Critical Mineral Resources of the United States – Cobalt

Course No: P01-006
Credit: 1 PDH

James R. Weaver, P.E.

Continuing Education and Development, Inc.
22 Stonewall Court
Woodcliff Lake, NJ 07677

P: (877) 322-5800
info@cedengineering.com

Cobalt

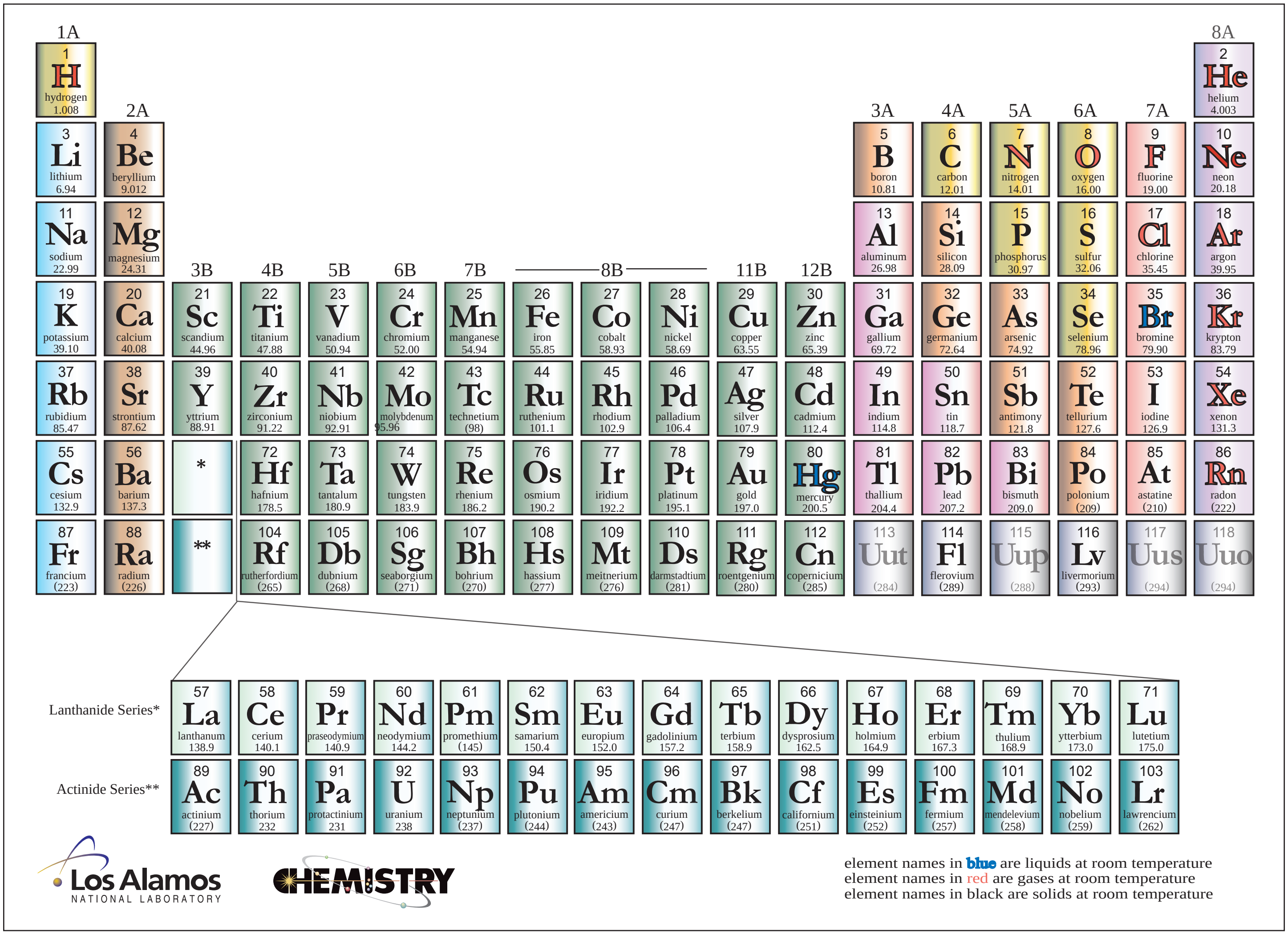
Chapter F of

Critical Mineral Resources of the United States—Economic and Environmental Geology and Prospects for Future Supply

Professional Paper 1802–F

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

Periodic Table of Elements



1A	2A	3B	4B	5B	6B	7B	8B			11B	12B	3A	4A	5A	6A	7A	8A
1 H hydrogen 1.008																	2 He helium 4.003
3 Li lithium 6.94	4 Be beryllium 9.012											5 B boron 10.81	6 C carbon 12.01	7 N nitrogen 14.01	8 O oxygen 16.00	9 F fluorine 19.00	10 Ne neon 20.18
11 Na sodium 22.99	12 Mg magnesium 24.31											13 Al aluminum 26.98	14 Si silicon 28.09	15 P phosphorus 30.97	16 S sulfur 32.06	17 Cl chlorine 35.45	18 Ar argon 39.95
19 K potassium 39.10	20 Ca calcium 40.08	21 Sc scandium 44.96	22 Ti titanium 47.88	23 V vanadium 50.94	24 Cr chromium 52.00	25 Mn manganese 54.94	26 Fe iron 55.85	27 Co cobalt 58.93	28 Ni nickel 58.69	29 Cu copper 63.55	30 Zn zinc 65.39	31 Ga gallium 69.72	32 Ge germanium 72.64	33 As arsenic 74.92	34 Se selenium 78.96	35 Br bromine 79.90	36 Kr krypton 83.79
37 Rb rubidium 85.47	38 Sr strontium 87.62	39 Y yttrium 88.91	40 Zr zirconium 91.22	41 Nb niobium 92.91	42 Mo molybdenum 95.96	43 Tc technetium (98)	44 Ru ruthenium 101.1	45 Rh rhodium 102.9	46 Pd palladium 106.4	47 Ag silver 107.9	48 Cd cadmium 112.4	49 In indium 114.8	50 Sn tin 118.7	51 Sb antimony 121.8	52 Te tellurium 127.6	53 I iodine 126.9	54 Xe xenon 131.3
55 Cs cesium 132.9	56 Ba barium 137.3	*	72 Hf hafnium 178.5	73 Ta tantalum 180.9	74 W tungsten 183.9	75 Re rhenium 186.2	76 Os osmium 190.2	77 Ir iridium 192.2	78 Pt platinum 195.1	79 Au gold 197.0	80 Hg mercury 200.5	81 Tl thallium 204.4	82 Pb lead 207.2	83 Bi bismuth 209.0	84 Po polonium (209)	85 At astatine (210)	86 Rn radon (222)
87 Fr francium (223)	88 Ra radium (226)	**	104 Rf rutherfordium (265)	105 Db dubnium (268)	106 Sg seaborgium (271)	107 Bh bohrium (270)	108 Hs hassium (277)	109 Mt meitnerium (276)	110 Ds darmstadtium (281)	111 Rg roentgenium (280)	112 Cn copernicium (285)	113 Uut (284)	114 Fl flerovium (289)	115 Uup (288)	116 Lv livermorium (293)	117 Uus (294)	118 Uuo (294)

Lanthanide Series*	57 La lanthanum 138.9	58 Ce cerium 140.1	59 Pr praseodymium 140.9	60 Nd neodymium 144.2	61 Pm promethium (145)	62 Sm samarium 150.4	63 Eu europium 152.0	64 Gd gadolinium 157.2	65 Tb terbium 158.9	66 Dy dysprosium 162.5	67 Ho holmium 164.9	68 Er erbium 167.3	69 Tm thulium 168.9	70 Yb ytterbium 173.0	71 Lu lutetium 175.0
Actinide Series**	89 Ac actinium (227)	90 Th thorium 232	91 Pa protactinium 231	92 U uranium 238	93 Np neptunium (237)	94 Pu plutonium (244)	95 Am americium (243)	96 Cm curium (247)	97 Bk berkelium (247)	98 Cf californium (251)	99 Es einsteinium (252)	100 Fm fermium (257)	101 Md mendelevium (258)	102 No nobelium (259)	103 Lr lawrencium (262)

element names in blue are liquids at room temperature
element names in red are gases at room temperature
element names in black are solids at room temperature

Modified from Los Alamos National Laboratory Chemistry Division; available at http://periodic.lanl.gov/images/periodictable.pdf.

Cover. Underground photo of the Skuterud Mine in Norway showing pink secondary erythrite (a hydrated cobalt arsenate mineral). Photograph by John F. Slack, U.S. Geological Survey.

Cobalt

By John F. Slack, Bryn E. Kimball, and Kim B. Shedd

Chapter F of

Critical Mineral Resources of the United States—Economic and Environmental Geology and Prospects for Future Supply

Edited by Klaus J. Schulz, John H. DeYoung, Jr., Robert R. Seal II, and Dwight C. Bradley

Professional Paper 1802–F

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

U.S. Department of the Interior
RYAN K. ZINKE, Secretary

U.S. Geological Survey
William H. Werkheiser, Acting Director

U.S. Geological Survey, Reston, Virginia: 2017

Suggested citation:
Slack, J.F., Kimball, B.E., and Shedd, K.B., 2017, Cobalt, chap. F *of* Schulz, K.J., DeYoung, J.H., Jr., Seal, R.R., II, and Bradley, D.C., eds., Critical mineral resources of the United States—Economic and environmental geology and prospects for future supply: U.S. Geological Survey Professional Paper 1802, p. F1–F40, https://doi.org/10.3133/pp1802F.

ISSN 2330-7102 (online)

Contents

Abstract F1
Introduction F1
  Cobalt Uses, Demand, and Availability of Supply F1
  Strategic and Critical Resource Issues F3
Geology F4
  Geochemistry F4
  Mineralogy F4
  Principal Deposit Types F4
    Stratiform Sediment-Hosted Cu-Co Deposits F4
    Ni-Co Laterite Deposits F4
    Magmatic Ni-Cu(-Co-PGE) Sulfide Deposits F5
  Other Deposit Types F5
    Black-Shale-Hosted Ni-Cu-Zn-Co Deposits F5
    Fe-Cu-Co Skarn and Replacement Deposits F5
    Iron Oxide-Cu-Au(-Ag-U-REE-Co-Ni) Deposits F8
    Metasedimentary-Rock-Hosted Co-Cu-Au Deposits F8
    Mississippi Valley-Type Zn-Pb(-Co-Ni) Sulfide Deposits F8
    Polymetallic (Ag-Ni-Co-As-Bi) and Other Cobalt-Rich Vein Deposits F8
    Volcanogenic Cu(-Zn-Co-Ag-Au) Massive Sulfide Deposits F8
    Sea-Floor Fe-Mn(-Ni-Cu-Co-Mo) Nodules F9
    Sea-Floor Fe-Mn(-Co-Mo-REE) Crusts F9
    Sea-Floor Volcanogenic Cu(-Zn-Co-Ag-Au) Massive Sulfide Deposits F9
Resources and Production F10
  Production and Identified Resources F10
    Grade-Tonnage Characteristics F10
    Mining Methods F13
    Typical Mine Life F14
    Ore-Processing Methods F14
  Undiscovered Resources F14
  Unconventional Resources F14
    Metamorphosed Black Shales F14
    Modern Sea-Floor Volcanogenic Massive Sulfide Deposits F15
    Ancient Ni-Co Laterites F15
    Ancient Fe-Mn(-Cu-Co-Ni) Nodules F15
    Ancient Cobalt-Rich Manganese Deposits F15
    Ultramafic Igneous Rocks F15
Exploration for New Deposits F15
Environmental Considerations F16
  Sources and Fate in the Environment F16
  Mine Waste Characteristics F16
  Human Health Concerns F17
  Ecological Health Concerns F18
  Mine Closure F19
Problems and Future Research F19
Acknowledgments F20
References Cited F20

Figures

F1. Pie chart showing major end uses of cobalt as a percentage of consumption worldwide in 2011 ....F2
F2. Bar chart showing world cobalt mine and refinery production and apparent consumption from 2007 to 2011 ....F2
F3. Graph showing world cobalt mine production from 1950 to 2011 ....F3
F4. Pie chart showing percentage of world cobalt mine production in 2011, by country F3
F5. Pie chart showing percentage of world cobalt mine production in 2011, by deposit type....F10
F6. Grade-tonnage plot for 214 cobalt deposits worldwide F11
F7. World map showing global distribution of major cobalt-bearing mineral deposits and selected smaller deposits that represent minor types....F12
F8. Pie charts showing proportions of cobalt contained in mineral deposits worldwide, by deposit type F13

Tables

F1. Location, grade, tonnage, and other data for selected cobalt deposits of the world....F34
F2. Cobalt concentrations in rocks, soils, waters, and air....F6

Conversion Factors

International System of Units to Inch/Pound

Multiply	By	To obtain
Length		
angstrom (Å) (0.1 nanometer)	0.003937	microinch
angstrom (Å) (0.1 nanometer)	0.000003937	mil
micrometer (µm) [or micron]	0.03937	mil
millimeter (mm)	0.03937	inch (in.)
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)
kilometer (km)	0.6214	mile (mi)
Area		
hectare (ha)	2.471	acre
square kilometer (km^2)	247.1	acre
square meter (m^2)	10.76	square foot (ft^2)
square centimeter (cm^2)	0.1550	square inch (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
Volume		
milliliter (mL)	0.03381	ounce, fluid (fl. oz)
liter (L)	33.81402	ounce, fluid (fl. oz)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)
cubic meter (m^3)	264.2	gallon (gal)
cubic centimeter (cm^3)	0.06102	cubic inch (in^3)
cubic meter (m^3)	1.308	cubic yard (yd^3)
cubic kilometer (km^3)	0.2399	cubic mile (mi^3)
Mass		
microgram (µg)	0.00000003527	ounce, avoirdupois (oz)
milligram (mg)	0.00003527	ounce, avoirdupois (oz)
gram (g)	0.03527	ounce, avoirdupois (oz)
gram (g)	0.03215075	ounce, troy
kilogram (kg)	32.15075	ounce, troy
kilogram (kg)	2.205	pound avoirdupois (lb)
ton, metric (t)	1.102	ton, short [2,000 lb]
ton, metric (t)	0.9842	ton, long [2,240 lb]
Deposit grade		
gram per metric ton (g/t)	0.0291667	ounce per short ton (2,000 lb) (oz/T)
Pressure		
megapascal (MPa)	10	bar
gigapascal (GPa)	10,000	bar
Density		
gram per cubic centimeter (g/cm^3)	62.4220	pound per cubic foot (lb/ft^3)
milligram per cubic meter (mg/m^3)	0.00000006243	pound per cubic foot (lb/ft^3)
Energy		
joule (J)	0.0000002	kilowatthour (kWh)
joule (J)	6.241×10^{18}	electronvolt (eV)
joule (J)	0.2388	calorie (cal)
kilojoule (kJ)	0.0002388	kilocalorie (kcal)

International System of Units to Inch/Pound

Multiply	By	To obtain
Radioactivity		
becquerel (Bq)	0.00002703	microcurie (µCi)
kilobecquerel (kBq)	0.02703	microcurie (µCi)
Electrical resistivity		
ohm meter (Ω-m)	39.37	ohm inch (Ω-in.)
ohm-centimeter (Ω-cm)	0.3937	ohm inch (Ω-in.)
Thermal conductivity		
watt per centimeter per degree Celsius (watt/cm °C)	693.1798	International British thermal unit inch per hour per square foot per degree Fahrenheit (Btu in/h ft^2 °F)
watt per meter kelvin (W/m-K)	6.9318	International British thermal unit inch per hour per square foot per degree Fahrenheit (Btu in/h ft^2 °F)

Inch/Pound to International System of Units

Length		
mil	25.4	micrometer (µm) [or micron]
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Volume		
ounce, fluid (fl. oz)	29.57	milliliter (mL)
ounce, fluid (fl. oz)	0.02957	liter (L)
Mass		
ounce, avoirdupois (oz)	28,350,000	microgram
ounce, avoirdupois (oz)	28,350	milligram
ounce, avoirdupois (oz)	28.35	gram (g)
ounce, troy	31.10 348	gram (g)
ounce, troy	0.03110348	kilogram (kg)
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ton, short (2,000 lb)	0.9072	ton, metric (t)
ton, long (2,240 lb)	1.016	ton, metric (t)
Deposit grade		
ounce per short ton (2,000 lb) (oz/T)	34.285714	gram per metric ton (g/t)
Energy		
kilowatthour (kWh)	3,600,000	joule (J)
electronvolt (eV)	1.602×10^{-19}	joule (J)
Radioactivity		
microcurie (µCi)	37,000	becquerel (Bq)
microcurie (µCi)	37	kilobecquerel (kBq)

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

$$°F = (1.8 \times °C) + 32$$

Temperature in degrees Celsius (°C) may be converted to kelvin (K) as follows:

$$K = °C + 273.15$$

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

$$°C = (°F - 32) / 1.8$$

Datum

Unless otherwise stated, vertical and horizontal coordinate information is referenced to the World Geodetic System of 1984 (WGS 84). Altitude, as used in this report, refers to distance above the vertical datum.

Supplemental Information

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in soils and (or) sediment are given in milligrams per kilogram (mg/kg), parts per million (ppm), or parts per billion (ppb).

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L), micrograms per liter (µg/L), nanogams per liter (ng/L), nanomoles per kilogram (nmol/kg), parts per million (ppm), parts per billion (ppb), or parts per trillion (ppt).

Concentrations of suspended particulates in water are given in micrograms per gram (µg/g), milligrams per kilogram (mg/kg), or femtograms per gram (fg/g).

Concentrations of chemicals in air are given in units of the mass of the chemical (milligrams, micrograms, nanograms, or picograms) per volume of air (cubic meter).

Activities for radioactive constituents in air are given in microcuries per milliliter (µCi/mL).

Deposit grades are commonly given in percent, grams per metric ton (g/t)—which is equivalent to parts per million (ppm)—or troy ounces per short ton (oz/T).

Geologic ages are expressed in mega-annum (Ma, million years before present, or 10^6 years ago) or giga-annum (Ga, billion years before present, or 10^9 years ago).

For ranges of years, “to” and (or) the en dash (“–”) mean “up to and including.”

Concentration unit	Equals
milligram per kilogram (mg/kg)	part per million
microgram per gram (µg/g)	part per million
microgram per kilogram (µg/kg)	part per billion (10^9)

Equivalencies

part per million (ppm): 1 ppm = 1,000 ppb = 1,000,000 ppt = 0.0001 percent

part per billion (ppb): 0.001 ppm = 1 ppb = 1,000 ppt = 0.0000001 percent

part per trillion (ppt): 0.000001 ppm = 0.001 ppb = 1 ppt = 0.0000000001 percent

Metric system prefixes

tera- (T-)	10^{12}	1 trillion
giga- (G-)	10^{9}	1 billion
mega- (M-)	10^{6}	1 million
kilo- (k-)	10^{3}	1 thousand
hecto- (h-)	10^{2}	1 hundred
deka- (da-)	10	1 ten
deci- (d-)	10^{-1}	1 tenth
centi- (c-)	10^{-2}	1 hundredth
milli- (m-)	10^{-3}	1 thousandth
micro- (µ-)	10^{-6}	1 millionth
nano- (n-)	10^{-9}	1 billionth
pico- (p-)	10^{-12}	1 trillionth
femto- (f-)	10^{-15}	1 quadrillionth
atto- (a-)	10^{-18}	1 quintillionth

Abbreviations and Symbols

δ-MnO_2	delta-manganese dioxide
µCi/mL	microcurie per milliliter
µg/g	microgram per gram
µg/kg	microgram per kilogram
µg/L	microgram per liter
Å	angstrom
AMD	acid mine drainage
CCD	carbonate compensation depth
CCZ	Clarion-Clipperton zone
cm	centimeter
Congo (Kinshasa)	Democratic Republic of the Congo
EC_{50}	effective concentration 50 (concentration that results in 50 percent exhibiting decreased functionality)
EEZ	Exclusive Economic Zone
EIS	environmental impact statement
EPA	U.S. Environmental Protection Agency
IOCG	iron oxide-copper-gold
LC_{50}	lethal concentration 50 (concentration that kills 50 percent of test population within a given timeframe)
m	meter
mg/kg	milligram per kilogram
mg/L	milligram per liter
MTR	Maderia-Tore Rise
MVT	Mississippi Valley-type
ng/m^3	nanogram per cubic meter
NTP	National Toxicology Program
PGE	platinum-group element
ppm	part per million
REE	rare-earth element
VMS	volcanogenic massive sulfide

Cobalt

By John F. Slack, Bryn E. Kimball, and Kim B. Shedd

Abstract

Cobalt is a silvery gray metal that has diverse uses based on certain key properties, including ferromagnetism, hardness and wear-resistance when alloyed with other metals, low thermal and electrical conductivity, high melting point, multiple valences, and production of intense blue colors when combined with silica. Cobalt is used mostly in cathodes in rechargeable batteries and in superalloys for turbine engines in jet aircraft. Annual global cobalt consumption was approximately 75,000 metric tons in 2011; China, Japan, and the United States (in order of consumption amount) were the top three cobalt-consuming countries. In 2011, approximately 109,000 metric tons of recoverable cobalt was produced in ores, concentrates, and intermediate products from cobalt, copper, nickel, platinum-group-element (PGE), and zinc operations. The Democratic Republic of the Congo (Congo [Kinshasa]) was the principal source of mined cobalt globally (55 percent). The United States produced a negligible amount of byproduct cobalt as an intermediate product from a PGE mining and refining operation in southeastern Montana; no U.S. production was from mines in which cobalt was the principal commodity. China was the leading refiner of cobalt, and much of its production came from cobalt ores, concentrates, and partially refined materials imported from Congo (Kinshasa).

The mineralogy of cobalt deposits is diverse and includes both primary (hypogene) and secondary (supergene) phases. Principal terrestrial (land-based) deposit types, which represent most of world's cobalt mine production, include primary magmatic Ni-Cu(-Co-PGE) sulfides, primary and secondary stratiform sediment-hosted Cu-Co sulfides and oxides, and secondary Ni-Co laterites. Seven additional terrestrial deposit types are described in this chapter. The total terrestrial cobalt resource (reserves plus other resources) plus past production, where available, is calculated to be 25.5 million metric tons. Additional resources of cobalt are known to occur on the modern sea floor in aerially extensive deposits of Fe-Mn(-Ni-Cu-Co-Mo) nodules and Fe-Mn(-Co-Mo-rare-earth-element) crusts. Legal, economic, and technological barriers have prevented exploitation of these cobalt resources, which lie at water depths of as great as 6,000 meters, although advances in technology may soon allow production of these resources to be economically viable.

Environmental issues related to cobalt mining concern mainly the elevated cobalt contents in soils and waters. Although at low levels cobalt is essential to human health (it is the central atom in the critical nutrient vitamin B_{12}), overexposure to high levels of cobalt may cause lung and heart dysfunction, as well as dermatitis. The ecological impacts of cobalt vary widely and can be severe for some species of fish and plants, depending on various environmental factors.

Introduction

Cobalt Uses, Demand, and Availability of Supply

Cobalt is a technologically important metal that has many diverse uses, including in batteries, superalloys, and cemented carbides and diamond tools (fig. F1). Globally, the leading use is in the manufacture of cathode materials for rechargeable batteries, primarily lithium-ion, nickel-cadmium, and nickel-metal-hydride batteries, which are used in consumer electronics, electric and hybrid-electric vehicles, energy storage units, and power tools. Superalloys are alloys developed for high-temperature service where relatively high mechanical stress is encountered and where surface stability is frequently required. The principal use for superalloys is in parts for turbine engines for jet aircraft and terrestrial energy generation. Cemented carbides, which are composite materials made of cobalt and tungsten carbide, are used as cutting tools and wear-resistant components by the metalworking, mining, oil and gas drilling, and construction industries. Diamond tools are similar to cemented carbides in that cobalt is the matrix that binds the wear-resistant particles together. Cobalt is used to make permanent and soft magnetic alloys. Cobalt-bearing steels include high-speed steels for cutting tools and maraging steels, which are characterized by their great strength, toughness, and workability. Other cobalt-bearing alloys are characterized by their resistance to corrosion and (or) wear or by their particular thermal expansion properties. Additional chemical applications for cobalt include animal feed additives; bonding agents in steel-belted radial tires; catalysts for chemical, petroleum, and other industries; drying agents for paint; glass decolorizers; ground coat frits for porcelain enamels; humidity indicators; magnetic recording media; pigments; and vitamin B_{12}.

In recent years, annual global cobalt consumption (shown as "apparent consumption" in fig. F2) has generally trended upward to approximately 75,000 metric tons. World apparent consumption is the sum of apparent consumption calculated for individual countries; the calculation for each country uses reported data for production, trade, and stock variations, where available. China, Japan, and the United States (in order of consumption amount) are the top three cobalt-consuming countries (Cobalt Development Institute and World Bureau of Metal Statistics, 2011; Cobalt Development Institute, 2012).

From 1950 to 2011, global mine production of cobalt increased by more than an order of magnitude (fig. F3). In 2011, approximately 109,000 metric tons of recoverable cobalt was produced in ores, concentrates, and intermediate products from cobalt, copper, nickel, platinum-group-element (PGE), and zinc operations (fig. F2). More than one-half of the world's cobalt was mined in the Democratic Republic of the Congo (Congo [Kinshasa]). Other leading countries where cobalt was mined are shown in figure F4 (Shedd, 2013a). Trends in cobalt mineral exploration and supply are discussed in Wilburn (2012), Menzie and others (2013), and Shedd (2013a). Deposit types from which cobalt currently is mined are discussed in the Resources and Production section of this chapter. Table F1 (back of chapter) gives locations and grade-tonnage data for significant cobalt deposits of the world.

In 2011, the United States produced a negligible amount of byproduct cobalt as an intermediate product from Stillwater Mining Co.'s PGE mining and refining operation in southeastern Montana. Since then, minor amounts of byproduct cobalt in nickel concentrate have been produced from Lundin Mining Corp.'s underground Eagle Mine, which is a high-grade magmatic Ni-Cu(-Co-PGE) sulfide orebody located northwest of Marquette, Michigan, where mining began in 2014. No U.S. production was from mines in which cobalt was the principal commodity. Other projects in the feasibility and development stages include Formation Metals Inc.'s underground cobalt mine to be constructed in a strata-bound Co-Cu-Au deposit in the Blackbird district (part of the Idaho cobalt belt) in Lemhi County and PolyMet Mining Corp.'s open pit mine to be constructed in the NorthMet Cu-Ni-Co-PGE deposit in the Duluth Complex, which is a large mafic intrusive complex in northeastern Minnesota. Cobalt would be produced as a byproduct from the NorthMet project.

China was the leading refiner of cobalt in 2011, with much of its production coming from cobalt ores, concentrates, and partially refined materials imported from Congo (Kinshasa). Other significant sources of refined cobalt were Australia, Belgium, Canada, Congo (Kinshasa), Finland, Norway, and Zambia. Refined cobalt from Belgium and Finland was wholly or mainly produced from imported material, respectively (Shedd, 2013a).

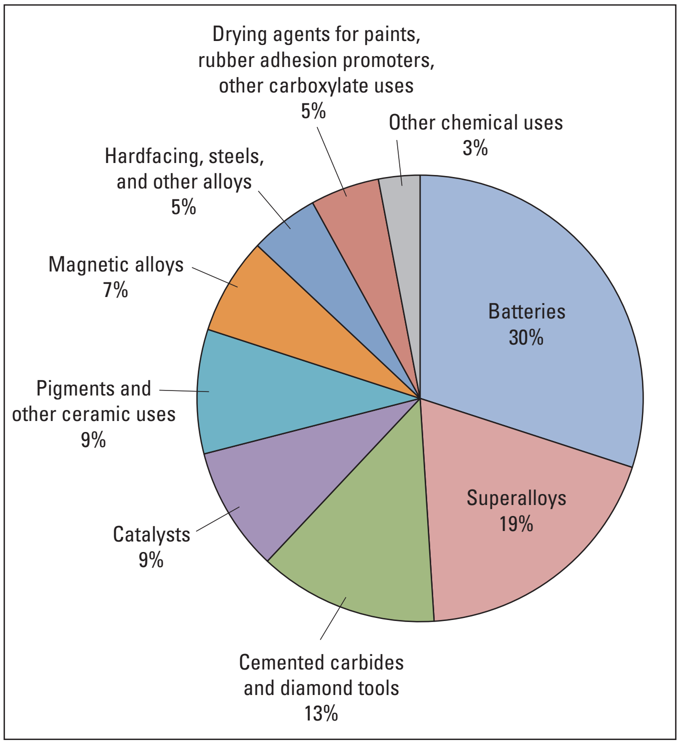


Figure F1. Pie chart showing major end uses of cobalt as a percentage of consumption worldwide in 2011. Data are from the Cobalt Development Institute (2012).

