Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
	Volume	
liter (L)	33.82	ounce, fluid (fl. oz)
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	1.308	cubic yard (yd^3)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
tonne	1.10231	ton, short
tonne	2204.62	pound (lb)
	Density	
gram per cubic centimeter (g/cm^3)	62.4220	pound per cubic foot (lb/ft^3)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8×°C)+32$$

Co-Cu-Au Deposits in Metasedimentary Rocks—A Preliminary Report

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Abstract

A compilation of data on global Co-Cu-Au deposits in metasedimentary rocks refines previous descriptive models for their occurrence and provides important information for mineral resource assessments and exploration programs. This compilation forms the basis for a new classification of such deposits, which is speculative at this early stage of research. As defined herein, the Co-Cu-Au deposits contain 0.1 percent or more by weight of Co in ore or mineralized rock, comprising disseminated to semi-massive Co-bearing sulfide minerals with associated Fe- and Cu-bearing sulfides, and local gold, concentrated predominantly within rift-related, siliciclastic metasedimentary rocks of Proterozoic age. Some deposits have appreciable Ag ± Bi ± W ± Ni ± Y ± rare earth elements ± U. Deposit geometry includes stratabound and stratiform layers, lenses, and veins, and (or) discordant veins and breccias. The geometry of most deposits is controlled by stratigraphic layering, folds, axial-plane cleavage, shear zones, breccias, or faults. Ore minerals are mainly cobaltite, skutterudite, glaucodot, and chalcopyrite, with minor gold, arsenopyrite, pyrite, pyrrhotite, bismuthinite, and bismuth; some deposits have appreciable tetrahedrite, uraninite, monazite, allanite, xenotime, apatite, scheelite, or molybdenite. Magnetite can be abundant in breccias, veins, or stratabound lenses within ore or surrounding country rocks. Common gangue minerals include quartz, biotite, muscovite, K-feldspar, albite, chlorite, and scapolite; many deposits contain minor to major amounts of tourmaline. Altered wall rocks generally have abundant biotite or albite. Mesoproterozoic metasedimentary successions constitute the predominant geologic setting. Felsic and (or) mafic plutons are spatially associated with many deposits and at some localities may be contemporaneous with, and involved in, ore formation. Geoenvironmental data for the Blackbird mining district in central Idaho indicate that weathering of abundant Fe, S, As, Co, and Cu in sulfide minerals of the deposits produces acidic waters, especially in pyrite-rich deposits; mine runoff has high concentrations of Fe, Cu, and Mn that exceed U.S. drinking water or aquatic life standards.

Introduction

This preliminary report provides an improved model for a specific type of Co-Cu-Au deposit that will be evaluated in the next U.S. Geological Survey (USGS) assessment of undiscovered mineral resources in the United States. Emphasis is on describing, in a modern context, a unified deposit model that includes both geologic and geoenvironmental aspects. The new model presented here supersedes previous USGS models by Earhart (1986) and Evans and others (1995), which are based solely on

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Table 1. Selected features of Co-Cu-Au deposits in metasedimentary rocks. Data sources are available from the U.S. Geological Survey.

[Mt, million metric tonnes; g/t, grams per tonne; NWT, Northwest Territories; NA, data not available; m, meter; %, percent; --, none identified]

