

# Tellurium

Chapter R of

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



Professional Paper 1802–R

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

# Periodic Table of Elements

1A 1 <b>H</b> hydrogen 1.008																	2 <b>He</b> helium 4.003
3 <b>Li</b> lithium 6.94	2A 4 <b>Be</b> beryllium 9.012											3A 5 <b>B</b> boron 10.81	4A 6 <b>C</b> carbon 12.01	5A 7 <b>N</b> nitrogen 14.01	6A 8 <b>O</b> oxygen 16.00	7A 9 <b>F</b> fluorine 19.00	10 <b>Ne</b> neon 20.18
11 <b>Na</b> sodium 22.99	12 <b>Mg</b> magnesium 24.31	3B	4B	5B	6B	7B	8B			11B	12B	13 <b>Al</b> aluminum 26.98	14 <b>Si</b> silicon 28.09	15 <b>P</b> phosphorus 30.97	16 <b>S</b> sulfur 32.06	17 <b>Cl</b> chlorine 35.45	18 <b>Ar</b> argon 39.95
19 <b>K</b> potassium 39.10	20 <b>Ca</b> calcium 40.08	21 <b>Sc</b> scandium 44.96	22 <b>Ti</b> titanium 47.88	23 <b>V</b> vanadium 50.94	24 <b>Cr</b> chromium 52.00	25 <b>Mn</b> manganese 54.94	26 <b>Fe</b> iron 55.85	27 <b>Co</b> cobalt 58.93	28 <b>Ni</b> nickel 58.69	29 <b>Cu</b> copper 63.55	30 <b>Zn</b> zinc 65.39	31 <b>Ga</b> gallium 69.72	32 <b>Ge</b> germanium 72.64	33 <b>As</b> arsenic 74.92	34 <b>Se</b> selenium 78.96	35 <b>Br</b> bromine 79.90	36 <b>Kr</b> krypton 83.79
37 <b>Rb</b> rubidium 85.47	38 <b>Sr</b> strontium 87.62	39 <b>Y</b> yttrium 88.91	40 <b>Zr</b> zirconium 91.22	41 <b>Nb</b> niobium 92.91	42 <b>Mo</b> molybdenum 95.96	43 <b>Tc</b> technetium (98)	44 <b>Ru</b> ruthenium 101.1	45 <b>Rh</b> rhodium 102.9	46 <b>Pd</b> palladium 106.4	47 <b>Ag</b> silver 107.9	48 <b>Cd</b> cadmium 112.4	49 <b>In</b> indium 114.8	50 <b>Sn</b> tin 118.7	51 <b>Sb</b> antimony 121.8	52 <b>Te</b> tellurium 127.6	53 <b>I</b> iodine 126.9	54 <b>Xe</b> xenon 131.3
55 <b>Cs</b> cesium 132.9	56 <b>Ba</b> barium 137.3	*	72 <b>Hf</b> hafnium 178.5	73 <b>Ta</b> tantalum 180.9	74 <b>W</b> tungsten 183.9	75 <b>Re</b> rhenium 186.2	76 <b>Os</b> osmium 190.2	77 <b>Ir</b> iridium 192.2	78 <b>Pt</b> platinum 195.1	79 <b>Au</b> gold 197.0	80 <b>Hg</b> mercury 200.5	81 <b>Tl</b> thallium 204.4	82 <b>Pb</b> lead 207.2	83 <b>Bi</b> bismuth 209.0	84 <b>Po</b> polonium (209)	85 <b>At</b> astatine (210)	86 <b>Rn</b> radon (222)
87 <b>Fr</b> francium (223)	88 <b>Ra</b> radium (226)	**	104 <b>Rf</b> rutherfordium (261)	105 <b>Db</b> dubnium (268)	106 <b>Sg</b> seaborgium (271)	107 <b>Bh</b> bohrium (270)	108 <b>Hs</b> hassium (277)	109 <b>Mt</b> meitnerium (276)	110 <b>Ds</b> darmstadtium (281)	111 <b>Rg</b> roentgenium (280)	112 <b>Cn</b> copernicium (285)	113 <b>Uut</b> (284)	114 <b>Fl</b> flerovium (289)	115 <b>Uup</b> (288)	116 <b>Lv</b> livermorium (293)	117 <b>Uus</b> (294)	118 <b>Uuo</b> (294)
Lanthanide Series*		57 <b>La</b> lanthanum 138.9	58 <b>Ce</b> cerium 140.1	59 <b>Pr</b> praseodymium 140.9	60 <b>Nd</b> neodymium 144.2	61 <b>Pm</b> promethium (145)	62 <b>Sm</b> samarium 150.4	63 <b>Eu</b> europium 152.0	64 <b>Gd</b> gadolinium 157.2	65 <b>Tb</b> terbium 158.9	66 <b>Dy</b> dysprosium 162.5	67 <b>Ho</b> holmium 164.9	68 <b>Er</b> erbium 167.3	69 <b>Tm</b> thulium 168.9	70 <b>Yb</b> ytterbium 173.0	71 <b>Lu</b> lutetium 175.0	
Actinide Series**		89 <b>Ac</b> actinium (227)	90 <b>Th</b> thorium 232	91 <b>Pa</b> protactinium 231	92 <b>U</b> uranium 238	93 <b>Np</b> neptunium (237)	94 <b>Pu</b> plutonium (244)	95 <b>Am</b> americium (243)	96 <b>Cm</b> curium (247)	97 <b>Bk</b> berkelium (247)	98 <b>Cf</b> californium (251)	99 <b>Es</b> einsteinium (252)	100 <b>Fm</b> fermium (257)	101 <b>Md</b> mendelevium (288)	102 <b>No</b> nobelium (259)	103 <b>Lr</b> lawrencium (262)	




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

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

**Cover.** Tellurium is a critical component for the development of efficient thin-film photovoltaic cells that are needed for the production of electricity from sunlight. A 2-megawatt, ground-mounted solar photovoltaic array occupies the site of a former landfill at Fort Carson, Colo. Photograph from the U.S. Department of Energy Western Area Power Administration.

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By Richard J. Goldfarb, Byron R. Berger, Micheal W. George, and Robert R. Seal II

Chapter R of

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

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

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

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

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

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# Conversion Factors

International System of Units to Inch/Pound

Multiply	By	To obtain
<b>Length</b>		
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)
<b>Area</b>		
hectare (ha)	2.471	acre
square kilometer (km <sup>2</sup> )	247.1	acre
square meter (m <sup>2</sup> )	10.76	square foot (ft <sup>2</sup> )
square centimeter (cm <sup>2</sup> )	0.1550	square inch (in <sup>2</sup> )
square kilometer (km <sup>2</sup> )	0.3861	square mile (mi <sup>2</sup> )
<b>Volume</b>		
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 <sup>3</sup> )	264.2	gallon (gal)
cubic centimeter (cm <sup>3</sup> )	0.06102	cubic inch (in <sup>3</sup> )
cubic meter (m <sup>3</sup> )	1.308	cubic yard (yd <sup>3</sup> )
cubic kilometer (km <sup>3</sup> )	0.2399	cubic mile (mi <sup>3</sup> )
<b>Mass</b>		
microgram (µg)	0.0000003527	ounce, avoirdupois (oz)
milligram (mg)	0.00003527	ounce, avoirdupois (oz)
gram (g)	0.03527	ounce, avoirdupois (oz)
gram (g)	0.03215075	ounce, troy
kilogram (kg)	32.15075	ounce, troy
kilogram (kg)	2.205	pound avoirdupois (lb)
ton, metric (t)	1.102	ton, short [2,000 lb]
ton, metric (t)	0.9842	ton, long [2,240 lb]
<b>Deposit grade</b>		
gram per metric ton (g/t)	0.0291667	ounce per short ton (2,000 lb) (oz/T)
<b>Pressure</b>		
megapascal (MPa)	10	bar
gigapascal (GPa)	10,000	bar
<b>Density</b>		
gram per cubic centimeter (g/cm <sup>3</sup> )	62.4220	pound per cubic foot (lb/ft <sup>3</sup> )
milligram per cubic meter (mg/m <sup>3</sup> )	0.0000006243	pound per cubic foot (lb/ft <sup>3</sup> )
<b>Energy</b>		
joule (J)	0.0000002	kilowatthour (kWh)
joule (J)	$6.241 \times 10^{18}$	electronvolt (eV)
joule (J)	0.2388	calorie (cal)
kilojoule (kJ)	0.0002388	kilocalorie (kcal)

## International System of Units to Inch/Pound—Continued

<b>Multiply</b>	<b>By</b>	<b>To obtain</b>
<b>Radioactivity</b>		
becquerel (Bq)	0.00002703	microcurie ( $\mu\text{Ci}$ )
kilobecquerel (kBq)	0.02703	microcurie ( $\mu\text{Ci}$ )
<b>Electrical resistivity</b>		
ohm meter ( $\Omega\text{-m}$ )	39.37	ohm inch ( $\Omega\text{-in.}$ )
ohm-centimeter ( $\Omega\text{-cm}$ )	0.3937	ohm inch ( $\Omega\text{-in.}$ )
<b>Thermal conductivity</b>		
watt per centimeter per degree Celsius ( $\text{watt/cm } ^\circ\text{C}$ )	693.1798	International British thermal unit inch per hour per square foot per degree Fahrenheit ( $\text{Btu in/h ft}^2 \text{ } ^\circ\text{F}$ )
watt per meter kelvin ( $\text{W/m-K}$ )	6.9318	International British thermal unit inch per hour per square foot per degree Fahrenheit ( $\text{Btu in/h ft}^2 \text{ } ^\circ\text{F}$ )

## Inch/Pound to International System of Units

<b>Length</b>		
mil	25.4	micrometer ( $\mu\text{m}$ ) [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)
<b>Volume</b>		
ounce, fluid (fl. oz)	29.57	milliliter (mL)
ounce, fluid (fl. oz)	0.02957	liter (L)
<b>Mass</b>		
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)
<b>Deposit grade</b>		
ounce per short ton (2,000 lb) (oz/T)	34.285714	gram per metric ton (g/t)
<b>Energy</b>		
kilowatthour (kWh)	3,600,000	joule (J)
electronvolt (eV)	$1.602 \times 10^{-19}$	joule (J)
<b>Radioactivity</b>		
microcurie ( $\mu\text{Ci}$ )	37,000	becquerel (Bq)
microcurie ( $\mu\text{Ci}$ )	37	kilobecquerel (kBq)

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

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

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

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

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

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

## Datum

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

## Supplemental Information

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius ( $\mu\text{S}/\text{cm}$  at 25 °C).

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

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L), micrograms per liter ( $\mu\text{g}/\text{L}$ ), nanograms per liter (ng/L), nanomoles per kilogram (nmol/kg), parts per million (ppm), parts per billion (ppb), or parts per trillion (ppt).

Concentrations of suspended particulates in water are given in micrograms per gram ( $\mu\text{g}/\text{g}$ ), milligrams per kilogram (mg/kg), or femtograms per gram (fg/g).

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

Activities for radioactive constituents in air are given in microcuries per milliliter ( $\mu\text{Ci}/\text{mL}$ ).

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

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

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

Concentration unit	Equals
milligram per kilogram (mg/kg)	part per million
microgram per gram ( $\mu\text{g}/\text{g}$ )	part per million
microgram per kilogram ( $\mu\text{g}/\text{kg}$ )	part per billion ( $10^9$ )

### Equivalencies

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

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

part per trillion (ppt): 0.000001 ppm = 0.001 ppb = 1 ppt = 0.000000001 percent

### Metric system prefixes

tera- (T-)	$10^{12}$	1 trillion
giga- (G-)	$10^9$	1 billion
mega- (M-)	$10^6$	1 million
kilo- (k-)	$10^3$	1 thousand
hecto- (h-)	$10^2$	1 hundred
deka- (da-)	10	1 ten
deci- (d-)	$10^{-1}$	1 tenth
centi- (c-)	$10^{-2}$	1 hundredth
milli- (m-)	$10^{-3}$	1 thousandth
micro- ( $\mu$ -)	$10^{-6}$	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
$\log fO_2$	log of oxygen fugacity
g/L	gram per liter
g/t	gram per metric ton
IOCG	iron oxide-copper-gold
kg	kilogram
kg CaCO <sub>3</sub> /t	kilogram of calcium carbonate per metric ton
m	meter
Ma	mega-annum
NI	National Instrument
PGM	platinum-group metal
ppb	part per billion
ppm	part per million
ppt	part per trillion
Te(II)	telluride
Te(IV)	tellurite
Te(VI)	tellurate
USGS	U.S. Geological Survey
VMS	volcanogenic massive sulfide

# Tellurium

By Richard J. Goldfarb, Byron R. Berger,<sup>1</sup> Micheal W. George, and Robert R. Seal II

## Abstract

Tellurium (Te) is a very rare element that averages only 3 parts per billion in Earth's upper crust. It shows a close association with gold and may be present in orebodies of most gold deposit types at levels of tens to hundreds of parts per million. In large-tonnage mineral deposits, such as porphyry copper and sea-floor volcanogenic massive sulfide deposits, sulfide minerals may contain hundreds of parts per million tellurium, although the orebodies likely have overall concentrations of 0.1 to 1.0 parts per million tellurium. Tellurium is presently recovered as a primary ore from only two districts in the world; these are the gold-tellurium epithermal vein deposits located adjacent to one another at Dashuigou and Majiagou (Sichuan Province) in southwestern China, and the epithermal-like mineralization at the Kankberg deposit in the Skellefteå VMS district of Västerbotten County, Sweden. Combined, these two groups of deposits account for about 15 percent (about 70 metric tons) of the annual global production of 450 to 470 metric tons of tellurium. Most of the world's tellurium, however, is produced as a byproduct of the mining of porphyry copper deposits. These deposits typically yield concentrations of 1 to 4 percent tellurium in the anode slimes recovered during copper refining. Present production of tellurium from the United States is solely from the anode slimes at ASARCO LLC's copper refinery in Amarillo, Texas, and may total about 50 metric tons per year. The main uses of tellurium are in photovoltaic solar cells and as an additive to copper, lead, and steel alloys in various types of machinery. The environmental data available regarding the mining of tellurium are limited; most concerns to date have focused on the more-abundant metals present in the large-tonnage deposits from which tellurium is recovered as a byproduct. Global reserves of tellurium are estimated to be 24,000 metric tons, based on the amount of tellurium likely contained in global copper reserves and on a 50 percent recovery rate from refinery anode slimes during the commonly used electrolytic process, also known as solvent extraction-electrolytic refining. If the more economical solvent-leach process—a process that does not recover tellurium—is increasingly used in the future to recover lower grades of copper from porphyry and other

large-tonnage deposits, then additional high-grade tellurium-rich gold deposits may become new primary sources for tellurium, particularly epithermal vein deposits associated with alkaline magmatism.