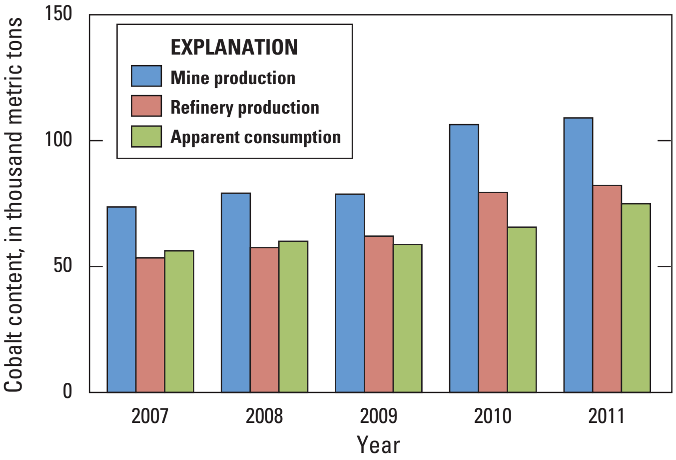


Figure F2. Bar chart showing world cobalt mine and refinery production and apparent consumption from 2007 to 2011. Mine production consists of the recoverable cobalt content of ores, concentrates, and intermediate products from cobalt, copper, nickel, platinum-group-element, and zinc operations. World apparent consumption is the sum of apparent consumption calculated for individual countries. The calculation for each country uses reported data for production, trade, and stock variations, where available. Apparent consumption data are from the Cobalt Development Institute and World Bureau of Metal Statistics (2011) and the Cobalt Development Institute (2012); production data are from Shedd (2013a).

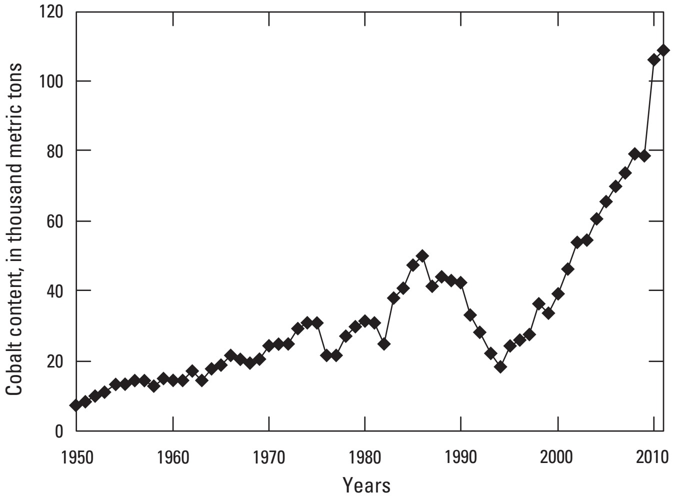


Figure F3. Graph showing world cobalt mine production from 1950 to 2011. Production consists of the recoverable cobalt content of ores, concentrates, and intermediate products from cobalt, copper, nickel, platinum-group-element, and zinc operations. Data are from U.S. Geological Survey (2013).

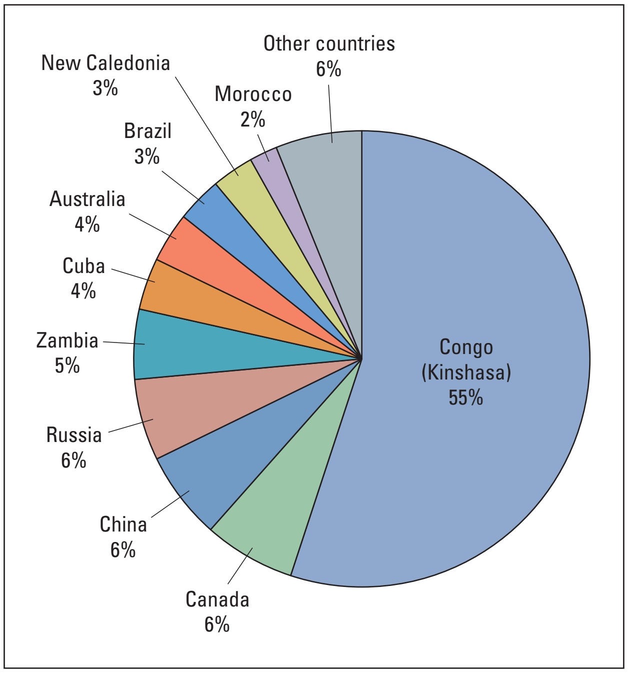


Figure F4. Pie chart showing percentage of world cobalt mine production in 2011, by country. The sources of production are cobalt, copper, nickel, platinum-group-element, and zinc operations. Data are from Shedd (2013a). Congo (Kinshasa) is a short-form name for Democratic Republic of the Congo.

Strategic and Critical Resource Issues

Cobalt is generally critical to the performance of the products in which it is used. Past periods of high prices and concern about availability have resulted in various efforts to conserve, reduce the use of, or substitute for cobalt. In many applications, further substitution would result in a loss in product performance and (or) increased cost. Cobalt's diverse uses—particularly in parts for aircraft turbine engines; in numerous magnet applications, including marine propulsion systems, missile guidance systems, sensors, and radar; and in machine tools—make it important to the U.S. military and civilian industries.

That nearly all cobalt is mined as a byproduct of other, more abundant metals, such as nickel or copper, means that production is driven primarily by the markets for the principal metals, not by the need for cobalt. This situation limits producers' flexibility in adjusting the amount of cobalt mined in response to changes in demand and can result in periods of oversupply or shortage. From 2009 to 2015, global cobalt production was higher than consumption, as production from new projects and from expansions to existing operations added to global supply. This trend led to a market surplus and downward pressure on prices (Shedd, 2013a, b; Searle, 2015; Spencer, 2016).

More than one-half of the world's cobalt supply is mined in Congo (Kinshasa). This country has a high risk index for doing business owing to poor infrastructure, resource nationalism, a high perception of corruption, and a lack of transparency as well as wars during the 1990s to early 2000s, persistent tension in the eastern part of the country with substantial risk of civil war, and conflicts with neighboring Rwanda (Bedder, 2013; The Coface Group, undated). Although civil unrest in the eastern part of Congo (Kinshasa) has not affected the cobalt-producing areas, problems with infrastructure (particularly power and transportation) and reviews of and changes to mining contracts have slowed some of the potential growth in mine development and production. In spite of these issues, the copper-cobalt mining industry in Congo (Kinshasa) has significantly recovered from the collapse in production that took place in the 1990s (Shedd, 2013a).

The United States is highly reliant on imports for its cobalt needs. In recent years, approximately 75 to 80 percent of the U.S. cobalt supply has come from imports and releases from the National Defense Stockpile; the remaining 20 to 25 percent has been from recycled scrap. This high reliance on imports increases the potential for supply disruption and high prices during supply shortfalls. The leading source of refined cobalt for the United States is China (Shedd, 2013a, b).

Geology

Geochemistry

Cobalt is a silvery gray metal with diverse uses based on certain key properties, including hardness, wear-resistance when alloyed with other metals, low thermal and electrical conductivity, high melting point, multiple valences, and production of intense blue colors when combined with silica. Cobalt also is ferromagnetic, and it retains this property at the highest temperature of any metal. Although pure cobalt is not found in nature, cobalt-bearing minerals and compounds are numerous and widespread. The ionic radius of cobalt is 0.72 angstroms (Å) for Co^{2+} and 0.63 Å for Co^{3+}, both of which are similar to the ionic radii of Mg^{2+}, Mn^{4+}, Fe^{2+}, Fe^{3+}, and Ni^{2+}, thus allowing substitution under favorable conditions for these elements by cobalt within many minerals and other phases. Among common rock types, the highest average cobalt content occurs in ultramafic igneous rocks, such as dunite and serpentinite, which contain, on average, 109 and 115 parts per million (ppm) cobalt, respectively (table F2); mafic igneous rocks such as basalt contain, on average, about 47 ppm cobalt. For comparison, Earth's bulk continental crust, including all rock types, contains 29 ppm cobalt, on average. Lower cobalt contents characterize shale (which averages 19 ppm), as well as granite and related felsic igneous rocks (which average 2 to 3 ppm) (table F2).

Mineralogy

The mineralogy of cobalt deposits is diverse and includes both primary (hypogene) and secondary (supergene) phases. In primary deposits, most cobalt is recovered from sulfide minerals, such as carrollite ($Cu(Co,Ni)_2S_4$), pentlandite ($(Fe,Ni,Co)_9S_8$), linnaeite (Co_3S_4), and siegenite ($(Co,Ni)_3S_4$); arsenide minerals, such as skutterudite ($(Co,Fe,Ni)As_{2\text{-}3}$) and safflorite ($(Co,Fe)As_2$); and sulfarsenide minerals, including cobaltite (CoAsS) and glaucodot ((Co,Fe)AsS). Cobaltiferous pyrite and pyrrhotite—$(Fe,Co)S_2$ and $(Fe,Co)_{1\text{-}x}S$, respectively—are mined in some deposits. Among secondary cobalt-rich phases, which form during surficial weathering, one of the most important historically was erythrite ($Co_3(AsO_4)_2 \cdot 8H_2O$), which is a bright pink mineral also known as "cobalt bloom." In modern mining of secondary cobalt-rich deposits, the principal economic phases, in addition to erythrite, are heterogenite (CoO(OH)) and asbolane ($(Ni,Co)_{2-x}Mn(O,OH)_4 \cdot nH_2O$), plus local heazlewoodite ($(Ni,Co)_3S_2$), together with cobaltiferous oxyhydroxides, including goethite ($Fe^{3+}O(OH)$), limonite ($FeO(OH) \cdot nH_2O$), and lithiophorite ($AlMnO_2(OH)_2$). With respect to the cobaltiferous oxyhydroxides, it is unclear from studies to date whether the contained cobalt is present in the crystal structure or adsorbed onto surfaces.

Principal Deposit Types

Cobalt deposits of economic or potential economic importance are diverse in terms of their geologic setting, age, morphology, mineralogy, geochemistry, origin, and grade-tonnage relations (for example, Crockett and others, 1987; Smith, 2001; British Geological Survey, 2009). The principal deposit types that account for most of the world's cobalt mine production are stratiform sediment-hosted Cu-Co deposits, Ni-Co laterite deposits, and magmatic Ni-Cu(-Co-PGE) sulfide deposits. These deposit types, together with selected examples, are described below.

Stratiform Sediment-Hosted Cu-Co Deposits

Most of the world's cobalt is produced as a byproduct of copper mining in sediment-hosted Cu-Co deposits that form strata-bound and commonly stratiform zones within siliciclastic or carbonate strata (Hitzman and others, 2005). Important ore hosts in some deposits are giant breccias that originated by the dissolution of former salt beds. Globally, the deposits contain chalcopyrite, pyrite, and carrollite, plus minor amounts of bornite and chalcocite, in gangue material composed mainly of potassium feldspar, muscovite, biotite, albite, quartz, and carbonate. The ages of the mineralization are principally Neoproterozoic and Permian, but some important deposits are Mesoproterozoic. Although current genetic models differ in some respects, the consensus opinion is that metalliferous saline hydrothermal fluids were introduced at low to moderate temperatures during diagenesis and the early stages of deformation and metamorphism (see Zientek and others, 2013).

The greatest amount of contained cobalt in this deposit type occurs in the Central African Copperbelt in Congo (Kinshasa) and Zambia (Selley and others, 2005; Taylor and others, 2013). Large deposits in this region from which byproduct cobalt is currently or has been produced include Kamoto, KOV, and Tenke Fungurume, all in Congo (Kinshasa) (El Desouky and others, 2010; Fay and Barton, 2012), and Nkana in Zambia (Brems and others, 2009).

Ni-Co Laterite Deposits

Laterites are red regoliths that develop in humid tropical climates during the weathering of diverse types of bedrock. Those that developed on ultramafic bedrock may contain important Ni-Co deposits (Freyssinet and others, 2005; Butt and Cluzel, 2013). Ni-Co laterites locally contain abundant scandium and, rarely, elevated concentrations of PGEs. Ni-Co laterite deposits consist of the following layers, from top to bottom: overburden, limonite, saprolite, and weathered ultramafic source rocks. Ore zones of laterite deposits range in thickness from about 10 meters (m) to as much as 40 m in some cases, and generally contain more than 1 percent nickel and less than 0.15 percent cobalt. Limonite developed over ultramafic rocks tends to have higher cobalt grades, whereas saprolite has higher nickel grades. Metal accumulation involves supergene processes and several key variables, including primary bedrock lithology, climate history, topography, and structural preparation (that is, the fracture or joint density of bedrock). Ages of the deposits typically are mid-Tertiary to Holocene; some fossil Ni-Co laterites are known. Major ore constituents include the following: (a) nickeliferous serpentine (garnierite), talc, and chlorite; (b) nickel- or cobalt-bearing clays (for example, nontronite, and montmorillonite); (c) erythrite, heterogenite, asbolane, heazlewoodite, and millerite; and (d) goethite, limonite, and lithiophorite. The gangue (non-ore) material may include various amounts of quartz, amorphous silica, clays, and serpentine.

The Kalgoorlie and the Murrin Murrin deposits in Western Australia (Elias and others, 1981; Gaudin and others, 2005) and the Goro deposit in New Caledonia (Wells and others, 2009) are examples of some of the world's many large Ni-Co laterite deposits. The manganiferous Nkamouna Co-Ni deposit in Cameroon is one of the few laterites known for which cobalt would be the principal economic metal to be mined (Lambiv Dzemua and Gleeson, 2012).

Magmatic Ni-Cu(-Co-PGE) Sulfide Deposits

Large resources (including reserves) of cobalt are contained in Ni-Cu(-Co-PGE) sulfide deposits hosted in mafic and ultramafic igneous rocks (Naldrett, 2004; Eckstrand and Hulbert, 2007). This deposit type comprises semimassive to massive sulfides that occur within or near the basal zones of layered intrusive complexes, in discordant magmatic conduits, and within ultramafic intrusions and lava flows. The ages of the deposits, which approximate those of the host intrusions, range from Archean to Tertiary. Nickel is the principal metal commodity, and it is accompanied by subequal proportions of copper in most deposits; cobalt and PGEs are mining byproducts. Cobalt resides mainly in cobaltiferous pentlandite and, to a lesser extent, in linnaeite. The gangue minerals consist mostly of primary magmatic minerals, such as olivine, pyroxene, and plagioclase. Mineralizing processes involve magmatic segregation of sulfides and, in some deposits, hydrothermal mobilization into post-magmatic structures.

Deposits of this type that currently feature significant byproduct production of cobalt include Voisey's Bay in Newfoundland and Labrador, Canada (Naldrett and Li, 2007); the Sudbury district in Ontario, Canada (Ames and Farrow, 2007); and the Norilsk-Talnakh district in Siberia, Russia (Naldrett and others, 1996).

Other Deposit Types

Types of deposits that on a global scale have produced relatively minor amounts of cobalt include the following: (a) black-shale-hosted Ni-Cu-Zn-Co, (b) Fe-Cu-Co skarn and replacement, (c) iron oxide-Cu-Au(-Ag-U-REE-Co-Ni), (d) metasedimentary-rock-hosted Co-Cu-Au, (e) Mississippi Valley-type Zn-Pb(-Co-Ni), (f) polymetallic (Ag-Ni-Co-As-Bi) and other cobalt-rich veins, and (g) volcanogenic Cu(-Zn-Co-Ag-Au) massive sulfides. Identified cobalt deposits on the sea floor, which may be mined in the future, include Fe-Mn(-Ni-Cu-Co-Mo) nodules, Fe-Mn(-Co-Mo-REE) crusts, and volcanogenic Cu(-Zn-Co-Ag-Au) massive sulfides.

Black-Shale-Hosted Ni-Cu-Zn-Co Deposits

Black shales are well known for containing elevated contents of many metals of economic interest, including Cu, Mo, Ni, Zn, Co, Cd, Ag, Au, Se, Cr, V, U, and PGEs (for example, Desborough and Poole, 1983; Coveney, 2003). Metals concentrated in black shales may reside in pyrite; organic matter; aluminosilicate minerals, such as illite; and locally in sphalerite and chalcopyrite. Some deposits contain very high contents of molybdenum, nickel, zinc, and (or) vanadium within primary sedimentary beds or laminae. In other deposits, high contents of cobalt formed by hydrothermal leaching, mobilization, and concentration into sulfide minerals during deformation and regional metamorphism.

One of the few black-shale-hosted deposits from which byproduct cobalt is recovered is the giant Talvivaara orebody in central Finland, which is being mined for nickel, zinc, and copper (Loukola-Ruskeeniemi and Lahtinen, 2013).

Fe-Cu-Co Skarn and Replacement Deposits

Pluton-related skarn and replacement deposits form by the introduction of hydrothermal fluids into chemically reactive rocks, mainly carbonate (limestone and dolostone), and by metasomatic processes that introduce metals and other components into the precursor strata. These deposits occur proximal or distal to intrusive bodies and contain a diverse suite of metals (Megaw, 1998; Meinert and others, 2005). Sulfide minerals may include pyrite, pyrrhotite, chalcopyrite, sphalerite, and galena, together with abundant magnetite in some deposits. Cobaltiferous deposits generally contain mainly copper residing in chalcopyrite; cobalt occurs in cobaltite or cobalt-rich pyrite. In replacement deposits, which commonly are located distal from pluton contacts, gangue minerals typically include quartz or carbonate. The gangue minerals of skarn deposits, which occur near plutons, are generally different and include garnet, pyroxene, amphibole, epidote, olivine, plagioclase, and (or) scapolite.

The Cornwall and the Morgantown (Grace Mine) Fe-Cu-Co deposits, which are two of only a few large cobaltiferous skarn deposits in the world, are located in southeastern Pennsylvania (Lapham, 1968) but are no longer operating. Another large deposit of this type, although it lacks significant amounts of iron, is Ruby Creek in northwestern Alaska (Bernstein and Cox, 1986). The Mount Elliott Cu-Au(-Co-Ni) skarn deposit in Queensland, Australia, differs in that it contains a significant amount of gold (Wang and Williams, 2001).

Table F2. Cobalt concentrations in rocks, soils, waters, and air.

[DOE, U.S. Department of Energy; EPA, U.S. Environmental Protection Agency; cm, centimeter; ppm, part per million; µg/g, microgram per gram; µg/L, microgram per liter; µm, micrometer; ng/m^3, nanogram per cubic meter]

Environment and (or) location	Cobalt concentration	Unit	Notes	Reference(s)
		Rocks		
Upper continental crust	10	ppm	Average	Taylor and McLennan (1995)
Bulk continental crust	29	ppm	Average	Taylor and McLennan (1995)
Lower continental crust	35	ppm	Average	Taylor and McLennan (1995)
Basalt	47	ppm	average	Krauskopf and Bird (1995)
Dunite (alpine-type)	109	ppm	Average	Gülaçar and Delaloye (1976)
Granite	2.4	ppm	Average	Krauskopf and Bird (1995)
Pyroxenite (alpine-type)	55.2	ppm	Average	Gülaçar and Delaloye (1976)
Serpentinite (alpine-type)	115	ppm	Average	Gülaçar and Delaloye (1976)
Shale	19	ppm	Average	Krauskopf and Bird (1995)
		Soils		
United States	5 to 30	ppm	Regional background soil in Idaho	Shacklette and Boerngen (1984)
United States	29 to 940	ppm	Near mining in the Idaho copper belt	Giles and others (2009)
Conterminous United States	0.5 to 160	ppm	0 to 5 cm depth; median is 7.2 ppm	Smith and others (2005)
Conterminous United States	1.8 to 14	ppm	O horizon, if present; median is 3 ppm	Smith and others (2005)
Conterminous United States	0.9 to 143	ppm	A horizon; median is 7.1 ppm	Smith and others (2005)
Conterminous United States	0.7 to 191	ppm	C horizon; median is 7.8 ppm	Smith and others (2005)
Western United States	7.1	ppm	Mean for 20 cm depth	Shacklette and Boerngen (1984)
Eastern United States	5.9	ppm	Mean for 20 cm depth	Shacklette and Boerngen (1984)
Canada	2 to 6	ppm	0 to 5 cm; distant from Sudbury mining district	Narendrula and others (2012)
Canada	22 to 37	ppm	0 to 5 cm; near Sudbury mining district	Narendrula and others (2012)
Canada	5 to 18	ppm	0 to 5 cm; distant from roast beds	Hutchinson and Symington (1997)
Canada	58 to 299	ppm	0 to 5 cm; near roast beds	Hutchinson and Symington (1997)
Congo (Kinshasa)	17 to 33	ppm	0 to 5 cm; distant from African copper belt mines	Narendrula and others (2012)
Congo (Kinshasa)	204 to 6,150	ppm	0 to 5 cm; near African copper belt mines	Narendrula and others (2012)
Egypt	13 to 25	ppm	0 to 20 cm; distant from industry	Zohny (2002)
Egypt	26 to 65	ppm	0 to 20 cm; pollution from industry	Zohny (2002)
Sweden	0.5 to 2.3	ppm	Range of profile developed on quartzite and gniess	Tyler (2004)
Proposed DOE benchmark	20	ppm	Contaminant screening benchmark for terrestrial plants	Efroymson and others (1997)
Soil-quality guideline	40	ppm	Canadian agricultural soil guideline	Canadian Council of Ministers of the Environment (2013)

Table F2. Cobalt concentrations in rocks, soils, waters, and air.—Continued

[DOE, U.S. Department of Energy; EPA, U.S. Environmental Protection Agency; cm, centimeter; ppm, part per million; µg/g, microgram per gram; µg/L, microgram per liter; µm, micrometer; ng/m^3, nanogram per cubic meter]

Environment and (or) location	Cobalt concentration	Unit	Notes	Reference(s)
		Waters		
Seawater, South Atlantic and Southern Oceans	0.0003 to 0.004	µg/L	Dissolved (<0.22 µm)	Bown and others (2012)
Seawater, Sargasso Sea	0.001 to 0.004	µg/L	Dissolved and colloidal (<0.4 µm)	Shelley and others (2012)
African rivers	0.04 to 0.43	µg/L	Dissolved load (<0.2 µm)	Gaillardet and others (2003)
European rivers	0.08 to 0.26	µg/L	Dissolved load (<0.2 µm)	Gaillardet and others (2003)
North American rivers	0.02 to 0.15	µg/L	Dissolved load (<0.2 µm)	Gaillardet and others (2003)
South American rivers	0.02 to 0.18	µg/L	Dissolved load (<0.2 µm)	Gaillardet and others (2003)
Huanghe River, China	0.006 to 0.03	µg/L	Dissolved load (<0.2 µm)	Gaillardet and others (2003)
Streamwater, Canada—Cobalt	3 to 20	µg/L	Dissolved load (<0.45 µm); mine drainage	Kwong and others (2007)
Streamwater, Sweden (northern)	0.057	µg/L	Median	Huser and others (2011)
Streamwater, Sweden (southern)	0.24	µg/L	Median	Huser and others (2011)
Streamwater, United States—Cobalt	0.67 to 30	µg/L	Samples distant from mines	Eppinger and others (2003)
Streamwater, United States—Cobalt	10 to 1,100	µg/L	Samples near mines	Eppinger and others (2003)
Sediment, world rivers	22.5	µg/g	Average suspended sediment	Viers and others (2009)
Tailings pore water, Khovu-Aksy, Russia	70 to 61,000	µg/L	Median is 540 µg/L	Bortnikova and others (2012)
Proposed EPA benchmark	1,500	µg/L	Tier II secondary acute value	Suter and Tsao (1996)
Proposed EPA benchmark	23	µg/L	Tier II secondary chronic value	Suter and Tsao (1996)
		Air		
Worldwide	0.13 to 37	ng/m^3	"Polluted air"; median is 3 ng/m^3	Reimann and de Caritat (1998)
South Pole	0.1 to 1.2	ng/m^3	None	Kabata-Pendias and Pendias (2001)
Greenland	70 to 150	ng/m^3	None	Kabata-Pendias and Pendias (2001)

Iron Oxide-Cu-Au(-Ag-U-REE-Co-Ni) Deposits

The iron oxide-Cu-Au(-Ag-U-REE-Co-Ni) class of mineral deposits is globally important as a major source of copper, gold, and in some cases, silver, uranium, and rare-earth elements (REEs) (Williams and others, 2005). These iron oxide-copper-gold (IOCG) deposits are mainly of Late Archean, Proterozoic, and Mesozoic ages, and they occur either near plutons or in metamorphic terranes without a clear link to intrusive bodies. Their ore mineralogy is dominated by magnetite, hematite, chalcopyrite, bornite, and gold, with concentrations in some deposits of uraninite, bastnäsite (or bastnaesite), monazite, cobaltite, glaucodot, bismuthinite, native bismuth, arsenopyrite, millerite, molybdenite, and galena; common gangue minerals are fluorite, barite, and quartz; and tourmaline is present locally. This deposit type is thought to have originated from one of the following fluid types and sources: magmatic-hydrothermal, metamorphic, and evaporitic brine.

Very large IOCG deposits that contain appreciable amounts of cobalt include, in Australia, the Olympic Dam deposit in South Australia (Reynolds, 2000) and the Ernest Henry deposit in Queensland (Mark and others, 2000), and in Brazil, the Sossego deposit (Monteiro and others, 2008).

Metasedimentary-Rock-Hosted Co-Cu-Au Deposits

Co-Cu-Au deposits hosted in metasedimentary rocks are strata-bound zones of semimassive to locally massive sulfides within deformed and metamorphosed siliciclastic strata chiefly of Proterozoic age (Slack, 2013). The mineralized zones range from strata-bound and discordant to stratiform and include lenses, veins, and breccias. The deposits consist of cobaltite and (or) other cobalt-rich sulfarsenide or sulfide minerals, or cobaltiferous pyrite, together with chalcopyrite and magnetite, in a gangue of quartz, muscovite, biotite, chlorite, potassium feldspar, albite, and (or) scapolite, accompanied in many deposits by minor amounts of tourmaline. The origins of these deposits are thought to be varied; a range of mineralizing processes, from diagenetic to epigenetic (the latter occurring both before and during metamorphism) are thought to be involved. In some deposits, geochronological and geochemical evidence suggests links to granitic and (or) gabbroic plutons, but the origin of most deposits of this type—and sources of the hydrothermal fluids and metals—are enigmatic.

The largest tonnages of cobalt in this deposit type are contained in the Blackbird district of east-central Idaho (Slack, 2013, and references therein), the Kuusamo belt of northeastern Finland (Vanhanen, 2001), and the NICO deposit in the Northwest Territories in Canada (Goad and others, 2000). Cobalt deposits of this type in the Modum district in Norway, especially those at the Skuterud Mine (Grorud, 1997), were historically important as the major European source of blue pigment used during the 17th and 18th centuries.

Mississippi Valley-Type Zn-Pb(-Co-Ni) Sulfide Deposits

Strata-bound Zn-Pb(-Co-Ni) sulfide concentrations hosted by carbonate strata are termed Mississippi Valley-type (MVT) deposits (Leach and others, 2005; Paradis and others, 2007). These deposits typically consist of various proportions of sphalerite and galena in a gangue of fluorite or barite; quartz is uncommon. The principal cobalt mineral is carrollite. Most deposits of this type are Phanerozoic, although a few Proterozoic examples are known. Mineralization characteristically involves the migration of low-temperature, highly saline brines and the subsequent precipitation of ore and gangue minerals as open-space fillings of paleokarst structures or as replacement zones in carbonate rocks.

MVT deposits generally lack high cobalt contents, but a few, such as the Mine La Motte-Fredericktown and the Higdon deposits in Missouri (Seeger, 2008; Parra and others, 2009) have produced minor amounts of cobalt as a byproduct of the mining of lead and zinc.

Polymetallic (Ag-Ni-Co-As-Bi) and Other Cobalt-Rich Vein Deposits

Cobalt-rich vein deposits fill fractures and faults within metasedimentary or metaigneous rocks of Proterozoic or younger age (Kissin, 1992). The majority of these deposits were mined for silver and cobalt; some also produced byproduct copper, lead, zinc, gold, uranium, and (or) barite. In these types of deposits, multistage mineralization is common, typified by a diverse ore mineralogy consisting of native silver and native bismuth, gold, argentite, rammelsbergite, safflorite, skutterudite, gersdorffite, niccolite, uraninite, arsenopyrite, pyrite, pyrrhotite, sphalerite, galena, bornite, chalcopyrite, tetrahedrite, and Sb-As-Ag sulfosalts. Gangue minerals may include quartz, carbonate, fluorite, and (or) barite. The origins of these deposits vary widely and include mineralization by magmatically derived hydrothermal fluids, metamorphic fluids, basinal brines, and meteoric waters.

