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Title: URANIUM MINERALIZATION OF THE METAMORPHIC AUREOLE OF THE SPIRIT PLUTON, STEVENS COUNTY, WASHINGTON

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Several uranium anomalies, with concentrations of U_3O_8 that average below 0.003 percent and reach maximums of 0.069 percent, are associated with black, fossiliferous, pyritic parts of the Ordovician Ledbetter Slate in northern Stevens County, Washington. The most uraniferous parts of the slate occur in small (average of 5 by 30 cm), tabular-shaped bodies of black argillite within the crests of several small-scale folds (amplitudes and wavelengths less than 1 m) along the contact between the Ledbetter Slate and Metaline Limestone from within 30 m of the southern border of the Late Cretaceous Spirit pluton.

The concentration of uranium in the slate varies in direct proportion to the amount of reduced organic matter and pyrite contained in the rocks as well as with the extent of contact metamorphism imposed on the slate during forceful intrusion of the Spirit pluton. Discrete phases of uranium-bearing minerals were not identifiable during the course of petrographic examinations, therefore, the uranium is believed to occur

as dispersed ionic disseminations that are physically and(or) chemically bonded to the minute particles of reduced organic matter in the rocks.

The uranium anomalies had a multi-stage genesis which may have included: 1) the extraction of uranium from the Ordovician sea by organic matter and the syngenetic accumulation of the uraniferous organics with muds in an euxinic depositional environment; 2) the localized remobilization and corresponding reconcentration of the uranium in the rocks adjacent to the sourthern border of the Spirit pluton in response to contact metamorphism; 3) the minor addition of uranium into the country rock from siliceous volatile-rich fluids may have originated from the late-stage differentiation of the Spirit pluton; and(or) 4) the possible supergene enrichment of uranium that may have been leached by meteoric waters from overlying igneous or metasedimentary rocks.

The realtively low-grade and small volume of the uraniferous parts of the Ledbetter Slate in the Bruce Creek study area render the uranium anomalies uneconomic. Nonetheless, an understanding of their distribution, genesis, and petrographic characteristics may lead to the discovery of similar and economically more viable deposits of uranium elsewhere in northeast Washington.

Uranium Mineralization of the Metamorphic Aureole of the Spirit Pluton, Stevens County, Washington

by

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URANIUM MINERALIZATION OF THE METAMORPHIC AUREOLE OF THE SPIRIT PLUTON, STEVENS COUNTY, WASHINGTON

INTRODUCTION

The mining industry has been active in Stevens County, Washington since the discovery of lead, zinc, and minor silver mineralization in the 1880's (Mills, 1977). Today, however, mining activity in the area is negligible as most lead-zinc production has ceased. Although vegorous exploration for new ore deposits is continuing in the area, recent discoveries have not been documented. However, geologists of BurWest, a Burlington Northern and Westinghouse uranium joint-venture, have discovered uranium anomalies in parts of the Cambrian-Ordovician metasedimentary rocks in contact with the Late Cretaceous Spirit pluton in the Bossburg District of Stevens County. Further investigation of uranium mineralization in the region may lead to a new period of mining activity in northeast Washington.

Geographic Setting

The Bossburg District is located approximately 24 km north of Colville, Washington (Fig. 1). The thesis area is accessible by the paved Clugston Creek Road from Colville and unimproved dirt roads reach within one kilometer of any part of the area. The area of detailed investigation, which will be called the Bruce Creek area in this report, is located in the northern part of secs. 2 and 3, T. 37 N., R. 39 E., in Stevens County, Washington (Fig. 2 and Plates

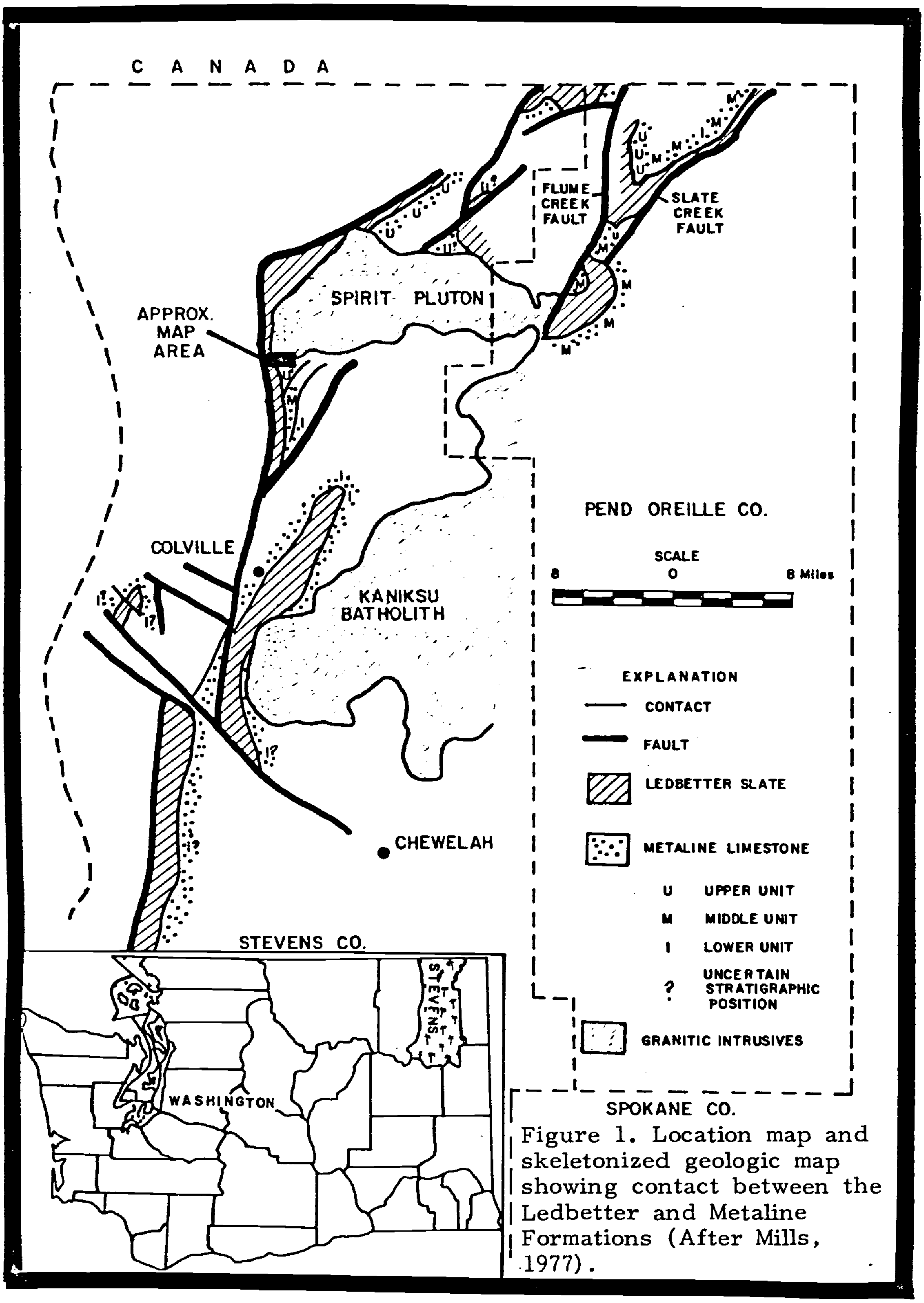


Figure 1. Location map and skeletonized geologic map showing contact between the Ledbetter and Metaline Formations (After Mills, 1977).

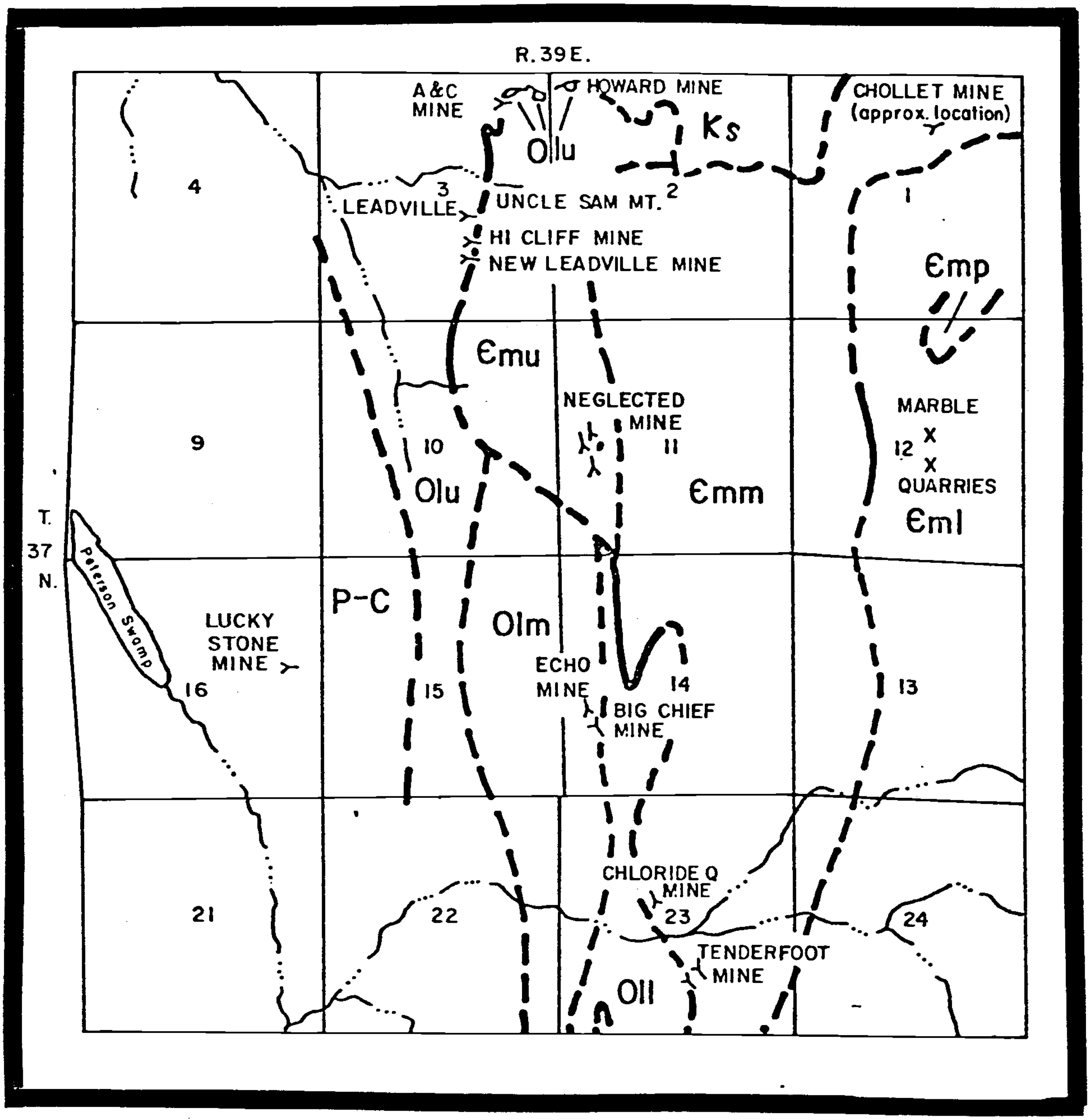


Figure 2. Generalized geology map showing the location of some of the lead-zinc mines and retional lithologies in the vicinity of the Bruce Creek study area. (Ks = Spirit pluton; Cmu, Cmm, and Cml = upper, middle, and lower members of the Metaline Limestone; Olu, Olm, and Oll = upper, middle, and lower units of the Ledbetter Slate; Cmp = Maitlen Phyllite; P-C = Permian-Carbiniferous rocks). Scale = 1: 48,000.

1 and 2). The Bruce Creek area included most of the uranium anomalies which are under investigation by BurWest.

The Bossburg District is situated in the Colville Mountains, which rise from a local base level of 366 m at the Columbia River to over 2,134 m in a distance of approximately 16 km. The Bruce Creek area is located near the Howard and the A and C mines at an elevation of 1,036 m along the sourthern slopes of Staghorn Mountain (Fig. 2 and Plate 1). These slopes are steep and rugged with a thick cover of brush and second growth timber consisting largely of conifers. Pleistocene glacial deposits mantle the lower elevations and limit the extent of outcrop exposures to 25 percent.

Previous Investigations

Most of the previous work done in northeast Washington has been confined to the lead and zinc occurrences of the more productive Metaline District located in neighboring Pend Oreille County. Excellent descriptions of the geology and ore deposits of the Metaline District have been produced by Park and Cannon (1943), Dings and Whitebread (1965), and McConnel and Anderson (1968). These reports are pertinent to an understanding of the geology of Stevens County because of the geologic similarities between the two regions.

Early investigations of the Stevens County area were conducted by Bancroft (1914), Weaver (1920), Patty (1921), and Jenkins (1924) and were primarily concerned with the occurrences of lead, zinc, and silver as were most subsequent reports. Yates (1964, 1971) has mapped the terrain north of the Bruce Creek area and described its regional geologic evolution (1976). Schuster (1976) has mapped the Clugston Creek Region, which is to the immediate south of the thesis area.

Mills (1977) has produced an updated overview concerning the lead-zinc mineralization of the carbonate rocks in Stevens County. Todd (1973) completed a doctoral thesis on the geology and mineralization of the Spirit pluton and its metamorphic aureole, but like previous workers did not mention the presence of the uranium mineralization in the area. Wong (1978) has completed a M. S. thesis concerning the behavior of uranium in the various phases of the Spirit pluton. However, because field investigations were not included in the study she was only able to speculate on the possibility of uranium mineralization in the metasedimentary rocks adjacent to the pluton.

Purpose and Methods of Study

It is of utmost importance to mining companies such as BurWest to acquire a better understanding of the mineralogy, petrology, and controls of the uranium mineralization in the metamorphic aureole of the Spirit pluton because published information concerning this subject is lacking. The primary purpose of this study is to determine the: 1) possible identity of the uranium-bearing minerals and their association with host rock mineralogy; 2) physical-chemical controls of the mineralization process(es); and 3) possible source(s) of the "ore fluids". This information will assist in establishing guides to uranium exploration in future projects in northeast Washington and elsewhere.

Field work was conducted during August, 1979. Geologic mapping utilized enlarged sections (1:6000) of the common corners of the Gilette

Mountain, Echo Valley, China Bend, and Onion Creek 7½-minute quadrangle maps published by the U. S. Geological Survey in 1952, 1952, 1969, and 1969, respectively. In addition, a large scale (1:1200) plane table map utilizing compass and tape was compiled to cover the contact metamorphic aureole in the northern half of secs. 2 and 3, T. 37 N., R. 39 E., Stevens County.

Rock samples were collected along traverses oriented normal to the formational strikes and contacts in the Bruce Creek area. Thin sections of these smaples were prepared by Mr. S. Balough of the University of Montana at Missoula. Mineral identifications were based on physical and optical properties observed with a Leitz petrographic microscope and the descriptions presented in Kerr (1959). The identification of carbonate minerals was aided by the staining methods described by Friedman (1959).

The colors assigned to hand samples of the rocks in this report conform to the codes that are presented in the Rock Color Chart published by the Geological Society of America (1970). The terminology utilized is defined in the Glossary of Geology (Gary and others, 1977). Geochemical analysis of the metallic constituents of the rock samples was performed by Chemical and Mineralogical Services, Salt Lake City, Utah. Major element analysis was conducted by Skyline Labs, Wheat Ridge, Colorado. Samples of the Ledbetter Slate were examined Utilizing X-ray powder diffraction techniques by the Colorado School of Mines Research Institute, Golden, Colorado.

REGIONAL GEOLOGY

The Bruce Creek area is situated in the southern end of a narrow, arcuate belt of complexly folded and faulted rocks termed the Kootenay Arc (Hedley, 1955). This north-northeast-trending belt of multiple deformation, which is part of a much larger province known as the Omineca Crystalline Belt (Brown and others, 1971), extends approximately 400 km from north of Revelstoke, British Columbia to the vicinity of the confluence of the Spokane and Columbia Rivers in Washington where it disappears beneath the Miocene Columbia River Basalt flows (Fig. 3).

The Kootenay Arc is structurally characterized by refolded folds, axial plane foliation, and reverse or thrust faults parallel to the axial plane foliation (mills, 1977). The rocks of the Kootenay Arc, which range in age from late Precambrian to Middle Jurassic, represent a transition between the Upper Precambrian to Lower Paleozoic miogeoclinal (miogeosynclinal ?) sedimentary province on the east and the Middle Paleozoic to Upper Mesozoic eugeosynclinal Pacific Borderland province on the west (Yates and others, 1966; Yates, 1970, 1976; Mills, 1977). The eastern region of the Kootenay Arc contains sandstones, mudstones, and carbonate rocks, most of which have been metamorphosed to quartzites, phyllites, mica schists, and marbles. The western region contains argillites, siltstones, graywackes, chert pebble conglomerates, allodapic limestones, and metavolcanics (Mills, 1977).

Yates (1970) has subdivided the Kootenay Arc south of the Internation Boundary (forty-ninth parallel) into four tectonic units

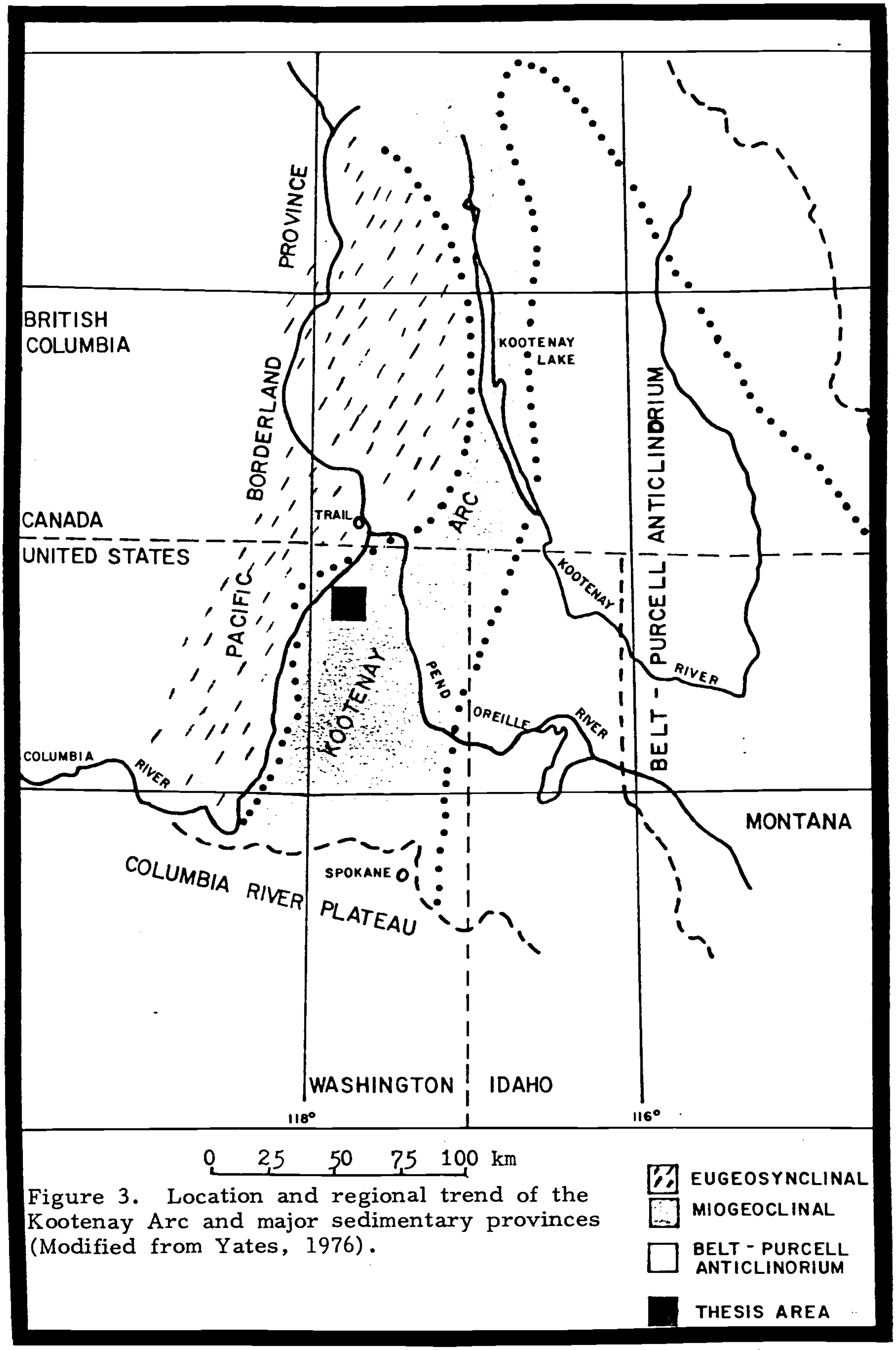


Figure 3. Location and regional trend of the Kootenay Arc and major sedimentary provinces (Modified from Yates, 1976).

