UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

VOLCANOGENIC CHARACTER OF SEDIMENT-HOSTED Co-Cu DEPOSITS IN THE BLACKBIRD MINING DISTRICT, LEMHI COUNTY, IDAHO--AN INTERIM REPORT

by

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Open-File Report 86-430

1986

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ABSTRACT

Cobalt-copper deposits of the Blackbird district are stratabound in quartzites and siltites of the Proterozoic Yellowjacket Formation, but display volcanogenic associations not evident from the regional geology. Recent exploration in the district documents the existence of at least 12 Co-Cu deposits within seven sequences rich in mafic tuff in a 1,000-m-thick middle part of the Yellowjacket. The deposits are in local sub-basins created by a combination of growth faults and clastic wedges. Cobalt-copper lodes are intimately associated with sequences rich in Fe-Si-Al-K that formed from tuffaceous and exhalative eruptions that are abundant only in a 10 km^2 area around the Blackbird mine. Arsenic-rich lodes of the Blackbird-type display variable degrees of metamorphism, shear, and redistribution. Pre-metamorphic, synsedimentary stages of ore deposition are preserved in the newly drilled Sunshine and Merle lodes that suffered little penetrative deformation.

The Sunshine lode is a 1- to 3-m thick layer contained within tuffaceous and siliceous beds interpreted to be chiefly exhalative. These beds contain prominent almandine garnet and chloritoid, along with biotite, muscovite, and minor clastic quartz. Tourmaline is abundant in some beds. Cobaltite occurs as the only ore mineral in fine laminations with quartz or biotite. Copper as chalcopyrite is erratically present and generally separated by mm to meters from cobaltite layers. Gold is a significant constituent and is associated with cobaltite. There is no significant ore-associated alteration in hangingwall or footwall rocks.

The Merle zone contains eight vertically stacked lodes that are coextensive with tuffaceous units 5 to 30 m thick. Some cobaltite is finely layered in biotite-rich beds, similar to the Sunshine exhalative ores, but most Co-Cu minerals are in cm- to m-scale disrupted zones that cut host rocks but do not extend into enclosing sand and silt beds. The disruption zones are filled by a swirled matrix of transported sand and clastic fragments cemented by relatively coarse grained quartz, siderite, biotite, muscovite, cobaltite, chalcopyrite, and pyrite (probably derived from pyrrhotite). The disruption zones appear to have formed in partly lithified rocks by fluidization, possibly induced by explosive geothermal eruptions and augmented by dewatering of underlying muddy sediments. Some early formed cobaltite may have been mechanically transported into the disruptions.

The Blackbird lodes are unusually rich in Fe, As, Bi, Au, as well as Co, compared with most clastic-hosted sulfide deposits. Mafic igneous rocks are a likely source of most of the ore metals; enrichment of Co>Ni possibly was caused by selective extraction and transport of Co in the submarine geothermal system below about 350°C. The Fe-rich composition of silicate minerals and rocks possibly reflects low sulfur activity and deposition from upwelling geothermal fluids similar to those known in modern "black smokers". Metamorphism remobilized chalcopyrite at mm- to m-scales, and changed silicate mineralogy, but seems to have had little effect on cobaltite and on bulk compositions of lodes that were not highly sheared.

INTRODUCTION

Cobalt-copper deposits of the Blackbird district are stratabound in clastic rocks of the Middle Proterozoic Yellowjacket Formation in a setting that is similar to many of the sediment-hosted deposits in North America, Europe, and Africa. However, some district- and smaller-scale features of sedimentation and geochemistry distinguish these deposits from most others and are keys for exploration models. The Blackbird ores are polygenetic in that geologic processes at several times have combined to create the present ore lodes, but in our opinion synsedimentary processes were crucial and must be considered for proper evaluation of these ores. Mafic volcanism and the associated submarine geothermal system that drove the initial stages of Co-Cu deposition will be emphasized here, although we recognize that other sedimentary-diagenetic processes also were important.

The Blackbird mine is in the eastern Salmon River Mountains of Lemhi County, Idaho, about 35 km west of Salmon (Fig. 1). The location is 114°21' west longitude, 45°08' north latitude. The area is characterized by steep-walled canyons and heavy conifer forest. There is about 2 percent outcrop.

Exploration and mining activity in the Blackbird district has been episodic, driven largely by gold prices and incentives for strategic metals. The area first drew attention for gold deposits in 1893. Cobalt was discovered in 1901, and claims were staked along Blackbird Creek, but there was little demand for cobalt until World War I. From 1917 to 1920 the previously recognized deposits were mined for about 9 tonnes of cobalt (Vhay, 1948). A zone at the south end of the Blackbird mine was mined for Cu-Ag-Au from 1938-1941 but drew a penalty for Co. In response to the need for strategic metals in World War II, the U.S. Geological Survey and U.S. Bureau of Mines explored the district in conjunction with Calera Mining Company, and outlined the Brown Bear, Chicago, and other lodes. Production from the Blackbird mine, chiefly between 1951 and 1959, totaled 6,350 tonnes Co; average grades were about 0.6 percent Co and 1.5 percent Cu. Operations ceased in 1960 with the loss of a government contract for cobalt, decreased copper prices, and competition from foreign cobalt suppliers.

From 1978 to 1982 Noranda Exploration Inc. reevaluated the district for additional reserves to support a new mine-mill complex. Noranda geologists recognized the stratabound character of mineralization, and associations with tuffaceous strata and specific styles of sedimentation (Hughes, 1983; Hahn and Hughes, 1984). Many Co-Cu prospects were known in the mine area from the 1950's, including some with favorable drill intercepts. The size of the prospects had been underestimated because of incorrect geologic interpretations that ore was emplaced in post-metamorphic shear zones. The Noranda exploration program defined 5.0 million tonnes mining reserves and 7.3 million tonnes indicated reserves, and located many new prospective lodes. Ore lodes were intersected in more than 75 percent of drill holes. The exploration model was effective, but economic conditions in the 1980's have prevented mine development.

This report presents a small part of the information gained during Noranda's exploration program, and preliminary results of USGS studies of the geochemistry of ore formation. Discussions here are based in part on unpublished chemical analyses of 312 samples of drill core; analyses for major elements were made by X-ray fluorescence (XRF), and 44 major and minor elements were determined by induction coupled plasma spectrometry (ICP). We thank J. E. Taggart, A. J. Bartel, P. H. Briggs, J. G. Crock, and others of the USGS for their assistance with analytical chemistry. We acknowledge the careful and creative work by many Noranda geologists, and cite especially the insights of G. J. Hughes, Jr., L. S. Sobel, M. D. Daggett, K. D. Loos, and G. Toth. We also appreciate discussions with J. J. Connor and K. V. Evans, USGS.

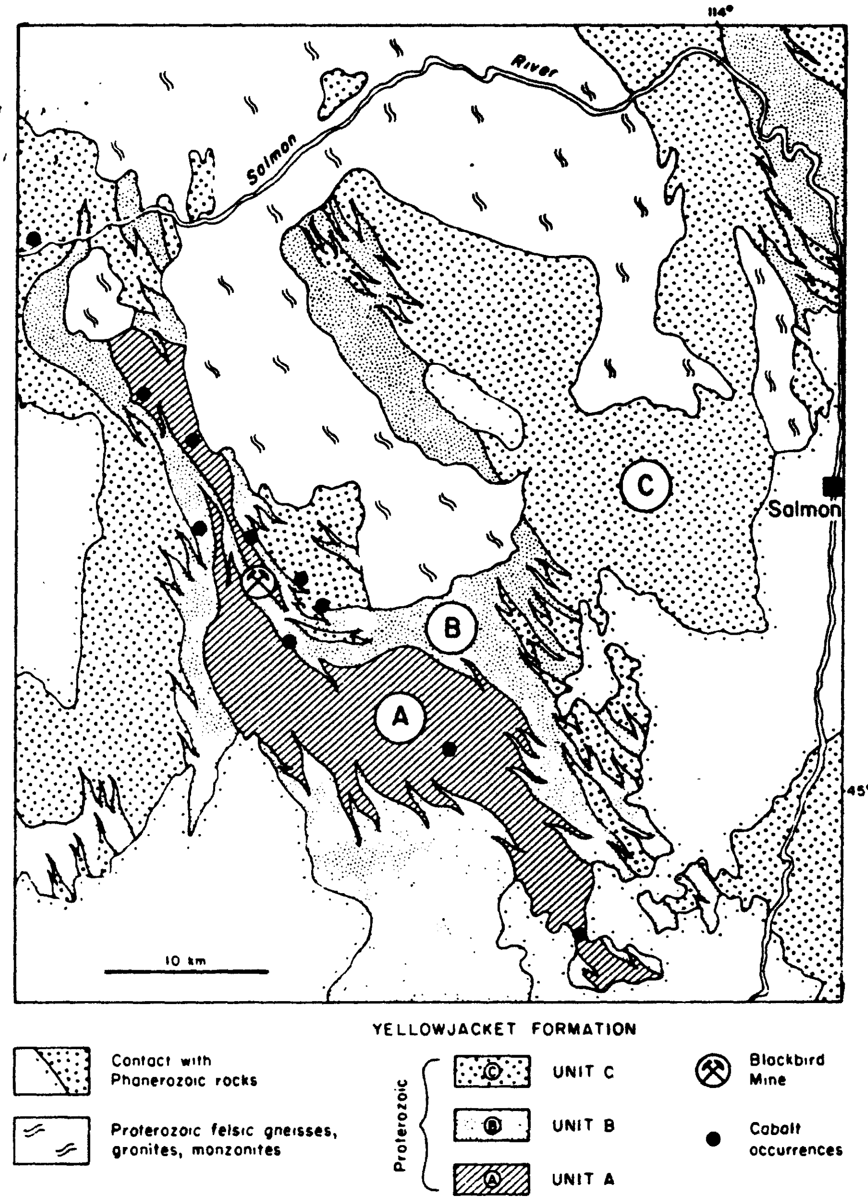


Figure 1. Location and generalized geology of the Idaho cobalt belt, Lemhi County, Idaho. From Hahn and Hughes (1984).

GEOLOGIC SETTING

Cobalt-copper deposits of the Blackbird district occur in clastic rocks of a Middle Proterozoic rift basin, about 150 km south of the better known Belt basin of Montana and Idaho. The deposits are stratabound within fine-grained clastic, volcaniclastic, and tuffaceous rocks that comprise only a small part of the Middle Proterozoic Yellowjacket Formation. Four thermal events may have influenced the Blackbird ores: (1) submarine geothermal system associated with Yellowjacket volcanism; (2) pre-1,370 m.a. regional metamorphism to biotite grade (Evans and Zartman, 1981); (3) regional metamorphism associated with 1,370 m.a. granitic plutons (Evans and Zartman, 1981); and (4) Cretaceous-Tertiary metamorphism associated with the Idaho Batholith that crops out 10 km to the west.