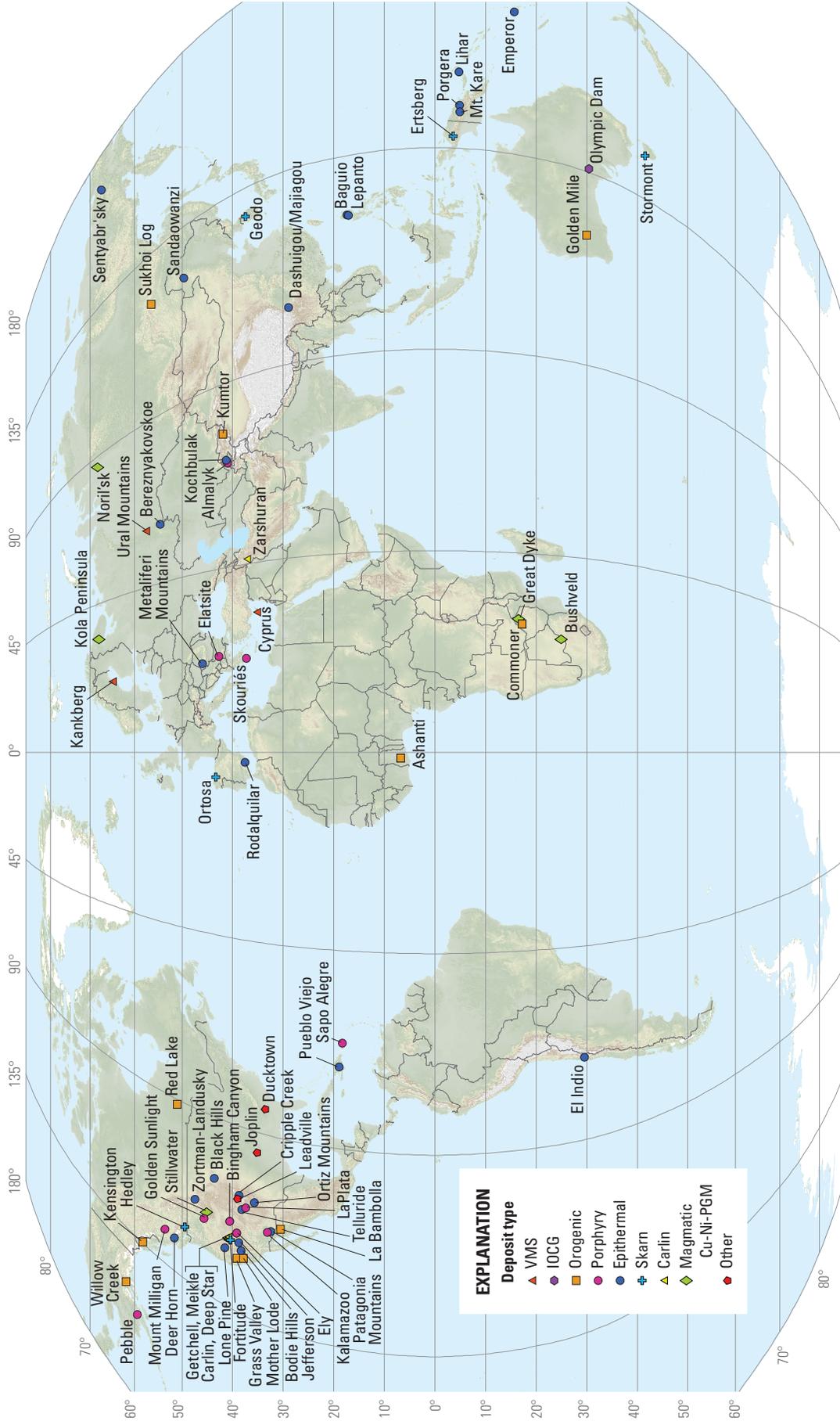
## Introduction

Tellurium (Te) is an element for which there is little reliable information about specific deposits and (or) primary production sources. Two vein deposits in southwestern China that are adjacent to one another and a possible deformed ancient sea-floor volcanogenic massive sulfide (VMS) deposit in Sweden may represent the only two locations in the world where tellurium is a primary resource (fig. R1).

Most tellurium is recovered as a byproduct in the anode slimes from the electrorefining of copper and other poly-metallic sulfide ores, which are typically mined from porphyry, VMS, magmatic nickel-copper-platinum-group-metal (PGM), and (or) skarn deposits. The tellurium received for processing at a refinery may have come from several different types of mineral deposits within a given country and (or) from another country or countries. If the tellurium is to be recovered as a final tellurium metal product at a refinery, it commonly requires upgrading to tellurium metal at a second industrial facility, which may be located in the same or a different country. In the United States, for example, all tellurium production is from a single refinery in Texas, but it is impossible to identify the specific deposits that have contributed the ore from which the tellurium is produced, although the sources are likely some of the large porphyry copper deposits scattered across the southwestern and western parts of the country.

The refined anode slimes from which tellurium is extracted are typically dominated by copper and silver, although most global refineries report contents of 1 to 4 percent tellurium in the anode slimes, and some copper refineries in central Asia and Russia report as much as 8 to 9 percent tellurium (Moats and others, 2007). A minor part of the world's tellurium is also recovered from the dust and gases produced during the smelting of sulfide-rich ores and from the skimmings (when a distillation process is used) at lead refineries.

<sup>1</sup>Deceased.



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

**Figure R1.** World map showing locations of selected tellurium-enriched mineral occurrences discussed in the text, by deposit type. Tellurium is produced as a primary commodity from the Kankberg deposit located in Västerbotten County, Sweden, and the Dashiugou and Majjagou deposits located in Sichuan and Shaanxi Provinces, respectively, in China. The deposit types shown here and discussed in the text are classified as follows: volcanogenic massive sulfide (VMS), iron oxide-copper-gold (IOCG), orogenic gold, porphyry, epithermal, skarn, Carlin-type gold, magmatic copper–nickel–platinum-group metal (Cu-Ni-PGM), and other deposits.

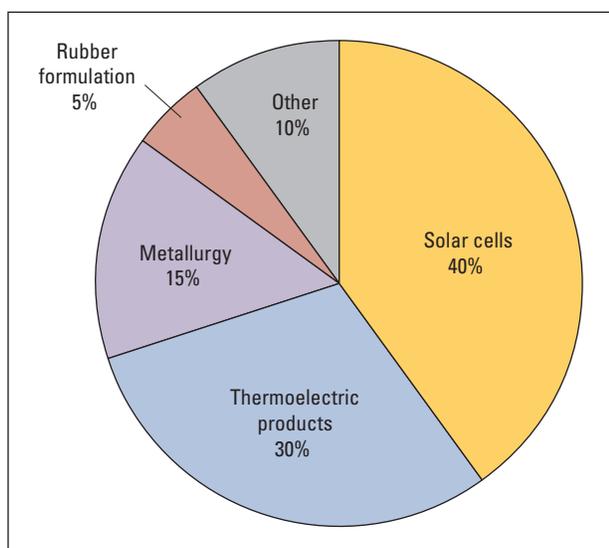
## Uses and Applications

The main use of tellurium is for development of cadmium-tellurium film in photovoltaic solar cells, which is considered to be an emerging application, particularly in the growing economies of China and India. In addition, tellurium is used as an additive to copper, lead, and steel alloys to improve machine efficiency, particularly in thermoelectric cooling products. Together, the photovoltaic solar and thermoelectric uses account for more than two-thirds of the world's tellurium usage (fig. R2; Anderson, 2015). About 5 percent of tellurium usage is for improving heat resistance during vulcanization of rubber. Tellurium is also used as an alloy with selenium in photoreceptors in copying machines and as a coloring agent in ceramics and glass. It is, in addition, applied in integrated circuits, laser diodes, and medical instrumentation; all these uses have had robust growth in recent years.

## Demand and Availability of Supply

The price of tellurium has fluctuated significantly since 2010. According to the U.S. Department of Energy, the supply of tellurium is not critical, although it is projected to be “near-critical” through 2025 (U.S. Department of Energy, 2010). Significant amounts of tellurium are available globally from the mining of major base-metal-rich deposits. Enrichments in precious-metal deposits are well known, although these deposits have generally not produced significant amounts of tellurium.

The solar energy industry represents the largest share of the tellurium market today, accounting for nearly 40 percent of annual tellurium consumption. Some consumption percentages have changed since 2010, as metallurgy use has decreased to about 15 percent from approximately 30 percent of total consumption, and thermoelectric products presently account for about 30 percent (fig. R2). Because of the demand for solar cells, an estimated 30 percent of the world's produced tellurium is used by First Solar Inc., which in 2016 continued to be the world's leading producer of cadmium-tellurium solar panels.



## Geology

### Geochemistry

Owing to its high volatility in the hydride phase and probable evaporative loss during Earth's early low-oxygen period, tellurium is an exceptionally rare chalcophile element in Earth's upper crust. Tellurium is in the family of Group 6A elements in the periodic table, which also includes oxygen, sulfur, and selenium, and its chemical behavior is similar to that of selenium and sulfur. Native tellurium typically appears as a brittle, silver-white substance. It has an atomic number of 52 and an atomic weight of 127.6. Tellurium combines with elements that are incapable of reducing their volume upon losing valence electrons (Sindeeva, 1964). The energy required to detach tellurium's first electron is much higher than for the alkaline and alkaline earth metals, and, therefore, tellurium does not tend to form ionic bonds; rather, it forms covalent and metallic bonds. Tellurium tends to combine with metals of high atomic number and similar atomic radii; for example, it typically forms minerals that also contain gold, silver, and platinum.

McDonough (2003) estimated an overall bulk Earth abundance of 300 parts per billion (ppb) tellurium, but 96 percent of Earth's tellurium remains in the core, which averages 885 ppb tellurium. Earth's mantle may have an average concentration of about 8 ppb tellurium, although local concentrations in peridotite can be twice that amount because residual sulfide phases in these rocks are commonly enriched in tellurium (Palme and O'Neil, 2003). Tellurium is preferentially retained in refractory sulfides in harzburgite in the mantle during melting processes (Hattori and others, 2002). Crustal tellurium values are extremely low, and Li and Schoonmaker (2003) estimate an average upper crustal abundance value of 3 ppb tellurium, which is about eight times less than that for gold and makes tellurium one of the least common elements in crustal rocks. Only a limited amount of abundance data for tellurium is available, and, in fact, tellurium is not listed in many modern-day comprehensive compilations of global element abundances (for example, table 2 in Rudnick and Gao, 2003). In marine shale, however, Li and Schoonmaker (2003) indicate much higher average concentrations of 70 ppb tellurium, which likely reflects the abundance of disseminated oceanic pyrite that has elevated levels of tellurium. Hein and others (2013) note mean values of 30 to 60 parts per million (ppm) tellurium in iron-manganese crusts formed on the floor of several oceans owing to the oxidation of tellurite (Te(IV)) to tellurate (Te(VI)).