(Fig. 4). From east to west they are the: 1) homoclinal belt; 2) fold belt; 3) thrust belt; and 4) Jurassic volcanic belt. The first three units represent increasing intensities of Mesozoic compressional deformation whereas the fourth represents eugeosynclinal volcanism. The homoclinal belt, which is situated southeast of the Slate Creek fault in the Metaline quadrangle of Pend Oreille County, is comprised of Precambrian and Cambrian rocks that strike northeast and dip northwest. The fold belt is the southwest extension of the Sheep Creek anticline of British Columbia and contains rocks of late Precambrian to Middle Mesozoic age. The thrust belt is the west and northwest part of the fold belt that has been deformed by later compression along an east-west axis. The Jurassic volcanic belt lies to the west of the main Kootenay Arc structure and is comprised of both Jurassic volcanic and nonvolcanic rocks of Pennsylvanian and Permian age.

The fold belt is further subdivided by Yates (1970, 1976) into three tectonic blocks which are bounded by Late Cretaceous to Eocene high-angle, N. 10° - 20°E. - trending faults. From northeast to southwest they are the: 1) Valley block; 2) Hooknose-Baldy block; and 3) Lime Creek Mountain block (Fig. 4). The thesis area is situated at the southern end of the Lime Creek Mountain block along the southern border of the Spirit pluton.

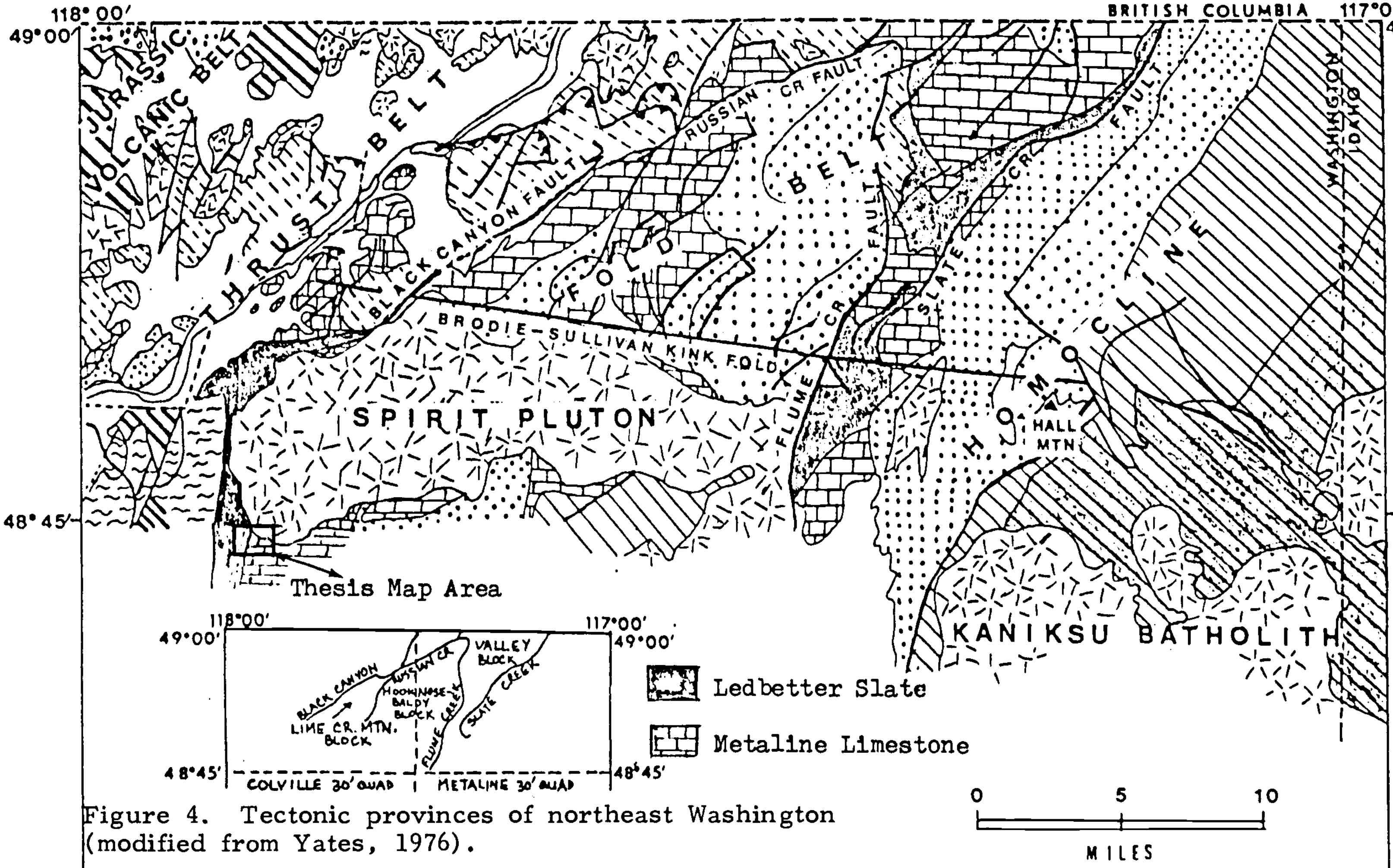


Figure 4. Tectonic provinces of northeast Washington (modified from Yates, 1976).

Folds

Three major events of folding are observed in the Stevens County region. In order of decreasing age they are the: 1) formation of northeast-trending folds that are commonly overturned to the northwest and display axial plane foliation (Crosby, 1968; Yates, 1970, 1976); 2) refolding of the previously developed folds into northeast-striking open asymnetric anticlines and synclines (Fyles and Hewlett, 1959; Yates, 1970, 1976); and 3) development of tight chevron or kink folds that trend east-west with well-developed crenulation foliation (Yates 1976). The first two events of folding preceded emplacement of the 100 m.y. (Yate and Engles, 1968) Spirit pluton, but the kink folds formed either prior to, or contemporaneous with, the intrusive event (Yates, 1976). According to Yates, the tectonic disturbance responsible for the northeast-trending folds was the Nevadan orogeny of Late Jurassic to Early Cretaceous age (King, 1977).

Faults

Thrust faults and high-angle extension faults are the two main types of faults observed in the southern region of the Kootenay Arc (Mills, 1977). The regional thrust faults trend a few degrees from east-west, dip to the south, are generally subparallel to bedding, and are believed to be younger than the first two events of folding as previously noted (Fyles and Hewlett, 1959; Yates, 1970, 1976). The high-angle extension faults have various attitudes and are younger than all other episodes of folding or faulting.

Intrusion and Metamorphism

The pre-Cretaceous rocks underwent greenschist metamorphism sometime during or after the northeast-trending folds were formed (Yates, 1976). Emplacement of the granodiorite and quartz monzonite intrusive bodies, such as the Spirit pluton and the Kaniksu batholith with which it is related, superimposed a contact metamorphic aureole up to a maximum of 3 km wide on the regionally metamorphosed country rocks (Yates, 1970; Mills, 1977). According to Todd (1973), rocks situated within 3 m of the border of the Spirit pluton belong to the hornblende-hornfels facies of contact metamorphism. In contrast, rocks unaffected by the intrusion belong to the quartz-albite-epidote-biotite subfacies of regional metamorphism (but could conceivably belong to the peripheral contact metamorphic facies assemblage of albite-epidote hornfels).

STRATIGRAPHY

The uranium anomalies that are under investigation by BurWest occur within parts of the following three formations: 1) the Metaline Limestone; 2) the Ledbetter Slate; and 3) the Spirit pluton. Other formations do not crop out in the Bruce Creek area, nor do any other formations, which are present in the surrounding region, have any genetic relationship with the uranium anomalies. The reader is referred to the work of Yates (1976) and Schuster (1976) for an excellent description of the complete stratigraphic section that is present in the region encompassing the thesis area.

Metaline Limestone

The Metaline Limestone is found extensively throughout Stevens and Pend Oreille Counties. The formation was named by Park and Cannon (1943) for the rocks exposed near Metaline Falls in Pend Oreille County. The Metaline Limestone crops out in the Bruce Creek area along a belt extending from secs. 25 and 26 northward to secs. 1, 2, and 3, T. 37 N., R. 39 E. (Fig. 2). The most continuous outcrops across the formation are found along the southern slopes of Staghorn Mountain and the western slopes of Uncle Sam Mountain in secs. 1, 2 and 3 (Plate 1). A mantle of Pleistocene glacial material and colluvium conceals the Metaline Limestone over approximately 75 percent of the valley floors and north-facing slopes in the Bruce Creek area.

Age and Correlation

The age of the Metaline Limestone, based on fossil evidence, ranges from Middle Cambrian to either Late Cambrian or Early Ordovician (Reptski, 1978). The Metaline Limestone is the lithologic and temporal equivalent of the Nelway Formation of British Columbia (Little, 1960) and it is the temporal equivalent of the Whipple Cave and the House Limestone of Nevada (Cook and Taylor, 1975).

Depositional Environment

According to Todd (1973)p. 102) outcrops of the Metaline Limestone in Stevens County exhibit features such as mudcracks, birdseye structures, and flat-pebble conglomerates that are evidence for a shallow water, peritidal (the region within and slightly above tidal range) depositional environment, possibly along an inner-continental self. Yates, (1976 p. 354) has suggested that the Metaline Limestone was deposited along a middle to outer shelf carbonate bank, but cites little in the way of physical evidence to support this concept.
Fischer (1980) has described evidence that the Metaline Limestone was deposited as a western or seaward part of an extensive Middle to Upper Cambrian algal shoal and tidal flat barrier sequence that may have extended from the region of the border between Stevens and Pend Oreille Counties eastward to the Libby Trough region of Montana.

Outcrops of the Metaline Limestone that are exposed in the Bruce Creek area within two kilometers of the border of the Spirit pluton have been recrystallized to calcite, dolomite, and tremolitic marbles which do not exhibit primary depoitional features. Despite the absence of depositional features, it is possible to speculate that the Metaline Limestone in the Bruce Creek region was deposited as fine-grained limey muds (micrites) along a subtidal, seaward-sloping western flank of the regional carbonate shelf system as proposed by Fischer (1980). In support of this hypothetical depositional environment for the Bruce Creek carbonates, which incorporates only the upper member of the Metaline Limestone, is the fact that shallow water (peritidal) depositional features have been reported only for areas to the east (paleo-shoreline) of the study area (Todd, 1973, Fischer, 1980), whereas features indicative of deeper environments have been observed in adjacent areas (Yates, 1976; Schuster, 1976). In addition, a greatly convoluted, thin (average of 3 cm in thickness), argillaceous interbed is present within parts of the upper member of the Metaline Limestone in secs. 2 and 3. This single interbed is subparallel to and within approximately 75 m of the contact between the Ledbetter Slate and Metaline Limestone. The deformed nature of this primary depositional unit suggests that it was deposited as an unstable muddy (hydroplastic) layer of sediment along a carbonate slope of unknown inclination and was pulled downslope by the force of gravity. Thus, it may be assumed that an outer, seaward-dipping slope of a carbonate shelf (bank or shoal system) was present in the Bruce Creek area during the Late Cambrian time. Carbonate muds were deposited on this submarine slope, with carbonate deposition being briefly interrupted by the influx of a layer of very fine-grained terrigenous clastics.

Internal Relationships, Thicknesses, and Contacts

Park and Cannon (1943) have divided the Metaline Limestone into three members which are: 1) a lower, thinly bedded, argillaceous limestone; 2) a middle, faintly bedded dolomite; and 3) an upper, massive, faintly mottled limestone. According to Schuster (1976), the lower, middle, and upper members of the Metaline Limestone in the area immediately to the south of the Bruce Creek area have apparent thicknesses of 793 m, 1,402 m, and 914 m, respectively. Schuster has also noted that all three members dip at moderate to steep angles (up to 87°, Plates 1 and 2) and appear to thin toward the south (Fig. 2).

Park and Cannon (1943) have stated that, on a regional scale, the contact between the Metaline Limestone and the underlying Maitlen Phyllite is gradational (sedimentary or depositional). However, Schuster (1976) has suggested that this lower contact may be faulted in the vicinity of the Bruce Creek area as may be the contacts between the lower, middle, and upper members of the Metaline Limestone. These contacts are not exposed within the Bruce Creek study area.

Schuster (1976) and Mills (1977) have provided ample evidence that the contact between the Metaline Limestone and the overlying Ledbetter Slate is a regional low-angle unconformity. The recognition of the erosional nature of this contact is important to the understanding of the genesis of the lead-zinc mineralization of the carbonate rocks of the Stevens County region. This subject will be discussed later in this report under the heading of Economic Geology.

Figure 5. The contact between the Metaline Limestone (left of arrow) and the Ledbetter Slate. View is to the south at the Clugston Creek Road cut at the point where the road swings sharply to the east (Plates 1 and 2). This locality is approximately 700 m to the sourth of the border of the Spirit pluton.

Lithology and Petrography

Only the upper member of the Metaline Limestone crops out within the Bruce Creek study area (Fig. 2). Outcrops of the upper member differ in appearance on opposite sides of the Clugston Creek Road (Plates 1 and 2). The limestone that is exposed on the south side of the road is similar in appearance to outcrops of the upper member that are exposed elsewhere in Stevens County as described by Yates (1976), Schuster (1976), and Mills (1977). Here, the upper member of the Metaline Limestone is a light-to-dark-gray mottled (N7 to N3), soft, massive, and very finely-crystalline dolomitic limestone with minor (less than one percent) siliceous (cherty ?) nodules up to two centimeters in diameter. The white-and-gray banding that characterizes outcrops on the north side of the road is absent in the carbonates on the south side, except for the small (approximately 15 by 30 m), pod-shaped outcrops that are adjacent to a granitic dike south of Howard Meadows in sec. 2 (Plate 2).

Outcrops of the upper member of the Metaline Limestone that are exposed on the north side of the Clugston Creek Road in secs. 2 and 3 appear as white-to-medium gray banded (N9 to N5), fine to coarsely crystalline dolomite and calcite marbles with irregularly distributed calc-silicate mineralization (mainly termolite and diopside). The banding in the carbonates varies from a few millimeters to several centimeters in thickness. The banding is oriented subparallel to the contact between the slate, limestone, and granitic rocks of the Bruce Creek area and it is better formed in the rocks that are progressively closer to the border of the Spirit pluton. In thin section, the darker banding appears to be the result of minute inclusions of black (carbonaceous ?) matter that have differentially segregated toward the margins of the carbonate crystals in parts of the rock during metamorphism. The lighter bands are composed of nearly equidimensional anhedra of sparry calcite and dolomite in varing amounts, which are slightly larger and contain fewer inclusions than the adjacent darker bands. The darker bands are composed of inclusion-rich anhedra of calcite and dolomite in varying amounts, which are elongated parallel to the plane of the banding. Crystal sizes range from less than 0.1 mm to more than 3 mm for both the equidimensional and elongate crystals, and they increase as the borders of the Spirit pluton are approached. The ratio of equidimensional-to-elongate crystal forms also increases toward the border of the pluton, as does the development of 120° triple junctions along the equidimensional crystal margins. These observations concerning the nature and distribution of the banding in the Metaline Limestone of the Bruce Creek area suggest that the banding resulted from contact metamorphism during the intrusion of the Spirit pluton (Fig. 6).

The banded carbonate rocks of the Bruce Creek area were examined in outcrop along traverses oriented normal to the subparallel contacts between the argillaceous, carbonate, and granitic rocks. The results of this field examination, together with the petrographic study of several thin sections made from these rocks (Table 1), indicate that the Metaline Limestone of the Bruce Creek area exhibits marked compositional variations on a scale of tens of meters, but more uniform and predictable variations on a scale of hundreds of meters. For example, the mineralogical composition of the carbonate rock may vary

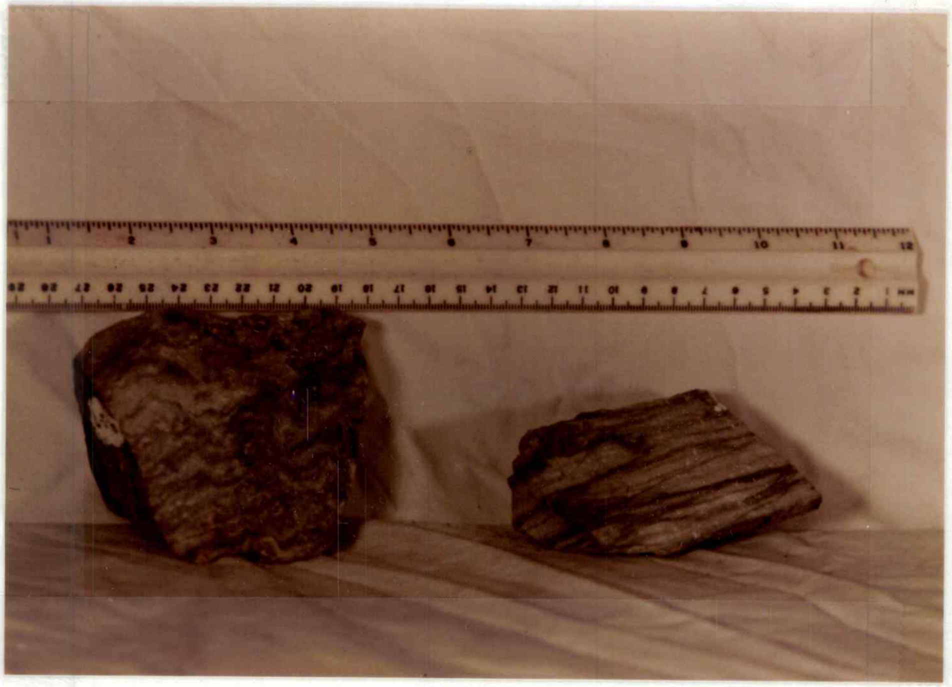


Figure 6. Samples of the Metaline Limestone collected at distances of 700 m (left) and 20 m (right) from the southern border of the Spirit pluton. Note the better-formed banding in the sample from the closer distance to the pluton. This banding is observed to be oriented parallel to subparallel to the borders of the pluton in the Bruce Creek area.

Table 1. Modal analysis (500 points) of Metaline Limestone lithology.