Stratigraphy

The Yellowjacket Formation in east-central Idaho is the oldest sedimentary unit in a Proterozoic section that is at least 15,000 m thick (Ruppel, 1975). Regionally, and in the mine area, three lithostratigraphic units can be distinguished (Hughes, 1983; Connor et al., 1985) (Fig. 1). The lower unit, more than 3,000 m thick, is predominantly gray-green phyllite and siltite with lesser amounts of fine quartzite and impure carbonate. Sedimentary features suggest deposition in a deep marine basin by turbidity currents as basin plain and distal turbidite deposits. The upper part of the lower unit contains some coarser clastics (fine-grained quartzite). No Co-Cu deposits of the Blackbird-type occur in the lower unit.

The middle unit, about 1,200 m thick, is economically most important as the host for the largest Co-Cu deposits (Fig. 2). The middle or B unit of Hughes (1983) is a complex of coarsening upward cycles of argillite, siltite, and fine quartzite, and contains distinctive interbeds of biotite-rich rock interpreted to be aquagene mafic tuffs. Zircon from a tuff in the middle unit yielded apparent U-Pb ages of about 1,670-1,700 m.a. (Hahn and Hughes, 1984), which should be considered to be maximum ages because of possible inherited radiogenic lead (K. V. Evans, written commun., 1986). Sedimentary structures are abundant in this unit and include graded beds, silt-sand couplets, flute casts, load structures, slumped beds, and sand dikelets or volcanos (Fig. 3A). These clastics were probably deposited in a submarine fan complex.

Biotite-rich rocks interpreted to be mafic tuffs are common in the middle unit (Fig. 2). Biotite schists were identified by many geologists in the 1940's and 1950's, but their importance was first recognized by Noranda geologists in 1978. Individual tuff beds are 1 to 20 cm thick. Their continuity on strike is not well known because of poor outcrop, but packages of tuff beds interbedded with siltite or quartzite (collectively 2 to 10 m thick) can be correlated between drill holes about 100 m apart. No textures or structures such as pillows have been recognized to suggest the presence of flows. Thus, these volcanic rocks do not have the features of some thick sequences of thick-bedded pyroclastics, aquagene tuffs, and interbedded pillow lavas (Carlisle, 1963; Fiske, 1963). The original character of the tuffs is masked by recrystallization to massive or weakly laminated rocks with more than 75 percent biotite (or biotite plus garnet, Fig. 3B-D), and some beds contain only a few percent clastic quartz. The high content of iron, and in places silica and boron (Fig. 3E), suggests that part of the material was chemical sediment. It is possible that the original tuff was a mixture of glassy fragments, clay, and gelatinous chemical sediments. Some argillites

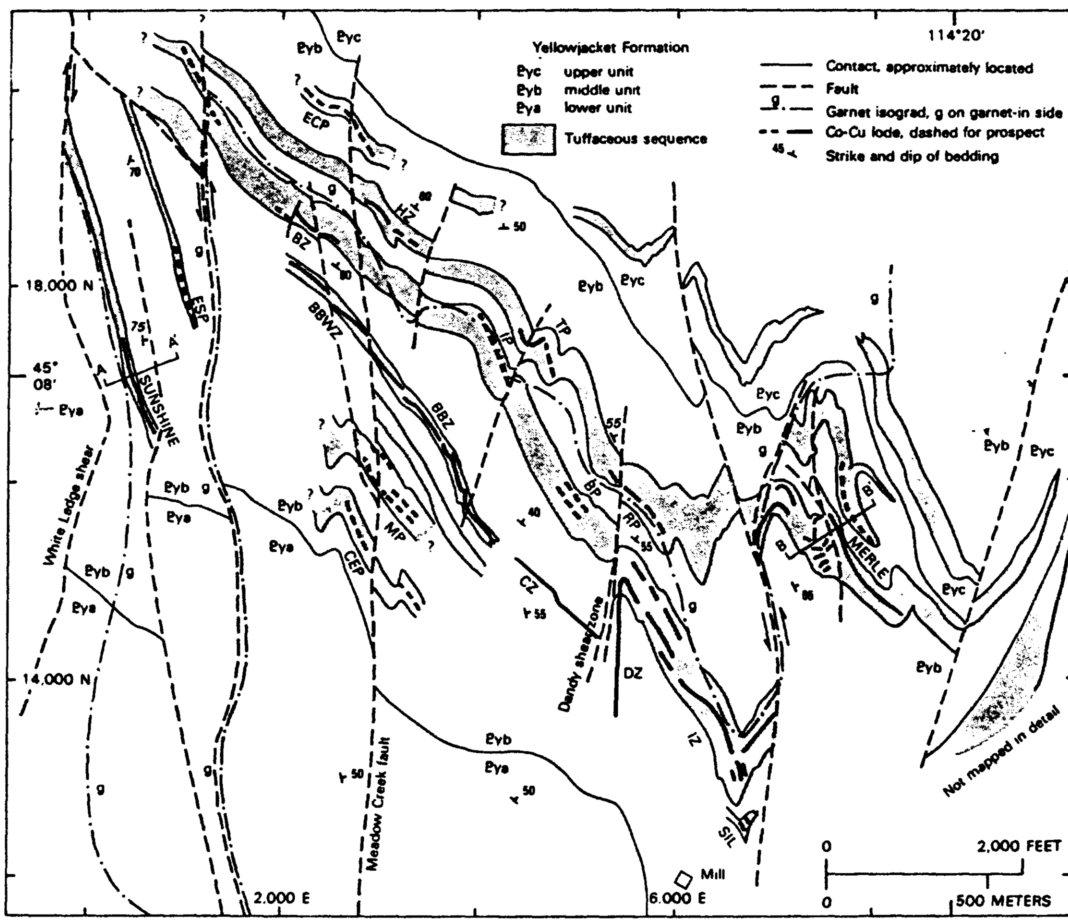


Figure 2. Generalized geology of the Blackbird mine area, showing the location of Co-Cu lodes and prospects (generalized from unpublished mapping, Noranda Exploration, Inc., 1982).

Abbreviations: BZ, Blacktail zone; BBZ, Brown Bear zone; BBWZ, Brown Bear West zone; BP, Buckeye prospect; CZ, Chicago zone; CP, Chelan prospect; CEP, Catherine-Ella prospect; DZ, Dandy zone; ECP, East Chelan prospect; ESP, East Sunshine prospect; HZ, Horseshoe zone; IZ, Idaho zone; IP, Iowa prospect; MP, Mushroom prospect; RP, Ridgetop prospect; SIL, South Idaho lode; TP, Toronto prospect.

resemble meta-tuffs, although argillites typically have finer, shreddy metamorphic biotite, graded beds, and are distinct from tuffs in thin sections. Tuffs generally have sharply defined bedding contacts with adjacent clastic beds, and are only vaguely laminated. Another criterion for defining tuffs or tuffaceous packages is elevated content of cobalt in soil samples, as first found by Canney et al. (1953) in geochemical surveys. The tuff packages, in part identified by soil geochemistry, are useful district scale map units (Fig. 2) and provide the best markers for structure.

The upper unit of the Yellowjacket in the mine area is more than 1,000 m thick and is typically distinctive quartzite with thick beds and planar laminations. Interbeds of fine clastics are rare and there is very little tuffaceous component. Cross-beds and ripples are the most common sedimentary structures. Sedimentation probably was in a mid-fan or shallow marine shelf, although some hummocky beds probably reflect shallow water wave action. No subaerial or intertidal environments are recognized in the mine area.

Mafic dikes and sills intrude the Yellowjacket and seem to be most abundant in the middle unit. The dikes generally have north-to-northwest strike. Only the thickest dikes crop out, but dikes 1 to 10 m thick are commonly seen in drill core and mine workings. The dikes are dark green to black and faintly porphyritic despite being metamorphosed to fine-grained, granular aggregates of biotite, zoisite, plagioclase, siderite, and minor quartz (Fig. 3F). Some gray dikes have equal amounts of plagioclase and mafic minerals. In places, the dikes seem to grade into mafic tuffs, and the chemical composition of tuffs and dikes is very similar. The dikes are thought to be coeval with tuffs and probably were feeders for tuffs and possibly were conduits for hydrothermal fluids.

Other Proterozoic clastic rocks, probably more than 9,000 m thick, overlie the Yellowjacket Formation in central Idaho. None of these units are present in the mine area (Fig. 2).

Proterozoic granitic rocks intrude the Yellowjacket about 3 km north and east of the Blackbird mine (Fig. 1). The granitic rocks generally have large K-feldspar phenocrysts and some have gneissic fabric. Samples from various phases of the large body yield discordant Rb/Sr ages of about 1,500 m.a. (Armstrong, 1975) and zircons yield a more reliable U-Th-Pb age of 1,370 m.a. (Evans and Zartman, 1981). Metamorphic grade increases toward the intrusive body, reaching a maximum grade of hornblende-cordierite-sillimanite in the contact zone.

Tertiary volcanic rocks of the Challis volcanic field cap some ridges about 5 km from the mine. Tertiary mafic and felsic dikes fill some fault zones and intrude the Yellowjacket in the mine.

Structure

Poor outcrop and paucity of reliable marker units hamper regional mapping of structure, although in the mine area tuffs are good markers. Presence of shear foliation often is used to map fault or shear zones, but offset rarely can be determined. The dominant structural features of the area are north-to-northwest-striking faults and shear zones. One of the largest of these, the White Ledge, appears to have substantial strike-slip movement and marks the western limit of tuffaceous strata in the mine area (Fig. 2). The garnet isograd is influenced by some of the N-trending faults, indicating post-metamorphic vertical displacement. Good structure descriptions were provided by Vhay (1948) who mapped in detail during early mining and drilling activity, chiefly along the Chicago-Brown Bear Co-Cu zone (Fig. 2). The apparent

