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Empirical recognition criteria for unconformity-type uranium deposits applied to some proterozoic terranes in the United States

By

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EMPIRICAL RECOGNITION CRITERIA FOR UNCONFORMITY-TYPE URANIUM DEPOSITS APPLIED TO SOME PROTEROZOIC TERRANES IN THE UNITED STATES[1/]

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INTRODUCTION

Ore is where you find it, so they say, and often the find is pure luck. Some unconformity-type deposits were found in uranium exploration programs with other environments in mind (Rabbit Lake, Cluff Lake, and Key Lake, Saskatchewan and Koongara, Northern Territory). Ranger, N.T. was found on a concession aquired for base-metal exploration. Serendipity works, but how do we in the United States improve the odds of finding new deposits now that we can review a decade of experience and dozens of discoveries in Australia and Canada? Models of many types are being developed today--what approach is best for these complex deposits? My conclusion is that in 1981 there is insufficient definitive information on ore-formation processes to formulate reliable genetic models. Until additional deposits and districts are mapped, and diagnostic laboratory studies completed, I favor use of generalized empirical geologic criteria for prospecting and resource evaluation so that possibly favorable terrane will not be prematurely eliminated.

Strategies for mineral evaluation are highly varied, and terms used are vague due to broad usage (e.g. Ruzicka, 1977, Wright, 1979, Finch and others, 1980). Some comments on terms, as I use them, are required because the limitations and merits of any system cannot be appreciated unless the terminology and underlying philosophy are understood. Numerous discussions with knowledgeable persons over the past few years indicate that terms such as "empirical", "geologic", and "genetic" have subtle differences of meaning.

1/ Text to accompany a talk delivered at the USDOE/USGS/BFEC Uranium Geology Symposium, Golden, Colorado, May 5, 1981.

Evaluation schemes are based on at least four approaches (fig. 1). The starting point for most approaches is field observations, which initially are relatively free of interpretation. An opposite approach is through concepts, often based on little information. Between these two opposite approaches are methods that emphasize observed and interpreted physical geology (ore habitat) or physico-chemical conditions of ore formation (ore-forming processes). It is important to recognize that habitat can be observed, although the relationship of ore to features commonly is moot, whereas ore processes cannot be directly seen in the field, but their record in isotopes and fluid inclusions can be direct evidence of conditions of ore formation. I believe the term "geologic" should be applied to the habitat side of the diamond (fig. 1), and "genetic" should be used for the ore-forming processes part. Ideally, and ultimately, thinking and modelling encompasses all four approaches. I add the modifier "empirical" to "geologic" to note emphasis on observations rather than interpretations. The advantage of the empirical geologic method is that it is relatively objective and generalized, but it has the disadvantage of being nonspecific--thus non-essential features probably are included. Finally, I present a list of criteria, not a model, because no systematic relationship of cause and effect has been established. Comments are offered on possible roles for individual criteria to explain the choice, but the criteria are not presented as a geologic or genetic system.

Scale is an important consideration in evaluation strategy. The first step toward identifying unconformity-type deposits in the United States is to locate favorable regions of about 1,000 to 10,000 km^2 in size. This size is approximately the scale of National Uranium Resource Evaluation (NURE) quadrangle investigations that effectively used 1:250,000 base maps. The criteria I propose are for a first evaluation, and use, as much as possible, features shown on geologic maps of this scale plus regional geochemical or geophysical surveys. Follow-up investigations and drilling programs need more specific criteria and more detailed data sets.

The geologic habitat of unconformity-type deposits is shown schematically on figure 2. Basement rocks are Archean granitic rocks (no. 1, fig. 2). Unconformably overlying the basement is several thousand feet of Proterozoic sedimentary rocks (no. 3, fig. 2), that are infolded and metamorphosed with the basement (no. 4). The metamorphic rocks were retrograded to greenschist

