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Geology of the Midnite uranium mine, Stevens County, Washington--
A preliminary report

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ABSTRACT

The Midnite mine is one of only two mines in the United States currently producing uranium from discordant deposits in crystalline host rocks. Ore bodies are in metamorphosed steeply dipping Precambrian pelitic and calcareous rocks of a roof pendant adjacent to a Cretaceous(?) porphyritic quartz monzonite pluton. Production during 14 years of operation has been about 8 million pounds of U_3O_8 from oxidized and reduced ores averaging 0.23 percent U_3O_8.

Uranium deposits are generally tabular in form and dimensions range up to 380 m long, 210 m wide, and 50 m thick. Deposits are bounded on at least one side by unmineralized intrusive ribs of granitic rock, and thickest mineralized zones invariably occur at depressions in the intrusive contact. Upper limits of some deposits are nearly horizontal, and upper elevations of adjacent mineralized zones separated by ribs of granite are similar. Near surface ore is predominantly autunite, but ore at depth consists of pitchblende and coffinite with abundant pyrite and marcasite. Uranium minerals occur as disseminations along foliation, replacements, and stockwork fracture-fillings.

No stratigraphic controls on ore deposition are recognized. Rather, mineralized zones cut across lithologic boundaries if permeability is adequate. Most ore is in muscovite schist and mica phyllite, but important deposits occur in calc-silicate hornfels. Amphibolite sills and mid-Tertiary dacite dikes locally carry ore where intensely fractured. High content of iron and sulfur, contained chiefly in FeS_2, appear to be an important feature of favorable host rocks.

Geometry of deposits, structural, and geochemical features suggest that uranium minerals were deposited over a span of time from late Cretaceous to late Tertiary. Ore occurs in but is not offset by a shear zone that displaces mid-Tertiary rocks. Economic zones of uranium are interpreted to have been secondarily enriched in late Tertiary time by downward and lateral migration of uranium into permeable zones where deposition was influenced by ground water controls and minerals that could reduce or neutralize uranium-bearing solutions.

INTRODUCTION

The Midnite mine is located in Stevens County, Washington, about 40 miles northwest of Spokane (fig. 1). The mine is on the Spokane Reservation north of the Spokane River. Deposits were discovered in the spring of 1954, and in 1955 Dawn Mining Co. was formed jointly by Midnite Mines Inc. and Newmont Mining Corp., with 49 and 51 percent interests, respectively. Dawn Mining Co. developed the property in 1956, erected a 440-ton-per-day mill, and began producing ore in early 1957. The mine and mill were operated until April 1965, when they were closed due to the unfavorable uranium market. Mining and milling resumed in January 1970. Production during the 14 years of operation has been about 8 million pounds of U_3O_8 from ore consistently averaging 0.23 percent U_3O_8.

The Midnite is one of only two mines in the U.S. currently producing uranium from discordant deposits in crystalline rocks. The other one is the Schwartzwalder mine, Jefferson County, Colorado; it produces uranium from vein-type deposits in Precambrian rocks. As we will see later, the Midnite mine deposits are structurally controlled but are not simple vein-type. Only a few percent of U.S. uranium production and reserves are in deposits like those of the Midnite and Schwartzwalder mines, whereas in other countries such as Canada, France, and Australia major reserves are in these deposits. In the quest for new sources of uranium to meet pressing national needs more attention should be given to deposits similar to those of the Midnite mine. Several factors make then relatively attractive targets for exploration: rock types and structural setting are common; ore grades are relatively high and tonnages greater than anticipated in the 1950's; the tabular orebody form makes a better target for exploration

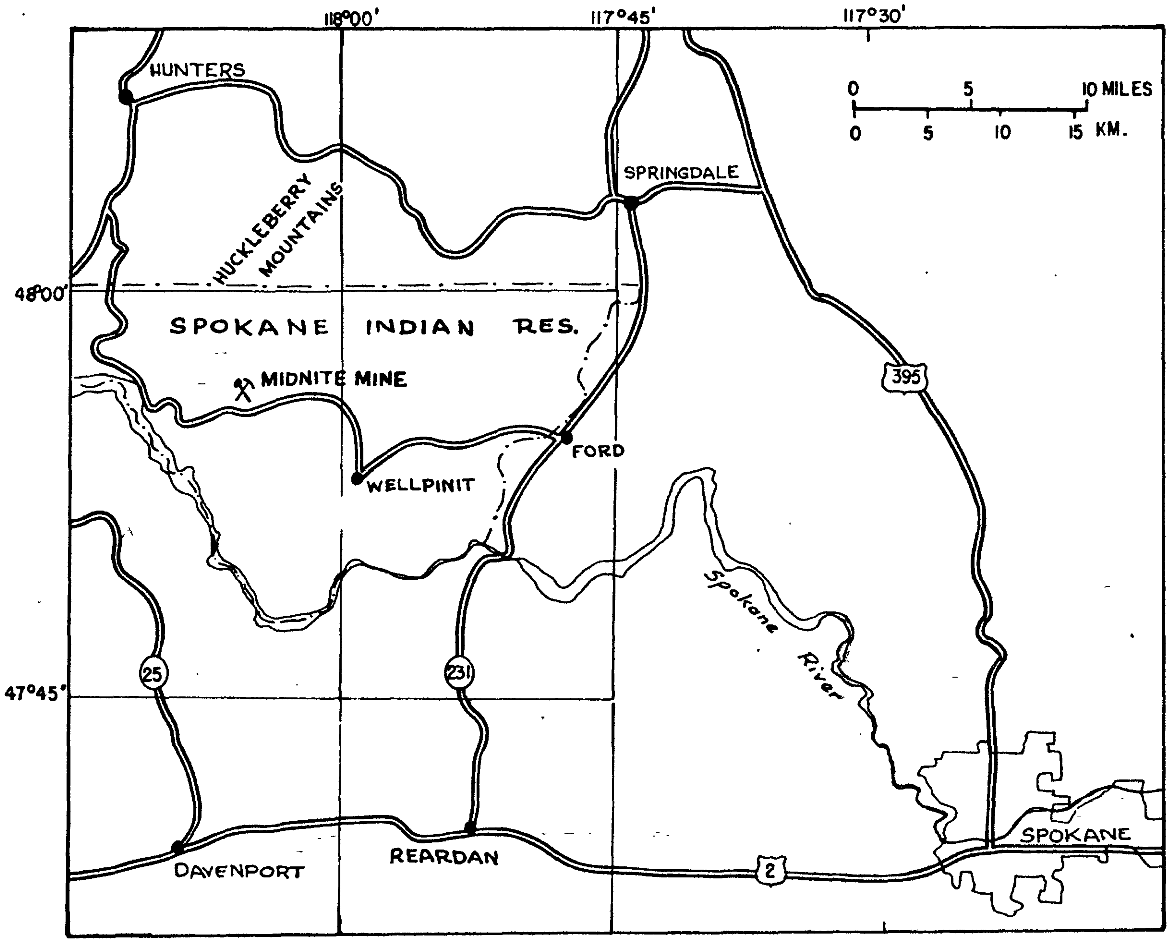

Figure 1.--Index map showing location of the Midnite mine.

than vein-type deposits; and cost of land acquisition is much lower than for terrain favorable for sandstone-type deposits.

The geologic setting of the deposits is well established by the comprehensive report and maps of Becraft and Weis (1963). Sheldon (1959) gave an excellent overview of the Midnite mine as of 1958, and Barrington and Kerr (1961) have described aspects of the mineralogy and alteration. The map by Campbell and Raup (1964) is helpful for the area to the north of the mine which has good potential for similar deposits of uranium. Miller and Clark (1975) describe in detail the geology of granitic rocks and metasediments in the Chewelah-Loon Lake area northeast of the mine and give a review of some regional geologic problems.

This report outlines some preliminary results of geologic studies undertaken jointly by the Geological Survey and Dawn Mining Co. in 1974 and 1975. Its chief purpose is to disseminate to interested parties the information presented orally at the Rocky Mountain section meeting of the Geological Society of America at Boise, Idaho, on May 6, 1975 (Nash and Lehrman, 1975). Further geologic, geochemical, and geophysical studies are underway and will provide more data upon which to make more complete description and interpretation.

ACKNOWLEDGMENTS

This study would not have been possible without the cooperation of Dawn Mining Co., Newmont Mining Corp., and Midnite Mines, Inc. We thank John Petty, Earl Craig, and Tibor Klobusicky of these organizations for their assistance. Don Schultz, mine engineer, provided base maps and survey information. We acknowledge the contributions of numerous mine geologists to geologic description of the deposits. F. C. Armstrong, F. N. Ward, and Katrin Zarinski of the U.S. Geological Survey are thanked for their assistance.

GEOLOGIC SETTING

Rocks ranging in age from Precambrian to Quaternary are exposed in the Turtle Lake quadrangle (Becraft and Weis, 1963). The Togo Formation of the Deer Trail Group (Precambrian) is the oldest rock unit and most important for its role as the host rock for uranium minerals at the Midnite mine (fig. 2). West of the mine are a sequence of younger Precambrian metasedimentary rocks and unconformably overlying Cambrian rocks. The Precambrian rocks (Deer Trail Group) in the mine area appear to correlate with the Wallace and Striped Peak Formations of the Belt Supergroup (Miller and Clark, 1975). All of these rocks are presently north-striking and steeply dipping in a major anticline. Eastward dipping beds in the mine area are interpreted to be overturned (Becraft and Weis, 1963), although no features indicative of tops of beds are recognized locally. The fold is clearly older than the granitic intrusions and is probably Mesozoic like similar deformation in north-central Washington.

Several bodies of granitic rock intrude and metamorphose Precambrian and Cambrian rocks. The granitic rocks have been considered to be part of the Cretaceous(?) Loon Lake batholith, but recent K-Ar age determinations from many plutons in northeastern Washington indicate a range of ages from about 200 to 50 million years (F. K. Miller, oral commun., 1974), hence the concept of a batholith seems invalid. The oldest phase is a granodiorite which crops out extensively east of the mine (fig. 2). A porphyritic quartz monzonite, characterized by prominent K-feldspar phenocrysts, intrudes the granodiorite. The porphyritic quartz monzonite is exposed over an area of about 90 km^2 and is in intrusive contact with the Togo Formation in the mine area. Lead-alpha age determinations of questionable validity are in the range 105 to 75 million years for the granodiorite and porphyritic quartz monzonite (Becraft and Weis, 1963).