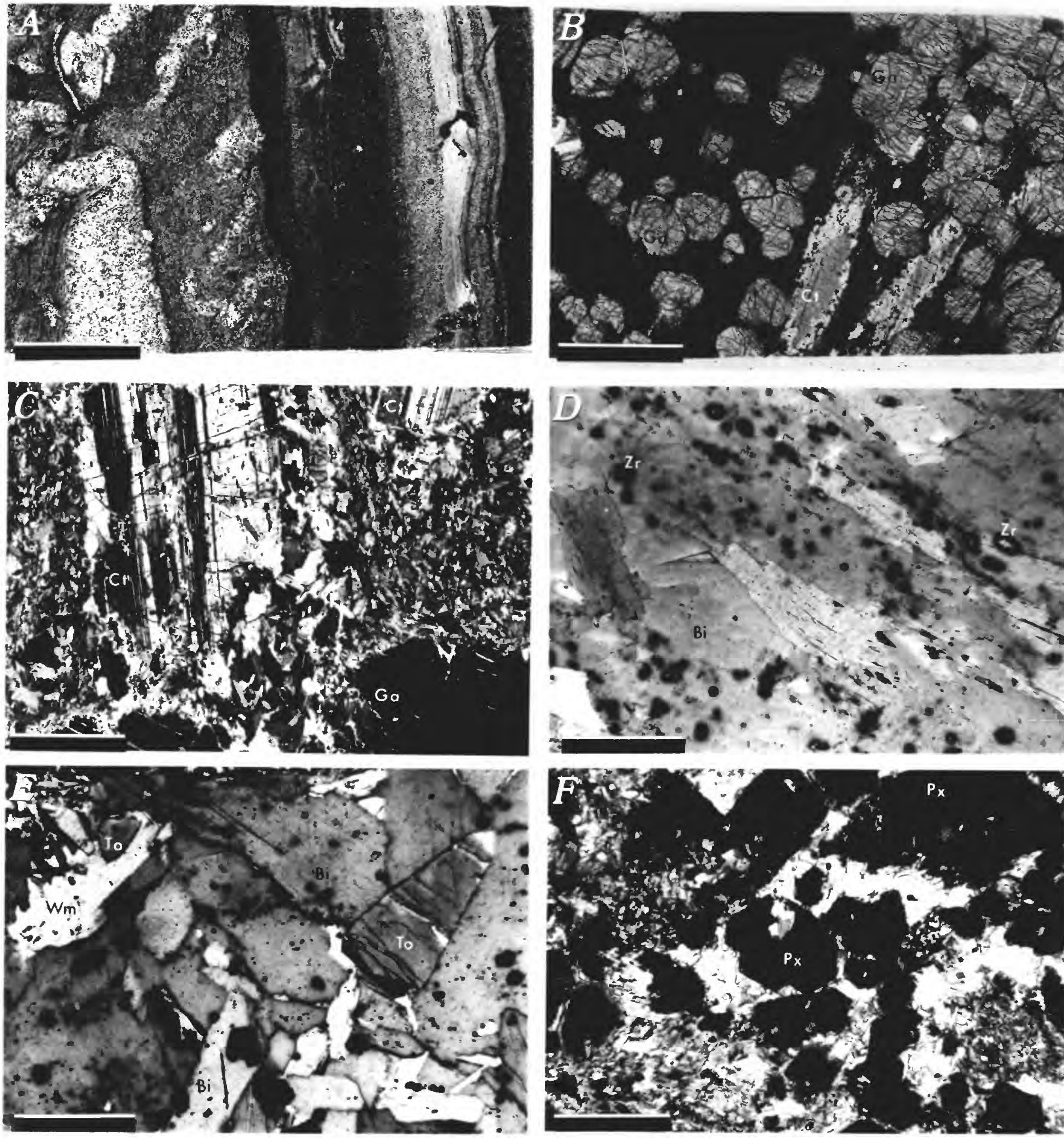


Figure 3. Photomicrographs of rock textures; all in transmitted light. (A) Graded bedding and sand injection structures in typical laminated siltite-quartzite; scale is 1 cm; (B) Garnet (Ga), biotite, and chloritoid (Ct) in granular rock derived from tuff, Sunshine lode; scale is 1 cm; (C) Garnet (Ga), chloritoid (Ct, twinned), biotite granofels; scale is 500 μ; crossed polarizers; (D) Biotite-rich bed derived from tuff with abundant zircons (Zr) that have pleochroic halos; scale is 200 μ; (E) Granular biotite (Bi) tourmaline (To)-white mica (Wm) derived from tuff-exhalite; scale is 200 μ; (F) Massive textured dike with altered pyroxene (Px) phenocrysts and biotite-rich matrix; scale is 500 μ.

Author's note: These copies of photomicrographs may not show all details in original photos, but the general textural features are displayed and are understandable.

association of Co-Cu ore zones with shear zones up to 30 m wide led Vhay and other geologists in the 1940's and 1950's to propose that ores formed by replacement of sheared rocks. Faults that deviate from the northerly trend tend to have little associated shear-foliation and several such faults offset Co-Cu lodes. Folds of many scales are present. Some tight folds are near N-trending shears and seem to be produced by drag. Other folds are associated with areas of soft-sediment deformation and are interpreted to be slump folds. The generally coherent stratigraphy of the region and mine area suggests that blocks are rotated between major faults, but not repeated by folding.

Synsedimentary structural activity is suggested by many varieties of soft-sediment deformation, slump folds, and local facies changes across growth faults. Local changes in abundance and thickness of sandy units appear to reflect clastic wedges from local sources; these features are evident in drill core and mine workings as aberations from the general lithostratigraphy of the area. Many features--such as disrupted bedding, loss of bedding, breccias with mixed round, angular, and bent fragments, sand dikelets, and compaction foliation parallel to axial planes at postulated slump folds--indicate deformation prior to total lithification. Zones of soft-sediment deformation contain much of the Co-Cu ore in the Merle zone, described below. The early, synsedimentary structural activity along N-trending basin growth faults, and associated mafic volcanism, is considered to be a key to emplacement of the Co-Cu lodes (Hughes, 1983).

COBALT-COPPER DEPOSITS

Three general types of Co-Cu deposits are recognized in the Yellowjacket Formation. (1) The most important are those of Blackbird mine type described here. These consist of approximately equal amounts of cobalt and copper minerals, generally cobaltite (CoAsS) and chalcopyrite, and variable gold and pyrite content, in stratabound lodes in close association with tuffaceous rocks. These deposits and prospects are shown on Figure 2. (2) Cobaltiferous-pyrite deposits, with variable chalcopyrite content, as at Iron Creek where lodes occur in fine clastics of the middle unit of the Yellowjacket Formation. These deposits contain abundant pyrite of very fine to coarse grain size, and zones rich in magnetite; both pyrite and magnetite are reworked and redeposited in zones of soft-sediment deformation. Dikes and volcaniclastic rocks, possibly similar to those at the Blackbird mine, are present but not abundant. (3) Cobaltite-bearing, tourmaline-cemented breccias are common in the lower unit of the Yellowjacket Formation for many kilometers south and east of the Blackbird mine. Only a few contain more than 0.1% Co. Included fragments of carbonate and mafic igneous rocks, not known in the immediate area, suggest explosive emplacement. Destruction of sedimentary structures in and around the breccia zones suggests formation prior to lithification.

Although these Co deposits differ, they share some common features: (1) they occur in the same general part of the Yellowjacket Formation; (2) they appear to have formed during or shortly after sedimentation; and (3) their locations seem to be related to N-trending basin growth faults (Hughes, 1983). All are interpreted to be stratabound, although many features indicate epigenetic formation, and there is variable degree of later redistribution.

The Blackbird mine produced ore from five zones known as the Idaho, Dandy, Chicago, Brown Bear, and Blacktail (Fig. 2; Vhay, 1948; Bennett, 1977). Recent mapping (Figs. 2 and 4) indicates that the lodes mined were in two different tuffaceous sequences, and that the Dandy zone is discordant to

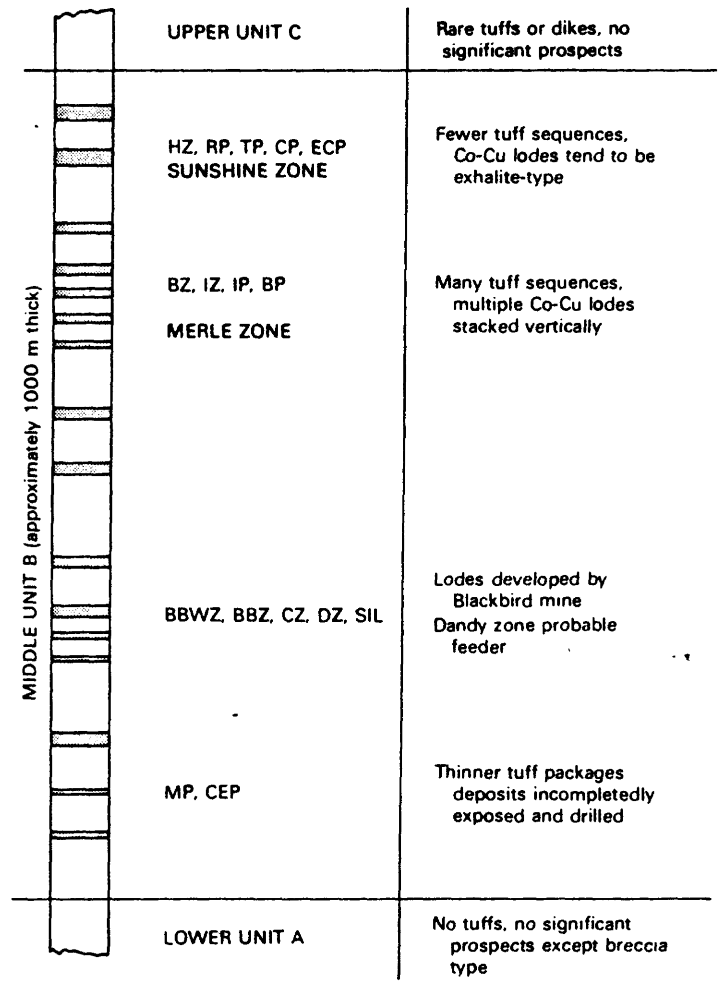


Figure 4. Schematic diagram of tuffaceous sequences and associated Co-Cu lodes in middle unit of Yellowjacket Formation in the Blackbird mine area. Abbreviations same as for figure 2.

the tuffaceous sequences. Rocks exposed in the Blackbird mine are locally sheared across widths of tens of meters (Vhay, 1948). The Dandy zone, notably discordant and not in tuffaceous rocks (Fig. 2), is uniquely rich in pyrrhotite and seems to be an epigenetic feeder zone for overlying stratabound lodes. Evidence for pre-metamorphic deposition of ore minerals can be found in less-deformed parts of the Blackbird mine, and particularly in outlying, little deformed zones such as the Sunshine and Merle (Fig. 2).

A unifying feature in more than a dozen Co-Cu lodes, but excluding the Dandy zone, is the intimate association with tuffaceous sequences (Figs. 2 and 4). Some of the sequences contain several Co-Cu lodes on strike, and some contain as many as eight stacked lodes, each in a tuffaceous package--as will be described later in the Merle zone. The tuffaceous sequences are time-stratigraphic markers, and the Co-Cu deposits are probably at least partly time equivalents. At all scales, from district to bed, the tuffs and Co-Cu lodes are unique markers of time and chemical processes during basin evolution.

Ore minerals observed in the Blackbird deposits are chiefly cobaltite, chalcopyrite, and pyrite. Small amounts of safflorite ($CoAs_2$), arsenopyrite (FeAsS), pyrrhotite, linnaeite (CO_3S_4), native silver, enargite, sphalerite, and galena were observed by Vhay (1948) and Anderson (1947). Gold is present in amounts up to about 0.1 oz/ton as native gold and would be a significant byproduct of some lodes. The wide variation in Co: As in assays suggest the presence of other Co-As or Co-S minerals, such as safflorite and linnaeite that were identified in Blackbird ores. Microprobe analyses indicate 1 to 8 percent Co in arsenopyrite, pyrite, and pyrrhotite from the Blackbird mine.