Deposit name	Country	State/Province	Size (Mt)	Co (%)	Cu (%)	Au (g/t)	Major metals	Minor associated metals
Blackbird-ICB[1]	USA	Idaho	14.343	0.58	1.24	0.58	Co, Cu, Fe	Y, REE, Bi, As, Ni, U
Cobalt Hill	Canada	Ontario	NA	NA	NA	NA	Co, Cu, Au	Ni, As, Hg Te
Contact Lake Belt	Canada	NWT	NA	NA[2]	NA[2]	NA[2]	Cu, Au, Ag, Co, U	Bi, Zn, As
Werner Lake	Canada	Ontario	NA	1.68	0.35	3.22	Cu, Co, Au	Mo, Zn, Ag, Ni
NICO	Canada	NWT	[3]30.986	0.12	0.04	0.91	Co, Au, Bi	As, W, Fe, Ba, P, Co, F, Be
Modum (Skuterud)	Norway		1.0	0.26	2.0	1	Cu, Co, Au	As, Ni, U, Th
Gladhammar	Sweden		0.006	NA	NA	NA	Co, Cu, Fe, Au	Zn, Pb, Mo, Bi
Solstad	Sweden		0.009	NA	NA	NA	Cu, Co, Au	Ni, Pb, Zn
Haarakumpu	Finland		4.680	0.17	0.34	NA	Co, Cu	Au, Bi, Ni
Hangaslampi	Finland		0.176	0.1	NA	6	Au, Co	Ag, Cu, REE, Ni, U, Mo, Pb, W
Jouhineva/Pöllä	Finland		0.450	0.18	0.81	0.88	Co, Cu, Au, Ag	Mo, Ni, REE, U
Juomasuo	Finland		1.800	0.2	NA	3	Au, Co	Cu, Ag, Mo, Ni, REE, U, Bi, Te, Pb, Zn
Kouvervaara	Finland		1.580	0.1	0.2	0.4	Co, Cu, Au	Zn, Mo, Bi, W
Kuumaso	Finland		NA	0.14	2.0	2.2	Co, Cu, Au	--
Lemmonlampi	Finland		0.090	0.3	0.4	0.15	Co, Cu, Au	--
Meurastuksenaho	Finland		0.284	0.25	0.28	2.3	Co, Au, Cu	Mo, U, REE
Sirkka	Finland		0.250	0.1	0.38	0.8	Co, Ni, Au, Cu	U, Zn, Ag, As
Mount Cobalt	Australia	Queensland	0.060	[4]0.05	0.33	NA	Cu, Co, W	As, Ni, Au, REE
Kendekeke	China	Qinghai	NA	NA	NA	NA	Co, Bi, Au, Cu	Bi, As, Zn, Pb, Te
Dahenglu	China	Jilin	NA	NA	NA	NA	Co, Cu	Zn, Pb, As

[1]ICB, Idaho cobalt belt; includes numerous separate deposits.

[2]0.27% Cu, 0.10% Co, 1.31% As, 0.15 g/t Au over 24 m.

[3]Does not include 6.5 Mt of marginal subeconomic resource.

[4]From 1919–1934 produced 20,000 tonnes of ore at an average grade of 4% Co (Nisbet and others, 1983).

Co-Cu deposits in the Blackbird mining district of central Idaho. This report is a broader synthesis of information on numerous Co-Cu-Au deposits in metasedimentary rocks worldwide (table 1) that share common geologic, mineralogical, and geochemical features. With one exception, deposits in the database contain on average ≥0.1 percent Co; Mount Cobalt, Australia, is included because it has past Co production from higher-grade ore zones (Nisbet and others, 1983). Six deposits that lack data for average Co grades are also included because each reportedly contains abundant Co. Many of the deposits are noteworthy as possible resources of Ag, Bi, W, Ni, Y, rare earth elements (REE), and U. Significantly, the grouping of Co-Cu-Au deposits in metasedimentary rocks presented in this report includes deposits that other workers have previously classified in different ways.

Tonnage and Grade Variations

Most of the Co-Cu-Au deposits described in this report comprise resources of 100 to 10,000 tonnes of contained Co (fig. 1). Sizes of the Co-Cu-Au deposits overlap those of sedimentary Cu deposits of the central African copperbelt in terms of total Co content. With the exception of the Blackbird district in central Idaho, the Co-Cu-Au deposits represent smaller Co resources than Co-rich volcanogenic massive sulfide (VMS) deposits (Windy Craggy, Canada; Outokumpu, Finland), and large magmatic Ni-Cu deposits (for example, Noril'sk-Talnakh, Russia). Some large cobaltiferous iron oxide-copper-gold (IOCG) deposits such as Olympic Dam and Ernest Henry in Australia contain significant Co resources (fig. 1), although Co is not currently produced from either deposit. Despite the smaller Co contents relative to other deposit types, Co-Cu-Au deposits in metasedimentary rocks can be important national resources—particularly deposits or groups of deposits as large as Blackbird—because the United States has few known Co resources of likely economic viability.

