Selenium

Chapter Q of

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

Professional Paper 1802–Q

U.S. Department of the Interior
U.S. Geological Survey
Periodic Table of Elements

<table>
<thead>
<tr>
<th>Group 1A (1s)</th>
<th>Group 2A (2s)</th>
<th>Group 3A (3s)</th>
<th>Group 4A (4s)</th>
<th>Group 5A (5s)</th>
<th>Group 6A (6s)</th>
<th>Group 7A (7s)</th>
<th>Group 8A (8s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1H</td>
<td>2He</td>
<td>3Li</td>
<td>4Be</td>
<td>5B</td>
<td>6C</td>
<td>7N</td>
<td>8O</td>
</tr>
</tbody>
</table>

| 1s | 2s | 2p | 3s | 3p | 4s | 3d | 4p | 5s | 4d | 5p | 6s | 4f | 5d | 6p | 7s | 5f | 6d | 7p | 8s | 6f | 7d | 8p |

- **Group 1A (1s)**: Lithium (Li), Sodium (Na), Potassium (K), Rubidium (Rb), Cesium (Cs), francium (Fr), element names in red are gases at room temperature.
- **Group 2A (2s)**: Beryllium (Be), Magnesium (Mg), Calcium (Ca), Barium (Ba), Actinium (Ac), element names in blue are liquids at room temperature.
- **Group 3A (3s)**: Boron (B), Aluminum (Al), Gallium (Ga), indium (In), thallium (Tl), element names in black are solids at room temperature.
- **Group 4A (4s)**: Carbon (C), Silicon (Si), Germanium (Ge), Tin (Sn), Lead (Pb), element names in white are solids at room temperature.
- **Group 5A (5s)**: Nitrogen (N), Phosphorus (P), Arsenic (As), Antimony (Sb), Bismuth (Bi), element names in cyan are solids at room temperature.
- **Group 6A (6s)**: Oxygen (O), Sulfur (S), Selenium (Se), Tellurium (Te), Polonium (Po), element names in magenta are solids at room temperature.
- **Group 7A (7s)**: Fluorine (F), Chlorine (Cl), Bromine (Br), Iodine (I), astatine (At), element names in purple are solids at room temperature.
- **Group 8A (8s)**: Neon (Ne), Argon (Ar), Krypton (Kr), Xe, Rn, element names in orange are solids at room temperature.

---

**Cover.** Dendrites, consisting primarily of naumannite (silver selenide) and lesser amounts of electrum, sphalerite, chalcopyrite, tetrahedrite, and other silver minerals (dark gray to black areas), quartz (light gray areas), and quartz and a minor amount of illite (beige to white areas). Sample is from the Buckskin National Mine, Humboldt County, Nevada. Photograph by Peter Vikre, U.S. Geological Survey.
Selenium

By Lisa L. Stillings

Chapter Q of

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

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

Professional Paper 1802–Q

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


For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment—visit https://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit https://store.usgs.gov/.

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Although this information product, for the most part, is in the public domain, it also may contain copyrighted materials as noted in the text. Permission to reproduce copyrighted items must be secured from the copyright owner.

Suggested citation:

ISSN 2330-7102 (online)
## Contents

Abstract................................................................................................................................. Q1  
Introduction.......................................................................................................................... Q1  
  Uses and Applications ......................................................................................................... Q2  
  Demand and Availability of Supply ..................................................................................... Q4  
    Supply............................................................................................................................... Q6  
    Demand............................................................................................................................ Q6  
    Recycling......................................................................................................................... Q7  
Geology..................................................................................................................................... Q7  
  Crustal Abundance .............................................................................................................. Q7  
  Mineralogy .......................................................................................................................... Q7  
  Deposit Types ..................................................................................................................... Q9  
    Magmatic and Associated Hydrothermal Deposits ............................................................. Q9  
    Selenide-Bearing Deposits ............................................................................................... Q13  
    Sedimentary Rocks .......................................................................................................... Q14  
Resources and Reserves ......................................................................................................... Q14  
  Identified Resources ........................................................................................................... Q19  
  Undiscovered Resources .................................................................................................... Q21  
Environmental Considerations ............................................................................................. Q21  
  Sources and Fate in the Environment .................................................................................. Q21  
    Natural and Anthropogenic Sources in Air, Water, and Soil ........................................... Q21  
    Average Ambient Concentrations in Air, Streams, Groundwater, and Soil ....................... Q23  
    Above-Background Concentrations of Selenium in the Environment Near Major Deposits and Enriched Bedrock ............................................................. Q23  
    Mobility in Water and Soils .............................................................................................. Q26  
Mine Waste Characteristics .................................................................................................... Q27  
Human Health Concerns ....................................................................................................... Q29  
  Pathways for Selenium Ingestion in Humans ................................................................... Q30  
  Related Diseases, Cancers, and Human Health Effects From Industrial Exposures ......... Q30  
  Human Health Guidelines ................................................................................................. Q30  
Ecological Health Concerns .................................................................................................. Q30  
  Pathways for Selenium Ingestion in Aquatic and Terrestrial Organisms ......................... Q31  
  Aquatic Toxicity and Aquatic Ecosystem Health Guidelines ............................................. Q32  
Problems and Future Research ............................................................................................. Q32  
Acknowledgments ................................................................................................................ Q32  
References Cited.................................................................................................................... Q33
Figures

Q1. Graph showing relative abundance of the chemical elements in Earth's upper crust ................................................................. Q2
Q2. Graph showing end uses for selenium in the United States from 1975 to 2012 .................. Q3
Q3. Graph illustrating a mass balance for selenium in the United States from 1943 to 2015 ................................................................. Q5
Q4. Graph showing average annual prices of commercial-grade selenium from 1970 to 2010 ................................................................. Q6
Q5. Map showing selenium concentrations in coal samples, by region of the United States ......................................................................... Q15
Q6. Maps showing locations of seleniferous sedimentary outcrops and deposits and plant samples with significant selenium content .................................................. Q18
Q7. A predictive map of selenium source rocks associated with organic-rich depositional marine basins ................................................................ Q22
Q8. Maps showing selenium concentrations in soils of the conterminous United States ......................................................................... Q24

Tables

Q1. Selenium minerals recognized by the International Mineralogical Association........ Q44
Q2. A summary of selenium concentrations in various selenides and sulfides from deposits around the world ..................................................................... Q49
Q3. Selenium concentrations in sulfide minerals and other phases, in various deposit types ................................................................. Q10
Q4. Selenium concentrations in copper-nickel ores in the Sudbury basin, Ontario, Canada ................................................................. Q12
Q5. Selenium concentrations in selected Earth and lunar materials ............................................... Q16
Q6. Estimated world selenium reserves in 2014, in metric tons................................................. Q21
Q7. National Institutes of Health recommended dietary reference intakes (DRIs) for selenium ................................................................ Q31
### Conversion Factors

**International System of Units to Inch/Pound**

<table>
<thead>
<tr>
<th>Multiply by</th>
<th>By</th>
<th>To obtain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| 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)      |

<table>
<thead>
<tr>
<th>Area</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>hectare (ha)</td>
<td>2.471</td>
<td>acre</td>
</tr>
<tr>
<td>square kilometer (km²)</td>
<td>247.1</td>
<td>acre</td>
</tr>
<tr>
<td>square meter (m²)</td>
<td>10.76</td>
<td>square foot (ft²)</td>
</tr>
<tr>
<td>square centimeter (cm²)</td>
<td>0.1550</td>
<td>square inch (ft²)</td>
</tr>
<tr>
<td>square kilometer (km²)</td>
<td>0.3861</td>
<td>square mile (mi²)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Volume</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>milliliter (mL)</td>
<td>0.03381</td>
<td>ounce, fluid (fl. oz)</td>
</tr>
<tr>
<td>liter (L)</td>
<td>33.81402</td>
<td>ounce, fluid (fl. oz)</td>
</tr>
<tr>
<td>liter (L)</td>
<td>1.057</td>
<td>quart (qt)</td>
</tr>
<tr>
<td>liter (L)</td>
<td>0.2642</td>
<td>gallon (gal)</td>
</tr>
<tr>
<td>cubic meter (m³)</td>
<td>264.2</td>
<td>gallon (gal)</td>
</tr>
<tr>
<td>cubic centimeter (cm³)</td>
<td>0.06102</td>
<td>cubic inch (in³)</td>
</tr>
<tr>
<td>cubic meter (m³)</td>
<td>1.308</td>
<td>cubic yard (yd³)</td>
</tr>
<tr>
<td>cubic kilometer (km³)</td>
<td>0.2399</td>
<td>cubic mile (mi³)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mass</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>microgram (µg)</td>
<td>0.0000003527</td>
<td>ounce, avoirdupois (oz)</td>
</tr>
<tr>
<td>milligram (mg)</td>
<td>0.00003527</td>
<td>ounce, avoirdupois (oz)</td>
</tr>
<tr>
<td>gram (g)</td>
<td>0.03527</td>
<td>ounce, avoirdupois (oz)</td>
</tr>
<tr>
<td>gram (g)</td>
<td>0.03215075</td>
<td>ounce, troy</td>
</tr>
<tr>
<td>kilogram (kg)</td>
<td>32.15075</td>
<td>ounce, troy</td>
</tr>
<tr>
<td>kilogram (kg)</td>
<td>2.205</td>
<td>pound avoirdupois (lb)</td>
</tr>
<tr>
<td>ton, metric (t)</td>
<td>1.102</td>
<td>ton, short [2,000 lb]</td>
</tr>
<tr>
<td>ton, metric (t)</td>
<td>0.9842</td>
<td>ton, long [2,240 lb]</td>
</tr>
</tbody>
</table>

**Deposit grade**

| gram per metric ton (g/t) | 0.0291667 | ounce per short ton (2,000 lb) (oz/T) |

<table>
<thead>
<tr>
<th>Pressure</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>megapascal (MPa)</td>
<td>10</td>
<td>bar</td>
</tr>
<tr>
<td>gigapascal (GPa)</td>
<td>10,000</td>
<td>bar</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Density</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>gram per cubic centimeter (g/cm³)</td>
<td>62.4220</td>
<td>pound per cubic foot (lb/ft³)</td>
</tr>
<tr>
<td>milligram per cubic meter (mg/m³)</td>
<td>0.0000006243</td>
<td>pound per cubic foot (lb/ft³)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Energy</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>joule (J)</td>
<td>0.0000002</td>
<td>kilowatthour (kW)</td>
</tr>
<tr>
<td>joule (J)</td>
<td>6.241 × 10⁻¹⁸</td>
<td>electronvolt (eV)</td>
</tr>
<tr>
<td>joule (J)</td>
<td>0.2388</td>
<td>calorie (cal)</td>
</tr>
<tr>
<td>kilojoule (kJ)</td>
<td>0.0002388</td>
<td>kilocalorie (kcal)</td>
</tr>
</tbody>
</table>
International System of Units to Inch/Pound

<table>
<thead>
<tr>
<th>Multiply</th>
<th>By</th>
<th>To obtain</th>
</tr>
</thead>
<tbody>
<tr>
<td>becquerel (Bq)</td>
<td>0.00002703</td>
<td>microcurie (μCi)</td>
</tr>
<tr>
<td>kilobecquerel (kBq)</td>
<td>0.02703</td>
<td>microcurie (μCi)</td>
</tr>
</tbody>
</table>

**Electrical resistivity**

<table>
<thead>
<tr>
<th>Unit</th>
<th>Conversion Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>ohm meter (Ω-m)</td>
<td>39.37</td>
</tr>
<tr>
<td>ohm-centimeter (Ω-cm)</td>
<td>0.3937</td>
</tr>
</tbody>
</table>

**Thermal conductivity**

<table>
<thead>
<tr>
<th>Unit</th>
<th>Conversion Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>watt per centimeter per degree Celsius (watt/cm °C)</td>
<td>693.1798</td>
</tr>
<tr>
<td>watt per meter kelvin (W/m-K)</td>
<td>6.9318</td>
</tr>
</tbody>
</table>

Inch/Pound to International System of Units

<table>
<thead>
<tr>
<th>Length</th>
<th>Conversion Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>mil</td>
<td>0.0254</td>
</tr>
<tr>
<td>inch (in.)</td>
<td>0.0254</td>
</tr>
<tr>
<td>inch (in.)</td>
<td>0.0254</td>
</tr>
<tr>
<td>foot (ft)</td>
<td>0.3048</td>
</tr>
<tr>
<td>mile (mi)</td>
<td>1.609</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Volume</th>
<th>Conversion Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>ounce, fluid (fl. oz)</td>
<td>0.2957</td>
</tr>
<tr>
<td>ounce, fluid (fl. oz)</td>
<td>0.02957</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mass</th>
<th>Conversion Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>ounce, avoirdupois (oz)</td>
<td>28,350,000</td>
</tr>
<tr>
<td>ounce, avoirdupois (oz)</td>
<td>28,350</td>
</tr>
<tr>
<td>ounce, avoirdupois (oz)</td>
<td>28.35</td>
</tr>
<tr>
<td>ounce, troy</td>
<td>31.10348</td>
</tr>
<tr>
<td>ounce, troy</td>
<td>0.03110348</td>
</tr>
<tr>
<td>pound, avoirdupois (lb)</td>
<td>0.4536</td>
</tr>
<tr>
<td>ton, short (2,000 lb)</td>
<td>0.9072</td>
</tr>
<tr>
<td>ton, long (2,240 lb)</td>
<td>1.016</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Deposit grade</th>
<th>Conversion Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>ounce per short ton (2,000 lb) (oz/T)</td>
<td>34.285714</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Energy</th>
<th>Conversion Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>kilowatthour (kWh)</td>
<td>3,600,000</td>
</tr>
<tr>
<td>electronvolt (eV)</td>
<td>1.602 × 10⁻¹⁹</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Radioactivity</th>
<th>Conversion Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>microcurie (μCi)</td>
<td>37,000</td>
</tr>
<tr>
<td>microcurie (μCi)</td>
<td>37</td>
</tr>
<tr>
<td>becquerel (Bq)</td>
<td>37</td>
</tr>
<tr>
<td>kilobecquerel (kBq)</td>
<td>0.00002703</td>
</tr>
</tbody>
</table>

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

°F = (1.8 × °C) + 32

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

K = °C + 273.15

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

°C = (°F – 32) / 1.8
Datum

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

Supplemental Information

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

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

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L), micrograms per liter (µg/L), 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 (µg/g), milligrams per kilogram (mg/kg), or femtograms per gram (fg/g).

