Cobalt—Styles of Deposits and the Search for Primary Deposits

By Murray W. Hitzman, Arthur A. Bookstrom, John F. Slack, and Michael L. Zientek

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
metric ton (t)	1.102	ton, short [2,000 lb]
metric ton (t)	0.9842	ton, long [2,240 lb]

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as °F = (1.8 × °C) + 32.

Abbreviations

Ag	silver
As	arsenic
Au	gold
Bi	bismuth
bn	bornite
bt	biotite
C	carbon
CACB	Central African Copperbelt
CCB	Congo Copperbelt
Cl	chlorine
Co	cobalt
cob	cobaltite
Congo (Kinshasa)	Democratic Republic of the Congo
cp	chalcopyrite (appears in this form on page 22 only; elsewhere,
cpy	cpy) chalcopyrite
cr	carrollite
Cr	chromite
Cu	copper
EEZ	exclusive economic zone
Fe	iron
hm	hematite
IOCG	iron oxide-copper-gold
Ma	mega-annum
Mg	magnesium
mgt	magnetite
Mn	manganese
MnS	alabandite
MVT	Mississippi Valley-type
Ni	nickel
Os	osmium
Pb	lead
PGE	platinum-group element
ppm	part per million
py	pyrite
q	quartz
Re	rhenium
REE	rare-earth element
saf	safflorite
to	toumaline
U	uranium
VMS	volcanogenic massive sulfide
ZCB	Zambian Copperbelt
Zn	zinc

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Abstract

Cobalt (Co) is a potentially critical mineral. The vast majority of cobalt is a byproduct of copper and (or) nickel production. Cobalt is increasingly used in magnets and rechargeable batteries. More than 50 percent of primary cobalt production is from the Central African Copperbelt. The Central African Copperbelt is the only sedimentary rock-hosted stratiform copper district that contains significant cobalt. Its presence may indicate significant mafic-ultramafic rocks in the local basement. The balance of primary cobalt production is from magmatic nickel-copper and nickel laterite deposits. Cobalt is present in several carbonate-hosted lead-zinc and copper districts. It is also variably present in Besshi-type volcanogenic massive sulfide and siliciclastic sedimentary rock-hosted deposits in back arc and rift environments associated with mafic-ultramafic rocks. Metasedimentary cobalt-copper-gold deposits (such as Blackbird, Idaho), iron oxide-copper-gold deposits, and the five-element vein deposits (such as Cobalt, Ontario) contain different amounts of cobalt. None of these deposit types show direct links to mafic-ultramafic rocks; the deposits may result from crustal-scale hydrothermal systems capable of leaching and transporting cobalt from great depths. Hydrothermal deposits associated with ultramafic rocks, typified by the Bou Azzer district of Morocco, represent another type of primary cobalt deposit.

In the United States, exploration for cobalt deposits may focus on magmatic nickel-copper deposits in the Archean and Proterozoic rocks of the Midwest and the east coast (Pennsylvania) and younger mafic rocks in southeastern and southern Alaska; also, possibly basement rocks in southeastern Missouri. Other potential exploration targets include—

- The Belt-Purcell basin of British Columbia (Canada), Idaho, Montana, and Washington for different styles of sedimentary rock-hosted cobalt deposits;
- Besshi-type VMS deposits, such as the Greens Creek (Alaska) deposit and the Ducktown (Tennessee) waste and tailings; and
- Known five-element vein districts in Arizona and New Mexico, as well as in the Yukon-Tanana terrane of Alaska; and hydrothermal deposits associated with ultramafic rocks along the west coast, in Alaska, and in the Appalachian Mountains.

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Cobalt—Properties and Uses

- Cobalt is a silvery gray metal.
- Key properties:
    - Ferromagnetism (even at high temperature).
    - Hardness and wear-resistance when alloyed with other metals.
    - Low thermal and electrical conductivity.
    - High melting point.
    - Intense blue color when combined with silica.
- Uses:
    - Cathodes in rechargeable batteries—lithium-ion, Ni-Cd, Ni-metal-hydride.
    - Superalloys for turbine engines in jets and terrestrial energy generation.
    - Magnet applications—marine propulsion, missile guidance, sensors, and radar.
    - Cemented carbides—cutting tools and wear-resistant components (for use in construction, oil and gas extraction, mining, metalworking).

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Cobalt—Critical Mineral?

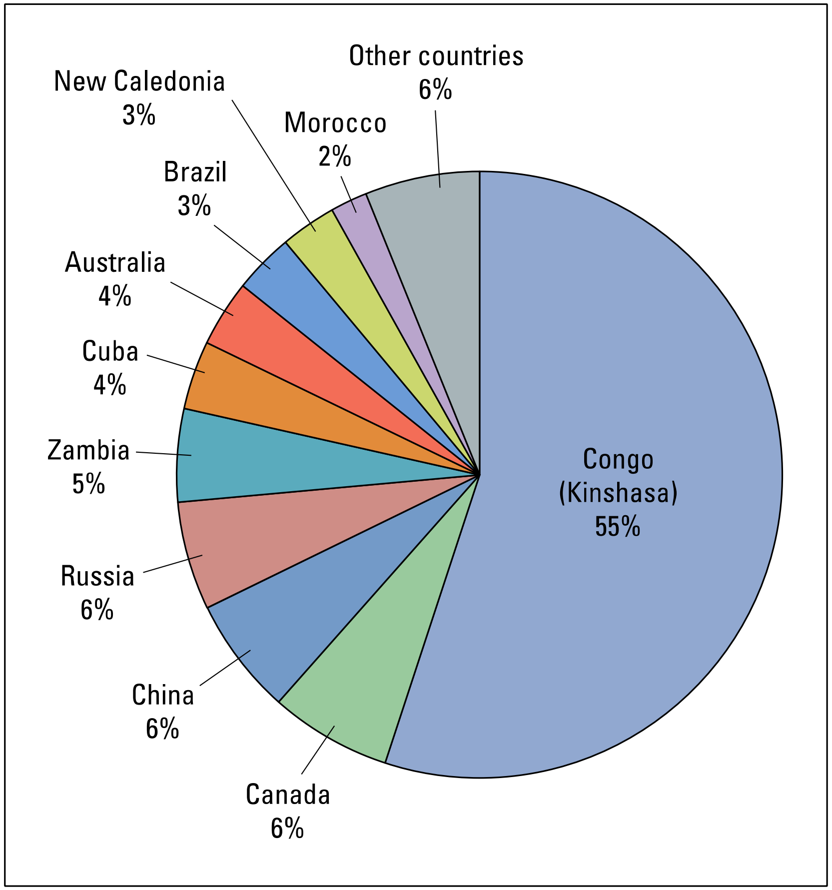
"Critical" means you need it; "strategic" means you don't have it

- Cobalt is not currently considered a "critical" mineral, but it has the potential to become one in the future (McCullough and Nassar, 2017).
- Most cobalt is produced as a byproduct (of copper or nickel mining), which limits the flexibility of producers to respond to changes in market demand and results in periods of oversupply or shortage.
- More than 50% of primary cobalt production is from Congo (Kinshasa)—a country that ranks high on the 'risk of doing business' index because of its political instability; another 16% of primary cobalt production is from Russia, Cuba, and China combined (U.S. Geological Survey, 2017, p. 52–53).
- The United States imports 75% to 80% of its supply. Most of the remaining 20% to 25% is from recycled scrap. The leading source of refined cobalt is China (U.S. Geological Survey, 2017, p. 52–53).

USGS

Cobalt—Current Sources of Primary Production

- The majority of the world's cobalt currently comes from Congo (Kinshasa).
- A number of other countries each contribute less than 10% to the total.
- In all cases except the Bou Azzer district (Morocco), cobalt is produced as a byproduct of other metals (Cu, Ni).



From Slack and others, in press.

Cobalt—Geochemistry

- The ionic radii of Co^{2+} and Co^{3+} are similar to the ionic radii of Mg^{2+}, Mn^{4+}, Fe^{2+}, Fe^{3+}, and Ni^{2+}.
- Cobalt can substitute for any of these elements in many minerals.
- The highest average cobalt content occurs in ultramafic rocks (dunite, serpentinite; ~110 ppm) > mafic igneous rocks (basalt; 47 ppm) > shales (19 ppm) > granite (3 ppm).

