BLACKBIRD CO-CU DEPOSITS
(MODEL 24d; Earhart, 1986)

by Karl V. Evans, J. Thomas Nash, William R. Miller, M. Dean Kleinkopf, and David L. Campbell

SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology
These deposits are stratabound iron-, cobalt-, copper-, and arsenic-rich sulfide mineral accumulations in nearly carbonate-free argillite/siltite couplets and quartzites with minor acid-consuming capacity; deposits have high acid-generating capacity.

Examples
Idaho cobalt belt, especially Blackbird Mine, Idaho.

Spatially and (or) genetically related deposit types
Associated deposit types (Cox and Singer, 1986) include Besshi massive sulfide deposits (Model 24b).

Potential environmental considerations
(1) Most ore is sulfide-mineral rich and contains almost no carbonate minerals. Host rocks are meta-clastic and have limited acid-buffering capacity. Locally, minor buffering capacity is provided by siderite gangue.
(2) Very high potential for generation of acid (pH 2 to 3) drainage with thousands of mg/l copper and sulfate, hundreds of mg/l cobalt and iron, tens of mg/l aluminum, hundreds of µg/l zinc, and tens of µg/l arsenic. After mining operations have ended, sulfide minerals in waste rock and tailings piles may continue to oxidize and produce acid drainage with elevated metal contents.
(3) If fractured host-rock allows oxygenated water to infiltrate underground sulfide ore and old mine workings, acid mine drainage generation may continue after mining is complete. Non-point source emission of acid water at surface seeps is both a known (Baldwin and others, 1978; Reiser, 1986) and potential hazard.
(4) Potential downstream environmental effects of acid drainage can be significant in spatial extent, especially if surrounding terrane is, as at Blackbird, dominantly quartzo-feldspathic meta-clastic strata and granite with low acid-buffering capacity. Downstream water can be highly acidic and contain elevated concentrations of copper, cobalt, iron, and, depending on pH, arsenic.
(5) Environmental mitigation should focus on isolating sulfide-mineral-bearing rock, especially that in easily oxidized waste-rock piles, from water and oxygen. Rerouting drainages around mine sites would reduce the quantity of water that required treatment.

Exploration geophysics
Various satellite and airborne multispectral remote sensing techniques can be used to identify alteration mineral assemblages and stressed vegetation sites. Purdy and others (1986) made a preliminary evaluation of stressed vegetation in the Blackbird mine area. They demonstrated that Englemann spruce and lodgepole pine growing in soil enriched in cobalt and copper had higher spectral reflectance, as measured by a field-portable spectroradiometer, than the same species growing in background areas. At the time of their study, they were unable to detect these differences using Landsat Thematic Mapper data, probably because of noise from canopy density variations and strong topographic control of tree distribution. More recently developed remote sensing technology may be able to identify the stressed vegetation whose presence Purdy and others (1986) identified in the Blackbird area.

In the vicinity of the Idaho cobalt belt, aeromagnetic methods may be the most useful geophysical method in regional exploration for cobalt-copper deposits. The Blackbird mine lies on the southwest flank of a prominent magnetic trough that parallels the Idaho cobalt belt (Lund and others, 1990). This trough may indicate a structural or lithologic zone that is relatively depleted of magnetite. However, the oxide zone (see below for discussion of this zone) lies stratigraphically below the Blackbird mine, and is characterized by enrichments of copper, cobalt, and magnetite. Connor (1991) used existing aeromagnetic data to suggest potential extensions of the oxide zone to the southeast of his study area. However, Tertiary and lower Paleozoic plutons impose strong control on regional aeromagnetic patterns (Lund and others, 1990), which indicates the need for care in making regional interpretations. Detailed surveys tied to similarly detailed ground control are probably needed to better define a geophysical exploration strategy for cobalt-copper deposits of the Blackbird type.