Economically, the most important vein deposits have been those in the Erzgebirge region of the Czech Republic and Germany (Hermann, 2005), the Kongsberg district of southern Norway (Neumann, 1944), the Cobalt district of Ontario, Canada (Marshall and Watkinson, 2000), and the Bou Azzer district of Morocco (Bouabdellah and others, 2016).

Volcanogenic Cu(-Zn-Co-Ag-Au) Massive Sulfide Deposits

Volcanogenic massive sulfide (VMS) deposits occur in marine volcanic and volcanosedimentary belts of Archean to Holocene age and are mined principally for copper, zinc, lead, silver, and gold (Galley and others, 2007; Shanks and

Thurston, 2012). These deposits precipitate from hydrothermal fluids on the sea floor within irregular chimneys and mounds, and in the subsurface within strata-bound or discordant zones. The major sulfide minerals are pyrite, pyrrhotite, chalcopyrite, and sphalerite; some deposits have appreciable amounts of galena, tetrahedrite, and gold. Gangue minerals may include quartz, muscovite, chlorite, siderite, and barite. Most VMS deposits lack elevated contents (>0.1 weight percent) of cobalt but several have higher grades, especially deposits hosted predominantly by ultramafic or mafic volcanic rocks. Extensive research on this deposit type has allowed the development of refined genetic models that involve subsea-floor emplacement of igneous magma that drives hydrothermal convection and seawater entrainment, coupled with upflow of metalliferous hydrothermal fluids and subsequent sulfide precipitation (see Shanks and Thurston, 2012, and references therein).

Among ancient deposits, the few that have significant amounts of contained cobalt include Outukumpu in central Finland (Peltonen and others, 2008), Windy Craggy in northwestern British Columbia, Canada (Peter and Scott, 1999), and Deerni in Qinghai Province, China (Hou and others, 1999).

Sea-Floor Fe-Mn(-Ni-Cu-Co-Mo) Nodules

Ferromanganese nodules on the modern sea floor contain large resources of several metals, including nickel, copper, cobalt, and molybdenum (Hein and others, 2013). These nodules occur mainly on abyssal plains at depths of 3,500 to 6,500 m, having formed by the precipitation of iron and manganese oxyhydroxide phases from seawater and pore fluids within enclosing sediments. The growth rates of nodules vary greatly, from a few millimeters per million years, where components are precipitated only from seawater, to as much as 250 millimeters per million years, where precipitation is dominantly from pore fluids. Nodule diameters typically are 2 to 8 centimeters (cm). Major constituents are delta-manganese dioxide (δ-MnO_2), todorokite, and other similar manganates, with lesser amounts of birnessite, iron oxyhydroxides, and detrital aluminosilicate minerals. Metals of economic interest, such as cobalt, are sorbed onto surfaces of the manganese oxyhydroxides, where they are retained by surface oxidation processes. The formational ages of the nodules generally are no older than the Holocene owing to dissolution of manganese oxides within anoxic pore fluids during diagenesis, but ancient nodules of Miocene and Cretaceous age also are known.

The best-documented and largest nodule fields are located in the Pacific Ocean between the Clarion and Clipperton fracture zones, in the Cook Islands Exclusive Economic Zone (EEZ), in the Penrhyn-Samoa Basin, the Peru Basin, and in the Pioneer area of the central Indian Ocean (Hein and others, 2013).

Sea-Floor Fe-Mn(-Co-Mo-REE) Crusts

Ferromanganese crusts on the modern sea floor also represent immense resources of cobalt, molybdenum, REEs, and other metals (Glasby and others, 2010; Hein and others, 2013). These crusts occur on seamounts, plateaus, and spreading ridges at relatively shallow depths of 800 to 3,000 m. Growth rates of the crusts are extremely slow, generally in the range of 1 to 6 millimeters per million years owing to precipitation of components only from seawater. The thickness of the crust varies from less than 1 cm to as much as 26 cm, and the thickest parts occur on the oldest seamounts. The principal minerals are δ-MnO_2, iron oxyhydroxides, and carbonate fluorapatite, together with local goethite and minor amounts of detrital minerals, such as quartz and feldspar. The incorporation of cobalt and other metals occurs by processes similar to those that take place in ferromanganese nodules.

The greatest resources in ferromanganese crusts are located in the Pacific prime crust zone of the central equatorial Pacific Ocean (Hein, 2002). Other regions contain appreciable resources, however, such as in the Nameless, Unicorn, and Maderia-Tore Rise (MTR) zones of the northeastern Atlantic Ocean (Muiños and others, 2013), and the Afanasiy-Nikitin seamount in the Indian Ocean (Parthiban and Banakar, 1999).

Sea-Floor Volcanogenic Cu(-Zn-Co-Ag-Au) Massive Sulfide Deposits

More than 100 VMS deposits have been discovered on the modern sea floor (Hannington and others, 2005). Cobaltiferous examples are few and limited to occurrences in ultramafic rocks. These relatively cobalt-rich VMS deposits are present in serpentinite, which is a rare lithology on the modern sea floor, having been exposed by detachment faulting and core complex formation that raise deeper rocks of the lower oceanic crust and upper mantle to the ocean floor. The major sulfide minerals present in ancient VMS deposits hosted in basalt are chalcopyrite, isocubanite, pyrite (locally cobaltiferous), sphalerite, and wurtzite; the gangue minerals consist of abundant serpentine and smectite, in addition to chlorite.

The Rainbow vent field on the Mid-Atlantic Ridge (Bogdanov and others, 2002) has VMS deposits that contain the greatest amount of cobalt known among modern sea-floor VMS deposits. Other deposits of this type that are found on the Mid-Atlantic Ridge occur in the Logatchev (Mozgova and others, 1999) and the Nibelungen fields (Melchert and others, 2008).

Resources and Production

Production and Identified Resources

Figure F5 shows cobalt production in 2011, by deposit type. Cobalt production from Congo (Kinshasa) and most of the output from Zambia was as a byproduct of the copper mining of stratiform sediment-hosted Cu-Co deposits. Cobalt mine production from most other countries was as a byproduct of nickel mining. Production from Cuba and New Caledonia was from Ni-Co laterite deposits. Production from Canada and Russia and most of the production from China was from magmatic Ni-Cu(-Co-PGE) sulfide deposits. Production from Australia and Brazil was from Ni-Co laterite and magmatic Ni-Cu(-Co-PGE) sulfide deposits. Only in Morocco was cobalt produced as the principal commodity from a current mining operation; the deposits in Morocco are hydrothermal polymetallic veins.

The proportion of cobalt produced from different deposit types has varied over time. During the 1990s, production from stratiform sediment-hosted Cu-Co deposits was relatively low owing to a period of civil unrest in Congo (Kinshasa) and a major collapse at the Kamoto Mine in Congo (Kinshasa) in 1990. The percentage of production from Ni-Co laterite deposits has increased since the mid-1990s owing to development of second-generation hydrometallurgical processes for refining those ores and investment by a Canadian company in one of the laterite operations in Cuba.

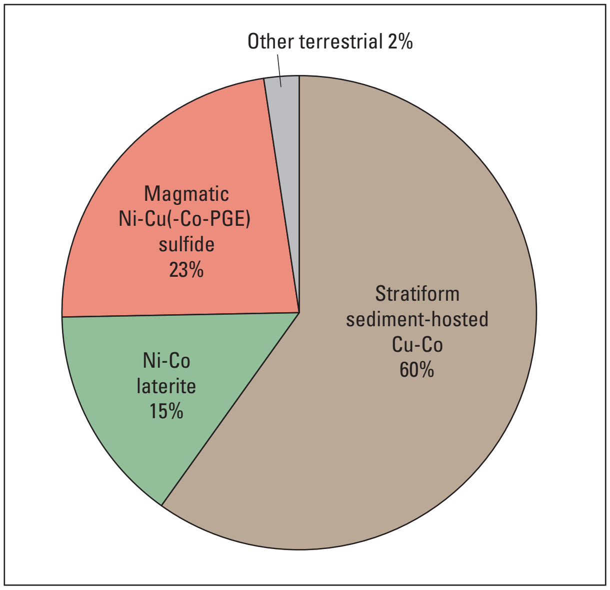


Figure F5. Pie chart showing percentage of world cobalt mine production in 2011, by deposit type. Other terrestrial deposits are grouped together and include black-shale-hosted Ni-Cu-Zn-Co deposits, polymetallic (Ag-Ni-Co-As-Bi) and other cobalt-rich veins, and volcanogenic Cu(-Zn-Co-Ag-Au) massive sulfide deposits. No recoverable cobalt was known to be produced in 2011 from deposit types not listed. The sources of production are cobalt, copper, nickel, platinum-group-element (PGE), and zinc operations. Ag, silver; As, arsenic; Au, gold; Bi, bismuth; Co, cobalt; Cu, copper; Ni, nickel; Zn, zinc

Grade-Tonnage Characteristics

The grade-tonnage plot in figure F6, which combines all types of cobalt-bearing mineral deposits and districts, shows a large range in the amounts of contained cobalt. In the figure, several to many deposits are grouped into districts for some areas (such as Sudbury, Ontario, Canada, and Norilsk-Talnakh, Russia) because, in these cases, grade and tonnage data for the individual deposits were not available. The sizes of the plotted deposits and districts, which include past production, reserves, and other resources (where known) are given in table F1. The summation of reserves and other resources has the potential to introduce double-counting when data are from reports in which reserves are included as part of resources. In table F1, where possible, reserves were not included when the potential for such double-counting was identified. Past production is included to give an indication of the original size of the deposit before mining. For many deposits—especially stratiform sediment-hosted Cu-Co, Ni-Co laterites, and magmatic Ni-Cu(-Co-PGE) sulfides—cumulative past production is small compared with the amount of cobalt contained in reserves and other resources. Figure F7 shows the global distribution of the largest cobalt deposits on land and on the sea floor; the terrestrial deposits shown in the figure also include selected small deposits that represent minor deposit types.

The total terrestrial cobalt resource (plus past production, where available) calculated from data in table F1 (back of chapter) is 25.5 million metric tons, which is very similar to the terrestrial cobalt resource of 26.1 million metric tons presented in a recent independent study by Mudd and others (2013). Among terrestrial deposits, contained cobalt can vary by three orders of magnitude or more (fig. F6). Most types of cobalt deposits contain between 5,000 and 500,000 metric tons of cobalt. The largest tonnages (greater than 500,000 metric tons of contained Co) are present in numerous magmatic Ni-Cu(-Co-PGE) sulfide deposits (some grouped into districts, such as Sudbury), several stratiform sediment-hosted Cu-Co deposits, and numerous lateritic Ni-Co deposits. Similarly, cobalt grades differ greatly—mostly low grades (0.01 to 0.2 percent cobalt) for magmatic Ni-Cu(-Co-PGE) sulfide deposits, intermediate grades (0.03 to 0.2 percent cobalt) for the majority of lateritic Ni-Co deposits, and relatively high grades (0.03 to 1.0 percent cobalt) for most stratiform sediment-hosted Cu-Co deposits. The highest average grades (about 1.5 percent cobalt) are in relatively small cobalt-rich vein deposits of the Bou Azzer district in Morocco. As shown in figures F6 through F8, the largest amount of cobalt on land is contained within stratiform sediment-hosted Cu-Co deposits (41 percent) and lateritic Ni-Co deposits (36 percent), followed at much lower proportions by that in magmatic Ni-Cu(-Co-PGE) sulfide deposits (15 percent) and other terrestrial deposits (8 percent), of which the greatest portion is in VMS deposits (2.7 percent).

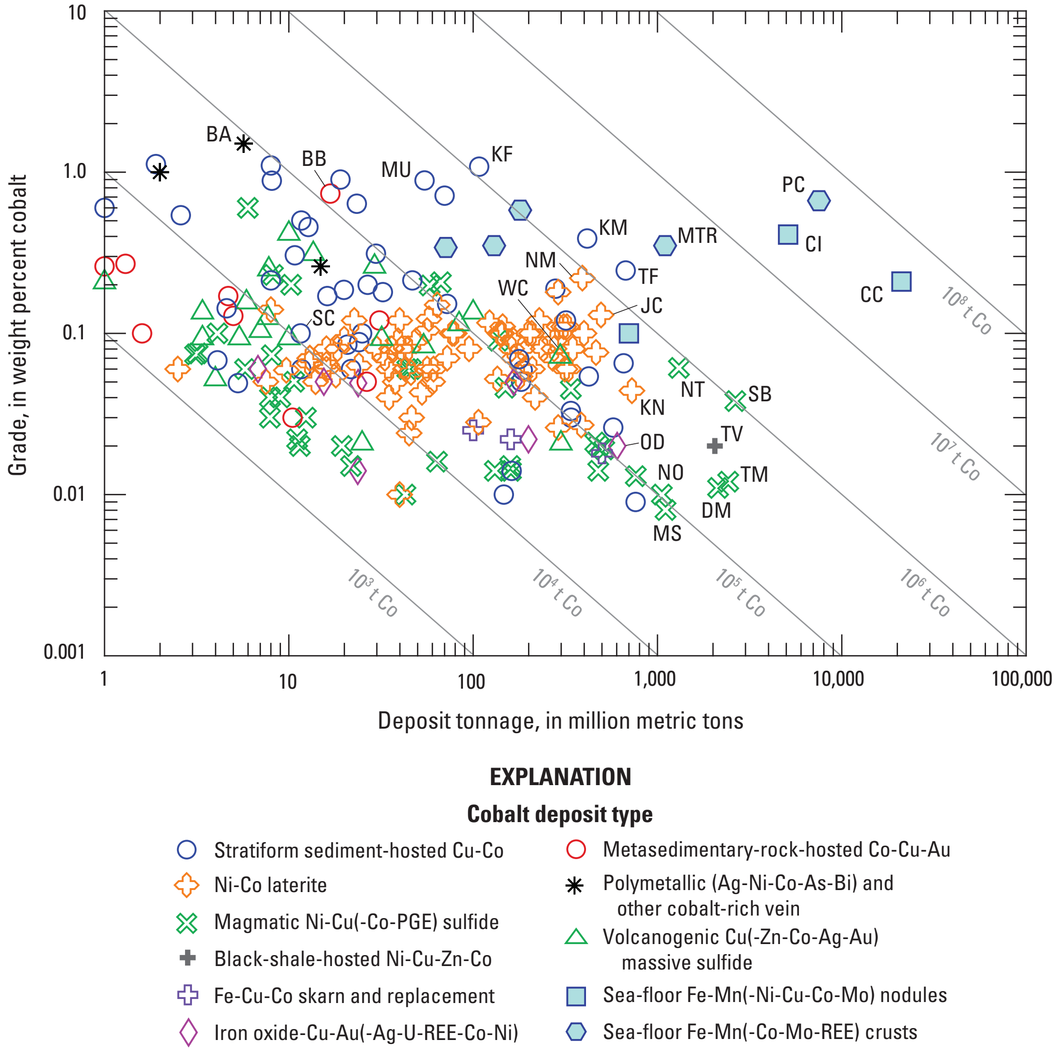


Figure F6. Grade-tonnage plot for 214 cobalt deposits worldwide. Grades and tonnages include production plus reserves plus other resources where known; reserve and resource data are from publicly available reports and company Web sites (see table F1), but in some cases are not defined by a National Instrument 43–101 standard, Joint Ore Reserves Committee code, or similar mineral-resource classification scheme. Labeled deposits represent most of those containing more than 500,000 metric tons (t) of cobalt, many of the U.S. deposits, some examples of the less common deposit types, and some that are discussed in the text. Small deposits—those with less than 1,000 metric tons of cobalt—are not shown. Diagonal lines are isolines of contained cobalt, in metric tons. Abbreviations: BA, Bou Azzer (Morocco); BB, Blackbird (Idaho); CC, Clarion-Clipperton zone (Pacific Ocean); CI, Cook Islands Exclusive Economic Zone (Pacific Ocean); DM, Dumont (Canada); JC, Jacaré (Brazil); KF, Kisanfu (Congo [Kinshasa]); KM, Kamoto–KOV–Musonoi–Mupine deposits (Congo [Kinshasa]); KN, Kalgoorlie Nickel (Australia); MS, Mesaba (Minnesota); MTR, Maderia-Tore Rise (Atlantic Ocean); MU, Mutanda (Congo [Kinshasa]); NM, Nkamouna (Cameroon); NO, Northmet (Minnesota); NT, Noril'sk Talnakh (Russia); OD, Olympic Dam (Australia); PC, Pacific prime crust zone (Pacific Ocean); SB, Sudbury (Canada); SC, Sheep Creek (Montana); TF, Tenke Fungurume (Congo [Kinshasa]); TM, Twin Metals (Minnesota); TV, Talvivaara (Finland); WC, Windy Craggy (Canada)

Base from U.S. Geological Survey Global 30 arc-second elevation data (1996) and from Natural Earth (2014); Robinson projection; World Geodetic System 1984 datum

Figure F7. World map showing global distribution of major cobalt-bearing mineral deposits (those containing equal to or more than 500,000 metric tons of cobalt) and selected smaller deposits that represent minor types. The sizes of the symbols for terrestrial (land-based) deposits reflect the amounts of contained cobalt. Additional data on these and other the deposits are given in table F1. Note that the Nameless and Unicorn sea-floor deposits (table F1) are within the area of the Maderia-Tore Rise, which is located west of Portugal (see Muiños and others, 2013). Au, gold; BSH, black-shale-hosted; Co, cobalt; Cu, copper; MSRH, metasedimentary-rock-hosted; Mt, million metric tons; Ni, nickel; SSH, stratiform sediment-hosted; Zn, zinc

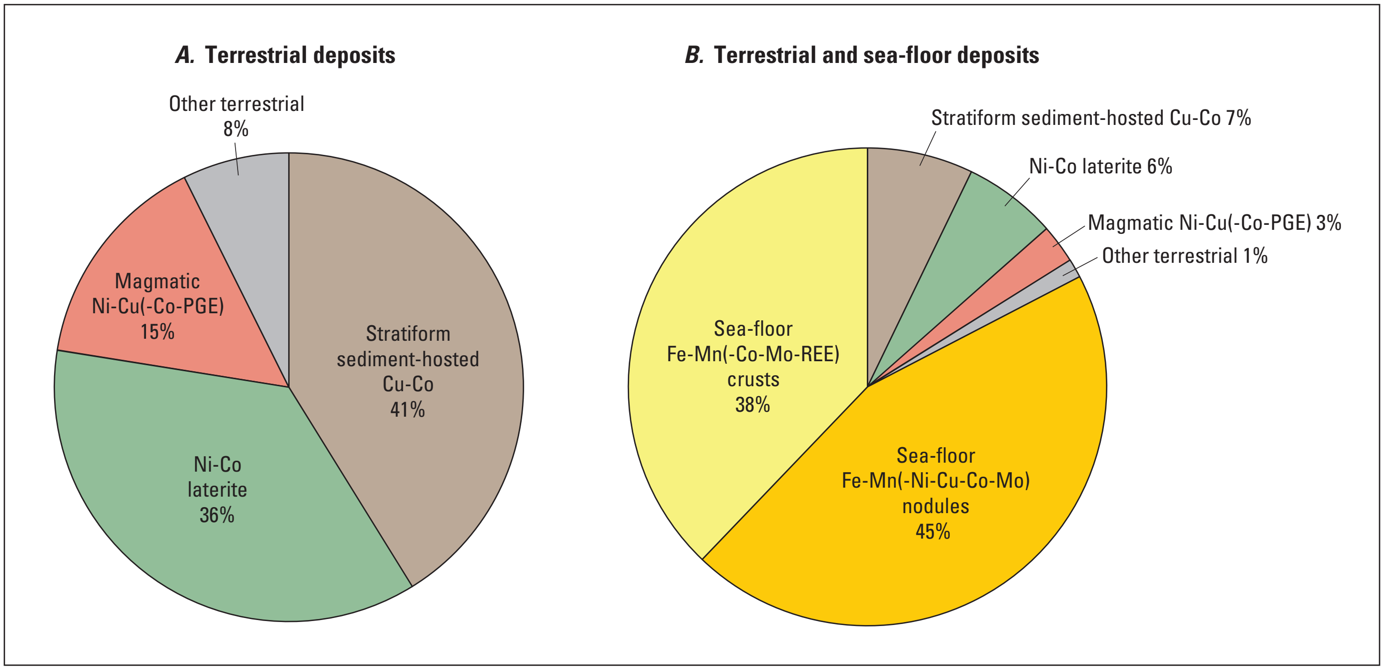


Figure F8. Pie charts showing proportions of cobalt contained in mineral deposits worldwide (cumulative past production plus reserves plus other resources), by deposit type, for *A*, terrestrial deposits, and *B*, terrestrial and sea-floor deposits. Mine production in 2011 from terrestrial deposit types is shown in figure F5. Globally, the amount of cobalt contained in reserves plus other resources in identified mineral deposits is significantly more than the amount of cobalt contained in past production. Co, cobalt; Cu, copper; Fe, iron; Mn, manganese; Mo, molybdenum; Ni, nickel; PGE, platinum-group element; REE, rare-earth element

The United States has 0.64 million metric tons of cobalt contained in several deposit types (table F1). The vast majority occurs within magmatic Ni-Cu(-Co-PGE) sulfide deposits of the Duluth Complex in northeastern Minnesota (which include the Nokomis deposit [291,000 metric tons], the Northmet deposit [92,400 metric tons], and the Mesaba deposit [89,000 metric tons]), and in metasedimentary-rock-hosted Co-Cu-Au deposits of the Blackbird district in east-central Idaho (123,000 metric tons). Much smaller amounts of cobalt are present within the Sheep Creek (Black Butte) stratiform sediment-hosted Cu-Co-Ag deposit in western Montana (17,700 metric tons) and the Eagle magmatic Ni-Cu(-Co-PGE) deposit in northern Michigan (4,000 metric tons). Resources also may be present in the Ni-Co laterites of southern Oregon and northern California (Foose, 1991, 1992). Compared with the estimated global terrestrial resources (plus past production, where available) of 25.5 million metric tons of cobalt, the United States has only 2.5 percent of the total amount of cobalt contained in mined ore (past production) plus reserves plus other resources.

On a global scale, the largest resources of cobalt occur in modern sea-floor ferromanganese nodules and crusts. Identified resources for eight different areas, each containing 0.2 to 50 million metric tons of cobalt, have been reported. Crusts tend to have slightly higher cobalt grades but a similar range in deposit sizes. Significantly, the amount of cobalt in the Pacific prime crust zone in the Pacific Ocean (fig. F6) is three to four times the cobalt reserves contained in all known terrestrial deposits (Hein and others, 2013).

Production of cobalt during the next several decades will likely be dominated by the mining of Ni-Co laterites and stratiform sediment-hosted Cu-Co deposits, with lesser contributions from magmatic Ni-Cu(-Co-PGE) sulfide deposits. The giant cobalt resources present in modern sea-floor ferromanganese nodules and crusts (table F1; fig. F6) will probably be mined in the future, but given the technological challenges, environmental issues, and uncertain economics involved in such deep-sea mining ventures, it is unclear when these sea-floor mineral resources might be exploited profitably for cobalt production.

Mining Methods

The mining of cobalt deposits is done by conventional underground and open pit methods. Underground mining is used for most magmatic Ni-Cu(-Co-PGE) sulfide, iron oxide-Cu-Au(-Ag-U-REE-Co-Ni), volcanogenic Cu-(Co-Zn-Ag-Au) massive sulfide, and metasedimentary-rock-hosted Co-Cu-Au deposits. In contrast, open pit mining is the predominant method used for stratiform sediment-hosted Cu-Co and Ni-Co laterite deposits. Ore from the black-shale-hosted Talvivaara Ni-Cu-Zn-Co deposit in Finland—the only one of its type presently being mined—is extracted from large open pits.

Typical Mine Life

The mine life for cobalt-bearing deposits depends on a variety of parameters, but it is ultimately limited by the size of the resource and the development of reserves, which is the economically extractable portion of the demonstrated resource. Mines that produce cobalt generally are worked for decades. For example, several stratiform sediment-hosted Cu-Co deposits in the Central African Copperbelt have been mined for more than 50 years, such as Chibuluma, which began production in 1955 and is still being mined (Metorex Pty Ltd., 2013). In some other countries, mining started earlier and continues to the present day; for example, the magmatic Ni-Cu(-Co-PGE) sulfide deposits at the Creighton Mine in the Sudbury district of Ontario were first worked in 1901 (Python Mining Consultants, 2013); mining of the cobalt-rich veins in the Bou Azzer district of Morocco began in 1928 (Ahmed and others, 2009), and mining of the magmatic Ni-Cu(-Co-PGE) sulfide deposits of the Norilsk-Talnakh district in Russia began in 1936 (Naldrett, 2004). Possibly the longest period of production has come from the Thio Ni-Co laterite mine in New Caledonia, which was first mined in 1880 and is still being mined (Eramet Group, 2013).

Ore-Processing Methods

Cobalt-bearing ores are processed by a wide variety of extractive metallurgical techniques, depending on the type of ore, the availability of energy, environmental concerns, market demand for primary products and byproducts, and overall project economics. Ni-Co laterite ores generally require minimal beneficiation before being refined. Ores from magmatic Ni-Cu(-Co-PGE) sulfide and stratiform sediment-hosted Cu-Co deposits are processed by standard rock crushing and grinding techniques, typically followed by froth flotation to produce mineral concentrates, which are then refined to recover the metals (De Cuyper, 1988).

The ores or concentrates can be processed in one of the following ways: (a) leaching, (b) roasting and then leaching, or (c) smelting and then leaching. The resulting solutions are purified and refined to separate out the individual metals. The purification and refining are generally carried out by one or more hydrometallurgical and (or) electrometallurgical methods, including chemical precipitation, electrowinning, hydrogen reduction, ion exchange, and solvent extraction. Leaching of cobalt-bearing ores can be done at various temperatures and pressures using acids or other solutions, such as ammonia, ammonia–ammonium carbonate, chloride, or chlorine (Kerfoot and Weir, 1988). For more detailed information on the processing of cobalt ores, see, for example, Crundwell and others (2011).

In a few cases, leaching is accelerated by the introduction of bacteria. For example, ore from the black-shale-hosted Talvivaara deposit in Finland is processed by bio-heapleaching (Saari and Riekkola-Vanhanen, 2012). Bacterial leaching was also used at Kasese, Uganda, to recover cobalt from stockpiled pyrite concentrates that were generated during earlier copper mining.

Undiscovered Resources

Because stratiform sediment-hosted Cu-Co, Ni-Co laterite, and magmatic Ni-Cu(-Co-PGE) sulfide deposits are the sources of the greatest amount of cobalt production and contain the largest reserves of cobalt, most undiscovered resources of cobalt are likely to occur in these same deposit types. Descriptive and genetic models for such deposits are relatively well developed; hence, the exploration for new orebodies probably will target geologic terranes that host known deposits. In the case of stratiform sediment-hosted Cu-Co deposits, prospective geologic settings have been thoroughly documented (for example, Hitzman and others, 2005; Taylor and others, 2013), yet potentially favorable terranes exist in many remote parts of the world where modern deposit models have not been applied. A similar situation exists for Ni-Co laterite deposits in that, despite a robust understanding of key ore-forming processes (for example, Freyssinet and others, 2005; Butt and Cluzel, 2013), areas that may contain deeply weathered ultramafic rocks have not been well explored. For magmatic Ni-Cu(-Co-PGE) sulfide deposits, the most important undiscovered resources are likely to be present in mafic and ultramafic igneous rocks, including large intrusive complexes (Naldrett, 2004; Eckstrand and Hulbert, 2007). The global distribution of such complexes is well known for those exposed at the surface, but in some remote parts of the world, buried mafic intrusive complexes still await discovery.

Unconventional Resources

Metamorphosed Black Shales

The black-shale-hosted Talvivaara Ni-Cu-Zn-Co deposit in Finland contains an average of 200 ppm cobalt (Loukola-Ruskeeniemi and Lahtinen, 2013); however, the economic part of this deposit is located within remobilized structures in which lower metal contents of the surrounding Proterozoic black shale were increased during deformation and metamorphism. Epigenetic cobalt enrichment has also been described for the Permian Kupferschiefer Cu-Ag-Au-PGE deposits in Germany and Poland, where elevated cobalt contents occur preferentially within small, paragenetically late veins (Schmidt and Friedrich, 1988; Sun and Püttmann, 1997). Other black shales may have potential for containing low-grade cobalt deposits, such as the Upper Devonian-Lower Mississippian Chattanooga Shale in the Southeastern United States that typically has 70 ppm cobalt but locally contains as much as 300 ppm (Leventhal and others, 1983).