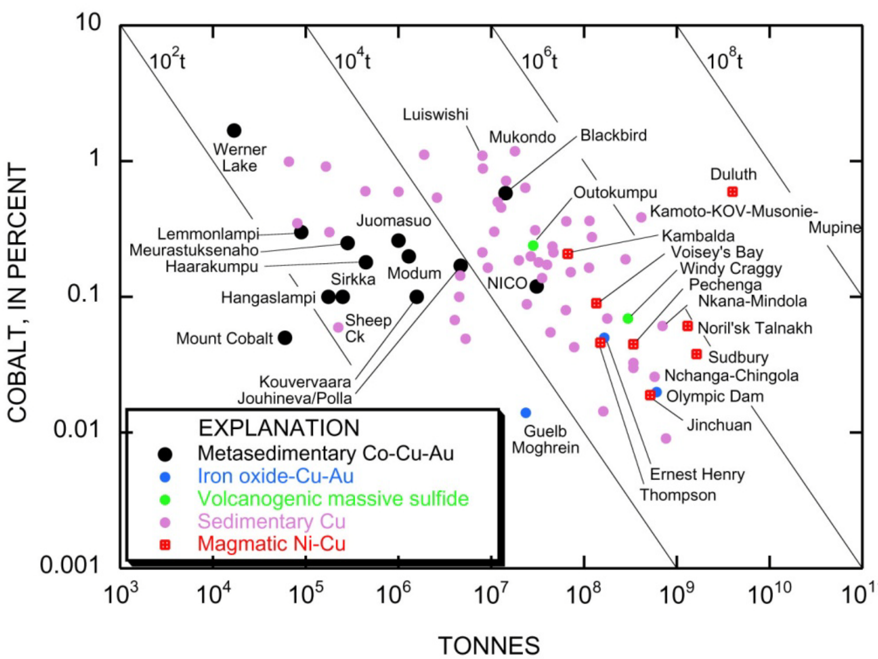

Figure 1. Plot of tonnage versus average Co grade for Co-Cu-Au deposits in metasedimentary rocks. Shown for comparison are data for other cobaltiferous deposit types including iron oxide-copper-gold (IOCG), volcanogenic massive sulfides (VMS), sedimentary Cu, and magmatic Ni-Cu. Data sources are available from the U.S. Geological Survey.

Average Co grades are plotted versus average Cu and average Au grades in figure 2A and 2B, respectively. In general, the metasedimentary Co-Cu-Au deposits considered in this report have more Co and less Cu, and higher Co/Cu ratios, than other deposit types, except for several Co-rich sedimentary Cu deposits of the central African copperbelt. Relatively high Au grades are a key distinguishing feature of the metasedimentary Co-Cu-Au deposits. Most of the Finnish deposits (table 1) have more than 2 grams per metric tonne (g/t) Au; some have as much as 6 g/t Au. By comparison, cobaltiferous sedimentary Cu, VMS, and IOCG deposits have less than 1 g/t Au, excluding the Guelb Moghrein (Mauritania) IOCG deposit that contains an average of nearly 1.5 g/t Au. The lack of associated redbed sedimentary rocks, or their metamorphosed equivalents (for example, magnetite-bearing quartzite), further distinguishes the Co-Cu-Au deposits considered here from Co-rich sedimentary Cu deposits of the central African copperbelt.