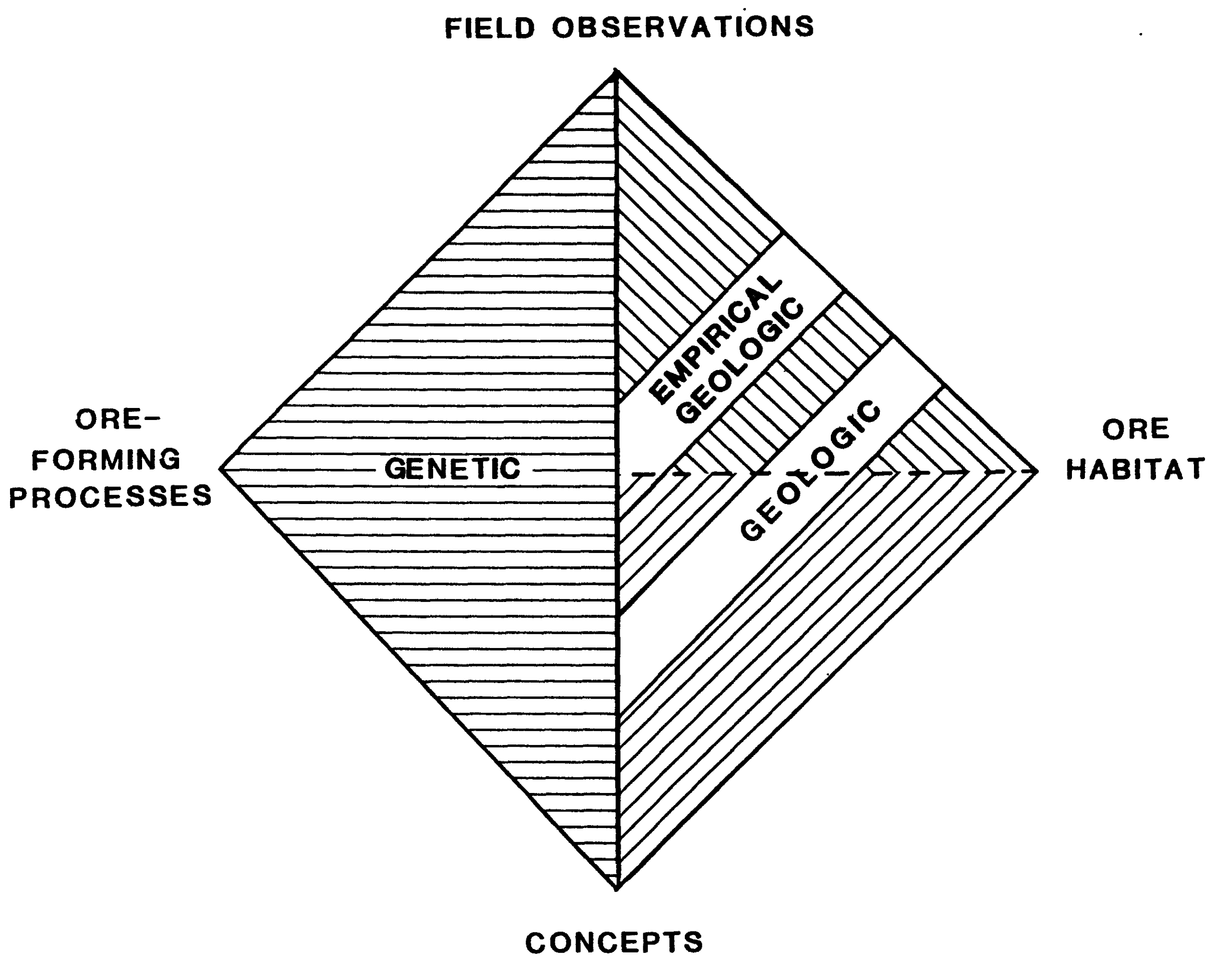

Figure 1.—Schematic diagram of relations between four approaches to resource evaluation. Geologic models emphasize physical, geologic features that can be seen in the field, whereas genetic models emphasize physicochemical conditions that cannot be seen.

