USGS PROFESSION PAPER 1802-P, RHENIUM

(USGS, 2017)

Rhenium

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

Professional Paper 1802–P

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

Periodic Table of Elements

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

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

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. Photographs of rhenium and rhenium compounds. Upper left, a single crystal of high-purity (99.999%) rhenium, a remelted rhenium bar, and a 1-cubic-centimeter rhenium cube. Photograph courtesy of Alchemist-hp/CC-BY-NC-ND-3.0 (http://commons.wikimedia.org/wiki/File:Rhenium_single_crystal_bar_and_1cm3_cube.jpg). Upper right, rhenium powder. Photograph courtesy of H.C. Starck. Lower left, ammonium perrhenate (NH_4ReO_4) powder, which is the most widely marketed form of rhenium. Photograph courtesy of Stanford Advanced Materials (http://www.samaterials.com/847/ammonium-perrhenate.jpg). Lower right, rheniite (ReS_2) crystals from high-temperature fumaroles on the Kudryavyy volcano, which is located on Iturup Island in Sakhalinskaya Oblast', Russia. Photograph courtesy of The Arkenstone, iRocks.com (http://www.irocks.com/minerals/specimen/42387).

Rhenium

By David A. John, Robert R. Seal II, and Désirée E. Polyak

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

Professional Paper 1802–P

U.S. Department of the Interior
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U.S. Geological Survey
William H. Werkheiser, Acting Director

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

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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 (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
Volume		
milliliter (mL)	0.03381	ounce, fluid (fl. oz)
liter (L)	33.81402	ounce, fluid (fl. oz)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)
cubic meter (m^3)	264.2	gallon (gal)
cubic centimeter (cm^3)	0.06102	cubic inch (in^3)
cubic meter (m^3)	1.308	cubic yard (yd^3)
cubic kilometer (km^3)	0.2399	cubic mile (mi^3)
Mass		
microgram (µg)	0.00000003527	ounce, avoirdupois (oz)
milligram (mg)	0.00003527	ounce, avoirdupois (oz)
gram (g)	0.03527	ounce, avoirdupois (oz)
gram (g)	0.03215075	ounce, troy
kilogram (kg)	32.15075	ounce, troy
kilogram (kg)	2.205	pound avoirdupois (lb)
ton, metric (t)	1.102	ton, short [2,000 lb]
ton, metric (t)	0.9842	ton, long [2,240 lb]
Deposit grade		
gram per metric ton (g/t)	0.0291667	ounce per short ton (2,000 lb) (oz/T)
Pressure		
megapascal (MPa)	10	bar
gigapascal (GPa)	10,000	bar
Density		
gram per cubic centimeter (g/cm^3)	62.4220	pound per cubic foot (lb/ft^3)
milligram per cubic meter (mg/m^3)	0.00000006243	pound per cubic foot (lb/ft^3)
Energy		
joule (J)	0.0000002	kilowatthour (kWh)
joule (J)	6.241×10^{18}	electronvolt (eV)
joule (J)	0.2388	calorie (cal)
kilojoule (kJ)	0.0002388	kilocalorie (kcal)

International System of Units to Inch/Pound

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

Inch/Pound to International System of Units

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

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

$$°F = (1.8 \times °C) + 32$$

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

$$K = °C + 273.15$$

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

$$°C = (°F - 32) / 1.8$$

Datum

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

Supplemental Information

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

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

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

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

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

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

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

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

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

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

Equivalencies

part per million (ppm): 1 ppm = 1,000 ppb = 1,000,000 ppt = 0.0001 percent
part per billion (ppb): 0.001 ppm = 1 ppb = 1,000 ppt = 0.0000001 percent
part per trillion (ppt): 0.000001 ppm = 0.001 ppb = 1 ppt = 0.0000000001 percent

Metric system prefixes

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

Abbreviations and Symbols

°C	degree Celsius
µm	micrometer
AFRG	alkali-feldspar rhyolite-granite
g/t	gram per metric ton
kg	kilogram
kg $CaCO_3$/t	kilogram of calcium carbonate per ton
km	kilometer
km^2	square kilometer
m	meter
Ma	mega-annum
mg/L	milligram per liter
OPEC	Organization of the Petroleum Exporting Countries
PGE	platinum-group element
ppb	part per billion
ppm	part per million
ppt	part per trillion
SX–EW	solvent extraction-electrowinning
USGS	U.S. Geological Survey
WHO	World Health Organization
wt. %	weight percent

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Abstract

Rhenium is one of the rarest elements in Earth's continental crust; its estimated average crustal abundance is less than 1 part per billion. Rhenium is a metal that has an extremely high melting point and a heat-stable crystalline structure. More than 80 percent of the rhenium consumed in the world is used in high-temperature superalloys, especially those used to make turbine blades for jet aircraft engines. Rhenium's other major application is in platinum-rhenium catalysts used in petroleum refining.

Rhenium rarely occurs as a native element or as its own sulfide mineral; most rhenium is present as a substitute for molybdenum in molybdenite. Annual world mine production of rhenium is about 50 metric tons. Nearly all primary rhenium production (that is, rhenium produced by mining rather than through recycling) is as a byproduct of copper mining, and about 80 percent of the rhenium obtained through mining is recovered from the flue dust produced during the roasting of molybdenite concentrates from porphyry copper deposits. Molybdenite in porphyry copper deposits can contain hundreds to several thousand grams per metric ton of rhenium, although the estimated rhenium grades of these deposits range from less than 0.1 gram per metric ton to about 0.6 gram per metric ton.

Continental-arc porphyry copper-molybdenum-gold deposits supply most of the world's rhenium production and have large inferred rhenium resources. Porphyry copper mines in Chile account for about 55 percent of the world's mine production of rhenium; rhenium is also recovered from porphyry copper deposits in the United States, Armenia, Kazakhstan, Mexico, Peru, Russia, and Uzbekistan. Sediment-hosted strata-bound copper deposits in Kazakhstan (of the sandstone type) and in Poland (of the reduced-facies, or Kupferschiefer, type) account for most other rhenium produced by mining. These types of deposits also have large amounts of identified rhenium resources. The future supply of rhenium is likely to depend largely on the capacity of the specialized processing facilities needed to recover rhenium from molybdenite concentrates.

The environmental consequences of rhenium recovery are closely linked to the consequences of mining large porphyry copper and strata-bound copper deposits; no additional environmental impact from recovery of rhenium from these deposits has been identified. No information is available regarding the potential toxic effects of rhenium on humans, partly because of the low natural abundance of rhenium.

Introduction

Rhenium (Re) is one of the rarest elements in Earth's continental crust; its average crustal abundance is about 0.4 part per billion (ppb), although estimates range from 0.2 to 2 ppb (Taylor and McLennan, 1995; Rudnick and Gao, 2003; Sun and others, 2003). This silvery-white metallic element's extremely high melting point (3,180 degrees Celsius [°C]) and heat-stable crystalline structure make it an excellent refractory metal (fig. P1).

Rhenium was the last stable, naturally occurring element discovered, although its existence was long predicted from the periodic table. The element was discovered in 1925 by German chemists Walter Noddack, Ida Tacke, and Otto Berg, who concentrated rhenium from gadolinite ore that contained about 10 parts per million (ppm) rhenium (Emsley, 2001). The German chemists subsequently separated 1 gram of rhenium from 660 kilograms (kg) of molybdenum ore.

Uses, Demand, and Availability of Supply

Since the late 1980s, the two most important uses of rhenium have been in high-temperature superalloys and in platinum-rhenium catalysts (fig. P2). The high-temperature alloys in which rhenium is used include several nickel-base superalloys that are used mainly in the manufacture of turbine blades for jet aircraft engines and in power-generation applications. The high-temperature properties of rhenium allow turbine engines to be designed with closer tolerances, thus enabling increased thrust and higher operating efficiency. Because the life cycle of turbine blades in jet engines is only about 10 years, significant quantities of used blades (which
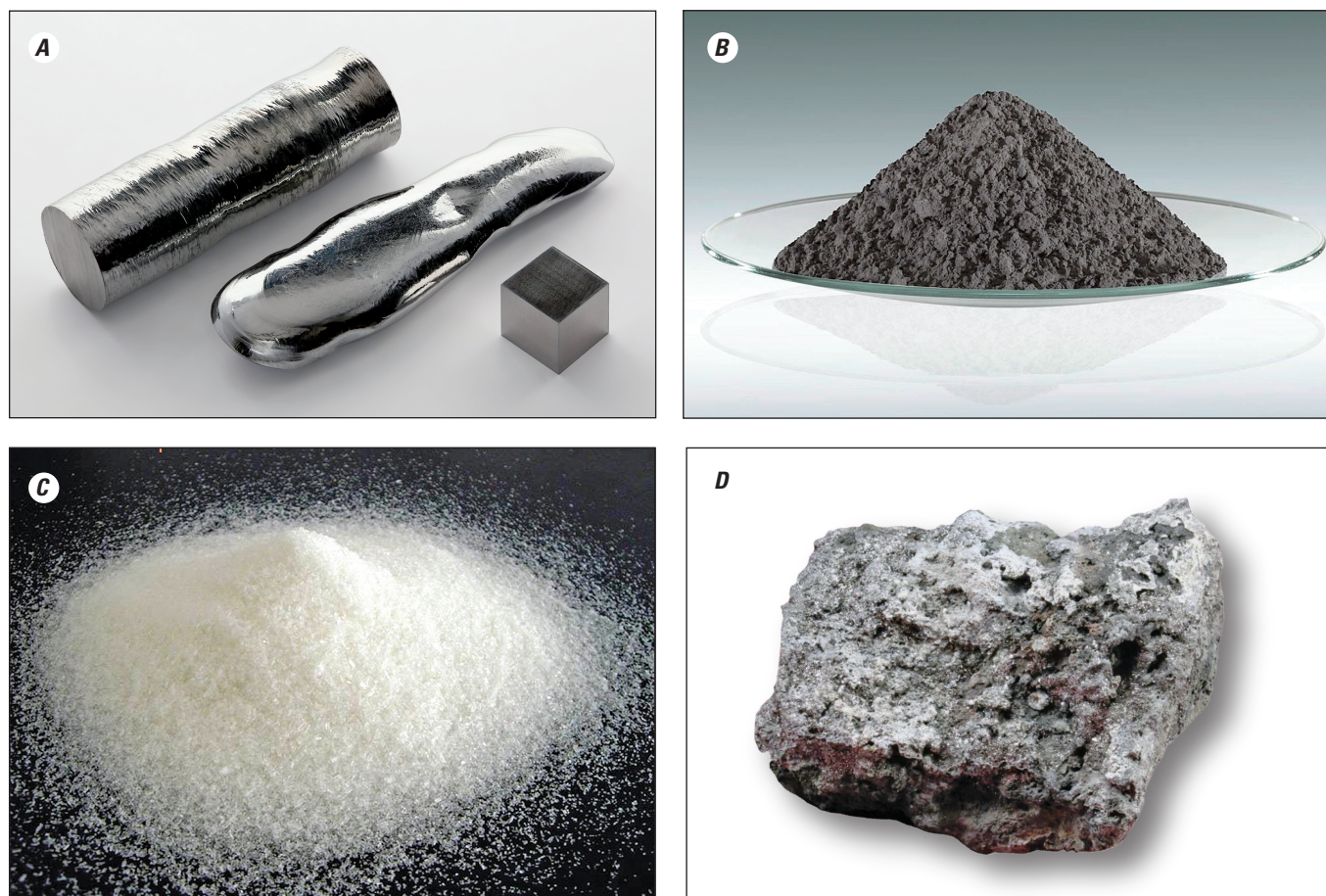
Figure P1.   Photographs of rhenium and rhenium compounds. *A*, A single crystal of high-purity (99.999%) rhenium (left), a remelted rhenium bar (center), and a 1-cubic-centimeter rhenium cube (right). Photograph courtesy of Alchemist-hp/CC-BY-NC-ND-3.0 (http://commons.wikimedia.org/wiki/File:Rhenium_single_crystal_bar_and_1cm3_cube.jpg). *B*, Rhenium powder. Photograph courtesy of H.C. Starck. *C*, Ammonium perrhenate (NH_4ReO_4) powder, which is the most widely marketed form of rhenium. Photograph courtesy of Stanford Advanced Materials (http://www.samaterials.com/847/ammonium-perrhenate.jpg). *D*, Rheniite (ReS_2) crystals from high-temperature fumaroles on the Kudryavyy volcano, which is located on Iturup Island in Sakhalinskaya Oblast', Russia. Photograph courtesy of The Arkenstone, iRocks.com (http://www.irocks.com/minerals/specimen/42387).

typically contain 3 percent rhenium, although some alloys contain 6 percent rhenium) are accumulating. Technology is continuing to be developed to allow recycling of these blades to recover the rhenium, which can then be used in the manufacture of new, second-generation blades. Recycling of rhenium from used turbine blades could potentially reduce the requirement for primary rhenium (that is, rhenium produced by mining rather than through recycling) by about 50 percent. Most rhenium recycling is currently performed in the United States and Germany.

World consumption of rhenium from primary sources was estimated to be between 50 and 54 metric tons in 2012 (Polyak, 2014). Approximately 83 percent (45 metric tons) of rhenium from primary sources was used in making superalloys, mainly for the aerospace industry (fig. P2). New types of catalysts in the petrochemical industry accounted for about an additional 10 percent (5 metric tons). The remaining 7 percent (4 metric

tons) of world consumption in 2012—primarily in the form of tungsten-rhenium and molybdenum-rhenium alloys—was used in a variety of other applications, including in the manufacture of electrical contact points, flashbulbs, heating elements, vacuum tubes, and X-ray tubes and targets. An additional 15 metric tons of rhenium is recycled each year from spent catalysts and is not included in the world consumption total shown in figure P2 (Lipmann Walton & Co. Ltd., 2010; Minor Metals Trade Association, 2012).

Platinum-rhenium catalysts are used to produce high-octane lead-free gasoline. In the early 1970s, Chevron Corp. of the United States developed a series of platinum-rhenium catalysts that do not react with sulfur. As a response to the Organization of the Petroleum Exporting Countries (OPEC) oil embargo in the 1970s and the oil crisis of the early 1980s, a second generation of more-efficient catalysts was developed with double the platinum-rhenium content, which boosted
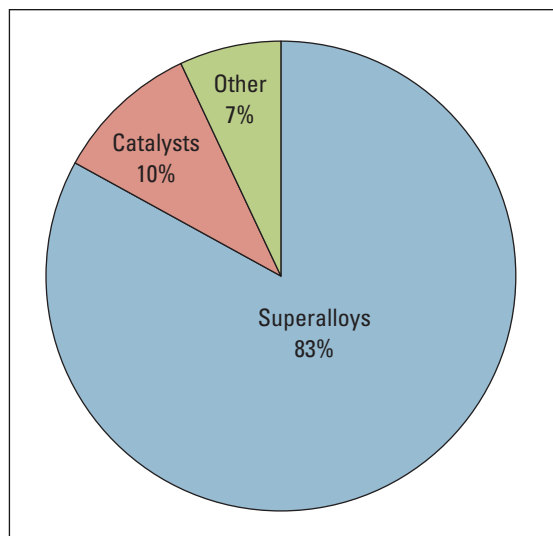
Figure P2. Pie chart showing major end uses of primary rhenium as a percentage of world consumption in 2012. Total world production for the year was between 50 and 54 metric tons. Approximately 83 percent of the rhenium from primary sources was used to make superalloys, mainly for the aerospace industry.

the refinery efficiency and the gasoline's octane levels. Ammonium perrhenate (NH_4ReO_4) is the most common form of rhenium used by catalyst manufacturers (fig. P1*C*). Petroleum-reforming platinum-rhenium catalysts are used mainly in North America and Europe, where demand for gasoline and diesel fuel is highest. These are also the locations of the major rhenium-platinum catalyst manufacturers.

The recovery of rhenium from platinum-rhenium catalysts is a mature business. A closed-loop recycling system operated by catalyst manufacturers, refiners, and secondary rhenium producers ensures that consumption of newly mined rhenium is kept to a minimum. The catalysts are recycled mainly to recover the platinum content, so much of the rhenium is recycled only because of the platinum content of the catalysts.

Rhenium in molybdenite concentrates derived from porphyry copper ores is recovered at some mines as a byproduct during the molybdenite roasting process. In the United States in 2012, three molybdenum mines had roasters associated with mines, but only one of the roasters was equipped to recover rhenium. This roaster, which is located at the Sierrita facility in Arizona, is operated by Freeport-McMoran Copper & Gold Inc. of the United States. This facility processes all the byproduct molybdenite concentrates from Freeport-McMoran mines and processes molybdenite concentrates on a toll basis for third parties. In contrast, Kennecott Utah Copper Corp. (which is owned by Rio Tinto plc of the United Kingdom) sends byproduct molybdenite concentrates from the Bingham Canyon Mine in Utah to Molymex S.A. de C.V.'s plant in Mexico for roasting; the recovered rhenium concentrate is then sent to Molibdenos y Metales S.A. (Molymet) in Chile for purification.

Substitutes for Rhenium

Substitutes for rhenium in platinum-rhenium catalysts are being evaluated on an ongoing basis. Iridium and tin have achieved commercial success in one application. Other metals being evaluated as possible substitutes for rhenium in catalysts include gallium, germanium, indium, selenium, silicon, tungsten, and vanadium. The use of these and other metals in catalysts might someday decrease rhenium's share of the existing catalyst market; however, rhenium-bearing catalysts that are being considered for use in several proposed gas-to-liquid projects likely would offset this decrease. Materials that can substitute for rhenium in various end uses are cobalt and tungsten for coatings on copper X-ray targets, rhodium and rhodium-iridium for high-temperature thermocouples, tungsten and platinum-ruthenium for coatings on electrical contacts, and tungsten and tantalum for electron emitters (Polyak, 2013). Aerospace superalloy producers continue to research new alloys with smaller quantities of rhenium; however, it has proven difficult to develop alloys with lower rhenium content for use in jet engines without a loss in performance.

Geology

Geochemistry

Rhenium has an atomic number of 75 and an atomic mass of 186.2 grams per mole. In the periodic table of elements, rhenium is a third row, heavy transition metal located in column 7*B* below manganese and technetium, adjacent to tungsten and the platinum-group elements (PGEs), and diagonally below molybdenum.

Rhenium has a density of 21.02 grams per cubic centimeter, making it the fourth densest element (iridium, osmium, and platinum have higher densities). It has a hexagonal close-packed crystal structure. The 3,180 °C melting point of rhenium is the third highest melting point of all the elements; only carbon (3,500 °C) and tungsten (3,422 °C) have higher melting points.

Rhenium has the widest range of valences of any element—nine in total, ranging from –1 to +7—although +7, +6, +4, and +2 are the most common ions. Rhenium forms three stable oxides—rhenium heptoxide (Re_2O_7), rhenium trioxide (ReO_3), and rhenium dioxide (ReO_2)—of which rhenium heptoxide is the most common. Rhenium heptoxide is a bright yellow volatile solid that dissolves in water to form rhenic acid ($HReO_4$). Rhenium has a marked affinity for sulfur and occurs mostly in nature as a substitute (solid solution) for molybdenum in molybdenite (MoS_2). Unusual features of rhenium compounds include the unusually high volatility of rhenium heptoxide and the high solubility of rhenium heptoxide in water. These properties facilitate rhenium's recovery from flue dusts produced by roasting of molybdenite concentrates.

The two dominant naturally occurring rhenium isotopes are ^{185}Re, which is stable and accounts for 37.4 percent of naturally occurring rhenium, and ^{187}Re, which is radiogenic and accounts for 62.6 percent of naturally occurring rhenium. Twenty-six other radioactive isotopes of rhenium have been recognized. ^{187}Re decays to ^{187}Os by beta decay and has a half-life of about 4.1×10^{10} years. The rhenium-osmium isotopic system is used to date sulfide minerals (most commonly molybdenite) in mineral deposits (McCandless and Ruiz, 1993; Stein and others, 2001).