Constituent	Percent of each thin section L-1	L-2	L-3	L-4
quartz	2.3	1.1	3.3	2.8
calcite	22.4	24.2	17.5	63.7
dolomite	75.3	68.5	69.3	33.5
tremolite	Tr.	2.3	2.8	Tr.
diopside	--	1.5	5.3	--
wollastonite	--	--	Tr.	--
opaques	Tr.	2.4	1.8	Tr.
Totals	100.0	100.0	100.0	100.0

Locality L-1	NW¼, SE¼, sec. 3, within 0.5 m of the slate-limestone contact exposed at the Clugston Creek Road cut.
Locality L-2	SW¼, NW¼, sec. 3, approximately 50 m north of the powerlines.
Locality L-3	SE¼, NW¼, NE¼, sec. 3, sec. 3, adjacent to the lower A and C adit.
Locality L-4	SE¼, NW¼, NE¼, sec. 3, approximately 15 m inside the upper A and C adit along the northern wall.

(The exact locations where these samples were collected are plotted on Plate 2).

from a pure calcite or dolomitic marble to a sulfide-bearing assemblage of calcite-dolomite-quartz-tremolite ± diopside, without obvious correlation with distance from the borders of the Spirit pluton. However on a scale of hundreds of meters the progressive appearance of calc-silicate minerals follows a more predictable pattern with the formation of tremolite, diopside, and minor wollastonite as the borders of the pluton are approached. The formation of the calc-silicate minerals is apparently a function of the thermal metamorphism of the impure carbonates and siliceous, sulfide-bearing Josephine Breccia carbonates of the Metaline Limestone in the Bruce Creek area, rather than the contact metasomatic addition of material from the pluton to these rocks.

In general, carbonate rocks situated one to two kilometers from the borders of the Spirit pluton contain the recrystallized assemblage calcite and (or) dolomite ± quartz that forms a moasic of very fine to fine (less than 0.1 mm to 0.5 mm), anhedral, interlocking crystals that are elongated in the plane of faint foliation that is visible in outcrop. These carbonates probably recrystallized during regional (greenschist) metamorphism (Todd, 1973; Yates, 1976) of the fine-grained limey muds or micrites prior to the intrusion of the Spirit pluton.

Carbonate rocks located within one kilometer to approximately ten meters from the pluton contain the assemblage calcite-dolomite-tremolite ± quartz forming a fine to medium (0.1 to 1.0 mm) mosaic of anhedral, elongate to equidimensional crystals. This assemblage may reflect the transition between regional and contact (thermal) metamorphism of the carbonate rocks of the Bruce Creek area.

Carbonate rocks situated within approximately ten meters of the border of the Spirit pluton in the Bruce Creek area contain the assemblage calcite-dolomite-diopside-tremolite ± quartz and traces of wollastonite forming a moasic of interlocking, medium to coarse (1.0 to 3.0 mm), equidimensional crystals. Todd (1973) assigned the rocks within ten meters from the border of the pluton to the hornblende-hornfels facies of contact metamorphism based on the mineralogical assemblages in both the carbonate and pelitic country rocks.

Josephine Breccia

Mills (1977) has defined the term "Josephine Breccia" as designating the zone of breccia that is present within the Metaline Limestone along a discontinuous, linear trend within a stratigraphic distance from a few meters to more than 275 meters from the overlying Ledbetter Slate. The Josephine Breccia is present throughout Stevens and Pend Oreille Counties as an irregularly-shaped, blanket-like body of angular, unsorted, medium-grained dolomite and limestone fragments that range from a few millimeters to over two meters in maximum dimension. On a local scale, the zone of breccia displays highly variable dimensions and grades from unbrecciated rock through a crackle breccia, in which there has been little rotation of the fragments, to the main breccia body, in which the fragments have been rotated, are self-supporting, and are cemented by black, finely to coarsely crystalline dolomite, jasperoid, and (or) calcite. The Josephine Breccia is the major host of the lead-zinc ore deposits of northeast Washington, but the term

"Josephine" is applicable whether the occurrences of breccia are mineralized or not (Mills, 1977).

Mills (1977) has provided convincing evidence that the Josephine Breccia and its contained sulfides formed in a manner similar to that which has been proposed by various workers to account for the creation of the Mississippi Valley-type lead-zinc deposits. According to Mills, epeirogenic uplift of the Metaline terrain during Late Cambrian or Early Ordovician time may have established a paleoaquifer system in which circulating meteoric waters created a karst topography and an associated zone of solution-collapse breccia. Harris (1971) has postulated a similar model to explain the lead-zinc mineralized breccia bodies of the Kingsport Formation and Mascot Dolomite of Tennessee and Virginia, and LeGrand and Stringfield (1971) have described a modern equivalent of such a karst aquifer system, which is present in the Tertiary carbonate rocks of the Southeastern States.

Roedder (1967) has considered the processes involved in the formation of sulfides that characterize the Mississippi Valley-type ore deposits. He concluded that these ore deposits formed from relatively hot (72° to 149°C.), saline (greater than 20 weight-percent salts) brines, based on fluid inclusion evidence. These brine would be in contrast to the less-saline, cooler, near-surface meteoric waters which are thought to have created the permeable breccia zone through which the ore-bearing brines subsequently migrated (Hill and Wedo, 1971). Additional details concerning the Josephine lead-zinc deposits will be discussed in a later section of this report under the heading of Economic Geology.

Fragments and blocks of light-colored argillite and black, graptolitic shale have been reported in the Josephine Breccia by previous workers (Park and Cannon, 1943; Dings and Whitebread, 1965; Schuster, 1976). Schuster has noted that graptolite-bearing blocks of argillite and shale up to two meters wide are incorporated in the Josephine Breccia approximately 275 m stratigraphically beneath the contact between the Ledbetter Slate and Metaline Limestone in the Clugston Creek region to the south of the Bruce Creek area. He concluded that these sediments washed into open spaces connected to the surface of the carbonate terrain during the initial stages of deposition of the Ledbetter Slate in Early to Middle Ordovician time. Similar blocks of black argillite have been observed within parts of the Metaline Limestone near the Ledbetter Slate contact in the Bruce Creek area. These argillites will be discussed further in the section titled Economic Geology. According to Mills (1977), conditions may have favored the episodic formation of the Josephine Breccia during various post-Ordovician times, and that lithified fragments of Ledbetter Slate may have spalled into the expanding zone of karst breccia.

Mills (1977) has suggested that mineralized parts of the Josephine Breccia are present along a discontinuous, irregularly-shaped zone that trends parallel to the contact between the Ledbetter Slate and Metaline Limestone in the Bruce Creek area. Although the obvious physical appearance of the zone of breccia becomes masked by contact metamorphism as the borders of the Spirit pluton are approached, Mills has provided ample evidence to show that the sulfide mineralization at the Howard and the A and C mines represents parts of the Josephine Breccia that have been truncated and metamorphically altered by the intrusion of the Spirit pluton.

Figure 7. An elongated fragement of dark argillite enclosed within Metaline Limestone in the vicinity of the contact between the slate and the Limestone near drill hole "D" in sec. 3. Note the penny for scale.

Ledbetter Slate

The Ledbetter Slate was named by Park and Cannon (1943) for the rocks that crop out along the slopes west of Ledbetter Lake, Pend Oreille County, Washington. The Ledbetter Slate is present throughout Stevens and Pend Oreille Counties and crops out along a nor-trending belt at the western margin of the Spirit pluton and Bruce Creek study area (Fig. 2 and Plate 2). The slate breaks down readily and forms soil-covered hills of relatively low relief. Much of the Ledbetter Slate of the Bruce Creek area is covered by Quaternary deposits, therefore exposures of outcrop are limited to approximately 20 percent of the total surface of the study area (Fig. 8).

The Ledbetter Slate has been dated on the basis of fossil evidence as ranging from late Early Ordovician to early Late Ordovician (Schuster, 1976). The Ledbetter Slate is the stratigraphic equivalent of the Active Formation of British Columbia (Little, 1960).

Depositional Environment

According to Schuster (1976), the Ledbetter Slate which is present in the Clugston Creek (and Bruce Creek) area was deposited as an onlapping assemblage from south to north over an erosional surface of low relief formed on the Metaline Limestone. Yates (1976) has suggested that the Ledbetter Slate was deposited as deep water, euxinic, black muds on the outer continental shelf. The muds were deposited in response to a eustatic rise in sea level or regional subsidence of the shelf.

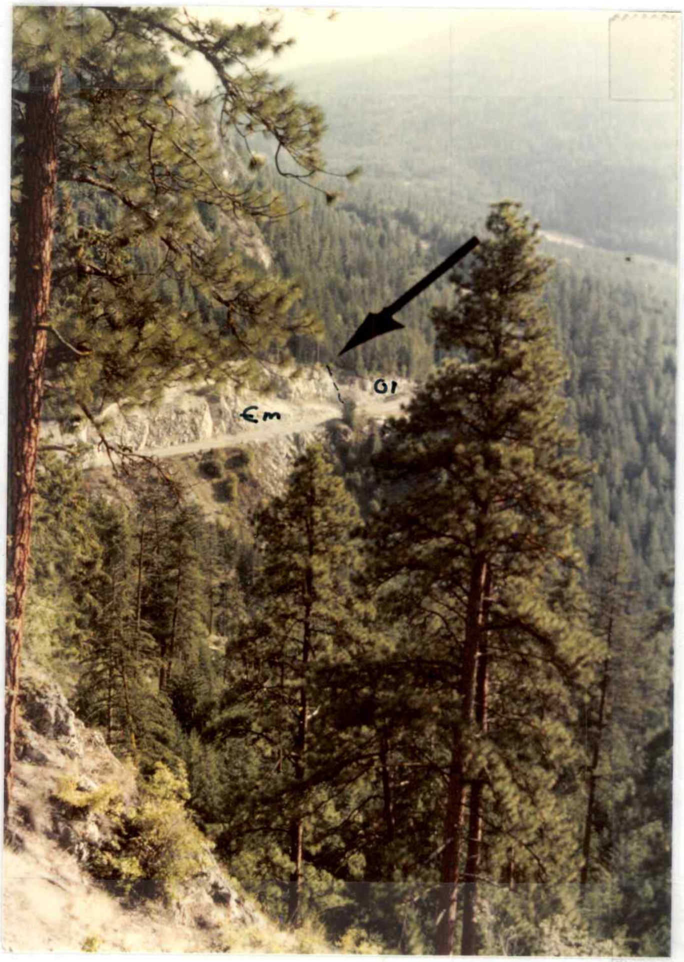


Figure 8. View looking south toward the roadcut location of Fig. 5 where the contact (arrow) between the Metaline Limestone (left) and Ledbetter Slate (right) is exposed. Note the low-relief, forested hills comprised of the slate in the right center. High hills in the distance are composed of rocks younger than Permian age.

The Ledbetter Slate was probably deposited in a miogeosyncline, rather than a eugeosyncline, environment because there have not been any reported occurrences of voluncanic, cherty, or pelagic components of the slate. Deposition of marine black muds does not require excessively deep water environments; simply that the depositional surface be situated below the denisty stratified column of water (pycnocline) that separates oxygen-rich from oxygen-poor waters (Degens and Stoffers, 1976). The anaerobic biofacies of Byers (1977) is characterized by a paucity of fossils, a lack of infaunal bioturbation, and the accumulation of thinly laminated organic-rich, euxinic, black muds, which may occur in water depths as shallow as 100 to 150 meters. The Ledbetter Slate which is present in the Bruce Creek area is a very fine-grained, graptolite-bearing, pyritic, thinly laminated black slate. The Ledbetter sediments were probably deposited as black, reductant-rick, muds in low energy euxinic environment that was at least 100 to 150 meters deep.

The sediment that comprises the Ledbetter Slate is similar to other graptolitic black shales that were deposited along the North America Cordillera and Arctic Archipelago continental margins during Ordovician through Silurian times (Jackson, 1966; Stewart and others, 1977). The deposition of euxinic black muds directly upon the subaerially-weathered carbonate terrain, as apparently was the case in Bruce Creek area during Early Ordovician time, reflects drastic environmental changes in a relatively short period of time.

There are not any reports in the literature of rapid eustatic rises in sea level which would correlate with the start of Ledbetter deposition in the Early Ordovician. On the contrary, Ledbetter deposition commenced during the final stages of eustatic regression that denotes the end of the Sauk depositional sequesnce of Sloss (1963). Furthermore, Jackson (1966) has noted that similar shifts from shelly (carbonate) to graptolitic (black shale) facies have occurred in various regions at different times along the continental margins of the North American Cordillera and Arctic Archipelago during Ordovician and Silurian times. These marked facies changes are attributed by Jackson to the regional subsidence of the continental shelf. According to Churkin (1974), the graptolitic facies were deposited in basins of restricted circulation on the continental shelf; possibly marginal basins that were associated with developing island arc systems as described by Karig (1971). However, the lack of convincing evidence for the existence of an island arc system off the western North American continent in the Ordovician rock record has led some workers to attribute the subsidence of the shelf to the reactivation of pre-existing faults; possibly in response to shifting depo-centers that were associated with the changing depo-tectonic regime of the Early Ordovician.

Regardless of the exact cause(s), the subaerially-exposed Metaline terrain began to subside and receive deposition of euxinic black nuds during the Early Ordovician. According to Schuster (1976) the Ledbetter Slate in the region of the Bruce Creek study area was deposited as an onlapping assemblage that overlies progressively younger Metaline Limestone from south to north. He has demonstrated that light-colored (oxygenated ?), fine-grained argillites containing early Early Ordovician triobites and graptolites were deposited on and washed into surface-connected open spaces within the karst carbonate topography south of the Bruce Creek area. Increasingly euxinic muds were deposited progressively northward and had reached north of the Bruce Creek area by late Middle Ordovician time. This south-to-north onlapping assemblage of Ledbetter Slate may represent deposition upon a progressively foundering continental margin in a manner similar to that described by Jackson (1966).

The only sedimentary structures present in the Ledbetter Slate of the Bruce Creek area are laminations (less than 1 cm thick) and thin beds (less than 3 cm thick) of graptolitic slate. As Schuster (1976) and Yates (1976) have observed, the graptolite-bearing bedding planes are noticeable only where the slaty cleavage, which is well-developed but irregularly distributed, is parallel to the original bedding surfaces (Fig. 9).

Internal Relationships, Thicknesses, and Contacts

Schuster (1976) has divided the Ledbetter Slate of the Clugston Creek area into three informal units which from oldest to youngest are: 1) a lower, tan-colored argillite and black slate unit that contains carbonate beds from 1.3 cm to 6.0 cm thick, comprising from five to ten percent of the unit; 2) a middle black slate and argillite unit that is similar to the lower unit, but contains quartzite interbeds that range from a few centimeters to more than six meters in thickness and comprise up to 25 percent of the unit; and 3) an upper, fossiliferous, black slate unit that contains minor (less than five percent) argillaceous, laminated limestone interbeds and lenses. According to Schuster (1976), the lower, middle, and upper units are approximately 475 m, 589 m, and 457 m thick, respectively.

Yates (1971) has mapped the terrain immediately to the north of the Bruce Creek area. On his map the upper-most of the three units of Schuster correlates with the lower-most of the three units of Ledbetter Slate as defined by Yates. The three units of Yates are: 1) a lower, black, graptolitic slate that is approximately 150 m thick; 2) a middle, "sooty", argillaceous limestone that is approximately 150 m thick; and 3) an upper unit of 180 m of fine-grained quartzite or 'siltite'.

Schuster (1976) has placed the contacts between his three informal units with respect to where the quartzite interbeds begin and end. The contacts between the three units described by Yates (1976) are also of a gradational (depositional) nature. Both Schuster and Yates believe that the upper contact between the overlying Permian (?) eugeosynclinal rocks to the west of the Bruce Creek area is a fault, but lack of any outcrop exposure precludes a definitive conclusion.

The contact between the Ledbetter Slate and the Metaline Limestone is the only depositional or stratigraphic contact present within the Bruce Creek area. In general, the contact strikes within a few degrees of north and dips steeply (up to 87°) to the west. Schuster (1976) has noted that, although in some places this contact is a fault, it is primarily a sedimentary contact along a regional, low relief, unconformable surface of erosion that transects all three members of the Metaline Limestone.

Previous workers (Todd, 1973; Schuster, 1976) have described the north-south-trending contact between the Ledbetter Slate and Metaline Limestone as being truncated in sec. 3 by the southwestern "nose" of the east-west-trending Spirit pluton (Plates 1 and 2). However, detailed mapping has revealed that the contact swings sharply to the east in the vicinity of the NE¼ of sec. 3 and continues to strike roughly eastward through sec. 2 until it is "consumed" by the southern margin of the Spirit pluton (Plate 2). Most of the more significant uranium anomalies are present along the erosional remnants of this contact which have been cut by apophysises of granitic rock along the southern border of the pluton. The contact between the slate and limestone in the Bruce Creek area was probably deformed into its present east-west-trend from its previous northeast-trend during the forceful emplacement of the Spirit pluton, as will be discussed in a subsequent section of this report.

Lithology and Petrography

Only the graptolitic black slate unit of the Ledbetter Slate is exposed in the Bruce Creek area. For descriptive purposes, outcrops of the black slate unit will be discussed in terms of three idealized "end members", which will be designated as types I, II, and III Ledbetter. The "end members" represent gradational variations in the petrography of the Ledbetter Slate which formed in response to both depositional and metamorphic processes.

Type I Ledbetter

Type I Ledbetter represents the least metamorphosed and stratigraphically lowest part of the graptolitic black slate unit. The best outcrop of type I Ledbetter is present in a roadcut where the Clugston Creek Road swings sharply from north to east in sec. 3 (Plates 1 and 2). Here, the Ledbetter Slate is characteristically a grayish-black (N2), graptolite-bearing, pyritic slate with well-developed slaty cleavage that is subparallel to bedding which strikes N 5° E. and dips 85° E. The slate breaks smoothly along bedding or cleavage planes into slabs that range from 0.1 to 3.8 cm in thickness. The slabs break almost conchoidally and release a slight fetid odor when struck with a hammer (Fig. 9).

A smaple of slate (S-1), which was collected from within 0.5 m of the contact with the Metaline Limestone at the previously mentioned roadcut (Fig. 5), was examined in detail by X-ray diffraction and thin section analyses (Table 2). The data reveal that the type I Ledbetter consists of approximately 45 percent black, opaque, clay-xize particles of carbonaceous matter and finely crystalline pyrite, 15 percent subangular quartz grains, 11 percent mica-illite (muscovite ?), 5 percent feldspar, 6 percent anhedral calcite and 7 percent anhedral dolomite crystals, and 10 percent chlorite-kaolinite. Most of the clasts are too fine-grained (less than 0.01 mm) to be properly identified microscopically, but infrequent ragged flakes of mica (muscovite ?) and chlorite, angular to subangular grains of quartz and biotite, and subhedral crystals of pyrite may be observed in thin section (Fig. 10).

Figure 9. Sample of type I Ledbetter collected from road cut location of Fig. 5 within 0.5 m from the contact with the Metaline Limestone. Note the graptolite impressions (arrow) along the bedding-cleavage planes.

