Silver- and uranium-bearing veins in the Sunshine Mine, Coeur d'Alene District, Idaho: A genetic relationship?

Rene L. Foehl
The University of Montana

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Silver- and Uranium-Bearing Veins

in the Sunshine Mine

Coeur d'Alene District, Idaho:

A Genetic Relationship?

by

Rene L. Foehl

Presented in partial fulfillment of the requirements for the

Degree of Master of Science

University of Montana

Approved by:

[Signatures]

Chairman, Board of Examiners

Dean of Graduate School

5-11-99

Date
The age, origin, and relationship between silver/base-metal and uranium-bearing veins in northern Idaho's Sunshine mine has been debated since the early 1950's because they are spatially associated. Radiometric age dating and spatial, petrographic, electron microprobe, and geochemical analyses were performed in order to characterize the veins and determine the nature of any possible genetic relationships between the two vein types. Uranium-bearing veins consist primarily of uraninite and quartz with lesser hematite and feldspars. Brannerite and uranium phosphates occur only in close proximity to silver-bearing veins, possibly formed by silver-bearing ore fluids affecting older uranium minerals.

"Jasperoid" alteration surrounding the uranium-bearing veins resulted from oxidation of pre-existing magnetite and sulfides contained within the host Proterozoic Belt Supergroup rocks. Uranium-bearing veins trend west-northwest and dip southward across a major regional fold, the Big Creek anticline. U-Pb radiometric age dating of two uranium minerals produced a concordia age of 885 Ma and a discordia age of 82 Ma.

Silver-bearing veins consist of argentiferous tetrahedrite with lesser chalcopyrite in a gangue of siderite and quartz. Veins trend east-west and seem to occur in tear fractures between major faults. Structural and isotopic evidence supports formation of the silver-bearing veins in Laramide time. No silver minerals occur within the uranium-bearing veins, though petrographic, geochemical, and microprobe analyses indicate some uranium occurs in silver-bearing veins. The uranium may have been remobilized into the silver-bearing veins.

The nature of the structural control, ore textures, and characteristics of the ore fluids necessary to form the silver-base metal/sulfide-rich veins and uranium oxide veins support vein formation in two discrete events. The veins seem to be related by having formed in similar tectonic stress fields, thereby explaining the similar trends and spatial distributions. Uranium may have been originally deposited in the Belt basin at 885 Ma during the East Kootenay orogeny and formed veins just prior to formation of the silver-bearing veins, which is roughly coincident with the intrusion of the Idaho batholith and regional tectonism. Alternately, the uranium-bearing veins may have formed during the late Cretaceous and simply contain older lead. Either model may account for the spatial and possible geochemical relationship between the two vein types in the Coeur d'Alene Mining District.
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INTRODUCTION

Purpose of Study

The Coeur d'Alene Mining District of northern Idaho has historically been the world's leading producer of silver, as well as a major source of zinc, lead, antimony, and copper. This study was undertaken to determine the nature of uranium-bearing veins occurring in the Sunshine mine and their relationship to younger silver-bearing veins. Research of uranium occurrences and ore potential followed discovery in the late 1940's, but almost no further examination of the uranium-bearing veins has occurred since then. Researchers and geologists in district mines have noted an apparent spatial association between uranium- and silver-bearing veins. Yet this relationship has not been examined in detail. In contrast, a great deal of research has been conducted on silver- and base metal-bearing veins throughout the mining district. In the following pages, new data gathered from uranium-bearing veins are compared to new and existing information on silver-bearing veins. This data permits an evaluation of the significance of the spatial relationship.

Scope of Work

Fieldwork was performed during the summer of 1998 at the Sunshine mine. Further data acquisition and report writing were undertaken in the following months. Methods used to examine both silver- and uranium-bearing veins began with a compilation of uranium occurrences throughout the mine. The result is a three-dimensional map which can be used to examine vein relationships. Polished thin sections, especially those with uranium- and silver-bearing minerals in close proximity, were
microprobe was used to further determine mineral phases, elemental distributions, and textural relationships. To re-examine the age of vein formation, dating of two uraninite samples was performed using the U-Pb radiometric method. Both silver and uranium minerals were geochemically analyzed, and both uranium-bearing quartz and silver-bearing siderite were examined for fluid inclusions to determine the nature of the ore fluids.

Previous Studies

A vast array of information is available about the Coeur d'Alene mining district including studies by Umpleby and Jones (1923), Shenon and McConnel (1939), Fryklund (1964), Hobbs and others (1965), Reid and Williams (1982), Leach and others (1988, 1998) and other references at the end of this paper. The first study of uranium in the Sunshine mine was conducted by Thurlow and Wright (1950). This was followed with reports by Kerr and Kulp (1952), Kerr and Robinson (1953), and Long and others (1959), in addition to several unpublished mine studies. Previous studies that focused upon the Sunshine mine include those by Anderson (1940), Colson (1958, 1961), Harris and others (1981), Fleck and others (1991), Bond and others (1992), Wavra and others (1994), and Eaton and others (1995).

Location

The Coeur d'Alene Mining District is located in northern Idaho, encompassing an area roughly 42 km east to west and 15 km north to south (Figure 1). The eastern limit is the crest of the Bitterroot Mountains at the Montana border, and the western boundary
extends past the town of Pinehurst, Idaho. Interstate 90, and the South Fork of the Coeur d'Alene River along which it runs, bisect the district and provide excellent accessibility. The terrain is mountainous and heavily forested, limiting most non-mining development to the narrow valley of the Coeur d'Alene River. Principal towns of the "Silver Valley", as the area is commonly known, are Kellogg (population approximately 3000) and Wallace (population approximately 1000). The district lies entirely within Shoshone County, and the nearest large cities are Spokane, Washington, 120 km to the west, and Missoula, Montana, 161 km to the east.
Geomorphology

The terrain of the Coeur d'Alene Mining District, lying at the northern end of the Bitterroot Range of the northern Rocky Mountains, is mountainous and very steep in places. The area is surrounded by poorly-defined mountain ranges extending into Montana, Canada, and southward into Idaho. To the west, mountains give way to the deserts of the Columbia Plateau. Elevations along the Coeur d'Alene River average about 800 meters, whereas those of higher peaks may reach 2000-2500 meters, providing great relief in the deeper valleys (Figure 2). The mountains are well drained by a great number of perennial streams that flow into the South Fork of the Coeur d'Alene River. Beginning near the crest of the Bitterroots along the Montana border, the river flows westward through the district, eventually feeding Lake Coeur d'Alene and then the Columbia River. Flowing through steeply dissected valleys, major tributaries of the river include Ninemile, Canyon, Pine, and Big Creeks.
Figure 2 - Valley drained by Big Creek, looking south, showing typical steep terrain and heavy forest cover. Viewpoint is just south of the Sunshine mine.
HISTORICAL AND PRODUCTION

History of the Coeur d'Alene Mining District

Gold was the metal that first led to the settlement of the country surrounding the upper Coeur d'Alene River. In the late 1870's, prospectors located placer gold in the river near present day Murray, Idaho. Other fortune seekers discovered lead veins at several spots along the valley to the south. The resultant rush produced a tangled web of overlapping claims that took many years in court to resolve. By autumn of 1887, a railway had been completed to Wallace, greatly simplifying the delivery of ore. Many mines began production of lead, copper and silver ores, most notably the Bunker Hill and Sullivan mine outside of Kellogg. The advent of a miner's union in the 1890's sparked labor unrest that culminated in the 1899 destruction of the Bunker Hill mill.

Martial law ushered in the new century, and an uneasy peace again settled throughout the Coeur d'Alene valley.

Hillsides were stripped of timber to supply burgeoning towns with lumber, and as support for mine stopes and shafts. Early in the district's history, the nearby river was a convenient waste dump for the mines, which poured tons of tailings and metals into its waters. Zinc, formerly a waste material, began to be recovered about 1920 as booming eastern industries produced a demand. World War II was the high point of the district's production, its mines churning out over two million tons of ore annually (Fryklund, 1964). Throughout these years, area mines were the largest producers of lead and silver in the United States. Exhaustion of ore, the advent of stricter environmental regulations in the 1960's, and weak metal prices have combined to close down most of the area's mines since that time. The Bunker Hill mine, the district's largest employer, closed in 1981.
Since then, it has been declared an EPA Superfund site. Though exploration continues throughout the region, the only mines still in production are the Lucky Friday, the Galena, and the Sunshine.

History of the Sunshine Mine

The Sunshine mine began with the discovery of the Yankee Boy silver claim in 1884 by the Blake brothers. The two worked the claim almost exclusively until 1910. In 1920, the Sunshine Mining Company of Spokane acquired the property, merging with other operators in the area. When the company decided to build a mill and concentrator in 1921, the ore was hand sorted and silver sold for about $1.00/ounce (Conley, 1982).

In 1931, at the height of the Great Depression, crews following the Sunshine vein from the new 1700' station discovered bonanza ore, causing profits to skyrocket. Suddenly one of the largest silver producers in the world, the mine increased production through 1937, when 12 million ounces of silver were recovered (Conley, 1982). In 1935 the Jewell Shaft began hoisting ore, followed in 1942 by the construction of a plant to extract antimony from the tetrahedrite.

The Chester vein, another high grade ore body, was discovered in 1943, just in time to replace production lost from the playing-out Sunshine vein. Over the years, internal winzes were sunk and additional property acquired to support the discovery and production of ore bodies such as the Syndicate, Yankee Girl, Copper, and West Chance veins. Construction began on #10 Shaft in 1959, which today, along with the Jewell Shaft, serves as the mine's primary internal shaft.

In May of 1972, a fire on the 3400' level emitted toxic gases which entered the nearby ventilation system. Carbon monoxide and dense smoke poured through the
underground workings, resulting in the deaths of 91 miners. This tragedy led to the institution of many new regulations by state and federal agencies that make the likelihood of a similar disaster very remote.

Sunshine Mining Company's silver plant, built onsite, began production in 1984. Since 1995, lower ore production forced the refinery to close, and ore was shipped to the ASARCO smelter in Helena, Montana. In 1991, in order to cut costs and return to profitability, Sunshine shut down many outlying areas of the mine and allowed the workings to flood below the 5000' level. The West Chance area was discovered in 1992, and production today occurs exclusively in this area. The West Chance is mined primarily by a ramp system using diesel equipment, but several conventional timbered stopes still remain. A cut-and-fill stope mining method is used to extract ore from the steeply dipping veins. Ore is then moved by electric trains to the Jewell Shaft for transport to the surface mill (Figure 3). Concurrent with development of this new area, all workings below the 4000' level were salvaged and allowed to flood.

Figure 3 - Electrically driven ore cars being dumped into "grizzly". 3700' Jewell Shaft station.
In 1995 Sunshine acquired the neighboring Consolidated Silver mine which serves as a secondary escapeway, the mines being connected on the 3000'-3100' level. Commencement of an exploratory drilling program, rehabilitation of the Con-Sil Silver Summit Shaft, and construction of a new ramp from the Sunshine 3700' level to the Con-Sil 4000' level began in 1998. However, these activities were halted recently in an attempt to improve production from the West Chance area in accordance with a production goal of 6,000,000 ounces of silver annually. Through the present day, the Sunshine mine is considered to be the largest silver producer in the world (Figure 4).

Figure 4 - The Sunshine mine in 1998, looking southeast.
History of Uranium in the District

Following World War II, the U.S. Atomic Energy Commission began a search for uranium sources at existing mines across the nation. Radioactivity in material processed through the Bunker Hill smelter led to a radiometric examination of the Coeur d'Alene District. This survey identified sources in the Sunshine and the Coeur d'Alene mine, 3 km to the east (Thurlow and Wright, 1950). Many kilometers of underground workings were subsequently examined, yielding additional uranium discoveries in the Bunker Hill, Crescent, Polaris, Lucky Friday, and Galena mines. Anomalously high radioactivity readings have also been found in the Page, Sherman, and Hercules mines (Fryklund, 1964; Radford, 1998). The largest amount of uranium by far is contained in the Sunshine mine, and it was there that the A.E.C. concentrated its search. The uranium is concentrated in veinlets that are surrounded by a red-colored, altered rock (Figure 5).

Figure 5 - Uranium-bearing specimen exhibiting red alteration. Gray metallic material is tetrahedrite; sample is 6 cm across. From 3700' R3 stope, pillar pull.
An AEC study began in 1950 to determine uranium reserves and the feasibility of production. At that time, accessible workings included those near the exhausted Sunshine vein and the Chester vein. Radiometric surveys, raise construction, 1750 meters of diamond drilling, and 220 meters of drifting, were performed to determine ore grade and tonnage (Thurlow and Reyner, 1954). Several uranium-bearing zones were identified from the 2900' to the 3700' level, the deepest in that part of the mine. One zone on the 3700' level contained 4500 tons of material assaying 0.38% uranium oxide (Thurlow and Reyner, 1954). Over one ton of the highest grade material was subsequently moved to the surface for further analysis by the A.E.C. In 1958, the A.E.C. established an ore reserve estimate totaling 10,100 tons of 0.41% uranium oxide (Granger and Hetland, 1961). It was concluded that production was uneconomic based upon the low grade and limited tonnage.

Since that time, uranium has been discovered down to the deepest levels of the mine. Though no uranium was ever commercially produced from the Sunshine mine, sporadic evaluation of the feasibility of production continued until late 1979. Today, the uranium-rich drifts have been sealed shut or flooded, and few veins are still accessible. Luckily, Rod Cleland, a mine geologist, collected a large number of samples from all over the mine in the past twenty years, and these were available for study. Today, the lack of economic potential has rendered the presence of the uranium a little known curiosity.
Introduction

The Coeur d'Alene Mining District consists of a number of mineral belts and mines arranged around the Osburn fault (Figure 6). Of primary interest here is the "Silver Belt", a region south of and parallel to the Osburn fault. This area hosts the Sunshine and Galena mines, which remain major silver producers. Outside of the Silver Belt, production of silver historically has been as a by-product. However, the Lucky Friday mine, which lies at the eastern end of the district, remains a major producer of silver as well as lead.