Non-metallic minerals present include biotite, quartz, garnet, tourmaline, muscovite, chloritoid, apatite and siderite. Clastic feldspars are common in most sandy beds, but are rare in ore lodes. Tourmaline is very fine-grained and dark blue to green-brown in thin section. Microprobe analyses to date indicate Fe:Fe+Mg in the range 0.4-0.8. Siderite, identified by scanning electron microscope-energy dispersive analysis (SEM/EDS), is present in tuffs, in premetamorphic disruption features, and in post-metamorphic gash fractures. Red garnet is abundant in many areas of higher-grade metamorphism, and a pinker garnet is present in some Co-Cu lodes. Several types of micas are present. Black biotite (Z = dark to medium green) tends to be more typical of tuffs and ore lodes; the grains are relatively coarse (100-500 μm), tabular, and randomly oriented. Prominent books of white mica are present in many tuffs and ore zones as coarse grains (100 to 1,000 μm) intergrown with coarse quartz, biotite, or garnet. Although some rocks look chloritic (bright to medium green), chlorite is relatively rare in thin sections. Retrograde chlorite commonly replaces garnet, but rarely replaces biotite. Preliminary semiquantitative SEM-EDS analyses of biotite and chloritoid indicate high content of Fe, and low Mg and Mn for a Fe:Fe+Mg+Mn about 0.9, about the same as that of the bulk rock. Garnets from some ore lodes have high Fe and Al, and low Ca, Mg, and Mn, thus are almandine.

Sunshine Lode

The Sunshine Lode is located 1 km west of the Blackbird mine in an area of N-trending faults (Fig. 2). The deposit is in tuffaceous rocks metamorphosed to biotite, garnet, and chloritoid. The area has been prospected several times, and the lode was intersected by one drill hole in the 1950's. Cobaltite was found at the surface and subsequent trenching defined the trace of the lode. Geometry of the lode was defined by drilling of 31 more holes from 1979 to 1981; 26 of the holes intersected the lode. Cobalt and copper minerals occur in a single lode that ranges up to 3.0 m thick, strikes consistently N 10° W and dips 70° east (Fig. 5). The measured length of the lode exceeds 550 m; the south end is cut off by a fault, and the north end is open down plunge. The footwall sequence is thinly laminated phyllite and argillite, with some zones of intense shearing, and the hangingwall is mostly biotitic quartzite. The lode itself, along with a few meters of enclosing rocks, is generally a garnet-rich (20-50%), biotite granofels with minor clastic quartz. Streaks and layers of fine-grained sugary quartz are a few mm to 10 cm thick.

The Sunshine lode contains very little pyrite and the copper (chalcopyrite) content is lower than most of the Blackbird-type lodes. Cobaltite occurs as fine euhedral crystals (20 to 100 μm in size), generally in trails or layers that are conformable with layering in biotite or silica (Fig. 6). Copper content is erratic, and often less than 0.1% in Co-rich intercepts, but the north end of the deposit contains more than 1 percent copper. Chalcopyrite generally has a ragged or lacey morphology, and when present with cobaltite appears to engulf it, suggesting later deposition or remobilization of chalcopyrite.

Current information, chiefly from drill core, leads us to conclude that the Sunshine lode formed as a siliceous-tuffite exhalite. Most of the lode contains relatively little clastic quartz. The granular rocks seem to be a recrystallized mixture of chemical sediment and tuff. Some parts were quite siliceous or cherty (now quartz), others were richer in Fe-Mg-Al tuffite (now garnet, chloritoid, and biotite). Chemical analyses show enrichments in boron to more than 1,000 ppm over a 0.3 to 0.6 m thickness, and thin sections show layers rich in tourmaline (Fig. 3E, 6C). Chemical analyses, summarized in Table 1, show that both As and Au correlate strongly with Co, and some scattered Co-rich intercepts are rich in rare earth elements (REE). Proximity to thermal sources or vents may be indicated by parts of the lode with higher Co:As, more total Co (computed as ft.% Co), as well as more abundant silica and gold. Fringes of the lode seem to have a higher Co:Cu ratio, and more abundant Mg relative to silica.

Merle Zone

The Merle zone of multiple Co-Cu lodes is 1 km east of the Blackbird mine (Fig. 2) in a sequence of tuffaceous rock equivalent to the Idaho and Blacktail zones at the mine. Geochemical exploration of this area in 1951 by the USGS and Northfield Mines Inc. (Canney et al., 1953) resulted in the discovery of three NW-trending Co anomalies in the range 100 to 600 ppm. Subsequent trenching and drilling found cobalt lodes related to the geochemical anomalies. One lode (Merle 5) was found to contain good Co and Cu grades in a zone 7 to 15 m wide and approximately 725 m long, but could not be developed in the late 1950's. Seven drill holes and many trenches tested the Merle 3 zone, and two holes intercepted significant Co-Cu mineralization in "biotite schist", but the results were interpreted as indicating small discontinuous pods. In 1980, Noranda initiated detailed geochemical and mapping studies, confirmed the very strong Co anomalies, and reinterpreted the Co-rich lithologies as mineralized mafic tuff that matched their exploration model. Diamond drilling in 1980-1981 was directed at tuffaceous packages in the Merle 3 zone, and 23 of 26 holes intersected one or more lodes. As suspected from reinterpretations of relations in the Blackbird mine, multiple lodes were intersected. As many as eight lodes are stacked in a stratigraphic

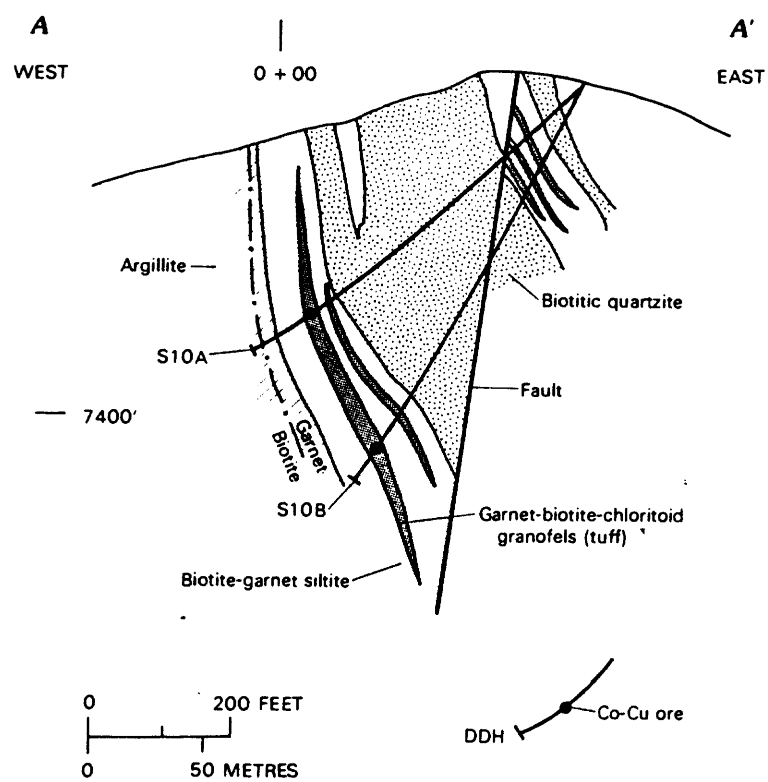


Figure 5. Geologic cross section of the Sunshine lode.

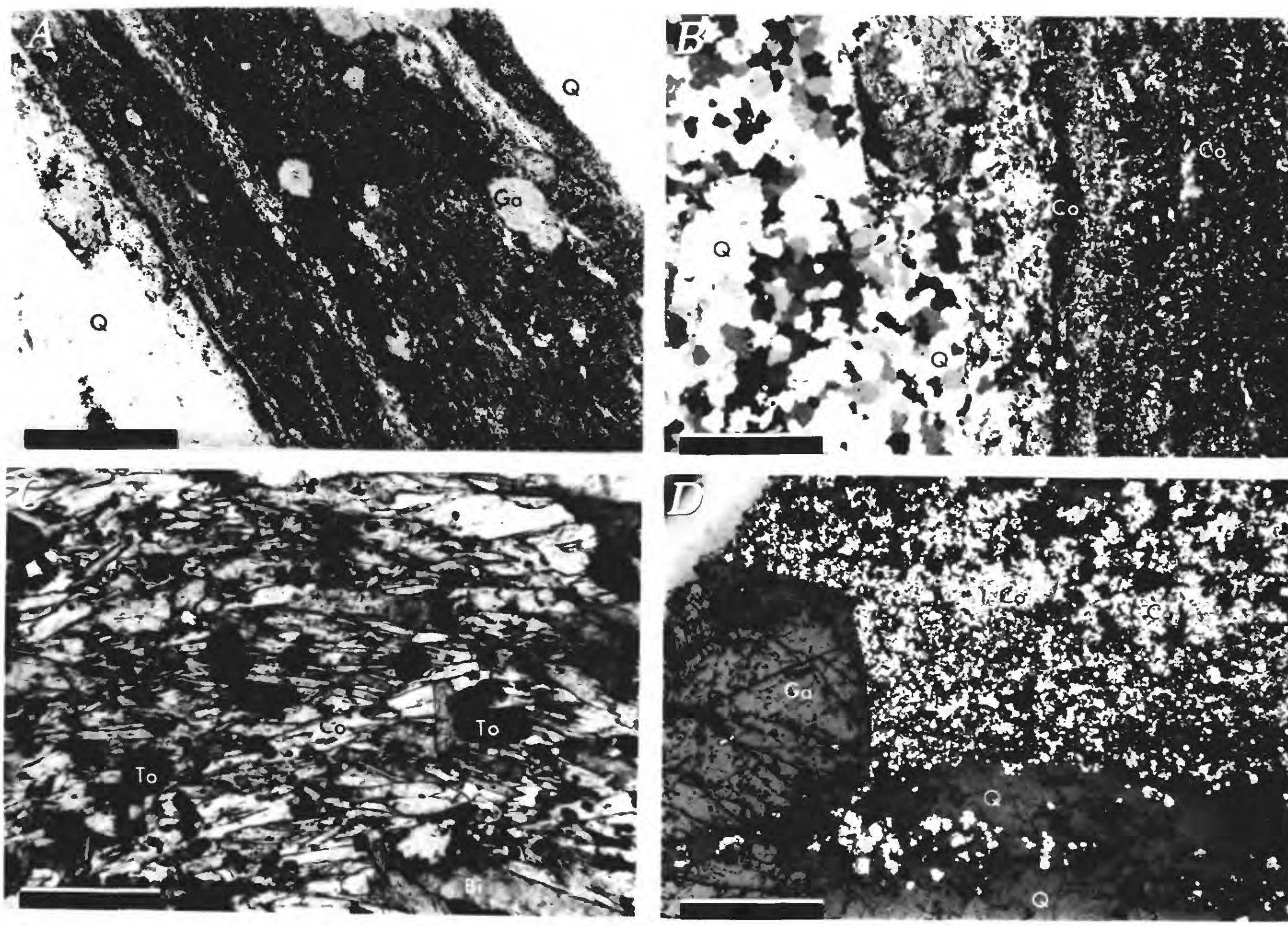


Figure 6. Photomicrographs of ore samples from Sunshine lode. (A) Stratiform fine-grained quartz (Q) and cobaltite (Co) with scattered porphyroblasts of garnet (Ga); most of the opaque grains are cobaltite; scale is 1 cm. (B) Enlargement of A showing granular quartz (Q) and laminated cobaltite (Co) in biotite-rich layer; scale is 500 μ. (C) Biotite-rich layer with fine cubes of cobaltite (opaque) and tourmaline (To); scale is 500 μ. (D) Cobaltite (Co) layer interupted by garnet porphyroblast (Ga); scale is 500 μ, reflected light.

