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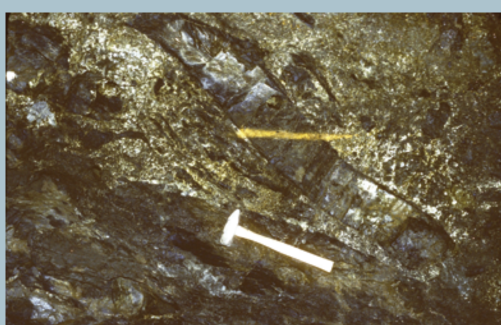
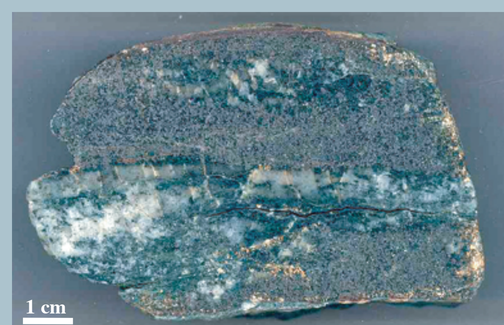
Descriptive and Geoenvironmental Model for Cobalt-Copper-Gold Deposits in Metasedimentary Rocks




Scientific Investigations Report 2010–5070–G

U.S. Department of the Interior
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COVER. Upper left, Blacktail open pit in the Blackbird district, central Idaho, U.S.A.; view looking approximately northwest (bulldozer for scale in bottom center). Upper right, Skuterud open pit in the Modum district, southern Norway; view looking south (wooden fence on left is about 1.5 meters high). Middle left, South Idaho underground mine in the Blackbird district, showing stratabound lenses and discordant veins of Cu-rich sulfide in dark argillite wall rock. Middle right, hand sample from the Sunshine open pit in the Blackbird district, showing layers of granoblastic cobaltite with a matrix of white quartz and dark green chlorite. Lower left, underground photo of the Skuterud mine showing pink secondary erythrite (a hydrated cobalt arsenate mineral). Lower right, water sampling of acid mine drainage in the Blackbird district, view looking approximately east.

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Edited by John F. Slack

Chapter G of
Mineral Deposit Models for Resource Assessment

Scientific Investigations Report 2010–5070–G

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

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Conversion Factors

Inch/Pound to SI

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)	1.0567	quart (qt)
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)
gram (g)	0.03220	ounce, troy (t oz)
tonne (t)	1.10231	ton, short
tonne (t)	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

Abbreviations Used in This Report

Units of Measure

Ga giga-annum, billion years (b.y)

Ma mega-annum, million years

μg/L micrograms per liter

mg/L milligrams per liter

per mil parts per thousand

ppm parts per million

mGal milligal

mS/m milliSiemens per meter

Mt million metric tonnes

nT nanoTeslas

ohm-m ohm-meter

Symbols

δD	delta deuterium (hydrogen-2)
$\delta^{18}O$	delta oxygen-18
$\delta^{34}S$	delta sulfur-34
eK	equivalent potassium
eTh/K	equivalent thorium/potassium ratio
eU/Th	equivalent uranium/thorium ratio

Chemical elements and compounds

Ag	silver
As	arsenic
Au	gold
Ba	barium
Be	beryllium
Bi	bismuth
Br	bromine
C	carbon
Ca	calcium
Cl	chlorine
Co	cobalt
CO_2	carbon dioxide
Cu	copper
F	fluorine
Fe	iron
Hf	hafnium
Hg	mercury
H_2O	water
H_2S	hydrogen sulfide
K	potassium
Mn	manganese
Mo	molybdenum
Na	sodium
Nb	niobium
Ni	nickel
O	oxygen
P	phosphorus
Pb	lead
S	sulfur
SO_4	sulfate
Ta	tantalum
Te	tellurium
Th	thorium
U	uranium
W	tungsten
Y	yttrium
Zn	zinc
Zr	zirconium

Initialisms

b.y.	billion years
EPA	U.S. Environmental Protection Agency
IOCG	iron oxide-copper-gold
REE	rare earth elements

SEDEX	sedimentary-exhalative
SHRIMP	sensitive high-resolution ion microprobe
USGS	U.S. Geological Survey
VMS	volcanogenic massive sulfide

1. Introduction

By John F. Slack

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Contents

Table

1. Introduction

By John F. Slack

This report is a revised model for a specific type of cobalt-copper-gold (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 (see Ferrero and others, 2012). Emphasis is on providing an up-to-date 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 deposits in the Blackbird mining district of central Idaho. This report is a broader synthesis of information on 19 Co-Cu-Au deposits occurring in predominantly metasedimentary successions worldwide (table 1–1) that generally share common geologic, mineralogical, and geochemical features; preliminary summary versions were presented in Slack and others (2010) and Slack and others (2011), which are superseded by this report. As defined herein, the individual Co-Cu-Au deposits are located more than 500 meters from similar deposits and contain 0.1 percent or more by weight of Co in ore or mineralized rock; some deposits included in the database lack reported average Co grades, but they contain high Co concentrations, at least locally. Most of the deposits also have high As contents, present in Co arsenide and sulfarsenide minerals. Type examples of the Co-Cu-Au deposits are those in the Blackbird district, Skuterud in Norway, and Kouvervarra and Juomasuo in Finland. Some deposits in the database have low grades for Cu (for example, NICO in Canada) or Au (for example, Lemmonlampi in Finland), but these deposits are included because their geological, mineralogical, and alteration features are similar to those of the type examples. Several deposits included in the model are partly hosted by metavolcanic or metaigneous rocks (including granite), but regionally these deposits are within metasedimentary successions; no deposits are wholly within granite or other plutonic igneous intrusions.

Despite having a lower average Co grade, the Mt. Cobalt deposit in Australia is included here because it has past Co production from higher-grade ore zones (Nisbet and others, 1983). The Black Pine deposit in the Idaho cobalt belt is included because it contains mineable Co- and Au-rich lenses within Cu-rich mineralized zones (Formation Metals, Inc., 2012). Six deposits that lack data for average Co grades are also included because each reportedly contains abundant Co (>0.1 weight percent Co), at least locally. Many of the deposits are noteworthy as possible resources of Ag, Bi, W, Ni, Y, REE, and (or) U. Detailed data on the deposits listed in table 1–1, including references, are available in appendix 1. Significantly, the grouping in this report of Co-Cu-Au deposits in metasedimentary rocks into a single model includes deposits that other workers have previously classified in different ways. For background information, a global overview of different types of Co deposits worldwide is given in Smith (2001).

Additional geologically and compositionally similar deposits are known, but have average Co grades less than 0.1 percent. Most of these deposits contain cobalt-rich pyrite and lack appreciable amounts of distinct Co sulfide and (or) sulfarsenide minerals. Such deposits are not discussed in detail in the following sections, but these deposits may be revelant to the descriptive and genetic models presented below. Examples include the Scadding Au-Co-Cu deposit in Ontario, Canada; the Vähäjoki Co-Cu-Au deposit in Finland; the Tuolugou Co-Au deposit in Qinghai Province, China; the Lala Co-Cu-U-REE deposit in Sichuan Province, China; the Guelb Moghrein Cu-Au-Co deposit in Mauritania; and the Great Australia Co-Cu, Greenmount Cu-Au-Co, and Monakoff Cu-Au-Co-U-Ag deposits in Queensland, Australia. Detailed information on these deposits is presented in appendix 2.

Table 1–1. Selected features of Co-Cu-Au deposits in metasedimentary rocks.

[%, percent; g/t, grams per tonne, Mt, million metric tonnes; NA, not available; m, meters. Data sources are in appendix 1]

Deposit	Country	Size (Mt)	Co (%)	Cu (%)	Au (g/t)	Major metals	Minor associated metals
Blackbird-ICB[1]	USA	16.80	0.735	1.37	1.04	Co, Cu, As, Au, Bi	Y, REE, Ni, Zn, U, Be
Black Pine[2]	USA	1.0	0.08	4.5	1.03	Co, Cu, As, Au	
Cobalt Hill	Canada	NA	NA	NA	NA	Co, Cu, Au, As	Ni, Hg, Te
Contact Lake Belt	Canada	NA	NA[3]	NA[3]	NA[3]	Cu, Au, As, Co, U	Bi, Ag, Zn
Werner Lake	Canada	1.34	0.27	0.27	0.31	Cu, Co, Au, As	Mo, Zn, Ag, Ni
NICO	Canada	[4]30.99	0.12	0.04	0.91	Co, Au, Bi, Cu, As	Ni, W, Mo, Te, Se, REE, F
Skuterud	Norway	1.0[5]	[5]0.26	2	1	Cu, Co, Au, As	Ni, U, Th
Gladhammar	Sweden	0.006	NA	NA	NA	Co, Cu, As, Au	Fe, Zn, Pb, Mo, Bi
Haarakumpu	Finland	4.68	0.17	0.34	NA	Co, Cu, As	Au, Bi, Ni
Hangaslampi[6, 11]	Finland	0.369	0.07	NA	5.0	Au, Co, As	Cu, REE, Ni, U, Mo, Pb, W
Juomasuo[7, 12]	Finland	5.04	0.13	0.03	1.96	Au, Co, As	Cu, Mo, Ni, REE, U, Bi, Te
Kouvervaara	Finland	1.58	0.1	0.2	0.4	Co, Cu, Au, As	Zn, Mo, Bi, W
Lemmonlampi	Finland	0.09	0.3	0.4	0.35	Co, Cu, Au, As	
Meurastuksenaho[8]	Finland	0.366	0.25	0.28	3.6	Co, Au, Cu, As	Mo, U, REE
Pohjasvaara[9]	Finland	0.095	0.1	0.3	4.9	Co, Cu, Au, As	Fe, Hg, Mo, Se, Te, U
Sirkka	Finland	0.25	0.1	0.38	0.8	Co, Ni, Au, Cu, As	U, Zn, Ag
Mt. Cobalt	Australia	[10]0.06	0.05	0.33	NA	Cu, Co, As, REE	W, Ni, Au
Kendekeke	China	NA	NA	NA	NA	Co, Bi, Au, As, Cu	Zn, Pb, Te
Dahenglu	China	NA	NA	NA	NA	Co, Cu, As	Zn, Pb

[1]ICB, Idaho cobalt belt; includes 14 separate deposits (appendix 1) including Idaho, Dandy, Chicago, Brown Bear, Blacktail, Merle, Horseshoe, Burl, Northfield, Ram, Sunshine, and East Sunshine.

[2]Contains mineable Co- and Au-rich lenses within Cu-rich zones (Formation Metals, Inc., 2012)

[3]0.27% Cu, 0.10% Co, 1.31% As, 0.15 g/t Au over 24 m.

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

[5]Estimate by the Geological Survey of Norway (T. Bjerkgård, oral commun., 2010).

[6]Recent exploration has identified drill core intervals having 156.9 g/t Au over 2.6 m and 30.2 g/t Au over 9.0 m (Dragon Mining Ltd., 2012a).

[7]Locally has Cu grades as high as 1% (Vanhanen, 2001) and Au grades as high as 45.7 g/t over 31.9 m (Dragon Mining Ltd., 2012a).

[8]Recent exploration has delineated a resource of 0.89 Mt at 0.20% Co and 2.3 g/t Au (Dragon Mining Ltd., 2012a).

[9]Recent exploration has delineated a resource of 0.13 Mt at 0.15% Co and 4.2 g/t Au (Dragon Mining Ltd., 2012a).

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

[11]A new mineral resource (measured+indicated+inferred) has been delineated for separate cobalt and gold domains, being 0.329 Mt @ 0.10% Co and 0.403 Mt @ 0.06% Co and 5.1 g/t Au, respectively (Dragon Mining Ltd., 2012b).

[12]A new mineral resource (measured+indicated+inferred) has been delineated for separate cobalt and gold domains, being 3.675 Mt @ 0.12% Co and 1.941 Mt @ 0.14% Co and 4.8 g/t Au, respectively (Dragon Mining Ltd., 2012b).

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2. Deposit Type and Associated Commodities

By John F. Slack, Craig A. Johnson, and J. Douglas Causey

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2. Deposit Type and Associated Commodities

By John F. Slack, Craig A. Johnson, and J. Douglas Causey

Name and Synonyms

The deposits described in this report are collectively termed Co-Cu-Au deposits in metasedimentary rocks. This is a new model name that is designed to include all deposits of this type that share similar geological, mineralogical, and geochemical features. Previous workers have used the terms "Blackbird sediment-hosted Cu-Co" (Höy, 1995) and "Blackbird Co-Cu deposits" (Earhart, 1986; Evans and others, 1995) to refer to deposits occurring in the Blackbird district of east-central Idaho.

Brief Description

The Co-Cu-Au deposits consist of disseminated to semi-massive Co-bearing sulfarsenide and sulfide minerals with associated Fe- and Cu-bearing sulfides, and local gold, concentrated predominantly in rift-related, siliciclastic metasedimentary successions chiefly of Proterozoic age.

Associated Deposit Types

Other types of mineral deposits that may have genetic links to the Co-Cu-Au deposits described in this report are iron oxide-copper-gold (IOCG) deposits (Williams and others, 2005; Corriveau, 2007). Some of the deposits classified here as Co-Cu-Au deposits in metasedimentary rocks have been classified by other workers as Co-rich variants of IOCG deposits (Slack, 2013; Slack, 2012). Volcanic-hosted analogs to the deposits in this model may include Co-Cu-Au deposits such as Kiskamavaara in northern Sweden (Martinsson, 2011). There are also mineralogical and geochemical similarities with some sediment-hosted stratiform copper deposits (Hitzman and others, 2005, 2010) and with so-called "five-element veins" (Kissin, 1992; Smith, 2001), but both of these deposit types have different geological features and settings, as discussed later in this volume, in Theory of Deposit Formation. The Co-Cu-Au deposits considered here, including those that have a stratabound morphology, lack clear metallogenic associations with other stratabound deposits, such as sedimentary-exhalative (SEDEX) deposits (Goodfellow and Lydon, 2007; Emsbo, 2009), sediment-hosted copper deposits (Hitzman and others, 2005, 2010), and volcanogenic massive sulfide (VMS) deposits (Galley and others, 2007; Shanks and Thurston, 2012).

Primary and Byproduct Commodities

The primary commodities of the deposits considered in this report (table 1–1) are Co, Cu, and Au. Some deposits have very high Au contents, whereas others have low Au. High As contents are characteristic of all of the deposits. Potential mining byproducts among the deposits are Ag, Bi, Mo, Ni, Pb, REE, U, W, Y, and Zn.

Trace Constituents

Metals and other elements that may be present as non-economic but anomalous trace constitutents in the Co-Cu-Au deposits include Ba, Be, F, P, Se, and Te.

Example Deposits

Among the 19 Co-Cu-Au deposits considered here, several stand out as well-documented examples of the deposit type. Based on availability of detailed data, relatively large size, and favorable metal grades, premier examples of the Co-Cu-Au deposits are Blackbird in Idaho (14 deposits; Bookstrom and others, 2007; appendix 1), Modum in Norway (Grorud, 1997), Werner Lake in Ontario in Canada (Pan and Therens, 2000), and Juomasuo in Finland (Vanhanen, 2001).

Tonnage-Grade Variations

A tonnage-grade plot (fig. 2–1) shows that most of the Co-Cu-Au deposits described in this report constitute known resources of 100 to 10,000 metric tonnes (t) of contained Co. Sizes of the Co-Cu-Au deposits overlap those of sedimentary Cu deposits of the central African copperbelt in terms of Co content; the Kamoto and related deposits in the Democratic Republic of Congo contain the greatest amount of cobalt. With the exception of the Blackbird district in central Idaho (123,480 t of Co in 16.8 million tonnes [Mt] at 0.735 percent combined production + reserves + resources for 14 deposits), the different Co-Cu-Au deposits considered here have smaller Co resources than two individual Co-rich VMS deposits (Windy Craggy, British Columbia, Canada; Outokumpu, Finland), and numerous magmatic Ni-Cu deposits (for example, Noril'sk-Talnakh, Russia). Some large cobaltiferous IOCG deposits, such as Olympic Dam and Ernest Henry in Australia, contain significant Co resources (fig. 2–1), although Co is not currently produced from either deposit. Despite the smaller Co tonnages 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 other Co reserves of likely economic viability (Shedd, 2012).

The only other individual deposit in the United States having a significant Co resource is Sheep Creek in western Montana, a stratiform, sediment-hosted deposit containing 12,700 t of Co in 12.2 Mt of ore at 0.106 percent Co (Tintina Resources, Inc., 2011). The greatest known potential Co resource in the United States is in the magmatic Ni-Cu deposits of the Duluth Complex in northeastern Minnesota, totaling 626,000 t of Co in 4,000 Mt of mineralized rock at 0.019 percent Co (Naldrett, 2004). The large Cornwall, Pennsylvania, iron deposit (84.5 Mt production; Lapham, 1968) contained appreciable Co in pyrite within replacement ores in limestone adjacent to a diabase intrusion, but no average Co grades are available. Elevated Co contents occur in some Mississippi Valley-type Pb-Zn deposits of southeastern Missouri, including

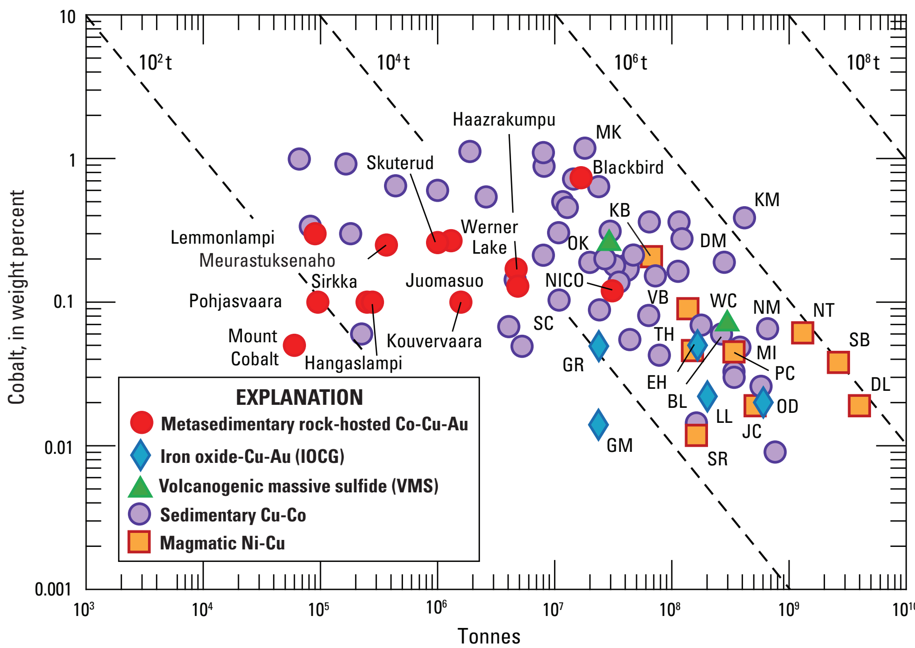

Figure 2–1. Tonnage-grade data for Co-Cu-Au deposits in metasedimentary rocks compared to data for other types of Co-bearing deposits. Not included are data for Co-bearing laterite deposits (for example, in New Caledonia, Cuba, and Cameroon); see Lambiv Dzemua and Gleeson, 2012, and references therein. Dashed lines show amounts of contained cobalt in tonnes (t). All Co-Cu-Au deposits plotted here are in Finland except NICO (Canada), Blackbird (USA), Black Pine (USA), Skuterud (Norway), Werner Lake (Canada), and Mt. Cobalt (Australia); complete data for these and similar deposits are in appendixes 1 and 2. Abbreviations for other types of deposits: BL, Boleo (Mexico); DL, Duluth (USA); DM, Dima (D.R. Congo); EH, Ernest Henry (Australia); GM, Guelb Moghrein (Mauritania); GR, Greenmount (Australia); JC, Jinchuan (China); KB, Kambalda (Australia); KM, Kamoto and related deposits (D.R. Congo); LL, Lala (China); MI, Mount Isa (Australia); MK, Mukondo (D.R. Congo); NM, Nkana-Mindola (Zambia); NT, Noril'sk Talnakh (Russia); OD, Olympic Dam (Australia); OK, Outukumpu-Keretti (Finland); PC, Pechenga (Russia); SB, Sudbury (Canada); SC, Sheep Creek (Montana); SR, Santa Rita (Brazil); TH, Thompson (Canada); VB, Voisey's Bay (Canada); WC, Windy Craggy (Canada). Sources of data: metasedimentary rock-hosted Co-Cu-Au deposits (table 1–1; appendix 1); iron oxide-Cu-Au deposits (Williams and Pollard, 2001; Kolb and others, 2006; Chen and Zhou, 2012); volcanogenic massive sulfide deposits (Peter and Scott, 1999; Eilu and others, 2003); sedimentary Cu-Co deposits (Gustafson and Williams, 1981; Wilson and others, 2013; Baja Mining Corp., 2011; Tintina Resources Inc., 2011); magmatic Ni-Cu deposits (Naldrett, 2004; Mirabela Nickel Ltd., 2011); data for the Mount Isa Cu deposit are from Croxford (1974), Mudd (2007), and Mining-technology.com (2012).

Mine La Motte-Fredericktown that contained an average of 0.2 percent Co (Seeger, 2008, and references therein), and the Higdon deposit that has a high Co grade of 0.14 percent (Parra and others, 2009), but no defined tonnage. High Co contents are also present in parts of the Boss-Bixby Fe-Cu-Co deposit in southeastern Missouri (Hagni and Brandom, 1993); no average Co grade is available. The large deposits of the Viburnum Trend also contain elevated Co, but this metal is not recovered during mining (Seeger, 2008). A possible Co resource also may exist in the large Ruby Creek (Bornite) Cu deposit in northern Alaska, which contains more than 100 Mt of potential ore with local concentrations of Co (Bernstein and Cox, 1986). Other potential Co resources in the United States are discussed in Peterson and others (1981). A recent report by Wilburn (2012) summarizes global mineral exploration and supply of cobalt from 1995 through 2013.

The relation of average Co grades versus average Cu (A) and Au (B) grades is shown in figure 2–2. 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 numerous Co-rich sedimentary Cu deposits of the central African copperbelt. Relatively high As and Au grades are key distinguishing features of the metasedimentary Co-Cu-Au deposits. Four of the Finnish deposits (table 1–1) average 2.0 to 6.2 grams per metric tonne (g/t) Au; recent exploration drilling of the Juomasuo and Hangaslampi deposits has identified very high grades of 10-45 g/t Au over intervals of as much as 25–35 m (Dragon Mining Ltd., 2012). By comparison, cobaltiferous sedimentary Cu, VMS, and IOCG deposits have less than 1 g/t Au, except the Guelb Moghrein (Mauritania) IOCG deposit that contains an average of nearly 1.5 g/t Au.

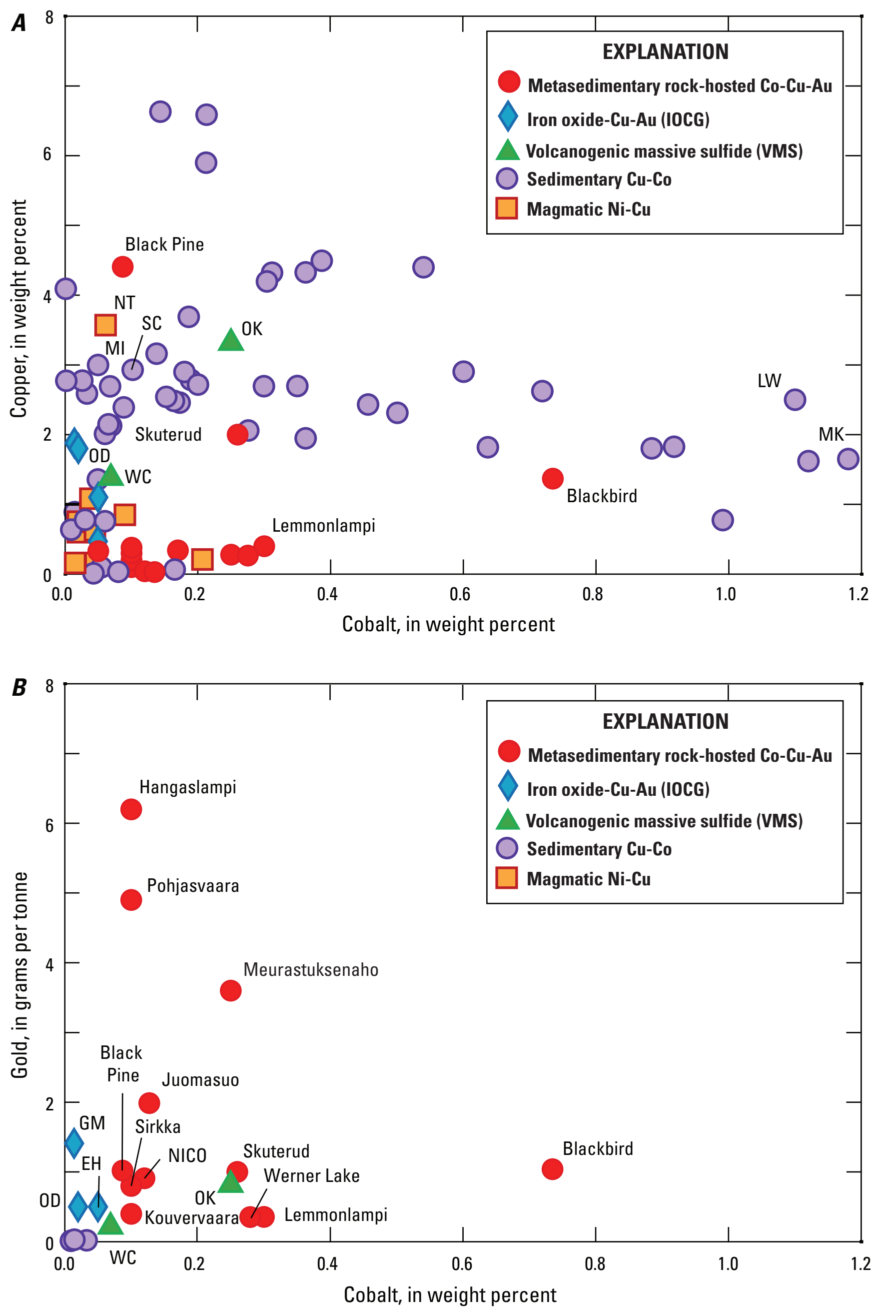

Figure 2–2. Co versus Cu (*A*) and Co versus Au (*B*) data for Co-Cu-Au deposits in metasedimentary rocks compared to those for other Co-bearing deposits. In *A*, sedimentary Cu-Co deposits having very high Cu grades (>4 weight percent) contain abundant supergene Cu. In *B*, samples without reported gold grades are not plotted. EH, Ernest Henry (Australia); GM, Guelb Moghrein (Mauritania); LW, Luiswishi (D.R. Congo); MI, Mount Isa (Australia); MK, Mukondo (D.R. Congo); NT, Noril'sk Talnakh (Russia); OD, Olympic Dam (Australia); OK, Outukumpu-Keretti (Finland); SC, Sheep Creek (Montana); WC, Windy Craggy (Canada). Sources of data: metasedimentary rock-hosted Co-Cu-Au deposits (table 1–1; appendix 1); iron oxide-Cu-Au deposits (Williams and Pollard, 2001; Kolb and others, 2006; Chen and Zhou, 2012); volcanogenic massive sulfide deposits (Peter and Scott, 1999; Eilu and others, 2003); sedimentary Cu-Co deposits (Gustafson and Williams, 1981; Wilson and others, 2013; Baja Mining Corp., 2011; Tintina Resources Inc., 2011); magmatic Ni-Cu deposits (Naldrett, 2004; Mirabela Nickel Ltd., 2011); data for the Mount Isa Cu deposit are from Croxford (1974), Mudd (2007), and Mining-technology.com (2012).

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3. Historical Evolution of Descriptive and Genetic Knowledge and Concepts

By John F. Slack

Descriptive and Geoenvironmental Model for Cobalt-Copper-Gold Deposits in Metasedimentary Rocks

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Contents

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Diverse models have been proposed for the origin of the Co-Cu-Au deposits considered in this report (table 1–1). For example, in the Blackbird district of east-central Idaho, the discordant character of vein and breccia deposits was highlighted by early workers, such as Anderson (1947), Vhay (1948), and Bennett (1977), as evidence of granite-related hydrothermal processes. In contrast, the broadly stratabound ores in the district were interpreted by numerous workers (Hughes, 1983; Modreski, 1985; Eiseman, 1988; Nash, 1989; Nash and Hahn, 1989; Nold, 1990) to be products of syngenetic mineralization, which formed prior to deformation and metamorphism either by volcanogenic massive sulfide (VMS) or sedimentary-exhalative (SEDEX) processes (see Galley and others, 2007; Goodfellow and Lydon, 2007). These pre-lithification, syngenetic to early diagenetic models were adopted by USGS and other workers including Earhart (1986), Evans and others (1995), Johnson and Bennett (1995), Höy (1995), and Bending and Scales (2001). It is important to note, however, that the stratabound morphology of the deposits does not require formation by syngenetic or early diagenetic processes, because such a morphology can equally reflect post-lithification mineralization along favorable structures, such as faults and shear zones, or the replacement of reactive beds, such as limestone. Ore deposition by these types of processes may occur prior to, during, or after regional metamorphism. Bookstrom and others (2007), for example, suggested that both the stratabound and discordant deposits in the Blackbird mine area formed initially as chemical sediments, but were subsequently recrystallized, remobilized, and possibly enriched in metals during Cretaceous regional metamorphism. A predominantly synmetamorphic Cretaceous origin for the deposits was proposed recently by Lund and others (2011), whereas a mainly pre-metamorphic Mesoproterozoic origin has been suggested by Slack (2012).

The Co-Cu-Au deposits in metasedimentary rocks elsewhere have also been attributed to diverse mineralizing processes. In the Modum district of southeastern Norway, stratabound Co-Cu-Au ores were the major source of cobalt blue pigment used in Europe during the late 18th and 19th centuries. These ore deposits were interpreted by Rosenqvist (1948) as having formed epigenetically from fluids related to nearby mafic intrusive rocks. Bugge (1978) invoked syngenetic processes linked to submarine volcanism; Gammon (1966) viewed the deposits as metamorphosed analogs of the polymetallic “five-element” veins of Cobalt, Ontario (for example, Kissin, 1992). A genetic model by Jøsing (1966) proposed a connection between the cobalt mineralization and synmetamorphic metasomatic formation of albitite in the district. Grorud (1997), on the basis of detailed textural and paragenetic studies, suggested that the Co sulfides and sulfarsenides in the Skuterud deposit formed contemporaneously with U and Th minerals during the Mesoproterozoic, prior to Sveconorwegian (1070- to 1040-mega-annum [million years, Ma]) metamorphism. Andersen and Grorud (1998) obtained Mesoproterozoic Pb-Pb ages on thorian uraninite intergrown with the Co sulfides and sulfarsenides, supporting this model of pre-Sveconorwegian sulfide mineralization.

Formation of the stratabound Co-Cu-Au Werner Lake deposit in Ontario, Canada, was attributed to post-metamorphic skarn processes by Parker (1998), whereas Pan and Therens (2000) suggested a syngenetic to diagenetic origin for the deposit. A predominantly syn- and post-metamorphic timing for mineralization has been proposed for the Mt. Cobalt Cu-Co-W-REE deposit in Queensland, Australia (Nisbet and others, 1983), and the Co-Au-U deposits of the Kuusamo schist belt of northeastern Finland (Pankka and Vanhanen, 1992; Eilu and others, 2003), respectively. Pankka (1997) and Eilu and others (2003) invoked an orogenic gold model (for example, Goldfarb and others, 2005) for the Kuusamo belt mineralization. Stratabound Co-rich deposits in China, such as Dahenglu (Co-Cu-Zn-Pb) and Kendekeke (Co-Bi-Au), have been interpreted as syngenetic in origin (Yang and others, 2001; Pan and Sun, 2003); the Tuolugou Co-Au deposit, which has a relatively low average Co grade of 0.06 weight percent, is also viewed as syngenetic in origin based on Re-Os isotope dating (Feng and others, 2009).

Studies of several of the Co-Cu-Au deposits have led workers to propose an epigenetic hydrothermal model and classification as iron oxide-copper-gold (IOCG) deposits. In addition to commonly abundant iron oxides, Cu, and Au, such IOCG deposits may contain economic concentrations of U, Co, rare earth elements (REE), Y, Ni, and Ag (Williams and others, 2005). With respect to the Co-Cu-Au deposits considered in this report, the first study to suggest an IOCG-related origin was Goad and others (2000) for the NICO Co-Bi-Au-Cu-Ni deposit in Northwest Territories, Canada. This was based on evidence from geology (Proterozoic rift setting), mineralogy (abundant iron oxides, K-feldspar alteration), and geochemistry (local REE concentrations). During the next decade, additional metasedimentary rock-hosted Co-Cu-Au deposits were assigned to the IOCG classification, including those in the Kuusomuo belt of northeastern Finland (Vanhanen, 2001) and the Gladhammar deposit in central Sweden (Eilu and others, 2007). Independently, Slack (2006, 2007) used mineralogical and geochemical data for ores of the Blackbird district, including high concentrations of Bi, REE, Y, and Ge and the local presence of magnetite-rich rocks, to suggest a genetic connection to IOCG deposits (see also Slack, 2012). This inferred link has been extended by Slack and others (2011), in proposing that other Co-Cu-Au deposits listed in table 1–1 may represent Co-rich variants of IOCG ores, similar to the Cloncurry-type classification of Corriveau (2007).

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4. Regional Environment

By Karen Lund

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Descriptive and Geoenvironmental Model for Cobalt-Copper-Gold Deposits in Metasedimentary Rocks

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Table

4. Regional Environment

By Karen Lund

Regional environments of the Cu-Co-Au deposits (table 1–1) are diverse in relation to local sedimentary, metamorphic, and igneous rocks and in relation to structural settings. As shown on table 4–1, the regional geologic environments are products of three geotectonic settings: intracontinental basin, oceanic rift and back-arc basin, and Andean-type volcano-plutonic complexes. Most of the regional environments involve multi-phase tectonic histories that complicate interpretations about which characteristics or processes were fundamental to mineralization and which were incidental. The Blackbird district, containing the largest Co resource in metasedimentary rocks of the United States, is in a complex setting about which there are many unanswered questions, particularly regarding the geologic history between the Mesoproterozoic deposition of the host rocks and superimposed Cretaceous metamorphism and deformation. Because of this gap in knowledge, interpretation of the regional geologic environment for the Blackbird district has changed dramatically during the course of 70 years of exploration and new detailed studies tied to structural context are required to clarify relations. At Blackbird and in many of the other districts described in this report, it remains unclear whether original tectonic environment, host rock character, or subsequent orogenic events were most significant to ore formation.

Geotectonic Environment

Many of the Co-Cu-Au deposits and districts in metasedimentary rocks (table 1–1) are hosted in deformed Proterozoic intracontinental basin rocks (table 4–1), including the Blackbird and Modum districts and the Mt. Cobalt and Cobalt Hill deposits. The basins underwent rapid subsidence and were filled with thick (multiple-kilometer), supracrustal successions, most of which contain both deep-water and shallow-water sedimentary deposits. All of these intracontinental basins were transformed by compressional orogenic events that inverted the basins and resulted in regional metamorphism, igneous activity, and deformation.

The Mesoproterozoic (about 1.4-giga-annum [Ga]) intracontinental Lemhi basin hosting the Blackbird district developed across the trend of an underlying 1.8-Ga basement suture system composed of juvenile mafic crust and island arcs (Sims and others, 2005). More than 9 km of sediment accumulated during basin development (Evans and Green, 2003). After deposition, the sedimentary rocks underwent several magmatic episodes, two periods of crustal extension, and an extended superterrane-continent collisional event (fig. 4–1; Lund and others, 2011). The Modum district lies in Mesoproterozoic 1.5- to 1.4-Ga platform sediments overlying a Paleoproterozoic collage of continental arc and calc-alkaline island arc rocks. This belt became a continental collision zone at 1.1-Ga (Sveconorwegian orogeny; Bingen and others, 2005; Andersen and others, 2007) and underwent rifting in the Permian during formation of the Oslo rift (Bingen and others, 2005). During sedimentation, intracontinental basins at Blackbird and Modum were mostly amagmatic, containing little or no synsedimentary intrusive or interlayered volcanic rocks, thus probably indicating only moderate extension of thick continental crust. In contrast, Paleoproterozoic intracontinental basin rocks at the Mt. Cobalt deposit were deposited during two basin-filling extensional events (Matthai and others, 2004; Giles and others, 2006). These and Paleoproterozoic passive-margin sedimentary rocks at the Cobalt Hill deposit (Schandl, 2004; Schandl and Gorton, 2007; Marshall and Watkinson, 2000) are characterized by mafic magmatism that was synchronous with sedimentation. The geologic framework of the Mt. Cobalt deposit further developed through large-scale basin inversion (Giles and others, 2006).

Another group of Cu-Co-Au deposits formed in rocks that were deposited in oceanic rift and back-arc basin settings. The Kuusamo belt and the Sirkka deposit developed in sedimentary basins that lie in the southeastern and central parts of the Central Lapland greenstone belt, respectively (Eilu and others, 2003; Sundblad, 2003). In the Kuusamo belt, Paleoproterozoic sedimentary and mafic igneous rocks formed in an intraplate rift that was possibly a back-arc basin; the rift system was terminated and the sedimentary-volcanic basin was deformed during a collisional event (Pankka and Vanhanen, 1992; Räsänen and Vaasjoki, 2001; Eilu and others, 2003, 2007; Sundblad, 2003). At Sirkka, Paleoproterozoic mafic metavolcanic and metavolcaniclastic rocks formed in an oceanic rift basin that was deformed during collisional compression and secondary transcurrent shearing (Eilu and others, 2003). The country rocks at the Gladhammar deposit include sedimentary successions that formed in an amagmatic, Paleoproterozoic passive-margin and a secondary back-arc setting; these successions were incorporated into an Andean-type arc-continent collisional zone (Beunk and Page, 2001). The collision zone evolved into a transpressional crustal boundary before being mineralized (Beunk and Page, 2001).

The Paleozoic host rocks for the Kendekeke deposit and the Archean host rocks at the Werner Lake deposit are interpreted to have formed in back-arc rift settings (He and others, 2010; Pan and Therens, 2000). Paleoproterozoic country rocks at the Dahenglu deposit formed in an intraplate rift setting (Zhao and others, 2005; Lu and others, 2006). The different-aged rift basins that host the Kendekeke and Dahenglu

Table 4–1. Regional environment.

Deposit/ district name	Geotectonic environment	Temporal (secular) relations	Relations to structures	Relations to igneous rocks	Relations to sedimentary rocks	Relations to metamorphic rocks
Deformed intracontinental basin setting						
Blackbird district (Lund and Tysdal, 2007; Lund and others, 2010b, 2011; Aleinikoff and others, 2012)	Mesoproterozoic (1.4 Ga) intracontinental amagmatic extensional basin formed across a 1.8 Ga suture zone. Superimposed continental breakup with magmatism at 686-650, 490 Ma. Arc-continent collisional orogeny at 100-80 Ma	Mesoproterozoic (1.38-1.1 Ga) or synorogenic Late Cretaceous polystage ore.	Mineral deposits in ramp system related to regional thrusts. Ore hosted by minor thrust, strain boundary, dilational zones	Multiple post-depositional magmatic events: granites of unknown genesis at 1.37 Ga; extension-related bi-modal magmatism at 0.67, 0.49 Ga, and 50-45 Ma; syn-compressional I- and S-type granites at 95-80 Ma	Hosted by arkosic siltstone and fine-grained sandstone rocks in 9-km thick intracontinental basin succession. Evaporite-bearing rocks thrust faulted above host rocks	Polyphase mineralization syn- and-late metamorphic. Regional metamorphism of middle greenschist to lower amphibolite facies driving regional dehydration and melting. Ore in metamorphic fabrics and related structures
Mt. Cobalt (Croxford, 1974; Nisbet and others, 1983; Matthai and others, 2004; Giles and others, 2006)	Paleoproterozoic 1.8-1.6 Ga sedimentary and volcanic rocks deposited in two cycles of intracontinental extension. Metamorphosed during Mesoproterozoic 1.6-1.5 Ga basin inversion and syntectonic ore. 1.5 Ga extension and magmatism	Synorogenic 1.6-1.5 Ga poly-stage mineralization	Ore in 1.6-1.5 Ga high-strain compressional zones within broad fault zone between rock packages. Late 1.5 Ga discordant Cu veins in extensional structures	Mafic metavolcanic (amphibolite) rocks were source of metals derived by metamorphic fluids. Late veins related to 1.5 Ga bimodal intrusive rocks	Multiple ore host rocks including sedimentary-origin rocks. Stratiform and stratabound Co-Cu-bearing pyrite source of some metals. Evaporites as source of Cl for hydrothermal fluids.	1.6-1.5 Ga amphibolite-facies metamorphism formed fluids. Veins hosted by metamorphic rocks
Modum (Gammon, 1966; Grorud, 1997; Andersen and Grorud, 1998; Sundblad, 2003; Bingen and others, 2005; Andersen and others, 2007)	Mesoproterozoic 1.5-1.4 Ga platform sediments on a collage of continental arc and of calc-alkaline/meta-graywacke island arc. Continental collision zone at 1.1 Ga	Ore 1.4-1.1 Ga, possibly 1.4 Ga ore remobilized by 1.1 Ga metamorphism.	Intrafolial ores in fold hinges and shear zones. 1.1 Ma isoclinal folding of host rocks	1.5-1.4 Ga pre-ore calc-alkaline mafic dikes. 1.22 Ga possibly post-ore gabbro and amphibolite metamorphosed and folded with sedimentary rocks.1.05 Ga post-ore granites and pegmatites	Ore hosted in fine-grained arkosic siliciclastic rocks containing minor anoxic-environment carbonate rocks. Ore Pb derived from sedimentary rocks	1.1-0.9 Ga granulite metamorphism, foliation, penetrative deformation locally remobilize ore
Cobalt Hill (Schandl and Gorton, 2007; Schandl 2004; Marshall and Watkinson, 2000)	2.5-2.2 Ga continental rift-related passive-margin sedimentary rocks. 1.9-1.8 Ga arc-continent convergent margin, 1.7 Ga collision-related granite magmatism	Ore possibly coeval with 2.2 Ga rift-related mafic intrusions and (or) with 1.7 Ga syn-metamorphic regional fluids	Ore possibly 1.7 Ga late syntectonic during collisional orogeny. Ore in shear and dilational zones	2.22 Ga mafic intrusions (pre- or syn ore) possible source of metals, 1.7 Ga syntectonic granite magmatism possibly syn ore. Ore cut by 1.24 Ga mafic dikes	Ore hosted in quartzite near unconformity with underlying Archean rocks. Sedimentary rocks possible source of brines	Lower greenschist

Table 4–1. Regional environment.—Continued

Deposit/ district name	Geotectonic environment	Temporal (secular) relations	Relations to structures	Relations to igneous rocks	Relations to sedimentary rocks	Relations to metamorphic rocks
Deformed oceanic rift and back-arc setting						
Gladhammar (Söderhielm and Sundblad, 1996; Sundblad, 2003; Beunk and Page, 2001; Billström and others, 2004)	Paleoproterozoic 1.9 Ga passive-margin metasedimentary rocks. Metamorphosed in 1.8 Ga back-arc and Andean subduction settings. Intruded by 1.8 Ga I-type batholith. 1.8-1.7 Ga transpressional collision shear zones host ore	Paleoproterozoic 1.8-1.7 Ga	Ore in 1.8 to 1.7 Ga steep shear zones related to Loftahammar-Linköping transpressional crustal boundary	1.8 Ga calc-alkaline I-type tonalite batholith sheared and mineralized during 1.8-1.7 Ga transpressional collision	Ore along shear zone cutting fluvial quartzite near contact with 1.8 Ga tonalite batholith	1.8 Ga amphibolite- facies metamorphism of country rocks occurred during back-arc and Andean-margin events prior to shearing event that created ore host sites
Kuusamo district (Juomasuo, Kouvervaara, Meurastuksenaho, Hangaslampi, Lemmonlampi, Kuumaso) (Pankka and Vanhanen, 1992; Vanhanen, 2001; Eilu and others, 2003, 2007; Räsänen and Vaasjoki, 2001)	Paleoproterozoic (2.5-2.0 Ga) intracratonic failed rift basin. Ore syntectonic with 1.9-1.8 Ga continent collision, basin inversion, transcurrent shearing, and synorogenic plutonism	Paleoproterozoic 1.86-1.82 Ga	Ore in penetrative deformation zones in axial planar and shear zones	2.2 Ga mafic dikes caused alteration and contact metamorphism that mobilized brines from sedimentary package. Ore zones in or at contact with meta-mafic dikes and komatiitic volcanic rocks	Some ore zones in mafic volcaniclastic and siliciclastic sedimentary rocks, and in mafic volcanic rocks mostly near contacts with mafic dikes. Minor evaporite layers contributed to brine formation in some deposits	Ore post- or retrograde metamorphic in upper greenschist to amphibolite facies rocks, especially in older contact metamorphic zones
Sirkka (Eilu and others, 2003, 2007)	Paleoproterozoic 2.4-2.1 Ga rift system forming greenstone belt. Ore syntectonic with 1.89-1.86 Ga collisional event during continental amalgamation	Paleoproterozoic 1.89-1.86 Ga	Structurally controlled ore within or near transcrustal 1.89-1.86 Ga Sirkka shear zone	Ore hosted in mafic metavolcanic (flow and tuff) rocks, minor intrafolial meta-komatiite	Some ore hosted by fine-grained volcaniclastic and black shale interlayered with mafic volcanic rocks	Mineralization syn or late peak greenschist metamorphism
Dahenglu (Yang and others, 2001; Zhao and others, 2005; Lu and others, 2006)	Paleoproterozoic 2.2-1.9 Ga intracontinental rift basin. 1.85 Ga basin inversion with deformation and magmatism	Multiphase: Paleoproterozoic ore enriched during basin inversion	Ore enriched during tectonism and controlled by 1.9 Ga thrust faults	Mafic volcanic rocks are local host rocks. Pre-metamorphic Paleoproterozoic (1.9 Ga) bimodal intrusions. Post-metamorphic (1.85 Ga) syenite and granite	Stratiform and divergent ore zones in fine-grained siliciclastic and carbonate rocks	Greenschist to amphibolite facies
Kendekeke (Pan and Sun, 2003; Pan and others, 2005; Feng and others, 2009; He and others, 2010)	Ordovician backarc setting built on Cambrian island arc basement. Late Paleozoic intracontinental subduction and Mesozoic continental collision	Multi-phase: Ordovician exhalative metals enriched during late Paleozoic and Mesozoic compressive tectonism	Mineralization as disseminations in penetrative foliation and as intrafolial veins	Host rocks include Cambrian spilite-keratophyre (basaltic) rocks. Triassic-Jurassic granites and Cretaceous felsic dikes	Inferred syngenetic-exhalative metals in 1-km-thick Cambrian-Silurian interlayered volcaniclastic and volcanic host rocks	Silurian-Devonian lower greenschist facies metamorphism

Table 4–1. Regional environment.—Continued

Deposit/ district name	Geotectonic environment	Temporal (secular) relations	Relations to structures	Relations to igneous rocks	Relations to sedimentary rocks	Relations to metamorphic rocks
Deformed oceanic rift and back-arc setting—Continued						
Werner Lake (Pan and Therens, 2000)	Archean greenstone belt. ~2.7 Ga fore-arc, accretionary prism, or back-arc setting mafic, intermediate, and ultramafic metavolcanic rocks and siliciclastic metasedimentary rocks. 2.69-2.67 Ga deformation	Inferred exhalative metal accumulation coeval with sedimentation and mafic and ultramafic magmatism. Enriched during metamorphic events	Ore hosted by metasedimentary, mafic, and ultramafic rocks near fault zone. Co ore bodies foliated, boudinaged, and folded	Inferred exhalative mineralization coeval with 2.7 Ga mafic and ultramafic magmatism. Post-ore granite and pegmatite dikes	Inferred SEDEX mineralization and minor exhalite(?) may have provided metals and brines	2.69 Ga granulite and 2.66-2.67 Ga retrograde metamorphic contribution to Co enrichment. Cu ores w/ retrograde phase
Andean volcano-plutonic setting						
Contact Lake belt (Mumin and others, 2007)	Paleoproterozoic 1.88-1.84 Ga Andean-type arc magmatism formed andesitic stratovolcano complex and subvolcanic intrusions	Episodic 1.87-1.85 Ga syn-magmatic mineralization in caldera complex	Mineralization in caldera-related fractures. Late ore hosted in 1.84-1.81 Ga strike-slip faults	Ore related to 1.88 Ga calc-alkaline igneous rocks. 1.84 Ga late-tectonic alkaline granite batholiths. S-isotope values indicate magmatic-origin sulfide minerals	1.88-1.87 Ga supracrustal subvolcanic and volcanogenic sandstone, siltstone, minor carbonate rocks, interlayered with volcanic rocks. Locally mineralized	Contact metamorphism related to subvolcanic intrusions
NICO (Goad and others, 2000a, b; Mumin and others, 2007)	Paleoproterozoic 1.87-1.85 Ga calc-alkalic volcano-plutonic complex formed in Andean-type margin	1.87-1.85 Ga syn-magmatic mineralization during volcano-plutonic episode	Mineralization in fractures related to subvolcanic intrusions, dikes, maar-related breccias	Ore coeval with calc-alkalic rhyolitic ignimbrite and intermediate pluton coeval with diatreme and maar facies host mineralization in shallow subvolcanic setting (Sue-Dianne)	1.88-1.87 Ga supracrustal subvolcanic, volcanogenic graywacke country rock mineralized as part of volcano-plutonic complex	Contact metamorphism related to subvolcanic intrusions

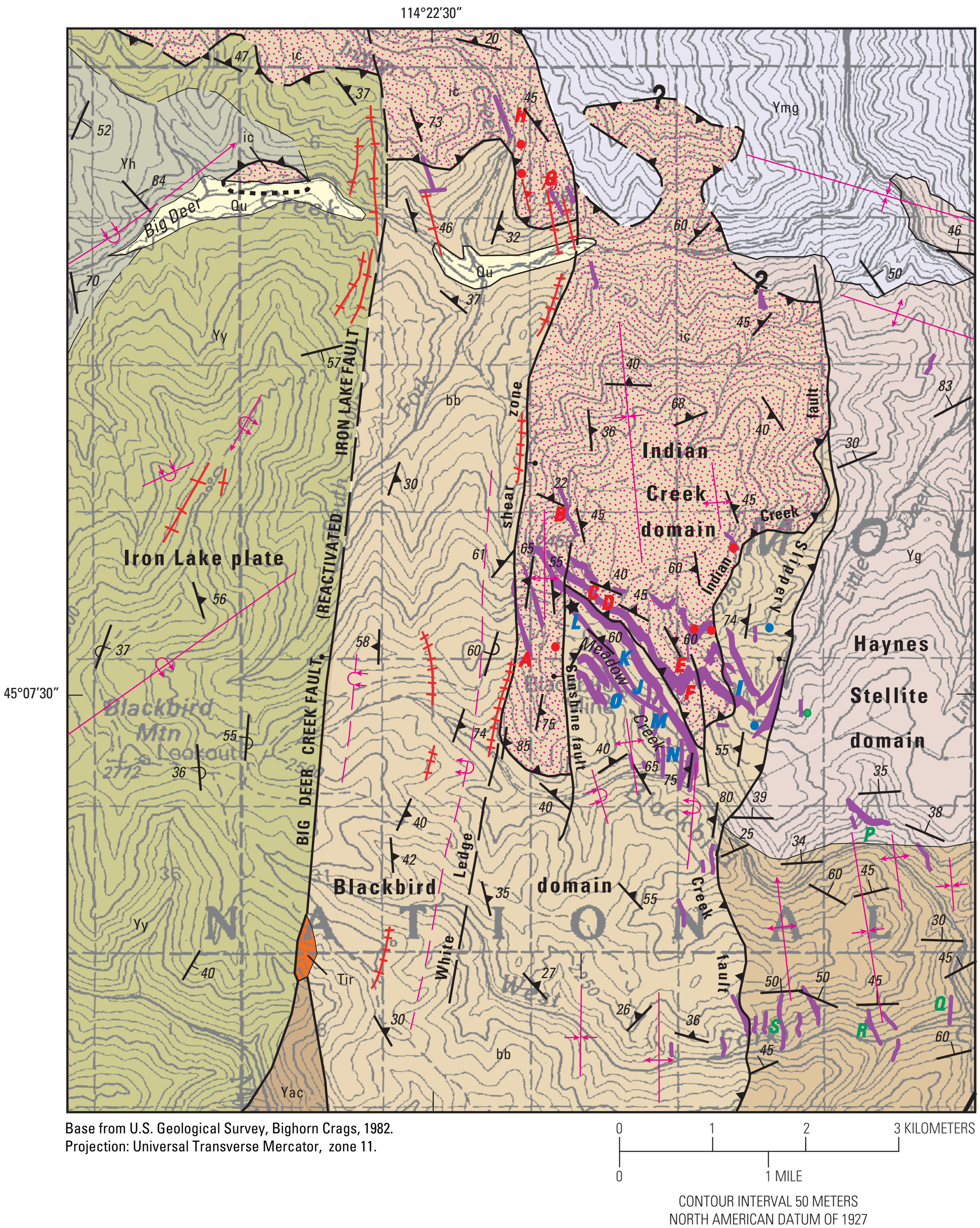
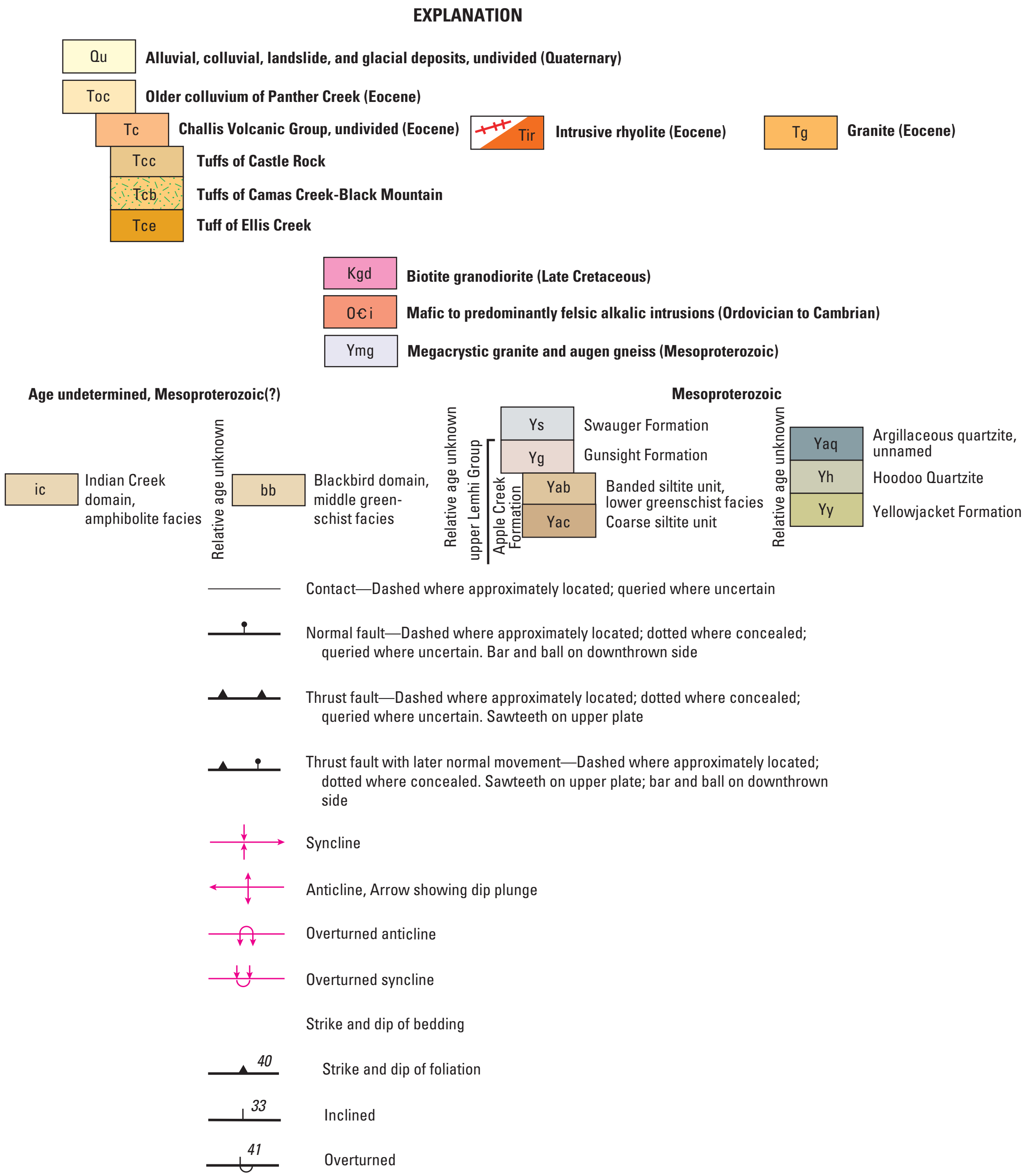


Figure 4–1. Geologic map of the area near the Blackbird district showing mineralized zones (from Lund and others, 2011). Purple, mineralized zones. Red dot pattern, rocks above garnet isograd (Indian Creek domain). Location of prospects and mines shown by colored letters and dots: red, occurrences in Indian Creek domain; blue, Blackbird domain; green, Haynes-Stellite domain. A, Sunshine lode, East Sunshine prospect; B, Ram deposit; C, Chelan, East Chelan prospects; D, Horseshoe zone; E, Toronto prospect; F, Ridgetop prospect; G, Tinkers Pride prospect; H, Bonanza Copper prospect; I, Merle zone; J, Chicago zone; K, Brown Bear zone; L, Blacktail open pit; M, Idaho zone; N, Uncle Sam mine; O, Catherine and Ella prospects; P, Haynes-Stellite mine; Q, Conicu prospect; R, Patty B prospect; S, Ludwig prospect.