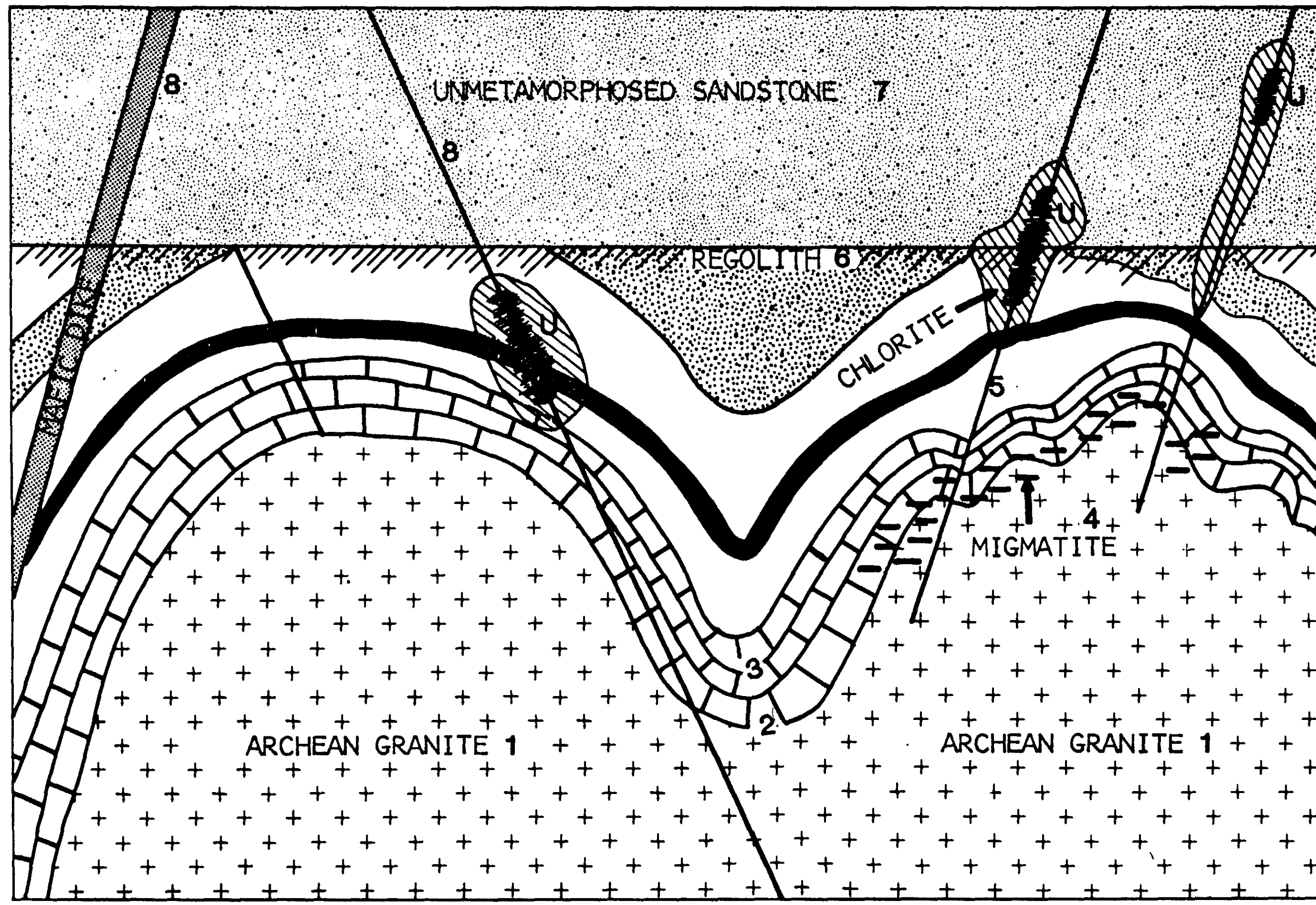

Figure 2.—Schematic cross section showing geologic habitat of unconformity-type uranium deposits. Numbers correspond to criteria in Table 1 and discussed in text. No scale.

grade along fault zones (no. 5), some of which contain ore. Following erosion, the metamorphic rocks were covered by sandstones (no. 7), which later were faulted and intruded by mafic dikes (no. 8). Known uranium deposits are in either metamorphic rocks or sandstone near the unconformity. More detailed information is given by Dahlkamp (1978), Hegge and Rowntree (1978), and Hoeve and Sibbald (1978). Reviews by Kalliokoski and others (1978), Eupene (1980), Nash (1981), and Dahlkamp and Adams (1981), offer additional information and speculation.

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EMPIRICAL RECOGNITION CRITERIA

Eight features observed in the deposits discovered to date in the Northern Territory and in Saskatchewan are proposed as recognition criteria (Table 1). They are arranged in order of decreasing age but are not ranked to avoid bias. Insofar as possible, the criteria are only descriptive, and none have been proven to have been factors in the formation of an orebody. Also, I believe that an orebody can form with one or more of the criteria lacking, but it would probably be of lower grade or tonnage.