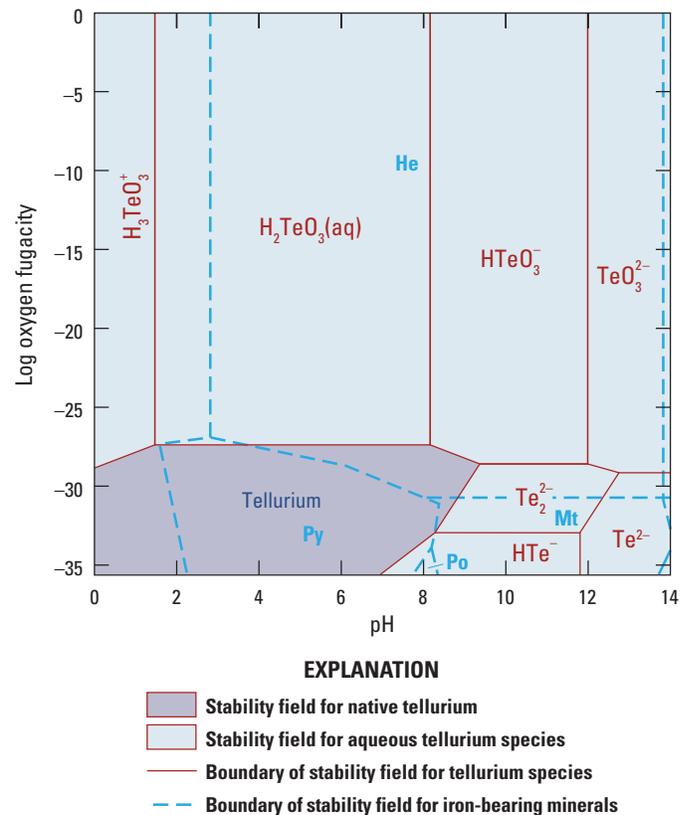
**Figure R2.** Pie chart showing major end uses of tellurium as a percentage of world consumption in 2010. Compiled using data from Selenium Tellurium Development Association, Inc. (2010) and Anderson (2015).

The solubility and transport of tellurium in magmatic and hydrothermal fluids are incompletely understood, particularly at the temperatures and pressures of igneous melt reservoirs and in high-grade metamorphic terranes. Taken together with the intrinsic low abundance of the element, the heterogeneity of the concentrations of tellurium within any mineral-deposit type and the very fine granularity of telluride minerals limit the ability to predict tellurium resources that might occur in a specific type of mineral deposit. Tellurium has a relatively low solubility in aqueous solutions; fields for the dominant aqueous tellurium species are shown as a function of pH and oxygen fugacity in figure R3. Given the high abundance of tellurium in some deposits, the low solubility suggests that tellurium may be transported predominantly in the vapor phase (for example, Cooke and McPhail, 2001), probably as solvated molecular species. Tellurium occurs in volcanic fumaroles, such as the high-tellurium amorphous arsenic-rich sulfurite at Vulcano, Sicilia, Italy (Garavelli and others, 2013) and in volcanic condensate sulfur from the Mendeleev volcano in the Kuril Islands, Sakhalinskaya Oblast', Russia, and the Mutnovskaya volcano on Russia's Kamchatka Peninsula (Sindeeva, 1964). Volatile transport of tellurium could also be enhanced owing to the suggested relatively high anhydrous volatility of the element, along with that of arsenic, mercury, and selenium (for example, Saunders and Brueske, 2012), where  $\text{Hg} > \text{As} > \text{Se} > \text{Te} > \text{Tl} > \text{Sb} > \text{Pb} > \text{Ag} > \text{Cu} > \text{Au}$ . In addition, the common enrichment of tellurium in nonmagmatic orogenic gold systems may indicate that carbon dioxide ( $\text{CO}_2$ ) immiscibility also is an important factor leading to the gaseous transport and concentration of tellurium.

Although tellurium varies in oxidation state from  $-2$  (telluride) to  $+4$  (tellurite) to  $+6$  (tellurate), tellurium is most soluble as tellurite in hydrothermal fluids. Hydrothermal waters in the areas of epithermal gold deposits may contain as much as 4 ppb tellurium, and some sea-floor hot springs have as much as 18 ppb tellurium (Grundler and others, 2013). In typical reduced hydrothermal fluids (for example,  $\log f_{\text{O}_2} < -30$ ),  $\text{Te}_2^{2-}$  is the dominant tellurium-bearing ion (Brugger and others, 2012), although under slightly more acidic or very reduced conditions  $\text{HTe}^-$  is dominant and  $\text{H}_2\text{TeO}_3$  could be important in very acidic and less reduced solutions (fig. R3; McPhail, 1995; Grundler and others, 2013). The  $\text{Te}_2^{2-}$  activity is controlled in aqueous solutions by the solubility of native tellurium, which is commonly deposited along with many telluride phases. The tellurate species are dominant under only very oxidizing conditions, such as in near-surface weathering of telluride-rich ores (fig. R3).

Some researchers have suggested that the common occurrence of gold-bearing telluride minerals implies the transport of gold as a soluble tellurium complex (for example, Jensen and Barton, 2000; Cooke and McPhail, 2001; Brugger and others, 2012), although most experimental evidence at magmatic conditions indicates the transport of gold either as a sulfide complex (Loucks and Mavrogenes, 1999) or as both chloride and sulfide complexes (Frank and others, 2011). Hydrothermal fluids with anomalous tellurium concentrations,

based on the abundance of telluride minerals, include both  $\text{CO}_2$ -rich fluids that form orogenic gold and alkalic-related epithermal gold deposits, and  $\text{CO}_2$ -poor fluids that typify most low- and high-sulfidation precious-metal-bearing epithermal ores. Therefore, it is unlikely that  $\text{CO}_2$  plays a significant role in the transport or concentration of tellurium. Furthermore, although typical tellurium enrichments in ore deposits are assumed to reflect magmatic-hydrothermal activity, the tellurium enrichment in many orogenic gold deposits, which are widely accepted to have formed from nonmagmatic metamorphic fluids, suggests that such a magmatic association is not necessary.



**Figure R3.** Phase diagram showing speciation calculations for tellurium in a hydrothermal fluid at 300 degrees Celsius ( $^{\circ}\text{C}$ ), as a function of pH and oxygen fugacity, with the following activities: tellurium= $10^{-10}$ , iron=0.1, sulfur= $10^{-4}$ , and chlorine=0.5. At an activity of tellurium of  $10^{-10}$ , a typical near-neutral to acidic, reduced aqueous fluid cannot carry much tellurium, and native tellurium will be stable (shaded area in lower left side of diagram). The low solubility of tellurium in aqueous solutions suggests that concentration of tellurium in a vapor may be important for mineral formation unless the fluid has a very high concentration of tellurium (that is, at an activity of  $\text{Te}=10^{-8}$  or greater). The oxygen-bearing tellurate species, although with large stability fields, are only significant under very oxidizing conditions above a log oxygen fugacity of about  $10^{-29}$  for any pH value. After Grundler and others (2013). aq, aqueous; He, hematite; Mt, magnetite; Po, pyrrhotite; Py, pyrite; and Te, tellurium

Studies of both liquid and vapor fluid inclusions from porphyry and epithermal deposits have indicated concentrations of hundreds of parts per million tellurium in the fluids that formed some deposits (Wallier and others, 2006; Pudack and others, 2009). For example, fluid inclusions in high-sulfidation epithermal veins in Romania contained as much as 3 weight percent tellurium, which appeared to correlate with enrichments in dissolved silver and gold (Kouzmanov and others, 2010). Grundler and others (2009, 2013) concluded that these unusually elevated tellurium concentrations indicate that aqueous tellurite was transported in a highly oxidized magmatic fluid and (or) in a fluid with basic pH (approximately greater than pH 8), with tellurite reduction by fluid-rock interaction or by fluid mixing that caused precipitation of telluride minerals. Available information suggests that any drastic change in fluid conditions, including a decrease in temperature, wallrock sulfidation, phase separation, pH

shifts, and (or) redox change, can destabilize tellurium-bearing complexes (for example, Cooke and McPhail, 2001; Ciobanu and others, 2006; Maslennikov and others, 2013). Most hypogene telluride minerals probably were deposited at temperatures of between 300 and 100 degrees Celsius (°C) (for example, Zhang and Spry, 1994; Shackleton and others, 2003), although in some magmatic copper-nickel-PGM deposits, palladium- and (or) lead-bearing tellurides are stable at temperatures of 400 °C (Vymazalová and Drábek, 2011).

## Mineralogy

The most common tellurium-bearing minerals are listed in table R1. These minerals occur in many different types of ore deposits, but the minerals themselves are typically too low in abundance to be sources for recoverable tellurium ore.

**Table R1.** Tellurium-bearing minerals, many of which are mentioned in this chapter.

Mineral name	Chemical formula	Mineral name	Chemical formula
Altaite	PbTe	Maslovite	PtBiTe
Benleonardite	Ag <sub>8</sub> (Sb,As)Te <sub>2</sub> S <sub>3</sub>	Melonite	NiTe <sub>2</sub>
Bezsmeritovite	Au <sub>4</sub> Cu(Te,Pb)	Merenskyite	PdTe <sub>2</sub>
Bilibinskite	PbCuAu <sub>3</sub> Te <sub>2</sub>	Michenerite	PdBiTe
Blakeite	(Fe <sub>2</sub> (TeO <sub>3</sub> ) <sub>3</sub> )	Moncheite	PtTe <sub>2</sub>
Bogdanovite	Au,Te,Pb) <sub>3</sub> (Cu,Fe)	Montainite	Bi <sub>3</sub> TeO <sub>4</sub> (OH) <sub>4</sub>
Buckhornite	AuPb <sub>2</sub> BiTe <sub>2</sub> S <sub>3</sub>	Montbrayite	(Au,Sb) <sub>2</sub> Te <sub>3</sub>
Calaverite	AuTe <sub>2</sub>	Museumite	[Pb <sub>2</sub> (Pb,Sb) <sub>2</sub> S <sub>8</sub> ][Te,Au] <sub>2</sub>
Cervelleite	Ag <sub>4</sub> TeS	Muthmannite	(AuAg)Te
Csiklovaite	Bi <sub>2</sub> TeS <sub>2</sub>	Nagyágite	Pb <sub>5</sub> Au(Te,Sb) <sub>4</sub> S <sub>5-8</sub>
Coloradoite	HgTe	Native tellurium	Te
Emmonsite	Fe <sub>2</sub> (TeO <sub>3</sub> ) <sub>3</sub> •2H <sub>2</sub> O	Pašavaite	Pd <sub>3</sub> Pb <sub>2</sub> Te <sub>2</sub>
Empressite	Ag <sub>5-x</sub> Te <sub>3</sub>	Petzite	Ag <sub>3</sub> AuTe <sub>2</sub>
Frohbergite	FeTe <sub>2</sub>	Poughite	Fe <sub>2</sub> (TeO <sub>3</sub> ) <sub>2</sub> SO <sub>4</sub> •3H <sub>2</sub> O
Goldfieldite	Cu <sub>12</sub> (Te, Sb, As) <sub>4</sub> S <sub>13</sub>	Rickardite	Cu <sub>4-x</sub> Te <sub>2</sub>
Grunlingite	Bi <sub>4</sub> TeS <sub>3</sub>	Rodalquilarite	H <sub>3</sub> Fe <sub>2</sub> (TeO <sub>3</sub> ) <sub>4</sub> Cl
Hedleyite	Bi <sub>7</sub> Te <sub>3</sub>	Rucklidgeite	(Bi, Pb) <sub>3</sub> Te <sub>4</sub>
Henryite	Cu <sub>4</sub> Ag <sub>3</sub> Te <sub>4</sub>	Stutzite	Ag <sub>7</sub> Te <sub>4</sub>
Hessite	Ag <sub>2</sub> Te	Sylvanite	AuAgTe <sub>4</sub>
Imgreite	NiTe	Teineite	Cu(Te, S)O <sub>4</sub> •2H <sub>2</sub> O
Joseite	Bi <sub>4</sub> (Te, S) <sub>3</sub>	Tellurantimony	Sb <sub>2</sub> Te <sub>3</sub>
Kawzulite	Bi <sub>2</sub> (Te, Se, S) <sub>3</sub>	Tellurobismuthite	Bi <sub>2</sub> Te <sub>3</sub>
Keithconnite	PdTe <sub>3</sub>	Telluropalladinite	Pd <sub>9</sub> Te <sub>4</sub>
Kostovite	CuAuTe <sub>4</sub>	Tetradymite	Bi <sub>2</sub> Te <sub>2</sub> S
Kotulskite	PdTe	Tsumoite	Bi <sub>4</sub> Te <sub>2</sub>
Krennerite	Au <sub>4</sub> AgTe <sub>10</sub>	Volynskite	AgBiTe <sub>2</sub>
Mackayite	Fe <sub>2</sub> (TeO <sub>3</sub> ) <sub>3</sub> nH <sub>2</sub> O	Weissite	Cu <sub>2-x</sub> Te

Tellurium is most strongly concentrated in telluride minerals, although some tellurium is also concentrated in sulfide minerals, particularly in sulfosalts, such as the mineral goldfieldite. In the gold-silver-tellurium system alone, 11 different tellurium-bearing phases have been identified (Zhang and Spry, 1994). Grundler and others (2013) indicate that calaverite typically coexists with native gold or the silver-bearing tellurides krennerite and petzite, whereas native tellurium is more commonly associated with other silver-bearing tellurides, such as hessite, stutzite, and sylvanite. Where the ratios of tellurium to gold plus silver are high, bismuth-bearing tellurides, coloradoite, or goldfieldite have been shown to be the dominant tellurium-bearing phases (Grundler and others, 2013). There are numerous palladium-bearing tellurides in the lead-palladium-tellurium system, including keithconite, kotulskite, merenskyite, pašavaite, and telluropalladinite, and these are sometimes common in magmatic copper-nickel-PGM deposits (Vymazalová and Drábek, 2011). Moncheite is a common platinum host in the deposit type.