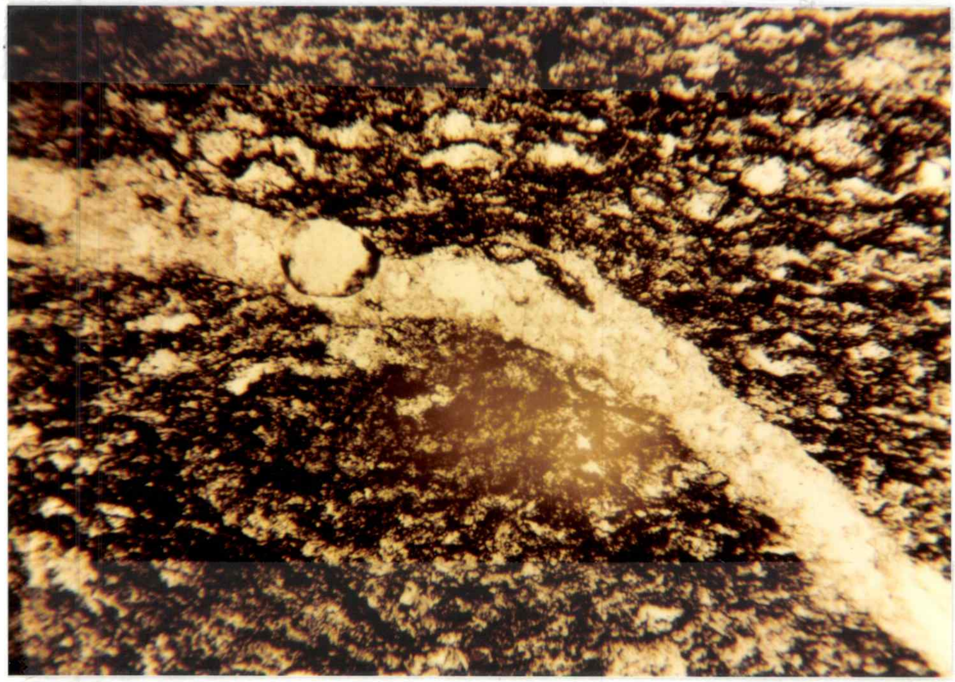


Figure 10. Photomicrograph of type I Ledbetter (plane light, 100X, 1.8 mm field of view).

Table 2. Mineralogical composition of the Ledbetter Slate (based on the combined data of X-ray and thin secion analyses, percentages are estimates with ± 5% error).

	*Location	quartz	fldspr.	diop.	trem.	bio.	dolo.	calc.	apatite	mica-illite	**opaques
S-1	NW¼, SE¼, sec. 3, Clg. Crk. rd. cut	15	5	--	--	1	7	6	--	11	45
S-2	SW¼, NE¼, sec. 3, 35 m W. of DDH-I	33	4	--	4	1	3	--	--	5	50
S-4	NW¼, NE¼, sec. 3,	29	12	2.5	2.5	1	5	--	--	3	45
S-5	SW¼, NE¼, sec. 3, near DDH-D	9	5	9	3	Tr.	4	--	10	--	60
S-6	SW¼, NE¼, sec. 3, 0.5 m from S-5	13	5	4	--	Tr.	--	9	--	9	60
S-9	NW¼, NE", sec. 3, upper A an C adit	6	2	12	2	--	--	3	9	11	65
S-10	surveyed corner of secs. 3, 33, and 34	32	3	--	--	1	3	31	--	--	30

*Exact sample locations are plotted on Plate 2. **Opaques include black carbonaceous(?) matter and finely crystalline pyrite.

The black, opaque matter coats all grain surfaces and is present as inclusions in most of the carbonate crystals and some of the quartz grains, but it is distributed (together with finely crystalline pyrite) most prominantly as "wavy", interstitial zones of concentrated cryptocrystalline particles that impart the dark color and lineation to the samples in thin section. In general, the longest dimension of the detrital minerals is commonly aligned with the faint lineation, which itself is parallel to the graptolite-bearing bedding and cleavage planes. Minor occurrences of sparry calcite-filled fractures, commonly less than 0.1 mm thick, cut across the lineation in the slate at various angles.

Type II Ledbetter

Type II Ledbetter crops out in numerous localities along a belt that trends north-south at the western end of the Bruce Creek area (Fig. 4). All of the Ledbetter Slate within approximately 100 m of the western border of the Spirit pluton (Plates 1 and 2) appears similar in hand specimen, and is assigned to the type II Ledbetter. This unit everywhere appears as a dense, massive hornfelsic slate which retains some graptolite-bearing bedding or cleavage surfaces in zones from 0.3 to 1.8 m thick. These bedded zones are oriented subparallel to the north-trending contact between the slate and granitic rock, and they are separated by hornfelsic zones from 0.3 to 7.6 m thick. Both the hornfelsic and the bedded zones weather a moderate reddish orange (10 R $^{6}/6$) to moderate reddish brown (10 R $^{4}/6$) as a result of the oxidation of their iron-bearing components, and appear dark gray (N4) on fresh surfaces. Graptolite impressions are not as "fresh-looking" as in the type I Ledbetter, and they are coated with a milky-white mineral that does not react with hydrochloric acid and(or) they are iron-stained. The graptolites are observable only where the slaty cleavage is parallel to beding planes. The only minerals identifiable in hand specimen are finely crystalline pyrite, or its limonite coated pseudomorphs, and thin (less than 1.5 mm) calcite-filled fractures.

A sample of slate collected from within approximately 50 m of the contact between the slate and granitic rock along the east summit of Staghorn Mountain in sec. 3 (Plates 1 and 2) was examined by X-ray diffraction and thin section analyses. The combined results of these analyses indicate that type II Ledbetter consists of approximately 45 percent black, opaque, organic matter and finely crystalline pyrite, 29 percent quartz, 3 percent mica-illite (mainly muscovite ?), 2.5 percent pyroxene (diopside ?), 2.5 percent amphibole (tremolite ?), 5 percent ferroan dolomite, 12 percent feldspar, and 1 percent biotite (Table 2).

The hornfelsic parts of the type II Ledbetter are composed of nearly equidimensional crystals of pyroxene, amphibole, microcrystalline quartz, feldspar, and rod-shaped grains of black, opaque carbonaceous (?) matter. All have maximum dimensions of less than 0.05 mm and the crystals are randomly oriented. The bedded parts of the type II Ledbetter are composed of subangular monocrystalline quartz, fedlspar, mica (muscovite and minor biotite), and carbonate crystals. All exhibit a weak preferred orientation that is subparallel to the wavy zones formed by concentrations of black, anhedral particles of carbonaceous (?) matter and finely crystalline pyrite. The slightly greater carbonate content of the type II Ledbetter, relative to the type I Ledbetter, is consistent with the observations of Schuster (1976) and Yates (1976) that the Ledbetter Slate is more calcareous with increasing stratigraphic position. The Ledbetter Slate classified as type II is exposed primarily in the area to the northwest of the Bruce Creek study area and includes parts of the middle and upper units described by Yates (1976), which are more calcareous than the lower slate unit that is present along the contact between the slate and limestone in secs. 2 and 3.

Type III Ledbetter

Outcrops of the type III Ledbetter are confined to localities that represent the erosional remnants of the east-trending part of the contact between the Ledbetter Slate and Metaline Limestone in secs. 2 and 3 of the Bruce Creek area. All of the type III Ledbetter crops out within approximately 50 m from the sourthern border of the Spirit pluton, and is everywhere a medium dark gray (N4), dense, massive hornfels, or a gradational equivalent of the type II Ledbetter.

A "typical" sample of type III Ledbetter consists of approximately 10 percent quartz, 5 percent fedlspar, 8 percent pyroxene (diopside ?), 3 percent amphibole (tremolite ?), 5 percent calcite and/or dolomite, ± mica and apatite. In addition to having varying amounts of apatite, the type III Ledbetter differs from types I and II Ledbetter in having greater amounts of carbonaceous (?) mater (up to a visually-estimated value of 60 percent in some samples collected from closer to the pluton).

A lack of continuous outcrop exposure makes the determination of petrographic zonations in the Ledbetter Slate difficult to accomplish.

Nonetheless, certain generalizations regarding this topic can be presented. Some of these generalizations are: 1) the Ledbetter Slate is more calcareous and less organics-rich with increasing stratigraphic position; 2) the carbonate content of the slates is more altered to calc-silicate minerals (diopside and tremolite) by contact metamorphism as the borders of the Spirit pluton are approached; 3) the primary mineral constituents of the Ledbetter Slate become increasingly recrystallized toward the border of the pluton, and thus the slaty texture becomes subordinant to the secondarily induced hornfelsic texture; 4) the most contact metamorphosed parts of the Ledbetter Slate are present along with erosional remnants of the contact between the slate and limestone adjacent to the southern border of the pluton in secs. 2 and 3 of the Bruce Creek area; and 5) a minor, discontinuous "zone" of apatite is present in the slate within approximately 2 m from the contact with the Metaline Limestone.

Todd (1973) noted systematic mineralogical variations of the Ledbetter Slate to correlate with proximity to the contact with the Spirit pluton. On the basis of textural and mineralogical differences, units of the slate within approximately 3 m of the pluton were assigned by Todd to the hornblende-hornfels facies of contact metamorphism, whereas elsewhere they were regarded as belonging to the quartz-albite-epidote-biotite subfacies of greenschist regional metamorphism.

Todd (1973) had the benefit of a regional view of the petrographic zonations in the country rocks adjacent to the Spirit pluton, whereas the present study was confined to a small area of the southwest part of the metamorphic aureole. The rocks of the Bruce Creek study area that are adjacent (within approximately 10 m) to the border of the Spirit pluton contain mineral assemblages which may be assigned either to the albite-epidote-hornfels or the hornblende-hornfels facies of contact metamorphism. The rocks located at greater distances from the pluton contain mineral assemblages which may be assigned either to the quartz-albite-epidote-biotite subfacies of greenschist regional metamorphism or a similar assemblage which constitutes the lower, peripheral assemblage of the albite-epidote-hornfels facies of contact metamorphism.

The Spirit Pluton

The Spirit pluton was named for the rocks that are exposed near the town of Spirit, Washington, which is located in sec. 4, T. 38 N., R. 41 E., Stevens County. The pluton is elongated in an east-west direction across Stevens and Pend Oreille Counties (Fig. 1), with the approximate dimensions of 11 by 32 km. The southwest border of the pluton is nose-shaped and projects southward into secs. 2 and 3 of the Bruce Creek study area (Fig. 4). The granitic rocks of the Spirit pluton form the prominent topographic highs comprising Staghorn Mountain, and exhibit approximately 60 percent outcrop exposure.

Lithology and Petrography

Todd (1973) classified the intrusive rocks of the Spirit pluton according to the system of Streckeisen (1967) and reported that the main central mass of the composite intrusive was a porphyritic monzogranite that was locally bordered by an equigranular quartz monzite. Outcrops toward the eastern end of the pluton contain inclusions and selvage remnants of two rock types that Yates and Engles (1964) believed were representative of the earlier stages of magma crystallization. Yates and Engles classified the two types of inclusions as a hornblende gabbro and a quartz diorite, but Todd has concluded that these rocks had been metamorphosed by subsequent phases of the pluton and, therefore, he classified them as an amphibolite and a metadiorite, respectively. In addition, Todd recognized a fifth phase that cut all of the earlier phases and classified it as a fine to medium-crystalline granodiorite which grades into aplitic granite in places.

Only the equigranular quartz monzonite and the granodiorite units are present within the Bruce Creek area. These units locally grade into each other, display minor petrographic variations, and are cut by aplite dikes and quartz veins.

The quartz monzonite unit is typically equigranular, a light-gray color (N7), fine to medium-crystalline (0.5 to 1.0 mm), and contains nearly equal proportions of equidimensional crystals of quartz, whice feldspars, and biotite. This unit comprises approximately 90 percent of the plutonic rock that is exposed in the Bruce Creek area.

The granodiorite is characterized by a nonporphyritic and fine to medium-crystalline (0.25 to 1.0 mm) texture, a very light gray color (N8), and nearly equal proportions of equidimensional crystals of quartz, white feldspars, and less than one percent biotite. This unit appears to form "chilled margins" surrounding minor inclusions of Ledbetter Slate within the quartz monzonite unit, with gradational contacts over a distance of approximately one meter (Fig 11). This gradational relationship is present wherever the plutonic rocks are in contact with the Ledbetter Slate.

The aplite dikes display local petrographic variations, with a few of the dikes having aplitic borders, with a relatively uniform grain size of less than 2 mm, and pegmatitic cores, with crystals of quartz and feldspar up to 4 cm. None of these dikes contain any noticeable sulfide mineralization.

Quartz veins range up to one meter in thickness and most veins are barren, but a few of them contain molybdenite mineralization. The mineralized vein sets will be discussed further in the section of this report that describes the economic geology of the Bruce Creek area.

The aplite dikes and quartz veins exhibit two distinct forms. Some are spaced from several centimeters to a few meters apart, they dip into the pluton at shallow angles (less than 45°), and vary from less than one centimeter to more than two meters in thickness. Others occur as complexly interfingering masses that are randomly oriented, grade into each other, range up to eight meters in thickness, and are commonly associated with roof pendant rock, such as that which contains the Howard and the A and C mines (Plates 1 and 2).

Figure 11. Hand specimen of plutonic rock of the Spirit pluton showing the gradational relationship between the coarser crystalline quartz monzonite and finer crystalline granodiorite. Note the small inclusion of black argillite (arrow).

Microscopic examination of a sample (G-1) of "typical" quartz monzonite, which was collected from the summit of Staghorn Mountain (Plates 1 and 2), indicates that this unit has a hypidomorphic-granular texture and does not exhibit any linear arrangements of the mineral constituents, except for the infrequent subparallel oreintation of some biotite books. The modal analysis of this sample indicates that the quartz monzonite unit contains quartz (13.2%), potassium-feldspar (34.6%, including 29.3% orthoclase, 21% perthite, and 3.2% microcline), plagioclase (35.5%), biotite (11.2%), amphibole (0.5%), accessories (1.4%), opaques (1.6%), and alternation minerals (2.0%), as depicted in Table 3.

The quartz monzonite unit contains large (2 and 3 mm), anhedral quartz crystals that have minor inclusions of biotite, fedlspar, and accessory minerals such as zircon and sphene. The quartz crystals commonly exhibit undulose extinctions. Anhedral to subhedral orthoclase crystals average 1.5 by 2.5 mm and display minor alternation to white mica. The plagioclase component consists of anhedral to subhedral lath-shaped crystals that average 1 and 2 mm, exhibit minor alternation to sericite, sausserite (?), and some calcite along crystal boundaries and within cores, and are both zoned (approximately 30%) and unzoned. The unzoned crystals of plagioclase feldspar generally range from $An_{25}$to An_{35}. In contrast, the zoned crystals exhibit a larger compositional variation with more calcic (An_{45}) cores and sodic (An_{20}) rims.

Table 3. Chemical analysis of rock units of the Spirit pluton in the Bruce Creek area (in percent).

Sample	*Location	SiO_2	Al_2O_3	MgO	CaO	Na_2O	K_2O	S
G-1	SE¼, NW¼, NE¼, sec. 3, Staghorn Mt.	67.4	15.7	0.93	3.8	4.4	3.1	0.05
G-2	NE¼, SW¼, NE¼, sec. 3.	74.1	12.8	0.2	1.1	3.2	5.9	0.05

*Exact location of smaples collected are plotted on Plate 2.

Table 4. Modal analysis (500 points) of rock units of the Spirit pluton (in percent per thin section).

Sample	Lithology	quartz	K-spar.	plag.	bio.	amph.	acces.	opaques	alt.
G-1	equigranular quartz monzonite	13.2	34.6	35.5	11.2	0.5	1.4	1.6	2.0
G-2	granodiorite	20.5	22.7	45.6	9.2	--	0.5	1.0	0.5

Ragged, anhedral to subhedral masses, flakes, and books of biotite represent the main mafic mineral components of the quartz monzonite. Minor alternation to chlorite, magnetite, and epidote occurs along the boundaries of some crystals of biotite, and approximately 25 percent of the biotite contains inclusions of zircon, sphene, and opaques. Pleochroic haloes were not observed in the biotite. The accessory minerals in the quartz monzonite include euhedral apatite, subhedral sphene, and euhedral zircon. Subhedral magnetite with minor hematitic alteration along some crystal boundaries is present throughout the sample, but tends to cluster near the biotite.

The granodiorite unit is petrographically a "sugary"-textured of interlocking, fine to medium-size crystals that range from 0.5 to 1.0 mm in maximum dimension. Minerals determined from a single modal analysis (Talbe 3 G-2) were quartz (20.5%), potassium-feldspar (22.7%, including 16.8% orthoclase, 5.7% perthite, and 0.2% microcline), plagioclase (45.6%), biotite (9.2%), accessories (0.5%). Anhedral crystals of quartz are relatively free of inclusions and commonly exhibit undulose extinction. Anhedral orthoclase commonly displays perthitic textures. Plagioclase feldspar is present primarily as subhedral laths that are zoned from cores of An_{12} to rims of An_5. There is minor sericitic alternation along the boundaries and within the cores of some feldspar crystals. Biotite is present in the form of anhedral masses and ragged, subhedral books and flakes, which average one by two millimeters in maximum dimension and display minor chloritic alteration along crystal margins. subhedral zircon and magnetite represent the only identifiable accessory and opque minerals, respectively, that are present in the granodiorite.

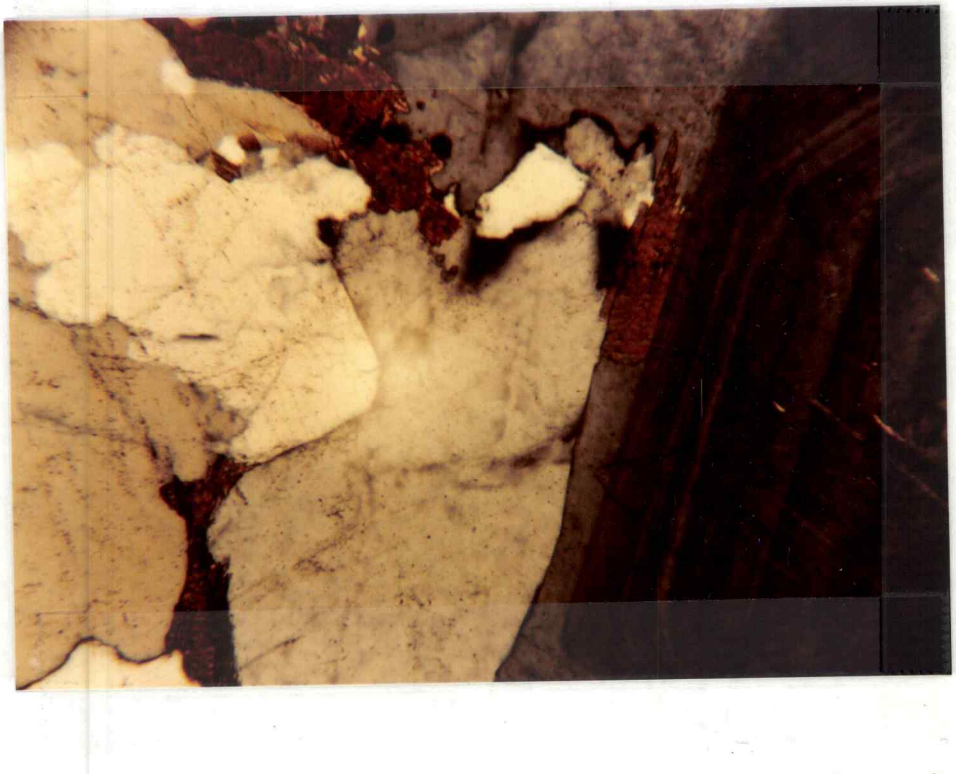


Figure 12. Photomicrograph (polarized light, 100X, 1.8 mm field of view) of a sample of "typical" nonporphyritic quartz monzonite collected from the summit of Staghorn Mountain. Note zoned plagioclase feldspar.