Author's note: These copies of photomicrographs may not show all details in original photos, but the general textural features are displayed and are understandable.

thickness of 170 m (Fig. 7), with individual lodes as thick as 4.1 m. The best of the lodes, called the "B lode", has a length of at least 500 m, and a width (down dip) of about 200 m (Fig. 7). The lodes are in biotite-rich packages, conformable with enclosing quartzites and sandy argillites. Grades range up to 1.9% Co over a true thickness of 1.7 m and 3.6% Cu over 3.3 m, and pyrite content is much higher than in the Sunshine lode (5 to more than 20 percent). Two types of ore are recognized: (1) stratiform-type with fine cobaltite >> chalcopyrite (probably syngenetic), and (2) disruption-type with chalcopyrite and pyrite > cobaltite in disruption features between unbroken competent beds (epigenetic).

Lithologies, ore textures and mineralogy, and chemistry are very similar among the stacked Co-Cu lodes. There probably is as much variation within individual lodes as there is between the eight lodes. The B lode has been studied most because of its larger size. In the B lode, as well as others, Co-Cu minerals are consistently within biotite-rich beds and do not extend into hangingwall or footwall argillites or quartzites except for some cm-size chalcopyrite stringers in the footwall within a few meters of Co-Cu lodes. Hangingwall and footwall rocks 1 to 10 m from ore are normal, well-laminated fine clastics with no unusual mineralogical features. Particularly notable is the lamination in footwall and hangingwall rocks, typical of the Yellowjacket, with well preserved primary structures such as graded beds, load structures, and sand dikelets. The biotite-rich tuffaceous rocks that host the Co-Cu minerals are markedly different from enclosing rocks in their darker color, faint color contrast between beds, or a total absence of bedding and primary features. Although some laminated beds a few centimeters thick are present, most ore is in biotitic rocks with massive to swirled or brecciated fabric. The breccias generally have rounded pebble-sized fragments of gray argillite or fine tuff with a matrix of coarser biotite, muscovite, granular quartz and siderite (Fig. 8). Cobaltite and chalcopyrite most commonly occur in the matrix, although some fragments contain fine cobaltite that resembles laminated cobaltite exhalite in the Sunshine lode.

Laminated fine cobaltite in layers parallel to siliceous and tuffaceous layers (Fig. 8A) resembles that found in the Sunshine lode. Finely laminated cobaltite generally is found on the upper meter of ore lodes. Some fragments in disrupted zones seem to be this laminated-type cobaltite (Fig. 8F). Although the evidence from drill core does not permit evaluation of the amount of syngenetic exhalative-type cobaltite in the Merle zone, we believe it likely that much of the cobalt in disruption features was chemically or mechanically reworked into those structures from nearby sites.

The disrupted zones in tuffaceous strata that carry most of the Co-Cu minerals in the Merle lodes are complex soft-sediment structures. Intersections in diamond drill core 5 cm in diameter provide clear but incomplete exposures of the features. In drill core, most of the disruptions seem to be less than a meter thick and confined between unbroken quartzite or sandy argillite layers. Some disruption zones cut beds at approximate right angles. In many drill intersections most of the lode is disrupted rock composed of several meters of unbedded, swirled, and mixed clastic material with biotite, muscovite, siderite, and quartz matrix and just a few unbroken quartzite beds. One drill hole that intersected the low grade fringe of the B lode displayed more than 25 disrupted zones 1 to 30 cm thick in a 30 m section of interbedded siltite, quartzite, and tuff; visible Co-Cu minerals were restricted to the disrupted zones in tuff or silt. The disruption features are incompletely understood, but several characteristics provide constraints on possible mechanisms of formation. (1) They contain mostly mechanically

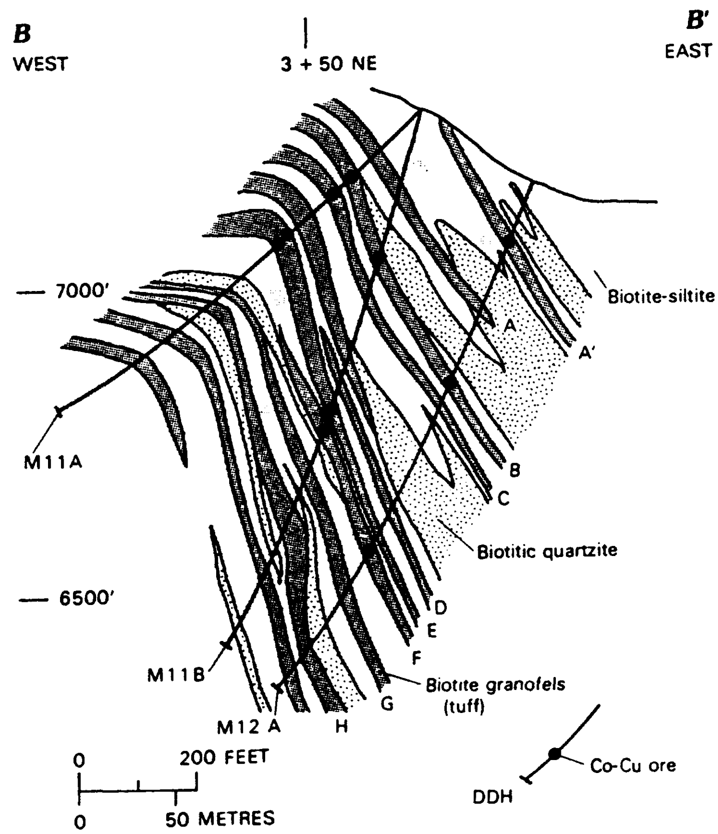
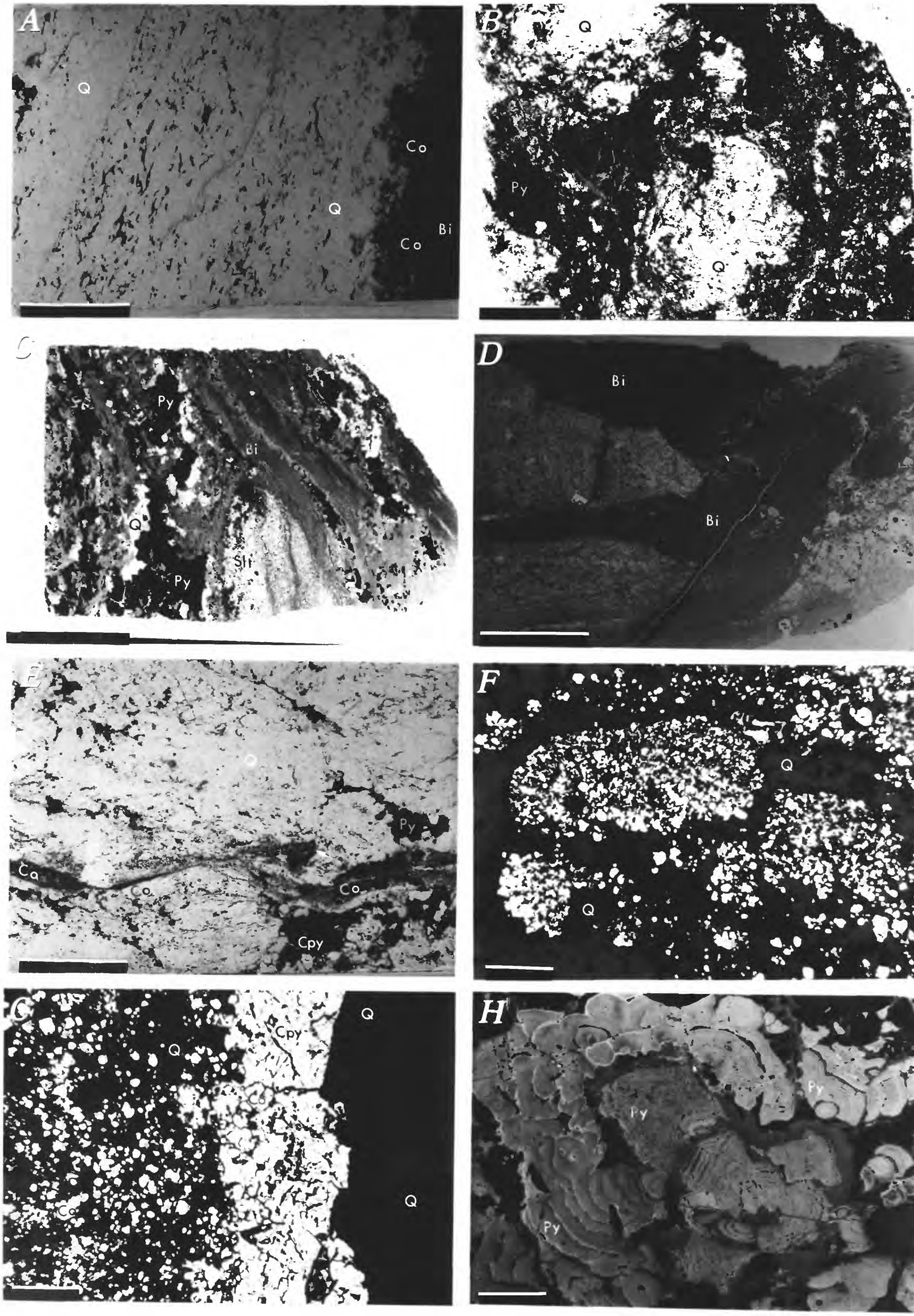


Figure 7. Geologic cross section of the Merle zone showing multiple Co-Cu lodes.


