, given the mineralogical and textural maturity of the formation and its apparent lack of indigenous uranium. Nonetheless, most of the geologic criteria necessary to the formation of an epigenetic vein-breccia deposit are present near Mora. These include (1) an oxidized permeable medium capable of transmitting an abundant flow of greatly oxygenated uranyl-rich solutions, above and in contact with (2) a more reduced medium with less oxidizing or with reducing waters, both penetrated by (3) channelways sufficiently developed to permit mixing of the diverse waters at some stratigraphic level. For example Hoeve and Sibbald (1978) suggest that ore bodies of reduced uranium species near the base of the mainly oxidized Athabasca Formation in Canada were precipitated by the interaction of oxidized, uranyl-rich water from above with reduced water from below. Because carbon dioxide and methane occur in the ores of the Athabasca Formation and because some of the graphitic units unconformably beneath the Athabasca Formation appear to have been decomposed, Hoeve and Sibbald suggest that the gases were formed by "hot" waters interacting with the carbonaceous strata.

Although there is no evidence of hydrothermal activity or of carbonaceous strata beneath the Terrane V sandstones in the Mora area, this model is pertinent because the precipitation of reduced uranium species is dependent only on the intermixing of reduced and oxidized waters. Thus, mineralization can occur beneath, along, or above an unconformity, depending on the nature of the hydrologic flow regime. Therefore, it is suggested that in the Mora area, the percolation of oxidizing solutions in the Keweenawan sandstones led to the intrastratal leaching of uranium. At the same time, the major northwest-trending faults provided access for the ground waters to great depths where they were locally reduced. Subsequently, both solutions interacted with each other to precipitate at least small quantities of reduced uranium species.

Terrane VI - Paleozoic Rocks

Paleozoic rocks of Late Cambrian, Early and Middle Ordovican and Late Devonian age underlie a large part of southeastern Minnesota where they define a broad southward-plunging syncline that corresponds to a depositional basin called the Hollandale embayment (Austin, 1972). Middle Ordovician rocks also occur in northwestern Minnesota where they define the eastern edge of the Williston basin (Webers, 1972).

The rocks of Terrane VI were deposited after a prolonged period of crustal stability, planation, weathering and leaching had led to the local development of residual soils of variable thickness and distribution. Much of Minnesota was covered by an epicontinental sea in Late Cambrian time that encroached from the south and east. Upper Cambrian sedimentary rocks deposited in this sea include texturally and mineralogically mature, medium- to coarse-grained, quartzose to locally glauconitic sandstones with intercalated thin beds of shale or various kinds of chemically precipitated limestone and dolomite. Abundant fossil fragments and a variety of sedimentary structures indicate that the clastic rocks were deposited in a high-energy environment, most likely along a transgressing strandline. The intercalated carbonate rocks also were deposited under shallow-water conditions presumably either some distance away from the shoreline of the epicontinental sea or during periods of time when the influx of clastic detritus was diminished. The Ordovician strata in southeastern Minnesota record the continuation of basically the same sedimentological regime except for a marked abundance of limestone and dolomite which were deposited as complex biohermal bank assemblages that developed under shallow-water, marine conditions. From time to time the carbonate banks were affected by interludes of clastic sedimentation, resulting in thin, generally restricted sandstone and shale beds within the dominantly carbonate sequence.

Upper Cambrian and Lower Ordovician rocks either were not deposited or were eroded prior to the deposition of Middle Ordovician strata in northwestern Minnesota. However, the similarity of the Middle Ordovician rock record in northwestern Minnesota to that in southeastern Minnesota, suggests that the two areas may once have been interconnected (Webers, 1972). Subsequent emergence of the Transcontinental Arch, diagonally across the state from southwestern to northeastern Minnesota, would have led to the removal of most of the possibly intervening strata. The bounding edges of the Hollandale embayment and the Williston basin are erosional unconformities rather than depositional strandlines.

After another prolonged period of emergence and erosion, southern Minnesota--particularly along the axis of the Hollandale embayment--was transgressed from the south in Late Devonian time by an epicontinental sea. The resulting Devonian strata are dominantly limestone and dolomitic limestone deposited under shallow-water conditions (Mossler, 1978).

Uranium Potential

The residuum that underlies the Upper Cambrian sedimentary rocks in southeastern Minnesota has no potential as an environment for uranium deposits. Kaolinite and well-ordered illite occur in the upper part of the residuum, but these minerals decrease in abundance downward and are replaced by mixed-layer illite/montmorillonite, with trace amounts of quartz, feldspar and biotite near the residuum-bedrock interface (Morey, 1972b). Clearly any uranium that was originally present would have been removed by weathering and leaching processes at a time when Minnesota stood as a positive area.