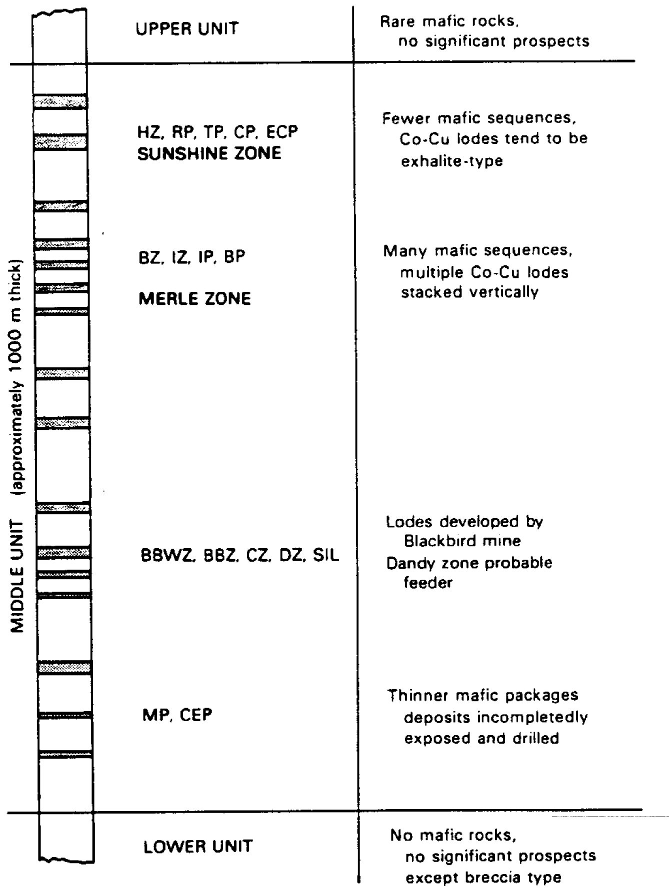

Figure 1. Schematic section of mafic rock-rich (biotitite-rich) sequences and associated Co-Cu lodes in the middle unit of the Yellowjacket Formation in the Blackbird mine area. Abbreviations are for lodes and prospects (see Nash and Hahn, 1989, for key and further information). From Nash and Hahn (1989).

References
Geology: Bennett (1977), Nash and Hahn (1989), Nash and Connor (1993), and Evans (in press).
Environmental geology, geochemistry: Baldwin and others (1978), Reiser (1986), McHugh and others (1987), and Desborough (1994).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size
These deposits are of small to intermediate size. Blackbird mine has about 12 million tonnes of combined mining and indicated reserves (Nash and Hahn, 1989). Available data (generally from unpublished sources) suggest that other known deposits in the Idaho cobalt belt are smaller than Blackbird, although none of these deposits have been as extensively explored as Blackbird.

Host rocks
Host rocks for these deposits are quartzo-feldspathic siltite-argillite couplets and quartzite intercalated with significant proportions of biotitite (biotite-dominant rock) (fig. 1). Biotitite probably formed either as a volcanogenic mafic tuff or as a chemical sediment.

Surrounding geologic terrane
The area surrounding the Idaho cobalt belt is primarily underlain by non-calcareous Middle Proterozoic quartzite, siltite, and argillite, Middle Proterozoic granite, and Eocene Challis Volcanic Group rocks (Evans and Zartman, 1990;

Evans, in press). These rocks have limited acid mine drainage buffering capacity.

Wall-rock alteration
Alteration is stratabound and coextensive with ore (Nash and Hahn, 1989). The transition from altered to unaltered rock is abrupt (<1 m) in many places. Altered rock in the Merle ore zone (fig. 1) at Blackbird is coincident with biotitite and intercalated rocks and contains elevated abundances of cobalt and arsenic. Alteration zoning consists of pyrite-siderite-quartz-muscovite in the core zone and grades outward into quartz-muscovite-(with lesser) pyrite. Potassic alteration has enhanced biotite crystallization across the entire ore zone. Acid mine drainage that encounters siderite is somewhat buffered; finer grained siderite has greater buffering capacity. Highly acidic water draining the Blackbird mine suggests that the buffering capacity of siderite is overwhelmed by acid-producing ore minerals.

Nature of ore
Deposits are closely associated with stratiform biotitites in the upper middle and lower upper stratigraphic units of the Yellowjacket Formation (Evans, in press). Other related, but smaller deposits include cobaltiferous-pyrite with variably abundant chalcopyrite that are associated with bedded magnetite in the lower Yellowjacket (oxide zone of Nash, 1989 and Nash and Connor, 1993; Jackass zone of Evans, in press), and relatively minor cobalt-bearing tourmaline breccias in the lower and middle units of the Yellowjacket (Modreski and Connor, 1991). Ore at Blackbird is both massive and disseminated. Fine- to very fine grained cobaltite and coarse-grained chalcopyrite dominate. Pyrite is erratically distributed at the deposit scale, but generally is present as coarse-grained crystals with chalcopyrite. Fine-grained pyrrhotite is present as cores in some concentrically banded pyrite crystals, but is most abundant in the probable feeder zone (Dandy zone) to the deposit.