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deposits filled with sedimentary and mafic volcanic rocks (Yang and others, 2001; Pan and Sun, 2003; Pan and others, 2005; Feng and others, 2009). At Werner Lake, an Archean back-arc rift filled with sedimentary rocks and mafic and ultramafic rocks (Pan and Therens, 2000; see z 5–6). These basins all underwent subsequent compressional deformation and metamorphism (Pan and Therens, 2000; Yang and others, 2001; Pan and Sun, 2003; Feng and others, 2009).

The Contact Lake belt and NICO deposits formed as parts of Paleoproterozoic Andean arc-continent collision zones in caldera systems built atop older Paleoproterozoic interlayered volcanogenic sedimentary and volcanic supracrustal rocks (Badham, 1975; Goad and others, 2000a; Eilu and others, 2003; Mumin and others, 2007).

Temporal (Secular) Relations

Deposits in the Modum district are Mesoproterozoic in age, possibly having formed during early post-depositional tectonism, but were transposed and remobilized during younger Mesoproterozoic continental collision (Andersen and Grorud, 1998; Andersen and others, 2007). Dating of uraninite in the Modum ores suggests a time span of about 300 m.y. between early and final stages of ore formation (Andersen and Grorud, 1998). In the Blackbird district, Mesoproterozoic strata host Mesoproterozoic (about 30 m.y. post-sedimentation) REE concentrations (Aleinikoff and others, 2012), and either contemporaneous, syn-magmatic Cu-Co-Au mineralization (Slack, 2012) or Cretaceous (about 1.3 b.y. post-sedimentation) syn-orogenic, polyphase Cu-Co-Au mineralization (Lund and others, 2011). At the Mt. Cobalt deposit, polyphase ore formed in Paleoproterozoic rocks during Mesoproterozoic deformation. At the Cobalt Hill deposit, Paleoproterozoic rocks host ore that formed during younger Paleoproterozoic orogenic events (about 200 m.y. post-sedimentation). In the Kuusamo belt, middle Paleoproterozoic host rocks were mineralized during late Paleoproterozoic collisional events (Pankka and Vanhanen, 1992).

The Gladhammar (Söderhielm and Sundblad, 1996; Sundblad, 2003) and Sirkka (Pankka and Vanhanen, 1992; Vanhanen, 2001) deposits formed about 200-300 m.y. after sedimentation, during deformation along Paleoproterozoic transcurrent structures. At the Werner Lake, Dahenglu, and Kendekeke deposits, available studies conclude that Archean, Paleoproterozoic, and Paleozoic strata, respectively (Pan and Therens, 2000; Yang and others, 2001; Pan and Sun, 2003; Feng and others, 2009), originally contained exhalative mineralization that was remobilized and enriched during metamorphic events about 0.5-2.0 b.y. after sedimentation. Among deposits that formed as part of Paleoproterozoic Andean volcano-plutonic systems, mineralization at the NICO and Contact Lake deposits was coeval with magmatism (fig. 5–4) and about 200 m.y. younger than Paleoproterozoic country rocks (Mumin and others, 2007).

Thus, most of the Cu-Co-Au deposits are hosted in Paleoproterozoic rocks although the Blackbird and Modum districts are in Mesoproterozoic rocks, Werner Lake is in Archean rocks, and Kendekeke is in Paleozoic rocks. Most of the deposits formed during subsequent metamorphism and deformation, generally about 100-200 m.y. after host-rock deposition, but the age span of mineralization ranges from about 50 m.y. to possibly more than 1.3 b.y. after sedimentation. Deposits at NICO and in the Contact Lake belt formed predominantly within siliciclastic sedimentary rocks, contemporaneously with caldera development.

Duration of Mineralizing Processes

The mineralizing events for most of these deposits are complex and multi stage (table 4–1), so the durations of mineralizing processes are difficult to determine. In the Blackbird district, 1.37-Ga Mesoproterozoic REE minerals (xenotime cores) in one prospect (Aleinikoff and others, 2012) are interpreted to date the Cu-Co-Au mineralization and to provide a genetic link to the emplacement of nearby 1.37-Ga plutons (Slack, 2012), suggesting a relatively short duration of hydrothermal activity. More broadly across the Blackbird district, xenotime rims, monazite, and muscovite intergrown with Cu-Co-Au ore minerals are dated at 110 to 83 Ma (Lund and others, 2011; Aleinikoff and others, 2012), ages that are synchronous with formation of the ore-hosting structures; this interpretation suggests that multi-phase mineralizing events spanned about 27 m.y. (Lund and others, 2011). The Mt. Cobalt deposit and Modum district display evidence of multiple periods of mineralization that may have occurred during more than one orogenic event (Nisbet and others, 1983; Krcmarov and Stewart, 1998; Grorud, 1997, respectively). Deposits in the Kuusamo belt are the product of two phases of Paleoproterozoic tectonic activity (Pankka and Vanhanen, 1992). Ore zones at the Gladhammar and Sirkka deposits formed during discrete orogenic events, but the durations are poorly resolved (Söderhielm and Sundblad, 1996). Deposits at Werner Lake, Kendekeke, and Dahenglu are interpreted as the products of two-stages of metals deposition and subsequent enrichment (Pan and Therens, 2000; Yang and others, 2001; Pan and Sun, 2003; Feng and others, 2009). The deposit at NICO formed during a caldera-building event (Mumin and others, 2007) and probably was of relatively short duration. Deposits in the Contact Lake belt formed in a similar magmatic setting to NICO, but a component of late mineralization during younger transcurrent faulting was critical (Mumin and others, 2007).

Although durations of mineralization for most of the Co-Cu-Au deposits are not constrained by geochronology, the striking aspect (except for NICO, Mumin and others, 2007; and Blackbird, if ore is Mesoproterozoic and syn-magmatic, Slack, 2012) is that multiple events were responsible for forming these deposits.

Relations to Structures

In the Blackbird district, recent structural and mineralogical studies conclude that the Co-Cu-Au deposits formed as successive vein types, co-located along Cretaceous fold hinges, cleavages, and shear zones within a thrust ramp in a regional thrust fault system (figs. 4–1, 4–2) and, thus, are structurally controlled. The deposits are interpreted as syn- to late-deformational because early-stage veins exhibit well-developed foliation, whereas progressively younger veins are less foliated or unfoliated (Lund and others, 2011). Other studies, which conclude that these are Mesoproterozoic deposits related to 1.37-Ga intrusive activity, do not infer a solely Cretaceous structural control of mineralization (Slack, 2012), although Mesoproterozoic structures have not been recognized or mapped in the region (Lund and others, 2011).

In the Modum district, ore zones lie in penetrative structures within foliation, in intrafolial cleavage, and along broad shear zones (fig. 5–3; Grorud, 1997). Although uraninite associated with the ore zones has an age of about 1.4-Ga (Andersen and Grorud, 1998), structural and mineralogic evidence indicates that the ore minerals grew or recrystallized during the Sveconorwegian collision event at about 1.1 Ga and were coeval with thrust faulting and isoclinal folding (Grorud, 1997; Bingen and others, 2005; Andersen and others, 2007).

The Mt. Cobalt deposit is a product of a 1.6- to 1.5-Ga, collision-driven orogeny that inverted the intracontinental basin rocks causing the host turbiditic succession to be thrust faulted over a shallow-water, evaporitic succession. Mineralization is localized within a broad thrust zone between the rock packages (Matthai and others, 2004; Giles and others, 2006). The main orebodies are in high-strain compressional zones including minor folds and faults located in a thrust ramp that created local dilational structures. Late-tectonic Cu veins are discordant to fabrics (Krcmarov and Stewart, 1998).

At Cobalt Hill, 2.2-Ga rift-related rocks were overprinted by deformation and magmatism related to 1.7-Ga, arc-continent convergence (Marshall and Watkinson, 2000; Schandl and Gorton, 2007). The Co-Cu-Au deposits are located along shear and dilational structures related to the convergent deformation and magmatism, but metals may have been introduced during older rift-related mafic magmatism (Marshall and Watkinson, 2000; Schandl and Gorton, 2007).

The 2.5- to 2.0-Ga volcanic-sedimentary rift-basin rocks of the Kuusamo schist belt were intercalated and tightly folded during 1.9- to 1.8-Ga continental collision (fig. 4–3; Pankka and Vanhanen, 1992; Räsänen and Vaasjoki, 2001; Sundblad, 2003). At Sirkka, the 2.4- to 2.1-Ga rift-basin rocks were involved in 1.89- to 1.86-Ga continental amalgamation and secondary transcurrent faulting that produced intercalation of mafic metavolcanic and metavolcaniclastic rocks by both faulting and isoclinal folding (Eilu and others, 2003). In both areas, Co-Cu-Au deposits are hosted along fold hinges and shear zones in older contact metamorphic zones adjacent to, as well as within, metamorphosed mafic dikes (Eilu and others, 2003, 2007).

In the Dahenglu, Kendekeke, and Werner Lake deposits, ore zones are structurally controlled and manifest as foliated disseminations and as intrafolial veins (Pan and Therens, 2000; Yang and others, 2001; Pan and Sun, 2003; Feng and others, 2009). The Gladhammar deposit is located along a shear zone that formed as part of a 1.8- to 1.7-Ga transpressional crustal boundary (Söderhielm and Sundblad, 1996; Beunk and Page, 2001; Billstrom and others, 2004; Eilu and others, 2007).

At the NICO deposit and in the Contact Lake belt, mineral deposits are hosted locally by brittle structures related to formation and collapse of calderas (Goad and others, 2000a, b; Mumin and others, 2007). In the Contact Lake belt, late-stage ore is also localized along strike-slip faults (Mumin and others, 2007).

Relations to Igneous Rocks

The region surrounding the Blackbird district was affected by three within-plate igneous events about 30, 700, and 900 m.y. after sedimentation (Evans and Green, 2003; Lund and Tysdal, 2007). Mesoproterozoic (about 1.4 Ga) strata of the Lemhi basin were intruded at 1.37 Ga by granite-granodiorite plutons (Evans and Zartman, 1990). Several generations of xenotime dated between 1.37 and 1.1 Ga (Aleinikoff and others, 2012) indicate that local hydrothermal fluid flow occurred during the Mesoproterozoic, including an event coeval with 1.37-Ga igneous rocks that is regarded by Slack (2012) as the time of Co-Cu-Au mineralization. In the Neoproterozoic-early Paleozoic, the Blackbird region was on the margin of a continental rift that produced several cycles of co-magmatic syenite-diorite intrusions (685-650 Ma and 500-485 Ma; Lund and others, 2010a). Country rocks in the central part of the district were intruded by undated mafic dikes that, based on proximity to several Cambrian plutons, are most likely part of the early Paleozoic extensional intrusive event and interpreted as pre-ore (Lund and others, 2011). Additionally, I- and S-type granites of the Cretaceous Idaho batholith lie less than 15 km west and north of the district and Eocene granites cut rocks within the district, but hydrothermal activities related to these are not thought to be related to the deposits (Lund and others, 2011).

In the region surrounding the Modum district, minor pre-ore calc-alkaline dikes were coeval with sedimentation (about 1.5–1.4 Ga). A younger set of gabbro and mafic dikes also intruded the sedimentary rocks at about 1.2 Ga. Early-stage mineralization is dated at about 1.4 Ga, between the two intrusive events (Grorud, 1997; Andersen and Grorud, 1998), but the structurally controlled ore zones formed, or were remobilized into these structures, at about 1.1 Ga (Grorud, 1997; Sundblad, 2003; Bingen and others, 2005; Andersen and others, 2007).

In the Paleoproterozoic sedimentary basin that hosts the Mt. Cobalt deposit, volcanic rocks were deposited in both cycles of intracontinental extension and basin filling (Matthai

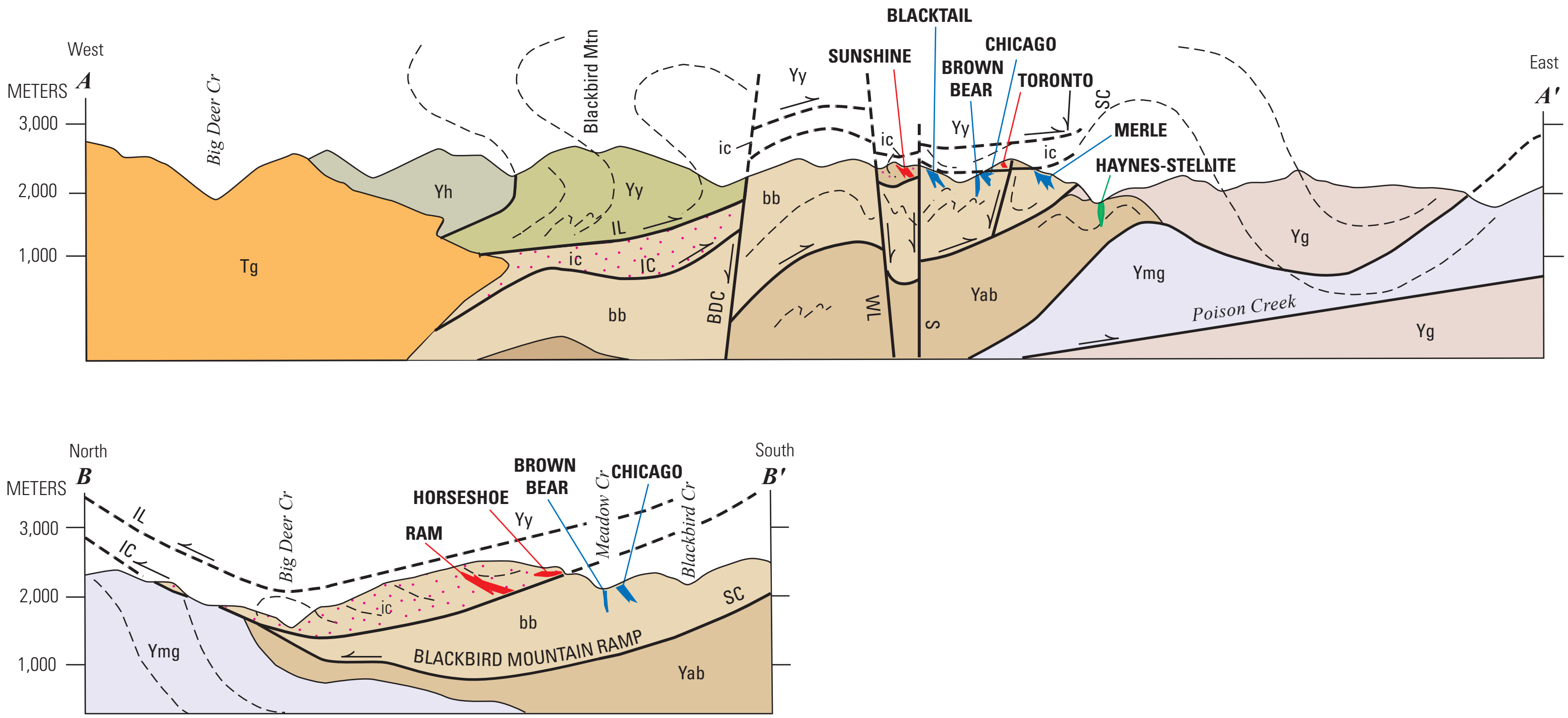

Figure 4–2. Cross sections showing structures near Blackbird mining district (from Lund and others, 2011). See fig. 4.1 for unit and symbol definitions. Prospects and deposits are projected into planes of cross section and keyed to domain by color: red = occurrences in Indian Creek domain, blue = Blackbird domain, green = Haynes-Stellite domain. BDC, Big Deer Creek fault; BM, Blackbird Mountain oblique ramp; IC, Indian Creek imbricate fault; IL, Iron Lake fault; SC, Slippery Creek fault; WL, White Ledge shear zone.

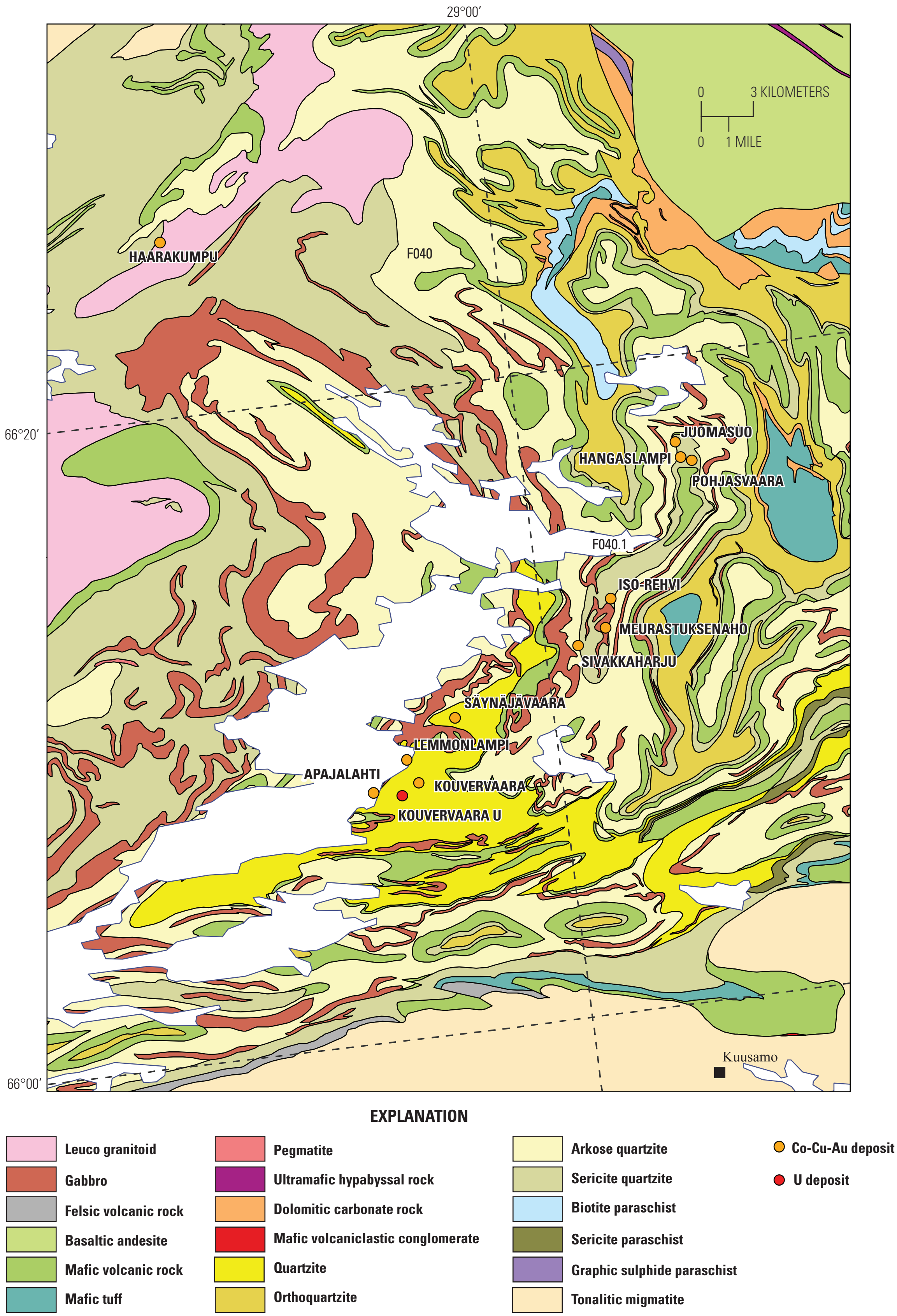

Figure 4–3. Generalized geologic map of the Kuusamo schist belt in northeastern Finland showing mineral deposits and occurrences. All rock units are Precambrian in age. White areas are of lakes. Modified from Eilu and others (2012).

and others, 2004; Giles and others, 2006). The Paleoproterozoic mafic volcanic rocks are interpreted to be the source of metals for later Paleoproterozoic structurally controlled veins, whereas late veins formed during regional intrusion of Mesoproterozoic bimodal intrusive rocks (Croxford, 1974; Nisbet and others, 1983; Krcmarov and Stewart, 1998).

In the region near the Cobalt Hill deposit, two ages of igneous rocks may have been important in ore deposit formation. The 2.22-Ga mafic intrusions may have been emplaced before or during mineralization and are possible sources of metals. Likewise, syn-tectonic, 1.7-Ga granite magmatism also was possibly coeval with ore formation (Schandl 2004; Schandl and Gorton, 2007). In the Kuusamo belt, contact metamorphic zones adjacent to 2.2-Ga mafic dikes focused younger deformation and mineralization in and near the contacts between the sedimentary-mafic volcanic succession and the mafic dikes (Pankka and Vanhanen, 1992; Eilu and others, 2003, 2007; Räsänen and Vaasjoki, 2001). The 1.8- to 1.7-Ga, structurally controlled Gladhammar deposit is adjacent to a 1.8-Ga calc-alkaline tonalite batholith that hosts the nearby Solstad Co-Cu-Au deposit (Söderhielm and Sundblad, 1996; Sundblad, 2003).

At Werner Lake, 2.7-Ga mafic and ultramafic igneous rocks are interpreted to be related to the formation of disseminated SEDEX mineralization that, after 2.69- to 2.67-Ga metamorphic remobilization, was localized and concentrated within the igneous rocks (Pan and Therens, 2000). Similarly, 2.2- to 1.9-Ga mafic rocks at Dahenglu and Ordovician mafic rocks at Kendekeke were coeval with sedimentation and with inferred original SEDEX metal accumulation that was enriched during subsequent metamorphism and deformation.

Mineralization at NICO and in the Contact Lake belt (Goad and others, 2000a, b; Mumin and others, 2007) was coeval with 1.88- to 1.84-Ga calc-alkaline arc magmatism. In addition to subvolcanic volcaniclastic and siliciclastic sedimentary rocks, a minor proportion of the ore is hosted by both intrusive and volcanic rocks (fig. 5–4; Badham, 1975; Goad and others, 2000a, b; Mumin and others, 2007).

Relations to Sedimentary Rocks

Host rocks to the Blackbird district were deposited in the Mesoproterozoic Lemhi basin and are preserved as a 9-km-thick succession of unfossiliferous, fine-grained, upward-shallowing, siliciclastic rocks (Tysdal 2000a, b). Where the environment of deposition is preserved without metamorphic and structural transformation, the host rocks retain evidence of being turbidite flow deposits and overlying marine and fluvial deposits (Tysdal, 2000a). Although syngenetic mineralization was invoked in several previous district studies and mineral deposit models (Earhart, 1986; Nash and Hahn, 1989; Höy, 1995; Evans and others, 1995; Bookstrom and others, 2007; Lydon, 2007), the most comprehensive and detailed studies indicate that no syngenetic deposits occur within the sedimentary rocks (Tysdal, 2000a, b; Evans and Green, 2003; Lund and others, 2011). Mineralized zones are transgressive to bedding, not bound to particular stratigraphic horizons, and occur in three stratigraphic units (Apple Creek and Gunsight Formations, fig. 4–1) through 4 km of stratigraphic thickness (Lund and others, 2011). Due to Cretaceous basin inversion, host rocks of the Blackbird district are structurally overlain by another Mesoproterozoic unit (Yellowjacket Formation; Lund and Tysdal, 2007) that originally contained evaporite beds (Tysdal and Desborough, 1997), but that lacks Cu-Co-Au deposits.

The Mt. Cobalt and Cobalt Hill deposits and the Modum district are also hosted in deformed intracontinental basins that underwent rapid subsidence and were filled with thick (multiple-km) supracrustal successions. These intracontinental basins included shallow depositional settings that produced evaporitic sediments. Although the tectonic settings were extensional, these basins were mostly amagmatic, containing little or no synsedimentary intrusive or interlayered volcanic rocks. At Modum, country rocks originated as fluvial and shallow marine rocks, including possible evaporites (Grorud, 1997; Bingen and others, 2005).

The Co-Cu-Au deposits of the Kuusamo belt are hosted in the Kuusamo schist belt, a package of mafic volcaniclastic-siliciclastic metasedimentary rocks with subequal proportions of mafic volcanic and intrusive (dike) rocks that are infolded in the southeastern part of the Central Lapland greenstone belt (Pankka and Vanhanen, 1992; Räsänen and Vaasjoki, 2001; Eilu and others, 2003; Sundblad, 2003). The deposits occur along the contact-metamorphosed and sheared contacts between the sedimentary rocks and the volcanic and dike rocks (fig. 5–8; Eilu and others, 2003, 2007). The Gladhammar deposit is set in passive-margin, quartzitic country rocks, whereas the Sirkka deposit is set in mixed sedimentary and volcanic rocks. However, both are hosted by faults that are mineralized across the region; relations of the ore deposits to the sedimentary rocks are unclear (Eilu and others, 2003, 2007).

At the Kendekeke, Dahlenglu, and Werner Lake deposits, disseminated metal accumulations are interpreted to have formed originally by syngenetic processes in volcaniclastic and volcanic rocks and to have been enriched during metamorphism and deformation (Yang and others, 2001; Pan and Sun, 2003; Feng and others, 2009). Calc-silicate rocks and garnetiferous quartzite juxtaposed against host rocks at the Werner Lake deposit are interpreted as metamorphosed exhalites (Pan and Therens, 2000).

At the Contact Lake (Mumin and others, 2007; Badham, 1975) and NICO (Goad and others, 2000a) deposits, supracrustal sedimentary rocks are a component of the country rocks and occur as subvolcanic units within caldera complexes. Subvolcanic sedimentary rocks, and their altered equivalents, host many of the mineralized zones at the NICO deposit (Goad and others, 2000a, b; Mumin and others, 2007) and in the Contact Lake belt (Mumin and others, 2007).

Relations to Metamorphic Rocks

Most of the deposits included in this model are in regional metamorphic rocks, but mineralization may have occurred before, during, or after the regional metamorphic events. A few deposits are located in contact metamorphic rocks. Because of these differences, there is significant variation in relations between mineralization and metamorphic rocks (table 4–1).

Among the deposits in deformed intracontinental basins and in rift basins, the sulfide minerals are typically intergrown with metamorphic minerals and lie within metamorphic fabrics that formed during medium-grade regional metamorphism. In the Blackbird district, polyphase mineralized zones are located within structural and metamorphic fabrics (Lund and others, 2011). Across the different structural domains, host structures range from (1) fold cleavage in middle greenschist facies rocks; (2) transposed layers, axial planar foliation, and shear zones in upper greenschist facies rocks; and (3) metamorphic compositional layers, intrafolial foliation, and shear zones in lower amphibolite facies rocks. Within the Late Cretaceous penetrative structures, Co- and Cu-bearing veins and breccia zones are discordant to bedding in the low-grade metamorphic rocks, but are progressively more parallel to compositional layering in the higher grade, transposed metamorphic rocks. Within the same structures, late-stage Cu veins are late metamorphic in age based on unoriented gangue minerals that cut foliated gangue minerals of earlier mineralizing stages (Lund and others, 2011).

In the Modum district, orebodies are located along synmetamorphic, penetrative shear zones within granulite-facies rocks of diverse origin that were structurally interleaved. Sets of crosscutting, fabric-discordant veins are related to distinctly younger, greenschist-facies retrograde events (Grorud, 1997; Bingen and others, 2005). Deposits at Mt. Cobalt also formed synchronously with amphibolite-facies metamorphism, where high-strain zones, including polyphase folds, pressure-solution, and slaty cleavage, are preferentially mineralized (Croxford, 1974; Nisbet and others, 1983). In the Kuusamo belt, the Cu-Co-Au mineralization occurred during syn- to late-peak, greenschist- to amphibolite-facies metamorphism and formed in fold and shear-zone fabrics where these fabrics overprinted earlier contact metamorphic zones. Late-stage quartz veins cut the peak-metamorphic fabrics and are related to second-order compressional structures (Pankka and Vanhanen, 1992; Vanhanen, 2001; Eilu and others, 2003, 2007).

Several of the deposits are more closely related to discrete shear zones than to regional metamorphic zones. At the Sirkka deposit, ore mineral formation occurred along a transcrustal shear zone during greenschist-facies regional metamorphism (Eilu and others, 2003, 2007). In contrast, at the Gladhammar deposit, the sedimentary country rocks were metamorphosed to greenschist facies prior to the transcurrent faulting that controlled mineralization (Söderhielm and Sundblad, 1996; Sundblad, 2003). For deposits in the Cobalt Hill area, it is unclear if mineralization formed prior to or during metamorphism (Marshall and Watkinson, 2000; Schandl and Gorton, 2007).

In another set of deposits, premetamorphic and possibly original SEDEX-type mineral occurrences were upgraded during later metamorphism. Medium-grade metamorphism and deformation resulted in the development of intrafolial veins within penetratively deformed rocks at Kendekeke (Pan and others, 2005; Feng and others, 2009) and in syn-metamorphic, thrust-fault-controlled ore accumulations at Dahenglu (Yang and others, 2001). At Werner Lake, granulite-facies metamorphism of fault-juxtaposed intrusive and sedimentary is inferred to have upgraded the Co content of SEDEX accumulations in sedimentary rocks and to have remobilized metals to form ore deposits in mafic and ultramafic rocks (fig. 5–5; Pan and Therens, 2000). Copper was enriched in the ore deposits during late-tectonic, retrograde greenschist-facies metamorphism (Pan and Therens, 2000).

The mineralized zones at the NICO deposit and in the Contact Lake belt are in greenschist-facies, graywacke hornfels at the contact with stocks and dikes, as well as in the unmetamorphosed igneous rocks (fig. 5–4; Badham, 1975; Mumin and others, 2007).

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5. Physical Description of Deposits

By John F. Slack

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Descriptive and Geoenvironmental Model for Cobalt-Copper-Gold Deposits in Metasedimentary Rocks

Scientific Investigations Report 2010–5070–G

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Geology and Dimensions in Plan View

Mineralized zones of the Co-Cu-Au deposits considered in this report (table 1–1) vary greatly in form and geometry. Most are less than 10 m thick and several hundred meters in length, but some zones are as much as 70 m thick and nearly 2 km long. Representative examples from several districts and deposits, including information on local geology, are described below.

Blackbird District, USA

The Co-Cu-Au deposits of the Blackbird district in east-central Idaho (fig. 5–1) contain the largest known reserves of cobalt in the United States (Nash and Hahn, 1989; Bookstrom and others, 2007). Host rocks are clastic metasedimentary strata of Mesoproterozoic age that are deformed by folds, thrust faults, and high-angle faults (Lund and Tysdal, 2007; Lund, 2013). The metasedimentary rocks are mostly siltite and argillite, accompanied by minor quartzite, quartzose granofels, biotite-rich schist, and pelitic schist. These strata are intruded by coeval granitic and gabbroic plutons, the former exposed in the northern part of the district at surface distances ranging from approximately 1 to 5 km. Sensitive High Resolution Ion Microprobe (SHRIMP) U-Pb geochronology by Aleinikoff and others (2012) yield a maximum sedimentation age of 1409 ±10 Ma for the ore hosting Apple Creek Formation based on data for detrital zircons, and a crystallization age of 1377 ± 4 Ma for megacrystic granite based on data for igneous zircons. Doughty and Chamberlain (1996) reported a U-Pb zircon age of 1378.7 ± 1.2 Ma for small intrusions of coarse metadiabase about 40 km to the northeast of the district, thus indicating regional contemporaneity of this Mesoproterozoic felsic and mafic magmatism. Igneous plutons of mainly felsic composition were also emplaced during Neoproterozoic, Cambrian, Cretaceous, and Eocene times (Lund and Tysdal, 2007; Lund and others, 2010a). Metamorphic grade in the region varies from middle greenschist in the Blackbird district to upper amphibolite at the Salmon Canyon copper deposit approximately 25 km to the northwest of the district (Nold, 1990; Bookstrom and others, 2007), which likely is a Cu-rich varient of the Co-Cu-Au deposits of the Blackbird district. During the Cretaceous, major thrust faults, shear zones, and folds developed contemporaneously with regional metamorphism that overprinted rocks and ore deposits throughout the district (Lund and Tysdal, 2007; Lund, 2013; Aleinikoff and others, 2012).

The Co-Cu-Au deposits consist of stratabound and discordant lenses, veins, and breccias. Stratabound deposits are generally <1 to 4 m thick and 300 to 500 m long, and show diverse features such as shearing and folding of mineralized bodies, boudins, cusps, and remobilized veins, all of which are hallmarks of the deformation and recrystallization of sulfide-rich rocks (for example, Marshall and Gilligan, 1989). Some deposits are as much as 9 m thick and 800 m long (Vhay, 1948). Pipelike deposits such as Haynes-Stellite (fig. 5–1) display a different geometry, typically consisting of disseminated Co ± Cu ± Au ± Y ± REE mineralization within discordant tourmalinized breccia bodies as much as 50 m in diameter (Modreski, 1985; Bookstrom and others, 2007; Slack, 2012).

Modum District, Norway

The Co-Cu-Au deposits of the Modum district in southeastern Norway are famous for being the main source of cobalt blue pigment used in Europe during the late 17th and 18th Centuries. Skuterud, at the southern end of the district, is the largest deposit, having been mined from three linear open pits and underground workings. The deposits occur within a Mesoproterozoic metasedimentary sequence that includes metagabbro and felsic (granitic and granodioritic) gneiss (fig. 5–2). Pelitic schist and quartzite are the principal hosts, together with lesser metagabbro and amphibolite, and sparse diopside-actinolite rock (Rosenqvist, 1948; Gammon, 1966; Jøsing, 1966). Albite-rich rocks (“albitite”) are spatially associated with most of the deposits (Munz and others, 1994); scapolite-rich rocks, mainly scapolitized metagabbro, also occur more widely in the district (Engvik and others, 2011), but their relationship to the Co-Cu-Au deposits is unclear. Impure marble and calc-silicate rock containing abundant diopside and actinolite occur locally (Munz and others, 1994). The deposits and their country rocks, including the metaigneous intrusions, were regionally metamorphosed to the upper amphibolite or granulite facies based on the widespread presence of sillimanite in the host pelitic schist and on metamorphic petrology studies (Munz, 1990). The maximum sedimentation age of the sequence is 1475 ± 20 Ma based on U-Pb dating of detrital zircons in a quartzite unit from inferred correlative strata in the Kongsberg area to the south (Bingen and others, 2001).

The Co-Cu-Au deposits in the district are stratabound and extend discontinuously for 9 km along strike. Dips of the ore zones and host rocks are uniformly steep. The Skuterud deposit is approximately 2 km in length and varies in width from less than one meter to as much as 16 m, with exploitable ore lenses typically 4 to 8 m thick (Horneman, 1936);

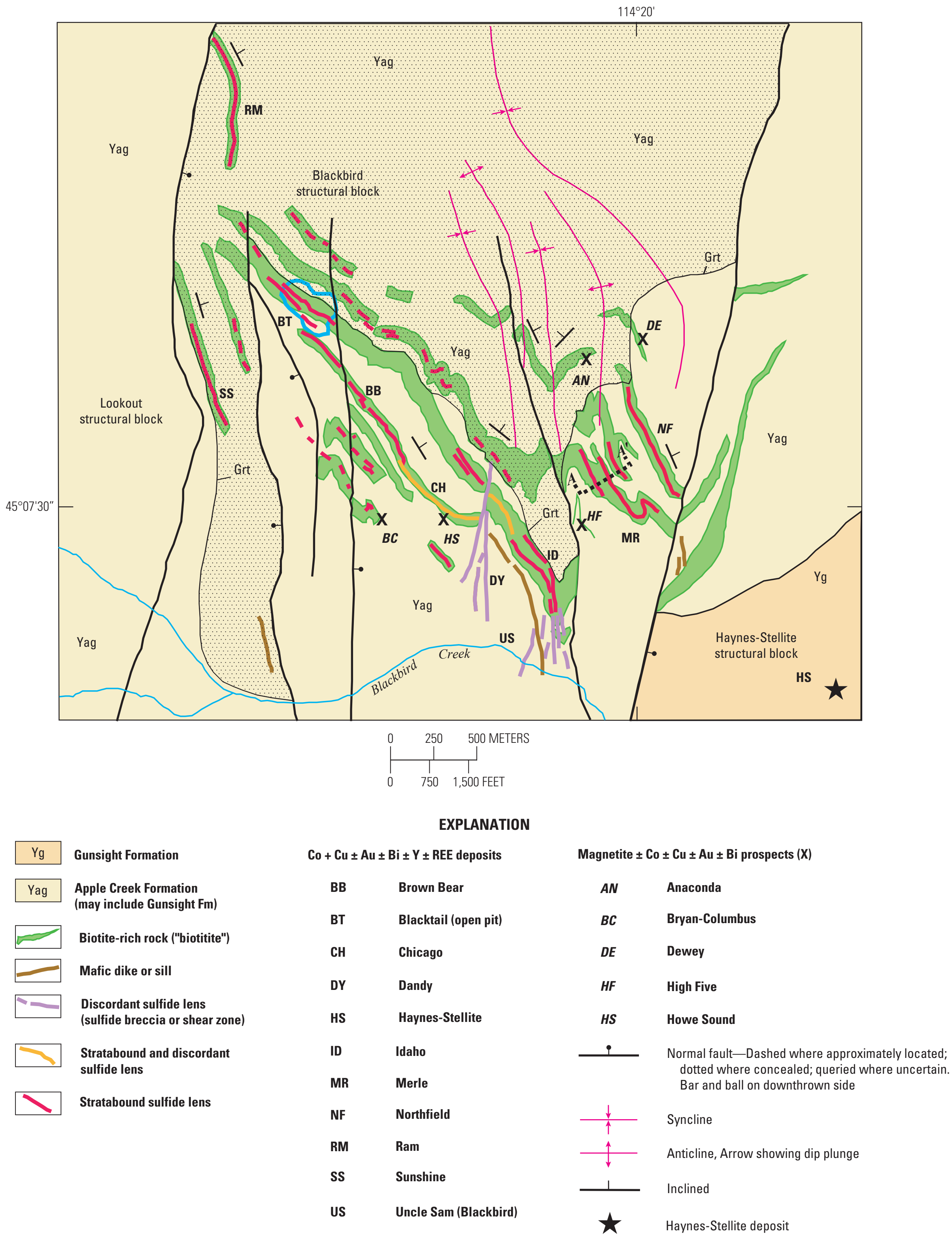

Figure 5–1. Generalized geologic map of the Blackbird district showing the settings of stratabound and discordant mineral deposits. Stippled pattern represents rocks at and above the garnet isograd (Grt); blue line is Blacktail open pit. Mesoproterozoic megacrystic granite and granitic augen gneiss (not shown) crop out 2 km north of the map boundary (see Lund, 2013). Modified from Bookstrom and others (2007).

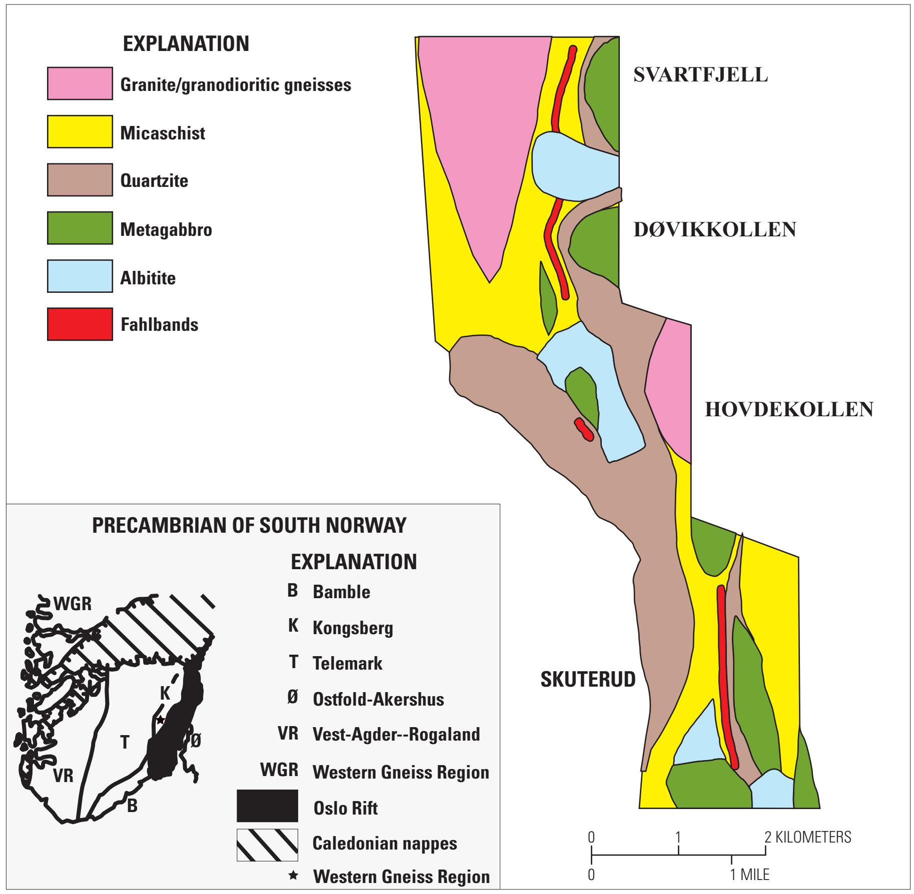

Figure 5–2. Geological map of the Modum district, southeastern Norway, showing the major Co-Cu-Au deposits and generalized distribution of associated albite-rich rock (albitite). Fahlbands are sulfide-rich layers and lenses (see Gammon, 1966). Modified from Andersen and Grorud (1998). Inset shows location of Modum district within the Kongsberg terrane of southeastern Norway.

high-grade Co ore zones range in thickness from 15 to 60 cm (T. Bjerkgård and J.S. Sandstad, oral commun., 2010). Two mineralogically different zones were mined at Skuterud, each consisting predominantly of cobaltite or skutterudite.

NICO Deposit, Canada

The NICO Co-Au-Bi-Cu-Ni deposit, in the Northwest Territories of Canada, is the largest known metasedimentary rock-hosted Co-Cu-Au deposit (table 1–1). This deposit is included in the dataset despite having a very low average Cu grade, because in places the mineralized zone has as much as 1 weight percent Cu. In addition, Cu-rich deposits and occurrences are present in the district, including the Summit Peak prospect about 500 m to the northwest. NICO occurs in the Great Bear magmatic zone within a late Paleoproterozoic continental arc sequence of metavolcanic and unconformably underlying metasedimentary rocks (fig. 5–3). The metavolcanic rocks, predominantly felsic, were deposited subaerially and intruded by quartz-feldspar and feldspar ± amphibole ± quartz dikes of Mesoproterozoic age (Gandhi and others, 1996). Following this plutonism, deformation in the region between 1840 and 1810 Ma produced conjugate transcurrent faults and subordinate normal and reverse faults (Hoffman and Bowring, 1984).

The Co-Au-Bi-Cu-Ni mineralized rock in the NICO area extends over a strike length of 7 km and includes the Bowl Zone deposit scheduled for mining in the near future. The Bowl Zone is localized within highly altered clastic wacke and felsic dikes (fig. 5–4). Sulfide-bearing lenses, broadly stratabound, are continuous for 1.9 km along strike and range in width from a few meters to as much as 70 m. The lenses are preferentially localized within ironstone bodies that contain abundant magnetite and (or) hematite. Breccias spatially related to the Co-Cu-Au mineralization are overlain by a zone of massive K-feldspar-altered rock, developed within rhyolite along the siltstone-rhyolite unconformity. Clasts in the breccia are mainly wacke and siltstone that have been variably altered to K-feldspar; the matrix consists of iron oxides (magnetite and hematite), biotite, amphibole, chlorite, and K-feldspar, but only sparse sulfides (Goad and others, 2000a, b).