Although the Paleozoic sandstones are highly permeable units affected by complex three-dimensional ground-water circulation, they are for the most part cleanly washed, mineralogically mature, end-cycle marine units that lack reducing horizons. Thus they do not appear to represent suitable environments for the deposition of epigenetic uranium deposits. In southeastern Minnesota, primary current structures indicating sediment transport from the north and northeast suggest that the detritus was derived from Terrane V sedimentary rocks, or from previously weathered, older Precambrian rocks. Furthermore, a careful search at several places for beach placer deposits [class (110) deposits as described by Jones, 1978b] has yielded negative results.

Lastly no favorable criteria for uranium concentration have been recognized in any of the Paleozoic carbonate rocks in Minnesota.

Terrane VII - Mesozoic Rocks

There is no depositional record in Minnesota of events between Late Devonian time and the Early Jurassic deposition of nonmarine red beds and associated gypsum in several southwest-trending valleys that had been cut into Ordovician and older rocks in northwestern Minnesota (Mossler, 1978). Subaerial weathering in much of Minnesota lasted from sometime in the Devonian until the Late Cretaceous. Parham (1970) concluded that most of the weathering took place in the earlier part of Late Cretaceous time, but the evidence is permissive rather than conclusive; the weathering may have started in Jurassic time.

Upper Cretaceous sedimentary rocks underlie much of southwestern Minnesota and occur as scattered outliers in southeastern Minnesota and northern Minnesota (fig. 1). The section includes a basal sequence of terrestrial to coastal origin and an overlying marine sequence that was deposited in an eastward-transgressing epicontinental sea on a surface with relief of as much as 100 m (Sloan, 1964). The basal beds are quartz-kaolin shales and sandstone derived locally from the subjacent weathered residuum. In places they are overlain by a thin layer of generally iron-rich, kaolinitic, pisolitic clay. The pisolitic units and subjacent kaolinitic sediments were dissected by a network of west-flowing streams, and the resulting channels were filled with a heterogeneous assemblage of organic-rich clay, variegated shale, and lignite. As the marine shoreline transgressed from west to east, the terrestrial rocks were overlain by marine sandstone, siltstone and shale.

Most of the Cretaceous units are thin and generally poorly indurated; consequently they were easily eroded after emergence and now form an erosionally dissected blanket characterized by numerous smaller outliers. Because of extensive pre-Quaternary erosion, the thickness of the Cretaceous strata varies widely, owing both to deposition on an uneven surface and to postdepositional erosion. Maximum thickness occurs along the western edge of Minnesota where 200 m to 300 m are preserved.

Uranium Potential

The Jurassic rocks in northwestern Minnesota have little potential for syngenetic uranium deposits. Any uranium indigenous to these rocks would have been oxidized and leached by circulating ground waters. Because these rocks appear to lack reductant beds, they are not favorable sites for epigenetic deposits.

The thick mantle of weathered Precambrian rocks that underlies Cretaceous sedimentary beds throughout much of western Minnesota has no potential as an environment for uranium deposits. The residuum consists almost entirely of kaolinite with lesser amounts of halloysite scattered throughout, and muscovite, illite, and montmorillonite in proximity to the residuum-bedrock interface (Parham, 1970). Any uranium originally present would have been removed from these rocks by weathering processes. The presence of this weathered zone is significant, however, because uranium leached away may have been concentrated in suitable sedimentary environments marginal to and within the Cretaceous depositional basin, and such deposits may be present in overlying Cretaceous strata. The degree to which this process may have operated, however, is strongly dependent on the timing of the weathering with respect to marine transgression, and also on details of the then prevailing hydrogeochemical system.

The Cretaceous sedimentary rocks and the unconformity beneath them represent a potentially favorable environment for uranium deposits. Consequently the Department of Energy drilled a number of exploratory holes along the Red River Valley between Minnesota and North Dakota (Moore, 1979). The results of this study were discouraging. Only a few scattered uranium occurrences were recognized. None appear to have much economic significance --they contain no more than about 20 ppm U_3O_8.