Ore in district mines is contained in veins deposited in fracture systems and/or shear zones. Veins commonly possess great horizontal and vertical continuity.
little change in mineralogy, and are typically oriented about 70° northwest, sub-parallel to major faults. These faults cut several folds of considerable size. Hosting the veins are rocks of the Precambrian Belt Supergroup, a series of regionally metamorphosed argillites, siltites, and quartzites. In places, these Belt rocks have been intruded by Cretaceous monzonite stocks, and dikes of various compositions and ages.

Regional Setting

The Coeur d'Alene Mining District lies near the western edge of the Belt Supergroup, which is overlain by rocks of the Windermere Supergroup and Cenozoic flood basalts near the Idaho-Washington border. The Lewis-Clark shear zone, a basement weakness intermittently active since Proterozoic time, bisects the district. To the east, Belt rocks and mountain ranges extend beyond Helena in west-central Montana. Across the Canadian border, uplifted basement rocks crop out and younger sedimentary rocks overlap the Belt Supergroup.

The St. Joe River flows westward along the St. Joe fault 15 km south of the district, marking a boundary in metamorphic grades. Metamorphic grade increases steadily south of this line, attributed to heat flow driven by the Bitterroot lobe of the Idaho batholith (Fleck and Criss, 1985; Criss and Fleck, 1990). Belt rocks have been metamorphosed to the sillimanite zone of the amphibolite facies 70 km south of the district, near the point where the batholith intrudes and obliterates these southernmost extensions of Belt rocks.
Petrology

Belt Supergroup

The Belt Supergroup is a set of conformable, clastic and carbonate rocks covering parts of northern Idaho, western Montana, southeastern British Columbia, and southwestern Alberta. The rocks are fine-grained and thickest in the Coeur d'Alene district and along the Montana border. The entire series ranges between 6600 and 9200 meters thick in the Coeur d'Alene District, but the basal units are not exposed and are of unknown thickness (Hobbs and others, 1965). An indeterminate amount of the upper units have been eroded away.

Belt rocks consist primarily of quartz, sericite, plagioclase feldspar, potassium feldspar and carbonate (Harrison and Grimes, 1970). Contacts between formations are gradational and poorly defined. Mostly monotonous in appearance and composition, Belt sediments were mostly deposited between 1500 and 1300 Ma in a basin of unknown size (Reynolds, 1984). They adjoin the Proterozoic continental margin and overlie crystalline basement rocks.

Rocks of the Belt Supergroup are dense, drab, and hard, and have been slightly metamorphosed. Harrison and Grimes (1970) categorized the four dominant lithologies as argillite, siltite, quartzite, and carbonate. Mudcracks, rip-up clasts, and ripple marks occur throughout, implying a shallow water or subaerial environment of deposition for most units. A summary of each formation in the Coeur d'Alene District is provided in Table 1.
Formation and estimated thickness (m)  | Predominant lithology
---|---
Striped Peak - 500  | Interbedded quartzite and argillite-mostly eroded away
Wallace - 1000  | Calcareous argillite and quartzite
St. Regis - 300  | Thinly laminated argillite at top to argillic quartzite at bottom
Revett - 1000  | Thick-bedded nearly pure quartzite
Burke - 1000  | Impure argillic quartzite
Prichard - 4000 +  | Bedded argillite with siltite & quartzite lenses; base unexposed

Table 1 - Stratigraphy of the Coeur d'Alene Mining District, in order of increasing age. Data compiled from Fryklund (1964), Hobbs and others (1965), and Winston and Link (1993).

Belt rocks host a large number of base and precious metal deposits besides those in the Coeur d'Alene District. The Sullivan massive sulfide deposit in British Columbia and Spar Lake silver-copper deposit in Montana are two type examples. Ore deposits occur in particular stratigraphic intervals, not only in northern Idaho, but across the Belt basin. For example, the Revett-St. Regis transition in both Montana and Idaho hosts substantial copper-silver mineralization, whereas the Burke-Prichard transition hosts a great amount of base metals (White, 1998a). These stratigraphic intervals contain coarser-grained sands, perhaps more permeable to ore fluids than surrounding units (White, 1998a).

Igneous Rocks

Various types of intrusions of different ages have penetrated the area. The monzonitic Gem stocks northeast of Wallace, are the largest of these. The Dago Peak stocks to the west are believed to be the severed tops of the Gem stocks, displaced by normal motion along the Dobson Pass fault (Bennett and Venkatakrishnan, 1982). Several generations of diabase and lamprophyre dikes cut the stocks, as well as Belt
rocks throughout the district. The dated age of these intrusions is late Cretaceous to early Tertiary (Hobbs and others, 1965; Leach and others, 1998).

Metamorphism

All Belt rocks in the district have undergone low-grade burial metamorphism. Southward towards the Idaho batholith the grade increases rapidly, as it does northeastward towards Montana (White, 1998a). Consequently, the area lies in a "metamorphic low", in which metamorphism has only reached greenschist facies (White, 1998b). In the Prichard Formation, pyrite has not yet altered to pyrrhotite as in the surrounding regions (Hobbs and others, 1965). Mineral adjustments include the recrystallization of quartz grains and alteration of clay minerals to sericite, commonly seen as strongly foliated in thin section.

Structure

Faults

Ore deposits and the evolution of the Coeur d'Alene District itself are structurally controlled. The main structure in the region is the Lewis-Clark shear zone or Montana lineament, a zone up to 10 km wide and 400 km long of parallel faults trending east-southeastward along an ancient basement weakness from Washington to west-central Montana. The Lewis-Clark line is locally represented by the Osburn fault, which bisects and offsets the core of the district (Figure 7). Hobbs and others (1965) did the most thorough mapping of the district and determined offset along the fault. They estimate 26 km of right lateral strike-slip motion. Most workers, believe that left-lateral strike-slip motion predates the right-lateral, Cenozoic age motion (Hobbs and others, 1965).
The Osburn fault is remarkably linear and generally controls the course of the South Fork of the Coeur d'Alene River through the area. The Osburn fault passes north of the Sunshine mine, but is present in the portal of the connected Silver Dollar mine. Here it dips steeply to the south and has heavily brecciated the Wallace Formation, necessitating extensive timbering to prevent portal collapse.

A great number of other faults cut the region. The Dobson Pass fault, which beheads the Gem Stocks, is one the major extensional faults north of the Osburn fault. The Thompson Pass and Placer Creek faults border the district on the north and south, respectively. Estimates of strike-slip displacement on these faults range between 1-3 km (Bennett and Venkatakrishnan, 1982). The Big Creek-Alhambra fault system exhibits reverse motion, and affects primarily the Crescent and Bunker Hill mines west of the
Sunshine. Most faults were formed by brittle fracturing, are only several meters wide, and widen greatly in zones of heavy gouge. Vein positions are controlled by faults and commonly segmented by a later generation of faulting. Hobbs and others (1965) examined fault relationships and noted that reverse faults host appreciable amounts of metals and predate the commonly barren normal faults. Strike-slip motion along the Osburn fault may have occurred continuously through both fault episodes.

Folds

Though a great number of folds occur in the region, the Big Creek anticline is the major fold affecting the Silver Belt. The anticline trends west-northwest, parallel to and south of the Osburn fault (Figure 6). Its ore-rich northern limb is overturned; the southern limb dips shallowly to the south and is relatively devoid of ore. Folds are cut by almost all generations of faults and are therefore the oldest structures in the district.

Folds north of the Osburn fault, however, have northward trends. This change in strike has puzzled geologists to this day. Hobbs and others (1965) attribute rotational motion, concurrent with right lateral movement on the Osburn fault, as responsible for dissecting what was once a continuous structure (Bennett and Venkatakrishnan, 1982; Reid, 1984).

Bennett and Venkatakrishnan (1982) have also performed a palinspastic reconstruction of the district, aligning all the major silver deposits in a hypothetical synclinorium, which was subsequently destroyed by later folding and faulting. White (1993), however, redefines traditional notions of the regions structural evolution by tracing north-south folds south across the Osburn fault. Here the plunges of west-northwest folds vary, indicating the north-south folds may actually continue across the
fault. If correct, this theory demonstrates two distinct generations of folding, disproving concepts of rotational kinematics along the Osburn fault.

Ore Deposits

Ore was deposited by hydrothermal solutions in veins of simple mineralogy. Both replacement and open-space filling textures are present. Veins lie in fractures of great depth and continuity that crosscut all folds and lithologies. These veins possess subtle mineral zoning and great horizontal and vertical extent, independent of the amount of fracture motion. Mineralization appears to have occurred in stages, controlled by the opening and closing of these fractures. The relative paragenesis of ore minerals is known and seems to be consistent districtwide. Uranium minerals, where present, are among the earliest vein minerals. They were followed sequentially by deposition of sphalerite, tetrahedrite and chalcopyrite, and galena (Mitcham, 1952). Quartz and siderite are the main gangue minerals. Deposits are clustered in belts of similar mineralogies.

Bleaching of the wall rocks surrounding veins was noted by early miners, and was used as an exploration guide for years (Weis, 1961). Though hydrothermal bleaching is far from prevalent, White (1998b) has established the presence of carbonate zoning around veins. Disseminated siderite extends from the vein outward, where it grades into a siderite-ankerite zone. Surrounding this zone is a distal calcite-ankerite halo, which eventually becomes ankerite only. Ankerite occurs throughout the district and is likely diagenetic in origin (White, 1998a). White (1998a) also notes that the siderite zone extends further away in strata that dip into the veins than strata that dip away from the veins (Figure 8). This relationship establishes that ore fluids flowed out of the veins and into the surrounding wall rocks.
Source of the Metals

The source of the ore metals is a question that remains unanswered to this day. Several sources are possible. These include:

1.) A deep point source, such as a buried Sullivan massive sulfide-type deposit underlying or close to the district.

2.) A magmatic source, such as the Idaho batholith, the Atlas pluton, or the roots of the Gem Stocks.

3.) A source in the Belt rocks themselves. Strata-bound lead is known to exist in the Prichard Formation in and near the Bunker Hill mine, the Revett Formation is known to be anomalously rich in copper and silver where it crops out northeast of the district, and the Prichard is known to also be rich in base metals elsewhere (Ramalingaswamy and Cheney, 1982; White, 1998b).

4.) A deep linear source, probably along basement weaknesses manifested today by faults along the Lewis-Clark Line. Crosby (1983) believed metals may have been exhaled onto the ocean floor along these structures.
Introduction and Geometry

The Sunshine mine extends east-west along the overturned north limb of the Big Creek anticline. Mining presently occurs in the West Chance area on the 2700', 3100' and 3700' levels (measured below the surface), all located along the western border of the Sunshine property. These workings approach to within several hundred meters of the adjacent Crescent mine, now flooded. To the east, the Sunshine property connects with the Polaris mine and the recently acquired Con-Sil mine. The Con-Sil property has been inactive for many years, and connects with the abandoned Coeur d'Alene mine along the westward extension of the Silver Belt. Mine workings in the Sunshine extend to more than 6000' below the surface, though they are now flooded below 4000'. The workings are presently serviced by the Jewell Shaft and the Con-Sil Silver Summit Shaft; internal winzes are used to a lesser degree and include #10 Shaft, #12 Shaft, and #4 Shaft. A cross section of mine geometry is shown in Figure 9.

Stratigraphy and Petrology

The Sunshine mine presently produces ore from the St. Regis and the Revett Formations. The Revett Formation is a greenish-gray, non-graded to poorly graded well-sorted quartzite with interbedded siltite and argillite. Bed contacts are commonly scoured and exhibit "mudskins" The Revett grades gradually upwards into the St. Regis Formation. In the Sunshine mine, this gradational zone is less than 35 meters thick.
Figure 9 - Long section of the Sunshine mine. The Jewell Shaft serves the Sunshine mine, and the Silver Summit Shaft serves the Con-Sil mine. The closed Coeur d'Alene mine is on the far right, and the closed Crescent mine is on the left. Modified from a Cole Carter drawing.

The purple-gray units characteristic of the St. Regis Formation consist of interbedded argillite and siltite with lesser amounts of quartzite. Argillic interbeds commonly show mud cracks, mud chips, ripple marks, and flame structures. The St. Regis Formation becomes less quartzose upwards towards the contact with the Wallace Formation. The Wallace Formation rarely hosts productive ore and consists of thinly laminated calcareous argillites and siltites. These formations are cut by a small number of dikes of various compositions.
Structure

The rocks hosting the Sunshine mine were affected folding which parallels the Big Creek anticline, and by several generations of south-dipping faults which cut the anticline into blocks. The faults controlled circulation of the ore fluids. Among the major faults are (south to north):

1.) Big Creek fault (reverse)-at the southern border of the mine.
2.) Chance fault (reverse).
3.) Silver Syndicate fault (reverse).
4.) Polaris fault (normal)-at the mine's northern border.

All of these faults are subparallel and trend west-northwest across the Big Creek anticline (Figure 10). Drag folds and slickenlines indicate mineralization occurred synchronously with dip-slip motion, followed by extension which induced normal motion. (Wavra and others, 1994).

A regional penetrative cleavage occurs throughout the mine. It is especially well-developed in argillic rocks, where it commonly obscures bedding. This cleavage is oriented northwesterly to southwesterly, dips steeply southward parallel to dip-slip fault motion, and transects the Big Creek anticline at a slight angle (Wavra and others, 1994). In the accompanying petrographic examination of the ore veins, strongly foliated sericite allowed identification of cleavage direction.
Figure 10 - Simplified cross section of Sunshine mine geology (modified from Wavra and others, 1994).
Geology of Silver-Bearing Veins

Previous Studies

A number of previous studies, including those by Mitcham (1952), Fryklund (1964), Harris and others (1981), Fleck (1991), Bond and others (1992), Eaton and others (1995), and Leach and others (1988, 1998) have examined the nature of the silver-bearing veins. Fluid inclusion studies of quartz veins associated with tetrahedrite indicate mineralizing solutions were complex N-CO₂-hydrocarbon-rich solutions, deposited at pressures greater than 1 kbar and at 250-350°C (Leach and others, 1988). However, several generations of quartz veins exist, and those particular samples analyzed may or may not be related to tetrahedrite deposition. An earlier fluid inclusion study of silver-bearing veins indicated that low salinity mineralizing fluids of about 350°C formed the veins (Landis and others, 1984).