Modern Sea-Floor Volcanogenic Massive Sulfide Deposits

Some VMS deposits on the modern sea floor contain elevated amounts of cobalt. Documented examples of high contents of cobalt in deposits on the Mid-Atlantic Ridge are all in settings underlain by ultramafic rocks, including in the Rainbow vent field (Bogdanov and others, 2002), in the Logatchev field (Mozgova and others, 1999), and in the Nibelungen field (Melchert and others, 2008). Samples of massive sulfide rock from the Logatchev field have as much as 1,310 ppm cobalt (Murphy and Meyer, 1998). None of these modern deposits has been explored sufficiently for resource delineation, however, because of their occurrence at relatively deep water depths of 3,000 m or more, which are considered unfavorable for the profitable mining of such deposits (Herzig and others, 2002). Despite this constraint, ultramafic-hosted modern VMS deposits may represent a resource for cobalt.

Ancient Ni-Co Laterites

Because Ni-Co laterite deposits of Cretaceous or younger ages are the predominant source of cobalt mined today (fig. F7; Berger and others, 2011), ancient laterites—if preserved and not eroded—could represent a nonconventional resource for nickel and cobalt. Gleeson and Herrington (2005) evaluated this potential, using the data of Bárdossy and Aleva (1990) on time periods of extensive global weathering, to suggest that fossil Ni-Co laterites preferentially formed during the Carboniferous, late Permian, Eocene-Oligocene, Miocene, and Pliocene, if favorable settings (including tropical to subtropical climates) existed at those times (see Thorne and others, 2012). Two examples of ancient laterites are the Çaldağ Ni-Co deposit in Turkey and the Ni-Co laterites of Greece, which formed during the Late Cretaceous to Eocene and Late Jurassic to Cretaceous, respectively (Çağatay and others, 1983; Valeton and others, 1987). Even older formational ages are possible, although paleoclimatic conditions during the Paleozoic and Precambrian are not well known.

Ancient Fe-Mn(-Cu-Co-Ni) Nodules

Ancient Fe-Mn(-Cu-Co-Ni) nodules are also a possible nonconventional resource of cobalt. Fossil nodules have been described from Miocene strata in Chile (Achurra and others, 2009) and Cretaceous strata in West Timor, Indonesia (Margolis and others, 1978). In both cases, however, the metal contents in the ancient nodules are much lower than those in modern nodules on the Pacific Ocean floor; such low metal concentrations may reflect shallow formation on continental slopes above the carbonate compensation depth (CCD). Metal-rich ancient nodules are most likely to be found within strata that formed in deepwater, abyssal plain settings below the CCD. These types of strata are generally carried on top of subduction zones and hence are not preserved, except in sedimentary sequences that are obducted onto continents.

Ancient Cobalt-Rich Manganese Deposits

Cobalt-rich manganese deposits occur in Pliocene alkaline basalts of the Calatrava region in central Spain (Crespo and Lunar, 1997). These unusual manganiferous deposits, which contain up to 1.7 weight percent cobalt, are interpreted to have formed in a hot-spring environment within a predominantly subaerial volcanic sequence. Although the known cobalt deposits are small, the potential may exist for larger deposits elsewhere in this volcanic field and also within other subaerial alkaline basaltic provinces that display evidence of hot-spring environments.

Ultramafic Igneous Rocks

The highest cobalt concentrations in common rock types are in ultramafic igneous rocks, including dunite, peridotite, and pyroxenite, and in altered varieties, such as serpentinite. Dunite tends to have the greatest contents because this rock type consists mainly of olivine, which is a ferromagnesian silicate mineral that preferentially concentrates cobalt. The average cobalt contents in dunite and serpentinite are 109 and 115 ppm, respectively (Gülaçar and Delaloye, 1976); hence, these rock types potentially could become large-tonnage and low-grade cobalt resources if the extraction of cobalt from olivine and serpentine can be made commercially viable. The large amount of energy required to extract such cobalt suggests that this type of deposit has only a small chance of being developed and mined, however.

Exploration for New Deposits

Because of the diversity of deposit types that contain economic cobalt concentrations, exploration methods vary greatly. In the exploration for stratiform sediment-hosted Cu-Co deposits, prospecting may involve the integration of data from soil geochemical surveys, as well as structure, stratigraphy, geophysical, and drilling data. For lateritic Ni-Co deposits, key exploration criteria are the presence of deeply weathered ultramafic rocks, development of a thick lateritic profile, and optimum topography and rainfall required to effectively concentrate cobalt and nickel within the weathering zone. Geochemical sampling, including of vegetation, is typically effective in locating Ni-Co laterite deposits. Many magmatic Ni-Cu(-Co-PGE) sulfide deposits occur within large mafic intrusive complexes where refined deposit models and local geologic knowledge can be used to focus exploration to geophysics and drilling. Exploration for this deposit type is centered on the basal zones of the complexes using mainly electrical and magnetic geophysical methods.

Environmental Considerations

Cobalt is an essential nutrient for most life, but it can cause toxic effects when present in solids or waters at concentrations that are significantly enriched relative to normal background levels. Such elevated concentrations may result from cobalt mining, processing, manufacturing, and use. Consequently, an understanding of the behavior of cobalt in the environment can assist in developing technologies and working practices that do not lead to potentially toxic concentrations of cobalt during its production and use. The control, mitigation, and prevention of potential environmental impacts from mining and related processing facilities will vary depending on the deposit type, but they are also dependent on regulations in place within the host country, State, and local area. Therefore, no attempt is made herein to describe every type of mine and its potential for cobalt pollution. Instead, the focus is on some of the better documented environmental impacts associated with cobalt mining.

Sources and Fate in the Environment

In weathering environments at Earth's surface, cobalt typically occurs in the +2 and +3 oxidation states, and may dissolve from host minerals and form complexes with hydroxide, fluoride, sulfate, phosphate, chloride, and (or) organic material. The behavior of cobalt in weathering environments follows that of iron and manganese. Manganese oxide minerals, in particular, have a strong capacity to sorb dissolved cobalt. Much of the literature about the behavior of dissolved cobalt focuses on optimizing cobalt sorption to various natural and synthetic solids as a means of removing dissolved cobalt from solution (for example, Chen and others, 2011).

The tendency for cobalt to be dissolved and transported largely depends upon the pH and temperature of weathering solutions. Because cobalt typically is concentrated in sulfide and arsenide minerals, it can be expected to be relatively mobile under some weathering conditions because of the instability of these minerals at Earth's surface. Dissolution of sulfide minerals, in particular, releases metals and forms sulfuric acid, and the low pH values thus produced allow higher concentrations of metals to be dissolved—potentially causing the environmental problem known as acid mine drainage (AMD). Metals, including cobalt, which are dissolved in AMD can be naturally attenuated through precipitation, sorption to (oxyhydr)oxide minerals, or dilution by mixing with water at circumneutral pH; if not fixed in this manner, these metals are transported downstream and become more widely dispersed in the environment.

Natural concentrations of cobalt in rocks, soils, waters, and air are given in table F2. The cobalt content in soil varies widely depending upon the type of parent rock, but soils unaffected by pollution from industry generally contain a range of 0.5 to 30 ppm cobalt (Shacklette and Boerngen, 1984; Hutchinson and Symington, 1997; Tyler, 2004; Smith and others, 2005; Narendrula and others, 2012). Cobalt concentrations in seawater are 0.0003 to 0.004 micrograms per liter (µg/L, or parts per billion) (Bown and others, 2012; Shelley and others, 2012). In streams and rivers, cobalt concentrations vary from 0.006 to 0.43 µg/L (Gaillardet and others, 2003; Huser and others, 2011). Elevated background concentrations of as high as 30 µg/L cobalt have been reported near Cobalt, Idaho (Eppinger and others, 2003). Suspended particulates in world rivers contain an average of 22.5 micrograms per gram cobalt (Viers and others, 2009). Cobalt occurs naturally in the atmosphere within mineral dust particles. In relatively clean air over the South Pole, cobalt ranges from 0.1 to 1.2 nanograms per cubic meter (ng/m^3) (Kabata-Pendias and Pendias, 2001, and references therein).

Concentrations of cobalt in the environment that are higher than background concentration can result from mining and ore processing (table F2). For example, soils near mines and processing facilities may contain as much as 22 to 6,150 ppm cobalt (Hutchinson and Symington, 1997; Zohny, 2002; Giles and others, 2009; Narendrula and others, 2012). Likewise, streams near the mining towns of Cobalt, Ontario, Canada, and Cobalt, Idaho, have 3 to 20 µg/L and 10 to 1,100 µg/L cobalt, respectively (Kwong and others, 2007; Gray and Eppinger, 2012). Extremely high cobalt concentrations of 70 to 61,000 µg/L (median is 540 µg/L) occur in the pore waters of mine waste impoundments at the Khovu-Aksy Mine in Russia (Bortnikova and others, 2012). Cobalt also can be emitted to the atmosphere during the metal refining process; air affected by industry may contain 0.13 to 37 ng/m^3 cobalt (Reimann and de Caritat, 1998, and references therein).

Mine Waste Characteristics

Mine waste is generally considered to be the material that originates and accumulates at a mine site but has no current economic value (Lottermoser, 2010); it includes both solid and liquid waste. The character of the waste generated from cobalt mining varies according to the geology of the deposit and the methods used to extract the ore. Mine wastes produced by the extraction of copper and nickel ores from which cobalt is produced typically consist of waste rock, tailings, and possibly pit lakes. Tailings are the residual silt- to fine sand-sized grains generated from ore grinding and processing, and generally are stored in dams or ponds.

The mining of cobalt typically produces large volumes of solid and liquid waste. Estimates for the amounts of solid waste generated from the mining of many deposits are difficult to obtain. The mining of laterite deposits requires the stripping of overburden before extraction of the exposed ore. As a result, reclamation of the mined area is often a significant issue, as soil needs to be reestablished and revegetated. Further, once the nickel and cobalt have been extracted, a volume of material nearly equal in volume to the original deposit must be secured in tailings so that it cannot be a source of contamination. Laterite deposits typically are between 20 and 200 million metric tons (table F1). In addition, laterite ores that are mined and then leached to recover nickel and cobalt can generate large amounts of metal-rich sludge that must be contained in impoundments, which are known as “dry stacks” (Power and others, 2011), or, if deemed environmentally safe, combined with additives to revegetate mined areas (Powers and Siemens, 1983).

Other open pit mines, such as those that are used to develop many strata-bound copper deposits, can be quite deep (for example, Taylor and others, 2013). A constraint on their economic viability is the stripping ratio, which determines how much waste rock must be moved. For example, the large Cu-Co mine at Tenke Fungurume (Congo [Kinshasa]) has an approximate stripping ratio of 3.3:1 (International Mining, 2012), which means that 3.3 metric tons of rock must be moved to extract 1 metric ton of ore. The result is that large volumes of rock must be moved and managed, and waste rock must be placed in holding areas and secured. Underground mines, such as those typically used to mine certain sulfide ore deposits (magmatic Ni-Cu sulfide deposits and some stratiform sediment-hosted Cu-Co deposits), generally produce less waste than open pit mines; however, the waste commonly is highly reactive because of its high content of sulfide minerals. These minerals are capable of producing significant amounts of AMD, which, if not contained, must be remediated. One example of waste generated from a past-producing sulfide-bearing cobalt mine is the Blackbird Mine near Cobalt, Idaho, which was mined intermittently from 1949 to 1960, yielding 4.8 million metric tons of waste rock and 2 million metric tons of tailings, and resulting in AMD (U.S. Environmental Protection Agency, 2012).

Solid mine waste includes overburden (the soil and rock that overlie an orebody that must be removed to access the ore in an open pit mine) and gangue (the material that surrounds or is mixed with the valuable metallic minerals in the ore deposit). The mineralogy of solid mine waste in cobalt-rich deposits tends to be similar to the mineralogy of the deposit, except that the proportion of ore minerals is lower relative to gangue minerals. Because of their association with sulfide minerals, trace elements present in many cobalt-bearing deposits and wastes typically include As, Au, Bi, Co, Cr, Cu, Pb, Se, and Zn, and locally include Ag, Ba, Fe, Hg, Mg, Ni, Sb, Sc, Sn, Ti, V, and PGEs (Evans and others, 1995; Foose and others, 1995; Lindsey and others, 1995). Common elements associated with lateritic Ni-Co deposits are Al, Co, Cr, Fe, Mg, Mn, Ni, and Si (Watling and others, 2011; Lambiv Dzemua and others, 2013). Under oxidizing and acidic ($pH < 3$) weathering conditions, which would be expected in mine waste having little to no acid-neutralizing capacity (such as those typically found in some stratiform sediment-hosted Cu-Co deposits, nearly all magmatic Ni-Cu(-Co-PGE) sulfide deposits, and in metasedimentary-rock-hosted Co-Cu-Au deposits), many of the aforementioned accessory elements are expected to be mobile (Smith and Huyck, 1999). The acid-neutralizing capacity of some stratiform sediment-hosted Cu-Co deposits is predicted to be greater owing to the presence of such gangue minerals as calcite and dolomite. For example, the paste pH of tailings samples from the mines in the Central African Copperbelt are as high as 6.9 at the Mindolo Mine and 8.5 at the Chambishi Mine (Sracek and others, 2010). Zinc in carbonate-hosted sulfide deposits of the Central African Copperbelt can make up a large percentage of the total dissolved metals that drain from the deposits and associated waste piles (Plumlee and others, 1999). Lateritic Ni-Co deposits generally lack acid-generating minerals, so the likely oxidizing and circumneutral ($5 < pH < 8$) weathering conditions in these and carbonate-bearing, stratiform sediment-hosted Cu-Co deposits allow many of the accessory elements listed above to be less mobile or immobile (Smith and Huyck, 1999).

Liquid waste includes ore-processing fluids that are stored onsite, as well as natural water that interacts with solid mine waste. Liquid mine waste can occur as surface water, groundwater, and soil pore water within and surrounding the mine site. As an example of liquid mine waste at a former cobalt mine, surface water draining from the Blackbird Mine near Cobalt, Idaho, is contaminated with As, Co, Cr, Cu, Fe, Mn, Ni, Pb, and Zn (Agency for Toxic Substances and Disease Registry, 1995). Cobalt concentrations in the waters in surrounding creeks may be nearly 70 times higher than background values (10 to 2,000 µg/L cobalt), as well as have high copper (10 to 1,800 µg/L copper), and arsenic (0.45 to 6.2 µg/L arsenic) concentrations (Mok and Wai, 1989). A survey of streams within the broader Idaho cobalt belt revealed elevated concentrations (in µg/L) of cobalt (0.67 to 1,100), copper (1 to 2,000), arsenic (less than 0.2 to 44), and iron (28 to 3,800) (Eppinger and others, 2003). Metal contamination of groundwater, surface water, soil, and stream sediments near the Blackbird Mine, as a result of runoff from waste rock, tailings, and mill debris, led to the proposed addition of the Blackbird Mine to the U.S. Superfund National Priorities List in 1993 (U.S. Environmental Protection Agency, 2012). Acid mine drainage like that at the Blackbird Mine may be typical for historic mining districts, but, with modern controls, similar damage can generally be avoided or the harmful effects can be mitigated.

Human Health Concerns

The Agency for Toxic Substances and Disease Registry (2004) provides a useful summary of the health effects of cobalt on humans. The general public is most likely to be exposed to cobalt through consumption of food and drinking water. Human dietary intake of cobalt typically ranges from 10 to 30 micrograms per day (Schrauzer, 2004). Occupational exposure generally results from inhalation of cobalt-bearing dust during cobalt processing and industrial activities that use cobalt, although the current use of appropriate protective equipment is thought to effectively minimize such exposure to levels that do not cause harm. At low levels, cobalt is essential to human health, particularly because it is the central atom in the critical nutrient vitamin B_{12}. Overexposure to high levels of cobalt, however, may cause lung and heart dysfunction, as well as dermatitis.

Isotopes of cobalt range from ^{50}Co to ^{71}Co. The naturally occurring isotope is ^{59}Co. ^{60}Co, which has a half-life of 5.27 years and is the most commercially important radioactive isotope of cobalt, is made by placing ^{59}Co in a nuclear reactor for 1.5 to 2 years (Reimann and de Caritat, 1998). ^{60}Co is used in commercial and medical applications. The Agency for Toxic Substances and Disease Registry (2004) stated that exposure to radiation from radioactive cobalt can damage cells and potentially cause nausea, vomiting, diarrhea, bleeding, coma, cancer, and, in rare cases, death. Additionally, nonradioactive cobalt does not appear to cause cancer in humans or animals when ingested, but when inhaled, animals have shown cancer development. More recently, the National Toxicology Program (NTP), made up of three U.S. Government health organizations, listed nonradioactive cobalt sulfate and cobalt-tungsten carbide in the Report on Carcinogens as *reasonably anticipated to be human carcinogens* (National Toxicology Program, 2014a, b). Beyond these listings, the NTP's recent report revealed that there is not enough unequivocal evidence connecting cancer development in humans with exposure to cobalt and cobalt compounds (National Toxicology Program, 2016).

Primary and secondary drinking water regulations for cobalt currently do not exist in the United States, but the Occupational Safety and Health Administration (2013) has set an exposure limit of 0.1 milligram per cubic meter for cobalt-bearing dust in workplace air over an 8-hour workday. Likewise, the U.S. Nuclear Regulatory Commission (2013a, b) limits radioactive cobalt in workplace air to $1x10^{-6}$ microcuries per milliliter (µCi/mL) of ^{57}Co and $7x10^{-8}$ µCi/mL of ^{60}Co.

Mining of cobalt-rich ore deposits can potentially mobilize elements that are known human toxins. Perhaps the best-known examples of the effects of elements that are known human toxins are the neurological impacts of lead on children (Holecy and Mousavi, 2012) and the carcinogenic effects of arsenic in drinking water (Gupta and others, 2012). Other commonly associated elements, such as nickel, copper, and zinc, also have the potential to affect human health when present above threshold concentrations in air, drinking water, and soil resources. The current U.S. National Ambient Air Quality Standard for lead is 0.15 microgram per cubic meter (U.S. Environmental Protection Agency, 2013), and the current U.S. primary and secondary drinking water standards for arsenic, lead, and copper are 0.01, 0.0, and 1.3 milligrams per liter (mg/L), respectively (U.S. Environmental Protection Agency, 2016). Canadian agricultural soil quality guidelines for nickel, copper, lead, and zinc are 50, 63, 70, and 200 milligrams per kilogram (mg/kg, which is equivalent to ppm), respectively (Canadian Council of Ministers of the Environment, 2013).

Ecological Health Concerns

Many studies focus on the ecological impacts of cobalt bioaccessibility in the environment. Various organisms, including fish, amphibians, crustaceans, insects, and plants, are used in chronic (lower doses over longer time periods) and acute (higher doses over shorter time periods) tests of a substance toxicity. The aquatic toxicity of cobalt depends on multiple factors, including its chemical form (for example, free cobalt ion [Co^{2+}], cobalt(II) chloride [$CoCl_2$], and cobalt (II) sulfate [$CoSO_4(H_2O)_x$]) and ambient physicochemical factors, such as pH, temperature, and overall water chemistry. One of several useful measurements used in toxicity tests is the lethal concentration that leads to 50 percent mortality (LC_{50}) after exposure to a substance for a certain amount of time. Another commonly used measure of toxicity is the effective concentration that results in 50 percent of the tested population exhibiting decreased functionality (EC_{50}), such as inhibited growth.

The freshwater amphipod *Hyalella azteca* is known to be sensitive to dissolved cobalt, exhibiting a 1-week LC_{50} of 16 µg/L in soft water and 61 µg/L in hard water (Borgmann and others, 2005). The toxic effects of cobalt on this and other species decrease with increasing water hardness because less toxic ions like Ca^{2+} and Mg^{2+} are able to outcompete Co^{2+} for biological sites. Acute toxicity tests with dissolved cobalt chloride and the freshwater green alga *Chlorella vulgaris* resulted in an EC_{50} of 530 µg/L cobalt, based on inhibited growth over 96 hours (Rachlin and Grosso, 1993). Fish appear to be more resistant to dissolved cobalt. For example, acute toxicity tests with dissolved cobalt (ranging from 0 to 2,000 mg/L) and rainbow trout (*Oncorhynchus mykiss*) showed no lethality and an LC_{50} value of 1.4 mg/L cobalt after 2 and 3 days of exposure, respectively (Marr and others, 1998). Interestingly, when this latter species was exposed to solutions containing dissolved copper only, dissolved cobalt only, or a mixture of the two metals, toxicity for time periods greater than 2 days decreased in the following order: 250 µg/L Co + Cu, 50 µg/L Co + Cu, Cu only, and Co only (Marr and others, 1998). These results indicate that exposure to the combination of dissolved cobalt and copper, which is closer to actual environmental conditions, is more toxic than exposure to either metal alone. Some regions of the United States have adopted secondary acute and chronic screening benchmarks of 1,500 µg/L cobalt and 23 µg/L cobalt, respectively, for aquatic freshwater life (Suter and Tsao, 1996).

Although cobalt may be toxic to some species, it is an essential nutrient for many life forms, primarily because it is an integral component in vitamin B_{12} (Schrauzer, 2004). Microorganisms are responsible for the biosynthesis of natural vitamin B_{12}. Some microorganisms secrete enzymes known as siderophores, which are known to have a high capacity for dissolving iron from relatively insoluble minerals, thereby increasing the bioavailability of iron in iron-limited environments. Recent work has shown that a commonly studied siderophore has a binding capacity for cobalt that is five orders of magnitude greater than that for iron (Duckworth and others, 2009). Microorganisms may use siderophores to increase cobalt solubility and bioavailability in cobalt-limited environments as a means of contending with the generally low cobalt concentrations in the environment (Bi and others, 2010). Microorganisms are responsible for synthesizing vitamin B_{12} in the gut of ruminants, including those that humans depend on for food, such as cows and sheep. Cobalt-deficient sheep and cattle may experience weight loss and frequent miscarriages, but such symptoms are often curtailed by adding cobalt salts to feed and cobalt additives to soil (Schrauzer, 2004).

Fewer studies have focused on the toxic effects of cobalt on higher level plants. The cobalt content of food plants varies widely (from 1.1 to 380 micrograms per kilogram) and depends upon the soil conditions and the species (Kabata-Pendias and Pendias, 2001, and references therein). This dependence is illustrated by a study that tested the phytotoxicity of cobalt to barley (*Hordeum vulgare* L.), oilseed rape (*Brassica napus* L.), and tomato (*Lycopersicon esculentum* L.) in 10 different soils collected from around the world (Li and others, 2009). The EC_{50}, based on decreased shoot growth and biomass, was highly variable. The most sensitive EC_{50} was 7 mg/kg of cobalt for oilseed rape growing in soil from Athens (Georgia), and the least sensitive EC_{50} was 1,708 mg/kg of cobalt for barley growing in soil from Brécy (France). The bladder campion (*Silene vulgaris* [Moench] Garcke) plant is native to Europe and is widespread in North America. This species has the capacity for high metal tolerance, as expressed by seedling specimens collected in Canada from mine tailings near Cobalt, Ontario, having a greater ability to withstand elevated arsenic, cobalt, and nickel concentrations in the growth medium than counterparts collected from an uncontaminated site near Baymouth, Ontario (Paliouris and Hutchinson, 1991). For healthy terrestrial plant growth, some regions of the United States have adopted a soil screening benchmark of 20 mg/kg cobalt (Efroymson and others, 1997). The Canadian agricultural soil quality guideline for cobalt is 40 mg/kg (Canadian Council of Ministers of the Environment, 2013).

Mine Closure

Most recent and new mining operations include closure plans that address issues related to the mine’s footprint. A mine’s footprint includes the waste left on site and locally affected soil and water, as well as ecological impacts, such as habitat destruction and loss of biodiversity. Long-term plans for closed mining operations where cobalt is an economic byproduct also depend upon country, state, and local regulations. Following mining in many cobalt-rich deposits, a typical long-term mine closure issue is the potential for AMD derived from the site. Acidic drainage may seep from waste piles or tailings ponds. Common methods for treating AMD include active water treatment facilities, passive limestone-lined channels, or constructed wetlands (Plumlee and Logsdon, 1999). The end result of both active and passive approaches is the eventual precipitation of dissolved metals. Precipitated metals in passive wetland systems tend to be more stable under the prevailing anoxic conditions, whereas the metal-rich precipitates that result from active treatment facilities form a sludge that can be similar to Ni-Co laterite processing wastes, and both materials can cause environmental problems if not disposed of responsibly.

At large mines, mine waste is typically consolidated into pits and submerged under water, forming a tailings pond or impoundment. Acid-generating minerals are less reactive under water, but any seepage usually needs to be treated. A tailings impoundment in the Chambishi catchment in Zambia covers 1.6 hectares and is submerged during the wet season, but becomes completely dry by the middle of the dry season (von der Heyden and New, 2004). The acid-neutralizing capacity of the Chambishi tailings is sufficient to attenuate groundwater cobalt, nickel, and zinc concentrations to within local drinking water guideline levels, but evaporation in the tailings impoundment causes precipitation of metal-bearing evaporite minerals that can be mobilized as wind-blown dust during the dry season (von der Heyden and New, 2004). Likewise, dried tailings pond dust has settled in soils near the Tuva cobalt plant (Khovu-Aksy Mine site, Russia), contributing to soil arsenic concentrations as high as 540 mg/kg (Bortnikova and others, 2012).

Another common long-term mine-closure issue related to the mining of cobalt-rich deposits is the generation of large volumes of waste rock and tailings piles. These waste piles have the potential to become unstable and can be a source of metal-rich dust. If the use of mine waste as backfill into mine workings is not an option, waste pile stability and dust-generating issues can often be addressed through grading and covering of the piles with vegetation. Securing waste piles and prevention and treatment of AMD typically are taken into account in the long-term costs of active and proposed metal mining projects.

Problems and Future Research

Several types of studies could benefit the delineation of new cobalt resources for the future and the mining and processing of known cobalt deposits. First would be better geologic models for cobalt-rich ores, which could be used in the exploration for new deposits. Second would be improved methods for increased recovery of cobalt from Ni-Co laterites based on the typically lower recovery rates for cobalt relative to nickel (Xu and others, 2005); in situ leaching of laterite deposits could also be evaluated. Third would be the development of processes for the efficient and economic recovery of cobalt from silicate minerals, such as olivine in dunite and other types of ultramafic rocks. Fourth, and last, would be technological advances to help make the mining and extraction of cobalt from deep-sea ferromanganese nodules and crusts economically profitable.

Considerable challenges exist for the profitable extraction of cobalt from sea-floor resources in ferromanganese nodules and crusts (figs. F6 and F8). These cobalt resources lie at water depths of as great as 6,000 m, so technological, economic, and legal barriers have prevented their exploitation to date. The International Seabed Authority has developed guidelines for the environmental impact statement (EIS) that must be submitted to governing bodies by companies applying for licenses to explore and mine sea-floor mineral deposits. According to the EIS guidelines, developers must address all environmental and social issues that could result from the mining activity, as well as the relevant mitigation measures (International Seabed Authority, 2012). Discussion of all potential issues is beyond the scope of this work. Interested readers can find more information in the various technical reports published online by the International Seabed Authority (2015).

Processing of sea-floor ferromanganese nodules and crusts would likely take place on land, so some of the same mine-waste issues for terrestrial cobalt resources will also apply to sea-floor resources. Additionally, perhaps one of the most controversial issues involving sea-floor mining is the potential impact on benthic, middepth, and pelagic ecosystems. Benthic ecosystems on abyssal plains are particularly threatened by mining in the Clarion-Clipperton zone (CCZ). The understanding of abyssal, benthic ecosystems has grown rapidly in the past several decades. An international effort to evaluate the biodiversity in the CCZ revealed that "high, unanticipated, and still poorly sampled levels of species diversity for all three sediment-dwelling faunal components (foraminifera, nematodes, and polychaetes) [exist] at [the] individual study sites" (International Seabed Authority, 2008, p. 2). These findings led to the recommendation that "marine protected areas" be maintained throughout the CCZ in order to preserve abyssal biodiversity (International Seabed Authority, 2008). Another major environmental concern relates to wastewater being discharged from the ships carrying out the sea-floor mining. This waste could contain crushed nodules and trace metals, and has the potential to disrupt photosynthesis by pelagic organisms and, being colder and denser than surface water, change the natural circulation patterns in the water column (Markussen, 1994). As a result, current conceptual designs are engineered to separate nodules from waste material (for example, clay, sediments, and muddy water) and to return waste to the sea floor at water depths of nearly 5,000 m, so as not to disturb the middepth and pelagic ecosystems (for example, Agarwal and others, 2012). As sea-floor mineral exploration continues and if mining begins in the future, the scientific community likely will be documenting its impacts on ocean life.