A
Q
Co
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Ca
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Cpy
Q
Q
H
Q
Cpy
Q
Co
Co
Py
Py
Py

FIG. 8

Figure 8. Photomicrographs of ore samples from the Merle zone. (A) Stratiform quartz (Q) and biotite (Bi) with cobaltite (Co) in biotite; scale is 1 cm. (B) Swirled texture of material filling disruption structure; quartzite clasts (Q) are cemented by pyrite (Py), biotite, and siderite; scale is 1 cm. (C) Disruption structure filled by clast of siltite (Slt), biotite (Bi), pyrite (Py), siderite, and quartz (Q); scale is 1 cm. (D) Fragments of siltite floating in a matrix of fine biotite (Bi) derived from tuff; scale is 1 cm. (E) Siliceous filling of disruption structure (Q) with trail of fine-grained cobaltite (Co) and coarser pyrite (Py) and chalcopyrite (Cpy); arrow points to area of fig. 8F; scale is 1 cm. (F) Enlargement of E showing possible clasts of fine cobaltite; reflected light, scale is 100 µ. (G) Fine-grained quartz (Q) and cobaltite (Co) in disruption structure with later, coarser chalcopyrite (Cpy) and quartz; scale is 200 µ, reflected light. (H) Pyrite (Py) in disruption structure showing porosity and differential hardness, probably resulting from alteration of pyrrhotite; scale is 200 µ, reflected light.

Author's note: These copies of photomicrographs may not show all details in original photos, but the general textural features are displayed and are understandable.

transported or fluidized clastic material, with lesser amounts of angular lithified fragments--which indicates formation prior to total lithification. (2) The zones appear to be confined between competent, lithified sandy layers, and extend between drill holes (50 to 200 m) as predictably as normal clastic lithologies--thus they may have originally been predominantly subhorizontal. (3) The abundance of matrix that cements the clastic material--quartz, biotite, muscovite, siderite, and ore minerals--as well as the fluidized fabric indicate that the disruption zones were highly permeable and accommodated the movement of large quantities of fluid. The disrupted zones clearly are post-depositional features, but probably formed during sedimentation of overlying beds. An unresolved matter is whether the disrupted zones formed a meter or hundreds of meters below the sea floor, and whether they formed individually or during a few periods of cataclysmic volcanic or seismic activity.

Penecontemporaneous soft-sediment deformation features have been recognized in many stratiform or massive sulfide deposits (e.g. Hashiguchi, 1983; Franklin et al., 1981), but described examples do not closely resemble those of the Merle zone. Possibly differences in style are in part related to the influence of clastic layers in the Merle zone, some of which may have become cemented shortly after sedimentation to provide coherent layers between unconsolidated muddy or tuffaceous beds. Hydrothermal eruptions (Henley and Thornley, 1979) may have provided the energy for the disruption structures and transport of infilling materials. Also probably contributing was pressure from pore fluids expelled from the tuff layers and from underlying muddy sediments. Mechanical transport of particles up to about 300 μ, but more commonly less than 50 μ, can be caused by fluidization during high velocity hydrothermal flow (Henley and Thornley, 1979), consistent with the fabric, grain sizes, and deposition of carbonate minerals (by boiling or degassing?) in the disruption structures. The "fluidized bed" model of sulfide grain transport (Henley and Thornley, 1979) may explain the occurrence of some cobaltite in disruptions by mechanical rather than chemical processes.

Geochemistry of the Merle ores is generally similar to that of the Sunshine ores (Table 1), although there is more S and Cu, less B and REE, and element associations of Co are different. Copper correlates strongly with S, Ag, Pb, and Zn, and is independent of Co. Cobalt is independent of most elements, suggesting that it may occur in many mineral associations; it is moderately associated with As, B, Y, and Yb. Preliminary evaluation of the chemistry of hangingwall and footwall samples in the Merle zone suggests that the two have essentially the same contents of Mg, Fe, Al, and minor elements. There is no chemical or lithologic evidence for a footwall alteration zone 1 to 20 m below the lodes.

PETROLOGY AND GEOCHEMISTRY

Mafic Igneous Rocks

Mafic igneous rocks in the mine area have experienced varying degrees of deformation and metasomatism during at least two periods of metamorphism, but original compositions can be estimated. Mafic dikes and sills are less modified than tuff; their igneous fabric can generally be discerned (Fig. 3F), and being strong, massive bodies they appear to have suffered smaller chemical changes.

Dikes are now composed of biotite, with variable amounts of amphibole, zoisite, plagioclase, siderite, quartz, and magnetite. Relicts of pyroxene phenocrysts 1 to 5 mm in size are distinctive, as are the non-aligned reddish brown biotite laths and disseminated magnetite. The chemistry of mafic dikes is summarized in Table 2. Content of alkalies is quite variable depending upon degree of alteration, and some are enriched in FeO, but contents of other elements are fairly uniform. The major element composition of freshest dikes (Table 2) falls in the general range of basaltic rocks (LeMaitre, 1976; De La Roche et al., 1980), and the CIPW norm computed for the best average dike composition (Table 2) is close to an alkali basalt, although computed corundum (4.2%) reflects loss of alkalies. Classification may be more reliable by criteria employing minor elements that are considered to be relatively immobile during post-magmatic or metamorphic alteration (e.g. Pearce and Cann, 1973; Floyd and Winchester, 1978; Davies et al., 1979). Minor element compositions are summarized in Table 2. According to the discriminating ratios Zr/TiO_2, Nb/Y, and Ga/Sc proposed by Floyd and Winchester (1978), most of the dike compositions fall in the alkali basalt field (Fig. 9A), and on the alkaline trend (Fig. 9B). According to the criteria of Pearce and Cann (1973), dike compositions suggest emplacement "within plates" and alkalic character. Minor- and rare-earth element abundances of the mafic rocks resemble alkaline basalts from continental rifts (Hahn and Hughes, 1984).

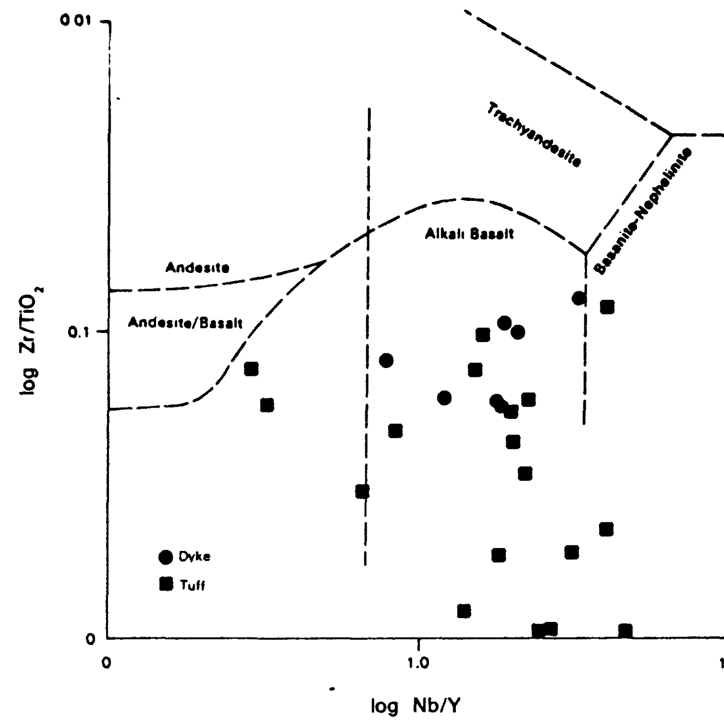
Mafic tuffs have a wide range in composition because of the effects of codeposition with terrigenous clastics and alteration. In addition to mesoscopic features described earlier, microscopic features that are diagnostic include: (a) non-oriented to weakly oriented tabular biotite (Fig. 3C, 6C); (b) grain size 100 to 500 μ, much coarser than for metapelites; (c) biotite with green pleochroism (Z = medium to dark green); (d) fine zircon crystals (10 to 100 μ) with dark pleochroic halos (Fig. 3C); (e) layers rich in tourmaline (Fig. 3D); and (f) low content of clastic quartz. Sideromelane glass shards and devitrification textures and deformed amphibolite lapilli are preserved in some samples (Hahn and Hughes, 1984).

Mafic tuffs are considered to be coeval with the mafic dikes by geologic criteria, but many samples have chemical compositions that deviate significantly from that of the dikes. Qualitatively, it is evident that impure and altered tuffs have compositions that range to higher SiO_2 and Al_2O_3 contents because of admixed clastic components, as well as having depleted CaO and Na_2O and elevated K_2O contents because of metasomatism. One reason for the scatter in chemical results is the fact that most samples of core were splits more than 0.3 m long, that included interbedded clastics. The purest tuffs were selected by petrologic criteria, and chemical criteria such as $TiO_2>1\%$. These "purest tuffs" (Table 2) have compositions that quite closely resemble that of the dikes, although the alkalies are clearly different. Minor element contents of some of the purest tuffs are plotted on Figure 9 and fall in the same general area as the dikes, but with considerably more scatter.

Classification of the mafic igneous rocks as alkali basalt seems fairly reliable according to these interim results. The alkalic mafic rocks tend to be in continental rifts and aulacogens (e.g. Mitchell and Garson, 1981), consistent with the proposed tectonic setting (Hahn and Hughes, 1984).

Ore Lodes

Petrology of ore minerals is seemingly simple. Cobaltite, chalcopyrite, and pyrite are the only abundant ore minerals observed in the Sunshine and Merle lodes. Small amounts of safflorite, linnaeite, and arsenopyrite are probably present to explain the range in Co:As from 0.4 to 1.5. Cobaltite is



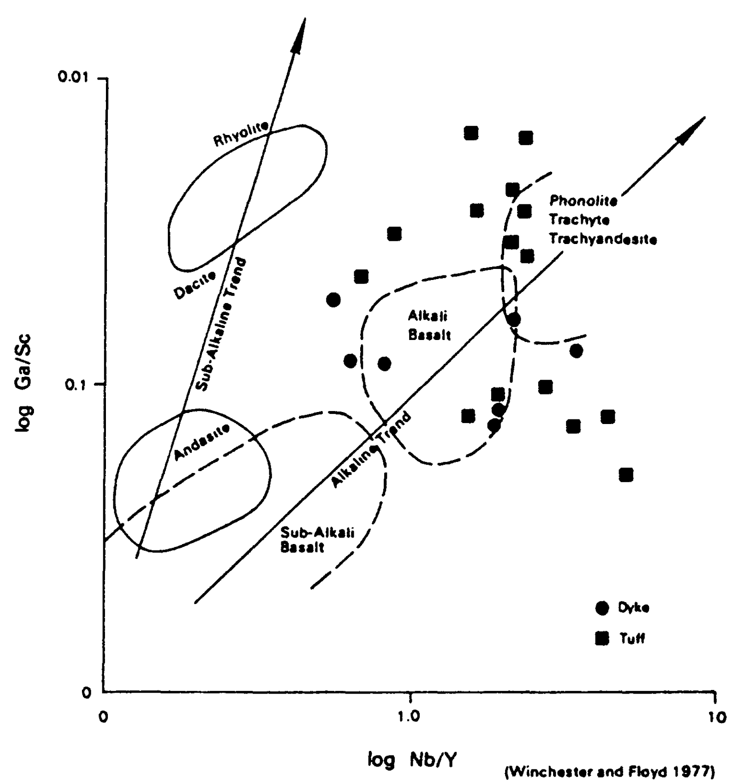


Figure 9. Minor element relations in mafic igneous rocks of the Blackbird mine area. (A) Discrimination diagram using Zr/TiO_2 and Nb/Y. (B) Discrimination diagram using Ga/Sc and Nb/Y, field boundaries from Winchester and Floyd (1977).