The granitic intrusions caused regional metamorphism of sedimentary rocks to predominantly greenschist facies with scattered localities of higher grade. All Precambrian and Cambrian rocks show at least mild recrystallization, but effects are most pronounced in rocks closer to the plutons where the metamorphism is best described as contact metamorphism. No polymetamorphism is recognized. Carbonate rocks remain dark colored where

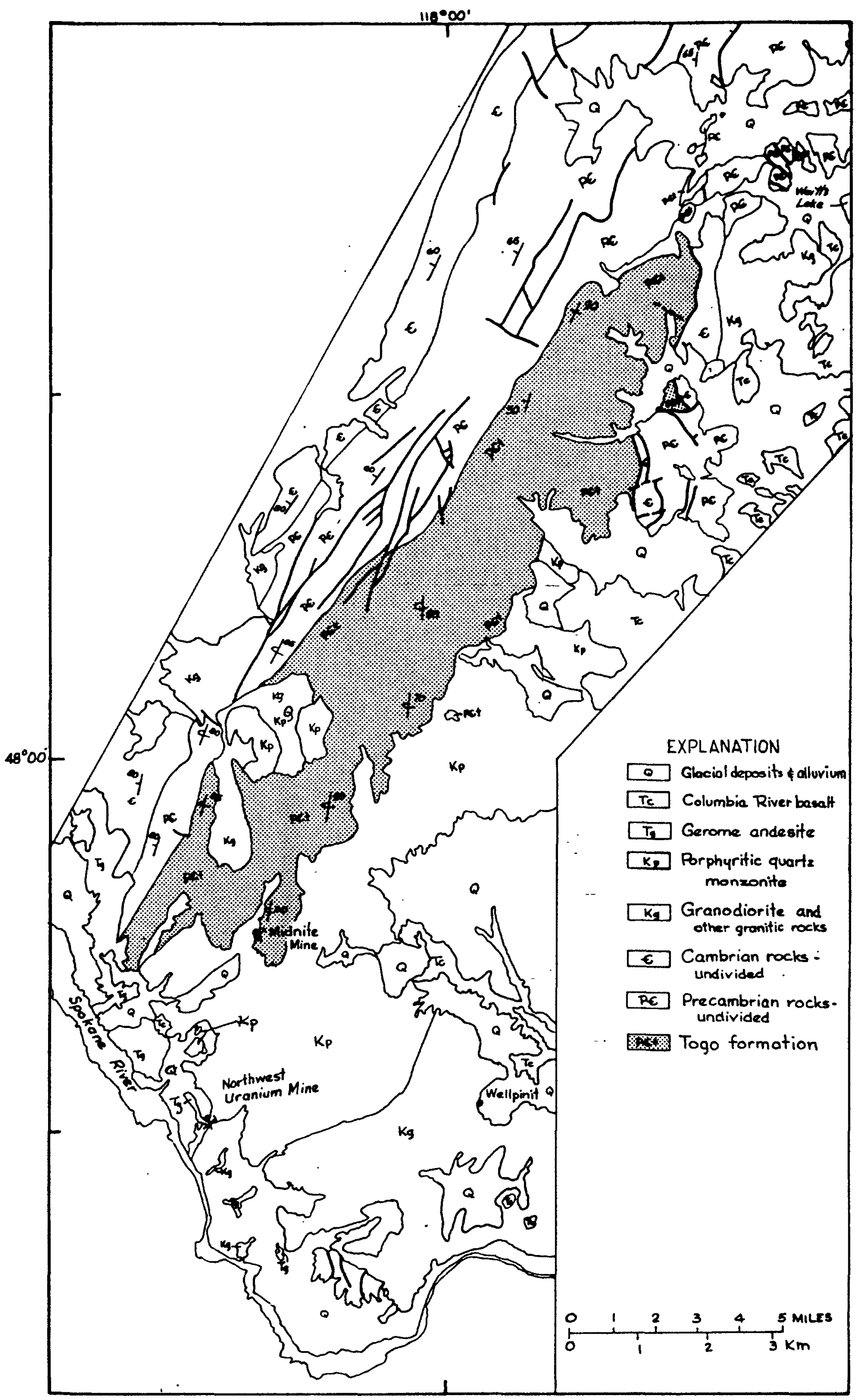

Figure 2.--Generalized geologic map of part of southern Stevens County showing relations of Precambrian and intrusive rocks. (Modified from Becraft and Weis, 1963: Campbell and Loofbourow, 1962; Campbell and Raup, 1964; Griggs, 1966; and F. K. Miller, written commun., 1974).

regionally metamorphosed, but are bleached close to intrusives. Pelitic rocks become spotted, and commonly schistose as plutons are approached. Metamorphic effects will be described in more detail in the next section.

Tertiary volcanic rocks unconformably overlie the granitic and older rocks. The mid-Tertiary Gerome andesite, consisting of basal clastic rocks, flows, breccias, and tuffs, crops out over large areas south of the Midnite mine and is the host rock for the Northwest (Sherwood) Uranium mine. Dikes of porphyritic dacite probably were feeders for extrusive rocks of the Gerome. Columbia River basalt flows unconformably overlie granitic rocks and Gerome andesite. The basalt covers extensive areas below 2,500 feet (760 m) elevation. Thick glacial deposits of silt, sand, and gravel occur in the Spokane River Valley but are not extensive in the mine area.

The major structural feature of the area is a broad fold involving Precambrian and Cambrian rocks. Eastward dipping beds in the mine area can be interpreted as overturned to the east. Small drag folds several feet in size are seen locally but their significance for regional structure is not clear. They could reflect only local change or shearing, or they could indicate tight isoclinal folding that is not otherwise evident.

Few faults have been recognized in the Turtle Lake quadrangle, possibly due to poor bedrock exposures and to the monotonous character of the Togo Formation which makes fault displacements difficult to detect. Faults older than the granitic plutons are not known but could be covered by younger rocks. Intrusive activity caused faulting with minor displacements in some areas, but pluton emplacement appears to have been generally passive. Mid-Tertiary faults with significant displacement cut the Gerome andesite at the Northwest Uranium mine (Becraft and Weis, 1973) and thoroughly shear a dacite dike in the Midnite mine.

In addition to the Midnite mine, three other properties in the Turtle Lake quadrangle have recorded production of uranium, and there are many additional uranium prospects in the area. The Midnite mine, Lowley Lease, and numerous prospects of uranium occur in metasedimentary rocks of the Togo Formation along contacts with granitic rocks (Becraft and Weis, 1963). Two other deposits, the Northwest Uranium and Big Smoke mines, occur in clastic, carbonaceous rocks of the mid-Tertiary Gerome andesite. The Northwest Uranium mine, also known as the Sherwood mine, contains reserves of eight million tons of uranium ore and will soon be mined by Western Nuclear, Inc. It is estimated that 14 million pounds of U_3O_8 will be recovered by a heap leaching process (Spokesman Review, Nov. 10, 1974).

GEOLOGY OF THE MIDNITE MINE AREA

Stratigraphy and structure

Geologic features of the mine area are shown on the plan map (fig. 3). This preliminary map is reduced from a map by Dawn Mining Company, largely from studies undertaken by Newmont Exploration Limited in the period 1955 to 1962, and modified by Nash on the basis of observations in 1974. The original scale was 400 feet to the inch; no suitable topographic base is available. Horizontal control is good in some areas from points such as diamond drill holes and stations along roads which were surveyed by Dawn Mining Co. A representative cross section through an ore body is shown on figure 4; it is constructed from pit geology, core, and rotary drill data.

Although exposures are generally poor in the area, extensive bull-dozing for mining and exploration reveal the clear northerly trend of metasedimentary units. Strike of bedding is generally in the range N. 10° W. to N. 20° E., and dips typically to the east (overturned) 50° to 80°. Westward dips and northwest strikes are local features. The pre-dominant metasedimentary rock in the roof pendant is a siliceous medium gray to yellow green calcareous hornfels in which diopside is the major constituent. In the central to western part of the pendant, large variations in calc-silicate metamorphic mineral content are noted, reflecting a large range in original composition from relatively pure limestone to impure limestone or marl that presumably contained large amounts of clay. The major metamorphic minerals are calcite, diopside, garnet, phlogopite, plagioclase, quartz, idocrase, scapolite, epidote, and wollastonite.

The western part of the pendant is pelitic rocks metamorphosed in varying degree to graphitic mica schist, phyllite, or hornfels. Bedding is not always clear in the pelitic rocks, and in foliated rocks may be confused with schistosity. However, bedding-cleavage and bedding-schistosity intersections are rarely seen in pit faces, drill core, or blocks of