In most ore deposits, telluride minerals consistently are deposited in the later stages of paragenetic sequences; that is, they form after the deposition of many iron- and base-metal-bearing sulfides. At the tellurium-rich Cripple Creek district gold deposits in Teller County, Colorado, Lovering and Goddard (1950) and Saunders (1986) documented a relative chronology of telluride mineral deposition. Generally, with time, telluride composition shifts from gold-rich to silver-rich during these late hydrothermal events (for example, Dye and Smyth, 2012). There are exceptions, however, such as at the Tinos Island precious-metal deposit in Notío Aigáio, Greece, where a silver-to-copper-to-gold paragenetic sequence characterizes telluride deposition (Tombros and others, 2010).

Native tellurium is reported from many precious-metal deposits, including numerous gold deposits in Japan. Nakata and Komuro (2011) indicate that quartz, quartz-goldfieldite, quartz-stutzite-hessite-sylvanite-tetradymite, and quartz-hessite-sylvanite-tellurantimony assemblages all contain native tellurium.

On the active sea floor along the Kermadec-Tonga trench in the Pacific Ocean, telluride minerals and native tellurium have been identified in massive chalcopyrite occurrences and in areas between sulfide chimneys of chalcopyrite and pyrite (Berkenbosch and others, 2012). Most of the telluride minerals are less than 5 micrometers in diameter, but some reach lengths of 80 micrometers. These are dominantly gold-rich (calaverite) and bismuth-rich (kawazulite, tellurobismuthite, and tetradymite) telluride minerals.

Oxidation of gold-rich tellurides can form tellurite and tellurate phases within the weathering zone. It can also lead to the formation of low reflectivity “mustard gold” through dissolution of calaverite and other gold-rich tellurides and subsequent reprecipitation processes (Zhao and others, 2009). In addition, gold pseudomorphs after tellurides may form. In the weathering environment, tellurium most likely undergoes sorption onto, and thus concentration within, clay-sized soil particles (Hayes and others, 2012)

## Deposit Types

Tellurium is present in many different types of mineral deposits. The diversity of mineral deposit types in which it occurs may reflect enrichment of the element in the structure of sulfide grains or the formation of discrete tellurium-bearing minerals. The deposit types listed here are only those for which there is, has been, or is projected to be some economic interest in their tellurium content.

### Magmatic Copper–Nickel–Platinum-Group-Metal Sulfide Deposits

Magmatic sulfide deposits are mafic and ultramafic igneous bodies that are enriched in copper, nickel, and (or) platinum-group metals (PGMs) (Naldrett, 2011). Little or no published information is available regarding tellurium production from and the concentration of tellurium in studied deposits of this type, but it is highly likely that these ores contribute to global tellurium production, as the tellurium is produced as a byproduct of the milling of the major mineral commodities. For example, some amount of tellurium is recovered in Russia from magmatic sulfide deposits. Telluride minerals, which contain the greatest concentrations of tellurium of any minerals, are present in many deposits of this type, but only in subeconomic quantities.

At the Sudbury district in Ontario, Canada, where Paleoproterozoic ore-related magmas were produced by shock waves from a meteor impact, hydrothermal activity in the footwall of the emplaced igneous complex has enriched the rocks with gold and PGMs. Much of the PGM mineralization is hosted in tellurium-rich phases that include kotulskite, merenskyite, and moncheite. In addition, bismuth-, mercury-, and silver-rich telluride phases have been noted (Péntek and others, 2013).

At Noril'sk in Krasnoyarskiy Krai, Russia, the magmatic copper-nickel-PGM deposits associated with the Triassic continental flood basalts have yielded minor amounts of byproduct tellurium (in the range of 5 metric tons per year) (Safirova, 2012). Tellurium of potential economic interest at Noril'sk is confined to sulfide minerals (Sindeeva, 1964). Chalcopyrite, for example, contains from 2 to 72 ppm tellurium; pyrrhotite, from 4 to 45 ppm; pentlandite, 13 ppm; and bornite, from 10 to 15 ppm tellurium (Sindeeva, 1964). Massive vein-type ores of copper contain the highest concentrations of tellurium, whereas disseminated ores contain lesser amounts of tellurium (from trace amounts to 12 ppm).

Some of the platinum and palladium resource in the Paleoproterozoic Merensky Reef in the eastern Bushveld Complex of Limpopo Province, South Africa, is contained in michenerite and maslovite, which are PGM-bearing bismuthotellurides that were suggested to have formed by remobilization of magmatic PGMs during an overprinting hydrothermal event (Rose and others, 2011). The minerals that host palladium and platinum most commonly in the Pana and Fedorov massifs of the Kola Peninsula, Russia, and the

Great Dyke, Zimbabwe, are arsenides and bismuthotellurides (Oberthür, 2002; Mitrofanov and others, 2005). In the Late Archean Stillwater Complex in Montana, mineralized samples with as much as 182 ppm palladium and 52 ppm platinum also contain as much as 17 ppm tellurium and significant amounts of arsenic and bismuth, reflecting a complex telluride mineralogy (Zientek and others, 1990).

## Iron Oxide-Copper-Gold Deposits

Iron oxide-copper-gold (IOCG) deposits represent a poorly defined and understood group of deposits of mainly Precambrian age (Groves and others, 2010). They are generally defined as sulfur-poor magmatic-hydrothermal deposits with large resources of copper, gold, iron, and (or) uranium in extensional cratonic settings. There are few data on tellurium in IOCG deposits. The anode slime at the refinery of the giant Mesoproterozoic Olympic Dam deposit in South Australia, Australia, which is the world's largest identified IOCG deposit, averages about 3.5 percent tellurium (Moats and others, 2007) and is a source of some tellurium production. This indicates that the tellurium produced from Olympic Dam is recovered from the bornite, chalcocite, and chalcopyrite ore minerals. Discrete telluride phases at Olympic Dam have not been reported.

## Volcanogenic Massive Sulfide Deposits

The volcanogenic massive sulfide (VMS) deposits consist of strata-bound sulfide minerals that formed at or near the sea floor in association with contemporaneous volcanism. The leading producers of tellurium in Russia are the VMS deposits in the Ural Mountains, which yield about 35 metric tons per year of tellurium (Safirova, 2012). Fine-grained telluride minerals are abundant in the Silurian and Devonian copper-zinc VMS deposits of the Urals (Vikentyev, 2006). Maslennikov and others (2013) described a variety of Ag-Pb-Bi-Te and Cu-Ag-Te-S solid-solution series phases and tellurium-rich sulfosalts in ancient sea-floor chimney structures. They suggest, however, that chalcopyrite is the most significant host for tellurium. In the Sibay VMS deposit in the Urals region of Bashkortostan Republic, Russia, tellurium is predominantly associated with copper ores (which average 11 ppm tellurium), whereas zinc-rich ores less frequently have detectable levels of tellurium (Sindeeva, 1964). In the Uchaly deposit, which is also located in the Urals region of Bashkortostan Republic, pyrite and pyrite-copper ores contain from 22 to 190 ppm tellurium (Sindeeva, 1964). No production data are available for individual deposits; tellurium is recovered from electrolytic refining of the copper-rich VMS ores, but the discrete telluride phases are unlikely to be important contributors.

Some VMS deposits are transitional with telluride-bearing epithermal precious-metal mineral occurrences, including those as old as Archean (for example, Côte-Mantha and others, 2012). The poorly understood Kankberg deposit in the

Paleoproterozoic (circa 1,890 mega-annum [Ma]) Skellefteå district in Västerbotten County, Sweden, was originally mined as a copper-zinc deposit into the 1990s, and it was classified by some workers as a VMS deposit. The deposit has been reopened as a gold-tellurium mine that is projected to produce approximately 10 percent of the world's tellurium, or about 41 metric tons per year, from 2012 to 2020 (Boliden Group, 2011). Thus, Kankberg represents one of the few presently active mining operations in which tellurium is a primary product and telluride minerals are the source of the tellurium. The ore averages approximately 4.1 grams per metric ton (g/t) gold and 186 g/t tellurium. The sea-floor deposit is thought to be rich in tellurium and is possibly a hybrid VMS-epithermal system that formed on a shallow part of the ocean floor. If this is correct, it would indicate that significant amounts of tellurium are available from sea-floor deposits and are not solely associated with the more classic subaerial epithermal ores described below (for example, Mercier-Langevin and others, 2013). Numerous VMS deposits—both ancient ones exposed on continents and modern ones presently forming on the sea floor—may thus be associated with an epithermal suite of trace elements (for example, Hannington and others, 2005; Berkenbosch and others, 2012) and potentially could be highly enriched in tellurium.

## Porphyry Deposits

Tellurium is enriched in sulfide and (or) telluride phases in most copper porphyry deposits and thus may be a recoverable byproduct during milling of some of these copper ores. Porphyry deposits are shallowly formed magmatic-hydrothermal deposits typically developed in the cupolas to porphyritic intrusions within active continental margins above subduction zones. The deposits are generally characterized by stockwork veinlets rich in copper- and (or) molybdenum-bearing minerals. The principal source of tellurium in the United States and the world is as a byproduct of copper refining of ores from large-tonnage, low-grade copper and copper-gold porphyry deposits. For example, the giant Carboniferous copper porphyry deposits of the Almalyk district in Toshkent Province, Uzbekistan, are a source of recovered tellurium; the deposits were estimated to contain 1,098 metric tons of tellurium in 1996 (Levine, 2011, citing report from United States Trade and Development Agency, 1996). In the Almalyk district, average concentrations in ore were 16 ppm tellurium at the Kal'makyr deposit and 7 to 8 ppm tellurium at the Dalnee deposit. In the world-class Cretaceous Pebble copper-gold-molybdenum deposit in Alaska, calaverite and petzite have been observed to contain some of the gold. Gregory and others (2013) estimate that 2.5 to 3.0 percent of the gold in the deposit is hosted by the two telluride phases. These phases occur as inclusions in chalcopyrite, which is the main copper ore mineral at the Pebble deposit. The majority of what is conjectured to be an enormous tellurium endowment at the Pebble deposit is potentially hosted in the structure of chalcopyrite and pyrite, however, assuming these phases contain tellurium concentrations similar

to sulfide minerals in many porphyry deposits, which provide much of the byproduct tellurium produced in the United States and the world. It is not clear whether tellurium recovery is planned if and when the Pebble deposit goes into production. Palladium is enriched in many porphyry copper-gold deposits, reflecting the presence of palladium-bearing telluride minerals as distinct grains or as inclusions in bornite and chalcopyrite. For example, merenskyite is a common tellurium-rich phase that is associated with lesser amounts of hessite and kotulskite in many porphyry deposits (Economou-Eliopoulos, 2005).

Eilers (1914) reported that the Tertiary Bingham Canyon deposit in Utah contained greater than 23 to 27 ppm tellurium in blister copper (the almost pure copper produced during refining), although tellurium was not detected in the partially refined copper from the porphyry deposits at Ely, Nevada. High-grade copper-molybdenum-gold ore from Bingham Canyon has been estimated to average 4.8 ppm tellurium (Austen and Ballantyne, 2011). Economou-Eliopoulos and Eliopoulos (2000) reported whole-rock concentrations of tellurium ranging from 0.33 to 2.7 ppm in mineralized samples from the Skouries deposit and the adjacent Fissoka prospect in the Peloponnisos region of Greece. Tokmakchieva (2002) and Tarkian and others (2003) reported as much as 106 ppm tellurium in ore samples from the Elatsite deposit in Sofiya, Bulgaria. Economou-Eliopoulos and Eliopoulos (2000) also estimated concentrations of 4.0 and 18.5 ppm tellurium in two samples of chalcopyrite from the Skouries deposit. Reported differences in concentrations from the deposits likely reflect sampling variability; higher concentrations result from analyses of samples of mainly copper-bearing sulfide minerals that may contain hundreds of parts per million tellurium, whereas samples of sulfide minerals in wallrock would have much lower concentrations.