Deposit trace element geochemistry
Blackbird mine: Co, Cu, Au, Fe, As, Bi, Cl, Cr, Mg, P, Sc, Ti, V, Y, Yb
Oxide zone: Fe, Cu, Sb, As, Au, Ba, Pb, Se, Zn, Co.

Complete analytical data for 372 samples of unoxidized drill core are available for several deposits in the Blackbird mine area (Nash and others, 1988). The following are ranges defined by the 10th and 90th percentile values and the means (in parentheses) for metals of particular interest. All values are in parts per million (ppm) unless otherwise indicated; nd indicates mean was not calculated because of strongly skewed data.
Fe: 6.6-18 (11.0) weight percent; S: <0.1-3.8 (0.2) weight percent; CO_2: <0.1-1.3 (0.2) weight percent; Ag: <1-1.5 (nd); As: 7-9,450 (130); Bi: <10-45 (nd); Cd: <1-<2 (nd); Co: 37-7,900 (180); Cr: 22-170 (46); Cu: 8-5,000 (250); Mo: <1-5 (nd); Ni: 10-380 (33); Pb: 2-15 (2.8); Se: <0.1-19 (9); Th: 5-19 (11); Zn: 14-62 (27).

Ore in the Blackbird mine area and associated alteration zones generally have very high abundances of iron, arsenic, cobalt, and copper; moderate to low sulfur in sulfide minerals; and relatively low to very low abundances of carbonate, silver, cadmium, chromium, molybdenum, nickel, lead, selenium, and zinc compared to other base-metal deposits.

Oxide zone deposits generally have abundances in the ranges suggested for deposits at Blackbird (Nash, 1989; Connor, 1991). Trace element environmental effects of oxide zone deposits are similar to those of Blackbird mine rocks, primarily due to the presence of acid-generating chalcopyrite and cobaltiferous pyrite.

Ore and gangue mineralogy and zonation
Potentially acid-generating minerals underlined. Blackbird mine (fig. 2): Major ore minerals-cobaltite, chalcopyrite, pyrite, pyrrhotite, native gold. Less abundant ore minerals and gangue-siderite, biotite, garnet, chloritoid, tourmaline, muscovite, arsenopyrite, linnaeite, safflorite, ±native silver, ±enargite, ±sphalerite, ±galena.
Distal deposits in Blackbird stratigraphic zone: Major ore minerals-pyrite, chalcopyrite, arsenopyrite, ±cobaltite.
Oxide zone: Major ore minerals-cobaltiferous pyrite, magnetite, hematite, chalcopyrite, arsenopyrite. Less abundant ore minerals and gangue-marcasite, pickeringite, chalcanthite.

Mineral characteristics
Blackbird mine: Cobaltite is present in very fine grained layers and thin stringers. Chalcopyrite is present in coarsely crystalline stringers and aggregates commonly enveloping cobaltite. Pyrite is coarsely crystalline, has internal concentric banding, and some contains fine-grained pyrrhotite cores.
Oxide zone: Pyrite is present in four forms: (1) fine-grained euhedral crystals interlaminated with argillite, (2) coarse-grained crystals, which form beds and cross-cutting structures, that enclose euhedral pyrite, (3) anhedral pyrite, which formed late in the paragenesis and encloses earlier crystals, and (4) corroded pyrite with a porous texture, probably