Cobalt—Primary (Hypogene) Mineralogy

- Sulfides:
  - Carrollite $Cu(Co,Ni)_2S_4$
  - Linnaeite Co_3S_4
  - Pentlandite $(Fe,Ni,Co)_9S_8$
  - Siegenite $(Co, Ni)_3S_4$
- Cobaltiferous iron sulfides:
  - Pyrite $(Fe,Co)S_2$
  - Pyrrhotite $(Fe,Co)_{1-x}S$
- Sulfarsenides:
  - Cobaltite CoAsS
  - Glaucodot (Co,Fe)AsS
- Arsenides:
  - Safflorite $(Co,As)As_2$
  - Skutterudite $(Co,Fe,Ni)As_{2-3}$

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Cobalt—Secondary (Supergene) Mineralogy

- Carbonate minerals:
  - Cobaltoan dolomite $(Ca,Mg,Co)CO_3$
- Other minerals:
  - Asbolane $(Ni,Co)_{2-x}Mn(O,OH)_4 \bullet nH_2O$
  - Cobaltiferous oxyhydroxides (geothite, limonite)—*it is unclear if the cobalt is within crystal structures or adsorbed onto surfaces*
  - Erythrite $Co_3(AsO_4)_2 \bullet 8H_2O$
  - Heterogenite $CoO(OH)$

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Cobalt—Occurs in a Wide Variety of Deposit Types

- Submarine nodules and crusts
- Ni-Co laterites
- Magmatic Ni-Cu sulfide deposits
- Sedimentary rock-hosted deposits
  - Stratiform copper deposits
  - Mississippi Valley-type (MVT) deposits
  - Other carbonate-hosted Cu-(Zn-Pb) deposits
- "Synsedimentary and (or) diagenetic"—a spectrum of types
- Co-Cu-Au deposits in metasedimentary rocks
- Iron oxide-copper-gold (IOCG) deposits
- Five-element vein deposits (Ag-Ni-Co-As-Bi) (Kissin, 1992)
- Hydrothermal deposits associated with ultramafic rocks

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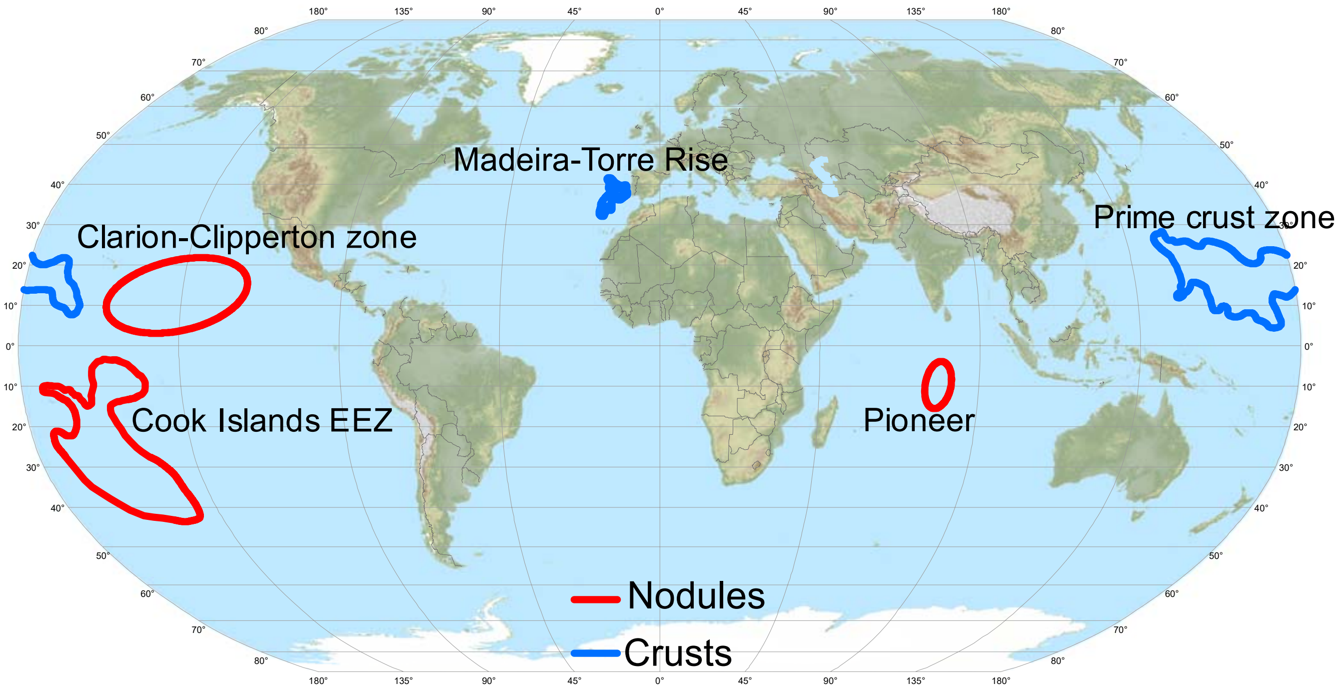
Cobalt—Submarine Resources

The largest known cobalt resources are found in submarine Fe-Mn nodules and crusts. Mining them is currently not economic because of legal and technical issues (inability to process the material economically).



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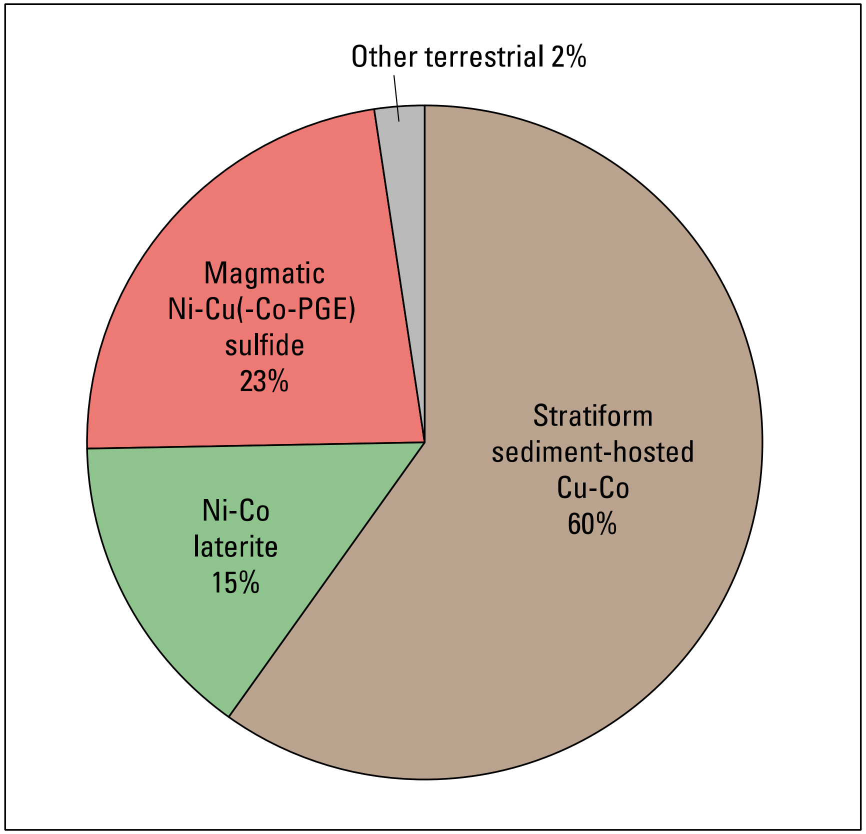
Cobalt—Deposit Types in Production

- Laterites (weathered ultramafic rock)
  - Australia
  - Brazil
  - Cuba
  - New Caledonia



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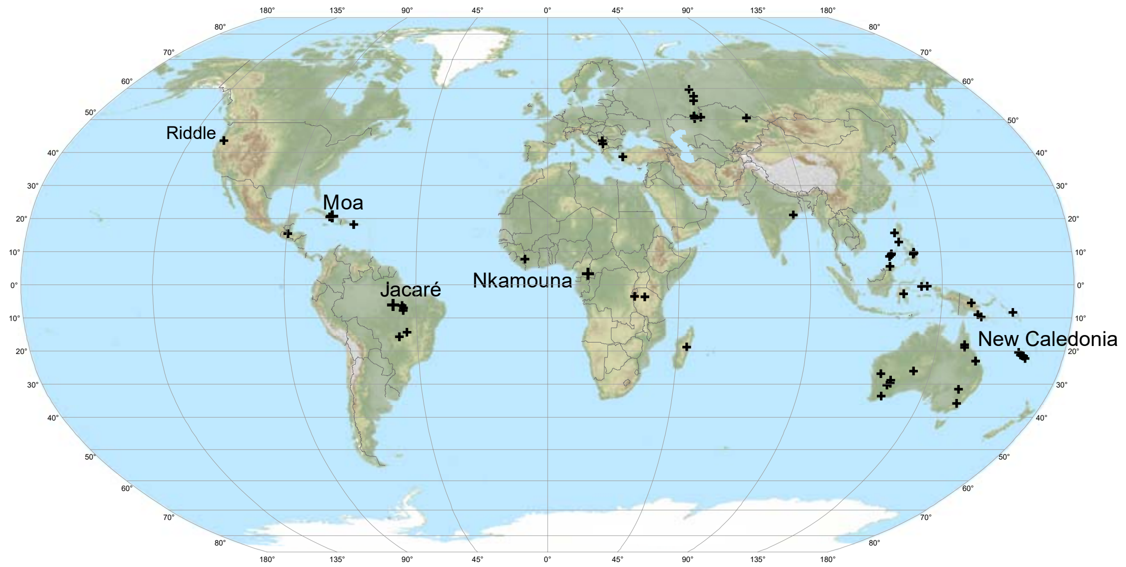
Cobalt—Ni-Co Laterites

- Consist of—
  - Overburden.
  - Limonite (higher Co grades).
  - Saprolite (higher Ni grades).
  - Weathered ultramafic rock.
- Range in thickness from 10 to 40 m.
- Cobalt contained in asbolane, clays (nontronite, montmorillonite), erythrite, goethite, heterogenite, limonite.
- Manganiferous Nkamouna Co-Ni deposit (Cameroon) has cobalt as principal metal recovered.