Acknowledgments

We thank Michael P. Foose (U.S. Geological Survey) and Andrew G. Gunn (British Geological Survey) for thorough and constructive reviews of the manuscript, and John H. DeYoung, Jr. (U.S. Geological Survey) for editorial suggestions. Comments by David Weight and Paul Marsh (The Cobalt Development Institute), and William Stubblefield (Oregon State University) are also appreciated. Keith Labay (U.S. Geological Survey) helped create the deposit location maps, and Suzanne Nicholson (U.S. Geological Survey) provided additional editorial comments after the technical review was complete.

References Cited

Note: All Web links listed were active as of the access date but may no longer be available.

Achurra, L.E., Lacassie, J.P., Le Roux, J.P., Marquardt, C., Belmar, M., Ruiz-del-Solar, J., and Ishman, S.E., 2009, Manganese nodules in the Miocene Bahía Inglesa Formation, north-central Chile—Petrography, geochemistry, genesis and palaeoceanographic significance: Sedimentary Geology, v. 217, nos. 1–4, p. 128–139. [Also available at http://www.sciencedirect.com/science/article/pii/S0037073809000761.]

African Eagle Resources Plc., 2013, Projects—Dutwa project—Resource—Table 1—JORC Mineral Resource statement, as at September 2012: African Eagle Resources Plc. Web page, accessed April 12, 2013, at http://www.africaneagle.co.uk/dutwa-resources.asp.

African Rainbow Minerals Ltd., 2011, Mineral resources and reserves 2011: African Rainbow Minerals Ltd., 31 p., accessed May 20, 2016, at http://www.arm.co.za/im/files/annual/2011/download/ARM-resources-and-reserves-2011.pdf.

Agarwal, B., Hu, P., Placidi, M., Santo, H., and Zhou, J.J., 2012, Feasibility study on manganese nodules recovery in the Clarion-Clipperton zone, v. 2 *of* Shenoi, R.A., Wilson, P.A., and Bennett, S.S., eds., Seabed exploitation—The LRET Collegium 2012 Series: Highfield, Southhampton, United Kingdom, University of Southampton, 128 p. [Also available at http://www.southampton.ac.uk/engineering/research/groups/fsi/lrf/lrf_collegium_2012_book_series.page.]

Agency for Toxic Substances and Disease Registry, 1995, Blackbird Mine, Cobalt, Lemhi County, Idaho: Atlanta, Ga., U.S. Department of Health and Human Services, Public Health Service Public Health Assessment, CERCLIS No. IDD980725832, accessed March 26, 2013, at http://www.atsdr.cdc.gov/hac/pha/pha.asp?docid=1040&pg=0.

Agency for Toxic Substances and Disease Registry, 2004, Toxicological profile for cobalt: Atlanta, Ga., U.S. Department of Health and Human Services, Public Health Service, CAS no. 7440–48–4, April, 417 p. plus 5 appendixes accessed March 26, 2013, at http://www.atsdr.cdc.gov/ToxProfiles/tp.asp?id=373&tid=64.

Ahmed, A.H., Arai, Shoji, and Ikenne, Moha, 2009, Mineralogy and paragenesis of the Co-Ni arsenide ores of Bou Azzer, Anti-Atlas, Morocco: Economic Geology, v. 104, p. 249–266. [Also available at http://dx.doi.org/10.2113/gsecongeo.104.2.249.]

Albidon Ltd., 2007, Munali nickel deposit: Albidon Ltd. Web page, accessed April 22, 2013, at http://albidon.com/our-projects/zambia.html.

Altona Mining Ltd., 2013, Resource and reserve estimates—Finland—Kylylahti Mine mineral resource and ore reserve estimates: Altona Mining Ltd. Web page, accessed April 12, 2013, at http://www.altonamining.com/finland/resource-and-reserve-estimates.

Ames, D.E., and Farrow, C.E.G., 2007, Metallogeny of the Sudbury mining camp, Ontario, *in* Goodfellow, W.D., ed., Mineral deposits of Canada—A synthesis of major deposit-types, district metallogeny, the evolution of geological provinces, and exploration methods: Geological Association of Canada Special Publication no. 5, p. 329–350.

Armstrong, Tracey, Puritch, Eugene, and Yassa, Antoine, 2010, Technical report on the Allammaq, Expo, Ivakkak, Mequillon, Mesamax and Puimajuq Ni-Cu-PGE deposits of the Nunavik nickel project, Nunavik, Quebec, NI 43–101 technical report prepared for Goldbrook Ventures Inc. [Filing date April 14, 2010]: P&E Mining Consultants Inc., accessed May 23, 2016, at www.sedar.com. [Goldbrook Ventures was taken over by Jilin Jien Nickel Industry Co., Ltd. in 2012.]

Baja Mining Corp., 2011, Resource and reserve [Boleo deposit]: Baja Mining Corp., accessed April 20, 2013, at http://www.bajamining.com/static/downloads/Resource%20&%20Reserve.pdf.

Banakar, V.K., 2010, Deep-sea ferromanganese deposits and their resource potential for India: Journal of the Indian Institute of Science, v. 90, no. 4, p. 535–541.

Bárdossy, György, and Aleva, G.J.J., 1990, Lateritic bauxites: New York, N.Y., Elsevier, Developments in Economic Geology Series, v. 27, 624 p., 24 pls.

Bedder, Jack, 2013, Cobalt production in the DRC—Major changes, minor implications?: The Cobalt Conference, Shanghai, China, May 22–23, presentation, 31 p., accessed June 11, 2013, via http://www.thecdi.com/.

Berger, V.I., Singer, D.A., Bliss, J.D., and Moring, B.C., 2011, Ni-Co laterite deposits of the world—Database and grade and tonnage models: U.S. Geological Survey Open-File Report 2011–1058, 26 p. [Also available at http://pubs.usgs.gov/of/2011/1058/.]

Bernstein, L.R., and Cox, D.P., 1986, Geology and sulfide mineralogy of the Number One orebody, Ruby Creek copper deposit, Alaska: Economic Geology, v. 81, p. 1675–1689. [Also available at http://dx.doi.org/10.2113/gsecongeo.81.7.1675.]

Bi, Yuqiang, Hesterberg, D.L., and Duckworth, O.W., 2010, Siderophore-promoted dissolution of cobalt from hydroxide minerals: Geochimica et Cosmochimica Acta, v. 74, no. 10, p. 2915–2925. [Also available at http://dx.doi.org/10.1016/j.gca.2010.02.028.]

Bogdanov, Y.A., Bortnikov, N.S., Vikent'ev, I.V., Lein, A.Y., Gurvich, E.G., Sagalevich, A.M., Simonov, V.A., Ikorskii, S.V., Stavrova, O.O., and Apollonov, V.N., 2002, Mineralogical-geochemical peculiarities of hydrothermal sulfide ores and fluids in the Rainbow field associated with serpentinites, Mid-Atlantic Ridge (36°14'N): Geology of Ore Deposits, v. 44, no. 6, p. 444–473. [Translated from Geologiya Rudnykh Mestorozhdenii, 2002,44(6), 510–542.]

Borgmann, Uwe, Couillard, Yves, Doyle, Patrick, and Dixon, D.G., 2005, Toxicity of sixty-three metals and metalloids to *Hyalella azteca* at two levels of water hardness: Environmental Toxicology and Chemistry, v. 24, no. 3, p. 641–652. [Also available at http://dx.doi.org/10.1897/04-177R.1]

Bortnikova, S., Bessonova, E., and Gaskova, O., 2012, Geochemistry of arsenic and metals in stored tailings of a Co-Ni arsenide-ore, Khovu-Aksy area, Russia: Applied Geochemistry, v. 27, no. 11, p. 2238–2250.

Bown, J., Boye, Marie, and Nelson, D.M., 2012, New insights on the role of organic speciation in the biogeochemical cycle of dissolved cobalt in the southeastern Atlantic and the Southern Ocean: Biogeosciences, v. 9, no. 7, July 27, p. 2719–2736, accessed March 19, 2016, at http://dx.doi.org/10.5194/bg-9-2719-2012.

Bouabdellah, Mohammed, Maacha, Lhou, Levresse, Gilles, and Saddiqi, Omar, 2016, The Bou Azzer Co-Ni-Fe-As (±Au ± Ag) district of central Anti-Atlas (Morocco)—A long-lived Late Hercynian to Triassic magmatic-hydrothermal to low-sulphidation epithermal system, *in* Bouabdellah, Mohammed, and Slack, J.F., eds., Mineral deposits of north Africa: Berlin, Germany, Springer-Verlag, p. 229–247.

Brems, D., Muchez, Ph., Sikazwe, O., and Mukumba, W., 2009, Metallogenesis of the Nkana copper-cobalt South orebody, Zambia: Journal of African Earth Sciences, v. 55, nos. 3–4, p. 185–196. [Also available at http://dx.doi.org/10.1016/j.jafrearsci.2009.04.003.]

British Geological Survey, 2009, Cobalt: Keyworth, Nottingham, United Kingdom, British Geological Survey Mineral Profile, August, 19 p., accessed March 19, 2016, at http://www.bgs.ac.uk/mineralsuk/statistics/mineralProfiles.html.

Broken Hill Prospecting Ltd., 2013, Cobalt deposits [Pyrite Hill and Big Hill]: Broken Hill Prospecting Ltd. Web page, accessed April 9, 2013, at http://www.bhpl.biz/projects/cobalt-deposits/.

Butt, C.R.M., and Cluzel, Dominique, 2013, Nickel laterite ore deposits—Weathered serpentinites: Elements, v. 9, no. 2, p. 123–128. [Also available at http://dx.doi.org/10.2113/gselements.9.2.123.]

Çağatay, Ahmet, Altun, Yılmaz, and Arman, Bülent, 1983, The mineralogy of Çaldağ (Manisa-Turgutlu) lateritic iron, nickel-cobalt deposits: Bulletin of the Mineral Research and Exploration [Institute of Turkey], v. 95–96, p. 81–96, plus 3 pls. [Also available at http://dergipark.ulakbim.gov.tr/bulletinofmre/issue/view/5000012082.]

CAMEC Plc., 2007, Central African Mining and Exploration Company Plc. (“CAMEC” or “the company”) Democratic Republic of the Congo acquisition and production update: CAMEC Plc., March 1, accessed April 22, 2013, at http://www.resourceinvestor.com/2007/03/02/camec-drc-update.

Canadian Council of Ministers of the Environment, [2013], Canadian soil quality guidelines for the protection of environmental and human health, chap. 7 *of* Canadian environmental quality guidelines: Winnipeg, Manitoba, Canada, Canadian Council of Ministers of the Environment, accessed April 16, 2016, at http://ceqg-rcqe.ccme.ca/en/index.html.

Chalice Gold Mines Ltd., 2012, Agreement to acquire the Mount Oxide copper-cobalt project in Queensland, Australia: Perth, Western Australia, Australia, Chalice Gold Mines Ltd., 5 p. plus 3 appendixes, accessed April 12, 2013, at http://www.chalicegold.com/investor-relations/asx-announcements/2008.html.

Chen, Liang, Huang, Yan, Huang, Lingli., Liu, Bin, Wang, Gang, and Yu, Shaoming, 2011, Characterization of Co(II) removal from aqueous solution using bentonite/iron oxide magnetic composites: Journal of Radioanalytical and Nuclear Chemistry, v. 290, p. 675–684. [Also available at http://dx.doi.org/10.1007/s10967-011-1337-y.]

Chen, W.T., and Zhou, M.-F., 2012, Paragenesis, stable isotopes, and molybdenite Re-Os isotope age of the Lala iron-copper deposit, southwest China: Economic Geology, v. 107, p. 459–480. [Also available at http://dx.doi.org/10.2113/econgeo.107.3.459.]

Cobalt Development Institute and World Bureau of Metal Statistics, 2011, Annual cobalt statistics 2008 to 2010: Guildford, United Kingdom, Cobalt Development Institute and World Bureau of Metal Statistics, June, CD–ROM.

Cobalt Development Institute, 2012, Cobalt facts—Cobalt supply & demand 2011: Guildford, United Kingdom, Cobalt Development Institute, accessed March 8, 2013, at http://www.thecdi.com/cobaltfacts.php.

Compass Resources NL, 2007, Resources—Base and specialty metals—Global base and specialty metals—Browns: Compass Resources NL Web page, accessed June 30, 2016, at https://web.archive.org/web/20070829110319/http://compassnl.com.au/resources_base_specialty_metals.htm.

Coveney, R.M., Jr., 2003, Metalliferous Paleozoic black shales and associated strata, *in* Lentz, D.R., ed., Geochemistry of sediments and sedimentary rocks—Evolutionary considerations to mineral deposit-forming environments: St. John’s, Newfoundland, Canada, Geological Association of Canada, Mineral Deposits Division, GEOText 4, p. 135–144.

Crespo, A., and Lunar, R., 1997, Terrestrial hot-spring Co-rich Mn mineralization in the Pliocene-Quaternary Calatrava Region (central Spain), *in* Nicholson, K., Hein, J.R., Bühn, B., and Dasgupta, S., eds., Manganese mineralization—Geochemistry and mineralogy of terrestrial and marine deposits: Geological Society of London Special Publication 119, p. 253–264. [Also available at http://dx.doi.org/10.1144/GSL.SP.1997.119.01.16.]

Crockett, R.N., Chapman, G.R., and Forrest, M.D., 1987, International Strategic Minerals Inventory summary report—Cobalt: U.S. Geological Survey Circular 930–F, 54 p. [Also available at https://pubs.er.usgs.gov/publication/cir930F.]

Crundwell, F.K., Moats, M.S., Ramachandran, Venkoba, Robinson, T.G., and Davenport, W.G., 2011, Extractive metallurgy of nickel, cobalt and platinum-group metals: Amsterdam, Netherlands, Elsevier, 610 p. [Also available at http://www.sciencedirect.com/science/book/9780080968094.]

De Cuyper, J., 1988, Milling of cobalt ores—An overview, *in* Tyroler, G.P., and Landolt, C.A., eds., Extractive metallurgy of nickel and cobalt, Proceedings of the symposium sponsored by the CuNiCo and Non-Ferrous Pyrometallurgy Committees of the Metallurgical Society, January 25–28, 1988: Phoenix, Ariz., The Metallurgical Society, Inc., p. 187–210.

Desborough, G.A., and Poole, F.G., 1983, Metal concentrations in some marine black shales of the United States, *in* Shanks, W.C., III, ed., Cameron volume on unconventional mineral deposits: New York, N.Y., Society of Mining Engineers, p. 99–110.

Direct Nickel Pty Ltd., 2013, Mambare nickel project: Direct Nickel Pty Ltd. Web page, accessed April 14, 2013, at http://www.directnickel.com/mambare-mine/.

Duckworth, O.W., Bargar, J.R., Jarzecki, A.A., Oyerinde, Oyeyemi, Spiro, T.G., and Sposito, Garrison, 2009, The exceptionally stable cobalt(III)-desferrioxamine B complex: Marine Chemistry, v. 113, January, p. 114–122.

Duluth Metals Ltd., 2012, Project summary [Twin Metals (Nokomis) deposit]: Toronto, Ontario, Canada, Duluth Metals Ltd., accessed March 22, 2013, at http://www.duluthmetals.com/s/ProjectSummary.asp.

Eckstrand, O.R., and Hulbert, L.J., 2007, Magmatic nickel-copper-platinum group element deposits, *in* Goodfellow, W.D., ed., Mineral deposits of Canada—A synthesis of major deposit-types, district metallogeny, the evolution of geological provinces, and exploration methods: Geological Association of Canada Special Publication no. 5, p. 205–222.

Efroymson, R.A., Will, M.E., Suter, G.W., II, and Wooten, A.C., 1997, Toxicological benchmarks for screening contaminants of potential concern for effects on terrestrial plants—1997 revision, report prepared for the U.S. Department of Energy by Lockheed Martin Energy Systems, Inc.: Oak Ridge, Tenn., Oak Ridge National Laboratory, ES/ER/TM–85/R3, November, 68 p. and two appendixes, accessed March 26, 2013, at http://www.esd.ornl.gov/programs/ecorisk/documents/tm85r3.pdf.

Eilu, Pasi, ed., 2012, Mineral deposits and metallogeny of Fennoscandia: Espoo, Finland, Geological Survey of Finland Special Paper 53, 401 p.

El Desouky, H.A., Muchez, Philippe, Boyce, A.J., Schneider, Jens, Cailteux, J.L.H., Dewaele, Stijn, and von Quadt, Albrecht, 2010, Genesis of sediment-hosted stratiform copper-cobalt mineralization at Luiswishi and Kamoto, Katanga copperbelt (Democratic Republic of Congo): Mineralium Deposita, v. 45, no. 8, p. 735–763.

Elias, M., Donaldson, M.J., and Giorgetta, N.E., 1981, Geology, mineralogy, and chemistry of lateritic nickel-cobalt deposits near Kalgoorlie, Western Australia: Economic Geology, v. 76, p. 1775–1783. [Also available at http://dx.doi.org/10.2113/gsecongeo.76.6.1775.]

Eppinger, R.G., Briggs, P.H., Rieffenberger, Betsy, Van Dorn, Carol, Brown, Z.A., Crock, J.G., Hageman, P.H., Meier, Allen, Sutley, S.J., Theodorakos, P.M., and Wilson, S.A., 2003, Geochemical data for stream sediment and surface water samples from Panther Creek, the Middle Fork of the Salmon River, and the main Salmon River, collected before and after the Clear Creek, Little Pistol, and Shellrock wildfires of 2000 in central Idaho: U.S. Geological Survey Open-File Report 01–0161, 32 p. (This report was superceded by U.S. Geological Survey Open-File Report 2003–152.) [Also available at http://pubs.usgs.gov/of/2003/152/.]

Eramet Group, 2013, Mining centres: Eramet Group brochure, 4 p., accessed April 9, 2013, at http://www.eramet.com/sites/default/files/eramet_nickel_division_mining_centres.pdf.

Evans, K.V., Nash, J.T., Miller, W.R., Kleinkopf, M.D., and Campbell, D.L., 1995, Blackbird Co-Cu deposits, chap. 17 *of* du Bray, E.A., ed., Preliminary compilation of descriptive geoenvironmental mineral deposit models: U.S. Geological Survey Open-File Report 95–831, p. 145–151. [Also available at http://pubs.usgs.gov/of/1995/ofr-95-0831/.]

Fay, I., and Barton, M.D., 2012, Alteration and ore distribution in the Proterozoic Mines Series, Tenke-Fungurume Cu-Co district, Democratic Republic of Congo: Mineralium Deposita, v. 47, no. 5, p. 501–519. [Also available at http://dx.doi.org/10.1007/s00126-011-0391-2.]

First Quantum Minerals Ltd., 2011, First Quantum Minerals issues updated resource and reserve estimates and progress report for Kevitsa project: Vancouver, British Columbia, Canada, First Quantum Minerals Ltd., accessed April 18, 2013, at http://www.marketwire.com/press-release/First-Quantum-Minerals-Issues-Updated-Resource-Reserve-Estimates-Progress-Report-Kevitsa-TSX-FM-1419900.htm.

Foose, M.P., 1991, Deposits containing nickel, cobalt, chromium, and platinum-group elements in the United States, *in* Gluskoter, H.J., Rice, D.D., and Taylor, R.B., eds., Economic geology, U.S.—The geology of North America: Boulder, Colo., The Geology Society of America, v. P–2, p. 87–102. [Also available at http://ebooks.geoscienceworld.org/content/economic-geology-us.]

Foose, M.P., 1992, Nickel—Mineralogy and chemical composition of some nickel-bearing laterites in southern Oregon and northern California, *in* DeYoung, J.H., Jr., and Hammarstrom, J.M., eds., Contributions to commodity geology research: U.S. Geological Survey Bulletin 1877, p. E1–E24. [Also available at http://pubs.usgs.gov/bul/1877/report.pdf.]

Foose, M.P., Zientek, M.L., and Klein, D.P., 1995, Magmatic sulfide deposits, chap. 4 *of* du Bray, E.A., ed., Preliminary compilation of descriptive geoenvironmental mineral deposit models: U.S. Geological Survey Open-File Report 95–831, p. 28–38. [Also available at http://pubs.usgs.gov/of/1995/ofr-95-0831/.]

Freeport-McMoRan Copper & Gold Inc., 2013, Form 10–K—2012: Freeport-McMoRan Copper & Gold Inc., accessed February 18, 2016, at http://investors.fcx.com/investor-center/financial-information/annual-reports-and-proxy/default.aspx.

Freyssinet, P., Butt, C.R.M., Morris, R.C., and Piantone, P., 2005, Ore-forming processes related to lateritic weathering, *in* Hedenquist, J.W., Thompson, J.F.H., Goldfarb, R.J., and Richards, J.P., eds., Economic Geology—One hundredth anniversary volume, 1905–2005: Littleton, Colo., Society of Economic Geologists, p. 681–722. [Appendixes are on a CD–ROM inside the back cover.]

Gaillardet, J., Viers, J., and Dupré, B., 2003, Trace elements in river waters, *in* Drever, J.I., ed., Surface and ground water, weathering, and soils, v. 5 *of* Holland, H.D., and Turekian, K.K., eds., Treatise on geochemistry: Oxford, United Kingdom, Elsevier-Pergamon, p. 225–272. [Also available at http://dx.doi.org/10.1016/B0-08-043751-6/05165-3.]

Galley, A.G., Hannington, M.D., and Jonasson, I.R., 2007, Volcanogenic massive sulphide deposits, *in* Goodfellow, W.D., ed., Mineral deposits of Canada—A synthesis of major deposit-types, district metallogeny, the evolution of geological provinces, and exploration methods: Ottawa, Ontario, Canada, Geological Association of Canada Special Publication no. 5, p. 141–161.

Gaudin, A., Decarreau, A., Noack, Y., and Grauby, O., 2005, Clay mineralogy of the nickel laterite ore developed from serpentinised peridotites at Murrin Murrin, Western Australia: Australian Journal of Earth Sciences, v. 52, no. 2, p. 231–241.

Geovic Mining Corp., 2013, Cameroon cobalt—Nkamouna: Denver, Colo., Geovic Mining Corp. Web page, accessed April 12, 2013, at http://www.geovic.net/projects.php.

Gifford, Mark, Cox, Dallas, Christie, Monte, and Sherrit, Ruth, 2011, Technical report for the Agata nickel laterite project, Mindanao, Philippines, NI 43–101 technical report prepared for Mindoro Resources Ltd.: South Brisbane, Queensland, Australia, Ausenco, 448 p. plus 2 appendixes, accessed April 12, 2013, at http://www.mindoro.com/i/pdf/NI_43_101_Technical_Report_20_12_2011.pdf.

Giles, S.A., Granitto, Matthew, and Eppinger, R.G., 2009, Selected geochemical data for modeling near-surface processes in mineral systems: U.S. Geological Survey Data Series 433, CD–ROM. [Also available at http://pubs.usgs.gov/ds/433/.]

Glasby, G.P., Mountain, Bruce, Vineesh, T.C., Banakar, Virupaxa, Rajani, Ramesh, and Ren, Xiangwen, 2010, Role of hydrology in the formation of Co-rich Mn crusts from the equatorial N Pacific, equatorial S Indian Ocean and the NE Atlantic Ocean: Resource Geology, v. 60, no. 2, June, p. 165–177.

Gleeson, S.A., and Herrington, R.J., 2005, Nickel laterites through geological time [abs.]: Geological Society of America Abstracts with Programs, v. 37, no. 7, p. 240. [Also available at https://gsa.confex.com/gsa/2005AM/webprogram/Paper90999.html.]

Glencore International plc., 2011, Mutanda report: Glencore International plc., accessed April 22, 2013, at http://www.hkexnews.hk/listedco/listconews/sehk/2011/0513/00805_1074520/EWPGLENCORE-20110511-44.pdf.

Goad, R.E., Mumin, A.H., Duke, N.A., Neale, K.L., Mulligan, D.L., and Camier, W.J., 2000, 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, no. 2, p. 123–140.

Gray, J.E., and Eppinger, R.G., 2012, Distribution of Cu, Co, As, and Fe in mine waste, sediment, soil, and water in and around mineral deposits and mines of the Idaho cobalt belt, USA: Applied Geochemistry, v. 27, no. 6, p. 1053–1062. [Also available at http://dx.doi.org/10.1016/j.apgeochem.2012.02.001.]

Grorud, Hans-Fredrik, 1997, Textural and compositional characteristics of cobalt ores from the Skuterud mines of Modum, Norway: Norsk Geologisk Tidsskrift, v. 77, p. 31–38. [Also available at http://foreninger.uio.no/ngf/ngt/pdfs/NGT_77_1_031-038.pdf.]

Gülaçar, O.F., and Delaloye, M., 1976, Geochemistry of nickel, cobalt and copper in alpine-type ultramafic rocks: Chemical Geology, v. 17, p. 269–280. [Also available at http://dx.doi.org/10.1016/0009-2541(76)90041-3.]

Gunson Resources Ltd., 2013, Annual report 2012: West Perth, Western Australia, Australia, Gunson Resources Ltd., accessed February 18, 2016, at http://www.strandline.com.au/irm/content/annual-reports.aspx?RID=326. [Company changed its name to Strandline Resources Ltd. in 2014.]

Gupta, V.K., Nayak, Arunima, Agarwal, Shilpi, Dobhal, Rajendra, Uniyal, D.P., Singh, Prashant, Sharma, Bhavtosh, Tyagi, Shweta, and Singh, Rakesh, 2012, Arsenic speciation analysis and remediation techniques in drinking water: Desalination and Water Treatment, v. 40, nos. 1–3, p. 231–243. [Also available at http://dx.doi.org/10.1080/19443994.2012.671250.]

Hannington, M.D., de Ronde, C.E.J., and Petersen, Sven, 2005, Sea-floor tectonics and submarine hydrothermal systems, *in* Hedenquist, J.W., Thompson, J.F.H., Goldfarb, R.J., and Richards, J.P., eds., Economic Geology—One hundredth anniversary volume, 1905–2005: Littleton, Colo., Society of Economic Geologists, p. 111–142. [Also available at http://eprints.uni-kiel.de/6271/.] [Appendixes are on a CD–ROM inside the back cover.]

Hard Creek Nickel Corp., 2013, Summary—Turnagain project preliminary economic assessment: Vancouver, British Columbia, Canada, Hard Creek Nickel Corp., 4 p., accessed April 12, 2013, at http://www.hardcreek.com/i/pdf/FACT-SHEET_AMC_PA_December-2011_Mark.pdf.

Hein, J.R., Mizell, Kira, Koschinsky, Andrea, and Conrad, T.A., 2013, Deep-ocean mineral deposits as a source of critical metals for high- and green-technology applications—Comparison with land-based resources: Ore Geology Reviews, v. 51, June, p. 1–14. [Also available at http://dx.doi.org/10.1016/j.oregeorev.2012.12.001.]

Hein, James, 2002, Cobalt-rich ferromanganese crusts—Global distribution, composition, origin and research activities, *in* International Seabed Authority, Polymetallic massive sulphides and cobalt-rich ferromanganese crusts—Status and prospects: Kingston, Jamaica, International Seabed Authority Technical Study no. 2, p. 36–89. [Also available at https://www.isa.org.jm/documents/polymetallic-massive-sulphides-and-cobalt-rich-ferromanganese-crusts-status-and-prospects.]

Hermann, Steffen, 2005, Geologie, erzgänge und mineralisation der Lagerstätte Schneeberg/Sachsen [Geology, ores and mineralization of the Lagerstätte Schneeberg/Sachsen]: Lapis, v. 30, p. 30–40.

Heron Resources Ltd., 2013, Kalgoorlie nickel project: Heron Resources Ltd. Web page, accessed April 22, 2013, at http://www.heronresources.com.au/knp.php.

Herrington, R.J., Zaykov, V.V., Maslennikov, V.V., Brown, Dennis, and Puchkov, V.N., 2005, Mineral deposits of the Urals and links to geodynamic evolution, *in* Hedenquist, J.W., Thompson, J.F.H., Goldfarb, R.J., and Richards, J.P., eds., Economic Geology—One hundredth anniversary volume, 1905–2005: Littleton, Colo., Society of Economic Geologists, p. 1069–1095. [Appendixes are on a CD–ROM inside the back cover.]