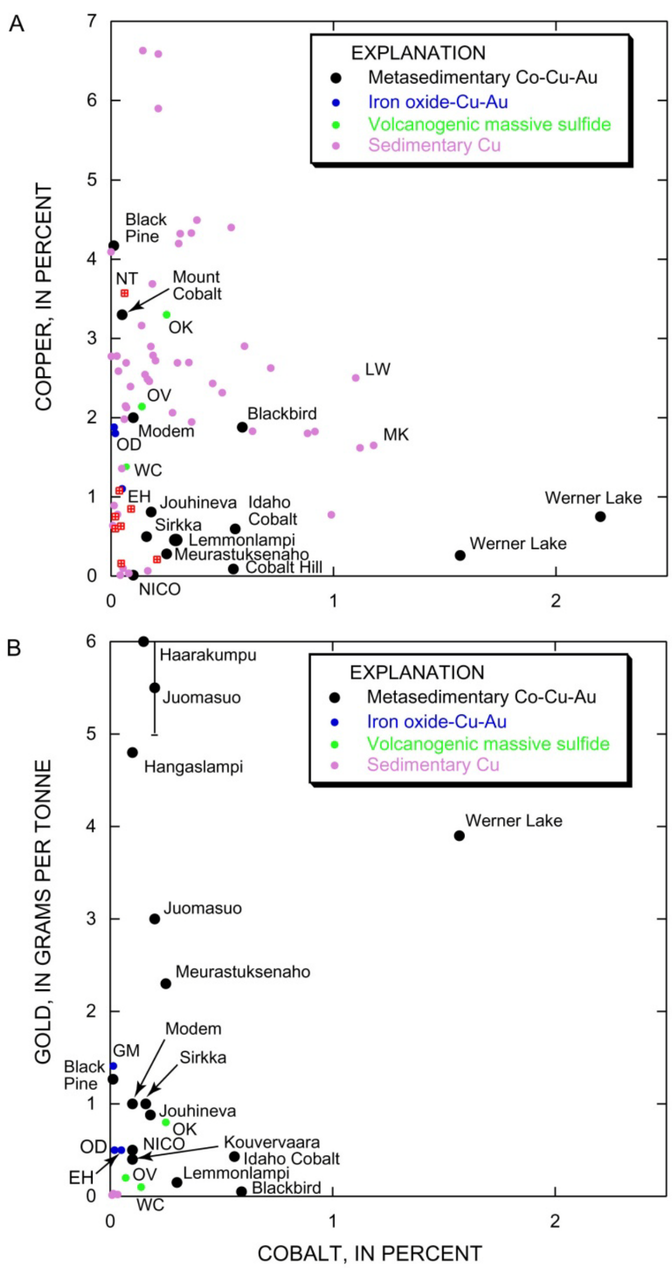

Figure 2. Plots of (A) average Co-Cu grade and (B) average Co-Au grade of Co-Cu-Au deposits in metasedimentary rocks. Abbreviations for other cobaltiferous deposit types: EH, Ernest Henry (Australia); GM, Guelb Moghrein (Mauritania); LW, Luiswishi (Democratic Republic of Congo); MK, Mukondo (Democratic Republic of Congo); NT, Noril'sk-Talnakyh (Russia); OD, Olympic Dam (Australia); OK, Outukumpu-Keretti (Finland); OV, Outukumpu-Vuono (Finland); WC, Windy Craggy (Canada). Data sources are available from the U.S. Geological Survey.

Regional Environment

Host rocks for Co-Cu-Au deposits in the Blackbird district (Lund and Tysdal, 2007) and for similar deposits elsewhere (table 1) are metasedimentary sequences that were deposited predominantly within intracontinental extensional basins. Most basins are of Proterozoic age, but several are Archean or Paleozoic. The basins are commonly filled by thick (multiple kilometer), supracrustal successions of fine- to medium-grained siliciclastic rocks. Although the tectonic environment was extensional, synsedimentary igneous rocks are rare in the stratigraphic sequences.

Subsequent intracontinental extension was superimposed on the sedimentary basins and resulted in post-depositional, volumetrically minor, extension-related, mafic to felsic igneous magmatism. In the region surrounding the Blackbird district, three post-depositional, intracontinental extensional events produced A-type, within-plate, igneous rocks about 30, 700, and 900 million years after Mesoproterozoic sedimentation but prior to Cretaceous formation of the structural fabrics that give the mineral deposits their present form (Lund and Tysdal, 2007; Aleinikoff and others, 2010).

Mineral deposits in this compilation occur near, but not within, the extensional igneous rocks. In the Blackbird district, the oldest extensional igneous event is the same age, within SHRIMP U-Pb analytical uncertainty, as xenotime (a Y-REE phosphate mineral) that occurs locally in the ores (Slack, 2006; Aleinikoff and others, 2010), suggesting that the extensional magmatism (1) was responsible for metal emplacement, (2) modified preexisting deposits, or (3) produced ground preparation (early rock alteration zones, rheology boundaries, and so on) for later mineralization.

Younger contractional deformation, caused by continental collision and translation of stress inboard, deformed the country rocks as part of regional thrust belts or other deep-crustal structures. The resulting structural inversion of the sedimentary basins produced deformation and regional metamorphism of the preexisting sedimentary and igneous rocks. Mineral deposits and districts are typically clustered along minor structures related to major, through-going, deep-crustal structures. The deep-crustal origin of the major structures is paired with generally medium to high metamorphic grades of the host rocks. The contractional phase was the final element in establishing the regional settings of the mineral deposits, providing a heat source, dehydration-derived fluids, and structural pathways for processes that either led to metal emplacement or modified preexisting deposits.

The ages of many of these mineral deposits are debated or undetermined. Several factors are responsible, including (1) poorly known ages of sediment accumulation due to the difficulty of precisely dating the mainly Precambrian sedimentary host rocks, (2) degree and complexity of metamorphic and tectonic overprint(s), and (3) large time intervals separating sedimentation and tectonic events. Likewise, the duration of mineralization is uncertain but may include a multi-stage, complex tectonic history spanning a significant time interval. An important factor common to several deposits appears to be a tectonic setting involving multiple episodes of reworking of continental crust, including (1) intracontinental extension resulting in crustal-scale structures and thick, syntectonic basin fill; (2) younger extension to give superposed, bimodal within-plate magmatism; and (3) compression resulting in deep-seated structures and circulation of metamorphic fluids through a thick crustal section. In the Blackbird district, Y and REE (and probably Be) were introduced in the Mesoproterozoic contemporaneous with the first episode of A-type granite emplacement (Aleinikoff and others, 2010). The Co-Cu-Au-Bi component of the deposits also may have formed during the Mesoproterozoic or possibly much later during regional Cretaceous orogenic events, a 1.3 billion year time span (Lund and Tysdal, 2007; Aleinikoff and others, 2010).

