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Geology of the Midnite Uranium Mine Area, Washington--Maps, Description, and Interpretation

By

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This report is preliminary and has not been edited or reviewed for conformity with U.S. Geological Survey standards and nomenclature.

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GEOLOGY OF THE MIDNITE URANIUM MINE AREA, WASHINGTON--MAPS, DESCRIPTION, AND INTERPRETATION

By J. Thomas Nash

Abstract

Bedrock geology of about 12 km^2 near the Midnite mine has been mapped at the surface, in mine exposures, and from drilling, at scales from 1:600 to 1:12,000 and is presented here at 1:12,000 to provide description of the setting of uranium deposits. Oldest rocks in the area are metapelitic and metacarbonate rocks of the Precambrian (Y) Togo Formation. The chief host for uranium deposits is graphitic and pyritic mica phyllite and muscovite schist. Ore also occurs in calc-silicate hornfels and marble at the western edge of a calcareous section about 1,150 m thick. Calcareous rocks of the Togo are probably older than the pelitic as they are interpreted to be near the axis of a broad anticline. The composition and structural position of the calcareous unit suggests correlation with less metamorphosed carbonate-bearing rocks of the Lower Wallace Formation, Belt Supergroup, about 200 km to the east. Basic sills intrusive into the Togo have been metamorphosed to amphibolite.

Unmetamorphosed rocks in the mine area are Cretaceous(?) and Eocene igneous rocks. Porphyritic quartz monzonite of Cretaceous age, part of the Loon Lake batholith, is exposed over one third of the mine area. It underlies the roof pendant of Precambrian rocks in which the Midnite mine occurs at depths of generally less than 300 m. The pluton is a two-mica granite and exhibits pegmatitic and aplitic textural features indicative of water saturation and pressure quenching. Eocene intrusive and extrusive rocks in the area provide evidence that the Eocene surface was only a short distance above the present uranium deposits.

Speculative hypotheses are presented for penesyngenetic, hydrothermal, and supergene modes of uranium emplacement. The Precambrian stratigraphy, similar in age and pre-metamorphic lithology to that of rocks hosting large uranium deposits in Saskatchewan and Northern Territory, Australia, suggests the possibility of uranium accumulation along with diagenetic pyrite in carbonaceous muds in a marine shelf environment. This hypothesis is not favored by the author because there is no evidence for stratabound uranium such as high regional radioactivity in the Togo. A hydrothermal mode of uranium emplacement is supported by the close apparent ages of mineralization and plutonism, and by petrology of the pluton. I speculate that uranium may have become enriched in postmagmatic fluids at the top of the pluton, possibly by hydrothermal leaching of soluble uranium associated with magnetite, and diffused outward into metasedimen-

tary wall rocks to create an aureole about 100 m thick containing about 100 ppm uranium. Chemistry of the hydrothermal process is not understood, but uranium does not appear to have been transported by an oxidizing fluid, and the fluid did not produce veining and alteration comparable to that of base-metal sulfide deposits. Uranium in the low-grade protore is believed to have been redistributed into permeable zones in the Tertiary to create ore grades. Geologic and isotopic ages of uranium mineralization, and the small volume of porphyritic quartz monzonite available for leaching, are not supportive of supergene emplacement of uranium.

Introduction

The geologic setting of the Midnite mine (Becraft and Weis, 1963) is seemingly simple, but geologic features within 2 km of the mine indicate a complexity greater than previously recognized. An area of about 12 km^2 has been mapped at scales from 1:600 to 1:12,000 and is presented here to provide more geologic description, along with some interpretation, to assist others in developing their own interpretation of the mine's setting. The Midnite mine is on the Spokane Indian Reservation, Stevens County, Washington, about 65 km northwest of Spokane (fig. 1). It is in the Turtle Lake 15-minute quadrangle, the geology of which was mapped at 1:62,500 by Becraft and Weis (1963). The Midnite mine is operated by the Dawn Mining Co., jointly owned by Newmont Mining Corp. and Midnite Mines, Inc.