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

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

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

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

<table>
<thead>
<tr>
<th>Concentration unit</th>
<th>Equals</th>
</tr>
</thead>
<tbody>
<tr>
<td>milligram per kilogram (mg/kg)</td>
<td>part per million</td>
</tr>
<tr>
<td>microgram per gram (µg/g)</td>
<td>part per million</td>
</tr>
<tr>
<td>microgram per kilogram (µg/kg)</td>
<td>part per billion (10^9)</td>
</tr>
</tbody>
</table>

Equivalencies

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

Metric system prefixes

<table>
<thead>
<tr>
<th>Prefix</th>
<th>Symbol</th>
<th>Value</th>
<th>Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>tera-</td>
<td>T-</td>
<td>10^12</td>
<td>1 trillion</td>
</tr>
<tr>
<td>giga-</td>
<td>G-</td>
<td>10^9</td>
<td>1 billion</td>
</tr>
<tr>
<td>mega-</td>
<td>M-</td>
<td>10^6</td>
<td>1 million</td>
</tr>
<tr>
<td>kilo-</td>
<td>k-</td>
<td>10^3</td>
<td>1 thousand</td>
</tr>
<tr>
<td>hecto-</td>
<td>h-</td>
<td>10^2</td>
<td>1 hundred</td>
</tr>
<tr>
<td>deka-</td>
<td>da-</td>
<td>10</td>
<td>1 ten</td>
</tr>
<tr>
<td>deci-</td>
<td>d-</td>
<td>10^-1</td>
<td>1 tenth</td>
</tr>
<tr>
<td>centi-</td>
<td>c-</td>
<td>10^-2</td>
<td>1 hundredth</td>
</tr>
<tr>
<td>milli-</td>
<td>m-</td>
<td>10^-3</td>
<td>1 thousandth</td>
</tr>
<tr>
<td>micro-</td>
<td>µ-</td>
<td>10^-6</td>
<td>1 millionth</td>
</tr>
<tr>
<td>nano-</td>
<td>n-</td>
<td>10^-9</td>
<td>1 billionth</td>
</tr>
<tr>
<td>pico-</td>
<td>p-</td>
<td>10^-12</td>
<td>1 trillionth</td>
</tr>
<tr>
<td>femto-</td>
<td>f-</td>
<td>10^-15</td>
<td>1 quadrillionth</td>
</tr>
<tr>
<td>atto-</td>
<td>a-</td>
<td>10^-18</td>
<td>1 quintillionth</td>
</tr>
</tbody>
</table>
## Abbreviations and Symbols

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>°C</td>
<td>degree Celsius</td>
</tr>
<tr>
<td>µg/d</td>
<td>microgram per day</td>
</tr>
<tr>
<td>AC</td>
<td>alternating current</td>
</tr>
<tr>
<td>AIDS</td>
<td>acquired immunodeficiency syndrome</td>
</tr>
<tr>
<td>CIGS</td>
<td>copper-indium-gallium-selenide</td>
</tr>
<tr>
<td>cm</td>
<td>centimeter</td>
</tr>
<tr>
<td>DC</td>
<td>direct current</td>
</tr>
<tr>
<td>EMPA</td>
<td>electron microprobe analysis</td>
</tr>
<tr>
<td>EPA</td>
<td>U.S. Environmental Protection Agency</td>
</tr>
<tr>
<td>g/d</td>
<td>gram per day</td>
</tr>
<tr>
<td>GWh</td>
<td>gigawatt-hour</td>
</tr>
<tr>
<td>HIV</td>
<td>human immunodeficiency virus</td>
</tr>
<tr>
<td>IMA</td>
<td>International Mineralogical Association</td>
</tr>
<tr>
<td>IOCG</td>
<td>iron oxide-copper-gold</td>
</tr>
<tr>
<td>kg</td>
<td>kilogram</td>
</tr>
<tr>
<td>kg/t</td>
<td>kilogram per metric ton</td>
</tr>
<tr>
<td>km</td>
<td>kilometer</td>
</tr>
<tr>
<td>lb</td>
<td>pound</td>
</tr>
<tr>
<td>MDEQ</td>
<td>Michigan Department of Environmental Quality</td>
</tr>
<tr>
<td>mg/d</td>
<td>milligram per day</td>
</tr>
<tr>
<td>ng/L</td>
<td>nanogram per liter</td>
</tr>
<tr>
<td>org-Se(-II)</td>
<td>organo-selenide</td>
</tr>
<tr>
<td>pm</td>
<td>picometer</td>
</tr>
<tr>
<td>ppb</td>
<td>part per billion</td>
</tr>
<tr>
<td>ppm</td>
<td>part per million</td>
</tr>
<tr>
<td>RDA</td>
<td>recommended daily allowance</td>
</tr>
<tr>
<td>Se(II)</td>
<td>selenide</td>
</tr>
<tr>
<td>Se(IV)</td>
<td>selenite</td>
</tr>
<tr>
<td>Se(VI)</td>
<td>selenate</td>
</tr>
<tr>
<td>USGS</td>
<td>U.S. Geological Survey</td>
</tr>
<tr>
<td>VMS</td>
<td>volcanogenic massive sulfide</td>
</tr>
<tr>
<td>WHO</td>
<td>World Health Organization</td>
</tr>
</tbody>
</table>
Selenium

By Lisa L. Stillings

Abstract

Selenium (Se) was discovered in 1817 in pyrite from copper mines in Sweden. It is a trace element in Earth’s crust, with an abundance of three to seven orders of magnitude less than the major rock-forming elements. Commercial use of selenium began in the United States in 1910, when it was used as a pigment for paints, ceramic glazes, and red glass. Since that time, it has had many other economic uses—notably, in the 1930s and 1940s, when it was used in rectifiers (which change alternating current to direct current), and in the 1960s, when it began to be used in the liner of photocopier drums. In the 21st century, other compounds have replaced selenium in these older products; modern uses for selenium include energy-efficient windows that limit heat transfer and thin-film photovoltaic cells that convert solar energy into electricity.

In Earth’s crust, selenium is found as selenide minerals, selenate and selenite salts, and as substitution for sulfur in sulfide minerals. It is the sulfide minerals, most commonly those in porphyry copper deposits, that provide the bulk of the selenium produced for the international commodity market. Selenium is obtained as a byproduct of copper refining and recovered from the anode slimes generated in electrolytic production of copper. Because of this, the countries that have the largest resources and (or) reserves of copper also have the largest resources and (or) reserves of selenium.

Because selenium occurs naturally in Earth’s crust, its presence in air, water, and soil results from both geologic reactions and human activity. Selenium is found concentrated naturally in soils that overlie bedrock with high selenium concentrations. Selenium mining, processing, use in industrial and agricultural applications, and disposal may all contribute selenium to the environment. A well-known case of selenium contamination from agricultural practices was discovered in 1983 in the Kesterson National Wildlife Refuge in California. There, waters draining from agricultural fields created wetlands with high concentrations of dissolved selenium in the water. The selenium was taken up by aquatic wildlife and caused massive numbers of embryonic deformities and deaths.

Regulatory agencies have since worked to safeguard ecological and human health by creating environmental exposure guidelines based upon selenium concentrations in water and in fish tissue. Any attempt to regulate selenium concentrations requires a delicate balance because selenium occurs naturally and is also a vital nutrient for the health of wildlife, domestic stock, and humans. Selenium is commonly added as a vitamin to animal feed, and in some regions of the United States and the world, it is added as an amendment to soils for uptake by agricultural crops.

The important role of selenium in economic products, energy supply, agriculture, and health will continue for well into the future. The challenge to society is to balance the benefits of selenium use with the environmental consequences of its extraction. Increased understanding of the elemental cycle of selenium in the earth may lead to new (or unconventional) sources of selenium, the discovery of new methods of extraction, and new technologies for minimizing the transfer of selenium from rock to biota, so to protect environmental and human health.

Introduction

Selenium (Se) was discovered in 1817 (and named in 1818) by the Swedish chemist Jöns Jacob Berzelius, who became interested in the sludge left over after the processing of pyrite from the copper mines at Falun, Sweden. The sludge was red in color and developed the unpleasant smell of rotten radishes when it was heated. Berzelius had first thought that the material, though having close affinities with tellurium, was a previously unknown element. Because of its affinity with tellurium (from Latin tellus, meaning Earth), the element was named selenium after the Greek word selene, meaning Moon, or satellite of Earth (Sindeeva, 1964; Lakin and Davidson, 1973; Boyd, 2011).

In the past, selenium has been described as a somewhat mysterious element, one that can be “a metal or nonmetal, a conductor or nonconductor, amorphous or crystalline, colorant or deodorant, [or] a hydrogenator or dehydrogenator” (Sargent, 1954, p. 1). It can be either red or black (Sargent, 1954) and, when ingested, either a necessary nutrient or a poison (Trelease and Beath, 1949). It is fair to say that today, almost 200 years after the discovery of selenium, scientific
understanding has reconciled these seemingly contradictory descriptions. The complexity of selenium chemistry in economic, environmental, and geologic contexts is better understood yet remains a topic of research.

Selenium is a trace element in Earth’s crust with an average crustal abundance of 0.05 part per million (ppm). Its abundance is three to seven orders of magnitude less than that of the major rock-forming elements (fig. Q1), and it is one-half to three orders of magnitude less abundant than the rare-earth elements. It is, however, more abundant (by one to four orders of magnitude) than the rarest metals, such as platinum, palladium, and gold.

Selenium is photovoltaic, meaning that it converts light into electricity. It is also photoconductive, meaning that its electrical conductivity increases with increasing light. These are the properties that make selenium useful in photovoltaic cells and solar panels, and are among the reasons why selenium has been classified as an energy-critical element (American Physical Society Panel on Public Affairs and the Materials Research Society, 2011). This chapter provides an overview of the geochemical cycle of selenium at Earth’s surface and includes sections on selenium’s occurrence in mineral deposits, its production and consumption, its presence in the environment, and its role in both human and environmental health.

Uses and Applications

Before World War I, according to Sargent (1954, p. 8), “selenium was regarded as the abomination of the smelterman and was discarded.” Today, in comparison, selenium is considered an “energy critical element” that is important for renewable energy technologies (American Physical Society Panel on Public Affairs and the Materials Research Society, 2011), and it is also known to be an essential nutrient for humans and livestock.

Commercial use of selenium in the United States began in 1910; at that time, selenium was used as a pigment for paints, ceramic glazes, and red glass. The first large-scale commercial use of selenium began in 1915, when selenium was substituted for manganese in glassmaking. Manganese, which was used to neutralize the green tint in glass caused by iron impurities, had previously been obtained from Russia, but the supply of manganese was disrupted during World War I. Selenium, in concentrations of 0.04 to 0.14 kilogram per metric ton (kg/t) in glass, was found to be a good substitute for manganese. In addition, greater concentrations of selenium were found to provide a pink tint to glass, and at concentrations of 0.45 to 2.3 kg/t, could produce a desirable ruby red glass for use in tableware, automobile taillights, and traffic signals. The modern sheet-glass industry uses selenium in energy-efficient
windows to help limit the heat transfer from sunlight (Sargent, 1954; Butterman and Brown, 2004).

After glassmaking, the next largest commercial use for selenium was the selenium rectifier. Rectifiers, which change alternating current (AC) to direct current (DC), had been known about since 1884, but they were not extensively used until inventors improved the devices in 1930 (Sargent, 1954). After this time, rectifiers began to be used in arc lamps, battery chargers, DC motors, electroplating, magnet coils, and welding. The military used selenium rectifiers in World War II for aircraft controls, ground starters for aircraft, guided missiles, radar equipment, and numerous other applications. In 1947, miniature rectifiers were developed that could be used in radio and television circuits. This miniaturization was a tremendous improvement because the new technology could deliver 200 to 500 volts of DC from a 117-volt AC source, thus eliminating the need for the older heavy and bulky transformers and rectifier tubes, and saving greater than 0.23 kilogram (kg) of copper and 3.4 kg of steel per television set (Sargent, 1954).

Soon after World War II, many other uses for selenium were developed. Selenium became important in the rubber industry where it acted as an accelerator and vulcanizing agent, and it was also used to improve the resilience of rubber by increasing its resistance to heat, oxidation, and abrasion. Selenium was used as a pigment to produce orange, red, and maroon colors in the post-World War II plastics industry and in ceramics, dyes, inks, leather, paints, paper, rubber, soap, and other products. It was used to either hydrogenate or dehydrogenate organic compounds, crude oil, and coal, and it assisted in the production of edible fats, plastics, soaps, and waxes. It provided antioxidant properties to inks and oils, as well as nondrying properties to linseed, oiticica, and tung oils. Selenium began to be used in personal care products, such as dandruff and dermatitis shampoos and soaps, and in deodorants. It was also included in fungicides, herbicides, and insecticides. Finally, selenium came to be used in the steel industry to improve the machinability of stainless steel. Forging steels contained 0.18 to 0.22 percent selenium, and machining-grade steel contained 0.30 to 0.35 percent. A small amount of selenium (0.01 to 0.05 percent) assured a fine-grained and bubble-free texture in cast steel. Selenium was also added to copper and copper alloys to improve machinability and tensile strength (Sargent, 1954; Butterman and Brown, 2004).