Deposit Features

The deposits are predominantly hosted by siliciclastic metasedimentary rocks, but a few deposits have lithologically different wall rocks, such as NICO (Canada), which is locally within metarhyolite (Goad and others, 2000). No deposits in our database are hosted by plutons, regardless of age or composition.

Mineralized zones vary greatly in form and geometry. Most are less than a few meters thick and several hundred meters in length, but some zones are much larger, such as those in the Blackbird district, which are up to 1 km long (Nash and Hahn, 1989; Bookstrom and others, 2007), and the Skuterud (Modum district) in Norway, which is about 2 km long (Grorud, 1997). The Bowl zone of the NICO deposit in Yukon, Canada, is up to 70 m thick and 1.9 km in length (Goad and others, 2000). Mineralized zones are known to be stratabound or discordant and typically are elongate parallel to local structures such as faults, shear zones, fold axes, and intersections of axial plane cleavage with bedding. A few deposits, such as some in the Blackbird district, are localized along lithologic contacts. Breccias are common hosts.

Mineralogy

The ore mineralogy of the deposits includes predominant Co ± As ± Ni sulfides such as cobaltite, glaucodot, skutterudite, safflorite, smaltite, carrollite, linnaeite, and gersdorffite. Accompanying ore minerals typically are chalcopyrite and gold, with generally minor arsenopyrite, pyrite, pyrrhotite, marcasite, millerite, tetrahedrite, bismuthinite, bismuth, uraninite, monazite, allanite, xenotime, apatite, and (or) molybdenite. Some deposits contain sparse to trace amounts of bornite, tellurobismuthite, gadolinite, Co-selenides, sphalerite, or stannite. Gangue minerals are chiefly quartz and muscovite, with locally abundant tourmaline, albite, biotite, chlorite, K-feldspar, and scapolite. Most deposits have appreciable magnetite and (or) hematite within the mineralized zones or in surrounding country rocks. Minor gangue constituents include apatite, barite, carbonate, fluorite, carbonates, garnet, pyroxene, amphibole, and graphite.

Discerning mineral paragenesis in the deposits considered herein is difficult owing to effects of varying recrystallization and remobilization during post-ore deformation and metamorphism. However, a general characteristic is paragenetically early magnetite veins, lenses, or breccias that are cut or replaced by later sulfides, gold, and other minerals. Tourmaline, where present, is also typically early in the paragenesis, although in some deposits such as at Blackbird it appears to be contemporaneous with ore deposition (Slack, 2007). Bismuth concentrations, commonly in native Bi and bismuthinite, tend to be spatially associated with gold, but in some cases gold appears to be texturally separate from, and paragenetically unrelated to, Bi minerals.

Hydrothermal Alteration

Hydrothermally altered rocks spatially associated with the deposits extend tens to hundreds of meters from the mineralized zones. Three distinctive types of altered rocks have been recognized, which consist of stratabound and locally stratiform lenses composed mainly of (1) Fe-rich biotite, such as the Fe- and Cl-rich biotite that occurs in wall rocks to the Blackbird deposits (Nash and Hahn, 1989); (2) Fe-rich tourmaline, especially well developed in the Blackbird district (Nash and Hahn, 1989; Slack, 2007); and (3) albite, such as in host rocks to the Skuterud deposit in the Modum district of Norway (Grorud, 1997). Scapolite also occurs in the wall rocks and country rocks surrounding several of the

Co-Cu-Au deposits listed in table 1, such as Modum, but the spatial relationship and paragenesis of this scapolite to the mineralized zones are unclear.

Geochemical Characteristics

In addition to Co, Cu, and local Au, some deposits have appreciable Ag ± Bi ± W ± Ni ± Y ± REE ± U. In a few deposits such as NICO in Canada and several of those in the Blackbird district, Bi concentrations in mineralized zones are locally as much as several percent (Goad and others, 2000; Slack, 2007) and hence constitute a possible byproduct commodity from mining. In some deposits, other possible economically recoverable metals include Y and REE (Slack, 2006).

Fluid inclusions have been identified in quartz from Co-Cu-Au deposits, but the relationship of the inclusions to the sulfide assemblages is difficult to determine due to changes in rock textures that commonly occurred during syn- or post-mineralization deformation or metamorphism. Multiple inclusion types are typically present and record complex fluid histories. Heating and freezing experiments on inclusions from several deposits have revealed both high salinity fluids (Nash and Hahn, 1989), with salt contents up to 10 times that of seawater and low salinity fluids containing CO_2. The roles that these two fluid types may have played in transporting metals to sites of ore deposition, or redistributing preexisting metal accumulations, is uncertain. Also uncertain is whether the measured homogenization temperatures for the inclusions, which typically are in the range 250 to 400°C, reflect sulfide precipitation or later metamorphic or hydrothermal events.