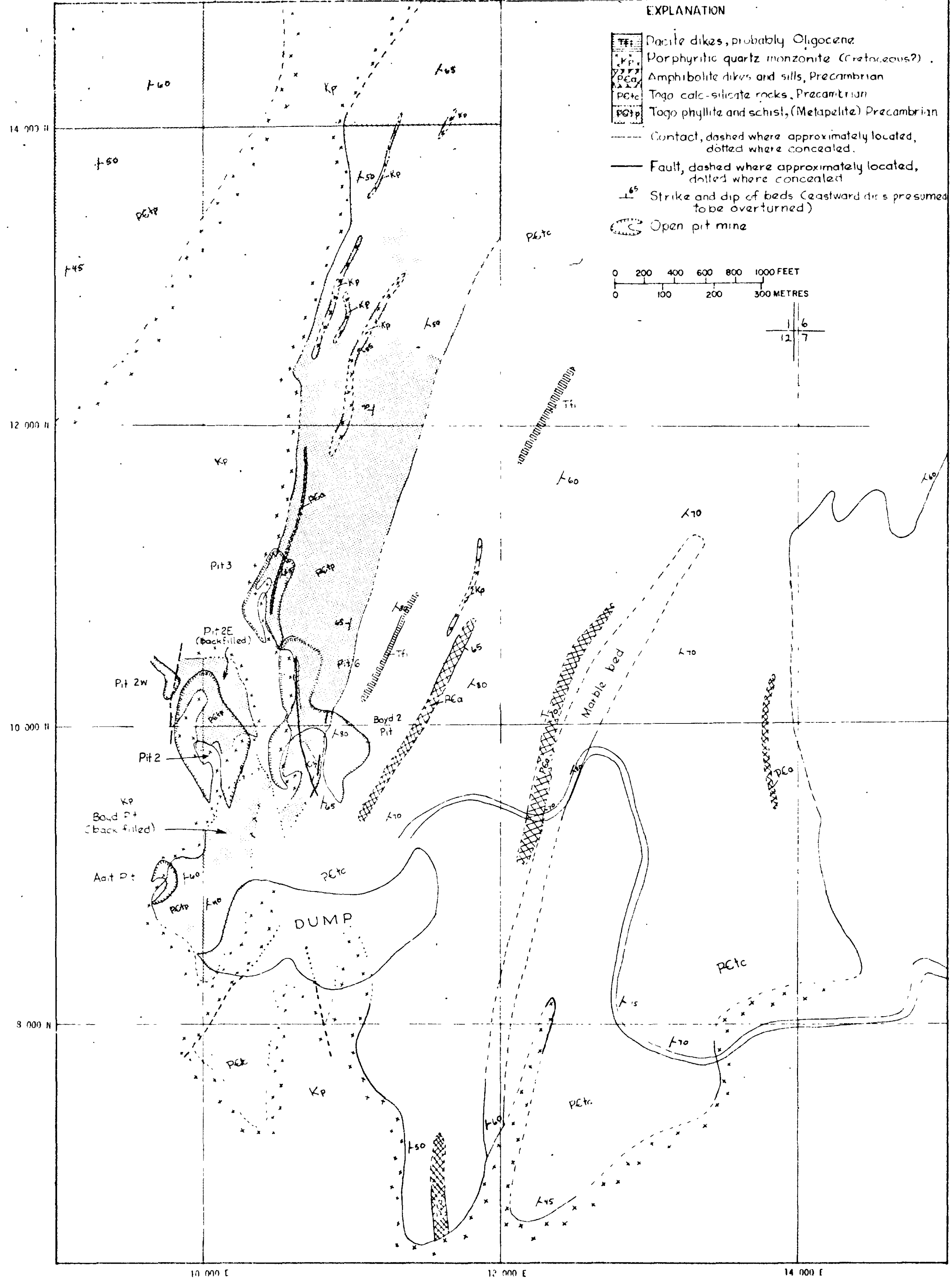

Figure 3.--Geologic map of the Midnite mine area. (Compiled from mapping by Dawn Mining Co., Newmont Exploration Ltd., and Nash).

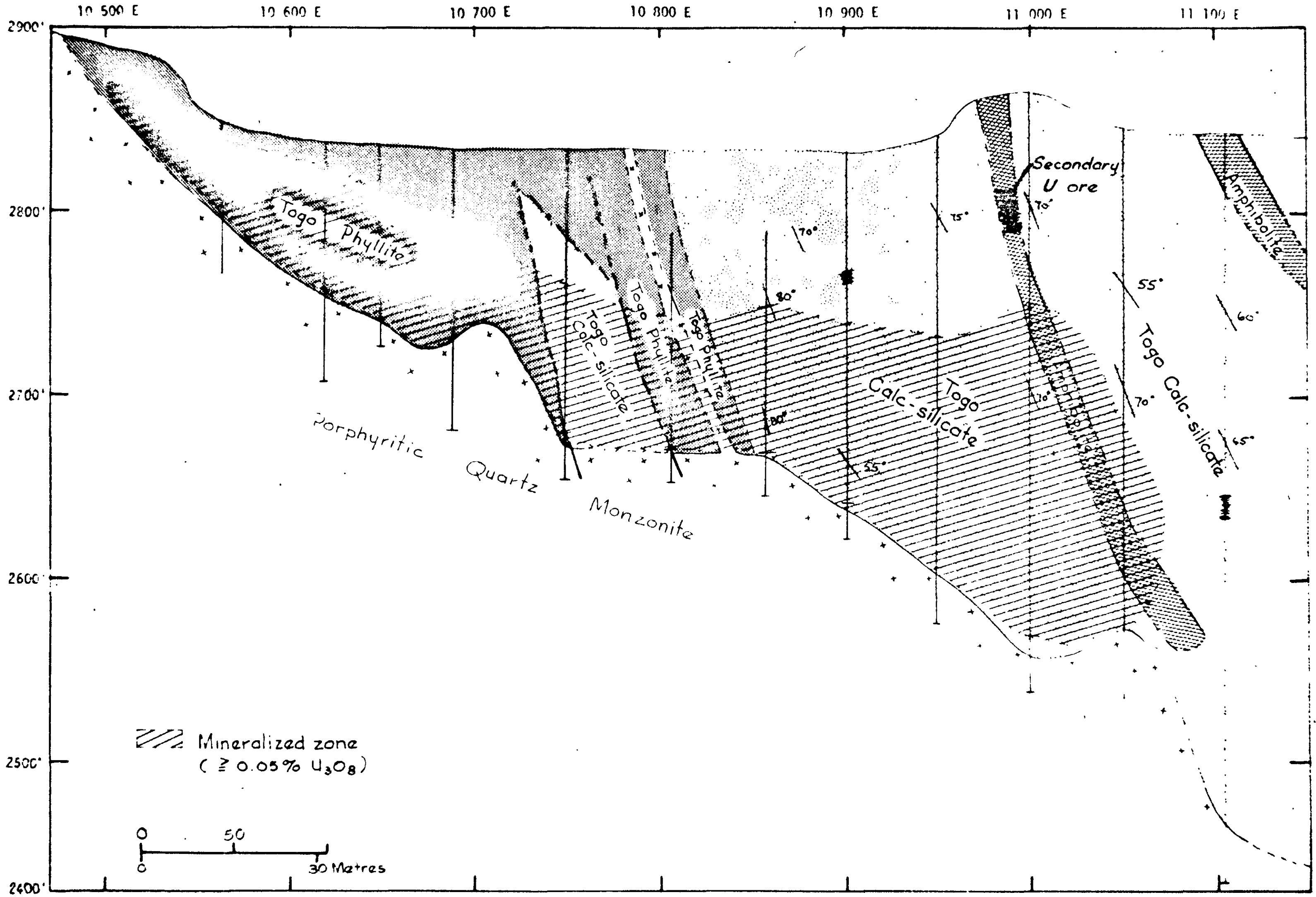

Figure 4.--Cross section through an ore zone in the Boyd 2 pit. Section at nine grid 9,900 ft N. Note the continuity of mineralization across the fault zone, which displaces a mid-Tertiary dike, and across lithologic boundaries. (Compiled from Dawn Mining Co. records, core logging by Lehrman, and logging and pit mapping by Nash.)

bulldozed material. Considering the large surface area of exceptionally well exposed rock examined in detail, it is concluded that foliation is typically in the plane of bedding except in local places of shear or drag folding. Strike of bedding (and foliation) in metapelites is typically N. 10° E. and dips range from 45° W. to 40° E. Metamorphic minerals are chiefly quartz and mica with smaller amounts of K-feldspar, graphite, and coarse porphyroblasts of andalusite. Within about 100 m of the main granitic body red-brown biotite and yellow tourmaline are present, and pyrite appears to be more abundant than in rocks more distant from the intrusion.

Dark-green amphibolite bodies, generally conformable to bedding, are numerous in the mine area. Four are shown on figure 3, and at least five others are known, some of which may be the same sill-like body. Several aspects of the amphibolites deserve mention. (1) They are commonly dense, massive bodies with no foliation apparent in the field or in thin section. When enclosed in sheared rocks, shearing apparently occurred along their margins rather than within the bodies. (2) Amphibolites are discontinuous on strike. In perfectly exposed areas, such as open pits, they commonly end abruptly and are missing for 50 m or more on strike before the next exposure is encountered. This geometry is possibly consistent with their emplacement as sills rather than dikes. Another explanation for the observed geometry is that the amphibolite acted as a strong body during deformation and broke apart as large boudins; this hypothesis implies large amounts of shear parallel to bedding which is not evident (nor can it be disproven) from structural features in enclosing metasedimentary beds. (3) Amphibolite bodies are generally not mineralized, although their composition suggests they should be a favorable reducing host. The paucity of uranium in amphibolites may be a consequence of their typical massive, unbroken character not permitting inflow of uranium-bearing fluids. Two amphibolites in the east Boyd 2 pit are favored host rocks for pitchblende where fractured thoroughly.

Porphyritic quartz monzonite in the mine area is tan to pink colored, coarsely crystalline, and contains K-feldspar phenocrysts up to 5 cm long. No hornblende is present and most, but not all samples contain muscovite of probable primary crystallization, hence this rock can be called a two-mica granite. (The term granite will be used subsequently in a textural rather than compositional sense.) Biotite and plagioclase are generally fresh but locally can be altered to chlorite and sericite respectively. The rock is generally massive and unaltered in unweathered exposures. Local textural and compositional variation is common, with either sharp or gradational contacts. Composite bodies of aplite with pegmatite cut or grade into normal porphyritic quartz monzonite. Dike- and sill-like offshoots 1 to 20 m thick are common near the intrusive contact. Xenoliths are rarely seen, but schlieren of biotite-rich material are frequently present in the upper 10 m of the main pluton near the intrusive contact. The contact with the metasediments is often concordant, hence steeply dipping, as will be seen in cross sections to be discussed later. The intrusive contact is generally tight and frequently gradational over as much as a metre owing to infusion of felsic material. No quartz or sulfide veins, or uranium mineralization of economic significance have been identified in the quartz monzonite. However, this rock regionally contains anomalous amounts of uranium (average 12 ppm), about three times normal abundance in rocks of this composition.

Faults in the mine area have small displacements and are not abundant. Small faults or shears in the pits generally trend near N-S, are steeply dipping, and generally die out along bedding planes. Some rock geometries immediately south of the mine dump (fig. 3) could be faults, or might be irregularities in the intrusive contact. Some faults in the Boyd 2 pit, whose displacement could not be determined, could be traced for about 100 m in metasediments but were observed to horsetail and die out within a few metres upon entering the porphyritic quartz monzonite. The fault with largest apparent displacement and crushing involved a felsic mid-Tertiary dike exposed 30 m north of the section shown on figure 4. A block of calc-silicate rock is displaced at least 20 m laterally from its closest source, or could be moved 30 to 50 m northward by strike slip movement. The ore zone continues with no apparent offset across this fault and shear zone which is about 20 m wide.