Mineralogy

Rhenium rarely occurs as a native element or as its own sulfide mineral. Trace amounts of native rhenium (Re^0) were recently discovered in ultramafic rocks in Ukraine (Bobrov and others, 2008). Microscopic crystals of rheniite (ReS$_2$) were first reported in 1986 in volcanic fumaroles on Mount Usu, Japan (Bernard and Dumortier, 1986), and megascopic crystals of rheniite were discovered in 1992 in high-temperature fumaroles on the Kudryavyy (also spelled Kudriavy) volcano on Iturup Island in Sakhalinskaya Oblast', Russia (fig. P1D; Korzhinsky and others, 1994). Rheniite also has been reported in the Pagoni Rachi porphyry copper-molybdenum prospect in northern Greece (Voudouris and others, 2009). Microscopic ($\leq$75 micrometers [μm]) crystals of rhenium-rich tarkianite ((Cu,Fe)(Re,Mo)$_4$S$_8$) have been discovered in sulfide concentrates from the Hitura nickel-copper-PGE mine at Nivala, Finland (Kojonen and others, 2004). None of these rhenium-rich minerals are economic sources of rhenium, however.

Dzhezkazganite forms microscopic collomorphic aggregates and veinlets in bornite, chalcocite, and galena and replaces bornite in sandstone-hosted strata-bound copper deposits at the Dzhezkazgan Mine in Qaraghandy, Kazakhstan (Poplavko and others, 1962; Abisheva and others, 2001). Dzhezkazganite was first inferred as a copper-rhenium sulfide (CuReS$_4$) mineral (Poplavko and others, 1962), but subsequent electron microprobe analyses suggest that it has a chemical formula of ReMoCu$_2$PbS$_6$ (Genkin and others, 1994). It is not a recognized mineral species by the International Mineralogical Association, however, because of the lack of structural data and uncertainty in its chemical formula (Fleischer, 1963).

Molybdenite is the principal source of rhenium. The rhenium content of molybdenite varies widely from less than 1 ppm to several weight percent, but molybdenite in porphyry copper deposits typically contains about 100 to 3,000 ppm rhenium (tables P1 and P2 at back of chapter; Fleischer, 1959; Giles and Schilling, 1972; Newberry, 1979; Berzina and others, 2005; Sinclair and others, 2009; John and Taylor, 2016).

In contrast, the rhenium content of molybdenite in porphyry molybdenum deposits generally is much lower, in many cases less than 20 ppm (table P2). Rhenium contents of molybdenite in other types of porphyry deposits and in quartz veins typically also are low (<10 to about 200 ppm) (for example, Terada and others, 1971; Giles and Schilling, 1972; Ishihara, 1988; Sinclair and others, 2009; Millensifer and others, 2014). Molybdenite in Australia's Merlin molybdenum-rhenium deposit (discussed below), however, averages about 1,000 ppm rhenium (Brown and others, 2010).

The rhenium content of molybdenite also varies widely within some porphyry copper deposits (for example, it ranges from 130 to 2,000 ppm at Bingham, Utah) (Giles and Schilling, 1972). The variable rhenium content, both within deposits and between different types of porphyry deposits, is not completely understood. Variations in the rhenium content of molybdenite within deposits may represent multiple generations of molybdenite that have different rhenium contents (for example, the Sar Cheshmeh Mine in Kermān Province, Iran; Aminzadeh and others, 2011). Rhenium concentration differences reflect a combination of factors, including changes in temperature and pressure, fluid composition (especially pH and sulfur content), oxidation state, and (or) transport mechanism (that is, brine, moderate-density liquid, or low-density vapor) during the complex magmatic-hydrothermal history of these deposits (John and Taylor, 2016).

Deposit Types

Nearly all primary rhenium production (rhenium produced by mining rather than through recycling) is as a byproduct of copper mining. Rhenium resources are dominantly contained in porphyry copper-molybdenum-gold deposits, which supply about 80 percent of the rhenium produced by mining (Polyak, 2013). Rhenium in porphyry copper deposits is contained primarily as ReS$_2$ in solid solution in molybdenite (Fleischer, 1959). Most of the remaining rhenium production is as a byproduct of mining sediment-hosted strata-bound copper deposits, both the sandstone (red bed) types in Kazakhstan and the reduced-facies (Kupferschiefer) types in Poland (Hitzman and others, 2005; Zientek and others, 2013). Smaller amounts of rhenium are recovered from the processing of roll-front-type sandstone uranium ore in Kazakhstan (Dahlkamp, 2009a). The Merlin molybdenum-rhenium zone of the Mount Dore copper deposit in Queensland, Australia, is a potential source of high-grade rhenium ore and is the only deposit known in which rhenium could be a primary commodity (Brown and others, 2010). The world's major rhenium-bearing deposits that are described in the text and (or) listed in table P1 are shown on the map in figure P3.

Figure P3. World map showing locations of major rhenium-bearing deposits listed in table P1, including porphyry copper-molybdenum-gold deposits; sediment-hosted strata-bound copper deposits in Poland (of the reduced-facies, or Kupferschiefer, type) and Kazakhstan (of the sandstone type); roll-front-type sandstone uranium deposits in Kazakhstan and Uzbekistan; and the Merlin (Mount Dore) molybdenum-rhenium deposit in Queensland, Australia. Additional information about the rhenium resources in these deposits is in table P1. Au, gold; Cu, copper; Mo, molybdenum; Re, rhenium; U, uranium

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

Table P1.   Summary of rhenium, copper, and molybdenum grades, deposit tonnage, and amount of contained rhenium in the rhenium-bearing deposits shown in figure P3.

[The names, locations, and types of most of the deposits are taken from the U.S. Geological Survey Mineral Resources Data System (MRDS) (U.S. Geological Survey, 2014). The minimum and maximum values are concentrations of rhenium in molybdenite separates; the estimated average is based on mill concentrates. Elements and compounds: Au, gold; Cu, copper; Mo, molybdenum; MoS_2, molybdenite; Os, osmium; Re, rhenium; U, uranium. Units of measure: g/t, gram per metric ton; Mt, million metric tons; ppm, part per million; t, metric ton; wt. %, weight percent. —, no data; n.a., not applicable to the deposit]

Deposit name	Country (State/Province)	Deposit type	Tectonic setting[1]	Deposit tonnage (Mt)	Grade (wt. % Cu)	Grade (wt. % Mo)	Minimum Re in MoS_2 (ppm)	Maximum Re in MoS_2 (ppm)	Estimated average Re in MoS_2 (ppm)
Bagdad	United States (Arizona)	Porphyry Cu-(Mo-Au)	CA	1,600	0.400	0.01	330	642	460
Bingham	United States (Utah)	Porphyry Cu-(Mo-Au)	PC	3,230	0.882	0.053	130	2,000	250
Butte	United States (Montana)	Porphyry Cu-(Mo-Au)	CA	5,220	0.673	0.028	—	—	240
Morenci	United States (Arizona)	Porphyry Cu-(Mo-Au)	CA	6,470	0.524	0.0095	270	640	455
Pebble	United States (Alaska)	Porphyry Cu-(Mo-Au)	PC	5,940	0.592	0.0243	329	2,070	1,100
Santa Rita	United States (New Mexico)	Porphyry Cu-(Mo-Au)	CA	3,030	0.468	0.008	700	1,200	800
Sierrita-Esperanza	United States (Arizona)	Porphyry Cu-(Mo-Au)	CA	2,262	0.294	0.0292	90	1,800	238
Chuquicamata-Radomiro Tomic	Chile	Porphyry Cu-(Mo-Au)	CA	21,277	0.860	0.04	93	262	265
El Salvador	Chile	Porphyry Cu-(Mo-Au)	CA	3,836	0.860	0.022	—	—	585
El Teniente	Chile	Porphyry Cu-(Mo-Au)	CA	20,731	0.620	0.019	25	1,154	420
La Escondida	Chile	Porphyry Cu-(Mo-Au)	CA	11,158	0.769	0.0062	95	1,805	886
Los Bronces–Rio Blanco	Chile	Porphyry Cu-(Mo-Au)	CA	16,816	0.601	0.02	104	898	265
Los Pelambres	Chile	Porphyry Cu-(Mo-Au)	CA	7,458	0.617	0.015	450	820	600
La Caridad	Mexico (Sonora)	Porphyry Cu-(Mo-Au)	CA	1,800	0.452	0.0247	72	570	570
Cerro Verde	Peru	Porphyry Cu-(Mo-Au)	CA	2,258	0.495	0.01	3,060	3,497	3,280
Toquepala	Peru	Porphyry Cu-(Mo-Au)	CA	2,320	0.550	0.04	387	1,496	600
Kadjaran (Kadzharan)	Armenia	Porphyry Cu-(Mo-Au)	CA	1,700	0.270	0.055	33	2,620	280

Table P1.   Summary of rhenium, copper, and molybdenum grades, deposit tonnage, and amount of contained rhenium in the rhenium-bearing deposits shown in figure 3.—Continued

[The names, locations, and types of most of the deposits are taken from the U.S. Geological Survey Mineral Resources Data System (MRDS) (U.S. Geological Survey, 2014). The minimum and maximum values are concentrations of rhenium in molybdenite separates; the estimated average is based on mill concentrates. Elements and compounds: Au, gold; Cu, copper; Mo, molybdenum; MoS$_2$, molybdenite; Os, osmium; Re, rhenium; U, uranium. Units of measure: g/t, gram per metric ton; Mt, million metric tons; ppm, part per million; t, metric ton; wt. %, weight percent. —, no data; n.a., not applicable to the deposit]

Number of Re analyses	Selected sample type[2]	Grade (g/t Re)	Contained Re (t)	Mo:Re ratio	Notes	Data sources	Deposit name
9	2	0.080	130	1,200	None	Sutulov, 1974; Nadler, 1997; Barra and others, 2003; Singer and others, 2008	Bagdad
43	1	0.221	714	2,400	None	Giles and Schilling, 1972; McCandless and Ruiz, 1993; Chesley and Ruiz, 1998; Singer and others, 2008; Austen and Ballantyne, 2010; J. Chesley, written commun., 2013	Bingham
1	1	0.112	585	2,500	None	Giles and Schilling, 1972; Singer and others, 2008	Butte
4	1	0.072	466	1,320	None	Giles and Schilling, 1972; McCandless and Ruiz, 1993; Singer and others, 2008	Morenci
8	3	0.446	2,650	545	Re grade from bulk molybdenite concentrate samples with 52% Mo; measured and indicated resources	Ghaffari and others, 2011; Lang and others, 2013	Pebble
9	3	0.107	324	746	None	Giles and Schilling, 1972; Sutulov, 1974; Singer and others, 2008	Santa Rita
6	2	0.116	262	2,520	None	Giles and Schilling, 1972; Sutulov, 1974; Nadler, 1997; Singer and others, 2008	Sierrita-Esperanza
9	3	0.18	3,800	2,300	None	Giles and Schilling, 1972; Sutulov, 1974; Nadler, 1997; Singer and others, 2008; Barra and others, 2013	Chuquicamata-Radomiro Tomic
3	3	0.215	825	1,020	None	Giles and Schilling, 1972; Sutulov, 1974; Nadler, 1997; Singer and others, 2008	El Salvador
17	3	0.133	2,760	1,430	None	Giles and Schilling, 1972; Sutulov, 1974; Nadler, 1997; Maksaev and others, 2004; Singer and others, 2008	El Teniente
7	2	0.092	1,030	672	None	Mathur and others, 2001; Singer and others, 2008; Romero and others, 2010	La Escondida
15	2	0.09	1,500	2,300	None	Mathur and others 2001; Singer and others, 2008; Deckart and others, 2013	Los Bronces-Rio Blanco
3	2	0.150	1,120	1,000	None	Mathur and others 2001; Singer and others, 2008	Los Pelambres
3	3	0.235	423	1,050	None	Nadler, 1997; Valencia and others, 2005; Singer and others, 2008	La Caridad
2	2	0.12	300	830	None	Mathur and others, 2001; Singer and others, 2008	Cerro Verde
5	3	0.40	930	1,000	None	Giles and Schilling, 1972; Sutulov, 1974; Nadler, 1997; Mathur and others, 2001; Singer and others, 2008	Toquepala
238	1	0.257	437	2,140	None	Nadler, 1997; Berzina and others, 2005; Singer and others, 2008	Kadjaran (Kadzharan)

Table P1.   Summary of rhenium, copper, and molybdenum grades, deposit tonnage, and amount of contained rhenium in the rhenium-bearing deposits shown in figure P3.—Continued

[The names, locations, and types of most of the deposits are taken from the U.S. Geological Survey Mineral Resources Data System (MRDS) (U.S. Geological Survey, 2014). The minimum and maximum values are concentrations of rhenium in molybdenite separates; the estimated average is based on mill concentrates. Elements and compounds: Au, gold; Cu, copper; Mo, molybdenum; MoS_2, molybdenite; Os, osmium; Re, rhenium; U, uranium. Units of measure: g/t, gram per metric ton; Mt, million metric tons; ppm, part per million; t, metric ton; wt. %, weight percent. —, no data; n.a., not applicable to the deposit]

Deposit name	Country (State/Province)	Deposit type	Tectonic setting[1]	Deposit tonnage (Mt)	Grade (wt. % Cu)	Grade (wt. % Mo)	Minimum Re in MoS_2 (ppm)	Maximum Re in MoS_2 (ppm)	Estimated average Re in MoS_2 (ppm)
Kalmakyr (Almalyk)	Uzbekistan	Porphyry Cu-(Mo-Au)	CA	2,000	0.380	0.006	700	2,000	1,500
Zuun Mod Molybdenum	Mongolia	Porphyry Cu-(Mo-Au)	CA	237	0.069	0.059	250	300	275
Lubin-Sieroszowice	Poland	Reduced-facies (Kupferschiefer) strata-bound Cu	n.a.	1,181	1.58	—	—	—	—
Mansfeld-Sangerhausen	Germany	Reduced-facies (Kupferschiefer) strata-bound Cu	n.a.	35	2.41	0.015	—	—	—
Mansfeld-Sangerhausen	Germany	Reduced-facies (Kupferschiefer) strata-bound Cu	n.a.	155	2.41	0.015	—	—	—
Dzhezkazgan	Kazakhstan	Sandstone strata-bound Cu	n.a.	2,000	1.1	—	—	—	—
Zhaman-Aibat (or Zhaman-Aybat) (Zhomart)	Kazakhstan	Sandstone strata-bound Cu	n.a.	161	1.69	—	—	—	—
Merlin	Australia (Queensland)	Undefined Mo-Re	n.a.	6.9	—	1.383	—	—	—
Sugraly	Uzbekistan	Roll-front sandstone U	n.a.	30	—	—	—	—	—
Suluchekinskoye	Kazakhstan	Roll-front sandstone U	n.a.	330	—	—	—	—	—

[1]Tectonic setting of porphyry copper deposits: CA, continental arc; PC, post-collisional.

[2]Sample type used in calculating Re grade: 1, molybdenite separate; 2, molybdenite separate used in Re-Os dating; 3, molybdenite mill concentrate.

Table P1. Summary of rhenium, copper, and molybdenum grades, deposit tonnage, and amount of contained rhenium in the rhenium-bearing deposits shown in figure 3.—Continued

[The names, locations, and types of most of the deposits are taken from the U.S. Geological Survey Mineral Resources Data System (MRDS) (U.S. Geological Survey, 2014). The minimum and maximum values are concentrations of rhenium in molybdenite separates; the estimated average is based on mill concentrates. Elements and compounds: Au, gold; Cu, copper; Mo, molybdenum; MoS_2, molybdenite; Os, osmium; Re, rhenium; U, uranium. Units of measure: g/t, gram per metric ton; Mt, million metric tons; ppm, part per million; t, metric ton; wt. %, weight percent. —, no data; n.a., not applicable to the deposit]

Number of Re analyses	Selected sample type[2]	Grade (g/t Re)	Contained Re (t)	Mo:Re ratio	Notes	Data sources	Deposit name
21	1	0.150	300	400	None	Sutulov, 1974; Singer and others, 2008; Pašava and others, 2010	Kalmakyr (Almalyk)
2	1	0.270	59	2,190	Average of range of Re contents in MoS_2	Clark and Baudry, 2011	Zuun Mod Molyb-denum
—	—	0.6	709	—	2011 end-of-year proven and prob-able reserves; average Re grade of ore mined in 2009	Smakowski and others, 2010; Bartlett and others, 2013	Lubin-Sieros-zowice
—	—	21	740	7.1	Estimated remaining resources after mining ceased in 1990	Jankowski, 1995	Mansfeld-Sanger-hausen
—	—	21	3,300	7.1	Estimated total resources before mining, which began in 1200 and ended in 1990	Jankowski, 1995	Mansfeld-Sanger-hausen
—	—	1.5	3,000	0.5 to 1.2	Ore averages 1 to 2 ppm Re	Seyfullin and others, 1974; Box and others, 2013	Dzhezkazgan
—	—	1.45	233	—	None	Box and others, 2013	Zhaman-Aibat (or Zha-man-Aybat) (Zhomart)
—	—	22.7	157	609	Average Re grade and tonnage of indi-cated and inferred resources	Lycopodium Minerals QLD Pty Ltd., 2012	Merlin
—	—	12.5	375	—	Ore averages 10 to 15 ppm Re	Dahlkamp, 2009b	Sugraly
—	—	1.5	495	—	Ore averages 1 to 2 ppm Re and 0.07 to 0.13% U	Dahlkamp, 2009a	Suluchekins-koye

Rhenium in Porphyry Copper Deposits

Large continental-margin arc porphyry copper-molybdenum-gold deposits dominate world rhenium resources (tables P1 and P2; figs. P3 and P4; John and Taylor, 2016). Porphyry copper deposits are large (in most cases, greater than 100 million metric tons), low-to–moderate grade (in most cases, 0.3 to 2.0 percent copper), disseminated, breccia and vein-hosted copper deposits (John and others, 2010). Porphyry copper deposits are parts of larger porphyry copper systems in which large volumes (10 to >100 cubic kilometers) of hydrothermally altered rock are centered on porphyry stocks and other intrusions. The deposits may include associated skarn, carbonate-replacement, sediment-hosted, and high- and intermediate-sulfidation epithermal base and precious-metal deposits (Sillitoe, 2010). Porphyry copper systems most commonly form above active subduction zones at convergent plate margins and are associated with calc-alkaline batholiths and volcanic arcs in both continental-margin and island-arc settings (Sillitoe, 1972; Richards, 2003). Some other porphyry copper systems form in post-collisional and other tectonic settings after subduction ends (Richards, 2009; Hou and others, 2011). Copper is the dominant metal produced from porphyry copper deposits; molybdenum, gold, and lesser amounts of silver, rhenium, and PGEs (mostly palladium) are important byproducts in some

deposits. Hydrothermal alteration of porphyry-copper-related intrusive rocks and their wallrocks is widely developed and includes alkali-dominated assemblages (potassic, sodic, and sodic-calcic), acid (low pH) assemblages (advanced argillic and sericitic), and propylitic assemblages. Alteration zoning can be highly variable, but acidic alteration is typically distal and shallow and, where it is found in the center of a deposit, it is late relative to alkali alteration assemblages. The deeper parts of porphyry copper systems (typically paleodepths of approximately 2 to 10 kilometers [km]) contain central porphyry copper ± molybdenum ± gold mineralization (fig. P5A) and may contain flanking copper, gold, and (or) zinc skarn, silver-lead-zinc carbonate replacement, and gold-silver sediment-hosted deposits. The shallow, overlying parts of these systems may host high- and intermediate-sulfidation epithermal gold-silver ± copper deposits. Copper, gold, and molybdenum mineralization is generally associated with potassic and sericitic alteration. Rhenium is invariably associated with molybdenum mineralization.