Harris and others (1981) determined the sulfur isotopic and geochemical composition of sulfides within the Chester vein. The study revealed a decrease in the amount of Cu in tetrahedrite upward in the veins. Enrichment of tetrahedrite in δ^{34}S over paragenetically earlier pyrite indicates that two different ore solutions were involved or that an early Fe-rich solution evolved into an Ag-Cu rich solution (Harris and others, 1981). Constantopoulos (1994) examined the oxygen isotope geochemistry of vein quartz and Belt rocks across the district and concluded that similar δ^{18}O values indicated equilibrium between the two. In contrast, Eaton and others (1995) analyzed Sunshine mine siderite, noting oxygen and carbon isotopic variations across the veins themselves.
The veins also proved to be not in isotopic equilibrium with wall rocks and the adjacent quartz veins (Eaton and others, 1995).

Results of all prior research indicate several important points:

1.) The veins are composite structures, containing minerals deposited at different times by ore fluids of varying or evolving compositions and temperatures.

2.) Vertical zonation of elements and isotopes, produced by cooling fluids rising along faults, indicates a deep, underlying source for vein materials. This idea is further supported by the data of Eaton and others (1995) indicating the isotopic disequilibrium of siderite with wall rocks. If true, the deposition of silver-bearing veins chiefly at the Revett-St. Regis transition zone must be explained.

3.) Vein quartz is in isotopic equilibrium with Belt rocks and possesses CO₂-rich fluid inclusions with uniform pressures and temperatures, both indicative of a metamorphic origin.

4.) Mineralization occurred at the same time as structural adjustments took place, and faulting continued well after deposition.

**Vein Mineral Composition**

Most silver is produced from tetrahedrite, which occurs as shoots within siderite veins. Accessory vein minerals include pyrite, chalcopyrite, arsenopyrite, bournonite, quartz, and galena. The composition of the tetrahedrite end member in the tetrahedrite-tennantite solid solution series is \((\text{Cu,Ag})_{10}(\text{Fe,Zn})_2(\text{Sb,As})_4\text{S}_{13}\), but the argentiferous variety from the mine may be simplified to \((\text{Cu,Ag})_{12}\text{Sb}_4\text{S}\) (Hackbarth and Petersen, 1984; Knowles, 1983). Sunshine mine tetrahedrite may contain up to 10% silver by weight, with the silver content increasing with the amount of antimony (Knowles, 1983). Silver is also recovered in much smaller amounts from galena.
Structure

All of the ore bodies lie in the deformed, overturned north limb of the Big Creek anticline, the oldest structure in the mine. Overall, the most productive silver-bearing veins occur in east-west trending fractures that appear to link northwest-oriented faults (Hardy, 1998). Veins observed in the West Chance area fill the Chance Fault and dip steeply to the south (Figure 11). Pinching and swelling of the veins is common; 5 meter thick veins can pinch out to several centimeters over a distance of 30 m. This is especially common where branching into multiple shoots or encountering a structure of shallower dip (Colson, 1958, 1961). Sericite at vein edges is lineated parallel to dip-slip motion, suggesting development of foliation, fault movement and mineralization.

Figure 11 Tetrahedrite/galena vein in the Chance Fault, 3100' level, E10 east stope. Vein consists of mixed tetrahedrite and galena in gangue of siderite (buff color) and lesser amounts of quartz. Looking east: rock hammer for scale.
occurred together. Slickenlines in galena pulled from the Chance Fault on the 2700' level prove that faults that crosscut the anticline remained active after mineralization ended.

Geology of Uranium-Bearing Veins

Previous Studies

Thurlow and Wright published the first study of uranium mineralization in the Sunshine mine in 1950. They concluded that the uranium occurs in uraninite in small spherules about 10 microns in diameter. A more detailed study was conducted by Kerr and Robinson (1953). This report established the structural and mineralogical paragenesis of uranium in the Sunshine mine. Crosscutting relationships and radiometric age dating identified the uranium-bearing veins as among the oldest veins in the district. Other unpublished reports by Robinson (1951), Thurlow and Reyner (1954), Granger and Hetland (1961), and Long (1977) deal primarily with uranium ore reserves in the Sunshine mine.

Vein Mineral Composition

Few studies have been performed on the uranium-bearing veins since the 1950's because they have never been economical to mine. Among the oldest veins yet found in the district, they may provide the key to understanding the evolution of the other, silver-bearing veins. The uranium-bearing minerals were originally identified as uraninite, a black uranium oxide which varies in composition between $\text{UO}_2$ and $\text{U}_3\text{O}_8$ (Thurlow and Wright, 1950; Kerr and Kulp, 1952; Kerr and Robinson, 1953). When fine-grained and powdery, it is also known as pitchblende. Early discoveries were sometimes associated with a cobalt "bloom" (Thurlow and Wright, 1950). A single uranium-bearing sample from the 5600' level was recently analyzed and identified as containing brannerite, a
uranium-titanium mineral with the simplified formula UTi₂O₆ (Zartman and Smith, in press).

The uranium veins are always associated with adjacent red-altered rock, the color of which varies in intensity with the radioactivity of the vein. The alteration, commonly referred to as "jasperoid", consists of silicified rock stained red by finely disseminated hematite grains. It only occurs in association with uranium minerals. Colson (1958) noted that the jasperoid forms larger halos about the veins on the 3100' level than the 3700' level, indicating the alteration may increase upwards in intensity. Minerals associated with uranium include fine-grained pyrite and arsenopyrite, which appear to predate uranium emplacement based upon their partial oxidation by uranium-bearing fluids. Uranium minerals may also lie in "ribbon veins", unusual parallel layers with alternating pyrite, siderite and quartz that may indicate multiple vein openings (Figure 12). Kerr

![Figure 12 - Ribbon vein of uraninite and quartz with arsenopyrite. 3700' level, across from #4 Shaft access drift. Tape measure for scale.](image_url)
and Robinson (1953) have identified an early generation of siderite that commonly occurs with uranium minerals. Argentiferous tetrahedrite, siderite, chalcopyrite, and a few galena veins crosscut and replace the uranium-bearing veins in many locations, creating a complex sequence of mineralization events.

Structure

Uranium-bearing veins, like the silver-bearing veins, occur in the overturned north limb of the Big Creek anticline. Uranium may also occur in pods, lenses, stockwork, and in brecciated veinlets with arsenopyrite. Veins are small, of variable grade, highly segmented, and may grade outwards into uranium-free quartz veins (Colson, 1958). The veins trend west-northwest and are cut by faults that predate and so do not affect the silver-bearing veins. Among these are "flat faults", low-angle faults which may follow bedding planes of the St. Regis Formation (Kerr and Robinson, 1953). These flat faults also crosscut an early generation of siderite that is barren of sulfides (Kerr and Robinson, 1953). Most uranium-bearing veins lie in sheared zones of fracture cleavage, unlike silver-bearing veins, which normally occur in larger fractures (Thurlow and Wright, 1950). Kerr and Robinson (1953) cite field evidence associating uranium mineralization with early northwest shearing, followed by later east-west shearing that hosts the silver-bearing veins. Both vein types are crosscut by post-mineralization extensional fractures.

Age of Veins

Previous Studies

The age of vein formation has been debated since the discovery of the district. Because crosscutting relationships throughout the district contradict the overall
paragenesis implied by most age dates, the issue of the exact timing of mineralization remains unclear.

Coeur d'Alene District age dates seem to cluster into three groups. The oldest dates are obtained from lead throughout the Belt basin and vein galena. These dates range from 1200-1500 Ma (Zartman and Stacy, 1971; Cannon and others, 1962; Marvin and Zartman, 1984). The second group consists of K-Ar and Ar-Ar dates of vein sericite and U-Pb radiometric dates of vein uraninite. These yield ages between 800-950 Ma, approximately the time of the East Kootenai orogeny (Leach and others 1988, 1998; Zartman and Smith, in press).

**Age of Silver-Bearing Veins**

A third group of dates is primarily associated with silver-bearing veins. These are agreed by most workers to have formed in the late Cretaceous-early Tertiary based upon the following (Leach and others, 1998; Armstrong, 1975):

1.) Radiometric age dates obtained by a number of workers (see Table 2).
2.) Fluids from the Idaho batholith seem to have reached the district in Laramide time, showing that the area was not isolated from the effects of regional tectonism and intrusions (Fleck and Criss, 1985; Criss and Fleck, 1990).
3.) Cambrian sedimentary rocks near Superior, Montana, are folded together with underlying Belt rocks. These folds are oriented similarly to east-trending folds in the Silver Belt and indicate that folding occurred after Cambrian time, but before Tertiary intrusions (White, 1998a).
4.) $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic analyses of Sunshine mine siderite is consistent with an age of vein formation within the last 200 Ma (Fleck and others, 1991).
5.) Previously obtained radiometric age dates of galena and base-metal veins contradict the crosscutting relationships observed in the field, calling their validity into question.

Though most workers now believe that silver-bearing veins formed in late Cretaceous-early Tertiary time, Leach and others (1988, 1998) identify various galena and base-metal veins as 850 Ma based upon Pb isotopic dating. This directly contradicts field evidence in the Sunshine mine showing galena veins crosscutting the Laramide silver-bearing veins.
However, geological relationships cannot be ignored. Remobilization of older material is required if many of the older dates are to be considered correct.

**Age of Uranium-Bearing Veins**

The age of the uranium-bearing veins was widely regarded to be Precambrian by early workers in the district. Kerr and Kulp (1952) used U-Pb isotopes to radiometrically date Sunshine mine uraninite, obtaining an age of 750 ± 10 Ma. A U-Pb date of 1250 ± 1 Ma was reported by Hobbs and others (1965), and since that time, the uraninite has been regarded as Precambrian. Yet Kerr and Robinson (1953) noted that the uranium-bearing veins always seemed to accompany later tetrahedrite veins in discrete but separate structures; increasing radioactivity indicated higher grades of silver. More recently, some workers have begun to believe that the uraninite was an early stage of silver mineralization.

Because the uranium-bearing veins crosscut the folds and fractures which host them, the folding has also been regarded as Precambrian. However, White (1998b) notes that Cambrian strata overlying Belt rocks near Superior, Montana are also folded in a similar manner. Furthermore, south of the district, rocks of the Idaho batholith intrude similarly oriented folds. If these interpretations are correct, the age of the folding occurred between the Laramide intrusion of the batholith and Cambrian time.

Further compounding the story, however, is the recent work of Zartman and Smith (in press). They obtained a single specimen of a uranium-bearing mineral from the 5600' level of the Sunshine mine and dated not only the uranium mineral itself, but the zircons therein using the U-Pb isotope method. Some zircon grains provided an older date on a concordia of about 1350 Ma-1800 Ma; these grains are interpreted as detrital and
volcanogenic in origin, indicating the ages of crystalline basement rocks that supplied the Belt basin with sediment. Younger dates of zircon grains, believed to have formed in a hydrothermal environment, yield dates of 1343 Ma with a discordia intercept at 136.4 Ma (Zartman and Smith, in press). The brannerite itself provides a date of about 1350 Ma with a discordia intercept at about 134 Ma (Zartman and Smith, in press). They interpret these results to show an initial episode of uranium emplacement at 1350 Ma, followed by a remobilizing event at about 130 Ma.
### Table 2 - Summary of Published Age Dates in the Coeur d'Alene District

<table>
<thead>
<tr>
<th>Material Dated</th>
<th>Age</th>
<th>Location</th>
<th>Method Used</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>uraninite</td>
<td>750 ± 10 Ma</td>
<td>Sunshine mine</td>
<td>U-Pb</td>
<td>(1)</td>
</tr>
<tr>
<td>uraninite</td>
<td>867 Ma</td>
<td>Sunshine mine</td>
<td>U-Pb</td>
<td>(2)</td>
</tr>
<tr>
<td>uraninite</td>
<td>1250 Ma</td>
<td>Silver Belt veins</td>
<td>U-Pb</td>
<td>(3)</td>
</tr>
<tr>
<td>uraninite</td>
<td>959, 1115 Ma</td>
<td>Sunshine mine</td>
<td>U-Pb</td>
<td>(4)</td>
</tr>
<tr>
<td>zircons in brannerite, brannerite</td>
<td>1344 ± 77 Ma (concordia) and 136 ± 2 Ma (discordia)</td>
<td>Sunshine mine</td>
<td>U-Pb</td>
<td>(5)</td>
</tr>
<tr>
<td>galena</td>
<td>1400 Ma</td>
<td>various mines</td>
<td>Pb-Pb</td>
<td>(6)</td>
</tr>
<tr>
<td>galena</td>
<td>1200-1500 Ma</td>
<td>various mines</td>
<td>Pb-Pb</td>
<td>(7)</td>
</tr>
<tr>
<td>galena</td>
<td>1200-1400 Ma</td>
<td>various mines</td>
<td>Pb-Pb</td>
<td>(8)</td>
</tr>
<tr>
<td>vein biotite</td>
<td>123 ± 6 Ma 100 ± 5 Ma</td>
<td>Hercules mine</td>
<td>K-Ar</td>
<td>(9)</td>
</tr>
<tr>
<td>parasite</td>
<td>73 ± 2 Ma 75 ± 2 Ma</td>
<td>Snowbird deposit</td>
<td>Th-Pb</td>
<td>(9)</td>
</tr>
<tr>
<td>vein sericite</td>
<td>829 ± 40 Ma 876 ± 43 Ma 447 ± 25 Ma 77 ± 5 Ma</td>
<td>Bunker Hill mine Lucky Friday mine Galena mine Sunshine mine</td>
<td>K-Ar</td>
<td>(10)</td>
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<tr>
<td>sericite from quartz veins</td>
<td>85.2 ± 0.5 Ma (thermal event α 74 Ma) 945.0 ± 1.7 Ma (thermal event α 64.4 Ma)</td>
<td>Sunshine mine Lucky Friday mine</td>
<td>Ar-Ar</td>
<td>(11)</td>
</tr>
<tr>
<td>siderite-tetrahedrite veins</td>
<td>&lt; 200 Ma</td>
<td>Sunshine mine</td>
<td>Rb/Sr ratios</td>
<td>(12)</td>
</tr>
<tr>
<td>siderite veins</td>
<td>Mesozoic or younger</td>
<td>Sunshine mine</td>
<td>Rb/Sr ratios</td>
<td>(13)</td>
</tr>
</tbody>
</table>