Irregularities in the intrusive contact often have spatially associated zones of intense fracturing. A protruding knob on the intrusive contact in the Boyd 2 pit (fig. 3) is surrounded by a stockwork fracture zone measuring at least 60 m by 45 m. Such fracturing is an important control on distribution of ore.

Petrology of host rocks

Petrographic and X-ray diffraction study of the Precambrian rocks is of considerable value in ascertaining their mineralogy and texture. Dark colors and fine grain size often obscure rock type and complicate identification. In the contact metamorphic environment of the mine area dark gray to green, massive graphitic mica hornfels, garnet-diopside hornfels, and amphibolite are easily confused but can be quickly and reliably identified under the polarizing microscope; X-ray diffraction is a cheaper and faster method for reliable identification of minerals, but of course does not provide textural information. Reliable petrologic identification is required for stratigraphic understanding of individual rock units when correlated in detail between drill holes on 50-foot (15-m) centers.

Some generalized conclusions regarding metasedimentary stratigraphy may orient the reader unfamiliar with these rocks. It appears that two basic depositional rock types are present in the Togo Formation: calcareous and pelitic. The pelitic type appears to have been deposited as a monotonous sequence of black shale with very few interbeds of differing composition or grain size. This conclusion is derived from field exposures and petrographic study of metamorphic assemblages. The calcareous type, on the other hand, is highly variable in present mineralogy and occurs in discontinuous lenses of a kilometre or so in length, and 50 m or less in thickness. In the latter rocks, lithology is highly variable because of differences, in both original composition and in metamorphism, whereas lithology of metapelites appears to be largely a function of degree of dynamic metamorphism. The short range lithologic variability, for different physical and chemical reasons, in both rock types severely hampers efforts to establish detailed stratigraphic relations.

The minerals quartz and muscovite are always most abundant in metapelites, and andalusite porphyroblasts several millimetres long are common in amounts of about 10 percent. K-feldspar may occur in bands (beds) in which andalusite is not present. Red-brown biotite, generally 0.1 to 0.5 mm in size, generally is present in rocks within about 50 m of the pluton. Metapelites near the pluton also contain small pleochroic yellow crystals of tourmaline. Fine-grained graphite is present in all metapelites, and pyrite, with or without pyrrhotite or marcasite, is present in amounts up to about 2 percent. Chlorite is not present in metapelites in the mine area except as a retrograde product replacing former biotite, and no cordierite has been recognized (but could have been retrograded to clay). The minerals present suggest metamorphic conditions of the quartz-andalusite plagioclase-chlorite subfacies of Abukuma-type (low pressure) metamorphism (Winkler, 1967).

Textural variations in metapelites are more prominent than mineralogical. Grain size of mica ranges from about 25 micrometres to several millometres. Rock textures range from massive hornfels to phyllite to schist. Mica (sericite) grain size in the hornfels and phyllite is less than 1/10 mm, whereas foliated metapelites contain porphyroblasts of mica (muscovite) 1 to 5 mm in size. A general increase in grain size is noted as the pluton is approached, but no simple rule of thumb could be established because local factors such as degree of shearing, and presumably water pressure, are important determinants of fabric. Rocks here called schist have megascopically visible muscovite and break easily along a foliation defined by thin laminae with differing content of major minerals; the laminations seem to be caused by mineral segregation during shear. Foliation in pelitic phyllites and schists generally appears to be parallel to bedding, although bedding-foliation intersections are recognized in some localities.

Calcareous rocks in the mine area are generally bleached to light shades of tan, green, or near white, and bed thickness ranges from about a centimetre to nearly a metre. The phases calcite, quartz, diopside, garnet, tremolite, plagioclase, and phlogopite are most abundant, but wollastonite, idocrase (vesuvianite), and scapolite also occur. These minerals form in either the hornblende-hornfels or pyroxene-hornfels facies (Turner, 1968). The mineralogical diversity of the calc-silicate rocks is interpreted as indicating a range in original composition as well as variation in intensive parameters (T, P_{H_2O}, P_{CO_2}) during metamorphism. Magnesium in these rocks is carried in diopside, phlogopite, and idocrase rather than in dolomite; no dolomite has been detected in numerous X-ray diffraction determinations. Calc-silicate rocks are generally fine grained: calcite grains are less than 1/2 mm and diopside commonly less than 1/10 mm, but garnet and idocrase porphyroblasts can be as large as 5 mm.

The fabric and composition of amphibolites is very consistent. The major mineral is invariably hornblende, which is present as equant to rectangular crystals generally less than 1 mm in size. Hornblende commonly occurs in radiating clusters set in a fine matrix of intergrown quartz and plagioclase. Amphiboles from various localities have colors ranging from deep blue green to pale green as seen under the microscope. The amount of amphibole relative to felsic matrix (quartz plus plagioclase) varies from about 50 to 75 percent amphibole. Some amphibole is altered to red-brown biotite or to chlorite, and iron oxides commonly are replaced by pyrite. Coarse crystals of sphene, in amounts to several percent, are a prominent feature. To the unaided or untrained eye fresh amphibolites have the appearance of diabase dikes, hence petrologic study is advised by any newcomer.

In weathering the pelitic and calcareous rocks react much differently. Pelitic rocks can survive nearly fresh to the surface, although pyrite invariably oxidizes leaving iron-oxide stained cubic molds. In some near-surface zones, metapelites are silvery colored rather than black, presumably from oxidation of graphite. In drill holes samples of metapelite are nearly always dark, coherent, sulfide-bearing, and fresh-appearing at depths of 30 m or less. Weathering characteristics of calc-silicate rocks depend upon their composition. Diopside-rich rocks appear to be least resistant, whereas siliceous varieties or nearly pure marbles can be quite resistant. In general calc-silicate rocks are less resistant to weathering than metapelites; this probably is one reason why very little calcareous Togo Formation is shown on published maps. In the Boyd 2 pit, calc-silicate rocks are punky from weathering to depths of about 60 to 75 m below the original surface. Amphibolite weathers to very dark brown soil for depths of several metres or can persist in a fresh state that is hard and coherent and forms coarse float.

DESCRIPTION OF URANIUM DEPOSITS

Deposits of oxidized and reduced uranium minerals occur in metasedimentary rocks along the intrusive contact at the western edge of the roof pendant. Seven open pits (indicated on fig. 3) have developed ore, but some of the orebodies are basically continuous across pit limits which were defined chiefly by economic factors including short term contracts. The general distribution of significant uranium is shown on figure 5. Note that on this figure the mineralized zone is that containing five or more feet averaging 0.05 or more percent U_3O_8; the zone marked may not always be ore. Some of the deposits, such as those mined by the adit pit, pit 2W and pit 2E (figs. 3 and 5) are clearly small but could be mined because they were near the surface. These orebodies contained oxidized uranium minerals, chiefly meta-autunite. An important feature shown on figure 5 is that two mineralized zones, mined as the Boyd 1 pit and number 2 pit on the west and Boyd 2 pit on the east (fig. 3) are respectively 380 m by 170 m and 300 m by 210 m. This description differs from previous ones (e.g. Sheldon, 1959) which state that orebodies range up to 700 feet (210 m) long by 200 feet (60 m) wide. The discrepancy comes from differing definitions of minimum grade of uranium zones. The presently defined size should be of interest to exploration geologists because it points out that the target is considerably larger than previously described. Major ore values in the three largest mineralized zones (fig. 5) came from reduced minerals (pitchblende and coffinite)[1]. Host rocks have been, in order of decreasing tonnage, metapelite, calc-silicate hornfels, amphibolite, and "granite".

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[1]All black uranium minerals observed by the authors are fine grained and yield X-ray patterns with broad peaks. The uranium oxide phase is best termed pitchblende because it contains only small amounts of lead and thorium and rare earth elements, often is colloform, and is poorly crystallized.