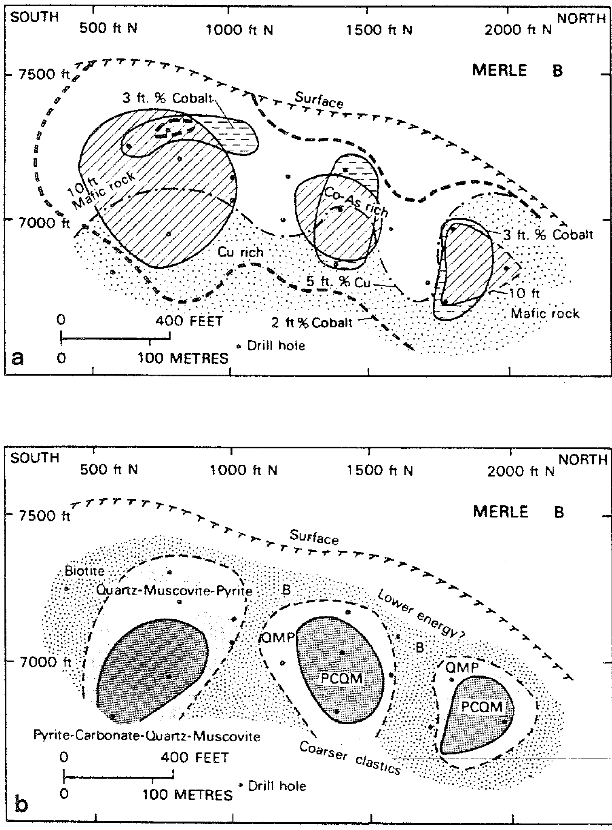

Figure 2. Schematic diagram of zoning in the Merle B lode, Blackbird mine. These longitudinal sections are essentially the same as plan maps of the originally subhorizontal lode. *A*, Zones of thickest mafic rock (biotitite) and richest concentrations of Co, As, and Cu expressed as feet/percent. *B*, Zones of gangue minerals pyrite (originally pyrrhotite), carbonate, quartz, and muscovite; biotite is present throughout the lode. From Nash and Hahn (1989).

indicating original precipitation as pyrrhotite. Some pyrite contains 2 to 4.5 weight percent cobalt; bismuth, lead, and zinc may also reside in the crystal lattice of pyrite. Chalcopyrite forms coarse-grained layers and cross-cutting structures that commonly surround pyrite. Magnetite is present in trace to major amounts as small, euhedral grains with very low cobalt content and <0.02 weight percent TiO_2. Magnetite grains form beds, with no evidence of a detrital origin, that may have formed by chemical sedimentation.

Secondary mineralogy

Secondary minerals include pickeringite, chalcanthite, malachite, azurite, limonite, and erythrite(?).

Topography, physiography

In the Blackbird region, topography is that of a deeply incised plateau with steep-walled canyons. Biotitite-rich strata weather easily and even quartzo-feldspathic strata tend to produce rubble and talus rather than prominent outcrops.

Hydrology

Most precipitation near Blackbird falls during the Winter. Baldwin and others (1978) indicate a seven-year average of about 124 cm of snow with a water content of about 38 cm. Streamflow peaks during Spring runoff (April through June) and falls to very low levels in late Summer and early Autumn. Highly fractured Yellowjacket Formation at Blackbird mine permits rapid correlated recharge and discharge of ground water. During the early part of the Spring runoff, drainage through acid-producing mine workings and waste rock/tailings piles flushes large quantities of soluble salts containing metals and acidity into surface drainages.

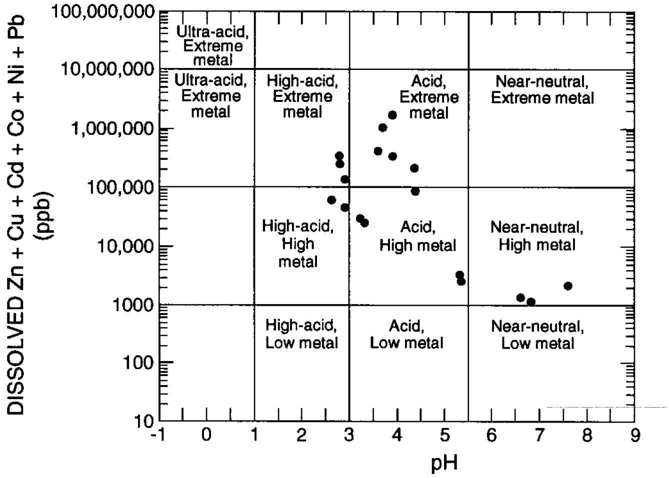

Figure 3. Ficklin plot (Plumlee and others, 1993; Smith and others, 1994) of pH versus the sum of dissolved base metals Zn, Cu, Cd, Co, Ni, and Pb in mine and natural water draining waste rock in the Meadow Creek/Blackbird Creek and Bucktail Creek drainages at Blackbird mine. Values shown are from water most closely associated with sources of acid mine drainage at Blackbird mine. Available data do not include analyses for all base metals summed in the diagram; therefore data points are minimum values. Data from Baldwin and others (1978) and McHugh and others (1987).

Mining and milling methods

Underground mining at Blackbird was from drifts following lenticular and tabular orebodies using room and pillar methods and block caving of overhead stopes. Sand recovered from the coarse fraction of the milling operation has been used in limited backfilling. Remaining tailings have been impounded. Open-pit mining was restricted to late operations at the Blacktail pit.