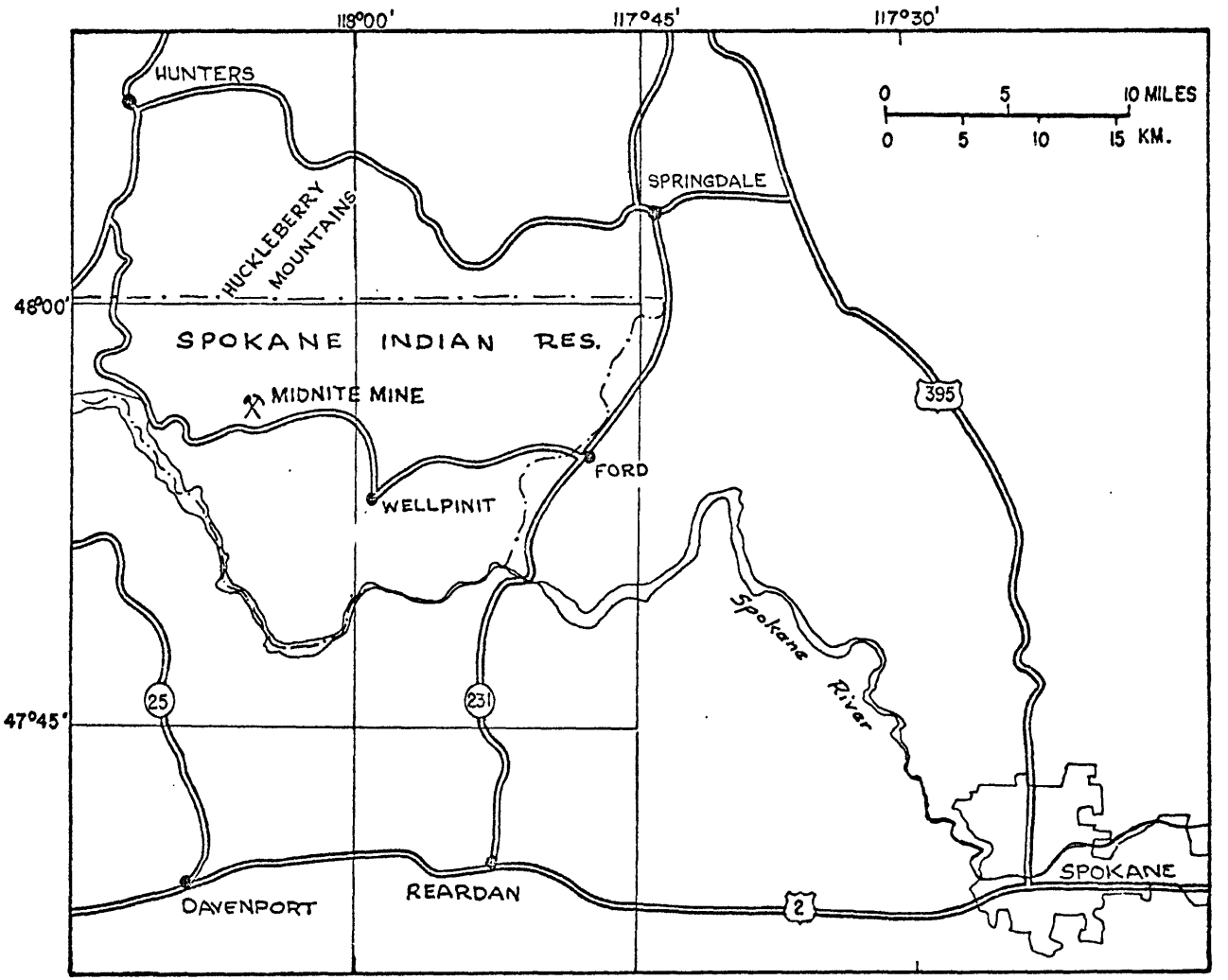

Figure 1.-- Location of the Midnite uranium mine, Stevens County, Washington.

Several aspects of the local geology and geography confound detailed mapping. Map units are thick, and variations in lithology are likely due to changes in metamorphic conditions. Exposures range from excellent near the mine to poor on north-facing slopes. Particularly troublesome are blanketing deposits of felsenmeer, 10 to 50 cm cobbles of frost-heaved rock in a matrix of soil, that are often more than 3 m deep--such that even deep bulldozer cuts do not expose bedrock. Most of Spokane Mountain is underlain by felsenmeer, and on those steep slopes, it is not clear how far the fragments have moved from their source. A third major problem is the uncertain stratigraphic identity of the thick marble and calc-silicate unit east of the mine.

Control for the map (plate 1) ranges from excellent to fair. Many locations could be referred to survey points of Dawn Mining Co., and most field locations could be spotted reliably on excellent 1:12,000-scale color photographs. Many section, quarter, and eighth-section corners could be recovered in the field and plotted on the photos, but some corners are not marked. Geology and selected topographic and cultural features were compiled from the photos on a Kern PG-2[1/] stereo plotter. There are no survey points

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[1/] Use of brand names in this report is for descriptive purposes only and in no way constitutes endorsement by U.S. Geological Survey.

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on the ridge west of the mine in section 11. Because the only topographic map in existence is the 1948 Turtle Lake quadrangle at 1:62,500, that topography is shown on plate 1 to give some topographic sense but it is not the base used for mapping.

Acknowledgments

I wish to acknowledge with thanks the cooperation of Dawn Mining Co. and Western Nuclear Inc. Both companies provided drill hole information and allowed the author to log and sample drill core. I have benefitted from discussions of geology with Norman Lehrman, Dawn Mining Co., and David Robbins and Lee Nesbitt, Western Nuclear Inc. Don Schultz, Dawn Mining Co., provided survey information for topographic control. Jim Derick, Geological Survey, assisted with stereo compilation. Fred Miller and Jack Harrison, Geological Survey, offered helpful comments on regional geologic problems.

Lithology

A great variety of lithologies are observed in the mine area, but only nine types are general enough to be used as map units. Metamorphic rocks display many different textures and mineralogical composition within three compositional types.

Aluminous or pelitic rocks have been transformed into phyllitic-, schistose-, and hornfelsic-textured rocks in which quartz, graphite, and white mica or muscovite are the conspicuous minerals. Pyrite, and iron-oxide pseudomorphs, andalusite, and biotite are commonly present. Fine-grained K-feldspar is present in many bands. All these rocks are mapped as Togo phyllite because all are presumed to have had the same original bulk composition. Textural variations due to differences in metamorphism (or polymetamorphism, see ahead) are obvious but are not stratigraphic in nature.

Calcareous rocks have been transformed to a great variety of hornfelsic rocks with differing mineralogy. Lithologic description, in a stratigraphic sense, of four drill holes is included (table 1) because these rocks have been poorly described in earlier reports. Fine-grained, pale green to gray-green rocks, in which diopside, quartz, and epidote are major minerals, are most common of the calc-silicate hornfelses. Calcite is commonly not present, hence,

Table 1.--Lithology of four drill holes in calcareous rocks.