Herzig, P.M., Petersen, S., and Hannington, M.D., 2002, Polymetallic massive sulphide deposits at the modern seafloor and their resource potential, *in* International Seabed Authority, Polymetallic massive sulphides and cobalt-rich ferromanganese crusts—Status and prospects: Kingston, Jamaica, International Seabed Authority, ISA Technical Study no. 2, p. 2–35. [Also available at https://www.isa.org.jm/documents/polymetallic-massive-sulphides-and-cobalt-rich-ferromanganese-crusts-status-and-prospects.]

Hitzman, Murray, Kirkham, Rodney, Broughton, David, Thorson, Jon, and Selley, David, 2005, The sediment-hosted stratiform copper ore system, *in* Hedenquist, J.W., Thompson, J.F.H., Goldfarb, R.J., and Richards, J.P., eds., Economic Geology—One hundredth anniversary volume, 1905–2005: Littleton, Colo., Society of Economic Geologists, p. 609–642. [Appendixes are on a CD–ROM inside the back cover.]

Holecy, E.G., and Mousavi, Aliyar, 2012, Lead sources, toxicity, and human risk in children of developing countries—A mini-review: Environmental Forensics, v. 13, no. 4, p. 289–292. [Also available at http://dx.doi.org/10.1080/15275922.2012.729010.]

Hou, Z.-Q., Deng, Jian, Sun, H.-T., and Song, S.-H., 1999, Volcanogenic massive sulfide deposits in China—Setting, feature, and style: Exploration and Mining Geology, v. 8, no. 3–4, p. 149–175.

Huser, B.J., Köhler, S.J., Wilander, A., Johansson, K., and Fölster, J., 2011, Temporal and spatial trends for trace metals in streams and rivers across Sweden (1996–2009): Biogeosciences, v. 8, p. 1813–1823. [Also available at http://dx.doi.org/10.5194/bg-8-1813-2011.]

Hutchinson, T.C., and Symington, M.S., 1997, Persistence of metal stress in a forested ecosystem near Sudbury, 66 years after the closure of the O'Donnel roast bed: Journal of Geochemical Exploration, v. 58, no. 2–3, p. 323–330. [Also available at http://dx.doi.org/10.1016/S0375-6742(96)00067-2.]

International Mining, 2012, Tenke Fungurume copper/cobalt mine progressing well with phase 2 expansion in the DRC: International Mining, January 4, accessed November 19, 2013, at http://www.im-mining.com/2012/01/04/tenke-fungurume-coppercobalt-mine-progressing-well-with-phase-2-expansion-in-the-drc/.

International Seabed Authority, 2008, Biodiversity, species ranges, and gene flow in the abyssal Pacific nodule province—Predicting and managing the impacts of deep seabed mining: Kingston, Jamaica, International Seabed Authority Technical Study no. 3, 38 p. [Also available at http://www.isa.org.jm/files/documents/EN/Pubs/TechStudy3.pdf.]

International Seabed Authority, 2012, Environmental management needs for exploration and exploitation of deep sea minerals: Kingston, Jamaica, International Seabed Authority Technical Study no. 10, 47 p. [Also available at http://www.isa.org.jm/files/documents/EN/Pubs/TS10/index.html.]

International Seabed Authority, 2015, Documents and publications: International Seabed Authority Home page, accessed December 1, 2015, at https://www.isa.org.jm/documents-and-publications.

Jervois Mining Ltd., 2013, Summervale (NSW): Cheltenham, Victoria, Australia, Jervois Mining Ltd. Web page, accessed April 15, 2013, at http://www.jervoismining.com.au/index.cfm?siteaction=tenement&tenementid=19.

Kabata-Pendias, Alina, and Pendias, Henryk, 2001, Trace elements in soils and plants (3d ed.): Boca Raton, Fla., CRC Press, 413 p.

Kerfoot, D.G.E., and Weir, D.R., 1988, The hydro and electrometallurgy of nickel and cobalt, *in* Tyroler, G.P., and Landolt, C.A., eds., Extractive metallurgy of nickel and cobalt, Proceedings of the symposium sponsored by the CuNiCo and Non-Ferrous Pyrometallurgy Committees of the Metallurgical Society, January 25–28, 1988: Phoenix, Ariz., The Metallurgical Society, Inc., p. 241–267.

Kissin, S.A., 1992, Five-element (Ni-Co-As-Ag-Bi) veins: Geoscience Canada, v. 19, no. 3, p. 113–124. [Also available at https://journals.lib.unb.ca/index.php/GC/article/view/3768/4282.]

Kolb, Jochen, 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, no. 1, p. 68–81. [Also available at http://dx.doi.org/10.1007%2Fs00126-005-0041-7.]

Krauskopf, K.B., and Bird, D.K., 1995, Introduction to geochemistry (3d ed.): New York, N.Y., McGraw-Hill, Inc., 647 p.

Kwong, Y.T.J., Beachemin, S., Hossain, M.F., and Gould, W.D., 2007, Transformation and mobilization of arsenic in the historic Cobalt mining camp, Ontario, Canada: Journal of Geochemical Exploration, v. 92, nos. 2–3, p. 133–150. [Also available at http://doi.org/10.1016/j.gexplo.2006.08.002.]

Lambiv Dzemua, Gideon, and Gleeson, S.A., 2012, Petrography, mineralogy, and geochemistry of the Nkamouna serpentinite—Implications for the formation of the cobalt-manganese laterite deposit, southeast Cameroon: Economic Geology, v. 107, p. 25–41. [Also available at http://dx.doi.org/10.2113/econgeo.107.1.25.]

Lambiv Dzemua, Gideon, Gleeson, S.A., and Schofield, P.F., 2013, Mineralogical characterization of the Nkamouna Co-Mn laterite ore, southeast Cameroon: Mineralium Deposita, v. 48, p. 155–171. [Also available at http://dx.doi.org/10.1007/s00126-012-0426-3.]

Lapham, D.M., 1968, Triassic magnetite and diabase at Cornwall, Pennsylvania, *in* Ridge, J.D., ed., Ore deposits of the United States, 1933–1967, The Graton-Sales Volume: New York, N.Y., American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., v. I, p. 72–94.

Leach, D.L., Sangster, D.F., Kelley, K.D., Large, R.R., Garven, Grant, Allen, C.R., Gutzmer, Jens, and Walters, Steve, 2005, Sediment-hosted lead-zinc deposits—A global perspective, *in* Hedenquist, J.W., Thompson, J.F.H., Goldfarb, R.J., and Richards, J.P., eds., Economic Geology—One hundredth anniversary volume, 1905–2005: Littleton, Colo., Society of Economic Geologists, p. 561–607. [Appendixes are on a CD–ROM inside the back cover.]

Leventhal, J.S., Briggs, P.H., and Baker, J.W., 1983, Geochemistry of the Chattanooga Shale, Dekalb County, central Tennessee: Southeastern Geology, v. 24, no. 3, p. 101–116.

Li, H.-F., Gray, Colin, Mico, Carolina, Zhao, F.-J., and McGrath, S.P., 2009, Phytotoxicity and bioavailability of cobalt to plants in a range of soils: Chemosphere, v. 75, no. 7, p. 979–986. [Also available at http://dx.doi.org/10.1016/j.chemosphere.2008.12.068.]

Lindsey, D.A., Woodruff, L.G., Cannon, W.F., Cox, D.P., and Heran, W.D., 1995, Sediment-hosted Cu deposits, chap. 28 *of* du Bray, E.A., ed., Preliminary compilation of descriptive geoenvironmental mineral deposit models: U.S. Geological Survey Open File Report 95–831, p. 214–224. [Also available at http://pubs.usgs.gov/of/1995/ofr-95-0831/.]

Lottermoser, B.G., 2010, Mine wastes—Characterization, treatment, and environmental impacts (3d ed.): Berlin, Germany, Springer-Verlag, 400 p. [Also available at http://dx.doi.org/10.1007/978-3-642-12419-8.]

Loukola-Ruskeeniemi, Kirsti, and Lahtinen, Hannu, 2013, Multiphase evolution in the black-shale-hosted Ni-Cu-Zn-Co deposit at Talvivaara, Finland: Ore Geology Reviews, v. 52, August, p. 85–99. [Also available at http://dx.doi.org/10.1016/j.oregeorev.2012.10.006.]

Lundin Mining Corp., 2012, Aguablanca NI 43–101: Lundin Mining Corp., accessed April 12, 2013, at http://www.lundinmining.com/s/Aguablanca.asp.

Margolis, S.V., Ku, T.L., Glasby, G.P., Fein, C.D., and Audley-Charles, M.G., 1978, Fossil manganese nodules from Timor—Geochemical and radiochemical evidence for deep-sea origin: Chemical Geology, v. 21, nos. 3–4, p. 185–198. [Also available at http://dx.doi.org/10.1016/0009-2541(78)90044-X.]

Mark, Geordie, Oliver, N.H.S., Williams, P.J., Valenta, R.K., and Crookes, R.A., 2000, The evolution of the Ernest Henry Fe-oxide-(Cu-Au) hydrothermal system, *in* Porter, T.M., ed., Hydrothermal iron oxide copper-gold & related deposits—A global perspective: Adelaide, South Australia, Australia, PGC Publishing, v. 1, p. 123–136.

Markussen, J.M., 1994, Deep seabed mining and the environment—Consequences, perceptions, and regulations, *in* Bergesen, H.O., and Parmann, Georg, eds., Green Globe yearbook of international co-operation on environment and development: Oxford, United Kingdom, Oxford University Press, p. 31–39.

Marr, J.C.A., Hansen, J.A., Meyer, J.S., Cacela, D., Podrabsky, T., Lipton, J., and Bergman, J.L., 1998, Toxicity of cobalt and copper to rainbow trout—Application of a mechanistic model for predicting survival: Aquatic Toxicology, v. 43, no. 4, p. 225–238. [Also available at http://dx.doi.org/10.1016/S0166-445X(98)00061-7.]

Marshall, Dan, and Watkinson, D.H., 2000, The Cobalt mining district—Silver sources, transport and deposition: Exploration and Mining Geology, v. 9, no. 2, p. 81–90. [Also available at http://dx.doi.org/10.2113/0090081.]

Megaw, P.K.M., 1998, Carbonate-hosted Pb-Zn-Ag-Cu-Au replacement deposits—An exploration perspective, *in* Lentz, D.R., ed., Mineralized intrusion-related skarn systems: Mineralogical Association of Canada Short Course Series, v. 26, p. 337–358.

Meinert, L.D., Dipple, G.M., and Nicolescu, Stefan, 2005, World skarn deposits, *in* Hedenquist, J.W., Thompson, J.F.H., Goldfarb, R.J., and Richards, J.P., eds., Economic Geology—One hundredth anniversary volume, 1905–2005: Littleton, Colo., Society of Economic Geologists, p. 299–336. [Appendixes are on a CD–ROM inside the back cover.]

Melchert, B., Devey, C.W., German, C.R., Lackschewitz, K.S., Seifert, R., Walter, M., Mertens, C., Yoerger, D.R., Baker, E.T., Paulick, H., and Nakamura, K., 2008, First evidence for high-temperature off-axis venting of deep crust/mantle heat—The Nibelungen hydrothermal field, southern Mid-Atlantic Ridge: Earth and Planetary Science Letters, v. 275, p. 61–69.

Menzie, W.D., Soto-Viruet, Yadira, Bermúdez-Lugo, Omayra, Mobbs, P.M., Perez, A.A., Taib, Mowafa, Wacaster, Susan, and staff, 2013, Review of selected global mineral industries in 2011 and an outlook to 2017: U.S. Geological Survey Open-File Report 2013–1091, 33 p. [Also available http://pubs.usgs.gov/of/2013/1091.]

Metallica Minerals Ltd., 2013, Resource tables: East Brisbane, Queensland, Australia, Metallica Minerals Ltd. Web page, accessed April 22, 2013, at http://www.metallicaminerals.com.au/resource-tables.]

Metals X Ltd., 2013, Globally significant nickel project: West Perth, Western Australia, Australia, Metals X Ltd. Web page, accessed April 22, 2013, at http://www.metalsx.com.au/nickel/.

Metorex Pty Ltd., 2013, Metorex mineral resources and ore reserves: Metorex Pty Ltd. Web page, accessed April 22, 2013, at http://www.metorexgroup.com/.

Minara Resources Pty Ltd., 2005, Purchase of Sons of Gwalia non-gold assets: Perth, Western Australia, Australia, Minara Resources Pty Ltd., accessed April 22, 2013, at http://www.minara.com.au/.

Minara Resources Pty Ltd., 2011, Annual report 2010: Perth, Western Australia, Australia, Minara Resources Pty Ltd., accessed April 22, 2013, at www.minara.com.au/files/docs/329_2010_Annual_Report_to_Shareholders.

Mirabela Nickel Ltd., 2012, Reserves and resources [Santa Rita]: Perth, Western Australia, Australia, Mirabela Nickel Ltd. Web page, accessed April 14, 2013, at http://www.mirabela.com.au/reserves.asp.

Mithril Resources Ltd., 2013, Project overview [Basil copper-cobalt deposit]: Norwood, South Australia, Australia, Mithril Resources Ltd., accessed April 12, 2013, at http://www.mithrilresources.com.au/projectoverview.php.

Mok, W.M., and Wai, C.M., 1989, Distribution and mobilization of arsenic species in the creeks around the Blackbird mining district, Idaho: Water Research, v. 23, no. 1, p. 7–13. [Also available at http://dx.doi.org/10.1016/0043-1354(89)90054-7.]

Monteiro, L.V.S., Xavier, R.P., de Carvalho, E.R., Hitzman, M.W., Johnson, C.A., de Souza Filho, C.R., and Torresi, Ignácio, 2008, Spatial and temporal zoning of hydrothermal alteration and mineralization in the Sossego iron oxide-copper-gold deposit, Carajás mineral province, Brazil—Paragenesis and stable isotope constraints: Mineralium Deposita, v. 43, no. 2, p. 129–159. [Also available at http://dx.doi.org/10.1007/s00126-006-0121-3.]

Mosier, D.L., Berger, V.I., and Singer, D.A., 2009, Volcanogenic massive sulfide deposits of the world—Database and grade and tonnage models: U.S. Geological Survey Open-File Report 2009–1034, 46 p. [Also available at http://pubs.usgs.gov/of/2009/1034/.]

Mount Isa Mines Ltd., 2012, Mount Isa copper: Mount Isa Mines Ltd., accessed April 22, 2013, at http://www.mountisamines.com.au/EN/aboutXMIM/Pages/CopperInMountIsa.aspx. [Company was acquired by Glencore plc in May 2013.]

Mozgova, N.N., Efimov, Andrey, Borodaev, Y.S., Krasnov, S.G., Cherkashov, G.A., Stepanova, T.V., and Ashadze, A.M., 1999, Mineralogy and chemistry of massive sulfides from the Logatchev hydrothermal field (14 degrees 45'N Mid-Atlantic Ridge): Exploration and Mining Geology, v. 8, no. 3, p. 379–395.

Mudd, G.M., Weng, Z., Jowitt, S.M., Turnbull, I.D., and Graedel, T.E., 2013, Quantifying the recoverable resources of by-product metals—The case of cobalt: Ore Geology Reviews, v. 55, November, p. 87–98. [Also available at http://dx.doi.org/10.1016/j.oregeorev.2013.04.010.]

Muiños, S.B., Hein, J.R., Frank, Martin, Monteiro, J.H., Gaspar, Luis, Conrad, Tracey, Pereira, H.G., and Abrantes, Fátima, 2013, Deep-sea Fe-Mn crusts from the northeast Atlantic Ocean—Composition and resource considerations: Marine Georesources & Geotechnology, v. 31, no. 1, p. 40–70. [Also available at http://dx.doi.org/10.1080/1064119X.2012.661215.]

Murphy, P.J., and Meyer, G., 1998, A gold-copper association in ultramafic-hosted hydrothermal sulfides from the Mid-Atlantic Ridge: Economic Geology, v. 93, p. 1076–1083. [Also available at http://dx.doi.org/10.2113/gsecongeo.93.7.1076.]

Mustang Minerals Corp., 2013, Makwa nickel: Toronto, Ontario, Canada, Mustang Minerals Corp., accessed April 15, 2013, at http://www.mustangminerals.com/projects/makwa/.

Naldrett, A.J., 2004, Magmatic sulfide deposits—Geology, geochemistry, and exploration: Berlin, Germany, Springer-Verlag, 727 p.

Naldrett, A.J., and Li, Chusi, 2007, The Voisey's Bay deposit, Labrador, Canada, *in* Goodfellow, W.D., ed., Mineral deposits of Canada—A synthesis of major deposit-types, district metallogeny, the evolution of geological provinces, and exploration methods: Geological Association of Canada Special Publication no. 5, p. 387–408.

Naldrett, A.J., Fedorenko, V.A., Asif, Mohammed, Lin, Shushen, Kunilov, V.E., Stekhin, A.I., Lightfoot, P.C., and Gorbachev, N.S., 1996, Controls on the composition of Ni-Cu sulfide deposits as illustrated by those at Noril'sk, Siberia: Economic Geology, v. 91, p. 751–773. [Also available at http://dx.doi.org/10.2113/gsecongeo.91.4.751.]

Narendrula, R., Nkongolo, K.K., and Beckett, P., 2012, Comparative soil metal analysis in Sudbury (Ontario, Canada) and Lubumbashi (Katanga, DR-Congo): Bulletin of Environmental Contamination and Toxicology, v. 88, no. 2, p. 187–192. [Also available at http://dx.doi.org/10.1007/s00128-011-0485-7.]

National Toxicology Program, 2014a, Cobalt sulfate, *in* Report on Carcinogens (13th ed.): Research Triangle Park, N.C., U.S. Department of Health and Human Services, Public Health Service, accessed May 9, 2016, at http://ntp.niehs.nih.gov/ntp/roc/content/profiles/cobaltsulfate.pdf.

National Toxicology Program, 2014b, Cobalt-tungsten carbide—Powders and hard metals, *in* Report on Carcinogens (13th ed.): Research Triangle Park, N.C., U.S. Department of Health and Human Services, Public Health Service, accessed May 9, 2016, at http://ntp.niehs.nih.gov/ntp/roc/content/profiles/cobalttungstencarbide.pdf.

National Toxicology Program, 2016, Report on carcinogens—Monograph on cobalt and cobalt compounds that release cobalt ions *in vivo*: Research Triangle Park, N.C., U.S. Department of Health and Human Services, Public Health Service, April 22, variously paged, accessed May 3, 2016, at http://ntp.niehs.nih.gov/ntp/roc/monographs/cobalt_final_508.pdf

Neumann, Henrich, 1944, Silver deposits at Kongsberg: Norges Geologiske Undersøkelse, v. 162, 133 p.

Nickel Asia Corp., 2011, Ore resources and reserves: Taguig City, Philippines, Nickel Asia Corp., accessed April 22, 2013, at http://www.nickelasia.com/oreReserves.html.

Nilsson, John, Simpson, R.G., and McKenzie, William, 2011, Expansion feasibilty [sic] study for the Tenke Fungurume Mine, Katanga Province, Democratic Republic of Congo [sic], NI 43–101 technical report prepared for Lundin Mining Corp. [Filing date December 15, 2011]: Nilsson Mine Services Ltd., GeoSim Services Inc., and Global Management Corp., December 15, 203 p., accessed June 30, 2016, at http://www.sedar.com.

Occupational Safety and Health Administration, 2013, Cobalt, metal, dust and fume (as Co): Occupational Safety and Health Administration, accessed March 27, 2013, at http://www.osha.gov/dts/chemicalsampling/data/CH_229100.html.

Owen, M.L., and Meyer, L.H.I., 2013, NI 43–101 technical report on the Eagle Mine, Upper Peninsula of Michigan, USA, prepared for Lundin Mining Corp.: Penryn, United Kingdom, Wardell Armstrong International, July, 241 p. plus 3 appendixes, accessed April 1, 2014, at http://www.lundinmining.com/i/pdf/2013-07-26_EagleMine_NI43-101.pdf.

Paliouris, Georgia, and Hutchinson, T.C., 1991, Arsenic, cobalt, and nickel tolerances in two populations of *Silene vulgaris* (Moench) Garcke from Ontario, Canada: New Phytologist, v. 117, p. 449–459. [Also available at http://dx.doi.org/10.1111/j.1469-8137.1991.tb00009.x.]

Panoramic Resources Ltd., 2012, Resources & reserves, Savannah project: Perth, Western Australia, Australia, Panoramic Resources Ltd., accessed April 14, 2013, at http://www.panoramicresources.com/media//RESOURCES-AND-RESERVES---Nickel.pdf.

Paradis, Suzanne, Hannigan, Peter, and Dewing, Keith, 2007, Mississippi Valley-type lead-zinc deposits, *in* Goodfellow, W.D., ed., Mineral deposits of Canada—A synthesis of major deposit-types, district metallogeny, the evolution of geological provinces, and exploration methods: Geological Association of Canada Special Publication no. 5, p. 185–204.

Parra, L.A., Childers, G.A., Fifarek, R.H., Guillemette, R.N., Palmer, J.R., and Taylor, D.R., 2009, Rediscovering southeast Missouri Mississippi Valley-type Pb-Zn deposits—The cobalt-nickel enriched Higdon deposit, Madison and Perry Counties [abs.]: Geological Society of America Abstracts with Programs, v. 41, no. 7, p. 86.

Parthiban, G., and Banakar, V.K., 1999, Chemistry and possible resource potential of cobalt rich ferromanganese crusts from the Afanasiy-Nikitin seamount in the Indian Ocean: The Indian Mineralogist, v. 33, no. 1, p. 125–132. [Also available at https://www.researchgate.net/publication/27668543_Chemistry_and_possible_resource_potential_of_cobalt_rich_ferromanganese_crust_from_Afanasiy-Nikitin_seamount_in_the_Indian_Ocean.]

Peltonen, P., Kontinen, A., Huhma, H., and Kuronen, U., 2008, Outokumpu revisited—New mineral deposit model for the mantle peridotite-associated Cu-Co-Zn-Ni-Ag-Au sulphide deposits: Ore Geology Reviews, v. 33, nos. 3–4, p. 559–617. [Also available at http://dx.doi.org/10.1016/j.oregeorev.2007.07.002.]

Peter, J.M., and Scott, S.D., 1999, Windy Craggy, northwestern British Columbia—The world's largest Besshi-type deposit: Reviews in Economic Geology, v. 8, p. 261–295. [Also available at https://www.researchgate.net/publication/257437794_Windy_Craggy_northwestern_British_Columbia_The_world's_largest_Besshi-type_deposit.]

Petruk, W., Jambor, J., and Boyle, R.W., 1971, History of the Cobalt and Gowganda area: Canadian Mineralogist, v. 11, no. 1, December, p. 1–11. [Also available at http://canmin.geoscienceworld.org/content/11/1/1.full.pdf+html.]

Pirajno, Franco, 2013, The geology and tectonic settings of China's mineral deposits: Dordrecht, Germany, Springer, 679 p. [Also available at http://dx.doi.org/10.1007/978-94-007-4444-8.]

Plumlee, G.S., and Logsdon, M.J., 1999, An Earth-system science toolkit for environmentally friendly mineral resource development, *in* Plumlee, G.S., and Logsdon, M.J.,eds., The environmental geochemistry of mineral deposits—Part A, Processes, techniques, and health issues: Littleton, Colo., Society of Economic Geologists, Reviews in Economic Geology Series, v. 6A, p. 1–27.

Plumlee, G.S., Smith, K.S., Montour, M.R., Ficklin, W.H., and Mosier, E.L., 1999, Geologic controls on the composition of natural waters and mine waters draining diverse mineral-deposit types, *in* Plumlee, G.S., and Filipek, L.H., eds., The environmental geochemistry of mineral deposits—Part B, Case studies and research topics: Littleton, Colo., Society of Economic Geologists, Reviews in Economic Geology Series, v. 6B, p. 373–409.

Polymet Mining Corp., 2013, Form 20–F—2013: Toronto, Ontario, Canada, Polymet Mining Corp., accessed April 22, 2013, at http://www.polymetmining.com/investors/financial-reports/.

Power, G., Gräfe, M., and Klauber, C., 2011, Bauxite residue issues—I. Current management, disposal and storage facilities: Hydrometallurgy, v. 108, nos. 1–2, p. 33–45. [Also available at http://dx.doi.org/10.1016/j.hydromet.2011.02.006.]

Powers, L.A., and Siemens, R.E., 1983, Examination of effluents generated from processing domestic laterites: U.S. Bureau of Mines Report of Investigations 8797, 13 p. [Also available at http://stacks.cdc.gov/view/cdc/10479/cdc_10479_DS1.pdf.]

Prokin, V.A., and Buslaev, F.P., 1999, Massive copper-zinc sulphide deposits in the Urals: Ore Geology Reviews, v. 14, no. 1, p. 1–69. [Also available at http://dx.doi.org/10.1016/S0169-1368(98)00014-6.]

Prophecy Platinum Corp., 2013a, Shakespeare: Vancouver, British Columbia, Canada, Prophecy Platinum Corp., accessed April 19, 2013, at http://prophecyplat.com/project_shakespeare.php.

Prophecy Platinum Corp., 2013b, Wellgreen: Vancouver, British Columbia, Canada, Prophecy Platinum Corp., accessed April 12, 2013, at http://prophecyplat.com/project_wellgreen.php.

Puget Ventures Inc., 2013, Karakul cobalt deposit: Vancouver, British Columbia, Canada, Puget Ventures Inc., accessed April 12, 2013, at http://cobaltinvestingnews.com/64-puget-ventures-inc-advanced-cobalt-property-werner-west-cobalt-mine/.

Python Mining Consultants, 2013, History of nickel mining in Sudbury: Hamilton, Ontario, Canada, Python Mining Consultants, accessed April 9, 2013, at http://www.pythongroup.ca/mining-news/article/id/37.

Rachlin, J.W., and Grosso, A., 1993, The growth response of the green alga *Chlorella vulgaris* to combined divalent cation exposure: Archives of Environmental Contamination and Toxicology, v. 24, no. 1, p. 16–20.

Reimann, Clemens, and de Caritat, Patrice, 1998, Chemical elements in the environment—Factsheets for the geochemist and environmental scientist: Berlin, Germany, Springer-Verlag, 398 p.

Reynolds, Lachlan, 2000, Geology of the Olympic Dam Cu-U-Au-Ag-REE deposit, *in* Porter, T.M., ed., Hydrothermal iron oxide copper-gold & related deposits—A global perspective: Adelaide, South Australia, Australia, PGC Publishing, v. 1, p. 93–104.

Rose, A.W., Herrick, D.C., and Deines, Peter, 1985, An oxygen and sulfur isotope study of skarn-type magnetite deposits of the Cornwall type, southeastern Pennsylvania: Economic Geology, v. 80, p. 418–433. [Also available at http://dx.doi.org/10.2113/gsecongeo.80.2.418.]

Saari, P., and Riekkola-Vanhanen, M., 2012, Talvivaara bioheapleaching process: Journal of the Southern African Institute of Mining and Metallurgy, v. 112, no. 12, p. 1013–1020. [Also available at http://www.saimm.co.za/Journal/v112n12p1013.pdf.]

Schmidt, F.-P., and Friedrich, G.H., 1988, Geologic setting and genesis of Kupferschiefer mineralization in West Germany, *in* Friedrich, G.H., and Herzig, P.M., eds., Base metal sulfide deposits in sedimentary and volcanic environments—Proceedings of the DMG-GDMB-SGA meeting, Aachen, 1985: Berlin, West Germany, Springer-Verlag, Society for Geology Applied to Mineral Deposits Special Publication no. 5, p. 25–59.

Schrauzer, G.N., 2004, Cobalt, *in* Merian, E., Anke, M., Ihnat, M., and Stoeppler, M.S., eds., Elements and their compounds in the environment—Occurrence, analysis and biological relevance: Weinheim, Germany, Wiley-VCH Verlag GmbH, p. 825–839.

Searle, P.J., 2015, Cobalt—Market balance in 2020s?: The Cobalt Conference, Toronto, Ontario, Canada, May 20–21, presentation, 21 p., accessed May 27, 2015, via http://www.thecdi.com/.

Seeger, C.M., 2008, History of mining in the southeast Missouri lead district and description of mine processes, regulatory controls, environmental effects, and mine facilities in the Viburnum Trend subdistrict, chap. 1 *of* Kleeschulte, M.J., ed., Hydrologic investigations concerning lead mining issues in southeastern Missouri: U.S. Geological Survey Scientific Investigations Report 2008–5140, 33 p. [Also available at http://pubs.usgs.gov/sir/2008/5140/.]