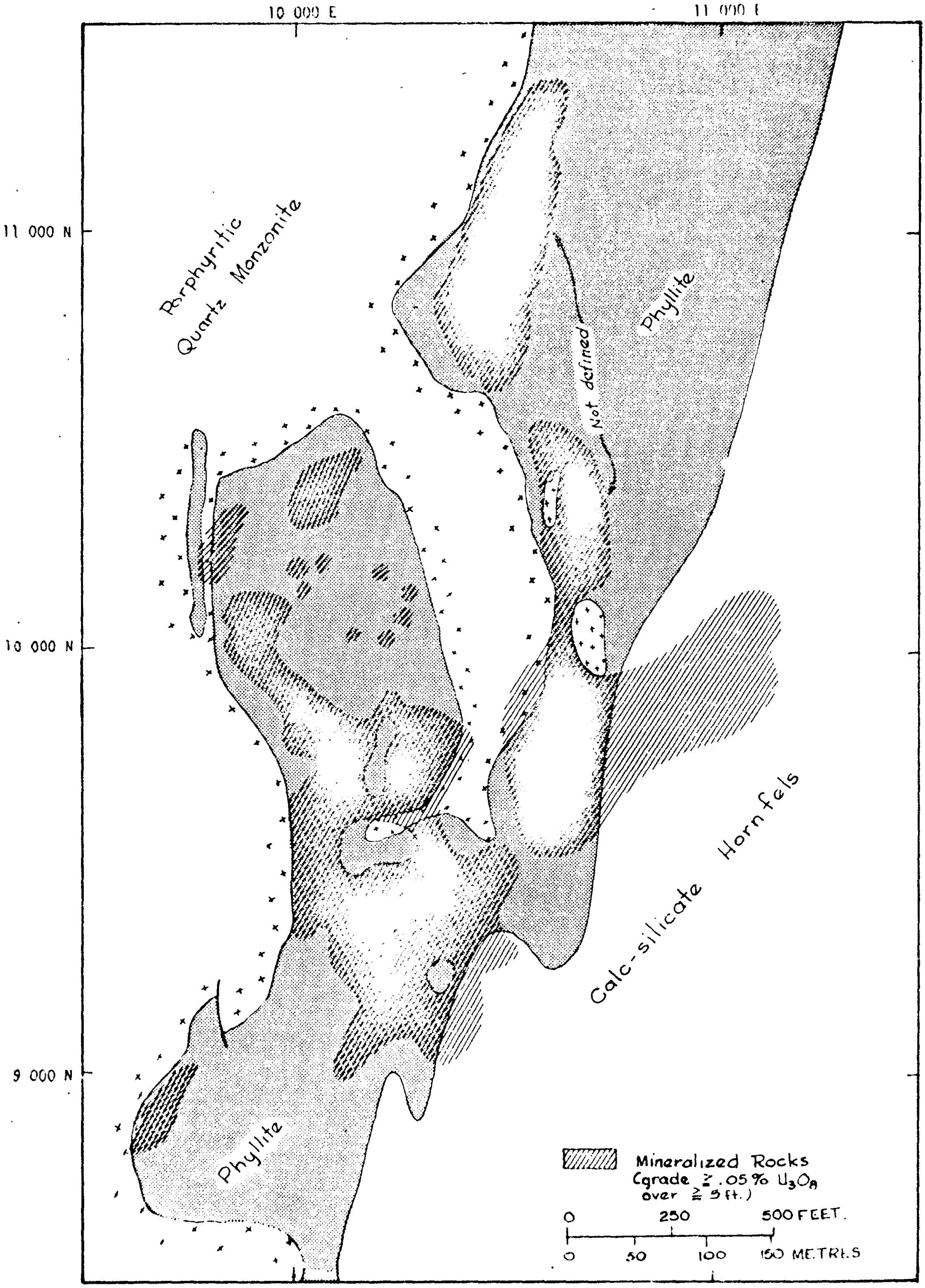

Figure 5.--Plan map of distribution of uranium mineralization at the Midnite mine. Mineralized rocks (crosshatched) contain ≥ 0.05 percent U_3O_8 over ≥ 5 ft. Also shown is generalized geology at original surface. (Compiled from Dawn Mining Co. records.)

Uranium in metapelites

Pelitic rocks metamorphosed to schist, phyllite, and hornfels have been the host for most of the uranium at the Midnite mine. The host rock in the Boyd 1, 2, and 3 pits is schist, whereas in pit 6 it is phyllite, and most of the western part of Boyd 2 pit is in mica hornfels. In schist and phyllite uranium minerals seem to have occurred chiefly along local shears, generally in the plane of foliation, and as disseminations along foliation; only a small amount of this ore has been observed by the author in remaining pit outcrops and in drill core. Massive mica hornfels in the Boyd 2 pit contained pitchblende and coffinite in numerous small stockwork fractures. The widest veinlet of pitchblende and pyrite seen by the authors is 6 mm and most are 2 to 3 mm wide.

Mineralogy of uranium-bearing metapelites seems to be the same as barren equivalents. Petrographic and X-ray diffraction studies of unweathered barren and mineralized metapelites disclose the same silicate minerals. No alteration selvages have been detected along the pitchblende veinlets studied. Very few grains of chalcopyrite and sphalerite have been observed other than in one 10 cm wide vein in the Boyd 2 pit; this vein contained very little uranium, and that present could easily be secondary. Molybdenite is observed in some metapelites within a metre of the intrusive. From available exposures and textural relations it seems that the base-metal sulfides are not the same age as the uranium minerals. Pyrite and marcasite are the sulfide minerals cogenetic with pitchblende and coffinite.

Hydrothermal quartz is extremely rare in metapelitic rocks. In more than 100 thin sections only a few grains of possible hydrothermal origin have been seen. Veinlets about a centimetre thick described by Barrington and Kerr (1961) most likely are metamorphic segregations. Also pyritic quartz bodies described as veins (Barrington and Kerr, 1961) are quartzite beds. Under the microscope they are seen to be recrystallized well sorted, nearly pure sandstone. In zones of shear these beds break apart into long boudins. No quartz observed to date is of the right age or type to use for fluid-inclusion studies of uranium emplacement. All fluid inclusions seen are secondary type, and probably formed during metamorphism.

Uranium in calc-silicate hornfels

Important amounts of ore occur in calc-silicate rocks in the south end of the Boyd 1 and east side of the Boyd 2 pits (figs. 3 and 5). Calc-silicate rocks were once believed to be an unfavorable host because they were considered to be too ductile for extensive fracturing (Sheldon, 1959). This analysis of structural behavior may be correct, but the conclusion is now known to be overgeneralized because uranium minerals have a different physical setting in the calcareous rocks as compared to metapelite hosts. In calc-silicate rocks uranium occurs chiefly along bedding laminations and in thoroughly altered (often crushed or brecciated) zones. Discordant fractures are important in some siliceous calc-silicate beds. Favorable host rocks generally have compositional banding in which layers (beds) of diopside, epidote, and tremolite alternate with calcite and quartz. The magnesian silicates, chiefly diopside, commonly are altered to green montmorillonite (as determined by numerous X-ray diffraction patterns; it has the appearance of chlorite). Broken zones a centimetre to a metre thick contain large amounts of montmorillonite clay. There is no simple spatial correlation of uranium (pitchblende) with montmorillonite altered bands and breccia, and textural features are ambiguous as to relative ages. Our impression is that the montmorillonite was important for uranium deposition, but that emplacement of uranium probably followed alteration.

Diopside- and montmorillonite-rich zones contain more pyrite than adjacent light colored beds, presumably because of higher initial content of iron. Pyrite in the hornfels has granular texture suggesting it could have formed along with the calc-silicate minerals during contact metamorphism. Pyrite also could have formed during montmorillonite alteration, a process that could have been retrograde metamorphism, hydrothermal alteration, or supergene alteration. (The problem here is partly semantics, but chiefly one of uncertainty as to times of formation.) The iron- and sulfide-rich character of the dark green bands probably was important chemically for localization of uranium.

Uranium in amphibolite

Sill-like bodies of amphibolite are exposed in five pits and have been intersected in numerous drill holes. In virtually all cases, the amphibolite is barren of uranium mineralization other than that in the outer few centimetres along the contact. Amphibolites in the immediate mine area are nearly always pyritic, the pyrite having replaced earlier magnetite. Because amphibolites are typically strong and massive with very few fractures, it may be presumed that uranium-bearing solutions could not enter the amphibolite in sufficient quantity to make ore. Chemically, the pyritic, iron-rich amphibolites should have been favorable host rocks.

Reduced and oxidized uranium minerals of ore grade have recently been encountered in the eastern part of the Boyd 2 pit where these amphibolite bodies are concordant with calc-silicate rocks. The sills are about 8 m thick and dip about 80°E. One body contained several thousand tons of autunite-type ore where the amphibolite was broken, weathered, and moderately oxidized (fig. 4). Enclosing calc-silicate rocks contained only minor autunite, hence the amphibolite must have provided a favorable environment. At greater depth two amphibolites contain important amounts of pitchblende ore (fig. 4). These amphibolite bodies are not known to be chemically or mineralogically distinct from other barren ones, but are cut by numerous brittle fractures. In this area the amphibolites carry better grade and thickness of ore than adjacent calc-silicate rocks. From this example we learn that amphibolite can be a favorable host for uranium if permeability is adequate

Uranium in granitic rocks

Granitic rocks (porphyritic quartz monzonite, aplite, and pegmatite called granite by miners) in the mine area are clearly the least favorable host for uranium. It is now axiomatic that uranium occurs in only a few centimetres of granite at the contact if at all, and in mining excavation generally stops right at the contact when that is practical. A few fractured zones contain local pockets of pitchblende ore at the contact, and much of the autunite-type ore in the adit pit (fig. 3) was in fractures in granite. Two factors seem to explain the general paucity of uranium in the granite: low permeability and lack of enough reductants. The main granite intrusive is not fractured nearly as much as the metasediments and faults tend to be tight. Chemically the granitic rocks are leucocratic, and generally not pyrite-bearing. Local biotite-rich xenoliths, schlieren, and hybrid zones near the intrusive seem to be uranium-bearing more commonly than normal compositions.

No quartz veins have been observed by the author in granitic rocks in the mine area, and none reported. Likewise no pitchblende veins have been reported. Granitic rocks generally show only mild deuteric alteration. Argillic alteration is observed in some drill core, but that could represent supergene effects as well as high temperature hydrothermal alteration. The paucity of clearly defined hydrothermal alteration and structural conduits seem to pose real problems for genetic models hypothesizing direct hydrothermal emplacement of uranium from the granite into adjacent wallrocks.

Geometry of uranium deposits

Distribution of uranium minerals as disseminations along foliation, in shear zones, and in stockwork fractures has been described earlier. Discussion will now focus on the gross geometry of deposits. Figure 3 conveys the horizontal extent of deposits in metasedimentary wallrocks. Figures 4 and 6 are cross sections through deposits. Together these figures demonstrate that the deposits are oriented horizontally rather than vertically. Deposit width nearly always exceeds depth. Other distinctive geometric features are (1) the close coincidence of thicker zones with depressions in the intrusive contact; (2) the subhorizontal upper limit of mineralization in many areas, (3) presence of intrusive ribs of granite bounding mineralized zones.

The plan map (fig. 7) of the western mineralized zone plotted on a topographic map of the intrusive contact documents in three dimensions the strong coincidence of thicker sections of mineralization with depressions in the granite contact. Clearly there is no one-to-one correspondence, but most sections of mineralization more than 20 feet (6 m) thick occur near the centers of basins or troughs in the granite. The small deposit mined as pit 2W (fig. 3; north end fig. 7) is enclosed in its own little basin, and the deposit mined as pit 2E occurs in a depression on the side of a larger basin. The majority of the western mineralized zone is enclosed except to the south, by the 2840 foot contour (fig. 6 and 7). Also, it should be pointed out that deposits occur at similar elevations on both sides of the north-trending granite rib between the Boyd 1 and Boyd 2 pits (figs. 3, 4, 6, and 7). Unfortunately records do not permit plotting of the elevations at which uranium mineralogy changed from predominantly oxidized to reduced.