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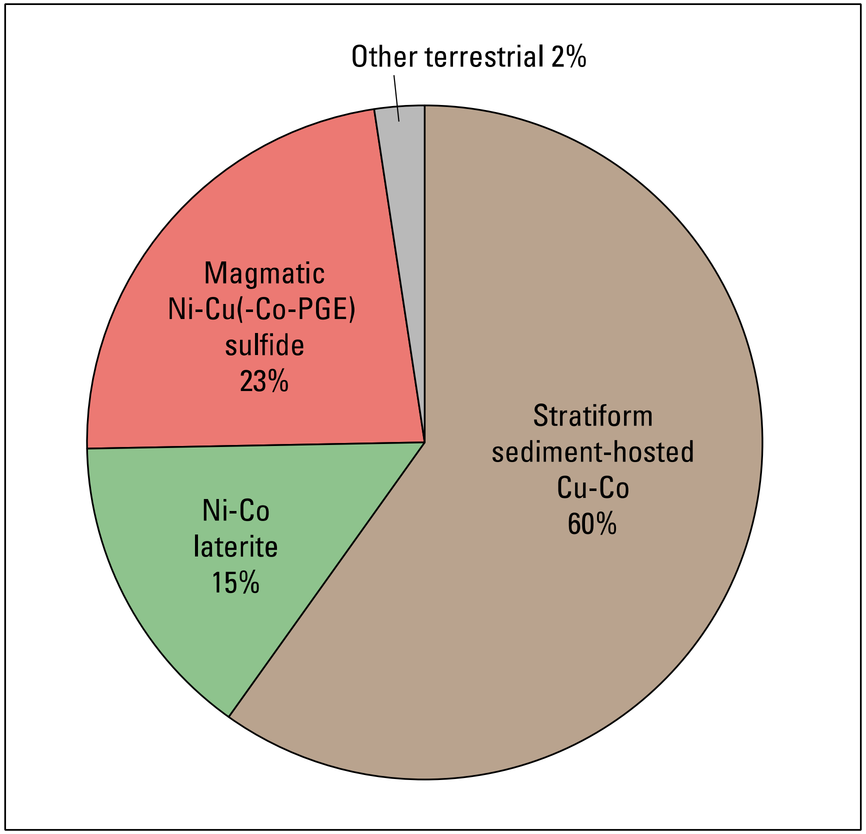
- Mined laterites generally contain >1% Ni, cobalt contents:
  - Highest: Nkamouna—0.22% Co.
  - Other higher grade: Moa, Cuba—0.18% Co; Jacaré, Brazil—0.13% Co; New Caledonia—~0.1% Co.
  - Most have <0.1% Co; as low as 0.04% Co.

Cobalt—Deposit Types in Production

- Laterites (weathered ultramafic rock)
  - Australia
  - Brazil
  - Cuba
  - New Caledonia
- Magmatic Ni-Cu sulfide deposits
  - Canada
  - China
  - Russia
    - Cobalt is a byproduct of sulfides mined for Ni-Cu-(PGEs) in mafic-ultramafic intrusions.
    - Cobalt is correlated with nickel grade; the higher the Ni grade, the higher the amount of Co.
    - Cobalt recoveries from magmatic ores are low—generally 20% to 66%.



From Slack and others, in press.

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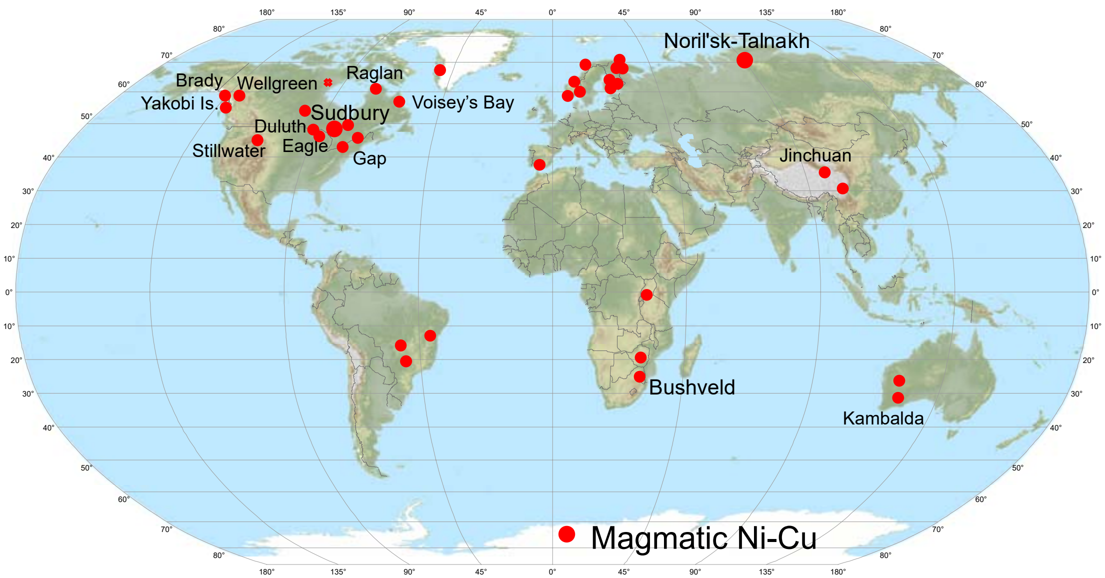
Cobalt—Magmatic Ni-Cu Sulfide Deposits

- Cobalt is a byproduct of sulfides mined for Ni-Cu-(PGEs) in mafic-ultramafic intrusions.
- Sulfides occur in disseminated, net-textured, and massive zones—
  - o As basal accumulations in komatiitic flows (Raglan, Kambalda), differentiated sills (Noril'sk-Talnakh), and layered intrusions (Sudbury, Duluth).
  - o As stratabound units in layered intrusions (Bushveld, Stillwater).
  - o In discordant magmatic conduits (Voisey's Bay, Eagle).
- Cobalt is found primarily in pentlandite, and in lesser amounts, in linnaeite.



Modified from Slack and others, in press.

- Wide range of cobalt grades:

Kambalda	0.21%	Raglan	0.06%
Voisey's Bay	0.09%	Sudbury	0.04%
Eagle	0.08%	Bushveld	0.03%
Noril'sk-Talnakh	0.06%	Duluth	0.01%

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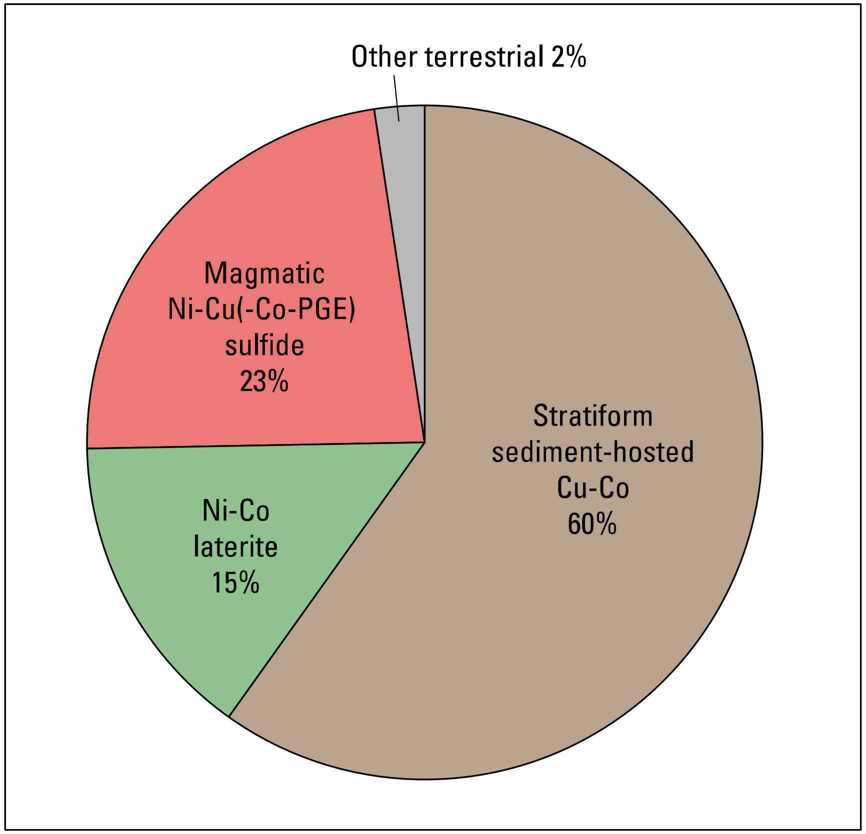
Cobalt—Deposit Types in Production