Age, Correlation, and Emplacement of the Spirit Pluton

Yates and Engles (1968) have obtained K-Ar dates of 100 m.y. for both the Spirit pluton and the adjacent Kaniksu batholith. Accordingly, Yates (1976) has suggested that the Spirit pluton is a west-projecting lobe of the Kaniksu batholith, although these intrusive bodies are nowhere observed to be in contact with each other.

Previous workers (Todd, 1973; Yates, 1976; Wong, 1978) have concluded that the Spirit pluton is a differentiated igneous body that grades from mafic and oldest in the northeast to felsic and youngest toward the southwest. Todd classified the emplacement of the pluton according to the criteria of Buddington (1959) and concluded that it was emplaced between the upper mesozone (with temperatures of 240° to 440°C. and depths of 6 to 12 km) and the lower epizone (temperatures less than 240°C., depths less than 6 km).

According to Yates (1976), the Spirit pluton was emplaced along, and consumed the eastern end of, the Magma fault. The Magma fault serves as the southern boundary of the Hook Nose-Baldy and Lime Creek Mountain tectonic blocks of Yates (1970), which are depicted in Figure 4 (p. 10). In addition, Todd (1973) has suggested that the Spirit magma rose along structural features, such as bedding planes, joints, and slaty cleavage surfaces in the Ledbetter Slate. The previously undetected eastward deflection in the contact between the Ledbetter Slate and Metaline Limestone, as defined by this investigation, also may have served as an east-west-trending zone of weakness which influenced the emplacement of the Spirit pluton.

The "S" and "Z"-shaped sections of the western border of the Spirit pluton, which are depicted on the map of Yates (1971), can be attributed to the tendency of the magma to intrude along planes of weakness in the Ledbetter Slate. Late-stage differentiates, such as the aplite dikes, aplitic granite, and both the barren and molybdenite-bearing quartz veins, are observed along the axes of the sawtooth-shaped, northeast-trending ridges that comprise much of the western border of the pluton. Most of the dikes and veins diminish in both size and abundance toward the central mass of the pluton, and at the outer boundary they may project several meters into the Ledbetter Slate. Some of the larger dikes and veins are themselves fractured and filled with angular fragments (up to 0.5 m in diameter) and masses of coarsely-crystalline granitic rock of similar composition to that which comprises the surrounding pluton. According to Todd (1973), the late-stage differentiates that evolved with magma crystallization may have been released through tectonically-induced fractures into the solidified outer rind of the pluton as it cooled; possibily in a manner analogous to the formation of the fractures described by Mackin (1974) in the intrusions of the Iron Springs District, Utah.

Results of this study indicate that the orientations of the foliation in the Metaline Limestone, the deformed contact between the limestone and slate formations, and the axes of the small folds along that contact are subparallel to the gently undulating southern border of the Spirit pluton. Thus, the evidence suggests that the pluton was emplaced as a viscous magma that deformed pre-existing, northeast-trending structures in the Ledbetter Slate and Metaline Limestone as described by Todd (1973). Further evidence in support of the forceful emplacement of the Spirit pluton is present near drill hole "D" in sec. 3 (Plate 2), where small knob-shaped bodies of granitic rock up to 2.5 m in diameter apparently intruded along, and caused the deformation of, joint sets in an outcrop of Ledbetter Slate. In addition, Todd (1973) noted that the western and southwestern borders of the pluton bulged outward in comparison to the other borders of the intrusive body, and that at such locations the Ledbetter Slate country rock was shouldered aside during the process of forceful intrusion.

Presumably a small but undertermined amount of stoping was also involved with the emplacement of the Spirit pluton, as is indicated by several small (less than 1 by 5 m) xenoliths of Ledbetter Slate which are oriented parallel to, and within approximately 15 m of, the southern border of the pluton in secs. 2 and 3 of the Bruce Creek area. In addition, the infrequent presence of relatively large (15 by 45 m) roof pendants, such as the "blocks" that contain the Howard and the A and C mines (Figure 2, Plates 1 and 2), also suggest that stoping was involved in the emplacement process. However, on the basis of field evidence the author would agree with Todd (1973) that the extent of stoping was minor.

STRUCTURE

Only small-scale features, which are related to the larger regional structures present in northeast Washington, are visible within the relatively small Bruce Creek study area. For example, characteristics of the northeast-trending regional folds are represented in the Bruce Creek area by axial plane foliation and small-scale "parasitic" folds, with similar orientations. The regional structure of northeast Washington was summarized in the introductory part of this report and will not be duplicated here. The reader is referred to the work of Todd (1973) and Yates (1976) for a detailed description of the regional geology present in northern Stevens County.

Folds

The rocks of the Bruce Creek area are situated along the west-northwest limb of the Gilette Mountain anticline. This regional structure is one of a series of northeast-striking open asymmetrical anticlines and synclines which formed prior to the emplacement of the 100 m.y. Spirit pluton. Axial plane foliation in the metasedimentary rocks of the study area is oriented parallel to the genetically related northeast-trending folds, and is more distinctly formed in the Ledbetter Slate than in the Metaline Limestone. This foliation is aligned subparallel to the graptolite-bearing bedding planes in the slate, which strike within a few degrees of north and dip steeply (more than 80°) to either the east or west. Axial plane foliation in the carbonate rocks is represented by the faint, mottled, gray-and-white banding present in the outcrops of the south side of the Clugston Creek

Road along the northern slopes of Uncle Sam Mountain (Plates 1 and 2). However, this banding is increasingly masked by sharply defined metamorphic foliation in the marbles toward the contact with the Spirit pluton in secs. 2 and 3 (Fig. 6).

The only obvious folds present in the Bruce Creek area are found along the contact between the slate and carbonate rocks adjacent to the southern border of the Spirit pluton. The axes of these small folds (amplitudes and wavelengths less than 1 m) are oriented subparallel to the erosional remnants of the east-striking segment of the contact, which has been deformed by the forceful intrusion of the pluton. These small structures formed during the intrusive event, and at least one of them appears to be a pre-existing, northeast-trending, parasitic fold (related to the regional northeast structure) that was refolded and is now, like the others, oriented subparallel to east-west trend of the southern margin of the pluton (Fig. 13). In general, most of the uranium anomalies under investigation by BurWest are present within black argillite (Ledbetter Slate) in the cores of these small-scale (drag ?) folds.

Faults

The only indication of faulting in the Bruce Creek area is provided by the presence of several slickensides in the limestone outcrops along the north slopes of Uncle Sam Mountain in sec. 3. The limited amount of exposure of these features inhibits their correlation with other faults outside of the study area. However, there appears to be an east-striking normal fault that dips steeply to the north separating the outcrops of limestone on the north and south sides of the Clugston Creek Road in secs. 2 and 3. This feature was not included on the thesis map coverage.

Joints, Dikes, and Veins

Joints present in the various rock units of the Spirit pluton can be classified as primary or secondary. The primary joints are filled with aplite, pegmatite, and(or) quartz and, therefore, are believed to have formed during emplacement of the pluton. In general, the primary joints present in the Bruce Creek area are oriented normal to the outbulged, east-west-trending southern margin of the pluton and dip at shallow angles (less than 25°) into it.

The secondary joints are sparesly distributed in the study area. They are oriented both normal and parallel to the primary joints, but are not filled with igneous material and, therefore, probably formed after the intrusive event. The secondary joints, like the primary sets, are spaced from a few centimeters to more than four meters apart, but dip more steeply into the pluton.

There are two sets of joints in the metamorphic aureole of the Spirit pluton in the Bruce Creek area. The more pervasive of these sets are oriented normal to the northeast-trending structures, but are parallel to the northwest-trending secondary joints in the granitic rocks. The second joint set in the metasedimentary rocks is parallel to the northeast-trending structures and, like the first joint sets, have steep dips. None of the joint sets in the rocks of the Bruce Creek area are mineralized, except for the minor presence of molybdenite mineralization in some of the quartz-filled primary joints in the granitic rocks. These mineralized structures will be discussed in the secion entitled Economic Geology.

All of the pre-existing, northeast-trending structures in the Bruce Creek area were deformed by the forceful emplacement of the Spirit pluton and are presently oriented subparallel to the east-west trending southern margin of the pluton (Plates 1 and 2).

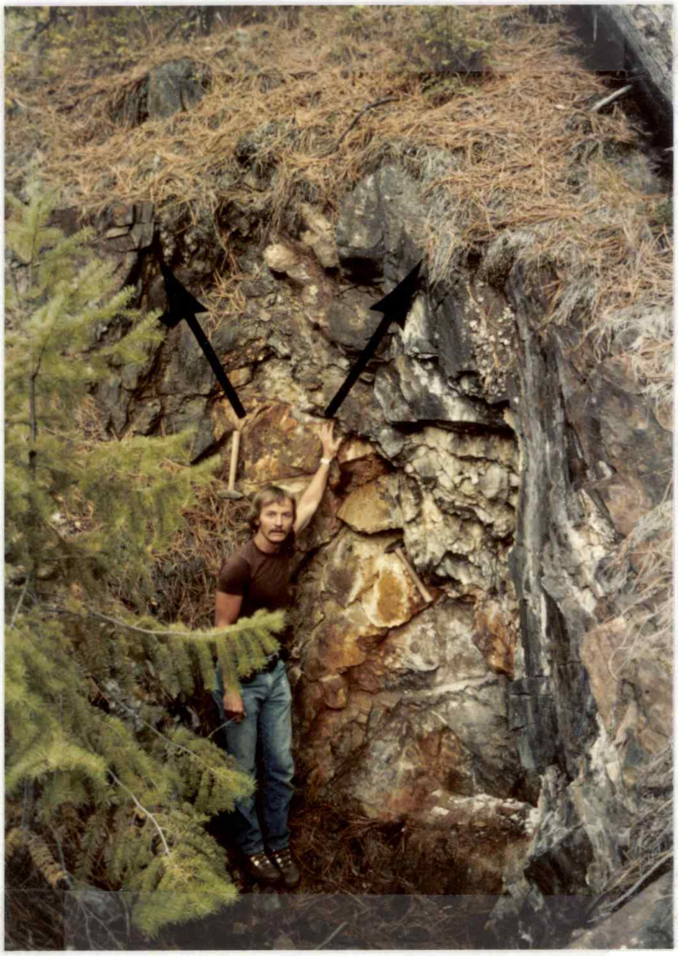


Figure 13. A prospect pit cut into one of the small folds along the contact between the Ledbetter Slate (01) and Metaline Limestone (Cm) adjacent to the sourthern margin of the Spirit pluton. This is a pre-existing northeast-trending structure that was refolded by the forceful intrusion of the pluton into a west-striking fold.

ECONOMIC GEOLOGY

The backbone of the mining industry in northeast Washington has been the production of lead-zinc sulfide ores from carbonate rocks of Cambrian age. The mines are located in Stevens (and Pend Oreille) county and they were active producers of lead, zinc, and minor silver from the 1980's until the late 1950's. The discovery and production or ore-grade uranium mineralization on the Spokane Indian Reservation in southern Stevens County during the late 1950's has resulted in a renewed interest concerning the economic geology potential of the region.

The present section of this report will concentrate on the characteristics of several local areas of anomalous radioactivity in the Cambrian-Ordovician metasedimentary rocks of the Bruce Creek study area. The presence of both lead-zinc sulfide and molybdenite mineralization in rocks of the study area was investigated in a cursory manner. The data and interpretations of previous workers who studied the sulfide ores more closely will be integrated with the results of this report whenever it will assist in the understanding of the genesis and distribution of the uranium anomalies in the Bruce Creek area. The reader is referred to the excellent work of Todd (1973), Schuster (1976), and Mills (1977) for a more extensive discussion concerning the lead, zinc, and molybdenite mineralization of the rocks of Stevens County.

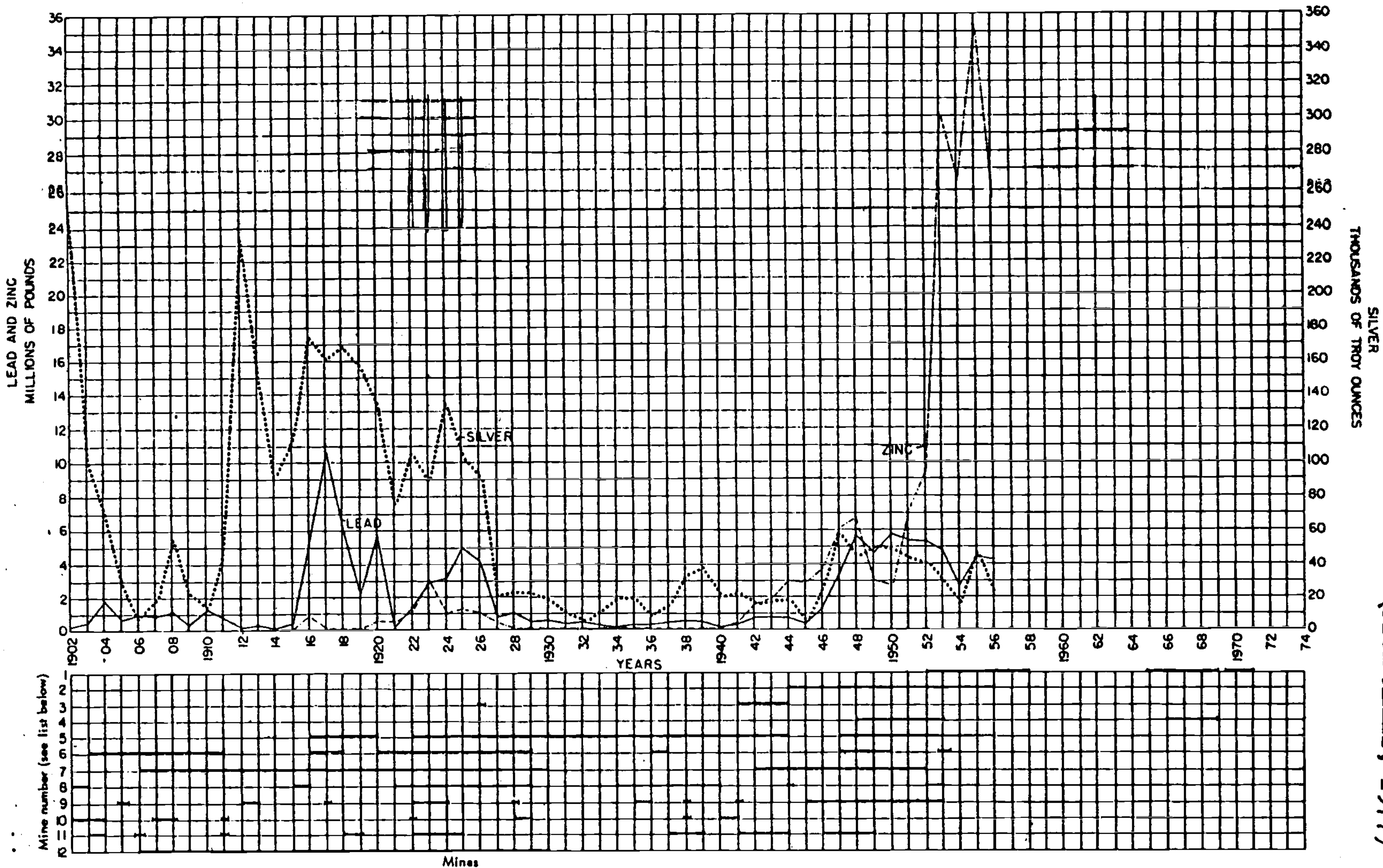
Lead, Zinc, and Silver Ores

Lode mining began in Stevens County in 1893 with the discovery of lead and silver mineralization east of the town of Colville. The completion of a railroad during the 1980's boosted mining activity in the region. Ore-grade galena mineralization was discovered in 1915 and production commenced the following year. None of the mines are active producers at the present time. A chart depicting the productive life of the principal producers of lead, zinc, and silver and a graph of their total production figures are shown in Figure 14.

Geology

Mills (1977) has classified the lead, zinc, and silver ore deposits of Stevens County into five main categories based on their easily recognizable characteristics such as form, lithology, and mineralogy. The five classes are:

1) Silver-bearing, discordant, randomly oriented quartz veins in differing host rocks of varying age;
2) Sulfide veins localized along fractures, faults, and shear zones in differing host rocks of varying age;
3) Concordant lead-zinc-silver ores in the "Yellowhead" breccia zone of the middle dolomite unit of the Metaline Limestone;
4) Concordant lead-zinc-silver ores in the Josephine Breccia zone of differing units of the Metaline Limestone; and
5) Concordant, contact metamorphosed lead-zinc-silver ores in banded dolomitic limestones and marbles that are



Mines

1 Van Stone
2 Deep Creek
3 Sierra Zinc
4 Calhoun
5 Gladstone and Electric Point
6 Last Chance, Great Western, and Black Rock
7 Bonanza
8 Old Dominion
9 Young America
10 Legal Tender, Silver Seal, Silver Queen
11 Cleveland
12 United Copper, Chewelah (much silver)

Data from Fulkerson and Kingston, 1958

Figure 14. Upper part depicts production figures and lower part shows operating life of Stevens County Pb-Zn mines.

(From Mills, 1977)

present in differing units of the Metaline Limestone adjacent to the Spirit pluton.

Evidence such as deformation and annealing twins, granoblastic polygonal texture, and preferred orientation of the lead and zinc sulfide minerals described by Mills (1977) indicates that the sulfide mineralization at the Howard and the A and C mines in the Bruce Creek area (Plates 1 and 2) are expamples of the concordant, contact metamorphosed ore deposits that were derived by the thermal metamorphism of the concordant lead-zinc-silver ore deposits in the Josephine Breccia. The Josephine Breccia and its metamorphic equivalents are the major hosts for the lead-zinc-silver ores of both Stevens and Pend Oreille Counties.

The lead-zinc mines in the region of the Bruce Creek study area area localized along the linear trend of the Josephine Breccia zone, which transects all three members of the Metaline Limestone. As previously noted, the Josephine Breccia is confined to a specific stratigraphic interval (approximately 300 m) beneath the contact between the Ledbetter Slate and Metaline Limestone, with which it is genetically related. The approximate position of the contact between the slates and limestones, prior to partial "consumption" by the Spirit pluton along parts of its southern margin, can be delineated by noting the geographic distribution of mines that are adjacent to the pluton. The mines situated several kilometers to the south of the Bruce Creek area are localized along a north-south-trend that changes abruptly to an east-west-trend in the vicinity of the A and C property in sec.3 (Plates 1 and 2). The mineralized belt continues to strike in an easterly direction as far as eight kilometers to the point where the southern margin of the pluton projects into the Metaline Limestone. Here, the pluton is in contact with rocks of the Metaline Limestone along most of the east-striking and discontinuously mineralized belt. However, in the vicinity of the bend in the contact between the slates and limestones in sec. 3, the pluton is in contact with erosional remnants of Ledbetter Slate which are in turn in contact with the Metaline Limestone. Apparently the Spirit pluton intruded along, and caused the regional deformation of, the contact between the slates and limestones.