Lithologies arranged to invert section to probable original position; all are listed from bottom to top as drilled. Locations given on plate 2. All hornfelses very fine grained. Lithology abbreviations: silic, siliceous; CS, calc-silicate; Hf, hornfels. Mineralogy listed in approximate order of abundance. Abbreviations: Bi, biotite; Cc, calcite; Chl, chlorite; Di, diopside; Ep, epidote; Ga, garnet; Ho, hornblende; Id, idocrase; Mont, montmorillonite; Plag, plagioclase; Phl, phlogopite; Qz, quartz; Sc, scapolite, n.d., not determined.

Thickness (meters)	Lithology	Mineralogy
	1. Western Side of Calcareous Unit, DDH A	
	Porphyritic quartz monzonite	
1.1	Massive gray green marble	Cc, Phl, Qz.
0.4	Layered garnet skarn	n.d.
1.2	Massive pale green silic. CS Hf	Qz,Di,Cc,Ga,Id.
1.5	Medium laminated gray silic. CS Hf	Qz,Di,Phl,Ga,Cc,Id.
1.4	Banded green/gray marble diopsidic beds	CC, Qz, Di, Mont.
1.3	Massive pale green silic. CS Hf	Qz,Cc,Di,Id,Mont.
0.7	Dark green altered CS Hf	Qz,Di,Mont,Cc.
2.9.	Medium laminated blue-gray marble	Cc,Phl,Di,Mont.
1.3	Dark green altered CS breccia	Cc,Qz,Ph, Mont.
1.6	Weakly laminated gray-blue marble	Cc,Phl,Qz,Di,Sc.

	2. Western Side of Calcareous Unit, DDH B	
100	Massive pale-gray marble, some thin pale green siliceous diopside beds	
	3. Central Part of Calcareous Unit, DDH C	
	Porphyritic quartz monzonite	
1.2	Dark green biotite hornfels	
4.3	Laminated gray green silic. Hf	Qz, Bi, Chl.
2.0	Massive calcareous quartzite(?)	Qz, Di.
4.3	Laminated dark green CS Hf	n.d.
2.3	Massive pale gray silic. marble	Cc, Qz, Phl.
11.3	Amphibolite sill	n.d.
2.4	Pale gray-blue marble	Cc, Phl, Qz.
2.3	Laminated CS Hf	Di, Qz, Ep.
2.5	Pale gray marble, garnet skarn layers	n.d.
3.3	Cherty tan Hf, gray phyllitic layers	n.d.
13.7	Massive pale gray marble, green diopside layers	n.d.

4. East Side of Calcareous Unit, DDH D		
	Porphyritic quartz monzonite	
10.1	Cherty tan Hf	Qz, Bi, Di.
1.4	Pale gray marble	n.d.
7.6	Pale green quartzite/Hf	Qz, Di.
10.2	Thick-bedded pale gray marble	n.d.
8.8	Massive greenish-yellow Hf, garnet skarn layers	Qz, Ep, Ga.
29	Massive pale gray marble, garnet skarn layers	n.d.
1	Laminated tan Hf	
6.6	Pale gray marble, garnet skarn layers	n.d.
3.3	Laminated gray green silic. Hf	n.d.
10	Thinly laminated tan and green silic. Hf	Qz, Di, Bi, Plag, Id, Ho.
13.7	Amphibolite sill	n.d.
15.7	Massive greenish yellow CS Hf	Qz, Di, Ep.

many calc-silicate hornfelses do not fizz when treated by dilute acid. Medium- to coarse-grained skarns occur in many places but are lens-like and generally are only a few meters thick, hence, do not make useful map units. Garnet and tremolite characterize many skarns and wollastonite and vesuvianite occur in some. Marble beds often make good markers because they are bright white and resist weathering; some of the larger marble beds are shown on plate 1. The marble is medium to coarse grained and composed of calcite with lesser amounts of quartz, phlogopite, and calc-silicate minerals. Dolomite has not been detected in any of the calcareous rocks, the magnesium having been incorporated into silicate minerals such as diopside or phlogopite. The composition, mineralogy, and fabric of the calcareous rocks are very similar to that of metamorphosed calcareous Wallace Formation adjacent to the Idaho Batholith (Hietanen, 1963).

Mafic rocks have been transformed into massive amphibolite consisting of approximately equal amounts of dark-green amphibole and fine-grained felsic minerals. These rocks are generally conformable with enclosing metasediments and are interpreted to be metamorphosed gabbroic sills emplaced in Precambrian time (Becraft and Weis, 1963).

Unmetamorphosed bedrock in the mine area includes Cretaceous(?) and Oligocene(?) igneous rocks. Porphyritic quartz monzonite

underlies about one third of the map area. It is tan colored when weathered, and pale pink when fresh, medium- to coarsely-crystalline, and contains prominent K-feldspar phenocrysts up to 5 cm long. Coarse quartz, often with rectangular form, also is characteristic; near the mine the quartz is smokey. Biotite and minor muscovite are present, but there is no amphibole. There is considerable textural variation in the quartz monzonite, such as the presence of both very coarse- and fine-grained variants near the contact with metasediments. The pegmatitic and aplitic textured rocks in the pluton display both gradational and sharp contacts with typical porphyritic quartz monzonite. Aplitic dikes, some of which extend into the wall rocks, are generally less biotitic and finer grained than the pluton.

Several dikes of very fine-grained dacite occur in the mine area. The dikes are almost always altered. Amphibole phenocrysts are set in an aphanitic matrix. The dikes on Spokane Mountain (east center sec. 1) are vesicular. A small outcrop of flow rock occurs in the northwest corner of section 13 (plate 1). The flow rock is porphyritic with dark amphibole phenocrysts in a dark brown aphanitic groundmass. This rock is identical to rocks to the south mappéd as Gerome andesite (Becraft and Weis, 1963), and now considered to be part of the Eocene Sandpoil Volcanics and dated at 51 m.y. (Pearson and Obradovich, 1977).