(1) Kerr and Kulp. 1952  
(2) Eckelman and Kulp. 1957  
(3) Hobbs and others. 1965  
(4) Stern. 1960; published in Zartman and Smith (in press)  
(5) Zartman and Smith (in press)  
(6) Long and others. 1960  
(7) Zartman and Stacey. 1971  
(8) Cannon and others. 1962  
(9) Armstrong. 1975  
(10) Leach and others. 1988  
(11) Leach and others. 1998  
(12) Fleck and others. 1991  
(13) Eaton and others. 1995
SPATIAL ANALYSIS OF URANIUM OCCURRENCES
IN THE SUNSHINE MINE

Method of Analysis

The occurrences of uranium-bearing veins in the Sunshine mine were plotted in order to examine possible spatial relationships to structures or other vein types. This was accomplished by plotting occurrences in a three dimensional coordinate system established in AutoCAD. The location of uranium-bearing veins was determined by several methods:

1.) Researching company diamond drill hole logs.
2.) Study of company geologic maps.
3.) Study of company A.E.C. reports.
4.) A traverse with a scintillometer across still accessible areas of the mine on the 3100' and 3700' levels. A similar traverse was attempted across the Con-Sil mine, but was unsuccessful due to scintillometer failure.

Well over 100 occurrences were plotted, and, wherever possible, vein orientation was also plotted. Upon plotting all known uranium-bearing occurrences, geology and mine workings were superimposed on to the drawing, creating a three dimensional map used to spatially analyze the vein geology.

The data-generated map has a number of weaknesses. These include areas that have never been mined or drilled and areas in which uranium may exist but was never identified underground or in drill cores. Furthermore, some older drill logs are no longer available and therefore could not be examined. Finally, accurate survey data were not available for all drill holes, and the position of these holes and their uranium occurrences was sometimes estimated. Nonetheless, the large number of plotted points should create a realistic idea of where in the mine uranium occurs.
Results

Plotting the uranium occurrences at a 1:500 scale identified some relationships between the geology of the Sunshine mine and uranium- and silver-bearing occurrences. Uranium-bearing veins and silver-bearing veins occur mostly on the north limb of the Big Creek anticline, with the former overwhelmingly confined to the Revett Formation. Silver-bearing veins continue stratigraphically higher into lower St. Regis formation. Silver-bearing veins dip southward, and, overall the uranium occurrences also dip generally southward (Figure 13), possibly also controlled by faults. Both vein types strike east across the mine at an acute angle to northwest-trending major faults. However, individual uranium-bearing veins commonly exhibit a slight northwesterly orientation as compared to silver-bearing veins (Figures 14). The overall dip to the south of the uranium-bearing veins indicates that they, like the silver-bearing veins, crosscut the Big Creek anticline.
Figure 13 - Cross section of Sunshine mine showing three selected levels (black), four shafts (violet), and occurrences of uranium and jasperoid alteration (orange and red-brown respectively). Overall trend of uranium/jasperoid occurrences is shown to dip southward. Faults and stratigraphic contacts omitted for clarity.
Figure 14 - Map of the Sunshine mine. Workings (black) and silver-bearing veins (blue) shown are plotted on 3700’ level; uranium occurrences (red dots) are summary of occurrences on all levels. Faults and stratigraphic contacts eliminated for clarity.
Methods of Analysis

To determine whether an association between silver- and uranium-bearing veins exists, various ore and wall-rock samples were collected from locations throughout the mine. These samples were analyzed by Bondar Clegg Laboratories of Vancouver, British Columbia, using neutron activation. This method produced a 50 element analysis of each sample, but was affected by very high levels of silver and/or uranium. In such cases, the concentrations of many elements could only be reported as less than a given number in parts per million (ppm). In addition, one batch of samples was assayed for Ag concentrations only by the Sunshine mine's assay lab. The sample batches analyzed, and the reason for each analysis, is listed below:

1.) **Sample Batch 1:** 7 samples were collected representing the various formations in the Coeur d'Alene District (excluding the Wallace Formation which hosts little ore) to get an idea of the average background levels of Ag and U. Samples were taken from inside the Sunshine and Con-Sil mines, except for the Burke and Prichard formation samples, of which neither formation is exposed near the mine. These were collected across the Osburn Fault, from outcrops at the base of 9 Mile Creek near Wallace, and from the base of Terror Gulch near Osburn, respectively. Two samples were collected from the Revett Formation, both randomly selected from drill core with no apparent ore minerals or alteration. Two more samples from the Revett Formation were collected from drill core, both containing concordant leucoxene-bearing layers. The last sample was a piece of drill core from apparently unaltered St. Regis Formation.

2.) **Sample Batch 2:** 3 samples of Ag-bearing concentrate were collected from the Sunshine assay lab. These samples were an average representation of all ore (tetrahedrite and galena) produced from the mine on three days in June of 1998. The concentrate had already been run through the mill and undergone the flotation process. These samples were produced entirely from about 12 active stopes in the West Chance area, the only area of the mine in production at that time. Extremely high levels of Ag and Sb limited the analysis of this batch to measuring U concentrations only. This area is notably poor in uranium-bearing minerals, and if the samples were discovered to be high in U.
this might be further evidence of a link between the uranium- and silver-bearing veins.

3. Sample Batch 3: 5 specimens of uranium minerals were obtained from Sunshine drill core, veinlets in the mine, and previously collected samples. An effort was made to gather samples with varying amounts of radioactivity, and therefore a variable U concentration. These specimens appeared representative of the samples as a whole, and only samples without other visible ore minerals were chosen. The strong radioactivity of the samples limited the accuracy of the 50 element analysis. These samples are of interest not only to examine the Ag concentration, but also to examine what other trace elements exist in the uranium minerals, potentially a clue to their origin.

4) Sample Batch 4: Upon return of Sample Batch 3, it was discovered that the upper detectable limit of Ag was 300 ppm. Because all but one sample exceeded this value, 8 representative specimens of uranium minerals were again selected and assayed by the Sunshine mine assay lab for Ag. Again, specimens were selected with variable amounts of radioactivity and with no other ore minerals visible. This sample batch was analyzed to determine the actual levels of Ag associated with the uranium minerals.

5.) Sample Batch 5: Though not a focus of this study, Pb concentrate from galena veins in the West Chance area was also analyzed. This material was collected from the assay lab after undergoing the milling and flotation process. Extremely high Pb levels prevented a full 50 element analysis, so only U levels were examined. However, the concentrations of several elements had already been determined by the assay lab. These 4 samples would prove useful in identifying any potential connection that may exist between galena veins and U- or Ag-bearing veins.

6.) Cominco American geochemical reports: In speaking to district geologists, I became aware of a geochemical study performed in the Pine Creek area west of the Sunshine mine. Hundreds of samples had been collected from various formations near the Bunker Hill mine from 1979-1981. The exact collection points of all of these samples is unknown due to the loss of the original map, but the sheer number of samples is useful. The lithology of each sample is listed, as well as the concentrations in ppm of 9 major elements. Unfortunately, U levels were not analyzed, but an idea of the geochemistry of local Belt rocks could be formed. In theory, this chemistry should be somewhat similar to the same units in the Sunshine mine 2 miles to the east.
Results

The results of the analyses are compiled here in the same order as previously listed. No sample data has been excluded, except for the Cominco American report, for which a summary is provided.

Table 3 - Detection Limits for Sample Batches 1, 2, 3, & 5:
(all values in ppm except where noted).

<table>
<thead>
<tr>
<th>Element</th>
<th>Detection Limit (low-high)</th>
<th>Element</th>
<th>Detection Limit (low-high)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au</td>
<td>5-10000 (ppb)</td>
<td>Cs</td>
<td>1-10000</td>
</tr>
<tr>
<td>Ag</td>
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<td>La</td>
<td>5-30000</td>
</tr>
<tr>
<td>Ir</td>
<td>100-1000 (ppb)</td>
<td>Ce</td>
<td>10-30000</td>
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<tr>
<td>Zn</td>
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<td>Sm</td>
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</tr>
<tr>
<td>Mo</td>
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<td>Eu</td>
<td>2-30000</td>
</tr>
<tr>
<td>Ni</td>
<td>20-30000</td>
<td>Tb</td>
<td>1-30000</td>
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<tr>
<td>Co</td>
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</tr>
<tr>
<td>Cd</td>
<td>10-2000</td>
<td>Rb</td>
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<td>As</td>
<td>1-10000</td>
<td>Lu</td>
<td>0.5-2000</td>
</tr>
<tr>
<td>Sb</td>
<td>0.2-9999</td>
<td>Se</td>
<td>0.5-2000</td>
</tr>
<tr>
<td>Fe</td>
<td>0.5-10 (%)</td>
<td>Hf</td>
<td>2-30000</td>
</tr>
<tr>
<td>Se</td>
<td>10-30000</td>
<td>Ta</td>
<td>1-2000</td>
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<tr>
<td>Te</td>
<td>20-20000</td>
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<td>Ba</td>
<td>100-20000</td>
<td>Na</td>
<td>0.05-10 (%)</td>
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<tr>
<td>Cr</td>
<td>50-30000</td>
<td>Br</td>
<td>1-30000</td>
</tr>
<tr>
<td>Sn</td>
<td>200-30000</td>
<td>Zr</td>
<td>500-10000</td>
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<td>W</td>
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<td>U</td>
<td>0.5-2000</td>
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Table 4 - Sample Batch 1:
Geochemistry of 7 Whole Rock Samples from
Various Formations in the Coeur d'Alene Mining District

Sample Description:

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<th>Formation &amp; Lithology</th>
<th>Collection Location</th>
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<tbody>
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<td>base of 9 Mile Creek, Wallace</td>
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<tr>
<td>Pr</td>
<td>Prichard Formation, argilite</td>
<td>base of Terror Gulch, Osburn</td>
</tr>
<tr>
<td>ZX40-4 470'</td>
<td>Revett Formation, quartzite</td>
<td>drill cor. Con-Sil mine</td>
</tr>
<tr>
<td>ZX40-4 506'</td>
<td>Revett Formation, quartzite with leucoxene layers</td>
<td>drill cor. Con-Sil mine</td>
</tr>
<tr>
<td>27-2171 178'</td>
<td>St. Regis Formation</td>
<td>drill core. Sunshine mine.</td>
</tr>
<tr>
<td>27-2208 147'</td>
<td>Revett Formation, quartzite with leucoxene layers</td>
<td>drill core. Sunshine mine.</td>
</tr>
<tr>
<td>31-2205 178'</td>
<td>Revett Formation, quartzite</td>
<td>drill core. Sunshine mine. boumonite vein area</td>
</tr>
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</table>

(all results in ppm except for Au and Ir (ppb) and Fe and Na (^o):
- preceding a value denotes a value less than that listed)

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<th>Zn</th>
<th>Mo</th>
<th>Ni</th>
<th>Co</th>
<th>Cd</th>
<th>As</th>
<th>Sb</th>
<th>Fe</th>
<th>Se</th>
<th>Te</th>
<th>Ba</th>
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<th>Cs</th>
<th>La</th>
<th>Ce</th>
<th>Sm</th>
<th>Eu</th>
<th>Tb</th>
<th>Yb</th>
<th>Lu</th>
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<td>-1</td>
<td>-5</td>
<td>0.6</td>
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<tr>
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<td>-2</td>
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<table>
<thead>
<tr>
<th>Sample #</th>
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<th>Na</th>
<th>Br</th>
<th>Rb</th>
<th>Zr</th>
<th>U</th>
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<td>95</td>
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<td>0.06</td>
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<td>120</td>
<td>2200</td>
<td>8.7</td>
</tr>
<tr>
<td>27-2171 178'</td>
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<td>0.06</td>
<td>-1</td>
<td>130</td>
<td>-500</td>
<td>1.8</td>
</tr>
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<td>0.06</td>
<td>-1</td>
<td>170</td>
<td>960</td>
<td>6.4</td>
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<td>0.06</td>
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<td>96</td>
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<td>1.9</td>
</tr>
</tbody>
</table>

The above results are unremarkable and reflect the lack of pervasive mineralization of Belt rocks outside of veins. These results are similar to those obtained by Harrison and Grimes (1970). Of interest are the elevated levels of Hf, Zr, U. and of
course Ti (not analyzed) in the leucoxene layers sampled from the Revett Formation.

Concordant to strata, they probably originated as detrital heavy mineral layers during Belt sedimentation. It is possible the uranium in these layers may have had some sort of effect on the uranium minerals isotopically age dated later in this study.