Controls of uranium distribution are certainly open to interpretation, but several descriptive and interpretive aspects bear emphasis. (1) Mineralized zones clearly cut across lithologic boundaries. The implications of this feature are at least twofold: that chemical factors do not predominate in uranium deposition, and that ore occurs where permeability is appropriate. (2) The tabular form of orebodies does not reflect any geologic feature in the metasediments. Major permeable zones (shears, foliation, bedding) are steeply dipping. The horizontal nature of ore zones is interpreted to reflect the influence of ground water controls such as ground water tables or perched ground water tables. The present distribution or redistribution of oxidized and reduced uranium minerals is presumed to reflect the combined influence of permeability and ground water controls. (3) Deposits occur above or adjacent to the intrusive. A geochemical reason for this is the presence of minerals in the metasediments that are potentially important for reduction (pyrite, graphite?, iron in silicates) or neutralization (calcite) of uranium-bearing solutions. Structurally, the metasediments have more permeability than the granite.

Permeability and ground water influence were emphasized by Sheldon (1959) for oxidized ores. Observations on pitchblende ores suggest that they also are subject to these controls. The reduced ores are nowhere either conclusively primary or secondary because, in our opinion, no unambiguous criteria exist to differentiate the two. The terms primary and secondary are not used to describe ore because they are clearly interpretive.

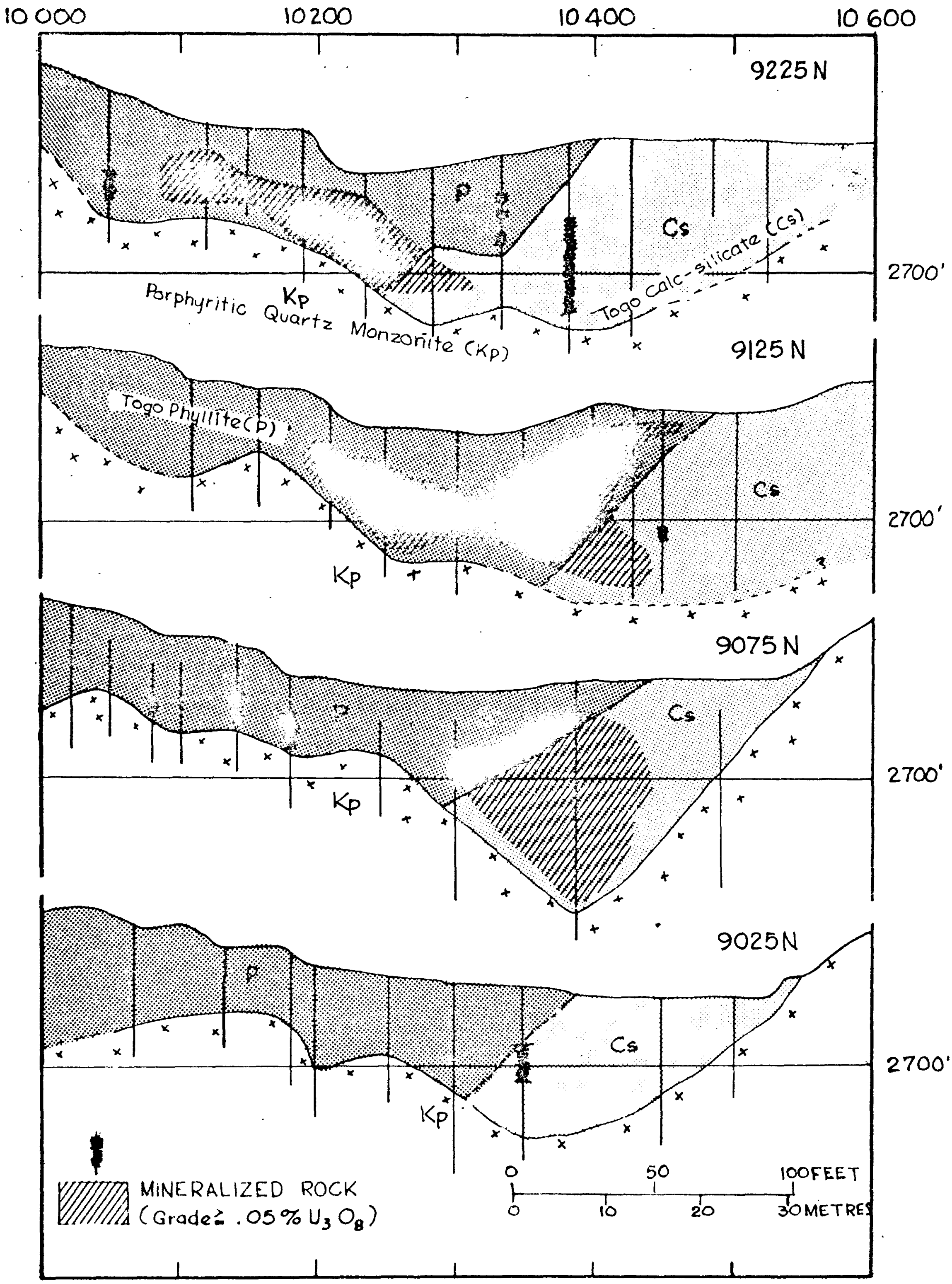

Figure 6.--Cross sections showing generalized geology and distribution of uranium mineralization in a western ore zone mined as Boyd 1, 2, 2W, and 2E pits. (Compiled from records of Dawn Mining Co.)