Table 1.--Empirical Recognition Criteria for unconformity-type deposits.
[Criteria are numbered in order of decreasing age]

8. Post-cover rock deformation
7. Covering sandstone
6. Paleosurface
5. Retrograde metamorphism
4. High-grade metamorphism
3. Supracrustal metasediments
2. Pre-metamorphic unconformity
1. Granitic basement

1. Granitic basement.--Granitic rocks, commonly in the form of reactivated gneiss domes, occur near the known deposits and probably were the source of clastic material making up the host rocks and also probably were the ultimate source of uranium. Some of these granitic rocks have anomalous uranium content. Basement granitic rocks in Northern Territory and in Saskatchewan are Archean, but I see no geochemical reasons why younger granite or rhyolite could not serve a similar role.

2. Pre-metamorphic unconformity.--There are two unconformities in the rock sequences that contain the known deposits, but the unconformity on granitic basement tends to be ignored. This unconformity establishes age relationships, and allows possible uranium enrichment during erosion and sedimentation.

3. Supracrustal metasediments.--The rocks containing or underlying the known deposits are, in a most general sense, supracrustal Proterozoic rocks as defined by King (1976, p. 72) as: "sedimentary and volcanic rocks that were laid down on the surface of the Earth, on a basement of rocks that had a more complex metamorphic and plutonic history." Many of these rocks in the type areas have been interpreted to be marginal-marine sequences (Nash, 1980). There is permissive evidence for uranium preconcentration during the diagenesis of the marginal-marine sequences. Carbonate rocks, commonly magnesian and containing algal structures, interbedded with carbonaceous pelites and

evaporites or sebkha facies, are a key to recognizing these rocks in the field or literature. Sedimentation probably occurred in intracratonic rifts characterized by gradual extension.

An additional attribute that many workers specify is an early Proterozoic age for the supracrustal rocks, because this is the age of rocks in the known districts. There are plausible reasons for this relationship, such as the unique, newly oxygenated ground water about 2.2 to 1.8 b.y. ago. However, there are several examples of much younger black shales that contain significant amounts of uranium. I know of no geochemical reasons for a change in the reactions of uranium over the period of about 2.2 to 0.4 b.y. ago. Thus, I conclude that restricting the search to supracrustal rocks of early Proterozoic age could eliminate some potentially favorable younger terrane.

4. High-grade metamorphism.--Amphibolite- or granulite-grade metamorphism is characteristic of the known districts. During the metamorphic event, the basement granitoid rocks rose, and the covering supracrustal rocks were partially melted onto the granitic cores. The behavior of uranium during the metamorphism is essentially unknown. Uranium may have been mobilized in the vicinity of the gneiss domes and migrated outward into sites of redeposition, or possibly it remained essentially in situ but was separated from carbonaceous material to form reactive uranium phases, making the schists "fertile", analagous to "fertile granites." However, some unconformity-type deposits do occur in lower grade metamorphic terrane, as at Rum Jungle, Northern Territory, and these deposits tend to have lower tonnage.

5. Retrograde metamorphism.--The known deposits typically are in zones of penetrative deformation and retrograde metamorphism. Magnesium metasomatism is characteristically developed in and around the deposits, as shown by chlorite, magnesite, and other magnesium minerals. The deformation tends to follow graphitic beds. Electromagnetic methods, especially airborne EM, can detect the sheared and altered zones to a depth of about 200 m if covering rocks are not highly conductive.

6. Paleosurface.--The empirical association of deposits with unconformities, and hence the unfortunate name for this class of deposits, now is highly

debated. The preliminary evidence of the early 1970's suggested to many geologists that the deposits formed by supergene processes operating below the paleosurface. Then new information indicated that some deposits, such as Key Lake and Midwest Lake, Saskatchewan occurred both below and above the unconformity, and others, such as Collins Bay, Saskatchewan, occurred entirely above the unconformity. Also, it was appreciated by some that other deposits, such as Koongara No. 2 and Jabiluka Two, Northern Territory, and Eagle Point, Saskatchewan, show little or no relation to the overlying unconformity. Some deposits, such as Michelin, Labrador, and Oklo, Gabon, which have features in common with unconformity-type deposits, are in sequences lacking unconformities. My conclusion is that these deposits can form without processes operating at the paleosurface. In concept, supergene enrichment can upgrade the ores, and chiefly for this reason, the paleosurface criterion is included. The zone immediately below the unconformity should not be given as much attention as most workers advocate; a zone about 500 m thick above and below the unconformity should be examined, and fault zones in the supracrustal sequence having no spatial association with the unconformity also should be considered.