Structure and Stratigraphy

Structure in the mine area is probably greatly oversimplified on plate 1. Poor exposures are part of the problem, but an even greater limitation is lack of stratigraphic units within the Togo Formation. Calcareous rocks, chiefly calc-silicate hornfels and marble, are much more common in the Togo than published descriptions would suggest. A thick block of calc-silicate rocks east of the mine (plate 1) is a distinctive unit that serves as a helpful marker.

Argillite and phyllite of the Togo Formation have been correlated with the upper part of Wallace Formation of the Belt Supergroup by Miller and Clark (1975, p. 19-22). If the calcareous rocks described here are indeed lower in the section, then they would correlate excellently with carbonate-rich quartzite and siltites of the Lower Wallace Formation. This correlation would give additional support to the regional correlation proposed by Miller and Clark (1975), who were not aware of the calcareous section east of the mine.

Stratigraphy of the Togo Formation.--The oldest rocks in the Deer Trail Group exposed in southern Stevens County are those of the Togo Formation, named for good exposures near the Togo mine about 12 km north of the Midnite mine (Campbell and Loofbourow, 1962). Lithology of the Togo is typically massive dark argillite, phyllite, or muscovite schist, depending upon degree of metamorphism, but

quartzite and carbonate units occur also. Outcrops of phyllite are generally poor and structures difficult to detect. Becraft and Weis (1963) estimated total thickness to be about 6,100 m based on outcrop width. However, Miller and Clark (1975, p. 19) point out that the structural complexity mapped in other units of the Deer Trail Group is not shown within the Togo and point out that it could be as thin as about 900 m. If the Togo is correlated with the Wallace Formation of the Belt Supergroup (Miller and Clark, 1975; see ahead), its age would be about 1300 M.Y. (Harrison, 1972).

Despite detailed study by many geologists of the Togo Formation in outcrop, mine and bulldozer cuts, and more than 15 km of drill core, only three broad stratigraphic units can be defined: an upper quartzite, a middle phyllite, and presumably the lower calcareous unit described in the next section. The upper quartzite is about 180 to 500 m thick, has distinctive massive lithology, and forms excellent outcrops. It is known to occur only in the northeast-trending belt about 5 km west of the mine. Between the quartzite and calcareous unit is a monotonous black phyllite with steep, probably overturned, eastward dip (Becraft and Weis, 1963).

Although geology within the Togo phyllite is surely more complex than documented in the literature, I can add only a few descriptive comments. Sulfide minerals seem most abundant in a northeast-trending zone approximately 1,000 m thick that contains

the Midnite mine. This zone, starting at the contact with calcareous rocks on its eastern side, is characterized by more than 1 percent of visible sulfide minerals, iron oxide casts after sulfides, or abundant iron oxide staining. Rocks west of the sulfidic phyllite seem to be more siliceous, and further west near Sand Creek (2.5 km west of the mine) the Togo is fine-grained mica phyllite and slate. Carbonate beds are not uncommon within the phyllite as penetrated by exploration drilling. The carbonate seems to be in local units, generally less than 20 m thick, and color ranges from dark to very light gray depending upon metamorphism.

Stratigraphic assignment of calcareous rocks.--There is a 1,150-m thick section of calcareous rocks calculated from outcrop width and average dip east of the mine in the roof pendant (plate 1, cross section). The eastern limit of the section is not known as it is cut out by intrusive rocks. The section could possibly be thickened by unrecognized structures, although bedding attitudes are very consistent. The section is dilated by about 85 m of amphibolite (intrusive sills). Scattered exposures, bulldozer cuts, and drilling indicate that the section comprises about 75 percent fine-grained calc-silicate hornfels (formerly calcareous silt, calcareous quartzite, and impure limestone), 20 percent marble (former relatively pure dolomite, limestone, and siliceous limestone), and 5 percent garnetiferous skarn (formerly clay-rich limestone). This is clearly

more than a "local discontinuous lens of dolomitic marble" as described by Becraft and Weis (1963; p. 7, their plate 1). It needs to be recognized as a distinctive composition in regional stratigraphy.

The author favors correlating the calcareous rocks with the lower Wallace Formation. This requires that it is older than the pelitic Togo section to the west, and there is permissive evidence for this. A more complex alternative is that the calcareous rocks were tectonically emplaced and correlate with younger dolomites in the Deer Trail Group. The evidence for this is not strong as the bedding plane faults exposed near the mine do not appear to be major structures. This possibility will not be considered further.

According to the regional geology of Becraft and Weis (1963), rocks in the mine area are on the overturned west limb of the broad Deer Trail anticline. By this interpretation the calcareous rocks would be older than the pelitic to the west. However, structure is probably more complex than presently mapped and comparable to the more tightly folded and faulted geology known in adjacent areas (Campbell and Raup, 1964; Miller and Clark, 1975). Although not abundant, local drag folds in the mine area are evidence for at least a local anticlinal axis to the west of the mine; and, hence, the eastward-dipping beds in the mine area might not be overturned. Because the upper Togo quartzite is not recognized in the eastern part of the Turtle Lake quadrangle, it does seem most likely that

the eastern limb of the Deer Trail anticline is not exposed and that the calcareous rocks in question are older than the pelitic Togo section.