The sulfide mineralization that is present in the carbonate rocks of the Bruce Creek area is confined to a discontinuous, Irregularly-shaped, blanket-like body that strikes east and is oriented parallel to and within 300 m of the contacts between the granite-slate-limestone and the granite-limestone. As noted previously, the sulfide mineralization is believed to represent mineralized parts of the contact metamorphosed Josephine Breccia zone which were not "consumed" by the intrusion of the Spirit pluton. Wherever sulfide-bearing carbonate rocks are in contact with the Spirit pluton in the Bruce Creek area, the mineralized structures, (such as fractures, faults, veins, joints, and dike sets) are not present in the rocks of the Bruce Creek area, nor are they present in other parts of the Spirit pluton or its metamorphic aureole according to Todd (1973). The one exception to this is the rare presence of molybdenite-bearing quartz veins, which will be discussed in the next section. The lead-zinc deposits adjacent to the Spirit pluton in the Bruce Creek area, as well as elsewhere (Todd, 1973), do not exhibit any obvious mineral zonations. These observations are in agreement with the conclusions of Todd (1973) and Mills (1977) that the host rocks of the Josephine Breccia zone were mineralized prior to the intrusion of the Spirit pluton.

Mineralogy

Outcrops of the carbonate rocks in the Bruce Creek area were traversed normal to the contacts between the granite, slate, and limestone approximately every 100 m. Over 40 samples were collected for study in hand specimen and thin section. Sphalerite is the dominant sulfide mineral present in hand samples of the carbonate rocks and is associated with lesser amounts of galena, pyrite, and pyrrhotite. The sulfide minerals are present as disseminations, streaks, lenses, elongate clusters, and vein-like masses and all have their long or tabular dimensions oriented parallel to the plane of bedding or banding in the host marbles. The size of the sulfide aggregates varies from a fraction of a centimeter to over 0.5 m in width and from a few centimeters to over 2.0 m in length, as does the metamorphic banding in the marble host rocks. Ore bodies comprise only a small part of the Josephine Breccia zone and their boundaries are "assay" contacts.

The principal gangue minerals viewed in outcrop, hand sample, and thin section are calcite, dolomite, and quartz with lesser amounts of tremolite, diopside, and traces of wollastonite (Table 1, p. 21). The calc-silicate minerals are randomly distributed when viewed in thin section, as well as on a scale of tens of meters in the field.

However, their distribution on a scale of hundreds of meters appears to follow a predictable pattern with the respective appearance of tremolite, diopside, and wollastonite as the borders of the Spirit pluton are approached (Table 1). Evidence suggests that the pluton did not metasomatically alter the adjacent country rocks, but merely imposed thermal and possibly pressure gradients during emplacement and cooling that caused isochemical changes in these host rocks. This interpretation is based on the lack of any significant metasomatic or hydrothermal alternations that might be indicative of mass transfer in the reactive carbonate rocks adjacent to the pluton, as well as on the absence of any typical hydrothermal zonations of the sulfide and gangue minerals. Thus, the calc-silicate gangue minerals are believed to have formed simply by contact metamorphism of the impure, siliceous-carbonate rocks of the Josephine Breccia zone rather than by the metasomatic or hydrothermal addition of material (including uranium ?) from the pluton.

Origin

As noted in an earlier section, the lead-zinc sulfide ores were probably derived from brines that flowed through the permeable Josephine solution-collapse breccia zone in the Metaline Limestone and were thermally metamorphosed by the intrustion of the Spirit pluton. An understanding of the structural and stratigraphic controls of the lead-zinc mineralization processes is important to the exploration for other such ores that may be present in the rocks of the Bruce Creek area. This topic will be discussed further in the following section. In addition, some of the characteristics of the Josephine Breccia zone, the metamorphosed ores, and the contact between the Ledbetter Slate and the Metaline Limestone which is genetically associated with the zone of breccia have a bearing on the genesis and distribution of some of the uranium anomalies in the Bruce Creek area. These topics will be discussed in a later section under the heading of Uranium Mineralization.

Guides to Exploration

Lead

Samples of the Spirit pluton and metasedimentary country rocks from the Bruce Creek area contain lead in amounts that range from 0.0005 to 0.5 percent with a mean average of 0.03 percent (Tables 5, 6, and 7). These relatively low values recorded for the concentration of lead in the rocks in the area suggest that the exploration for lead ores alone would not be an economically profitable venture.

Zinc

Ores of zinc, unlike those of lead, have been produced profitably from the mines in the Bruce Creek area (Fig. 5). The concentration of zinc as recorded from the carbonate and pelitic rocks are as great as 15 and 1.5 percent, respectively (Tables 6 and 7). These high values were recorded from samples of calcite marble (L-5) and hornfelsic slate (S-6) which were collected from within 3.0 m of the Spirit pluton in the vicinity of drill hole "D" in sec. 2 (Plate 2). This "zone" is one of several situated along the southern margin of the Spirit pluton in the Bruce Creek area that may represent contact metamorphosed parts of the mineralized Josephine Breccia zone.

Although there are at least five adits and mine prospect pits within the Bruce Creek area, it cannot be assumed that all of the zinc mineralization and ore has been discovered. The early miners apparently confined their efforts to the rocks of the metamorphic aureole along the southern border of the Spirit pluton probably because they believed that the sulfide mineralization was formed by hydrothermal processes which were genetically related to the intrusion of the pluton. According to Mills (1977), however, the mineralization is stratigraphically and structurally controlled by the presence or absence of the contact between the Ledbetter Slate and Metaline Limestone and the genetically related Josephine Breccia zone, which may or may not be contact metamorphosed depending on the proximity of the Spirit pluton.

Undiscovered horizons favorable to ore may occur at depth between the area of Howard Meadows (plates 1 and 2) and the Van Stone mine, which is located approximately eight kilometers to the east. Among the complicating factors that will inhibit future exploration for zinc ores are the lack of sufficient outcrop exposure, the highly variable geometry of the Josephine Breccia zone, and the truncation and "consumption" of the zone of breccia by parts of the Spirit pluton. The best zinc exploration target at the present time is the area situated between Howard Meadows and the northern slopes of Uncle Sam Mountain (Plates 1 and 2), where BurWest recorded geophysical and geochemical anomalies that may be indicative of a zone of sulfide mineralization that is oriented subparallel to the erosional remnants of the contact between the Ledbetter Slate and Metaline Limestone in the Bruce Creek area. This target is within the proper stratigraphic distance beneath the slate-limestone contact and thus might contain a mineralized part of the Josephine Breccia zone.

Silver

The measured amounts of silver in the rocks of the Bruce Creek area do not exceed 0.00015 percent and average less than 0.0001 percent (Tables 5, 6, and 7). The amount of silver that has been produced from the mines in this area is also relatively insignificant (Fig. 5). For example, the A and C mine produced only 31 grams of silver during its operating life. The future exploration for deposits of silver in the Bruce Creek area is not considered to be a geologically reasonable endeavor.

Molybdenite Mineralization

The molybdenite mineralization of the Bruce Creek area is present in both the plutonic and the metasedimentary country rocks. The highest grades of molybdenite mineralization are present in the nonporphyritic quartz monzonite border phase of the Spirit pluton, and in the associated late-stage aplite dikes and quartz veins located along its southwestern margin. The concentration of molybdenite in these rocks ranges from 0.0003 to 2.35 percent with a mean average of 0.18 percent (Tables 5, 6, and 7).

The molybdenum is present in the form of sulfide rosettes (approximately 0.5 cm in diameter), irregularly shaped masses (up to 8 cm in length), disseminations, stringers, and blebs in the quartz veins and hydrothermally altered granitic rocks. Lesser amounts of molybdenum (averaging less than 0.001% Mo) are present along the surfaces of joint sets and fractures in parts of the Ledbetter Slate and Metaline Limestone which are in contact with the molybdenite-bearing phases of the Spirit pluton (Todd, 1973). According to Todd the molybdenite that is disseminated in the country rocks presumably migrated out from the igneous rocks during the intrusion of the pluton and subsequent hydrothermal activity.

The areas with the most significant amounts of molybdenite mineralization are present along the outbulged or convex margins of the Spirit pluton. As previously noted, these areas served as the sites for the extensive emplacement of late-stage aplite dikes and quartz veins.

Origin

Although the ionic radii of molybdenum permit it to substitute for elements such as Fe^{+3}, Ti, and Al in the crystal lattices of the rock-forming minerals, molybdenum tends to be concentrated in the late-stage differentiates of magmatic crystallization in the upper lithosphere (Krauskopf, 1955). In an open system, in which material may escape through fractures in the solidified rind of a cooling igneous body, molybdenum may be incorporated into aplites, pegmatites, and quartz veins in the peripheral parts of the intrusive, as well as in the adjacent country rocks. In contrast, in a closed system molybdenum may be localized in the more siliceous phases of magmatic crystallization or it can be present as disseminations throughout the peripheral parts of an igneous body. The molybdenite mineralization of the rocks in the Bruce Creek area is localized in association with dikes, viens and the adjacent country rocks along the west and southwest borders of the pluton. This is in agreement with the conclusions of Toll (1973) and Wong (1978) that the Spirit pluton crystallized as an open system.

Guides to Exploration

Most of the rock samples collected from the Bruce Creek area contain less than 0.001 percent molybdeum. Nonetheless, three anomalous samples contain 0.29, 0.59, and 2.35 percent molybdenum, respectively. All three of the samples contain visible molybdenite in the form of disseminations, small rosettes or clusters, and vein-like stringers.

One sample (G-7) came from a small mass (approximately 1 by 1.5 m) of quartz monzonite located along the contact between the granitic and carbonate rocks at the upper end of the prospect trench adjacent to the upper A and C adit in the NE¼, sec. 3 (Plate 2). Although weathered, this sample exhibits sericitic and argillic alteration, whereas the adjacent carbonate rocks did not appear to be metasomatically altered. This sample was collected from the only area of noticeable hydrothermal or deuteric alteration in the granitic rocks that are present in the Bruce Creek area and contains 2.35 percent Mo.

The second anomalous sample was collected from one of several small (approximately 15 cm by 1 m) molybdenite-bearing quartz veins that are present in the NE¼, sec. 3 approximately 150 m to the northeast of the upper A and C adit (Plate 2). This sample (G-6) contains 0.29 percent molybdenum. The quartz veins dip at shallow angles into the pluton and strike in a northeast direction.

The third sample of molybdenite-bearing rock was collected from a quartz vein at the American Moly prospect, which is located in the SE¼, SW¼, sec. 16, T. 38 N., R. 39 E. or approximately 5.5 km to the north of the Bruce Creek area. The vein averages 1.5 m in thickness and strikes N. 10° E. and dips 10° SE. It can be traced over a distance of 30 m along strike before pinching out in the pluton at one extremity and the Ledbetter Slate at the other. The quartz vein contains up to 0.59 percent molybdenum and the adjacent granitic (G-4) and metasedimentary (S-13) rocks contain 0.18 and less than 0.0005 percent molybdenum, respectively.

The exploration potential for depsits of molybdenite "ore" in the Bruce Creek area is severaly limited by the relatively small size and restricted occurrence of these showings. Exploration efforts should be directed to areas along the west and southwest margins of the Spirit pluton where the late-stage dikes and veins are localized. However, it should be noted that this area has been carefully examined, and that any additional molybdenite mineralization either is present at depth, and thus will require a drilling program, or more likely has been lost to erosion.

Uranium Mineralization

The following brief discussion concerning the nature and the distribution of uranium minerals is a compilation of some of the concepts that are presented in: Klepper and Wyant (1957); Heinrich (1958); Curtis (1960); Fix (1960); Armstrong (1974); Bohse and others (1974); and Rich and others (1977).

Uranium is concentrated in the upper lithosphere in the range of 0.0001 to 0.0002 percent. The average concentration in rocks of similar composition to those of the Bruce Creek area is: 0.00024 percent in igneous rocks of intermediate composition; 0.0004 percent in silicous igneous rocks; 0.0003 percent in carbonate rocks; 0.0004 percent in shales; and 0.0025 percent in marine black shales. The average grade of uranium ore mined between 1948 and 1972 was 0.235 percent U_3O_8.

Uranium can be present in oxides, hydroxides, silicates, carbonates, phosphates, sulfates, and vanadates, but not in native elements, sulfides, sulfosalts, or tellurides. Uranium ions can be present in either the tetravalent (U^{+4}) or the hexavalent (U^{+6}) state. In general, the U^{+6} ions are capable of being transported in an oxygenated medium and can be reduced to the U^{+4} state, which is stable in subsurface or anoxic environments. Uranium can occur in igneous, metamorphic, and sedimentary rocks as well as in natural waters.

Uranium in the Spirit Pluton

Previous workers have documented the tendency of uranium ions to be concentrated in the late-stage members of a differentiated sequence of igneous rocks (Klepper and Wyant, 1957; Heinrich, 1958; Larsen and Gottfried, 1961; Bohse and others, 1974; and Rich and others, 1977). The uranium ions are believed to be partitioned into the residual phases during the crystallization of a magma because they do not readily substitute into the crystal lattices of the common rock-forming minerals as a consequence of ionic coordination restrictions, the relatively large radii of the uranium ions (1.57 Å), and their high valence states.

Some workers have noted that the concentration of uranium tends to decrease slightly in the products of extreme differentiation, such as muscovite quartz monzonite or aplitic granite (Larsen and Gottfried, 1961; Bohse and others, 1974; and Wong, 1978). This apparent difficiency of uranium in late-stage differentiates may be attributed to one or more possible mechanisms. First, the siliceous, uraniferous parts of an intrusive body, such as the roof or border zones, may have had the uranium content leached out by meteoric waters (Heinrich, 1958). Second, if the magmatic body cooled as an open system as proposed by Todd (1973) to explain the emplacement of the Spirit pluton, the uranium may have escaped with volatile-rich fluids during the late stages of crystallization (Bohse and other, 1974). Finally, the magma may have been initially depleted with respect to uranium and thus little was available in the melt to be incorporated in the late-stage products of crystallization (Larsen and Gottfried, 1961).

Wong (1978), who conducted a detailed petrographic examination of the units of the Spirit pluton, has noted that the uranium content increased in the younger, felsic members of the differentiation series, but then decreased slightly in the aplitic rocks. She attributed this decrease, as well as the overall low average concentration of uranium for all units of the Spirit pluton (0.00024 percent U_3O_8), to the possible escape of uranium with late-stage volatiles during magmatic crystallization. According to Wong, the uranium should be presently located in the rocks along the west and southwest margins of the Spirit pluton, particularly within the late-stage aplite dikes, molybdenite-bearing quartz veins, and associated reductant-rich (reduced organic matter and pyrite) country rocks of the Ledbetter Slate.

Samples of a "typical" aplite dike, two molybdenite-bearing quartz veins, and Ledbetter Slate adjacent to the quartz veins were collected from the west and southwest borders of the Spirit pluton and were analyzed for their uranium content. The aplite dike (G-2) contains 0.00055 percent U_3O_8 (Table 5). The molybdenite-bearing quartz veins (G-5 and G-6) contain less than 0.00005 percent U_3O_8 (Table 5) as does the sample of Ledbetter Slate (Table 7, S-13).

The comparatively low concentrations of uranium that were recorded from the samples of the late-stage dikes and veins and the associated country rock, relative to the uranium in the granodiorite and quartz monzonite units of the Spirit pluton (Table 5), suggest that:

1) little uranium is present in the late-stage differentiates and adjacent country rocks, and therefore, it is doubtful that

any significant amounts of uranium could have escaped from the pluton in the manner proposed by Wong (1978);

2) the uranium was introduced into the country rocks and is yet to be discovered (at depth ?) or has since been lost to erosion;
3) the uranium crystallized with late-stage dikes and veins (open system cooling) or silicous apical parts of the pluton (closed system cooling) which are undiscovered or have been lost to erosion; or that
4) the Spirit pluton crystallized from a magmatic source that was initially depleted with respect to uranium.

If significant amounts of uranium had been introduced into the silicous phases of the Spirit pluton or into the country rocks, then they must have been lost either to erosion of these rocks (or leached from them by meteoric waters) or they must be present at depth. This is based on the fact that the surface exposures of the Spirit pluton have been carefully examined by BurWest (and others) and anomalies of uranium have not been detected.

According to Heinrich (1958), the concentrations and locational sites of uranium in igneous rocks are variable as a consequence of its occurrences as:

1) a minor constituent forming ionic substitutions in the crystalline structure of accessory minerals such as zircon, sphene, allanite, apatite, and monazite;
2) a major constituent forming small amounts of primary (U^{+4}) or secondary oxidized (U^{+6}) uranium minerals;

Table 5. Geochemical analysis of the metallic constituents of the Spirit pluton (in percent).

Sample	Lithology	Location	U_3O_8	Mo	Pb	Zn	Cu	Ag	Mn
G-1	quartz monzonite	SE¼, NW¼, NE¼, sec. 3, Staghorn Mt.	0.0025	0.0003	0.0015	0.0050	0.0004	0.00007	0.0420
G-2	granodrite	NE¼, SW¼, NE¼, sec. 3.	0.0022	0.0007	0.0018	0.0085	0.0008	0.00005	0.0001
G-3	aplite dike	NE¼, SW¼, NE¼, sec. 3.	0.0006	0.0035	0.0005	0.0005	0.0004	0.00003	0.0001
G-4	quartz monzonite	near Mo-qt vein SE¼, SW¼, sec. 16, T. 38 N., R. 39 E.	0.0009	0.1770	0.0018	0.0030	0.0024	0.00006	0.0460
G-5	white quartz vein	same as sample G-4	0.0001	0.5880	0.0006	0.0012	0.0040	0.00005	0.0013
G-6	white quartz vein	NW¼, NE¼, sec. 3.	0.0001	0.2890	0.0020	0.0080	0.0005	0.00006	0.0013
G-7	altered qt. monzonite	NW¼, NE¼, sec. 3, near upper A & C adit.	*nd	2.348	nd	nd	nd	nd	nd
**	granodiorite		0.00024	nd	nd	nd	nd	nd	nd
**	qt. monz.		0.00027	nd	nd	nd	nd	nd	nd
***	granodiorite		0.00024	nd	nd	nd	nd	nd	nd
***	qt. monz.		0.00039	nd	nd	nd	nd	nd	nd

* = not determined; ** = average concentration of U_3O_8 in Spirit pluton reported in Wong (1978);
*** = average U_3O_8 in mesozoic batholiths of western U. S. reported in Larsen and Gottfried (1961).

3) interstitial material along crystal boundaries;
4) solid inclusions in rock-forming minerals; and(or) as
5) disseminations in fluid inclusions or intergranular fluids.

Wong (1978) concluded that the uranium present in various phases of the Spirit pluton is in the form of ionic substitutions in the crystal lattices of accessory minerals, most notably in zircon, sphene, and apatite, as well as along crystal lattice defects in the feldspar minerals. According to Wong, discrete minerals of uranium are not present in the igneous host rocks.

The predominant rock unit of the Spirit pluton in the Bruce Creek area is the equigranular quartz monzonite unit which comprises most of the border phase of the pluton. A thin section of a sample of this unit was analyzed in detail (Table 4, G-1), and several others were examined briefly. The results are similar to the previously noted conclustions of Wong (1978). Distinct uranium minerals were not observed, which may be considered somewhat unusual because of the relatively large concentration of uranium (0.0025 percent U_3O_8, which is an order of magnitude greater than the 0.00024 percent average recorded by Wong for the entire pluton) from parts of the quartz monzonite border phase of the Spirit pluton (Table 5).

According to Heinrich (1958), the peripheral parts of an intrusive igneous body commonly contain more uranium than the central parts (as is apparently the case for the Spirit pluton). Reasons for this peripheral distribution may be:

1) the tendency for uranium ions to be partitioned into the residual phases, which commonly crystallize along the peripheral parts of an intrusive body;
2) the peripheral assimilation of uraniferous wall rocks (such as the uraniferous Ledbetter Slate of the Bruce Creek area); and(or)
3) the supergene enrichment of uranium that was leached from overlying igneous and(or) metasedimentary rocks.