Available sulfur isotope analyses of sulfide minerals show positive $\delta^{34}S$ values, with means for individual deposits ranging from 1 permil for Werner Lake (Pan and Therens, 2000) to 21 permil for Modum (C.A. Johnson, U.S. Geological Survey, unpublished data). Variations in $\delta^{34}S$ are small at Blackbird and Werner Lake, for which standard deviations about the mean are about 1 permil, but data for Modum show a broad $\delta^{34}S$ range of approximately 16 permil. High mean $\delta^{34}S$ values at Blackbird—about 8 permil—(Johnson and others, 2007) and Modum—about 18 permil—suggest that sulfur in the ores was derived predominantly from sedimentary sources. A lower mean $\delta^{34}S$ value at Werner Lake may reflect a magmatic component at this deposit, although a sedimentary source is not precluded. Limited variation in $\delta^{34}S$ at Blackbird and Werner Lake contrasts with sulfur isotope values for most sedimentary exhalative (SEDEX) Pb-Zn deposits, for example, and precludes sulfide formation from H_2S that was produced by bacterial sulfate reduction during sedimentation or diagenesis.

Limited hydrogen and oxygen isotope analyses reveal hydrothermal effects in metasedimentary wall rocks to the ores. Decreases in δD and $\delta^{18}O$ have been observed within meters to perhaps a few hundred meters of the Co-Cu-Au deposits, consistent with fluid-rock isotope exchange at elevated temperatures. Carbon isotopes in carbonate minerals show evidence for multiple carbon sources, including sedimentary organic matter (or mobile hydrocarbons derived therefrom), and magmatic or metamorphic CO_2.

Metasedimentary Host Rocks

The depositional environment of the metasedimentary host rocks to most of the deposits considered herein is obscured by metamorphism and deformation. However, at Blackbird, the host rocks probably originated as turbidite flows and, to a lesser extent, as fine-grained marine sandstones (see discussion in Lund and Tysdal, 2007). Near Blackbird, a separate, thrust-bounded package of shallow-water siliciclastic rocks includes scapolite-bearing metacarbonate layers that originated as evaporates (Lund and Tysdal, 2007). In some analogous Co-Cu-Au deposits elsewhere, evaporative or exhalative rocks also are present regionally in strata that are broadly correlative with the mineralized sequence.

Metamorphic grade of the Blackbird host rocks is middle greenschist to lower amphibolite facies. Host rocks in several similar deposits are at granulite grade. The metamorphic mineralogy is similar to that of the unmetamorphosed, stratigraphically equivalent rocks (muscovite, biotite, feldspar, quartz), but the original sedimentary grains were coarsened by metamorphism, producing fine- to medium-grained schist or gneiss.

The metamorphic fabrics change across the region and the Blackbird district from fold-related cleavage in middle greenschist-facies rocks, to transposed layering and axial-planar foliation in upper greenschist-facies rocks, and to intrafolial foliation and metamorphic compositional layering in lower amphibolite facies rocks (Lund and Tysdal, 2007). Because of the range in metamorphic grades, the geometries of resultant mineralized zones range from bedding-oblique cleavage zones to metamorphic-tectonite-parallel zones. The complex sequence of sulfide and gangue minerals invaded the regional metamorphic fabrics, and the resultant mineralized zones were deformed further during continued tectonism. The range of metamorphic mineral assemblages and fabrics across the Blackbird district includes variations in metamorphic grade and fabric of country rocks; grain size, metamorphic mineral assemblage, and complexity of mineralized zones; and the proportions of different metals in the mineralized zones. From the textural and fabric evidence, the structurally concordant ore assemblages formed during peak to post-peak metamorphic and syntectonic to late syntectonic phases (Lund and Tysdal, 2007). In previous studies, the compositional layer-parallel geometry of the deposits led to interpretations that these were originally stratiform deposits and that the original metal deposition was synsedimentary or synvolcanic in origin (Earhart, 1986; Nash and Hahn, 1989; Evans and others, 1995). Late-metamorphic, brittle, discordant structures controlled late-phase mineralization. Analogous deposits also display evidence of late-stage mineralization during late-tectonic or retrograde metamorphism.