Although the main copper±gold ores in porphyry deposits at Ely, White Pine County, Nevada, are not enriched in tellurium, mineralized rock in the silver-rich halo is highly anomalous in tellurium, averaging about 100 ppm tellurium (Gott and McCarthy, 1966). Watterson and others (1977) also found high concentrations of tellurium in silicified rocks in a halo surrounding the copper ores. Chaffee (1982) identified two zones with anomalous whole-rock tellurium at the Kalamazoo deposit in Pinal County, Arizona. The highest concentrations of tellurium were present in the outer pyritic halo of the porphyry deposit, whereas lower anomaly values corresponded with the copper-gold ore zone. Cox and others (1975) identified a similar zonation at the Sapo Alegre deposit in Puerto Rico. Therefore, although much of the present tellurium production is a byproduct from copper production from porphyry copper ores, future primary resources may be considered in the alteration halos of many porphyry deposits if tellurium demand increases. Because tellurium is relatively volatile compared with many other elements, it is not surprising that there are high tellurium concentrations in alteration zones surrounding the main bulk-minable copper resources.

Many of the porphyry systems with abundant telluride minerals are specifically associated with subduction-related

alkalic porphyritic intrusions. These include those of the Late Triassic-Early Jurassic continental arc in British Columbia, Canada. The Mount Milligan copper-gold deposit, which is one of the larger deposits of the group, is characterized by a late-stage “subepithermal” or intermediate-sulfidation overprinting event that deposited an Au-PGM-As-Sb-Bi-Te-Hg assemblage, perhaps by way of vapor transport (LeFort and others, 2011). Many gold-rich epithermal deposits, particularly those related to alkalic igneous rocks, contain significant tellurium concentrations and may reflect late-stage events in an evolving porphyry-epithermal magmatic-hydrothermal system. The La Plata deposit in La Plata County, Colo., may be such an example, where gold-telluride vein and replacement deposits surround an alkaline intrusion that is rich in gold and copper (Jones, 1992).

Some workers have suggested that epithermal gold-silver-tellurium mineralization is closely linked to the more molybdenum-rich alkalic porphyry deposits (Rice and others, 1985; Saunders, 1991). Spry and others (1996), for example, described the Golden Sunlight deposit in Jefferson County, Montana, as an epithermal gold deposit that developed in alteration surrounding an alkaline, low-grade molybdenum-bearing Late Cretaceous porphyry intrusion. They described bismuth-, gold-, and silver-rich telluride minerals in a breccia pipe that overprints the earlier stockwork molybdenum mineralization and represents the later stages of a magmatic-hydrothermal system. Whether or not tellurium is also concentrated in early-stage molybdenite and is recovered as a byproduct from milling of molybdenum porphyry deposits is uncertain. In the United States, all tellurium production is from ASARCO LLC’s copper refinery in Amarillo, Texas, which processes copper ore but not molybdenum ore (David A. John, Research Geologist, U.S. Geological Survey, written commun., 2013); consequently, porphyry molybdenum deposits located in the Rocky Mountains of Colorado are not a present-day source of domestic tellurium production.

## Skarn Deposits

Copper-bearing skarn deposits that were formed in areas of replacement of carbonate rock by garnet, pyroxene, and other calc-silicate minerals commonly are associated with porphyry copper deposits where carbonate rocks are part of the country-rock assemblage. Fuertes-Fuente and others (2000) report hedleyite in the Ortosa deposit in Asturias, Spain, and Prendergast and others (2005) report altaite, hessite, petzite, and tetradymite in the Big Gossan and Wanagon skarn deposits in the Ertzberg district of Papua Province, Indonesia. In the Darwin district of Inyo County, California, bismuth tellurides, rickardite, and tellurium-rich sulfosalts occur (Affi and others, 1988). In many gold-rich skarns, bismuth and tellurium are both enriched (for example, at the Hedley deposit in British Columbia, Canada [Meinert, 2000]; the Fortitude deposit in Lander County, Nev. [Meinert, 2000]; the Stormont deposit in Tasmania, Australia [Cockerton and Tomkins, 2012]; and the Geodo deposit in Gangwon, Republic of Korea [Kim and

others, 2012]). It is unknown whether skarns contribute to any of the world's tellurium production. If large refineries that recover copper from numerous porphyry deposits also handle some ores from surrounding skarns, then potentially some byproduct tellurium may have been produced from the skarns.

## Epithermal Deposits

Epithermal gold and silver deposits may or may not be associated with porphyry deposits. They are more shallowly formed deposits commonly consisting of veins associated with volcanic activity. Tellurium typically is more abundant and tellurium-bearing minerals are more diverse in epithermal deposits than in porphyry and other types of magmatic deposits. Tellurium in epithermal deposits occurs in telluride minerals, as native tellurium, and as tellurium-bearing sulfosalts in unoxidized ores, as well as in the form of tellurites in secondary ores. Tellurium is enriched in both main subclasses of the epithermal type; that is, the so-called high-sulfidation and low-sulfidation epithermal varieties (for example, White and Hedenquist, 1990). The high-sulfidation subclass, which is spatially associated in many instances with porphyry deposits (Simmons and others, 2005), typically is characterized by an alteration assemblage that includes alunite, kaolinite, quartz, and pyrophyllite. The low-sulfidation subclass is typically characterized by an alteration assemblage that includes adularia, quartz, and sericite (illite). Some epithermal districts contain both high-sulfidation and low-sulfidation types of ores.

Low-sulfidation epithermal deposits occur with a wider variety of igneous rock compositions than do high-sulfidation deposits, but they also occur in some hydrothermal systems that lack any obvious magmatic input. Tellurium-bearing minerals may constitute economically significant gold ores, such as at deposits in the Cripple Creek district of Teller County, Colo., or they may be minor accessories, such as at deposits in the Telluride district of San Miguel County, Colo. Although not in all cases, economically significant tellurium-bearing ores occur in epithermal-like veins with a polymetallic character, which are sometimes referred to as intermediate-sulfidation epithermal deposits; that is, they contain significant amounts of copper, lead, and zinc sulfide and sulfosalt minerals, and are sometimes considered a transitional deposit type between epithermal and porphyry ores (Simmons and others, 2005).

Most epithermal deposits are associated with subduction-related oceanic or continental magmatic arcs. One subtype of the low-sulfidation-type gold-silver epithermal deposit is associated with alkaline to subalkaline, light-rare-earth-element-enriched magmatism in back-arc and post-subduction settings, and is notably enriched in tellurium (Jensen and Barton, 2000; Kelley and Spry, 2016). These alkaline gold deposits include those of (a) the Rocky Mountain System of the United States (for example, the Zortman-Landusky district in Phillips County, Mont.; the northern Black Hills of South Dakota; the Cripple Creek district in Teller County, Colo.; and the Ortiz Mountains of New Mexico), (b) the Himalayan foreland of southwestern China (for example,

the Dashuigou deposit and the Majiagou deposit [Sichuan Province]) (Mao and others, 2002), and (c) Papua New Guinea and Fiji (for example, in Papua New Guinea, the Porgera deposit in Enga Province, the Mt. Kare deposit in Enga Province, and the Lihir deposit in New Ireland Province; and in Fiji, the Emperor deposit in Viti Levu). In the Cripple Creek district, Gott and others (1967) reported the district-wide background as 2.7 ppm tellurium in volcanic rocks, with an average value of 10.7 ppm tellurium in areas of anomalous gold. In China, the adjacent Dashuigou and Majiagou deposits are rare examples in which tellurium is the main ore commodity; it is recovered mainly from tetradymite. Many deposits in this alkaline subtype are typically characterized by a fluorine-gold-tellurium-vanadium magmatic-hydrothermal geochemical signature (Jensen and Barton, 2000; Simmons and others, 2005).

Saunders and Brueseke (2012) suggested that alkaline, tellurium-rich low-sulfidation epithermal deposits of the Western United States are preferentially located over Precambrian basement rocks east of the initial  $^{87}\text{Sr}/^{86}\text{Sr}=0.706$  isopleth. They show a distinct break in epithermal ore geochemistry, as tellurium is more abundant than selenium to the east and selenium is more abundant than tellurium to the west of the ancient cratonic margin. The tellurium-rich epithermal province, which extends from Montana to New Mexico, has mainly alkalic magmatism, whereas the selenium-rich ores occur with more typical calc-alkaline rocks. Saunders and Brueseke (2012) related the different patterns to differences in the volatility of the metalloids within a subducting Laramide slab; less volatile tellurium is released later and at greater depths, and thus further inboard than the selenium. There are, however, notable exceptions to this pattern, including tellurium-rich low- and high-sulfidation gold ores at Bodie in eastern California (David A. John, Research Geologist, U.S. Geological Survey, written commun., 2013).

About 5 metric tons of tellurium were produced in the early 1960s from the Lone Pine deposit in the Wilcox district in Catron County, New Mexico, where fluorite, gold, and silver have also been recovered in minor amounts (Lueth and others, 1996). Low-sulfidation ores are hosted by Oligocene rhyolitic intrusions in a caldera ring complex. Telluride minerals (krennerite?) and native tellurium are reported. The weathering of pyrite and native tellurium led to formation of many different iron tellurate minerals. The original hypogene telluride mineralization was best developed at the pyrite-fluorite transition, where the deposit was upwardly zoned from pyrite to pyrite-tellurides to fluorite (Lueth and others, 1996).

Pals and Spry (2003) report that telluride minerals associated with alkaline magmatism account for 10 to 50 percent of the gold in the Emperor deposit at Vatukoula in Fiji's Western Division. Sylvanite is the main precious-metal-hosting phase, although the epithermal ores also include benleonardite, coloradoite, and native tellurium. Grab samples of these ores contain as much as 345 ppm tellurium, which correlates with very high concentrations of fluorine, gold, selenium, and silver (Kwak, 1990).

The Dashuigou deposit in the alkalic magmatic province of southwestern China (Sichuan Province) hosts a reported 9,400-metric-ton indicated resource averaging 1.40 percent tellurium and a 20,800-metric-ton inferred resource averaging 0.51 percent tellurium, for a total resource of 240 metric tons of tellurium. The indicated and inferred resources at the similar nearby Majiagou deposit in Sichuan Province contain an estimated 272 metric tons of tellurium; the average grade of the resources is about 2 percent tellurium. The ores contain even larger bismuth resources, reflecting the composition of the tetradyomite ( $\text{Bi}_2\text{Te}_2\text{S}$ )—59.27 percent bismuth, 36.19 percent tellurium, and 4.55 percent sulfur, by weight (Behre Dolbear Asia Inc., 2009). The tellurium resource occurs in low-sulfidation epithermal veins with highly variable grades that locally reach 8 percent tellurium (Behre Dolbear Asia Inc., 2009). Many parts of the orebodies consist of massive pyrrhotite, which were previously mined for iron. The ores also contain anomalous gold, which is interpreted to have been deposited after both the tellurium-bearing phases and native tellurium (Mao and others, 2002). The current annual production of these two deposits is unknown, but Anderson (2015) estimated it to be between 10 and 30 metric tons per year of tellurium.

Cook and Ciobanu (2005) importantly stressed that although there is definitely a common genetic link between tellurium-bearing gold deposits and alkalic magmatism, many low-sulfidation epithermal systems with significant volumes of telluride minerals are also associated with normal calc-alkaline magmatism. For example, calc-alkaline-related telluride ores are diverse and were historically economic across a 600-square-kilometer area in the Munții Metaliferi (Metaliferi Mountains) in western Romania, which is one of Earth's richest epithermal ore regions (Alderton and Fallick, 2000). The western Romania telluride minerals include hedleyite, rucklidgeite, and tsumoite, which are not common in most tellurium-rich epithermal deposits and tend to occur in the shallowest parts of the deposits (Cook and Ciobanu, 2004). Over several centuries, until 1941, the Sacarimb deposit, which is located in Hunedoara County in the Metaliferi Mountains, is estimated to have cumulatively produced 30 metric tons of gold, 85 metric tons of silver, and 60 metric tons of tellurium from ores that averaged 20 g/t tellurium and 10 g/t gold. Ore minerals were mainly nagyagite and sylvanite that were deposited in Neogene calc-alkaline volcanic rocks (Popescu and Neacsu, 2004). This deposit is also the type locality for krennerite, museumite, muthmannite, nagyágite, petzite, and stutzite. The telluride minerals were deposited at temperatures of between 200 and 300 °C from very dilute hydrothermal solutions (Cook and others, 2005).

Other low-sulfidation epithermal deposits with an abundance of telluride minerals could be future sources of tellurium resources. For example, the Jefferson gold-silver project, which is located a few kilometers east of the giant Round Mountain low-sulfidation epithermal deposit in Nye County, Nev., has also been evaluated as a primary tellurium resource (Mexivada Mining Corp., 2008). This evaluation

is still very speculative, however, as such a possibility is based solely upon a small number of drill intersections with assays of tens to hundreds of parts per million tellurium.

High-sulfidation epithermal deposits are a significant gold source, and some have produced appreciable amounts of copper (for example, the Lepanto deposit in Benguet Province, Philippines, and the El Indio deposit in the Coquimbo region of Chile). The deposits are synvolcanic in the centers of andesite-dacite volcanic complexes. Copper-arsenic-antimony sulfosalts are the principal copper-bearing minerals. Tellurium commonly substitutes for arsenic and antimony in tennantite locally and in sufficient abundance to form the tellurian endmember goldfieldite. In all well-studied high-sulfidation epithermal deposits, precious-metal telluride minerals have been documented, although they are generally less economically important than native gold and electrum. At the El Indio deposit, native tellurium is associated with high-sulfidation alteration (Siddeley and Araneda, 1986).