The 1960s saw yet another expansion in the industrial use of selenium—as a coating on photocopier drums. Xerography, which was the forerunner to modern-day photocopying machines, was invented in 1938 and patented in 1942. It gained commercial popularity in the late 1950s when an automated process was developed using a cylindrical drum coated with selenium. Even today, in the 21st century, the majority of paper documents are produced xerographically, either on photocopiers or laser printers, which employ a similar process but use materials other than selenium as the photoreceptor (Owen, 2004).

By 1973, 40 percent of the selenium consumed in the United States was a high-purity grade used for electrostatic printing (xerography), rectifiers, exposure meters, photoelectric cells, and optical lenses. Thirty percent went toward the manufacturing of glass. Fourteen percent was used for inorganic pigments, mainly in the form cadmium sulfoselenide, which have good light stability and heat resistance and were used in enamels, inks, paints, plastics, and rubber. In the 1990s, amorphous silicon and organic compounds started to replace selenium in xerographic drums, and the use of selenium in the photocopier industry began to decline (fig. Q2; Lakin and Davidson, 1973).

By 1973, 40 percent of the selenium consumed in the United States was a high-purity grade used for electrostatic printing (xerography), rectifiers, exposure meters, photoelectric cells, and optical lenses. Thirty percent went toward the manufacturing of glass. Fourteen percent was used for inorganic pigments, mainly in the form cadmium sulfoselenide, which have good light stability and heat resistance and were used in enamels, inks, paints, plastics, and rubber. In the 1990s, amorphous silicon and organic compounds started to replace selenium in xerographic drums, and the use of selenium in the photocopier industry began to decline (fig. Q2; Lakin and Davidson, 1973).

In the 21st century, potentially large-scale demand for selenium could result from the manufacture of thin-film photovoltaic cells that employ a copper-indium-gallium-selenide (CIGS) alloy for converting solar energy into electricity. As of 2010, silicon-based photovoltaic cells still dominated the solar energy market and accounted for greater than 90 percent of all photovoltaic cells in use. These photovoltaic cells are comparatively inefficient, however, and convert only about 15 percent of adsorbed light to electricity in actual outdoor use (Bleiwas, 2010). Recent research on the second-generation
photovoltaic thin-film cells that use CIGS technology is showing increased efficiencies of 20 to 40 percent and leading to lower production costs. Selenium is a critical element in the CIGS technology and contributes to the higher levels of light absorption and conversion to electricity demonstrated by these second-generation thin-film cells.

Bleiwas (2010) described the quantities of selenium and other metals required to produce thin-film CIGS photovoltaic cells with enough capacity (1 gigawatt) to produce 8,760 gigawatt-hours (GWh) of electricity (enough to supply 800,000 average U.S. households) annually. He calculated that 180 metric tons of selenium would be needed to produce this quantity of CIGS photovoltaic cells, which is 7.6 percent of the estimated 2013 world refinery production of selenium. The required quantities of gallium and indium necessary for this technology are 30 and 90 metric tons, or 7 percent and 11 percent of the 2014 worldwide production of these metals, respectively (Bleiwas, 2010).

**Demand and Availability of Supply**

Sargent (1954) provided a picture of selenium as a critical element in the post-World War II years. As noted above, 1947 was a critical year because of the development of a miniature selenium rectifier. For much of the 1940s and 1950s, selenium consumption outpaced primary refinery production, and the difference was made up from imports and releases from industry stockpiles (fig. Q3).

To safeguard the supply of selenium, the Federal Government had begun holding selenium in a strategic stockpile in the 1940s, although data on the size of the stockpile were confidential (Clark, 1950). Increased concerns regarding possible shortages became apparent when, in February 1952, the National Production Authority placed both imported and domestically produced selenium under a “complete allocation” in order to meet essential defense requirements with respect to steelmaking and rectifiers. This allocation was discontinued in early 1953, although consumption continued to be higher than domestic production through 1960 (with the exception of 1957, fig. Q3; Sargent, 1954; Massachusetts Institute of Technology, 2010; American Physical Society Panel on Public Affairs and the Materials Research Society, 2011). Ingerson (1964) noted that, throughout the 1950s and early 1960s, production and consumption of selenium was “nip and tuck,” and that there was not a sufficient stockpile of selenium to last more than a few months. The situation was so “precarious” that selenium was constantly listed in Group I (that is, one of the most important) in the national stockpile list of strategic and critical materials. In 1961, the U.S. Bureau of Mines reported that the Federal stockpile held 254,000 pounds (lb) (115 metric tons) of selenium (U.S. Bureau of Mines, 1963), and, in 1964, the Office of Emergency Planning increased the stockpile objective for selenium to 475,000 lb (215 metric tons) (U.S. Bureau of Mines, 1965).

By 1970, the balance between supply and demand had shifted—selenium consumption became consistently less than the total available supply (primary refinery production plus imports plus release from stockpiles) and the excess selenium was available for export (fig. Q3; Lakin and Davidson, 1973). In August 1971, Congress authorized the disposal of the national stockpile, and the last lot was sold on May 26, 1976 (U.S. Bureau of Mines, 1973, 1978). Despite the sufficient domestic supply of selenium, however, there was some concern in 1973 of an impending shortage of selenium owing to (a) the increased use of in situ leaching for copper production from its ores, which did not allow for recovery of associated selenium, and (b) the discovery that selenium was necessary for animal nutrition. It was learned that selenium deficiency in commercial feed could result in death and disease for poultry and livestock; this happened in a number of countries and led to heavy economic losses. The deficiency could be reversed, however, by adding selenium to fertilizer for agricultural lands. Lakin and Davidson (1973) estimated that 5.7 million kilograms per year of selenium would be required to treat the most severely deficient agricultural lands in the United States.

Jensen (1985) tracked the supply of and demand for selenium from 1973 to 1983 by comparing selenium production from U.S. mines to total U.S. supply, including available stockpiles. During this period, U.S. primary refinery production peaked at 360 metric tons in 1973, dropped to a low of 140 metric tons in 1980, and recovered to 350 metric tons (revised) in 1983 (U.S. Bureau of Mines, 1989). The total U.S. supply was always higher than mine production during this period, with a high of 831 metric tons in 1974 and a low of 581 metric tons in 1977. (Jensen’s calculations include the entire quantity of selenium held in stockpiles, and not the change in stockpile mass, as indicated in fig Q3.) The difference between mine production and total supply was owing to the refineries’ use of U.S. Government selenium stockpiles, selenium imports, and industry stockpiles. The largest releases from the U.S. Government stockpile took place in 1973 and 1974 (150 and 55 metric tons, respectively) (U.S. Bureau of Mines, 1980). The last shipment took place in 1976, and since then, refineries have relied on an increased supply of selenium from imports (fig. Q3).

George (2013) tracked the price of selenium from 1970 to 2010 (fig. Q4). As with any commodity, the price reflects supply and demand. By using yearly prices in 1992 constant dollars, George showed that the price of selenium in the 1970s was higher than it was in 2010. Prices spiked far above 2010 prices during 1974–76 because of the elimination of the U.S. Government selenium stockpile, low commercial inventories, reduced domestic inventories, and increased demand for plain-paper copiers. Prices remained relatively steady from 1981 to 2003, at approximately $4 to $12 per pound (in 1992 dollars), because there was sufficient worldwide supply, because selenium substitutes were available for many industrial applications, and because there were no new large-scale uses for selenium. The price rise and volatility for
Figure Q3. Graph illustrating a mass balance for selenium in the United States from 1943 to 2015. The supply of selenium to the United States is estimated from primary refinery production plus imports for consumption (meaning that material is added to the supply for that year), minus exports from the United States (removal of selenium from the supply for that year—shown as a negative quantity), plus or minus changes in Government and industry stockpiles (releases are shown as positive quantities and additions are shown as negative quantities), to calculate domestic apparent consumption.

Data from 1943 to 2014 are from U.S. Geological Survey (2014c), and data for 2015 are from U.S. Geological Survey (2017). Primary refinery production numbers are not available for 1985 to 1987, and from 1997 to 2015, they are withheld because they are proprietary; hence, no primary refinery production data are plotted for these years. For the years 1985 to 1987, apparent consumption data have been estimated by linear interpolation. For 1997 to 2015, domestic apparent consumption data are withheld to avoid disclosing company proprietary data, and imports for consumption are used as a proxy for apparent consumption (U.S. Geological Survey, 2014c, 2017). The Federal Government held selenium in a strategic stockpile in the 1940s, but data on the size of the stockpile were confidential (Clark, 1950, p. 1342). The U.S. Bureau of Mines reported the quantity of selenium held in the national stockpile in 1961 (U.S. Bureau of Mines, 1966, p. 1071) and continued to report the size of the stockpile until the last of the selenium was sold on May 26, 1976 (U.S. Bureau of Mines, 1978, p. 1467), and there has been no stockpile since 1976. The USGS reported numbers for the industry-held stockpile from 1944 through 1984, but these values have been withheld since 1985 to avoid disclosing company proprietary data (U.S. Geological Survey, 2014c). Domestic secondary production of selenium (selenium recovered from recycled rectifiers, catalysts, and photocopier drums) was never a large percentage of domestic supply and was inconsistently reported during the period 1943–2016 and thus is not included in this compilation.
selenium since 2003 is attributed mainly to increased demand for selenium from manganese producers in China. Manganese, which is an alloying element in steel production, is produced by an electrolytic process. Substitution of selenium dioxide ($\text{SeO}_2$) for sulfur dioxide ($\text{SO}_2$) lowers the energy requirements of the electrolytic cells, allowing manganese to be produced more cheaply.

Supply
The period from 1945 to 1960 was a period when selenium demand (apparent consumption) outpaced supply from primary refinery production (1957 was an exception). During this time, U.S. primary refinery production averaged 290 metric tons per year; U.S. producers were American Smelting & Refining Co., U.S. Metals Refining Co., and International Smelting & Refining Co. (fig. Q3). During 1961–64, the total supply of selenium was greater than consumption, and the extra supply was stored in industry and Government stockpiles (fig. Q3). Primary refinery production decreased in 1965–68, and selenium was released from stockpiles to meet demand. Beginning in 1969, the total supply of selenium has been sufficient to meet demand, and excess supply has been exported.

Domestic production from 1947 to 1953, which was the beginning of selenium consumption for modern technologies, contrasts markedly with production nearly 50 years later. The latest available report of domestic selenium production was for 1996, when 379,000 kg (379 metric tons) of selenium was produced as a primary product. Production figures were not published after 1996 to avoid disclosing proprietary data from the one or two known domestic refineries, and because selenium-containing residues and anode slimes from other domestic copper refiners were exported for processing.

Just as U.S. domestic production of selenium increased in the years following 1947, so did global production. Sargent (1954) reported that during 1926–31, the Soviet Union produced between 2.3 and 2.7 metric tons per year of selenium. In 1946, Canada produced 237 metric tons, although this production level could not be sustained owing to a reduction in output of selenium-rich high-grade ores from the Horne Mine at Noranda, Quebec, Canada; by 1950, Canada’s production fell to less than 160 metric tons. In 1951, Sweden produced 41 metric tons; Belgium, 10 metric tons; and West Germany, 7.3 metric tons. In 1952, Belgium increased its production to 17 metric tons, and Africa produced 14 metric tons. Belgium increased production again in 1953 to about 27 metric tons, and production in the Soviet Union in that year was estimated to have increased to 45 metric tons.

Total global production in 1996 (the last year for which domestic production numbers were reported) was 2,250 metric tons, and the United States accounted for almost 17 percent of global production, or about 380 metric tons. U.S. production ranked third behind Canada (694 metric tons) and Japan (588 metric tons). During the years 1997 to 2015, Japan was the leading international producer of selenium, although it briefly slipped into second place in 2005. Germany was the second-ranked international producer in 2015. China and the United States produced selenium during this time period as well, but their production numbers are not available (U.S. Geological Survey, 1997–2014).

Demand
From 1943 to 2015, U.S. consumption of selenium was between 184 (1946) and 896 (1969) metric tons per year (fig. Q3) and was affected by increased substitution

![Graph showing average annual prices of commercial-grade selenium from 1970 to 2010. Both the nominal (unadjusted) prices and real prices (in 1992 constant dollars) are shown. Graph is from George (2013).](image)
of other materials for selenium and changes in technology that made many selenium products obsolete. As examples, high-purity silicon replaced, or has become a major substitute for, selenium in rectifiers; silicon can substitute for selenium in photovoltaic cells; and amorphous silicon and organic photoreceptors have replaced selenium in photocopier drums. Organic pigments can substitute for cadmium sulfoselenide pigments; cerium oxide (CeO) can substitute for selenium in glass; tellurium can substitute for selenium in pigments and rubber compounding; bismuth, lead, and tellurium can substitute for selenium in metal alloys; and tellurium can substitute for selenium in lead-free brass. Even with a potential increased use of selenium in CIGS photovoltaic solar cells, the demand for selenium will likely remain steady for the near future.