Rhenium is produced from several Tertiary porphyry copper deposits in the Andes Mountains in South America, including the giant Chuquicamata-Radomiro Tomic and El Teniente deposits in Chile, and Toquepala in Peru; from Late Cretaceous to mid-Tertiary deposits in the Western United States; and from deposits in Armenia, Kazakhstan, Russia, and Uzbekistan (fig. P3). Rhenium in porphyry copper
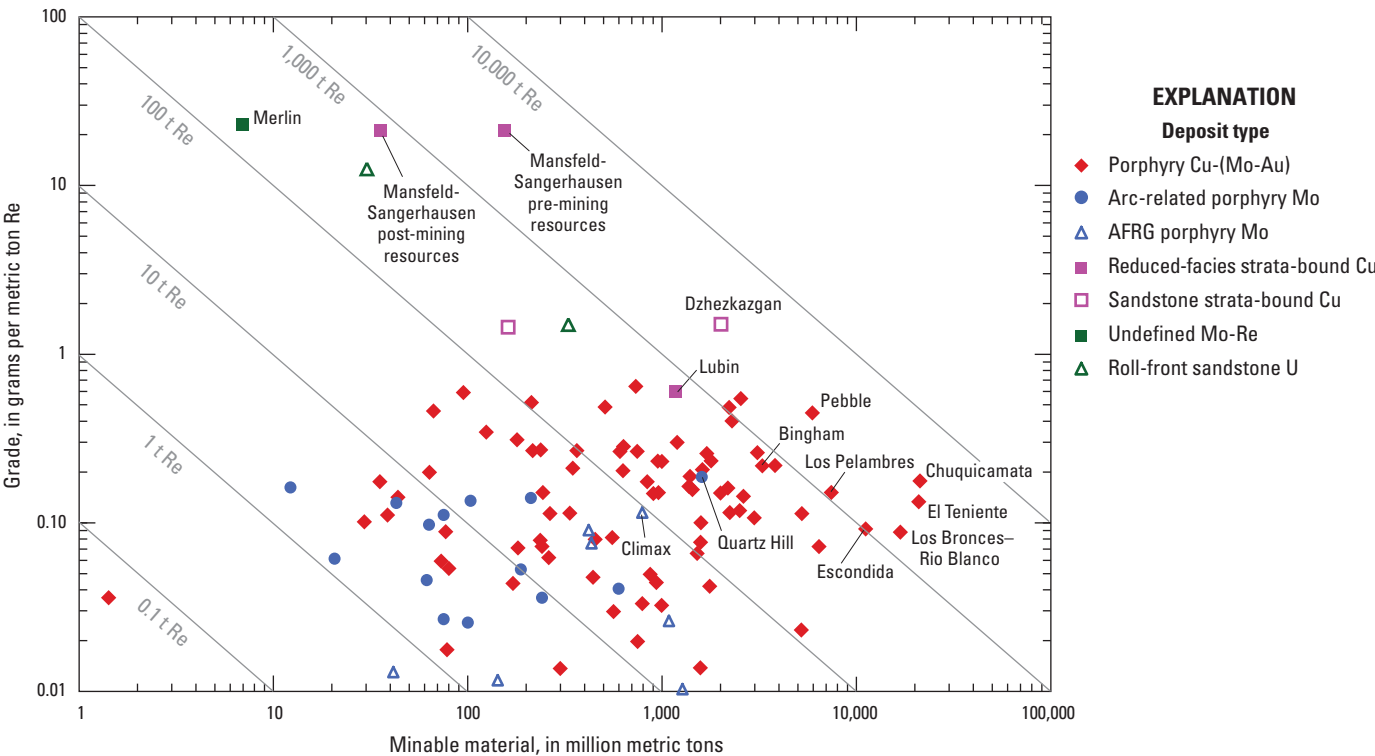
Figure P4.   Plot of rhenium grade versus deposit tonnage for major rhenium-bearing deposits in the world, including those shown in figure P3. The diagonal lines are isolines of contained rhenium, in metric tons. Additional resource data for these deposits, and sources, are given in table P1. AFRG, alkali-feldspar rhyolite-granite; t, metric ton. Elements: Au, gold; Cu, copper; Mo, molybdenum; Re, rhenium, U, uranium
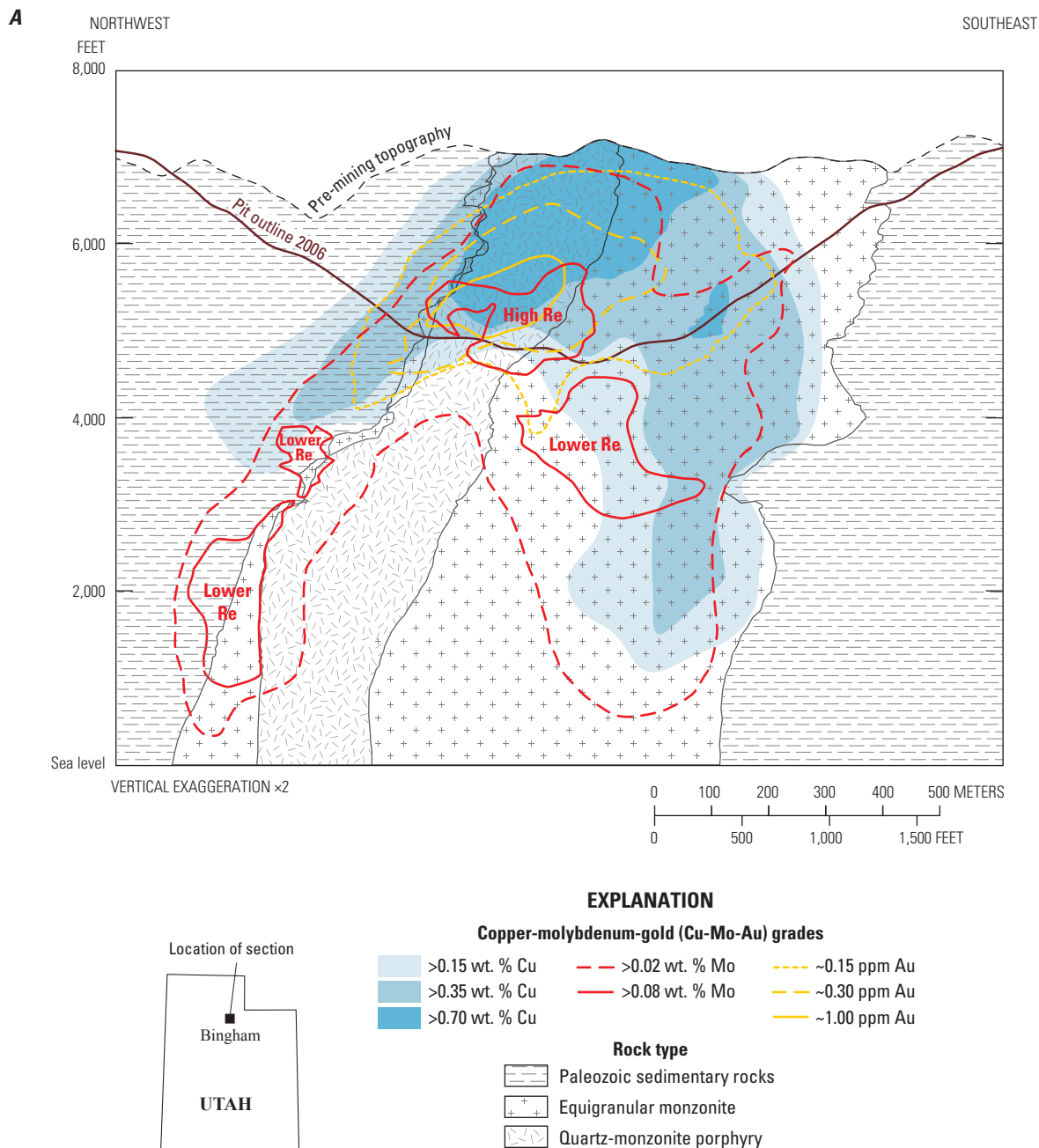
Figure P5.   Cross sections illustrating rhenium occurrences in major deposit types from which rhenium is recovered or potentially recoverable. *A*, Bingham Canyon porphyry copper-molybdenum-gold (Cu-Mo-Au) deposit in Utah showing metal zoning around porphyry intrusions. Molybdenum (in molybdenite) is displaced to deeper levels than copper and gold, which are mostly deposited earlier than molybdenum. Rhenium (Re) grades apparently are highest in the copper-molybdenum-gold ores in the center of the deposit ("High Re") and lower in the deep molybdenum-only ore ("Lower Re") (Austen and Ballantyne, 2010). Figure modified from Landtwing and others (2010) and Seo and others (2012). ppm, part per million; wt.%, weight percent

deposits is contained primarily as ReS$_2$ in solid solution in molybdenite (Fleischer, 1959) at concentrations ranging from less than 10 ppm to about 1 weight percent (table P1). Rhenium grades of porphyry copper deposits are low, generally less than 0.5 gram per metric ton (g/t) (table P1; fig. P4; Sinclair and others, 2009; John and Taylor, 2016), but the large tonnage of ore processed, the presence of sufficient molybdenite to make molybdenum recovery economic, and the presence of specialty circuits that allow recovery of the rhenium contained in molybdenite means that a relatively large proportion of rhenium production is from these deposits.

Rhenium contents of molybdenite in porphyry molybdenum deposits are generally much lower than in molybdenite in porphyry copper deposits (table P2; Giles and Schilling, 1972; Sinclair and 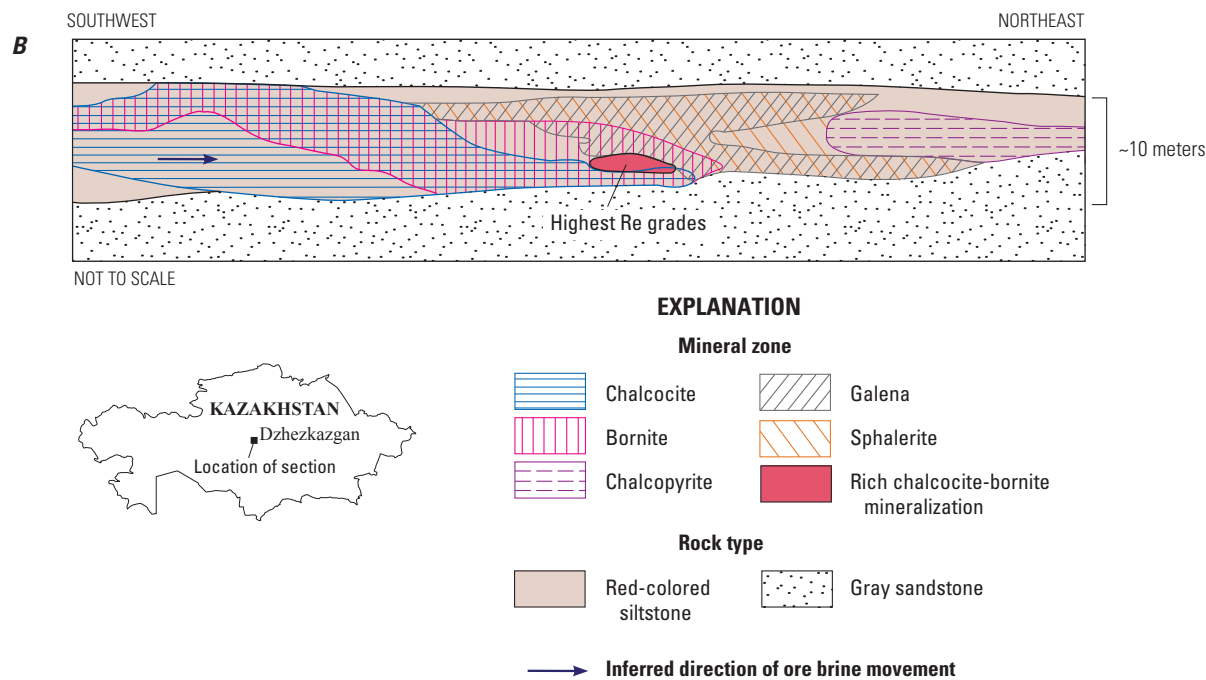others, 2009; John and Taylor, 2015). Thus, despite their higher molybdenum grades, rhenium grades of porphyry molybdenum deposits are generally less than those of porphyry copper deposits (table P2; fig. P4). The relatively low grades and small sizes of most porphyry molybdenum deposits result in small rhenium resources (table P2; fig. P4), and rhenium is not recovered from these deposits.

Rhenium is recovered from molybdenite concentrates that are separated from copper-iron sulfides by flotation methods. During roasting of the molybdenite concentrates to produce molybdenum oxide, rhenium is oxidized to Re$_2$O$_7$ and passes up the flue stack with the sulfur gases. When the flue dusts and gases are scrubbed, rhenium is dissolved in the resulting sulfuric acid and is eventually precipitated out as ammonium perrhenate (NH$_4$ReO$_4$) (Sutulov, 1974; Nadler, 1997). Ammonium perrhenate is a white crystalline powder that contains about 69 weight percent rhenium and is the principal form in which rhenium is marketed (fig. P1*C*).

Rhenium in Sediment-Hosted Strata-Bound Copper Deposits

Sediment-hosted strata-bound copper deposits are the other major primary source of rhenium. Rhenium is recovered during processing of copper ores from sandstone-type (red bed) copper deposits in Kazakhstan and from reduced-facies (Kupferschiefer)-type copper-silver deposits in Poland. Sediment-hosted strata-bound copper mineralization consists of fine-grained copper and copper-iron sulfide minerals in strata-bound-to-stratiform disseminations in siliciclastic or dolomitic sedimentary rocks (Hitzman and others, 2005; Zientek and others, 2013). Ore minerals are characteristically zoned laterally and vertically across bedding from hematite to chalcocite to bornite to chalcopyrite to pyrite in the inferred direction of fluid flow (figs. P5*B* and P5*C*). Deposits are hosted in reduced sedimentary strata within or above a thick section of oxidized red beds. These deposits are inferred to form by the flow of oxidized, metal-rich brines through permeable red-bed sedimentary rocks (mostly sandstones). Interaction of the oxidized ore fluids with a reducing agent, such as hydrocarbons (oil or natural gas), reduced organic carbon, and (or) sulfide minerals, results in deposition of the zoned sequence of iron,

Figure P5—Continued   *B*, Sandstone-type strata-bound copper deposit at Dzhezkazgan, Qaraghandy, Kazakhstan, showing mineral zoning and rock type. Rhenium (Re) is enriched in all the ore zones, but the highest concentrations are thought to be in the copper zones, especially in chalcocite-bornite ore (Seyfullin and others, 1974). Figure modified from Box and others (2013) based on Daukeev and others (2004).

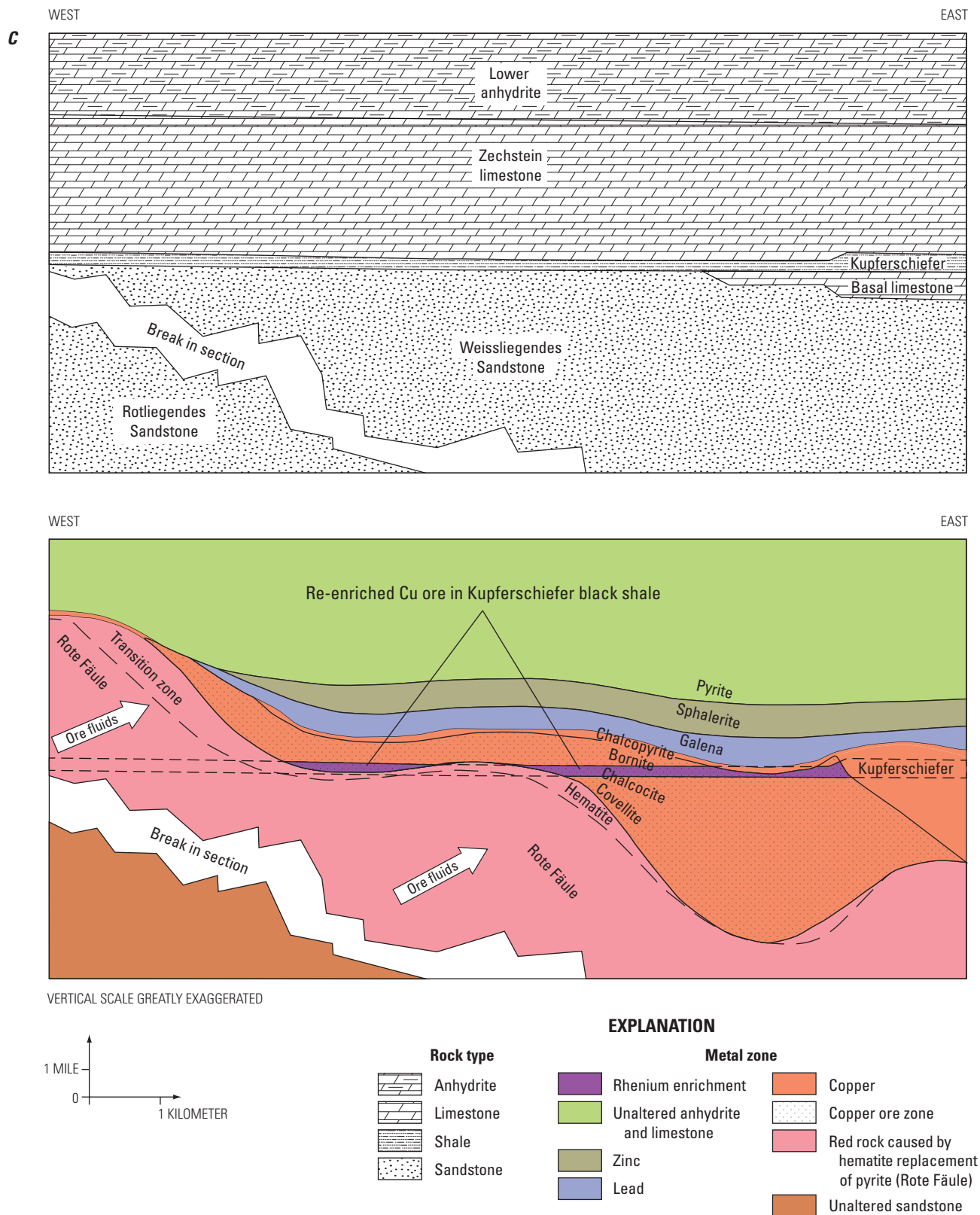**Figure P5.— Continued** *C,* Kupferschiefer (reduced-facies-type) strata-bound copper deposits showing lithology (top cross section) and copper ore distribution (stippled pattern) and metal and mineral zoning (bottom cross section). Rhenium is concentrated in copper ore in the Kupferschiefer black shale. Transitions between predominant sulfide minerals are gradational. Figure is based on Jowett (1986) and Oszczepalski (1999).

copper, lead, and zinc sulfide and oxide minerals. Unlike porphyry copper deposits, in which rhenium is clearly associated with molybdenite and is derived from magmatic sources, the site and source of rhenium in sediment-hosted strata-bound copper deposits are poorly understood.

Occurrences in Sandstone-Type Strata-Bound Copper Deposits

In central Kazakhstan, rhenium is recovered from Late Paleozoic sandstone-type strata-bound copper deposits in the Chu-Sarysu basin (Dzhezkazgan and Zhaman-Aybat [also spelled Zhaman-Aibat] deposits) (fig. P3; Box and others, 2013). The deposits consist of copper sulfide minerals (bornite, chalcocite, and chalcopyrite) that form intergranular cement and replace grains in sandstone and conglomerate within a 600- to 1,000-m-thick Pennsylvanian fluvial red-bed sequence. Copper grades of individual deposits range from about 0.8 to 1.7 percent and average 1.1 percent, and the deposits contain significant quantities of silver and rhenium. The copper minerals are inferred to have precipitated from an oxidized, metal-rich brine that was progressively reduced by interaction with hydrogen sulfide (H_2S)-bearing petroleum fluids as it flowed through permeable sandstone beds. The copper minerals are zoned from chalcocite to bornite to chalcopyrite in the inferred direction of the fluid (brine) flow (fig. P5*B*). The main deposits in Kazakhstan from which rhenium is recovered are the Zhaman-Aybat deposit (which has an average rhenium grade of 1.45 g/t and includes local zones that exceed 9 g/t), and the Dzhezkazgan deposit (which has an average grade of 1 to 2 g/t rhenium). Both deposits are located in Qaraghandy Province. In the Zhaman-Aybat deposit, the highest rhenium grades (>9 g/t) are associated with the boundary between the chalcopyrite and the bornite-chalcocite zones in more central parts of the deposit.