Northwest-trending fault zone.--A major geologic discontinuity is observed on the south slope of Spokane Mountain. The calcareous unit terminates on a structure that must trend northwesterly as shown on plate 1. Three thin intervals of calcareous rock, about 50 m thick, occur along the lower road to the top of Spokane Mountain and none can be traced to the north in mixed good and poor exposures. These are interpreted to be slices of rock in a northwest-trending fault zone about 75 to 275 m wide. A marble unit about 150 m thick occurs to the northeast of the fault zone at the eastern edge of the pendant. With the exception of the marble just mentioned, no calcareous rocks are known in outcrop, float, or drill holes north of the fault zone. Hence, a major structure is required to cut out the calcareous unit that a short distance to the south has a reliable outcrop width of about 1,100 m. The fault zone is not known to offset the porphyritic quartz monzonite, hence a pre-Cretaceous age is indicated.

The southern fault strand is drawn through several good outcrops that indicate appreciable right-lateral offset. A notable point is the drill hole in the saddle about 500 m SW of the Lookout on Spokane Mountain that penetrated several faults, sheared calc-silicate

rock, and about 30 m of mid-Tertiary dacite dike above mica schist. Here, as in the Midnite mine, the dacite dike intruded along a probably pre-existing fault. The quartzite to the southeast is interpreted to terminate on the fault; exposures in that area are very poor but I would expect to see at least quartzite float to the north if it did continue on strike. The northernmost fault is drawn across an area of very poor exposures in which thick deposits of felsenmeer occur on steep slopes. None of the felsenmeer is calc-silicate rock and the slivers of calcareous rock and a dacite dike appear to terminate as shown. Indirect evidence for the fault zone comes from the apparent rapid change in elevation of the top of the pluton along this line as shown on plate 2 (discussed ahead). A fault within phyllite about 700 m to the northwest could possibly be a northwestward continuation of the fault zone. The configuration of the pluton roof in the northeast corner of section 1 (plate 2) also may indicate such a continuation.

The northwest-trending fault zone appears to have about 800 m of right lateral displacement. The best marker seems to be the contact between phyllite and marble of the carbonate section. The magnitude of displacement may be in considerable error, however, because there probably also are smaller faults roughly parallel to bedding, and units may not be correctly correlated across the fault zone.

Isolated blocks of phyllite and quartzite.--Isolated blocks of phyllite and quartzite are observed east of the mine in NE corner sec. 12, and NW corner sec. 7, respectively. The quartzite, observed as float and in poor exposures in a trench, is massive, unbedded, and milky white color. To the northwest and southeast are exposures of calc-silicate rocks; on apparent strike to the northeast, the unit disappears under colluvium. The approximate thickness calculated from outcrop width is 60 m. Discontinuous lenses of quartzite like this are known in the Wallace and Edna dolomite formations (Becraft and Weis, 1963; Miller and Clark, 1975). Black phyllite is exposed in float and in a bulldozer cut in an area of very poor exposures in section 12. The limits of phyllite and its structural nature are not known. It is possible that this is a lens of phyllite within the calcareous rocks, although no other such lenses have been observed in outcrop or drill core. Also, it is possible that the unit has been folded or faulted into place.

Porphyritic Quartz Monzonite

Lithologic variations.--Textural and compositional variation is observed in the Cretaceous(?) porphyritic quartz monzonite. Textures range from pegmatoid, with giant crystals up to about 0.4 m, down to porphyries with aphanitic groundmass. Graphic intergrowths of quartz and K-feldspar occur locally, generally

cross cutting normal textured rock. Relative amounts of quartz and K-feldspar phenocrysts, and their abundance relative to groundmass, are variable. Biotite content is generally 3 to 5 percent, and trace amounts of muscovite of probable primary crystallization is present. Dikes differ from the main pluton chiefly in lower phenocryst content; average grain size tends to be somewhat finer, but often is equally coarse. Most conspicuous textural variation within the pluton seems to occur near its contacts. Pegmatoidal varieties, generally gradational into aplitic textures, are most common within about 50 m of contacts. Finer grain sizes are not typical of contact zones (except for hybrid rocks), but some occur about 5 m below contacts. Textures do not seem to be different adjacent to carbonate as opposed to pelitic metasediments. Although not evident from the geologic map (plate 1), and not rigorously quantified, I have the impression that there are more offshoot dikes and pegmatite and aplite zones on the west side of the roof pendant than observed elsewhere in the mine area or the quadrangle in general.

Megascopic compositional variation is chiefly biotite content. Dike rocks tend to contain less biotite than those of the main pluton, and biotite is much more abundant in hybrid zones about 1/2 to 2 m thick at the contact with metasediments. Biotite-rich schlieren are fairly abundant in the upper 50 m of the pluton, along with some xenoliths; these are rarely seen in dikes. Pervasive green montmorillonite alteration of feldspar is common below cal-

careous rocks, but the age and nature of this transformation is not understood. According to gamma spectrometric analyses, potassium content is quite consistent (about 4.8±0.5 percent K_2O) for rocks of all textures.

Textural and compositional variations can be applied to interpretation of magmatic-postmagmatic conditions that bear on possible hydrothermal emplacement of uranium, and to distinguishing thick dikes from the main pluton during drilling. Granitic rocks that are leucocratic, relatively equigranular, and do not contain many schlieren or xenoliths probably are dikes. However, drill holes penetrating rocks with textures and mineralogy suggestive of dikes should be deepened in an attempt to reach underlying metasediments that could be mineralized. Because ore has not been found in the pluton, except for small pockets at the contact, and from knowledge that uranium is generally richest just above the main pluton (Nash and Lehrman, 1975), it is important that exploration drilling penetrate the pluton but not be wasted within it.