Werner Lake Deposit, Canada

The Werner Lake Co-Cu-Au deposit occurs in the English River subprovince of the Superior Province in western Ontario, Canada. The Co-Cu-Au mineralization at Werner Lake is hosted, on a regional scale, mainly by clastic metasedimentary and felsic metaigneous rocks of Archean age. Detrital zircon U-Pb geochronology from distal, but apparently correlative,

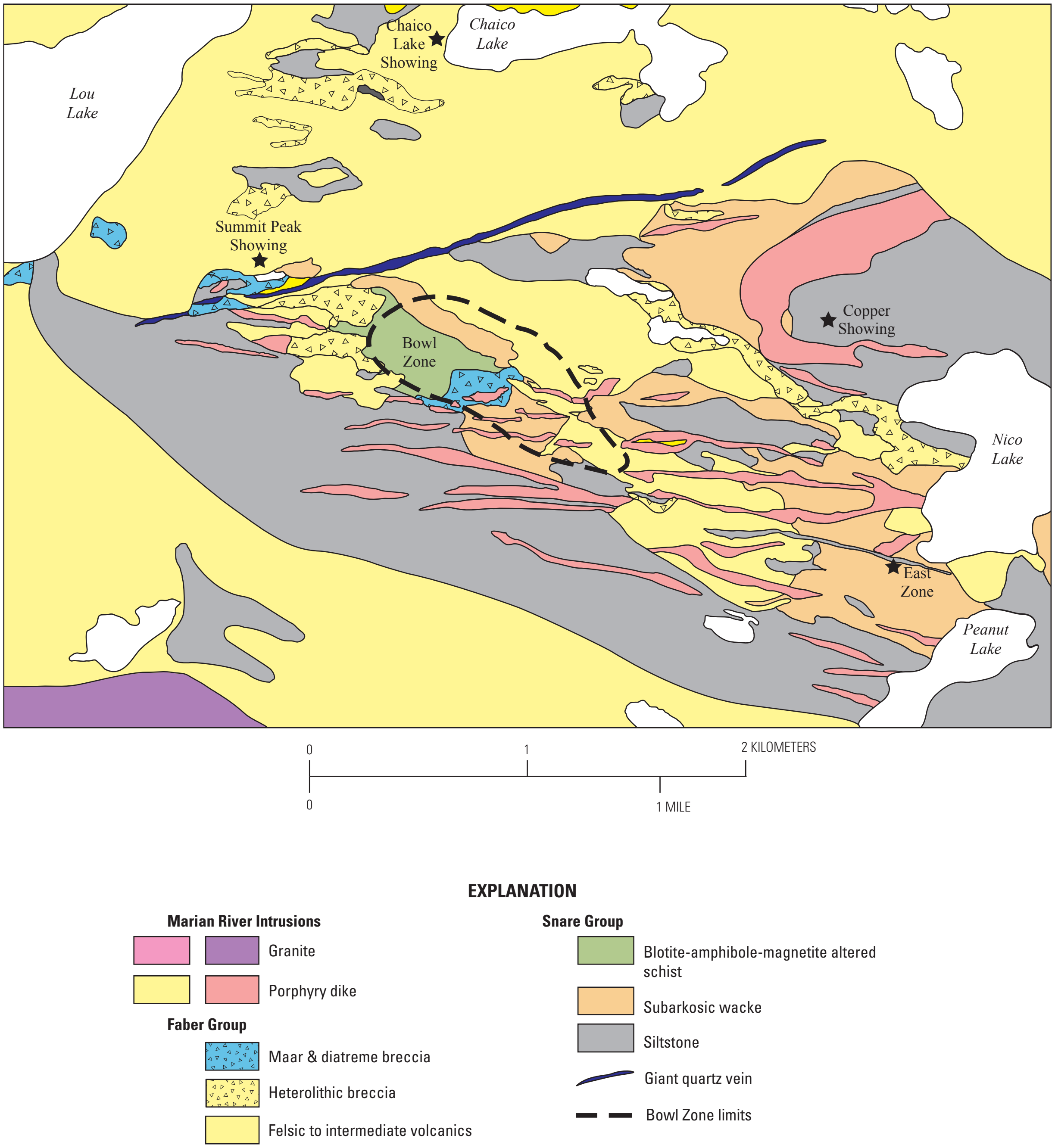

Figure 5–3. Geology of the NICO Co-Au-Bi-Cu-Ni deposit, Northwest Territories, Canada, including the Bowl ore zone. Note that the protolith of the biotite-amphibole-magnetite-altered schist is interpreted to be sedimentary wacke. Modified from Goad and others (2000b).

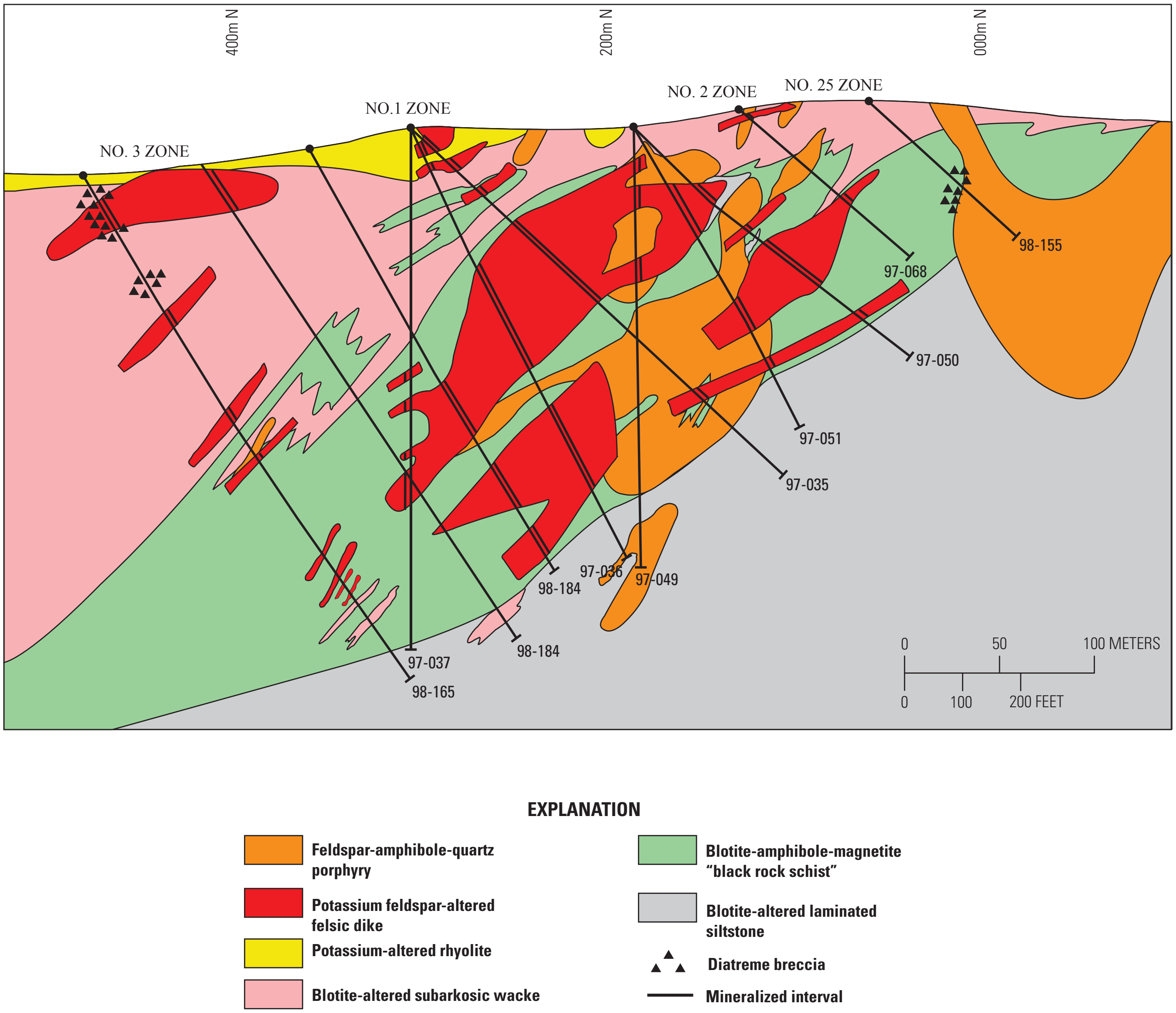

Figure 5–4. Geologic cross section of the Bowl zone of the NICO deposit, Northwest Territories, Canada. Drill holes and numbers are shown. Note that the protolith of the "black rock schist" is interpreted as sedimentary wacke. Modified from Goad and others (2000b).

strata provides a maximum sedimentation age of about 2703 Ma (Davis, 1998). Granitoid plutons in the area were intruded at 2698 ± 2 Ma (Corfu and others, 1995), prior to polyphase deformation and high-T/low-P granulite-facies metamorphism that occurred at 2690 Ma; younger peraluminous (S-type) granites were emplaced at 2670 to 2658 Ma (Pan and others, 1999).

The sulfide deposits (fig. 5–5) are within a lithologically diverse sequence of clastic metasedimentary rocks, amphibolite, garnetiferous biotite schist, and minor ultramafic rock, calc-silicate rock, and garnet-rich quartzite (Pan and Therens, 2000). Ore zones, hosted chiefly in garnetiferous biotite schist, occur discontinuously for approximately 1.2 km along strike, are as much as 3 m thick, and are conformable to layering of wall rocks within a tight to isoclinal synform. Sulfide minerals form disseminations in garnetiferous biotite schist and calc-silicate rock, and semi-massive concordant lenses as much as 3 m in maximum dimension that thicken in F2 fold hinges. Sulfide lenses include both Co- and Cu-rich varieties, the latter occurring both proximal and distal to the former (Pan and Therens, 2000). Deposit-scale zoning is reflected by occurrence of semi-massive Co-rich lenses to the south and disseminated Co minerals in garnetiferous biotite schist to the north.

Kuusamo Schist Belt, Finland

The Kuusamo schist belt in northeastern Finland contains 15 metasedimentary rock-hosted Co-Cu-Au deposits (Vanhanen, 2001; Eilu and others, 2003). This belt, which extends across the border into Russia, is an early Paleoproterozoic terrane that consists mainly of pelitic schist and sericitic quartzite, with generally minor metabasalt and amphibolite, local dolerite and syenite intrusions, and syenite dikes (Pankka and Vanhanen, 1992). Metamorphic grade ranges from middle greenschist to lower amphibolite. Ages of the metasedimentary and mafic metaigenous rocks are poorly known, but the rocks are clearly Proterozoic; most workers assign an age range of 2.5 to 2.0 Ga for the sequence (for example, Corfu and Evins, 2002; Eilu and others, 2007). Sizes of the deposits vary greatly, ranging from less than 0.1 Mt for Lemmonlampi to as much as 1.8 Mt for Juomasuo (table 1–1). Most deposits are localized within two parallel, northeast-trending antiforms or near the intersections of these antiforms with younger faults (Vanhanen, 1991; Pankka, 1997). Characteristic are stratabound deposits that are mainly concordant with the geometry and layering of wall rocks and the predominant metamorphic fabric. The mineralized zones have widths and lengths that generally range from 5 to 30 m and from 100 to 650 m, respectively; the Kouvervaara deposit has a maximum width of 100 m (Vanhanen, 2001). Host rocks are highly altered units within sericitic quartzite and siltstone, including biotite schist, chlorite schist, talc-rich schist, albite-rich schist, albitite, and dolomite schist. Other spatially related wall rocks may contain abundant dolomite, tourmaline, and quartz.

A U-Pb age of approximately 1829 ± 5 Ma determined by Mänttäri (1995) on inclusions of brannerite [(U,Ca,Ce)(Ti,Fe)$_2$O$_6$] in pyrrhotite from the Hangaslampi deposit is within the age range of 1840 to 1800 Ma for emplacement of late orogenic granites in the central Lapland granite complex (Nironen, 2005). It is unclear whether this U-Pb age on brannerite records the timing of Co-Cu-Au mineralization or a younger event.

Size of Hydrothermal System Relative to Extent of Economically Mineralized Rock

The diverse nature of the Co-Cu-Au deposits produces large size differences between the total hydrothermal systems and individual orebodies. Minimal differences are shown by deposits in the Blackbird district of Idaho where alteration zones only 0.3 m thick composed of biotite-rich rock surround orebodies as much as 9 m thick (Nash and Hahn, 1989; Bookstrom and others, 2007). These relatively thin alteration zones suggest that mineralization occurred by highly focused fluid flow and (or) that wall rocks, such as sandstone and siltite, were chemically unreactive with the ore-forming fluids. In contrast, there are examples of wide alteration zones that extend for hundreds of meters beyond much thinner orebodies. In the Kuusamo belt of Finland, thicknesses of the Hangaslampi and Juomasuo deposits (<50 m) are much less than those of the enclosing altered rocks that are several hundred meters or more thick (Vanhanen, 2001). In the NICO deposit, Canada, mineralized zones range in thickness from 10 to 70 m, whereas altered host rocks there are as much as 300 m thick (Goad and others, 2000b).

Vertical Extent

The vertical extent of most of the deposits is less than 300 m. Where drilling and (or) mining have fully delineated the deposits, maximum vertical dimensions are as great as 300 m, such as in the NICO deposit (Goad and others, 2000b). In the Kuusamo belt, the Co-Cu-Au and Au-Co deposits display a range of vertical extents from 70 m for the Hangaslampi deposit, 160 m for the Kouvervaara deposit, 210 m for the Meurastuksenaho deposit, and at least 300 m for the Juomasuo deposit (Vanhanen, 2001). The Skuterud deposit was mined to a depth of 140 m (Horneman, 1936; Rosenqvist, 1948), but it is unclear if this is the limit of economic mineralization. In the Blackbird district, the majority of deposits have maximum depths of about 100 m, but drilling has identified Co-Cu-Au zones in the Sunshine and Ram deposits that extend to 100 to 250 m, below which the zones are truncated by shear structures (Lund and others, 2011, and references therein). Maximum vertical extent of the Werner Lake deposit, at the eastern end, is approximately 40 m (fig. 5–5B).

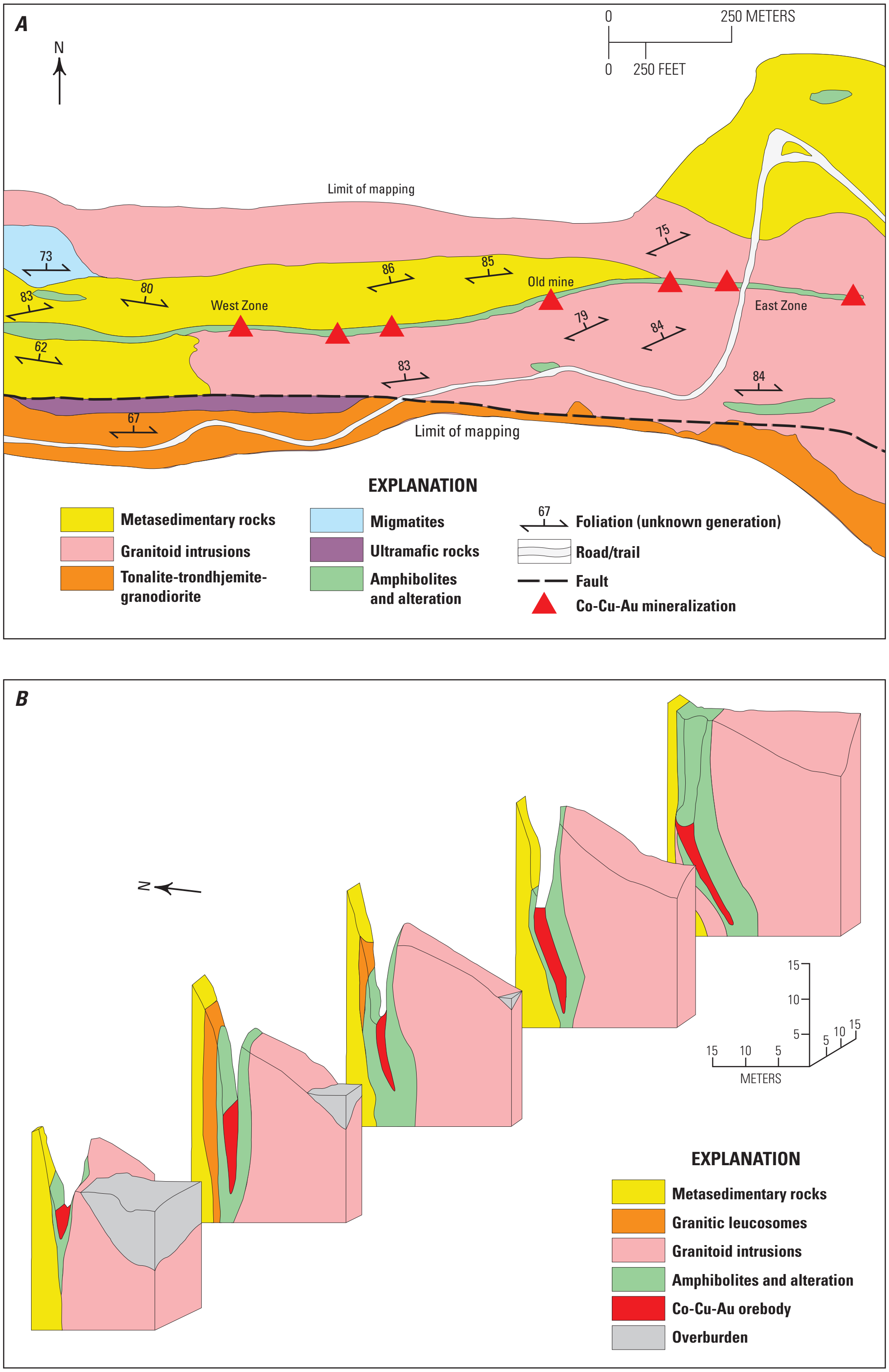

Figure 5–5. Geologic map (*A*) and block diagram (*B*) of the Werner Lake Co-Cu-Au deposit, Ontario. Note that the regional setting of the deposit is dominated by metasedimentary rocks with local granitoid intrusions. Modified from Pan and Therens (2000).

Form and (or) Shape

The most common form of the Co-Cu-Au deposits is a deformed lens in which the length is much greater than the width. Well-documented examples are in the Blackbird district (Vhay, 1948; Bookstrom and others, 2007; Lund and others, 2011), the Skuterud deposit (Jøsing, 1966; Gammon, 1966), the Kuusamo belt (Vanhanen, 2001); and the Dahenglu deposit (Yang and others, 2001). Orebodies are variably folded and sheared, and in places offset by irregular to planar faults (for example, Lund and others, 2011). The ore lenses typically pinch and swell along strike and down dip; many display boudins and cusps, and "durchbewegung structure" characterized by semimassive to massive sulfide infolded with schistose wall rock, and fragments of folded wall rock forming isolated rafts within this sulfide (Marshall and Gilligan, 1989). In some deposits, both concordant and discordant mineralized breccias are present, such as in the Blackbird district (Nash and Hahn, 1989; Bookstrom and others, 2007; Slack, 2012) and the NICO deposit (Goad and others, 2000a, b). Veins of multiple generation are widespread in the Blackbird district, some of which cut all metamorphic fabrics and hence are paragenetically late (Lund and others, 2011). Pipelike deposits are less common, being limited to tourmalinized fragmental bodies and breccias that locally contain Co-Cu-Au-Y-REE mineralization (Modreski, 1985; Bookstrom and others, 2007; Slack, 2012).

Host Rocks

The Co-Cu-Au deposits are hosted mainly by siliciclastic metasedimentary rocks having diverse textures and fabrics. Predominant lithologies include pelitic schist, quartzite, siltstone, argillite, and metagraywacke. Less common host rocks, on a local scale, are metagabbro or amphibolite, metarhyolite, and granite; no deposits are wholly within plutons or other types of igneous intrusions. Calc-silicate rocks are rare, generally occurring only in small areas at or near a few deposits. Depending on the nature and extent of deformation and metamorphism, these lithologies may display cleavage, age, one or more foliations, or a shear fabric; cataclastic and mylonitic textures are rare. Mineral assemblages reflect bulk composition, precursor mineralogy, and local metamorphic grade (greenschist, amphibolite, granulite).

Structural Setting(s) and Controls

In the Blackbird district, the work of Vhay (1948) and Bookstrom and others (2007) has shown that the ore zones are typically elongate parallel to local structures such as faults, shear zones, and fold axes, and to intersections of axial planar cleavage with bedding. Some of the deposits are localized along lithologic contacts; breccias are common hosts locally. Studies by Lund and others (2011) indicate a strong structural control for mineralized veins, preferentially along axial planar cleavage, intrafolial foliation, and shears. In the Kuusamo schist belt of Finland, Co-Cu-Au deposits are distributed along a regional anticline, and are mainly localized by ductile shear zones as exemplified by the Juomasuo deposit (Vanhanen, 2001). The distribution of the NICO and related deposits in Canada is attributed by Goad and others (2000b) to occurrence of a pre-ore regional unconformity between lower siliciclastic metasedimentary rocks that host the deposits and an overlying, mostly unmineralized unit of metarhyolite.

Remote Sensing

No remote sensing data from high-altitude surveys or satellites are known to be available for the Co-Cu-Au deposits. Vanhanen (2001) described the use of Landsat satellite imagery in the Kuusamo belt of Finland, but only for gold exploration. Some of the Co-Cu-Au deposits including Blackbird (USA), Mt. Cobalt (Australia), and Kendekeke (China) occur in sparsely vegetated terrain, and thus these deposits may be amenable to remote sensing studies (for example, airborne multispectral imaging; Kruse, 2012). Such studies could provide valuable information on the distribution of alteration minerals spatially related to a deposit and the possible occurrence of similar alteration assemblages elsewhere in the region that may have exploration potential.

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6. Geophysical Characteristics

By Klaus J. Schulz

Descriptive and Geoenvironmental Model for Cobalt-Copper-Gold Deposits in Metasedimentary Rocks

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6. Geophysical Characteristics

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Disseminated to massive Co-Cu-Au sulfide deposits occur predominantly in deformed siliciclastic metasedimentary rocks originally deposited in intracratonic extensional basins, or in oceanic rifts and back-arc basins. Deposits and districts are typically structurally controlled and are clustered along folds, shear zones, and breccia zones related to major, through-going, deep-crustal faults. Extension-related mafic to felsic igneous rocks may be temporally related with mineralization, although they are not generally spatially coincident. In addition to ore-bearing Co ± As ± Ni sulfides, accompanying minerals in the deposits can include pyrite, chalcopyrite, pyrrhotite, gold, magnetite, and (or) hematite in ores and surrounding country rocks. Highly potassic (biotite or K-feldspar) and (or) sodic (albite) alteration zones commonly form haloes in country rocks surrounding deposits. The distinct tectonic and geologic features of the Co-Cu-Au deposits make them amenable to various regional- and property-scale geophysical exploration surveys, including magnetic, gravity, electromagnetic, and radiometric methods (Goad and others, 2000; Smith, 2002; Ford and others, 2007).

Magnetic Signature

The magnetic method is the oldest and most widely used geophysical tool. It can effectively delineate regional bedrock structural trends, and directly detect magnetic anomalies associated with metallic mineral deposits where magnetite or other magnetic minerals such as pyrrhotite are present. However, because the magnetic susceptibilities of different rock types may overlap, assignment of rock type on the basis of magnetic signature is often ambiguous. Most magnetic anomalies reflect variations in the quantity and physical nature of ferromagnetic iron oxide minerals, particularly magnetite, and these anomalies typically have amplitudes ranging from a few nanoTeslas (nT) to several thousand nT. In comparison, for much of the United States, Earth's background geomagnetic field is approximately 55,000 nT.

Regionally, the magnetic characteristics of the metasedimentary basins hosting Co-Cu-Au deposits can be complex depending on a number of factors, including the volume and nature of sediment, amount of extension-related mafic to felsic magmatism, and the degree of subsequent deformation and metamorphism. Granitic plutons, which in some districts appear contemporaneous with mineralization, can display distinctive positive or negative magnetic responses, depending in part on the characteristics of the surrounding rocks. Because of the common occurrence of plutons, volcanic rocks, and particularly iron-rich alteration zones in basins hosting Co-Cu-Au deposits, the basins generally have "magnetically active" signatures (for example, NICO district in Canada and Kuusamo area in Finland), although individual deposits are not necessarily coincident with a discrete magnetic anomaly (Smith, 2002). In addition, because iron oxides are generally more widely distributed than Co-Cu-Au mineralization, many magnetic anomalies may lack economic significance.

In the Kuusamo area of northeastern Finland, most of the Co-Cu-Au deposits are hosted by the Sericite Quartzite Formation that in regional aeromagnetic maps appears as a magnetic low surrounded by high and continuous magnetic anomalies related to mafic sills and volcanic rocks (fig. 6–1). However, at the scale of the airborne maps (1:3,000), anomalies within the Sericite Quartzite Formation appear to be fuzzy and exact locations of anomaly sources cannot be determined precisely. In addition, sulfide-bearing occurrences can be between the 200-m-spaced flight lines without any anomaly recorded on the maps (fig. 6–2). These problems are mitigated with more detailed ground magnetic surveys, which resolve the diffuse airborne map anomaly of the Juomasuo deposit in the northeastern end of the Kuusamo area into several small positive magnetic anomalies (fig. 6–2). Drilling of these anomalies has identified several separate sulfide-bearing lodes (Turunen and others, 2005). To the south of the Juomasuo deposit (Circle 2 in fig. 6–2) is an area marked by a diffuse rise in the airborne magnetic map with an anomaly intensity of less than 100 nT. A systematic ground magnetic survey over this area identified a 2,000-nT anomaly with a diameter of 100 m associated with the Hangaslampi deposit. Moreover, the Pohjasvaara sulfide-magnetite deposit south of Juomasuo (Circle 3 in fig. 6–2) shows as a 400-nT anomaly in the airborne survey but as a 4,000-nT anomaly in the ground survey (Turunen and others, 2005). In addition to positive magnetic anomalies, the Co-Cu-Au deposits in the Kuusamo area are also characterized by positive electromagnetic anomalies (see below and Turunen and others, 2005).

Magnetic surveys have proven useful for deposit identification in the Lou Lake area of the southern Great Bear magmatic zone, Northwest Territories, Canada (Gandhi and others, 1996; Goad and others, 2000). In this area, both fixed-wing airborne geophysical surveys and more detailed helicopter surveys show positive total-field and vertical magnetic-gradient anomalies coinciding with a regional positive Bouguer-gravity anomaly (Goad and others, 2000). The regional-scale surveys also show that geophysical features are transected by a series of northeast-trending linear magnetic (and VLF) anomalies related to a prominent set of transverse splays from the major north-trending Wopmay Fault. In addition, areas having the greatest magnetic response (about 1,000 nT above apparent

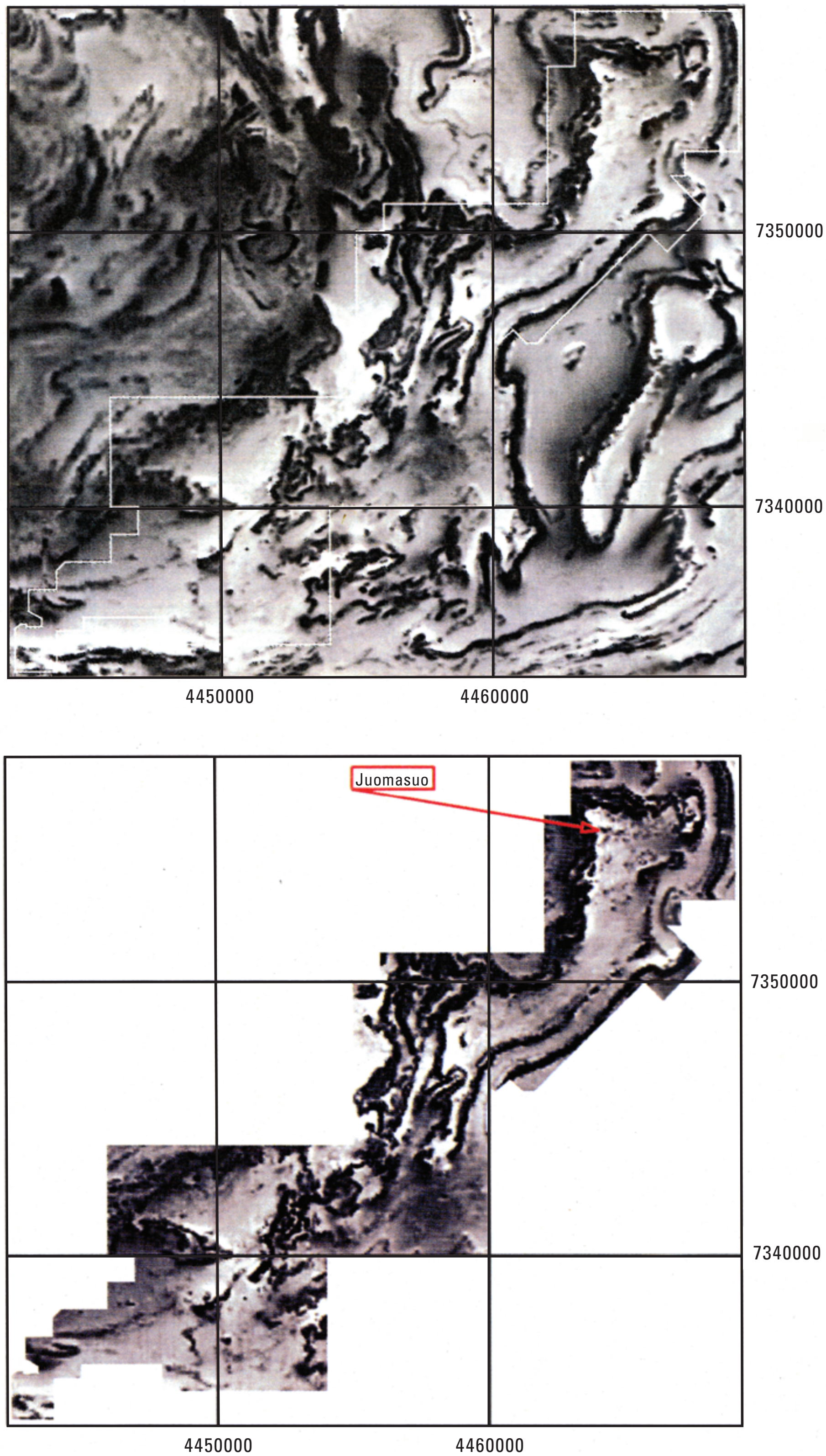

Figure 6–1. Airborne magnetic total component field (upper) and ground vertical component magnetic (lower) anomaly from the Sericite Quartzite Formation of the Kuusamo area, Finland (from Turunen and others, 2005).

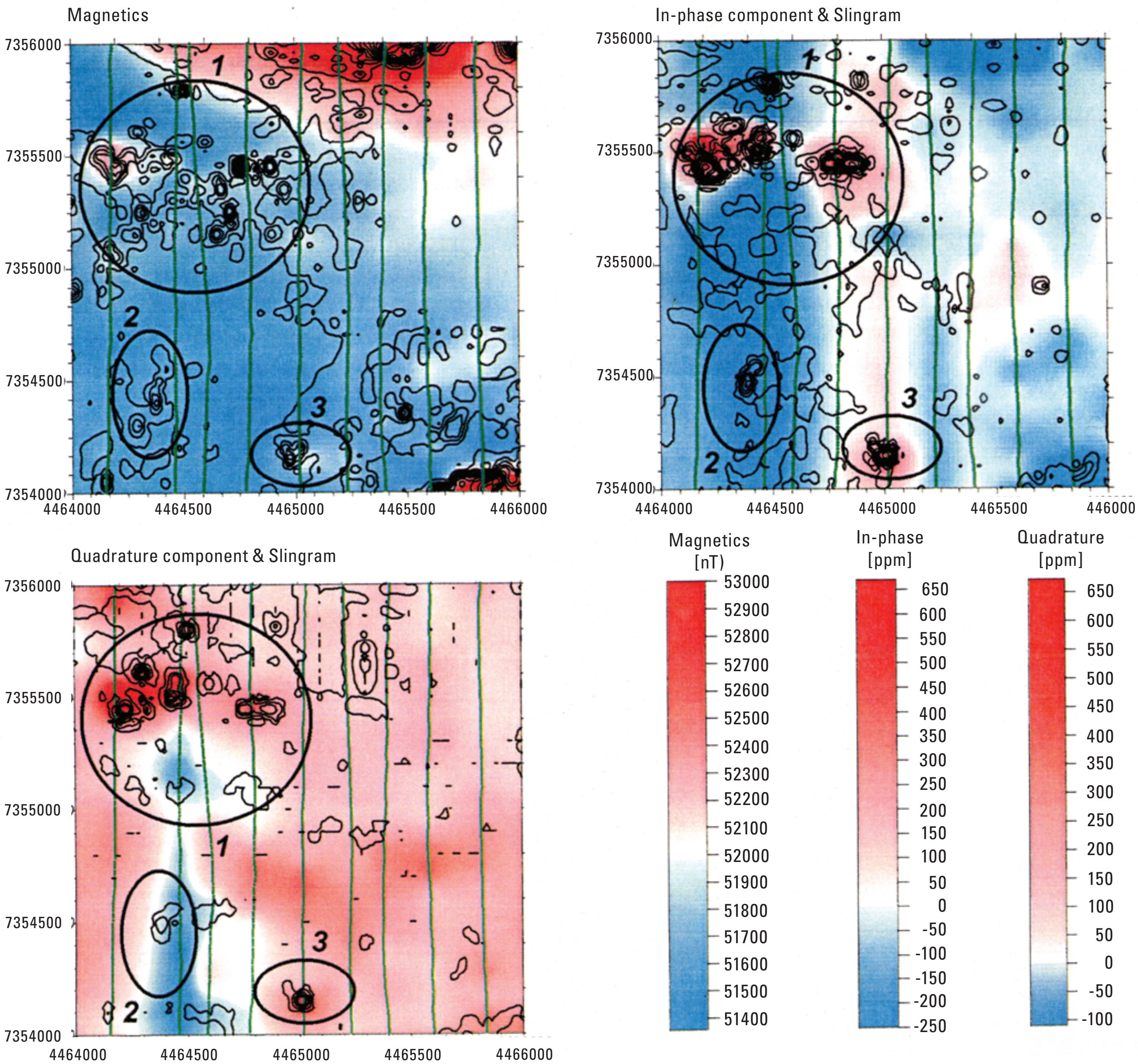

Figure 6–2. Magnetic field (upper left), in-phase electromagnetic field (upper right), and quadrature electromagnetic field (lower left) for the Juomasuo deposit and surrounding area, Kuusamo belt, Finland. Airborne data in red-blue shading (scale shown lower right), contours are for ground data, green lines denote flight paths. Sulfide deposits are circled: 1, Juomasuo, 2, Hangaslampi, 3, Pohjasvaara. (From Turunen and others, 2005).

background) are coincident with discrete radiometric anomalies marking the presence of hydrothermal centers (fig. 6–3). Abundant magnetite produces characteristically strong positive magnetic anomalies (thousands of nanoTeslas); however, a predominance of hematite tends to produce only low-intensity anomalies (Goad and others, 2000).

Gravity Signature

The gravity method is applied to investigate subsurface geology by measuring small variations in Earth's gravity field that is sensitive to variations in rock density. Local mass excesses or deficiencies are most commonly expressed as Bouguer anomalies, which typically range from less than one milligal (mGal) to several tens of milligals. In comparison, Earth's total gravity field is approximately 980,000 mGal (for example, Telford and others, 1990). Because the gravity field is not solely a function of density, several corrections must be applied to observed gravity data in order to resolve variations related to crustal causes. These corrections include variations in time, latitude, elevation, tides, and topography.

Local mass excesses or deficiencies expressed as Bouguer anomalies reflect subsurface variations in density, which in turn are related to variations in mineral composition and porosity. Typical densities of Earth materials range from about 2.00 gm/cc for unconsolidated sediment to about 2.95 gm/cc for mafic igneous rocks. However, sulfide minerals and magnetite have densities between about 4 and 5 gm/cc and even relatively small mineral deposits are capable of producing positive Bouguer anomalies of as much as several milligals (Ford and others, 2007).

Gravity has been used effectively in the exploration program in the Lou Lake area of Canada. The area is characterized by a regional positive Bouguer-gravity anomaly that ranges from 3 to 6.5 mGal above background and coincides with positive magnetic anomalies (Goad and others, 2000). The area of positive gravity anomaly is bounded by granite batholiths and plutons that have negative Bouguer-gravity anomalies ranging from 2 to 10 mGal below background. Within the regional gravity anomaly are several small, but distinct positive Bouguer-gravity anomalies, at least some of which correspond with known Co-Cu-Au sulfide zones. For example, a detailed gravity survey over the Bowl Zone of the NICO deposit shows that it is characterized by a 3.1 mGal Bouguer-gravity anomaly (Goad and others, 2000).

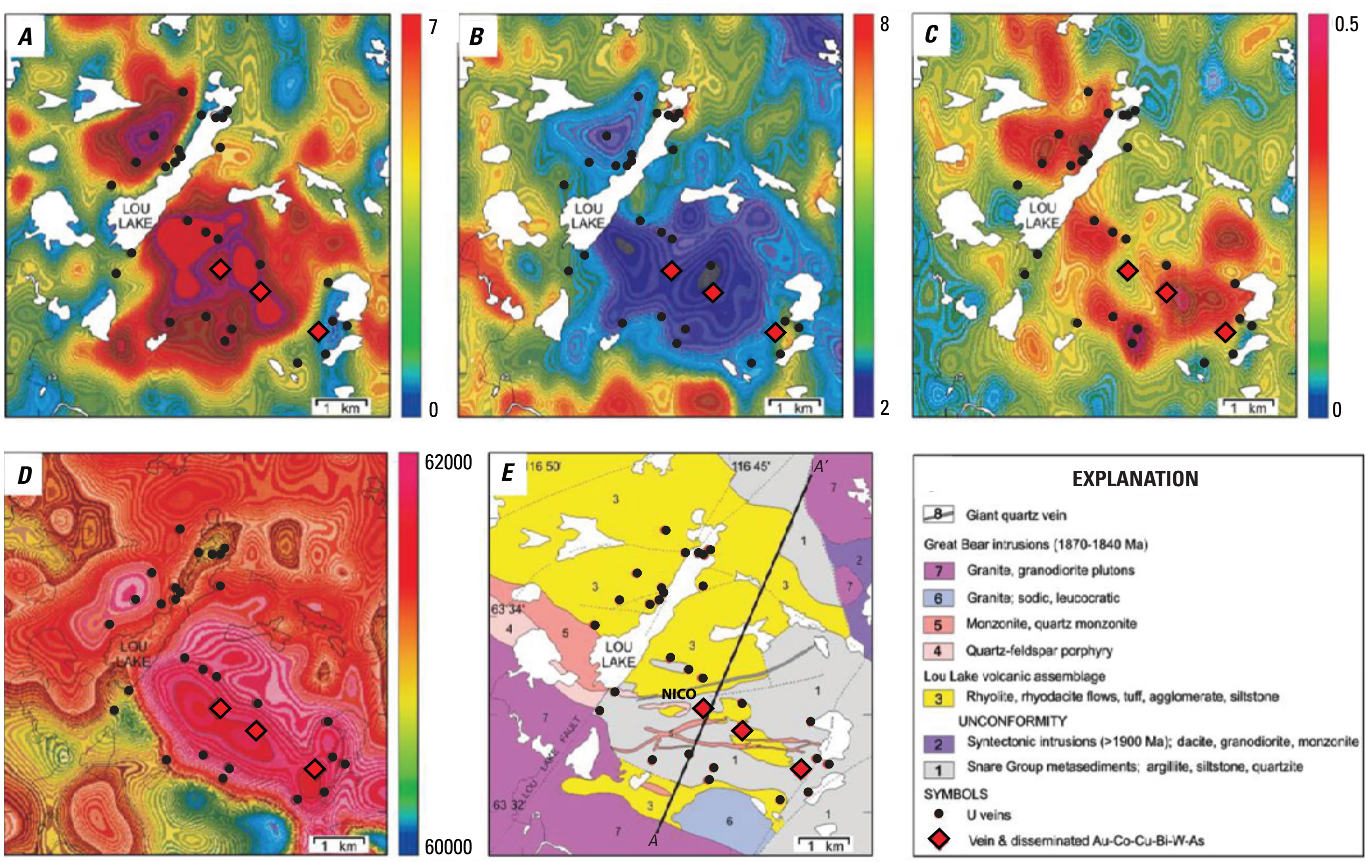

Figure 6–3. Potassium (*A*), eTh/K (*B*), eU/Th (*C*), total magnetic field (*D*), and geology (*E*) images with geology explanation (*F*) for the area near Lou Lake, Northwest Territories, Canada (from Ford and others, 2007). Cross section along line *A-B* in the geologic map (*E*) is shown in figure 6–4.

Electrical Signature

Electrical methods respond to the electrical conductivity of rocks and minerals that may vary by 20 orders of magnitude, the largest variation for any physical property (Ford and others, 2007). Sulfide minerals, such as chalcopyrite and pyrrhotite, are conductive (1 to 6.7 milliSiemens per meter [mS/m]), whereas minerals such as quartz are essentially nonconductive. Granite is essentially nonconductive, whereas the electrical conductivity of shale ranges from 0.5 to 100 mS/m and the conductivity of iron formations ranges from 0.5 to 3300 mS/m (Ford and others, 2007). Water content increases conductivity and can have a significant influence on its magnitude. Because the conductivity of sulfides may be similar to that of other, nonmineralized materials such as graphite or clays, unequivocal identification of mineral deposits can be difficult using electrical methods alone.

Three principal electrical methods are employed in geophysical surveys: (1) electrical resistivity, (2) induced polarization, and (3) spontaneous potential. The first two methods use an artificial current that is introduced via a separate pair of electrodes. In contrast, spontaneous potential relies on small, passive currents already present within the shallow subsurface. Because spontaneous potential only penetrates to shallow depths, it is not generally employed in mineral exploration programs. Variations of electrical properties at depth are determined in all three methods by deploying standard electrode arrays and systematically varying the position and spacing of the electrodes. Because these electrical methods require ground-based deployment, they are typically used only on specific targets identified through earlier geologic, geophysical, and geochemical studies.

Electrical resistivity (ER) surveys measure the degree to which materials resist electrical current (the inverse of conductivity), with results expressed in ohm-meters (ohm-m). Resistivity for most Earth materials is a function of the quantity and quality of interstitial water, and ranges from a few tens of ohm-meters for clays and shales to ≥1000 ohm-m for fresh crystalline rocks (Sharma, 1997). Sulfide minerals have extremely low resistivities (much less than 1 ohm-m), but sulfide minerals can be difficult to effectively image where they occur within discrete, three-dimensional volumes rather than in broad, layer-like features.

Induced polarization (IP) surveys measure how well materials tend to retain electrical charges or their chargeability. The IP effect is based on the decay of residual potential once a current has been turned off (time domain IP measured in milliseconds [msec]), or as apparent resistivity observed at two discrete current frequencies (frequency domain IP measured as percent frequency effect [PFE]). The IP technique is mostly concerned with measuring the electrical surface polarization of metallic minerals. Because the IP effect is proportional to the interactive area, disseminated sulfide mineralization is more likely to produce a pronounced IP effect than massive sulfide. However, disseminated sulfide haloes commonly surround massive sulfides and can produce a significant IP response. Induced polarization/ER surveys have been applied with some success in the Lou Lake area of Canada (Goad and others, 2000). Detailed IP surveys over the Bowl Zone of the NICO deposit reveal complex chargeability and resistivity anomalies that are coincident with sulfide mineralization.

Electromagnetic Signature

Electromagnetic (EM) methods are used extensively in the exploration for sulfide deposits because these methods are particularly sensitive to the high conductivities of sulfide minerals and can be deployed in airborne surveys (Ford and others, 2007). Most EM surveys utilize artificially induced currents that are produced by fluctuating magnetic fields from a transmitter coil or antenna. Two approaches are typically used: frequency domain, where the EM response is observed at varying frequencies, or time domain, where the decay of induced currents is observed following the introduction of a pulsed EM signal. The EM receiver measures both the in-phase and out-of-phase (quadrature) components of the primary field, and the ratio of the secondary field to the primary field in parts per million (ppm). Although EM methods span a wide range of frequencies, most methods used in sulfide exploration operate with frequencies between 1 and 1,000 hertz. The maximum depth at which a deposit can be detected depends on its size and conductivity, and on the conductivity of host rocks and overburden. Typically, airborne time-domain EM can detect deposits/conductors at depths to about 300 m, whereas ground time-domain surveys using large loops can detect conductive units at depths in excess of 1 km (Ford and others, 2007). However, conductive overburden, lakes, and swamps can effectively mask bedrock conductors.

Airborne EM surveys have been conducted with some success in both Finland and Canada. In Finland, EM conductive anomalies were detected at the Juomasuo deposit and several other deposits in the Kuusamo area (fig. 6–2; Turunen and others, 2005). At Juomasuo, both in-phase and quadrature electromagnetic anomalies are 600 ppm, which is one of the strongest anomalies related to a Co-Cu-Au sulfide deposit in the Kuusamo area. In the Lou Lake area in Canada, helicopter-airborne surveys detected a 2.2-km by 0.7-km discrete, resistivity-low anomaly on the 7200 hertz frequency, accompanied by several small, single-line conductors (<1 siemen) within a broader, less-intense, resistivity-low anomaly (Goad and others, 2000). The more intense resistivity lows occur in the center of large radiometric and magnetic anomalies, and these lows are coincident with the Bowl Zone mineralization at the NICO deposit.

Gamma-Ray Spectrometric Signature

The three most abundant, naturally occurring radioactive elements are potassium (K), uranium (U), and thorium (Th). Potassium is a major constituent of most rocks and, where abundant, is diagnostic of alteration associated with a number of mineral deposit types including Co-Cu-Au deposits. Uranium and Th, although generally present in only trace amounts, have varying concentrations in rocks and can also be effective in the direct detection of some types of alteration and mineralization. Disequilibrium, when one or more of the daughter products in the 238U decay series is added or removed, can be a significant source of error, especially in areas of extreme surficial weathering. To highlight the assumption of equilibrium in the measurement of U and Th concentrations by gamma-ray spectrometry, values are often reported as “equivalent U” (eU) and equivalent Th (eTh). However, the assumption of equilibrium is almost always valid for the Th decay series (Ford and others, 2007). Gamma-ray surveys only measure near-surface chemical composition (<60 cm depths) because of the strong attenuation of gamma rays by rock or soil. In addition, because of the typically inhomogeneous nature of the land surface, the absolute values of K, eU, and eTh may be much less significant than the radioelement patterns.

Because highly potassic (biotite or K-feldspar) alteration with accompanying uranium enrichment commonly forms haloes in country rocks surrounding Co-Cu-Au 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 of Canada, the NICO deposit is associated with discrete positive eK and negative eTh/K anomalies that are coincident with positive magnetic anomalies (fig. 6–4; Goad and others, 2000). Areas having enriched uranium also are characterized by increased eU/Th anomalies. Low eTh/K ratios suggest strong secondary potassium enrichment because normal igneous processes tend to enrich both Th and K, do not lead to such low eTh/K ratios, and are taken to mark the presence of hydrothermal centers (Gandi and others, 1996; Goad and others, 2000; Ford and others, 2007).

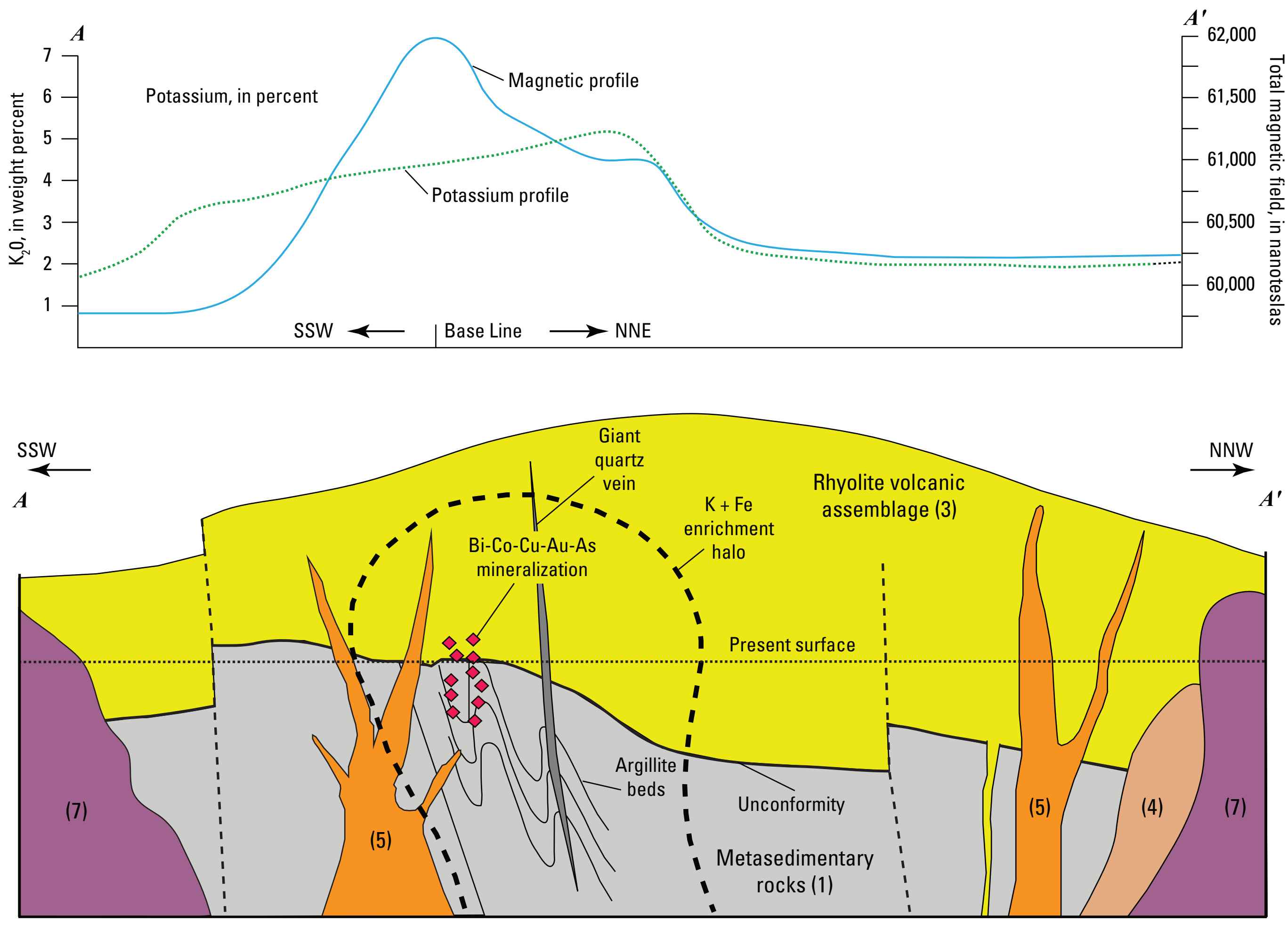

Figure 6–4. Total magnetic field and potassium profiles (top) and geological cross section (below) crossing the mineralized zone at the NICO deposit (line *A-A′* fig. 6–3*E*). For unit identification see explanation in figure 6–3. (Modified after Gandhi and others,1996).