strongly ideomorphic, which adds to its appearance of being an early phase. More pertinent is the occurrence of cobaltite alone in many layers or microstructures, with chalcopyrite or pyrite cutting those structures or engulfing cobaltite. Crystals range in size from 2 µ to 500 µ, with the largest ones probably being compound intergrown crystals. Cobaltite in layers parallel to bedding tends to be mostly 10 to 50 µ in size. Fine crystals of cobaltite are enclosed by metamorphic minerals such as biotite, garnet, and chloritoid, and some cobaltite layers are deflected by garnet porphyroblasts (Fig. 6D)--both of these textures are considered to be evidence for pre-metamorphic deposition of cobaltite. In the Merle lodes, fine-grained cobaltite often occurs as thin stringers next to biotite-rich matrix or clastic fragments (Fig. 8E,G). This texture in disrupted zones might reflect fluid transport of "rafted" particles by high velocity hydrothermal fluids (Henley and Thornley, 1979).

Chalcopyrite occurs in coarsely crystalline stringers or aggregates that commonly have feathery edges. Chalcopyrite tends to engulf cobaltite and pyrite, or occur alone on microstructures that are distinct from those containing cobaltite. The mesoscopic and microscopic position of chalcopyrite indicates deposition or redistribution after cobaltite.

Pyrite is erratically distributed at deposit scale, and where present, tends to be in the same microstructures with chalcopyrite. Pyrite crystals generally are coarse (200-1,000 µ) with odd internal features. Many zones are very porous and polish poorly; some zones tarnish in air to brown or purple colors; and some concentric zones are hollow (Fig. 8H). At 500 X with oil immersion, some of the FeS_2 consists of intergrown 1 µ laths that have faint anisotropism--suggesting some marcasite is present. Some pyrite textures resemble that of melnikovite pyrite thought to be caused by rhythmic precipitation of FeS_2 and FeS at low temperatures (Ramdohr, 1980). More likely, the porous texture and concentric bands reflect so-called "birds-eye" texture produced during alteration of pyrrhotite. Ramdohr (1980, p. 603-608) discusses this alteration at length and provides photomicrographs that closely resemble textures in Merle samples. Small areas of pyrrhotite (about 10 in size) occur in the cores of some pyrite aggregates in the Merle zone, and pyrrhotite is abundant in parts of the Blackbird mine. Siderite is intergrown with the iron sulfides and produces some ragged replacement boundaries, but with distinctly different geometry from the birds-eye textures. The FeS_2 alteration is not likely the result of weathering because most of these samples are from drill core well below indications of oxidation.

The chemistry of bulk samples of ore (0.3 to 1 m splits of core) largely confirms mesoscopic and microscopic observations of ore-mineral associations (Table 1). Foremost is the low content of Pb-Zn-Ag in the Merle and Sunshine lodes, and the independent behavior of Cu (chalcopyrite) and Co (cobaltite). For these interim descriptions, we have utilized ICP results for 89 ore samples, 81 hangingwall samples, and 78 footwall samples from the Sunshine and Merle lodes. According to multivariate statistical tests and scatterplots of the data, the ore suite is Fe, S, As, Au, B, Bi, Ce, Co, Cu, La, Nd, Y, and Yb. Footwall and hangingwall rocks tend to contain significantly higher contents of Al, Na, K, Ti, Sc, Sr, V, and Zn relative to ore lodes; Mn and Ca are erratically higher in lode samples relative to footwall and hangingwall samples. Cobalt correlates strongly with As, Au, Ce, Eu, La, Nd, Ni, Y, and Yb, whereas Cu correlates strongly with S, Fe, Ag, Pb, and Zn, and is independent of REE. Elemental associations of Co and Cu are somewhat different in footwall and hangingwall samples relative to ore samples. A stronger association of Co with Cu, S, Ag, Pb, and Zn is possibly explained by residence of more Co in pyrite rather than cobaltite. Sunshine ore-lode samples tend to be richer in Mn, As, B, and REE, whereas the Merle ore-lode samples are richer in S, Cu, Ni, Pb, and Zn.

The enrichments of REE's with Co were not expected but are consistent with the postulated volcanogenic association. The various REE determined by ICP correlate strongly with each other, but do not show a systematic association with P, although grains rich in REE and P have been determined by SEM-EDS analysis. Further analytical work is required to substantiate the apparent REE-Co association.

Nickel content of the Co ores is relatively low, although a maximum value of 5,500 ppm occurs in one very high grade Co ore sample. In 273 analyzed samples the Co:Ni ranges from 0.38 to 264, with a geometric mean of 7.1; the geometric mean is 30 for 56 samples with Co content greater than 3,000 ppm. Co:Ni ratios less than 1 are in barren footwall or hangingwall rocks, whereas ratios greater than 100 are in Co-As rich ores with low Cu, chiefly in the Sunshine lode. Co:Ni correlates significantly with Co and As, and to a lesser extent with total S, and is independent of Ni and Cu. It is well known that for most rocks the abundance of Ni generally exceeds Co, and for mafic igneous rocks Co:Ni is about 0.3 (Turekian and Wedepohl, 1961). The cobalt enrichment seems to reflect separation of the metals at the hydrothermal source. Although the solution chemistry of Co and Ni are very similar because of their similar electronic configuration (Crerar et al., 1985), Ni has a larger ligand-field stabilization energy. From this property Crerar et al. (1985) predict: (1) Ni is not very soluble below 250°C, relative to Co and Cu (regardless of chloride concentration), and (2) Ni should be less leachable than Co from source rocks.

The deposits obviously are highly enriched in As, and also in the related element Bi. At this time we have no data for Sb. Contents of As and Bi are very low in most rocks, including mafic igneous rocks. Shales and deep sea clay seem to have the highest As contents (about 13 ppm; Turekian and Wedepohl, 1961) thus the pelitic rocks in the Yellowjacket might be the source of As. Better understanding of the distribution and solution chemistry of As would provide insights to the behavior of this key element in the Blackbird deposits.

Alteration

Mineralogical evidence of ore-associated alteration around the Co-Cu lodes is subtle, only partly because of metamorphic overprinting. No systematic lithologic changes are evident in footwall or hangingwall rocks that look very much like normal Yellowjacket facies to within about a meter of ore. In particular, there is no lithologic evidence in drill holes through and below the Sunshine and Merle lodes for footwall stockwork fractures and associated alteration. The ores and alteration are conformable with enclosing clastic rocks, resembling that of "distal-type" stratiform deposits (Large, 1977; Franklin et al., 1981). There are no significant differences in major or minor element chemistry between 87 footwall and 91 hangingwall samples (other than slightly greater Cu and B in the footwall set); these samples are 0.3 to 20 m from ore lodes. Gradients of Co, Cu, As, and related elements drop off very sharply from thousands of ppm to hundreds or tens of ppm in less than 0.3 m. From these alteration and chemical patterns we conclude that the hydrothermal processes were focused in the lodes.

Cobaltite and most chalcopyrite are predominantly in biotite-rich rocks described earlier as tuffs. The entire tuffaceous package is not uniformly rich in Co-Cu-As-S, although most of it is enriched. The precursor to the biotite-rich (or biotite-garnet) rock in both layered zones and disruptions is coeval with the ore minerals, thus is not exactly an "alteration" product. The precursor was notably rich in Fe-Al-Si-K to yield the mafic silicate minerals. The comments of McLeod and Stanton (1984) on the neoformation of silicates early in the exhalative-diagenetic history of stratiform ores are appropriate for these rocks, and their suggestion that glauconite may be the precursor to biotite is a good one.

This system was generally much richer in Fe than Mg according to rock and mineral compositions, thus differs from many stratabound sulfide systems that tend to be enriched in Mg near sulfides (e.g. Franklin et al., 1981; Large, 1977). Also, this system differs from many clastic-hosted deposits in showing no evidence for substantial Mn-enrichment or sulfate deposition. These trends probably are explained by deposition and modification of the Blackbird sequences under anoxic, deep-water conditions with low content of total sulfur. The observed high Fe/Mg may also reflect formation in upflow zones of the sea-floor geothermal system and relatively high water/rock ratios (Mottl, 1983), consistent with the lodes being close to geothermal vents.

Coarse vein-like quartz that fills Merle disruption structures contains abundant fluid inclusions indicating highly saline fluids were present at some time. Textural relations do not permit unequivocal determination of ages, but we do not see many highly saline inclusions in metamorphic bull quartz veins. The inclusions are consistently liquid-rich, and one variety contains one to as many as six daughter minerals including halite, sylvite, and several unidentified birefringent varieties. The inclusions are generally less than 5 μ in size, which hampers detailed study, but some preliminary heating tests indicated halite solution temperatures of 250-350°C and filling temperatures of 275-375°C (although some daughter minerals did not dissolve). We do not know the age of these hot, highly saline fluids relative to stages of Co-Cu deposition, but we feel they indicate that brines with roughly ten times the salinity of seawater evolved in the volcaniclastic rocks by processes such as membrane-filtration, and possibly boiling.

The ore lodes probably are mineralogically and chemically zoned relative to vents. There is large variation in Co/As and S/As in rock analyses but there is not much pattern to these ratios, although we suspect that analyses of cobaltite may provide useful information on zoning. In the Sunshine lode, zones with high Co:As, high ft.% Co, gold, and silica may reflect proximity to a vent. In the Merle B lode (Fig. 10), several features are zoned together to suggest probable vents. Three zones richest in Co and As, expressed as ft.%, coincide with parts of the lode with thickest tuff. These three zones are coincident with gangue mineral zones that seem to grade outward from a central most intensely disrupted zone with abundant pyrite plus siderite, plus quartz and muscovite, to chiefly quartz plus muscovite and less pyrite, then an outer zone of less disrupted rocks with little or no added quartz, pyrite, or muscovite. Green biotite is present across all the lode. Laminated biotite (tuff) with fine tourmaline and cobaltite layers occurs in the eastern fringe area that seems to be farthest from the vent(s). Sand wedges thicken to the east (Fig. 7), suggesting the major growth fault is in that direction, and delicately laminated parts of the lode are on the western side. The three nodes of intense mineralization may reflect E-W second-order cross fractures that served as local vents. More information, such as would be provided by mine exposures, is needed to properly document these relations.