The occurrence and mineralogy of rhenium in the Kazakhstan deposits is uncertain. Satpaeva and others (1959, summarized in Fleischer, 1960) and Seyfullin and others (1974) reported rhenium contents of different types of ores at Dzhezkazgan and other strata-bound copper deposits in Kazakhstan. Their data show that rhenium is present in appreciable abundances in lead-rich and zinc-rich ores, as well as in copper-rich ores, and that rhenium apparently is not associated with molybdenite. In particular, Seyfullin and others (1974) showed that the ratio of molybdenum to rhenium (Mo:Re) in copper ore averaged 1.2 in the Dzhezkazgan deposit and varied from 0.4 to 75 in other deposits in Kazakhstan, which indicates significant enrichment of rhenium relative to molybdenum in these deposits. For comparison, Mo:Re ratios in porphyry copper deposits range from about 100 to >10,000 and average about 2,050 (table P2), which is close to estimates for the average Mo:Re ratios in continental crust, which range from 2,500 to 2,750 (Taylor and McLennan, 1995; Rudnick and Gao, 2003).

Poplavko and others (1962) reported discovery of dzhezkazganite, a new rhenium mineral, at the Dzhezkazgan deposit and suggested that it had a chemical formula of $CuReS_4$.

Subsequent electron microprobe analyses suggested a more complex formula of $ReMoCu_2PbS_6$ for this microscopic (typically <1 μm) phase (Genkin and others, 1994). Recent analyses of copper ore minerals in two samples from the Dzhezkazgan deposit show that the rhenium contents of chalcopyrite and bornite range from 3.3 to 10.1 ppm (Box and others, 2013), which are extremely high concentrations of rhenium in nonmolybdenite samples (Ruiz and Mathur, 1999; Selby and others, 2009). These data suggest that significant amounts of rhenium may be present in copper-iron sulfide minerals, although mass balance relations between copper and rhenium indicate that most of the rhenium is likely present in dzhezkazganite.

Occurrences in Reduced-Facies-Type (Kupferschiefer) Strata-Bound Copper Deposits

The thin black shale that forms the Upper Permian Kupferschiefer (copper slate) hosts the largest copper and silver deposits in Europe (Mansfeld-Sangerhausen and Lubin-Sieroszowice deposits) (fig. P3; Vaughan and others, 1989; Jankowski, 1995; Kucha, 2003; Hitzman and others, 2005). These reduced-facies-type strata-bound copper deposits also contain large rhenium resources. In the Kupferschiefer, rhenium is currently produced from the Lubin-Sieroszowice orebody in southwestern Poland (Bartlett and others, 2013), and high rhenium contents have been reported in the formerly mined Mansfeld-Sangerhausen deposits in southern Germany (Jankowski, 1995). Ore reserves in these deposits are large; 2011 end-of-year reserves for the Legnica-Glogów copper belt in Poland, which includes the Lubin-Sieroszowice orebody, were 1,181 million metric tons of ore at average grades of 1.58 percent copper and 48 g/t silver (Bartlett and others, 2013); large undeveloped deposits have also been identified elsewhere in the Kupferschiefer in Poland. The average rhenium content of the Polish copper ores mined in 2009 was 0.6 g/t, but the rhenium grade varied from about 1.1 g/t in shale ore to about 0.4 g/t in sandstone ore (Smakowski and others, 2010). In contrast, Jankowski (1995) reported a much larger average rhenium content of 21 ppm in Kupferschiefer ores in the Mansfeld-Sangerhausen deposits in Germany, suggesting that more than 2,500 metric tons of rhenium was contained in ores mined from 1200 through 1990. Only small amounts of rhenium were recovered from flue dusts near the end of mining of these deposits, however, and production data from 1962 suggests that rhenium recovery was only about 0.1 g/t (Kruger, 2006).

The Kupferschiefer deposits occur along the southern margin of the Rotliegendes-Zechstein basin (part of an Early Permian intracontinental rift basin) where it overlies Paleozoic continental sedimentary and bimodal volcanic rocks (Vaughan and others, 1989; Kucha, 2003; Hitzman and others, 2005). The volcanic rocks in the Lower Rotliegendes are extensively albitized and may have supplied some of the copper in the Kupferschiefer deposits (Hitzman and others, 2005). The overlying Upper Rotliegendes is a thick red-bed sequence

composed of fluvial, eolian, and playa (sabkha) deposits that is locally overlain by white eolian sandstones (Weissliegendes). The Upper Permian Kupferschiefer is a thin (typically 30 to 70 centimeters thick) organic carbon-rich black shale that covers more than 800,000 square kilometers (km^2) in central Europe. It forms the basal unit of the Zechstein layer and was deposited during the initial stages of a rapid marine transgression over the Rotliegendes-Weissliegendes sequence. The Kupferschiefer black shale is overlain by Zechstein carbonates (dolomite and limestone) and evaporites (anhydrite and halite), which may have supplied some of the sulfur in the ores. Copper, gold, PGEs, and silver are hosted by both the black shales and the underlying white sandstones (fig. P5C). Thin base-metal sulfide zones in the Kupferschiefer are tens to hundreds of square kilometers in area, and immediately adjacent hematitic alteration (in the Rote Fäule) covers more than 40,000 km^2.

In the Kupferschiefer deposits, hydrothermal minerals and metals typically are zoned upward from hematite (Fe^{3+}) to the sequence of covellite, chalcocite, bornite, chalcopyrite (copper zone), to galena (lead zone), to sphalerite (zinc zone), and finally to pyrite (Fe^{2+}) (fig. P5C; Oszczepalski, 1999; Kucha, 2003; Hitzman and others, 2005). Gold and PGEs are concentrated in the transition zone between hematite and copper minerals, and silver is concentrated in the copper ores. The Kupferschiefer mineralization is complex, probably formed in multiple stages, and likely involved influx of oxidizing, metal-rich brines that moved through the oxidized red beds (Rote Fäule) from the Rotliegendes basin into the reduced Kupferschiefer (Zechstein) sediments (fig. P5C; see summary in Hitzman and others, 2005). The three main stages of ore formation involved (1) early diagenetic formation of iron monosulfides and possibly chalcocite near the sediment-water interface; (2) diagenetic replacement of iron monosulfides and (or) pyrite by copper-iron sulfides at least partly associated with Rote Fäule alteration, and (3) diagenetic remobilization of earlier copper sulfide mineralization during later Rote Fäule alteration and formation of gold-PGE mineralization (for example, Vaughan and others, 1989; Wodzicki and Piestrzynski, 1994; Kucha, 2003; Hitzman and others, 2005).

Rhenium in the Kupferschiefer is associated with molybdenum in copper-rich shale ore (Hammer and others, 1990; Kucha, 2003). Kucha (2003) stated that copper, lead, and potassium-castaingite (cuprian molybdenite) have molybdenum-to-rhenium ratio of 70:1, although he did not report actual rhenium analyses. Jankowski (1995) reported molybdenum-to-rhenium ratio of 7:1 for ores in the Mansfeld-Sangerhausen mines but did not report rhenium mineralogy. As in the Kazakhstan strata-bound copper deposits, these molybdenum-to-rhenium ratios suggest significant rhenium enrichment relative to molybdenum.

Geochemical studies of the Sangerhausen basin in Germany show large variations in the rhenium content of rocks; the content ranges from 0.24 to 27 ppm, and the highest rhenium concentrations are in the copper facies of the Kupferschiefer (Hammer and others, 1990). Pašava

and others (2010) reported rhenium concentrations ranging from 63.6 to 1,380 ppb in six samples of unmineralized Kupferschiefer black shale in Poland (the copper content was less than or equal to 106 ppm and the molybdenum content was between 20 and 340 ppm). In these samples, rhenium strongly correlates with molybdenum ($r^2 = 0.93$) and is concentrated in the lower part of the black shale. Pašava and others (2007b) reported rhenium concentrations ranging from 249 to 22,000 ppb for six copper-rich black shale samples (the average copper grade was 4.9 percent and no molybdenum content was reported), whereas six samples from PGE- and gold-rich but copper-poor horizons had rhenium concentrations that ranged from 221 to 558 ppb (Pašava and others, 2007a). Comparison of the minor element composition of unmineralized Kupferschiefer sediments in the Lower Rhine basin in northwestern Germany to black shales in the Late Devonian Exshaw Formation in Canada and to modern black shales indicate similar high levels of enrichment in arsenic, cadmium, molybdenum, nickel, rhenium, antimony, uranium, and vanadium, which are typical of syngenetic mineralization (Lüschen and others, 2000a, b). These data suggest that rhenium in Kupferschiefer ores could have been derived from the black shales and was locally remobilized into the copper-rich zones.

Rhenium is produced from the Kupferschiefer deposits by roasting copper ore. During roasting, sulfur and rhenium are released as gases that precipitate in the flues. Wet scrubbing of the flue dusts produces sulfuric acid that contains dissolved rhenium. Resins are then used to adsorb the rhenium from the acid, and the rhenium is ultimately precipitated as ammonium perrhenate. All processing of Kupferschiefer ores and recovery of rhenium are done by KGHM Polska Miedź S.A. at their facilities in Lubin, Poland.

Rhenium in Sandstone-Type Uranium Deposits

Rhenium was formerly produced as a byproduct from roll-front-type sandstone uranium deposits in Uzbekistan, and rhenium is currently recovered from similar uranium deposits in Kazakhstan (figs. P3 and P5D; Dahlkamp, 2009a, b; Seltmann and others, 2012). Small amounts of rhenium were also recovered from sandstone uranium deposits in Texas from 1969 to 1974 (Millensifer, 1997). Sandstone uranium deposits are generally hosted in permeable medium- to coarse-grained sandstones that were deposited in fluvial or nearshore marine environments. The large sandstone deposits in Kazakhstan and Uzbekistan are hosted in large Cretaceous to early Tertiary continental basins. The deposits form by the dissolving of uranium from nearby strata in oxidized groundwaters that flow through the sandstones. Uranium is precipitated at a redox boundary (the "roll-front") when the oxidized ore fluids intersect and react with reducing agents in sandstone host rocks, such as carbonaceous (plant and algal) material, sulfide minerals, hydrocarbons, or interbedded volcanic rocks. Roll-front-type uranium deposits are crescent-shaped orebodies that crosscut the bedding in the sandstones (fig. P5D).

D

EXPLANATION

- ::: Medium-grained sandstone
- :·: Fine-grained sandstone
- ─ Clay and siltstone
- ||| Oxidized zone
- ▰ Uranium orebody
- ▰ Uranium halo
- ⧄ Rhenium halo—Concentration >0.1 ppm
- ⧄ Selenium halo—Concentration >50 ppm
- → Inferred direction of ore fluid movement

KAZAKHSTAN

■ Moynkum

Location of section
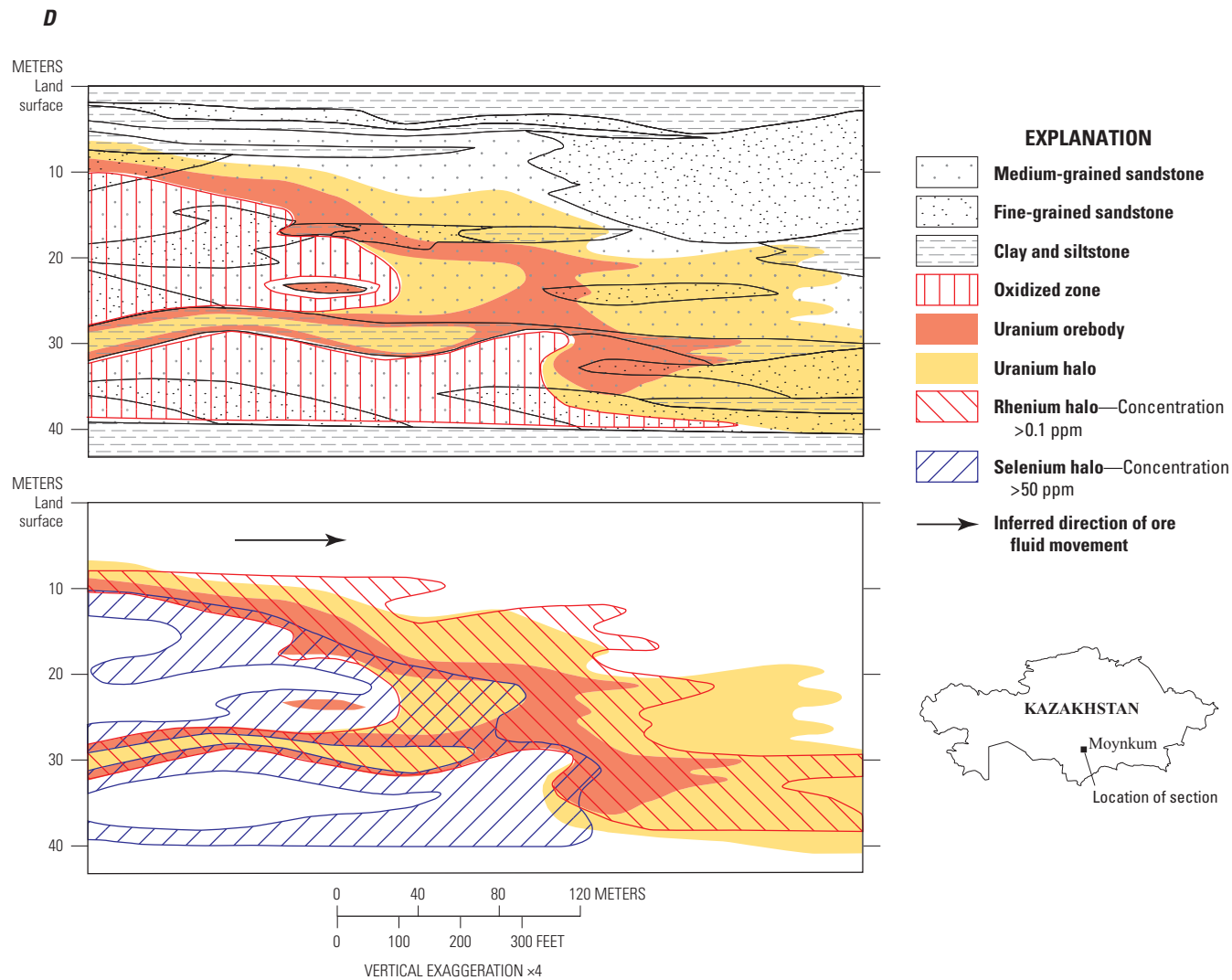
Figure P5.—Continued   *D*, Roll-front-type sandstone uranium deposit in the Moynkum-Tortkuduk sector of the Chu-Sarysu basin, Kazakhstan, showing lithological and reduction-oxidation (redox) control on uranium, rhenium, and selenium mineralization. Rhenium and uranium are enriched at the front of the roll in reduced rocks, whereas selenium is concentrated in oxidized rocks. The top cross section shows the oxidized zone; the bottom cross section shows the zone of selenium enrichment. Figure modified from Dahlkamp (2009a). ppm, part per million

At the Sugraly deposit in the Zarafshan mining district in Uzbekistan, rhenium was recovered along with selenium and molybdenum as byproducts of the mining of uranium deposits in Cretaceous to Eocene sandstone strata in the Kyzylkum basin (Dahlkamp, 2009b). Underground mining began in 1977 and was later switched to in situ leaching until mining ended in 1994. The Sugraly deposit was a typical roll-front-type deposit with complex uranium-selenium-molybdenum-rhenium ores that formed orebodies that were from several hundred meters to 20 km long and from 100 to 500 meters (m) wide. Rhenium content varied from 10 to 15 ppm (Seltmann and others, 2012). Rhenium was reportedly present in the form of ReS_2 and ReO_2 (Dahlkamp, 2009b).

Rhenium is reported in several roll-front-type sandstone uranium deposits in Kazakhstan (Dahlkamp, 2009a). These include deposits in the Moynkum (Moinkum), the Kanzhugan, and the Kenze-Budenovskaya mining districts in the Chu-Sarysu basin, and deposits in the Suluchekinskoye district. In the Moynkum and Kanzhugan districts, numerous uranium orebodies are associated with redox fronts in Paleogene sandstone aquifers. Rhenium grades generally range from 0.08 to 0.38 g/t with rhenium content of as much as 4.8 g/t in some deposits. In the Tortkuduk sector at the north end of the Moynkum deposit, uranium mineralization is contained in a 40-m-thick arenite unit sandwiched between clay-silt beds (fig. P5*D*). Uranium mineralization extends for about 10 km along a winding redox front. The forward sections of the rolls are about 20 m thick; tails may be up to several meters thick and more than 400 m long. A rhenium halo ($>$0.1 ppm rhenium), which coincides with the uranium distribution, surrounds the front of the roll and extends for up to 60 m into the reduced rocks (fig. P5*D*). A selenium zone with greater than 50 ppm selenium is in the rear part of the roll (fig. P5*D*).

At the Zhalpak and the Akdala deposits in the Kenze-Budenovskaya mining district, Cretaceous sandstones host roll-front uranium mineralization. Several orebodies in these deposits have rhenium content of as much as 62 ppm (Dahlkamp, 2009a; Seltmann and others, 2012). Samples containing greater than 0.2 ppm rhenium have higher uranium contents. In the Suluchekinskoye district in the Ily basin, roll-front-type orebodies are hosted by Cretaceous to Paleogene sandstones. Orebodies are zoned laterally from rhenium in reduced rocks, followed by a uranium-rhenium zone at the redox boundary, and then a selenium zone that forms the rear of the roll in oxidized rocks. Rhenium contents range from 1 to 24 ppm and average 1 to 2 ppm.

Uranium and rhenium in the Kazakhstan deposits are recovered using in situ leaching (also known as solution mining). In mining that uses in situ leaching, ore minerals are dissolved by circulating groundwater fortified with sulfuric or other acids through undisturbed underground deposits (World Nuclear Association, 2013). The resulting pregnant solutions are pumped to the surface, and uranium, rhenium, and other metals are recovered using methods similar to those used in processing milled uranium ore.

Rhenium in the Merlin Deposit

The Merlin molybdenum-rhenium deposit in the Mount Isa Inlier in northwestern Queensland, Australia, is a high-grade rhenium resource in which rhenium and molybdenum are the primary commodities and only minor amounts of copper are present (fig. P3; Brown and others, 2010; Lycopodium Minerals QLD Pty Ltd., 2012). Mineralized rock consists dominantly of molybdenite in veins, infilling breccias and stylolites, and disseminated grains in a zone that is about 1 km long and up to 20 m thick. Rhenium is contained in molybdenite grading an average of about 1,000 ppm rhenium. In 2012, indicated and inferred mineral resources were 6.9 million metric tons averaging 1.38 percent molybdenum and 22.7 ppm rhenium (Lycopodium Minerals QLD Pty Ltd., 2012).

The Merlin deposit was discovered in 2008 during drilling of the northern extension of the Mount Dore copper deposit, which mostly lies above and south of the Merlin deposit (Brown and others, 2010). The Merlin and the Mount Dore deposits are hosted by Early Proterozoic carbonaceous metashale and metasiltstone that are structurally overlain by the 1,500-mega-annum (Ma) anorogenic Mount Dore Granite along a moderately dipping reverse fault. The Merlin molybdenum-rhenium mineralization is associated with silica-albite alteration and interstitial clays that formed along reactivated fractures and shear zones and replaced the matrix of structurally controlled breccias. At Mount Dore, early regional-scale sodic-calcic alteration is cut by potassic alteration and quartz veins and by breccias that host an early phase of copper mineralization. A second phase of brecciation was followed by deposition of dolomite and a second stage of copper mineralization. The molybdenum-rhenium mineralization at the Merlin deposit cuts the copper mineralization in the Mount Dore deposit but is likely part of the same system. Zircon uranium-lead dating of the Mount Dore Granite and rhenium-osmium dating of molybdenite in the Mount Dore deposit show that both formed at about 1,500 Ma and suggest that copper-molybdenum mineralization at Mount Dore probably is related to a late-stage, evolved magmatic fluid that generated potassic alteration (Duncan and others, 2011). The average Mo:Re ratio of 600 is also consistent with an igneous origin.

Resources and Production

Identified Resources

Estimates of grades and tonnages of major rhenium-bearing deposits are shown in figure P4 and presented in tables P1 and P2. There are no published grade and tonnage models for rhenium in porphyry deposits, although Sinclair and others (2009) and Millensifer and others (2014) present plots of rhenium grade versus deposit tonnages for some porphyry and other types of deposits. Publicly available data on rhenium contents in porphyry deposits are limited and often inconsistent when more than one data source is available. Very few grade and tonnage data are available for other types of deposits that produce rhenium. Descriptions of data compilation methods and limitations of these data are in appendix P1.