- Laterites (weathered ultramafic rock)
  - Australia
  - Brazil
  - Cuba
  - New Caledonia
- Magmatic Ni-Cu sulfide deposits
  - Canada
  - China
  - Russia
- Sedimentary rock-hosted stratiform copper deposits
  - Congo (Kinshasa)
  - Zambia



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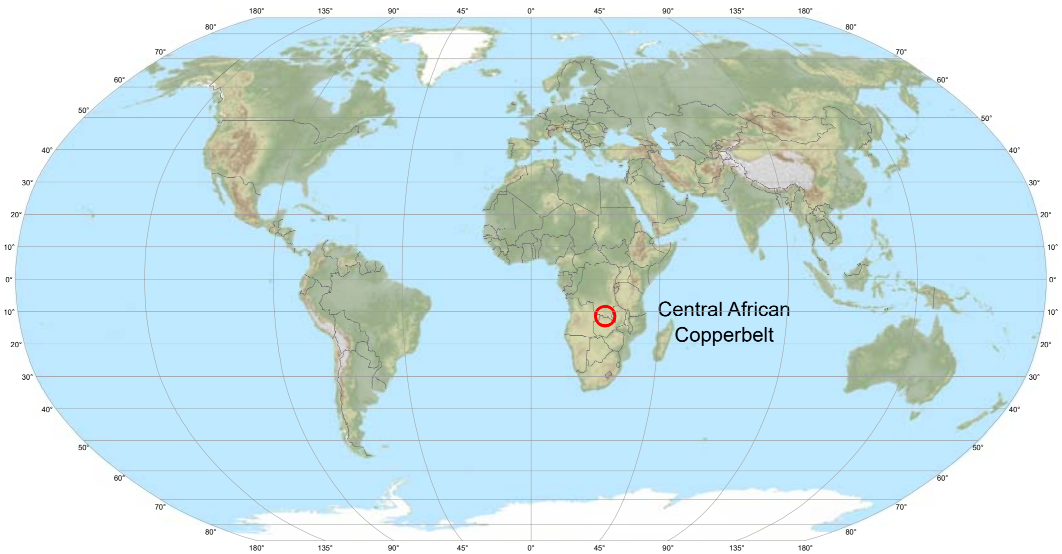
Cobalt—Sedimentary Rock-Hosted Stratiform Copper

- Only one sedimentary rock-hosted stratiform copper district contains economic cobalt resources—the Central African Copperbelt (CACB).
- In this district, only some deposits have economic (byproduct) cobalt:
  - Western portion of the Zambian Copperbelt (ZCB).
  - Most of the Congo Copperbelt (CCB), with the exception of the new Kamoa-Kakula deposit.
  - Tilwezembe structure (in the CCB) contains the most cobalt-rich deposits; several have grades sufficient for primary cobalt production (Kisanfu).
- Cobalt occurs as carrollite (hypogene).



Modified from Slack and others, in press.

- Cobalt grades:

Kisanfu	1.1%	Kolwezi	0.4%
Mukondo	0.7%	Tenke	0.3%
Tilwezembe	0.6%	Luanshya	0.2%
Nchanga	0.4%	Nkana	0.1%

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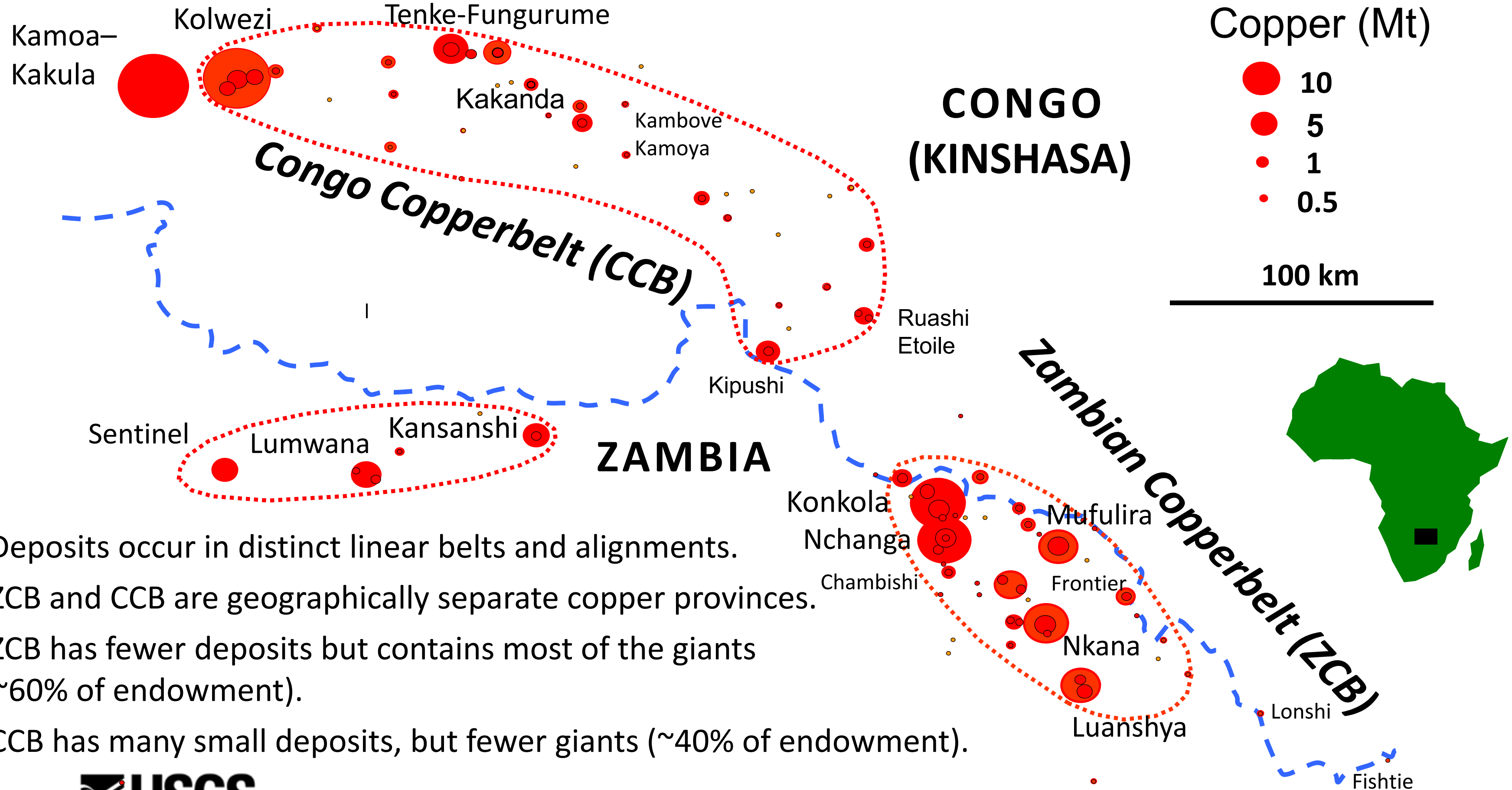
Spatial Distribution of Central African Copperbelt Copper Deposits



- Deposits occur in distinct linear belts and alignments.
- ZCB and CCB are geographically separate copper provinces.
- ZCB has fewer deposits but contains most of the giants (~60% of endowment).
- CCB has many small deposits, but fewer giants (~40% of endowment).