More speculatively, much of the biotite might have formed in the initial geothermal system. If temperatures were in the range 300-350°, as in some

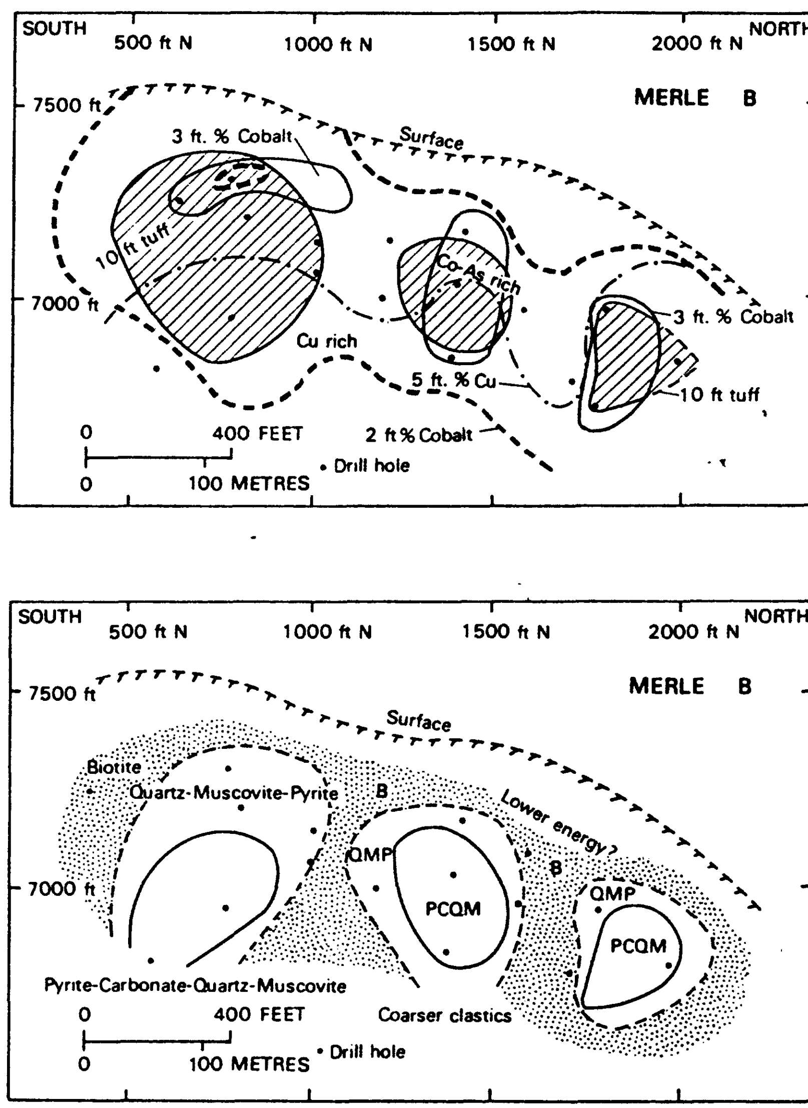


Figure 10. Schematic diagram of zoning in the Merle B lode; these longitudinal sections are essentially the same as plan maps of the originally subhorizontal lode. (A) Zones of thickest tuff, and richest Co, As, and Cu expressed as ft.%. (B) Zones of gangue minerals pyrite (former pyrrhotite), carbonate, quartz, and muscovite; biotite is present throughout the lode.

modern "Black Smoker" type geothermal systems (Henley and Thornley, 1979; Goldfarb et al., 1983; Cathles, 1983), and pressures about 100 bars, the iron-rich sediment might have reacted much differently than in conventional metamorphic systems at 2 to 4 kilobars. Biotite clearly forms in low pressure ore systems near 300°C (e.g. Beane and Titley, 1981).

Metamorphism

The area probably has experienced one period of geothermal metamorphism during Yellowjacket time and three periods of regional metamorphism. We believe that Co and Cu were introduced into the deposits prior to Proterozoic regional metamorphism. Mineral ages and zonation indicate that regionally extensive biotite-garnet-chloritoid facies predate contact metamorphism produced by the Proterozoic pluton. Hornblende, cordierite, and sillimanite occur close to the pluton but not in the mine area. The ore lodes and adjacent rocks contain some unusual assemblages involving biotite ± garnet ± chloritoid ± muscovite. The assemblage quartz-biotite-garnet-chloritoid, common near the Sunshine lode, is thought to have a very small stability field and require unusually high Fe/Mg and relatively high Al (Winkler, 1974, p. 205). No alumino-silicates or staurolite have been observed in the mine area. Details of metamorphic conditions will require study of mineral compositions, but for economic geology the importance of these assemblages is their indication of unusual compositions produced by volcanic and exhalative contributions to the sedimentary pile. These iron-rich metamorphic minerals should be useful indicators of possibly favorable volcaniclastic lithologies.

Regional metamorphism has modified silicate mineralogy but caused minor changes in ore mineralogy and in chemistry. Metamorphic minerals faithfully mimic sedimentary features and disruption features. The largest change in ore lodes was remobilization of chalcopyrite at mm to m scales. In contrast to chalcopyrite, cobaltite seems to be very refractory and little changed by metamorphism. These interim conclusions are consistent with recent interpretations (Franklin et al., 1981; McLeod and Stanton, 1984) that sulfide ores retain most of their pre-metamorphic compositions and ore mineralogy.

DISCUSSION

The association of Blackbird Co-Cu deposits with mafic tuffaceous rocks at regional, district, and bed scales provides an empirical exploration criterion for these deposits. The volcanic and exhalative component in the Yellowjacket basin also appears to explain many of the unusual characteristics of the deposits, as well as the few similarities and many differences in comparison with other clastic or volcanic associated sulfide deposits. Only two deposit types seem to show similar cobalt enrichment: (1) part of the Zambian copper belt enriched in Co in apparent association with intrusive or extrusive basic igneous rocks (Annels and Simmonds, 1984); and (2) Besshi-type massive sulfide deposits in basalt-clastic sequences with cobaltiferous-pyrite (Franklin et al., 1981). No other clastic- or volcanic-associated deposits seem to be uniformly rich in arsenic. The low contents of Ag, Pb, and Zn in the Blackbird ores distinguish them from most stratabound deposits. We believe that most of the ore suite of elements (Co-Cu-Au-Bi-REE) reflects the mafic volcanic input to the system.

The submarine volcanism seems to have been important in setting up the thermal system that created the synsedimentary stage of mineralization. The perceptive remarks of Cathles (1983) and Henley and Thornley (1979) are appropriate to the Blackbird deposits. Dikes probably were important in creating high heat flow, and possibly also were the sites of sea-floor vents. Three stages of the geothermal system probably were important: (1) sea-floor discharge of hot brines--rich in many metals as well as silica to create the chemical sediment component in the local basins; (2) explosive hydrothermal activity capable of fluidizing semilithified clastics and ore grains and triggering soft-sediment deformation; and (3) late or decay stage hydrothermal circulation, possibly important for introducing or redistributing copper.

Basin evolution and the clastic component of the Yellowjacket basin, not emphasized here, were important also (Hughes, 1983). Basin growth faults influenced styles of sedimentation and the location of mafic intrusions and eruptions. Deepwater clastic fans created small sub-basins favorable for the accumulation of tuffaceous and exhalative components. The combination of loading by sandy units and volcanism probably caused periodic dewatering of muddy sediments; this pore fluid may have been an important component of the ore fluids and possibly provided potassium, boron, arsenic, and other metals.

The following empirical exploration model is a simplistic summary of current knowledge of the Blackbird deposits.

I. Regional Setting: Rifted continental margin.

II. Local Setting: Deepwater turbidites, rapid facies changes across growth faults, mafic dikes and sills, mafic tuffs.

III. Geochemical Expression: Iron-rich volcaniclastic sediments; Fe, B, and Si exhalites; Co, Cu, As strongly anomalous in rock and soil samples.

IV. Ore Target: Contained within Fe-Si-Al-K rich tuffaceous or exhalitive layers; zones of soft-sediment deformation favorable; multiple stacked lodes possible.

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Table 1.--Geochemistry of mineralized rocks, Blackbird mine area, Idaho.

[Selected minor elements expressed in part per million, except for S, Fe, Mg, Ca in wt. %, analysis by ICP.]

Element	Ore Lode		Hanging Wall		Foot Wall	
	Geom Mean	Max	Geom Mean	Max	Geom Mean	Max
As	3866	70,000	149	37,000	110	13,000
Co	4062	66,000	153	6,400	164	2,500
Cu	994	50,000	188	13,000	339	70,000
S tot(%)	1.13	29.9	0.06	2.6	0.06	6.6
Fe%	12.6	33.0	10.4	25.0	10.2	23
Mg%	1.1	13.0	1.1	6.3	0.99	5.1
Ca%	0.13	2.9	0.10	0.72	0.10	0.67
Ag	1.8	6.0	1.5	3.0	1.6	12
B	47	1,940	42	600	54	500
Bi	26	530	8.0	50	7.9	50
Ce	20	2,200	13	140	22	230
Cr	64	1,400	54	530	53	840
La	24	1,000	15	64	18	110
Nb	0.51	43	3.1	34	8.5	93
Ni	229	5,500	32	510	30	330
Pb	0.1	22	0.0	350	0.0	37
Sc	7.6	23	9.6	30	9.6	28
Se	11	68	0.5	8.0	1.1	7.0
V	31	180	44	220	43	190
Y	29	560	11	250	11	63
Zn	22	140	26	85	28	200

Table 2.--Geochemistry of mafic tuffs and dikes, Blackbird mine area, Idaho

[Major element analysis by XRF; minor elements by ICP, major elements recomputed to 100 percent.]

Element	Mafic dikes[1]	Mafic tuffs[2]
	Geometric mean	
	Major elements in weight percent	
SiO_2	46.6	47.5
Al_2O_3	16.2	14.9
Fe_2O_3	1.7	3.1
FeO	13.2	17.0
MgO	7.0	7.0
CaO	4.7	0.59
Na_2O	2.6	0.15
K_2O	3.0	6.5
TiO_2	3.0	2.2
P_2O_5	0.77	0.40
MnO	0.16	0.06
S tot	0.09	0.05
Co_2	0.94)	0.59
LOI (950°)	(2.5)	(2.4)
Total	100.0	100.0
	Selected minor elements in PPM	
As	22.	56.
Co	98.	206.
Cu	196.	333.
Ni	88.	161.
Ce	93.	55.
Cr	145.	304.
La	50.	31.
Nb	34.	27.
Y	23.	14.
Zr	190.	154.

[1]Six samples from drill core selected as least altered by megascopic and petrographic features, and contents of alkalies and sulfur.

[2]Nine samples from drill core selected as purest according to megascopic features, and contents of SiO_2 (<55%), TiO_2 (>1.0%).