Production

Worldwide mine production of rhenium in 2012 was estimated to be 52,600 kg, of which about 27,000 kg, or 51 percent, was produced from porphyry copper mines in Chile (fig. P6; Polyak, 2014). Because specialized processing facilities are required to recover rhenium from molybdenite concentrates, however, a significant amount of rhenium (approximately 15 to 20 metric tons) is contained in molybdenite concentrates roasted at facilities other than where it is mined (for example, molybdenite concentrates from the Bingham Canyon Mine), thereby making estimates of the sources of rhenium difficult. In recent years, rhenium also was recovered from porphyry copper deposits in the United States, Armenia, Kazakhstan, Mexico, Peru, Russia, and Uzbekistan. Porphyry copper deposits formed in continental arcs are the main sources of both rhenium production and resources (tables P1 and P2; fig. P3). All primary rhenium production in the United States is from processing facilities at the Sierrita Mine in Arizona, where rhenium is recovered from molybdenite concentrates produced at several porphyry copper mines. Rhenium resources in the United States are located mainly in Arizona and Utah, although smaller resources are located in Montana, New Mexico, and Nevada. The Pebble deposit in Alaska also contains a large inferred rhenium resource.

Sediment-hosted strata-bound copper deposits in Poland and Kazakhstan were the other major primary sources of rhenium in 2011, and both the Kupferschiefer deposits in Poland and the Dzhezkazgan deposit in Kazakhstan have large identified rhenium resources (fig. P4). Ore reserves in the underground deposits in Kupferschiefer deposits in the Legnica-Glogów copper belt, Poland, are sufficient to maintain the current production rate of about 30 million metric tons per year for 30 to 40 years (Bartlett and others, 2013).

Sandstone uranium deposits in Kazakhstan produce some byproduct rhenium, and published grade and tonnage
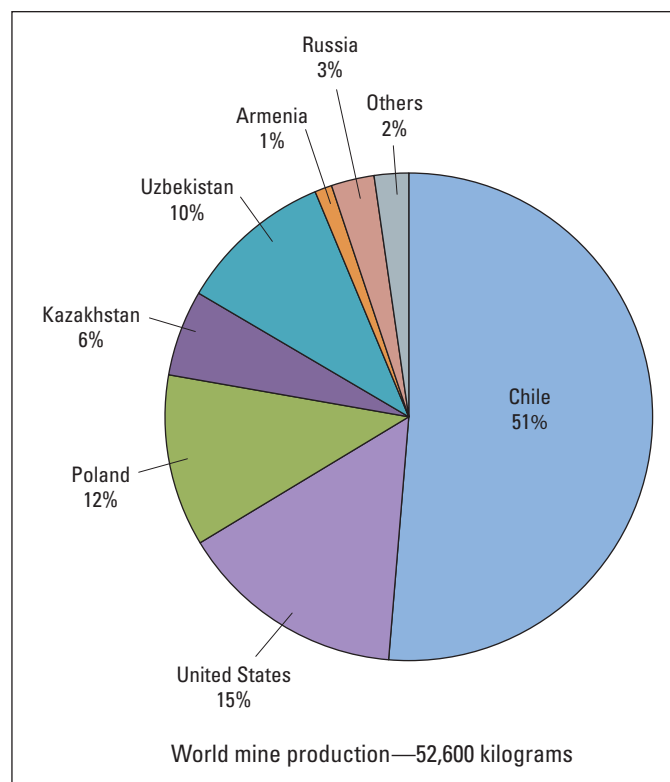
Figure P6. Pie chart showing world rhenium mine production in 2012, by country and percent of world total. Compiled using data from Polyak (2014).

data suggest significant rhenium resources in some deposits (Dahlkamp, 2009a). The lack of grade and tonnage data for most deposits, however, precludes a thorough assessment of these resources (table P1; fig. P4). Similar deposits in the southern and middle Ural Mountains in Russia may produce rhenium, but no production or resource estimates are available (Khalezov, 2009).

The Merlin molybdenum-rhenium deposit in Queensland, Australia, is unique because rhenium is a primary commodity. Despite its high rhenium grade (22.7 ppm), the contained rhenium resources are relatively small compared with the resources of other deposit types (fig. P4).

Undiscovered Resources

Rhenium resources likely are present in undiscovered porphyry copper deposits formed in continental arcs throughout the world. Recent U.S. Geological Survey (USGS) assessments of porphyry copper deposits in the Southwestern United States (Ludington and others, 1996), the Andes Mountains in South America (Cunningham and others, 2008), Mexico (Hammarstrom and others, 2010), the Province of British Columbia and the Yukon Territory in Canada (Mihalasky and others, 2013), and the Tethys region, including Armenia, Azerbaijan, Georgia, Iran, and Turkey

(Lukas Zürcher, U.S. Geological Survey, written commun., 2013) concluded that there is significant potential for undiscovered porphyry copper deposits in these regions. Because known porphyry copper deposits in these areas contain some of the largest identified rhenium resources in the world, it is highly probable that significant rhenium resources remain to be discovered in these areas.

In the United States, additional rhenium resources in porphyry copper deposits are most likely to occur in Arizona, where there are numerous identified deposits—several of which contain recoverable rhenium—and where there is a high probability of undiscovered deposits. Also, recent delineation of the giant Pebble porphyry copper-molybdenum-gold deposit in Alaska, which has estimated rhenium resources that represent more than 40 years of production at the current level of worldwide mine production (Ghaffari and others, 2011; Lang and others, 2013), suggests that there is the potential for significant rhenium resources in undiscovered porphyry copper deposits in Alaska.

Mongolia is another area where significant porphyry copper deposits have been discovered recently (for example, the giant Oyu Tolgoi porphyry copper-gold deposit in Omnogovi Aymag) (Khashgerel and others, 2006). The incompletely defined Zuun Mod molybdenum deposit has modest rhenium resources (table P1; Clark and Baudry, 2011). The presence of these deposits suggests the potential for significant undiscovered rhenium resources in Mongolia.

According to the recent USGS assessment of sediment-hosted strata-bound copper deposits, a significant number of undiscovered reduced-facies-type strata-bound copper deposits that have large resources are likely present in the Kupferschiefer in Poland (M.L. Zientek, U.S. Geological Survey, written commun., 2013) and sandstone-type strata-bound copper deposits in Kazakhstan (Box and others, 2012). Because known deposits in these areas are enriched in rhenium and contain significant rhenium resources (fig. P4), the undiscovered deposits also likely contain significant rhenium resources. Other large sediment-hosted strata-bound copper deposits, such as Udokan in the Transbaikalia Region in Russia and deposits in the Democratic Republic of the Congo, do not have reported anomalous rhenium contents (Hitzman and others, 2005; Zientek and others, 2013).

The recent discovery of the Merlin deposit in Australia opens up the possibility that there are other high-grade molybdenum-rhenium deposits in which these metals are the primary commodities. Until the genesis of the Merlin deposit is better understood, however, it is premature to speculate on the probability of the occurrence of similar deposits.

Exploration for New Deposits

With the exception of the Merlin molybdenum-rhenium deposit, all identified rhenium resources are contained in deposits mined primarily for other mineral commodities. In porphyry copper deposits, rhenium is recovered mostly from molybdenum, which is another byproduct. Until a better understanding of the genesis of the Merlin deposit emerges and it is determined that this type of deposit is economic, exploration for other primary rhenium deposits is unlikely to take place. Therefore, the discovery of significant new rhenium resources is likely to depend on successful exploration for porphyry copper deposits, especially in frontier areas, such as Alaska and Mongolia, where there have been recent discoveries of large porphyry copper deposits that may contain byproduct molybdenum and rhenium (for example, the Pebble and the Oyu Tolgoi deposits). Future exploration for porphyry copper deposits likely will involve increased remote sensing, geophysical (both potential field and electrical techniques), and lithogeochemical studies to discover covered deposits (for example, Graybeal and Vikre, 2010).

Environmental Considerations

Rhenium is present in Earth's crust at very low concentrations, and its production is nearly always as a byproduct commodity from copper mining. Therefore, the environmental characteristics of rhenium extraction are closely linked to those associated with the mining of the two types of copper deposits that represent its main sources. The primary source of rhenium is from the mineral molybdenite (the main ore mineral of molybdenum) derived from porphyry copper deposits. Rhenium is also produced from sediment-hosted copper deposits. The economic geology of the two mineral deposit types that are the predominant sources of byproduct rhenium are significantly different from one another, which means that the environmental geology of these deposit types are also different. The environmental geology of porphyry copper deposits is dominated by their large size (which means that they are commonly mined by open pit methods), their low grade, and the variable potential of their solid mine wastes to generate minor amounts of acid drainage or neutralize it (John and others, 2010). The environmental geology of sediment-hosted copper deposits is characterized by their moderate size, the tabular geometry of their ores, their low grade, and the low potential of their solid mine wastes to generate acid drainage (Hayes and others, 2015).

Sources and Fate in the Environment

Concentrations of rhenium in the natural environment, including in groundwater, surface water, sediment, soils, and biota, are low, which is a reflection of rhenium's low crustal abundance (table P3). The distribution of rhenium in environmental samples is further influenced by its relatively higher solubility in oxygenated waters and its lower solubility in oxygen-free (anoxic) waters.

The overall concentration of rhenium in water is similarly lower than that of many other base and precious metals, as summarized by Colodner and others (1993) and Hodge and others (1996). In fact, the natural concentration of rhenium in surface water, groundwater, and seawater falls in the parts-per-trillion range (table P3). Experimental studies suggest that the maximum solubility of ReO_2 in water at room temperature (25 °C) is less than 160,000 parts per trillion (ppt) (0.16 ppm), but could be as low as 20 ppt (Kim and Boulègue, 2003; Xiong and others, 2006). Dissolved concentrations in the ocean average 8.3 ppt and do not vary with depth (Colodner and others, 1993). Variations in rivers span four orders of magnitude, from 0.004 to 76 ppt (Colodner and others, 1993; Rahaman and others, 2012). The geology of the watershed influences the rhenium concentration. Watersheds underlain by black shales typically have higher concentrations of rhenium than do those underlain by other rock types. Rhenium in seawater and surface water behaves conservatively, meaning that it stays dissolved and does not bind or adsorb to particulate matter, such as clays. Reducing sediments (sediments rich in organic matter and sulfide minerals) are known to be important for the removal of rhenium from the water column, however (Koide and others, 1986). The observation that black shales can serve as sources of elevated concentrations of rhenium in surface water is a reflection of this process operating in the geologic record (Rahaman and others, 2012).

In solid environmental media (soil, sediment, and biological material), the rhenium concentrations are also low, although they are higher than those typically found in water (table P3). River sediments, oxygenated marine sediments, and soils all have concentrations that are comparable to the average crustal abundance (0.4 ppb). Organic-rich, anoxic sediments have concentrations that can be significantly higher (1.8 to 110 ppb) (Koide and others, 1986). Plants are known to accumulate rhenium at concentrations greater than local soil concentrations (Bozhkov and Borisova, 2003).

Information on pre-mining environmental concentrations of rhenium is limited, in part because of its low concentrations. Leybourne and Cameron (2008) investigated the concentrations of arsenic, copper, molybdenum, rhenium, and selenium in groundwater associated with the undeveloped Spence porphyry copper deposit in the Atacama Desert in northern Chile. They found that groundwater concentrations within the deposit reached a maximum rhenium concentration of 30.7 ppb. Outside of the deposit, the minimum rhenium concentration was as low as 0.2 ppb. From an environmental perspective, baseline concentrations of other trace elements and related constituents associated with porphyry copper deposits or sediment-hosted copper deposits are of greater environmental interest than are those for rhenium because these elements can be present in significantly higher concentrations.

Environmental baseline characterization studies of porphyry copper deposits are limited in the literature, particularly with regard to the diversity of climatic settings in which the deposits are found. Some information is available in mine permit applications for recently proposed mines, however. Studies from such diverse climates as the cold climate of southwestern Alaska (Fey and others, 2008); the tropical climate of Puerto Rico (Learned and Boissen, 1973; Plaza-Toledo, 2005); and the hot, arid climates of

Table P3.   Rhenium concentrations in rocks, soils, biota, waters, and sediments.

[ppb, part per billion; ppt, part per trillion]

Environment	Rhenium concentration	Reference(s)
Upper continental crust	0.4 ppb	Taylor and McLennan (1995)
Soils	0.208 to 1.72 ppb	Uchida and others (2005)
Leaves, dried, birch and fir, unimpacted	4 to 6 ppb	Bozhkov and Borisova (2003)
Leaves, dried, acacia, smelter and mine site vicinity	902 to 2,430 ppb	Bozhkov and Borisova (2003)
Seawater (Atlantic Ocean and Pacific Ocean)	8.3±0.1 ppt	Colodner and others (1993)
Rivers	0.004 to 76.7 ppt	Colodner and others (1993); Rahaman and others (2012)
Groundwater	0.9 to 35.4 ppt	Colodner and others (1993); Hodge and others (1996)
Groundwater, porphyry copper deposits	0.09 to 30.7 ppb	Leybourne and Cameron (2006)
River sediment	0.233 to 0.285 ppb	Uchida and others (2005)
Pelagic sediments	<0.1 ppb	Koide and others (1986)
Anoxic sediments	1.8 to 110 ppb	Koide and others (1986)

Arizona and Chile (Chaffee, 1976, 1977; Chaffee and others, 1981; Leybourne and Cameron, 2006, 2008) show similar geochemical features. Soils show elevated concentrations of, in decreasing order of maximum concentration, iron (2.3 to 7.4 weight percent), sulfur (0.02 to 0.87 weight percent), copper (3.2 to 1,830 ppm), zinc (36 to 142 ppm), arsenic (7 to 78 ppm), molybdenum (0.6 to 27.1 ppm), lead (7.1 to 17.4 ppm), and cadmium (<0.1 to 0.6 ppm). Stream sediments show elevated concentrations of, in decreasing order of maximum concentration, iron (6.3 to 10.6 weight percent), copper (64 to 804 ppm), zinc (59 to 291 ppm), lead (<4 to 17 ppm), molybdenum (<2 to 10 ppm), arsenic (<10 ppm), and cadmium (<2 ppm).

Only a limited amount of pre-mining baseline data are available in the literature for soil, stream sediment, groundwater, and surface water from a variety of deposits. Plaza-Toledo (2005) found that surface waters downstream from undeveloped porphyry copper deposits in the Cordillera Central of Puerto Rico contained maximum dissolved concentrations of 110 ppm sulfate, 15.9 ppm iron, 0.56 ppm aluminum, 0.13 ppm copper, and 0.04 ppm zinc. The pH was high (7.7 to 8.6). Fey and others (2008) documented surface-water pH values of between 4.1 and 7.3 in the vicinity of the Pebble deposit in southwestern Alaska. Alkalinity ranged between 0 and 100 ppm calcium carbonate ($CaCO_3$) equivalent; sulfate, between 1 and 85 ppm; and hardness of water, between 2 and 130 ppm $CaCO_3$ equivalent. Dissolved trace element concentrations showed a range of values for, in decreasing order of maximum concentration, iron (<20 to 4,260 ppb), copper (<0.5 to 688 ppb), zinc (<0.5 to 68 ppb), arsenic (<1 to 36.2 ppb), molybdenum (<2 to 21.9 ppb), lead (<0.05 to 18.8 ppb), and cadmium (<0.2 to 11.6 ppb). Leybourne and Cameron (2006, 2008) documented high salinity in groundwaters associated with the undeveloped Spence deposit where the salinity reached 10,000 to 55,000 ppm, with one outlier sample at 145,000 ppm. The pH of the groundwaters varied widely, between 4.7 and 9.2. Dissolved sulfate concentrations in groundwaters were between 5,000 and 10,000 ppm. Dissolved trace element concentrations showed a range of values for, in decreasing order of maximum concentration, iron (4 to 54,454 ppb), copper (9 to 28,991 ppb), zinc (5 to 1,344 ppb), molybdenum (2 to 475 ppb), arsenic (<10 to 160.9 ppb), and lead (0.025 to 23.8 ppb).

Environmental baseline characterization studies of sediment-hosted copper deposits are more limited than those for porphyry copper deposits. For sedimentary-hosted copper deposits, soil and stream sediments may contain anomalous abundances of copper, lead, silver, and possibly arsenic, mercury, and zinc in the vicinity of the deposits (Lindsey and others, 1995). Stream-sediment samples collected in the Kafue River (Zambia) upstream from sediment-hosted copper deposits contained copper in concentrations of between 15 and 146 ppm, some of which were just below the stream-sediment criterion (that is, the probable effects concentration, or the concentration at which toxic effects would be expected for aquatic organisms) of 149 ppm (MacDonald and others, 2000; Pettersson and others, 2000; Pettersson and Ingri, 2001). Also, soil and sediment associated with some sandstone deposits in Montana contained anomalous copper (up to 2,000 ppm), lead (greater than 150 ppm), and silver (greater than 0.5 ppm), as reported by Cazes and others (1981) and Wells and others (1981).

In contrast to some of the sediment and soils that have anomalous metal concentrations, surface water in the Kafue River upstream from the mining area in Zambia contains low levels of copper (up to 3 ppm) and other trace elements (Norrgren and others, 2000; Pettersson and Ingri, 2001). The draft environmental impact statement for the Montanore Project, which is a proposed mine in the Rock Creek-Montanore deposit in Montana, describes the surface-water quality in streams and lakes near the proposed mine as being "excellent," which presumably means that all trace elements meet environmental criteria. The concentrations of total suspended solids, total dissolved solids, major ions, nutrient concentrations, and metal concentrations are generally low and frequently at or below detection limits. The surface waters generally contain iron, copper, and silver in low concentrations that are well below environmental guidelines. The surface waters tend to be slightly acidic (U.S. Department of Agriculture, Forest Service, and others, 2009).

Mine Waste Characteristics

The amount of mine waste associated with porphyry copper and sediment-hosted deposits varies with the size of the deposit. Porphyry copper deposits range from 30 million metric tons to more than 20 billion metric tons with a median size of 250 million metric tons. Because copper grades are typically less than 1 percent copper (median grade of 0.44 percent copper), more than 95 percent of the material mined ends up as solid mine waste of one form or another. The solid mine waste typically falls into one or more of the following three types: tailings, waste rock, and leach-pad waste. Tailings and waste rock are usually found at all mines, whereas leach-pad waste is found only at those mines where the ores are amenable to a copper extraction method known as solvent extraction-electrowinning (SX–EW). SX–EW is viable only for deposits that have been subject to prolonged periods of weathering, which has produced a zone near the surface where sulfide minerals have been oxidized to copper oxide or copper carbonate minerals. The oxide zone will overlie an unweathered sulfide zone. The oxide ore is mined and crushed to a coarse grain size and placed on lined pads. The piles are leached with a sulfuric acid solution, which is recovered to collect the leached copper. Oxide zones are not universally present at porphyry copper deposits, so this type of mine waste is not always present at porphyry copper deposits.

Tailings are produced when the ore is crushed to a sand or silt size to facilitate the separation of the copper sulfide and other metal-sulfide ore minerals from gangue minerals (minerals of no value) using a technique known as froth flotation. After separation of gangue minerals, the tailings are discarded as a slurry or trucked dry to a tailings storage facility. Tailings storage facilities are typically impoundments surrounded by a retaining dam.

The other type of solid waste is waste rock. Because of their large size and low grade, porphyry copper deposits are commonly mined by open pit methods. Waste rock is uneconomic rock that must be removed (stripped) to access the ore. Waste rock is disposed of on site. It can also be used for construction on site if tests determine that it will not generate acid-rock drainage when it is exposed to the atmosphere and water. For open pit porphyry copper mines, waste-to-ore (stripping) ratios commonly can exceed 2:1, which means that for each ton of ore mined, two tons of waste rock must be removed (Porter and Bleiwas, 2003). Porphyry copper deposits at depth can also be mined by block caving. A vertical shaft or spiral decline is built to the base of the orebody, and the orebody is mined from below, leaving a large, unsupported cavity where the ore was removed. With this type of mining, the amount of waste rock is less than that in open pit mining and the waste material is dominated by tailings.

