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**

1A 2A 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

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

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)

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)

104 **Rf** rutherfordium (261)

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*

Actinide Series**

Los Alamos NATIONAL LABORATORY

CHEMISTRY

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.

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

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

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U.S. Geological Survey

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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 (in 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)	0.0000003527	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)	0.0000006243	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 ($\Omega\text{-m}$)	39.37	ohm inch ($\Omega\text{-in.}$)
ohm-centimeter ($\Omega\text{-cm}$)	0.3937	ohm inch ($\Omega\text{-in.}$)
Thermal conductivity		
watt per centimeter per degree Celsius (watt/cm $^{\circ}\text{C}$)	693.1798	International British thermal unit inch per hour per square foot per degree Fahrenheit (Btu in/h ft ² $^{\circ}\text{F}$)
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 $^{\circ}\text{F}$)

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 ($^{\circ}\text{C}$) may be converted to degrees Fahrenheit ($^{\circ}\text{F}$) as follows:

$$^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32$$

Temperature in degrees Celsius ($^{\circ}\text{C}$) may be converted to kelvin (K) as follows:

$$\text{K} = ^{\circ}\text{C} + 273.15$$

Temperature in degrees Fahrenheit ($^{\circ}\text{F}$) may be converted to degrees Celsius ($^{\circ}\text{C}$) as follows:

$$^{\circ}\text{C} = (^{\circ}\text{F} - 32) / 1.8$$

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 ($\mu\text{S}/\text{cm}$ 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 ($\mu\text{g}/\text{L}$), nanograms 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 ($\mu\text{g}/\text{g}$), 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 ($\mu\text{Ci}/\text{mL}$).

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 ($\mu\text{g}/\text{g}$)	part per million
microgram per kilogram ($\mu\text{g}/\text{kg}$)	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 = 0.000000001 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

$\delta\text{-MnO}_2$	delta-manganese dioxide
$\mu\text{Ci/mL}$	microcurie per milliliter
$\mu\text{g/g}$	microgram per gram
$\mu\text{g/kg}$	microgram per kilogram
$\mu\text{g/L}$	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 B₁₂), 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 B₁₂.

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 south-eastern 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 ($\text{Cu}(\text{Co},\text{Ni})_2\text{S}_4$), pentlandite ($(\text{Fe},\text{Ni},\text{Co})_9\text{S}_8$), linnaeite (Co_3S_4), and siegenite ($(\text{Co},\text{Ni})_3\text{S}_4$); arsenide minerals, such as skutterudite ($(\text{Co},\text{Fe},\text{Ni})\text{As}_{2-3}$) and safflorite ($(\text{Co},\text{Fe})\text{As}_3$); and sulfarsenide minerals, including cobaltite (CoAsS) and glaucodot ($(\text{Co},\text{Fe})\text{AsS}$). Cobaltiferous pyrite and pyrrhotite— $(\text{Fe},\text{Co})\text{S}_2$ and $(\text{Fe},\text{Co})_{1-x}\text{S}$, respectively—are mined in some deposits. Among secondary cobalt-rich phases, which form during surficial weathering, one of the most important historically was erythrite ($\text{Co}_3(\text{AsO}_4)_2 \cdot 8\text{H}_2\text{O}$), 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 ($\text{CoO}(\text{OH})$) and asbolane ($(\text{Ni},\text{Co})_{2-x}\text{Mn}(\text{O},\text{OH})_4 \cdot n\text{H}_2\text{O}$), plus local heazlewoodite ($(\text{Ni},\text{Co})_3\text{S}_2$), together with cobaltiferous oxyhydroxides, including goethite ($\text{Fe}^{3+}\text{O}(\text{OH})$), limonite ($\text{FeO}(\text{OH}) \cdot n\text{H}_2\text{O}$), and lithiophorite ($\text{AlMnO}_2(\text{OH})_2$). 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).

F6 Critical Mineral Resources of the United States—Cobalt

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/m³, 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/m³, 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 north-eastern 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 ($\delta\text{-MnO}_2$), 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 $\delta\text{-MnO}_2$, 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

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

refining those ores and investment by a Canadian company in one of the laterite operations in Cuba.

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)

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; Valet 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 ($\mu\text{g/L}$, 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 $\mu\text{g/L}$ (Gaillardet and others, 2003; Huser and others, 2011). Elevated background concentrations of as high as 30 $\mu\text{g/L}$ 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 $\mu\text{g/L}$ and 10 to 1,100 $\mu\text{g/L}$ cobalt, respectively (Kwong and others, 2007; Gray and Eppinger, 2012). Extremely high cobalt concentrations of 70 to 61,000 $\mu\text{g/L}$ (median is 540 $\mu\text{g/L}$) 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 ($\text{pH} < 3$) 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 ($5 < \text{pH} < 8$) 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 $\mu\text{g/L}$ cobalt), as well as have high copper (10 to 1,800 $\mu\text{g/L}$ copper), and arsenic (0.45 to 6.2 $\mu\text{g/L}$ arsenic) concentrations (Mok and Wai, 1989). A survey of streams within the broader Idaho cobalt belt revealed elevated concentrations (in $\mu\text{g/L}$) 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 B₁₂. Overexposure to high levels of cobalt, however, may cause lung and heart dysfunction, as well as dermatitis.

Isotopes of cobalt range from ⁵⁰Co to ⁷¹Co. The naturally occurring isotope is ⁵⁹Co. ⁶⁰Co, which has a half-life of 5.27 years and is the most commercially important radioactive isotope of cobalt, is made by placing ⁵⁹Co in a nuclear reactor for 1.5 to 2 years (Reimann and de Caritat, 1998). ⁶⁰Co 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 ⁵⁷Co and 7x10⁻⁸ μCi/mL of ⁶⁰Co.

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 (Holec 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 [Co²⁺], cobalt(II) chloride [CoCl₂], and cobalt (II) sulfate [CoSO₄(H₂O)_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 (LC₅₀) 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 (EC₅₀), such as inhibited growth.

The freshwater amphipod *Hyaella azteca* is known to be sensitive to dissolved cobalt, exhibiting a 1-week LC₅₀ 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 Ca²⁺ and Mg²⁺ are able to outcompete Co²⁺ for biological sites. Acute toxicity tests with dissolved cobalt chloride and the freshwater green alga *Chlorella vulgaris* resulted in an EC₅₀ 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 LC₅₀ 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 B₁₂ (Schrauzer, 2004). Microorganisms are responsible for the biosynthesis of natural vitamin B₁₂. 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 B₁₂ 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 EC₅₀, based on decreased shoot growth and biomass, was highly variable. The most sensitive EC₅₀ was 7 mg/kg of cobalt for oilseed rape growing in soil from Athens (Georgia), and the least sensitive EC₅₀ was 1,708 mg/kg of cobalt for barley growing in soil from Brécly (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.

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

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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	Longitude	Tonnage (Mt)	Grade (% Co)	Co content (Mt)	Principal data source and notes
		(decimal degrees WGS 84)					
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)
Nicaró	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 (decimal degrees WGS 84)	Longitude	Tonnage (Mt)	Grade (% Co)	Co content (Mt)	Principal data source and notes
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)
Kouervaaara	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	Petruck 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	Longitude	Tonnage (Mt)	Grade (% Co)	Co content (Mt)	Principal data source and notes
		(decimal degrees WGS 84)					
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)

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

²Data 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.

³Territory of the United States.

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

⁵Size and grade estimated.

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