Structural and textural aspects of the porphyritic quartz monzonite are generally suggestive of emplacement of a crustal level of about 6 to 8 km according to characteristics of mesozonal and transitional epizonal-mesozonal plutons (Buddington, 1959). The importance of this depth setting, equivalent to about 2 kilobars pressure, is chiefly its effect on volatile elements in the magma,

and in turn, their influence on rock crystallization and separation of metallic elements. Processes such as the development of a free aqueous phase explains the crystallization of pegmatites, and release of water pressure by reduction in confining pressure (pressure quenching) can cause aplite crystallization (Jahns and Burnham, 1969). Also, muscovite is stable only at water pressures greater than about 2 kilobars, unless stabilized by lithium or fluorine (Wones, 1967). In addition, pressure has a strong influence in the solubility of water in magmas, and the timing of vapor release from a crystallizing magma (Whitney, 1975). In a later section I speculate on the separation of a uranium-bearing hydrothermal fluid that could have carried uranium outward into the metasedimentary wall rocks.

Geometry of intrusive contact.--Geometry of the intrusive contact of porphyritic quartz monzonite with metasediments is important as an ore control in uranium deposits of the Midnite mine (Nash and Lehrman, 1975). Geologic maps and sections in that report show (1) deposits are adjacent to steeply dipping ribs of quartz monzonite; (2) deposits are localized above subhorizontal and locally depressed portions of the contact, and (3) thicker ore zones tend to be in and above depressions in the contact. A map of mineralization thickness plotted on a detailed structure contour map of the upper surface of porphyritic quartz monzonite (the intrusive contact) (Nash and Lehrman, 1975, fig. 7) gives particularly impressive descriptive information on ore controls.

Away from the mine area the contact between intrusive and metamorphic rocks can generally be located quite reliably from rounded outcrops and isolated boulders of quartz monzonite, and change in soil types. On heavily wooded northern slopes with thick soil and felsenmeer cover on the order of 5 to 10 m thick a hand-carried magnetometer can be used to locate the contact within about 10 m by the higher magnetic susceptibility of the granitic rocks. However, it is almost always impossible to judge the dip of the contact--a matter of concern to those attempting to drill to the contact. Drill holes shown on plate 2 provide data for estimating dips and shape of the contact. I thank Dawn Mining Co. and Western Nuclear Inc. for providing this data. It should be noted that much more drilling has been done in the area than shown in simplified manner here.

According to the data on plate 2, the configuration of the intrusive contact is very simple. There is a broad flat top to the pluton below about 75 to 200 m of metasediment (plate 1, cross section). The greatest thickness of metasediment in the pendant (east of the mine) penetrated by drilling is about 340 m. The intrusive contact generally dips under the pendant. Calculated average dips of the intrusive contact are less than 15° in many places, but locally steepen to about 50°-60°. The great irregularity in the intrusive contact in the mine (Nash and Lehrman, 1975) is

not apparent elsewhere, although considerable variation could occur between drill holes.

In the northern part of the map area there are two abrupt changes in pluton roof elevation. In the northeast corner of section 1 contact elevations drop very sharply from about 3,200 feet (980 m) to less than 2,400 feet (730 m). Although less well documented, there is a similar change in contact elevations south of Spokane Mountain. Quite probably the two features are related and define a curving northwest to north-trending zone. This zone is in approximately the same position as the fault zones shown on plate 1 and previously described. The observed geometry could be explained in at least two ways: (1) it reflects a pre-intrusive fault, and the intrusive stoped its way to higher elevations to the northeast, or (2) it reflects a post-intrusive fault in which the northeast side is up 200 to 300 m. A post-intrusion fault of such magnitude probably could be observed in the pluton and would offset the exposed trace of the intrusive contact. The geometry most likely reflects a pre-existing zone of weakness.

Comments on Polymetamorphism

There is direct and indirect evidence for three stages of metamorphism of Precambrian sedimentary rocks. The earliest, and most obscure metamorphism is presumed to have been very low grade

in late Precambrian time. Thermally, this could be related to injection of sills and volcanism that created the Huckleberry Formation of the Windermere Group at about 800 m.y. (Harrison, 1972; Miller and Clark, 1975). No structures in the mine area are relatable to this period of metamorphism, although broad folding is known in southern British Columbia (Harrison, 1972).

Folding and a second stage of regional metamorphism in the area is pre-intrusion, probably Jurassic-Early Cretaceous as deciphered in Ferry County to the northwest (e.g., Parker and Calkins, 1964). During this orogeny rocks in the mine area were folded into their present steeply dipping attitudes. The excellent foliation of phyllites was imparted at this time and brittle rocks such as amphibolites broken apart into large boudin-like bodies by bedding plane slip. Fine-grained quartz-pyrite bodies, generally less than a meter thick, up to 100 m long, and conformable with bedding, may have been created at this time by metamorphic segregation. Interpretation of conditions of regional metamorphism is complicated by the effects of superimposed contact metamorphism (below), but seems to have been lowest greenschist-grade (quartz-albite-muscovite-biotite-chlorite subfacies). Sillimanite is not present, andalusite probably formed by contact metamorphism, and garnet and cordiorite are absent (but possibly explained by bulk composition of pelites). Metamorphic hornblende, biotite, and plagioclase in mafic sills probably formed in later contact metamrophism. I have no descrip-

tions of mineralogical changes in calcareous rocks at this stage because no rocks of this composition were observed in positions more than about 300 m from intrusive rocks.