Petrology of Related Igneous Rocks

Intrusive igneous rocks temporally associated with Co-Cu-Au deposits range in composition mostly from diorite, granodiorite, tonalite, monzodiorite, and quartz monzonite to granite and syenogranite. Intrusions may show evidence for mixing and mingling of granitoid melts with more basic magma (for example, Pollard and others, 1998), such as in the Blackbird region where coeval granite and gabbro were emplaced about 1.37 Ga (Doughty and Chamberlain, 1996; Aleinikoff and others, 2010). Quartz monzonites and granites locally have well-developed, rapakivi-textured K-feldspar. Textures range from medium- to coarse-grained hypidiomorphic granular to porphyritic. Chemically, the intrusive rocks are mostly subalkaline to alkaline, high-potassium to shoshonitic, metaluminous to weakly peraluminous, I- to A-type granitoids. The intrusions occurring in Proterozoic provinces are mainly ilmenite series (reduced) and contain abundant highly incompatible trace elements such as Th, U, Nb, Ta, Zr, Hf, and light REE, plotting in within-plate fields on tectonic discrimination diagrams (Pollard and others, 1998; Pollard, 2006). Their geochemical and isotopic characteristics suggest that they are mainly products of partial melting of older crust, possibly as a result of underplating and (or) intrusion into the lower crust of mantle-derived magmas.

Mafic rocks, generally in the form of dikes and sills, are typically present in proximity to Co-Cu-Au deposits and have been suggested as possible sources of some ore components, such as Ni and Co (Pollard, 2000). Although the timing of mafic magmatism generally is not well defined, in some cases field relationships suggest commingling of felsic and mafic magma and that the mafic magmatism was comagmatic with the felsic plutons (Doughty and Chamberlain, 1996). In the Blackbird district, mafic intrusions have within-plate, alkali basalt-like compositions (Nash and Hahn, 1989), but in other areas they are continental tholeiitic basalts (Frost and Frost, 1997).

The importance of igneous rocks to Co-Cu-Au deposits is unclear, in part because many deposits show a clear temporal, but not spatial, relationship to major magmatic intrusions like the settings of many IOCG deposits (Groves and others, 2010). However, abundant isotopic data, including both radiogenic and stable isotopes, and fluid inclusion data from a number of IOCG deposits suggest that magmatic fluids were a major contributor to ore formation (Pollard, 2000; 2006; Williams and others, 2005). Similar studies are needed on Co-Cu-Au deposits in metasedimentary rocks in order to better evaluate possible genetic links between magmatism and mineralization.

Genetic Models

The broadly stratabound character of mineralized zones in most of the Co-Cu-Au deposits considered herein led many previous workers to invoke syngenetic mineralizing processes like those that formed VMS and SEDEX deposits. However, reevaluation of these deposits in the present study instead suggests an origin involving epigenetic hydrothermal processes long after sedimentation and diagenesis. The presence in most of the Co-Cu-Au deposits of magnetite-rich rocks, abundant K-rich (biotite) minerals or Na-rich (albite) minerals in altered wall rocks, and in some cases high concentrations of Y, REE, and U, provides permissive evidence for a link to IOCG-type deposits (for example, Davidson and Large, 1998; Hitzman, 2000; Williams and others, 2005; Corriveau, 2007). In this speculative model, the metasedimentary-hosted Co-Cu-Au deposits described herein may represent a Co-rich variant of IOCG deposits, similar to the Cloncurry-type category of Corriveau (2007). It is important to note, however, that the highly deformed and metamorphosed character of most of the Co-Cu-Au deposits obscures or masks primary features of hydrothermal mineralogy, texture, and alteration, such that discerning the nature and timing of original mineralization is difficult at best. Testing an IOCG model for the deposits included in this report will require more detailed geological, geochemical, and mineralogical studies, including high-precision U-Pb dating and (or) other geochronological methods in order to better evaluate the age of mineralization in each deposit relative to the history of local sedimentation, diagenesis, metamorphism, and plutonism.

Geophysical Characteristics

Owing to the presence of magnetite in many metasediment-hosted Co-Cu-Au deposits, regional geophysical surveys that include magnetics and gravity can be useful in identifying potentially mineralized zones. Significantly, deposits are not necessarily coincident with a discrete magnetic anomaly but typically occur in areas having “magnetically active” signatures (Smith, 2002). Aeromagnetic data have been obtained for the Idaho cobalt belt where the Blackbird deposit lies on the southwest flank of a prominent magnetic trough that parallels the belt (Evans and others, 1995; Lund and others, 1989). Aeromagnetic data, together with very-low-frequency (VLF) electromagnetic surveys, aid in identifying regional-scale, structural lineaments, faults, and shear zones that may be important in localizing deposits. The presence of plutonic bodies, however, can have a strong control on regional geophysical patterns (for example, the Idaho cobalt belt; Lund and others, 1989), potentially complicating interpretations.