Recycling

Traditionally, selenium has been used in U.S. manufacturing for glass decolorizers, pigments, fertilizers, animal feeds, and metal alloys. These have been termed “dissipative” uses because of the small amounts of selenium involved, the sheer number of these products, and the difficulty in recovering selenium from them because of the disposal or recycling practices for the products. Even when selenium-containing glass and metal alloys are recycled, they are not segregated from other forms of scrap, and the selenium content is probably volatilized during melting. Major nondissipative uses for selenium have been as photoreceptors in photocopier drums and as rectifiers; however, manufacturers began to replace selenium with organic photoreceptor compounds in the 1980s; consequently, there is no longer a substantial supply of photocopier drums containing selenium for recycling, and large selenium rectifiers have been replaced with ones that use silicon. Even the use of selenium in AC current rectifiers has ended, as silicon-based rectifiers have been developed that are cheaper and more reliable. As a result of this lack of supply, no selenium recycling facilities remain in operation in the United States. This may change in the future as selenium is increasingly used in the manufacture of thin-film CIGS photovoltaic cells for solar panels (George and Wagner, 2009).

Geology

The distribution of selenium in Earth’s crust is closely associated with that of sulfur (S), and because of their similar ionic radii—198 picometers (pm) for Se(−II) versus 184 pm for S(−II)—selenium readily substitutes for sulfur in structures of sulfide minerals. Selenium is less commonly found in sulfate deposits. Selenium is brought to Earth’s surface by way of magmatic intrusions, where it is found in sulfide minerals, and by way of volcanic emissions, where it is vented as the gases selenium dioxide (SeO₂) and hydrogen selenide (H₂Se).

Crustal Abundance

The crustal abundance of selenium has been estimated in different ways. Sindeeva (1964) estimated 0.14 ppm selenium for rocks in the Soviet Union; Brunfelt and Steinnes (1967) estimated 0.04 ppm based on standard rock samples provided by the U.S. Geological Survey (USGS), and Wells (1967) reported an average of 0.6 ppm selenium in volcanic ash samples from New Zealand and 0.4 ppm in New Zealand lava flows (Lakin and Davidson, 1973, and references therein).

An indirect method for estimating selenium abundance was suggested by Goldschmidt and Strock (1935) based upon an estimated sulfur-to-selenium ratio of 6,000:1 in sulfide minerals. Starting with the crustal abundance for sulfur of 520 ppm, they divided this number by the sulfur-to-selenium ratio and arrived at an estimate of 0.09 ppm selenium in Earth’s crust. Turekian and Wedepohl (1961) revised the crustal abundance of sulfur to 300 ppm, and by using the same sulfur-to-selenium ratio of 6,000:1, they estimated 0.05 ppm selenium in Earth’s crust. This figure of 0.05 ppm remains the accepted estimate of the crustal abundance of selenium today (fig. Q1; Greenwood and Earnshaw, 1997).

Mineralogy

Selenium forms selenide minerals and selenite and selenate salts with chalcophile elements (for example, bismuth, copper, lead, mercury, and silver). Some of the natural selenides, such as berzelianite (Cu₃Se), clausthalite (PbSe), guanajuatite (Bi₂Se₃), krutaite (Cu₂Se₃), tiemannite (HgSe), and umangite (Cu₃Se₃) form from selenium-rich hydrothermal fluids (Pirri, 2002) in deposits that “span the magmatic-hydrothermal spectrum” (Ciobanu and others, 2006, p. 163)—from 65 to 300 degrees Celsius (°C), as determined from fluid inclusion and isotopic studies, up to 800 °C in laboratory synthesis studies. Other selenium-bearing minerals, such as aguilarite (Ag₂Se₃), contain selenium and sulfur in isomorphous substitution, and some systems show a continuous solid solution between selenium and sulfur end members. Selenium forms only one oxide mineral: downeyite (SeO₂). The selenium minerals recognized by the International Mineralogical Association (IMA) are listed in table Q1 at the back of this chapter. In a literature survey of selenium concentrations reported in worldwide sulfide and selenide deposits, selenium concentrations in selenides can be as high as 70.23 weight percent, such as in trogtaelite (Co₂Se₃), which is found in the Musanori Mine in the Democratic Republic of the Congo (Congo [Kinshasa]), and up to 4,617 ppm in sulfides, such as in bornite (Cu₅FeS₄) in the Glava Mine (in Sweden) and the Grusen, Moberg, Tinnås, and Tjostolflaten Mines (all in Norway) (table Q2 at back of chapter).

In the Dana classification system for minerals (Gaines and others, 1997), selenium minerals are included in Classes 02 and 03 with sulfides and sulfosalts, respectively. This hierarchical
system emphasizes the similarity between sulfides and selenides with respect to their chemistry, atomic characteristics, and crystal structure. In selenium-bearing hydrothermal systems, selenium may commonly substitute into sulfides, such as bornite, chalcocite (Cu₃S), chalcopyrite (CuFeS₂), digenite (Cu₅S₄), galena (PbS), molybdenite (MoS₂), pyrite (FeS₂), and vaesite (NiS₂) (Simon and others, 1997).

Significant selenium concentrations can be found in sulfide minerals, and numerous studies have been conducted to determine whether the selenium-sulfur content represents a continuous solid solution between end members, whether a compositional gap exists in an apparent solid-solution series, or whether the presence of selenium in a sulfide mineral is merely an opportunistic isomorphic substitution.

Phases in the silver-gold-sulfur-selenium system show ready substitution of selenium for sulfur and, in some cases, continuous solid solution exists; for example, from αAg₄Se to αAg₄AuSe₂ (α indicates the high temperature structural modification of these phases—naumannite [Ag₄Se] to fischesserite [Ag₄AuSe₂]) (Simon and Essene, 1996). Many mineral phases in this system are found in the Broken Hills deposit of the Hauraki goldfield in New Zealand. Using electron microprobe analysis (EMPA), Cocker and others (2013) observed phases with morphologies and compositions similar to the known minerals aguilarite and fischesserite, and uytenbogaardtite (Ag₄Au₃S₄) and petrovskite (Au₃Ag₃S₄), but with atomic sulfur-to-(sulfur+selenium) ratios falling between the known members. For example, they observed substitution of selenium into uytenbogaardtite, with a sulfur-to-(sulfur+selenium) ratio that ranges from 0.55 to almost 1. They noted, however, that uytenbogaardtite and fischesserite cannot be end members of a solid solution series because the two minerals possess different crystal structures (tetragonal and isometric [cubic], respectively).

Likewise, solid solution would not be expected between the phases acanthite (Ag₂S) and aguilarite (Ag₄SeS) because they belong to different crystal systems. Whereas chemical analyses have shown significant substitution of sulfur and selenium between these two phases, this may be an analytical error owing to their occurrence as fine intergrowths with one another. It is unclear whether the chemical analyses come from chemically homogenous grains or whether the size of the analytical spot size produces a composite analysis. Many of the phases in the Broken Hills deposit showed compositions that do not match known minerals and may form a continuum between approximately (Ag,Au)₄S₃ and (Ag,Au)₄Se₃ (Cocker and others, 2013).

Sometimes a solid solution may be present in only one polymorph of a mineral composition. For example, solid solution may exist between the low-temperature orthorhombic mineral structures of naumannite, and aguilarite at temperatures from below 120 to 135 °C. At higher temperatures, they invert to their cubic polymorphs (Petruk and others, 1974). EMPA analyses of Cocker and others (2013) show a compositional gap between these low-temperature orthorhombic phases, but data from Izawa and others (1990) suggest that these phases may show solid solution between atomic selenium-to-(selenium+sulfur) ratios of 0.57 to 0.88.

Other systems with solid solution compositions include lead-sulfur-selenium systems, where solid solution has been observed between clausenthalite (PbSe) and galena (PbS) (Simon and Essene, 1996). Examples are found in various uranium-vanadium deposits of the Colorado Plateau (Coleman, 1959) and in the Niederschlema-Alberoda uranium-selenium-polymetallic deposit in Erzgebirge, Germany, where Förster (2005) documented the entire clausenthalite to galena solid solution covering the range of PbS₀.₃₀ to Pb(Sₐ₄Se₀.₇₀). Complete solid solution can also be found between cinnabar (HgS) and tiemannite (HgSe); sphalerite (ZnS) and stilleite (ZnSe); and native selenium (Se⁰) and native tellurium (Te⁰). Quaternary systems show extensive or complete solid solution at higher temperatures (Simon and Essene, 1996). At 800 °C, Drabek (1995) observed a complete solid solution between molybdenite (MoS₂) and molybdenum diselenide (MoSe₂) under dry laboratory conditions with a high fugacity of selenium to sulfur (fₛ₂/fₐ₂) ratio.

Selenium-bearing sulfides may form as a replacement texture in ore deposits. Paniagua (1995) suggested that selenium-rich vaesite (Ni(S,Se)₂) and selenium-rich villaninite ((Cu,Ni,Co,Fe)(S,Se)₂) of the Providencia Mine in Leon, Spain, are breakdown products of copper-nickel disulfides and that these phases show incremental substitution of sulfur by selenium with increasing copper-nickel contents because of increasing bonding distances within the structure. Many studies point to the formation of selenium-bearing sulfides during late stages of ore mineralization. For example, in epithermal gold-silver deposits in western Nevada, selenium enrichment is observed in late-stage stibnite (Sb₂S₃) and sphalerite, and in arsenian rims on earlier formed pyrite and marcasite (FeS₂; John and others, 2003). John and others (2003) conclude that selenides are common in late-stage ores found in veins and breccias that fill open-spaces, and form from the reaction of late-stage selenium-rich ore fluid (formed after substantial boiling and loss of hydrogen sulfide [H₂S] to vapor) with the initial alteration sulfide assembly.

Because of the close association between selenium and sulfur, Simon and Essene (1996) made a systematic thermodynamic study of the stability of selenide minerals relative to sulfides, oxides, and native elements. Their conclusions were that (a) the stability fields of selenides, in general, are more restricted than sulfide minerals, given similar fugacity values of S₂(g) and Se₂(g) (represented by fₐ₂/S₂(g) and fₛ₂/Se₂(g) respectively); (b) in hydrothermal fluids, most oxide minerals are unstable relative to their corresponding selenide mineral; and (c) for a given selenide, the larger the stability field, the more commonly it is found in ore deposits; for example, clausenthalite.

In a companion paper to the above, Simon and others (1997) discussed the thermodynamic conditions that favor deposition of selenide minerals instead of selenium-substituted sulfide minerals. They conclude that an oxidizing environment is needed to form most selenide minerals. High oxygen
fugacity values (\(f_{O^2}\)) enhance separation of selenium from sulfur, leading to high \(Se_{0.2}/S_{0.2}\) which enables deposition of selenide minerals and limits the formation of sulfide minerals. In contrast, mineralizing systems characterized by low oxygen fugacity and the presence of sulfide minerals can deposit only silver selenides and selenium-substituted sulfide minerals.

Although some selenium is produced from gold and silver selenide deposits that have anomalously high concentrations of selenium (table Q2), most of the world's production of selenium metal is from copper, copper-nickel, and some lead and zinc sulfide deposits where selenium is found in isomorphous substitution with sulfur (Bleiwas, 2010). Table Q2 illustrates the range of selenium concentrations found in sulfur and selenium minerals worldwide.

**Deposit Types**

The compilation of selenium deposits provided by Sindeeva (1964) remains one of the most exhaustive in today’s literature. Because the information is well organized and informative in its original form, the reader is referred to table 7 (p. 174) in “Mineralogy and Types of Deposits of Selenium and Tellurium” (modified as table Q3 in this report). Here, the author noted that selenium can be found in several genetic deposit types—magmatic, volcanic, hydrothermal, and exogenic (that is, produced by chemical and mechanical weathering at Earth’s surface; Jackson, 1997). In Sindeeva’s table, examples from hydrothermal deposits outnumber the rest combined. In the majority of the examples, selenium is found substituted into sulfide minerals, such as chalcopyrite, cinnabar, cobaltite \((CoAsS)\), galena, molybdenite, pentlandite \((Fe,Ni,Co)S\), pyrite, pyrrhotite \((Fe_{1-x}S)\), sphalerite, and stibnite. Selenium minerals are less common than selenium-sulfide deposits that have anomalously high concentrations of selenium (table Q2), most of the world’s production of selenium metal is from copper, copper-nickel, and some lead and zinc sulfide deposits where selenium is found in isomorphous substitution with sulfur (Bleiwas, 2010). The compilation includes some deposits where selenium can be found as selenites, selenates, and native selenium (for example, volcanic tuffs in Shoshone and Riverton, Wyoming).

As a result of a thorough investigation into selenium content of ore deposits and its mineral associations, Sindeeva (1964) concluded the following:

- Deposits containing independent selenium minerals are rare; instead, selenium usually occurs as an isomorphous substitution for sulfur in sulfide minerals.
- The largest resources of selenium are connected with ultrabasic and basic rocks and found in magmatic and hydrothermal chalcopyrite-pentlandite-pyrrhotite deposits, especially in sulfide veins that occur during late stages of formation.

- Pyrite deposits contain large resources of selenium, which seem to accompany late stages of mineralization.
- Copper and molybdenum deposits contain selenium, where the enrichment occurred in late-stage molybdenites.
- Polymetallic lead-zinc deposits can contain selenium.
- Gold deposits can contain selenium. Selenium will form independent minerals in these deposits if the ore contains very little sulfur; otherwise, it will be dispersed in sulfide minerals.
- Quartz-wolframite \((Fe,Mn)WO_4\)-bismuth and cassiterite \((SnO_2\)-quartz sulfide deposits are sometimes accompanied by selenium.
- Cobaltite-selenide-telluride resources that contain selenium are not frequently observed, but selenium can be associated with chloritization in this assemblage.
- Uranium deposits carry selenium but the co-occurrence of these elements could use more study.
- Cinnabar-stibnite deposits might contain appreciable selenium and could use more study.