7. Covering sandstone.--The known deposits show a clear spatial relation to overlying or hosting unmetamorphosed sandstones. Some workers (e.g. Kalliokoski and others, 1978) specify that the sandstone must be non-marine. I prefer to think of the cover rock as an aquifer, so its genesis is not as important as its physical character. This interpretation leads me to consider other types of aquifers that are capable of introducing oxidizing ground water that can upgrade uranium derived from the supracrustal sequence. Sandstone as an aquifer is a plausible explanation for the association of known deposits with large sandstone bodies in broad basins of more than 50,000 km^2.

8. Post-cover rock deformation.--In the known districts, the covering sandstones have undergone little deformation but are locally cut by high- and low-angle faults. These faults contain ore in several places and, in general, are probably reactivated faults. These young faults appear to focus remobilization of uranium and permit uranium transport into the sandstone from underlying supracrustal rocks. Mafic dikes occur in or near many of the

deposits, and in the Athabasca Basin are the same age as a stage of uranium minerals. The dikes seem important as heat sources for hydrothermal systems that remobilize and upgrade uranium concentrations. The mafic dikes are characterized by strong magnetic anomalies in airborne surveys.

The presence of uranium anomalies and occurrences might be another recognition criterion because uranium is a good guide to uranium deposits. On the other hand, near-surface uranium occurrences are normally highly oxidized, difficult to characterize, and generally are not a reliable guide to a specific type of uranium deposit. Further, the abundance of uranium occurrences has no demonstrated relationship to ore potential. Thus, I conclude that uranium occurrences can be both useful and misleading, and probably are not a reliable recognition criterion for the presence of a specific type of deposit.

APPLICATION OF RECOGNITION CRITERIA TO SOME PROTEROZOIC TERRANE

The United States clearly does not have large areas underlain by Proterozoic metamorphic rocks (within 1.5 km of the surface) (fig. 3), but several areas have been recommended as possibly favorable for the occurrence of unconformity-type deposits. Eight areas are considered in the Lake Superior region, northern Rocky Mountains, southern Basin-and-Range province, and central Appalachian region as a general illustration of how the criteria can be applied. As noted earlier, the criteria are not proven, and my knowledge of the areas under test is limited, hence the comments on favorability made here are certainly not final. Also, other types of uranium deposits not considered here may well exist.

1. Michigamme Formation and Jacobsville Sandstone.--In the Iron River $1^{\circ} \times 2^{\circ}$ quadrangle, Michigan and Wisconsin (Cannon, 1978; Frishman, 1981), basement rocks are Archean granite, granitic gneiss, and a variety of mafic metamorphic rocks. The unconformably overlying Michigamme Formation, was folded and metamorphosed (greenschist grade in the area of interest) 1.9 to 1.7 b.y. ago. Details of early Proterozoic sedimentation are lacking, but the known Michigamme lithologies are chiefly mafic volcanic rocks, metagraywacke, and slate. Iron-formations in the Michigamme are the volcanic (Algoma) type, not the shallow-water Superior type. No carbonates are reported from the