Contact metamorphism is observed near the porphyritic quartz monzonite pluton. Within about 300 m of the pluton, andalusite and biotite are present in metapelites, thus are interpreted to be products of contact metamorphism. Also, in some exposures these minerals penetrate foliation. The calcic phases such as garnet, wollastonite, idocrase, scapolite, tremolite, and possibly diopside and epidote are judged to be of contact metamorphic origin. The metamorphic grade of rocks within the aureole is the hornblende-hornfels facies of Winkler (1967). No cordierite has been observed, although some units should have appropriate Mg-Al compositions for its formation. Temperatures may not have been quite high enough, or once-formed cordierite may have retrograded to micas. Schistosity, produced by alignment of coarse muscovite plates more than a centimeter in width and compositional layers several millimeters thick, is noted in many places near the intrusive contact and may be explained by shear and recrystallization during intrusion. Local kinking of foliation, which is quite rare, probably occurred at this stage. Also, metapelites with massive hornfelsic fabric rather than foliation are noted within about 100 m of the intrusive contact, especially above flatlying portions of the contact.

Eocene Igneous Rocks and Paleogeography

Observations on Eocene intrusive and extrusive rocks provide relations from which mid-Tertiary paleogeography can be reconstructed. Feeder dikes north of the mine (SE sec. 1) are vesicular and interpreted to have been emplaced near the Eocene surface. Flow rocks unconformably overlying porphyritic quartz monzonite at about 2,450 ft (745 m) elevation (NW1/4 sec. 13, plate 1) likewise provide a datum for the Eocene surface. I interpret that only about 50 to 150 m of Eocene and older rocks covered the uranium deposits in the Oligocene. Flow rocks are not known to occur above 2,720 ft (830 m) elevation within 10 km.

This reconstruction indicates that the uranium deposits were very close to the surface in Eocene time, and oxidizing surficial water could have entered permeable zones to emplace new uranium, to supplement that probably already there, or to secondarily enrich pre-existing uranium deposits (Nash, 1975). Also, this reconstruction indicates that the area has been very stable and topography only slightly modified since the Eocene--an interpretation that has important implications to the enrichment and preservation of uranium deposits.

1955), although this seems unlikely considering that the pluton was probably water saturated. The chief problem is the lack of evidence for stratabound uranium in the Togo. I was biased in favor of this concept in 1974, but could not produce radioactivity or chemical data to support it. All ground radiometric data, including traverses by a USGS truck-mounted spectrometer with large crystal, show no abnormal radioactivity in any units of the Togo near the mine. Present content of uranium is about 5 ppm U. Also only a few uranium occurrences are known in the Togo and all are within 300 m of the porphyritic quartz monzonite.

In conclusion, there is evidence that the sedimentological setting of host rocks for the Midnite deposits is generally similar to that of several other important uranium deposits, such as Rabbit Lake and Cluff Lake, Saskatchewan, and Ranger and Jabiluka, Northern Territory, Australia. The similarities include presence of carbonate and carbonaceous pelitic rocks (now metamorphosed), and Middle Precambrian ages (about 1300 to pre-1800 m.y.) of sedimentation. Because there is no evidence suggestive of penesyngenetic accumulation of uranium, this mode of origin is not favored for uranium at the Midnite mine.

Hydrothermal emplacement of uranium.--There is indirect evidence for emplacement of uranium from plutonic rocks by a hydrothermal process--but it must be emphasized at the outset that such a process must have been chemically much more subtle than the rather well

Speculation on three Modes of Uranium Emplacement

Penesyngenetic accumulation of uranium in Togo Formation.--One possible source of uranium is the metasedimentary rocks that enclose the deposits. Positive evidence for this mode of genesis has been presented for the Alligator Rivers region, Australia, by the Australian Bureau of Mineral Resources (e.g., Dodson and others 1974; Smart and others, 1975) through regional geologic and geophysical studies. There the Lower Proterozoic Koolpin Formation is the host for major uranium deposits such as Jabiluka and Ranger that collectively contain about 24 percent of the western world's reasonably assured uranium resources. The geology discussed previously suggests the following possible model for the Midnite mine area: Carbonate-bearing sediments formed in a near-shore marine environment of the Belt basin, about 1300 m.y. ago (Harrison, 1972). Carbonaceous muds were subsequently deposited above the carbonates, possibly in a restricted basin or lagoon. Shortly after sedimentation, or during diagenesis, uranium accumulated in the reducing environment and pyrite formed from seawater sulfate. Younger sediments were silts and sands that contained less organic material, and did not become enriched in uranium and pyrite. The stratabound uranium was mobilized during several periods of deformation and metamorphism and moved toward the pluton during intrusion. Most of this geologic scenario is geologically plausible, including the possibility of fluids migrating toward the pluton (e.g., Kennedy,

understood processes of hydrothermal emplacement of base-metal sulfide deposits (viz, Barnes, 1967). The supportive evidence includes some of the following features. (1) Age determinations on the porphyritic quartz monzonite and a sample of pitchblende from the Midnite mine are approximately the same, about 100 m.y. (2) Many drill holes in the mine area penetrate very low grade uranium (0.0X percent) adjacent to the pluton. (3) The porphyritic quartz monzonite contains anomalous amounts of uranium, about 16 ppm in freshest samples. Further, fission track "mica maps" prepared from thin sections of porphyritic quartz monzonite have textures indicating that most uranium is associated with magnetite in the rock. I interpret this association to mean that the uranium would be available for leaching by hydrothermal fluids, unlike uranium in refractory minerals such as zircon. (4) Petrology of the porphyritic quartz monzonite indicates that the magma may have been rich in volatives and there must have been release of these volatiles. Consequences of this are features such as pegmatite, aplite, and porphyritic texture, and crystallization of primary muscovite. High water pressure, combined with peraluminous composition, may explain the crystallization of muscovite plus magnetite, rather than more typical assemblages including biotite and hornblende. The magma probably had unusually high oxygen fugacity, which could explain the seemingly important magnetite-uranium association within the pluton. From features indicative of pressure quenching, I infer that the magma released volatiles and speculate that the released