**Magmatic and Associated Hydrothermal Deposits**

Aside from selenium minerals, selenium-bearing sulfide deposits represent the greatest known concentration of selenium in Earth’s crust. The reported average selenium concentration in magmatic sulfides is 0.02 percent (Sargent, 1954). In intrusive rocks, selenium will substitute for sulfur in sulfide minerals because of their similar ionic radii. High-temperature sulfides, such as pentlandite and pyrrhotite, have a sulfur-to-selenium ratio of 7,000:1, and Goldschmidt (1954) estimated hydrothermal pyrite to have a sulfur-to-selenium ratio of between 10,000 and 20,000:1. In the Falun mining area of Sweden, selenium is present in the following sulfide minerals, in decreasing order of concentration: galena, chalcopyrite, arsenopyrite, sphalerite, pyrite, and pyrrhotite (Sindeeva, 1964).

Attempts have been made to standardize the estimate of selenium in sulfide ore minerals and the most commonly used number for the average selenium content in magmatic and associated hydrothermal sulfides is 0.02 percent. Other ratios exist; for example, in porphyry copper ore with 0.5 percent copper, the selenium content is 2.5 ppm, or a copper-to-selenium ratio of 2,000:1 (Sargent, 1954; Lakin and Davidson, 1973). The U.S. Geological Survey and the former U.S. Bureau of Mines have long based their selenium production estimates on copper production figures using a factor of 0.0215 percent. Because copper ore from Canada has a higher selenium content, however, a factor of 0.064 percent is used to estimate selenium produced from its ores (for example, selenium in ore from mines located in the Sudbury basin of Ontario, Canada (table Q4; Jensen, 1985; George and Wagner, 2009).
### Table Q3. Selenium concentrations in sulfide minerals and other phases, in various deposit types.

[Data are from Sindeeva, 1964. Do., do., ditto; wt. %, weight percent; n.r., not reported, although the deposit was described as containing selenium and (or) selenide minerals; b.d.l., below detection limit; Hg, mercury; S, sulfur; Se, selenium]

<table>
<thead>
<tr>
<th>Deposit type</th>
<th>Deposit name, Location</th>
<th>Mineral phase</th>
<th>Selenium concentration (weight percent unless otherwise indicated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrothermal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chalcopyrite-molybdenite</td>
<td>Agarak deposit, Armenia</td>
<td>Chalcopyrite</td>
<td>0.004</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Molybdenite</td>
<td>0.0131 to 0.0134</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Pyrite</td>
<td>0.006</td>
</tr>
<tr>
<td>Do.</td>
<td>Dastakert deposit, Armenia</td>
<td>Bornite</td>
<td>0.0066</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Chalcopyrite-pyrite</td>
<td>0.003</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Galena</td>
<td>0.0057</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Molybdenite</td>
<td>0.0016</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Pyrite</td>
<td>0.0036</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Sphalerite</td>
<td>n.r.</td>
</tr>
<tr>
<td>Do.</td>
<td>Dzhindara deposit, Armenia</td>
<td>Molybdenite</td>
<td>0.04</td>
</tr>
<tr>
<td>Do.</td>
<td>Kadzharan deposit, Armenia</td>
<td>Chalcopyrite</td>
<td>0.0052</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Molybdenite</td>
<td>0.028 to 0.0513</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Pyrite</td>
<td>0.0015 to 0.0063</td>
</tr>
<tr>
<td>Do.</td>
<td>Miskhana deposit, Armenia</td>
<td>Molybdenite</td>
<td>0.0056</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Pyrite</td>
<td>0.008</td>
</tr>
<tr>
<td>Cinnabar-stibnite</td>
<td>Almaden, Idria, Spain</td>
<td>Mercury ores may contain</td>
<td>n.r.</td>
</tr>
<tr>
<td>Do.</td>
<td>San Onofrio, Mexico</td>
<td>Onofrite, Hg(S,Se)</td>
<td>1:3.9 S:Se ratio</td>
</tr>
<tr>
<td>Cobaltite-selenide-telluride</td>
<td>Upper Seymchanskoje deposit, Verina River basin, Russia</td>
<td>Selenide ore</td>
<td>0.0001 to 0.002</td>
</tr>
<tr>
<td>Gold-selenium</td>
<td>Eisenberg, near Korbach, Germany</td>
<td>Clausthalite (common)</td>
<td>n.r.</td>
</tr>
<tr>
<td>Gold-silver-quartz-adularia</td>
<td>Comstock and Goldfield, Nevada, United States</td>
<td>n.r.</td>
<td>n.r.</td>
</tr>
<tr>
<td>Do.</td>
<td>El Oro, Mexico</td>
<td>n.r.</td>
<td>n.r.</td>
</tr>
<tr>
<td>Do.</td>
<td>Redzhang Lebong deposit, Sumatra, Indonesia</td>
<td>n.r.</td>
<td>0.02</td>
</tr>
<tr>
<td>Pyritic</td>
<td>Uchaley deposit, Russia</td>
<td>Pyrite with chalcopyrite and sphalerite</td>
<td>0.0004 to &gt;0.01</td>
</tr>
<tr>
<td>Quartz-gold ore</td>
<td>Kirovskoje deposit, Russia</td>
<td>Arsenopyrite</td>
<td>0.0006 to 0.019</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Bismuthinite</td>
<td>0.2800 to 0.3275</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Chalcopyrite</td>
<td>0.0008 to 0.003</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Jamesonite</td>
<td>≤0.003</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Pyrite</td>
<td>≤0.003</td>
</tr>
</tbody>
</table>
Table Q3. Selenium concentrations in sulfide minerals and other phases, in various deposit types.—Continued

[Data are from Sineeva, 1964. Do., do., ditto; wt. %, weight percent; n.r., not reported, although the deposit was described as containing selenium and (or) selenide minerals; b.d.l., below detection limit; Hg, mercury; S, sulfur; Se, selenium]

<table>
<thead>
<tr>
<th>Deposit type</th>
<th>Deposit name, Location</th>
<th>Mineral phase</th>
<th>Selenium concentration (weight percent unless otherwise indicated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrothermal—Continued</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quartz-wolframite-bismuth</td>
<td>Bukuka deposit, Russia</td>
<td>Bismuthinite</td>
<td>0.016</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Chalcopyrite</td>
<td>0.0012</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Galena</td>
<td>0.0116</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Molybdenite</td>
<td>0.006</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Pyrite</td>
<td>0.0175</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Pyrrhotite</td>
<td>0.0013</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Sphalerite</td>
<td>0.0017</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Wolframite</td>
<td>b.d.l.</td>
</tr>
<tr>
<td>Selenide</td>
<td>Pacajake deposit, Bolivia</td>
<td>Blockite (penroseite) is main ore mineral, also naumannite; mined for gold in World War II</td>
<td>n.r.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uranite-selenide</td>
<td>Katanga deposit, Democratic Republic of the Congo (Congo [Kinshasa])</td>
<td>Reported to contain selenides</td>
<td>n.r.</td>
</tr>
<tr>
<td>Do.</td>
<td>Shinkolobse deposit, Democratic Republic of the Congo (Congo [Kinshasa])</td>
<td>Selenide minerals in 114th horizon</td>
<td>19</td>
</tr>
<tr>
<td>Magmatic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magmatic</td>
<td>Noril’sk, Siberia, Russia</td>
<td>Bornite</td>
<td>0.01 to 0.015</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Chalcopyrite</td>
<td>0.005 to 0.020</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Magnetite</td>
<td>Trace</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Millerite</td>
<td>0.001</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Pentlandite</td>
<td>0.0067</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Pyrite</td>
<td>Trace</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Pyrrhotite</td>
<td>0.0036 to 0.014</td>
</tr>
<tr>
<td>Volcanic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Andesite tufts</td>
<td>Shoshone, Jasper, and Riverton deposits, Wyoming, United States</td>
<td>n.r.</td>
<td>0.003 to 0.012</td>
</tr>
<tr>
<td>Native sulfur</td>
<td>Hawaiian Islands</td>
<td>n.r.</td>
<td>5.18</td>
</tr>
<tr>
<td>Do.</td>
<td>Kurile Islands, additional Kamchatka locations, Russia</td>
<td>n.r.</td>
<td>0.0005 to 0.19</td>
</tr>
<tr>
<td>Do.</td>
<td>Lipari Islands, Italy</td>
<td>n.r.</td>
<td>1.13</td>
</tr>
<tr>
<td>Do.</td>
<td>Mendeleev Volcano, Kunashir Island, Russia</td>
<td>n.r.</td>
<td>0.12</td>
</tr>
<tr>
<td>Do.</td>
<td>Mutnovskii Volcano, Kamchatka, Russia</td>
<td>n.r.</td>
<td>0.08</td>
</tr>
<tr>
<td>Do.</td>
<td>New Zealand</td>
<td>n.r.</td>
<td>0.3 and 0.19</td>
</tr>
<tr>
<td>Do.</td>
<td>Paramushir Island, Russia</td>
<td>n.r.</td>
<td>0.19</td>
</tr>
</tbody>
</table>
Exceptions can always be found to these general estimates; for example, selenium can be present in concentrations of hundreds of parts per million in tuffaceous rocks, and concentrations of several percent can be found in sulfides that host mercury and antimony deposits (Lakin and Davidson, 1973).

In magmatic sulfide deposits associated with mafic rocks, selenium may be found substituted for sulfur in sulfide veins. Sindeeva (1964) estimated the selenium content in such deposits to vary between 0.002 and 0.01 percent, although concentrations of as high as 0.017 percent and as low as 0.0003 percent have been found. The Permian-to-Triassic age Noril’sk group of sulfide deposits, which are located in Siberia, Russia, inside the Arctic Circle, are representative of this type of mineralization (table Q3), as are the sulfide deposits from the Sudbury basin in Ontario, Canada (table Q4).

At Noril’sk, the selenium of economic interest is contained in sulfide minerals, where it occurs from isomorphous substitution for sulfur in concentrations of 2 to 74 ppm. Massive vein deposits at Noril’sk display greater concentrations of selenium than its disseminated ores, with a range of 0.036 to 0.015 percent selenium in massive vein deposits owing to the greater proportion of copper sulfides in the vein deposits; however, no correlation has been found between selenium and any of the elements copper, lead, nickel, sulfur, or tellurium. Distribution of selenium depends upon the composition of the ore as well as the location of the sample within the orebody and with respect to the structural setting (table Q3). The rocks surrounding the ore deposits (andesites, diabases, and gabbros) contain merely 0.00001 percent (0.1 ppm) selenium (Sindeeva, 1964).

In addition to magmatic sulfide ores, Sindeeva (1964) considered the volcanic deposits of native sulfur and tuffs. She observed selenium concentrations of 0.0005 to 5.18 percent in sulfur deposits and 0.003 to 0.012 percent selenium in andesite tuffs that had partially transformed to bentonite in the Oligocene-age Jasper, Riverton, and Shoshone deposits in Wyoming (table Q3).

The porphyry copper deposits that host much of the selenium produced worldwide are large breccia and vein-hosted deposits found genetically related to granitoid porphyry intrusions. They form at convergent plate margins, and most are of Cenozoic or Mesozoic age, although they can range from Archean to Quaternary (John and others, 2010). John and others (2010) argued that porphyry copper mineralization forms from magmatic fluids released during emplacement of porphyritic stocks. Selenium in sulfides of porphyry copper deposits is originally transported in hypogene fluids but may also be remobilized during hydrothermal alteration of the porphyry copper system.

Many workers have attempted to employ the selenium-to-sulfur ratio in the ore minerals to ascertain whether external sulfur was involved in the genesis of mineralization. Selenium-to-sulfur ratios ranging from 0.00023:1 to 0.00035:1 have been assigned to mantle-derived rocks (Eckstrand and Hulbert, 1987), and ratios lower than this are found when sulfur is contributed from external fluids and (or) host rocks (for example, Ripley, 1990). Fitzpatrick (2008) measured selenium-to-sulfur ratios in minerals from three deposits: a volcanic massive sulfide (VMS) deposit in Flin Flon, Canada; a high-sulfidation epithermal deposit in Pierina, Peru; and an iron oxide-copper-gold (IOCG) deposit in Mantoverde, Chile. By combining the selenium-to-sulfur ratios with δ34S values, Fitzpatrick demonstrated that the VMS and epithermal deposits displayed high selenium-to-sulfur ratios and low δ34S values, which is typical of magmatic fluids; the IOCG deposit, however, showed the opposite signal, suggesting dilution of a magmatic fluid with a seawater-derived basal fluid. He concluded that selenium-to-sulfur ratios can help identify the fluid source(s) for mineralization, and that the addition of δ34S values extended the usefulness of this tracer.

Other studies have employed selenium as an exploration ‘vector’ to discriminate among mineralization signatures found proximal or distal to a fluid source. Bornite and chalcolite show some potential for this work (Cook and others, 2011). Zonation of selenium concentration has also been observed in marine systems, and high selenium concentrations have been observed in black smoker deposits and iron-copper massive sulfides associated with the East Pacific Rise. Here, high selenium values occur in high-temperature mineral assemblages of the inner part of the deposit, which are in equilibrium with pure, unmixed hydrothermal fluids. The lowest selenium values are found in the outer part of the deposit, where mineralization is influenced by mixing of hydrothermal fluids and seawater (Auclair and others, 1987).