In summary, the data derived from this study (as well as from that obtained from other BurWest exploration projects that included geophysical, geochemical, and radiometric surveys in the region) suggest that:

1) relatively little uranium (0.00024 to 0.0025% U_3O_8) is present in the various rock units of the Spirit pluton in the Bruce Creek area (or elsewhere, according to Wong, 1978);
2) relatively little uranium (0.00005 to 0.0009% U_3O_8) is present in the late-stage aplite dikes and quartz veins located along the southwest margin of the Spirit pluton;
3) relatively little uranium was introduced into the country rocks from the Spirit pluton; and that
4) the Spirit pluton may have crystallized from a magmatic source which was initially depleted with respect to uranium.

Uranium in the Metaline Limestone

The carbonate minerals that comprise the Metaline Limestone are not directly associated with any anomalous uranium mineralization in the Bruce Creek area. The concentration of uranium in four samples of carbonate rock collected at various distances (approximately 5.0 to 600 m) from the Spirit pluton ranges from 0.0002 to 0.0004 percent U_3O_8 (Table 6). This concentration of uranium compares favorably with the average value of 0.0003 percent U_3O_8 in carbonate rocks according to Rich and others (1977). Radiometric field surveys in the Bruce Creek area did not detect any significant correlation between the amount of radioactivity and the lithologic variations in the carbonate rocks, or with the distance from contacts of the Spirit pluton.

The only significant anomalies that were detected in the Metaline Limestone of the Bruce Creek area are present in argillitic material that is enclosed within the carbonate host and exhibits two different modes of occurrence. The first type of argillite is present as minor interbeds that exhibit soft sediment deformation and were described in an earlier section (P. 15). A sample of these interbeds (G-11) was collected from the vicinity of the lower A and C adit in the NE¼, sec. 3 (Plate 2) and contains 0.00095 percent U_3O_8 (Table 7). This is considered anomalous only to the extent that it is twice the value of concentration of uranium that is found in the surrounding rock.

The second type of argillite is present in the host that comprises the roof pendant containing the A and C mine. Here, a "zone" of black argillite containing 0.0091 percent U_3O_8 (Table 7, S-9) is exposed

Table 6. Geochemical analysis of the metallic consituents of the Metaline Limestone (in percent).

Sample	Lithology	U_3O_8	Mo	Pb	Zn	Cu	Ag	Mn
L-1	dolomitic marble	0.0002	0.0005	0.0007	0.036	0.0018	0.00008	0.0040
L-2	dolomitic marble	0.0004	0.0015	0.0085	0.010	0.0008	0.00003	0.0002
L-4	calcite marble	0.0003	0.0007	0.0220	1.064	0.0006	0.00010	0.0350
L-5	calcite marble	nd*	nd	0.550	15.000	nd	nd	nd

*nd = not determined

Locality L-1	NW¼, SE¼, sec. 3, within 0.5 m from the slate-limestone contact exposed at the Clugston Creek raod cut (Plates 1 and 2).
Locality L-2	SW¼, NW¼, sec. 3, approximately 50 m to the north of the powerlines (Plates 1 and 2).
Locality L-4	SE¼, NW¼, NE¼, sec. 3, approximately 15 m inside the upper A and C adit along the northern wall.
Locality L-5	SW¼, NE¼, sec. 3, at the 14 to 15 m interval of diamond drill hole "D" (Plate 2).

(Exact locations of samples collected are plotted on Plate 2) along the eastern wall of the upper A and C adit. The carbonate rock that is in contact with the uraniferous argillite (Table 6, L-4) at this locality contains only 0.0003 percent U_3O_8 and is not altered by contact metasomatism (Table 1).

The "zone" of black, uraniferous argillite pinches and swells from a few centimeters to more than one meter in thickness along a distance of approximately 25 m. The argillite is enclosed in barren calcite marble that is surrounded by sparsely mineralized (lead-zinc sulfides) tremolitic marble. This sulfide mineralization is assigned by Mills (1977) to the category of "concordant, contact metamorphosed lead-zinc ores in banded dolomitic limestones and marbles", which are interpreted to be the metamorphic equivalent of the Mississippi Valley-type ore deposits in the Josephine (solution-collapse) Breccia zone.

The argillite inside the A and C mine is similar in appearance and composition (Table 2) to the black, phosphatic, uraniferous slate that is present along the contact between the Ledbetter Slate and Metaline Limestone approximately 300 m to the east of the A and C mine. The relatively close proximity of this contact between the slate and limestone and the compositional similarities to the lithologies at this contact collectively suggest that the argillite in the A and C adit was derived from a similar sediment source as that of the argillite forming the basal parts of the Ledbetter Slate of the Bruce Creek area. The argillite in the adit was probably formed by clay-size sediment that washed into open spaces, which were connected to the erosional surface of the Metaline terrain, in an expanding zone of solution-collapse breccia as described by Schuster (1976). The forceful intrusion of the Spirit pluton probably deformed the cavern-filling of argillite into its present convoluted form.

Uranium in the Ledbetter Slate

The following discussion concerning the presence of uranium in marine black shales is a compilation of some of the information that is presented in Klepper and Wyant (1957), Heinrich (1958), Fix (1960), and Mickle (1978).

Uranium was first discovered in marine black shales in 1893 in the Alum Shale of Sweeden and has since been found in marine black shales throughout the world. The uranium content of these shales generally ranges between 0.001 and 0.03 percent, with 0.0005 percent being considered the minimum value for classifying a shale as being uraniferous.

Uraniferous marine black shales are characteristically rich in organic matter, pyritic, very fine-grained, noncalcareous, and commonly phosphatic. These shales are massive to thinly laminated, break almost conchoidally, and are generally of lower Paleozoic age. The black shales are typically deposited on an euxinic substrate beneath a density-stratified column of marine water of brackish to nearly normal salinity. The sediment supplied to the strongly reducing bottom environment generally consists of silt-size particles of quartz, feldspar, and mica as well as abundant detrital and colloidal clay minerals and organic matter.

Humic and sapropelic organic matter and finely crystalline pyrite comprise the dark, opaque material that imparts the black color to the shales. The humic material consists of carbonized wood and coalified terrestrial plant matter that is high in carbon and oxygen but low in hydrogen. The sapropelic material contains spores, pollen grains, and marine plants and algae and is high in carbon and hydrogen but low in oxygen. Marine black shales characteristically contain greater amounts of sapropelic than humic matter (Brown, 1956; Andreyev and Chumachenko, 1964, Mickle, 1978).

In general, the amount of uranium contained in black shales is directly proportional to the amounts of organic matter and pyrite (or total "blackness" of the shale) contained therein. However, it may be proportional to the contents of terrigenous detrital and carbonate material. The finer grained and thinner laminated parts of a black shale unit are generally the most uraniferous. This textural relationship suggests that a slow sedimentation rate is an important factor in the syngenetic accumulation of uranium with the shales.

Distinct varieties of uranium minerals have not been identified from unweathered outcrops of black shale, but secondary (oxidized) uranium minerals are infrequently reported from weathered outcrops. According to Klepper and Wyant (1957) and Heinrich (1958), uranium cna be present in marine black shales as:

1) inclusions or ionic substitutions in both light and heavy detrital minerals;
2) adsorbed ions on the surfaces of colloidal clay minerals and organic matter;

3) a component of chemically-bonded, isomorphous, urano-organic acids; and(or)

4) an element isomorphous in collophane.

Klepper and Wyant (1957) have stated that, in general, uranium (U^{+6}) is transported by streams and rivers to the sea where it is deposited in tranquil, density-stratified waters and is reduced to the stable U^{+4} state in the anoxic bottom environment. However, other workers have suggested that strongly reducing bottom conditions are necessary only for the preservation of the tetravalent uranium ions, and that biochemical processes which operate in living marine organisms are responsible for the extraction and fixation of hexavalent uranium ions from the ocean (Rankama and Sahama, 1950; Degens and others, 1977).

Andreyev and Chumachenko (1960) have noted that the efficient reduction-fixation of U^{+6} to U^{+4} is a complex fundtion of pH, Eh, and the types of associated organic matter. For example, the maximum reduction of uranium ions occurs under conditions of low pH in the presence of humic material, but occurs under conditions of high pH in the presence of sapropelic matter. In general, the reduction-fixation of uranium ions in marine black shales is most likely to occur under acidic conditions, because as stated earlier, these sediments have a high sapropelic content.

According to Heinrich (1958) and Getxeva (1958), metamorphism may cause the uranium in black shales to recrystallize to very finely crystalline "sooty" pitchblende. The crystals of pitchblende would be difficult to observe under the microscope because the uranium ions are believed to be absorbed between layers of graphite in carbonaceous matter (McKelvey and others, 1956). Mickle (1978) has noted that the concentration of uranium in black shales remains relatively uniform in lateral extent (a function of geography), but can vary in vertical extent (a function of lithology of beds) in a single formation. He suggested that the spotty or irregular distribution of uranium within a shale bed or series of beds suggests that epigenetic enrichment or redistribution of uranium has occurred. The distribution of uranium in the Ledbetter Slate of the Bruce Creek area was observed to be very erratic, therefore, epigenetic processes may have localized uranium mineralization in these rocks.

Prior to presenting information concerning petrographic and mineralization trends which are apparent in the rocks of the Bruce Crekk area, two problems should be mentioned which might influence the validity of the interpretations derived from this study. First, the present study was confined to a relatively small area (approximately 3 km^2) and it considered only a single unit (the black graptolitic slate unit) out of a regionally extensive sequence of Ordovician to Silurian black argillites of which the Ledbetter Slate is only the basal part. Any attempt to apply these conclusions that were derived from local observations to the rocks outside of the Bruce Creek study area should be tempered with caution. Secondly, the accurate detection of any petrographic zonations that may be present in the Ledbetter Slate of the study area is inhibited by two factors; 1) the lack of continuous outcrop exposures because the slate weathers readily to form hills of low relief that are covered with soil and trees, and

2) the fact that the Spirit pluton intruded the Ledbetter Slate in an essentially concordant manner (Plates 1 and 2), thereby masking any primary vertical or lateral sedimentary mineralogical variations with secondary metamorphic alterations.

Despite these problems, certain generalizations can be offered regarding the petrographic patterns that are present in the outcrops of Ledbetter Slate in the Bruce Creek area. These generalizations are derived from the results of petrographic examination (Table 2) and geochemical analysis (Talbe 7) of samples of slate which were collected at various distances (approximately 5.0 to 600 m) from the southwest border of the Spirit pluton (Plate 2).

The data in Table 2 are in agreement with the conclusions previously advanced by Schuster (1976) and Yates (1976) concerning the lithologic variations in the Ledbetter Slate. This formation is 1) more argillacous and contains less organic matter and pyrite in its lower parts (rocks exposed to the south of the Bruce Creek area), 2) richer in reduced organic material and pyrite in the rocks within the study area, and is 3) more calcareous and less enriched with organic matter with increasing straigraphic position (rocks exposed to the northwest of the Bruce Creek area). The data in Table 2 list some of these lithologic variations, except for those rocks exposed to the south of the study area that were examined only at outcrops.

The data presented in Tables 2 and 7 and Figure 15 indicate two possibly interrelated patterns of uranium distribtion in the slate. First, the concentration of uranium in these rocks appears to be related to their variations in lithology. For example, more uranium

Table 7. Geochemical analysis of the metallic constituents of the Ledbetter Slate (in percent).

Sample	*Location	U_3O_8	Mo	Pb	Zn	Cu	Ag	Mn
S-1	NW¼, SE¼, sec. 3, at the Clugston Creek Rd. cut.	0.0004	0.0025	0.0025	0.0180	0.0025	0.00007	0.0009
S-2	SW¼, NE¼, sec. 3, 35 m west of drill hole "I"	0.0008	0.0030	0.0025	0.0090	0.0030	0.00010	0.0095
S-4	NW¼, NE¼, sec. 3.	0.0010	0.0040	0.0020	0.0010	0.0030	0.00007	0.0012
S-5	SW¼, NE¼, sec. 3, near diamond drill hole "D"	0.0230	0.0680	0.0130	1.0400	0.0050	0.00006	0.0007
S-6	from within 0.5 m of sample S-5.	0.0230	0.0380	0.0040	1.4500	0.0160	0.00008	0.0007
S-7	NE¼, NW¼, sec. 3, on west Staghorn summit.	0.0010	0.0040	0.0025	0.0010	0.0030	0.00007	0.0012
S-8	NE¼, NW¼, sec. 3, near aplite dike and S-7.	0.006	0.0015	0.0018	0.0018	0.0008	0.00003	0.0013
S-9	NW¼, NE¼, sec. 3, in upper A and C adit.	0.0091	0.0170	0.0320	0.4080	0.0085	0.00008	0.0015
S-10	surveyed corner of secs. 3, 33, and 34.	0.0003	0.0018	0.0030	0.0180	0.0015	0.00012	0.0065
S-11	arglt. intrbds, near lower A and C adit.	0.0009	0.0025	0.0040	0.0050	0.0010	0.00008	0.0015
S-12	NW¼, NW¼, sec. 2, near upper Howard adit.	0.0690	**nd	nd	nd	nd	nd	nd
S-13	SE¼, SW¼, sec. 16, T. 38 N., R. 39 E.	0.0004	0.0004	0.0014	0.0050	0.0004	0.00004	0.0400

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*Exact location of samples collected are plotted on Plate 2.
**nd = not determined

(from 0.0008 to 0.069 percent U_3O_8) is present in the Ledbetter Slate of the Bruce Creek area (Table 7, samples S-2 to S-12) than in the stratigraphically higher and lower parts of the formation (Table 7, samples S-10 and S-1, respectively), in which less than 0.0004 percent U_3O_8 is present. This pattern follows the previously noted trend in which concentrations of uranium vary directly with the amount of reduced organic matter and pyrite, and inversely with the amount of carbonate and detrital material in marine black shales.

Second, the data in Table 7 and Figure 15 indicate that the uranium content of the Ledbetter Slate of the Bruce Creek area increases in the rocks that are progressively closer to the contacts with the Spirit pluton. For example, a sample of slate collected from over 700 m to the south of the pluton (S-1) contains only 0.0004 percent U_3O_8 (Table 7). This value is less than that suggested by Mickle (1978) as being the lower cutoff (0.0005% U_3O_8) for classifying a shale as uraniferous. Three samples of slate collected at distances ranging from between 1 km and 10 m to the contact of the Spirit pluton (S-2, and S-8) contain concentrations of uranium ranging from 0.0006 to 0.001 percent (Table 7). Five samples of slate collected within 10 m of the pluton (S-4, S-5, S-6, S-9, and S-12) contain from 0.001 to 0.069 percent U_3O_8, which indicates that uranium is distributed erratically throughout the rocks that are adjacent to the southern border of the intrusive body. Figure (15) depicts the general increase in the concentration of uranium in the rocks closer to the

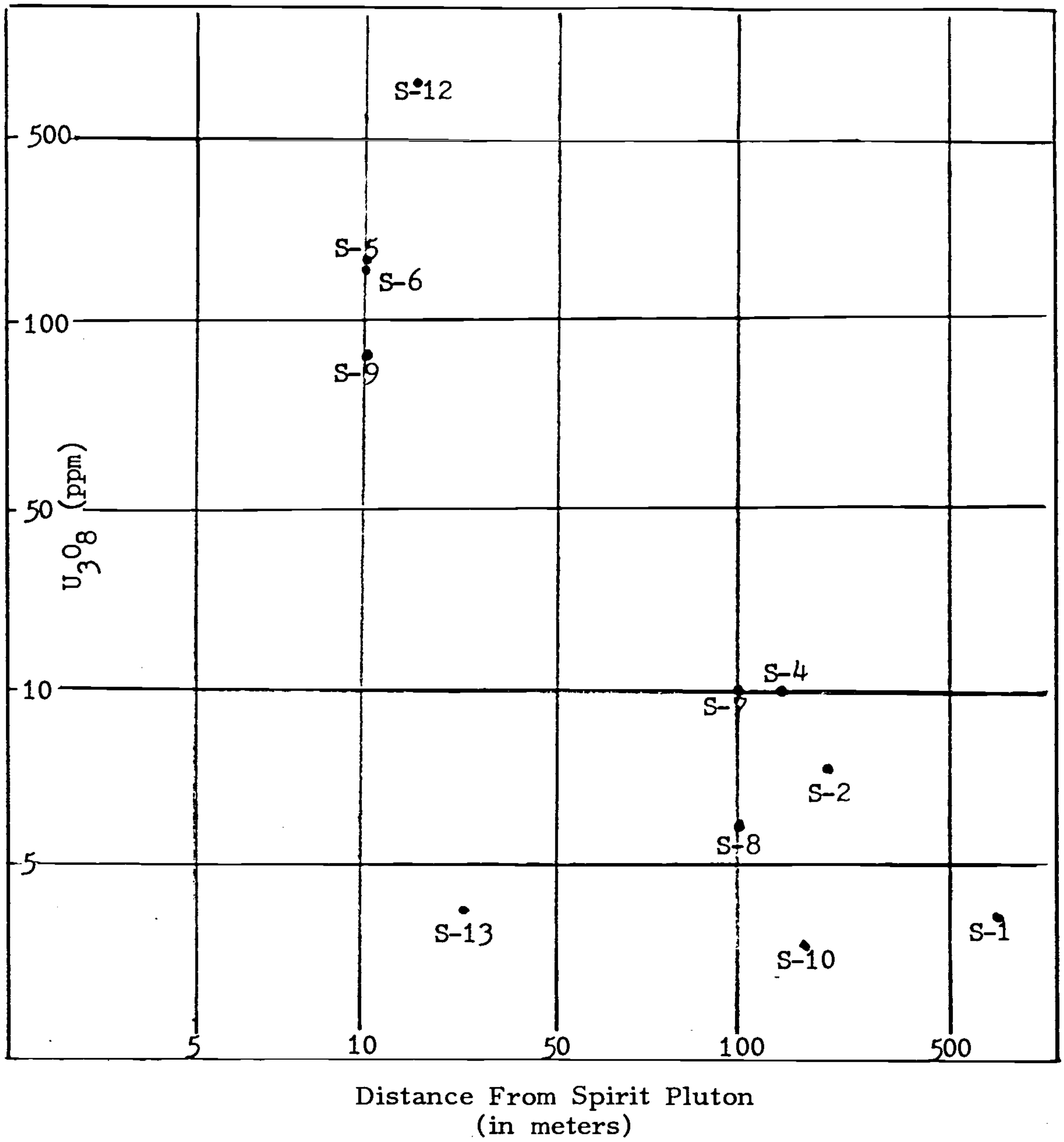

Figure 15. Relationship between the concentration of uranium in 11 samples of Ledbetter Slate and distance from the contact with the Spirit pluton in the Bruce Creek area. Note the general increase in the uranium content of the slates closer to the pluton, and the marked variation of this concentration in the rocks within 10 m from the intrusive body on this logarithmic plot. These trends are a result of both syngenetic uranium mineralization and epigenetic enrichment (see text). All distances are approximate with ± 10 percent error.

contact with the Spirit pluton, as well as the variations in the amounts of uranium contained in the samples collected from local areas closest to the pluton.

The most radioactive samples of Ledbetter Slate were collected from the cores of several small-scale folds along the contact between the slate and the Metaline Limestone in secs. 2 and 3 (Plate 2). The most uraniferous parts of these folded slates are confined to small tabular-shaped zones (approximately 5 by 30 cm in average dimension) that are commonly within a few centimeters from the folded contact between the slate and limestone. Two samples collected from the crest of one of these folds (near drill hole "D", Plate 2) contain 0.023 percent U_3O_8 (Table 7, samples S-5 and S-6), and one from a fold near drill hole "G" (the "discovery trench" on Plate 2) contains 0.069 percent U_3O_8 (Table 7, S-12).