aqueous fluid could have transported uranium into the wall rocks. The evolution of an aqueous fluid phase from a magma during intrusion has been discussed by Whitney (1975) and that analysis focuses attention on initial water content of the magma and depth of crystallization. Depending upon water content and depth, three times the fluid exsolution seem possible: (1) while the magma is rising, and pressure is released--this might produce a front of uranium-rich fluid above the crystallizing magma; (2) during crystallization, saturation occurs and the aqueous phase passes out through a mush of crystals and melt; and (3) saturation very late in crystallization (if water content was low and pressure relatively high), with fluid phase moving outward through a consolidated or semiconsolidated rind at the top of the pluton. Release of a uranium-rich fluid at times 1 and 2 could have been prior to crystallization of most pegmatites and aplites and the fluid would have moved through unconsolidated igneous rocks, hence signs of fluid transfer could have been obliterated by later magmatic crystallization.

My speculation on the behavior of uranium is as follows: Uranium may have accumulated in upper portions of the magma chamber and been mobilized in hydrothermal fluids in greatest quantities in zones showing signs of pressure release (zones of aplite, pegmatite, dikes). It is not known what the solution species of uranium was, but may have been a uranyl-carbonate as recent experiments at 400° and 500°C at the high oxygen fugacity of the magnetite-hematite

buffer show very high solubility of uranium in carbonate-bearing solutions (Nguyen Trung and Poty, 1976). The uranium is thought to have diffused outward into the metasedimentary wall rocks and precipitated within about 100 m or less of the contact. Approximately 100 ppm may have been disseminated in the contact halo. Uranium precipitation may have been caused by reduction reactions involving iron sulfides (pyrite or pyrrhotite) or graphite. Two aspects of this reaction deserve comment: first, graphite probably is kinetically effective as a reductant at high temperatures, but is probably ineffective at low temperatures (J. Leventhal, oral commun., 1977). Secondly, the apparent lack of oxidation of iron sulfides, which is contrary to what would be expected if they had acted as reductants, may not be a problem considering the small amount of uranium involved and the possibility that the iron phases could have later been resulfidized to form the observed fine-grained pyrite and marcasite. The uranium in the low-grade protore is believed to have later been leached and redeposited in permeable zones to create zones in the range 0.05 to about 3 percent that make ore (Nash and Lehrman, 1975; Nash, 1975).

Tests of this hypothesis are ambiguous if traditional criteria for hydrothermal processes (e.g., Meyer and Hemley, 1967) are applied. Criteria such as patterns of hydrothermal alteration, alteration assemblages, and vein structure and mineralogy are generally based on field experience and experiments on base-metal sulfide deposits. If these criteria are applied to the pluton and wall

rocks at the Midnite mine, the inferences are negative. However, there is fluid-inclusion and mineralogical evidence that fluids released from the porphyritic quartz monzonite were not rich in chloride and sulfur, hence would not have the chemistry that produces the hydrogen metasomatism that characterizes alteration in base metal deposits (Meyer and Hemley, 1967). Further, the lack of veins in the pluton and wall rocks does not necessarily preclude hydrothermal activity. I speculate that post-magmatic hydrothermal fluids moved outward from the pluton by diffusion rather than by flow along faults that would become filled with vein-forming minerals.

A corollary to this speculative hypothesis is that the low-grade uranium protore might be anticipated adjacent to zones of the pluton showing unusual textural irregularity or pre-intrusion faults. Pre-intrusion faults (allowing release of volatiles from the magma) may be the explanation of some zones of the aplite and pegmatite (see Miller and Clark, 1975, p. 45). Also, the great irregularity in the intrusive contact well known in the Midnite open pits, described earlier, might have played a role in initial uranium emplacement (or might have been more important in later enrichment); these contacts might reflect pre-intrusion faults. Features such as aplite and pegmatite zones, pre-intrusion faults, and irregularities in intrusive contacts, to the extent that they can be recognized, may serve as a general field guide to locating uranium mineralization in nearby metasedimentary rocks. Also, presence of

carbonate rocks may be important as a source of CO_2 for uranium-carbonate complexes.

Supergene emplacement of uranium.--A third possible way to emplace uranium is by supergene processes that could leach uranium from the porphyritic quartz monzonite and transport it to sites of deposition as oxidized and reduced uranium minerals. By the Eocene the mine area had been exhumed and during the Miocene(?) excelsior weathering period deep weathering created clay deposits from granitic rocks (Hosterman and others, 1960). Vertical profiles in the porphyritic quartz monzonite demonstrate that more than 50 percent of original whole rock uranium has been leached, presumably during the Late Tertiary. Although the gross geometry of ore zones and the lack of hydrothermal alteration associated with uranium (Nash and Lehrman, 1975) might be considered as evidence for supergene emplacement, several finds of evidence negate the supergene mechanism. Existing Pb-U dates on pitchblende are clearly too old for supergene processes to have been operative, and pitchblende ores are fragmented by a fault zone filled by an Eocene dacite dike. Also, a limiting aspect seems to be the amount of the pluton with hydrologic position that would permit ground water transport of leached uranium into the ore zones. Using data from plate 2, I estimate that only about 0.2 to 0.3 km^3 of porphyritic quartz monzonite had appropriate vertical position relative to the uranium deposits. This volume of source rock contains enough

uranium to form the ore deposits, but to collect the amount of epigenetic uranium in the mine area (ore plus mineralization grading down to about 10 ppm) would require essentially 100 percent efficiency in leaching, transport, and redeposition. Supergene processes may have added uranium to rocks previously mineralized by Cretaceous metasomatism, and were important in secondary enrichment.

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