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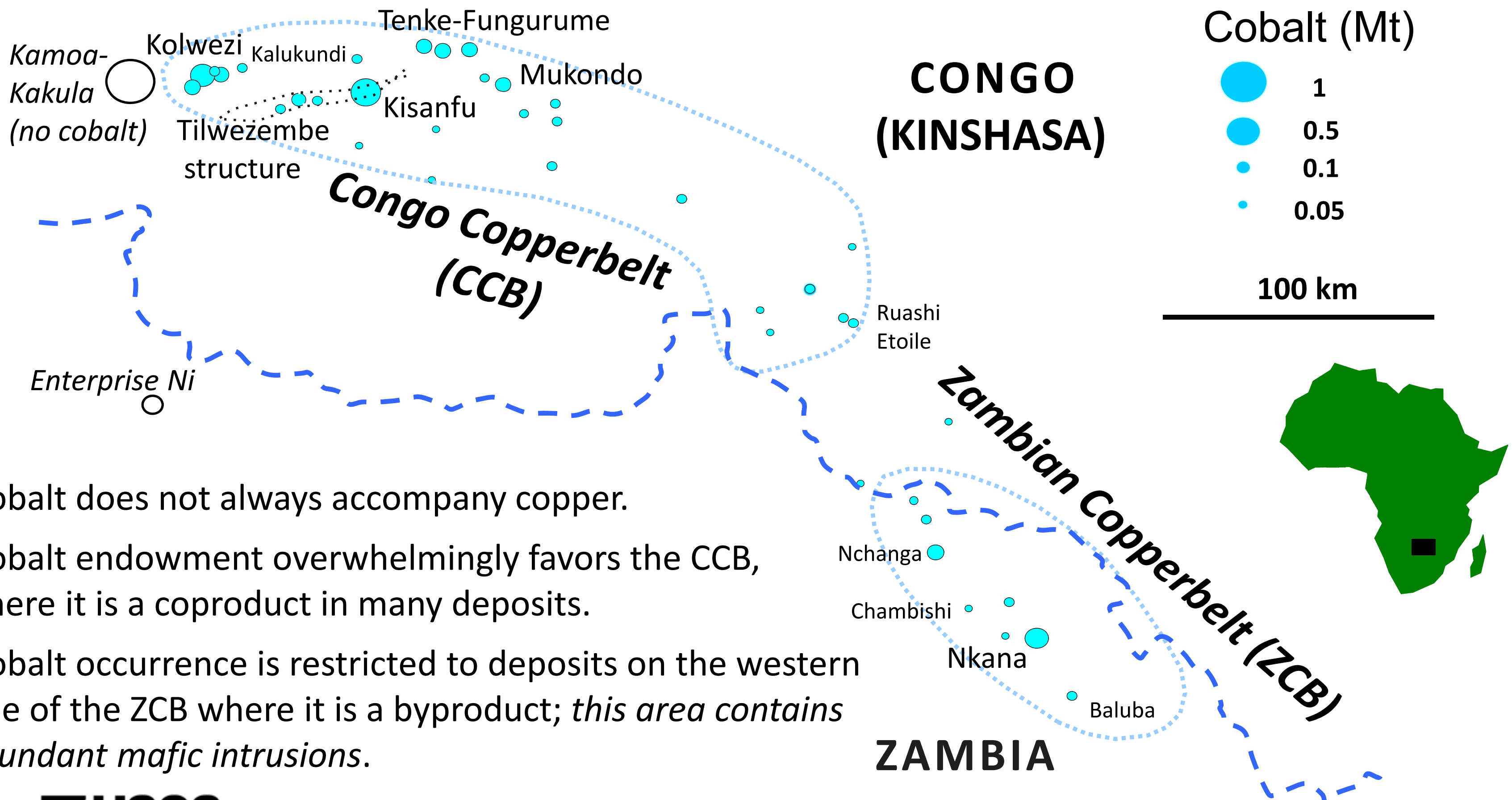
Spatial Distribution of Central African Copperbelt Cobalt Deposits



- Cobalt does not always accompany copper.
- Cobalt endowment overwhelmingly favors the CCB, where it is a coproduct in many deposits.
- Cobalt occurrence is restricted to deposits on the western side of the ZCB where it is a byproduct; *this area contains abundant mafic intrusions*.

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Cobalt—Sedimentary Rock-Hosted Stratiform Copper

- Although sedimentary rock-hosted stratiform copper deposits currently account for ~60% of the world's cobalt production, virtually all this output is from one district (CACB).
- An abundance of gabbroic intrusive rocks in the western ZCB and the presence of hydrothermal Ni deposits in the CACB (for example, Enterprise; Capistrant and others, 2015) suggest that mafic rocks may be an important metal source.
- Other sedimentary rock-hosted stratiform copper districts generally contain no or very minor amounts of cobalt (for example, Spar Lake [Montana], Kupferschiefer [central Europe], and Dzhezkazgan [Kazakhstan]).

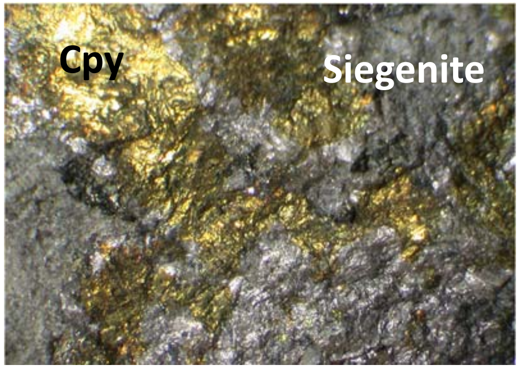
This type of deposit should not be considered a typical cobalt exploration target.

Cobalt—Other Deposit Types

- Sedimentary rock-hosted deposits
  - Mississippi Valley-type (MVT) deposits
  - Other carbonate-hosted Cu-(Zn-Pb) deposits
- "Synsedimentary and (or) Diagenetic"—a spectrum of deposits
- Co-Cu-Au deposits in metasedimentary rocks
- IOCG deposits
- Five-element vein deposits (Ag-Ni-Co-As-Bi)
- Hydrothermal deposits associated with ultramafic rocks

Cobalt—Mississippi Valley-Type (MVT) Deposits

- Several southeastern Missouri lead district (Old Lead Belt and Viburnum Trend) deposits have copper-rich zones beneath the lead orebodies that have in the past been mined for copper with byproduct cobalt.
- Cobalt occurs primarily in siegenite.
- Southeastern Missouri is an anomalous MVT district:
  - Pb>>Zn; presence of Cu-(Co, Ni).
  - Deposits formed close to Precambrian basement.



Gray metallic siegenite with brassy chalcopyrite in dull gray limestone. From Fredericktown, Missouri. Field of view is about 1.5 cm across. Photograph by W. Cordua, Minerals of Wisconsin, http://WGNHS.UWEX.edu/minerals/siegenite.

MVT carbonate-hosted Zn-Pb deposits generally do not contain cobalt.

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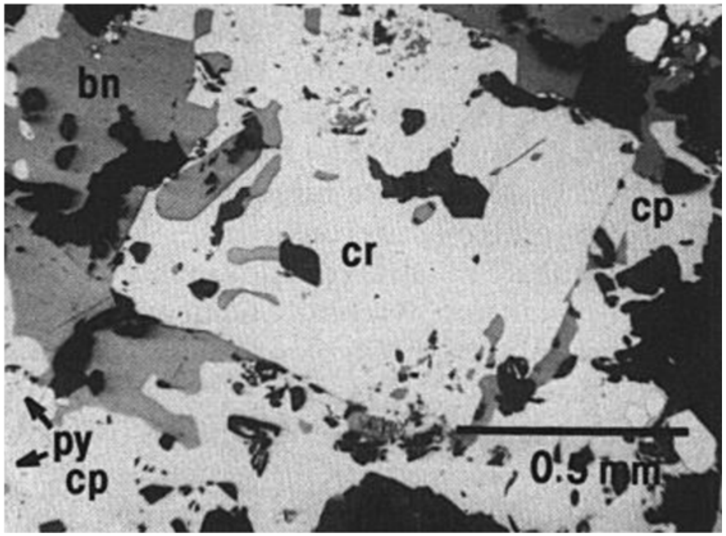
Cobalt—Other Carbonate-Hosted Cu-(Zn-Pb) Deposits

- Diverse group of deposits, some of which contain cobalt:
  - Ruby Creek (Bornite), Alaska—High-grade portions of the deposit contain up to 0.1% Co in early cobaltiferous pyrite and later carrollite replacing this pyrite.
  - Walford Creek Cu-Zn deposit (Australia) contains cobaltiferous pyrite (Vardy zone; 6.6 Mt at 0.16% Co; Aeon Metals Ltd., 2017, p. 8).
  - Mt. Isa Cu and Zn-Pb orebodies (Australia) contain cobaltiferous pyrite.



Carrollite intergrown with bornite and chalcopyrite and replacing cobaltiferous pyrite, Ruby Creek deposit, Alaska (Hitzman, 1986, fig. 17). bn, bornite; cp, chalcopyrite; cr, carrollite; py, pyrite

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Cobalt—“Synsedimentary and (or) Diagenetic” Deposits

Spectrum of deposits—**Besshi-type volcanogenic massive sulfide (VMS) deposits**.

- VMS deposits with enhanced cobalt—often termed “Besshi” after Cu-Zn-(Ag,Au) deposits in Japan—that contain ~0.05% Co in cobaltiferous pyrite, are generally iron sulfide rich, and occur in reduced C-rich (some Mn-rich) sediments with associated mafic-ultramafic rocks in back arc and oceanic rift environments.
    - Besshi (Japan)—30 Mt at 0.05% Co.
    - Windy Craggy (Canada)—138 Mt at 0.66% Co.
    - Outokumpu (Finland)—29 Mt at 0.25% Co.
    - Ducktown (Tennessee)—163 Mt, Co grade is unknown.

Pyritic massive sulfide from the Windy Craggy deposit. Image courtesy of Jan Peter.

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Cobalt—"Synsedimentary and (or) Diagenetic" Deposits

Spectrum of deposits—**Black shale deposits**.

- In black (C-rich) shales deposited in a rift basin with ultramafic rocks (now talc-carbonate).
- Shales may contain manganese as alabandite (MnS).
- Cobalt occurs primarily in cobaltiferous pyrite.
- Primary example is the Talvivaara deposit (Finland)—1,550 Mt at 0.02% Co, 0.22% Ni, 0.13% Cu, and 0.49% Zn.