Selley, David, Broughton, David, Scott, Robert, Hitzman, Murray, Bull, Stuart, Large, Ross, McGoldrick, Peter, Croaker, Mawson, Pollington, Nicky, and Barra, Fernando, 2005, A new look at the geology of the Zambian copperbelt, *in* Hedenquist, J.W., Thompson, J.F.H., Goldfarb, R.J., and Richards, J.P., eds., Economic Geology—One hundredth anniversary volume, 1905–2005: Littleton, Colo., Society of Economic Geologists, p. 965–1000. [Appendixes are on a CD–ROM inside the back cover.]

Shacklette, H.T., and Boerngen, J.G., 1984, Element concentrations in soils and other surficial materials of the conterminous United States: U.S. Geological Survey Professional Paper 1270, 105 p. [Also available at http://pubs.usgs.gov/pp/1270/.]

Shanks, W.C. Pat, III, and Thurston, Roland, eds., 2012, Volcanogenic massive sulfide occurrence model, chap. C *of* Mineral deposit models for resource assessment: U.S. Geological Survey Scientific Investigations Report 2010–5070–C, 345 p. [Also available at http://pubs.usgs.gov/sir/2010/5070/c/.]

Shedd, K.B., 2013a, Cobalt, *in* Metals and minerals: U.S. Geological Survey Minerals Yearbook 2011, v. I, p. 19.1–19.21. [Also available at http://minerals.usgs.gov/minerals/pubs/commodity/cobalt/index.html#myb.]

Shedd, K.B., 2013b, Cobalt: U.S. Geological Survey Mineral Commodity Summaries 2013, p. 46–47. [Also available at https://minerals.usgs.gov/minerals/pubs/commodity/cobalt/mcs-2013-cobal.pdf.]

Shelley, R.U., Sedwick, P.N., Bibby, T.S., Cabedo-Sanz, P., Church, T.M., Johnson, R.J., Macey, A.I., Marsay, C.M., Sholkovitz, E.R., Ussher, S.J., Worsfold, P.J., and Lohan, M.C., 2012, Controls on dissolved cobalt in surface waters of the Sargasso Sea—Comparisons with iron and aluminum: Global Biogeochemical Cycles, v. 26, no. 2. [Also available at http://dx.doi.org/10.1029/2011GB004155.]

Slack, J.F., ed., 2013, Descriptive and geoenvironmental model for cobalt-copper-gold deposits in metasedimentary rocks (ver. 1.1, March 14, 2014): U.S. Geological Survey Scientific Investigations Report 2010–5070–G, 218 p. [Also available at http://dx.doi.org/10.3133/sir20105070G.]

Smith, C.G., 2001, Always the bridesmaid, never the bride—Cobalt geology and resources: Institution of Mining and Metallurgy Transactions, v. 110, sec. B (Applied Earth Science), p. B75–B80.

Smith, D.B., Cannon, W.F., Woodruff, L.G., Garrett, R.G., Klassen, Rodney, Kilburn, J.E., Horton, J.D., King, H.D., Goldhaber, M.B., and Morrison, J.M., 2005, Major- and trace-element concentrations in soils from two continental-scale transects of the United States and Canada: U.S. Geological Survey Open-File Report 2005–1253, 20 p. [Also available at https://pubs.usgs.gov/of/2005/1253/.]

Smith, K.S., and Huyck, L.O., 1999, An overview of the abundance, relative mobility, bioavailability, and human toxicity of metals, *in* Plumlee, G.S., and Logsdon, M.J., eds., The environmental geochemistry of mineral deposits—Part A, Processes, techniques and health issues: Littleton, Colo., Society of Economic Geologists, v. 1, p. 29–70.

Spencer, Edward, 2016, Cobalt supply and demand—A global perspective: : The Cobalt Conference, Seoul, Republic of Korea, May 11–12, presentation, 22 p., accessed June 23, 2016, via http://www.thecdi.com/.

Sracek, O., Mihaljevič, M., Křibek, B., Majer, V., and Veselovský, F., 2010, Geochemistry and mineralogy of Cu and Co in mine tailings at the copperbelt, Zambia: Journal of African Earth Sciences, v. 57, nos. 1–2, p. 14–30. [Also available at http://dx.doi.org/10.1016/j.jafrearsci.2009.07.008.]

Staples, L.P., Bernier, S.B., Lane, G.S., Penswick, D.P., Scott, C.C., Murphy, B.A., and Bertrand, V.J., 2012, Technical report on the Dumont project, Launay and Trécesson Townships, Quebec, Canada, prepared for Royal Nickel Corp.: Vancouver, British Columbia, Canada, Ausenco Solutions Canada Inc., no. 2139–RPT–003, July 18 (revision of report dated June 22, 2012), accessed April 14, 2013, at http://www.royalnickel.com/_docs/dumont-jun-22-2012.pdf.

Starfield Resources Inc., 2013, Ferguson Lake mineralization: Toronto, Ontario, Canada, Starfield Resources Inc., accessed April 14, 2013, at http://starfieldres.com/SiteResources/ViewContent.asp?DocID=134&v1ID=&RevID=335&lang=1.

Sun, Y.-H., and Püttmann, Wilhelm, 1997, Metal accumulation during and after deposition of the Kupferschiefer from the Sangerhausen basin, Germany: Applied Geochemistry, v. 12, no. 5, p. 577–592. [Also available at http://dx.doi.org/10.1016/S0883-2927(97)00015-2.]

Suter, G.W., II, and Tsao, C.L., 1996, Toxicological benchmarks for screening potential contaminants of concern for effects on aquatic biota—1996 revision: Oak Ridge, Tenn., Lockheed Martin Energy Systems Inc., ES/ER/TM-96/R2, variously paged, accessed March 3, 2013, at http://www.esd.ornl.gov/programs/ecorisk/documents/tm96r2.pdf.

Talvivaara Mining Company plc, 2013, Operations—Mineral resources: Espoo, Finland, Talvivaara Mining Company plc, accessed April 9, 2013, at http://www.talvivaara.com/operations/Mineral_resources.

Taylor, C.D., Causey, J.D., Denning, P.D., Hammarstrom, J.M., Hayes, T.S., Horton, J.D., Kirschbaum, M.J., Parks, H.L., Wilson, A.B., Wintzer, N.E., and Zientek, M.L., 2013, Descriptive models, grade-tonnage relations, and databases for the assessment of sediment-hosted copper deposits—With emphasis on deposits in the Central African Copperbelt, Democratic Republic of the Congo and Zambia: U.S. Geological Survey Scientific Investigations Report 2010–5090–J, 154 p. and data files. [Also available at http://pubs.usgs.gov/sir/2010/5090/j/sir2010-5090j_text.pdf.]

Taylor, S.R., and McLennan, S.M., 1995, The geochemical evolution of the continental crust: Reviews of Geophysics, v. 33, no. 2, p. 241–265. [Also available at http://dx.doi.org/10.1029/95rg00262.]

Teck Resources Ltd., 2010, Mesaba Ni-Cu project—2010 IPS field trip: Vancouver, British Columbia, Canada, Teck Resources Ltd., June 7, accessed April 14, 2013, at http://www.d.umn.edu/prc/Pt%20Symp%20FT/Mesaba.pdf.]

The Coface Group, [undated], Congo, the Democratic Republic of the: Paris, France, The Coface Group, accessed March 11, 2013, at http://www.coface.com/CofacePortal/COM_en_EN/pages/home/risks_home/country_risks/country_file/Congo, the Democratic Republic of the?extraUid=572108.

Thorne, R.L., Roberts, Stephen, and Herrington, Richard, 2012, Climate change and the formation of nickel laterite deposits: Geology, v. 40, no. 4, p. 331–334. [Also available at http://dx.doi.org/10.1130/G32549.1.]

Tiger International Resources Inc., 2006, Sabah Tavai nickel project applied for by Tiger International: Laguna Hills, Calif., Tiger International Resources Inc. press release, April 3, 2 p., accessed April 12, 2013, at http://www.tigerresources.com/newsrel/Apr3-06.pdf.]

Tintina Resources Inc., 2016, Black Butte copper project: Vancouver, British Columbia, Canada, Tintina Resources Inc., accessed March 30, 2016, at http://www.tintinaresources.com/assets/docs/ppt/2016_tau_cp.pdf.

Tyler, Germund, 2004, Vertical distribution of major, minor, and rare elements in a Haplic Podzol: Geoderma, v. 119, nos. 3–4, p. 277–290. [Also available at http://dx.doi.org/10.1016/j.geoderma.2003.08.005.]

U.S. Environmental Protection Agency, 2012, Explanation of significant differences for the record of decision for the Blackbird Mine, Lemhi County, Idaho: U.S. Environmental Protection Agency, 16 p. plus 1 attachment, accessed March 26, 2013, at http://www.epa.gov/region10/pdf/sites/blackbird_mine/blackbirdmine_ESD_053112.pdf.

U.S. Environmental Protection Agency, 2013, National ambient air quality standards (NAAQS)—Lead (Pb) standards—Table of historical Pb NAAQS: U.S. Environmental Protection Agency, accessed February 18, 2013, at http://www.epa.gov/ttn/naaqs/standards/pb/s_pb_history.html.

U.S. Environmental Protection Agency, 2016, National primary drinking water regulations: U.S. Environmental Protection Agency Web page, accessed May 3, 2016, at http://water.epa.gov/drink/contaminants/index.cfm.

U.S. Geological Survey, 2013, Cobalt statistics, *in* Kelly, T.D., and Matos, G.R., comps., Historical statistics for mineral and material commodities in the United States (2013 version): U.S. Geological Survey Data Series 140, accessed December 17, 2013, at http://pubs.usgs.gov/ds/2005/140/.

U.S. Nuclear Regulatory Commission, 2013a, Cobalt-57: U.S. Nuclear Regulatory Commission Web page, accessed March 27, 2013, at http://www.nrc.gov/reading-rm/doc-collections/cfr/part020/appb/Cobalt-57.html.

U.S. Nuclear Regulatory Commission, 2013b, Cobalt-60: U.S. Nuclear Regulatory Commission Web page, accessed March 27, 2013, at http://www.nrc.gov/reading-rm/doc-collections/cfr/part020/appb/Cobalt-60.html.

Valeton, I., Biermann, M., Reche, R., and Rosenberg, F., 1987, Genesis of nickel laterites and bauxites in Greece during the Jurassic and Cretaceous, and their relation to ultrabasic parent rocks: Ore Geology Reviews, v. 2, no. 4, p. 359–404. [Also available at http://dx.doi.org/10.1016/0169-1368(87)90011-4.]

Vangold Resources Ltd., 2013, Uganda—Gold, nickel, platinum, copper, and cobalt—Kilembe: Vancouver, British Columbia, Canada, Vangold Resources Ltd., accessed April 12, 2013, at http://www.vangold.ca/s/Kilembe.asp.]

Vanhanen, Erkki, 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 399, 229 p.

Viers, Jérôme, Dupré, Bernard, and Gaillardet, Jérôme, 2009, Chemical composition of suspended sediments in world rivers—New insights from a new database: Science of the Total Environment, v. 407, no. 2, p. 853–868. [Also available at http://dx.doi.org/10.1016/j.scitotenv.2008.09.053.]

von der Heyden, C.J., and New, M.G., 2004, Groundwater pollution on the Zambian copperbelt—Deciphering the source and the risk: Science of the Total Environment, v. 327, nos. 1–3, p. 17–30. [Also available at http://dx.doi.org/10.1016/j.scitotenv.2003.08.028.]

Votorantim Group, 2006, Metals [reserves and resources]: São Paulo, Brazil, Votorantim Group, accessed April 22, 2013, via http://www.votorantim.com.br/en-US/Pages/home.aspx.]

Wang, S.-Q., and Williams, P.J., 2001, Geochemistry and origin of Proterozoic skarns at the Mount Elliott Cu-Au (-Co-Ni) deposit, Cloncurry district, NW Queensland, Australia: Mineralium Deposita, v. 36, no. 2, p. 109–124. [Also available at http://link.springer.com/article/10.1007%2Fs001260050292.]

Watling, H.R., Elliot, A.D., Fletcher, H.M., Robinson, D.J., and Sully, D.M., 2011, Ore mineralogy of nickel laterites—Controls on processing characteristics under simulated heap-leach conditions: Australian Journal of Earth Sciences, v. 58, no. 7, p. 725–744. [Also available at http://dx.doi.org/10.1080/08120099.2011.602986.]

Wells, M.A., Ramanaidou, E.R., Verrall, Michael, and Tessarolo, Christian, 2009, Mineralogy and crystal chemistry of “garnierites” in the Goro lateritic nickel deposit, New Caledonia: European Journal of Mineralogy, v. 21, no. p. 467–483. [Also available at http://dx.doi.org/10.1127/0935-1221/2009/0021-1910.]

Wilburn, D.R., 2012, Cobalt mineral exploration and supply from 1995 through 2013: U.S. Geological Survey Scientific Investigations Report 2011–5084, 16 p. [Also available at http://pubs.usgs.gov/sir/2011/5084/.]

Williams, P.J., and Pollard, P.J., 2001, Australian Proterozoic iron oxide-Cu-Au deposits—An overview with new metallogenic and exploration data from the Cloncurry district, northwest Queensland: Exploration and Mining Geology, v. 10, no. 3, p. 191–213. [Also available at http://dx.doi.org/10.2113/0100191.]

Williams, P.J., Barton, M.D., Johnson, D.A., Fontboté, Lluís, de Haller, Antoine, Mark, Geordie, Oliver, N.H.S., and Marschik, Robert, 2005, Iron oxide copper-gold deposits—Geology, space-time distribution, and possible modes of origin, *in* Hedenquist, J.W., Thompson, J.F.H., Goldfarb, R.J., and Richards, J.P., eds., Economic Geology—One hundredth anniversary volume, 1905–2005: Littleton, Colo., Society of Economic Geologists, p. 371–405. [Appendixes are on a CD–ROM inside the back cover.]

Wilson, A.B., Causey, J.D., Denning, P.D., Hayes, T.S., Horton, J.D., Kirschbaum, M.J., Parks, H.L., Taylor, C.D., and Zientek, M.L., 2013, Appendix A—Relational database of sediment-hosted copper deposits, resources, and production in the Central African Copperbelt, Democratic Republic of the Congo and Zambia, *in* Taylor, C.D., Causey, J.D., Denning, P.D., Hammarstrom, J.M., Hayes, T.S., Horton, J.D., Kirschbaum, M.J., Parks, H.L., Wilson, A.B., Wintzer, N.E., and Zientek, M.L., Descriptive models, grade-tonnage relations, and databases for the assessment of sediment-hosted copper deposits—With emphasis on deposits in the Central African Copperbelt, Democratic Republic of the Congo and Zambia: U.S. Geological Survey Scientific Investigations Report 2010–5090–J, p. 103–144. [Also available at http://pubs.usgs.gov/sir/2010/5090/j/.]

Xstrata plc, 2011, Mineral resources & ore reserves: Xstrata plc, accessed April 22, 2013, at http://www.xstrata.com/publications/reservesandresources/.

Xu, Y.-B., Xie, Y.-T., Yan, Lan, and Yang, R.-D., 2005, A new method for recovering valuable metals from low-grade nickeliferous oxide ores: Hydrometallurgy, v. 80, no. 4, p. 280–285. [Also available at http://dx.doi.org/10.1016/j.hydromet.2005.08.007.]

Xu, Yong, and Zhu, Xinyou, 2000, Cobalt deposits in the central China orogenic belt: Acta Geologica Sinica, v. 74, no. 3, p. 540–543.

Zientek, M.L., Hayes, T.S., and Hammarstrom, J.M., 2013, Overview of a new descriptive model for sediment-hosted stratabound copper deposits, chap. 1 *of* Taylor, C.D., Causey, J.D., Denning, P.D., Hammarstrom, J.M., Hayes, T.S., Horton, J.D., Kirschbaum, M.J., Parks, H.L., Wilson, A.B., Wintzer, N.E., and Zientek, M.L., Descriptive models, grade-tonnage relations, and databases for the assessment of sediment-hosted copper deposits—With emphasis on deposits in the Central African Copperbelt, Democratic Republic of the Congo and Zambia: U.S. Geological Survey Scientific Investigations Report 2010–5090–J, p. 2–16. [Also available at http://pubs.usgs.gov/sir/2010/5090/j/.]

Zijin Mining Group Co. Ltd., 2010, Information of Deziwa and Ecaille C copper-cobalt projects: Longyan, Fujan, China, Zijin Mining Group Co. Ltd., accessed April 22, 2013, at www.zjky.cn/portals/1/ltn20100507861.pdf.

Zohny, E.A.M., 2002, Cobalt in alluvial Egyptian soils affected by industrial activities: Journal of Environmental Sciences (China), v. 14, no. 1, p. 34–38.

Table F1

Table F1. Location, grade, tonnage, and other data for selected cobalt deposits of the world.

[Tonnage and grade include reserves, other resources, and past production (where available). WGS 84, World Geodetic System of 1984; negative values for latitude indicate that the deposit is in the Southern Hemisphere; negative values for longitude indicate that the deposit is in the Western Hemisphere; Congo (Kinshasa), Democratic Republic of the Congo; EEZ, Exclusive Economic Zone; Mt, million metric tons; %, percent. Element: Ag, silver; Au, gold; As, arsenic; Bi, bismuth; Co, cobalt; Cu, copper; Fe, iron; Mn, manganese; Mo, molybdenum; Ni, nickel; REE, rare-earth elements; Zn, zinc]

Deposit	Country	Latitude	Longitude	Tonnage (Mt)	Grade (% Co)	Co content (Mt)	Principal data source and notes
		(decimal degrees WGS 84)					
Stratiform sediment-hosted Cu-Co deposits							
Browns	Australia	–13.07	131.08	84.0	0.120	0.101	Compass Resources NL (2007)
Emmie Bluff	Australia	–31.10	137.17	25.0	0.100	0.025	Hitzman and others (2005)
Mount Gunson	Australia	–31.45	137.25	11.7	0.060	0.007	Hitzman and others (2005)
Mount Isa	Australia	–20.57	139.47	182.0	0.050	0.091	Mount Isa Mines Ltd. (2012)
Pyrite Hill-Big Hill	Australia	–32.12	141.20	20.8	0.085	0.018	Broken Hill Prospecting Ltd. (2013)
Windabout	Australia	–31.30	137.16	18.7	0.050	0.009	Gunson Resources Ltd. (2013)
Tangdan (Dongchuan)	China	26.12	103.17	146.8	0.010	0.015	Hitzman and others (2005)
Deziwa	Congo (Kinshasa)	–10.78	25.77	319.4	0.120	0.383	Zijin Mining Group Co. Ltd. (2010)
Dilala East	Congo (Kinshasa)	–10.70	25.47	19.1	0.900	0.172	Metorex Pty Ltd. (2011)
DIMA	Congo (Kinshasa)	–10.74	25.38	280.0	0.189	0.530	Wilson and others (2013)
Disele	Congo (Kinshasa)	–10.75	26.25	4.1	0.068	0.003	Wilson and others (2013)
Écaille C	Congo (Kinshasa)	–10.76	26.12	21.8	0.060	0.013	Zijin Mining Group Co. Ltd. (2010)
Etoile (Ruashi)	Congo (Kinshasa)	–11.63	27.58	52.6	0.300	0.158	Metorex Pty Ltd. (2011)
Kababankola	Congo (Kinshasa)	–10.73	26.42	1.9	1.120	0.021	Wilson and others (2013)
Kabolela	Congo (Kinshasa)	–10.69	26.45	11.7	0.501	0.059	Wilson and others (2013)
Kakanda	Congo (Kinshasa)	–10.74	26.40	32.4	0.180	0.058	Wilson and others (2013)
Kalukundi-Kii	Congo (Kinshasa)	–10.62	25.91	12.8	0.457	0.058	Wilson and others (2013)
Kambove	Congo (Kinshasa)	–10.85	26.61	46.9	0.213	0.100	Wilson and others (2013)
Kamfundwa	Congo (Kinshasa)	–10.81	26.59	26.8	0.200	0.054	Wilson and others (2013)
Kamoto-KOV-Musonoi-Mupine	Congo (Kinshasa)	–10.72	25.40	416.0	0.387	1.608	Wilson and others (2013)
Kananga	Congo (Kinshasa)	–10.68	25.48	8.1	0.884	0.072	Wilson and others (2013)
Kazibizi	Congo (Kinshasa)	–10.83	26.57	1.0	0.600	0.006	Wilson and others (2013)
Kipapila	Congo (Kinshasa)	–12.02	27.90	2.6	0.540	0.014	Wilson and others (2013)
Kipoi Central	Congo (Kinshasa)	–11.26	27.10	4.6	0.143	0.007	Wilson and others (2013)
Kipoi North	Congo (Kinshasa)	–11.26	27.10	5.3	0.049	0.003	Wilson and others (2013)
Kisanfu	Congo (Kinshasa)	–10.77	25.98	108.0	1.080	1.166	Freeport-McMoRan Copper & Gold Inc. (2013)
Luishia	Congo (Kinshasa)	–11.17	27.01	72.3	0.152	0.110	Wilson and others (2013)
Luiswishi	Congo (Kinshasa)	–11.51	27.42	8.0	1.100	0.088	Wilson and others (2013)
Lupoto	Congo (Kinshasa)	–11.60	27.26	24.1	0.088	0.021	Wilson and others (2013)
M’Sesa	Congo (Kinshasa)	–10.85	26.58	8.0	0.213	0.017	Wilson and others (2013)
Mukondo (includes C19 and C21)	Congo (Kinshasa)	–10.73	26.35	70.0	0.714	0.500	CAMEC Plc (2007)
Mutanda	Congo (Kinshasa)	–10.79	25.81	299.5	0.59	1.767	Glencore International plc (2011)
Mutoshi	Congo (Kinshasa)	–10.65	25.51	10.8	0.304	0.033	Wilson and others (2013)
Tenke Fungurume[1]	Congo (Kinshasa)	–10.58	26.19	674.0	0.245	1.651	Nilsson and others (2011)
Tilwezembe	Congo (Kinshasa)	–10.80	25.69	23.4	0.637	0.149	Wilson and others (2013)

Table F1. Location, grade, tonnage, and other data for selected cobalt deposits of the world.—Continued

[Tonnage and grade include reserves, other resources, and past production (where available). WGS 84, World Geodetic System of 1984; negative values for latitude indicate that the deposit is in the Southern Hemisphere; negative values for longitude indicate that the deposit is in the Western Hemisphere; Congo (Kinshasa), Democratic Republic of the Congo; EEZ, Exclusive Economic Zone; Mt, million metric tons; %, percent. Element: Ag, silver; Au, gold; As, arsenic; Bi, bismuth; Co, cobalt; Cu, copper; Fe, iron; Mn, manganese; Mo, molybdenum; Ni, nickel; REE, rare-earth elements; Zn, zinc]

Deposit	Country	Latitude (decimal degrees WGS 84)	Longitude (decimal degrees WGS 84)	Tonnage (Mt)	Grade (% Co)	Co content (Mt)	Principal data source and notes
Stratiform sediment-hosted Cu-Co deposits—Continued							
Boleo	Mexico	27.33	–112.30	424.5	0.054	0.231	Baja Mining Corp. (2011)
Kilembe	Uganda	0.22	30.05	16.2	0.170	0.028	Vangold Resources Ltd. (2013)
Sheep Creek (Black Butte)	United States	46.73	–110.90	11.6	0.100	0.012	Tintina Resources Inc. (2016)
Baluba-Muliashi-Luanshya	Zambia	–13.50	28.38	339.0	0.033	0.111	Wilson and others (2013)
Chambishi Southeast	Zambia	–12.66	28.05	178.0	0.069	0.123	Wilson and others (2013)
Chibuluma-Chibuluma West	Zambia	–12.92	28.08	19.9	0.186	0.037	Wilson and others (2013)
Chimiwungo	Zambia	–12.18	25.85	761.0	0.009	0.069	Wilson and others (2013)
Chingola-Nchanga	Zambia	–12.51	27.87	576.0	0.026	0.149	Wilson and others (2013)
Kalumbila	Zambia	–12.21	25.35	340.0	0.030	0.102	Wilson and others (2013)
Malundwe	Zambia	–12.16	25.75	162.0	0.014	0.023	Wilson and others (2013)
Mindola-Nkana N-S	Zambia	–12.80	28.18	656.0	0.065	0.429	Wilson and others (2013)
Nama	Zambia	–12.26	27.62	185.8	0.059	0.109	Wilson and others (2013)
Ni-Co laterite deposits							
Bell Creek-Neck-Minnamoolka	Australia	–18.14	144.79	18.4	0.050	0.009	Metallica Minerals Ltd. (2013)
Cawse	Australia	–30.38	121.15	217.0	0.040	0.087	Berger and others (2011)
Claude Hills	Australia	–26.00	129.30	33.3	0.070	0.023	Metals X Ltd. (2013)
Greenvale-Kokomo-Lucknow	Australia	–18.97	144.94	59.5	0.070	0.042	Metallica Minerals Ltd. (2013)
Kalgoorlie Nickel[2]	Australia	–30.10	121.05	727.0	0.044	0.320	Heron Resources Ltd. (2013)
Marlborough	Australia	–23.01	149.89	210.0	0.060	0.126	Berger and others (2011)
Murrin Murrin	Australia	–28.77	121.89	464.0	0.076	0.351	Minara Resources Pty Ltd. (2011)
Ora Banda	Australia	–30.24	121.00	30.0	0.080	0.024	Berger and others (2011)
Ravensthorpe	Australia	–33.65	120.40	386.0	0.027	0.104	Berger and others (2011)
Summervale/Westlynn	Australia	–31.55	147.17	16.0	0.064	0.010	Jervois Mining Ltd. (2013)
Weld Range	Australia	–26.82	117.75	330.0	0.060	0.198	Minara Resources Pty Ltd. (2005)
Wingellina	Australia	–26.06	128.97	347.7	0.080	0.278	Metals X Ltd. (2013)
Yerilla	Australia	–29.73	122.04	135.4	0.052	0.070	Heron Resources Ltd. (2013)
Young	Australia	–35.77	148.82	167.0	0.070	0.117	Jervois Mining Ltd. (2013)
Jacaré	Brazil	–6.21	–52.86	495.0	0.130	0.644	Berger and others (2011)
Niquelandia	Brazil	–14.35	–48.40	56.3	0.060	0.034	Berger and others (2011)
Santa Fe	Brazil	–15.67	–51.12	61.0	0.060	0.037	Berger and others (2011)
Serra do Tapa	Brazil	–6.85	–49.33	60.3	0.050	0.030	Berger and others (2011)
Vale dos Sonhos	Brazil	–6.97	–49.26	13.0	0.070	0.009	Berger and others (2011)

Table F1. Location, grade, tonnage, and other data for selected cobalt deposits of the world.—Continued

[Tonnage and grade include reserves, other resources, and past production (where available). WGS 84, World Geodetic System of 1984; negative values for latitude indicate that the deposit is in the Southern Hemisphere; negative values for longitude indicate that the deposit is in the Western Hemisphere; Congo (Kinshasa), Democratic Republic of the Congo; EEZ, Exclusive Economic Zone; Mt, million metric tons; %, percent. Element: Ag, silver; Au, gold; As, arsenic; Bi, bismuth; Co, cobalt; Cu, copper; Fe, iron; Mn, manganese; Mo, molybdenum; Ni, nickel; REE, rare-earth elements; Zn, zinc]