ENVIRONMENTAL SIGNATURES

Drainage signatures

Mine-drainage data: Water draining the Blackbird mine and waste rock/tailings piles is highly acidic and contains high to extreme dissolved metal concentrations (fig. 3), including thousands of mg/l copper and sulfate, hundreds of mg/l cobalt and iron, tens of mg/l aluminum, hundreds of µg/l zinc, and tens of µg/l arsenic (Baldwin and others, 1978; Reiser, 1986; McHugh and others, 1987). In light of the arsenic-rich cobaltite (CoAsS)-bearing ore, dissolved arsenic concentrations are less than might be expected, probably as a consequence of efficient arsenic adsorption by hydrous iron oxide minerals in stream channels with low pH. If treatment of acid mine drainage at Blackbird involves large-scale "liming" to raise pH, considerable amounts of arsenic may be desorbed and mobilized.

Natural drainage water: Geochemical data for the Special Mining Management Zone—Clear Creek is presented by McHugh and others (1987); see Lund and others, 1983 for a description of the geology of this area. Available studies of water chemistry for the Blackbird area have concentrated on streams draining mined areas and do not provide adequate background values for anthropogenically undisturbed regions. McHugh and others (1987) collected a few samples from drainages in mineralized but unmined areas; the results may indicate a very small copper-cobalt anomaly. However, sampling was conducted in July, after Spring runoff, when anomalous abundances (if present) are generally most pronounced. A study in which samples are collected throughout the annual hydrologic cycle, including geographically distributed samples from mineralized and unmineralized parts of the Yellowjacket stratigraphy, is needed to properly define natural drainage chemistry.

Potentially economically recoverable elements: High abundances of dissolved copper and cobalt are potentially recoverable by redox-reaction methods or capture by resins or zeolites (Desborough, 1994, 1995).

Metal mobility from solid mine wastes

Numerous studies indicate very high mobility of metals and acid water from solid mine waste primarily due to the ready availability of iron sulfide minerals (Baldwin and others, 1978; Reiser, 1986; McHugh and others, 1987; and sources referenced by these reports). Capillary action coupled with evaporation on waste piles during winter months and during dry periods through the remainder of the year produce readily dissolved salts that contain metals and produce acid. Flushing during the early part of Spring runoff and also during thunderstorms causes dissolution of these salts; large metal load and acidity increases result from these flushing events (Baldwin and others, 1978; Farmer and Richardson, 1980; Reiser, 1986). High metal content (especially copper) of streams draining the Blackbird mine area have had a detrimental effect on anadromous fish populations (Reiser, 1986 and references cited therein).

Soil, sediment signatures prior to mining

A pioneering geochemical soil sample survey (Canney and others, 1953) clearly delineated areas with anomalous cobalt and copper abundances and led to discovery of the Blacktail ore zone at Blackbird. Bennett (1977) also conducted a geochemical soil sample survey at and adjacent to Blackbird. Geochemical data for stream sediment samples are given by Bennett (1977) and Evans and others (1993); these data, including streams both affected and unaffected by past mining, readily identify areas with anomalously high metal abundances, especially cobalt and copper.

Potential environmental concerns associated with mineral processing

Sulfide-mineral-rich ore in nearly carbonate-free meta-clastic rock with limited acid-buffering capacity indicates very high potential for spatially extensive acid drainage containing thousands of mg/l copper and sulfate, hundreds of mg/l cobalt and iron, tens of mg/l aluminum, hundreds of µg/l zinc, and tens of µg/l arsenic. Fractured host-rock facilitates interaction between oxygenated water and underground sulfide ore, thereby perpetuating acid mine drainage.

Smelter signatures

High arsenic and sulfur ore contents are a major hazard. Current laws restrict smelting to specific sites designed to mitigate arsenic hazards. Historic smelting involved simplistic nineteenth-century methods that relied on volatilization of arsenic and sulfur, thus producing severe and widespread contamination. Recent proposals for refining Blackbird-type ore have emphasized electrochemical methods; all methods are subject to stringent environmental regulation.

Climate effects on environmental signatures

Capillary action and evaporation, which lead to the formation of soluble secondary salts during the winter and dry periods, result in early spring and thunderstorm-related runoff with high metal loads and acidity. Mineralogical work is needed to detail information on the salts and their relation to the annual hydrologic cycle.

Geoenvironmental geophysics

Various electrical geophysical techniques can identify potential sources of acid mine generation and trace plumes of contaminated water away from their sources; these techniques have not been systematically applied to Blackbird deposits, however.

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