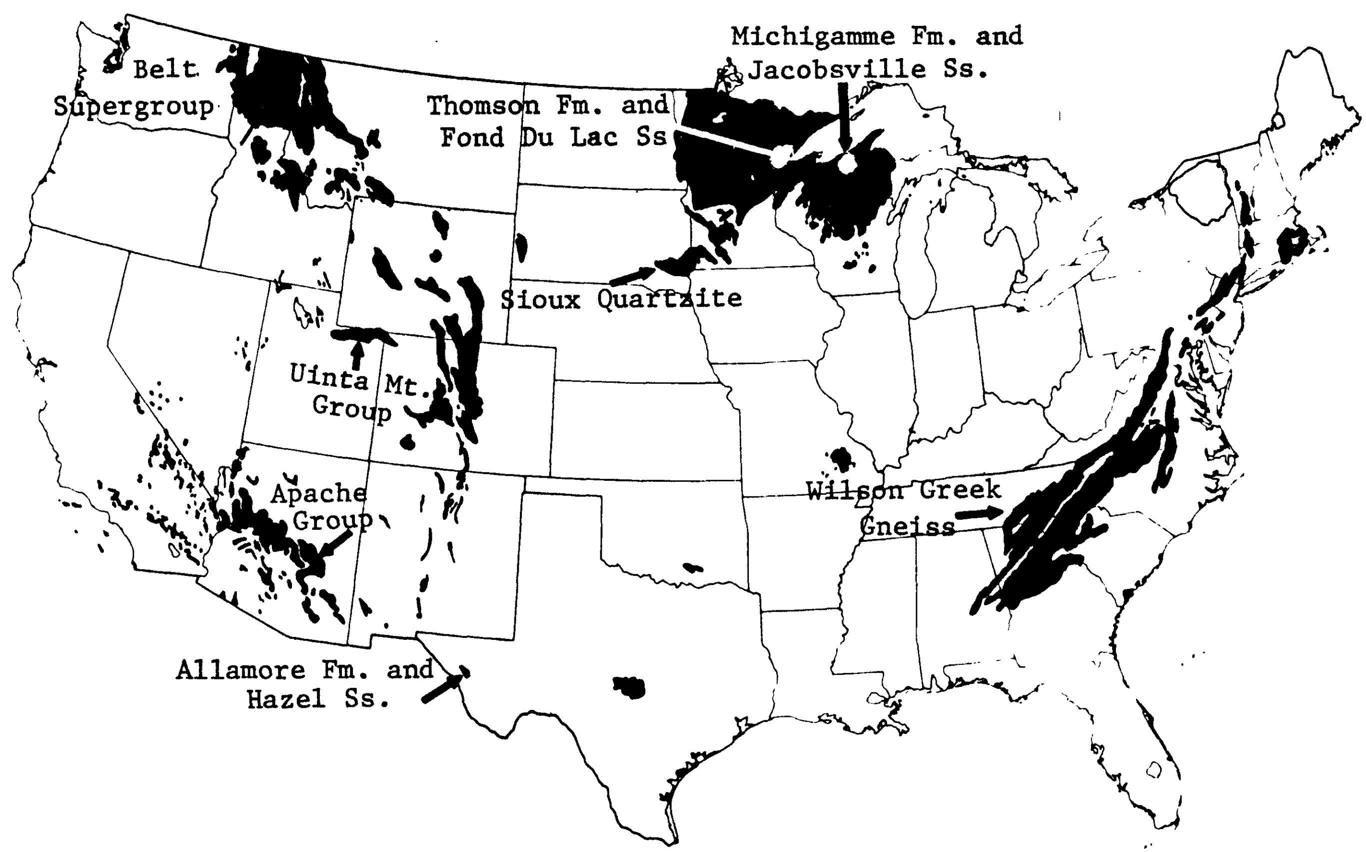

Figure 3.--Map of the conterminous United States showing distribution of exposed Precambrian rocks (from King, 1976), and the location of eight geologic sequences discussed in the text.

Michigamme. In the Iron River quadrangle, the Michigamme appears to have been deposited in the deep-water turbidite environment of the northeast-trending Animikie basin (Cannon and Klasner, 1975; Larue and Sloss, 1980). Thick mafic flows rest unconformably on the Michigamme along most of the sub-Jacobsville unconformity. The Jacobsville Sandstone, probably about 1.0 b.y. old, overlies the flows. Sedimentary structures and lithology of the Jacobsville closely resemble the Kombolgie and Athabasca Formations (Kalliokoski and others, 1978). Post-Jacobsville faults are rare, and no younger intrusive rocks were reported. The Jacobsville Sandstone is an aquifer, and several uranium occurrences are known near it, but other features of the Michigamme and Jacobsville do not fit the postulated criteria. Particular problems are the deep-water sediments in the Michigamme and the thicks flows between the supracrustal rocks and the sandstone.