Table 5 - Sample Batch 2:
Elemental Concentrations of 3 Ag Concentrates from the Sunshine mine. West Chance area

(all data obtained from Sunshine mine assay offices except for U concentrations obtained from Bondar Clegg Laboratories; - in preceding a value denotes a value less than that listed)

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Date</th>
<th>Ag (oz/ton)</th>
<th>Pb %</th>
<th>Cu %</th>
<th>Fe %</th>
<th>As %</th>
<th>Sb %</th>
<th>H₂O %</th>
<th>U (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5915</td>
<td>6/2/98</td>
<td>1397.1</td>
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<td>15.8</td>
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<td>13.69</td>
<td>11.80</td>
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<td>5918</td>
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<td>.90</td>
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<td>10.69</td>
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</table>

Results of the above analyses are inconclusive because the uranium levels of the concentrate were not determined precisely. If the concentrate contains uranium at the upper level of the listed values, it is indeed enriched in uranium. However, if values are routinely less than 10-20 ppm, the silver-bearing veins in the West Chance area probably have no relationship to earlier uranium emplacement in the mine.
Table 6 - Sample Batch 3:
Geochemistry of 5 Uranium Mineral Samples from the Sunshine mine

Sample Description:

<table>
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<tr>
<th>Sample #</th>
<th>Approx. % U:</th>
<th>Collection Location:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>3100' level. approx. 41 m northwest of &quot;U stope&quot; on main drift</td>
</tr>
<tr>
<td>2</td>
<td>23</td>
<td>48-3W stope</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>48-K4E stope. east side. end of cut (sample age dated)</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>44-CF4 stope. center of raise + 60 m. floor # 7</td>
</tr>
<tr>
<td>5</td>
<td>0.15</td>
<td>40-R3E stope. center of raise + 23 m. track + 50 m</td>
</tr>
</tbody>
</table>

* denotes measurement with portable geiger counter

(all results in ppm except for Au and Ir (ppb) and Fe and Na (%): detection limits listed in Table II: - preceding a value denotes a value less than that listed. + denotes a value greater than listed)

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Au</th>
<th>Ag</th>
<th>Ir</th>
<th>Zn</th>
<th>Mo</th>
<th>Ni</th>
<th>Co</th>
<th>Cd</th>
<th>As</th>
<th>Sb</th>
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<th>Se</th>
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<td>-5</td>
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<th>Na</th>
<th>Br</th>
<th>Rb</th>
<th>Zr</th>
<th>Ba</th>
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<td>-920</td>
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</tr>
<tr>
<td>3</td>
<td>-5</td>
<td>-10</td>
<td>-2.4</td>
<td>-17</td>
<td>-39</td>
<td>-3900</td>
<td>-3800</td>
<td>-1</td>
<td>-470</td>
<td>-2000</td>
</tr>
<tr>
<td>4</td>
<td>-26</td>
<td>-11</td>
<td>-35.9</td>
<td>-279</td>
<td>-190</td>
<td>-14000</td>
<td>-9000</td>
<td>-7</td>
<td>-1500</td>
<td>-2000</td>
</tr>
<tr>
<td>5</td>
<td>-5</td>
<td>-5.3</td>
<td>-5.8</td>
<td>-71</td>
<td>-33</td>
<td>-1700</td>
<td>-1000</td>
<td>-1</td>
<td>-170</td>
<td>1550</td>
</tr>
</tbody>
</table>
Several points are important about the data in Table 6. Accurate values could not be given to most elements, and only upper limits were assigned. Most importantly, with a low upper detection level of 300 ppm, Ag values could not be accurately determined, and all but one sample exceeded this limit. Secondly, the importance placed upon this analysis must be minimized because of the effect of radiation on the analytical procedure.

The data may show increasing concentrations of many elements from the lowest U concentration (sample # 5) to the highest U concentration (sample # 2). Especially anomalous are Zr, Au, Sm, Ce, Sn, Te, Sb, Mo, Ba, and As. The uranium minerals sampled may be associated with many usually rare elements, including rare earth and large ion lithophile elements.

Table 7 - Sample Batch 4: Ag Levels in 8 Uranium-rich Samples from the Sunshine Mine (all data obtained from Sunshine mine assay offices)

<table>
<thead>
<tr>
<th>Sample # (location collected)</th>
<th>Radioactivity (mr/hr)</th>
<th>Ag Level (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>42-J8W</td>
<td>0.20</td>
<td>146</td>
</tr>
<tr>
<td>48-3W &quot;B&quot;</td>
<td>55</td>
<td>955</td>
</tr>
<tr>
<td>31-mainline</td>
<td>1.0</td>
<td>8492</td>
</tr>
<tr>
<td>44-CF4</td>
<td>0.90</td>
<td>1012</td>
</tr>
<tr>
<td>44-CF ramp</td>
<td>0.30</td>
<td>64</td>
</tr>
<tr>
<td>50-597 80-85'</td>
<td>0.45</td>
<td>151</td>
</tr>
<tr>
<td>48K4 FW</td>
<td>78</td>
<td>51</td>
</tr>
<tr>
<td>48-3W &quot;A&quot;</td>
<td>30</td>
<td>1202</td>
</tr>
</tbody>
</table>

*denotes average measurement from portable scintillometer

These data further refine the data accumulated in the previous sample batch by providing accurate Ag values for the samples tested. There does not appear to be any correlation between increased radioactivity (and therefore higher U levels) and increased Ag levels. For example, the sample with the highest radioactivity contained the lowest concentration of Ag, and the sample with the highest Ag concentration possessed only an
average amount of radioactivity. Though this sample batch is limited in number, it likely provides an accurate representation of uranium and silver levels throughout the mine.

Table 8 - Sample Batch 5:
Ag Levels of 4 Pb Concentrates from the Sunshine Mine. West Chance Area
(- denotes less than the listed value)

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Date</th>
<th>Ag (oz/ton)</th>
<th>Pb %</th>
<th>Cu %</th>
<th>Fe %</th>
<th>As %</th>
<th>Sb%</th>
<th>H₂O %</th>
<th>U (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>158-98</td>
<td>8/5/98</td>
<td>59.90</td>
<td>37.1</td>
<td>0.67</td>
<td>15.8</td>
<td>1.01</td>
<td>0.71</td>
<td>1.05</td>
<td>13</td>
</tr>
<tr>
<td>164-98</td>
<td>8/13/98</td>
<td>108.14</td>
<td>32.7</td>
<td>2.07</td>
<td>16.3</td>
<td>1.20</td>
<td>2.02</td>
<td>11.1</td>
<td>-0.5</td>
</tr>
<tr>
<td>169-98</td>
<td>8/19/98</td>
<td>92.21</td>
<td>33.7</td>
<td>1.31</td>
<td>17.3</td>
<td>1.08</td>
<td>1.33</td>
<td>10.54</td>
<td>-0.5</td>
</tr>
<tr>
<td>174-98</td>
<td>8/25/98</td>
<td>61.61</td>
<td>41.4</td>
<td>0.71</td>
<td>13.6</td>
<td>0.72</td>
<td>0.81</td>
<td>10.08</td>
<td>0.5</td>
</tr>
</tbody>
</table>

The data in Table 8 clearly show the lack of a relationship between uranium-bearing and galena veins. This data could be flawed if uranium was separated from the lead during processing, but the lack of any spatial relationship in the mine seems to preclude any association.

Cominco American Geochemical Analyses

The hundreds of samples analyzed by Cominco American along Pine Creek, near the Bunker Hill mine south of Smelterville, are taken from the Prichard, Burke, Revett, and St. Regis Formations. Ag, Au, Cu, Ba, Zn, Pb, Mn, and Ni were analyzed for each sample. Average concentrations are as follows:

- Au: <0.01 ppm
- Ag: <1.0 ppm
- Cu: ~30 ppm
- Ba: 200-600 ppm
- Zn: 30-80 ppm
- Pb: 20-50 ppm
- Mn: highly variable
- Ni: 20-50 ppm

A brief summary of each sample lithology was also provided. Upon examination of any Ag level exceeding 1.0 ppm, the lithology was noted. Silver values greater than 1.0 ppm always occurred in silty or quartzose material, but never in argillite.

Furthermore, the few values greater than 5.0 ppm always occurred in quartzose material.
This is also true in the Sunshine mine, where argentiferous tetrahedrite in some vein systems occurs primarily in coarser grained quartzites. No association of Ag with any other metallic element was discernible from the data.
PETROGRAPHY

Methods of Analysis

Forty polished thin sections were prepared from uranium-bearing specimens taken from drill core and geology department samples. Thin sections were examined for mineral assemblages and textural relationships in both translucent and reflected light. Photomicrographs were taken of typical examples of each mineral paragenesis and crosscutting relationships, and uranium mineral-tetrahedrite interfaces.

Results

Mineral grains in most uranium-bearing thin sections are very fine-grained and highly altered, and the rocks contain evidence at least two episodes of mineralization. This caused difficulties with petrographic analysis and mineral identification. However, several points are readily apparent. Crosscutting relationships indicate that the uranium-bearing minerals were emplaced prior to argentiferous tetrahedrite and siderite. This was also seen by earlier workers. Siderite and/or tetrahedrite veinlets can be seen extending into and cutting the red silicified rock associated with the uranium (Figure 15).

Furthermore, tiny carbonate rhombohedrons were observed dispersed in the jasperoid alteration, clearly establishing the relative paragenesis of the vein minerals (Figure 16).

Identification of uranium-bearing minerals in thin section proved extremely difficult due to the very fine grain sizes and lack of any obvious identifying features. These minerals generally appear as opaque, anhedral grains occurring in small clusters.
Figure 15 - Typical jasperoid alteration consisting of fine-grained quartz (white) with minor hematite, sericite, and feldspars, crosscut by siderite veinlet (light brown). Sample from 37-S78W stope, transmitted light, crossed nicols. Magnified 16X, ~3 mm left to right.

Figure 16 - Jasperoid associated with uranium minerals, consisting primarily of quartz (white-gray) flooded with euhedral carbonate rhombohedrons (blue-green). Sample from 37-S78W stope, transmitted light, crossed nicols. Magnified 160X, ~0.4 mm left to right.
In a number of thin sections uranium-bearing minerals could be identified by radiation halos in the surrounding siderite. Without these halos, positive identification of uranium minerals in sulfides and jasperoid was difficult. The specific uranium-bearing minerals could not be determined without the aid of a microprobe. Examination also revealed what appeared to be uncommon veinlets of uranium-bearing minerals into siderite (Figure 17).

Figure 17 - Uranium minerals (opaque) in siderite (brown). Note dark brown radiation halos surrounding uranium. Opaque veinlet in center (extending top to bottom) apparently crosscuts younger siderite; veinlet also contains minor chalcopyrite.
   Note quartz (white) scattered through uranium-rich area.
   Sample from 37-031E stope, transmitted light, uncrossed nicols.
   Magnified 16X, ~3 mm left to right.

Sericite, quartz, and sulfides were also observed to crosscut the siderite, sometimes with textures indicating periodic reopening of fractures (Figure 18).

The observed multiple stages of mineralization suggest that the older uranium minerals were either remobilized to some extent by later ore fluids and mixed with
Figure 18 - Texture indicates possible periodic fracture reopening. Siderite (brown) is crosscut by parallel sericite/pyrite veinlet (yellow/brown & opaque) and quartz veinlet (white/black). Sample from stope 37-R3PR, transmitted light, crossed nicols. Magnified 16X, ~3 mm left to right.

younger material in silver-bearing veins, or a second generation of uranium was introduced. Replacement of the original uranium-bearing material seems to be far more common than remobilization. The uranium minerals in siderite always occur with scattered fine-grained quartz, possibly the remains of the original alteration during vein formation.

Several slides show clusters of arsenopyrite needles within areas of weak jasperoid alteration. Arsenopyrite and pyrite were identified as the oldest vein minerals in the mine along with the uraninite (Kerr and Robinson, 1953). Both are readily apparent near uranium minerals, but never within the zone of intense red alteration. Approaching the red alteration, these minerals become less common and appear oxidized along their edges. Also, one thin section slab contains several areas from 0.5 to 1 cm across that are surrounded by intense red alteration, yet have cores that are black in color. Further
examination revealed a core of magnetite that "fades" outwards towards the alteration. The red silicification that contains the uranium was therefore caused by oxidation of previously existing iron sulfides and magnetite by the uranium-bearing fluids.

Sericite occurs within the jasperoid and extends outward into un-mineralized wall rock. The sericite lies along foliation planes in most areas parallel to cleavage and dip-slip motion on adjacent faults. The sericite rarely crosscuts the uranium minerals, siderite or any of the sulfides, suggesting fault motion began along cleavage planes before the emplacement of vein minerals. Sericite also occurs along the edges of silver-bearing veins, and along grain boundaries between tetrahedrite/siderite and jasperoid alteration.

Tetrahedrite in silver-bearing veins is always associated with siderite, and uncommonly with pyrite. The siderite is generally euhedral and undeformed, and may be crosscut by white quartz veins. Tetrahedrite commonly occurs together with chalcopyrite in sub-equal proportions near uranium-bearing veins (Figure 19), but is much less abundant elsewhere. Because both are evenly distributed and each show evidence of replacing each other, deposition seems to have occurred simultaneously. The veins contain several generations of pyrite, which both replaced and are being replaced by tetrahedrite and chalcopyrite. Multiple pyrite generations could possibly provide further evidence for the periodic reopening of veins.

Figure 19 - Typical association of tetrahedrite (white) and chalcopyrite (yellow) in siderite matrix (green/brown). Sample from 37-D31E stope, reflected light, uncrossed nicols. Magnified 32X, ~2 mm left to right.
ELECTRON MICROPROBE

Methods of Analysis

In order to more fully examine the fine-grained mineral assemblage associated with the uranium-bearing veins, thin sections were studied with a CAMECA electron microprobe at Washington State University. They were first coated with a layer of carbon about 100 Å thick. The microprobe was then calibrated for U and Ag using pure reference minerals, and set so that an audible alarm was emitted in areas rich in a selected element. In addition to studying previously noted areas of unidentified minerals, random scans were run over each of the slides in order to detect U or Ag in any previously unknown areas. Finally, uranium-bearing minerals were scanned for anomalous Ag levels and tetrahedrite was scanned for anomalous amounts of U. Unknown minerals were identified by graphs of X-ray scatter which detected high elemental concentrations. Also, a number of electron backscatter images were recorded. Upon completion, thin sections were repolished for further study.