Kesler and others (2003) documented the distribution of tellurium in the high-sulfidation epithermal deposits of the Pueblo Viejo district in Sánchez Ramírez Province, Dominican Republic. They concluded that tellurium appears to increase steadily upward in the deposit. In the district's Monte Negro orebody, higher tellurium concentrations generally correspond to higher gold concentrations, and both increase steadily upward in the deposit. Lehmann and others (1999) discussed the abundance of telluride minerals in the Bereznyakovskoe high-sulfidation epithermal deposit in Chelyabinskaya Oblast' in the Urals. They noted that precious-metal mineralization was associated with a tetrahedrite-telluride hydrothermal stage, and that mineralized and altered rock varied from tens to hundreds of parts per million tellurium. At the Lepanto deposit, Benguet Province, Philippines, enargite grains were noted to contain many hundreds of parts per million tellurium (Deyell and Hedenquist, 2011). Chaffee and others (1981) analyzed stream sediment samples from the Patagonia Mountains in Arizona and found tellurium anomalies (>399 ppb) consistently associated with high-sulfidation alteration, as well as a high local background of 100 to 399 ppb tellurium and a broader regional background of 15 to 99 ppb tellurium in samples more distal to the mineralization.

The variety of telluride minerals in high-sulfidation deposits is not extensive. The common telluride minerals are calaverite, hessite, krennerite, petzite, and sylvanite. Arribas and others (1995) reported the occurrence of the secondary tellurite minerals blakeite, emmonsite, and rodalquilarite at Rodalquilar, Andalusia, Spain.

The Deer Horn intermediate-sulfidation epithermal deposit in west-central British Columbia, Canada, contains high gold and silver grades with abundant base-metal sulfides and telluride minerals. A National Instrument (NI) 43-101 resource evaluation (Deer Horn Metals Inc., 2012) suggested resources of 66 metric tons of tellurium, as well as 2,100 kilograms (kg) (68,000 troy ounces) of gold and 65,000 kg (2.1 million troy ounces) of silver. Tellurium concentrations in drill intercepts with the highest

precious-metal grades are generally 150 to 250 ppm, and some of the highest values were in the thousands of parts per million tellurium; analyses of these zones indicate a silver-to-tellurium ratio that is generally about 1:1.

The Sandaowanzi intermediate-sulfidation epithermal deposit in Heilongjiang Province is one of the many extension-related Early Cretaceous epithermal and porphyry deposits of northeastern China. The deposit contains more than 15 metric tons of gold and has been mined since 2006. It is almost entirely characterized by micrometer- to millimeter-size disseminated and quartz vein-hosted, coarse-grained silver- and gold-bearing telluride minerals, with lesser amounts of lead- and mercury-bearing telluride minerals; the largest grains are 3 centimeters in diameter (Liu and others, 2011, 2013). Tellurium is likely being recovered, although the amount being recovered is not available.

Some tellurium-rich deposits have descriptive attributes of both low- and high-sulfidation deposits; for example, the deposit at Kochbulak in Toshkent Province, Uzbekistan. Here, the telluride mineral assemblage is more diverse than is typical of high-sulfidation deposits, and the tellurium content of ores averages 101.6 ppm (Plotinskaya and others, 2006). In the Baguio district, Benguet Province, Philippines, both intermediate- and high-sulfidation epithermal mineral deposits are present, whereas abundant telluride minerals are associated only with the advanced argillic alteration in the high-sulfidation ores.

## Orogenic Gold Deposits

Structurally controlled gold deposits in metamorphic rocks, or orogenic gold deposits, may contain high abundances of tellurium-bearing mineral phases. High concentrations of tellurium are present in both Precambrian deposits in greenstone belts and in Phanerozoic gold deposits hosted in metasedimentary rock-dominant orogens. Similar to the epithermal deposits, these concentrations of tellurium have so far not been recovered during gold mining, although gold-bearing tellurides can constitute a significant amount of the recovered gold ore. In many districts, specific deposits hosted by local intrusions, rather than those in widespread meta-volcanic or metasedimentary country rocks, tend to contain a high abundance of telluride minerals (see the discussion of Kirkland Lake and Kensington below), suggesting that oxidation of ore fluids by the felsic to intermediate igneous rocks provides, in some cases, a major control on destabilizing hydrothermal tellurium complexes. Abundant tellurides and the presence of hydrothermal hematite in other deposits, such as the Golden Mile deposit in Western Australia, Australia, and the Commoner deposit in Mashonaland West, Zimbabwe, also suggest some degree of oxidation of the ore fluids.

The world's largest Archean orogenic gold deposit, the Golden Mile, which is hosted in mainly mafic metavolcanic rocks of the Yilgarn Craton of Western Australia, contains 1,500 metric tons of gold. Although the majority of the ore is hosted in arsenic-rich pyrite, about 20 percent of the

resource is hosted in late-stage telluride minerals (Lindgren, 1906; Mueller and Muhling, 2013). Many of the higher-grade gold zones contain hundreds of parts per million tellurium. Recognized minerals that concentrate gold, mercury, and (or) silver, as well as the tellurium, include calaverite, coloradoite, hessite, and petzite, with a total of 19 distinct telluride phases identified. Mueller and Muhling (2013) described a zoning of telluride minerals that progressed from a core of calaverite to hessite to an outer, very late coloradoite zone. Shackleton and others (2003) noted the telluride minerals occur as fine-grained composite aggregates, massive segregations, composite grains with native gold, inclusions in and intergrowths with pyrite and tetrahedrite-group minerals, or inclusions in carbonates, quartz, and tourmaline. Eilu and others (1998) measured tellurium anomalies of greater than 10 ppm in mafic volcanic rocks for more than 100 meters (m) beyond the Western Australia ore zones and suggested that tellurium is a very important geochemical pathfinder for orogenic gold in the Yilgarn Craton.

Similarly, many of the world-class Archean gold deposits of the Abitibi and Yellowknife greenstone belts in Canada may have elevated concentrations of tellurium, typically in gold-bearing telluride minerals. Telluride minerals are common in deposits in the Kirkland Lake and Red Lake districts of Ontario, Canada. As in other deposits, the tellurides, as well as much of the gold, are typically paragenetically late stage (for example, Thomson, 1928). Native gold in the syenite-hosted gold-bearing veins at the Kirkland Lake deposit occurs with altaite, calaverite, coloradoite, and petzite, as well as sericite. Highest grade ore samples of about 200 to 400 ppm gold also contain about 200 to 500 ppm molybdenum and 300 to 700 ppm tellurium, with a typical gold-molybdenum-tellurium signature interpreted as representing an alkali magmatic ore fluid source that is unusual in the district (Ispolatov and others, 2008). Boyle (1979) reported that the tellurium in the ores of the Yellowknife mining district in Northwest Territories, Canada, contained, in the main sulfide stage, as much as 1,000 ppm tellurium in galena, 100 ppm tellurium in stibnite, and 100 ppm tellurium in lead-bearing sulfosalt minerals.

A strong gold-tellurium association is also recognized at Ashanti in Western Region, Ghana, which hosts the world's largest Paleoproterozoic orogenic gold deposit. Four microscopic telluride minerals (altaite, coloradoite, hessite, and petzite) and seven submicroscopic telluride minerals have been analyzed at Ashanti within a hematite-quartz-telluride assemblage; the assemblage was deposited with minor amounts of native gold that formed after an earlier event that deposited the bulk of the gold ore (Bowell and others, 1990). The telluride mineral distribution is zoned from an inner coloradoite-rich assemblage in the veins to an assemblage dominated by altaite along the vein walls and in the country rocks. The late telluride event was shown to reflect a cooling of fluid temperature and associated oxidation, because hypogene hematite and goethite were deposited with the telluride minerals.

The Phanerozoic deposits in accreted metasedimentary rock belts are also commonly characterized by an abundance of gold- and silver-rich telluride minerals. Altaite, calaverite, melonite, petzite, and sylvanite are associated with the main mineralization event that formed the gold veins, stockworks, and breccias in the early Paleozoic clastic rocks at the Kumtor deposit, Ysyk-Kol Oblusu, Kyrgyzstan (Ivanov and others, 2000). The Cretaceous California Mother Lode deposits have been long recognized for their common gold-, lead-, nickel-, and silver-bearing telluride minerals that are associated with native gold (Turner and Becker, 1894). As noted above, intrusions emplaced into these terranes, which are often structurally favorable hosts for the vein deposits, tend to have greater abundances of telluride minerals. The Eocene Kensington gold deposit in the Juneau gold belt, southeastern Alaska, is dominated by veins within an intermediate stock with native gold, calaverite, and petzite, and lesser amounts of alatite, hessite, sylvanite, tellurobismuthite, and volynskite (Casey, 2000). Much of the gold endowment is hosted in the two main telluride minerals. Similarly, the tonalite-hosted Willow Creek district in the Matanuska-Susitna Borough of south-central Alaska contains abundant telluride minerals in the main ore assemblage; coloradoite is the dominant mineral, and altaite and nagyagite occur in lesser amounts (Burleigh, 1987). Interestingly, the main gold ores of the Grass Valley district of Nevada County, Calif., are hosted by north-striking veins cutting granodiorite, but these lack telluride minerals; only auriferous east-west-striking veins in adjacent mafic and ultramafic country rocks contain lead- and silver-bearing telluride minerals (Johnston, 1940).

Many Russian and central Asian Phanerozoic gold deposits report significant platinum and palladium grades. Whereas some of this may reflect high backgrounds of PGMs in black shale host rocks, some PGMs are clearly associated with numerous tellurium-bearing minerals. For example, at the Sukhoi Log gold deposit in Irkutskaya Oblast', eastern Russia, palladium-bearing telluride minerals are present, as well as many bismuth-, gold-, lead-, and silver-rich telluride minerals (Distler and Yudovskaya, 2005).

Low-grade (<1 g/t gold) disseminated-style mineralization is associated with the bulk-tonnage open pit mining operations along the Mojave-Sonora megashear zone in northern Sonora, Mexico. A small, recently worked underground operation along the southeastern side of the shear zone, the La Bambolla deposit in the Moctezuma district (Mexivada Mining Corp., 2008; E.O. Monteagudo, unpub. data, 2009) developed ores from gold-hematite-quartz-pyrite-telluride veins, which averaged, in order of value, 4 g/t gold, 5 g/t silver, and 2.5 g/t tellurium; it is not clear, however, whether any of the tellurium was recovered along with the precious metals. Some mineralized grab samples were reported to contain as much as 3.2 percent tellurium. Although classification of this deposit is not clear, it occurs in a belt of orogenic gold deposits, and La Bambolla would be one rare example of an orogenic gold deposit from which tellurium is produced as a primary commodity.

## Carlin-Type Gold Deposits

The Carlin-type gold deposits in Nevada are Tertiary replacement ores in carbonate-dominant rock sequences that have undergone decarbonization and sulfidation, and ores occur as submicron-sized gold in disseminated pyrite. In contrast to the epithermal and orogenic gold ores, Carlin-type ores are not widely recognized for containing abundant telluride minerals. In part, this may reflect the exceptional fine-grained nature of the ores, so that the telluride minerals are rarely visible. Nevertheless, Harris and Radtke (1976), in one of the first geochemical studies of the Carlin gold deposit itself (which is located in Eureka County, Nev.), indicated a strong gold-tellurium correlation, which would favor the presence of telluride minerals in this deposit type. Emsbo and others (2003) noted minor amounts of telluride minerals and as much as 130 ppm tellurium in ore-related pyrite in the Meikle deposit of Elko County, Nev. Cail and Cline (2001) report values for ores of as much as 180 ppm tellurium in the Getchell trend in Humboldt County, Nev., and Heitt and others (2003) indicate as much as 84 ppm tellurium at the Deep Star deposit in Eureka County, Nev. Ore-stage pyrites in the Carlin ores may contain thousands of parts per million tellurium (Muntean and others, 2011).

Whereas telluride minerals are typically not reported from the classic Carlin ores in Nevada, the Carlin-like Zarshuran deposit in West Azerbaijan Province, Iran, contains coloradoite and tellurium-bearing orpiment that were deposited with arsenian pyrite during the main gold event (Asadi and others, 2000). This could suggest either variability in the metal source or hydrothermal fluid chemistries among Carlin-type gold deposits, or more-significant differences in deposit type than originally thought between the defined Carlin deposits of Nevada and the Zarshuran ores.

## Resources and Production

### Identified Resources and Reserves

Specific global and domestic sources for tellurium are very poorly known because tellurium is mostly a byproduct of the mining of a number of different base-metal-rich deposit types. Tellurium concentrations are highest in precious-metal-bearing deposits that contain abundant telluride minerals; these deposits, however, currently are not significant sources of tellurium because the ore-processing method to extract gold and silver is not amenable to tellurium recovery. Instead, tellurium concentrated in sulfide minerals in base-metal-rich deposits is the current main source of tellurium because the refining process for such base-metal-rich ores is amenable to tellurium recovery. The only certain present-day primary sources for tellurium ore are the Kankberg VMS deposit in Västerbotten County, Sweden, which produces about 10 percent of the world's tellurium, and the Dashuigou and Majiagou epithermal deposits in China, which together produce from 2 to 7 percent of the world's tellurium (fig. R1).