The size of sediment-hosted copper deposits depends upon their subtype (reduced type, red bed, or sandstone) and is smaller than most porphyry copper deposits. The volume of mine waste and tailings produced from a deposit depends on the deposit size, depth, geometry, ore grade, and mining method. Sediment-hosted copper deposits can be mined by underground or open pit methods. The reduced-facies-type deposits are generally high tonnage (the median tonnage is 33 million metric tons) with a high copper grade (the median grade is 2.3 percent) (Lindsey and others, 1995; Cox and others, 2003). Red-bed deposits are generally low tonnage (the median tonnage is 1.2 million metric tons), have an intermediate copper grade (the median grade is 1.2 percent), and are mined either by open pit or underground methods. Sandstone deposits are intermediate tonnage (the median tonnage is 14 million metric tons) but they have lower copper grades (the median grade is 0.79 percent). Because of the low copper grades, most of the mined rock is waste. Copper can be separated by froth flotation of finely ground ore or by SX-EW recovery from oxidized ores.

The mineralogy of the ore and waste in porphyry copper and sediment-hosted copper mines determines the environmental characteristics of these deposits. In terms of both ecological risks and human health risks, the mineralogy dictates the acid-generating potential of the ores and wastes and the mobility of trace elements. In porphyry copper deposits, sulfide minerals, such as bornite, chalcopyrite, enargite, galena, molybdenite, pyrite, and sphalerite, are the main hosts of the trace elements that are of environmental concern; in total, they typically constitute less than 5 percent of the ore (John and others, 2010). In sediment-hosted copper deposits, the sulfide minerals are dominated by, in general order of decreasing abundance, chalcocite, digenite, bornite, chalcopyrite, pyrite, and subordinate galena and sphalerite (Hayes and others, 2015). The trace element geochemistry of tailings and waste dumps reflects the mineralogy of the waste. For porphyry copper deposits, tailings typically contain significant concentrations of copper (475 to 5,100 ppm), manganese (67 to 700 ppm), molybdenum (12 to 235 ppm), zinc (40 to 210 ppm), and arsenic (3.5 to 136 ppm) (John and others, 2010). Tailings from sediment-hosted copper deposits generally contain 1 to 4 weight percent iron, 0.1 to 0.3 weight percent copper, and 300 to 800 ppm cobalt (Hayes and others, 2015).

Approaches for managing solid waste depend upon its acid-generating potential. Acid generation can be considered a "master variable" for aqueous risks. Metals and many other trace elements tend to be more soluble at low pH (acidic) than at neutral or high pH (alkaline). Therefore, the acid-generating or acid-neutralizing potentials of the waste rock, tailings, and other solid waste material are of prime importance in identifying the potential environmental risks associated with mining and ore beneficiation. The acid-generating potential of mine waste is expressed in terms of the amount of calcium carbonate it would take to neutralize it; it is measured in kilograms of calcium carbonate per metric ton of mine waste (kg $CaCO_3$/t) (Price, 2009; International Network for Acid Prevention, 2011). The acid-generating potential resides primarily in pyrite. Mine waste can also have acid-neutralizing potential, which resides in carbonate minerals, such as calcite, and in some silicate minerals, such as feldspars.

The rocks associated with porphyry copper deposits, in general, tend to straddle the boundary between having net acid-generating potential and not having net acid-generating potential. During mining and processing of porphyry copper deposits, a variety of materials with differing acid-base accounts may be encountered and produced, and each type must be managed according to its acid-generating potential. Net alkaline waste does not require any special handling and can be used for construction purposes, whereas net acid waste has to be managed to mitigate acid-mine drainage problems. As an example, the net neutralizing potentials for the hypogene and supergene ores from Morenci, Arizona, range from dominantly net acid to slightly net alkaline (–257.0 to 1.1 kg $CaCO_3$/t) (Enders and others, 2006). The net acid-neutralization potentials reported in the literature for tailings from several porphyry copper deposits in Chile are net acid generating, ranging from –101.6 to –18.2 kg $CaCO_3$/t (Dold and Fontboté, 2001). Tailings derived from metallurgical testing on an exploratory drill core from the Pebble deposit in southwestern Alaska have net neutralization potentials ranging from –110 to 27.2 kg $CaCO_3$/t (Pebble Partnership, 2011).

For sediment-hosted copper deposits, the abundance of carbonate minerals and slightly less reactive minerals, principally chlorite- and epidote-group minerals, determine the acid-neutralizing capacity, whereas the acid-generating potential is determined by the abundance of sulfides, such as pyrite and chalcopyrite. Many deposits contain a significant amount of carbonate and (or) silicate minerals in the ore or host rock, which neutralize the acidity generated by sulfide weathering. As for acid-generating sulfides, the ore for all three subtypes contain low pyrite contents. The pyrite content of the host rock for all types of sediment-hosted copper deposits is less than 1 volume percent (Hayes and Einaudi, 1986).

Limited acid-base accounting data have been reported in the literature for sediment-hosted copper deposits. For tailings, no acid-generating potential has been detected in samples from the White Pine Mine in Michigan (Williams and others, 2002), whereas high acid-neutralizing capacities and neutral-to-alkaline conditions have been reported in samples from the Zambian copperbelt. For the Zambian tailings, the neutralization potential ratios are between 3.4 and 84; most samples at depth have values of greater than 20, and the highest values are for the leached surface materials (Sracek and others, 2010).

The mean net neutralization potentials of ore, waste rock, and tailings from sandstone deposits at Montanore, Rock Creek, and Troy, Montana, were summarized in the environmental impact statement for these projects (U.S. Department of Agriculture, Forest Service, and others, 2009). Ore from the Montanore deposit has a mean net neutralization potential of –4 kg $CaCO_3$/t, with values ranging from –24 to 11 kg $CaCO_3$/t, meaning that its average value has a slight acid-generating potential, but ranges from having a slight excess of acid-generating potential to having a slight excess of acid-neutralizing potential. Values for the Rock Creek and the Troy ore samples average 5 and 8 kg $CaCO_3$/t, respectively, meaning that they have acid-generating potential. The mean net neutralization potentials for the tailings from these sandstone deposits range from 2.8 to 10 kg $CaCO_3$/t. These acid-base accounting results reflect the low amounts of sulfides in the tailings. The mean net neutralization potentials for the mine waste from these deposits range from 3.6 to 15 kg $CaCO_3$/t.

Human Health Concerns

No information is available for rhenium and its toxic effects on humans, partly (presumably) because of its low natural abundance. The U.S. Agency for Toxic Substances and Disease Registry (http://www.atsdr.cdc.gov/toxprofiles/index.asp) does not have a toxicological profile for rhenium nor does the U.S. Environmental Protection Agency have drinking-water standards or soil guidelines for rhenium. Unnatural (not naturally occurring) radioisotopes of rhenium (^{188}Re and ^{186}Re), however, are being investigated for management of metastatic bone pain in cancer patients (Finlay and others, 2005).

Instead, the more significant human health risks associated with rhenium production are found with the broader aspects of the mining of porphyry and sediment-hosted copper deposits. Contaminated groundwater plumes associated with tailings impoundments may threaten drinking-water supplies, depending upon the geologic and hydrologic setting and engineering aspects of the mine and the waste piles for both deposit types. Host rocks with higher acid-neutralization potentials, such as carbonate rocks, tend to limit the mobility of metals and related compounds. Hydrologic and climatic settings that have net evaporative loss of water may cause evaporative concentration of solutes that may enter groundwater used as drinking-water supplies in the vicinity of mines and waste piles. Improperly constructed water-containment structures may allow contaminated mine waters to enter surrounding groundwater. For both porphyry copper deposits and sediment-hosted deposits, elements or compounds with the greatest likelihood of causing problems for drinking-water sources include aluminum, arsenic, copper, iron, manganese, sulfate, and zinc. The U.S. Environmental Protection Agency has primary drinking-water standards, meant to protect human health, for arsenic, cadmium, copper, and lead, and nonenforceable secondary standards meant to protect the cosmetic and aesthetic qualities of water (skin or tooth discoloration, taste, odor, and color) for aluminum, cadmium, iron, lead, manganese, sulfate, and zinc (U.S. Environmental Protection Agency, 2009a). The potential for groundwater contamination depends upon the waste and water management practices at any given mine.

An additional human health risk associated with porphyry copper and sediment-hosted copper deposits is from the smelting of ore concentrates. Historically, it was more common for each mine or mining district to operate its own smelter. In contrast, modern mines typically ship ore concentrates to smelters that may be far away from the mines. Therefore, smelter sites are not a necessary feature of a proposed mine. Smelters may emit carbon monoxide, hydrocarbons, metals, nitrogen oxide, particulates, and sulfur dioxide, which can contaminate surrounding soils, although in the United States, these emissions are currently regulated to protect the environment. For example, numerous studies on the soil surrounding the Głogów and the Legnica smelters in Poland, which serve sediment-hosted copper mines, reported high metal concentrations, especially of, in decreasing order of maximum concentration, lead (90 to 18,000 ppm), copper (250 to 10,000 ppm), zinc (55 to 4,000 ppm), and cadmium (0.3 to 10.9 ppm), that vary with the dominant wind direction and distance from the smelter (Roszyk and Szerszen, 1988; Helios Rybicka and Jędrzejczyk, 1995; Karczewska, 1996; Pilc and others, 1999; Grzebisz and others, 2001; Kabala and Singh, 2001). The concentrations of cadmium and lead in groundwater and surface waters in the vicinity of the two smelters (Pilc and others, 1999) exceed the World Health Organization (WHO) guidelines for drinking water (World Health Organization, 2006).

Ecological Health Concerns

No information is available for rhenium and its toxic effects on aquatic or terrestrial ecosystems, presumably because of its low crustal abundances. Therefore, as with human health risks, the more significant ecosystem risks associated with rhenium production are found with the broader aspects of the mining of porphyry and sediment-hosted copper deposits. Many of the ecological risks associated with both porphyry copper deposits and sediment-hosted deposits focus on the ability of mine wastes to generate acid, and the ability of the resulting acid-mine drainage to carry metals and other inorganic contaminants. As described above with respect to mine-waste characteristics, the acid-generating potential of mine waste is primarily found in its pyrite content, and it may be offset by the acid-neutralizing potential found in carbonate or less significantly silicate (chlorite and epidote group) minerals. Residual ore minerals in the waste material are the primary hosts of many metals and arsenic in mine drainage. Silicate minerals are common sources of aluminum, iron, and manganese in mine drainage. Sound waste management practices can mitigate these effects. Tailings are prone to being transported by waters, especially in the case of a tailings dam failure, and wind, because of the sand- to silt-size grains. Thus, they present additional potential risks to aquatic organisms through sediment contamination.

Mine-drainage data are available for porphyry copper deposits in British Columbia, Canada (Day and Rees, 2006); the Globe mining district in Arizona (Eychaner, 1991; Stollenwerk, 1994; Brown and others, 1998; Lind and others, 1998; Conklin and others, 2001); the Morenci mining district, Arizona (Enders and others, 2006); and Iran (Khorasanipour and others, 2011). Many of the values exceed relevant water-quality guidelines for the protection of aquatic ecosystems (U.S. Environmental Protection Agency, 2009b). In British Columbia, Canada, Day and Rees (2006) documented mine waters with pH values ranging from 2.0 to 8.5, and sulfate was the dominant anionic species (1 to 30,000 ppm). The concentrations of trace elements varied widely: aluminum ranged from 0.001 to 1,000 ppm; copper, 0.0005 to 1,000 ppm; iron, 0.005 to 1,000 ppm; manganese, 0.001 to 100 ppm; and zinc, 0.001 to 100 ppm. Khorasanipour and others (2011) found similar geochemical trends, but in a more arid environment, for drainage associated with waste-rock dumps at the Sar Cheshmeh Mine in Kermān Province, southeastern Iran. The pH values ranged from 3.1 to 6.3, and the concentration of sulfates was between 365 and 1,590 ppm. The concentrations of aluminum ranged from less than 0.05 to 60 milligrams per liter (mg/L); manganese, from 14.6 to 95.8 ppm; copper, 2.15 to 70 ppm; and zinc, 2.4 to 27.4 ppm. In the Globe mining district in Arizona, a stream was blocked by mill tailings, causing a lake to form. Water from this lake entered an alluvial aquifer by seepage, and the aquifer and a stream to the north were contaminated (Eychaner, 1991; Stollenwerk, 1994; Brown and others, 1998; Lind and others, 1998; Conklin and others, 2001). The most contaminated groundwater in the aquifer had a pH of 3.3 and contained about 9,600 ppm sulfate, 2,800 ppm iron, 300 ppm aluminum, and 190 ppm copper. As the plume traveled north through the aquifer, the concentration of constituents decreased as the plume interacted with carbonate-bearing alluvium and was diluted by uncontaminated water (including groundwater flowing upward from lower basin fill, water in uncontaminated streams that join the contaminated wash, and surface rainwater). Enders and others (2006) reported analyses of seeps and springs in the Morenci district of Arizona, which had pH values of between 2.6 and 4.6. Sulfate concentrations were between 550 and 4,300 ppm; copper, between 0.46 and 960 ppm; iron, between 15 and 420 ppm; aluminum, between 0.48 and 370 ppm; and zinc, between 0.8 and 159 ppm.

Pit lakes, particularly in porphyry copper mining districts that have extensive historical underground mine workings, such as the Butte district in Montana, which has a 140-year mining history, can be problematic. The Berkeley Pit lake at Butte contains more than 100 billion liters of pH-2.5 mine water (Gammons and others, 2005; Gammons and Duaime, 2005). The pit lake has high levels of dissolved solids and elevated concentrations of copper, iron, sulfate, and zinc (Gammons and Duaime, 2005). In contrast, pit lakes in the Yerington and Robinson districts in Nevada have pH values that typically range from 7.0 to 8.5 with a few outliers near 4.7, which have been attributed to discharge from solvent-extraction operations rather than groundwater-rock interactions in the vicinity of the pits (Shevenell and others, 1999). In Nevada, the total dissolved solids are generally less than 6,000 ppm, and concentrations of manganese are less than 5 ppm; iron, less than 4.5 ppm; selenium, less than 0.14 ppm; and arsenic, less than 0.05 ppm.

Several studies provide insights into the ecosystem risks associated with sediment-hosted copper deposits. Detailed ecological studies have been carried out along the Kafue River in Zambia, which flows through the Zambian Copperbelt Province's mining district. Syakalima and others (2001) analyzed water downstream of the mining-affected areas of two national parks. This study found concentrations of lead in water of between 0.29 and 0.36 ppm compared with the WHO drinking-water guideline of 0.01 ppm. Other studies focused on the toxic effects of metals in the Kafue River on tropical fish. River sediment collected downstream of several mines and near a city that has a major ore-processing facility was significantly more toxic to zebrafish (*Pterois volitans*) and tilapia (both redbreast tilapia [*Tilapia rendalli*] and spotted tilapia [*Tilapia mariae*]) than sediment collected further downstream (Mwase and others, 1998). The toxicity was directly related to the contamination of sediments by the mining activities (Mwase and others, 1998). The results of another study showed that tilapia exposed in situ to Kafue River water for 2 weeks bioaccumulated several trace elements (cadmium, chromium, cobalt, copper, and nickel) for experiments located downstream of mining activities and other industrial point sources (Norrgren and others, 2000).

The Zambian copperbelt contains both reduced-facies and red-bed-associated deposits, and stream sediments from the Kafue River—an area affected by mining of these deposits—contains up to 0.8 weight percent sulfur, 12,855 ppm copper, and 1,030 ppm cobalt (Pettersson and others, 2000; Pettersson and Ingri, 2001).

A study by the mining company to assess the local and long-term effects on Lake Superior from the discharge from the White Pine Mine in Michigan was conducted in 1991. The study indicated that discharge from the mine area was not causing measurable effects based on a lack of observable impact on the benthic community, an insignificant increase in chloride from mine discharges, and a lack of detectable effects on local water intakes (U.S. Environmental Protection Agency, 1994). According to the Surface Water Quality Division of the Michigan Department of Natural Resources, a diverse fish community exists in the nearby river that receives drainage from the mine. According to the U.S. Environmental Protection Agency (1994), the Michigan Department of Natural Resources report did show a reduced macro-invertebrate community downstream from the mine drainage compared with upstream in the river. They suggested that this reduction may be owing to major physical and natural stream quality differences in the White Pine area.

Several environmental impact statements for sandstone deposits in Montana discuss the mobility of trace elements to surface water. Tailing effluent and mine water chemistries for the Spar Lake (Troy) Mine had concentrations of cadmium, copper, and lead in the tailings outflow that exceed aquatic ecosystem guidelines (U.S. Department of Agriculture, Forest Service, and others, 1992).

Carbon Footprint

Rhenium extraction through mining does not have a unique carbon footprint beyond the general energy requirements of mining. In terms of its uses, rhenium is most directly linked to the global carbon cycle through its use in platinum-rhenium catalysts to produce high-octane, lead-free gasoline (Polyak, 2013).

Mine Closure

The methods used to close porphyry copper mines and sediment-hosted copper mines depend primarily on the method of mining and the characteristics of the waste material. Open pit mining of either deposit type produces at least three different features after mining: the open pit, tailings storage facilities, and waste rock piles. Backfilling pits is typically not practical for a variety of reasons. If the water table is above the bottom of the pit, the pit will become a lake. The water quality of the lake will depend upon a number of factors, including the characteristics of the wall rock, the extent of underground mine workings that connect to the pit, the water

level and volume in the pit, the local hydrology, and climate, among others (Castendyk and Eary, 2009).

The long-term fate of tailing storage facilities depends upon the nature of the tailings and the method of construction of the facility. Some tailings storage facilities can be regraded, capped, and revegetated. Others are designed to have a water cover in perpetuity to limit sulfide oxidation. Either type may have seepage that could require some form of water treatment. The long-term fate of waste rock piles typically includes regrading, capping, and revegetation. Depending upon the acid-generating potential of the waste, some piles may also require some form of water treatment.

For underground mines, tailings and waste rock may be handled similarly to how they are handled at open pit mines. Some of the tailings may be transferred back into the mined-out workings, depending upon how the orebody is mined. The entire volume of tailings cannot be placed back in the mine workings, however, because of the volume expansion associated with crushing and milling the ore and the relatively small volume of the mineral commodity that is recovered.

Problems and Future Research

The lack of published data about the rhenium contents of most deposits, including many deposits from which rhenium is produced, hinders understanding of where additional resources may be located. The many uncertainties in the estimates of rhenium grades and rhenium contents of identified deposits preclude more-detailed analysis of rhenium resources.

The geology and geochemistry of rhenium-enriched deposits are not fully understood. Areas of future research will likely include investigating the following: (a) why rhenium is generally more enriched in molybdenite that occurs in porphyry copper deposits (where the rhenium content is in the hundreds to thousands of parts per million) than in molybdenite that occurs in porphyry molybdenum deposits (where the rhenium content ranges from less than one to tens of parts per million) and why molybdenite in gold-rich porphyry copper deposits tends to have higher rhenium concentrations than it does in other subtypes of porphyry copper deposits; (b) where rhenium occurs in sediment-hosted strata-bound copper deposits and in sandstone uranium deposits; (c) the source of rhenium in sediment-hosted strata-bound copper deposits; and (d) the origin of the Merlin molybdenum-rhenium deposit.

Acknowledgments

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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 P2 and Appendix P1

Table P2.   Rhenium data for selected porphyry copper and porphyry molybdenum deposits of the world.