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7. Hypogene Ore and Gangue Characteristics

By John F. Slack

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Descriptive and Geoenvironmental Model for Cobalt-Copper-Gold Deposits in Metasedimentary Rocks

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By John F. Slack

Mineralogy

The ore mineralogy of the Co-Cu-Au deposits (table 1–1) is dominated by Co ± Ni sulfarsenides and sulfides including cobaltite (CoAsS), glaucodot [(Co,Fe)AsS], skutterudite [$(Co,Fe,Ni)As_{2-3}$], safflorite [$(Co,Fe)As_2$], smaltite ($CoAs_2$), siegenite [$(Ni,Co)_3S_4$], carrollite ($Cu(Co,Ni)_2S_4$), linnaeite (Co_3S_4), and gersdorffite (NiAsS). Some deposits contain only one Co-rich mineral such as cobaltite; the Blackbird district of east-central Idaho has the entire suite (Slack, 2012, and references therein). Alloclasite, a rare dimorph of glaucodot, occurs at the Mt. Cobalt deposit (Croxford, 1974). Cobalt also may be concentrated in other sulfides such as cobaltian pyrite, which occurs in deposits of the Iron Creek area southeast of the Blackbird district (Nash, 1989) and in the Dahenglu deposit in China (Yang and others, 2001). Cobaltian arsenopyrite and cobaltian loellingite are common in the NICO deposit in Northwest Territories, Canada (Goad and others, 2000a, b).

Accompanying ore minerals in most deposits are chalcopyrite and gold, with generally minor arsenopyrite, pyrite, pyrrhotite, marcasite, tetrahedrite, bismuthinite, bismuth, apatite, and (or) molybdenite. Gold is commonly in native form, but in the NICO deposit it occurs in alloys with Bi, Te, and (or) Sb (Goad and others, 2000b); some of the deposits in the Kuusamo belt also contain appreciable gold tellurides (Vanhanen, 2001). A gold-rich zone in the core of the NICO deposit has grades ranging from 1 to 60 g/t, with an average of 3 to 5 g/t Au. Recent exploration of the Juomasuo and Hangaslampi deposits in the Kuusamo belt of Finland has discovered extremely high "bonanza" gold grades of as much as several hundred g/t Au over intervals in drill core of nearly 20 m (Dragon Mining Ltd., 2012). In the Blackbird district, gold is preferentially associated with cobaltite, forming inclusions, vein fillings, or adjacent grains (Nash and others, 1987; Eiseman, 1988). In the Skuterud deposit, gold forms inclusions with or without intergrown Bi-Te phases, enclosed within cobaltite and magnetite (J.F. Slack, unpublished data). At Werner Lake, gold is most common in Cu-rich lenses and late Cu-rich veins (Pan and Therens, 2000).

Bismuth minerals are particularly common in the NICO deposit and in the Blackbird district where selected samples have as much as 9.2 weight percent Bi (Goad and others, 2000b; Slack, 2012). Bismuth tellurides occur in some of the deposits of the Kuusamo belt (Vanhanen, 2001). Sphalerite and galena are generally absent, or occur only in trace amounts, except in a few deposits such as Dahenglu and Gladhammar. Scheelite is relatively abundant in the Mt. Cobalt and NICO deposits; ferberite also occurs at NICO (Nisbet and others, 1983; Goad and others, 2000b). The Blackbird deposits have locally abundant Y and rare earth elements (REE), including as much as 3.7 weight percent $\Sigma REE+Y_{oxides}$ (sum of REE and Y oxides), which are hosted in allanite, xenotime, and monazite; one deposit contains appreciable amounts of gadolinite-Y, a Fe-Be-Y-Ce silicate mineral (Slack, 2006, 2007, 2012). The Mt. Cobalt deposit in Australia has abundant allanite and xenotime (Nisbet and others, 1983). Concentrations of allanite are also present in the Meurastuksenaho Co-Cu-Au deposit in Finland (Vanhanen, 2001). Minor uraninite occurs in the Modum, Werner Lake, Juomasuo, and Blackbird deposits (Grorud, 1997; Andersen and Grorud, 1998; Pan and Therens, 2000; Vanhanen, 2001; Slack, 2012). Sparse to trace amounts of bornite, tellurobismuthite, Co-selenides, or stannite also may be present. Relatively high Ni concentrations (~0.1-0.8 weight percent) occur in deposits in the Modum and Blackbird districts, the Ni residing mainly in nickeliferous cobaltite and nickeliferous pyrite, respectively (Grorud, 1997; Slack, 2012).

Gangue minerals are chiefly quartz and muscovite, with locally abundant albite, biotite, chlorite, tourmaline, K-feldspar, scapolite, and magnetite or hematite. Carbonates can be prominent in some deposits, such as several in the Blackbird district that contain minor to major amounts of siderite (Slack, 2012) and the Kouvervaara deposit in Finland that has ferroan dolomite. In the Modum district, cobaltite-rich ores in places contain coarse albite grains; albite is a common gangue mineral also in this district and in deposits of the Kuusamo schist belt, northeastern Finland, such as Juomasuo (Grorud, 1997; Vanhanen, 2001). Biotite is especially prominent in the Blackbird district and in the NICO deposit, being characterized by very iron- and chlorine-rich compositions including as much as 1.9 weight percent Cl at Blackbird and 1.2 weight percent Cl at NICO (Nash and Connor, 1993; Goad and others, 2000b). Some of the Blackbird deposits have abundant chloritoid; sparse albite occurs in early pre-ore and late post-ore veinlets (Lund and others, 2011). Tourmaline is particularly prominent in the Dahenglu deposit and in parts of the Blackbird district (Yang and others, 2001; Trumbull and others, 2011; Slack, 2012), and is abundant locally in the Skuterud deposit (Grorud, 1997). Most deposits have appreciable magnetite within the mineralized zones or in surrounding country rocks; however, in the Blackbird district, magnetite is volumetrically rare, although several small Co-Cu-Au-Bi prospects contain abundant magnetite gangue (Slack, 2012). Also, stratabound magnetite-rich rocks 35 km to the southeast of the district contain cobaltiferous pyrite and minor chalcopyrite (Nash, 1989). The NICO deposit in Canada has appreciable magnetite and (or) hematite within amphibole-K-feldspar-biotite altered rocks (Goad and others, 2000a, b); magnetite is common in the Meurastuksenaho and Hangaslampi deposits in the Kuusamo belt of Finland as veins, semi-massive bodies, and disseminations with sulfides or silicates in ore zones and altered wall rocks (Vanhanen, 2001). Minor gangue constituents include apatite, barite, garnet, pyroxene, cordierite, amphibole, and graphite.

Mineral Paragenesis

Discerning mineral paragenesis in the Co-Cu-Au deposits is difficult owing to effects of varying recrystallization and remobilization during post-ore deformation and metamorphism. Examples of such recrystallization and remobilization are described in the Modum district, the NICO and Werner Lake deposits, and the Blackbird district (Grorud, 1997; Goad and others, 2000a, b; Pan and Therens, 2000; Slack, 2012). A common feature is paragenetically early cobalt minerals that are overprinted by later chalcopyrite. Magnetite, where present, is typically cut or replaced by sulfides, gold, and other minerals, as at the NICO deposit in Canada (Goad and others, 2000b) and the Skuterud deposit in Norway (J.F. Slack, unpublished data). In the Juomasuo deposit, Finland, coarse-grained magnetite within chlorite-rich altered rock was replaced during potassic alteration by biotite and pyrite (Vanhanen, 2001). Tourmaline is also generally early in the paragenesis, although in some deposits, such as those in the Blackbird district, it appears to be contemporaneous with cobalt mineralization (Trumbull and others, 2011). Albite in this district occurs as a minor gangue mineral in early pre-ore and late post-ore veins (Lund and others, 2011). High Bi concentrations (~1-10 weight percent), commonly in native Bi and bismuthinite, tend to be spatially associated with gold, but in some cases gold seems to be texturally separate from, and paragenetically unrelated to, Bi minerals (Slack, 2012).

Zoning Patterns

Systematic mineralogical and metal zoning is only documented in a few of the Co-Cu-Au deposits. At Skuterud, Norway, two broadly parallel orebodies contain different proportions of cobalt minerals—one having predominantly cobaltite and the other mainly skutterudite (Grorud, 1997). In the Blackbird district, a broad gangue mineral zoning is expressed by chiefly siliceous (quartz) gangue occurring in deposits within the northern and western parts (for example, Sunshine and Ram), in contrast to deposits in the east and southeast (for example, Merle) that have a more biotite-rich gangue (Bookstrom and others, 2007).

Some of the deposits in the Kuusamo schist belt display metal zoning (Vanhanen, 2001). At the Meurastuksenaho deposit, detailed analyses of three mineralized intervals in one drill core show patterns of Fe, Cu, light REE, Au, and Mo concentrations that differ from those of Co, As, Bi, Te, and Se. The Hangaslampi deposit displays similar metal differences for two mineralized intervals in one drill core, accompanied by relatively high concentrations of Pb (as much as ~800 ppm) and U (as much as ~2,000 ppm) that only partially coincide with the Co- and As-rich intervals. At the Juomasuo deposit, metal zoning is less pronounced based on data for one drill core, in which high concentrations of Fe, Co, As, Cu, Bi, Se light REE, Pb, and U occur mostly at the same two intervals (Vanhanen, 2001). Recent exploration drilling of the Hangaslampi and Juomasuo deposits by Dragon Mining Ltd. (2012) has discovered very high "bonanza" gold grades over significant widths. For example, one intercept at Juomasuo of 31.9 m has an average of 45.7 g/t Au. Most of the Au-rich zones in this deposit coincide with Co-rich zones, but some do not; light REE concentrations occur in the Au-rich zones and in separate zones (Dragon Mining Ltd., 2012). It is uncertain whether these metal zoning patterns in the deposits of the Kuusamo schist belt resulted from one mineralizing event or from two or more unrelated events.

Textures and Structures

The different Co-Cu-Au deposits have variable textures and structures that include massive ore, breccia ore, veins, and disseminations. In some districts, such as Blackbird, Modum, and Werner Lake, mineralization chiefly consists of semi-massive to massive cobaltite, locally with other ore minerals, that are broadly stratabound within enclosing siliciclastic metasedimentary host rocks. Breccia ore is less common overall, although present in the Blackbird district (Bookstrom and others, 2007; Slack, 2012) and the NICO deposit (Goad and others, 2000a, b). Sulfide-rich veins occur in most, if not all, of the deposits, but their relationship with respect to local structures such as metamorphic fabric is not well established.

Grain Size

Grain sizes of ore and gangue minerals range widely for the Co-Cu-Au deposits. The principal control appears to be the nature and extent of post-ore deformation and metamorphism, including synmetamorphic fluid flow, which can vary greatly among deposits and, in some cases, within individual orebodies. Cobaltite, pyrite, and arsenopyrite tend to form relatively coarse porphyroblastic grains several millimeters to several centimeters in diameter (Pan and Therens, 2000; Slack, 2012). In contrast, more plastic sulfides, such as chalcopyrite and pyrrhotite, generally display finer grain sizes of less than one millimeter. Both sulfides may be remobilized into late veins or fractures, accompanied in places by native Bi (Slack, 2012). Gold typically is very fine-grained (~10–50 μm), commonly occurring as inclusions in pyrite (Blackbird district; Slack, 2012) or magnetite (Skuterud deposit; J.F. Slack, unpublished data). In the NICO deposit, gold shows a large range in grain size, from less than 1 to greater than 100 µm, mainly occurring as inclusions in cobaltian arsenopyrite (Goad and others, 2000b).

Gangue minerals show a larger range in grain sizes. Quartz typically is granoblastic and fine grained (<0.5 cm), whereas other silicates can be coarse grained, such as albite at the Skuterud deposit (as much as ~ 3 cm). Tourmaline also can form coarse prismatic grains, as much as 5 cm long, particularly in wall rocks and in paragenetically late quartz veins (Trumbull and others, 2011).

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8. Hydrothermal Alteration

By John F. Slack

Descriptive and Geoenvironmental Model for Cobalt-Copper-Gold Deposits in Metasedimentary Rocks

Scientific Investigations Report 2010–5070–G

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

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Relations Among Alteration, Gangue, and Ore

Many of the Co-Cu-Au deposits have spatially related alteration zones that are mineralogically and texturally distinct. In general, the alteration zones surround the orebodies for map distances of tens to hundreds of meters. However, in some of the Finnish deposits, the ores and sulfide zones are coextensive with altered rocks containing abundant garnet, amphibole, and (or) chlorite + biotite + sericite. The close spatial association of the diverse types of altered rocks to the orebodies is consistent with a temporal and genetic link, but caution must be observed in this context owing to the possibility of multistage hydrothermal processes within the metamorphic terranes that contain the Co-Cu-Au deposits considered here.

Mineralogy and Textures

Five principal types of altered rocks have been recognized in and near the Co-Cu-Au deposits, consisting mostly or wholly of albite, biotite, scapolite, tourmaline, or quartz. Each of these types is described below, using examples from selected deposits. The interested reader is referred to other publications on less common types of alteration such as carbonate, sericite, and talc that occur in and near deposits of the Kuusamo schist belt in Finland (Vanhanen, 2001), and K-feldspar that occurs widely in the NICO deposit (Goad and others, 2000a, b) and locally in the Blackbird district (Slack, 2012).

Albite

The most common type of alteration in the Co-Cu-Au deposits is albite. Both district- and deposit-scale albite alteration are documented. Albite-rich rocks occur extensively in the Kuusamo schist belt of northeastern Finland that contains several metasedimentary rock-hosted Co-Cu-Au deposits (Vanhanen, 2001). The albitic alteration is localized for tens of kilometers within major shear zones and other structures and extends for as much as several kilometers laterally from these structures (Pankka and Vanhanen, 1992; Eilu and others, 2003). Varieties that occur proximal to the deposits include albite schist, albitite, quartz-albite rock, albitized quartzite, albite-chlorite schist, albite-biotite rock, albite-muscovite rock, albite-carbonate rock, and albite-talc rock. Albite-rich rocks at the Kouvervaara Co-Cu-Au deposit envelop the mineralized zone for as much as 400 m, particularly quartz-albite rock that is interpreted as the outer alteration zone, with garnet-rich rock (no albite) at the center and biotite-chlorite (± amphibole ± albite) rocks occupying an intermediate zone (fig. 8–1). At the Juomasuo Au-Co deposit, pervasively albitized rocks surround the mineralized zone for several hundred meters (Vanhanen, 2001). These Na-rich rocks, which in places show relict bedding and crossbedding, contain a variety of subordinate phases including carbonate, chlorite, amphibole, and sericite. Wall rocks of the Juomasuo deposit also contain unmineralized lenses of chlorite-talc-amphibole rock that are considered to be altered ultramafic flows or sills, unrelated to the Au-Co mineralization. The albite alteration, which preceded Fe-Mg metasomatism that produced the abundant biotite, chlorite, and talc in and near many of the Co-Cu-Au deposits, may have made the metasedimentary rocks more rigid and competent, increasing susceptibility to fracturing and faulting as a means for preferentially localizing hydrothermal fluid flow and mineralization (see Eilu and others, 2003, and references therein). This widespread albitic alteration was considered by Pankka and Vanhanen (1992) and Vanhanen (2001) to record pre- to syn-metamorphic, regional circulation of magmatic-hydrothermal fluids and (or) basinal brines.

In the Modum district of Norway, albite-rich rocks occur near all of the major Co-Cu-Au deposits (fig. 5–3). Munz and others (1994) described two main types, the predominant one consisting of massive foliated albitite, and the less-common type being coarse-grained and discordant. Most of the albite-rich rocks are within or along the contacts of metagabbro bodies, but other occurrences are within clastic metasedimentary rocks. Associated minerals in both types are actinolite, chlorite, quartz, and talc. Uranium-Pb geochronology on titanite occurring within foliated albitite and low initial Nd isotope compositions were used by Munz and others (1994) as evidence that the albitite-rich rocks formed during a Neoproterozoic retrograde fluid infiltration event at 1080 ± 3 Ma. If this age on titanite records the timing of albitization, then this type of alteration postdates the Co-Cu-Au mineralization by about 400 m.y., based on a Pb-Pb age of 1434 ± 29 Ma determined for minor uraninite in the Skuterud deposit (Andersen and Grorud, 1998). However, more recent studies have demonstrated that titanite U-Pb ages are commonly reset during metamorphism (for example, Bibikova and others, 2001; Slack and others, 2008), thus the true age of this metasedimentary rock–hosted albitization in the Modum district remains uncertain, and could be much older and possibly coeval with the Co-Cu-Au mineralization. In-situ SHRIMP U-Pb dating of titanite within the foliated albitite of the district may resolve this paragenetic uncertainty.

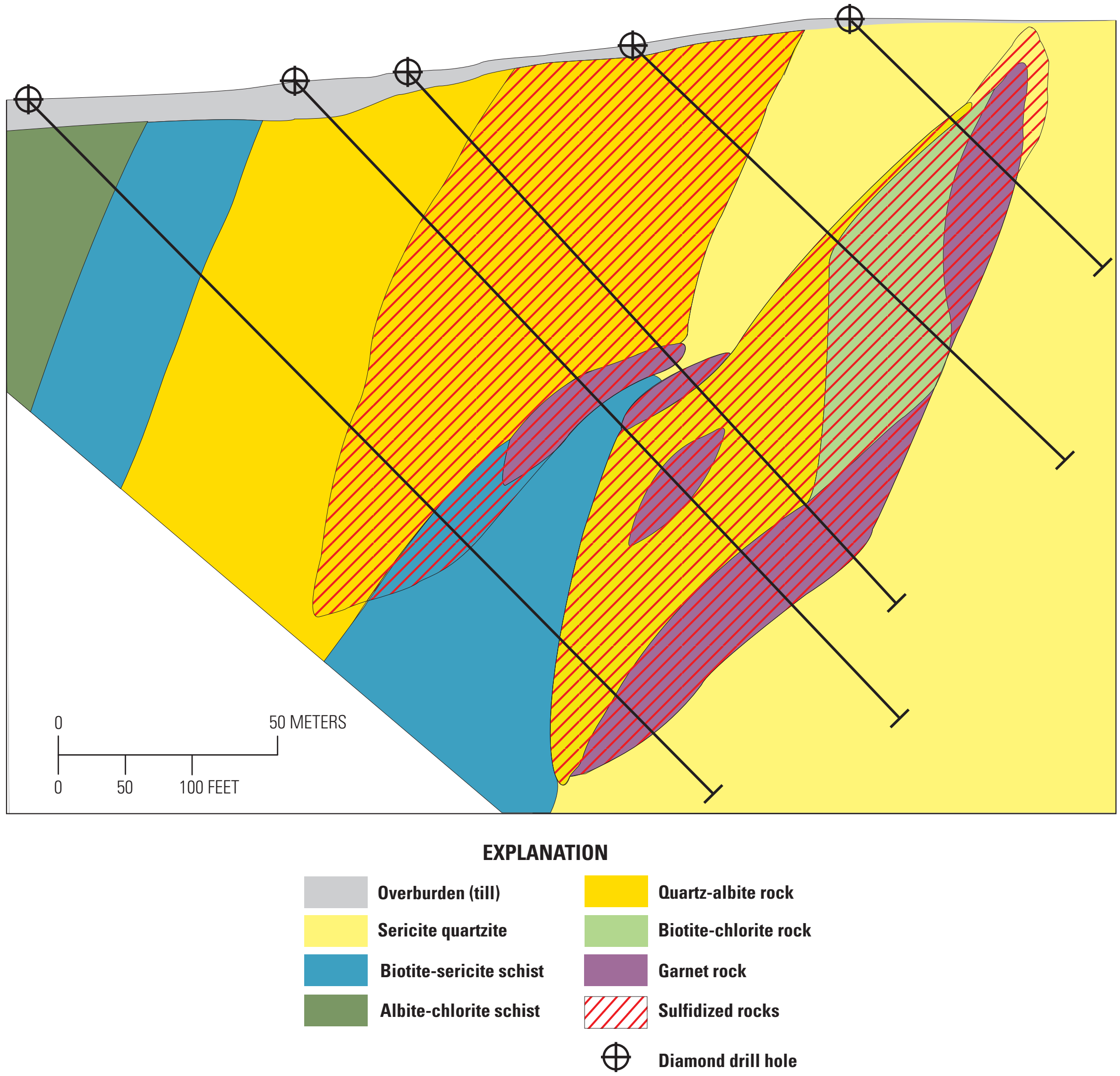

Figure 8–1. Geological cross section of the Kouvervaara Co-Cu-Au deposit in the Kuusamo schist belt of northeastern Finland, showing the distribution of albite-rich rocks relative to sulfide mineralized zones. Modified from Vanhanen (2001).

Albite-rich rock is the principal host for the Mt. Cobalt Co-Cu-Au deposit in Queensland, Australia. Nisbet and others (1983) showed that stratabound layered albitite, containing more than 95 volume percent albite, occurs preferentially along the contact between mineralized amphibolite and micaceous quartzite. Layering, which is conformable to the predominant fabric in the enclosing units, is defined by minor biotite- and tourmaline-rich layers alternating with major albite-quartz layers.

Biotite

Biotite-rich rocks are prominent and distinctive units in and near the Co-Cu-Au deposits of the Blackbird district. Stratabound and locally stratiform rocks in this district that consist mainly (>50 vol percent) of biotite, termed "biotitite" by previous workers (for example, Nash and Hahn, 1989; Bookstrom and others, 2007), are laterally continuous along strike for as much as 4 km (fig. 5.1), but extend no more than a few meters from the ore zones. The biotitite is a dark greenish black to black rock that consists of fine-grained biotite, with or without minor porphyroblastic garnet and chloritoid, accompanied in places by disseminated fine-grained cobaltite and (or) chalcopyrite. Nash and Hahn (1989) showed that biotitite is spatially associated with many of the stratabound Co-Cu-Au lodes in the Blackbird district (fig. 8–2). Lithogeochemical and electron microprobe studies indicate that the biotite is very Fe- and Cl-rich, including bulk and mineral compositions having as much as 1.1 weight percent Cl and 1.87 weight percent Cl, respectively (Nash and Connor, 1993).

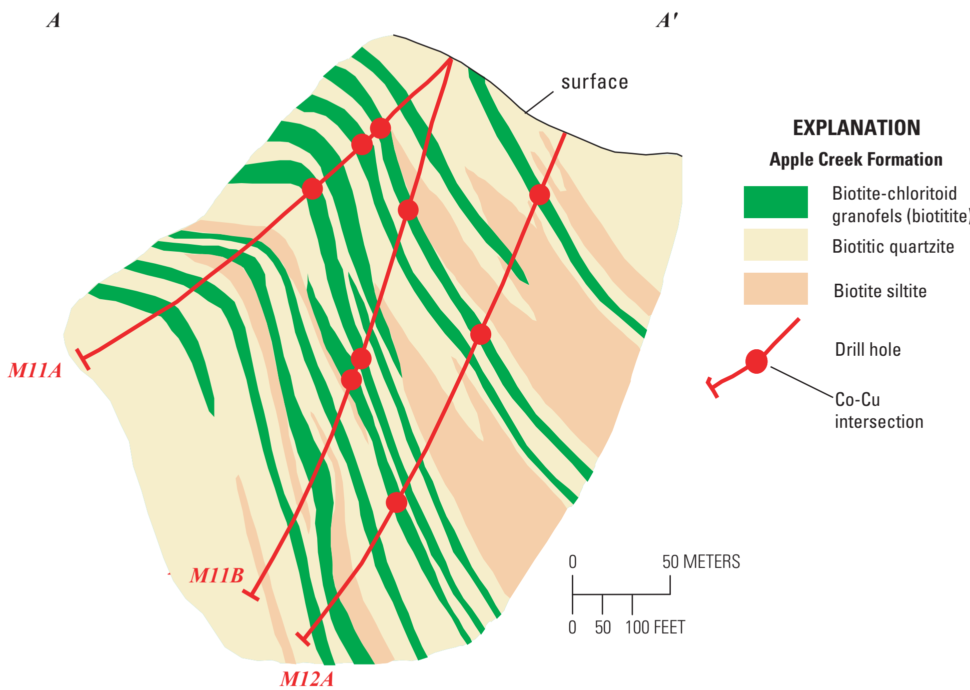

Figure 8–2. Geological cross section of the Merle deposit in the Blackbird district, Idaho, showing the distribution of biotite-rich lenses ("biotitite") relative to intersections of Co-Cu mineralized zones in drill cores. Modified from Nash and Hahn (1989).

The NICO deposit in Northwest Territories of Canada contains biotite-rich units within both mineralized zones and wall rocks including arkosic wacke and rhyolite. A widespread metasomatic "black rock" (originally sedimentary wacke) comprises massive, banded, and in places, schistose assemblages dominated by biotite, amphibole, magnetite, hematite, and K-feldspar, with lesser silicates, carbonates, and ore minerals; the biotite is Fe-rich and Cl-rich, containing approximately 1.2 weight percent Cl (Goad and others, 2000b). At the Werner Lake Co-Cu-Au deposit in Canada, garnetiferous biotite schist is a major wall rock (Pan and Therens, 2000). The Mt. Cobalt deposit is localized within a biotite-scapolite-tourmaline unit that marks the boundary between amphibolite and micaceous quartzite (Nisbet and others, 1983). In the Kuusamo schist belt of Finland, biotite alteration is prominent in a few deposits (for example, Kouvervaara, Lemmonlampi), where it is interpreted to have preceded mineralization (Vanhanen, 2001).

Scapolite

Rocks containing abundant scapolite occur in the Modum district, the Blackbird district, and at the Mt. Cobalt deposit. In the latter two areas, scapolite preferentially occurs in biotite-rich rocks (Nisbet and others, 1983; Slack, 2012). However, despite broad spatial associations, no direct evidence exists that the scapolite alteration in these areas was genetically related to Co-Cu-Au mineralization. In the Modum district, scapolite occurs in the contact zone between metagabbro and siliciclastic metasedimentary rocks, as replacements of plagioclase in metagabbro, and in veins with coarse-grained albite and calcite (Munz, 1990; Engvik and others, 2011). The veins are younger than the fine-grained albitites that are widespread in the district. Geochemical, isotopic, and geochronological studies by Engvik and others (2011) indicate that the replacement scapolite has a large component of the Cl-rich meionite endmember ($3CaAl_2Si_2O_8 \cdot CaCO_3$) and that scapolitization of the metagabbro took place during Sveconorwegian amphibolite-facies metamorphism at 1070 to 1040 Ma, by an evaporite-derived fluid based on the low initial Sr isotope ratios (0.704-0.709) and Cl-rich nature of the scapolite. If this age range is indeed the time period during which scapolitization in the Modum district took place, then the scapolite alteration postdates ore formation by about 400 m.y.

Scapolite is abundant in parts of the Idaho cobalt belt, but scapolite rarely is in proximity to the Blackbird Co-Cu-Au deposits (Nash and Connor, 1993). Biotite-scapolite schist occurs for several meters into the structural footwall of the small Sweet Repose deposit, at the northeastern end of the district (see Slack, 2012), but it is unclear whether this scapolite formation was coeval with mineralization. Characteristic are layers 0.5- to 2-m-thick, composed of biotite and porphyroblastic scapolite, which occur in siliciclastic metasedimentary strata of the Apple Creek Formation that hosts the Co-Cu-Au deposits. This scapolite has high Cl contents—one sample contains 2.2 weight percent Cl and 6.3 weight percent Na_2O

(Nash and Connor, 1993), thus indicating a large component of the marialite ($3NaAlSi_3O_8 \cdot NaCl$) endmember. It is unclear whether this deposit-distal Cl-rich scapolite is related to the deposit-proximal Cl-rich biotite in the district, which has an average of 1.29 weight percent Cl (Nash and Connor, 1993). The Yellowjacket Formation, broadly contemporaneous with the Apple Creek Formation, locally contains scapolite-rich rocks and carbonate strata that suggest shallow-water, intertidal to supratidal settings including evaporite deposition (Tysdal and Desborough, 1997; Tysdal, 2003). This sedimentary facies may have been the basinal source of the Cl present within the abundant Cl-rich biotite that characterizes many of the ore zones in the Blackbird district (fig. 8–2).

At the Mt. Cobalt deposit, scapolite is widespread and abundant in the border zone between amphibolite and micaceous quartzite that hosts the ores (Nisbet and others, 1983). Scapolite-rich rocks occur within a stratabound unit that is as much as 10 m wide and several hundred meters in length. The most common assemblage is scapolite-biotite, with lesser scapolite-biotite-plagioclase and scapolite-hornblende, all of which are characterized by the presence of foliated scapolite. Veins composed of scapolite and biotite also cut scapolitized amphibolite (Nisbet and others, 1983). Electron microprobe analyses of the different types of scapolite show approximately 55 percent of the meionite endmember (Devlin, 1980).

Tourmaline

Among the Co-Cu-Au deposits considered to comprise this model, tourmaline alteration is less common than albite alteration. The Blackbird district and surrounding metasedimentary strata of the Idaho cobalt belt are well known for containing diverse types of tourmaline-rich rocks (Modreski, 1985; Nash and Hahn, 1989; Bookstrom and others, 2007). Abundant tourmaline occurs in discordant pipes and breccias as very fine-grained (~10-50 µm) crystals either with or without coexisting cobaltite, chalcopyrite, or xenotime, and in biotite-rich wall rocks containing variable amounts of chloritoid, garnet, and (or) cobaltite. Detailed studies of the tourmaline by Trumbull and others (2011) indicate predominantly schorl or Fe-rich dravite compositions, and $\delta^{11}B$ values of -6.9 to +3.2 per mil that suggest boron derivation chiefly from sedimentary marine sources such as evaporites and carbonates.

Tourmaline alteration at the Dahenglu Co-Cu-Au deposit (Yang and others, 2001) forms stratabound zones of abundant tourmaline (tourmalinite) over thicknesses of 5 to 20 m between multiple folded ore lenses within the siliciclastic metasedimentary host rocks. In the area of the Mt. Cobalt Cu-Co-Au deposit, tourmaline occurs distal to the orebody (>100 m) as layers in albitite and in veins that cut biotite-rich altered rocks (Nisbet and others, 1983); electron microprobe analyses indicate dravite (Mg-rich) compositions (Devlin, 1980). Altered siliciclastic metasedimentary rocks at the NICO deposit include minor tourmaline within assemblages containing more abundant biotite, amphibole, magnetite, hematite, K-feldspar, and (or) Fe-Co-Cu-As-Bi-W minerals (Goad and others, 2000a, b). Tourmaline also occurs in the Co-Cu-Au deposits of the Kuusamo schist belt in Finland, including at the Juomasuo Au-Co deposit within albitized wall rocks and at the Lemmonlampi deposit as fine-grained concentrations (Pankka and Vanhanen, 1992; Vanhanen, 2001). However, the proximity of this tourmaline to the Co-Cu-Au orebodies is unknown.

Quartz

Silicification is a locally prominent type of alteration in the Blackbird district (Nash and Hahn, 1989; Bookstrom and others, 1997). Stratabound and local stratiform lenses of fine- to coarse-grained, granoblastic quartz constitute the predominant wall rock to Co-Cu-Au mineralization in several of the deposits, both in greenschist- and amphibolite-facies settings (Eiseman, 1988; Bookstrom and others, 2007). These quartzose lenses lack the characteristics of quartz veins, either in geometry or grain size, and as a result have generally been interpreted as products of ore-related silicification (Bookstrom and others, 2007). Cobaltite and other sulfide minerals commonly are disseminated in the quartzose lenses.

Late silicification has been described in the Co-Cu-Au deposits of the Kuusamo schist belt of Finland (Vanhanen, 2001). This alteration, either syn- or post-ore in timing, is expressed by small lenses and seams of quartz that are elongate parallel to local metasedimentary rock fabrics; such lenses and seams are not vein quartz.

Mineral Assemblages

Both simple and complex mineral assemblages occur within the alteration zones of the Co-Cu-Au deposits. Simple assemblages are mainly restricted to predominantly one mineral, such as biotite or quartz in the Blackbird district (Bookstrom and others, 2007; Slack, 2012), and albite or garnet in several deposits of the Kuusamo belt (Vanhanen, 2001). More mineralogically diverse assemblages, such as amphibole-biotite-magnetite-hematite-K-feldspar, occur in the NICO deposit, Canada (Goad and others, 2000a, b) and albite-amphibole-quartz-carbonate in the Juomasuo Au-Co deposit of the Kuusamo belt (Vanhanen, 2001).

Lateral and Vertical Dimensions

Hydrothermally altered rocks that are spatially associated with the Co-Cu-Au deposits generally extend tens to hundreds of meters from the mineralized zones. Such dimensions are well documented in the NICO deposit in Canada (Goad and others, 2000a, b) and in deposits of the Kuusamo belt of Finland (Vanhanen, 2001). In contrast, the most prominent biotite-rich alteration zones associated with the Blackbird deposits in Idaho extend only a few meters at most from the orebodies (Nash and Hahn, 1989; Bookstrom and others, 2007). Where orebodies extend to significant depths, such as in the Juomasuo deposit, spatially associated alteration zones continue in adjacent wall rocks for as much as several hundred meters down the dip of the ore zone (Vanhanen, 2001). In other Co-Cu-Au deposits and districts, however, limited outcrop and minimal drilling make it difficult to determine the dimensions of the alteration zones.

Alteration Intensity

The intensity of hydrothermal alteration in the deposits varies greatly. Intensity is apparently greatest where single alteration minerals predominate, such as in wall rocks of the Blackbird deposits in Idaho (biotite, quartz) or those of the Kuusamo belt in Finland (albite, garnet). Mineralogically diverse alteration assemblages likely record less-intense alteration processes. No studies have determined quantitative compositional changes during alteration related to any of the Co-Cu-Au deposits.

Zoning Patterns

Spatial zoning of hydrothermal alteration is not described for most of the Co-Cu-Au deposits. Exceptions occur in Finland, where such zoning is well documented (Vanhanen, 2001). At the Meurastuksenaho Co-Au-Cu deposit, the sulfide zone is coextensive with separate zones of garnet rock, amphibole rock, and chlorite-biotite-sericite rock for as much as 30 m in diameter, and the sulfide zone is enclosed by a zone of albitized quartzite that extends 10 to 50 m from the orebody. At the Kouvervaara Co-Cu-Au deposit, the sulfide zone also interfingers with garnet rock, on a scale of tens of meters, and in plan view is surrounded by an elongate zone of quartz-albite rock as much as 300 m from the orebody. The albite-rich alteration zone that encloses the Hangaslampi Au-Co deposit, as much as 40 m thick, differs in having abundant carbonate (Vanhanen, 2001).

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9. Supergene Ore and Gangue Characteristics

By John F. Slack

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Descriptive and Geoenvironmental Model for Cobalt-Copper-Gold Deposits in Metasedimentary Rocks

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9. Supergene Ore and Gangue Characteristics

By John F. Slack

A variety of supergene minerals occurs in the metasedimentary rock-hosted Co-Cu-Au deposits. Most common are secondary iron-rich phases including limonite, goethite, hematite, jarosite, and melanterite. Secondary copper minerals—such as covellite, chrysocolla, azurite, and malachite—are present locally (for example, Evans and others, 1995). Native copper and silver were reported in the Blackbird district by Eiseman (1988). The visually most prominent supergene mineral in the deposits is erythrite [$Co_3(AsO_4)_2 \cdot 8H_2O$], which is also known as "cobalt bloom" because of its distinctive pink to lilac color. More detailed descriptions of the supergene minerals occurring in the deposits considered herein, and related chemical processes that form them in the weathering environment, are given in this volume (Johnson and Gray, 2013).

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10. Weathering/Supergene Processes

By Craig A. Johnson and John E. Gray

Descriptive and Geoenvironmental Model for Cobalt-Copper-Gold Deposits in Metasedimentary Rocks

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10. Weathering/Supergene Processes

By Craig A. Johnson and John E. Gray

Among the minerals found in the Co-Cu-Au deposits, sulfides, sulfarsenides, and arsenides are the most susceptible to weathering. At most of the localities listed in table 1–1, these are dominantly cobaltite (CoAsS), chalcopyrite ($CuFeS_2$), covellite (CuS), pyrite (FeS_2), and pyrrhotite ($Fe_{1-x}S$). Weathering of these minerals proceeds by oxidation via pathways that can be categorized as biotic (mediated by microbes) or abiotic, and direct (oxidation driven by O_2) or indirect (oxidation driven by O_2 and Fe^{3+}). Details of pyrite and chalcopyrite weathering pathways have received much study; discussions of these can be found in recent reviews (Nordstrom and Alpers, 1999; Plumlee, 1999; Lottermoser, 2010). The pathways by which cobaltite weathers have not been studied, but summary reactions can be hypothesized based on the behavior of the chemical analog arsenopyrite (FeAsS; Walker and others, 2006; Lengke and others, 2009). Possible summary reactions include:

Direct:

$$CoAsS + \frac{13}{4}O_2 + \frac{3}{2}H_2O = Co^{2+} + HAsO_4^{2-} + SO_4^{2-} + 2H^+ \quad (1)$$

$$CoAsS + \frac{7}{2}O_2 + H_2O = Co^{3+} + HAsO_4^{2-} + SO_4^{2-} + H^+ \quad (2)$$

$$CoAsS + \frac{39}{12}O_2 + \frac{25}{6}H_2O = \frac{1}{3}Co_3(AsO_4)_2 \cdot 8H_2O(\text{erythrite}) + \frac{1}{3}HAsO_4^{2-} + SO_4^{2-} + \frac{8}{3}H^+ \quad (3)$$

Indirect:

$$CoAsS + 13Fe^{3+} + 8H_2O = 13Fe^{2+} + Co^{2+} + HAsO_4^{2-} + SO_4^{2-} + 15\,H^+ \quad (4)$$

Cobalt ions released by weathering can be sequestered in secondary minerals. Cobalt is known to coprecipitate with manganese oxides (for example, Dillard and Crowther, 1982) by a mechanism that involves the oxidation of Co^{2+} by precipitated Mn^{3+} (Hem and others, 1985). In the Blackbird deposits, a possible substrate mineral for this process is akhtenskite (MnO_2), which has been identified in underground workings (G.N. Breit, U.S. Geological Survey, written commun., 2007). Another secondary host for cobalt is erythrite ($Co_3(AsO_4)_2 \cdot 8H_2O$), a red-purple or pink mineral known informally as cobalt bloom that is common as coatings and crusts in workings in the Blackbird and Modum districts and has been reported in the Mt. Cobalt and NICO deposits (Nisbet and others, 1983; Gandhi and Lentz, 1990; Evans and others, 1995).

Copper and iron ions released by weathering may form sulfates or oxyhydroxides. Chalcanthite ($CuSO_4 \cdot 5H_2O$) has been identified in the Blackbird district, as have jarosite ($KFe_3(OH)_6(SO_4)_2$), limonite ($FeO(OH) \cdot nH_2O$), and iron sulfates of uncertain mineralogy (Evans and others, 1995; G.N. Breit, U.S. Geological Survey, written commun., 2007; Giles and others, 2009). In some Co-Cu-Au deposits, secondary copper carbonates are also known, including azurite ($Cu_3(CO_3)_2(OH)_2$) and malachite ($Cu_2CO_3(OH)_2$) (Evans and others, 1995; Mumin and others, 2007).

Arsenic ions released during weathering may precipitate together with cobalt as erythrite. Arsenic also can be sequestered in limonite inasmuch as hydrous ferric oxides strongly sorb this element over a broad range of pH conditions (Lottermoser, 2010). Secondary scorodite ($FeAsO_4 \cdot 2H_2O$) is abundant in weathered zones in the Blackbird district (G.A. Hahn, written commun., 2011), and occurs on surface exposures at the NICO deposit (Gandhi and Lentz, 1990).

Other secondary minerals present in and surrounding the Co-Cu-Au deposits include native sulfur, gypsum ($CaSO_4 \cdot 2H_2O$), chrysocolla, and pickeringite ($MgAl_2(SO_4)_4 \cdot 22H_2O$); Evans and others, 1995; G.N. Breit, U.S. Geological Survey, written commun., 2007; Giles and others, 2009). The native sulfur is an intermediate product in the overall sulfide oxidation process.

Oxidation of cobaltite, chalcopyrite, and pyrite produces acidity, which tends to lower the pH of infiltrating waters (Plumlee, 1999). In the Blackbird district, the weathering of mined and unmined mineral deposits has the potential to generate highly acidic runoff. Surface waters in the district have pH values as low as 2–4 (Beltman and others, 1993; Giles and others, 2009). With decreasing pH, the iron released from pyrite and chalcopyrite is increasingly soluble and becomes available to drive additional sulfide oxidation by indirect pathways. For pyrite, indirect oxidation is faster than direct oxidation, so weathering can accelerate as pH declines. Indirect oxidation also produces more hydrogen ions and, thus, more acidity (compare reaction 4 with reactions 1–3). The kinetics of oxidation are probably also enhanced by microbial catalysis, given the ubiquity of iron- and sulfur-oxidizing bacteria and the possible presence of arsenite-oxidizing strains in waters that interact with mine wastes (Nordstrom and Alpers, 1999).

Some of the acidity produced by sulfide oxidation can be sequestered temporarily in secondary sulfate minerals that form where mine runoff undergoes evaporation. This phenomenon has been documented at a variety of metal mines

(Nordstrom and Alpers, 1999); the presence of iron and copper sulfates in underground workings of the Blackbird district suggests that the same phenomenon can occur at mines exploiting Co-Cu-Au deposits of the type under consideration in this report. The storage of acidity is temporary because most iron and copper sulfates are soluble enough that they readily dissolve during precipitation events that lead to renewed runoff. Thus, thunderstorms can mobilize the accumulated acidity and cycle it rapidly through watersheds (Evans and others, 1995; Nordstrom and Alpers, 1999; Jambor and others, 2000).

Many of the deposits listed in table 1–1 are contained in sedimentary sequences that are dominated by mature siliciclastic rocks. The abundance of quartz and alkali feldspar within these lithologies and paucity of calcite and readily weathered aluminosilicates provide little buffering capacity for the acidity produced by sulfide weathering. Where the host lithologies are locally mafic or ultramafic, as is the case for several of the deposits in northern Finland, some acid buffering would be expected due to the presence of calcic feldspar, olivine, and other silicates that are more susceptible to hydrolysis reactions.

Within Co-Cu-Au ores or in associated hydrothermally altered rocks, calcite is either absent or present in only minor amounts (Nisbet and others, 1983; Schandl, 2004; Mumin and others, 2007). In deposits of the Blackbird district, weathering of siderite ($FeCO_3$), a minor gangue mineral, can consume acidity under certain circumstances. However, where weathering is driven by oxygenated waters, the acid consumption is offset by acid production resulting from the oxidation, hydrolysis, and precipitation of iron in the siderite (Lottermoser, 2010).

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11. Geochemical Characteristics

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Table

11. Geochemical Characteristics

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Trace Elements and Element Associations

As a group, Co-Cu-Au deposits in metasedimenatry rocks (table 1–1) are characterized by a diverse suite of anomalous element concentrations that includes siderophile elements (Mo, Ni), chalcophile elements (Ag, As, Bi, Hg, Pb, Se, Te, Zn), and lithophile elements (B, Be, Cl, F, REE, Th, U, W, Y). Most districts or deposits, however, contain only a subset of this suite.

The associated elements vary in a general way with the lithology of the deposit host rocks, suggesting that the minor and trace element chemistry of the ores depends on the chemical constituents that were available locally to circulating hydrothermal fluids. For example, where the host rocks contain abundant metapelite, or metamorphosed argillaceous sedimentary rock, there is a tendency for the ore deposits to be richer in elements that are characteristically high in shales relative to other rock types, such as As and B. Examples include the deposits of the Blackbird district and the Skuterud and Werner Lake deposits. Where metapelites are volumetrically minor relative to non-argillaceous metasedimentary rocks, arsenic concentrations in the ores are lower. This is observed at the Gladhammer, Juomasuo, and Dehenglu deposits, which are associated with metaquartzite rather than metapelite, and in which Co occurs partly in As-poor minerals such as linnaeite (Co_3S_4) and siegenite ($(Co,Ni)_3S_4$), rather than in the sulfarsenide mineral cobaltite (CoAsS), the dominant Co host in most other deposits listed in table 1–1.

Other element associations reflect whether local igneous rocks are predominantly ultramafic to mafic or predominantly intermediate to felsic. For example, the deposits in northern Finland are associated with siliciclastic metasedimentary rocks that lie within greenstone belts. Although the immediate host rocks to the deposits are more commonly metasedimentary than metaigneous, the host terranes contain large volumes of mafic and ultramafic lithologies, including tholeiite, metagabbro, and komatiite (Sundblad, 2003; Eilu and others, 2003). Many of the northern Finland deposits are anomalously high in Ag and Ni—elements that are abundant in mafic and ultramafic rocks. The Werner Lake deposit shows the same relationship; mafic and ultramafic igneous rocks are abundant near ores that are high in Ag and Ni (Pan and Therens, 2000). In contrast, where the associated igneous rocks are predominantly intermediate to felsic in composition, the suite of associated elements is less likely to contain Ag and (or) Ni—as in the NICO, Goldhammer, and Contact Lake deposits. Instead, the ores of these deposits contain trace and minor elements that are more commonly associated with felsic igneous activity, including F, U, and W (NICO, Contact Lake).

Some of the Co-Cu-Au deposits listed in table 1–1 occur in terranes that contain a wide variety of rock types, perhaps most notably the deposits of the Blackbird district. These ores can display a diverse suite of associated elements, probably reflecting hydrothermal scavenging of elements from a combination of pelitic rocks (for example, As, B), felsic igneous rocks (Y, REE, U, Be), and mafic igneous rocks (Ni) (Nash and Hahn, 1989; Slack, 2012). Thus, the trace elements and associated elements in Co-Cu-Au deposits within metasedimentary rocks depend at least partly on lithologies that are present locally, which can vary from one district to another or from one deposit to another.

Fluid Inclusion Thermometry and Geochemistry

Fluid inclusions have been examined in quartz from deposits of the Blackbird district and the Cobalt Hill deposit. Both localities contain populations of highly saline inclusions and CO_2-rich inclusions; additional types were recognized at Cobalt Hill (table 11–1). For Cobalt Hill, Schandl (2004) used petrographic observations to link the sulfide-gold assemblages to a fluid inclusion population having 26–46 equivalent weight percent NaCl, an entrapment temperature of about 400 °C, and an entrapment pressure of 1.3 kilobars. For Blackbird, the relationship between sulfides and fluid inclusions is difficult to decipher due to the effects of syn- or post-mineral deformation and metamorphism. However, halite dissolution temperatures for the highly saline inclusions indicate that these fluids were hot (250–350 °C), which is permissive evidence

Table 11–1. Fluid inclusion types recognized in Co-Cu-Au deposits in metasedimentary rocks.[1]

Deposit	Fluid Inclusion Types[2]		
	High-salinity	CO_2-rich	Other types[3]
Blackbird, Idaho	~35	Present	
Cobalt Hill, Ontario	35±10	Present	~25

[1]Sources of data: Blackbird, Nash and Hahn (1989), Landis and Hofstra (2012); Cobalt Hill, Schandl (2004).

[2]Numerical values represent equivalent weight percent NaCl.

[3]Schandl (2004) reported a third inclusion type that has lower salt contents than the high-salinity inclusions and extends to lower homogenization temperatures.

that the fluids played a role in metal transport, either during initial emplacement of the metals or during a subsequent metal remobilization event (Nash and Hahn, 1989). Leachates from quartz-hosted fluid inclusions from the Blackbird district show Na-Cl-Br systematics that are consistent with the presence of seawater that had evaporated to the point of salt precipitation (Landis and Hofstra, 2012). Independent evidence for seawater evaporation in the district has been found by Tysdal and Desborough (1997), who documented the presence of scapolite-rich strata, probable metamorphosed halite-bearing evaporites, in exposures of the Yellowjacket Formation southwest of Blackbird (see also Lund, 2013). Because the complex textures of Blackbird ores do not clearly indicate a genetic relationship of the saline fluid inclusions to the sulfide-gold assemblages, uncertainty remains as to whether the evaporated seawater finding pertains to the original emplacement of the metals or to later metal redistribution(s) during the Cretaceous that gave the ores their present form.

Stable Isotope Geochemistry

Sulfide sulfur isotope data are available for five of the localities listed in table 1–1. All five show positive $\delta^{34}S$ values, with means ranging from 1 per mil at the Werner Lake deposit to 21 per mil at the Skuterud deposit (fig. 11–1). For deposits of the Blackbird district, the Skuterud deposit, and the Dhenglu deposit, the $\delta^{34}S$ values are high enough to suggest that the ore sulfur was derived, at least partly, from sedimentary rock sources. Sulfides at the Werner Lake and Mt. Cobalt deposits have $\delta^{34}S$ values near 0 per mil, which is consistent with sulfur derivation from an igneous source, either offgassing from crystallizing magmas or scavenging of sulfur from plutonic or volcanic rocks by hydrothermal fluids. However, sedimentary sulfur can also have near-zero $\delta^{34}S$ values (for example, Seal, 2006), thus sulfur sources for the Werner Lake and Mt. Cobalt deposits are not determined uniquely without additional information.