Moore (1979) has pointed out that the present ground-water regime is inappropriate for the concentration of uranium. Recharge of brackish or saline waters in the Cretaceous strata is away from the center of the Williston basin toward the basin margin in Minnesota, and apparently has been in that direction since the Black Hills were uplifted in early Tertiary time. This ground-water flow pattern significantly reduces the uranium favorability of the area because westward recharge by oxidizing and potentially uranium-bearing solutions from the Canadian Shield into potential host sandstones along the Williston basin margins has not occurred since the present flow regime was initiated. This, however, should not entirely exclude the area from further consideration, for the presence of a deep channel system at the basin margin, which possibly sloped southwestward just before deposition of Jurassic strata, suggests a potential for westward slopes and basinward flow of ground water during this and perhaps earlier periods of time. Consequently, the possibility of paleo-uranium deposits in the Cretaceous strata should be evaluated more completely before the area is entirely discounted as having no uranium deposits.

Moore's (1979) study along the Red River Valley is not entirely applicable to the remainder of the Cretaceous strata in Minnesota, and the favorability of much of the Cretaceous section has been neither demonstrated nor disproved. Although widely distributed in Minnesota, the Cretaceous strata are exposed at only a few places (fig. 2), and subsurface information indicates that these exposures are not particularly representative. However, the existing subsurface data are totally inadequate for properly evaluating the favorability of the Cretaceous strata. Only a few sets of water-well cuttings are available as direct evidence on Cretaceous rock types, and these are of poor quality. Descriptive logs prepared by water-well drillers comprise the principal data base for mapping Cretaceous bedrock in the subsurface. From the water-well driller's point of view, there is little difference between gray till of Pleistocene age and gray shale of Cretaceous age, and many interpretations in the logs are ambiguous. Although a considerable amount of hydrogeochemistry has been done over Cretaceous bedrock, this ambiguity also handicaps the interpretation of ground-water geochemistry because it is uncertain in many cases whether a given ground-water sample is from a Cretaceous or a Quaternary aquifer. Consequently the Cretaceous rocks of Minnesota should be considered as an unevaluated environment at this time because of a totally inadequate data base (see Southwick and others, 1981; Morey and others, 1981).

Terrane VIII - Quaternary Deposits

Much of Minnesota is mantled by a thick and nearly ubiquitous cover of Pleistocene surficial materials that include multiple layers of glacial till interstratified with various kinds of outwash and glacial lake deposits. Additionally many parts of the state are covered by Holocene lake deposits, having substantial quantities of peat and marl (for a summary see Wright, 1972 and Goebel and Walton, 1979).

Uranium Potential

The Quaternary materials appear to differ regionally in uranium content and other hydrogeochemical parameters (ORGDP, 1978, 1979a, 1979b, 1979c, 1981a, 1981b, 1981c; Morey and Lively, 1980). In general, ground waters from tills derived from Cretaceous and related strata in western Minnesota contain more dissolved uranium than the waters from tills in northeastern and east-central Minnesota that were derived from Precambrian igneous and metamorphic rocks. These differences, however, reflect complex mixing of source-rock components in the various till units rather than a coherent mineralizing process, and there is no reason to believe that the Quaternary deposits of Minnesota have any potential for uranium deposits.

DISCUSSION

Several environments in Minnesota have a geologically reasonable potential for uranium deposits of one kind or another. It should be emphasized, however, that all of the environments described above, at least as presently known, contain uranium values far below the average grade of known production areas. Furthermore, geologic exploration elsewhere in the world has demonstrated that most so-called "favorable environments" do not contain uranium occurrences of commercial size or grade. Undoubtedly this also will be true of the favorable environments recognized at this time in Minnesota.

Most of the so-called favorable environments occur in that 10 percent of the state where the bedrock is at or near the surface (fig. 4). There is no reason to believe that the remaining 90 percent of the state does not contain an equal or greater number of potentially favorable environments. However, exploration for any kind of a deposit where the Quaternary materials are thick is at best difficult, and at worst, impossible. This is particularly true of exploration for uranium. Despite extensive hydrogeo-