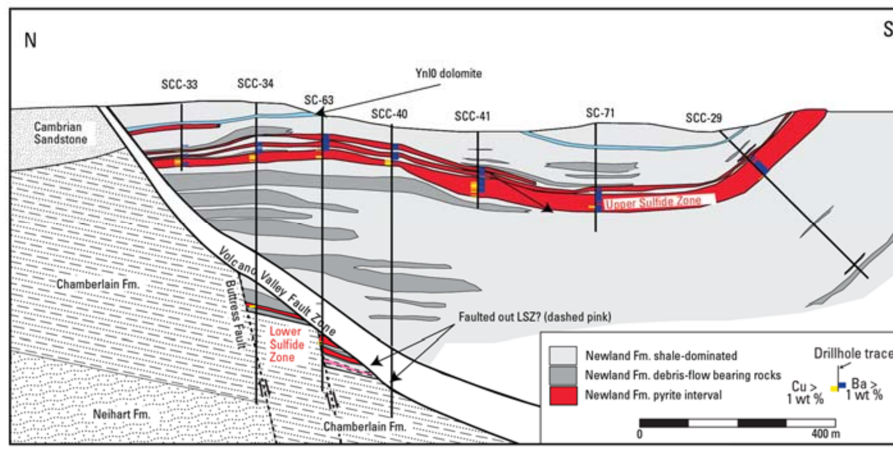
USGS

Cobalt—Other Sediment-Hosted Deposits

Spectrum of deposits—**Shale-hosted deposits**.

- Sullivan deposit (Canada) contained cobalt in arsenopyrite (not recovered).
- Sheep Creek (Black Butte), Montana, contains 9.1 Mt at 0.12% Co in cobaltiferous pyrite (minor amount of siegenite).

Stratiform pyrite, Sheep Creek, Montana (Graham and others, 2012, fig. 5e).



Cross section, Sheep Creek, Montana (Graham and others, 2012, fig. 7).

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Cobalt—“Synsedimentary and (or) Diagenetic” Deposits

Spectrum of deposits—**Mn-rich deposits**.

- Atlantis II Zn-Cu-(Ag, Co) (Red Sea)
  - Mudstones and chemical sediments in small basins in oceanic rift with evaporites above mafic volcanic and intrusive rocks.
  - Upper Mn-rich zone and lower Fe-rich zone (~89 Mt). Mn and Fe as oxyhydroxides with 0.05% Co.
- Boleo Cu-Zn-(Co) (Mexico)
  - Mudstones interbedded with siltstones and conglomerates deposited adjacent to evaporites and above basalts in proto-Gulf of California rift.
  - Stacked mantos of sulfide and Fe- and Mn-oxide-rich material (sulfide—264 Mt of 0.06% Co—in oxyhydroxides and cobaltiferous pyrite).

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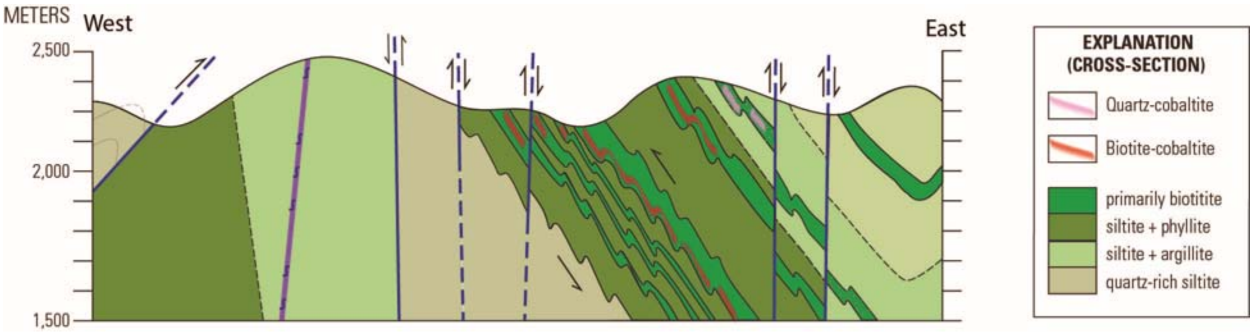
Spectrum of Co-bearing “Synsedimentary and (or) Diagenetic” Deposits

- These deposits formed on or near the sea floor surface by exhalation and infiltration of hydrothermal fluids (heated seawater) that reacted with sediments and mafic-ultramafic rocks to derive Fe-Cu-Zn-Co-Ni.
- These are fundamentally iron sulfide (and in some cases iron and manganese oxide) deposits with relatively minor amounts of trace metals.
- The presence of manganese is probably controlled by water depth and the oxidation state of both the hydrothermal fluids and the ocean water.
- The tectonic environments vary from incipient rifts with oceanic crust to back arc basins. The presence of evaporites in the section probably helps to increase hydrothermal fluid salinity and the ability of the fluids to carry additional cobalt.

Cobalt—Co-Cu-Au in Metasedimentary Rocks

- Stratabound to discordant zones of semimassive to locally massive sulfides within deformed siliciclastic metasedimentary rocks.
- Contain cobaltite with lesser amounts of (and later formed) chalcopyrite, pyrite, pyrrhotite, and cobaltiferous arsenopyrite.
- Primary example is the Blackbird district (Idaho) for which historical production plus current reserves total 17 Mt at 0.7% Co, 1.4% Cu, and 1 ppm Au (individual deposits are open at depth).

Cross section, Blackbird district: Sulfides are predominantly stratabound within metamorphosed Mesoproterozoic biotite-rich banded siltites of the Apple Creek Formation.



Modified from Bookstrom and others, 2014.

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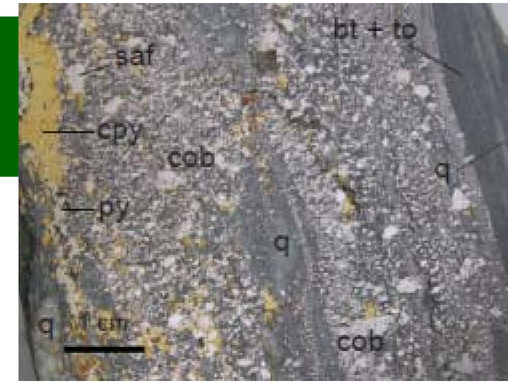
Cobalt—Blackbird District, Idaho



Photograph by Art Bookstrom.

- Host sediments are older than 1,410 Ma.
- Absence of significant mafic rocks in the area.
- The mineralized banded siltite unit was also pervasively biotitized (Fe^{2+}, Cl-rich).
- The cobaltite-biotite-(tourmaline-xenotime-Au) ore (dominant) is younger than the xenotime dated 1,370 Ma but older than the xenotime dated 1,316 to 1,270 Ma (Aleinikoff and others, 2012); the Re-Os age is 1,349$\pm$76 Ma (Saintilan and others, 2017). Time period includes an orogenic event.
- The mineralizing fluids were probably reduced and highly saline.
- There was an overprinting Cretaceous-age quartz-chalcopyrite-pyrite-cobaltiferous arsenopyrite-(Au) event.

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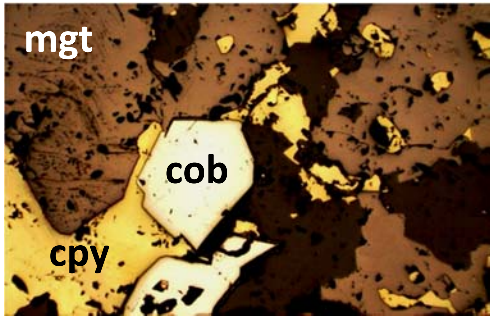
Cobalt—Iron Oxide-Copper-Gold (IOCG) Deposits

- IOCG deposits are a still poorly understood class of deposits apparently formed by crustal-scale hydrothermal systems that consist of significant iron oxides (magnetite and [or] hematite) with chalcopyrite and gold. They commonly contain a variety of trace metals, including U, Ag, Co, Ni, Bi, and often have extensive zones of potassic alteration enclosing the ore.
- Currently, no IOCGs are producing byproduct cobalt, although a number contain significant resources. The NICO deposit in Canada (Cu-poor IOCG variant) is slated to come into production as a primary cobalt producer.

Olympic Dam (Australia)	650 Mt at 0.02%
Ernest Henry (Australia)	166 Mt at 0.05%
Boss Bixby (Missouri)	40 Mt at 0.04%
NICO (Canada)	31 Mt at 0.12%
Guelb Moghrein (Mauritania)	24 Mt at 0.14%



Guelb Moghrein (Kirschbaum, 2011).

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Cobalt—Five-Element Vein Deposits

- Ag-Ni-Co-As-Bi-(U-REE) veins have been recognized as a distinctive ore type since the early 20th century (Bastin, 1939) and were the historic silver mines of Europe (Erzebirge [Czechoslovakia, Germany]; Schwarzwald [Germany]; Kongsberg [Norway]). In Canada, major districts are Cobalt-Gowganda, Thunder Bay, and Echo Bay. In the United States, similar deposits were mined at Wickenberg (Arizona) and Black Hawk (Silver City, New Mexico). All these deposits produced silver, some produced uranium, and a few produced cobalt.
- Grades and tonnage at many deposits are hard to determine owing to old records.
    - Keeley-Frontier Mine (Cobalt district) produced nearly 1,500 Mt at grades of 0.5% Co and 1,644 g/t Ag (The Northern Miner, 2017).