2. Thomson Formation and Fond du Lac Sandstone.--In east-central Minnesota, basement rocks are the McGrath Gneiss, a pluton of Archean age, which is one of the most radioactive rock units in Minnesota (Ojakangas, 1976). The early Proterozoic Thomson Formation, unconformably overlies the McGrath. Most of the Thomson is metagraywacke, metasiltstone, and slate of turbidite origin (Morey and Ojakangas, 1970). However, at one locality southeast of Denham, Minn., more than 75 m of marble and quartzite are present and contain clasts derived from the McGrath Gneiss (Keighin and others, 1972). The Thomson was tightly folded and metamorphosed to green-schist facies 1.7 b.y. ago. The Fond du Lac Formation of late Proterozoic age unconformably overlies the Thomson, but nowhere is the unconformity exposed. The Fond du Lac is a permeable quartzose sandstone of fluvial-deltiac origin (Ojakangas, 1976) and is very similar to the Athabasca Formation of Saskatchewan (R. W. Ojakangas, written commun., 1980). A few faults cut the Fond du Lac, but all reported intrusive rocks are older than it. This sequence of rocks seems to meet only a few of the recognition criteria proposed here. If more shelf sediments could be identified on the flank of the McGrath Gneiss, those sediments would be more favorable for deposits than the typical deep-water metasediments of the Thomson.

3. Sioux Quartzite area.--The middle Proterozoic Sioux Quartzite of southwestern Minnesota and eastern South Dakota has attracted interest because its age, extent, and lithology resemble the Athabasca Formation (Ojakangas, 1976). Basement rocks, known from sparse outcrops and scattered wells, are mostly granite and mafic schist of probable Archean to early Proterozoic age (Lidiak, 1971). No supracrustal rocks, as defined earlier, are present. The sub-Sioux unconformity is nowhere exposed, but deep tropical weathering has been advocated to explain the aluminous clays in the Sioux. The Sioux is generally a very clean, well-sorted, thoroughly indurated quartzite, although some conglomerate and clay-rich beds occur locally. The Sioux was gently folded, and was intruded by some mafic dikes. The Proterozoic sequence in this area fits the recognition criteria very poorly. In particular, the pre-Sioux rocks do not resemble those in the productive districts, and the Sioux probably was too well cemented to be an aquifer in the Proterozoic (it is not one today).

4. The Belt Supergroup.--The middle Proterozoic Belt basin (Harrison, 1972) of the northwestern United States and the sedimentary rocks of the Belt Supergroup are, in many ways, the most similar to the productive areas that I know of. Several other aspects of the history of these rocks do not compare well with the productive areas, but some variations might be possible. Basement in several places is known to consist of pre-Belt granitic rocks about 1.5 b.y. old, and more are being identified as mapping and dating progress. The Belt basin has extent and facies reminiscent of the Pine Creek geosyncline, Northern Territory, expecially the abundant shallow-water sediments, including carbonates. Metamorphism of the Belt rocks in the Proterozoic was very low grade, but high grades were reached adjacent to some Cretaceous-Tertiary intrusions, such as the Idaho batholith. Several unconformities are in the section, and there are several covering sandstones such as the Cambrian Flathead Sandstone and Addy Quartzite in the eastern and western parts respectively of the Belt Basin. Perhaps we should look closely for uranium in a unit within the Belt such as the Wallace Formation, and particularly for evidence of remobilization or uranium in zones of contact metamorphism, which might be a possible variation on processes forming the type unconformity deposits.

5. Uinta Mountain Group.--Middle Proterozoic rocks in northeastern Utah are believed to have formed in a pericontinental basin similar to the Belt basin, but the shallow-water sediments typical of the Belt Supergroup are lacking (Crittendon and Wallace, 1973). The oldest rocks in the area are Archean metamorphic rocks of the Red Creek Quartzite (King, 1976). The overlying Uinta Mountain Group, of probable early Proterozoic age, is predominantly fluvial arkose and quartzite, and siltstone and shale of paralic-sublittoral deposition. No carbonate rocks are known. The Red Pine Shale, the uppermost formation of the Uinta Mountain Group, has a minimum age of 950 m.y. Rocks of the Uinta Mountain Group have very little in common with other productive districts.