### Table Q4. Selenium concentrations in copper-nickel ores in the Sudbury basin, Ontario, Canada.

<table>
<thead>
<tr>
<th>Mine name</th>
<th>Ore type</th>
<th>Selenium concentration (parts per million)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Murray</td>
<td>Massive sulfide</td>
<td>32 to 64</td>
</tr>
<tr>
<td></td>
<td>Gabbro peridotite inclusion sulfide</td>
<td>82</td>
</tr>
<tr>
<td>Creighton</td>
<td>Interstitial sulfide</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>Ragged disseminated sulfide</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Gabbro peridotite inclusion sulfide</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>Massive sulfide</td>
<td>65</td>
</tr>
<tr>
<td>Garson</td>
<td>Contorted schist inclusion sulfide</td>
<td>22</td>
</tr>
<tr>
<td>Levack</td>
<td>Interstitial sulfide in sublayer norite</td>
<td>25</td>
</tr>
<tr>
<td>Frood</td>
<td>Disseminated sulfide in quartz diorite</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>Interstitial sulfide</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>Ragged disseminated sulfide</td>
<td>20</td>
</tr>
</tbody>
</table>

1Ore type classification is from Schwarcz (1973).
2Selenium analysis is from Nriagu and Wong (1983).
Selenide-Bearing Deposits

In contrast to Sindeeva (1964), who discussed all selenium-bearing deposits whether they contained selenium-bearing sulfides, selenides, selenates, selenites, or native selenium, Simon and others (1997) discussed deposits that contained selenide minerals only. Their purpose was to “determine the conditions that favor deposition of selenide minerals over substitution of selenium in sulfide minerals” (Simon and others, 1997, p. 468). Deposits were grouped into the following four types: (a) telethermal selenide vein-type, (b) unconformity-related uranium deposits, (c) sandstone-hosted uranium deposits (roll-front type), and (d) gold-silver epithermal volcanic-hosted deposits. The following brief descriptions of these four deposit types are taken mostly from Simon and others (1997):

a. Telethermal selenide vein-type deposits include selenide-bearing deposits like those of the Tilkerode-Zorge-Lerbach deposit in the Harz Mountains of Germany, the Pacajake and El Dragon deposits in Bolivia, the Hope’s Nose deposit in the United Kingdom, and the Sierra de Umango and Sierra de Cacheuta deposits in Argentina. In these deposits, selenide minerals occur in veins or veinlets with carbonate minerals, gold, hematite \( \text{Fe}_2 \text{O}_3 \), platinum-group elements, and rare sulfides, and are commonly hosted in sedimentary rocks. Some of these deposits were classified as the “selenide-type” by Sindeeva (1964). Conditions for formation of these deposits include \( f_{\text{O}_2(g)} \) above the hematite-magnetite buffer (that is, in the hematite stability field) and a ratio of selenium-to-sulfur fugacities that is greater than one \( (f_{\text{Se}_{2(g)}}/f_{\text{S}_{2(g)}>1}) \). Simon and others (1997) argue that the high \( f_{\text{O}_2} \) value helps to separate selenium from sulfur, thus preventing the incorporation of selenium into sulfides and allowing the system to form selenide minerals.

b. Selenide minerals in unconformity-related uranium deposits are found in vein deposits in the Bohemian Massif of the Czech Republic, the Massif Central of France, and the Athabasca area of northern Saskatchewan, Canada. Cobalt, copper, and nickel selenides in these deposits are associated with carbonates; cobalt, copper, and nickel sulfides and arsenides; hematite; and uraninite minerals. As with the vein-type deposits above, the conditions for selenide formation include \( f_{\text{O}_2(g)} \) values within the hematite stability field and a ratio of selenium-to-sulfur fugacities that is greater than one \( (f_{\text{Se}_{2(g)}}/f_{\text{S}_{2(g)}>1}) \).

c. Selenium-bearing sandstone-hosted uranium deposits (roll-front-type) include the uranium and vanadium sandstone deposits of the Colorado Plateau, and similar deposits in Oklahoma, Wyoming, and Texas (Davidson, 1963; Howard, 1977). Davidson (1963) surveyed uranium deposits in oxidized sandstones ranging from Paleozoic to Cenozoic age in several States across the United States and found selenium concentrations that ranged from 3 to 4,500 ppm. In a survey by Coleman and Delevaux (1957), selenium concentrations up to 3 weight percent were measured in uranium deposits of the Colorado Plateau.

In the roll-front uranium deposits, selenium is commonly found in isomorphic substitution for sulfur in chalcocite, galena, marcasite, and pyrite. It is also found as the selenide minerals ferroselite (\( \text{FeSe}_x \)), clausthalite, and native selenium. Howard (1977) provided a good description of the location of selenium mineralization with respect to the redox interface of a roll-front-type uranium orebody. He described the uranium ore deposits as forming in gently dipping permeable sandstone units, sandwiched between units of lower permeability. Mineralization occurred as oxidizing meteoric solutions moved through the host sandstone and dissolved pyrite and other redox-active minerals. At the front of the plume of meteoric water, the solution lost its oxidizing potential and deposited iron, selenium, and uranium at the interface between oxidizing and reducing environments. In this model, selenium is commonly found as native selenium in the sandstone on the oxidized side of the redox boundary, as ferroselite in both goethite \( (\text{FeO(OH)}) \)-hematite and pyrite-marcasite associations on either side of the redox interface, and as ferroselite and native selenium within the uraninite-coffinite \( (\text{U(SiO}_2 \text{)}_{1-x} \text{)(OH)}_x \) assemblages of the orebody. In the unaltered reduced rock, selenium will be found as ferroselite or in isomorphous substitution with sulfur in pyrite. It is the continued cycle of oxidative dissolution (of reduced minerals in the unaltered rock) and redeposition (at the redox interface at the front of the groundwater plume) that serves to concentrate selenium, iron, and the uranium-ore minerals of these deposits (Howard, 1977).

d. Selenide-bearing gold-silver epithermal volcanic-hosted deposits are found at Hishikari, Japan; the western Great Basin, Nevada; the Great Barrier Island, New Zealand; Salida and Redzhang Lobong, Indonesia; Guanajuato, Mexico; and Prasolovskoye, Kunashir Island, Russia. Selenium in these deposits is primarily found in silver selenides and, less commonly, in bismuth, copper, and lead selenides, all associated with sulfides, sulfosalts, and native elements. John (2001) observed that the silver selenides aguilariite and naumannite are found in almost all low-sulfidation epithermal gold-silver deposits associated with Miocene bimodal magmatism in the Great Basin, Nevada. Selenium-bearing stibnite and sphalerite
are found among the ore-stage minerals, and selenium can be enriched in the gold-bearing arsenian rims found on pyrite and marcasite. It is thought that these deposits formed from hydrothermal fluids with $f_{O_{2(g)}}$ below the hematite-magnetite buffer and have a ratio of selenium-to-sulfur fugacities that is less than one ($f_{Se_{2(g)}} / f_{S_{2(g)}} < 1$) (Simon and others, 1997). These conditions lead to a greater abundance of sulfides than selenides.

### Sedimentary Rocks

The substitution of selenium for sulfur in biological processes leads to the presence of selenium in pyrite contained in black shales and coal, yet compared with magmatic rocks, the sulfur-to-selenium ratio in diagenetic pyrite is estimated to be 200,000:1 or higher (Goldschmidt, 1954). Selenium in detrital organic matter may be enriched many times above its crustal abundance. Highly organic shales may contain up to 1,500 ppm selenium. Marine phosphorites may contain as much as 300 ppm selenium. Coals of the United States have a geometric mean concentration of 1.7 ppm (Coleman and others, 1993).

Selenium concentrations in coal have been a topic of interest for many decades owing to the release of trace elements to the atmosphere during coal combustion. Coal contains 5 to 300 times the amount of selenium as average sedimentary and igneous rocks, and it is enriched 82 times above the average selenium concentration in Earth’s crust (table Q5; Coleman and others, 1993). The study by Coleman and others (1993) analyzed almost 9,000 coal samples from across the United States (fig. Q5) and found that the highest selenium values (with a geometric mean of 4.9 ppm) are found in coals from Texas. Coal found in the Atlantic Coast region (Virginia and North Carolina) and coal in Alaska have the lowest geometric means, at 0.2 and 0.42 ppm selenium, respectively. The highest concentration in an individual sample (75 ppm) was observed in coals from northern Appalachia. Because of the close association of selenium with sulfur, it might be expected that selenium concentrations would correlate with concentrations of pyritic sulfur or organic sulfur, but this was not generally observed throughout the dataset. Coleman and others (1993) speculated that the lack of correlation may be owing to multiple sources of selenium, including detrital particles, plant matter, volcanic ash, surface water and groundwater, and epigenetic mineralization. They note, in addition, that selenium concentrations can be modified by diagenetic processes. Whereas selenium is shown to be closely associated with the organic fraction in coal, it is also found in selenium-bearing pyrite and galena, and as clastthalite. Selenium is also found in water-soluble and ion exchangeable forms.

Much of the Western United States is underlain by seleniferous sedimentary rocks whose ages range from Permian (for example, the Phosphoria Formation, which has phosphate rock members containing 1 to 1,200 ppm selenium), to Cretaceous (for example, the Niobrara Formation and the Pierre Formation, which have selenium concentrations of 0 to 113 ppm, and 0 to 103 ppm, respectively) to Upper Cretaceous-Paleogene (for example, the Moreno Formation and the Kreyenhagen Formation of the California Coast Ranges, which have selenium concentrations that together range from 0.6 to 45 ppm) (table Q5; figs. Q6A–C; Presser and others, 1990). Trelease and Beath (1949) extensively mapped and documented the widespread extent of seleniferous bedrock in the Western United States as part of their study of the source of selenium in livestock food and forage (figs. Q6A–B).

Seiler and others (2003) extended this survey in their work to identify the source of selenium contamination to irrigation waters in the Western United States (fig. Q6C). Presser and others (2004) attributed the high selenium concentration in these sedimentary bedrock units to its depositional origin in marine basins with high primary biological productivity. Selenium is cycled from ocean waters into bacteria, algae, fungi, and plants with the production of selenium-containing amino acids. Deposition of these species as organic detritus on the sea floor, and subsequent loss of organic matter from diagenesis resulted in accumulation and concentration of selenium and other trace elements in the sediments. This is the general model for trace-element enrichment in the Permian Phosphoria Formation (Piper, 1994, 2001) as well as in the Cretaceous and Paleogene marine formations of the Western United States (Presser and others, 2004). Preservation of selenium and other trace elements in these rocks is attributed to their high initial concentrations, retention by the sediments (often in an organic fraction), and extremely low accumulation of other diluting phases.

### Resources and Reserves

More than 80 percent of global production of selenium is obtained as a byproduct of copper refining; it is recovered from anode slimes generated in electrolytic production of copper (Brown, 2002). The blister copper (that is, the partly refined copper formed during smelting) that serves as the anode in an electrolytic cell contains an average of 0.05 percent selenium (0.5 kg of selenium per metric ton of copper), but recovery ranges from 0.02 percent to 0.038 percent (0.2 to 0.38 kg of selenium per metric ton of copper; Lakin and Davidson, 1973). Other methods of refining copper, such as in situ leaching or the ISASMELT™ technology, do not recover selenium; hence, the global production of selenium is dependent on the method of copper refining. Because selenium production is mainly a byproduct of copper refining, countries with selenium resources and (or) reserves are those with resources and (or) reserves of copper, and they include Canada, Chile, China, Congo (Kinshasa), Mexico, Peru, the Philippines, Russia, the United States, and Zambia (Jensen, 1985; John and others, 2010). Minor amounts of selenium have also been recovered from lead, nickel, and zinc ores.
Figure Q5. Map showing selenium concentrations (in parts per million) in coal samples, by region of the United States. Selenium concentrations were analyzed in almost 9,000 U.S. coal samples. Data are plotted as the geometric means of samples from 24 regions. The map shows the highest selenium values (with a geometric mean of 4.9 ppm) are found in coals from Texas. Coal found in the Atlantic Coast region (Virginia and North Carolina) and coal in Alaska (not shown on the map) have the lowest geometric means, at 0.2 and 0.42 ppm selenium, respectively. The highest concentration in an individual sample (75 ppm) was observed in coals from the northern portion of the Appalachian region. Map is from Coleman and others (1993).
### Table Q5. Selenium concentrations in selected Earth and lunar materials.