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Cobalt—Five-Element Vein Deposits (Continued)

- These deposits generally occur in crystalline terranes (metamorphic or granitic rocks) and do not appear to be genetically associated with magmatic rocks (mafic or felsic).
- The deposits typically consist of open-space-filling veins up to several meters in width that pinch and swell.
- Maximum depths to which veins have been mined is approximately 500 m and, in some districts, the veins are barren at depth.
- There is virtually no wallrock alteration around the veins. Where wallrock alteration is present, it is weak chloritization.

Five-Element Vein Deposits—Sequential Mineralogical Stages

(1) Early quartz with minor amounts of pyrite, sphalerite, galena.

(2) Uraninite-quartz.

(3) Native silver with Ni-Co arsenide minerals and sometimes native bismuth with calcite or dolomite.

(4) Pyrite, sphalerite, galena, chalcopyrite with native silver and argentite and calcite, and minor amounts of quartz, fluorite, and barite.

(5) Late-stage calcite, sometimes with barite or fluorite.

Cobalt—Five-Element Vein Deposits

- Several fluid inclusion studies indicate progression to the highest temperature (300 to 500 °C) during the Ag-Ni-Co stage, down to 150 °C during the sulfide stage, and to below 125 °C for late-stage calcite.
- Evidence of multiple pulses of fluids, multiple T maxima. High-temperature-stage fluids (Ag, Co, Ni, As) were NaCl saturated.
- Evidence of boiling in some districts, and trapping pressures at Cobalt, Ontario, suggest ore deposition at 700 m (Kerrich and others, 1986).

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Cobalt—Metased Co-Cu-Au—IOCG—Five-Element Vein

- These deposit types, though distinct, have some similarities:
  - Metal suite (Co, Ni, Ag, Au) with differences regarding amount of Fe, Cu, As, U, and Bi.
  - Formed by hydrothermal fluids that do not appear to be directly related to igneous activity.
  - Fluids with high salinity and low reduced sulfur content (generally low iron sulfides) at temperatures of ~500 to 250 °C.

Causative fluids formed by deep crustal heating?

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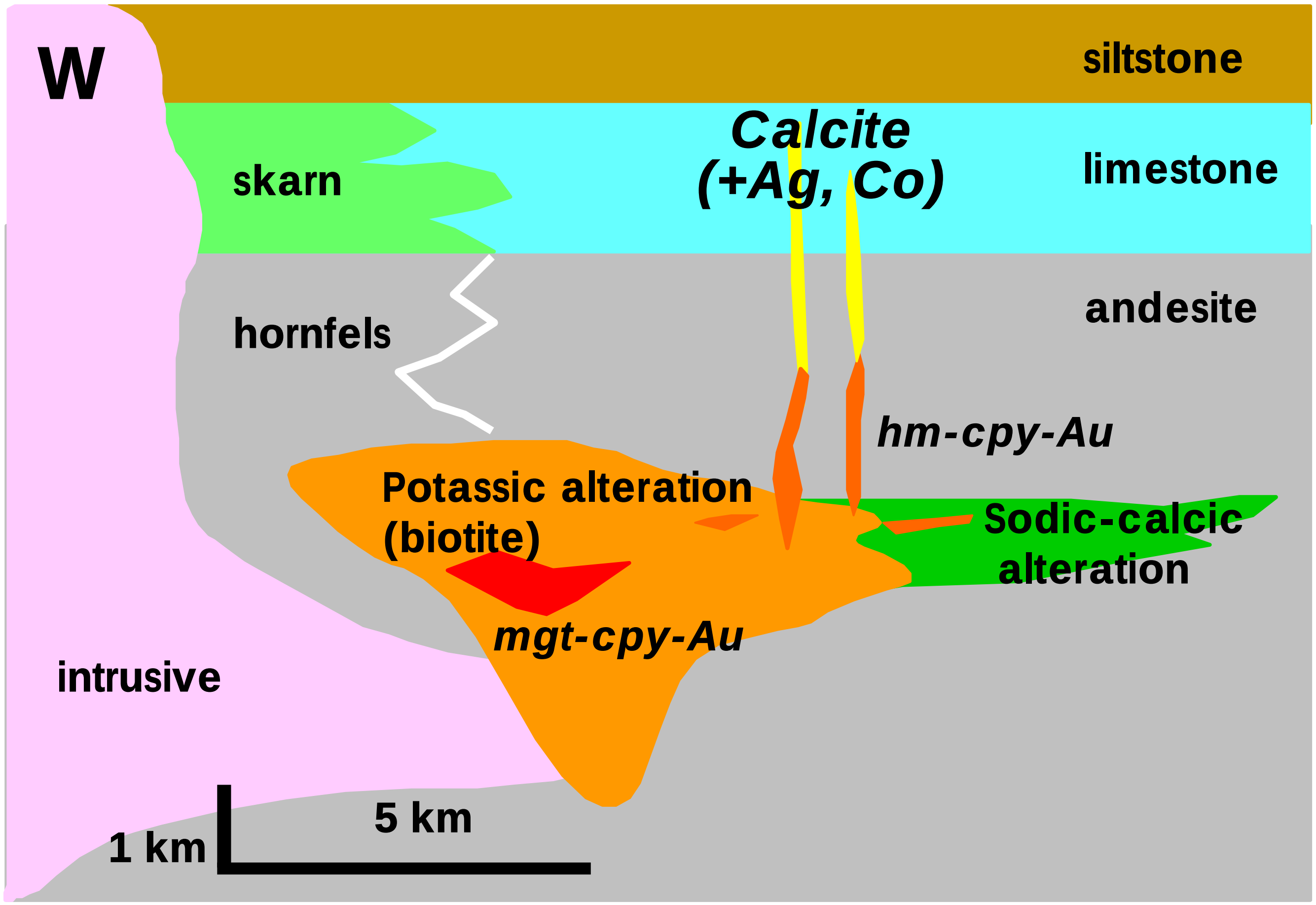
Candelaria District, Chile—A Model to Tie Together IOCG, Metased Co-Cu-Au, and Five-Element Vein Deposits?

- IOCG system with deep magnetite zone and hematite zone above the magnetite zone.
- Massive biotitite—analogy to Blackbird?
- System is capped by calcite veins containing Ag and Co (five-element veins).