6. Apache Group and Troy Quartzite.--Middle Proterozoic rocks in central Arizona may be favorable for uranium deposits having unconformity-type features, if the age and metamorphic characteristics of the Saskatchewan and Northern Territory deposits are not applied literally (a concept that I favor). The basement rocks are 1.4 b.y. and older granites, metarhyolites, and schists (King, 1976). The Apache Group (Shride, 1967) fits the supracrustal criterion very well, as it contains abundant shallow-water (or lacustrine) sandstones and algal carbonates. Metamorphism is very low grade. The Dripping Spring Quartzite of the Apache Group contains numerous deposits and occurrences (Granger and Raup, 1969), and the uranium in the upper part of the Dripping Spring has recently been interpreted as initially enriched during diagenesis (Nutt, 1981). The Apache Group was weathered but not deformed or metamorphosed prior to deposition of the middle Proterozoic Troy Quartzite. The Apache Group and Troy Quartzite were faulted and intruded by thick mafic dikes and sills about 1.2 b.y. years ago. The metamorphic-hydrothermal event produced by the mafic intrusions probably caused remobilization of uranium into some ore deposits. I agree with Nutt (1981) that events and processes in the Dripping Spring Quartzite were probably very similar to those in the type unconformity deposits. Major uncertainties are the effects of low metamorphic grade as compared to higher grades in the major deposit areas, and the role the Troy Quartzite might have had, if any.

7. Allamore Formation and Hazel Sandstone.--The Van Horn area of west Texas was investigated during the NURE program with uncertain results (Davidson and others, 1980). Application of the proposed recognition criteria to this area indicates that the sub-Hazel unconformity is a more likely locus for deposits than the younger sub-Van Horn unconformity. Although basement rocks and metamorphic grade of supracrustal rocks in this area do not resemble the productive areas, the late Proterozoic Allamore Formation contains talcose phyllite and dolomite that are similar to the supracrustal rock criterion. The late Proterozoic Hazel Formation, consisting of conglomerate, sandstone, and limestone, rests unconformably on the Allamore. Davidson and others (1980) reported uranium anomalies near the sub-Hazel unconformity but did not comment on the possible similarities to unconformity-type deposits as they seemed to be focusing on the younger unconformity at the base of the Proterozoic Van Horn Sandstone. The Allamore and Hazel sequence may warrant further study. This example illustrates how empirical recognition criteria can be used to interpret geochemical anomalies.

8. Wilson Creek Gneiss.--In the area of the Grandfather Mountain window in western North Carolina more than 20 uranium occurrences have aroused unusual interest for an eastern United States area, and there has been speculation that the occurrences may be in an unconformity-type environment. The occurrences are in basement rock, the approximately 1.0-b.y.-old Wilson Creek Gneiss, a pluton that has been extensively deformed (Bryant and Reed, 1970). Narrow fractures and cataclastic zones in the gneiss contain pitchblende and hexavalent uranium minerals with minor associated alteration. No supracrustal metasediments (in the sense used here) are known in the area. The basement rocks are overlain unconformably by poorly sorted conglomerate, arkose, and siltstone of the upper Proterozoic Grandfather Mountain Formation. I do not think that the rocks in this area fit the recognition criteria very well. The uranium veins, and associated graphite and phyllonite, are enigmatic (R. I. Grauch, oral commun., 1976) and of interest as indicators of possible additional uranium resources, but not of the unconformity-type.

CONCLUDING REMARKS

The empirical recognition criteria proposed here obviously need refinement and testing through additional research. The criteria seem to be useful for a general comparison of new areas with productive districts. However, literal application of empirical criteria can be misleading. Some of the criteria may be insignificant or sufficient, but those necessary for ore formation need confirmation. If the genesis of unconformity-type deposits involves many stages, and I believe it does, then what is the effect of missing a stage? Some missing stages probably would merely decrease grade or tonnage, but others might negate possibilities for ore formation altogether.

More specific criteria and integrated geologic models are needed, but until we truly understand these complex deposits we must be wary of dogmatic views based on preconceptions (F. J. Dahlkamp, oral commun., 1981). Better understanding should allow recognition of new variations on known deposits and suggest new, favorable terrane. One speculative variation that seems promising is ore formation during or after contact metamorphism in rocks that meet criteria 1, 2, 3, as in the Apache Group (Nutt, 1981) or Belt Supergroup. If we use foresight, rather than hindsight, some of the areas considered here that do not seem to be favorable for known unconformity-type deposits may well be favorable for other types of deposits.

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