[Biologic samples are dry weight unless otherwise noted. Abbreviations: ppm, part per million; ppb, part per billion; ng/L, nanogram per liter; nmol/kg, nanomole per kilogram]

<table>
<thead>
<tr>
<th>Material</th>
<th>Source of material</th>
<th>Selenium concentration (and additional explanation)</th>
<th>Unit</th>
<th>Reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rocks</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Earth’s crust</td>
<td>Continental crust</td>
<td>0.05 ppm</td>
<td>ppm</td>
<td>Taylor (1964, p. 1280)</td>
</tr>
<tr>
<td>Earth’s crust</td>
<td>Granite</td>
<td>0.01 to 0.05 ppm</td>
<td>ppm</td>
<td>Kabata-Pendias and Pendias (1984, p. 186)</td>
</tr>
<tr>
<td>Earth’s crust</td>
<td>Limestone</td>
<td>0.03 to 0.10 ppm</td>
<td>ppm</td>
<td>Kabata-Pendias and Pendias (1984, p. 186)</td>
</tr>
<tr>
<td>Earth’s crust</td>
<td>Phosphate rock</td>
<td>1 to 300 ppm</td>
<td>ppm</td>
<td>McNeal and Balistrieri (1989, and references therein)</td>
</tr>
<tr>
<td>Earth’s crust</td>
<td>Sandstone</td>
<td>0.05 to 0.08 ppm</td>
<td>ppm</td>
<td>Kabata-Pendias and Pendias (1984, p. 186)</td>
</tr>
<tr>
<td>Earth’s crust</td>
<td>Shale</td>
<td>0.6 ppm (average)</td>
<td>ppm</td>
<td>Adriano (1986, p. 392)</td>
</tr>
<tr>
<td>Coal</td>
<td>World</td>
<td>3 ppm</td>
<td>ppm</td>
<td>Minkin and others (1984)</td>
</tr>
<tr>
<td>Coal</td>
<td>China</td>
<td>3.65 ppm</td>
<td>ppm</td>
<td>Zhang and others (1999)</td>
</tr>
<tr>
<td>Coal</td>
<td>United States</td>
<td>0.46 to 10.65 ppm</td>
<td>ppm</td>
<td>Pillay and others (1969, p. 480)</td>
</tr>
<tr>
<td>Coal</td>
<td>United States</td>
<td>1.7 ppm (geometric mean)</td>
<td>ppm</td>
<td>Coleman and others (1993)</td>
</tr>
<tr>
<td>Marine shale</td>
<td>Kreyenhagen Formation</td>
<td>8.7 ppm (median)</td>
<td>ppm</td>
<td>Presser (1994, p. 145)</td>
</tr>
<tr>
<td>Marine shale</td>
<td>Mancos Formation</td>
<td>0.1 to 5.46 ppm</td>
<td>ppm</td>
<td>Tuttle and others (2007, appendix tables)</td>
</tr>
<tr>
<td>Marine shale</td>
<td>Mead Peak Member, Phosphoria Formation</td>
<td>1 to 1,200; 182 (average)</td>
<td>ppm</td>
<td>Presser and others (2004)</td>
</tr>
<tr>
<td>Marine shale</td>
<td>Moreno Formation</td>
<td>6.5 (median)</td>
<td>ppm</td>
<td>Presser (1994, p. 145)</td>
</tr>
<tr>
<td>Marine shale</td>
<td>Niobrara Formation</td>
<td>0 to 30 ppm</td>
<td>ppm</td>
<td>Moxon and others (1938, p. 797–799)</td>
</tr>
<tr>
<td>Marine shale</td>
<td>Pierre Formation</td>
<td>0 to 103 ppm</td>
<td>ppm</td>
<td>Moxon and others (1938, p. 799–802)</td>
</tr>
<tr>
<td>Moon rocks</td>
<td>Apollo 11</td>
<td>0.12 to 1.6 ppm</td>
<td>ppm</td>
<td>Leutwein (1972, p. 34-C-3)</td>
</tr>
<tr>
<td>Moon rocks</td>
<td>Apollo 16</td>
<td>0.40 to 314 ppb</td>
<td>ppb</td>
<td>Krähenbühl and others (1973, p. 1328)</td>
</tr>
<tr>
<td><strong>Soils and dusts</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil</td>
<td>Worldwide, seleniferous, upper limit</td>
<td>1,200 ppm</td>
<td>ppm</td>
<td>Winkel and others (2012, p. 572)</td>
</tr>
<tr>
<td>Soil</td>
<td>Worldwide, selenium-deficient, lower limit</td>
<td>&lt;0.01 ppm</td>
<td>ppm</td>
<td>Winkel and others (2012, p. 572)</td>
</tr>
<tr>
<td>Soil</td>
<td>England and Wales</td>
<td>&lt;0.01 to 4.7 ppm</td>
<td>ppm</td>
<td>Thornton and others (1983; as cited in McNeal and Balistrieri, 1989)</td>
</tr>
<tr>
<td>Soil</td>
<td>Finland, near a Cu-S orebody</td>
<td>0.1 to 5.5 ppm</td>
<td>ppm</td>
<td>Koljonen (1976, p. 263)</td>
</tr>
<tr>
<td>Soil</td>
<td>Ireland, seleniferous</td>
<td>≤1,200 ppm</td>
<td>ppm</td>
<td>Fleming (1962, p. 30)</td>
</tr>
<tr>
<td>Soil</td>
<td>Italy, volcanic</td>
<td>0.12 to 2.25 ppm</td>
<td>ppm</td>
<td>Floor and others (2011, p. 238)</td>
</tr>
</tbody>
</table>
### Table Q5. Selenium concentrations in selected Earth and lunar materials.—Continued

[Biologic samples are dry weight unless otherwise noted. Abbreviations: ppm, part per million; ppb, part per billion; ng/L, nanogram per liter; nmol/kg, nanomole per kilogram]

<table>
<thead>
<tr>
<th>Material</th>
<th>Source of material</th>
<th>Selenium concentration (and additional explanation)</th>
<th>Unit</th>
<th>Reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soils and dusts—Continued</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil</td>
<td>Sweden, agricultural</td>
<td>0.065 to 1.7 ppm</td>
<td>ppm</td>
<td>Johnsson (1992, section 4.1)</td>
</tr>
<tr>
<td>Soil</td>
<td>Sweden, background, not affected by agriculture</td>
<td>&lt;0.45 ppm</td>
<td>ppm</td>
<td>Johnsson (1992, section 4.1)</td>
</tr>
<tr>
<td>Soil</td>
<td>United States</td>
<td>&lt;0.1 to 4.3 ppm</td>
<td>ppm</td>
<td>Shacklette and Boerngen (1984, p. 4); Tidball (1984, p. H6)</td>
</tr>
<tr>
<td>Soil</td>
<td>United States</td>
<td>&lt;0.2 to 8.3 ppm</td>
<td>ppm</td>
<td>Smith and others (2014, p. 197–202)</td>
</tr>
<tr>
<td>Soil</td>
<td>United States, seleniferous</td>
<td>2.7 to 90 ppm</td>
<td>ppm</td>
<td>Trelease and Beath (1949, p. 111–112)</td>
</tr>
<tr>
<td>Soil</td>
<td>United States, Hawaii, volcanic</td>
<td>1 to 20 ppm</td>
<td>ppm</td>
<td>Floor and Román-Ross (2012, p. 521)</td>
</tr>
<tr>
<td>Atmospheric dust</td>
<td>Major U.S. cities, 1941</td>
<td>0.05 to 10 ppm</td>
<td>ppm</td>
<td>Lakin and Byers (1941, p. 20)</td>
</tr>
<tr>
<td>Biologic samples</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Algae</td>
<td>Freshwater</td>
<td>&lt;2.0 ppm</td>
<td>ppm</td>
<td>Jenkins (1980; as cited in McNeal and Balistrieri, 1989)</td>
</tr>
<tr>
<td>Animal tissue</td>
<td>Domestic stock</td>
<td>0.44 to 4.0 ppm</td>
<td>ppm</td>
<td>Frost (1972, p. 471)</td>
</tr>
<tr>
<td>Whole fish</td>
<td>Freshwater</td>
<td>0.05 to 2.87 (wet weight)</td>
<td>ppm</td>
<td>May and McKinney (1981, p. 35)</td>
</tr>
<tr>
<td>Whole fish</td>
<td>Marine</td>
<td>0.1 to 20 ppm</td>
<td>ppm</td>
<td>Hall and others (1978, p. 94–98)</td>
</tr>
<tr>
<td>Water</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seawater</td>
<td>Pacific Ocean, 18° N., 108° W.</td>
<td>0.95 to 2.44 nmol/kg</td>
<td>nmol/kg</td>
<td>Cutter and Bruland (1984, p. 1183)</td>
</tr>
<tr>
<td>River water</td>
<td>Amazon River</td>
<td>0.00021 ppm</td>
<td>ppm</td>
<td>Kharkar and others (1968, p. 290)</td>
</tr>
<tr>
<td>River water</td>
<td>Colorado River, United States</td>
<td>0.01 to 0.4 ppm</td>
<td>ppm</td>
<td>Scott and Voegeli (1961; as cited in McNeal and Balistrieri, 1989)</td>
</tr>
<tr>
<td>River water</td>
<td>Finland, stream sediments</td>
<td>0.26 ppm</td>
<td>ppm</td>
<td>Wang (1994; as cited in Parkman and Hultberg, 2002)</td>
</tr>
<tr>
<td>River water</td>
<td>Mississippi River, United States</td>
<td>0.000114 ppm</td>
<td>ppm</td>
<td>Kharkar and others (1968, p. 290)</td>
</tr>
<tr>
<td>Lake water</td>
<td>Finland, lakes affected by agriculture</td>
<td>76.8 ng/L</td>
<td>ng/L</td>
<td>Wang (1994; as cited in Parkman and Hultberg, 2002)</td>
</tr>
<tr>
<td>Lake water</td>
<td>Finland, lakes, background, not affected by agriculture</td>
<td>56 to 62 ng/L</td>
<td>ng/L</td>
<td>Wang (1994; as cited in Parkman and Hultberg, 2002)</td>
</tr>
<tr>
<td>Lake water</td>
<td>Sweden</td>
<td>43 to 209 ng/L</td>
<td>ng/L</td>
<td>Parkman and Hultberg (2002)</td>
</tr>
<tr>
<td>Lake water</td>
<td>United States, Lake Michigan</td>
<td>0.083 ppb</td>
<td>ppb</td>
<td>Robberecht and Van Grieken (1982, p. 839)</td>
</tr>
<tr>
<td>Lake water</td>
<td>Finland, lake sediment</td>
<td>0.27 to 3.64 ppm</td>
<td>ppm</td>
<td>Wang (1994; as cited in Parkman and Hultberg, 2002)</td>
</tr>
</tbody>
</table>
In 1973, the USGS estimated the world’s identified resources of selenium to be almost 13 million metric tons (28.6 billion pounds) based upon the selenium content of identified resources of coal, copper, lead, and pyrite. Estimates from copper resources were made using a ratio of 0.325 kg of selenium recovered per metric ton of copper produced. Selenium from lead ores was estimated based upon an average of 10 ppm selenium in galena and the estimate of identified lead resources. Estimates for selenium in pyrite were made assuming 10 ppm selenium in pyrite and estimates of the sulfur resources in pyrite. Selenium resources in coal were estimated using estimates for coal resources and an average of 1.5 ppm Se in coal. Lakin and Davidson (1973) noted that although the estimated resource of selenium in coal was two orders of magnitude greater than that in copper resources, it could not be easily recovered. As of 2016, the recovery of selenium from coal is technically feasible but not economical.

In contrast, modern estimates of selenium reserves in table Q6 are based only on copper reserves and do not include selenium found in other copper resources or in lead,

---

**Figure Q6.** Maps showing locations of seleniferous sedimentary outcrops and deposits and plant samples with significant selenium content. This map, A, shows the spatial relation among locations of Cretaceous, seleniferous, marine sedimentary outcrops and plant samples with greater than or equal to 50 parts per million (ppm) selenium. Map A is from Trelease and Beath (1949) and, with map B, shows the widespread extent of seleniferous bedrock across the Western United States and its correlation with selenium in plant samples.
pyrite, and coal resources. The fraction of copper reserves expected to be recovered by leaching and electrowinning is subtracted from the total because these processes do not recover selenium. The estimates are derived, as mentioned previously, by using a recovery factor of 0.215 kg of selenium per metric ton of primary recoverable electrolytic copper (0.0215 percent). In Canada, where the selenium content of copper ore is higher, a factor of 0.64 kg of selenium per metric ton of copper (0.064 percent) is employed (Butterm and Brown, 2004; George and Wagner, 2009). Global supplies of selenium have steadily increased over the past few years owing to an increase in copper production.

**Identified Resources**

No deposits in the world are mined for selenium alone. Instead, as discussed above, selenium is produced mostly as a byproduct of copper refining. Whereas Japan and Germany (in order of output) were the leading producers of selenium in the world in 2015 (U.S. Geological Survey, 1997–2014), the selenium was sourced from copper concentrates and residues supplied from mining operations in Africa, Asia, Australia, and South America (Bleiwas, 2010). Of the global reserves of 120,000 metric tons of selenium, almost 60 percent is located in Chile, China, and Russia combined, whereas

---

**Figure Q6.—Continued**  Maps showing locations of seleniferous sedimentary outcrops and deposits and plant samples with significant selenium content. This map, B, shows the spatial relation among locations of Paleocene and Eocene, seleniferous, marine sedimentary outcrops and plant samples with greater than or equal to 50 ppm selenium. Map B is from Trelease and Beath (1949) and, with map A, shows the widespread extent of seleniferous bedrock across the Western United States and its correlation with selenium in plant samples.
Figure Q6.—Continued Maps showing locations of seleniferous sedimentary outcrops and deposits and plant samples with significant selenium content. This map, C, shows locations of potentially seleniferous marine and continental sedimentary deposits in the Western United States. Map C is from Seiler and others (2003, p. 51, fig. 20) and shows additional areas with potentially seleniferous bedrock not identified by Trelease and Beath (1949).
the United States has an estimated 10,000 metric tons of world selenium reserves, or about 8 percent. As of 2012, the leading copper-producing mines in the United States were located in Arizona, Nevada, New Mexico, and Utah and accounted for all U.S. domestic selenium reserves (Brininstool, 2015).

Globally, the countries with the largest mine production of copper in 2012 were Australia, Canada, Chile, China, Congo (Kinshasa), Indonesia, Kazakhstan, Mexico, Peru, Poland, Russia, the United States, and Zambia (Brininstool, 2015). Copper mines from these countries account for the global reserves of selenium and are the sources of concentrates and residues for the leading selenium producers.