Whether the orogenic gold-tellurium deposits in Sonora, Mexico, are also active primary tellurium producers is not clear (for example, La Bambolla with a possible eastern extension at AuroTellurio). Importantly, prior to leaching and recovery, most gold ores are roasted or subjected to other pre-leaching processes. Tellurium is not recovered during this pretreatment and is typically lost from later recovery.

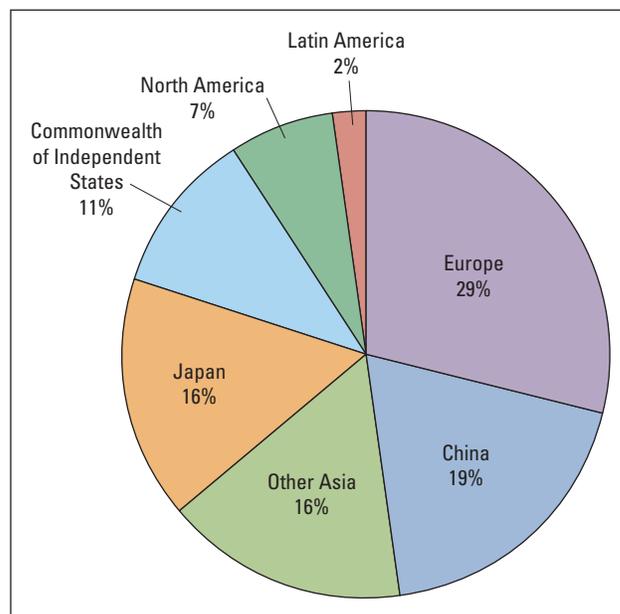
The availability of economically recoverable tellurium depends on the production of copper as a (or the) primary product. Reliance on mining tellurium as a primary material would drastically increase its cost. At least 75 percent of the world's recovered tellurium is produced as a byproduct of copper mining, although not all the mined tellurium is recovered at the copper refineries (Anderson, 2015). Tellurium can only be extracted from copper that is refined by the electrolytic process, a technique that is cost-effectively applied to high-grade copper ores (Moss and others, 2011). In such a process, tellurium and other impurities, such as gold, silver, and platinum, are concentrated at and removed from the crude copper anodes. Typically, the slimes contain from 1 to 4 percent tellurium, although as much as 8 to 9 percent tellurium in the slimes has been reported at some refineries. These numbers reflect a recovery rate of a little less than 50 percent of the available tellurium within the slimes. For refining lower grade copper ores, the most economical process is the solvent-leach refining process, which is currently not capable of recovering tellurium. The global decrease in the supply of high-grade copper ores may constrain the future supply of tellurium from copper (Moss and others, 2011). In addition to copper refineries, as much as 8 to 10 percent of the world tellurium supply is recovered from lead refinery skimming and from the flue dust and gases of copper smelting (Moss and others, 2011). Not only are data from many of these milling operations unavailable, but also little information about the source of the ores is available. Concentrates are commonly shipped to a mill in a different country than that in which the ore is mined and, therefore, the original source of the recovered tellurium is not known.

A small amount of tellurium is currently recovered from recycled sources, such as selenium-tellurium solar cells. The leading cadmium-tellurium solar cell manufacturer has a free-of-charge recycling program for discarded photovoltaic solar cell panels, which could become more important in the future. When large volumes of currently installed panels reach their end-of-life stage, they will be recycled for secondary tellurium or cadmium-tellurium. Pilot recycling facilities recover as much as 95 percent of semiconductor material and can provide feedstock for future production of photovoltaic solar panels (Moss and others, 2011).

In the United States, tellurium demand is met partly domestically and partly by imports. Almost all the domestic commercial-grade tellurium production is from ASARCO's copper refinery in Texas, where it is recovered as a byproduct of copper anode slimes and lead refinery skimming. Resulting exports from the United States in 2012 were 47 metric tons of tellurium, whereas 36 metric tons of tellurium was imported

from refineries abroad. About 66 percent of the tellurium was imported from China and Canada, and lesser amounts were imported from the Philippines and Belgium (George, 2014b).

Global reserves of tellurium were 24,000 metric tons in the beginning of 2014, which includes estimates of 3,600 metric tons in Peru, 3,500 metric tons in the United States, and 800 metric tons in Canada (George, 2014b). The lack of reserves in Chile is surprising, given that its porphyry deposits make Chile the world's leading copper producer; this indicates the lack of publicly available data for Chile, which also is characteristic of much of the global tellurium supply. Refineries around the world are estimated to produce 450 to 470 metric tons of tellurium annually as tellurium metal, crude tellurium dioxide, or crude copper telluride; the latter two commodities must be further processed to produce tellurium metal. Data for tellurium metal recovered in specific countries in 2010 include 41 metric tons from Sweden, 40 metric tons from Japan, 35 metric tons from Russia, 30 metric tons from Peru, more than 30 metric tons from China, and 6 to 10 metric tons from Canada. Data from the United States are proprietary, but the British Geological Survey estimates that 50 metric tons of tellurium are recovered in the United States (Brown and others, 2013). Other production of tellurium metal comes from refineries in Australia, Belgium, Chile, Colombia, Germany, Kazakhstan, Mexico, the Philippines, and Poland. Estimated refinery production by world region is shown in figure R4.



**Figure R4.** Pie chart showing percentage of estimated world tellurium refinery production in 2013, by country or region. Except for two primary producers in Sweden and China, which may contribute 15 percent of the annual global production of approximately 450 to 470 metric tons of tellurium, the majority of global production is as a byproduct from the refining of copper and other base-metal ores. Compiled using data from various sources, including George (2014a).

## Undiscovered Resources

There are no available estimates of undiscovered resources of tellurium. Hypothetically, existing waste piles from the milling of large-tonnage copper, iron, and other massive base-metal orebodies may contain economically recoverable amounts of tellurium. Maness (2010) suggests a potential for economic amounts of tellurium, as well as for other critical and near-critical elements, could exist in waste from massive sulfide ores in locations such as the Ducktown (Tennessee), Leadville (Colorado), and Joplin (Missouri) districts, as well as high-sulfur coal waste dumps in the United States. He pointed out that the world's best potential source for such elements could be the giant copper-slag heaps on the island of Cyprus from centuries of mining. Detailed analytical studies of sulfide-rich waste material in such old mining camps could fingerprint areas in the United States and elsewhere with the highest potential as future sources of readily recoverable tellurium (Cone, 2013).

Whereas only a few gold deposits worldwide are producers of tellurium, abundant gold-telluride minerals are the one viable source for the mining of primary tellurium ores. As noted previously, most (likely as much as 80 to 85 percent) of the world's tellurium is produced from anode slimes collected during the electrolytic refining of copper. If, however, the more economical solvent-leach procedure is increasingly used in the future to recover lower grades of copper from porphyry and other large-tonnage deposits, which is a process that does not recover tellurium, then additional high-grade, tellurium-rich gold deposits may become new primary sources for tellurium. This is likely particularly true of the epithermal gold deposits associated with alkaline magmatism, such as those in the Cripple Creek district of Teller County, Colo. Improved extraction techniques for the recovery of tellurium from telluride-mineral-rich ores, coupled with lesser amounts of tellurium recovered from electrolytic refining, could lead to the production of tellurium from ore milled at deposits such as Cripple Creek.

Unconventional resources of tellurium in the world's oceans may become economic in the future should sea-floor mining become feasible. As pointed out by Hein and others (2013), iron-manganese crusts that precipitate onto the surface of seamounts, ridges, and plateaus at depths of 400 to 7,000 m can contain tens of parts per million tellurium. This is about three orders of magnitude greater than concentrations found in tellurium-enriched marine black shales that are now preserved on continents. It is possible that, in future decades, the global tellurium demand could be met by recovery of tellurium-rich crusts from some of the shallower marine operations.

## Exploration for New Deposits

Watterson and others (1977) point out that tellurium is a useful pathfinder element to aid in the exploration for the many types of ore deposits described above. They define well-developed tellurium dispersion halos associated with porphyry, epithermal, and polymetallic vein deposit types. In the weathering zone, tellurites (for example, emmonsite and poughite) become enriched relative to sulfates because sulfates are much more soluble. They note that average concentrations of about 2 ppm tellurium occur in gossans surrounding the porphyry copper ores in Ely, Nev. Anomalous tellurium was detected surrounding silver-lead-zinc veins in central Colorado more than a few hundred meters beyond any visible alteration (Watterson and others, 1977). Values of as much as 1 ppm tellurium in stream sediments were noted to be excellent indicators of upstream gold-bearing telluride ores in the southwestern Pacific epithermal deposits (Rytuba and Miller, 1990). Tellurium gave the broadest halos of any pathfinder surrounding orogenic gold deposits in Western Australia, Australia (Eilu and others, 1998).

These tellurium anomalies obviously do not indicate ore deposits with tellurium as a main commodity, but rather, deposits of a variety of types where tellurium could be present at levels that would make it an important recoverable byproduct. Because tellurium as a primary commodity is extremely rare, exploration for "tellurium deposits" is essentially almost never undertaken by the private sector. Geochemical ore pathfinder elements and geophysical exploration techniques will differ by mineral deposit type, and because tellurium can be enriched in many common varieties of hydrothermal ore deposits, specific exploration guides for potential tellurium deposits are not definable.

## Environmental Considerations

The environmental characteristics of tellurium extraction are closely linked to those associated with the mining of the two types of copper deposits that represent its main sources: porphyry copper and VMS deposits. These two deposit types differ from one another significantly in terms of their geology and their environmental characteristics. Tellurium also occurs at elevated concentrations in some precious-metal deposits, but tellurium is presently produced from these in only a few locations.

The environmental geology of porphyry copper deposits has recently been reviewed by John and others (2010). Because the deposits are large in size and of low grade, they are commonly mined by open pit methods. The solid mine wastes have variable potential to generate minor amounts of acid drainage or neutralize it. The environmental geology of VMS deposits has been reviewed by Seal and Hammarstrom (2003), Seal and Piatak (2012), and Shanks and

Thurston (2012). The deposits are typically of moderate size, having lens-like or tabular ore geometries, high grades of base metals, and a high potential of solid mine wastes to generate acid drainage.

## Sources and Fate in the Environment

The abundance of tellurium in the upper continental crust is quite low (3 ppb) (Li and Schoonmaker, 2003). The low environmental concentrations of tellurium in all environmental media are a reflection of its low crustal abundance. Because of its low abundance, tellurium is rarely included in environmental surveys unless there is a specific interest. Therefore, data on its concentration in environmental media are limited. Andreae (1984) reported concentrations of 0.51 and 3.32 parts per trillion (ppt) for rainwater. Seawater concentrations of tellurium are significantly lower and range between 0.03 and 0.87 ppt (Andreae, 1984; Lee and Edmond, 1985). Under oxygenated conditions in surface water, tellurium is present as the oxidized species tellurate (Te(VI)); the solubility of tellurium at 25 °C at pH 7 is approximately 25 ppb (McPhail, 1995).

For solid environmental media, data are available for tellurium in soils and plants. In the national geochemical survey of soil in the United States, Smith and others (2013) reported concentrations of tellurium ranging between less than 0.1 and 50.5 ppm, with most values less than 0.1 ppm. Cowgill (1988) documented concentrations in plants with mean values (dry basis) that ranged between 4.2 and 25.9 ppb, and found a strong correlation between soil and plant concentrations.

Information on pre-mining environmental concentrations of tellurium is lacking owing to its low concentrations. From an environmental perspective, baseline concentrations of other elements of environmental interest associated with porphyry copper or VMS deposits are of greater interest than those of tellurium because of the potential during mining to significantly elevate their concentrations in the environment. Few environmental baseline studies of porphyry copper deposits have been conducted, particularly with respect to the diversity of climatic settings in which they are found; however, some pre-mining soil and sediment information is available in mine permit applications for recently proposed mines. Studies from diverse climates, such as the cold climates of southwestern Alaska (Anderson and others, 2011); tropical climates of Puerto Rico (Learned and Boissen, 1973; Plaza-Toledo, 2005); and hot, arid climates of Arizona and Chile (Chaffee, 1976, 1977; Chaffee and others, 1981; Leybourne and Cameron, 2006, 2008) show similar geochemical features. Soils and sediments show elevated concentrations of iron, arsenic, cadmium, copper, molybdenum, lead, and zinc.