[The names, locations, and types of most of the deposits are taken from the U.S. Geological Survey Mineral Resources Data System (MRDS) (U.S. Geological Survey, 2014). The minimum and maximum values are concentrations of rhenium in molybdenite separates; the estimated average is based on mill concentrates. Elements and compound: Au, gold; Cu, copper; Mo, molybdenum; MoS$_2$, molybdenite; Os, osmium; Re, rhenium. Units of measure: g/t, gram per metric ton; Mt, million metric tons; ppm, part per million; t, metric ton; wt. %, weight percent. —, no data; None, no minimum and maximum values are available because only a single analysis was used to calculate the Re grade]

Deposit name	Country	Deposit subtype[1]	Tectonic setting	Grade (wt. % Cu)	Grade (wt. % Mo)	Grade (g/t Au)	Minimum Re in MoS$_2$ (ppm)	Maximum Re in MoS$_2$ (ppm)	Estimated average Re in MoS$_2$ (ppm)
				Porphyry copper deposits					
Agarak	Armenia	Cu	Continental arc	0.56	0.025	0.6	57	6,310	820
Ajax West	Canada	Cu	Island arc	0.31	0.005	0.2	None	None	3,161
Aksug	Russia	Cu	Post-collisional	0.67	0.015	0.12	None	None	460
Aktogai (or Aktogay)	Kazakhstan	Cu-Mo	Continental arc	0.39	0.01	0.026	50	2,700	850
Bagdad	United States	Cu-Mo	Continental arc	0.4	0.01	0.0011	330	642	460
Berg	Canada	Cu-Mo	Continental arc	0.39	0.031	0.06	67	215	152
Bethlehem–Huestis	Canada	Cu-Mo	Island arc	0.4	0.005	0.012	None	None	417
Bethlehem–Iona	Canada	Cu-Mo	Island arc	0.52	0.006	0.012	None	None	1,015
Bethlehem–JA	Canada	Cu-Mo	Island arc	0.43	0.017	0.01	200	246	222
Bingham	United States	Cu	Post-collisional	0.882	0.053	0.38	130	2,000	250
Borly	Kazakhstan	Cu	Continental arc	0.34	0.011	0.3	250	5,500	3,160
Boschekul	Kazakhstan	Cu-Mo	Island arc	0.67	0.0023	0.049	230	1,500	825
Brenda	Canada	Cu-Mo	Island arc	0.152	0.037	0.013	80	145	115
Bronson Slope	Canada	Cu-Au	Island arc	0.17	0.006	0.44	None	None	180
Butte	United States	Cu-Mo	Continental arc	0.673	0.028	0.042	None	None	240
Cananea	Mexico	Cu	Continental arc	0.45	0.002	0.035	None	None	700
Casino	Canada	Cu	Continental arc	0.25	0.025	—	65	289	197
Castle Dome (Pinto Valley)	United States	Cu-Au	Continental arc	0.33	0.0055	0.34	1,200	1,750	1,750
Cerro Verde	Peru	Cu	Continental arc	0.495	0.01	—	3,060	3,497	3,280
Chuquicamata-Radomiro Tomic	Chile	Cu-Mo	Continental arc	0.86	0.04	0.013	93	262	265
Collahuasi	Chile	Cu-Mo	Continental arc	0.592	0.04	0.01	368	448	395
Copper Creek	United States	Cu	Continental arc	0.75	0.0046	—	534	2,107	1,165
Cuajone	Peru	Cu	Continental arc	0.69	0.0214	—	None	None	580

Table P2.   Rhenium data for selected rhenium porphyry copper and porphyry molybdenum deposits of the world.—Continued

[The names, locations, and types of most of the deposits are taken from the U.S. Geological Survey Mineral Resources Data System (MRDS) (U.S. Geological Survey, 2014). The minimum and maximum values are concentrations of rhenium in molybdenite separates; the estimated average is based on mill concentrates. Elements and compound: Au, gold; Cu, copper; Mo, molybdenum; MoS_2, molybdenite; Os, osmium; Re, rhenium. Units of measure: g/t, gram per metric ton; Mt, million metric tons; ppm, part per million; t, metric ton; wt. %, weight percent. —, no data; None, no minimum and maximum values are available because only a single analysis was used to calculate the Re grade]

Number of Re analyses[2]	Grade[3] (g/t Re)	Deposit tonnage (Mt)	Contained Mo (t)	Contained Re (t)	Mo:Re ratio	Data sources	Deposit name
				Porphyry copper deposits			
106, 0, 0	0.342	125	31,300	43	730	Berzina and others, 2005; Singer and others, 2008	Agarak
1, 0, 0	0.263	365	18,300	96	190	Sinclair and others, 2009	Ajax West
0, 0, **1**	0.115	337	50,600	39	1,300	Berzina and others, 2005; Singer and others, 2008	Aksug
30, 0, 0	0.14	2,636	260,000	370	700	Berzina and others, 2005; Singer and others, 2008	Aktogai (or Aktogay)
0, **7**, 2	0.08	1,600	160,000	130	1,200	Sutulov, 1974; Nadler, 1997; Barra and others, 2003; Singer and others, 2008	Bagdad
4, 0, 0	0.079	238	73,800	19	4,000	Sinclair and others, 2009	Berg
1, 0, 0	0.035	1.4	70	0.05	1,400	Sinclair and others, 2009	Bethlehem–Huestis
1, 0, 0	0.102	30	1,780	3.0	590	Sinclair and others, 2009	Bethlehem–Iona
4, 0, 0	0.063	260	44,200	16	2,700	Sinclair and others, 2009	Bethlehem–JA
36, 6, **1**	0.221	3,230	1,710,000	714	2,400	Giles and Schilling, 1972; McCandless and Ruiz, 1993; Chesley and Ruiz, 1998; Singer and others, 2008; Austen and Ballantyne, 2010; J.T. Chesley, Ph.D., written commun., 2013	Bingham
19, 0, 0	0.579	94	10,400	55	190	Berzina and others, 2005; Singer and others, 2008	Borly
23, 0, 0	0.032	1,000	23,000	32	730	Singer and others, 2008; Sinclair and others, 2009	Boschekul
11, 0, 2	0.071	182	67,200	13	5,200	Sutulov, 1974; Sinclair and others, 2009; W.D. Sinclair, Ph.D., Geological Survey of Canada, written commun., 2013	Brenda
1, 0, 1	0.018	79	4,740	1.4	3,300	Sinclair and others, 2009	Bronson Slope
1, 0, 0	0.112	5,220	1,460,000	585	2,500	Giles and Schilling, 1972; Singer and others, 2008	Butte
0, 0, **1**	0.023	5,141	103,000	118	871	Giles and Schilling, 1972; Sutulov, 1974; Singer and others, 2008	Cananea
4, 0, 0	0.082	559	140,000	46	3,100	Sinclair and others, 2009	Casino
3, 0, 2	0.160	1,438	79,090	230	344	Giles and Schilling, 1972; Singer and others, 2008	Castle Dome (Pinto Valley)
0, **2**, 0	0.12	2,528	250,000	300	830	Mathur and others, 2001; Singer and others, 2008	Cerro Verde
1, 6, **2**	0.18	21,277	8,500,000	3,800	2,300	Giles and Schilling, 1972; Sutulov, 1974; Nadler, 1997; Singer and others, 2008; Barra and others, 2013	Chuquicamata-Radomiro Tomic
0, **3**, 0	0.26	3,100	1,200,000	820	1,500	Mathur and others, 2001; Masterman and others, 2004; Singer and others, 2008	Collahuasi
0, **3**, 0	0.089	75	3,500	6.7	520	McCandless and Ruiz, 1993; Barra and others, 2005; Singer and others, 2008	Copper Creek
1, 0, **1**	0.207	1,630	348,800	337	1,030	Nadler, 1997; Mathur and others, 2001; Singer and others, 2008	Cuajone

Table P2.   Rhenium data for selected porphyry copper and porphyry molybdenum deposits of the world.—Continued

[The names, locations, and types of most of the deposits are taken from the U.S. Geological Survey Mineral Resources Data System (MRDS) (U.S. Geological Survey, 2014). The minimum and maximum values are concentrations of rhenium in molybdenite separates; the estimated average is based on mill concentrates. Elements and compound: Au, gold; Cu, copper; Mo, molybdenum; MoS_2, molybdenite; Os, osmium; Re, rhenium. Units of measure: g/t, gram per metric ton; Mt, million metric tons; ppm, part per million; t, metric ton; wt. %, weight percent. —, no data; None, no minimum and maximum values are available because only a single analysis was used to calculate the Re grade]

Deposit name	Country	Deposit subtype[1]	Tectonic setting	Grade (wt. % Cu)	Grade (wt. % Mo)	Grade (g/t Au)	Minimum Re in MoS_2 (ppm)	Maximum Re in MoS_2 (ppm)	Estimated average Re in MoS_2 (ppm)
Porphyry copper deposits—Continued									
Cuatro Hermanos	Mexico	Cu	Continental arc	0.431	0.035	—	None	None	469
Cumobabi	Mexico	Cu-Mo	Continental arc	0.266	0.099	—	189	368	279
Dastakert	Armenia	Cu	Continental arc	0.62	0.048	—	130	300	220
Duobaoshan	China	Cu	Island arc	0.46	0.016	0.128	122	885	560
Elatsite (or Elatzite)	Bulgaria	Cu	Continental arc	0.39	0.01	0.26	273	2,740	1,250
El Salvador	Chile	Cu	Continental arc	0.86	0.022	0.1	None	None	585
El Teniente	Chile	Cu-Mo	Continental arc	0.62	0.019	0.005	25	1,154	420
Ely	United States	Cu	Continental arc	0.613	0.01	0.27	1,250	2,840	1,600
Erdenet (Erdene-tuin-Obo)	Mongolia	Cu	Post-collisional	0.62	0.025	—	104	534	199
Gibraltar	Canada	Cu	Island arc	0.29	0.006	0.07	238	750	443
Granisle (or Bell)	Canada	Cu	Continental arc	0.43	0.005	0.13	522	528	526
Highmont West Pit	Canada	Cu-Mo	Island arc	0.15	0.05	0.04	137	176	157
Huckleberry	Canada	Cu	Continental arc	0.49	0.014	0.04	247	258	253
Hushamu	Canada	Cu-Au	Island arc	0.198	0.0092	0.278	None	None	3,140
Ingerbelle (or Similco)	Canada	Cu-Au	Island arc	0.329	0.002	0.17	None	None	1,620
Island Copper	Canada	Cu	Island arc	0.338	0.0088	0.19	1,654	1,863	1,730
Kadjaran (Kadzharan)	Armenia	Cu	Continental arc	0.27	0.055	0.65	33	2,620	280
Kalmakyr (Almalyk)	Uzbekistan	Cu-Au	Continental arc	0.38	0.006	0.6	700	2,000	1,500
Kemess South	Canada	Cu-Au	Island arc	0.22	0.008	0.65	3,106	4,609	3,858
Kounrad	Kazakhstan	Cu	Continental arc	0.589	0.011	0.19	620	4,050	1,540

Table P2.   Rhenium data for selected rhenium porphyry copper and porphyry molybdenum deposits of the world.—Continued

[The names, locations, and types of most of the deposits are taken from the U.S. Geological Survey Mineral Resources Data System (MRDS) (U.S. Geological Survey, 2014). The minimum and maximum values are concentrations of rhenium in molybdenite separates; the estimated average is based on mill concentrates. Elements and compound: Au, gold; Cu, copper; Mo, molybdenum; MoS_2, molybdenite; Os, osmium; Re, rhenium. Units of measure: g/t, gram per metric ton; Mt, million metric tons; ppm, part per million; t, metric ton; wt. %, weight percent. —, no data; None, no minimum and maximum values are available because only a single analysis was used to calculate the Re grade]

Number of Re analyses[2]	Grade[3] (g/t Re)	Deposit tonnage (Mt)	Contained Mo (t)	Contained Re (t)	Mo:Re ratio	Data sources	Deposit name
			Porphyry copper deposits—Continued				
0, **1**, 0	0.274	233	81,600	64	1,300	Barra and others, 2005; Singer and others, 2008	Cuatro Hermanos
0, **2**, 0	0.460	67	66,000	31	2,100	Barra and others, 2005; Singer and others, 2008	Cumobabi
8, 0, 1	0.176	36	17,000	6.2	2,700	Sutulov, 1974; Berzina and others, 2005; Global Metals (ARM) Ltd., 2015	Dastakert
0, **8**, 0	0.149	951	152,000	142	1,070	Zhao and others, 1997; Singer and others, 2008; Deng and others, 2013	Duobaoshan
19, 0, 0	0.21	350	35,000	73	480	Singer and others, 2008; Sinclair and others, 2009	Elatsite (or Elatzite)
1, 0, **2**	0.215	3,836	844,000	825	1,020	Giles and Schilling, 1972; Sutulov, 1974; Nadler, 1997; Singer and others, 2008	El Salvador
1, 14, **2**	0.133	20,731	3,940,000	2,760	1,430	Giles and Schilling, 1972; Sutulov, 1974; Nadler, 1997; Maksaev and others, 2004; Cannell, 2004; Klemm and others, 2007; Singer and others, 2008	El Teniente
4, 0, **1**	0.27	754	75,000	200	380	Giles and Schilling, 1972; Sutulov, 1974; Singer and others, 2008	Ely
2, 1, **1**	0.043	1,780	445,000	77	5,810	Watanabe and Stein, 2000; Berzina and others, 2005; Singer and others, 2008	Erdenet (Erdene-tuin-Obo)
3, 0, 1	0.044	935	56,100	41	1,360	Sinclair and others, 2009; W.D. Sinclair, Ph.D., Geological Survey of Canada, written commun., 2013	Gibraltar
0, 0, **5**	0.044	171	8,560	7.5	1,100	Sinclair and others, 2009; W.D. Sinclair, Ph.D., Geological Survey of Canada, written commun., 2013	Granisle (or Bell)
2, 0, 0	0.13	0.8	400	0.10	3,800	Sinclair and others, 2009	Highmont West Pit
2, 0, 0	0.059	73	10,300	4.3	2,378	Sinclair and others, 2009	Huckleberry
1, 0, 0	0.481	510	46,900	245	191	Giroux and Casselman, 2012	Hushamu
1, 0, 0	0.054	78	1,600	4.2	380	Sinclair and others, 2009	Ingerbelle (or Similco)
0, 0, **11**	0.262	600	52,800	157	336	Sinclair and others, 2009; W.D. Sinclair, Ph.D., Geological Survey of Canada, written commun., 2013	Island Copper
237, 0, 1	0.257	1,700	935,000	437	2,140	Nadler, 1997; Berzina and others, 2005; Singer and others, 2008	Kadjaran (Kadzharan)
20, 0, 1	0.150	2,000	120,000	300	400	Sutulov, 1974; Singer and others, 2008; Pašava and others, 2010	Kalmakyr (Almalyk)
2, 0, 0	0.514	213	17,000	109	155	Sinclair and others, 2009	Kemess South
20, 0, 1	0.282	637	70,100	180	390	Sutulov, 1974; Berzina and others, 2005; Singer and others, 2008	Kounrad

Table P2.   Rhenium data for selected porphyry copper and porphyry molybdenum deposits of the world.—Continued

[The names, locations, and types of most of the deposits are taken from the U.S. Geological Survey Mineral Resources Data System (MRDS) (U.S. Geological Survey, 2014). The minimum and maximum values are concentrations of rhenium in molybdenite separates; the estimated average is based on mill concentrates. Elements and compound: Au, gold; Cu, copper; Mo, molybdenum; MoS_2, molybdenite; Os, osmium; Re, rhenium. Units of measure: g/t, gram per metric ton; Mt, million metric tons; ppm, part per million; t, metric ton; wt. %, weight percent. —, no data; None, no minimum and maximum values are available because only a single analysis was used to calculate the Re grade]

Deposit name	Country	Deposit subtype[1]	Tectonic setting	Grade (wt. % Cu)	Grade (wt. % Mo)	Grade (g/t Au)	Minimum Re in MoS_2 (ppm)	Maximum Re in MoS_2 (ppm)	Estimated average Re in MoS_2 (ppm)
			Porphyry copper deposits—Continued						
La Caridad	Mexico	Cu	Continental arc	0.452	0.0247	—	72	570	570
La Escondida	Chile	Cu-Au	Continental arc	0.769	0.0062	0.25	95	1,805	886
Lomex	Canada	Cu-Mo	Island arc	0.404	0.014	0.006	286	427	351
Los Bronces-Rio Blanco (Andina)	Chile	Cu-Mo	Continental arc	0.601	0.02	—	104	898	265
Los Pelambres	Chile	Cu-Mo	Continental arc	0.617	0.015	0.028	450	820	600
Machangqing	China	Cu-Au	Collision belt(?)	0.64	0.08	0.35	31	125	80
Maggie	Canada	Cu-Mo	Continental arc	0.28	0.029	—	None	None	643
Majdanpek	Serbia	Cu-Au	Continental arc	0.6	0.005	0.35	2,320	3,550	2,770
Medet	Bulgaria	Cu	Continental arc	0.37	0.01	0.1	None	None	905
Miami	United States	Cu-Mo	Continental arc	0.63	0.01	0.009	None	None	600
Mineral Park (Ithaca Peak)	United States	Cu	Continental arc	0.489	0.011	—	250	290	270
Mission-Pima	United States	Cu	Continental arc	0.52	0.015	—	None	None	600
Mitchell (Sulphurets)	Canada	Cu-Au	Island arc	0.18	0.005	0.69	7,012	8,170	7,590
Morenci	United States	Cu-Mo	Continental arc	0.524	0.0095	0.028	270	640	455
Mt. Tolman	United States	Cu-Mo	Continental arc	0.09	0.054	—	None	None	182
OK	Canada	Cu	Continental arc	0.34	0.016	—	None	None	746
Pebble	United States	Cu	Post-collisional	0.592	0.0243	0.342	329	2,070	1,100
Qulong	China	Cu-Mo	Post-collisional	0.52	0.032	—	16	303	125
Ray	United States	Cu	Continental arc	0.68	0.001	—	440	1,500	820
San Manuel-Kalamazoo	United States	Cu-Mo	Continental arc	0.6	0.011	0.017	700	1,200	900
Santa Rita	United States	Cu	Continental arc	0.468	0.008	0.056	700	1,200	800

Table P2.   Rhenium data for selected rhenium porphyry copper and porphyry molybdenum deposits of the world.—Continued

[The names, locations, and types of most of the deposits are taken from the U.S. Geological Survey Mineral Resources Data System (MRDS) (U.S. Geological Survey, 2014). The minimum and maximum values are concentrations of rhenium in molybdenite separates; the estimated average is based on mill concentrates. Elements and compound: Au, gold; Cu, copper; Mo, molybdenum; MoS_2, molybdenite; Os, osmium; Re, rhenium. Units of measure: g/t, gram per metric ton; Mt, million metric tons; ppm, part per million; t, metric ton; wt. %, weight percent. —, no data; None, no minimum and maximum values are available because only a single analysis was used to calculate the Re grade]

Number of Re analyses[2]	Grade[3] (g/t Re)	Deposit tonnage (Mt)	Contained Mo (t)	Contained Re (t)	Mo:Re ratio	Data sources	Deposit name
Porphyry copper deposits—Continued							
0, 2, **1**	0.235	1,800	444,600	423	1,050	Nadler, 1997; Valencia and others, 2005; Singer and others, 2008	La Caridad
0, 7, 0	0.092	11,158	691,800	1,030	672	Mathur and others, 2001; Singer and others, 2008; Romero and others, 2010	La Escondida
2, 0, **20**	0.081	460	64,400	37	1,728	Sinclair and others, 2009; W.D. Sinclair, Ph.D., Geological Survey of Canada, written commun., 2013	Lomex
0, **13**, 2	0.09	16,816	3,400,000	1,500	2,300	Mathur and others, 2001; Singer and others, 2008; Deckart and others, 2013	Los Bronces-Rio Blanco (Andina)
0, **3**, 0	0.150	7,458	1,120,000	1,120	1,000	Mathur and others, 2001; Singer and others, 2008	Los Pelambres
0, 0, **5**	0.11	39	31,000	4	7,429	Hou and others, 2006	Machangqing
1, 0, 0	0.311	181	52,600	56	932	Sinclair and others, 2009	Maggie
3, 0, 0	0.231	1,000	50,000	231	216	Todorov and Staikov, 1985; Singer and others, 2008	Majdanpek
22, 0, 1	0.15	244	24,000	37	651	Sutulov, 1974; Berzina and others, 2005; Singer and others, 2008	Medet
1, 0, 0	0.10	1,591	160,000	160	1,000	Berzina and others, 2005; Singer and others, 2008	Miami
2, 0, 1	0.050	876	96,400	44	2,200	Giles and Schilling, 1972; Sutulov, 1974; Singer and others, 2008	Mineral Park (Ithaca Peak)
0, 1, 1	0.150	900	135,000	135	1,000	Sutulov, 1974; McCandless and Ruiz, 1993; Singer and others, 2008	Mission-Pima
2, 0, 0	0.633	734	36,700	465	79	Sinclair and others, 2009	Mitchell (Sulphurets)
3, 1, 0	0.072	6,470	614,700	466	1,320	Giles and Schilling, 1972; McCandless and Ruiz, 1993; Singer and others, 2008	Morenci
0, 0, **1**	0.163	2,177	1,180,000	355	3,330	Carten and others, 1993; W.D. Sinclair, Ph.D., Geological Survey of Canada, written commun., 2013	Mt. Tolman
1, 0, 0	0.199	64	10,000	13	790	Sinclair and others, 2009	OK
0, 6, **2**	0.446	5,940	1,443,000	2,650	545	Ghaffari and others, 2011; Lang and others, 2013	Pebble
0, **4**, 0	0.067	1,517	485,000	102	4,770	Singer and others, 2008; Hou and others, 2009	Qulong
9, 0, 0	0.014	1,583	15,800	22	710	Giles and Schilling, 1972; Singer and others, 2008	Ray
2, 0, **2**	0.165	1,390	153,000	229	667	Giles and Schilling, 1972; Sutulov, 1974; Nadler, 1997; Singer and others, 2008.	San Manuel-Kalamazoo
8, 0, 1	0.107	3,030	242,000	324	746	Giles and Schilling, 1972; Sutulov, 1974; Singer and others, 2008	Santa Rita