Deposit	Country	Latitude	Longitude	Tonnage (Mt)	Grade (% Co)	Co content (Mt)	Principal data source and notes
		(decimal degrees WGS 84)					
			Ni-Co laterite deposits—Continued				
Vermelho	Brazil	–6.24	–49.75	290.0	0.026	0.075	Berger and others (2011)
Vila Oito	Brazil	–7.79	–49.35	12.9	0.065	0.008	Berger and others (2011)
Musongati	Burundi	–3.79	30.19	185.0	0.080	0.148	Berger and others (2011)
Nyabikere	Burundi	–3.28	30.09	46.4	0.030	0.014	Berger and others (2011)
Waga	Burundi	–3.56	29.91	35.0	0.040	0.014	Berger and others (2011)
Nkamouna (includes Mada)	Cameroon	3.27	13.81	391.5	0.220	0.860	Geovic Mining Corp. (2013)
Moa	Cuba	20.60	–74.96	290.0	0.180	0.522	Berger and others (2011)
Nicaro	Cuba	20.63	–75.54	200.0	0.100	0.200	Berger and others (2011)
Pinares de Mayari	Cuba	20.54	–75.72	400.0	0.100	0.400	Berger and others (2011)
Punta Gorda	Cuba	20.63	–74.89	310.0	0.110	0.341	Berger and others (2011)
Sechol	Guatemala	15.43	–89.66	36.1	0.080	0.029	Berger and others (2011)
Bhimatangar	India	21.01	85.74	63.9	0.150	0.096	Berger and others (2011)
Kansa	India	21.06	85.86	40.9	0.080	0.033	Berger and others (2011)
Saruabil	India	21.06	85.82	18.4	0.080	0.015	Berger and others (2011)
Gag Island	Indonesia	–0.45	129.88	240.0	0.080	0.192	Berger and others (2011)
Halmahera/Weda Bay	Indonesia	–0.50	127.94	277.0	0.090	0.249	Berger and others (2011)
La Sampala	Indonesia	–2.70	121.93	162.0	0.080	0.130	Berger and others (2011)
Tiuba-Biankouma	Ivory Coast	7.74	–7.62	293.0	0.110	0.322	Berger and others (2011)
Gornostai	Kazakhstan	50.61	78.76	9.7	0.059	0.006	Berger and others (2011)
Kempirsai	Kazakhstan	50.34	58.28	179.7	0.054	0.097	Berger and others (2011)
Cikatova	Kosovo	42.22	21.26	13.0	0.070	0.009	Berger and others (2011)
Glavica	Kosovo	42.54	21.01	7.5	0.050	0.004	Berger and others (2011)
Ržanovo	Macedonia	41.17	21.99	43.0	0.060	0.026	Berger and others (2011)
Ambatovy	Madagascar	–18.87	48.35	164.4	0.091	0.150	Berger and others (2011)
Analamay	Madagascar	–18.85	48.37	56.3	0.104	0.059	Berger and others (2011)
Tavai	Malaysia	5.58	117.33	270.0	0.070	0.189	Tiger International Resources Inc. (2006)
Goro	New Caledonia	–22.31	166.93	323.0	0.110	0.355	Berger and others (2011)
Kouaoua	New Caledonia	–21.42	165.74	30.0	0.080	0.024	Berger and others (2011)
Nakety	New Caledonia	–21.51	166.05	229.0	0.120	0.275	Berger and others (2011)
Nepoui	New Caledonia	–21.22	165.04	16.0	0.080	0.013	Berger and others (2011)
Thio	New Caledonia	–21.62	166.18	208.0	0.100	0.208	Berger and others (2011)
Tiébaghi	New Caledonia	–20.45	164.22	39.2	0.090	0.035	Berger and others (2011)
Mambare	Papua New Guinea	–9.00	147.70	162.5	0.090	0.146	Direct Nickel Pty Ltd. (2013)
Ramu	Papua New Guinea	–5.53	145.19	143.2	0.100	0.143	Berger and others (2011)
Wowo Gap	Papua New Guinea	–9.68	148.96	190.0	0.060	0.114	Berger and others (2011)

Table F1. Location, grade, tonnage, and other data for selected cobalt deposits of the world.—Continued

[Tonnage and grade include reserves, other resources, and past production (where available). WGS 84, World Geodetic System of 1984; negative values for latitude indicate that the deposit is in the Southern Hemisphere; negative values for longitude indicate that the deposit is in the Western Hemisphere; Congo (Kinshasa), Democratic Republic of the Congo; EEZ, Exclusive Economic Zone; Mt, million metric tons; %, percent. Element: Ag, silver; Au, gold; As, arsenic; Bi, bismuth; Co, cobalt; Cu, copper; Fe, iron; Mn, manganese; Mo, molybdenum; Ni, nickel; REE, rare-earth elements; Zn, zinc]

Deposit	Country	Latitude	Longitude	Tonnage (Mt)	Grade (% Co)	Co content (Mt)	Principal data source and notes
		(decimal degrees WGS 84)					
Ni-Co laterite deposits—Continued							
Acoje/Zambales	Philippines	15.72	120.04	72.3	0.070	0.051	Berger and others (2011)
Agata/Bolobolo/Karihatag	Philippines	9.28	125.52	35.0	0.060	0.021	Gifford and others (2011)
Berong	Philippines	9.39	118.14	275.0	0.080	0.220	Berger and others (2011)
Cagdianao	Philippines	9.92	125.67	8.0	0.140	0.011	Berger and others (2011)
Ipilan	Philippines	8.97	117.98	77.0	0.100	0.077	Berger and others (2011)
Mindoro	Philippines	12.94	121.07	315.0	0.060	0.189	Berger and others (2011)
Nonoc	Philippines	9.84	125.62	144.7	0.110	0.159	Berger and others (2011)
Rio Tuba (Coral Bay)	Philippines	8.59	117.41	57.7	0.123	0.071	Nickel Asia Corp. (2011)
Taganaan	Philippines	9.78	125.72	20.0	0.092	0.018	Nickel Asia Corp. (2011)
Taganito/Adlay	Philippines	9.53	125.83	123.0	0.116	0.143	Nickel Asia Corp. (2011)
Guanajibo	Puerto Rico[3]	18.13	–67.16	44.4	0.080	0.036	Berger and others (2011)
Las Mesas	Puerto Rico[3]	18.19	–67.10	22.7	0.120	0.027	Berger and others (2011)
Akkermanov	Russia	51.21	58.23	40.0	0.010	0.004	Berger and others (2011)
Buruktal	Russia	50.85	60.83	79.0	0.100	0.079	Berger and others (2011)
Cheremshanskoe	Russia	56.12	60.30	45.0	0.024	0.011	Berger and others (2011)
Lipovskoe	Russia	57.43	61.11	46.0	0.057	0.026	Berger and others (2011)
Rogozhinskoe	Russia	56.17	60.26	2.5	0.060	0.002	Berger and others (2011)
Serovskoe	Russia	59.71	60.56	52.8	0.043	0.023	Berger and others (2011)
Sinarskoe	Russia	56.07	60.40	18.0	0.055	0.010	Berger and others (2011)
Rudjinci	Serbia	43.59	20.84	14.0	0.050	0.007	Berger and others (2011)
Isabela Island (Bugotu)	Solomon Islands	–8.39	159.71	24.0	0.063	0.015	Berger and others (2011)
Dutwa	Tanzania	–3.67	33.42	107.0	0.028	0.030	African Eagle Resources Plc (2013)
Çaldağ	Turkey	38.62	27.77	37.9	0.050	0.019	Berger and others (2011)
Magmatic Ni-Cu(-Co-PGE) sulfide deposits							
Kambalda	Australia	–31.64	121.65	67.0	0.207	0.139	Naldrett (2004)
Mt. Keith	Australia	–27.71	120.53	478.0	0.014	0.067	Naldrett (2004)
Savannah (Sally Malay)	Australia	–17.35	128.02	8.1	0.073	0.006	Panoramic Resources Ltd. (2012)
Americano do Brasil (Salgado)	Brazil	–16.10	–50.08	7.9	0.040	0.003	Votorantim Group (2006)
Fortaleza de Minas	Brazil	–21.00	–48.50	10.3	0.200	0.021	Votorantim Group (2006)
Santa Rita	Brazil	–14.19	–39.73	159.3	0.015	0.024	Mirabela Nickel Ltd. (2012)
Dumont	Canada	48.65	–78.44	2,134.2	0.011	0.226	Staples and others (2012)
Ferguson Lake	Canada	62.92	–96.97	44.2	0.080	0.035	Starfield Resources Inc. (2013)
Makwa (Maskwa)	Canada	50.47	–95.43	19.1	0.010	0.002	Mustang Minerals Corp. (2013)

Table F1. Location, grade, tonnage, and other data for selected cobalt deposits of the world.—Continued

[Tonnage and grade include reserves, other resources, and past production (where available). WGS 84, World Geodetic System of 1984; negative values for latitude indicate that the deposit is in the Southern Hemisphere; negative values for longitude indicate that the deposit is in the Western Hemisphere; Congo (Kinshasa), Democratic Republic of the Congo; EEZ, Exclusive Economic Zone; Mt, million metric tons; %, percent. Element: Ag, silver; Au, gold; As, arsenic; Bi, bismuth; Co, cobalt; Cu, copper; Fe, iron; Mn, manganese; Mo, molybdenum; Ni, nickel; REE, rare-earth elements; Zn, zinc]

Deposit	Country	Latitude	Longitude	Tonnage (Mt)	Grade (% Co)	Co content (Mt)	Principal data source and notes
		(decimal degrees WGS 84)					
Magmatic Ni-Cu(Co-PGE) sulfide deposits—Continued							
Nunavik (includes Mesamax)	Canada	61.57	–73.26	27.1	0.048	0.013	Armstrong, Puritch, and Yassa (2010)
Raglan	Canada	61.59	–74.29	44.0	0.060	0.026	Xstrata plc (2011)
Shakespeare	Canada	46.35	–81.83	11.8	0.020	0.002	Prophecy Platinum Corp. (2013a)
Sudbury	Canada	46.63	–81.38	2,648	0.038	1.006	Naldrett (2004)
Thompson	Canada	53.76	–98.81	150.0	0.046	0.069	Naldrett (2004)
Turnagain	Canada	58.48	–128.83	763.0	0.013	0.102	Hard Creek Nickel Corp. (2013)
Voisey's Bay	Canada	45.50	–73.57	137.0	0.090	0.123	Naldrett (2004)
Wellgreen	Canada	60.75	–139.50	461.0	0.021	0.097	Prophecy Platinum Corp. (2013b)
Jinchuan	China	38.47	102.17	515.0	0.019	0.098	Naldrett (2004)
Yangliuping	China	30.67	102.00	63.8	0.016	0.010	Pirajno (2013)
Hitura	Finland	63.84	25.05	19.4	0.020	0.004	Eilu (2012)
Kevitsa	Finland	67.70	29.97	435.4	0.015	0.064	First Quantum Minerals Ltd. (2011)
Kotalahti	Finland	62.52	27.68	12.4	0.030	0.004	Eilu (2012)
Laukunkangas	Finland	62.05	28.77	7.9	0.030	0.002	Eilu (2012)
Stormi	Finland	61.33	24.90	9.0	0.040	0.004	Eilu (2012)
Bruvann (Råna)	Norway	68.33	16.94	43.0	0.010	0.004	Eilu (2012)
Ertelien	Norway	60.07	10.05	3.1	0.074	0.002	Eilu (2012)
Flåt	Norway	58.60	7.87	3.2	0.075	0.002	Eilu (2012)
Stormyra (including Dalen)	Norway	61.34	9.66	11.1	0.022	0.002	Eilu (2012)
NKT	Russia	67.94	32.82	8.2	0.230	0.019	Eilu (2012)
Noril'sk-Talnakh area	Russia	69.36	88.31	1,309.0	0.061	0.798	Naldrett (2004)
Pechenga	Russia	69.33	29.74	339.0	0.045	0.153	Naldrett (2004)
Sopchuaivench	Russia	67.88	32.82	131.2	0.014	0.018	Eilu (2012)
Nkomati	South Africa	–25.67	30.50	290.6	0.020	0.058	African Rainbow Minerals Ltd. (2011)
Aguablanca	Spain	37.85	–6.18	6.0	0.600	0.036	Lundin Mining Corp. (2012)
Kabanga	Tanzania	–2.87	30.58	58.2	0.198	0.115	Xstrata plc (2011)
Eagle	United States	46.75	–87.90	5.2	0.080	0.004	Owen and Meyer (2013)
Mesaba (Babbitt/ Minnamax)	United States	47.63	–91.88	1,106.5	0.008	0.089	Teck Resources Ltd. (2010)
Northmet	United States	47.60	–91.97	923.9	0.010	0.092	Polymet Mining Corp. (2013)
Twin Metals (Nokomis)[4]	United States	47.80	–91.76	2,425.9	0.012	0.291	Duluth Metals Ltd. (2012)
Munali	Zambia	–16.00	28.00	27.7	0.069	0.019	Albidon Ltd. (2007)
Black-shale-hosted Ni-Cu-Zn-Co deposits							
Talvivaara	Finland	63.98	28.17	2,053	0.020	0.411	Talvivaara Mining Company Plc (2013)

Table F1. Location, grade, tonnage, and other data for selected cobalt deposits of the world.—Continued

[Tonnage and grade include reserves, other resources, and past production (where available). WGS 84, World Geodetic System of 1984; negative values for latitude indicate that the deposit is in the Southern Hemisphere; negative values for longitude indicate that the deposit is in the Western Hemisphere; Congo (Kinshasa), Democratic Republic of the Congo; EEZ, Exclusive Economic Zone; Mt, million metric tons; %, percent. Element: Ag, silver; Au, gold; As, arsenic; Bi, bismuth; Co, cobalt; Cu, copper; Fe, iron; Mn, manganese; Mo, molybdenum; Ni, nickel; REE, rare-earth elements; Zn, zinc]

Deposit	Country	Latitude	Longitude	Tonnage (Mt)	Grade (% Co)	Co content (Mt)	Principal data source and notes
		(decimal degrees WGS 84)					
Fe-Cu-Co skarn and replacement deposits							
Goroblagodat	Russia	61.42	60.50	160.0	0.022	0.035	Herrington and others (2005)
Magnitogorsk	Russia	53.42	59.10	500.0	0.018	0.090	Herrington and others (2005)
Cornwall	United States	40.27	–76.40	100.0	0.025	0.025	Rose and others (1985); grade calculated
Iron oxide-Cu-Au(-Ag-U-REE-Co-Ni) deposits							
Basil	Australia	–22.07	135.55	26.5	0.050	0.013	Mithril Resources Ltd. (2013)
Ernest Henry	Australia	–20.43	140.70	166.0	0.050	0.083	Williams and Pollard (2001)
Greenmount	Australia	–21.03	140.53	23.8	0.049	0.012	Williams and Pollard (2001)
Mount Oxide	Australia	–19.48	139.47	15.5	0.050	0.008	Chalice Gold Mines Ltd. (2012)
Olympic Dam	Australia	–30.43	136.88	605.0	0.020	0.121	Williams and Pollard (2001)
Rover 1	Australia	–20.00	133.66	6.8	0.060	0.004	Metals X Ltd. (2013)
Lala (Lalachang)	China	26.10	101.90	200.0	0.022	0.044	Chen and Zhou (2012)
Guelb Moghrein	Mauritania	19.75	–14.38	23.7	0.014	0.003	Kolb and others (2006)
Metasedimentary-rock-hosted Co-Cu-Au deposits							
NICO	Canada	63.55	–116.75	31.0	0.120	0.037	Slack (2013)
Werner Lake	Canada	50.47	–94.97	1.3	0.270	0.004	Slack (2013)
Haarakumpu	Finland	66.42	28.57	4.7	0.170	0.008	Slack (2013)
Juomasuo	Finland	66.29	29.20	5.0	0.128	0.006	Slack (2013)
Kouvervaara	Finland	66.13	28.82	1.6	0.100	0.002	Slack (2013)
Vähäjoki	Finland	66.11	25.28	10.5	0.030	0.003	Slack (2013)
Skuterud	Norway	59.91	9.89	1.0	0.260	0.003	Slack (2013)
Blackbird (district)	United States	45.12	–114.35	16.8	0.735	0.123	Slack (2013)
Polymetallic (Ag-Ni-Co-As-Bi) and other cobalt-rich veins							
Cobalt-Gowganda (districts)	Canada	47.40	–79.69	2.0	1.000	0.020	Petruk and others (1971)
Bou Azzer (district)	Morocco	30.53	–6.91	[5]5.7	[5]1.500	0.085	Bouabdellah and others (2016)
Karakul	Russia	49.91	89.55	14.9	0.260	0.039	Puget Ventures Inc. (2013)
Volcanogenic Cu(-Zn-Co-Ag-Au) massive sulfide deposits							
Chu Chu	Canada	51.38	–120.06	7.0	0.100	0.007	Mosier and others (2009)
Soucy No. 1	Canada	58.32	–69.87	5.4	0.090	0.005	Mosier and others (2009)
Windy Craggy	Canada	59.73	–137.73	297.0	0.069	0.205	Peter and Scott (1999)
Deerni	China	34.40	100.13	54.0	0.080	0.043	Galley and others (2007)
Dur’ngoi	China	34.33	100.24	31.9	0.089	0.028	Xu and Zhu (2000)
Luikonlahti	Finland	62.92	28.67	3.4	0.130	0.004	Mosier and others (2009)
Outokumpu	Finland	62.73	29.01	29.2	0.250	0.073	Mosier and others (2009)

Table F1. Location, grade, tonnage, and other data for selected cobalt deposits of the world.—Continued

[Tonnage and grade include reserves, other resources, and past production (where available). WGS 84, World Geodetic System of 1984; negative values for latitude indicate that the deposit is in the Southern Hemisphere; negative values for longitude indicate that the deposit is in the Western Hemisphere; Congo (Kinshasa), Democratic Republic of the Congo; EEZ, Exclusive Economic Zone; Mt, million metric tons; %, percent. Element: Ag, silver; Au, gold; As, arsenic; Bi, bismuth; Co, cobalt; Cu, copper; Fe, iron; Mn, manganese; Mo, molybdenum; Ni, nickel; REE, rare-earth elements; Zn, zinc]

Deposit	Country	Latitude (decimal degrees WGS 84)	Longitude (decimal degrees WGS 84)	Tonnage (Mt)	Grade (% Co)	Co content (Mt)	Principal data source and notes
			Volcanogenic Cu(-Zn-Co-Ag-Au) massive sulfide deposits—Continued				
Outokumpu (Kylylahti)	Finland	62.72	29.00	7.8	0.240	0.019	Altona Mining Ltd. (2013)
Outokumpu (Luikonlahti)	Finland	63.60	27.40	7.7	0.120	0.009	Eilu (2012)
Outokumpu (Saramäki)	Finland	62.94	29.13	3.4	0.090	0.003	Eilu (2012)
Outokumpu (Vuonos)	Finland	62.76	29.09	5.9	0.150	0.009	Eilu (2012)
Gaiskoye (Gai and Gai East)	Russia	51.46	58.49	300.0	0.020	0.060	Prokin and Buslaev (1999)
Ishkinino	Russia	51.45	58.28	1.0	0.200	0.002	Herrington and others (2005)
Ivanovskoe	Russia	52.45	57.92	10.0	0.400	0.040	Mosier and others (2009)
Komsomolskoye	Russia	51.23	56.97	25.0	0.020	0.005	Prokin and Buslaev (1999)
Letneye	Russia	51.06	59.37	10.0	0.090	0.009	Prokin and Buslaev (1999)
Sibaiskoye	Russia	52.70	58.63	100.0	0.130	0.130	Prokin and Buslaev (1999)
Kure (Asikoy)	Turkey	41.81	33.69	13.6	0.300	0.041	Mosier and others (2009)
Turner Albright	United States	42.00	–123.76	4.0	0.050	0.002	Mosier and others (2009)
			Sea-floor Fe-Mn(-Ni-Cu-Co-Mo) nodules				
Pioneer	Indian Ocean	–14.00	74.00	700.0	0.100	0.700	Banakar (2010)
Clarion-Clipperton zone	Pacific Ocean	10.00	–140.00	21,100.0	0.209	44.00	Hein and others (2013)
Cook Islands EEZ	Pacific Ocean	–10.00	–170.00	5,122.0	0.410	21.00	Hein and others (2013)
			Sea-floor Fe-Mn(-Co-Mo-REE) crusts				
Maderia-Tore Rise (MTR)	Atlantic Ocean	36.00	–15.00	1,100.0	0.350	3.800	Muiños and others (2013)
Nameless	Atlantic Ocean	35.20	–15.00	71.0	0.340	0.240	Muiños and others (2013)
Unicorn	Atlantic Ocean	34.60	–14.50	130.0	0.350	0.450	Muiños and others (2013)
Afanasiy-Nikitin seamount	Indian Ocean	–3.00	83.00	180.0	0.580	1.044	Parthiban and Banakar (1999)
Pacific prime crust zone	Pacific Ocean	15.00	160.00	7,533.0	0.664	50.00	Hein and others (2013)

[1] Data for Tenke Fungurume include results for 7 deposits: Fwaulu, Fungurume, Kansalawile, Kwatebala, Mambilima, Mwadinkomba, and Tenke.

[2] Data for Kalgoorlie Nickel include results for 10 deposits: Big Four, Black Range, Bulong, Ghost Rocks, Goongarrie Hill, Goongarrie South, Highway, Kalpini, Siberia, and Siberia North.

[3] Territory of the United States.

[4] Cobalt data from D.M. Peterson, Duluth Metals Ltd., written commun. to J.F. Slack, March 25, 2013.

[5] Size and grade estimated.

For more information concerning this report,
please contact:

Mineral Resources Program Coordinator

U.S. Geological Survey

913 National Center

Reston, VA 20192

Telephone: 703–648–6100

Fax: 703–648–6057

Email: minerals@usgs.gov

Home page: https://minerals.usgs.gov

Prepared by the USGS Science Publishing Network
Reston Publishing Service Center
Edited by J.C. Ishee
Illustrations by Caryl J. Wipperfurth
Layout by Caryl J. Wipperfurth and Cathy Y. Knutson
Posting by Angela E. Hall

Slack and others—**Critical Mineral Resources of the United States—Cobalt**—Professional Paper 1802–F

ISSN 2330-7102 (online)
https://doi.org/10.3133/pp1802F

COBALT

(Data in metric tons of cobalt content unless otherwise noted)

Domestic Production and Use: In 2020, the nickel-copper Eagle Mine in Michigan produced cobalt-bearing nickel concentrate. In Missouri, a company produced nickel-copper-cobalt concentrate from historic mine tailings. Most U.S. cobalt supply comprised imports and secondary (scrap) materials. Approximately six companies in the United States produced cobalt chemicals. About 43% of the cobalt consumed in the United States was used in superalloys, mainly in aircraft gas turbine engines; 10% in cemented carbides for cutting and wear-resistant applications; 16% in various other metallic applications; and 31% in a variety of chemical applications. The total estimated value of cobalt consumed in 2020 was $300 million.

Salient Statistics—United States:	**2016**	**2017**	**2018**	**2019**	**2020^e**
Production:^{e}					
Mine	690	640	480	500	600
Secondary[1]	2,750	2,750	2,750	2,750	2,100
Imports for consumption	12,800	11,900	11,900	13,900	10,000
Exports	4,160	5,690	6,950	4,070	3,500
Consumption (includes secondary):					
Reported	9,010	9,240	9,290	9,050	7,300
Apparent[2]	11,500	8,950	7,700	12,500	8,700
Price, average, dollars per pound:					
U.S. spot, cathode[3]	12.01	26.97	37.43	16.95	16.00
London Metal Exchange (LME), cash	11.57	25.28	32.94	14.88	14.00
Stocks, yearend:					
Industry[4]	969	1,020	1,060	1,090	1,000
LME, U.S. warehouse	195	160	130	102	80
Net import reliance[5] as a percentage of apparent consumption	76	69	64	78	76

Recycling: In 2020, cobalt contained in purchased scrap represented an estimated 29% of cobalt reported consumption.

Import Sources (2016–19): Cobalt contained in metal, oxide, and salts: Norway, 20%; Canada, 14%; Japan, 13%; Finland, 10%; and other, 43%.

Tariff: **Item**	**Number**	**Normal Trade Relations 12–31–20**
Cobalt ores and concentrates	2605.00.0000	Free.
Chemical compounds:		
Cobalt oxides and hydroxides	2822.00.0000	0.1% ad val.
Cobalt chlorides	2827.39.6000	4.2% ad val.
Cobalt sulfates	2833.29.1000	1.4% ad val.
Cobalt carbonates	2836.99.1000	4.2% ad val.
Cobalt acetates	2915.29.3000	4.2% ad val.
Unwrought cobalt, alloys	8105.20.3000	4.4% ad val.
Unwrought cobalt, other	8105.20.6000	Free.
Cobalt mattes and other intermediate products; cobalt powders	8105.20.9000	Free.
Cobalt waste and scrap	8105.30.0000	Free.
Wrought cobalt and cobalt articles	8105.90.0000	3.7% ad val.

Depletion Allowance: 22% (domestic), 14% (foreign).

Government Stockpile:[6] See the Lithium chapter for statistics on lithium-cobalt oxide and lithium-nickel-cobalt-aluminum oxide.

		FY 2020		**FY 2021**	
Material	**Inventory as of 9–30–20**	**Potential acquisitions**	**Potential disposals**	**Potential acquisitions**	**Potential disposals**
Cobalt	302	—	—	—	—
Cobalt alloys, gross weight[7]	3	—	—	50	—

Prepared by **Kim B. Shedd [(703) 648–4974, kshedd@usgs.gov]**

COBALT

Events, Trends, and Issues: Congo (Kinshasa) continued to be the world’s leading source of mined cobalt, supplying approximately 70% of world cobalt mine production. With the exception of production in Morocco and artisanally mined cobalt in Congo (Kinshasa), most cobalt is mined as a byproduct of copper or nickel. China was the world’s leading producer of refined cobalt, most of which was produced from partially refined cobalt imported from Congo (Kinshasa). China was the world’s leading consumer of cobalt, with more than 80% of its consumption being used by the rechargeable battery industry.

Cobalt mine and refinery production were forecast to decrease in 2020. Estimated annual average cobalt prices declined from those of 2019. Cobalt production in Madagascar was suspended to prevent the spread of COVID-19. Increased production from recently started operations in Congo (Kinshasa) was more than offset by reduced production at other operations in response to low prices and restrictions resulting from the COVID-19 pandemic.

World Mine Production and Reserves: Reserves for multiple countries were revised based on industry reports.

	Mine production		Reserves[8]
	2019	2020[e]	
United States	500	600	53,000
Australia	5,740	5,700	[9]1,400,000
Canada	3,340	3,200	220,000
China	2,500	2,300	80,000
Congo (Kinshasa)	100,000	95,000	3,600,000
Cuba	3,800	3,600	500,000
Madagascar	3,400	700	100,000
Morocco	2,300	1,900	14,000
Papua New Guinea	2,910	2,800	51,000
Philippines	5,100	4,700	260,000
Russia	6,300	6,300	250,000
South Africa	2,100	1,800	40,000
Other countries	6,320	6,400	560,000
World total (rounded)	144,000	140,000	7,100,000

World Resources:[8] Identified cobalt resources of the United States are estimated to be about 1 million tons. Most of these resources are in Minnesota, but other important occurrences are in Alaska, California, Idaho, Michigan, Missouri, Montana, Oregon, and Pennsylvania. With the exception of resources in Idaho and Missouri, any future cobalt production from these deposits would be as a byproduct of another metal. Identified world terrestrial cobalt resources are about 25 million tons. The vast majority of these resources are in sediment-hosted stratiform copper deposits in Congo (Kinshasa) and Zambia; nickel-bearing laterite deposits in Australia and nearby island countries and Cuba; and magmatic nickel-copper sulfide deposits hosted in mafic and ultramafic rocks in Australia, Canada, Russia, and the United States. More than 120 million tons of cobalt resources have been identified in manganese nodules and crusts on the floor of the Atlantic, Indian, and Pacific Oceans.

Substitutes: Depending on the application, substitution for cobalt could result in a loss in product performance or an increase in cost. The cobalt contents of lithium-ion batteries, the leading global use for cobalt, are being reduced; potential commercially available cobalt-free substitutes use iron and phosphorus. Potential substitutes in other applications include barium or strontium ferrites, neodymium-iron-boron, or nickel-iron alloys in magnets; cerium, iron, lead, manganese, or vanadium in paints; cobalt-iron-copper or iron-copper in diamond tools; copper-iron-manganese for curing unsaturated polyester resins; iron, iron-cobalt-nickel, nickel, ceramic-metallic composites (cermets), or ceramics in cutting and wear-resistant materials; nickel-based alloys or ceramics in jet engines; nickel in petroleum catalysts; rhodium in hydroformylation catalysts; and titanium-based alloys in prosthetics.

---

[e] Estimated.

[1] Estimated from consumption of purchased scrap.

[2] Defined as secondary production + imports – exports + adjustments for Government and industry stock changes for refined cobalt.

[3] As reported by Platts Metals Week. Cobalt cathode is refined cobalt metal produced by an electrolytic process.

[4] Stocks held by consumers and processors; excludes stocks held by trading companies and held for investment purposes.

[5] Defined as imports – exports + adjustments for Government and industry stock changes for refined cobalt.

[6] See Appendix B for definitions.

[7] Inventory is cobalt alloys; potential acquisitions are samarium-cobalt alloy; excludes potential disposals of nickel-base and aerospace alloys.

[8] See Appendix C for resource and reserve definitions and information concerning data sources.

[9] For Australia, Joint Ore Reserves Committee-compliant reserves were 640,000 tons.