With the possible exception of the Skuterud deposit, none of the localities listed in table 1–1 shows the $\delta^{34}S$ variations of 10 per mil or more that characterize ores formed by sedimentary and early diagenetic processes, reflecting bacterial reduction of local sulfate (for example, SEDEX and sedimentary copper type deposits; Leach and others, 2005; Hitzman and others, 2005). For the Werner Lake deposit, which was metamorphosed at granulite grade, the isotopic uniformity could reflect homogenization during high-grade metamorphic recrystallization (for example, Crowe, 1994). However, for deposits of the Blackbird district and the Dhenglu deposit, which are contained in host rocks that were metamorphosed only at greenschist grade, metamorphic homogenization is unlikely. Hence, the isotopic uniformity is probably a primary feature of the ores. The narrow ranges of $\delta^{34}S$ values suggest that the sulfur sources for these deposits were deeper-seated than normal diagenetic environments, and that isotopic

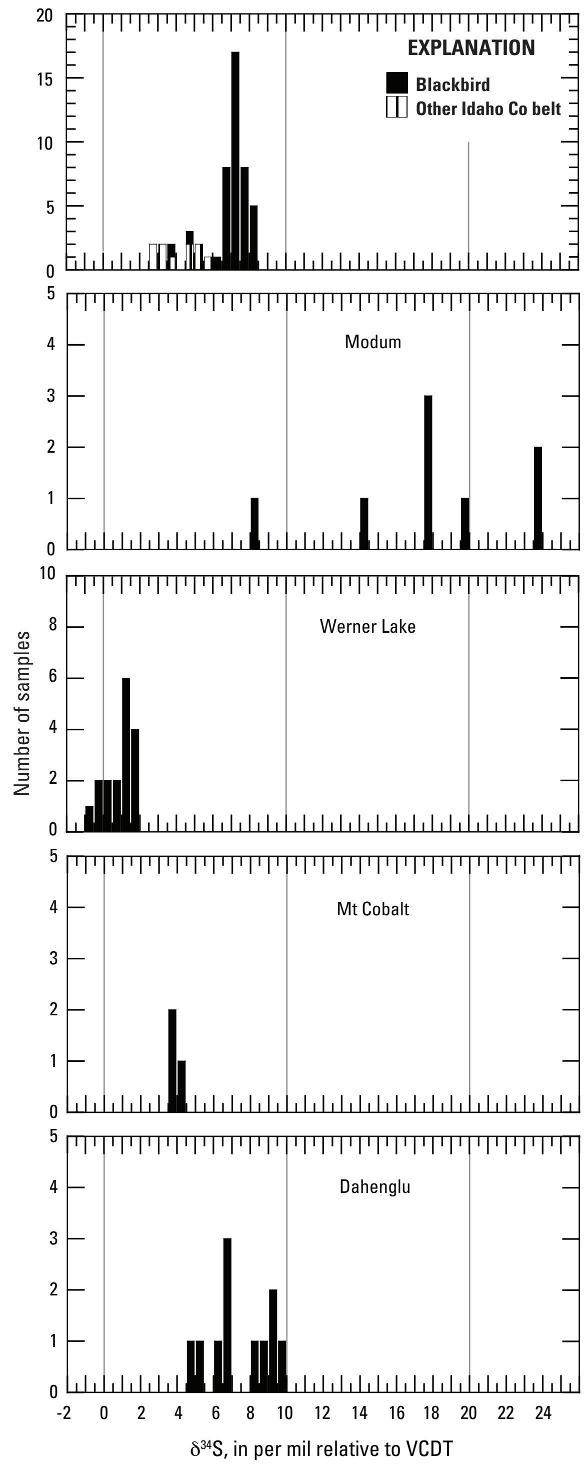

Figure 11–1. Sulfur isotopic compositions of sulfide minerals from Co-Cu-Au deposits in metasedimentary rocks. Abbreviations: $\delta^{34}S$, delta S-34; VCDT, Vienna Cañon Diablo Troilite. Sources of data: Blackbird and Idaho cobalt belt, Howe and Hall (1985), Panneerselvam and others (2012), Johnson and others (2012); Modum, C.A. Johnson, U.S. Geological Survey, unpub. data, 2010; Werner Lake, Pan and Therens (2000); Mt. Cobalt, Davidson and Dixon (1992); Dahenglu, Yang and others (2001).

homogeneity was promoted by thermochemical sulfate reduction or hydrothermal transport of sulfur as H_2S (Johnson and others, 2012).

Data obtained for Idaho cobalt belt deposits distal to the Blackbird district show that $\delta^{34}S$ values of ore sulfides can vary systematically on the scale of kilometers or tens of kilometers. The Iron Creek and Black Pine deposits in the southeastern part of the belt (see Nash, 1989; Slack, 2012) have an average $\delta^{34}S$ value of 5 per mil, which is significantly lower than the 8 per mil average displayed by deposits of the Blackbird district near the middle of the belt. This regional variation could reflect sulfur acquisition from different sedimentary strata, inasmuch as the southeastern deposits occur in a lower stratigraphic unit (Nash and Hahn, 1989; Lund and Tysdal, 2007), or a greater magmatic component within the Black Pine and Iron Creek deposits.

Oxygen and hydrogen isotope data are available for the Blackbird district (Johnson and others, 2012) and the Werner Lake deposit (Pan and Therens, 2000). For the Blackbird district, analyses of biotite- and tourmaline-bearing wall rocks suggest that hydrothermally altered rocks are about 10 per mil lower in their δD values than nearby unaltered rocks (absolute values depend on location; see Johnson and others, 2012). There is no corresponding difference in $\delta^{18}O$ values. Thus, hydrogen isotopic analysis may be useful in identifying subtle alteration in exploration for deposits of this type. Calculated δD values for the hydrothermal fluid are above (less negative than) –40 per mil for any reasonable range of assumed hydrothermal temperature (250–500 °C) and pressure (<2–400 bars). Calculated $\delta^{18}O$ values for this same range of conditions are 6 ± 3 per mil. These values do not allow discrimination between sedimentary formation waters, metamorphic waters, or mixtures of magmatic water and either seawater or isotopically heavy meteoric water as the source of the hydrothermal fluid. The values are a poor match for the modified seawaters that form volcanogenic massive sulfide deposits (for example, Shanks, 2012). For the Werner Lake deposit, garnet-biotite schists associated with the ore have $\delta^{18}O$ values of 4–6.5 per mil, lower than nearby amphibolite (6.8–8.3 per mil), which is thought to be the unaltered equivalent of the schist. The lower $\delta^{18}O$ values are consistent with isotopic exchange with fluids that were hot, low in $\delta^{18}O$, or both. Pan and Therens (2000) inferred that the ore-forming fluid was derived from seawater, although other fluid sources are possible.

Radiogenic Isotope Geochemistry

Isotopic studies in the U-Th-Pb system have been carried out on suites of samples from the Modum and Blackbird districts (Andersen and Grorud, 1998; Paneerselvam and others, 2012). In the Modum district, initial Pb isotopic ratios for ore minerals resemble initial Pb isotopic ratios for sedimentary rocks, but not other local lithologies, as constrained by the 1434 ± 29 Ma mineralization age based on an isotopic correlation in the mineral separates. Thus, the ore lead—and by analogy perhaps other ore metals—were derived from the local quartzofeldspathic sedimentary host rocks. In the Blackbird district, ore lead is highly radiogenic, shown by Pb isotope values that extend well beyond crustal growth model curves on lead isotope correlation plots. Panneerselvam and others (2012) suggest that this isotopic signature reflects ore formation by the leaching of metals from local sedimentary rocks of the Apple Creek Formation, which is Mesoproterozoic in age (see Aleinikoff and others, 2012). Uranium and lead concentrations are available for only one sample from the Blackbird district, however, which precludes modeling of the data to definitively identify the source of the ore lead.

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12. Petrology of Associated Igneous Rocks

By Klaus J. Schulz

Descriptive and Geoenvironmental Model for Cobalt-Copper-Gold Deposits in Metasedimentary Rocks

Scientific Investigations Report 2010–5070–G

U.S. Department of the Interior
U.S. Geological Survey

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12. Petrology of Associated Igneous Rocks

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The importance of igneous rocks to metasedimentary rock-hosted Co-Cu-Au deposits remains uncertain. A variety of igneous rock types may be present in the sequences hosting Co-Cu-Au deposits, ranging from mafic to felsic volcanic rocks to diabasic, gabbroic, and granitic intrusions. Some workers have suggested that igneous intrusions were the source of metals and (or) fluids for a deposit (Anderson, 1947; Vhay, 1948; Bennett, 1977; Slack, 2012). Others, viewing the deposits as syngenetic in origin, have speculated that mineralizing processes are linked to submarine mafic volcanic and intrusive activity (Hughes, 1983; Modreski, 1985; Eiseman, 1988; Nash, 1989; Nash and Hahn, 1989; Nold, 1990). In contrast, some workers have viewed these deposits as derived from metamorphic fluids with igneous activity providing at most a heat source for metamorphism and fluid circulation (Nisbet and others, 1983; Krcmarov and Stewart, 1998). Clearly, more detailed studies are needed on the Co-Cu-Au deposits in metasedimentary rocks, including accurate dating of mineralization, in order to better evaluate possible genetic links between magmatism and mineralization.

Although uncertainties remain, recent studies in the Blackbird district of Idaho suggest that Mesoproterozoic igneous intrusions may have played an important role in the formation of the district's Co-Cu-Au deposits (Aleinikoff and others, 2012; Landis and Hofstra, 2012). The Mesoproterozoic intrusions of the Blackbird district are described below. It should be noted, however, that compositionally similar intrusions have not been recognized in all of the districts and areas that have Co-Cu-Au deposits.

The Co-Cu-Au deposits of the Blackbird district in east-central Idaho are hosted by deformed Mesoproterozoic clastic metasedimentary rocks. These strata are intruded by granitic and gabbroic plutons north and east of the district, which give similar Mesoproterozoic U-Pb zircon ages of 1377 ± 4 Ma and 1378.7 ± 1.2 Ma, respectively (Doughty and Chamberlain, 1996; Aleinikoff and others, 2012). These ages overlap, within analytical error, the oldest age determined for hydrothermal xenotime in biotite at the Merle deposit (1370 ± 4 Ma; Aleinikoff and others, 2012), suggesting that the coeval granitic and gabbroic magmatism may have been responsible for the hydrothermal system that resulted in Y-REE mineralization and possibly Co-Cu-Au mineralization, either as a direct source of mineralizing solutions or as a heat source to drive the hydrothermal fluids.

Metamorphosed mafic dikes and sills are also common in and around the Blackbird district and have been suggested to be an important source of metals for the deposits (Nash and Hahn, 1989). Hahn and Hughes (1984) described three suites of mafic intrusions. Most common are thin (generally <2 m thick), black-to-violet, foliated, carbonate-rich, biotite-bearing, alkaline dikes and sills. A second suite is plagioclase porphyritic, massive, non-foliated (except along some margins), gabbroic intrusions that are 3 to 30 m thick. The third suite is carbonatite-ultramafic diatremes containing clasts of carbonate and intensely serpentinized ultramafic rocks. Although these mafic dike-sill suites have not been dated, most dikes in the ore zones appear to be post-ore, although some are cut by cobaltite-bearing veins and mineralized fault zones (Bookstrom and others, 2007; A.A. Bookstrom, written commun., 2011). Biotite-rich wall rocks in the district, originally considered metamorphosed alkaline mafic tuffs by Nash and Hahn (1989), are now interpreted as the product of Fe-metasomatism of clastic sedimentary rocks (A.A. Bookstrom, written commun., 2011).

North of the Blackbird district, a group of steeply dipping, sill-like bodies of gabbro-diabase, diorite, and amphibolite are concordantly intercalated with paragneiss and granitic gneiss on a scale of 50–100 m (Spence, 1984). These gabbroic intrusions are interpreted as partially differentiated sills rotated to steep dips during rotation on thrust faults (Doughty and Chamberlain, 1996). The mafic intrusions are reported to have subalkaline tholeiitic basalt compositions with slightly enriched light REE (about 30 times chondrite) (L.S. Reed, R.F. Burmester, and T.P. Frost, written commun., 2010). These intrusions appear to be compositionally distinct from the biotite-rich alkaline dikes in the Blackbird district described by Nash and Hahn (1989), but they may be similar to the plagioclase-porphyritic gabbroic dikes there (Hahn and Hughes, 1984).

Temporally associated with the mafic intrusions are granitic plutons, which are locally deformed into augen gneiss (Doughty and Chamberlain, 1996; L.S. Reed, R.F. Burmester, and T.P. Frost, oral commun., 2010). Augen are as much as 5 cm in length and consist of alkali feldspar, alkali feldspar rimmed by plagioclase (rapakivi), and plagioclase (L.S. Reed, R.F. Burmester, and T.P. Frost, oral commun., 2010). Modal quartz-alkali feldspar-plagioclase determinations plot in the granite field; the protolith was probably a muscovite-biotite rapakivi granite. Spence (1984) and Doughty and Chamberlain (1996) described a number of features, including veined agmatites and pillows and rounded globular masses of diabase within augen gneiss, which strongly suggest commingling and mixing of mafic and felsic magmas.

Compositionally, the augen gneiss is fairly uniform with only a small range in SiO_2 (71–75 weight percent) and other major and trace elements (Lewis and Frost, 2005). Although partially overlapping in composition with A-type granites from the Eureka Supersuite in Australia, the augen gneiss is ferroan to magnesian, calcic to calc-alkalic, and peraluminous (fig. 12–1). Rare earth element and extended trace element patterns of the augen gneiss are enriched in light REE and Th and have pronounced negative Nb-Ta anomalies (fig. 12–2). The compositional characteristics of the augen gneiss are similar to those of A-type granites (Bonin, 2007); samples mostly plot in the within-plate granite field on tectonic discrimination diagrams (for example, fig. 12–3*D*).

Samples of augen gneiss from near Elk City, Idaho, have variable initial $^{87}Sr/^{86}Sr$ isotope ratios (Sr_i) calculated at 1370 Ma of 0.707 to 0.723 with one exceptionally radiogenic sample of 0.769 (Criss and Fleck, 1987). However, Evans and Zartman (1990) noted that the Rb-Sr system in the augen gneiss has been significantly disturbed, making it impossible to determine reliable Sr_i values. Values of εNd (epsilon neodymium) calculated at 1370 Ma for the augen gneiss range from -1.5 to 3.8 (Fleck, 1990; Doughty and Chamberlain, 1996). In contrast, metasedimentary rocks in the region have more negative εNd values (calculated at 1370 Ma) ranging from -2.1 to -4.3 (Fleck, 1990; Doughty and Chamberlain, 1996), whereas Archean basement would have values lower than -10. These data indicate that neither Archean basement nor the regional metasedimentary rocks were the dominant source for the Proterozoic granite magmas. One sample of diabase has an εNd value calculated at 1370 Ma of +1.10 (Doughty and Chamberlain, 1996).

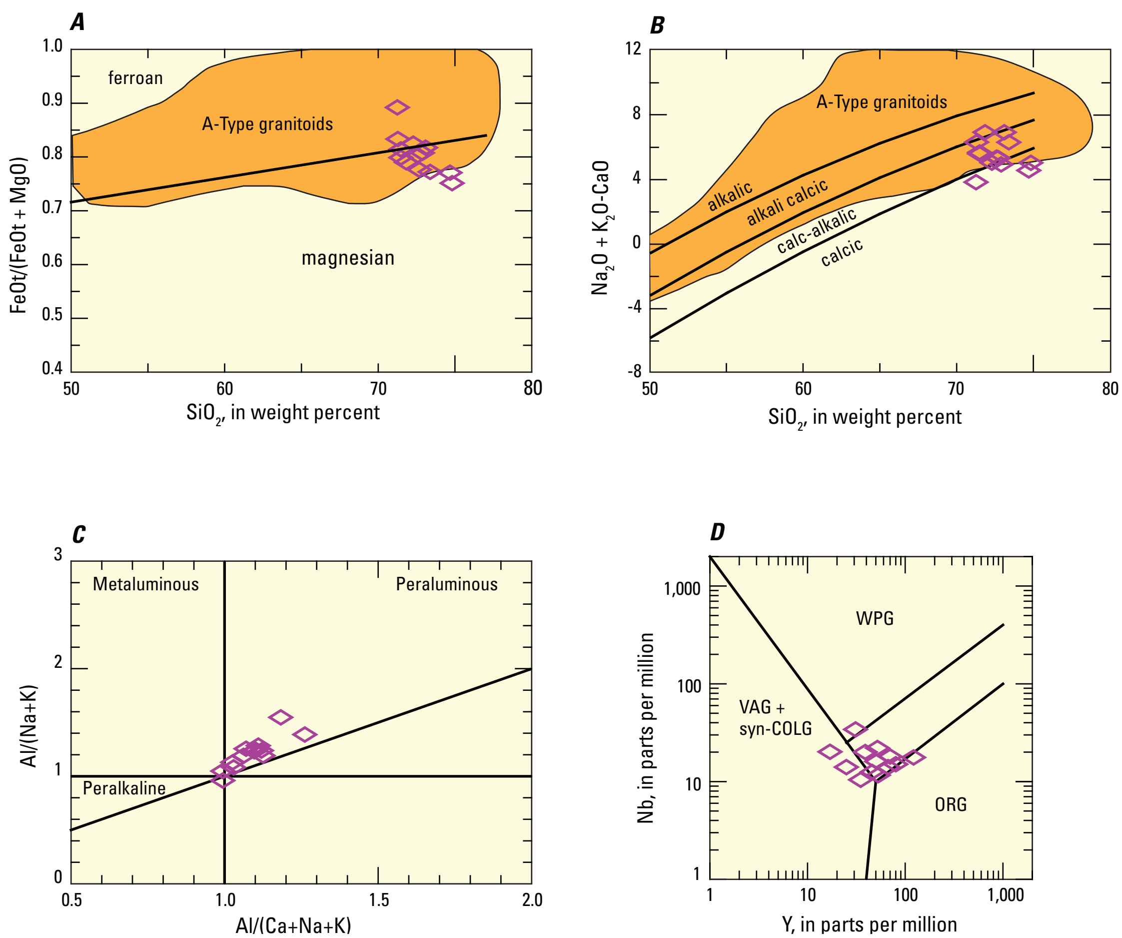

Figure 12–1. Compositional characteristics of metagranitic augen gneiss from north of the Blackbird district (data from Lewis and Frost, 2005). (A) $FeO^t/(FeO^t + MgO)$ versus SiO_2. Boundary line and field for A-type granitoids from Frost and others, 2001. (B) $Na_2O + K_2O$ - CaO versus SiO_2. Boundary lines and field for A-type granitoids from Frost and others, 2001. (C) molar Al/(Na + K) versus Al/(Ca + Na + K) (after Maniar and Piccoli, 1989). (D) Nb versus Y tectonic discrimination diagram (after Pearce and others, 1984). WPG = Within-plate granite; ORG = Ocean ridge granite; VAG = Volcanic arc granite; syn-COLG = syn-collisional granite.

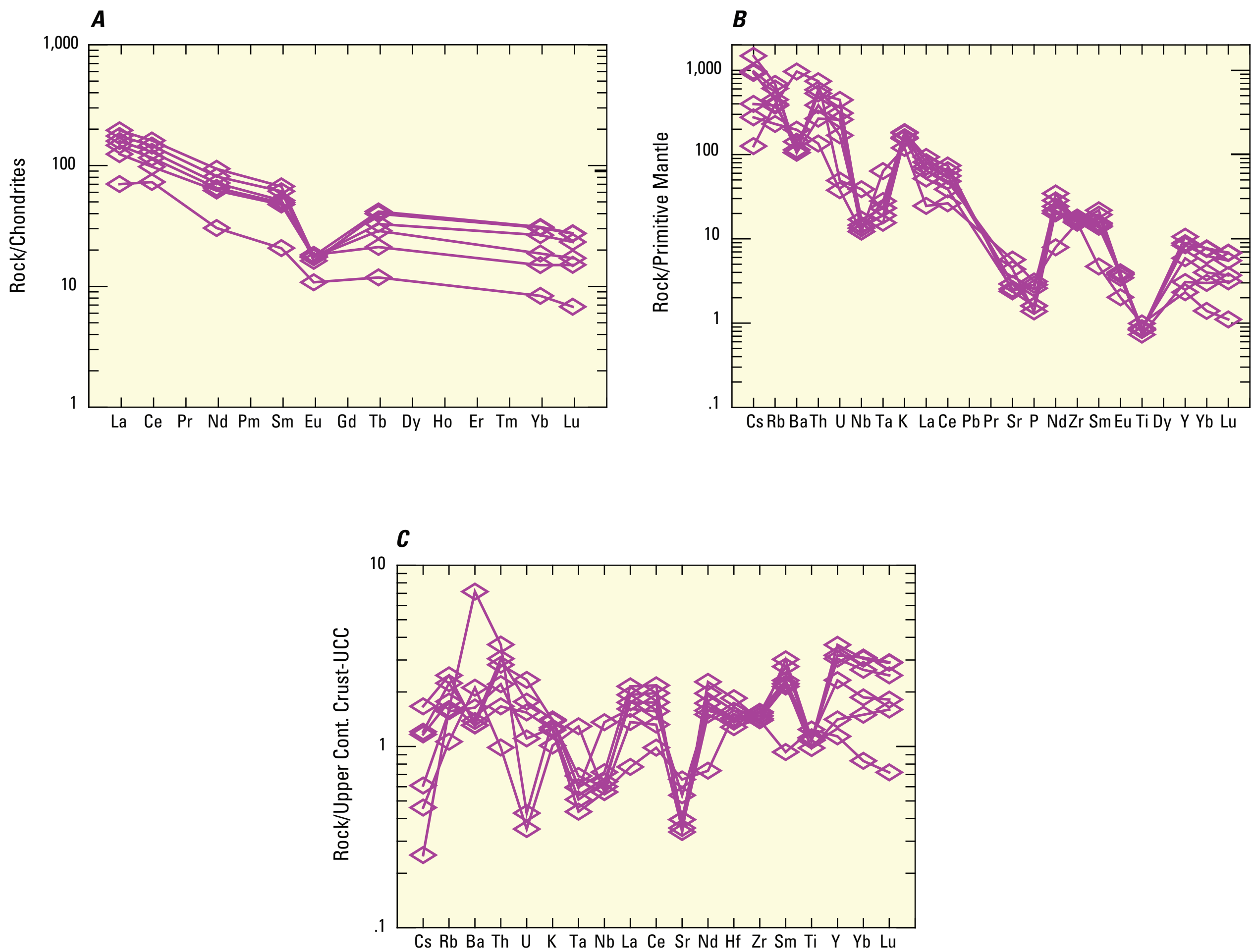

Figure 12–2. (*A*) Chondrite-normalized REE patterns for metagranitic augen gneiss from north of the Blackbird district (chondrite values from Nakamura, 1974). (*B*) Primitive mantle-normalized trace element patterns (primitive mantle values from Sun and McDonough, 1989). (*C*) Upper continental crust-normalized trace element patterns (average upper continental crust values from Taylor and McLennan, 1985).

The overall compositional characteristics of the augen gneiss are similar to those of other North American Mesoproterozoic anorogenic (rapakivi) granites including high $FeO^t/(FeO^t + MgO)$ and K_2O/Na_2O ratios, high incompatible element contents including REE, but low Co, Sc, Cr, Ni, Ba, Sr, and Eu contents (Anderson and Morrison, 2005). In addition, the augen gneiss has variable, but mostly low Fe_2O_3/FeO ratios (< 1), suggesting reduced ilmenite-series affinities similar to other rapakivi granite systems (Frost and Frost, 1997). Frost and Frost (1997) argued that reduced rapakivi granites are derived from tholeiitic mafic sources either by extreme differentiation of basaltic melts or by partial melting of underplated basalts and their differentiated equivalents. The presence of coeval tholeiitic mafic magmas (gabbro intrusions) with the augen gneiss precursor and the mostly positive εNd values are compatible with a mafic source for the original rapakivi granite in the Blackbird region.

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13. Petrology of Associated Sedimentary Rocks

By Karen Lund

Descriptive and Geoenvironmental Model for Cobalt-Copper-Gold Deposits in Metasedimentary Rocks

Scientific Investigations Report 2010–5070–G

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Table

13. Petrology of Associated Sedimentary Rocks

By Karen Lund

Importance of Sedimentary Rocks to Deposit Genesis

Most of the Co-Cu-Au deposits formed in rocks that originated as part of thick, siliciclastic sedimentary successions (table 13–1). These deposits formed post-sedimentation but, during mineralization that was coeval with metamorphism. In many cases, metals, brine components, or sulfur required for the ore-forming fluids and deposits may have originated from the host sedimentary rocks. Several of the deposits are inferred to have formed by metamorphic conversion or upgrading of sedimentary-exhalative (SEDEX) metals accumulation within the sedimentary succession. Some deposits are located within structures or in caldera complexes where igneous rocks are also mineralized, and where the role of sedimentary rocks in deposit genesis is less clear.

In the Blackbird district, several previous studies and mineral deposit models described bedded, syngenetic mineralized zones (Earhart, 1986; Nash and Hahn, 1989; Höy, 1995; Evans and others, 1995; Bookstrom and others, 2007; Lydon, 2007). However, bedded ore was not confirmed by recent detailed regional and district studies (Tysdal, 2000a, b; Evans and Green, 2003; Lund and others, 2011). Syngenetic protoore also is unrecognized in the Modum district (Grorud, 1997). Nevertheless, isotopic data from both of these districts suggest that metals and (or) sulfur originated mainly from the siliciclastic country rocks (Johnson, 2013). Stratiform disseminated pyrite is recognized within the stratigraphic package that hosts the Mt. Cobalt deposit; both sedimentary rocks and amphibolite are considered to be metal sources (Croxford, 1974; Nisbet and others, 1983; Matthai and others, 2004), but isotopic data are inconclusive as to the source of sulfur (Johnson, 2013).

Metacarbonate or scapolite-bearing rocks, which originated as evaporite layers, are locally present in stratigraphic units in the Blackbird district (Tysdal and Desborough, 1997; Johnson and others, 2012), and at Mt. Cobalt (Krcmarov and Stewart, 1998) and Cobalt Hill (Schandl and Gorton, 2007). These strata are significant as they likely contributed brine components that mobilized metals during mineralization. The origin of carbonate-bearing rocks in the Modum district is undetermined (Grorud, 1997). Calc-silicate rocks and garnetiferous quartzite structurally juxtaposed adjacent to the host rocks at the Werner Lake deposit are interpreted as metaexhalites (Pan and Therens, 2000).

At Kendekeke and Dahenglu, primary metal accumulations (SEDEX-type) in the sedimentary successions are interpreted to have originally formed during sedimentation and subsequently were remobilized into deposits during later orogeny (Pan and Sun, 2003; Feng and others, 2009; Yang and others, 2001). Subvolcanic sedimentary rocks are present and mineralized at NICO (Mumin and others, 2007). The deposit at Gladhammar formed along a transcurrent fault where it cuts quartzitic metasedimentary rocks (Sundblad, 2003).

Rock Names/Mineralogy/Texture/Grain Size

Intracontinental basin rocks of the Blackbird district include (1) arkosic siltstone and fine-grained arkosic sandstone from the middle part of the Lemhi Group, and (2) rocks of similar original composition, but metamorphosed and structurally transposed such that stratigraphic correlations are undetermined. A major thrust plate, exposed on the western side of the district (fig. 4–2), is composed of interlayered arkosic shale and fine-grained arkosic sandstone, but it also contains zones that originated as evaporite beds (Tysdal and Desborough, 1997). Prior to erosion, this plate overlay the district and its ore-hosting rocks (Lund and Tysdal, 2007).

At the Mt. Cobalt deposit, intracontinental basin host rocks consist of interlayered siliciclastic rocks, some sulfide-bearing, and lesser mafic volcanic rocks. Minor carbonate and evaporite rocks are also part of the succession (Matthai and others, 2004; Giles and others, 2006). In the Modum district, country rocks originated as graywacke and intercalated arkosic sandstone, black shale, and minor carbonate (Grorud, 1997).

The Cobalt Hill deposit is hosted by conglomerate, quartz arenite, and arkosic quartzite, with minor carbonate and silty carbonate units (Schandl, 2004; Schandl and Gorton, 2007). Gladhammar host strata are quartzite and siliciclastic rocks (Söderhielm and Sundblad, 1996; Sundblad, 2003). Prior to metamorphism, the Kuusamo district host rocks were volcaniclastic sandstone, graywacke, and shale interlayered with andesitic, basaltic, and komatiitic volcanic rocks; minor metaevaporite rocks are present locally (Pankka and Vanhanen, 1992; Vanhanen, 2001; Eilu and others, 2003, 2007). At Sirkka, the host rocks comprise minor fine-grained, volcanogenic siltstone and black shale underlying a mafic volcanic succession (Eilu and others, 2003; Hanski and Huhma, 2005). Kendekeke and Tuolugou host rocks include quartz-albitite of evaporite origin within a metamorphosed volcano-sedimentary package composed of black shale, sandstone, dacitic tuff, and volcaniclastic sandstone (He and others, 2010). In the Contact Lake belt and at NICO, host

Table 13–1. Setting and character of sedimentary rocks associated with Co-Cu Au assemblage deposits.

Deposit/district name	Importance of sedimentary rocks to deposit genesis	Rock names/mineralogy/texture/ grain size	Environment of deposition
Deformed intracontinental basin setting			
Blackbird district (Lund and Tysdal,2007; Lund and others, 2010b, 2011)	Host rock originally sedimentary.Unit containing evaporite structurally juxtaposed during Cretaceous compression, possibly contributed to brine formation	Finely laminated arkosic siltstone and sandstone. Very fine to fine grained	Intracontinental extensional basin, 9-km thick sedimentary package. Turbidite (density) flow succeeded by marine and fluvial sandstone. Structurally juxtaposed shallow-water succession contained evaporite layers
Mt. Cobalt (Croxford, 1974; Nisbet and others, 1983; Giles and others, 2006)	Host rock interlayered siliciclastic and mafic volcanic rocks. Sedimentary and igneous rock sources for brines, metals	Interlayered siliciclastic, some sulfide-bearing, and mafic volcanic rocks. Minor carbonate and evaporite rocks	Intracontinental extensional basin. Filled during two cycles of extension. Turbidite in deepening phase
Modum (Grorud, 1997; Andersen and Grorud, 1998; Sundblad, 2003; Bingen and others, 2005; Andersen and others, 2007)	Host rock originally sedimentary and volcanic. Ore Pb derived from sedimentary succession	Alternating shale, shaley sandstone, thick sandstone, minor calcareous horizons in anoxic environment	Continental platform sedimentary rocks
Cobalt Hill (Schandl, 2004; Marshall and Watkinson, 2001; Schandl and Gorton, 2007)	Preferential host site is unconformity between sedimentary rocks and underlying Archean basement. Sedimentary rock origin for ore brines and metals	Conglomerate, quartz arenite, and arkosic quartzite with minor silty carbonate and carbonate units	Rift-origin, trailing (passive) margin sedimentary basin, 12-km thick sedimentary package
Deformed oceanic rift and back-arc setting			
Gladhammar (Söderhielm and Sundblad, 1996; Sundblad, 2003; Beunk and Page, 2001; Billström and others, 2004)	Ore hosted along shear zone cutting sedimentary country rocks	Quartzite and siliciclastic rocks	Continental-margin fluvial and deltaic depositional environment
Kuusamo schist belt (Juomasuo, Kouvervaara, Meurastuksenaho, Hangaslampi, Lemmonlampi, Kuumaso) (Pankka and Vanhanen, 1992; Vanhanen, 2001; Eilu and others, 2003, 2007; Räsänen and Vaasjoki, 2001)	Different host rocks, some originally sedimentary. Preferential ore locations at contacts with mafic igneous rocks. Sedimentary rock source for halite, chlorine, pyrrhotite	Volcaniclastic and siliciclastic rocks interlayered with subequal andesitic-basaltic volcanic rocks, minor evaporitic rocks	Supracrustal volcaniclastic/siliciclastic and interlayered volcanic rocks in failed rift basin, 2.5-km thick succession. Subaerial to shallow-water with minor evaporite layers
Sirkka (Eilu and others, 2003; Hanski and Huhma, 2005)	Host rocks interlayered volcaniclastic and mafic tuffaceous rocks. Sulfide bearing	Minor volcanogenic siltstone and black shale in mafic volcanic succession. Fine-grained	Gradually deepening, narrow oceanic rift basin
Dahenglu (Yang and others, 2001; Feng and Zhang, 2004; Zhao and others, 2005; Lu and others, 2006)	Host rocks include volcanic, siliciclastic, and carbonate rocks. Metal accumulation interpreted to be syngenetic-exhalative	Phyllitic quartzite, bi-modal volcanic, phyllite, minor carbonate	Intracontinental rift basin
Kendekeke (Pan and Sun, 2003; Pan and others, 2005; Feng and others, 2009; He and others, 2010)	Volcaniclastic sandstone and underlying mafic volcanic rocks host to inferred syngenetic ore	Quartz-albitite of possible evaporite origin within metamorphosed volcano-sedimentary package of black shale, sandstone, metadacite and tuff, and volcaniclastic sandstone	Back-arc basin sedimentary rocks overlying island arc volcanic rocks
Werner Lake (Pan and Therens, 2000)	Sedimentary rocks (some interpreted as exhalites) structurally juxtaposed against ore-hosting mafic-ultramafic rocks. Possible source of metals and brine components	Quartzo-feldspathic, pelitic rocks and minor exhalite(?) structurally juxtaposed against host rocks	Fore-arc or back-arc basin.
Andean volcano-plutonic setting			
Contact Lake belt (Mumin and others, 2007) Camsell River district (Badham, 1975)	Host rocks include supracrustal volcano-sedimentary rocks	Subvolcanic sandstone, siltstone, minor carbonate rocks. Thin bedded	Caldera-fill sedimentary rocks in Andean arc setting
NICO (Goad and others, 2000a, b; Mumin and others, 2007)	Ore hosted in contact metamorphosed subvolcanic sedimentary rocks	Graywacke section, including arenite (subarkosic wacke), dolostone, siltstone, shale. Overlain by rhyolite ignimbrite	Caldera-fill sedimentary rocks in Andean arc setting

rocks include graywacke, arenite, dolostone, siltstone, and shale, all of which are overlain by rhyolite ignimbrite and constitute part of a caldera-fill succession (Badham, 1975; Goad and others, 2000a; Mumin and others, 2007).

Environment of Deposition

The intracontinental-basin sedimentary rocks hosting Blackbird, Mt. Cobalt, Cobalt Hill, and Modum formed in extensional basins on continental crust that underwent rapid subsidence and that were filled with thick (multiple to tens of kilometers) supracrustal successions of fine- to medium-grained arkosic siliciclastic rocks (table 13–1). Most of these basins also had shallow depositional settings in which evaporitic sediments formed. The extensional basins, rocks of which later hosted the Blackbird and Modum districts, were mostly amagmatic, containing little or no interlayered volcanic rocks. The Mt. Cobalt and Cobalt Hill deposits formed in interlayered sedimentary and mafic to felsic volcanic rocks of intracontinental basins.

In the structural domains of the Blackbird district, where sedimentary features are preserved and the environment of deposition can be determined, the host rocks originated as coarse-grained siltstone and fine-grained sandstone of turbidite (gravity flow) origin, as well as fine-grained sandstone of marine and fluvial origins (Tysdal, 2000a). The intracontinental extensional basin that hosted the Mt. Cobalt deposit was filled during two cycles of extension and by deepening phases characterized by turbidite flow rocks (Matthai and others, 2004; Giles and others, 2006). At Modum, siliciclastic and minor carbonate-bearing country rocks originated in a fluvial and shallow marine continental platform in an intracontinental extensional setting (Grorud, 1997; Bingen and others, 2005). The succession that hosts the Cobalt Hill deposit is a 12-km-thick sedimentary package deposited in a rift-origin, trailing (passive) margin basin that formed on transitional crust (Schandl, 2004; Schandl and Gorton, 2007; Marshall and Watkinson, 2000). Gladhammar host rocks were deposited in a continental-margin, fluvial and deltaic depositional environment (Söderhielm and Sundblad, 1996; Sundblad, 2003).

Deposits that formed in oceanic rift and back-arc settings are hosted within interlayered sedimentary and volcanic successions. The Kuusamo district is hosted by a 2.5-km-thick succession of supracustal rocks that was deposited in a subaerial to shallow-water environment, within a failed rift basin that became part of the Central Lapland greenstone belt (Pankka and Vanhanen, 1992; Vanhanen, 2001; Eilu and others, 2003, 2007). Also in the greenstone belt, the Sirkka deposit is in siliciclastic rocks underlying a mafic volcanic succession (Eilu and others, 2003; Hanski and Huhma, 2005). In contrast, host rocks at Kendekeke were deposited in a back-arc basin (He and others, 2010).

The sedimentary host rocks in Andean volcano-plutonic settings, including some in the Contact Lake belt at NICO, are parts of caldera-fill successions overlain by rhyolite ignimbrite (Badham, 1975; Goad and others, 2000a; Mumin and others, 2007).

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14. Petrology of Associated Metamorphic Rocks

By Karen Lund

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Descriptive and Geoenvironmental Model for Cobalt-Copper-Gold Deposits in Metasedimentary Rocks

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Table

14. Petrology of Associated Metamorphic Rocks

By Karen Lund

Importance of Metamorphic Rocks to Deposit Genesis

Most of the Cu-Co-Au deposits (table 1–1) are in regionally metamorphosed rocks in which the relative timing of mineralization ranges from pre-metamorphic, through syn-metamorphic, to post-metamorphic (table 14–1). Another small group of deposits is in contact metamorphosed rocks.

In the Blackbird district, host rocks range in metamorphic grade from middle greenschist to lower amphibolite facies according to their structural setting in different thrust-fault domains. Cobalt- and Cu-bearing veins and related breccia zones lie within and along Late Cretaceous penetrative structures. Mineralized zones are discordant to bedding in rocks at low metamorphic grade, but the zones are progressively more parallel to metamorphic compositional layering in the higher metamorphic grade rocks. In addition to geochronologic data (Lund and others, 2011; Aleinikoff and others, 2012), these fabrics were used to interpret a syn-metamorphic timing for mineralization (Lund and others, 2011). Highest recoverable Au grades (Bending and Scales, 2001) are in rocks that were at the highest metamorphic temperatures during late-stage mineralization (Lund and others, 2011).

At the Mt. Cobalt deposit, syn-metamorphic ore is hosted within high strain zones in amphibolite-facies regional metamorphic rocks (Croxford, 1974; Nisbet and others, 1983; Krcmarov and Stewart, 1998; Giles and others, 2006). In the Modum district, despite evidence of earlier uraninite formation in the deposit, Co-Cu-Au ore minerals formed during Sveconorwegian collision, preferentially along syn-metamorphic, penetrative shear zones in granulite-facies rocks (Grorud, 1997; Bingen and others, 2005). Those events may have caused remobilization of an earlier mineralization (Andersen and Grorud, 1998).

In the Kuusamo district, volcaniclastic and volcanic rocks were hydrothermally altered by mafic dolerite dikes that intruded the layered rocks (fig. 4–3; Pankka and Vanhanen, 1992; Eilu and others, 2003, 2007). Subsequent regional metamorphism and structural intercalation of the rocks formed ore deposits within both lithologies in and near the early dike contact zones (Pankka and Vanhanen, 1992; Eilu and others, 2007).

In the Dahenglu and Kendekeke deposits, inferred syngenetic metal occurrences were upgraded during metamorphic events that remobilized metals and localized ore in axial planar and intrafolial vein systems (Pan and Sun, 2003; Pan and others, 2005; Feng and others, 2009). At the Werner Lake deposit, a similar SEDEX origin has been invoked for the metals, followed by remobilization from evaporitic sedimentary rocks during metamorphism, resulting in the formation of veins and pods of ore within meta-mafic intrusive rocks that were juxtaposed by faults against the metasedimentary rocks (fig. 5–5; Pan and Therens, 2000).

Deposits in the Contact Lake belt and at NICO formed during magmatic events. The ore zones are within contact metamorphic zones in subvolcanic sedimentary rocks and in altered felsic igneous rocks (fig. 5–4; Goad and others, 2000a; Mumin and others, 2007).

Rock Names/Mineralogy and Assemblages/Grain Size

At Blackbird, the metamorphic mineralogy across the district is similar to that of the unmetamorphosed rocks in that both are dominated by quartz and feldspar. Throughout the district, quartz is recrystallized, feldspar is intergrown with other minerals, metamorphic biotite is ubiquitous but exhibits different grain size depending on metamorphic grade, and minor amounts of muscovite and tourmaline are present locally. The structurally controlled, contrasting grades of metamorphic rocks in different parts of the district resulted in differing amounts of coarsening and differentiation of minerals. Depending on structural domain, the rocks range from fine-grained phyllite to medium- and coarse-grained schist and gneiss (Lund and Tysdal, 2007). Biotite-rich layers in the metamorphic rocks originated as (1) interlaminated siltstone, (2) gangue in veins and in Fe-metasomatized sedimentary rocks, and (3) pre-metamorphic mafic dikes. Within rocks at higher metamorphic grade, biotite-rich zones that formed as gangue and in alteration zones, containing more than 75 volume percent biotite termed biotitite, also contain coarse porphyroblasts of garnet and (or) chloritoid. Scapolite is an important metamorphic mineral in meta-evaporite zones in the unit that was thrust over the host rocks and also is common along high-angle faults in the non-evaporite-bearing rocks of the district (Lund and others, 2011).

In the Modum district, host rocks are fine- to medium-grained, quartzo-feldspathic schist, quartzite, sulfidiic schist, graphitic schist, and marble. Metagabbro and amphibolite, which are intercalated with the metasedimentary rocks, originated as dikes (Grorud, 1997). At Mt. Cobalt, host rocks are graphitic quartz-mica schist containing garnet and staurolite porphyroblasts (Croxford, 1974; Nisbet and others, 1983).

Table 14–1. Petrology of associated metamorphic rocks.

Deposit/district name	Importance of metamorphic rocks to deposit genesis	Rock names	Mineral facies	Deformation and textures
		Deformed intracontinental basin setting		
Blackbird district (Lund and Tysdal, 2007; Lund and others, 2011)	Ore hosted in regional metamorphic fabrics and related minor structures. Late-stage Au enrichment in highest metamorphic grade settings	Country rock: biotite-feldspar-quartz phyllite to schist and biotite-feldspar-quartz gneiss. Gangue: tourmaline-biotite and tourmaline-chloritoid-garnet-biotite	Middle greenschist to middle amphibolite. Alteration assemblage about same facies as country rock. Retrograde white mica, chlorite with younger ore stages	Metamorphism occurred during Late Cretaceous compression, forming pervasive foliation, polyphase folding, and shear zones
Mt. Cobalt (Croxford, 1974; Nisbet and others, 1983; Matthai and others, 2004; Giles and others, 2006)	Syn-metamorphic ore hosted in regional metamorphosed and deformed rocks	Quartz, mica, graphitic schist w/ garnet, staurolite porphyroblasts, albitite layers. Amphibolite.	Amphibolite. Alteration assemblage (Cl-rich biotite-scapolite) same grade as country rock, retrograde tourmaline	Syn-metamorphic, polyphase folding, pressure-solution and slaty cleavage in fold hinges. High strain zones are mineralized. Later high-angle faults
Modum (Grorud, 1997; Andersen and Grorud, 1998; Sundblad, 2003; Bingen and others, 2005; Andersen and others, 2007)	Pre-metamorphic ore remobilized by 1.1 Ga metamorphism	Quartzo-feldspathic schist, quartzite, sulfididic schist, graphitic schist, marble. Metagabbro, amphibolite	Granulite	1.1 Ga granulite-facies metamorphism overprinted greenschist metamorphism. Ore along penetrative deformation and axial planar zones
Cobalt Hill (Marshall and Watkinson, 2001; Schandl 2004; Schandl and Gorton, 2007)	Ore may be related to rift-origin mafic intrusive rocks or may be related to late syn-metamorphic regional fluids	Quartzite, arkosic quartzite	Lower greenschist	
		Deformed oceanic rift and back-arc setting		
Gladhammar (Söderhielm and Sundblad, 1996; Sundblad, 2003; Beunk and Page, 2001; Billström and others, 2004)	Prograde metamorphism is pre-ore. Ore related to local retrograde metamorphism along Loftahammar-Linköping shear zone	Quartzite	Amphibolite grade country rocks. Ore in retrograde shear zones	Ore along transpressional shear zones related to local retrograde metamorphism
Kuusamo belt (Juomasuo, Kouvervaara, Meurastuksenaho, Hangaslampi, Lemmonlampi, Kuumaso) (Pankka and Vanhanen, 1992; Vanhanen, 2001; Eilu and others, 2003, 2007; Räsänen and Vaasjoki, 2001)	Mineralization syn- to late-peak metamorphism	Albite-quartz rock (sericitic quartzite), albite-amphibole rock (mafic lava), sericite-chlorite rock (mafic lava), chlorite-talc rock (komatiite)	Upper greenschist to lower amphibolite	Quartz veins in and across penetrative fabrics related to second-order compressional structures near major regional structures
Sirkka (Eilu and others, 2003)	Ore formed syn- to late-peak metamorphic	Mafic metavolcanic, metatuffite, (meta) komatiite, graphitic phyllite, sulfide-facies iron formation	Middle to upper greenschist	Ore is structurally controlled and intrafolial within or near transcrustal shear zone
Dahenglu (Yang and others, 2001; Zhao and others, 2005; Lu and others, 2006)	Inferred syngenetic ore upgraded during metamorphic remobilization	Phyllite, quartzite	Greenschist	Pervasive deformation fabrics
Kendekeke (Pan and Sun, 2003; Pan and others, 2005; Feng and others, 2009; He and others, 2010)	Stratabound deposits enriched during metamorphism. Metamorphic overprint formed veins deposits and late Au enrichment	Spilite-keratophyre and meta-volcaniclastic sandstone	Greenschist	Syngenetic ore remobilized to form disseminated and vein mineralization in penetrative fabrics related to ductile folding

Amphibolite, originally mafic volcanic rock, is present as a minor component. The Gladhammar and Cobalt Hill deposits are hosted by quartzite and meta-arkosic quartzite that contain relatively simple mineral assemblages (Söderhielm and Sundblad, 1996; Schandl and Gorton, 2007).

In the Kuusamo district, the ore hosting sericitic quartzite is altered to albite-quartz rock, mafic flows to albite-amphibole or sericite-chlorite rock, and komatiite to chlorite-talc rock (Pankka and Vanhanen, 1992; Vanhanen, 2001; Eilu and others, 2003, 2007). At Sirkka, rocks are phyllitic with granoblastic textures. Metasedimentary rocks consist of albite-quartz-sericite-chlorite-biotite phyllite, whereas the metamorphosed mafic and ultramafic volcanic rocks are talc-chlorite phyllite, albite-calc-silicate phyllite, and quartz-albite-chlorite phyllite (Eilu and others, 2003). At the Werner Lake deposit, the host rocks consist of amphibolite, meta-ultramafic rock, and garnet-biotite schist (mafic metavolcanic rock) that were structurally juxtaposed adjacent to calc-silicate gneiss and garnet quartzite (inferred meta-exhalite) (fig. 5–5; Pan and Therens, 2000).

In the NICO deposit, subvolcanic sedimentary rocks, which host some of the ore zones, were contact metamorphosed to biotite-amphibole-magnetite hornfels, biotite-altered subarkosic hornfels, and calc-silicate hornfels by (potassium feldspar-altered) felsic dikes (Goad and others, 2000a; Mumin and others, 2007).

Mineral Facies

The Cu-Co-Au deposits occur in both regional and contact metamorphic rocks (table 14–1). Host rocks to the Blackbird district range in metamorphic grade from middle greenschist to lower amphibolite facies in different thrust-plate domains (Lund and Tysdal, 2007). Mt. Cobalt host rocks were metamorphosed to amphibolite facies (Croxford, 1974; Nisbet and others, 1983; Matthai and others, 2004; Giles and others, 2006); those of the Cobalt Hill deposit were metamorphosed to lower greenschist facies (Schandl and Gorton, 2007; Marshall and Watkinson, 2001). Ore deposits in the Modum district formed when host rocks, and possibly early metal accumulations, were metamorphosed to granulite facies (Grorud, 1997; Andersen and Grorud, 1998). In the Kuusamo district and at the Sirkka deposit, the interlayered sedimentary and volcanic rocks were in-folded into the Central Lapland greenstone belt and later were contact metamorphosed during emplacement of mafic dikes. Subsequently, country rocks and dikes were overprinted by greenschist- to amphibolite-facies metamorphism contemporaneous with mineralization (Pankka and Vanhanen, 1992; Vanhanen, 2001; Eilu and others, 2003, 2007). Host rocks at Werner Lake were metamorphosed to granulite facies and overprinted by retrograde greenschist metamorphism; both metamorphic events were coeval with mineralization (Pan and Therens, 2000). Scant available information about mineral assemblages at the Chinese deposits suggests that host rocks and inferred syngenetic metal endowments were metamorphosed to lower greenschist facies at Kendekeke and to greenschist-amphibolite facies at Dahenglu (Pan and Sun, 2003; Pan and others, 2005; Feng and others, 2009).

At NICO and Contact Lake, caldera-related subvolcanic graywacke underwent upper greenschist and lower amphibolite facies contact metamorphism imposed by crosscutting igneous rocks, and later was altered and mineralized as part of the caldera-building process (Goad and others, 2000a; Mumin and others, 2007).

Deformation and Textures

Textural and deformational features in mineralized rocks of the Co-Cu-Au deposits include both pervasive oriented fabrics in regional metamorphic settings and hornfels in less common contact metamorphic settings.

Sedimentary characteristics of most host rocks in the Blackbird district were obscured to different degrees by subsequent metamorphism and deformation. Across the different structural domains in the district (fig. 4–2), metamorphic fabrics change from (1) fold cleavage in middle greenschist facies rocks; to (2) transposed layering, axial planar foliation, and shear zones in upper greenschist facies rocks; and to (3) metamorphic compositional layering, intrafolial foliation, and shear zones in lower amphibolite facies rocks (Lund and Tysdal, 2007; Lund and others, 2011). The Co- and Cu-bearing veins and breccia zones are discordant to bedding and lie along fold cleavage in the low metamorphic grade rocks, but ore zones are progressively more parallel to compositional layering in the transposed rocks at higher metamorphic grade. The degree to which gangue minerals in Co ore zones are foliated decreases for younger veins in all structural domains, indicating a syn- to late-metamorphic and syn- to late-ductile deformation age of introduction for these ore zones (Lund and others, 2011). Late-metamorphic, Cu-bearing zones are characterized by unoriented metamorphic gangue minerals intergrown with sulfide minerals (Lund and others, 2011). Garnet porphyroblasts that overprint early ore zones in the highest metamorphic grade domain, monazite and xenotime within foliated biotite of early ore veins in the highest and intermediate metamorphic grade domains, and unoriented muscovite surrounding late-stage veins are all dated as Late Cretaceous (Zirakparvar and others, 2007; Lund and others, 2011; Aleinikoff and others, 2012). The alternative model of Slack (2012) involves epigenetic Mesoproterozoic Co-Cu-Bi-Au-REE mineralization that was significantly remobilized into Cretaceous structures.

In the Modum district, host rocks were structurally interleaved during continental collision (Sveconorwegian) events and granulite facies metamorphism (Bingen and others, 2005). Ore is located along foliation, axial planar fabrics, and penetrative shear zones (Grorud, 1997; Andersen and Grorud, 1998). Crosscutting, fabric-discordant veins are related to younger continental rifting (Grorud, 1997). At the Mt. Cobalt deposit, vein and disseminated orebodies formed in shear zones, fault hinges, and penetrative fabrics. These high-strain, compressional structures developed during regional metamorphism due to collision-related basin inversion (Matthai and others, 2004).

In the Kuusamo schist belt, Paleoproterozoic compressional collision events closed the original Paleoproterozoic rift basin, causing medium-grade metamorphism, isoclinal folding, and shearing of interlayered volcaniclastic, siliciclastic, and mafic volcanic rocks together with mafic dikes that had intruded the layered succession (Pankka and Vanhanen, 1992; Eilu and others, 2003, 2007). The ore is late metamorphic in timing, localized in fold hinges and shear zones (Pankka and Vanhanen, 1992; Eilu and others, 2003, 2007; Sundblad, 2003). At the Kendekeke and Dahenglu deposits, inferred syngenetic metal concentrations in the sedimentary rocks were remobilized into disseminated and vein ore zones within penetrative fabrics that formed during ductile folding (Pan and Sun, 2003; Pan and others, 2005; Feng and others, 2009).