Results

Microprobe analysis clarified earlier petrographic studies by identifying many of the tiny minerals in uranium-rich zones that were too small to be previously detected or identified. Study of uranium minerals established the presence of three mineral types:

a.) Uranium oxides. These are composed of uraninite, originally identified by Thurlow and Wright (1950) (Figure 20). Uranium oxides comprise about 80% of all uranium minerals occurring in the thin sections.

b.) Uranium-titanium oxides. Identified by Zartman and Smith (in press) as brannerite, forming long needlelike crystals and commonly exhibiting exsolution of titanium and uranium oxides (Figure 21).
c) Uranium-phosphates. Only a few grains of these are present, and the specific mineral remains unidentified (Figure 22). Elemental analyses would be necessary to further identify the uranium phosphate, of which 48 minerals are known to exist.

Figure 20 - Typical X-ray diffraction graph produced by uranium oxide. Large peak labeled Ag corresponds to high U levels. Smaller peak above 2.00 corresponds to anomalous O level. Peak at far left is C from thin section coating. Sample from stope 37-R3 pillar pull.

Figure 21 - Typical X-ray diffraction graph produced by brannerite. Large peak labeled Ag corresponds to high U levels. Smaller peak at 6.50 corresponds to anomalous Ti level. Ti levels were highly variable throughout brannerite. Smaller peak above 2.00 corresponds to anomalous O level. Peak at far left is C from thin section coating. Thin section from sample U1 (unknown location).
Microprobe analyses reveal that brannerite (UTi$_2$O$_6$) and uranium-phosphate minerals occur primarily in areas with large amounts of siderite and tetrahedrite. Uraninite, while ubiquitous, is the only uranium occurrence in areas of intense red alteration and away from paragenetically later silver-bearing veins. This suggests that the younger silver mineralization may have altered the older uranium minerals into new ones by the addition of titanium and phosphorus. Belt rocks do contain ample concentrations of both elements (in ilmenite/leucoxene and apatite) so that circulating ore fluids could possibly leach wall rocks and add these elements (Ti, P) to recrystallized/remobilized uranium minerals. Tiny grains of uranium minerals do in fact appear to be remobilized in several locations. These were seen "invading" silver-bearing veins along microfractures. Brannerite needles were readily observed under higher magnification and possess exsolution textures of Ti and U oxides, as also noted by Zartman and Smith (in press).
Random scans of the fine-grained minerals within the uranium-bearing veinlets revealed that much of the material is feldspar. Potassium feldspars were more common than plagioclase, and hematite was also common. Arsenopyrite and fine-grained pyrite are common near the veinlets, but no sulfides were present in areas of intense jasperoid alteration. No unusual elements were found in any abundance, such as those prior geochemical analyses indicated may be present.

Random scans for high Ag levels (several hundred parts per million) showed that none exist outside tetrahedrite and associated sulfosalt minerals. Chalcopyrite is also Ag-poor and typically intergrown with the tetrahedrite in equal proportions (Figure 23).

Figure 23 - Backscatter electron image of typical chalcopyrite (orange) intergrown with argentiferous tetrahedrite (yellow) in siderite matrix (brown). Relict crystal structure (?) may be seen in tetrahedrite in center of image. Sample from stope 37-S78W. Magnified 200X, 900 μ left to right.
In some areas it rings the tetrahedrite, and in others the opposite situation occurs, indicative of relatively contemporaneous deposition. Random scans for U in the silver-bearing veins yielded a large number of discoveries. Uranium minerals occur in silver-bearing veins in three locations:

a.) Encapsulated in quartz, hematite, or feldspar as a discrete inclusion within a siderite, tetrahedrite, chalcopyrite, or pyrite matrix (Figure 24).

b.) Surrounded and replaced by younger sulfides within the veins (Figure 25).

c.) As discrete grains within the younger vein material, with no apparent alteration, replacement, or other mineral association (Figure 26).

Figure 24 - Backscatter electron image of brannerite (white-yellow) in quartz inclusion (dark brown) within a siderite matrix (medium brown). Sample from 4400 West Chance 140 crosscut (CF02 stope). Magnified 200X, 900 μ left to right.
Figure 25 - Backscatter electron image of uraninite (white) rimmed and being replaced by tetrahedrite (orange) in a matrix of siderite, sericite, and quartz. Sample from diamond drill hole 44-1537. Magnified 800X, 180 μ left to right.
Figure 26 - Backscatter electron image of uraninite (white-yellow) in discrete grains within tetrahedrite (medium brown) and siderite (dark brown).
Sample from diamond drill hole 44-1532.
Magnified 800X, 180 μ left to right.
Uranium minerals occur in silver-bearing veins, which supports the aforementioned geochemical analyses. Uranium concentrations in these veins are highly variable; some contain no uranium minerals whereas and others contain many. However, geochemical analyses performed in this study in the West Chance area, which is not known to contain any uranium veins, also indicate that anomalous concentrations of uranium exist in silver-bearing veins as well.
Method of Analysis

Three samples containing uranium minerals were chosen from available specimens for age dating. Care was taken to ensure that they possessed only uranium vein minerals, and that the samples were from different areas of the Sunshine mine. The samples were sent to Geochron Laboratories in Cambridge, Massachusetts, where they were forwarded to the Massachusetts Institute of Technology for analysis. There, uranium and lead were separated from the samples and isotopically analyzed. One sample yielded 2 points on a $^{206}\text{Pb}/^{238}\text{U}$: $^{207}\text{Pb}/^{235}\text{U}$ concordia diagram, whereas the other produced three. Several months later, the last sample had not yet yielded enough uranium to analyze, and a decision was made to forego that particular analysis. As the other two samples produced reasonably concordant dates, the third analysis was deemed unnecessary. The two tested samples are:

(both samples actual size)

Figure 27 - Sample SS2518: from diamond drill hole 50-574 50' (Syndicate area). ~3 % U (measured on a portable geiger counter); gray uranium mineral with red altered wall rock and visible quartz.

Figure 28 - Sample SS2519: from stope 48-K4E footwall, east side at the end of the cut. ~33 % U (measured on a portable geiger counter); gray uranium mineral with red altered wall rock.
Results

Table 9 - U-Pb Isotopic Analysis of Sample SS2518 (2 sample points)

<table>
<thead>
<tr>
<th></th>
<th>Sample SS2518, point 1</th>
<th>Sample SS2518, point 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (mg)</td>
<td>0.0100</td>
<td>0.0100</td>
</tr>
<tr>
<td><strong>Concentrations:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U (ppm)</td>
<td>3453.15</td>
<td>7689.43</td>
</tr>
<tr>
<td>Pb (ppm)</td>
<td>106.47</td>
<td>138.10</td>
</tr>
<tr>
<td><strong>Atomic Ratios:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{206}\text{Pb}/^{204}\text{Pb}$</td>
<td>1008.01</td>
<td>697.25</td>
</tr>
<tr>
<td>$^{208}\text{Pb}/^{206}\text{Pb}$</td>
<td>0.001</td>
<td>0.000</td>
</tr>
<tr>
<td>$^{206}\text{Pb}/^{238}\text{U}$</td>
<td>0.03175</td>
<td>0.01808</td>
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<tr>
<td>% error</td>
<td>0.06</td>
<td>0.07</td>
</tr>
<tr>
<td>$^{207}\text{Pb}/^{235}\text{U}$</td>
<td>0.26841</td>
<td>0.13545</td>
</tr>
<tr>
<td>% error</td>
<td>0.09</td>
<td>0.11</td>
</tr>
<tr>
<td>$^{207}\text{Pb}/^{206}\text{Pb}$</td>
<td>0.06132</td>
<td>0.05433</td>
</tr>
<tr>
<td>% error</td>
<td>0.06</td>
<td>0.08</td>
</tr>
<tr>
<td><strong>Ages (Ma):</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{206}\text{Pb}/^{238}\text{U}$</td>
<td>201.5</td>
<td>115.5</td>
</tr>
<tr>
<td>$^{207}\text{Pb}/^{235}\text{U}$</td>
<td>241.4</td>
<td>129.0</td>
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<tr>
<td>$^{207}\text{Pb}/^{206}\text{Pb}$</td>
<td>650.5</td>
<td>384.6</td>
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<td>correction coefficient</td>
<td>0.713</td>
<td>0.677</td>
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<tr>
<td>Total common Pb (pg)</td>
<td>67.8</td>
<td>125.2</td>
</tr>
</tbody>
</table>
Table X - U-Pb Isotopic Analysis of Sample SS2519 (3 sample points)

<table>
<thead>
<tr>
<th></th>
<th>Sample SS2519, point 1</th>
<th>Sample SS2519, point 2</th>
<th>Sample SS2519, point 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (mg)</td>
<td>0.0030</td>
<td>0.0058</td>
<td>0.0106</td>
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<td>Concentrations:</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>U (ppm)</td>
<td>206571.89</td>
<td>370017.97</td>
<td>173247.55</td>
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<tr>
<td>Pb (ppm)</td>
<td>19797.93</td>
<td>16366.13</td>
<td>11997.10</td>
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<tr>
<td>Atomic Ratios:</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$^{206}\text{Pb}/^{204}\text{Pb}$</td>
<td>91.35</td>
<td>142.94</td>
<td>118.89</td>
</tr>
<tr>
<td>$^{208}\text{Pb}/^{206}\text{Pb}$</td>
<td>0.003</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>$^{206}\text{Pb}/^{238}\text{U}$</td>
<td>0.05501</td>
<td>0.03162</td>
<td>0.04566</td>
</tr>
<tr>
<td>% error</td>
<td>0.14</td>
<td>0.15</td>
<td>0.19</td>
</tr>
<tr>
<td>$^{207}\text{Pb}/^{235}\text{U}$</td>
<td>0.49502</td>
<td>0.26543</td>
<td>0.40211</td>
</tr>
<tr>
<td>% error</td>
<td>.72</td>
<td>.35</td>
<td>.43</td>
</tr>
<tr>
<td>$^{207}\text{Pb}/^{206}\text{Pb}$</td>
<td>0.06527</td>
<td>0.06089</td>
<td>0.06387</td>
</tr>
<tr>
<td>% error</td>
<td>0.66</td>
<td>0.50</td>
<td>0.36</td>
</tr>
<tr>
<td>Ages (Ma):</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$^{206}\text{Pb}/^{238}\text{U}$</td>
<td>345.2</td>
<td>200.7</td>
<td>287.8</td>
</tr>
<tr>
<td>$^{207}\text{Pb}/^{235}\text{U}$</td>
<td>408.3</td>
<td>239.0</td>
<td>343.2</td>
</tr>
<tr>
<td>$^{207}\text{Pb}/^{206}\text{Pb}$</td>
<td>783.1</td>
<td>635.3</td>
<td>737.2</td>
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<tr>
<td>correction coefficient</td>
<td>0.508</td>
<td>0.536</td>
<td>0.544</td>
</tr>
<tr>
<td>Total common Pb (pg)</td>
<td>28302.8</td>
<td>33107.1</td>
<td>50235.9</td>
</tr>
</tbody>
</table>
Both samples were then plotted on $^{206}\text{Pb}/^{238}\text{U}, ^{207}\text{Pb}/^{235}\text{U}$ concordia diagrams:

Figure 29 - Sample SS2518 points (blue squares) plotted on U-Pb concordia diagram (2 stage growth curve).

Figure 30 - Sample SS2519 points (blue squares) plotted on U-Pb concordia diagram (2 stage growth curve).
Figure 31 - Samples SS2518 and SS2519 points (blue squares) plotted on U-Pb concordia diagram (2 stage growth curve).

Though the individual points on each sample are highly discordant, both plot on a discordia that is remarkably linear. This discordia represents an event that affected the uranium minerals enough to change the U-Pb isotopic ratios of the minerals. The above data indicate that both specimens are about the same age and that both experienced some sort of thermal event at the same time. Because the analyzed grains did not appear to be detrital, it is assumed that they were hydrothermally emplaced. The age of emplacement must be one of the two dates obtained (either 850-890 Ma or 82-88 Ma). Whatever the case, the samples do contain a mixture of two different leads: an older, less radiogenic lead and a younger, more radiogenic lead. These ages are not comparable with those of brannerite and uranium mineral-hosted zircons U-Pb dated by Zartman and Smith (in press)(see Table 2), but both this and Zartman and Smith's (in press) age dating attempts do conclude that the samples contain a mixture of older and younger Pb.
At least two possible scenarios exist concerning the age of the uranium minerals:

a.) The uranium minerals are old (885-890 Ma) and have undergone significant Pb loss in Laramide time.

b.) The uranium minerals were emplaced approximately 82 Ma and contain a significant component of older lead.

Two types of lead are known in the district: the first yields radiometric age dates of 1200-1500 Ma ("Coeur d'Alene type" lead), whereas the second is associated with the silver-bearing veins and yields Cretaceous-Tertiary dates. No lead has yet been identified which provides dates of 850-900 Ma, or the age of the uranium minerals. If the uranium minerals were to contain a significant component of older lead, the lead would probably be one of these two known types. This suggests that the uranium minerals may be old and have undergone Pb loss during the Laramide.

Additional age dates and knowledge regarding the district's evolution are necessary to determine which of these scenarios is correct. It should also be noted that the small number of points obtained from each sample renders these samples not statistically significant. However, the concordance of the points is significant. A wide variety of other age dates have been obtained throughout the district (Table II), and this information further adds to an already confused picture. It seems that the uranium-bearing veins at the Sunshine mine contain a mixture of older and younger lead, and probably have experienced some sort of recrystallization or thermal event.
Fluid Inclusions

Attempts were made to determine the nature of uranium- and silver-bearing solutions by analyzing fluid inclusions within vein quartz and siderite. Though a number of samples were prepared, no suitable primary inclusions were found. Inclusions in both jasperoid and siderite are uncommon and extremely small. Furthermore, the few observed inclusions were secondary.