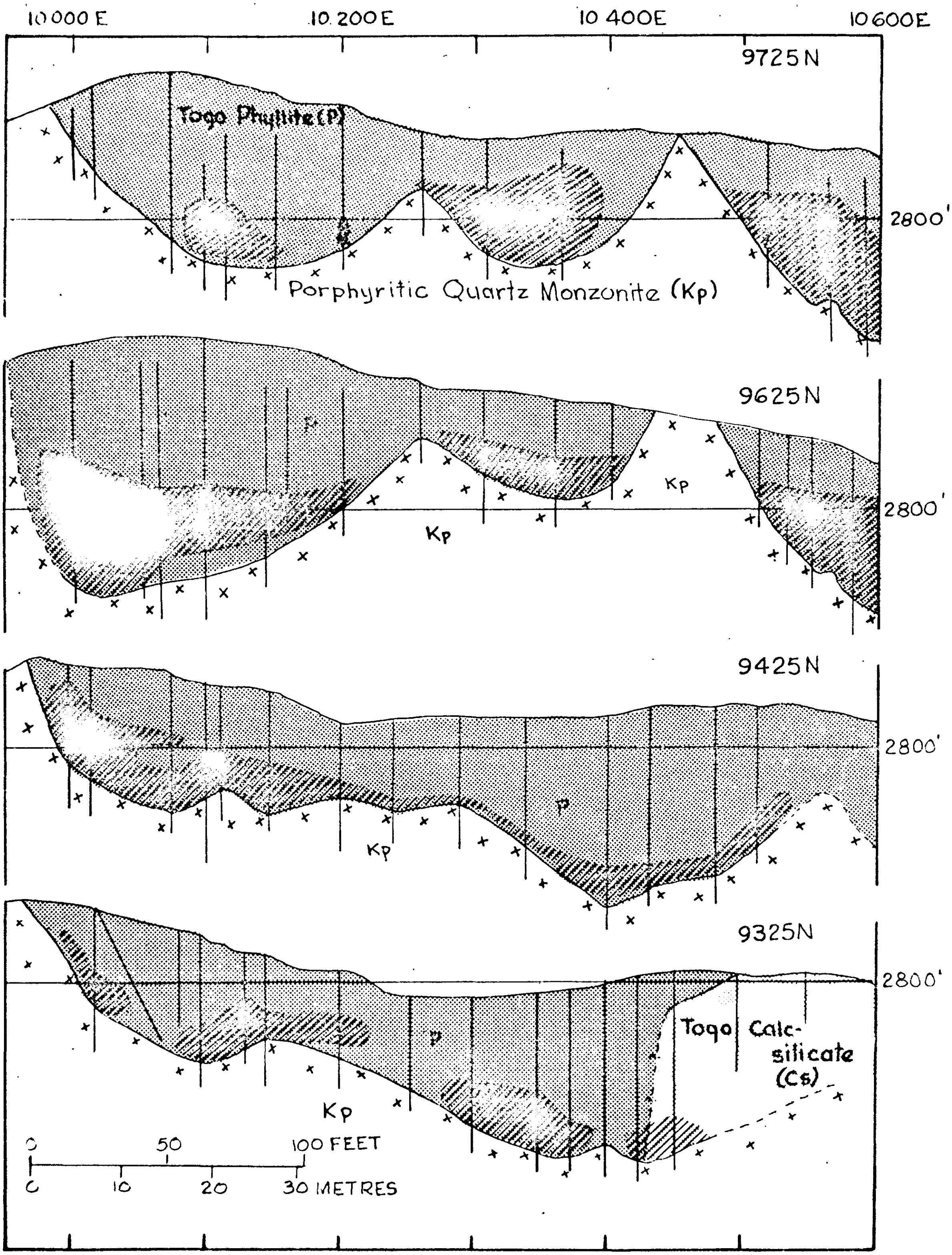

Figure 6.--Continued

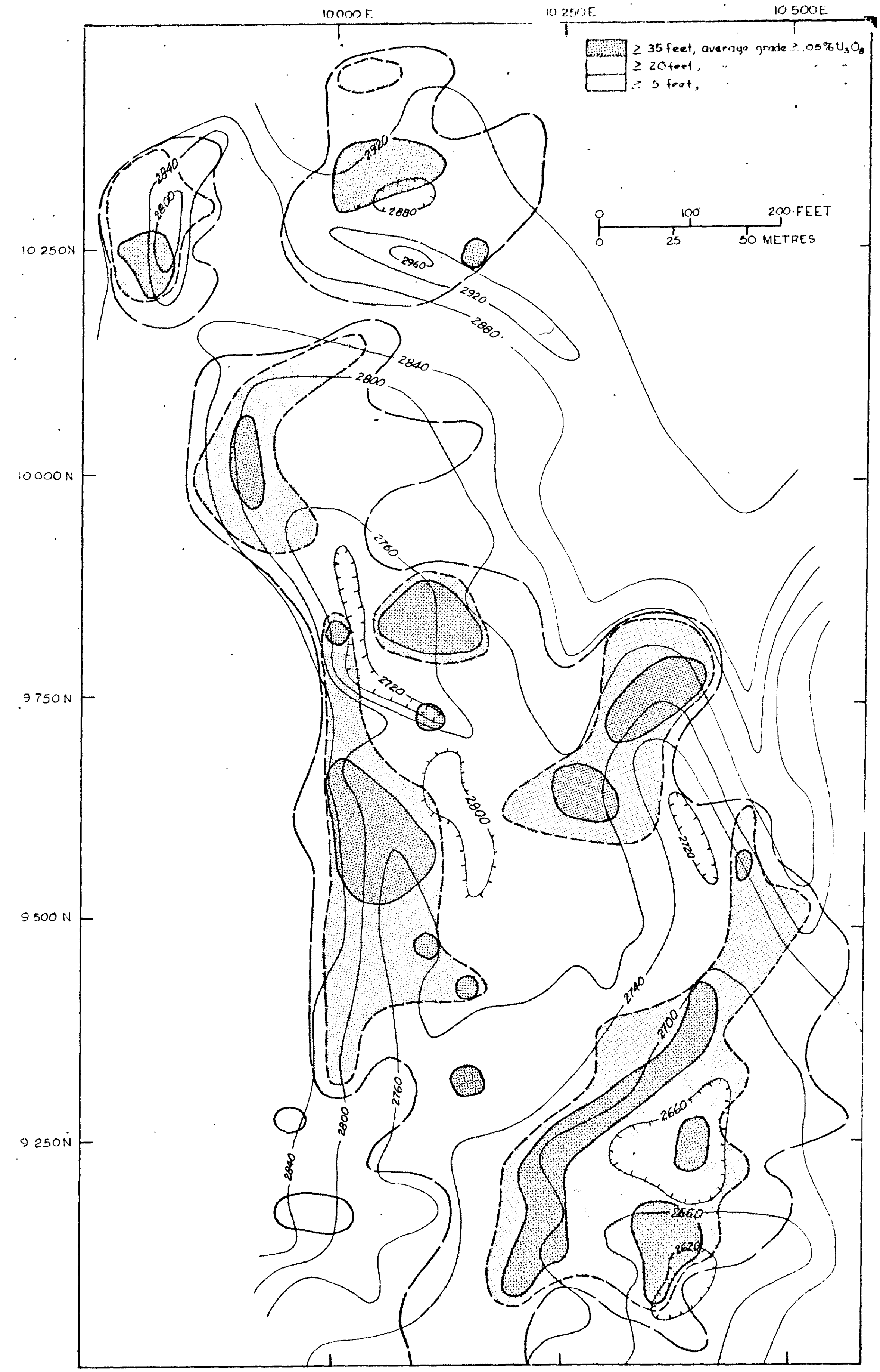

Figure 7.--Plan map of western ore zone showing thickness of mineralized zones and topography of the upper surface of granite body (contours on intrusive contact). Note the good correspondence of thicker mineralized zones with depressions in the granite. (Compiled from records of the Dawn Mining Co.)

MINOR ELEMENT GEOCHEMISTRY

Averages of chemical analyses of 42 samples of mineralized and unmineralized metasedimentary rocks are in table 1. Most elements were determined by six-step D.C. arc spectrography by J. M. Motooka and R. T. Hopkins. Total sulfur was determined by combustion and titration with iodine, and total carbon (carbon plus carbonate) gravimetrically by absorption on ascarite; analyst for S and C was Z. C. Stephenson. Se was determined by a fluorometric procedure by George Crenshaw. The data available suggest that only a few elements are anomalous in the ore zones and that the magnitude of these anomalies is small. Best pathfinder elements seem to be Mn, Nb, S, Cu, and possibly Mo.

Data for metapelites are in three classes: background (<20 ppm U, collected more than 1 mile from the mine), low grade (up to 300 ppm U), and ore (greater than 300 ppm, collected from ore zones). Background samples may not be truly representative because they are surface samples, and although very fresh have undergone oxidation. Elements of possible utility in defining halos are Cu, Mo, Co, Ni, Nb, Mn, and S. The elements As, Nb, Pb, W, and Y seem to be enriched right in the ore zone and probably would not serve as a guide to ore. Molybdenite is visible in granitic rocks and in metasediments within about 1 m of the intrusive, but has not been seen in ore samples. Most Mo probably is a contact metasomatic addition to wallrocks and probably predates uranium, and smaller quantities may have been redistributed by later processes; Mo may not be a relaiable guide to uranium. Co and Ni anomalies are modest and because these elements are chalcophile they surely occur primarily in sulfides, hence may serve best as an indicator for sulfur. Total sulfur, mostly as sulfide, is enriched in ore zones, and together with iron is suspected to be important as a reductant, hence it is a significant element to determine in geochemical exploration. Total iron may be enriched in the mineralized zone, hence may provide a clue to favorable areas.

Elemental abundances are different, as one might expect, in the calc-silicate rocks as compared to the metapelites (table 1). Some elements considered anomalous in metapelite ores are not anomalous in mineralized calc-silicate rocks (viz. As, Mo, Nb). Only Cu, Fe, and S seem anomalous in calc-silicate rocks.

Table 1.--Chemical analyses of metasedimentary rocks from the Midnite mine area.

[Looked for but not detected: Au, Bi, Cd, Sb, Sn. J. M. Motooka, R. T. Hopkins, Z. C. Stephenson, and George Crenshaw, analysts.]

	Metapelitic rocks			Calc-silicate rocks	
	Background	Low grade	Ore	Low grade	Ore
	Minor elements in parts per million				
Ag	ND[1]	0.1	0.1	ND	0.3
As	ND	ND	120	50	25
B	53	43	24	10	18
Ba	500	320	410	620	540
Be	1.2	1.6	2.2	1.1	1.0
Co	5	23	32	26	15
Cr	82	58	67	62	45
Cu	12	48	49	23	140
La	50	57	49	48	13
Mo	0.5	39	47	7	5
Nb	ND	12	81	18	9
Ni	8	43	39	24	16
Pb	10	15	41	21	16
Sc	15	13	20	10	9
Se	.2	.9	1.5	0.5	1.4
Sr	ND	5	11	300	260
Th	16	18	19	10	11
V	130	130	150	72	71
W	ND	14	25	8	19
Y	27	36	83	57	49
Zn	ND	ND	90	17	42
	Major elements in weight percent				
Fe	1.4	2.1	2.7	2.0	3.3
Mg	0.6	0.7	1.1	2.4	2.5
Ca	0.05	.1	0.3	9.3	10.6
Mn	0.1	.7	0.9	1.0	1.2
S	0.01	1.2	1.5	.69	.41
C	0.3	0.8	0.9	3.8	3.4
N	5	11	9	6	12

[1]ND, not detected.

Thorium concentrations in mineralized rocks are low and do not correlate with uranium. This behavior suggests that uranium has been separated from thorium. Separation of uranium and thorium could have occurred by selective transport of uranium by hydrothermal or surficial fluids, possibly by oxidized carbonate-rich solutions known to render uranium soluble. The paucity of thorium in the ores might be evidence against hydrothermal emplacement of uranium to its present position, or might simply mean that the hydrothermal fluids could not transport thorium.

These preliminary analytical results are not very encouraging for application of geochemical prospecting to exploration for this type of ore. Only a few elements appear to be anomalous in ore and their abundance is low. Manganese and sulfur can be expected to be erratic in surface samples because of oxidation effects, hence probably would be unreliable. Copper, cobalt, nickel, and niobium may be valid and detectable pathfinder elements. Anomalies in surface samples would probably be of small magnitude and difficult to recognize relative to background.

Analyses of granitic rocks for U and Th by Carl Bunker using multichannel gamma ray spectrometry indicate that the uranium content of the porphyritic quartz monzonite is roughly three times the crustal average for rocks of this composition. Average content of radon equivalent U (Ra eU) and Th are 12.5 and 28.9 ppm, respectively, for "fresh" samples of porphyritic quartz monzonite; this rock is enriched in Th but not as much as in U. Samples of granodiorite average 5.0 ppm Ra eU and 15.8 ppm Th, and samples of quartz monzonite from other intrusive bodies in the Turtle Lake quadrangle (cf. Becraft and Weis, 1963) average 5.1 ppm Ra eU and 18.3 ppm Th; these plutonic rocks have normal content of U and Th. Aplitic stringers and pegmatite within the porphyritic quartz monzonite contain an average of 4.2 ppm Ra eU and 20.7 ppm Th; there does not appear to have been enrichment in U and Th during differentiation.

The regional content of uranium determined here for the porphyritic quartz monzonite (average 12.5 ppm) should be considered a minimum estimate because no samples could be collected from deep or unweathered locations. The value of about 12 ppm U is clearly highest for the plutonic rocks of the area and suffices to define this rock as anomalous and as a possible source of uranium. Slightly weathered granitic rocks in other areas with similar uranium content should be considered favorable for formation of uranium deposits (cf. Marjaniemi and Basler, 1972).

EMPLACEMENT OF URANIUM

Conditions of uranium emplacement are poorly understood because of uncertaintly regarding the time(s) of uranium deposition and the lack of mineral assemblages that are diagnostic of temperature and pressure. The following discussion is directed at the reduced ores.

It is possible that pitchblende ores have been deposited over a span of time from immediately following intrusion of the porphyritic quartz monzonite (Cretaceous?) to recent. Evidence for emplacement of uranium during Cretaceous(?) magmatism is largely circumstantial. Lead-uranium age determinations on pitchblende are 102 and 108 million years, but true ages could be younger if the discordant ages indicate that isotopic leaching occurred (Becraft and Weis, 1963). A fault which displaces a dacite dike, probably Oligocene in age, contains oxidized and reduced uranium minerals and does not appear to offset the Boyd 2 ore zone (fig. 4). It is quite possible that much of the stockwork fracturing in the Boyd 2 pit is related to the mid-Tertiary faulting; uranium in those fractures was deposited (or redeposited) at some later date. Present ground water in the mine area is rich in uranium and oxidized uranium minerals are forming today where the ground water table fluctuates, hence black uranium minerals might also be forming today in the reduced zone.

Times of formation of clay minerals are ambiguous. It is conventional to regard the minerals kaolinite and montmorillonite as hydrothermal, as Barrington and Kerr (1961) have argued. However, these minerals also can form by weathering. Also, the Oligocene dacite dikes are extensively altered to montmorillonite and appear to have created an argillic alteration halo as much as 10-20 m from the dikes. Hence it seems possible that there were several times of alteration. Further confusing the age problem is the fact that uranium veinlets do not have alteration envelopes, hence the uranium could be much younger than the alteration.