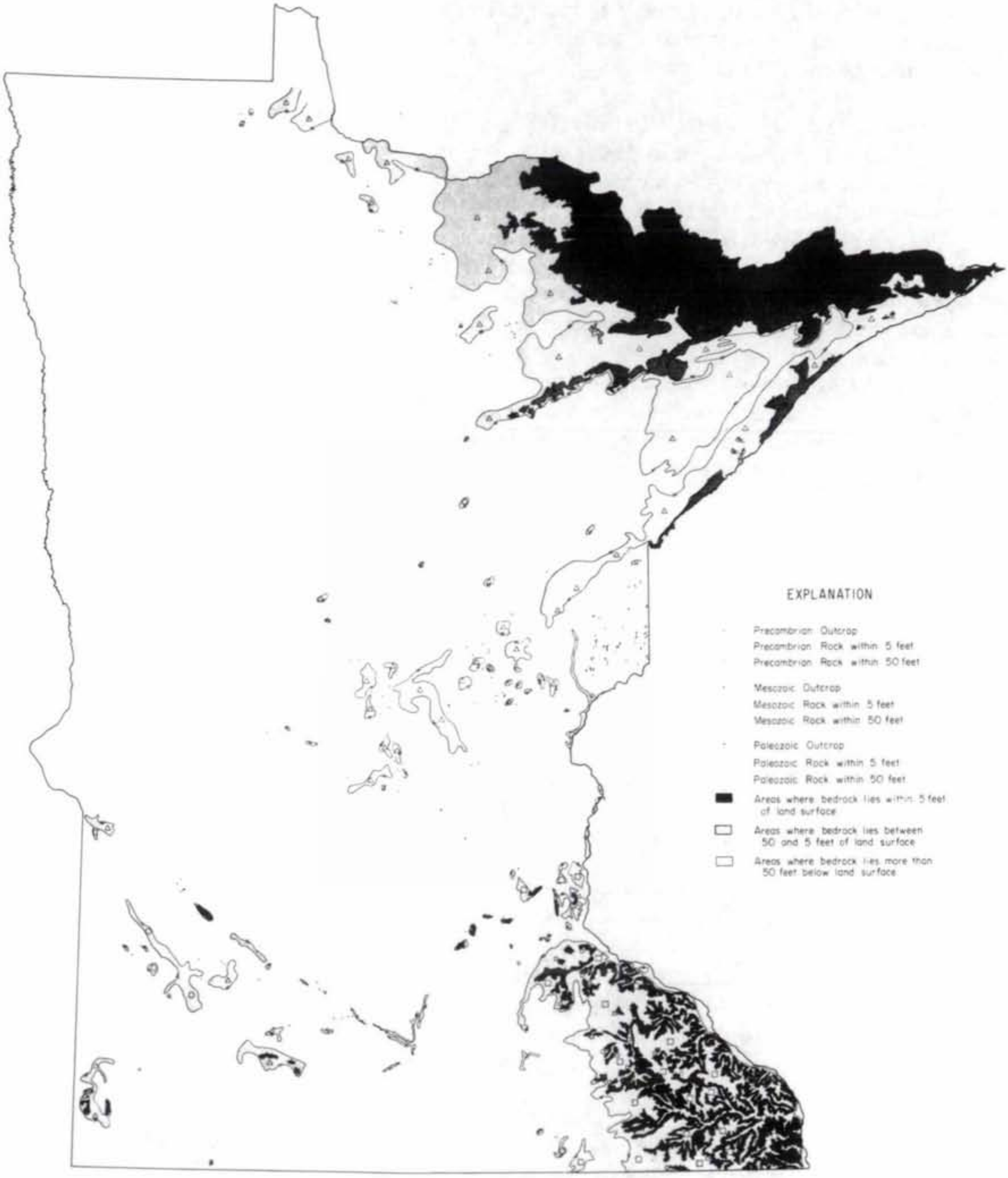

Figure 4. Generalized map showing the distribution of bedrock exposures in Minnesota (modified from Morey, 1981).

chemical surveys (ORGDP, 1978, 1979a, 1979b, 1979c, 1981a, 1981b, 1981c; Morey and Lively, 1980), no potentially favorable environments have been recognized in areas where the Quaternary deposits are more than 20 m thick. Furthermore aeroradiometric surveys in such areas (geoMetrics, 1979) have detected only small anomalies that reflect either local variations in the composition of the Quaternary materials or culturally induced features such as roads and plowed fields.

Relationships between the bedrock geology and the anomalies detected in hydrogeochemical surveys are difficult to establish and assess. Most of the ground-water samples that have been analyzed to date by the Department of Energy were collected from water wells finished in Quaternary deposits, and all of the stream-sediment samples were from streams flowing over Quaternary deposits. Substantive hydrologic data on the degree of interconnection between ground water in the bedrock and in the Quaternary deposits, and on the details of geochemical association between bedrock and overlying drift are lacking. The hydrogeochemical results, except for very specific areas, are therefore ambiguous indicators of real concentrations of uranium beneath the Quaternary cover (for example see Lively and Morey, in press). Exploration in the drift-covered areas of Minnesota requires new and innovative techniques, a requirement which presents a challenge that will persist for some time into the future.

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