The Geochemistry of Uranium

Uranium is different from most other metals in terms of ionic radii and charge, and therefore is rarely incorporated into other minerals. Uranium averages 2.8 ppm in the continental crust, and has 3 naturally occurring isotopes: $^{238}$U, $^{235}$U, and $^{234}$U. Three oxidation states are common: $U^{+4}$, $U^{+5}$, and $U^{+6}$. $U^{+5}$ is not believed to be common, so most uranium geochemistry involves the hexavalent and quadravalent species.

The uranyl ion ($U^{+6}$) has a strong affinity for oxygen, and commonly occurs in nature as $UO_2^{+2}$ (Nash and others, 1981). The oxidized uranyl ion easily combines with several soluble oxygen complexes. These include $OH^-$, $CO_3^{2-}$, $HCO_3^-$, $PO_4^{3-}$, $SO_4^{2-}$, and $AsO_4^{3-}$ complexes (Nash and others, 1981). The uranous ion ($U^{+4}$), however, is highly insoluble and occurs in very few minerals. Minerals formed by the uranyl ion include uraninite, brannerite, and ningyoite (a uranium phosphate) (Nash and others, 1981). These minerals are all present in the Sunshine mine, indicating that the uranium is present in a reduced state. The uranium-bearing veins are hydrothermal in origin, and therefore the U was almost certainly transported in an oxidized state. Deposition likely occurred at
oxidation-reduction boundaries within Belt rocks, uranium minerals forming from the reduced, quadravalent ion species.

Many uranium deposits show a close association between uraninite and hematite. This may be due to the reduction of the uranyl ion in solution by ferrous iron, which subsequently oxidizes to hematite, forming a red alteration halo around the uranium. Belt rocks in the Sunshine mine do contain magnetite and minor amounts of sulfides, which predate the uranium. Furthermore, petrography revealed the lack of magnetite or sulfides within the red alteration halos, though both increase in quantity outside the altered areas. Therefore, magnetite or sulfides could have acted as reducing agents for the uranium-bearing ore fluids, inducing uranium deposition and forming red alteration halos upon oxidation.

Because the solubility of uranium in solution drops sharply above 300°C, the temperature of the uranium-bearing fluids was probably below this point (Tilsley, 1988). Parks and Pohl (1988) state that uranium in solution is not affected by changes in pH between 100-300°C, making the pH of the fluids difficult to determine. The stability fields of uraninite and hematite on an Eh-pH diagram (Figure 32) indicate that the fluids were probably nearly neutral to slightly basic.
Figure 32 - Eh-pH diagram of iron and oxygen in water at 25°C and 1 atm superimposed on Eh-pH diagram of uranium and oxygen in water at 25°C and 1 atm. Hematite is stable at moderate to basic pH; uraninite is stable at moderate to basic pH and was probably deposited by lowering of Eh at oxidation-reduction boundaries. Field of deposition shown in green, with most likely deposition within the left portion of the green area. (modified from Nash and others, 1981, and from Garrels and Christ, 1965).
The Geochemistry of Silver

Silver is a chalcophile element that averages 0.07 ppm in the continental crust (Boyle, 1968). It has three common oxidation states: +1, +2, and +3. Silver and gold possess similar charge characteristics and atomic radii, allowing continuous substitution in mineral lattices where both are present. Copper and silver may also substitute for each other, though far less easily. The lattices of most lead minerals are elastic, commonly allowing the entry of silver (Boyle, 1968). Silver occurs in many minerals, the most common of which are argentite and acanthite (Ag₂S), tennantite-tetrahedrite ((Cu,Fe,Zn,Ag)₁₂(Sb,As)₄S₃), pyrargyrite (Ag₃SbS₃), proustite (Ag₃AsS₃), and chlorargyrite (AgCl), as well as occurring in its native form.

Silver and base metals are best transported in solution within chloride complexes ions at temperatures above 350°C (Romberger, 1991). However, they may also move in bisulfide complex ions at lower temperatures. Prior studies all conclude that silver-bearing veins were deposited at temperatures less than 325°C, making transport in HS⁻ complexes the likely mode of transport (Harris and others, 1981; Leach and others, 1988; Eaton and others, 1995). These complexes are stable under reducing conditions at a moderate to high pH (Figure 34). Deposition of the siderite that hosts the silver also requires neutral to slightly basic fluids. Furthermore, petrographic inspection revealed few open space fill textures within the siderite-hosted veins. If acidic, oxidizing ore fluids bearing metals hosted in Cl⁻ complex ions later deposited the tetrahedrite later, open space filling might be more common. Therefore, the ore fluids that deposited the veins were probably neutral to slightly basic, reducing, and less than about 300°C.
Figure 34 - Oxygen activity (Eh)-pH diagram of silver and oxygen in water at 250°C and 6 weight % NaCl showing carrying capacities of Ag in HS⁻ and Cl⁻ complex ions. Black line indicates oxidation/reduction boundary: pH of 5.5 is neutral (modified from Romberger, 1991).
DISCUSSION

Implications of the Data on the Relationship Between Uranium- and Silver-Bearing Veins

The purpose of this study was to examine the relationship between uranium- and silver-bearing veins and ascertain whether they are temporally and/or genetically related. This was accomplished by:

1.) Characterizing the mineralogy, geochemistry, and alteration and textural assemblages of the uranium-bearing veins.
2.) Noting the spatial distribution and structural controls of the uranium-bearing veins.
3.) Radiometric age dating of uranium-bearing minerals.

Differences and similarities between the uranium-bearing and the silver-bearing veins were then examined in light of the possible relationships between the veins.

Model One: Uranium and Silver Were Deposited in a Continuum:

The first possibility is that uranium mineralization evolved over time into silver/base-metal mineralization. There are some indications that this may have occurred. These include:

1.) Textural relationships demonstrate that Ag/base-metal minerals replaced older uranium minerals.
2.) Geochemical analyses possibly indicate anomalously high uranium in silver-bearing veins, even in areas without known uranium minerals.
3.) The occurrence throughout the district of uranium minerals almost exclusively in the "Silver Belt".
4.) Both uranium-bearing, and especially silver-bearing veins are associated with siderite.

However, too many major differences exist between the veins for them to have been deposited in a continuum. The differences include:

1.) The trends of the veins differ slightly, indicating significant structural adjustments occurred between mineralization events.
2.) One vein type may occur without the other.
3 ) No silver minerals were observed in uranium-bearing areas away from tetrahedrite/siderite veins.
4 ) Uranium-bearing veins are quartz-rich and contain a wide variety of rare earth and large ion lithophile elements, whereas the silver-bearing veins are rich in sulfur, iron, copper, and other metals.
5 ) Ore fluids were different. Uranium-bearing fluids were oxidizing and slightly acidic, whereas silver-bearing fluids were reducing and slightly basic.
6 ) Radiometric age dating of uranium minerals always produces a Precambrian concordia date, which is believed to predate the formation of silver-bearing veins. Ar-Ar radiometric dating and Rb/Sr isotopic ratios indicate that the silver-bearing veins are Mesozoic or younger (Leach and others, 1998; Fleck, 1991; Eaton and others, 1995).

These observations are most compatible with the formation of the two vein types in two discrete events.

**Model Two: Uranium-bearing Veins Chemically and/or Structurally Prepared the Host Rocks for the Formation of the Silver-Bearing Veins:**

Uranium-bearing veins may have aided formation of younger silver-bearing veins by silicifying the host Belt rocks, thereby making them more brittle. Brittle host rocks would be prone to fracture development, aiding in the formation of the silver-bearing veins. Alternatively, the creation of an oxidation-reduction boundary would facilitate silver deposition. This condition could occur by the interaction of ferric iron within the earlier "jasperoid" alteration and the reduced, Ag-bearing ore fluids. The result may have diminished the silver carrying capacity of bisulfide complex ions.

No evidence supports the model of chemical and/or structural preparation of host rocks for silver-bearing veins by older uranium-bearing veins. Evidence showing that this did not occur includes:

1.) No structural preparation by uranium-bearing veins for younger vein material was observed in thin section.
2.) Both vein types never occur within the same fractures. Each vein type commonly exists independently of the other.
3.) If uranium-bearing ore fluids chemically prepared the host rocks for tetrahedrite deposition, a strong association between uranium-bearing veins...
and tetrahedrite should be evident. However, the argentiferous tetrahedrite is commonly associated with siderite, not uranium minerals.

For these reasons, chemical and/or structural preparation by the uranium-bearing veins apparently did not occur.

**Model Three: The Veins Formed in Distinct Events:**

Another model is that the veins formed separately. In this model, any relationship may be either coincidental or a result of the silver-bearing vein formation being superimposed upon older uranium-bearing veins. Evidence supporting vein formation in two discrete events includes:

1.) Uranium-bearing veins trend west-northwest and dip southward, whereas silver-bearing veins trend west and dip southward. These spatial differences suggest changes in the tectonic regime between vein formation.

2.) Mineralogic, textural, and alteration assemblages are completely different between the two vein types. Older uranium-bearing veins contain primarily uraninite and quartz, and are extremely fine-grained. Silver-bearing veins are much coarser-grained and contain a more diverse mineral assemblage, which includes pyrite, chalcopyrite, tetrahedrite, and silver sulfosalts.

3.) Uranium-bearing veins were deposited by moderately oxidizing fluids, whereas silver-bearing veins were deposited by more reduced fluids.

4.) No silver minerals were observed within uranium-bearing veins, except where crosscut by the tetrahedrite/siderite veins. Fine-grained uranium minerals were observed within tetrahedrite and siderite. This data suggests discrete mineralization events, with silver-bearing fluids either remobilizing older uranium or introducing younger uranium into the veins.

5.) Radiometric age dates for uranium minerals always provide a Precambrian date on a concordia. Dates of silver-bearing veins indicate that they formed within the last 200 Ma.

For these reasons, the vein types appear to have formed during two distinct events. However, two distinct events do not explain the apparent spatial and possible geochemical association between the two vein types, and whether this association is entirely coincidental.
The Significance of the Spatial Relationship Between Uranium- and Silver-Bearing Veins

A Coincidental Relationship?

Uranium- and silver-bearing veins appear have formed during two discrete events. However, the association of both vein types was noted long ago by Sunshine mine geologists and researchers (Kerr and Robinson, 1953). If the association of the two vein types is coincidental, then the spatial relationship between them must be explained. It is highly unlikely that uranium minerals would occur almost exclusively in silver-producing areas of the district if the association is purely coincidental.

The vein types also may be geochemically associated. This is especially apparent today in the West Chance area, where silver is mined but no uranium-bearing veins are known to exist. Yet analysis of silver ore from this area showed possible anomalous U concentrations that may indicate a relationship.

The Causes of the Relationship

The spatial relationship between the two vein types implies that both were created in similar tectonic stress fields. The likelihood of two similar tectonic events followed by mineralization, separated by many millions of years, is unlikely at best. It is more probable that the uranium-bearing veins formed shortly before the silver-bearing veins, probably in Laramide time. This is supported by the spatial association of uranium with silver throughout the Silver Belt. Also, if uranium-bearing veins formed shortly before the silver-bearing veins, the younger ore fluids may have been able to utilize similar paths of fluid movement, increasing the likelihood of mingling with the uranium-bearing veins.
If a geochemical association between the two vein types does exist, the most likely cause is remobilization of uranium from older uranium minerals by younger silver-bearing fluids. This model could account for the uranium mineral grains within siderite and tetrahedrite, observed with the petrographic microscope and electron microprobe. It would also explain the possible geochemical association between the two elements. Furthermore, because fine grained uranium minerals occur in fractures in tetrahedrite, as observed with the microprobe, remobilization of uranium from older minerals is a significant possibility.

A large hydrothermal event such as that which formed the silver-bearing veins would surely have had a significant effect on pre-existing uranium minerals. Even if only small amounts of uranium were remobilized into silver-bearing veins, geochemical studies, such as that performed in the West Chance area, would reveal anomalously high U concentrations. Because the veins are commonly intermingled and no evidence exists for the introduction of a second generation of uranium, remobilization of older uranium minerals is the simplest and most likely explanation for a geochemical relationship between the veins.

If remobilization of uranium minerals by silver-bearing ore fluids occurred, a problem arises regarding the geochemical characteristics of the ore fluids and the method of uranium transport. Silver-bearing fluids are believed to have been reduced and slightly basic, and therefore incapable of mobilizing uranium in oxidizing complex ions. This problem may be explained in at least three ways:

1.) $\text{U}^{4+}$ may be mobile in solution as a uranous carbonate complex ion in solutions with high carbonate concentrations (Nash and others, 1981). Silver-bearing ore fluids contain high carbonate concentrations and are rich in CO$_2$ (Leach and others, 1988).
2. ) \( \text{U}^{4+} \) is moderately soluble under slightly reducing conditions from pH 1 to pH 7 (Nash and others, 1981).

3. ) The solution geochemistry of uranium may not be completely understood. The uranous ion may well form complexes with ions that have not yet been identified.

Uranium occurs in relatively low concentrations (several hundred ppm) within the silver-bearing veins, suggesting that only moderate amounts of uranium were remobilized.

Therefore, a highly efficient method of uranium transport by silver-bearing fluids would not be necessary to produce anomalous uranium concentrations within the silver-bearing veins.

Age of Mineralization

The exact timing of both uranium and silver/base-metal mineralization events is unknown, but it seems likely that uranium mineralization occurred in late Cretaceous or early Tertiary time, slightly predating the formation of silver-bearing veins. This is supported by discordia age dates, relatively closely oriented structural trends of the vein sets, and the occurrence of uranium minerals primarily in the Silver Belt.

Two possibilities exist concerning the age of the uranium-bearing veins:

1. ) The uranium-bearing veins formed at 82 Ma and the older concordia date resulted from the addition of Pb. Lead may have been added to the veins either by a later hydrothermal event, or by the interaction of uranium-bearing fluids with the host Belt rocks.