Table P2.   Rhenium data for selected porphyry copper and porphyry molybdenum deposits of the world.—Continued

[The names, locations, and types of most of the deposits are taken from the U.S. Geological Survey Mineral Resources Data System (MRDS) (U.S. Geological Survey, 2014). The minimum and maximum values are concentrations of rhenium in molybdenite separates; the estimated average is based on mill concentrates. Elements and compound: Au, gold; Cu, copper; Mo, molybdenum; MoS_2, molybdenite; Os, osmium; Re, rhenium. Units of measure: g/t, gram per metric ton; Mt, million metric tons; ppm, part per million; t, metric ton; wt. %, weight percent. —, no data; None, no minimum and maximum values are available because only a single analysis was used to calculate the Re grade]

Deposit name	Country	Deposit subtype[1]	Tectonic setting	Grade (wt. % Cu)	Grade (wt. % Mo)	Grade (g/t Au)	Minimum Re in MoS_2 (ppm)	Maximum Re in MoS_2 (ppm)	Estimated average Re in MoS_2 (ppm)
Porphyry copper deposits—Continued										
Sar Cheshmeh	Iran	Cu	Continental arc	1.2	0.03	0.27	11	517	597
Schaft Creek	Canada	Cu	Island arc	0.25	0.019	0.18	None	None	590
Sierrita-Esperanza	United States	Cu-Mo	Continental arc	0.294	0.0292	0.003	90	1,800	238
Silver Bell	United States	Cu-Mo	Continental arc	0.66	0.013	0.026	340	620	531
Skouriés	Greece	Cu-Au	Post-collisional	0.35	0.002	0.47	800	1,000	900
Snowfields	Canada	Cu-Au	Island arc	0.08	0.008	0.50	None	None	3,600
Sora (Sorsk)	Russia	Cu	Post-collisional?	0.17	0.058	—	6	18	14
Tominskoe	Russia	Cu	Island arc	0.58	0.004	0.12	None	None	1,080
Tongchankou	China	Cu	uncertain	0.94	0.04	—	176	235	208
Toquepala	Peru	Cu-Mo	Continental arc	0.55	0.04	—	387	1,496	600
Tsagaan-Suvarga	Mongolia	Cu	Continental arc	0.53	0.018	0.084	80	156	118
Twin Buttes	United States	Cu-Mo	Continental arc	0.502	0.023	0.019	None	None	600
Valley Copper	Canada	Cu-Au	Island arc	0.44	0.0067	0.006	None	None	294
Veliki Krivelj	Serbia	Cu	Continental arc	0.44	0.004	0.068	None	None	302
Wunugetushan	China	Cu-Mo	Post-collisional?	0.46	0.053	—	142	369	199
Yulong	China	Cu-Au	Post-collisional?	0.99	0.028	0.35	291	665	444
Zuun Mod Molybdenum	Mongolia	Cu-Mo	Continental arc?	0.069	0.059	—	250	300	275
Porphyry molybdenum deposits										
Boss Mountain	Canada	Arc-related	Continental arc	—	0.074	—	49	157	80
Carmi	Canada	Arc-related	Continental arc	—	0.064	—	10	139	58
Endako	Canada	Arc-related	Continental arc	0.002	0.07	—	15	67	35
Glacier Gulch (Davidson)	Canada	Arc-related	Continental arc	0.04	0.177	—	34	41	38

Table P2. Rhenium data for selected rhenium porphyry copper and porphyry molybdenum deposits of the world.—Continued

[The names, locations, and types of most of the deposits are taken from the U.S. Geological Survey Mineral Resources Data System (MRDS) (U.S. Geological Survey, 2014). The minimum and maximum values are concentrations of rhenium in molybdenite separates; the estimated average is based on mill concentrates. Elements and compound: Au, gold; Cu, copper; Mo, molybdenum; MoS_2, molybdenite; Os, osmium; Re, rhenium. Units of measure: g/t, gram per metric ton; Mt, million metric tons; ppm, part per million; t, metric ton; wt. %, weight percent. —, no data; None, no minimum and maximum values are available because only a single analysis was used to calculate the Re grade]

Number of Re analyses[2]	Grade[3] (g/t Re)	Deposit tonnage (Mt)	Contained Mo (t)	Contained Re (t)	Mo:Re ratio	Data sources	Deposit name
						Porphyry copper deposits—Continued	
15, 0, **5**	0.30	1,200	360,000	360	1,000	Singer and others, 2008; Aminzadeh and others, 2011	Sar Cheshmeh
1, 0, 0	0.187	1,393	265,000	260	1,020	Sinclair and others, 2009	Schaft Creek
6, **1**, 2	0.116	2,262	660,500	262	2,520	Giles and Schilling, 1972; Sutulov, 1974; McCandless and Ruiz, 1993; Nadler, 1997; Singer and others, 2008	Sierrita-Esperanza
18, **1**, 0	0.115	268	34,900	31	1,130	Giles and Schilling, 1972; Barra and others, 2005; Singer and others, 2008	Silver Bell
4, 0, 0	0.030	568	11,400	17	670	Singer and others, 2008; Sinclair and others, 2009	Skouriés
1, 0, 0	0.480	2,203	17,600	1,060	17	Armstrong and others, 2011	Snowfields
9, 0, 0	0.014	300	174,000	4.2	41,000	Sotnikov and others, 2001; Berzina and others, 2005; Berzina and Korobeinikov, 2007	Sora (Sorsk)
1, 0, 0	0.072	241	9,640	17	560	Singer and others, 2008; Sinclair and others, 2009	Tominskoe
0, **6**, 0	0.14	45	18,000	6.2	2,900	Xie and others, 2007; Singer and others, 2008	Tongchankou
1, 2, **2**	0.40	2,320	930,000	930	1,000	Giles and Schilling, 1972; Sutulov, 1974; Nadler, 1997; Mathur and others, 2001; Singer and others, 2008	Toquepala
0, **2**, 0	0.035	240	43,200	8.4	5,100	Watanabe and Stein, 2000; Singer and others, 2008	Tsagaan-Suvarga
0, 0, **1**	0.230	940	216,000	216	1,000	Sutulov, 1974; Singer and others, 2008	Twin Buttes
0, 0, **1**	0.033	791	53,000	26	2,030	Sinclair and others, 2009; W.D. Sinclair, Ph.D., Geological Survey of Canada, written commun., 2013	Valley Copper
1, 0, 0	0.020	750	30,000	15	2,000	Singer and others, 2008; Sinclair and others, 2009	Veliki Krivelj
0, **7**, 0	0.176	850	450,000	150	3,000	Chen and others, 2011	Wunugetushan
0, 0, **2**	0.207	628	176,000	130	1,350	Hou and others, 2006	Yulong
2, 0, 0	0.270	218	129,000	59	2,190	Clark and Baudry, 2011	Zuun Mod Molybdenum
						Porphyry molybdenum deposits	
7, 0, 0	0.099	63	46,600	6.2	7,500	Sinclair and others, 2009	Boss Mountain
3, 0, 0	0.062	21	13,300	1.3	10,000	Sinclair and others, 2009	Carmi
14, 12, 1	0.04	600	420,000	25	17,000	Giles and Schilling, 1972; Selby and Creaser, 2001; Sinclair and others, 2009; W.D. Sinclair, Ph.D., Geological Survey of Canada, written commun., 2013	Endako
2, 0, 0	0.112	75	134,000	8.4	16,000	Sinclair and others, 2009	Glacier Gulch (Davidson)

Table P2.   Rhenium data for selected porphyry copper and porphyry molybdenum deposits of the world.—Continued

[The names, locations, and types of most of the deposits are taken from the U.S. Geological Survey Mineral Resources Data System (MRDS) (U.S. Geological Survey, 2014). The minimum and maximum values are concentrations of rhenium in molybdenite separates; the estimated average is based on mill concentrates. Elements and compound: Au, gold; Cu, copper; Mo, molybdenum; MoS_2, molybdenite; Os, osmium; Re, rhenium. Units of measure: g/t, gram per metric ton; Mt, million metric tons; ppm, part per million; t, metric ton; wt. %, weight percent. —, no data; None, no minimum and maximum values are available because only a single analysis was used to calculate the Re grade]

Deposit name	Country	Deposit subtype[1]	Tectonic setting	Grade (wt. % Cu)	Grade (wt. % Mo)	Grade (g/t Au)	Minimum Re in MoS_2 (ppm)	Maximum Re in MoS_2 (ppm)	Estimated average Re in MoS_2 (ppm)
Porphyry molybdenum deposits—Continued									
Kitsault (Lime Creek)	Canada	Arc-related	Continental arc	0.004	0.115	—	36	129	71
Lucky Ship	Canada	Arc-related	Continental arc	—	0.067	—	None	None	41
Mount Haskin	Canada	Arc-related	Continental arc	—	0.09	—	None	None	108
Nithi Mountain	Canada	Arc-related	Continental arc	—	0.02	—	None	None	76.9
Quartz Hill	United States	Arc-related	Continental arc	0.003	0.0762	—	None	None	149
Red Bird	Canada	Arc-related	Continental arc	0.07	0.065	—	6	43	25
Red Mountain	Canada	Arc-related	Continental arc	—	0.10	—	None	None	32
Storie Moly	Canada	Arc-related	Continental arc	—	0.078	—	15	22	20
Thompson Creek	United States	Arc-related	Continental arc	—	0.071	—	None	None	120
Trout Lake (Max)	Canada	Arc-related	Continental arc	—	0.12	—	56	73	56
Adanac (Ruby Creek)	Canada	Alk-granite/ hybrid?	Extensional continental arc	0.001	0.059	—	8	22	12
Climax	United States	Alk-granite	Continental rift	—	0.20	—	10	80	13
Donggou	China	Alk-granite	Collision belt	—	0.116	—	4.1	4.3	4.2
Jinduicheng	China	Alk-granite	Collision belt	—	0.099	—	15.5	16.2	15.9
Questa	United States	Alk-granite	Continental rift	—	0.15	—	6	145	36
Shapinggou	China	Alk-granite	Collision belt	—	0.126	—	0.4	14.7	4.7
Urad-Henderson	United States	Alk-granite	Continental rift	—	0.228	—	7	20	20
Xiaodonggou	China	Alk-granite	Collision belt(?)	—	0.109	—	4.5	8.4	7.1

[1]Cox and Singer (1992) porphyry Cu models; Taylor and others (2012) and Ludington and Plumlee (2009) porphyry Mo models.

[2]Number of analyses of MoS_2 separates, MoS_2 analyzed for Re-Os dating, MoS_2 mill concentrates. Number in bold indicates samples used to calculate Re grade. In cases where no number is bold, average grade of total resources calculated from drilling was used as Re grade.

[3]Re grade calculated from mean Re content of MoS_2 and Mo grade of deposit.

Table P2. Rhenium data for selected rhenium porphyry copper and porphyry molybdenum deposits of the world.—Continued

[The names, locations, and types of most of the deposits are taken from the U.S. Geological Survey Mineral Resources Data System (MRDS) (U.S. Geological Survey, 2014). The minimum and maximum values are concentrations of rhenium in molybdenite separates; the estimated average is based on mill concentrates. Elements and compound: Au, gold; Cu, copper; Mo, molybdenum; MoS_2, molybdenite; Os, osmium; Re, rhenium. Units of measure: g/t, gram per metric ton; Mt, million metric tons; ppm, part per million; t, metric ton; wt. %, weight percent. —, no data; None, no minimum and maximum values are available because only a single analysis was used to calculate the Re grade]

Number of Re analyses[2]	Grade[3] (g/t Re)	Deposit tonnage (Mt)	Contained Mo (t)	Contained Re (t)	Mo:Re ratio	Data sources	Deposit name
Porphyry molybdenum deposits—Continued							
9, 0, 0	0.136	104	120,000	14	8,500	Sinclair and others, 2009	Kitsault (Lime Creek)
1, 0, 0	0.046	62	41,000	2.8	15,000	Sinclair and others, 2009	Lucky Ship
1, 0, 0	0.16	12	11,000	2.0	5,600	Sinclair and others, 2009	Mount Haskin
0, **1**, 0	0.03	240	47,900	6.2	7,700	Selby and Creaser, 2001; Mosher, 2001	Nithi Mountain
0, 0, **1**	0.189	1,600	1,220,000	302	4,030	Hudson and others, 1979; Wolfe, 1995; W.D. Sinclair, Ph.D., Geological Survey of Canada, written commun., 2013	Quartz Hill
2, 0, 0	0.027	75	49,000	2.0	24,000	Sinclair and others, 2009	Red Bird
1, 0, 0	0.05	187	190,000	10	19,000	Sinclair and others, 2009	Red Mountain
3, 0, 0	0.026	101	78,400	2.6	30,000	Sinclair and others, 2009	Storie Moly
0, 0, **1**	0.142	212	151,000	30	5,000	Carten and others, 1993; W.D. Sinclair, Ph.D., Geological Survey of Canada, written commun., 2013	Thompson Creek
1, 0, **1**	0.11	43	51,000	4.8	11,000	Sinclair and others, 2009	Trout Lake (Max)
4, 0, 0	0.012	144	84,800	1.7	50,000	Sinclair and others, 2009	Adanac (Ruby Creek)
13, 0, **4**	0.04	800	1,600,000	35	45,000	Giles and Schilling, 1972; Nadler, 1997; Singer and others, 1993; Sinclair and others, 2009; W.D. Sinclair, Ph.D., Geological Survey of Canada, written commun., 2013	Climax
0, **2**, 0	0.008	594	689,000	4.8	145,000	Mao and others, 2011; Deng and others, 2013	Donggou
0, **7**, 0	0.026	1,089	1,080,000	28	38,000	Mao and others, 2011; Deng and others, 2013	Jinduicheng
14, **8**, 1	0.090	424	640,000	38	17,000	Giles and Schilling, 1972; Singer and others, 1993; Rosera and others, 2013; W.D. Sinclair, Ph.D., Geological Survey of Canada, written commun., 2013	Questa
0, **9**, 0	0.010	1,270	1,600,000	13	126,000	Mao and others, 2011; Deng and others, 2013	Shapinggou
2, 0, **2**	0.076	437	996,000	33	30,000	Giles and Schilling, 1972; Nadler, 1997; Seedorff and Einaudi, 2004; Markey and others, 2007; W.D. Sinclair, Ph.D., Geological Survey of Canada, written commun., 2013	Urad-Henderson
0, **6**, 0	0.013	42	45,000	0.5	83,000	Zheng and others, 2010	Xiaodonggou

Appendix P1. Rhenium Data Sources and Limitations of Data Used in Rhenium Resource Estimates

Publicly available data for rhenium resources are limited. Of more than 225 porphyry copper deposits with published molybdenum grades and tonnages (Singer and others, 2008), rhenium concentrations are available for only about 80 deposits, several of which are represented by a single rhenium analysis (table P1; John and Taylor, 2016). There are similarly few rhenium data available for porphyry molybdenum deposits. The available rhenium analytical data are a mixture of analyses of (a) small molybdenite separates (for example, Giles and Schilling, 1972; Sinclair and others, 2009), (b) small molybdenite separates used in rhenium-osmium dating studies (for example, McCandless and Ruiz, 1993; Barra and others, 2013), and less commonly, (c) bulk molybdenite mill concentrates (mostly from Sutulov, 1974, and Nadler, 1997). The molybdenite separates and mill concentrates are subject to impurities, and some of the variation in rhenium content within deposits may be the result of variable purity of these molybdenite separates. Electron microprobe analyses of rhenium contents of molybdenites are available for some deposits (Newberry, 1979; McCandless and others, 1993), but these analyses have relatively high detection limits and low precision and were not included in the data compilation.

Calculated rhenium resources in porphyry copper and porphyry molybdenum deposits are based on the average concentration of rhenium in molybdenite, the average molybdenum grade for the entire deposit, and the total tonnage of the deposit. The type of analysis used to determine rhenium concentrations in molybdenite is indicated in table P1.

Molybdenum grades and tonnages for porphyry copper deposits are mostly from Singer and others (2008) and are subject to the rules specified in their data compilation. For example, average molybdenum grades and the associated tonnages are based on the total production, reserves, and resources at the lowest possible cutoff grade, and all mineralized and altered rock within 2 km are combined into one deposit. Tonnages, therefore, are pre-mining resources. Because many porphyry copper deposits have been mined for decades or longer (for example, the Bingham Canyon deposit has been mined since 1906), remaining tonnages and rhenium resources for these deposits are smaller than indicated in table P1.

Rhenium data for strata-bound copper deposits are limited to a few deposits in the Kupferschiefer in Poland and Germany and two deposits in Kazakhstan.

Kupferschiefer resources in Poland.— Ore reserves in deposits in the Legnica- Glogów copper belt, Poland, which includes the Lubin-Sieroszowice orebody, are estimated to be 1,180 million metric tons (Bartlett and others, 2013) that averages 0.6 ppm rhenium (Smakowski and others, 2010). These tonnage and grade data suggest a rhenium resource of 709 metric tons.

Kupferschiefer resources in the Mansfeld-Sangerhausen area, Germany.—Jankowski (1995) reported production of 120 million metric tons of ore from 1200 to 1990 that had an estimated average rhenium grade of 21 grams per metric ton (g/t). This suggests that more than 2,500 metric tons of rhenium was mined (but not recovered). Jankowski (1995) lists a pre-mining resource of 155 million metric tons with an average grade of 21 g/t, which suggests a total pre-mining resource of about 3,300 metric tons of rhenium and that about 800 metric tons of rhenium remains. Jankowski (1995) also reports remaining resources of 35.4 million metric tons of ore with an average rhenium grade of 21 g/t, which suggests that about 740 metric tons of rhenium remains in these deposits.

Average rhenium grades and deposit tonnages for the Dzhezhazgan and the Zhaman-Aybat sandstone-type strata-bound copper deposits in Kazakhstan are available from Box and others (2013). Rhenium grades for other similar deposits in Kazakhstan are not available.

Rhenium contents of some roll-front-type sandstone uranium deposits in Kazakhstan and Uzbekistan are reported by Dahlkamp (2009a, b). For most deposits, however, total contained uranium or total uranium production and ranges of uranium and (or) rhenium concentration data are reported, which precludes calculation of rhenium grades, tonnages, and resources.

The estimated tonnage and rhenium grade for the Merlin deposit in Australia is a Canada National Instrument 43–101-compliant estimate of indicated and inferred mineral resources made in April 2012 (Lycopodium Minerals QLD Pty Ltd., 2012).

Because of these limitations in the data for known deposits, estimated rhenium resources in table P1 and shown in figure P4 are likely imprecise, but are accurate enough to allow discussion of some aspects of U.S. and global rhenium resources.

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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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