Because highly potassic (biotite or K-feldspar) and (or) sodic (albite) alteration commonly forms halos around the deposits, regional radiometric surveys can be useful in recognizing alteration in areas where unweathered rocks are exposed at the surface (Wellman, 1999; Goad and others, 2000). For example, in the Lou Lake area, Northwest Territories, Canada, the NICO deposit is associated with discrete positive eK and negative eTh/K anomalies that are coincident with positive magnetic anomalies

(Goad and others, 2000). Areas having high U concentrations also are characterized by increased eU/Th anomalies.

Deposit-scale geophysical signatures are typically more complex than regional features. Abundant magnetite will produce characteristically strong positive magnetic anomaly (values up to 16,000 nanoteslas (nT) above background); however, a predominance of hematite tends to yield only low-intensity anomalies (Goad and others, 2000). Because iron oxides and related iron-rich silicate minerals have relatively high densities (5.2 g/cm^3 and 3.0 to 3.4 g/cm^3, respectively) compared with those of typical continental crust (2.5 to 2.7 g/cm^3), the resulting density contrast may generate subtle to distinct Bouguer-gravity anomalies (Goad and others, 2000; Smith, 2002). A range of electrical methods has been used for direct detection of these deposits, because most deposits are at least weak conductors. Transient electromagnetic methods (TEM) and induced polarization (IP) have been generally successful in detecting these deposits, but they also respond to the presence of both iron oxides and barren sulfides, which commonly are more laterally extensive than the target mineralized zone. Standard electromagnetic geophysical methods (EM) have generally not been as successful, probably because massive, continuous mineralization is rare in many of the deposits considered herein.

Geoenvironmental Features and Anthropogenic Mining Effects

The environmental geochemistry of Co-Cu-Au deposits was evaluated using published data for mine waste, stream sediment, soil, mine runoff water, and stream water collected in the Blackbird area. No published environmental geochemical data are known for other, similar Co-Cu-Au deposits elsewhere; therefore the descriptions herein are limited to data for deposits in the Blackbird district. Because host rocks to these deposits are mostly fine-grained siliciclastic metasedimentary strata with little carbonate, surrounding rocks have little acid neutralizing capacity. As a result of mining, greater than 3,500,000 m^3 of tailings are estimated to be present in the Blackbird Creek area (Beltman and others, 1993). Weathering of Blackbird deposits and mine wastes results in a high potential to generate acidic water in mine runoff, and stream water of pH 2 to 4 has been reported (Beltman and others, 1993). Acid water generation is primarily due to the oxidation of sulfide minerals such as pyrite and pyrrhotite. Metal concentrations in mine runoff water and sediment are highly elevated relative to regional baseline concentrations; several studies have indicated that the most problematic contaminants of concern are Co, Cu, As, Fe, and Mn (Rocky Mountain Consultants, 1995; Mebane, 1997; CH2MHill, 2001; Eppinger and others, 2003; Giles and others, 2009).

Analyses of unfiltered stream water in the Blackbird area indicate that concentrations of Co, Cu, Fe, and Mn generally exceed drinking water or chronic aquatic life standards (intended to be protective of the majority of the aquatic communities), whereas concentrations of As in water are generally below established standards. Concentrations of Cu in stream water collected below mines vary from 18 to 49,000 µg/L; most samples exceed the U.S. Environmental Protection Agency (USEPA) drinking water standard for Cu of 1,000 µg/L and the chronic aquatic life standard of 2.7 µg/L (at a water hardness of 25 mg/L). No water standards have been established for Co, but concentrations of Co are as high as 1,470,000 µg/L in mine runoff water in the Blackbird area, whereas Co contents are much lower in stream water collected from regional uncontaminated sites, ranging from <0.02 to 6.3 µg/L. Concentrations of As in water are a potential human health concern because As is highly toxic and a known carcinogen. Stream water samples contain As that varies from <1 to 18 µg/L, most being below the USEPA drinking water standard for As of 10 µg/L; all are below the chronic aquatic life standard of 190 µg/L with the exception of one water seep containing As of 930 µg/L. Mine water runoff and streams proximal to mines contain Fe concentrations varying from <6.8 to 159,000 µg/L. Most water samples exceed the USEPA secondary (maximum contaminant limit goal) drinking water standard for

Fe of 300 µg/L and the USEPA chronic aquatic life standard of 1,000 µg/L for Fe. The only established water standard for Mn is the USEPA secondary drinking water standard of 50 µg/L. Concentrations of Mn vary widely in mine water runoff and streams in the Blackbird area, ranging from 2.5 to 35,000 µg/L, many of which exceed the drinking water standard for Mn.

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