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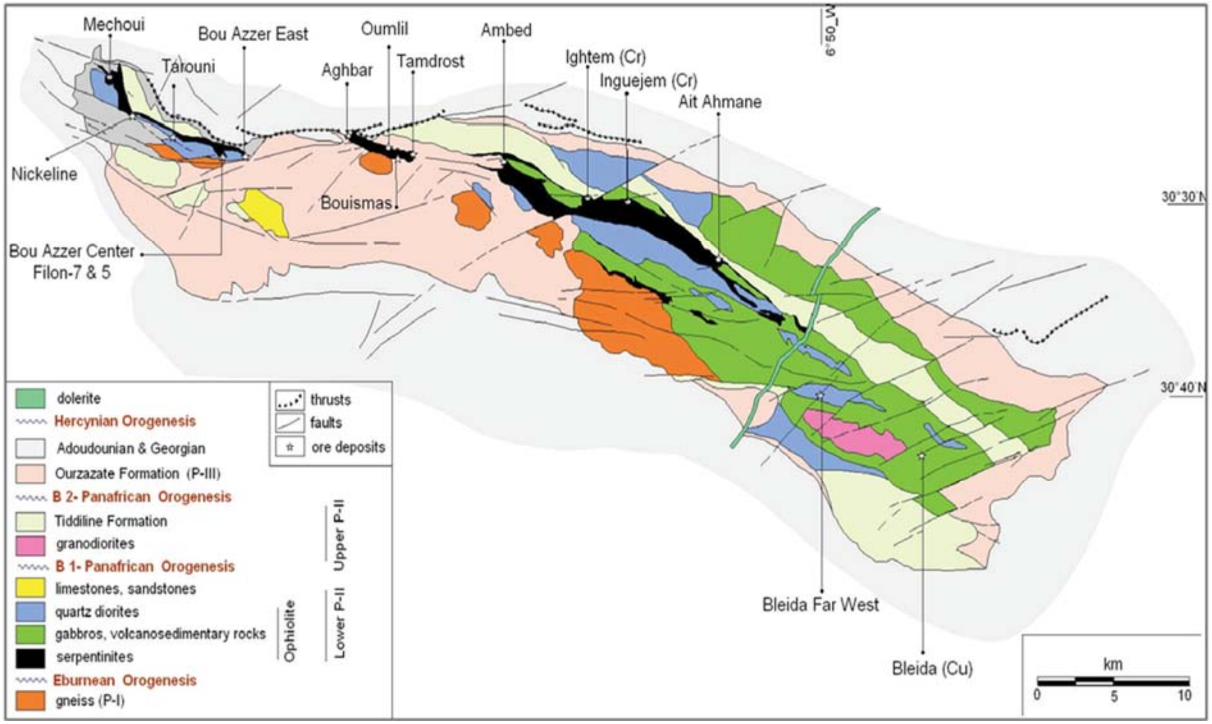
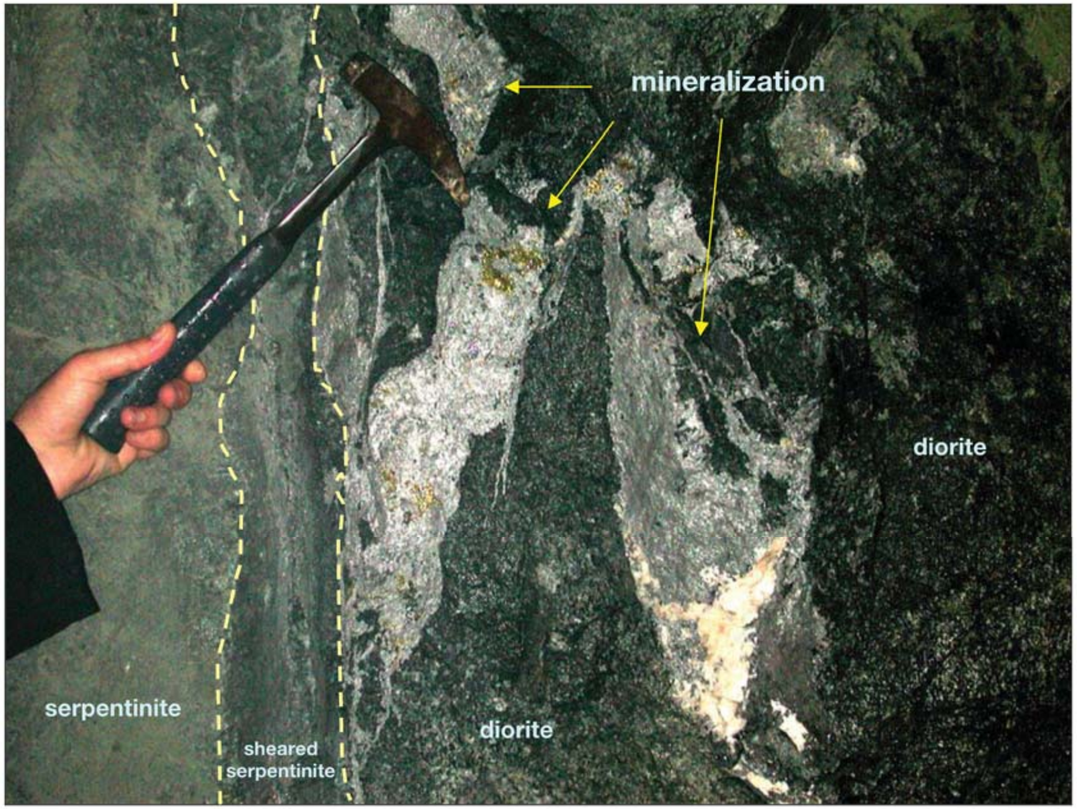
Cobalt—Hydrothermal Deposits Associated with Ultramafic Rocks (Bou Azzer District, Morocco)

- The Bou Azzer district of Morocco is a primary producer of cobalt (with byproduct nickel and gold).
- More than 60 individual deposits are known.
- District contains approximately 6 Mt at 1% Co, 1% Ni, and 3 g/t Au.



From Oberthür and others, 2009, fig. 1.

Cobalt—Hydrothermal Deposits Associated with Ultramafic Rocks



From Oberthür and others, 2009, fig. 2.

- Deposits occur as quartz-calcite veins immediately adjacent to Neoproterozoic serpentinites that are part of an ophiolite along a Pan-African suture zone.
- Mineralization occurred during the Hercynian orogeny (~310 Ma; Oberthür and others, 2009).

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Cobalt—Bou Azzer Cobalt Deposit

- There is a sequential increase in Co and As precipitation through time from Ni monoarsenides (nickeline) to Ni-Co diarsenides (rammelsburgite) to cobalt triarsenides (skutterudite) to sulfarsenides (arsenopyrite) to copper sulfides. Quartz and carbonate minerals fill spaces and fractures between ore minerals.
- The mineralogical paragenetic sequence is probably the result of decreasing temperatures, increasing pH, and decreasing oxygen fugacity—possibly owing to mixing of hydrothermal and meteoric fluids.
- Co, Ni, Fe, Cu and As were probably leached from the serpentinites by relatively low pH, saline fluids.
- The predominance of Co over Ni arsenide minerals despite the high Ni-Co ratio in the serpentinites is probably owing to the difference in the solubility of the elements in the hydrothermal fluid (Ahmed and others, 2009).

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Cobalt—Summary and Speculation

- Many cobalt deposits are associated with mafic-ultramafic rocks. The association can be:
  - *Close*—Ni-Co laterites, magmatic Ni-Cu sulfide deposits, hydrothermal deposits associated with ultramafic rocks.
  - *Intermediate*—Besshi-type VMS deposits, black shale deposits.
  - *Distant*—Central African Copperbelt, southeastern Missouri.
- The association is least evident in the metasedimentary Co-Cu-Au, IOCG, and five-element vein deposits.

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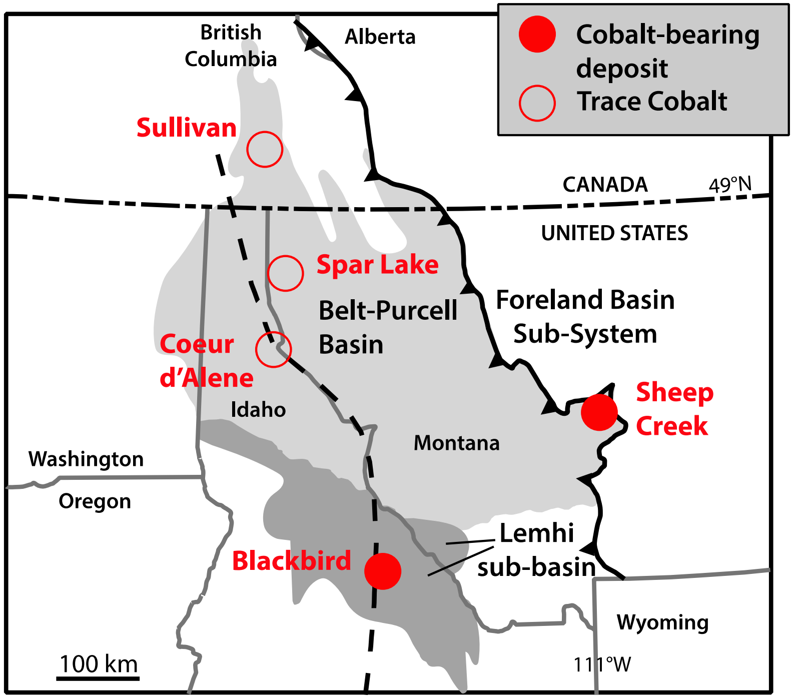
Cobalt—Summary and Speculation (Continued)

- The CACB is probably cobalt-rich owing to mafic-ultramafic rocks in the underlying basement.
- Most deposits in the Belt-Purcell basin also contain at least minor amounts of cobalt, suggesting that it may be similar to the CACB.
- Other styles of sedimentary rock-hosted cobalt deposits may be present in this basin.



Modified from Bookstrom and others, 2016.

Cobalt—Summary and Speculation (Continued)

- Primary Co deposits are restricted to hydrothermal deposits associated with ultramafic rocks and possibly some five-element vein deposits.
- Both deposit types—
  - Have relatively poorly defined exploration models.
  - Are small targets with weak alteration halos.
  - Probably represent primarily Ni-As-Co-Ag geochemical anomalies (elements that have not been routinely analyzed for in the past).
  - Are not significant geophysical targets.
  - Represent targets for which little exploration has yet been done.

Cobalt—U.S. Exploration

- Magmatic Ni-Cu in the Archean and Proterozoic rocks of the Midwest and the east coast (Pennsylvania) and younger mafic rocks in southeastern and southern Alaska. Also basement rocks in southeastern Missouri?
- Belt-Purcell basin for different styles of sedimentary rock-hosted cobalt deposits.
- Besshi-type VMS deposits—Is cobalt present in any of the ore lenses at the Greens Creek (Alaska) deposit? Cobalt resource present in Ducktown (Tennessee) waste and tailings?
- Known five-element vein districts in Arizona and New Mexico and potential for additional districts in crystalline rocks in and adjacent to the Basin and Range Province. Additionally, in the Yukon-Tanana terrane of Alaska, which has geologic similarities to European Hercynian terranes.
- Hydrothermal deposits associated with ultramafic rocks along the west coast, in Alaska, and in the Appalachian Mountains.

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