At the NICO deposit, sulfide minerals are intergrown with undeformed hornfels minerals within contact metamorphic haloes that developed in sedimentary rocks adjacent to felsic dikes, which also contain ore zones (fig. 5–4; Goad and others, 2000a; Mumin and others, 2007).

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15. Theory of Deposit Formation

By John F. Slack

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Descriptive and Geoenvironmental Model for Cobalt-Copper-Gold Deposits in Metasedimentary Rocks

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Evidence for Epigenetic Mineralization

Abundant evidence of epigenetic mineral deposition exists for most of the Co-Cu-Au deposits considered in this report. Characteristic are sulfide-rich lenses, veins, or breccias that are variably discordant to bedding or layering in metasedimentary host rocks such as those in the Blackbird district in Idaho and the Kuusamo schist belt in Finland (Lund, 2013a; Slack, 2013a). These discordant ore zones are typically localized by faults, shear zones, and fold axes, and hence formed after sedimentation and diagenesis. Most of the Co-Cu-Au deposits (table 1–1) are deformed and metamorphosed, as reflected by pervasive recrystallization of cobaltite and other ore and gangue minerals in the Blackbird district, the Modum district in Norway, the Werner Lake deposit in Ontario, and Mt. Cobalt in Australia (Slack, 2013a, and references therein). In several deposits, such as those in the Blackbird district (Slack, 2012), remobilized sulfides occur in piercement cusps and in "durchbewegung" structures in which sulfide-rich rock is brecciated and locally rotated within a single layer or lens (see Marshall and Gilligan, 1989; Marshall and others, 2000). Also in the Blackbird district, cobaltite locally is encased in euhedral garnet (Eiseman, 1988; Slack, 2012). These metamorphogenic features demonstrate clearly that in some deposits, Co-Cu-Au mineralization predated the latest stages of deformation and regional metamorphism.

Several of the Co-Cu-Au deposits have been attributed to SEDEX hydrothermal activity. This non-epigenetic model has been applied to the Werner Lake (Pan and Therens, 2000), Dahenglu (Yang and others, 2001), and Kendekeke (Pan and others, 2005) deposits (Lund, 2013a). These authors recognized the deformed and metamorphosed nature of the ores but interpreted the original mineralization as having occurred contemporaneously with deposition of the host sedimentary and (or) volcanic rocks. Principal evidence used to support this SEDEX model is the broadly stratabound and locally stratiform (bedded) nature of the ore zones, but such geometry can also form by selective replacement of reactive sedimentary rocks, such as limestone, or by filling of bedding-parallel shear zones or faults. The SEDEX origins attributed by other workers to the Werner Lake, Dahenglu, and Kendekeke deposits are thus problematic and require careful evaluation by additional studies. As a result, the origin of these deposits is considered uncertain.

Age of Mineralization

Absolute ages of mineralization in the deposits are in most cases unknown. Broad constraints are recorded by the typically post-sedimentation and the pre- to syn-metamorphic nature of the ore zones, but with few exceptions the ages of sedimentation and metamorphism are not firmly established. Only deposits in the Blackbird and Modum districts, and some in the Kuusamo schist belt, have been directly dated by geochronology. At Blackbird, SHRIMP U-Pb geochronology of the cores of xenotime grains intergrown with cobaltite yields a Pb-Pb age of 1370 ± 4 Ma, which is within analytical uncertainty of the SHRIMP U-Pb zircon age of 1377 ± 4 Ma obtained for a nearby megacrystic granite (Aleinikoff and others, 2012). Slack (2012) used textural and geochemical data for the Blackbird district, including widespread intergrowths of cobaltite with xenotime, to propose that this metal suite was introduced together with Y and REE in the xenotime, and with associated Bi (residing mainly in native bismuth and bismuthinite) and Be (in gadolinite), from predominantly magmatic-hydrothermal fluids generated during emplacement of the nearby granite; some components also were derived from the metasedimentary host rocks based on isotope data (Johnson, 2013a). In contrast, Lund and others (2011) presented microtextural data and Ar-Ar ages of 83 Ma for white mica in post-ore veinlets as the basis for a model in which the Co-Cu-Au mineralization is Cretaceous and genetically unrelated to the Mesoproterozoic xenotime present in the ore zones. Additional in-situ geochronological studies will be needed to resolve these conflicting interpretations.

In the Modum district, uraninite intergrown with cobaltite from the Skuterud deposit has a Pb-Pb age of 1434 ± 29 Ma (Andersen and Grorud, 1998). This age does not correspond to any known major intrusive igneous event in the district, although it is within analytical uncertainty of the 1472 ± 69 Ma Sm-Nd isochron age of alkaline mafic dikes in the Bamble sector approximately 150 km to the south (Nijland and others, 2000). No geochronological data are available on the granitic and granodioritic gneisses of the district (fig. 5–2), but lithologically similar felsic orthogneisses in the region have U-Pb zircon ages of 1.52 to 1.48 Ga (Bingen and others, 2005). The local metagabbro bodies were emplaced at 1224 ± 15 Ma based on a Sm-Nd isochron age obtained by Munz and Morvik (1991). High-grade metamorphism in the Modum complex is constrained by Pb-Pb ages of 1102 ± 28 Ma and 1066 ± 10 Ma on zircon rims (Bingen and others, 2001) and a Pb-Pb age of 1092 ± 1 Ma on monazite (Bingen and others, 2008). The 1434 ± 29 Ma age of uraninite in the

Skuterud deposit was interpreted by Andersen and Grorud (1998) as recording Co-Cu-Au-U mineralization within an "orogenic interlude" between the local Gothian/Kongsbergian (~1.5 Ga) and regional Sveconorwegian (1.2–0.9 Ga) orogenies. This interpretation is consistent with the pervasively recrystallized nature of the Co-sulfides and other minerals in the deposits (Grorud, 1997), thus implying that the Co-Cu-Au mineralization predates the predominant Sveconorwegian metamorphism in the region; it is unclear whether this mineralization took place during or after the older Gothian/Kongsbergian metamorphic event. Because scapolite alteration in the district is superimposed on the metagabbro bodies (Engvik and others, 2011), this alteration postdates the mineralization by at least ~210 m.y. and hence must have formed by unrelated processes. The widespread albite alteration in the district reportedly formed at 1080 ± 3 Ma based on U-Pb dating of titanite (Munz and others, 1994), but U-Pb isotope systematics of this mineral commonly are reset by metamorphism (for example, Bibikova and others, 2001; Slack and others, 2008). Hence, this age is questionable and as a result the relative timing of Co-Cu-Au mineralization and albite alteration in the Modum district remains uncertain. A similarly young Re-Os age of 1112 ± 4 Ma determined on molybdenite grains within cobaltite from the Skuterud deposit reflects post-ore growth or recrystallization of the molybdenite during Sveconorwegian metamorphism (Bingen and others, 2008).

In the Kuusamo schist belt, Mänttäri (1995) obtained a U-Pb age of 1829 ± 5 Ma on inclusions of brannerite [$(U,Ca,Ce)(Ti,Fe)_2O_6$] in pyrrhotite from the Hangaslampi deposit. This age is coeval with emplacement in the belt of late orogenic granites of the Central Lapland granite complex at 1840 to 1800 Ma (Nironen, 2005), but no genetic link is known between Co-Au mineralization in this deposit and intrusion of the granites. However, the 1829 ± 5 Ma age of the brannerite is within the 1840-1880 Ma age range of the predominant deformation and metamorphism in the Kuusamo schist belt (Lahtinen and others, 2003; Sorjonen-Ward and others, 2003).

Petrologic studies of the Werner Lake deposit in Ontario provide strong evidence that Co mineralization predated regional metamorphism at 2690 Ma. Prograde metamorphic silicates within the deposit—including spinel, olivine, and pyroxene—contain elevated Co contents that suggest metamorphic equilibration between these gangue minerals and Co sulfides, in which fluid exchange during metamorphism resulted in the growth of Co-bearing silicates (Pan and Therens, 2000). These authors interpreted the ores as being of SEDEX origin, but this model is problematic, for reasons given above. Hence, the age of mineralization at the Werner Lake deposit is considered uncertain. A similar uncertain timing for mineralization is applied to the Dahenglu and Kendekeke deposits in China.

At the Gladhammar deposit in Sweden, mineralization was controlled by transcurrent faulting that postdated greenschist-facies metamorphism of the host metasedimentary rocks (Söderhielm and Sundblad, 1996; Sundblad, 2003).

Ore Deposit System Affiliations

The diversity of mineralization among the Co-Cu-Au deposits considered in this report (table 1–1) makes it difficult to present a unified genetic model. Previous workers, for example, have invoked a wide spectrum of origins including syngenetic or early diagenetic mineralization like that documented in SEDEX and VMS systems (Goodfellow and Lydon, 2007; Galley and others, 2007), diagenetic mineralization as observed in many sediment-hosted stratiform copper systems (Hitzman and others, 2005), post-tectonic mineralization as in so-called "five-element" veins (Kissin, 1992; Marshall and Watkinson, 2000); and syn-metamorphic mineralization similar to that in orogenic gold and iron oxide-copper-gold (IOCG) systems (Goldfarb and others, 2005; Williams and others, 2005). In the following discussion, these different ore-forming systems are evaluated as possible genetic models for the Co-Cu-Au deposits.

Evaluation of SEDEX and VMS Affiliations

The common presence of post-lithification epigenetic features in the Co-Cu-Au deposits, and the absence of documented exhalative chemical sedimentary rocks (exhalites), argue against a predominantly SEDEX model. A VMS model is rejected on similar grounds, and because metavolcanic rocks—hallmarks of VMS systems (for example, Galley and others, 2007; Shanks and Thurston, 2012)—are absent or volumetrically minor in or near the Co-Cu-Au deposits, except at NICO where metarhyolite occurs above most of the ore zones (Goad and others, 2000b). Additional evidence against both VMS and SEDEX models comes from the narrow range of sulfur isotope values for sulfide minerals in most of the Co-Cu-Au deposits that contrasts with the much broader range known for VMS and SEDEX deposits, the former suggesting sulfide deposition by high-temperature thermochemical sulfate reduction and the latter by low-temperature microbial reduction of seawater sulfate (Johnson, 2013).

The occurrence of laterally extensive, stratabound magnetite-rich rocks such as those in the Iron Creek area southeast of the Blackbird district were classified as syngenetic iron formation by previous workers (Nash, 1989). However, these magnetite-rich rocks are not uniformly layered as in typical synsedimentary iron formation (for example, Peter, 2003; Bekker and others, 2010), and they locally contain high contents of Bi, Y, and Te (Slack, 2012; 2013a)—unknown in true iron formation. Magnetite- and hematite-rich lenses and breccias also occur in the NICO deposit in Canada, but similarly are not considered synsedimentary iron formation (Goad and others, 2000b). In summary, geological, mineralogical, and geochemical data argue strongly against SEDEX or VMS models for the Co-Cu-Au deposits.

Evaluation of Sediment-Hosted Stratiform Copper Affiliations

Sediment-hosted stratiform Cu deposits also have some features in common with the Co-Cu-Au deposits described in this report, including high Co contents (fig. 2–1). However, three major differences are evident. First is the lack of associated redbed sedimentary rocks or their metamorphosed equivalents (for example, magnetite-bearing quartzite), which are characteristic of sediment-hosted stratiform Cu deposits in the central African copperbelt and worldwide (Hitzman and others, 2005). Second, the Co-Cu-Au deposits typically have high As contents, present in Co-bearing sulfarsenide and arsenide minerals, whereas the stratiform Cu deposits generally lack anomalously high As concentrations. Third, most of the Co-Cu-Au deposits have much higher Au grades relative to the stratiform Cu deposits (fig. 2–2), excluding rare deposits such as Kolwezi in the Democratic Republic of Congo that contain elevated Au and several other deposits in the copperbelt with post-kinematic quartz-carbonate veins containing Cu-U-Mo-(Au) mineralization (Hitzman and others, 2005, and references therein). These major differences suggest that the Co-Cu-Au deposits are not linked genetically to stratiform Cu deposits. However, some stratiform Cu deposits, such as those in the Zambian copperbelt, contain zones of pervasive albite alteration (Large and others, 2006; Hitzman and others, 2008), similar to many of the Co-Cu-Au deposits (Slack, 2013b). Although the albite alteration in the Zambian copperbelt deposits has been attributed to formation prior to ore deposition, syn-ore biotite alteration is also present (Large and others, 2006) that may be analogous to that recognized in the Blackbird district (Slack, 2013b). One interpretation of these mineralogically similar alteration zones is that sodic and potassic alteration in sedimentary rock-hosted ore deposits record major involvement of evaporite-derived brines in the hydrothermal systems (for example, Barton and Johnson, 1996), independent of the style or timing of mineralization or the metal(s) deposited. Alternatively, the Co-Cu-Au deposits considered in this model could have formed from hydrothermal systems like those related to the stratiform Cu-Co deposits of the central African copperbelt, with the important difference that later, during or after regional metamorphism, Au was added to the resulting deposits.

Evaluation of Five-Element Vein Affiliations

The Co-Cu-Au deposits have some geochemical similarities to “five-element” Ag-Ni-Co-As-Bi veins (Kissin, 1992; Marshall and Watkinson, 2000). In particular is the typical metal assemblage of Co together with As, Ni, and Bi, which occur in nearly all of the Co-Cu-Au deposits (table 1–1). A major difference is the absence or scarcity of high Cu and Au concentrations within these veins. Two additional differences are evident. First, the five-element veins are entirely post-tectonic in origin, filling planar faults and fractures (Kissin, 1992), in contrast to the pretectonic to—in some cases—syntectonic timing of mineralization that characterizes the Co-Cu-Au deposits (Lund, 2013a; Slack, 2013a). Second, the five-element veins lack the widespread sodic or potassic alteration zones that are spatially associated with the Co-Cu-Au deposits (Slack, 2013b). These fundamental geologic and geochemical differences indicate that the five-element Ag-Ni-Co-As-Bi veins are genetically unrelated to the Co-Cu-Au deposits considered in this report.

Evaluation of Orogenic Gold Affiliations

Orogenic gold deposits have some similarities to the Co-Cu-Au deposits. Chief among these is occurrence of many of the former deposits within ductile structures in metamorphic terranes (for example, Goldfarb and others, 2005). An orogenic gold model was applied to the Co-Cu-Au deposits of the Kuusamo schist belt in Finland by Pankka (1997) and Eilu and others (2003), based on the localization of these deposits in similar ductile structures and their generally high Au concentrations (fig. 2–2). However, orogenic gold deposits lack high contents of Co, or the high Y and REE concentrations found in several of the Co-Cu-Au deposits, such as Juomasuo, Mt. Cobalt, and those in the Blackbird district (Slack, 2013a). Furthermore, magnetite-rich rocks and widespread sodic- or potassic-rich alteration zones that characterize most of the Co-Cu-Au deposits are absent in orogenic gold systems (Goldfarb and others, 2005). These fundamental mineralogical and geochemical differences imply that the Co-Cu-Au deposits are unrelated in a direct way to orogenic gold deposits. Nevertheless, their common localization in ductile structures, together with stable isotope signatures that suggest metamorphic fluid involvement in the Co-Cu-Au deposits (Johnson, 2013), allow for the possibility that the latter deposits formed by similar metamorphogenic processes. Additional isotopic studies of the Co-Cu-Au deposits may provide the data required to better evaluate this possibility.

Evaluation of IOCG Affiliations

A potential genetic affiliation exists with IOCG deposits. Deposits included within this classification are epigenetic and generally pre- to syn-tectonic, and contain, in addition to Cu, Au, and iron oxides, locally abundant U, Co, Ni, Mo, Ag, Bi, Y, and (or) REE (Williams and others, 2005; Groves and others, 2010). This is the same metal suite that occurs, overall, within most of the metasedimentary rock-hosted Co-Cu-Au deposits (table 1–1; appendix 1). Such metallogenic similarities, together with geological and geochemical data, were used by Goad and others (2000a, b) and Vanhanen (2001) to argue for IOCG affinities for the NICO and Kuusamo belt deposits, respectively. Eilu and Niiranen (2002) suggested that the latter deposits are transitional between orogenic gold and IOCG deposits. For comparison, other Cu-Co-Au deposits and prospects that also contain abundant iron oxides are most commonly classified as IOCG systems, including Ahmavuoma, Sweden (Tertiary Minerals, Plc., 2006), Vähäjoki, Finland (Eilu, 2007), and Guelb Moghrein, Mauritania (Kolb and others, 2006).

Slack (2006, 2012) has proposed that the Co-Cu-Au-Bi-Y-REE deposits of the Blackbird district also belong to the IOCG class. The presence of abundant albite and (or) biotite in alteration zones spatially related to most of the Co-Cu-Au deposits included herein (Slack, 2013b) supports this interpretation, based on the widespread occurrence of such alteration zones in IOCG deposits (Williams and others, 2005). Albitic alteration is more characteristic, whereas biotite alteration is uncommon except in the Blackbird district, possibly reflecting mineralization at an intermediate depth, above the deep zone of albitic alteration (see Barton and Johnson, 2004; Pollard, 2006). Occurrences of highly saline and CO_2-rich fluid inclusions in the Blackbird and Cobalt Hill Co-Cu-Au deposits are also consistent with the IOCG classification, although an important caveat is that the paragenesis of fluid inclusions in these deposits is unconstrained (Johnson, 2013). Also noteworthy in this context is the volcanic rock-hosted Kiskamavaara Cu-Co-Au deposit in northern Sweden, which has been interpreted by Martinsson (2011) to be an IOCG deposit.

Some key features of the Co-Cu-Au deposits could be viewed as prohibiting an IOCG classification. Primary among these is the limited amount of iron oxides, except for the NICO deposit that contains abundant hematite and magnetite (Goad and others, 2000a, b). In the Blackbird district, magnetite-rich rocks occur in several small Co ± Cu ±Au ± Bi prospects (fig. 5–1; see Slack, 2012), but not within the relatively large ore zones that have been mined in the past or are currently being developed and explored. Nevertheless, the laterally extensive lenses of magnetite-rich rock in the Iron Creek area, to the southeast of the district, locally contain high Co, Cu, Bi, Te, or Y concentrations (Nash, 1989; Slack, 2012) that suggest a genetic link to the Co-Cu-Au deposits of the Blackbird district, despite the distance of ~25 km between the two areas. The lack of magnetite-rich rocks within the large Co-Cu-Au deposits of the Blackbird district may be analogous to some of the iron oxide-poor IOCG deposits, such as the Moonta Cu-Au orebody in the Gawler craton of South Australia (Skirrow and others, 2002) and the Mount Dore Cu-Au and Greenmount Cu-Au-Co deposits in the Cloncurry district of Queensland (Beardsmore, 1992; Krcmarov and Stewart, 1998; Duncan and others, 2011). An IOCG affinity has also been proposed by Williams (2010) for the Mount Cobalt deposit that lacks iron oxides. The formation of sulfide-rich Co-Cu-Au deposits, with minor or no associated iron oxides, could reflect high S contents and high S/Cl ratios of the hydrothermal fluids as suggested by other workers (Barton and Johnson, 2004; Schandl and Gorton, 2007). Additional textural, geochemical, and geochronological studies of the Co-Cu-Au deposits will be required to fully evaluate an IOCG model for their genesis.

Sources of Metals and Other Ore Components

Limited stable and radiogenic isotope data for the Co-Cu-Au deposits suggest that the majority of sulfur and lead in the ores was derived from the host sedimentary rock successions (Johnson, 2013). Sulfur isotope values for sulfide minerals from deposits in the Blackbird and Modum districts and from three other deposits (Werner Lake, Mt. Cobalt, Dahenglu) show a total range from -1 to 24 per mil. All of these deposits, except those in the Modum district, display relatively narrow ranges of $\delta^{34}S$ values of less than 6 per mil, which suggest that sulfur sources were not seawater or pore fluid sulfate (reduced by low-temperature bacterial processes) in shallow environments, but instead the host sedimentary sequences (Johnson, 2013). Values near 0 per mil, such as those reported for the Werner Lake deposit, could reflect a predominantly igneous source for the sulfur, either directly by derivation from magmatic-hydrothermal fluids or indirectly by the leaching of plutonic or volcanic rocks; alternatively, these values could record only a sedimentary source. Lead isotope ratios for sulfides in the Blackbird deposits are extremely radiogenic and require that the lead source(s) are predominantly Precambrian upper crustal rocks, which may include the host metasedimentary strata in the district (Panneerselvam and others, 2012). It is important to emphasize that these lead isotope results do not necessarily apply to other metals that are concentrated in the Co-Cu-Au deposits such as Co, Cu, Ni, Au, Bi, Y, REE, and Be, which could have other sources including mafic and felsic magmas.

Mineralogical and geochemical data for some of the Co-Cu-Au deposits provide permissive evidence for a felsic magmatic contribution to the orebodies. Key data are the high concentrations of Y and REE present in several deposits of the Blackbird district (as much as 0.83 and 2.56 weight percent, respectively), the Kuusamo schist belt, and at NICO and Mt. Cobalt (Slack, 2012; table 1–1; appendix 1). Mineralogical residence of the Y and REE is chiefly in xenotime, monazite, and allanite (Nisbet and others, 1983; Goad and others, 2000b; Vanhanen, 2001; Slack, 2012); bastnäsite is also an important host mineral of REE at the Juomasuo deposit (Dragon Mining Ltd., 2012). The Scadding Au-Co-Cu deposit in Ontario and some Blackbird district deposits also have high Be contents present in the Y-Fe-Be silicate gadolinite (Schandl and Gorton, 2007; Slack, 2012). Occurrence of this distinctive element suite of Y + REE ± Be suggests an origin from magmatic-hydrothermal fluids derived from evolved felsic plutons, or possibly from igneous carbonatite intrusions. In the Blackbird district, a temporal link between Y-REE-Be mineralization and nearby megacrystic granite is suggested by coeval SHRIMP ages for cores of xenotime grains within the deposits and zircon grains in the granite (Aleinikoff and others, 2012), which has a peraluminous A-type composition (Schulz, 2013). By analogy, the concentrations of Y and REE in the NICO, Mt. Cobalt, and some of the Kuusamo belt deposits similarly could have been derived from magmatic-hydrothermal fluids. Potential contributions of Co, Cu, and

Au by magmatic-hydrothermal fluids to the metasedimentary rock-hosted deposits (table 1–1) also should be considered, including the possibility that deposits spatially associated with gabbroic plutons are distal products of skarn-type mineralization like that attributed to the Cu-Co-Au-Ag magnetite deposit at Cornwall, Pennsylvania (see Lapham, 1968; Rose and others, 1985).

Sources of Fluids and Ligands Involved in Ore Component Transport

In a recent study of the Blackbird district, Landis and Hofstra (2012) report chemical and isotopic analyses of gas extracts and leachates from fluid inclusions in quartz gangue within the Co-Cu-Au deposits. Leachates obtained on samples from three ore zones display a narrow range of ion ratios (Na, K, NH_4, Cl, Br, F) that suggest a mixed fluid composed of magmatic and basinal brine; helium isotope data for quartz gangue indicate a mantle source for the He (Landis and Hofstra, 2012). Relatively high boron isotope values of tourmaline in the ores of the Blackbird deposits (-6.9 to 3.2 per mil) suggest a boron source derived predominantly from marine evaporites, although the possibility of a minor component of magmatic boron cannot be excluded (Trumbull and others, 2011). Carbon and oxygen isotope data for siderite gangue in deposits of the Blackbird district (Johnson and others, 2012) suggest that the contained carbon is a mixture of sedimentary organic carbon and magmatic and (or) metamorphic carbon; oxygen and hydrogen isotope systematics of biotite- and tourmaline-rich wall rocks do not identify a distinct fluid source.

Several of the Co-Cu-Au deposits are noteworthy for containing Cl-rich hydrous silicate gangue minerals. Examples are biotite in deposits of the Blackbird district and scapolite in distal metasedimentary host rocks (Nash and Conner, 1993), and biotite in the NICO deposit (Goad and others, 2000b). High-salinity and CO2-bearing fluid inclusions are also characteristic of some of the deposits (Johnson, 2013), including Cobalt Hill and several in the Blackbird district (Schandl, 2004; Landis and Hofstra, 2012). These features suggest that the ore-forming fluids acquired high salinities either by dissolution of evaporites or evaporation of seawater, but an important caveat is that the paragenesis of fluid inclusions in the Blackbird deposits relative to Co-Cu-Au mineralization remains uncertain (see Johnson, 2013). The presence of CO_2-rich fluid inclusions in the above deposits is consistent with ore deposition from metamorphic or deeply exsolved magmatic fluids.

Evaporites also may have played a role in Co-Cu-Au mineralization in deposits of the Kuusamo schist belt by providing a source of abundant chlorine for leaching by hydrothermal fluids. Strata that host these deposits locally contain inferred meta-evaporite units. The Proterozoic supracrustal succession that contains the Kuusamo deposits includes dolomite, dolomite-cemented quartzite, and stromatolites that Vanhanen (2001) interpreted as a sequence of metamorphosed shallow-water and evaporitic sediments.

Chemical Transport and Transfer Processes

Transport of most metals in hydrothermal fluids is within chloride or sulfide complexes. For Fe, Cu, and Co, chloride complexes are likely the principal metal-bearing aqueous species at elevated temperatures above ~200 °C (Seward and Barnes, 1997; Migdisov and others, 2011). Such chloride complexes are important because they greatly increase the solubility of metals in the hydrothermal fluids. Sulfide and bisulfide complexes also may play a major role in hydrothermal transport of metals, including Cu and Au (Mountain and Seward, 2003; Stefánsson and Seward, 2004; Williams-Jones and others, 2009). The presence of high-salinity fluid inclusions in the ores of some deposits supports metal transport mainly by chloride complexes (for example, Landis and Hofstra, 2012), but more detailed studies are needed in order to fully evaluate the complexes involved in ore formation.

Fluid Drive, Including Thermal, Pressure, and Geodynamic Mechanisms

The characteristic setting of the Co-Cu-Au deposits within greenschist- to amphibolite-facies metamorphic terranes (Lund, 2013a, Lund, 2013b) and the typical epigenetic timing of mineralization in the deposits can be used as a framework for constraining the mechanisms that drove fluid flow and ultimately ore deposition. Based on the likelihood of significant depths for mineralization in the deposits, as inferred from ductile structures that host many of the orebodies, fluid migration probably was driven by hydraulic gradients between deep fluid reservoirs and shallower networks of faults and shear zones (for example, Cox, 2005). By analogy with orogenic Au deposits, large pressure fluctuations during seismic events may have played a major role in developing such hydraulic gradients (Goldfarb and others, 2005).

Another process that may have driven the migration of ore-forming fluids is the emplacement of igneous plutons (for example, Norton, 1978). Emplacement of plutons into the middle and upper crust typically generates hydrothermal convection cells that can result in mineral deposit formation. However, among the Co-Cu-Au deposits considered in this report (table 1–1), only those in the Blackbird district have a likely genetic link to igneous plutons, specifically the Y-REE-Be mineralization based on coeval SHRIMP U-Pb ages of ~1375 Ma for cores of xenotime grains and granitoid-hosted zircons (Aleinikoff and others, 2012). However, no direct connection is known between this Mesoproterozoic granitoid pluton or coeval gabbroic plutons and the Co-Cu-Au mineralization in the district. Other Co-Cu-Au deposits included in this report that have spatially associated granitoid or gabbroic plutons, such as Skuterud in Norway, similarly lack robust evidence for the involvement of magmatically derived fluids in the formation of the ores.

Character of Conduits/Pathways that Focus Ore-Forming Fluids

The localization of many of the Co-Cu-Au deposits within ductile faults and shear zones (Lund, 2013a; Slack, 2013a) suggests that deposit formation involved focused fluid flow under high fluid/rock conditions. These faults and shear zones were the probable conduits for ore-forming fluids, within the limits of the deposits. However, the nature of fluid pathways at depth remains unknown, mainly because such deeper upflow zones and peripheral recharge zones are difficult to characterize, particularly in the deformed and metamorphosed terranes that host most of the Co-Cu-Au deposits.

Nature of Traps and Wallrock Interaction that Trigger Ore Precipitation

Causes of ore deposition in the Co-Cu-Au deposits are unknown, but possibilities include interaction of the hydrothermal fluids with wall rocks; mixing of metal-rich and sulfur-poor brines with sulfur-bearing fluids of sedimentary or metamorphic origin; sulfidation of pre-existing ironstones; pressure fluctuations; or redox and pH buffering by host rocks (see Skirrow and Walshe, 2002; Mark and others, 2006; Hunt and others, 2007; de Haller and Fontboté, 2009). Johnson and others (2012) suggest that in the Blackbird district, sulfur-based redox reaction was not crucial for deposit formation. Based on the experimental study of Migdisov and others (2011), Co in the hydrothermal fluids was likely transported by the $CoCl_4^{2-}$ complex, assuming fluid temperatures of ≥250 °C, with dilution having been mainly responsible for deposition of the Co-bearing minerals.

Structure and Composition of Residual Outflow Zones

Residual outflow zones have not been identified for any of the Co-Cu-Au deposits.

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16. Exploration/Resource Assessment Guides

By John F. Slack and Klaus J. Schulz

Descriptive and Geoenvironmental Model for Cobalt-Copper-Gold Deposits in Metasedimentary Rocks

Scientific Investigations Report 2010–5070–G

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
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Figure

16. Exploration/Resource Assessment Guides

By John F. Slack and Klaus J. Schulz

Geological

A first-order guide to the exploration and assessment for metasedimentary rock-hosted Co-Cu-Au deposits is a thick succession of siliciclastic metasedimentary rocks that was deposited in a rift-type marine basin, locally with intercalated mafic metaigneous rocks (Lund, 2013a). Although ages of these successions range from Archean to Paleozoic, a greater probability for occurrence of the Co-Cu-Au deposits is within Proterozoic strata because most of the deposits are hosted by successions of this age (appendix 1). The cause of this age distribution is unknown, but may relate to preferential occurrence in the Proterozoic of thick and buoyant, subcontinental lithospheric mantle (SCLM) that is linked to abundant magmatism and metamorphism in the middle crust, and related formation of epigenetic hydrothermal ore deposits (Groves and others, 2005).

Although some deposits in the Blackbird district show geochemical and geochronological links between emplacement of granitoid plutons and the deposition of Y, REE, Be, and Bi in the Co-Cu-Au deposits (Slack, 2012), the other deposits included in this study (table 1–1) lack such a link, despite spatial associations with granitoids in many cases (Schulz, 2013a). Recognition of a strong structural control on the localization of the deposits (Lund, 2013a; Slack, 2013) suggests that regional-scale shear zones and map- to mesoscopic-scale fold axes are favorable sites for Co-Cu-Au mineralization.

Certain types of hydrothermally altered rock are key guides in favorable metasedimentary terranes. Occurrence of areally widespread rocks containing abundant albite, biotite, K-feldspar, and (or) tourmaline are particularly valuable, based on the presence of such altered rocks at and near the Co-Cu-Au deposits considered in this report (Slack, 2013b). Within each type of altered rock, the predominant mineral commonly makes up greater than 50 volume percent, and in some cases as much as 90 volume percent of the rock. An important caveat is that for very fine-grained albite-rich rocks (for example, Kuusamo schist belt, Finland) and tourmaline-rich rocks (for example, Blackbird district, Idaho), these minerals may be difficult or impossible to identify in the field, even in upper greenschist to amphibolite-facies terranes where the grain size of most metamorphic rocks is generally coarse enough for easy mineral identification. Scapolite-rich rocks (for example, Modum district, Norway) also may have relevance for exploration and resource assessment, based on spatial relationships of such rocks to known Co-Cu-Au deposits, although clear genetic links between their formation have not yet been established (Slack, 2013a).

Geochemical

Potential geochemical guides for the exploration and assessment for the metasedimentary rock-hosted Co-Cu-Au deposits include diverse sample media: (1) rocks, (2) minerals, (3) stream sediments including heavy mineral concentrates, (4) soils and soil gases, (5) glacial till and contained heavy minerals, and (6) water. Rocks have logically received the greatest effort, involving searches for elevated contents of the major metals of economic interest (Co, Cu, Au), as well as for associated elements, such as As, and, in most deposits, Bi, Ni, and U. Occurrence of the pink to lilac, secondary Co mineral erythrite (Johnson and Gray, 2013) is an obvious visual guide in the field. Highly sodic and (or) potassic rocks can be important guides as recorders to hydrothermal alteration that are closely related to many of the Co-Cu-Au deposits, such as those in the Kuusamo schist belt, the Modum district, the Blackbird district, and the NICO area (Slack, 2013c). The most effective mineralogical guides are primary and secondary Co-rich minerals, such as cobaltite and erythrite.

Geochemical surveys using stream sediments and (or) panned concentrates are critical components of many mineral exploration and assessment programs. Early studies of the geochemistry of stream sediments in the Blackbird district were by Hawkes (1952) and Bennett (1977). In this same district, Erdman and Modreski (1984) found that in steep terrain and in streams having high flow rates and limited sediment available for sampling, aquatic mosses are more effective sample media than stream sediments. This is because the mosses have much higher contrast in contents of Cu and, particularly, Co between mineralized and background areas; concentrations are as much as 35,000 ppm Cu and 2000 ppm Co in mosses from the mineralized areas. No published data are known for surveys surrounding the other Co-Cu-Au deposits (table 1–1), but in most cases high Co and Cu contents would be expected in stream sediments, and in places, high gold contents in panned concentrates. Elevated concentrations of these metals, as well as Bi, Y, and (or) REE, conceivably could be used as vectors to Co-Cu-Au mineralization, although such vectors have not yet been delineated for a specific deposit. Soil geochemistry was the foundation for the discovery in 1996 of the 2.64 Mt. Ram Co-Cu-Au deposit in the Blackbird district (see

U.S. Geological Survey, 1997). Compositions of soil gases may also be useful in exploration (for example, Kelley and others, 2006), although no application to Co-Cu-Au deposits is known.

McMartin and others (2009, 2011) conducted an orientation study of heavy minerals in bedrock and till samples surrounding the NICO Co-Au-Bi-Cu-Ni deposit and found that the abundance, size, and shape of gold grains, and compositions of magnetite and hematite, best characterize the mineralization. In their study, magnetite and hematite grains from till collected above or down-ice from the deposit have lower Ti and V contents relative to those in magnetite and hematite from up-ice sample sites. Till geochemistry has been a component of exploration programs in the Kuusamo schist belt, but it has not proven successful (Vanhanen, 2001). Water geochemistry may have potential in the exploration and assessment for the Co-Cu-Au deposits, based on the presence in the Blackbird district of ~1,000 µg/L dissolved Co in stream waters as much as 8 km from known sulfide deposits, relative to background values of <100 µg/L Co in district stream waters (Eppinger and Gray, 2013).

Isotopic

No published studies are available that report the use of isotope geochemistry in the exploration for metasedimentary rock-hosted Co-Cu-Au deposits. However, analogy with other hydrothermal ore deposits suggests that this approach could have merit. Most applicable is whole-rock oxygen isotope analysis, for identifying cryptic altered zones produced by high-temperature fluid flow, like those identified in the wall rocks of numerous VMS deposits (Shanks and Thurston, 2012). Among the Co-Cu-Au deposits considered in this report (table 1–1), only Werner Lake and the Blackbird district have been studied. Pan and Therens (2000) analyzed garnet-biotite schist spatially related to the ore at Werner Lake, finding slightly lower $\delta^{18}O$ values than in amphibolite protoliths—thus implying premetamorphic isotopic exchange with hydrothermal fluids, which also could have been low in $\delta^{18}O$. In the Blackbird district, biotite- and tourmaline-rich rocks adjacent to ore zones lack ^{18}O depletions, relative to unaltered wall rocks, although both have lower δD values (Johnson, 2013; Johnson and others, 2012). More whole-rock oxygen isotope studies are needed on other Co-Cu-Au deposits, such as those at NICO and in the Modum district, to fully evaluate the exploration potential of this technique.

Geophysical

Owing to the presence of magnetite and sulfides in most metasedimentary rock-hosted Co-Cu-Au deposits, geophysical surveys including magnetics and gravity can be useful in identifying potentially mineralized zones (Schulz, 2013b). Both airborne and ground surveys have advantages. Airborne surveys are fast, economic, mostly independent of terrain hindrances, allow measurement of many components simultaneously on the same area, and have good stability and low noise levels (Turunen and others, 2005). In contrast, ground surveys permit denser measuring profiles, remeasurement of significant anomalies, and direct field investigations (Turunen and others, 2005). A simplified flow chart for selecting airborne geophysical anomalies for further investigation is presented in figure 16–1.

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. Deposits, although not necessarily coincident with a discrete magnetic anomaly, typically occur in areas having "magnetically active" signatures (Smith, 2002; Turunen and others, 2005). Granitic plutons, which in many districts appear to be contemporaneous with mineralization, can display distinctive positive or negative gravity and magnetic responses, depending on the characteristics of the surrounding rocks. However, regional deformation may have a strong control on regional geophysical patterns (for example, Idaho cobalt belt, Lund and others, 1990), potentially complicating interpretations.

Regional radiometric surveys can be useful in recognizing altered rocks associated with Co-Cu-Au mineralized zones in areas where unweathered rocks are exposed at the surface (Wellman, 1999; Goad and others, 2000). For example, the NICO and Sue-Dianne deposits in Canada are associated with discrete positive eK (equivalent K) and negative eTh/K (equivalent Th/K) anomalies that are coincident with positive magnetic anomalies (Goad and others, 2000b). Areas having enriched uranium also are characterized by increased eU/Th (equivalent U/Th) anomalies.

At the deposit scale, geophysical signatures are generally more complex than those determined by airborne surveys. Strong local magnetic and gravity anomalies and high electromagnetic anomalies characterize some Co-Cu-Au deposits (Goad and others, 2000b; Turunen and others, 2005). Intense potassium and iron oxide alteration associated with some deposits (for example, NICO) can produce large coincident radiometric and magnetic highs that are well above the regional background (Goad and others, 2000b). In the Kuusamo schist belt, radiometric anomalies in and near the deposits are also produced by disseminated uraninite and allanite, the latter mineral carrying elevated contents of U and Th due to formation of metamict grains (Vanhanen, 2001). Transient electromagnetic methods (TEM) and induced polarization (IP) have been generally successful in detecting these deposits because most are at least weak conductors. However, these methods also respond to both iron oxides and barren sulfides, which commonly are more laterally extensive than the target mineralization. Standard electromagnetic geophysical methods (EM) have generally not been as successful, probably because massive, continuous mineralized zones are rare in these deposits.

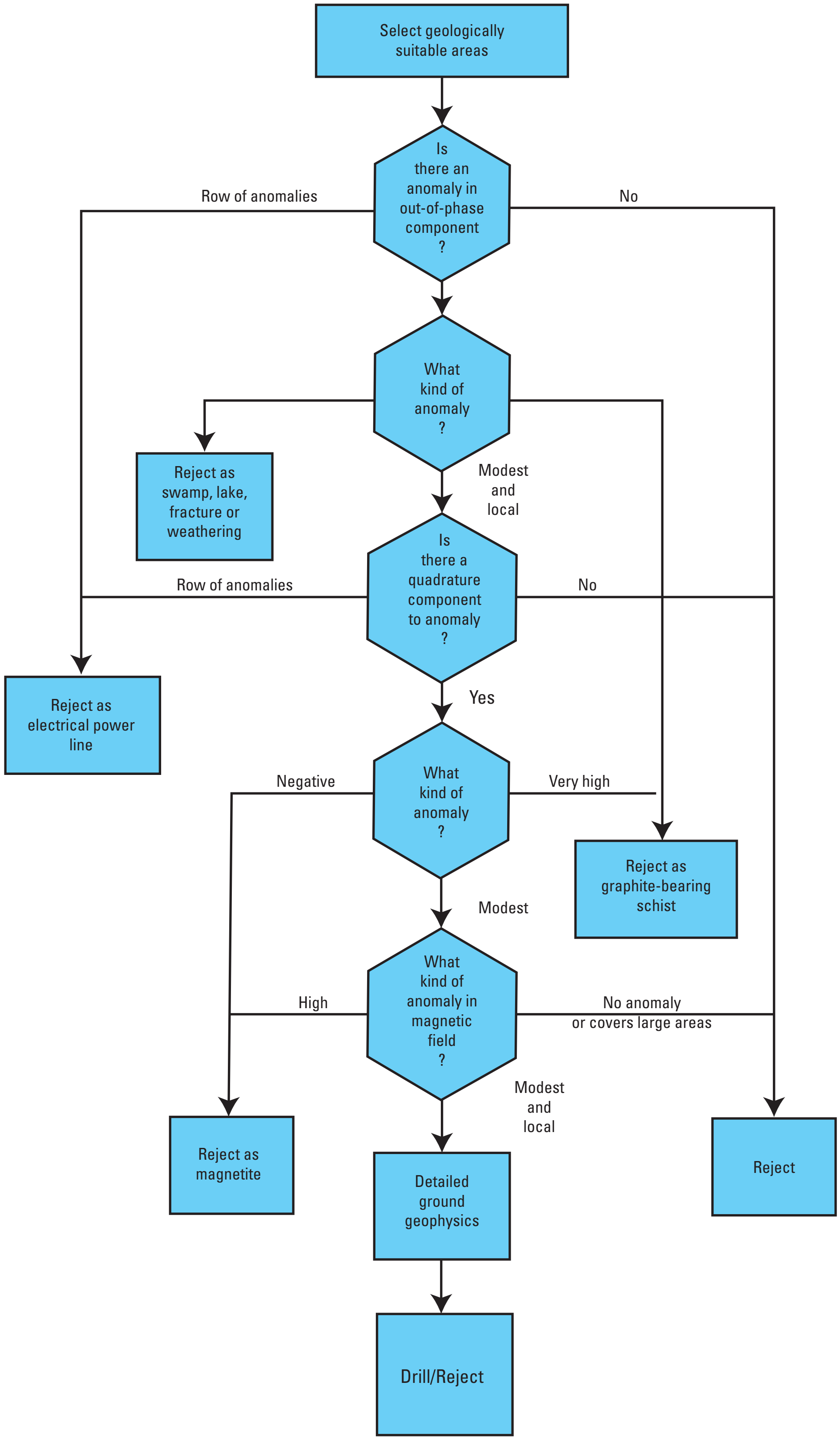

Figure 16–1. Simplified flow chart for selecting airborne geophysical anomalies for further investigation (after Turunen and others, 2005).

Attributes Required for Inclusion in Permissive Tracts at Various Scales

As defined by Singer (1993), a permissive tract in mineral resource assessments is an area where geologic features permit the occurrence of one or more deposit types. Among many parameters, favorable geology is the most important attribute for identifying a permissive tract (for example, Raines and Mihalasky, 2002). In assessments for Co-Cu-Au deposits similar to those considered in this report (table 1–1), key geologic criteria are: (1) Proterozoic rift-facies metasedimentary rocks (Lund, 2013a; Lund, 2013b); (2) occurrence of major faults and shear zones (Lund, 2013a; Slack, 2013c); (3) widespread hydrothermal alteration zones, particularly those containing abundant albite, biotite, K-feldspar, or tourmaline (Slack, 2013b); and (4) presence of known deposits or prospects that have a Co-Cu-Au metallogenic signature, with or without accompanying Bi, Y, REE, or Ni concentrations. Permissive, but not required geologic criteria include the presence within the tract of magnetic geophysical anomalies (Schulz, 2013b). Other positive criteria are anomalously high contents of Co, Cu, As, or Au in stream sediments and (or) panned concentrates.

Particular importance must be given to geologic map scales because different scales can produce major differences in the shape and size of permissive tracts. For example, the use of large-scale maps can result in misleading generalization of a given tract, or arbitrary enlargement of a tract in order to include deposit types that occur in restricted settings. As emphasized by Singer and Menzie (2008), use of such maps commonly causes inappropriate inclusion of geologic settings that are not permissive for a given deposit type. This problem of map scale was quantified for the assessment of VMS deposits by Singer and Menzie (2008), indicating that a geologic map having twice the detail of a more generalized map will decrease the area of a permissive VMS tract by 50 percent.

Factors Influencing Undiscovered Deposit Estimates (Deposit Size and Density)

The size and density of undiscovered mineral deposits are affected by several factors. Size estimates rely chiefly on statistical data for grades and tonnages for a given deposit type (for example, Cox and Singer, 1986). Giant orebodies typically contain the largest resources, thus very small or low-grade deposits do not greatly affect grade-tonnage distributions; differences in cutoff grades and other economic factors similarly are not significant (Singer, 1993). Statistical studies of relationships between permissive area and deposit density can be used together with grade-tonnage models as predictors of the number of undiscovered deposits and the total amount of undiscovered metals (Singer, 2008).

By analogy with VMS deposits (Galley and others, 2007), the diameter of clustered deposits, such as those in the Blackbird district and Kuusamo schist belt, reflects regional-scale hydrothermal alteration systems; the location of deposits within each cluster reflects the distribution of favorable faults and shear zones. Together, these factors directly influence the density of deposits in a given cluster.

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17. Geoenvironmental Features and Anthropogenic Mining Effects

By Robert G. Eppinger and John E. Gray

Descriptive and Geoenvironmental Model for Cobalt-Copper-Gold Deposits in Metasedimentary Rocks

Scientific Investigations Report 2010–5070–G

U.S. Department of the Interior
U.S. Geological Survey

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Figures

Table

17. Geoenvironmental Features and Anthropogenic Mining Effects

By Robert G. Eppinger and John E. Gray

Published geoenvironmental data for Co-Cu-Au deposits in metasedimentary rocks worldwide are limited. However, there have been several studies published that report surface geochemical data (mine waste, water, stream sediment, and soil) for the Blackbird mine and other deposits of the Idaho cobalt belt (ICB) (for example, Baldwin and others, 1978; Reiser, 1986; Beltman and others, 1993; Mebane, 1994; Rocky Mountain Consultants, 1995; CH2MHill, 2001; Idaho Department of Environmental Quality, 2001; Eppinger and others, 2003; Giles and others, 2009). No published reports have been found containing surface geochemical data for other deposits worldwide with geochemical and geological characteristics similar to those of Co-Cu-Au deposits in metasedimentary rocks (table 1–1). Thus, the geoenvironmental characteristics described in this section are based solely on information available for the mines and deposits of the ICB.

Mining Methods and the Volume of Mine Waste and Tailings

Mining of Blackbird deposits began in 1893 when gold was initially recovered (Reed and Herdlick, 1947; Nash and Hahn, 1989). Cobalt was discovered in 1901, but there was little demand for this metal until World War I. As a result, Co and Cu were mined and milled in the area from 1917 to 1967 (Nash and Hahn, 1989; Idaho Department of Environmental Quality, 2001). Production of Co in the Blackbird area was primarily from 1951 to 1959 and totaled about 6,400 t (Lund and others, 1983; Nash and Hahn, 1989; Johnson and others, 1998). Additional production from Blackbird has been reported as 24,000 t of Cu, 0.5 t of Pb, 1.08 t of Au, and 2.47 t of Ag (Lund and others, 1983; Johnson and others, 1998). There has been no mining in the Blackbird area since 1967 (Rocky Mountain Consultants, Inc., 1995), but the Blackbird district contains one of the largest Co resources in the United States (Slack and others, 2013).

Mining methods used in the Blackbird district included underground and open-pit mining. Most of the underground workings and numerous waste rock piles are located along Meadow Creek, which flows into Blackbird Creek. The now-reclaimed Blacktail open pit covered about 46,500 m^2 and is at the headwaters of Bucktail Creek, which flows into Big Deer Creek and eventually into Panther Creek (fig. 17–1). At least 750,000 t of ore was removed from this open pit (Rocky Mountain Consultants, Inc., 1995). Large blocks of ore were present in the Blacktail pit and were exposed to surface weathering. The Blackbird mine had 12 levels, 9 portals, at least 16 km of underground mine workings, and numerous adits, shafts, winzes, and portals (Reiser, 1986; Beltman and others, 1993). Several mine portals were plugged in an attempt to limit mine water discharge; however, mine drainage presently continues to seep into the Blackbird ecosystem. As a result, the U.S. Environmental Protection Agency (USEPA) listed Blackbird Creek, Bucktail Creek, Big Deer Creek, and Panther Creek as contaminated with metals (Idaho Department of Environmental Quality, 2001); consequently, the area underwent several years of reclamation in the 1980s and 1990s. One remediation effort was the installation of a drainage tunnel that diverted water from the Blacktail open pit and some of the underground workings to a water treatment plant with a design capacity of as much as 1,000 gallons per minutes (gpm), which used conventional lime precipitation to remove metals (Rocky Mountain Consultants, Inc., 1995; CH2MHill, 2001). Water from the treatment plant was discharged into Blackbird Creek and monitoring indicated that loads of Cu and Co in discharge effluent from the treatment plant were reduced by as much as 50 percent (Rocky Mountain Consultants, Inc., 1995). However, remaining in this area are point sources, such as ore, mine wastes, mill tailings, and contaminated stream sediments that, during weathering and leaching, contribute metal-rich water to Blackbird Creek and its tributaries (CH2MHill, 2001).