2. ) The concordia age date of 885 Ma may represent the original formation of the uranium minerals within Belt rocks, fitting well with other dates in the district. Furthermore, from 850-900 Ma the East Kootenay orogeny and continental rifting affected the region (McMechan and Price, 1982). Tectonism then could possibly have concentrated the uranium and/or allowed for formation of uranium minerals. The discordia age date of 82 Ma approximately coincides with the intrusion of the Idaho batholith and radiometric age dating of silver-bearing veins in the Sunshine mine. At this time, oxidizing fluids may have flushed the uranium and lead into the veins present in the Sunshine mine.
If the uranium minerals were deposited in veins at 885 Ma, the probability of them having similar structural trends to the much younger silver-bearing veins is small. Furthermore, the distribution of the uranium minerals almost exclusively within the Silver Belt would be difficult to explain. Also, White (1998a) identifies the Big Creek anticline as bracketed in age between Cambrian and Laramide time. If his interpretation is correct, then the uranium-bearing veins, which appear to crosscut the anticline, must be Cambrian or younger and could not have formed at 885 Ma.

Petrography revealed that lineated vein sericite does not crosscut uranium minerals. Sericite is lineated parallel to mineralized fractures and a penetrative cleavage that transects regional folds. These features are all believed to be of similar age, which radiometric dating of silver-bearing veins identified as late Cretaceous (Leach and others, 1988, 1998; Wavra and others, 1994). If the uranium veins were Precambrian, they would also be cut by lineated sericite, an instance which was not observed.

Deposits With Similar Characteristics

The silver-copper-lead deposits of the Sunshine mine bear many resemblances to other deposits in the Belt basin. Silver-copper deposits exist in the Superior, Clinton, and Phillipsburg Districts in Montana and at the Spar Lake deposit outside Troy, Montana. Almost all of these deposits also occur in the upper strata of the Revett Formation and have similar mineral and/or elemental suites. Furthermore, "Coeur d'Alene" type lead, yielding radiometric age dates between 1200-1500 Ma, is present in many of these Belt deposits.

Lange and Sherry (1983) studied copper-silver deposits along the Idaho-Montana border, including the Spar Lake mine. These deposits are also fault controlled and exhibit
decreases in Cu/Pb and Cu/Ag ratios outward, similar to that in the Sunshine mine. This zonation and vertical stacking of ore in permeable strata led them to conclude that fluids moved up along fault zones and outward into the most permeable strata (Lange and Sherry, 1983). Also present are red bed-green bed oxidation-reduction fronts, exhibiting mineral depletion in oxidized red beds and deposition in reduced green beds (Lange and Sherry, 1983). White (1998b) speculates that similar oxidation-reduction fronts may be influential in mineralization in the Coeur d'Alene District. A large number of other copper-silver deposits are scattered throughout the Belt basin, and all possess similar characteristics to the Coeur d'Alene deposits.

The Sunshine mine in many ways also resembles the "5 element" Ni-Co-As-Ag-Bi type deposits described by Kissin (1993). Deposits of this type exist at Thunder Bay, Ontario, Great Bear Lake, Northwest Territories, northern Saskatchewan, and in the Erzgebirge, Germany and the Czech Republic. These deposits possess the following similarities to Sunshine mine veins:

1.) Polymetallic veins containing mixed oxides, carbonates, and sulfides. Uranium may be present in pods, lenses, veins, and breccia fillings, and is commonly surrounded by a hematitic aureole (Marmont, 1987).

2.) Similar paragenetic sequences, summarized by Kissin (1993), in which ore fluids evolve over time and mineralization occurs in pulses, typically separated by fault motion:
   a.) Early barren stage- quartz sometimes with minor base-metal sulfides.
   b.) Uraninite stage- with quartz; this stage is sometimes completely absent
   c.) Ni-Co-arsenide-silver stage- silver and Ni-Co arsenides, sometimes with bismuth, usually in a carbonate gangue
   d.) Sulfide stage- base-metal sulfides with silver in calcite gangue
      with quartz, fluorite, and barite: may contain As-Sb-Ag sulfosalts, and is gradational from previous stage.
   e.) Late stage- calcite, sometimes with barite or fluorite.

3.) Vein minerals are commonly rich in rare earth elements (Kissin, 1993).
4) Deposits are structurally controlled, and in most cases, mineralization is believed to be late- or post-tectonic. "5 element" deposits always occur in continental crust and are sometimes associated with continental rifts (Kissin, 1993).

5) The genesis of these deposits is unknown and contentious, but is agreed to be non-magmatic (Kissin, 1993).

Differences exist between the Sunshine mine and "5-element" type deposits, but a comparison between them may increase understanding of the evolution of the Coeur d'Alene veins. In Canada's Echo Bay District, uranium-bearing fluids were determined by fluid inclusion analyses to be 150-250°C, oxidizing, and of variable salinity (Robinson and Ohmoto, 1973; Fryer and Taylor, 1987; Changakakoti and others, 1986). In a study at the Karpinka Lake uranium deposit in northern Saskatchewan, Williams-Jones and Sawiuk (1985) determined that brannerite commonly formed by U adsorption onto Fe-Ti oxides.

Tilsley (1988) notes that sedimentary phosphates may easily contain 10-100 ppm uranium, and similar minerals do occur in the Sunshine mine. Not only does the Sunshine mine possess characteristics of "5-element" type deposits, but it bears similarities to sandstone-hosted deposits as well. These include a strong association with iron, oxidation-reduction fronts, and permeable sedimentary host rocks.

Oxidation-reduction fronts exist within the Burke formation in the Coeur d'Alene District, and uranium may have originally been concentrated in a similar way (White, 1998b). These "roll-front" deposits are common in sedimentary basins across the western United States and include the Spar Lake mine (Lange and Sherry, 1983). Uranium is concentrated by oxidizing fluids, and deposited at an oxidation/reduction boundary. Though the source of the uranium in this type of deposit varies, oxidizing, meteoric fluids
are always believed to be the primary method of transport and concentration (Tilsley, 1988). Though no roll-front uranium deposits have been reported in the Coeur d'Alene District, they may have concentrated uranium within Belt rocks prior to the formation of veins.

Proposed Model of Mineralization in the Sunshine Mine

Uranium veins in Belt rocks may have originated from one of several sources:

1.) It was an original constituent of Belt rocks, which are believed to have been eroded from granitic source areas. A granitic source area would account for the typical mineralogy of Belt rocks and the anomalous concentrations of uranium and possibly other incompatible elements occurring within the uranium-bearing veins. However, typical Belt rocks are not known to be enriched in these elements. Furthermore, uranium-bearing veins would occur throughout the Belt basin and not be isolated to the Coeur d'Alene District.

2.) It was brought in by granitic intrusions during the East Kootenay orogeny or intrusion of the Idaho batholith. Once again, granitic magmas would serve as an excellent way to concentrate uranium. This explanation could also account for the radiometric age dates obtained on uranium minerals. However, though intrusions of this age exist to the west of the district, none are known to exist within the district itself.

3.) The uranium and other metals may have also been the product of seafloor exhalatives along the Lewis-Clark Line. However, uranium is usually sourced from granitic magma, which, along with ground water, is most common method of concentration. Also, no other known uranium-bearing veins exist at other mineralized areas along the Lewis-Clark Line, or at the Sullivan mine, a seafloor exhalative deposit in Canadian Belt rocks.

Formation of the uranium-bearing veins occurred during the late Cretaceous, either from uranium introduced at this time or from older uranium deposited within the Belt at 885 Ma. Regional tectonism and intrusive activity affected the region during late Cretaceous time. Fleck and Criss (1985) and Criss and Fleck (1990) used oxygen isotope maps to establish that fluids from the Idaho batholith reached the Coeur d'Alene district. Though batholith fluids were probably reducing, convection of oxidizing, meteoric water may have resulted. These oxidizing fluids would have been ideal for transporting the
uranium into faults and fractures crosscutting the Big Creek anticline. Uranium minerals provide a radiometric discordia age date of 82 Ma, corresponding with the age of Idaho batholith intrusion. This relationship indicates that the uranium-bearing veins may be related to this intrusion.

Fractures hosting the uranium-bearing veins were probably opened by motion along the Lewis-Clark line. Deposition would have occurred in reduced strata, aided by the presence of pre-existing sulfides and magnetite. Brannerite and uranium phosphate minerals formed where uranium encountered elements such as Ti and P in Belt rocks, or where Ti and P were introduced by later fluids. Continued fault motion segmented the veins, and later opened another set of major fractures. Additional tectonism and/or intrusion of the Idaho batholith induced another pulse of mineralizing fluids. Siderite veins formed, were reopened, and invaded by silver-bearing fluids, which moved upwards and laterally out into the brittle, quartzose Revett and lower St. Regis formations. Silver-bearing ore fluids followed a similar path to the uranium-bearing fluids that preceded them, and partially replaced many of the earlier veins. Vein formation continued until regional tectonism ended in early Tertiary time.
CONCLUSIONS

Characteristics of Uranium-Bearing Veins:

1.) Uranium-bearing veins consist primarily of uraninite, hematite, quartz, and feldspar
2.) The red hematitic alteration resulted from oxidation of pre-existing magnetite and sulfides. Greater flow of the uranium-bearing fluids increased the intensity of the red alteration and the radioactivity of the veins.
3.) Brannerite and uranium phosphates are present in close proximity to silver-bearing veins, possibly as a result of the silver-bearing fluids affecting the uranium minerals.
4.) Uranium minerals were commonly replaced by later siderite and tetrahedrite-bearing veins, and textures were observed which indicate that some U was probably remobilized by younger silver-bearing fluids.
5.) The overall trend of the uranium veins is parallel to the axis of the Big Creek anticline, in fractures which trend slightly northwest.
6.) U-Pb radiometric age dating produced a concordia age of 885 Ma and a discordia age of 82 Ma, indicating the uranium veins are either old and have experienced Pb loss at 82 Ma, or the uranium veins are young with a substantial component of older Pb.

Characteristics of Silver-Bearing Veins:

1.) Silver-bearing veins consist of approximately equal parts chalcopyrite and argentiferous tetrahedrite, contain several generations of pyrite, and are hosted by siderite and lesser amounts of quartz.
2.) Silver veins occur most commonly in siltite and especially quartzite, which are coarser-grained and perhaps more brittle than surrounding argillites.
3.) High concentrations of Ag are only found in tetrahedrite and uncommon sulfosalts.
4.) Silver-bearing veins trend almost due west, and seem to occur primarily in tear fractures in between major faults.
5.) Both structural and isotopic evidence support formation of Ag-bearing veins during Laramide time.

The Nature of the Relationship Between Uranium- and Silver-Bearing Veins

Uranium- and silver-bearing veins were deposited in discrete events. The two vein systems are related by having formed under similar tectonic stress fields. The fluids that deposited each vein type may have originated during the same tectonic event and
probably utilized similar flow paths. Therefore, they possess similar trends and spatial
distributions in the Sunshine mine as well as throughout the Coeur d'Alene District.

Younger silver-bearing ore fluids replaced and remobilized older uranium
minerals. Silver-bearing ore fluids probably came into extensive contact with uranium
minerals in the Sunshine mine, redistributing some uranium into silver-bearing veins.
This model may account for the apparent spatial association between the two vein types
in the Sunshine mine and throughout the Coeur d'Alene Mining District.
REFERENCES


After the completion of this research, the clay fraction of a single sample of both a uranium-bearing vein and a silver-bearing vein were analyzed by X-ray diffraction. The samples were taken from the following locations:

<table>
<thead>
<tr>
<th>Sample</th>
<th>Location</th>
<th>Vein Minerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>DDH 44-1537, 228'</td>
<td>Uraninite, quartz, pyrite</td>
</tr>
<tr>
<td>Ag</td>
<td>F vein, 3700' level</td>
<td>Tetrahedrite, siderite, minor chalcopyrite</td>
</tr>
</tbody>
</table>

Both samples were pulverized and ultrasonically disaggregated in de-ionized water. The clay fraction of the samples (< 2μ) was separated by placing each sample in a centrifuge at 1000 rpm for 2 minutes. The cation of the uranium-bearing vein (sample U) clay fraction was controlled by washing with 0.1 molar strontium chloride solution. The clay was then rolled onto a glass slide. The silver-bearing vein sample (sample Ag) was prepared by coating a glass slide with a solution containing the suspended silver-bearing clay fraction. The result was two oriented samples that were subsequently saturated with ethylene glycol.

Both samples were analyzed on a Philips X-ray diffractometer at the University of Montana. Experimental parameters on the diffractometer are as follows:

- 30 Ma, 20 Kv, time constant = 2, range = 500
- 2θ angles: 35 to 2°, 1°-1° slits, strip chart speed: 0.5"/minute
- Goniometer speed: 1°/minute

X-ray diffraction patterns were digitally recorded (Figures 34 and 35) and analyzed using NEWMOD.
Results

X-ray diffraction patterns were produced for each sample.

Figure 34 - Digital X-ray diffraction pattern of sample U.

Figure 35 - Digital X-ray diffraction pattern of sample Ag.
The uranium-bearing vein shown in Figure 34 contains a mixture of discrete iron-rich chlorite and mixed iron-rich chlorite-smectite layers. This mixture implies two hydrothermal events: the first event probably formed discrete chlorite and the second probably formed the mixed chlorite-smectite layers. NEWMOD modeling indicated that the chlorite-smectite layers were composed of approximately equal chlorite and smectite components with R1 ordering.

The silver-bearing vein shown in Figure 35 contains a clay fraction with a 10Å peak, indicating a content of either an iron-rich illite or a di-octahedral mica (muscovite or sericite). Petrographic examination previously revealed that sericite is a common minor constituent of the silver-bearing veins, and therefore probably constitutes the clay fraction of the sample.

The presence of a single mineral in the clay fraction of the silver-bearing veins indicates that the veins underwent a single hydrothermal event. The uranium-bearing veins contain a mixture of two discrete clays and were therefore subjected to two different events. The second event may have been related to the introduction of silver-bearing ore fluids, and/or could have affected the lead isotopic composition of the veins. Addition of older Pb during this event could have produced a concordia date of 885 Ma; alternately, a Pb loss may have affected the uranium minerals and produced a discordia date of 82 Ma.