Pre-mining surface water and groundwater data are also limited. Plaza-Toledo (2005) and Anderson and others (2011) conducted pre-mining water-quality studies in the humid settings of Puerto Rico and southwestern

Alaska (Pebble deposit), respectively, and Leybourne and Cameron (2006, 2008) investigated groundwater quality in the arid Atacama Desert of Chile. In humid settings, the pH ranged between 4.1 and 8.6. Alkalinity ranged between 0 and 100 ppm calcium carbonate (CaCO<sub>3</sub>) equivalent; sulfate, between 1 and 85 ppm; and hardness, between 2 and 130 ppm CaCO<sub>3</sub> equivalent. Dissolved trace element concentrations showed a range of values, including arsenic (<1 to 36.2 ppb), cadmium (<0.2 to 11.6 ppb), copper (<0.5 to 688 ppb), iron (<20 to 15,900 ppb), lead (<0.05 to 18.8 ppb), molybdenum (<2 to 21.9 ppb), and zinc (<0.5 to 68 ppb). Leybourne and Cameron (2006, 2008) documented high-salinity groundwater associated with the undeveloped Spence copper deposit in the Atacama Desert, Chile, reaching salinities of 1.0 to 5.5 percent, with one outlier at 14.5 percent. 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 arsenic (<10 to 160.9 ppb), copper (9 to 28,991 ppb), iron (4 to 54,454 ppb), molybdenum (2 to 475 ppb), lead (0.025 to 23.8 ppb), and zinc (5 to 1,344 ppb).

The geologic and geochemical features of VMS deposits are manifested in the surrounding environmental media, such as soil, stream sediment, surface water, and groundwater. Soils and stream sediments surrounding undeveloped deposits can have elevated concentrations of arsenic, barium, cadmium, copper, iron, lead, nickel, and zinc. The surface water and groundwater data associated with undisturbed VMS deposits span a range in pH from 3 to 10; a range of dissolved iron (a dominant cation) from <0.02 to 300 ppm; and dissolved sulfate (also the product of pyrite or pyrrhotite weathering) from <0.1 to 4,000 ppm (Seal and Hammarstrom, 2003; Eppinger and others, 2007; Seal and Piatak, 2012;). Other dissolved constituents surrounding undeveloped deposits span a range of values, including for aluminum (<0.002 to 100 ppm), arsenic (<0.1 to 430 ppb), cadmium (<0.1 to 600 ppb), copper (<0.003 to 20 ppm), lead (<0.1 to 500 ppb), and zinc (<3 to 200 ppm).

## Mine Waste Characteristics

The amount of mine waste associated with porphyry copper and VMS deposits varies with the size of the deposit. Porphyry copper deposits range from 30 million metric tons to greater than 20 billion metric tons of “ore” with a median size of 250 million metric tons (John and others, 2010). Because copper grades are typically less than 1 percent copper (median grade is 0.44 percent copper), more than 95 percent of the material mined will end up as solid mine waste of one form or another. The VMS deposits are variable in size, ranging from 1 to 600 million metric tons; the copper, lead, and zinc ore grades are also very variable, but typically average 2 to 5 percent (Seal and Hammarstrom, 2003).

Solid mine waste at porphyry copper and VMS deposits typically falls into two main types: tailings and waste rock. A third type, leach pad waste, is present only at those mines where the ores are amenable to copper extraction by the electrolytic refining process, or where a leached cap may have residual gold grades that are amenable to extraction. The electrolytic process is not amenable to tellurium recovery. 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 using a technique known as froth flotation. This technique yields a “concentrate” of sulfide minerals, and a waste material, known as tailings, which can be pumped as a slurry or trucked dry to a tailings storage facility on site. The copper concentrate is sent to a smelter and refinery complex, where copper and other mined commodities, such as tellurium, are recovered. Tailings storage facilities are typically impoundments surrounded by a retaining dam.

Waste rock is uneconomic rock that must be removed to access the ore. Waste rock is disposed of on site. For open pit porphyry copper mines, waste-to-ore (stripping) ratios commonly 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 a method known as block caving. A vertical shaft or spiral decline is built to the base of the orebody, and the ore is mined from below, leaving a large, unsupported cavity from which the ore was removed. With this type of mining, the amount of waste rock is minimal and the waste material is dominated by tailings. As with porphyry copper deposits, the amount of waste rock associated with VMS deposits depends on the mining method, which in turn depends on the geometry of the orebody.

The mineralogy of the ore and waste in porphyry copper and VMS mines serves as the foundation for understanding the environmental characteristics of these deposits. In terms of both ecological risk and human health risk, the mineralogy influences the acid-generating potential of the ores and wastes and the mobility of trace elements. In porphyry copper deposits, ore minerals such as bornite, chalcopyrite, enargite, galena, molybdenite, pyrite, and sphalerite are the main hosts of trace elements of environmental concern; in total, they typically constitute less than 5 percent of the ore (John and others, 2010). Tellurium is typically hosted by trace amounts of gold-, silver-, or PGM-bearing tellurides. In VMS deposits, the ore minerals are dominated by pyrite and pyrrhotite, with varying amounts of chalcopyrite, galena, and sphalerite, and a variety of accessory minerals (Shanks and Thurston, 2012). The trace-element geochemistry of tailings reflects the mineralogy of the waste material. For porphyry copper deposits, tailings typically contain significant concentrations of arsenic, copper, manganese, molybdenum, and zinc (John and others, 2010). Tailings from copper-dominant VMS deposits can contain elevated concentrations of aluminum, arsenic, cadmium, copper, iron, lead, sulfur, and zinc (Seal and Hammarstrom, 2003; Seal and Piatak, 2012).

Approaches for managing solid waste depend upon its acid-generating potential. Metals and many other trace elements tend to be more soluble at low pH rather than at neutral or high pH. Therefore, the acid-generating or acid-neutralizing potentials of the waste rock and tailings 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. Therefore, the units are kilograms of calcium carbonate per metric ton of mine waste ( $\text{kg CaCO}_3/\text{t}$ ) (Price, 2009; International Network for Acid Prevention, 2011). The acid-generating potential primarily resides in pyrite. Mine waste can also have acid-neutralizing potential that resides in carbonate minerals, such as calcite, and some silicate minerals, such as feldspars.

The rocks associated with porphyry copper deposits tend, in general, to straddle the boundary between having net acid-generating potential and having net acid-neutralizing potential, but the amount of either is relatively small compared with the high acid-generating potential associated with VMS deposits. For example, at the Pebble porphyry copper deposit in Alaska, the various mine waste materials are expected to span a range from a net acid-generating potential of  $110 \text{ kg CaCO}_3/\text{t}$  to a net acid-neutralizing potential of  $27 \text{ kg CaCO}_3/\text{t}$  (Pebble Partnership, 2011, written commun.). In contrast, mine waste from VMS deposits typically has net acid-generating potential, commonly ranging between 100 and  $350 \text{ kg CaCO}_3/\text{t}$ , although some waste can have net neutralizing potential locally (Lindsay and others, 2009; Seal and Piatak, 2012).

## Human Health Concerns

Tellurium does not appear to be an essential trace element for human health (Kobayashi, 2004; Ba and others, 2010). No information is available on the toxic effects of tellurium on humans, presumably in part because of its low natural abundance. The Agency for Toxic Substances and Disease Registry does not have a toxicological profile for tellurium, nor does the U.S. Environmental Protection Agency have drinking water standards or soil guidelines for tellurium. Animal studies, using large doses of tellurium administered either through ingestion, inhalation, or intravenously, indicated the target sites for tellurium toxicity are the kidneys, nervous system, skin, and brain in a fetus (Taylor, 1996). The reduced species, tellurite, is more toxic than either arsenite or selenite, and, tellurite is 10 times more toxic than the oxidized species tellurate (Taylor, 1996).

The more significant human health risks associated with tellurium production are found with the broader aspects of mining porphyry copper and VMS deposits. Contaminated groundwater plumes associated with tailings impoundments may pose threats to drinking-water supplies, depending upon the geologic and hydrologic setting and the engineering aspects of the mine and the waste piles for both deposit types. Host rocks with higher 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 VMS deposits, elements or compounds with the greatest likelihood of causing problems for drinking-water sources include aluminum, arsenic, cadmium, copper, iron, manganese, sulfate, and zinc. The potential for groundwater contamination depends upon the waste- and water-management practices in place at any given mine.

## Ecological Health Concerns

As with the human health guidelines, no information is available for tellurium and its toxic effects on aquatic or terrestrial ecosystems, whether through surface water, soil, or sediment. The U.S. Environmental Protection Agency does not have surface water or sediment guidelines for tellurium. Thus, the more significant ecosystem risks associated with tellurium production are found with the broader aspects of mining porphyry copper and VMS deposits. Many of the ecological risks associated with both deposit types 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 controlled by the pyrite content, which may be offset by the acid-neutralizing potential of carbonate or silicate minerals. Tailings are prone to water transport, particularly in the case of a tailings dam failure, and wind transport, because of the fine-size sand and silt grains. Thus, tailings 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 district in Arizona (Eychaner, 1991; Stollenwerk, 1994; Brown and others, 1998; Lind and others, 1998; Conklin and others, 2001); the Morenci district in Greenlee County, Ariz. (Enders and others, 2006); and the Sar Cheshmeh deposit in Iran (Khorasanipour and others, 2011). Many of these values exceed relevant water-quality guidelines for the protection of aquatic ecosystems for aluminum, copper, iron, manganese, and zinc (U.S. Environmental Protection Agency, 2009). The pH can commonly range from 2 to 8.5, and sulfate, which is the dominant anion, can locally reach 30,000 ppm.

Pit lakes, particularly in porphyry copper mining districts that are riddled with historical underground mine workings, such as at Butte, Mont., 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 Duaime, 2005; Gammons and others, 2005). The pit lake has high dissolved solids and elevated concentrations

of copper, iron, sulfate, and zinc (Gammons and Duaime, 2005). In contrast, pit lakes in the Yerington (Lyon County) and Robinson (White Pine County) districts, 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, total dissolved solids are generally less than 6,000 ppm; concentrations of iron reach a maximum of 4.5 ppm; arsenic, less than 0.05 ppm; manganese, less than 5 ppm; and selenium, less than 0.14 ppm.

The VMS mines are noted for their significant impacts on the aquatic ecosystem associated with abandoned historical mines, such as at Iron Mountain, Calif. Iron Mountain is unique among abandoned mines in that its effluent and seeps within the mine workings have extremely low pH (−4 to 1.5) and dissolved copper, iron, sulfate, and zinc are present in concentrations reaching hundreds of grams per liter (Alpers and others, 2003). The unusual chemistry of mine drainage at Iron Mountain is the result of an atypical combination of factors related to its geologic, hydrologic, and climatic setting. In contrast, the pH values from mine drainage from a broader spectrum of VMS mines are typically much lower than the values recorded at Iron Mountain, ranging from 2 to 8, including concentrations of dissolved copper (<0.1 ppb to 3 ppm), iron (1 ppb to 3 grams per liter [g/L]), sulfate (1 ppm to 10 g/L), and zinc (<1 ppb to 1 g/L) (Seal and Hammarstrom, 2003). Other trace elements found in environmentally significant concentrations associated with abandoned VMS mines include arsenic, cadmium, lead, and nickel.

## Carbon Footprint

Tellurium extraction through mining does not have a unique carbon footprint beyond the energy requirements of mining in general. In terms of its uses, the most direct link of tellurium to the global carbon cycle is in its use in cadmium-telluride photovoltaic cells (Anderson, 2015).

## Mine Closure

The nature of mine closure for porphyry copper and VMS deposits depends primarily on the method of mining and the characteristics of the waste material. Open pit mines for either deposit type display at least three different features after mining: the open pit, tailings storage facilities, and waste-rock piles. Because of the scale of mining, backfilling of the pits is typically not practical. If the water table is above the bottom of the pit, then it will become a lake. The water quality of the lake will depend upon a number of factors, including the characteristics of the wallrocks, the extent of interconnected underground mine workings that open to the pit, the water level in the pit, the local hydrology, and climate (Castendyk and Eary, 2009).

The long-term fate of tailing storage facilities will depend upon the nature of the tailings and the method of construction of the facility. Some 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 may require some form of water treatment. The long-term fate of waste-rock piles may include regrading, capping, and revegetation. Depending upon the acid-generating potential of the material, some piles may require some form of water treatment.

For underground mines, tailings and waste rock may be handled in a similar fashion to the approaches used at open pit mines. The potential exists to dispose of some of the tailings back into the mined out workings, depending upon how the orebody is mined; however, the entire volume of tailings cannot be placed back in the mine workings because of the volume expansion associated with crushing and milling the ore.

## Problems and Future Research

In the near future, recovery of lower copper grades may force recovery of oxidized copper ores by solvent extraction; in this process, it is not possible to recover the tellurium as a byproduct, as is possible through the smelting of higher grade copper sulfide concentrates. This change in method could potentially lead to a greater emphasis on precious-metal deposits to meet global and domestic tellurium demands. Demand has decreased for tellurium in recent years, but as China and other developing countries adopt more solar technologies, increased demand in the near future is a possibility.

Future research may focus on methods to recover tellurium from two new sources. First, future advances in processes for sea-floor mining will be critical if tellurium is recovered from extreme enrichments in iron-manganese crusts on the ocean floor. Second, investigations of old mine and mill tailings from historic large-scale operations may fingerprint deposits and deposit types with previously unrecognized, extreme abundances of tellurium in old waste piles.

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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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