Mining and ore processing in and along Blackbird Creek has resulted in a disturbed area estimated at about 40 km^2, which includes Blackbird Creek, Meadow Creek, Bucktail Creek, and the West Fork of Blackbird Creek (Beltman and others, 1993). Water and sediment runoff from the mined areas affects the larger ecosystem farther downstream including Panther and Big Deer Creeks (Eppinger and others, 2007), although these streams are generally not disturbed by mining activities related to Blackbird. Throughout the Blackbird area, several waste rock and tailings piles are present. As a result of ore processing, greater than 3,500,000 m^3 of tailings were estimated in the Blackbird Creek area (Beltman and others, 1993). The largest part of these tailings is stored behind a dam constructed in the 1950s on the West Fork of Blackbird Creek near its confluence with Blackbird Creek, which contains over 1,500,000 m^3 of tailings (Reiser, 1986). Settling ponds and pipelines were constructed along Blackbird Creek in the 1940s and l950s, but these containment measures were ineffective (Reiser, 1986). Periodic spills from the pipelines that carried tailings from the mill to the West Fork Creek dam resulted in the release of large quantities of tailings into Blackbird Creek and eventually into Panther Creek (Beltman and others, 1993). During mining in the early 1900s, some mine tailings were discarded directly into Blackbird Creek, and part of these wastes

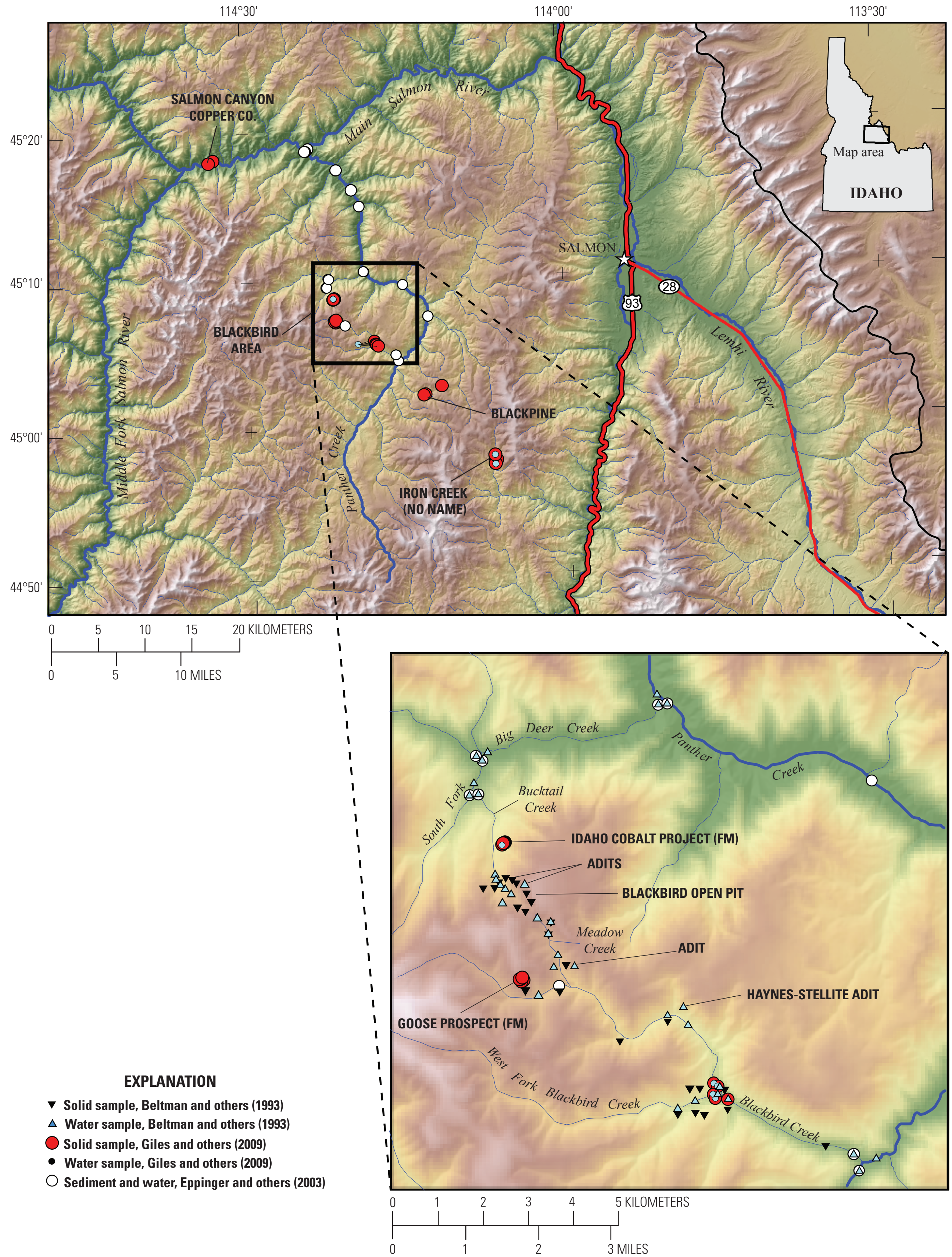

Figure 17–1. Sample locations in the Idaho cobalt belt. [Idaho Cobalt Project, formerly known as the Ram prospect].

was dredged from Blackbird Creek in the 1970s and 1980s and placed along the banks of Blackbird Creek (Baldwin and others, 1978; Reiser, 1986; Beltman and others, 1993).

Ore Processing and Smelting

Information on mining methods, ore processing, and milling of ore from mines in the Blackbird area is limited. Several piles of discarded mill tailings exist along Blackbird and Meadow Creeks. Separation of Co- and Cu-sulfide ore minerals from gangue and Fe-sulfides was dominantly by flotation processes in the Blackbird district. Wells and others (1948) indicated that the intimate association of Cu and Co minerals in ore made the production of separate Cu and Co concentrates difficult. The separation of cobaltite from pyrite and chalcopyrite in high-grade sulfide ores was also noted as being complicated (Wells and others, 1948). In about 1915, a 10-stamp concentration mill was operating on Blackbird Creek, and from 1938 to 1941, a 68-t flotation mill was operating at the portal of the Uncle Sam mine on the east bank of Blackbird Creek (Reed and Herdlick, 1947; Wells and others, 1948). Reed and Herdlick (1947) reported that a high recovery of metal was made from Blackbird ore using bulk flotation methods following grinding or milling of ore. Liberation of cobaltite inclusions in chalcopyrite and quartz stringers required grinding to minus 200-mesh (Wells and others, 1948). Generally, milling of ore necessary for successful flotation leads to increased sulfide mineral surface area exposure, and thus, during surface weathering there is a potential increase in metal contamination in runoff sediment and water. Separation of economically important metals was improved using additional flotation techniques and recovery of about 93 percent for Co and Cu and 73 percent for Au was obtained (Bending and Scales, 2001).

Flotation of various sulfide minerals is affected by pH (Shanks and others, 2009). Additions of compounds such as lime (CaO) and sodium carbonate (Na_2CO_3) are commonly used to increase pH during flotation procedures and such compounds have a significant effect on water geochemistry following discharge from mill tailings (Shanks and others, 2009). However, it is unclear what influence flotation procedures, or the use of potential additives during flotation, had on surface runoff in the area.

Research carried out at Blackbird in the 1940s by the U.S. Bureau of Mines (USBM) also used combined techniques of flotation, low-temperature calcination, and re-flotation on high-grade sulfide ore for separation of cobalt from Fe-sulfides (Wells and others, 1948). However, it is unclear if these USBM research techniques were standard practices used throughout the district. Smelting was not carried out in the Blackbird Creek area, and milled and processed ore concentrates were reported to have been shipped to smelters in Niagara Falls, New York, Anaconda, Montana, and Tacoma, Washington (Reed and Herdlick, 1947). Thus, there are no known geoenvironmental effects in the Blackbird district related to smelting.

Climate and Geographic Effects

Climate significantly affects runoff from mined areas in the Blackbird district and downstream environmental geochemistry. This region in Idaho is characterized by mild summers and cold winters with snow from November to April, and rain during the remainder of the year when thunderstorms are common (Rocky Mountain Consultants, Inc., 1995). Temperatures average 29 °F (-1.7 °C) in December and 83 °F (28.3 °C) in July. Precipitation varies with elevation, but annual average precipitation is about 46 cm near the abandoned townsite of Cobalt (elevation 1,535 m, 45°06´N, 114°14´W) and is about 67 cm at an elevation of 2,100 m (Baldwin and others, 1978). The region is also characterized by rounded mountain tops with steep slopes reaching approximately 40 degrees. Peaks are as high as 2,694 m. Creek gradients are as steep as 20 percent. In the higher elevations, vegetation is forested with pine, fir, and spruce trees, whereas the lower elevations are covered with various shrubs, grasses, sagebrush, and some pine, fir, and spruce (Baldwin and others, 1978; Rocky Mountain Consultants, Inc., 1995). Areas that have been mined or covered with waste rock are generally devoid of vegetation, and this lack of vegetation combined with the effects of steep elevation and periods of high precipitation lead to significant erosion as evidenced by occurrence of numerous deep gullies on the slopes of mine waste piles (Rocky Mountain Consultants, Inc., 1995).

Seasonal variations affect the environmental geochemistry in the Blackbird district; for example, snow pack and its eventual melting affects surface runoff in the region. The steep, open-pit walls and other windblown areas are generally snow-free most of the winter (Mebane, 1994). Dust blowing from these highly contaminated areas is metal-rich and settles on snow pack. Such dust also contains water-soluble secondary minerals that may contribute acid water upon melting as well as highly elevated metal concentrations in runoff water. Soluble, metal-rich compounds in the dust are quickly flushed from the snow during the initial spring thaw, producing a spike in metal concentrations several weeks before peak spring runoff (Mebane, 1994). Stream discharge and metal concentrations in surface water in the Blackbird mining area were shown to be closely interrelated (Baldwin and others, 1978). Metal concentrations in mine runoff water were (1) low during winter months, (2) increased sharply during the initial spring runoff period, (3) were again lower during the latter part of the spring runoff, and (4) increased gradually during later summer months (Baldwin and others, 1978).

Human Health and Ecosystem Effects

Human health effects of the Blackbird mines and deposits are primarily associated with exposure to metals by ingestion or inhalation. The ingestion pathway is generally via contaminated water, but in addition, contaminated particles can be inhaled or ingested. Ecosystem effects are dominantly related to contamination of sediment, soil, water, and to exposure of toxic elements to aquatic organisms. Metal concentrations in mine runoff water and sediment are highly elevated relative to regional background concentrations (table 17–1). Several studies have indicated that the primary concern is human exposure to elevated concentrations of Cu, Co, As, Fe, and Mn, which have been listed as the contaminants of concern in the Blackbird area (Baldwin and others, 1978; Reiser, 1986; Mok and Wai, 1989; Beltman and others, 1993; Rocky Mountain Consultants, 1995; Mebane, 1997; CH2MHill, 2001).

Generation of acidic water is another potential effect on ecosystem health in the Blackbird region. As discussed above, the oxidation of pyrite, and to a lesser degree other sulfide minerals, generates acidic water as indicated by the following reaction:

$$FeS_2 + 15/4\ O_2 + 7/2\ H_2O \rightarrow Fe(OH)_3 + 2\ H_2SO_4$$

Some water samples collected from adits, mine pits, seeps, and effluent from tailings in the Blackbird area have pH <6.5 and are of concern (table 17–1, fig. 17–2). In addition, stream water collected adjacent or proximal to mine wastes (for example, Blackbird, Meadow, and Bucktail Creeks) also has pH <6.5, but stream water collected downstream and distal from mines of the ICB is circum-neutral due to natural dilution by surrounding streams. Acidic water most likely has an adverse effect only in areas directly draining mines, mine wastes, or mill tailings. Most of the larger streams and rivers in the region have water pH ranging from 6.5 to 9.0, which is recommended as acceptable by the USEPA (U.S. Environmental Protection Agency, 2009).

Concentrations of Cu in water were highly elevated in the Blackbird area, particularly in mine adit water, where concentrations were as high as 312,000 µg/L (table 17–1). The EPA drinking water guideline for Cu is 1,300 µg/L (this is a MCLG, maximum contaminant limit goal) at a water hardness of 100 mg/L. However, open streams in the Blackbird area are generally not sources of public drinking water. Two other water guidelines for comparison are (1) the 12-µg/L EPA chronic aquatic life guideline for Cu at a water hardness of 100 mg/L, which is the concentration intended to be protective of the majority of the aquatic communities; and (2) the 14-µg/L LC-50 concentration (fig. 17–3), which has been found to be a lethal concentration of Cu producing a 50 percent mortality of rainbow trout during laboratory experiments (Marr and others, 1998). Concentrations of Cu in mine waste and stream sediment collected downstream from mines in the Blackbird area ranged from 170 to 17,000 µg/g, all of which exceeded the probable effect concentration (PEC) for Cu of 149 µg/g, the concentration above which harmful effects are likely in sediment-dwelling organisms (MacDonald and others, 2000). Considering that concentrations of Cu in stream water and stream sediment collected proximal to mines in the Blackbird area were generally an order of magnitude higher than environmental guidelines, such streams should be considered contaminated and these ecosystems adversely affected with respect to Cu. Similarly, Cu concentrations in soil collected prior to any disturbances at the active Ram (now the Idaho Cobalt Project) and Goose prospects ranged from 360 to 1,600 µg/g and were elevated compared to regional backgrounds (39 to 230 µg/g; table 17–1). However, such soil Cu concentrations were below the USEPA residential soil screening level of 3,100 µg/g (table 17–1).

There are no known human health criteria for Co, but concentrations of Co were as high as 75,000 µg/L in water draining mines and mine waste in the Blackbird area, whereas Co in stream water collected from background sites in this region ranged from <0.02 to 6.3 µg/L (table 17–1). An important Co concentration to evaluate ecosystem effects is an LC-50 concentration of 346 µg/L (fig. 17–4), which was the lethal concentration of Co found to result in a 50 percent mortality of rainbow trout during laboratory experiments (Marr and others, 1998). Concentrations of Co in stream water collected proximal to mined areas exceeded the LC-50 concentration for Co by more than 200 times, and there is likely an adverse effect to rainbow trout on these creeks. There are few environmental guidelines for Co in sediment, but similar to Co in water, Co concentrations in stream sediment collected proximal to mines (ranging from 26 to 7,400 µg/g) were significantly higher than Co found in stream sediment from regional background areas (ranging from 4.0 to 59 µg/g). Concentrations of Co in undisturbed soil collected in the Idaho Cobalt Project area ranged from 29 to 940 µg/g (fig. 17–5), exceeding the EPA residential soil screening level for Co of 23 µg/g (table 17–1).

Concentrations of As found in water and sediment in the Blackbird area are a potential human health concern because As is highly toxic and a known carcinogen. The USEPA drinking water guideline for As is 10 µg/L (U.S. Environmental Protection Agency, 2009). Although few water samples collected from mine seeps, adits, and tailings piles exceeded the drinking water guideline for As (table 17–1), most stream water samples contain As concentrations that were below the 10-µg/L EPA drinking water guideline. However, as previously mentioned, streams in the Blackbird area are generally not sources of public drinking water. Nearly all of the water samples collected in the Blackbird region contained As concentrations below the 190 µg/L chronic aquatic life guideline for As, and only one mine-seep water sample that contained 930 µg/L exceeded this guideline. Conversely, mine waste and stream sediment collected proximal to mines in the Blackbird area contained highly elevated As concentrations that ranged from 350 to 17,000 µg/g, all of which exceeded the PEC of 33 µg/g for As (MacDonald and others, 2000), suggesting probable harmful effects to sediment-dwelling organisms. Concentrations of As in undisturbed soil collected in the Idaho cobalt project area ranged from 37 to 610 µg/g (Giles and others, 2009), which greatly exceeded the USEPA residential soil screening level for As of 0.39 µg/g (table 17–1).

Streams in the Blackbird region have been known for many years to contain Fe precipitates and highly elevated concentrations of Fe in sediment and water (Baldwin and others,

Table 17–1. Geochemical data for water, mine waste, stream sediment, and soil collected proximal to mines and from background sites in the Idaho cobalt belt. [Data from Beltman and others (1993), Eppinger and others (2003), Giles and others (2009), and USEPA (2009)]. Table modified from Gray and Eppinger (2012).

			Water			
Sample type	**Co (µg/L)**	**Cu (µg/L)**	**As (µg/L)**	**Fe (µg/L)**	**Mn (µg/L)**	**pH**
Adits, seeps, open pits	<1.3-75,000	8.5-312,000	<1.6-930	138-159,000	3.9-35,000	2.7-6.8
Streams proximal to mines	420-49,000	250-310,000	<1-18	28-25,000	54-6,900	3.3-8.1
Regional background stream water	<0.02-6.3	<0.5-67	<0.2-8.2	9.4-150	0.11-10	6.4-8.6
Water Guidelines						
EPA Chronic Aquatic Life guideline		*12	190	1,000		6.5-9.0
EPA Drinking water guideline		*1,300	10	300	50	
LC-50 rainbow trout	346	14				
			Mine Waste, Stream Sediment, and Soil			
	Co (µg/g)	**Cu (µg/g)**	**As (µg/g)**	**Fe (µg/g)**	**Mn (µg/g)**	
Mine waste	90-7,400	680-17,000	440-17,000	82,000-234,000	85-660	
Stream sediment proximal to mines	26-700	170-6,800	350-2,900	14,000-320,000	65-760	
Regional background stream sediment	4.0-59	7.0-230	3.0-47	14,000-45,000	230-1,100	
Soil proximal to mines	29-940	360-1,600	37-610	44,000-73,000	160-440	
Regional background soil	14-59	39-230	11-47	26,000-42,000	380-1,100	
Sediment and Soil Guideliness						
EPA Residential Soil Screening Level	23	3,100	0.39	55,000		
EPA Industrial Soil Screening Level	300	41,000	1.6	720,000		
Probable Effect Concentration		149	33			

* Water Hardness = 100 mg/L

1978; Beltman and others, 1993; Mebane, 1994). Mine water runoff and streams proximal to mines contained Fe concentrations that ranged from 28 to 159,000 µg/L and generally exceeded both the USEPA drinking water guideline (300 µg/L) and chronic aquatic life guideline (1,000 µg/L) for Fe (table 17–1). Conversely, stream water samples collected from background sites in the Blackbird area contained Fe concentrations that ranged from 9.4 to 150 µg/L, all below the water quality guidelines. Concentrations of Fe in samples of mine waste and stream sediment were elevated (as high as 320,000 µg/g), but there is no PEC established for Fe in sediment. Concentrations of Fe in undisturbed soil collected in the Idaho Cobalt Project area ranged from 44,000 to 73,000 µg/g, most of which were below the EPA residential soil screening level for Fe (55,000 µg/g, table 17–1).

There are few water quality guidelines and no sediment or aquatic life guidelines established for Mn. The only established guideline for Mn in water is the USEPA maximum contaminant limit goal of 50 µg/L. Concentrations of Mn varied widely in adit, seepage, and discharge water collected from mined areas in the Blackbird area, and ranged from 3.9 to 35,000 µg/L; mine water generally exceeded the 50-µg/L goal (table 17–1). Water collected from background sites contained much lower Mn concentrations and ranged from 0.11 to 10 µg/L, well below the Mn goal. Mine waste and stream sediment collected proximal to Blackbird mines contained Mn concentrations that ranged from 65 to 760 µg/g, whereas stream sediment samples collected from background areas contained similar, but generally higher, Mn concentrations that ranged from 230 to 1,100 µg/g. Similarly, Mn concentrations in undisturbed soil collected in the Idaho Cobalt Project area ranged from 160 to 440 µg/g (Eppinger and others, 2003; Giles and others, 2009), whereas soil collected from background areas contained generally higher Mn concentrations that ranged from 380 to 1,100 µg/g (Beltman and others, 1993; table 17–1). Because there are no sediment or soil quality guidelines for Mn, it is unclear if concentrations of Mn in stream sediment and soil in the Blackbird region are of concern for ecosystem health.

Human exposure to metals through potential inhalation of mine waste particulates or ingestion via hand-to-mouth contact in the Blackbird mine area was investigated by the ATSDR (Agency for Toxic Substances and Disease Registry, 1995, 1998). These studies concluded that the Blackbird mine site could pose a public health hazard for hikers, campers, fishermen, former mine employees, site investigators, and site workers, through ingestion, inhalation, or skin contact with dust or airborne particulates. In the second study (Agency for Toxic Substances and Disease Registry, 1998), cleanup workers at the Blackbird mine site had elevated As concentrations in their hair samples, and soil and indoor dust samples collected from businesses and residences in the region had elevated As

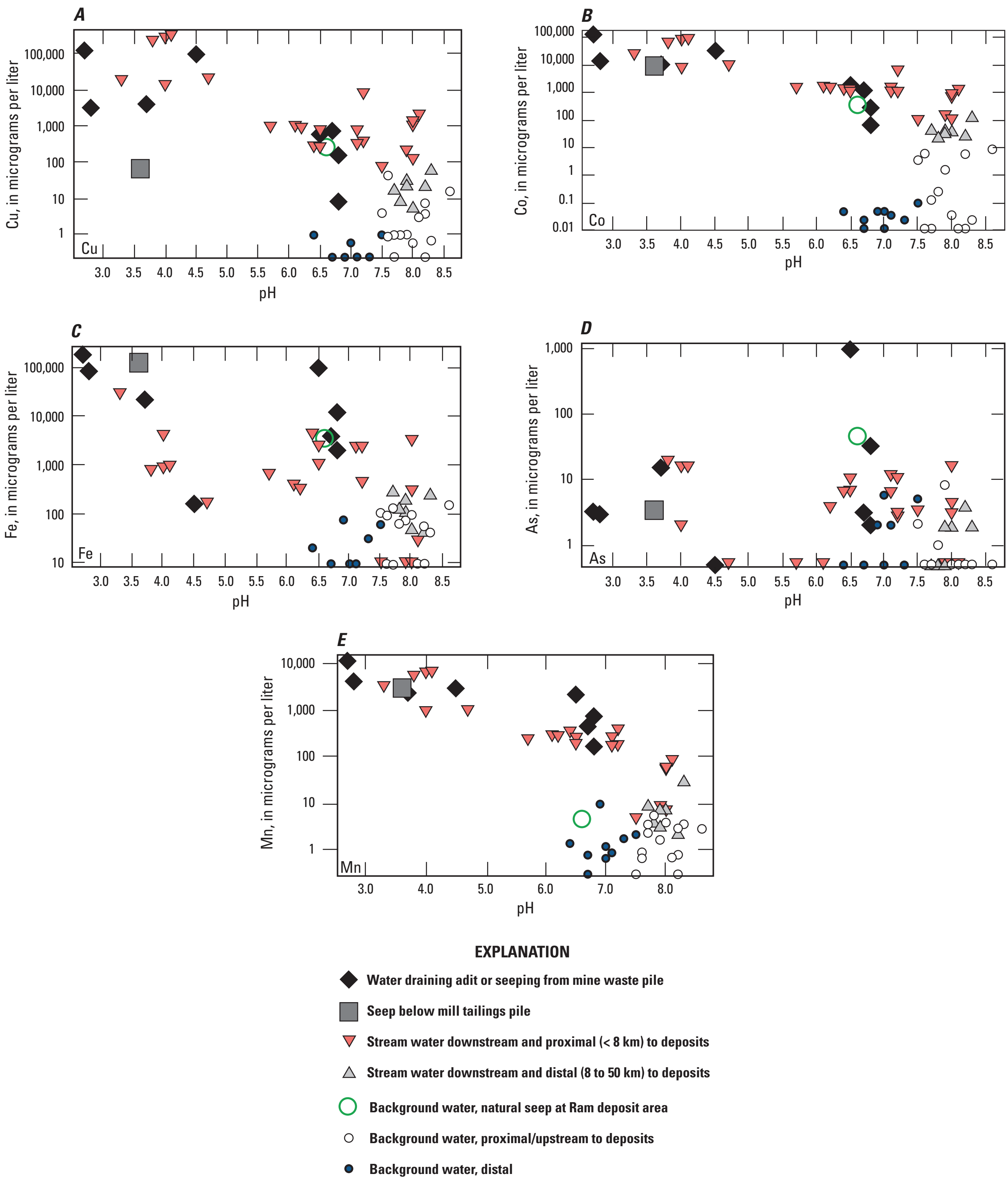

Figure 17–2. Concentration of Cu, Co, Fe, Mn, and As versus pH for unfiltered water from the Idaho cobalt belt. Data from Giles and others (2009), Eppinger and others (2003), and Beltman and others (1993).

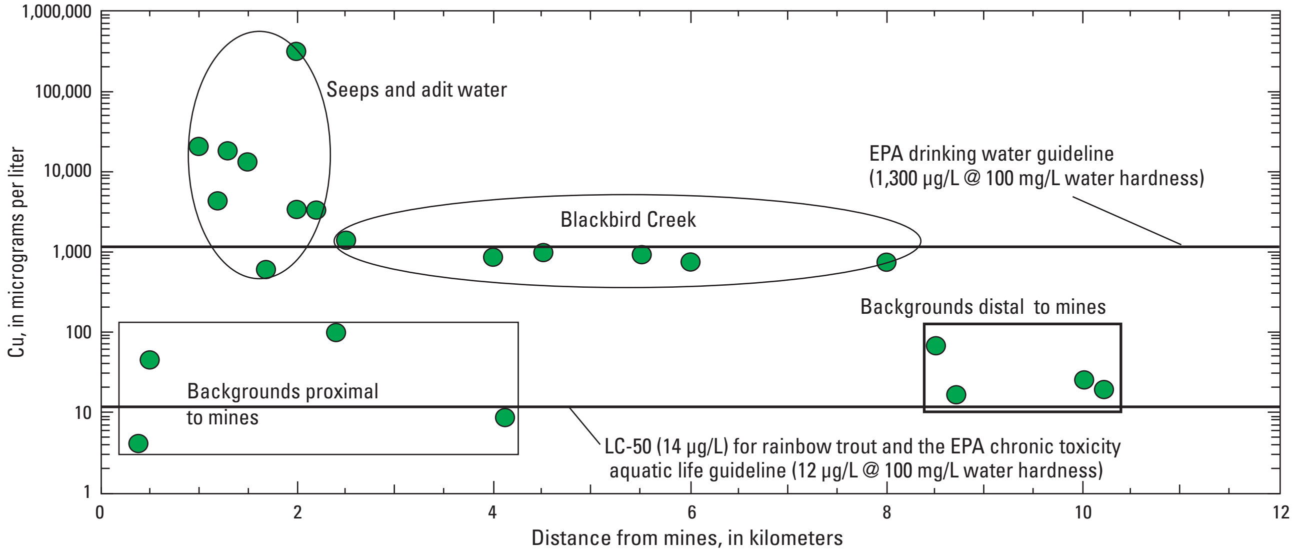

Figure 17–3. Concentration of Cu in unfiltered water versus distance from mines in the Blackbird area. Water data are from Beltman and others (1993), an LC-50 concentration is from Marr and others (1998), and the guidelines are from U.S. Environmental Protection Agency (2009).

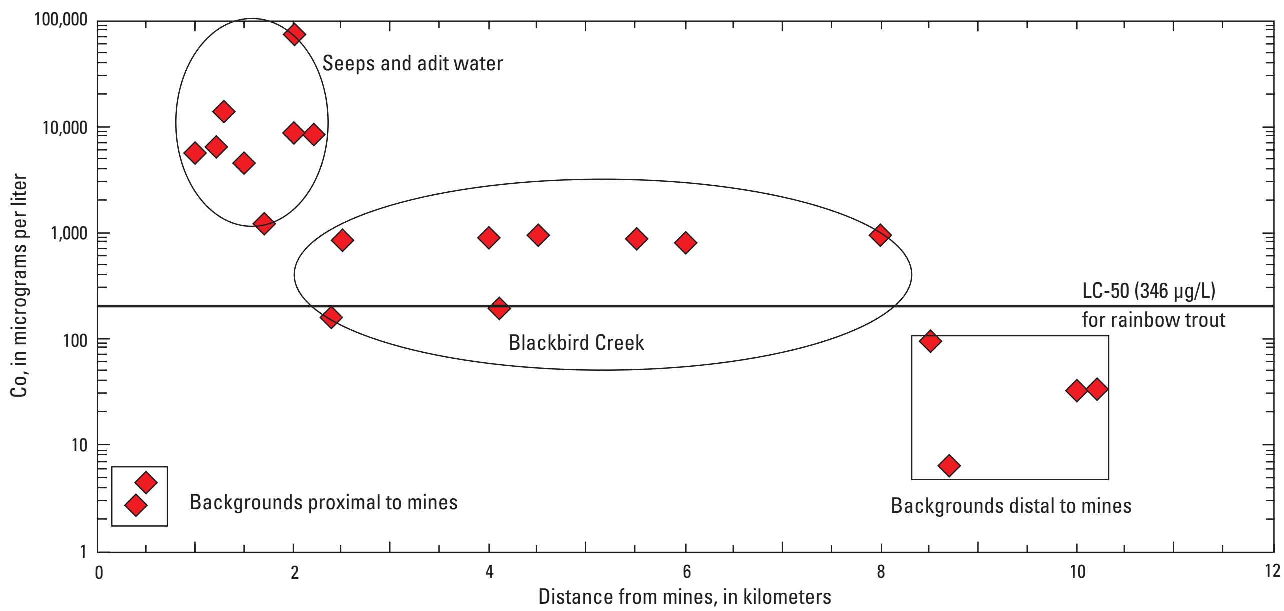

Figure 17–4. Concentration of Co in unfiltered water versus distance from mines in the Blackbird area. Water data are from Beltman and others (1993) and an LC-50 concentration is from Marr and others (1998).

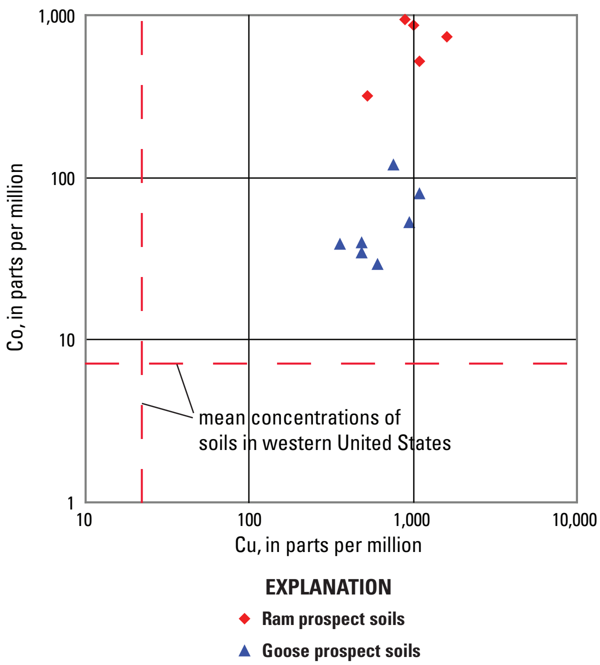

Figure 17–5. Concentration of Cu versus Co in soil collected from the Ram (now called the Idaho Cobalt project) and Goose prospect areas, Idaho cobalt belt. Values for mean concentrations of soil in western U.S. from Smith and Huyck (1999).

concentrations as well. The As in indoor dust was reported to be transported by workers at the Blackbird mine, who carried contaminated dust home on their shoes and clothing (Agency for Toxic Substances and Disease Registry, 1998).

Potential human exposure to highly elevated concentrations of Cu, Co, and As is through ingestion or inhalation of mine waste particulates. Additional concerns are mine wastes used for road or other construction materials and permanent living structures (for example, homes) built on, or adjacent to, mined areas that may lead to human exposure to these elements.

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18. Knowledge Gaps and Future Research Directions

By John F. Slack, Klaus J. Schulz, John E. Gray, and Robert G. Eppinger

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Descriptive and Geoenvironmental Model for Cobalt-Copper-Gold Deposits in Metasedimentary Rocks

Scientific Investigations Report 2010–5070–G

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2013

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Contents

18. Knowledge Gaps and Future Research Directions

By John F. Slack, Klaus J. Schulz, John E. Gray, and Robert G. Eppinger

This review of Co-Cu-Au deposits in metasedimentary rocks has identified several topics that warrant further research. These topics are itemized in the following list (unranked).

Age of Mineralization

a. Detailed textural and paragenetic studies using light microscopy and scanning electron microscopy (SEM) imaging

b. High-precision geochronology of ore and gangue minerals

Relationship to Igneous (Granitic) Rocks

a. High-precision geochronology of spatially-associated plutons and orthogneisses

b. Evaluation of possible role of magmatic fluids in deposit genesis

Timing of Alteration Relative to Deposit Formation

a. Detailed textural and paragenetic studies of spatially associated alteration zones

b. High-precision in-situ geochronology of alteration minerals (for example, titanite, rutile, tourmaline)

c. Geologic and geochemical studies of ironstones to discriminate from iron formations

Role of Sedimentary Rocks in Deposit Genesis

a. Definition of lithostratigraphic architecture of the sedimentary basins

b. Search for meta-evaporites within the sedimentary successions

Role of Tectonism in Deposit Genesis

a. Detailed structural studies to discern timing of ore formation relative to tectonic events

b. Importance of discriminating primary from tectonically remobilized mineralization

Possible Relationship to Iron Oxide-Copper-Gold (IOCG) Deposits

a. Constraints of minor to no-iron-oxide gangue in some of the Co-Cu-Au deposits

b. Co-rich metal suite of Co-Cu-Au deposits versus Co-poor suite in most IOCG deposits

c. Evaluate possible zoning in terms of proximal and distal Co-Cu-Au deposits

d. Stable and radiogenic isotope studies to determine sources of metals and fluids

Geoenvironmental Issues

a. With the exception of deposits in the Idaho cobalt belt, geoenvironmental data for other Co-Cu-Au deposits worldwide could not be located in public literature sources

b. Monitoring of Cu, Co, and As in surface sediment and water runoff is needed for Cu-Co-Au deposits worldwide in addition to the Blackbird district

c. Additional surface geochemical data could lead to a more thorough understanding of affects on water quality and ecosystem health.

Appendix 1. Database for Co-Cu-Au Deposits Included in This Report

By J. Douglas Causey and John F. Slack

The deposits described in this appendix are the ones that we believe are representative of the Co-Cu-Au deposit model type.

This appendix contains a concise description of the deposit records that are stored in a master relational database. The information in the database was gleaned from personal contacts and published reports, which are cited in the description of each deposit.

Information shown on the following pages was extracted from the database using queries of tables to select the pertinent data. A database form was used to provide structure to the data and printout of the deposit descriptions. Names associated with each piece of data on the forms are usually abbreviations and their full meaning is described below.

Name	Description
DepID	Unique deposit identification number.
Deposit name	Main name for the deposit.
Other names	Alternate name(s) for the deposit.
Includes	Names of mines, claims, owners, etc. which are included in the deposit description.
Country	Country or countries in which deposit occurs.
State/Province	State(s) or Province(s) in which deposit occurs.
Latitude	Latitude of center of deposit in WGS 84 (World Geodetic System, 1984).
Longitude	Longitude of center of deposit in WGS 84.
Major Metals	Major metals in the deposit.
Minor Metals	Minor or associated metals.
Regional Tectonic Set	Regional tectonic setting of the deposit.
Metamorphic Grade	Metamorphic grade - list maximum and describe any retrograde metamorphism.
Deposit geometry	Deposit geometry - length, width, and depth (in meters).
Host Rk Age	Age of the host rock.
Cntry Rk Lithol	Lithology of the country rock.
Wall Rk Lithol	Lithology of the wall rock.
Ore Mineral	Ore minerals present.
Gangue Mineral	Gangue minerals present.
Supergene Min	Supergene minerals present.
Hydrot Alteration	Hydrothermal alteration.
Assoc Pluton	If there are plutons present are they felsic, mafic, both and any names.
Assoc Mag-rich Rk	List any associated magnetite-rich rocks. (this does not include hematite-rich rocks)
Min Age	Age of mineralization.
Struct Control	Structural controls of ore deposit.
Hi Salinity?	Do fluid inclusions indicate high salinity? (yes or no)
Isotope Sig	Description any isotopic signatures.
References	References for data in this deposit record.
Metric tons	Tonnage of deposit in metric tons.
Cu grd	Grade of copper in weight percent.
Co grd	Grade of cobalt in weight percent.
Au grd	Grade of gold in g/t.
Resource desc	Resource description and other pertinent information.

DepID	Deposit name	Country	State/Province	Latitude	Longitude
13	Blackbird-Idaho Cobalt belt	USA	Idaho	45.1229	-114.3486

Other names

Associated magnetite-rich rock

Includes Ram, Sunshine, Chicago, Uncle Sam, Idaho, Dandy, Merle, Blacktail, Brown Bear, Northfield, St. Joe, Hawkeye, Burl, Calera

Major metals Co, Cu, Fe

Hi salinity? ☐

Minor metals Au, Y, REE, Bi, As, Ni, Zn **Min Age** Mesoproterozoic **Host rock age** Mesoproterozoic

Ore mineral cobaltite, chalcopyrite, native gold, pyrite, glaucodot, bismuth, arsenopyrite, pyrrhotite, bismuthinite, monazite, xenotime, marcasite, gadolinite-(Y), tellurobismuthite(?), gersdorffite(?), millerite, safflorite, sphalerite

Gangue mineral iron-rich biotite (annite), quartz, albite, microcline, apatite, zoisite, tourmaline, siderite, calcite, ankerite, ilmenite, zircon, magnetite, garnet, chloritoid, muscovite, chlorite, epidote, graphite, allanite

Supergene mineral erythrite, covellite, chrysocolla, azurite, malachite, bornite, chalcocite, cuprite, native copper, native silver

Cntry rock lithology Apple Creek Formation - banded siltite unit (meta-siltite and meta-argillite) with biotite, Gunsight Formation - metasandstone and minor metashale

Wall rock lithology Biotitite, biotite phyllite, biotite-tourmaline phyllite, sugary quartz, schistose, and siliceous rock

Hydrothermal alteration Silicification, tourmalinization, biotitization

Regional tectonic settting Folded strata in fault-bounded Blackbird structural block

Metamorphic grade Middle greenschist to lower amphibolite

Deposit geometry 12 ore zones - each with multiple lodes in 4 km x 2 km block

Structural control Axial plane cleavage in folds; shear zones, and breccias

Associated pluton Mesoproterozoic granite (peraluminous, two-mica granite to quartz monzonite with rapakivi megacrysts) (1.37 Ga), augen gneiss, and 1.379 Ga gabbroic pluton

Isotopic signature δ 34S = 7-9; carbonate sample: δ13C = -4.0 permil (relative to VPDB), and δ18O = 9.6 permil (relative to VSMOW)

References

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Kunter, Richard, and Prenn, Neil, 2008, Formation Capital Corp. Technical Report Idaho Cobalt Property Feasibility Study (Ram Deposit): Samuel Engineering, Inc. NI 43-101 Technical Report for Formation Capital Corp., 142 p.

Nash, J.T., Hahn, G.A., and Sauners, J.A., 1987, The occurrence of gold in siliceous Co-Cu exhalite deposits of the Blackbird mining district, Lemhi County, Idaho: U.S. Geological Survey Open-File Report 87-410, 14 p.

Prenn, Neil, 2006, Geology and resources Idaho Cobalt Project feasibility study, Lemhi County, Idaho USA, prepared for Formation Capital Corporation: Mine Development Associates, Mine Engineering Services, 140 p. plus appendices.

Slack, J.F., 2006, High REE and Y concentrations in Co-Cu-Au ores of the Blackbird district, Idaho: Economic Geology, v. 101, p. 275-280.

Vhay, J.S., 1948, Cobalt-copper deposits of the Blackbird district, Lemhi County, Idaho: U.S. Geological Survey, U.S. Strategic Minerals Investigations Preliminary Report no. 3-219 (U.S.G.S. Open-File Report 48-1), 26 p.

Metric ton	Co %	Cu %	Au g/t	Resource Description	Citation
16,800,000	0.735	1.37	1.04	Tonnage and grades calculated in 2011 by Art Bookstrom and rounded	Anderson (1943), Anderson (1947), Bennett (1977), G.A. Hahn and S.G. Peters (1979) written commun., S.G. Peters (1981) written commun., K.D. Loose (1982) written commun., Prenn (2006), Kunter and Prenn (2008)

DepID	Deposit name	Country	State/Province	Latitude	Longitude
40	Cobalt Hill deposit	Canada	Ontario	46.84	-80.63

Other names

Associated magnetite-rich rock

Includes

Major metals Co, Cu, Au

Hi salinity? ✔

Minor metals Ni, As, Hg, Te

Min Age Paleoproterozoic

Host rock age Paleoproterozoic

Ore mineral pyrite, chalcopyrite, pyrrhotite, bravoite, gersdorffite, pentlandite, chalcocite, gold, coloradoite

Gangue mineral albite, chert, quartz, mica, chlorite, calcite, ferroan dolomite, ankerite, fuchsite, monazite, rutile

Supergene mineral

Cntry rock lithology Huronian sedimentary rocks: quartzite, arkosic quartzite

Wall rock lithology Arkosic quartzite

Hydrothermal alteration Regional albitization (1.7 Ga), silicification, pyritization and locally, chlorite, hematized

Regional tectonic settting Collisional orogeny and the development of the Killarney Magmatic Belt. Huronian Supergroup deposited at the southern margin of a rift, and the passive margin evolved into a “convergent tectonic regime”

Metamorphic grade Lower greenschist

Deposit geometry About 100 m diameter

Structural control Brecciated faults and shear zones

Associated pluton Murray Granite, at 2.45 and 2.47 Ga, Nipissing gabbro (2.22 Ga)

Isotopic signature

References Schandl, E.S., 2004, The role of saline fluids in base-metal and gold mineralization at the Cobalt Hill prospect northeast of the Sudbury igneous complex, Ontario: A fluid-inclusion and mineralogical study: Canadian Mineralogist, v. 42, p. 1541-1562.

Metric ton	Co %	Cu %	Au g/t	Resource Description	Citation
				No data	

DepID	Deposit name	Country	State/Province	Latitude	Longitude
10	Contact Lake Belt	Canada	Northwest Territories	66	-118

Other names Port Radium-Echo Bay-Contact Lake Belt

Associated magnetite-rich rock

Includes Contact Lake Mine, Bornite Lake, Azurite Mag Hill 1, Mag Hill 2, J1, K1, K2

Major metals Cu, Au, Ag, Co, U

Hi salinity? ☐

Minor metals Bi, Zn, As

Min Age

Host rock age Proterozoic

Ore mineral pyrite, chalcopyrite, bornite, cobaltian arsenopyrite, covellite, glaucodot, pitchblende, malachite, erythrite, chalcocite, marcasite

Gangue mineral albite, magnetite, hematite, biotite, sericite, chlorite, quartz, K feldspar, manganese oxide, tourmaline, carbonate, jasper

Supergene mineral

Cntry rock lithology Echo Bay Formation: andesite stratovolcano complex; Cameron Bay Formation: sandstone, siltstone, mudstone, felsic to intermediate ignimbrites and ash-flow tuffs; and granodiorite (on Bornite Lake claims)

Wall rock lithology Surprise Lake Member: porphyritic andesite

Hydrothermal alteration Propylitic, phyllic, potassic, hematite, albitic, silicification, sulfidation, albitization

Regional tectonic settting Folded subduction-related volcano-plutonic arc complex (NW-trending flank of a collapsed andesite stratovolcano complex in Great Bear Magmatic Zone-1.88 to 1.84 Ga Andean-type calc-alkaline volcano-plutonic arc complex.)

Metamorphic grade Amphibolite facies

Deposit geometry K2 - discontinuous minimum 3 km x 200-400 m wide, K1 - 4 discontinuous outcrops up to 100 m x 40 m, Bornite Lake

Structural control Fractures, veins, stockworks, breccias, and replacement zones

Associated pluton Mystery Island Intrusive Complex (diorite to monzonite to granodiorite)-Contact Lake Pluton, Great Bear batholith (granite, monzonite, granodiorite, syenogranite)

Isotopic signature

References

Fingler, J., 2005, Technical report on the Contact Lake property, District of Mackenzie, Northwest Territories, Canada: Alberta Star Development Corporation, Internal Report, August 4, 2005, 93 p. plus appendices.

Mumin, A.H., Corriveau, L., Somarin, A.K., and Ootes, L., 2007, Iron oxide copper-gold-type polymetallic mineralization in the Contact Lake belt, Great Bear magmatic zone, Northwest Territories, Canada: Exploration and Mining Geology, v. 16, p. 187-208.

Metric ton	Co %	Cu %	Au g/t	Resource Description	Citation
				Drill interval. 0.27%Cu, 0.10% Co, 1.31%As, 0.15 g/t Au over 24 meters. No resource calculations done.	Fingler (2005)

DepID	Deposit name	Country	State/Province	Latitude	Longitude
18	Dahenglu deposit	China	Jilin Province	41.9	126.4

Other names

Associated magnetite-rich rock

Includes

Major metals Co, Cu

Hi salinity? ☑

Minor metals Zn, Pb, As

Min Age

Host rock age Proterozoic

Ore mineral siegenite, cobaltite, skutterudite, Co-bearing pyrite, chalcopyrite, sphalerite, galena

Gangue mineral quartz, calcite

Supergene mineral

Cntry rock lithology B-rich and C-rich phyllite, quartzite. Ore body composed of C-bearing sericite phyllite, tourmaline-bearing sericite phyllite, quartzite and tourmalite. In Dalizi Formation in Laoling Group

Wall rock lithology

Hydrothermal alteration

Regional tectonic settting Liaoji Proterozoic rifting zone

Metamorphic grade Greenschist-high to amphibolite metamophic facies

Deposit geometry 360～1,400 m long, 95～800 m wide, 3～108.7 m thick

Structural control

Associated pluton basic-intermediate acidic vein rock, and tonalite-trondhjemite

Isotopic signature

References

Wei, Yan Guang, Wang, Ke Yong, Yang, Yan Chen, Zhao, Hong Jun, and Liu, Zong Xiu, 2002, The features of metamorphic minerogenetic fluid of Dahenglu Cu-Co deposit in Baishan County, Jilin Province: Journal of Jilin University (Earth Science Edition), 2002 issue 2, p. 128-133, accessed November 16, 2011, at http://en.cnki.com.cn/Article_en/CJFDTOTAL-CCDZ200202004.htm [in Chinese with English abstract].

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Guo, Wen-xiu, Liu, Jian-min, 2002, The Geologic Features of Dahenglu Cu, Co Deposit and Ore-Controling Factors in Jinlin Province, China: Progress In Precambrian Research, issue Z1, p. 206-213 accessed November 16, 2011, at http://en.cnki.com.cn/Article_en/CJFDTOTAL-QHWJ2002Z1018.htm, [in Chinese with English abstract].

Metric ton	Co %	Cu %	Au g/t	Resource Description	Citation
				No data	

DepID	Deposit name	Country	State/Province	Latitude	Longitude
41	Gladhammar	Sweden	Småland	57.7196	16.4249

Other names Gladhammars gruvfält, Lunds, Solberga

Associated magnetite-rich rock massive magnetite / hematite quartzite

Includes Bonde Mine, Holtandare or Baggen Mine, Svensk Mine, Odelmark Mine, Knut Mine, Ryss Mines

Major metals Co, Cu, Fe, Au

Hi salinity? ☐

Minor metals Zn, Pb, Mo, Bi

Min Age

Host rock age Paleoproterozoic

Ore mineral gladite, hammarite, lindströmite (Pb-Cu-Bi sulfosalts); cobaltite, chalcopyrite, bornite, sphalerite, carrollite, pyrite, tellurförande, arsenopyrite, galena, molybdenite

Gangue mineral quartz, ilmenite, magnetite, mica

Supergene mineral

Cntry rock lithology Västervik Formation - rocks are weathering products of old, volcanic ashes and lavas - metamorphosed to quarzites and amphiboles

Wall rock lithology Quartzite

Hydrothermal alteration

Regional tectonic settting Early Svecofennian supracrustal sequences; tensional regime, possibly an ensialic continental rift, penecontemporaneous with folding, migmatization and formation of 'lateorogenic' anatectic granites

Metamorphic grade Amphibolite?

Deposit geometry Discontinuous 3 to 5 foot thick seams over 8,000 feet along strike and 300 feet deep.

Structural control Folds, shear zones

Associated pluton ~1.8 Ga Småland batholith - granitoids (I-granites)

Isotopic signature

References

Geological Survey of Finland, Geological Survey of Norway, and Geological Survey of Sweden, 2009, Fennoscandian Ore Deposit Database (FODD): Geological Survey of Finland (GTK), accessed May 5, 2010, at http://en.gtk.fi/ExplorationFinland/fodd/. (ID = 1916 in database).

Joansson, Åke, 1988, The age and geotectonic setting of the Småland -Värmland granite-porphyry belt: GFF (Journal of the Geological Society of Sweden), v. 110, part 2, p. 105-110.

Sandberg, Fredrik, Palm, Veronica, Carlsson, Eva, and Nilsson, Nicholas, 2009, Gladhammars gruvor: Kalmar Läns Museum, Arkeologisk rapport 2009:52, 198 p. (in Swedish).

Metric ton	Co %	Cu %	Au g/t	Resource Description	Citation
5,894				No average grades reported. Mined 1874-1934. 15% average cobalt grade mentioned in one mine on the deposit (Davies, 1884, p. 268).	Geological Survey of Finland and others (2009)

DepID	Deposit name	Country	State/Province	Latitude	Longitude
27	Haarakumpu	Finland	Oulu	66.4243	28.574

Other names Kuusamo-Panajärvi-Kuolajärvi Au-Co district

Associated magnetite-rich rock

Includes

Major metals Co, Cu

Hi salinity?

Minor metals Au, Bi, Ni **Min Age** Paleoproterozoic **Host rock age** Paleoproterozoic

Ore mineral cobaltian pyrite, pyrrhotite, chalcopyrite, cobaltian pentlandite, native gold, native bismuth

Gangue mineral magnetite, albite

Supergene mineral

Cntry rock lithology Quartzite, mica schist (skarn quartzite, tremolite-bearing mica schist, tremolite skarn, amphibolite and mica schist are the most common rocks of the schist formation.)

Wall rock lithology Tremolite-garnet altered quartz-sericite schist

Hydrothermal alteration Regional albitization of sedimentary rocks and spillitization of volcanic rocks (pre-ore), carbonate, Fe-Mg-K metasomatism and silicification (mineralizing phase)

Regional tectonic settting Kuusamo Schist Belt - metamorphosed, intracratonic, extensively albitised, supracrustal sequence in a failed rift system

Metamorphic grade Greenschist/amphibolite

Deposit geometry Upper lens: 500 m x 250 m x 6.5 m, Lower lens: 1000 m x 150 m x 6 m; RefID 140 - one ore body 800 x 200m x10-20m thick open along strike and down dip.

Structural control Cross structures in Hyvaniemi - Maaninkavaara anticline and brecciated zones

Associated pluton Central Lapland Granitoid Complex granite

Isotopic signature

References

Franklin, J.M., 2006, Technical Report on the Kuusamo Properties, prepared for Belvedere Resources Ltd, November 14, 2006: Franklin Geosciences Ltd., Ontario, Canada, 55 p.

Geological Survey of Finland, Geological Survey of Norway, and Geological Survey of Sweden, 2009, Fennoscandian Ore Deposit Database (FODD): Geological Survey of Finland (GTK), accessed May 5, 2010, at http://en.gtk.fi/ExplorationFinland/fodd/. (ID = 335 in database).

Västi, K., 2010, FINCOPPER – A public database on copper deposits in Finland: Geological Survey of Finland, Version 1.1, accessed April 19, 2011, at http://en.gtk.fi/ExplorationFinland/Commodities/Copper/haarakumpu.html. (Deposit_id = 85 in database).

Metric ton	Co %	Cu %	Au g/t	Resource Description	Citation
4,680,000	0.17	0.34		Tonnage, Cu, and Co calculated weighted average from FINCOPPER database	Västi (2010)

DepID	Deposit name	Country	State/Province	Latitude	Longitude
32	Hangaslampi deposit	Finland	Oulu	66.2808	29.2036

Other names Kuusamo-Panajärvi-Kuolajärvi Au-Co district

Associated magnetite-rich rock

Includes

Major metals Au, Co

Hi salinity? ☐

Minor metals Ag, Cu, REE, Ni, U, Mo, Pb, W **Min Age** 1822±5 Ma **Host rock age** Paleoproterozoic

Ore mineral pyrite, pyrrhotite, molybdenite, Co-pentlandite, chalcopyrite, cobaltite, uraninite, radiogenic galena, selenides, calaverite, altaite, frohbergite, melonite, gold, brannerite(?)