A period of possible importance to the formation of uranium deposits in Washington was the Excelsior weathering period (Miocene?), during which deep weathering created clay deposits (Hosterman and others, 1960). Granitic rocks were among those weathered to clay deposits up to 30 m deep; this process could easily have freed uranium to ground water for migration to sites of deposition as oxidized or reduced minerals.

Geochemistry of uranium deposition can be estimated from several phase relations, but only approximate limits can be set for temperature because the uranium and associated phases are stable over a broad range of temperatures. The association of pyrite and marcasite with reduced ores indicates reducing conditions as are known to be required for pitchblende and coffinite. Marcasite is a sulfide whose formation remains open to question; some believe it is formed from solutions which are slightly sulfide deficient relative to pyrite. Marcasite often forms elsewhere by replacing pyrrhotite; this reaction possibly indicates metastable formation or sulfide deficiency. Pyrrhotite has been identified from Midnite mine, but is not associated with uranium and is found elsewhere in the Togo Formation. Hydrothermal experiments suggest that pyrite or pyrrhotite are the stable Fe-S phases down to temperatures of at least 150° C, at which temperature experiments are not reliable owing to slow reaction rates (B. Rising, written commun., 1973).

Clay minerals associated with uranium do not provide much geochemical information because they may not have formed with the uranium minerals and because they have broad stability fields. Montmorillonite is the clay most likely to be contemporaneous with pitchblende--its formation indicates neutral to alkaline solutions as seems logical for fluids in equilibrium with carbonate rocks. Although most iron in montmorillonite is generally ferric, some ferrous iron probably was present and could have served as a reductant. Associated pyrite could also have served as reductant. If solutions in phyllite and schist were near neutral, mica in those rocks would be stable, hence no alteration would be expected--this may be the explanation for the apparent lack of alteration in most metapelites.

Additional information may possibly be derived from the presence of a brown-black to black, vitreous, apparently X-ray amorphous phase called hisingerite. If correctly identified this phase is a hydrous iron silicate, probably containing manganese and other minor elements. If hisingerite behaves basically like $FeSiO_3$, phase diagrams for Fe-S-SiO_2 (Garrels and Christ, 1965, p. 224-227) show that the iron silicate displaces magnetite and hematite in neutral to alkaline solutions at 25° C. This seems geologically reasonable for an amorphous phase in and near calc-silicate rocks. Hisingerite is a common occurrence in stockwork veinlets in the Boyd 2 pit and can easily be confused for pitchblende. Some hisingerite-bearing veinlets contain pyrite, pitchblende, coffinite, and cryptocrystalline quartz. This assemblage could form at pH 7 to 8, -0.4 volts Eh, at about 25° C.

The role of carbonate complexes in transportation of uranium has been widely discussed for sandstone-type deposits (Hostetler and Garrels, 1962), and this mechanism should be considered for transport of uranium to the Midnite mine deposits. Carbonate solutions are clearly good solvents for uranium under oxidizing conditions. Uranium can be deposited as pitchblende by breaking carbonate complexes through reduction or decreasing pH to about 7 or 8. The supply of carbonate solutions from carbonate rocks in the mine area may have been an important factor in formation or enrichment of deposits.

The following model for multistage emplacement of uranium presently appears to explain observed features; the model is clearly hypothetical and is not fully documented or proven.

1. Emplacement of porphyritic quartz monzonite, fracturing of enclosing metasediments, and introduction of some uranium as fracture-fillings and disseminations. Deposits at this stage were possibly of low average grade and dispersed over a greater vertical range than at present, hence probably would not be economic.

2. Emplacement at shallow depth of mid-Tertiary dacite dikes with shearing and fracturing. Heat and fracturing disrupt ground water conditions and cause hydrothermal alteration. Probably some uranium in wallrocks was mobilized, possibly resulting in downward reprecipitation and enrichment.

3. Weathering of granitic and metasedimentary rocks during late Tertiary. Lateral (chiefly to south?) and downward migration of uranium, formation of oxidized uranium minerals above, and reduced minerals below a fluctuating water table. Probable introduction of additional uranium which had been leached from granitic rocks. Present ore grades probably established at this stage where permeability and ground water table were favorable.

SUGGESTIONS FOR EXPLORATION

These preliminary findings and interpretations suggest some new approaches to exploration for deposits like those of the Midnite mine. The suggestions of Sheldon (1959) remain valid with some minor qualifications. The following suggestions are arranged in order of scale.

1. Select an area with a likely source for either hypogene or supergene fluids carrying uranium. Granitic rocks are perhaps most likely, but volcanic rocks should not be discounted. The reconnaissance of granitic rocks in the western U.S. by Marjaniemi and Basler (1972) may provide a starting reference.

2. Prospect areas should contain sedimentary or metasedimentary rocks suspected to possess favorable physical and chemical properties. Sedimentary or fracture permeability and compositions which are carbonaceous, pyritic, or ferromagnesian are favorable.

3. Airborne gamma radiation surveys, preferably multichannel, may be helpful in defining areas for exploration or land acquisition. However, problems from thick soil cover, typical leaching of uranium near the surface, and rugged topography may invalidate radiation surveys in most terrain, especially in the northwest U.S. Airborne very low frequency (V.L.F.) surveys may be useful for definition of fault zones or stratigraphic zones containing conductors such as sulfides or graphite with favorable geochemical properties for localization of uranium.

4. More specific studies after land acquisition should include geologic mapping, and possibly one or more of the following techniques. (a) Geochemical prospecting using soil or stream sediment samples. This technique is considered to be of questionable validity considering the weak minor element characterization of even fresh ore samples and the well known mobility of uranium. Some soil sampling in the Togo Formation has demonstrated considerably larger anomalies of uranium, up to about 100 ppm, than the average of samples taken over and adjacent to Midnite mine deposits. Preliminary results of a biogeochemical survey using uranium in the ash of Ponderosa pine needles are encouraging and the method is being tested further. (b) Ground geophysical surveys using electrical methods induced polarization (IP), resistivity, and V.L.F. These techniques may be useful in delineating conducting zones with possible sulfides, magnetite, or graphite, which could localize uranium. Electrical surveys also appear to be the best geophysical technique for determination of the configuration of the granite-metasediment contact (D. Campbell and B. Smith, oral commun., 1975). (c) Magnetics. Ground magnetometer surveys might be useful if magnetite or pyrrhotite is present in a mineralized zone, and could assist in defining concealed bodies of granite, and are good for defining contacts of igneous rocks. Results to date suggest that this method is not as useful for characterizing possible ore zones as electrical methods. (d) Microscopic and X-ray studies. These studies will provide important information on hydrothermal alteration, sulfide and ferromagnesian silicate minerals, and permeability along fractures, foliation, or bedding.

5. Subsurface information is vital for evaluating prospect areas, hence drilling will have to be considered at some stage of exploration. Based on the dimensions of mineralized zones presented here (fig. 5), initial drilling at 500-foot (150 m) intervals might be sufficient to evaluate a prospect. Core drilling is more important when exploring for these deposits than for sandstone-type because structural and stratigraphic information must be known in detail. However, the additional information probably is not required for all holes and does not justify the much higher cost of core drilling (or "coring").

The combined input from geologic mapping, drilling, and geophysics should be adequate to define in three dimensions the orientation of permeable zones, favorable host rocks, and units of low permeability such as an intrusive body or quartzite bed. The configuration of these features may suggest zones of possible supergene enrichment during the Tertiary or earlier periods. Particular attention should be given to flat-lying contacts or to synclines which could serve as traps for downward moving solutions with potential for secondary enrichment of uranium.

References

Barrington, Jonathan, and Kerr, P. F., 1961, Uranium mineralization at the Midnite mine, Spokane, Washington: Econ. Geology, v. 56, p. 241-258.

Becraft, G. E., and Weis, P. L., 1963, Geology and mineral deposits of the Turtle Lake quadrangle, Washington: U.S. Geol. Survey Bull. 1131, 73 p.

Campbell, A. B., and Raup, O. B., 1964, Preliminary geologic map of the Hunters quadrangle, Stevens and Ferry Counties, Washington: U.S. Geol. Survey Mineral Inv. Field Studies Map MF 276, scale 1:48,000.

Campbell, Ian, and Loofbourow, J. S., Jr., 1962, Geology of the magnesite belt and Stevens County, Washington: U.S. Geol. Survey Bull. 1142F, p. F1-F53.

Garrels, R. M., and Christ, C. L., 1965, Solutions, minerals, and equilibria: New York, Harper and Row, 450 p.

Griggs, A. B., 1966, Reconnaissance geologic map of the west half of the Spokane quadrangle, Washington and Idaho: U.S. Geol. Survey Misc. Geol. Inv. Map I-464, scale 1:125,000.

Hosterman, J. W., Sheid, V. E., Allen, V. T., and Sohn, I. G., 1960, Investigations of some clay deposits in Washington and Idaho: U.S. Geol. Survey Bull. 1091, 147 p.

Hostetler, P. B., and Garrels, R. M., 1962, Transportation and precipitation of uranium and vanadium at low temperatures, with special reference to sandstone-type uranium deposits: Econ. Geol., v. 57, p. 137-167.

Marjaniemi, D. K., and Basler, A. L., 1972, Geochemical investigations of plutonic rocks in the Western United States for the purpose of determining favorability for vein-type uranium deposits: Lucius Pitkin, Inc., Grand Junction, Colo., report GJO-912-16, 134 p.

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Miller, F. K., and Clark, L. D., 1975, Geology of the Chewelah-Loon Lake area, Stevens and Spokane Counties, Washington: U.S. Geol. Survey Prof. Paper 806, 74 p.

Nash, J. T., and Lehrman, Norman, 1975, Geology of the Midnite uranium mine, Stevens County, Washington--a preliminary report (abs.): Geol. Soc. America, Abstracts with Programs, v. 7, no. 5, p. 634-635.

Sheldon, R. F., 1959, Midnite mine geology and development: Mining Engineering, v. 11, no. 5, p. 531-534.

Turner, F. J., 1968, Metamorphic petrology: New York, McGraw-Hill Book Co., 403 p.

Winkler, H. G. F., 1967, Petrogenesis of metamorphic rocks: New York, Springer-Verlag, Inc., 237 p.