Finally, X-ray and thin section analyses indicate that a few samples of Ledbetter Slate, which were collected from within 10 m of the contact between the slate and limestone in sec. 2 (near drill hole "D", Plate 2), contain as much as 10 percent apatite (Table 2, samples S-5 and S-9). The apatite (probably carbonate-fluorapatite) is distributed along thin discontinuous zones (approximately 1 by 4 cm) that are aligned parallel to the faint foliation (bedding ?) in the slate. According to Klepper and Wyant (1957), uranium ions tend to substitute for calcium ions in the structure of carbonate-fluorapatite, and uranium is preferentially concentrated in the phosphatic parts of a black shale unit. However, the apparent association between the uraniferous and apatitic parts of the Ledbetter Slate may have more of a coincidental than a genetic signifcance, because samples of both apatitic (Table 2, sample S-5 contains 10 percent apatite) and non-apatitic slate (Table 2, sample S-6), which were collected from within 0.5 m of each other, contain indentical concentrations of uranium (Table 7, 0.023 percent).

The apparent increase in the concentration of uranium in the samples of slate collected progressively closer to the contact with the Spirit pluton may be attributed to one or more mechanisms relating to the geochemical behavior of uranium during the genesis of igneous, sedimentary, and metamorphic rocks. These might include processes suggesting that:

1) the uranium content of the slates is entirely syngenetic to diagenetic; for example, the Ledbetter muds were deposited as organic-rich, phosphatic (in part) sediment that accumulated uranium together with the reduced organic matter and preserved the tetravalent ions in the euxinic bottom environment;
2) the black muds may have had a syngenetic concentration of uranium that ranged from approximately 0.0004 to 0.001 percent, and which may have been uniformaly distributed originally throughout the sediments, but later underwent localized enrichment possibly as the result of;
    a) the redistribution of uranium ions during the compaction and dewatering of the sediments,
    b) the mobilization and removal of uranium from one area of shale and its subsequent reconcentration in

an adjacent area as a result of regional and(or) contact metamorphism, and(or)

c) supergene enrichment of uranium that was transported by meteoric, connate, or hydrothermal waters which may have migrated along structural channelways (such as the contact between the slate and limestone or bedding planes, joints, fracture cleavage, etc.) and was redeposited in the reductant-rich slate; and(or)

3) the syngenetic concentration of uranium in the sediment underwent secondary or epigenetic enrichment as minor amounts of uranium were introduced into the rocks from volatile-rich fluids that escaped from the Spirit pluton during late-stages of magma crystallization.

The erratic distribution of uranium in the Ledbetter Slate of the Bruce Creek area, as previously noted, suggests that in addition to the syngenetic accumulation of uranium (1), one or more of the processes of secondary or epigenetic enrichment (2 and 3) must have subsequently taken place. The processes of enrichment as a result of either compaction-dewatering or regional metamorphism could be reliably documented only by an extensive investigation conducted on a regional scale, and well beyond the scope of the present local study.

As noted in an earlier section, previous workers have suggested that metamorphism of uranium-bearing host rocks may cause local increases and corresponding decreases in the originally uniform concentration of syngenetic uranium as a result of remobilization from one area and reconcentration in another. Such a mechanism of enrichment may have operated during the forceful intrusion of the Spirit pluton, with contact metamorphism causing the local variations in the concentration of uranium in the Ledbetter Slate. The general increase in the concentraiton of uranium in the slates toward the contact with the pluton (Table 7 and Fig. 15), together with the observation that the most-uraniferous parts of the meta-pelites are present within small folds along the contact between the slate and limestone, offers permissive evidence that uranium may have been locally remobilized and reconcentrated in parts of the Ledbetter Slate of the Bruce Creek area.

The addition of significant amounts of uranium from late-stage, volatile-rich fluids is not considered to be a viable mechanism for causing the irregular distribution of uranium mineralization in the Ledbetter Slate. The lack of anomalous concentrations of uranium in the aplite dikes, molybdenite-bearing quartz veins, and in the associated country rocks adjacent to these dikes and veins strongly implies that little or no uranium was derived from the pluton itself (Tables 5, 6, and 7). In addition, the absence of significant hydrothermal alteration and metasomatic addition of minerals to the country rocks (particularly the highly reactive carbonates) suggests that little or no material was derived from hyrdothermal activity related to the Spirit pluton.

Finally, the irregular distribution of uranium in the slates could have possibly resulted from processes of supergene enrichment. However, it would be difficult to attribute this mineralization exculsively to such near-surface processes without demonstrating that certain parts of the Ledbetter Slate were more receptive to the introduction and retention of uranium than others. Physical and(or) chemical evidence indicative of the processes of supergene enrichments, such as oxidized versus un-oxidized zones, paleoaquifer channelways, etc., were not observed from the available exposures of Ledbetter Slate in the Bruce Creek area.

In summary, it may be concluded that the forceful intrusion of the Spirit pluton possibly resulted in:

1) the essentially isochemical alteration of the country rocks that are present in the poorly-formed contact metamorphic aureole of the pluton;
2) the deformation of northeast-trending regional structures in the Metaline Limestone and Ledbetter Slate, including the easterly deflection of the contact between the slate and limestone;
3) the formation of small folds along the contact between slate and limestone, as well as the refolding of at least one pre-existing northeast-trending fold; and
4) the remobilization and reconcentration of uranium in parts of the Ledbetter Slate that are present in the Bruce Creek area.

Nonetheless, it is possible that at least minor amounts of uranium may have been added to the Ledbetter Slate by the processes of supergene enrichment (leaching of uranium from overlying granitic or metasedimentary rocks, for example) and(or) from hydrothermal mineralization. However, there is little evidence present in the available outcrops to suggest that either of these processes, if operative at all, were anything but a minor event in the formation of the existing uranium anomalies in the Bruce Creek area.

Guides to Exploration

The most geologically significant deposit of uraniferous marine black shale in the U. S. is the Devonian Chattanooga Shale of the western Appalachian region of Tennessee (Conant and Swanson, 1961). The most uraniferous part of the Chattanooga Shale is the relatively thin (average of 1.5 m), widespread (over 80,000 km^2) Gasseway Member, which contains an average concentration of 0.0057 percent U_3O_8 (Mutschler and others, 1976). Mickle (1978) has reported that the Gasseway Member contains an estimated 4.2 to 5.1 million short tons of uranium in 76 to 91 million short tons of shale rock.

In contrast to the Chattanooga Shale, the uraniferous parts of the Ledbetter Slate in the Bruce Creek area contain an average concentration of less than 0.003 percent U_3O_8 in an estimated volume of 650,000 m^3 of rock. The most radioactive parts of the slate are present within the crests of several small folds along the contact between the pelitic and carbonate country rock adjacent to the Spirit pluton. Although these rocks contain as much as 0.068 percent U_3O_8 (Table 7), they represent an estimated volume of only 100 m^3. Obviously, the uraniferous parts of the Ledbetter Slate of the Bruce Creek area are of much less economic interest than the Chattanooga Shale, which itself is considered to be an uneconomic source of uranium ore at the present time.

Even though the anomalous occurrences of uranium mineralization of the Ledbetter Slate are not of economic importance, an understanding of their gensis and distribution may lead to the discovery of better exploration targets in northeast Washington or elsewhere. The most favorable conditions for the formation of uranium mineralization should be found in the blackest (most organic-rich), pyritic, contact metamorphosed parts of the Ledbetter Slate in close proximity to the contacts with the granitic and carbonate rocks in Stevens (Spirit pluton) and Pend Oreille (Kanidsu batholith) Counties. BurWest has discovered other regions with similar mineralization, but none of these areas are better mineralized than the slates of the Bruce Creek area. If a large volume of uraniferous argillite is present in the region, it must be hidden at depth and would require the utilization of subsurface exploration techniques to delineate the trends of mineralization.

The presence of the actively producing Midnite Mine in southern Stevens County continues to serve as a stimulus to the exploration for uranium deposits in northeast Washington. This mine is located on property of the Spokane Indian Reservation, which is approximately 90 km to the south of the Bruce Creek area. According to Nash (1977), the uranium at this mine is present in tabular-shaped ore bodies that measure approximately 300 by 200 by 50 m, and contain an average concentration of 0.15 percent U_3O_8. These ore bodies occupy "topographic lows" along the contact zone between the Precambrian metasedimentary rocks of the Togo Formation and the Cretaceous Loon Lake batholith (Fig. 16). Of possible encouragement to the geologists conducting exploration projects in northeast Washington is the fact that the ore bodies at the Midnite Mine presented only minimal physical evidence in outcrop that would be indicative of their presence in the subsurface.

The exact mode of genesis of the uranium ores at the Midnite Mine is subject to debate. Some workers have attributed the mineralization to the presence of syngenetic uranium that was originally disseminated throughout the Precambrian pelitic sediments and that later underwent remobilization and reconcentration as a result of contact metamorphism during the intrusion of the batholith (Barrington and Kerr, 1961; Nash and Lehrman, 1975). Alternatively, the uranium may have been introduced into the metasedimentary rocks by the metasomatic addition of material from the igneous intrusive body during the late-stages of magma crystallization (Nash, 1977).

If exploration efforts in northeast Washington resulted in the discovery of uranium deposit of similar size and grade to those of the Midnite Mine, then the mining industry in this region might regain some of the inertia it lost with the ceasation of lead-zinc production in the late 1950's.

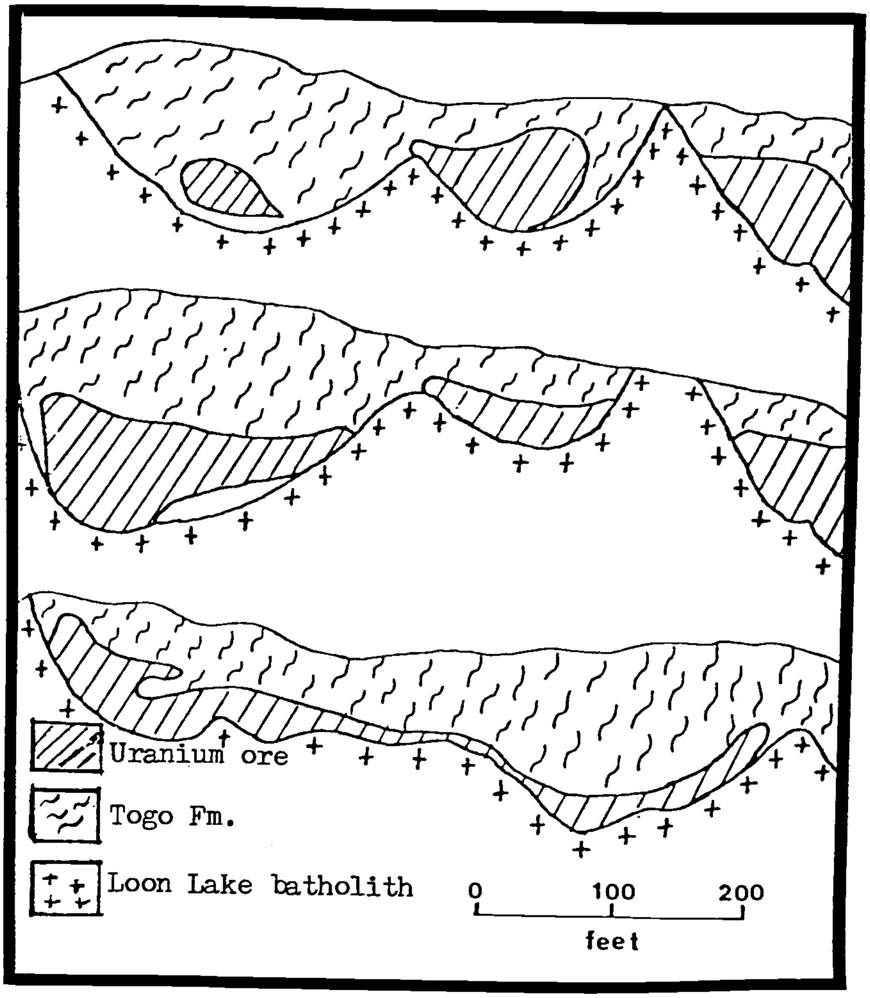

Figure 16. Geologic cross section of the uranium mineralization of the rocks at the Midnite Mine, Stevens County, Washingotn (redrawn from Nash and Lehrman, 1975 by Rich and others, 1977).

SUMMARY AND CONCLUSIONS

The carbonate rocks of the Bruce Creek area represent the deposition of calcareous muds (micrite) in Middle Cambrian to Early Ordovician time which may have accumulated along the outer edge of a regionally extensive shoaling carbonate platform as described by Fischer (1980). The combined effects of a postulated Early Ordovician epeirogenic uplift of the Metaline terrain (Mills, 1977) and eustatic regression of the sea resulted in the exposure of the carbonate platform. Subaerial weathering formed a karst topographic surface as meteoric waters reacted with the limestone and created a solution-collapse breccia zone within a stratigraphic interval of approximately 300 m beneath the surface of erosion (Mills, 1977). Prior to Mesozoic time, additional periods of formation and expansion of the permeable zone of breccia occurred, as did the low-temperature mineralization of lead-zinc sulfides in these rocks, and dolomitization of parts of the limestone formation (Yates, 1976; Mills, 1977).

The weathered surface of the carbonate terrain subsided beneath density-stratified marine waters during Early to Middle Ordovician time and this event was accompanied by the deposition of euxinic black muds (Ledbetter Slate) (Schuster, 1976; Yates, 1976; Mills, 1977). Some of these muds washed into open spaces within the zone of breccia which were connected to the erosional surface of the carbonate formation (Schuster, 1976; Mills, 1977).

Uranium accumulated with the sediments in an anoxic environment. This uranium was 1) biochemically extracted from the ocean by living marine organisms which settled to the oxygen-deficient bottom after death, 2) adsorbed onto the surface of colloidal clay minerals and particles of organic matter, and(or) was 3) chemically bonded to organic material in isomorphous urano-organic acids (Klepper and Wyant, 1957; Heinrich, 1958; Degens and others, 1977). Subsequent compaction and dewatering of the black shales may have resulted in the local enrichment of uranium in parts of the Ledbetter sediment relative to others.

Regional metamorphism (greenschist facies) coverted the shales and carbonates to slates and marbles, respectively, during Mesozoic time (Todd, 1973; Yates, 1976; Mills, 1977). Contact (thermal) metamorphism altered the slates to hornfels and the impure (silicous) dolomitic and calcite marbles to calc-silicate-bearing hosts during the forceful intrusion of the Cretaceous Spirit pluton (Todd, 1973; Yates, 1976; Mills, 1977). This episode of metamorphism may have been responsible for the local remobilization and reconcentration of uranium in parts of the Ledbetter Slate adjacent to the contact with the pluton. The greatest concentration of uranium present in these rocks occurs within the crests of several small folds along the contact between the Ledbetter Slate and Metaline Limestone in secs. 2 and 3 of the Bruce Creek study area. As much as 0.069 percent U_3O_8 is present in small tabular-shaped zones within the folded slate approximately one meter from the contact with the limestone.

Minor amounts of uranium may have been introduced into parts of the Ledbetter Slate as a result of either hydrothermal mineralization or supergene enrichment. However, there is little evidence present in the available outcrops in the Bruce Creek area that would indicate such processes as these were important factors in the formation of the anomalous occurrences of uranium.

Conclusions

Some of the more important conclusions that are derived from the data and observations presented in this report include:

1) The Late Cretaceous Spirit pluton forcefully intruded the Middle Cambrian to Early Ordovician Metaline Limestone and the Ordovician Ledbetter Slate of the Bruce Creek area, and caused the deformation of the northeast-trending regional structures, including the easterly deflection of the contact between the slate and limestone formations.
2) The intrusion of the pluton caused both the contact metamorphism and truncation of the Mississippi Valley type lead-zinc deposits in the Josephine (solution-collapse) Breccia zone, which had formed prior to Mesozoic time.
3) Channels for hydrothermal mineralization are not present in the sulfide-bearing hosts adjacent to the Spirit pluton, nor are there any obvious mineralogical zonations in the lead-zinc sulfide deposits in themetamorphic aureole of the pluton. The sparsely-formed molybdenite deposits in the quartz monzonite border phase of the Spirit pluton represent the only form of primary hydrothermal mineralization in the Bruce Creek area.
4) Minor amounts of uranium (average of less than 0.00024 percent U_3O_8 according to Wong, 1978) are present in the

various rock units of the Spirit pluton, primarily in the form of ionic substitutions in the accessory minerals.

5) The uranium anomalies discovered by Bur West occur in association with;

    a) phosphatic (in part), graptolite-bearing, pyritic, black slate and hornfels along the contact between the slate and Metaline Limestone within approximately 30 m from the contact with the pluton,

    b) small tabular-shaped bodies of slate present within the cores of several small-scale folds along the contact between the slate and limestone,

    c) a "zone" of black, apatitic argillite enclosed within a contact metamorphosed part of the lead-zinc sulfide-bearing Josephine Breccia zone located within the upper A and C mine, and with

    d) small fragments of uraniferous argillite that spalled into the episodically expanding zone of breccia within the Metaline Limestone.

6) The uranium contained in the Ledbetter Slate is present in physical and(or) chemical association with the black, pyritic, silt and clay-size particles of reduced organic matter that are disseminated throughout the Ledbetter Slate.

7) The uranium present in the slates was possibly derived from;

   a) the syngenetic extraction of uranium ions from the Ordovician sea and the preservation of these ions in a reduced valence state (U^{+4}) within the euxinic muds which were deposited beneath a density-stratified column of marine water,
   b) the less likely addition of minor amounts of uranium into the slate from uranium-bearing, late-stage, volatile-rich fluids which originated from the Spirit pluton as it cooled.
   c) the possible local remobilization and subsequent reconcentration of uranium in parts of the slate formation, and(or) from
   d) minor supergene enrichment of uranium derived from overlying igneous or metasedimentary rocks.

8) The anomalous occurrences of uranium mineralization of the Ledbetter Slate in the Bruce Creek area do not constitute an economic source of uranium ore. However, an understanding of the petrographic characteristics and patterns of distribution of these anomalies may lead to the discovery of better exploration targets in the region.

9) Continued exploration for deposits of zinc sulfides in the Bruce Creek area is warranted by the large assay values (as much as 15% Zn) that were recorded from some of the carbonate rocks (Josephine Breccia).

In conclusion, there are three major suggestions for future studies concerning the exploation for uranium deposits and the data presented in this study. These suggestions include:

1) The present study was confined to a relatively small area of northern Stevens County. Therefore, the conclusions presented herein regarding the uranium mineralization of the Ledbetter Slate of the Bruce Creek area should be tested in other regions of similar lithologic and stratigraphic relationships.
2) The present study was primarily intended to be a field oriented investigation of the anomalous occurrences of uranium that are present in the Bruce Creek area. Many of the conclusions presented in this report are supported only by permissive geochemical evidence. A more rigorous geochemical and(or) petrographic examination of these anomalous occurrences of uranium mineralization should be undertaked if more definitive solutions are sought.
3) The sedimentary basins that are adjacent to the Spirit pluton should be explored for the possible presence of uranium-bearing rocks which may represent the eroded material derived from the roof pendant-parts of the Ledbetter Slate which were shouldered aside during the forceful intrusion of the pluton. For example, the Tertiary Tiger Formation of the Cusick Basin in neighboring Pend Oreille County contains conglomerates which are similar in physical appearance and

radioactivity to the uraniferous parts of the Ledbetter Slate of the Bruce Creek area.

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