Gangue mineral quartz, sericite, chlorite, biotite, albite, rutile, magnetite, hematite, scheelite, ferberite

Supergene mineral

Cntry rock lithology Sericite Quartzite Formation and tholeiitic Greenstone Formation II: Albite-biotite-carbonate rock

Wall rock lithology Contact zone between mafic metavolcanic rocks and metasedimentary rocks (sandy siltstone, mafic volcanic rocks)

Hydrothermal alteration Regional: albitization, Ore related: Mg-Fe metasomatism, K±S metasomatism, biotitisation, chloritisation, sericitisation, silicification, carbonation

Regional tectonic settting Metamorphosed, intracratonic, extensively albitised, supracrustal sequence in a failed rift system

Metamorphic grade Greenschist to lower-amphibolite

Deposit geometry 2 lodes 40 m apart: larger lode: 200 m x 70 m x 30 m

Structural control WNW-trending faults cut across a doubly-plunging area in the Käylä-Konttiaho Anticline

Associated pluton

Isotopic signature

References

Dragon Mining NL, 2005, Annual Report 2004: Dragon Mining NL Annual Report 2004, Perth. 80 p., accessed at www.dragon-mining.com.au/pdf/Dragon2004Annual.pdf.

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Eilu, P., and Pankka, H., 2010, FINGOLD – A public database on gold deposits in Finland: Geological Survey of Finland, Version 1.1, accessed May 6, 2010, at http://en.gtk.fi/Geoinfo/DataProducts/latest/. (ID = 93 in database).

Eilu, P., Sorjonen-Ward, P., Nurmi, P., and Niiranen, T., 2003, A review of gold mineralization styles in Finland: Economic Geology, v. 98, p. 1329-1353.

Geological Survey of Finland, Geological Survey of Norway, and Geological Survey of Sweden, 2009, Fennoscandian Ore Deposit Database (FODD): Geological Survey of Finland (GTK), accessed May 5, 2010, at http://en.gtk.fi/ExplorationFinland/fodd/. (ID = 34 in database).

Metric ton	Co %	Cu %	Au g/t	Resource Description	Citation
278,000	0.1	0.1	6.2	Spreadsheet from Pasi Eilu (2011).	Eilu (2011) written communication

DepID	**Deposit name**	**Country**	**State/Province**	**Latitude**	**Longitude**
17	Juomasuo deposit	Finland	Oulu	66.2888	29.1995

Other names Kuusamo-Panajärvi-Kuolajärvi Au-Co district

Associated magnetite-rich rock

Includes

Major metals Au, Co

Hi salinity?

Minor metals Cu, Ag, Mo, Ni, REE, U, Bi, Te, Pb, Zn

Min Age Paleoproterozoic

Host rock age Paleoproterozoic

Ore mineral pyrite, pyrrhotite, cobaltite, Co-pentlandite, linneaite, chalcopyrite, molybdenite, uraninite, galena, gold, altaite, calaverite, frohbergite, melonite, rucklidgeite, tellurobismuthite, mattagamite, kawazulite, clausthalite, scheelite

Gangue mineral sericite, quartz, Fe dolomite, chlorite, biotite, albite, magnetite, ilmenite, rutile

Supergene mineral

Cntry rock lithology Sericite Quartzite Formation (of the Kuusamo Schist Belt) containing metasedimentary and metavolcanic rocks, and dolerites

Wall rock lithology Albite-amphibolite and albite-quartz

Hydrothermal alteration Regional: albitisation; Ore-related: Mg-Fe metasomatism, K±S metasomatism, carbonation, silicification

Regional tectonic settting Kuusamo Schist Belt - metamorphosed, intracratonic, extensively albitised, supracrustal sequence in a failed rift system

Metamorphic grade Peak regional metamorphism: lower-amphibolite facies: staurolite porphyroblasts in Al-rich rocks, during D1? followed by retrograde greenschist-facies metamorphism: sericitisation of staurolite, during D2?

Deposit geometry Oval- or sheet-shaped, 50 x 100 x >300 m (depth) in size, NW-trending, dip approx. 50° to the SW; two satellite lodes have the same strike and dip. Mineralization open at depth.

Structural control NW-trending ductile shear zone which cut across the regional, NE-trending Käylä-Konttiaho Anticline close to the contact between Sericite Quartzite and Greenstone II Formations

Associated pluton Mafic and/or ultramafic dikes: altered, mineralised, conformably related to the metasedimentary rocks

Isotopic signature

References

Dragon Mining NL, 2005, Annual Report 2004: Dragon Mining NL Annual Report 2004, Perth, 80 p., accessed, at www.dragon-mining.com.au/pdf/Dragon2004Annual.pdf.

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Pankka, H.S., and Vanhanen, E.J., 1992, Early Proterozoic Au-Co-U mineralization in the Kuusamo district, northeastern Finland: Precambrian Research, v. 58, p. 387-400.

Vanhanen, E., 2001, Geology, mineralogy, and geochemistry of the Fe-Co-Au(-U) deposits in the Paleoproterozoic Kuusamo schist belt, northeastern Finland: Geological Survey of Finland Bulletin, v. 399, 229 p.

Metric ton	Co %	Cu %	Au g/t	Resource Description	Citation
5,039,000	0.128	0.03	1.96	Summed resources from Dragon Mining (2011, 2012), then calculated weighted average cobalt and gold. Copper grade from Eilu	Dragon Mining (2011), Dragon Mining (2012), Eilu (2011) written communication

DepID	Deposit name	Country	State/Province	Latitude	Longitude
20	Kendekeke deposit	China	Qinghai Province	37.019	91.77

Other names

Associated magnetite-rich rock

Includes

Major metals Co, Bi, Au, Cu

Hi salinity? ☐

Minor metals Bi, As, Zn, Pb, Te **Min Age** Mesozoic **Host rock age** Late Ordovician

Ore mineral skutterudite, pyrite, arsenopyrite, bismuthinite, bismite, tellurbismuthite, chalcopyrite, malachite, tetrahedrite, galena, sphalerite, erythrite

Gangue mineral magnetite, K-spar, fluorite

Supergene mineral

Cntry rock lithology Tieshidasi Group volcanic rocks - basalt and minor acid tuff

Wall rock lithology Sedimentary (carbonate. Chert, shale)

Hydrothermal alteration Skarnification, silicification, sericitization, carbonatization, chloritization, epidotization, K-alteration

Regional tectonic settting Kunlun collision belt, Qiman Tag orogen

Metamorphic grade Not described

Deposit geometry

Structural control early Paleozoic back-arc basin of the Kunbei fracture zone

Associated pluton Monzonite porphyry (Indosinian-Yanshanian magma)

Isotopic signature

References

Papan Tong, 2008, Geochemical features and origin of siliceous rocks of Kendekeke Co-Au deposit in the eastern Kunlun metallogenic belt, Qinhai: accessed 5/12/2010, at http://en.cnki.com.cn/Article_en/CJFDTOTAL-DZKT200802010.htm

Pan, Tong, and Sun, Fengyue, 2003, The mineralization characteristics and prospecting of Kendekeke Co-Bi-Au deposit in Dongkunlun, Qinghai Province: Geology and Prospecting, v. 39, no. 1, p. 18-22 [in Chinese with English abstract].

Pan, Tong, Zhao, Caisheng, and Sun, Fengyue, 2005, Metallogenic dynamics and model of cobalt deposition in the eastern Kunlun Orogenic Gelt, Qinghai Province, in Mao, Jingwen and Bierlein, F.P., editors, Mineral Deposit Research: Meeting the Global Challenge: Springer, Berlin, p. 1551-1553.

Metric ton	Co %	Cu %	Au g/t	Resource Description	Citation
				No data	

DepID	**Deposit name**	**Country**	**State/Province**	**Latitude**	**Longitude**
31	Kouvervaara deposit	Finland	Oulu	66.1312	28.8186

Other names Kuusamo-Panajärvi-Kuolajärvi Au-Co district

Associated magnetite-rich rock

Includes

Major metals Co, Cu, Au

Hi salinity? ☐

Minor metals Zn, Mo, Bi, W

Min Age Paleoproterozoic

Host rock age Paleoproterozoic

Ore mineral pyrrhotite, chalcopyrite, cobaltite, Co-pentlandite, pyrite, native gold, molybdenite, jaipurite, mackinawite, linnaeite, scheelite, ferberite, native Bi, maldonite, bismuthinite, hedleyite

Gangue mineral rutile, magnetite, ilmenite, albite, biotite, fuchsite, microcline, tourmaline, zircon

Supergene mineral

Cntry rock lithology Sericite Quartzite Formation - sericite quartzites and sericite schists (actinolite-garnet-biotite rock in sericite quartzite)

Wall rock lithology Sericitic quartzite

Hydrothermal alteration Regional: albitization; Ore-related: Mg-Fe metasomatism, K±S metasomatism, carbonation, silicification, further Au mineralisation and brittle deformation.

Regional tectonic settting Intracratonic, failed rift filled by a subaerial to shallow-water volcanosedimentary sequence deposited on late Archaean basement

Metamorphic grade Upper-greenschist facies or transition between upper-greenschist to lower-amphibolite facies at 500±50°C

Deposit geometry Four gold lodes are reported to overprint the 900 m long, 200 m wide zone

Structural control Intersection of two parallel, WNW-trending, faults and the ENE-trending Hyväniemi-Maaninkavaara Anticline

Associated pluton

Isotopic signature

References

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Eilu, P., Sorjonen-Ward, P., Nurmi, P., and Niiranen, T., 2003, A review of gold mineralization styles in Finland: Economic Geology, v. 98, p. 1329-1353.

Geological Survey of Finland, Geological Survey of Norway, and Geological Survey of Sweden, 2009, Fennoscandian Ore Deposit Database (FODD): Geological Survey of Finland (GTK), accessed May 5, 2010, at http://en.gtk.fi/ExplorationFinland/fodd/. (ID = 29 in database).

Metric ton	Co %	Cu %	Au g/t	Resource Description	Citation
1,580,000	0.1	0.2	0.4	1.58 Mt: 0.1% Co, 0.4 ppm Au; estimated as 10x10x10 m blocks by linear kriging with a cut off grade of 0.05% Co.	Geological Survey of Finland and others (2009)

DepID	Deposit name	Country	State/Province	Latitude	Longitude
33	Lemmonlampi deposit	Finland	Oulu	66.1437	28.8069

Other names Kuusamo-Panajärvi-Kuolajärvi Au-Co district

Associated magnetite-rich rock

Includes

Major metals Co, Cu, Au

Hi salinity? ☐

Minor metals

Min Age Paleoproterozoic

Host rock age Paleoproterozoic

Ore mineral pyrite, pyrrhotite, chalcopyrite, Co-pentlandite, cobaltite

Gangue mineral magnetite, ilmenite, albite, carbonate, biotite, quartz, muscovite, garnet, anthophyllite, rutile

Supergene mineral

Cntry rock lithology Greenstone belt: komatiite, metadolerite, mica schist, quartzite

Wall rock lithology Garnet-anthophyllite gneiss, albite-carbonate rock

Hydrothermal alteration Regional: albitization; Ore-related: Mg-Fe metasomatism, K±S metasomatism, carbonation, silicification, further Au mineralisation and brittle deformation.

Regional tectonic settting Metamorphosed, intracratonic, extensively albitised, supracrustal sequence in a failed rift system

Metamorphic grade Upper-greenschist to lower-amphibolite

Deposit geometry

Structural control NE-trending fault in the NE-trending Käylä-Konttiaho Anticline (ductile/brittle deformation)

Associated pluton Differentiated, 2050 Ma dolerite, altered, predates gold mineralisation

Isotopic signature

References

Eilu, P., and Pankka, H., 2010, FINGOLD – A public database on gold deposits in Finland: Geological Survey of Finland, Version 1.1, accessed May 6, 2010, at http://en.gtk.fi/Geoinfo/DataProducts/latest/. (ID = 80 in database).

Eilu, P., Sorjonen-Ward, P., Nurmi, P., and Niiranen, T., 2003, A review of gold mineralization styles in Finland: Economic Geology, v. 98, p. 1329-1353.

Geological Survey of Finland, Geological Survey of Norway, and Geological Survey of Sweden, 2009, Fennoscandian Ore Deposit Database (FODD): Geological Survey of Finland (GTK), accessed May 5, 2010, at http://en.gtk.fi/ExplorationFinland/fodd/. (ID = 414 in database).

Metric ton	Co %	Cu %	Au g/t	Resource Description	Citation
90,000	0.3	0.4	0.35	Spreadsheet from Pasi Eilu (2011).	Eilu (2011) written communication

DepID	Deposit name	Country	State/Province	Latitude	Longitude
36	Meurastuksenaho deposit	Finland	Oulu	66.1985	29.0796

Other names Mutka-Aho 4

Associated magnetite-rich rock

Includes

Major metals Co, Au, Cu

Hi salinity?

Minor metals Mo, U, REE **Min Age** Paleoproterozoic **Host rock age** Paleoproterozoic

Ore mineral pyrrhotite, pyrite, chalcopyrite, Co pentlandite, cobaltite, magnetite, bornite, covellite, molybdenite, ilmenite, rutile, uraninite, selenides, tellurides, gold

Gangue mineral biotite, sericite, calcite, quartz, albite, magnetite, rutile, chlorite, tremolite, garnet, epidote

Supergene mineral

Cntry rock lithology Mafic lava, Komatiite, Dolerite - greenstone belt

Wall rock lithology Sericite quartzite

Hydrothermal alteration Albitisation, Mg-Fe metasomatism, K±S metasomatism, carbonation, silicification

Regional tectonic settting Kuusamo Schist Belt - metamorphosed, intracratonic, extensively albitised, supracrustal sequence in a failed rift system

Metamorphic grade Greenschist facies

Deposit geometry >220 m x10-30 m x >210 m deep

Structural control The NE-trending Käylä-Konttiaho Anticline

Associated pluton

Isotopic signature

References

Dragon Mining, 2011, Resource increase for the Kuusamo Gold Project, Finland: Dragon Mining ASX Announcement 03 November 2011, accessed January 30, 2012, at http://www.dragon-mining.com.au/sites/default/files/2011-11-03_juomasuo_resource_update_v2.pdf.

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Eilu, P., Hallberg, A., Bergman, T., Feoktistov, V., Korsakova, M., Krasotkin, S., Lampio, E., Litvinenko, V., Nurmi, P.A., Often, M., Philippov, N., Sandstad, J.S., Stromov, V., and Tontti, M., 2007, Fennoscandian ore deposit database: http://en.gtk.fi/ExplorationFinland/fodd/. (ID = 32 in database).

Vanhanen, E., 1989, :Geological Survey of Finland, Report M19/4611/-89/1/10, 20 p. (in Finnish).

Metric ton	Co %	Cu %	Au g/t	Resource Description	Citation
366,000	0.25	0.28	3.6	Spreadsheet from Pasi Eilu (2011). Dragon Mining (2011) reported 892,000 tonnes ore at 0.2 % Co and 2.3 g/t Au, but is not used because they did not report copper grade.	Eilu (2011) written communication

DepID	Deposit name	Country	State/Province	Latitude	Longitude
24	Mount Cobalt deposit	Australia	Queensland	-21.71	140.47

Other names

Associated magnetite-rich rock Selwyn Hematites (massive hematite-magnetite rock)

Includes

Major metals Cu, Co, W

Hi salinity? ☐

Minor metals As, Ni, Au, REE

Min Age

Host rock age Proterozoic

Ore mineral cobaltite, scheelite, chalcopyrite, alloclasite, (?) glaucodot, cobaltian arsenopyrite, pyrite, pyrrhotite, erythrite

Gangue mineral quartz, chlorite, ilmenite, allanite, xenotime, apatite, jasperoid, siderite

Supergene mineral malachite, azurite, native copper, hematite

Cntry rock lithology Kuridala Formation - pelitic schists, shale, acid and basic volcanics, quartzitic sediments (recrystallized carbonaceous quartz dolomite siltstones and cherts?)

Wall rock lithology Silica-dolomite, vitric tuff layers. Mineralization in shear zones at the contact between an amphibolite and enclosing pelitic schists, and within the amphibolite itself

Hydrothermal alteration Biotite-oligoclase/andesine-scapolite assemblage, tourmaline alteration

Regional tectonic settting Mt. Isa Inlier, 3 generations of folding

Metamorphic grade Upper greenschist-amphibolite

Deposit geometry "Surface mineralization is largely confined to the eastern contact of the main amphibolite (Fig. 3) and extends for about 1300 m from Mt. Cobalt to New Hope."

Structural control Shear zones at the contact between an amphibolite and enclosing pelitic schists

Associated pluton biotite and hornblende-biotite granites (1509 ± 22 m.a.) -Williams Granite, Gin Creek Granite, Mt. Cobalt Granite

Isotopic signature

References

Croxford, N.J.W., 1974, Cobalt mineralization at Mount Isa, Queensland, Australia, with references to Mount Cobalt: Mineralium Deposita, v. 9, p. 105-115.

Davidson, G.J., and Dixon, G.H., 1992, Two sulphur isotope provinces deduced from ores in the Mount Isa eastern succession, Australia: Mineralium Deposita, v. 27, p. 30-41.

Nisbet, B.W., Devlin, S.P., and Joyce, P.J., 1983, Geology and suggested genesis of cobalt-tungsten mineralization at Mt Cobalt, northwestern Queensland: Proceedings of the Australasian Institute of Mining and Metallurgy, v. 287, p. 9-17.

Metric ton	Co %	Cu %	Au g/t	Resource Description	Citation
60,000	0.05	0.33		Values are from copper mill feed percents. Produced 779 tons of cobalt.	Croxford (1974)

DepID	Deposit name	Country	State/Province	Latitude	Longitude
9	NICO	Canada	Northwest Territories	63.7	-116.9

Other names

Includes

Associated magnetite-rich rock ironstone

Major metals Co, Au, Bi

Hi salinity? ☐

Minor metals As, W, Fe Ba, P, Cu, F, Be **Min Age** **Host rock age** Proterozoic

Ore mineral arsenopyrite/cobaltite, bismuthinite, pyrite, pyrrhotite, chalcopyrite, scheelite

Gangue mineral magnetite, hematite, biotite, amphibole, K-feldspar, quartz, tourmaline, diopside, carbonate, chlorite

Supergene mineral

Cntry rock lithology Potassium feldspar- (±hematite ±magnetite) altered rhyolite. Biotite-magnetite-amphibole-hematite-K-feldspar ironstone in subarkosic wacke and rhyolite (2011 - The mineralization at NICO is hosted in brecciated clastic sedimentary rocks of the Snare Group near their unconformity with overlying felsic volcanic rocks of the Faber Group).

Wall rock lithology Altered wackes

Hydrothermal alteration Host wackes are pervasively metasomatized to a "black rock" alteration assemblage-massive, banded and locally schistose biotite amphibole, magnetite, hematite, K-feldspar, ± minor chlorite, quartz, tourmaline, diopside, carbonate and ore minerals

Regional tectonic settting Great Bear magmatic zone, major basement discontinuity with a major transverse fault

Metamorphic grade None described

Deposit geometry Mineralized lenses can be traced continuously along a 1.9 km strike length and width between 250 m and 700 m

Structural control Diatreme and fracture breccias, schists at intersection of structural lineaments, unconformity?

Associated pluton Marian River granites and porphyry dikes

Isotopic signature

References

Fortune Minerals Limited, 2010, Annual Information Form, Fiscal year ended December 31, 2009: Fortune Minerals Limited, March 22, 2010, 43 p.

Goad, R.E., Mumin, A.H., Duke, N.A., Neale, K.L., Mulligan, D.L., and Camier, W.J., 2000a, The NICO and Sue-Dianne Proterozoic, iron oxide-hosted, polymetallic deposits, Northwest Territories: Application of the Olympic Dam model in exploration: Exploration and Mining Geology, v. 9, p. 123-140.

Goad, R.E., Mumin, A.H., Duke, N.A., Neale, K.L., Mulligan, D.L., and Camier, W.J., 2000b, Geology of the Proterozoic iron oxide-hosted NICO cobalt-gold-bismuth, and Sue-Dianne copper-silver deposits, Southern Great Bear Magmatic zone, Northwest Territories, Canada, in Porter, T.M., (Ed,), Hydrothermal iron oxide copper-gold & related deposits: A global perspective: Adelaide, PGC Publishing, v. 1, 249-267.

Metric ton	Co %	Cu %	Au g/t	Resource Description	Citation
30,986,000	0.12	0.04	0.91	p. 21. In addition to the mineral reserves, there are 6.5 Mt of marginal sub-economic material.	Fortune Minerals Limited (2010)

DepID	Deposit name	Country	State/Province	Latitude	Longitude
42	Pohjasvaara	Finland	Oulu	66.27815	29.21701

Other names Kuusamo-Panajärvi-Kuolajärvi Au-Co district

Associated magnetite-rich rock

Includes

Major metals Au, Co, Cu

Hi salinity?

Minor metals Ag, As, Au, B, Fe, Hg, K, Mo, S, Se, Te, U

Min Age Paleoproterozoic

Host rock age Paleoproterozoic

Ore mineral Pyrrhotite, chalcopyrite, pyrite; Co-pentlandite, cobaltite, molybdenite, uraninite, selenides, tellurides, gold

Gangue mineral Quartz, carbonate, sericite, epidote

Supergene mineral

Cntry rock lithology Sericite Quartzite Formation rocks of the Kuusamo Schist Belt, close to the contact to the Greenstone Formation

Wall rock lithology

Hydrothermal alteration Albite-sericite

Regional tectonic settting Kuusamo Schist Belt -metamorphosed, intracratonic, extensively albitised, supracrustal sequence in a failed rift system

Metamorphic grade Greenschist facies

Deposit geometry

Structural control WNW-trending faults which cut across the antiform

Associated pluton

Isotopic signature

References

Dragon Mining, 2011, Resource increase for the Kuusamo Gold Project, Finland: Dragon Mining ASX Announcement 03 November 2011, accessed January 30, 2012, at http://www.dragon-mining.com.au/sites/default/files/2011-11-03_juomasuo_resource_update_v2.pdf.

Geological Survey of Finland, 2010, On-line mineral deposit database: accessed May 6, 2010, at http://en.gtk.fi/ExplorationFinland/Commodities/Gold/depositlist.html.

Metric ton	Co %	Cu %	Au g/t	Resource Description	Citation
95,000	0.1	0.3	4.9	Spreadsheet from Pasi Eilu (2011). Dragon Mining (2011) reported 130,000 tonnes ore at 0.15 %Co and 4.2 g/t Au, but is not used because they did not report copper	Eilu (2011) written communication

DepID	Deposit name	Country	State/Province	Latitude	Longitude
34	Sirkka deposit	Finland	Lapland	67.8143	24.7322

Other names

Associated magnetite-rich rock Sulfide-facies iron-formation nearby

Includes Sirkka kaivos, Sirkka W

Major metals Co, Ni, Au, Cu

Hi salinity? ☐

Minor metals U, Zn, Ag, As

Min Age Paleoproterozoic

Host rock age Paleoproterozoic

Ore mineral pyrite, pyrrhotite, chalcopyrite, ilmenite, pentlandite, graphite, Ag pentlandite, sphalerite, mackinawite, violarite, arsenopyrite, gersdorffite, cobaltite, gold, melnikovite

Gangue mineral quartz, ankerite, siderite, Fe-dolomite, albite, sericite, fuchsite, biotite, carbonate, rutile, tourmaline

Supergene mineral

Cntry rock lithology Black shale, quartzite, dolerite, mafic lavas, tuffs, and tuffites

Wall rock lithology Volcano-metasedimentary in the footwall and metakomatiite in the hanging wall

Hydrothermal alteration Regional: albitization and carbonatization; Ore-related: sericitisation, sulfidation, carbonatisation

Regional tectonic settting FennoScandian Shield, intracratonic rift (2.5-1.9 Ga) related volcano-sedimentary sequence - Central Lapland Greenstone Belt

Metamorphic grade Mid- to upper-greenschist

Deposit geometry E-W trending 1.5 km long, 100-200 m wide

Structural control The Sirkka Line Shear Zone which here has a E-W trend.

Associated pluton

Isotopic signature

References

Eilu, P., and Pankka, H., 2010, FINGOLD – A public database on gold deposits in Finland: Geological Survey of Finland, Version 1.1, accessed May 6, 2010, at http://en.gtk.fi/Geoinfo/DataProducts/latest/.

Geological Survey of Finland, Geological Survey of Norway, and Geological Survey of Sweden, 2009, Fennoscandian Ore Deposit Database (FODD): Geological Survey of Finland (GTK), accessed May 5, 2010, at http://en.gtk.fi/ExplorationFinland/fodd/. (ID = 48 in database).

Holma, M.J., Eilu, P., Keinänen, V.J., and Ojala, V.J., 2007, The Sirkka Au-Cu-Ni-Co occurrence, northern Finland: An orogenic gold deposit with multimetallic, atypical metal association, in Andrew, C.J., et al., eds., Digging deeper: Proceedings of the Ninth Biennial Meeting of the Society for Geology Applied to Mineral Deposits: Dublin, Irish Association for Economic Geology, 20-23 August, 2007, v. 1, p. 581-584.

Metric ton	Co %	Cu %	Au g/t	Resource Description	Citation
250,000	0.1	0.38	0.8	Holma and Keinänen (2007), p. 167: Produced three kg of gold from 3000 t of ore (1 g/t Au, 0.16 % Co, 0.5 % Cu, 0.9% Ni.	Eilu and Pankka (2010)

DepID	Deposit name	Country	State/Province	Latitude	Longitude
11	Werner Lake deposit	Canada	Ontario	50.47	-94.96

Other names

Associated magnetite-rich rock

Includes West Werner Lake

Major metals Cu, Co, Au

Hi salinity? ☐

Minor metals Mo, Zn, Ag, Ni

Min Age

Host rock age Meso-Neoarchean

Ore mineral chalcopyrite, cobaltite, cobalt pentlandite, pentlandite, pyrrhotite, pyrite, linnaeite, molybdenite, sphalerite, native gold, native silver, altaite, chalcocite, covellite, erythrite, malachite, magnetite

Gangue mineral Wall Rock is gangue - phlogopite-biotite, garnet, quartz, K-Feldpar, plagioclase, sillmanite, orthoclase, muscovite, epidote, prehnite, albite, magnetite, ilmenite, rutile, hercynite, apatite, uraninite, monazite, zircon, calcite, olivine, ankerite

Supergene mineral

Cntry rock lithology The Werner Lake Co-Cu-Au deposit is confined to a mixed unit of orthopyroxene- bearing amphibolites, ultramafic rocks, lherzolitic peridotite, pyroxenite, garnetiferous biotite schists, calc-silicate rocks, and garnet-rich quartzites.

Wall rock lithology Garnetiferous biotite schists. Calc-silicate rocks and garnet-rich quartzites are present. locally, pyroxenite, amphibolite , and gabbro also host sulfides.

Hydrothermal alteration Carbonatization (mainly calcite), epidotization, chloritization, sulfidation (mainly pyrite), serpentinization

Regional tectonic settting Faulted, multiply deformed metasedimentary belt interpreted to represent fore-arc basin to island-arc system, an accretionary prism, or back-arc basin. The current structural geometry of the English River subprovince is a result of polyphase deformation.

Metamorphic grade Granulite facies (temperature estimates of 680° to 780°C)

Deposit geometry Numerous small lenses of mineralization

Structural control F2 fold hinges, S2 foliation

Associated pluton Marijane Lake batholith and the Gone Lake stock (tonalite-trondhjemite-granodiorite)

Isotopic signature $\delta^{34}S$ Near zero value of cobaltite and sulfides. whole-rock $\delta^{18}O$ values of the cobaltite-rich ores and calc-silicates are 6.5 to 7.6 and 5.6 to 8.3 per mil, respectively

References

Hrabi, R.b., and Cruden, A.R., 2006, Structure of the Archean English River subprovince: implications for tectonic evolution of the western Superior Province, Canada: Canadian Journal of Earth Sciences, v. 43, p. 947-966.

Puget Ventures, 2011, Reserves & resources: Puget Ventures website, accessed April 25, 2011 at, http://www.pugetventures.com/properties.php?bp=682.

Pan, Y., and Therens, C., 2000, The Werner Lake Co-Cu-Au deposit of the English River subprovince, Ontario, Canada: Evidence for an exhalative origin and effects of granulite facies metamorphism: Economic Geology, v. 95, p. 1635-1656.

Metric ton	Co %	Cu %	Au g/t	Resource Description	Citation
1,337,607	0.27	0.27	0.31	Recalculated tonnage and grade from reference. "Proven reserves total 140,031 tonnes of 0.47% cobalt, 0.26% copper and 0.008 oz/t gold. Probable reserves total 40,829 tonnes of 0.25% cobalt, 0.43% copper and 0.030 oz/t gold. Indicated resources total 51,456 tonnes of 0.13% cobalt, 0.20% copper and 0.003 oz/t gold. Inferred resources total 869,378 tonnes of 0.29% cobalt, 0.28% copper and 0.011 oz/t gold. The Eastern Shallows deposit contains total indicated resources of 63,517	Puget Ventures (2012)

	tonnes with 0.29% cobalt and 0.63% copper. The Big Zone deposit contains total indicated resources of 172,396 tons with 0.26% copper, 0.62%nickel, 0.02% cobalt, 0.009 oz/t platinum and 0.030 oz/t palladium." Includes Norpax deposit, West Cobalt deposit, the Werner Lake Mine site Cobalt deposit, the Eastern Shallows Cobalt deposit, and the Big Zone deposit.	

Appendix 2. Database for Co-Cu-Au Deposits Not Included in This Report

By J. Douglas Causey and John F. Slack

The deposits described in this appendix have many of the characteristics of the deposits used in our Co-Cu-Au deposit model, but these are reported as containing less than the 0.1 percent Co cutoff used in the model.

This appendix contains a concise description of the deposit records stored in a master relational database. The information in the database was gleaned from published reports, which are cited in the description of each deposit.

The information shown on the following pages was extracted from the database using queries of tables to select the pertinent data. A database form was used to provide structure to the data and printout of the deposit descriptions. Names associated with each piece of data on the forma are usually abbreviations and their full meaning is described in table A–1 in appendix 1.

DepID 21	**Deposit name**	**Country**	**State/Province**	**Latitude**	**Longitude**
	Great Australia deposit	Australia	Queensland	-20.717	140.521

Other names

Includes

Assoc magnetite-rich rock finely bedded magnetite/albite-bearing metasediments

Major metals Cu, Au, Co

Hi salinity ☑

Minor metals

Min age

Host rock age Proterozoic

Ore mineral chalcopyrite, pyrite, gold, malachite, chrysocolla, cuprite, chalcocite, native copper, bornite, atacamite, brocknerite, azurite, claringbullite, connellite, cornetite, gerhardtite

Gangue mineral magnetite, albite, carbonate, chlorite, anhydrite, hematite, biotite, muscovite, quartz, actinolite, biotite

Supergene mineral malachite, chrysocolla, cuprite, chalcocite, native copper, bornite, atacamite, brocknerite, azurite, claringbullite, connellite, cornetite, gerhardtite

Cntry rock lithology Toole Creek Volcanics (TCV)- basaltic meta-andesite with interbedded sediments and intrusive diorites, and finely bedded magnetite/albite-bearing metasediments; Corella Fm - bedded calc silicate rocks (meta-carbonates and metasiliciclastics)

Wall rock lithology Hanging wall - metabasalt, Footwall - metasediments (dominant dolomite)

Hydrothermal alteration Sodic-calcic I -albite/magnetite/actinolite assemblage (pre-ore). Potassic -biotite replacing albite and actinolite; sericite, carbonate, hematite. Sodic-calcic II - albite, magnetite, actinolite, chalcopyrite, pyrite, carbonate, chlorite

Regional tectonic settting Major splay of the Cloneurry fault, which forms a regional tectonic contact with the metasedimentary Corella Formation in part of Mt Isa inlier formed in a series of rifts

Metamorphic grade Retrograde greenschist facies containing some amphibolite facies minerals

Deposit geometry About 150 m by 400 m

Structural control Fault/dilational vein (brittle deformation) - breccia/crackle breccia

Associated pluton sodically altered granitic Naraku batholith to north and Williams batholith to south

Isotopic Signature Quartz δ18O=11.4 to 13.4 per mil, Dolomite δ18O= 13.9-18.4%, Calcite δ13C= -3.1 to -6.1%, Calcite δ18O= 10.0-16.7%

Reference

Anderson, Michael, 2010, EXCO's project pipeline, Australian Au & Cu: EXCO Resources Limited presentation at Mining 2010 - Brisbane, 28 October, 2010, 24 slides, accessed March 9, 2011 at, http://www.excoresources.com.au/investors-center/conferences-exhibitions/Mining-2010-Resources-Convention.aspx.

Cannell, J., and Davidson, G.J., 1998, A carbonate-dominated copper-cobalt breccia/vein system at the Great Australia deposit, Mt. Isa eastern succession: Economic Geology, v. 93, p. 1406-1421.

Metric ton	Co %	Cu %	Au g/t	Resource Description	Citation
2,100,000		1.54	0.13	Indicated = 1,400,000 t @1.53 %Cu, 0.13 g/t Au; Inferred = 800,000 t @ 1.57 %Cu, 0.14 g/t Au.	Anderson (2010)

DepID 5	**Deposit name**	**Country**	**State/Province**	**Latitude**	**Longitude**
	Greenmount deposit	Australia	Queensland	-21.029	140.535

Other names

Assoc magnetite-rich rock yes

Includes

Major metals Cu, Au, Co

Hi salinity ☐

Minor metals Zn

Min age

Host rock age Mesoproterozoic

Ore mineral chalcopyrite, pyrite, covellite, chalcocite, cobaltite, marcasite, sphalerite

Gangue mineral microcline with subordinate albite, sericite (retrogressed microcline) and lesser hematite, rutile, tourmaline, quartz, dolomite ± sulfides ± magnetite

Supergene mineral

Cntry rock lithology Calcareous and evaporitic metasediments with subordinate altered basalts of the Staveley Formation (fine- to medium-grained, massive to wellbedded sandstone unit with subordinate proportions of siltstone calcareous, albitic, dolomitic rocks, BIF)

Wall rock lithology

Hydrothermal alteration Magnetite alteration, potassic-hematite alteration, Ca-Mg-Fe carbonate metasomatism, silicification, microcline and scapolite metasomatism tourmaline and rutile alteration

Regional tectonic settting Mary Kathleen group, Eastern Fold Belt of Mt Isa Inlier. North-northwest- to north-trending dextral fault zones associated with the Caravan Fault Zone-Some structures have a sinistral component. East-southeast-trending structures (sinistral)

Metamorphic grade Lower to middle greenschist facies

Deposit geometry 600 m long

Structural control Breccia, sedimentary contact

Associated pluton mafic and felsic intrusions, bi-modal, sodic I-type granite, gabbro, dolerite

Isotopic Signature

Reference Krcmarov, R.L., and Stewart, J.I., 1998, Geology and mineralisation of the Greenmount Cu-Au-Co deposit, southeastern Marimo basin, Queensland: Australian Journal of Earth Sciences, v. 45, p. 463-482.

Hodgson, G.D., 1998, Greenmount copper-cobalt-gold deposit, in Geology of Australian and Papua New Guinean mineral deposits: Monograph 22, p. 769-774.

Metric ton	Co %	Cu %	Au g/t	Resource Description	Citation
3,600,000	0.042	1.5	0.78	inferred resource of approximately 3.6 Mt at about 1.5% Cu, 0.78 g/t Au and 420 ppm Co (23.8 Mt grading 0.47% Cu and 493 g/t Co: Hodgson, 1998).	Krcmarov and Stewart (1998)

DepID 22	**Deposit name**	**Country**	**State/Province**	**Latitude**	**Longitude**
	Guelb Moghrein deposit	Mauritania		19.7504	-14.4252

Other names **Assoc magnetite-rich rock**

Includes

Major metals **Hi salinity** ☐

Minor metals **Min age** 2489 ±8 Ma **Host rock age** Late Archean - Early Proterozoic

Ore mineral chalcopyrite, pyrrhotite, chalcopyrite, Fe–Co–Ni arsenides, arsenopyrite, cobaltite, uraninite and Bi–Au–Ag–Te minerals

Gangue mineral Mg-rich Fe–Mg carbonate, Fe–Mg clinoamphibole, calcite, chlorite, monazite, magnetite

Supergene mineral

Cntry rock lithology The host rocks to the mineralization are mainly a metacarbonate body composed of coarse-grained Mg-rich siderite and intercalating Fe-rich metapelites represented by clinoamphibole-chlorite phyllonites (Fig.1; Kolb et al., 2006).

Wall rock lithology

Hydrothermal alteration

Regional tectonic settting Central Mauritanides fold and-thrust belt - allochthonous terranes lying unconformably onto the western margin of the West African Craton

Metamorphic grade Lower greenschist-facies retrogression at 1742+12 Ma, amphibolite-facies hornblende–plagioclase paragenesis, upper greenschist-facies garnet–biotite paragenesis

Deposit geometry

Structural control

Associated pluton

Isotopic Signature Chalcopyrite has a δ34S of 0.1 to 1.1 ‰, pyrrhotite -0.5 to 0.4 ‰ and cobaltite -0.2 ‰ VCD. Graphite: δ13C values at 27.3 ‰ PDB.

Reference

Kolb, J., Meyer, F.M., Vennemann, T., Hoffbauer, R., Gerdes, A., and Sakellaris, G.A., 2008, Geological setting of the Guelb Moghrein Fe oxide-Cu-Au-Co mineralization, Akjoujt area, Mauritania, in Ennih, N., and Liégeois, J.-P., eds., The boundaries of the West African craton: Geological Society Special Publication 297, p. 53-75.

Kolb, J., Sakellaris, G.A., and Meyer, F.M., 2006, Controls on hydrothermal Fe oxide-Cu-Au-Co mineralization at the Guelb Moghrein deposit, Akjoujt area, Mauritania: Mineralium Deposita, v. 41, p. 68-81.

Sakellaris, G.A., and Meyer, F.M., 2008, A metamorphic origin of the Guelb Moghrein Fe oxide-copper-gold-cobalt deposit, Mauritania: RMS DPI 2008-1-101, p. 169-172.

Strickland, C.D., and Martyn, J.E., 2002, The Guelb Moghrein Fe-oxide copper-gold-cobalt deposit and associated mineral occurrences, Mauritania: A geological introduction, in Porter, T. M., ed., Hydrothermal iron oxide copper-gold & related deposits: A global perspective: Adelaide, Australian Mineral Foundation, v. 2, p. 275-291.

Metric ton	Co %	Cu %	Au g/t	Resource Description	Citation
23,600,000	0.0143	1.88	1.41	total measured and indicated resource of 23.6 Mt @1.88 % Cu, 1.41 g/t Au and 143 ppm Co	Strickland and Martyn (2002)

DepID 2	Deposit name	Country	State/Province	Latitude	Longitude
	Lala deposit	China	Sichuan Province	26.68158	102.25

Other names Lalachang

Assoc magnetite-rich rock magnetic quartzite

Includes

Major metals Cu, REE, Au

Hi salinity ☐

Minor metals

Min age 1000

Host rock age Mesoproterozoic

Ore mineral magnetite, chalcopyrite, pyrite, minor bornite, molybenite, REE-rich apatite, cobaltite, pyrrhotite, native gold, native silver, chalcocite, rare telluride

Gangue mineral albite, carbonate, biotite, quartz, fluorite, sericite, almandine, K-feldspar, minor chlorite, tourmaline

Supergene mineral

Cntry rock lithology Hekou Group: spilite, keratophyre, keratophyre volcanics, intrusive rocks, magnetic quartzite, mica schist, marble

Wall rock lithology

Hydrothermal alteration Albitization and sericitization

Regional tectonic settting

Metamorphic grade Upper greenschist to amphibolite facies

Deposit geometry vein to lens shaped interrupted by breccia zones

Structural control

Associated pluton

Isotopic Signature

Reference

Li, Z.-Q., Hu, R.-H., Wang, J.-Z., Liu, J.-J., Li, C.-Y., Liu, Y.-P., and Ye, L., 2002, Lala Fe-oxide-Cu-Au-U-REE ore deposit, Sichuan, China: An example of superimposed mineralization: Bulletin of the Chinese Society of Mineralogy, Petrology and Geochemistry, v. 21, p. 258-260 [in Chinese with English abstract].

Meyer, Michael, Schardt, Christian, Sindern, Halbach, Peter, Lahr, Janine, and Li, Jiao, 2011, Characteristics and origin of the Lala iron oxide Cu-Co-(U, REE) deposit: Sichaun Southern China (abs.): Anchorage, Alaska, Alaska Miners Association 2011 Annual Convention Abstracts, p. 10-12.

Wang, Jiangzhen, Li, Zeqing, and Li, Chaoyang, 2005, The La-La iron-oxide (Cu-Au-REE) deposit, China: REE mineralization: Goldschmidt Conference Abstracts 2005 Ore Deposits, p. A573.

Metric ton	Co %	Cu %	Au g/t	Resource Description	Citation
200,000,000	0.022	0.92	0.16	The deposit contains 200 Mt at 0.92% Cu, 0.018% Mo, 0.022% Co, 0.25% REE oxides, 0.16 ppm Au, and 1.89 ppm Ag.	Meyer and others (2011)

DepID 23	**Deposit name**	**Country**	**State/Province**	**Latitude**	**Longitude**
	Monakoff deposit	Australia	Queensland	-20.6252	140.6888

Other names

Assoc magnetite-rich rock

Includes

Major metals Cu, Au, Co, U, Ag

Hi salinity ☐

Minor metals Pb, Zn, As, Sb, W, REE (La, Ce)

Min age

Host rock age Proterozoic

Ore mineral chalcopyrite, sphalerite, galena, arsenopyrite, mackinawite, molybdenite, brannerite, davidite, pentlandite, linnaeite, malachite

Gangue mineral barite, siderite, carbonate, fluorite, magnetite, pyrolusite, ponite (Fe-rhodochrosite), pyrite, tourmaline, monazite

Supergene mineral

Cntry rock lithology Magnetite-bearing muscovite pelite, psammo-pelite, metadolerite arenite, quartzo-feldspathic arenite, carbonaceous pelite, metagreywacke, metabasalt, iron formation, garnet-biotite schist, basaltic tuff

Wall rock lithology Sheared magnetite-bearing siltstones

Hydrothermal alteration Carbonate-quartz/barite, muscovite/sericite. Near-ore alteration is porphyroblastic spessartine-biotite-quartzplagioclase-chloritoid-tourmaline-biotite development in the meta-andesite

Regional tectonic settting Pumpkin Gully Syncline, Monakoff Shear

Metamorphic grade Amphibolite. Peak metamorphism exceeded the almandine isograd

Deposit geometry Main western zone: 700 m long x 2-10 m thick, unknown depth extent, Eastern mineralisation: ~ 100 m northeast of the end of the western zone, forms a pipe-like body that plunges very steeply west, with a 40 m strike length at surface

Structural control Faults/shear zones, folds

Associated pluton Naraku Batholith, meta-dolerite

Isotopic Signature

Reference

Anderson, Michael, 2010, EXCO's project pipeline, Australian Au & Cu: EXCO Resources Limited presentation at Mining 2010 - Brisbane, 28 October, 2010, 24 slides, accessed March 9, 2011 at, http://www.excoresources.com.au/investors-center/conferences-exhibitions/Mining-2010-Resources-Convention.aspx.

Davidson, G.J., Davis, B.K., and Garner, A., 2002, Structural and geochemical constraints on the emplacement of the Monakoff oxide Cu-Au (-Co-U-REE-Ag-Zn-Pb) deposit, Mt Isa inlier, Australia, in Porter, T.M., ed., Hydrothermal iron oxide copper-gold & related deposits: A global perspective: Adelaide, PGC Publishing, v. 2, p. 49-75.

Metric ton	Co %	Cu %	Au g/t	Resource Description	Citation
4,000,000		1.32	0.42	Monakoff and Monakoff East: Indicated = 2,000,000 t @ 1.39 %Cu, .44g/t Au, Inferred = 2,000,000 t @ 1.3 %Cu, 0.4 g/t Au.	Anderson (2010)

DepID 8	**Deposit name**	**Country**	**State/Province**	**Latitude**	**Longitude**
	Scadding deposit	Canada	Ontario	46.65	-80.62

Other names **Assoc magnetite-rich rock**

Includes

Major metals **Hi salinity** ☐

Minor metals **Min age** 1700 **Host rock age**

Ore mineral pyrite, chalcopyrite, chalcocite, bornite, arsenopyrite, pentlandite, millerite, violarite, pyrrhotite

Gangue mineral Ti-poor magnetite and hematite, albite, quartz, rutile, ilmenite, biotite, stilpnomelane, calcite, dolomite, ankerite, Th-poor hydrothermal monazite, gadolinite, bastnäsite-(Ce), synchysite, gadolinite, allanite

Supergene mineral

Cntry rock lithology Serpent Formation of the Huronian Supergroup (predominantly of metasedimentary units with subordinate volcanic rocks). The quartzite unit contains all of the orebodies, and consists of almost pure quartz, lesser arkosic quartzite, and calcareous, argillaceous sandstone.

Wall rock lithology Overlying rocks: argillites and greywackes of the Gowganda Formation. Underlying rocks: The southern part of the deposit is underlain by greywackes and conglomerates of the Bruce Formation.

Hydrothermal alteration

Regional tectonic settting Margin of a rift ("convergent tectonic regime")

Metamorphic grade

Deposit geometry

Structural control

Associated pluton

Isotopic Signature

Reference Schandl, E.S., and Gorton, M.P., 2007, The Scadding gold mine, east of the Sudbury igneous complex, Ontario: An IOCG-type deposit?: Canadian Mineralogist, v. 45, p. 1415-1441.

Metric ton	Co %	Cu %	Au g/t	Resource Description	Citation
				No data	

DepID 3	**Deposit name**	**Country**	**State/Province**	**Latitude**	**Longitude**
	Tuolugou deposit	China	Qinghai Province	35.8	94.8

Other names **Assoc magnetite-rich rock**

Includes

Major metals Co, Au **Hi salinity** ☐

Minor metals Cu **Min age** 429±29 Ma (2σ) **Host rock age** Late Ordovician to Early Silurian

Ore mineral pyrite; minor arsenopyrite, chalcopyrite, bornite, sphalerite, linnaeite, carrollite, rare cobalt pentlandite, cobalt-bearing pyrite, native gold, native copper

Gangue mineral quartz, albite, carbonate (including ferrodolomite, calcite), minor sericite, chlorite, tourmaline, zircon

Supergene mineral

Cntry rock lithology Nachitai Group - volcano-sedimentary sequence metamorphosed rock (metamorphosed black shale, metamorphosed tuff and sandstone, metamorphosed volcano-sedimentary rocks, and metamorphosed sandstone)

Wall rock lithology Quartz–albitite rock

Hydrothermal alteration

Regional tectonic settting Central part of the eastern Kunlun orogenic belt

Metamorphic grade Lower greenschist facies

Deposit geometry 30

Structural control

Associated pluton

Isotopic Signature δ34S values for pyrite=–1.8 to –0.2%. Quartz δ18O=11.4 to 15.6%

Reference Feng, C.-Y., Qu, W.-J., Zhang, D.-Q., Dang, X.-Y., Du, A.-D., Li, D.-X., and She, H.-Q., 2009, Re-Os dating of pyrite from the Tuolugou stratabound Co(Au) deposit, eastern Kunlun orogenic belt, northwestern China: Ore Geology Reviews, v. 36, p. 213-220.

Metric ton	Co %	Cu %	Au g/t	Resource Description	Citation
12,800,000	0.06		0.75	Gold grade is average of 0.45 to 1.05 g/t given in reference. Jinxing Mining Company carried out detailed exploration and extensive drilling in the Duangou ore block from 2002 to 2004, and established reserves of 12.8 Mt ore.	Feng and others (2009)

DepID 28	**Deposit name**	**Country**	**State/Province**	**Latitude**	**Longitude**
	Vähäjoki deposit	Finland		66.1115	25.2791

Other names

Assoc magnetite-rich rock yes

Includes 29 magnetite ore bodies

Major metals Co, Cu, Fe

Hi salinity ☐

Minor metals Au, As **Min age** **Host rock age** Paleoproterozoic

Ore mineral cobaltite, chalcopyrite, native gold, pyrite, arsenopyrite, sphalerite, galena, mackinawite, linneaite, bornite, marcasite, pyrrhotite,

Gangue mineral magnetite, hematite, marcasite, tremolite-actinolite, cummingtonite, hornblende chlorite, dolomite, Fe dolomite, calcite, ankerite, Mg-rich biotite, Fe-rich biotite, Ba-rich biotite, talc, quartz, plagioclase, epidote, spinel, graphite

Supergene mineral None reported

Cntry rock lithology Peräpohja Schist Belt - dolomitic marble and tuffites of the 2.14–2.0(?) GaTikanmaa Formation

Wall rock lithology The lodes are vein networks, blobs and bands in "amphibole skarn" (mafic metavolcanics) and conformable bands in tremolite-chlorite schist and mica schist.

Hydrothermal alteration Hot brines reacted with the host sequence and produced the ironstone bodies. This was followed by circulation of low-salinity H2O-CO2 fluids

Regional tectonic settting Peräpohja schist belt contains a N-S array of 29 magnetite bodies.

Metamorphic grade Upper-greenschist facies (peak metamorphic - 465° ± 50°C, 2–4 kbars)

Deposit geometry The lodes are in a N-S trending domain of about 1.5 x 3.5 km in horizontal extent, and are open at depth of 100 m.

Structural control North-south trending fault zone, and a fold hinge in proximity to a major eastwest–trending fault

Associated pluton No intrusive rocks have been detected in the vicinity of Vähäjoki.

Isotopic Signature

Reference

Eilu, P., and Pankka, H., 2010, FINGOLD – A public database on gold deposits in Finland: Geological Survey of Finland, Version 1.1, accessed May 6, 2010, at http://en.gtk.fi/Geoinfo/DataProducts/latest/. (ID = 75 in database).

Eilu, P., Sorjonen-Ward, P., Nurmi, P., and Niiranen, T., 2003, A review of gold mineralization styles in Finland: Economic Geology, v. 98, p. 1329-1353.

Geological Survey of Finland, Geological Survey of Norway, and Geological Survey of Sweden, 2009, Fennoscandian Ore Deposit Database (FODD): Geological Survey of Finland (GTK), accessed May 5, 2010, at http://en.gtk.fi/ExplorationFinland/fodd/ (ID = 36 in database).

Metric ton	Co %	Cu %	Au g/t	Resource Description	Citation
10,500,000	0.029	0.17	0.2	ID = 36 in reference	Geological Survey of Finland and others (2009)

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