Undiscovered Resources

Although selenium is produced currently from copper ores—mostly from porphyry copper deposits—it also occurs in many other types of mineral deposits and earth materials (tables Q2 through Q5). The highest concentrations of selenium are likely to occur in deposits that host selenide minerals, such as the selenide vein-type deposits described by Simon and others (1997). Although the selenium grade is high in selenide deposits, the overall tonnage is low. Deposits of native sulfur may also contain high concentrations of selenium (table Q3), yet the tonnage of these deposits compared with that of porphyry copper deposits is also low.

The close association of selenium with sulfur is the reason that copper ores are a resource for selenium. One approach to identifying new selenium resources would be to investigate this selenium-to-sulfur relationship in other rock types. Rocks enriched in organic carbon are likely to have high selenium concentrations, where selenium has substituted for sulfur in diagenetic sulfide minerals. These resources might be coal (where selenium recovery is technically feasible but not currently economic), marine phosphate deposits, or oil shales. Presser and others (2004) have mapped a global distribution of selenium-rich rocks found in sedimentary basins enriched in organic carbon (fig. Q7). Although the purpose of their mapping was to identify selenium source rocks that might create environmental concerns, their analysis might also be useful in identifying new selenium resources.

Environmental Considerations

Selenium is both a necessary nutrient and a potential hazard to Earth ecosystems, and it is present in the environment both naturally and as a result of human activity. Selenium mining, processing, use, and disposal may all potentially release selenium to the environment. Environmental considerations are integral to decisions regarding extraction and use of selenium.
deposited onto surfaces by dry deposition or incorporated into water droplets and removed by wet deposition.

After selenium has been introduced to the upper crust, it cycles among the atmosphere, biosphere, and hydrosphere. Natural biologic emissions that cycle selenium between the biosphere and atmosphere account for approximately one-half to two-thirds of atmospheric selenium (Mosher and others, 1987); these emissions are composed mostly of dimethyl selenide gas from marine biogenic sources and account for 70 percent of natural biologic emissions of selenium. Other natural sources of atmospheric selenium are the continental biosphere (20 percent), volcanoes (8 percent), sea salt (2 percent), and crustal weathering (less than 1 percent) (Cahill and Eldred, 1998).

Anthropogenic selenium emissions to the atmosphere are derived mostly from coal and oil combustion (50 percent and 10 percent, respectively), and base-metal production of copper, zinc, and lead (20 percent, 4 percent, and 4 percent, respectively) using roasters and autoclaves (Cahill and Eldred, 1998; Winkel and others, 2012). It has been known for some time that coal combustion is a major source of selenium to the environment and that coal can contain 5 to 300 times the amount of selenium as other rocks (table Q5). Emission controls on coal-fired powerplants are limited in their ability to remove volatile selenium species (Ranville and others, 2010); hence, selenium escapes into the atmosphere. Coal combustion also generates fly ash that can concentrate selenium 10 to 25 times beyond its original concentration in the coal (Lemly, 1985). Other than coal, the remaining anthropogenic selenium emissions come from other forms of combustion and from ceramic and glass manufacturing (Cahill and Eldred, 1998).

One important natural source of selenium to surface and groundwaters is weathering of marine shales. A significant portion of the bedrock in the Western United States is composed of marine shales (most notably of Cretaceous age but with a range of Permian to Paleogene ages). These shales are noted for their high selenium content (table Q5) derived from the volcanic eruptions that were especially extensive during the Cretaceous Period. Selenium became incorporated into marine sediments, often substituting for sulfur in pyrite, and then mobilized as sediments were uplifted and weathered. Selenium-rich soils in the northern Great Plains of the United States owe their selenium content to the underlying shales of the Pierre Formation and the Niobrara Formation (Trelease and Beath, 1949; Mayland, 1985). Moxon and others (1938) hypothesized that the selenium content of the Pierre Formation and the Niobrara Formation was inversely related to the rate of sediment deposition because they observed that thin stratigraphic sections (which were produced from low deposition rates) had high concentrations of selenium, whereas thicker

Figure Q7. A predictive map of selenium source rocks associated with organic-rich depositional marine basins. This map is useful both for identifying selenium source rocks that could be of potential environmental concern and for identifying potential new selenium resources. Modified from Presser and others (2004, p. 313).
sections (representing fast deposition rates) had low selenium concentrations. Other marine shales, such as the Meade Peak member of the Permian Phosphoria Formation in southeastern Idaho and western Wyoming (Stillings and Amacher, 2004; Presser and others, 2004), the Cretaceous-Paleogene Moreno Formation, and the Eocene-Oligocene Kreyenhagen Formation in the California Coast Range (Presser, 1994) are sources of selenium to groundwater, surface water, and soil. Additionally, coal and other organic-rich sediments release selenium through weathering (McNeal and Balistrieri, 1989).

In other regions of the United States where the soils are selenium-deficient, and in other countries, selenium is added to soils by way of selenium-containing fertilizers, lime, and manure. It is widely recognized that selenium is a necessary dietary nutrient for humans, as well as for other animals, and in the United Kingdom, selenium fertilizers are used in pastures and forage areas to increase the human intake of selenium through meat and dairy products. In Finland, a national-scale use of selenium fertilizers began in 1984 and has resulted in a fourfold increase in the intake of dietary selenium in the human study population (Winkel and others, 2012, and references therein). Because crops take up only 5 to 20 percent of the selenium applied in fertilizers, the rest of the selenium is either immobilized in the soil through chemical reduction or leached from the soil and added to surface runoff waters. The Finnish study calculated that application of selenium fertilizers was expected to have increased selenium in soils by 20 percent, but because no increase in the soil was observed, selenium must have been leached from the soils. In Tennessee, the use of selenium in fertilizers has caused selenium runoff in surface waters, resulting in an accumulation in aquatic biota (Winkel and others, 2012, and references therein).

Average Ambient Concentrations in Air, Streams, Groundwater, and Soil

Ambient concentrations of selenium in the environment are dependent upon selenium concentrations in the underlying bedrock. Soils in the United States that overlie pre-Cretaceous-age sedimentary rocks, volcanic ash, or granitic rock tend to be low in selenium because most of these bedrock materials are also low in selenium (McNeal and Balistrieri, 1989).

Recent data on soil chemistry in the conterminous United States show selenium concentrations to range from less than 0.2 to 8.3 ppm (figs. Q8A–C; Smith and others, 2014). The data were collected from three soil sections—0 to 5 centimeters (cm) depth, the A horizon, and the C horizon. Although the spatial distribution of selenium varied among the three soil sections (figs. 8A–C), the concentration range and histogram of selenium concentrations were fairly consistent among them—from less than 0.2 to 6.9 ppm for the 0-to-5-cm-depth section; from less than 0.2 to 8.3 ppm for the A horizon section; and from less than 0.2 to 7.5 ppm for the C horizon section. Many of the general trends in selenium concentration in the Western United States, as mapped by Trelease and Beath (1949), were confirmed by current maps, as illustrated in figs. Q8A and Q8B. A striking feature in the recent maps, however, is the trend of high concentrations of selenium in the Dakotas, and eastward through the mid-continent and into the Appalachian and New England regions. Future scientific studies may debate the authigenic versus anthropogenic origin of this selenium.

Scandinavia is another region with low selenium content in the bedrock. In Sweden, 89 percent of the mineral soils have less than 0.45 ppm selenium, which is comparable to the blue-to-light-orange regions of the United States shown in figs. Q8A–C, and is the minimum concentration needed for forage to provide the necessary selenium for stock animals (Parkman and Hultberg, 2002, and references therein). In contrast, selenium-amended agricultural soils show increased selenium of 0.065 to 1.7 ppm. Lake waters in Sweden—both those affected by and those not affected by selenium effluent—show between 43 and 209 nanograms per liter (ng/L) of total selenium (total = particulate + dissolved), and this concentration is independent of the trophic status of the lake (Parkman and Hultberg, 2002, and references therein).

In Finland, background concentrations of dissolved selenium in lake waters are estimated to be 56 to 62 ng/L, and although no seasonal variations were observed, researchers did find spatial variations caused by human activities. As a comparison, in lakes affected by agricultural runoff, the selenium concentration was 76.8 ng/L. In these lakes, the total selenium concentration was distributed among (1) selenium in organic materials, such as humic acids, which was greater than or equal to 50 percent of the total; (2) particulate selenium that was approximately 10 percent of the total selenium concentration; (3) dissolved selenite and selenate, which accounted for 8 to 9 percent of the total selenium concentration; and (4) selenium associated with neutral humic acids, which made up approximately 5 percent (Parkman and Hultberg, 2002). Sediments in these lakes show an increase in selenium concentration during the 20th century, most likely because of selenium-containing fertilizers. In 1992, concentrations in nine lakes ranged between 0.27 and 3.64 ppm, and concentrations were higher in oligotrophic lakes than in mesotrophic or eutrophic lakes. In stream sediments in Finland, the mean concentration of selenium was 0.26 ppm (Parkman and Hultberg, 2002, and references therein).

Above-Background Concentrations of Selenium in the Environment Near Major Deposits and Enriched Bedrock

Soils can have highly variable selenium concentrations, ranging from less than 0.01 ppm in deficient soils to up to 1,200 ppm in selenium-rich soils (Winkel and others, 2012, and references therein). Seleniferous soils can be found overlying selenium-rich rocks, such as black shales, carbonaceous limestones, carbonaceous cherts, mudstones, and seleniferous coal (Winkel and others, 2012).
Some examples of seleniferous soils are those that develop over seleniferous marine shales in the United States. Presser (1994) found that salinized soils of alluvial fans in the San Joaquin Valley, California, could contain as much as 4.5 ppm of selenium, with a median of 1.8 ppm. These soils developed from weathering of the Upper Cretaceous-Paleocene Moreno Formation and the Eocene-Oligocene Kreyenhagen Formation, which themselves contained concentrations of selenium up to 45 ppm, with median concentrations of 6.5 and 8.7 ppm, respectively (table Q5). Even higher concentrations have been recorded in shales of the Cretaceous Pierre Formation and the Niobrara Formation in the Western United States (maximums of 103 and 113 ppm, respectively) (table Q5; Moxon and others, 1938; Trelease and Beath, 1949; Presser, 1999).

High concentrations of selenium can develop in irrigation drainage waters and wetland environments when these waters interact with seleniferous soils. The wetlands of the Kesterson National Wildlife Refuge in San Joaquin Valley, Calif., were the site of an ecological crisis beginning in 1983, when it was discovered that high concentrations of dissolved selenium caused massive numbers of embryonic deformities and deaths of aquatic wildlife (Garone, 1999; Ohlendorf, 2002). The wetlands developed at the terminus of irrigation drainage within the San Joaquin Valley, and the drainage waters held high concentrations of selenium (in the range of 106 to 452 parts per billion (ppb), with an average concentration of 300 ppb) leached from seleniferous, salinized soils that developed over high-selenium-content marine shales. The link between high selenium concentrations and selenium toxicity is discussed in the sections of this chapter on human and ecological health.

Soils in the vicinity of sulfide orebodies may show naturally high concentrations of selenium, and this association has been cited in models for exploration geochemistry (Koljonen, 1976). The Luikonlahti copper orebody in eastern Finland displays elevated selenium concentrations in soils and glacial deposits immediately adjacent to sulfide-rich rocks (0.1 to 0.4 ppm selenium), in colloid- and organic-rich river and lake sediments downstream from the orebody.

---

**Figure Q8 (pages Q24 and Q25).** Maps showing selenium concentrations in soils of the conterminous United States. The selenium concentrations shown are in A, the top 0 to 5 centimeters of surface soils, B, the A horizon of surface soils, and C, the C horizon of surface soils. A visual comparison of the soils maps with the bedrock and plant maps in fig. Q6 shows many correlations in the Western United States. Maps are from Smith and others (2014, p. 197–202, figs. 95, 96, and 97).

ppm, parts per million
(0.2 to 1.1 ppm selenium), in forest mull humus atop the orebody (2.3 to 5.5 ppm selenium), and in sulfate- and iron-oxide-rich gossans developed above the orebody (2.9 to 13.0 ppm selenium). In contrast, similar soils and sediments from nonmineralized regions in Finland showed background selenium concentrations of 0.0 to 0.2 ppm selenium, with iron-rich lake and bog ores containing 0.4 ppm selenium (Koljonen, 1976).

Groundwaters near an undisturbed porphyry copper deposit in the Atacama Desert of Chile also display above-average concentrations of selenium. Leybourne and Cameron (2008) measured naturally occurring concentrations of up to 800 ppb selenium within 2 kilometers (km) downstream of the deposit. They attribute these high concentrations to Eh-pH conditions and pH, which put the waters at the boundary between Fe(III) and Fe(II) speciation. Limited quantities of solid iron oxyhydroxides are present in environments with these values of Eh-pH; therefore, adsorption reactions with iron oxyhydroxides did not reduce dissolved concentrations of selenium.

In contrast, sorption reactions may be an important control on selenium mobility in volcanic soils (Floor and Román-Ross, 2012). High concentrations of selenium have been recorded in volcanic soils owing to weathering of seleniferous parent materials and deposition of atmospheric selenium. Floor and Román-Ross (2012) reported 1,200 ppm of selenium in volcanic soils from Ireland, and 1 to 20 ppm of selenium in soils from Hawaii. Floor and others (2011) reported a range of 0.12 to 2.25 ppm selenium in soils from the Mount Etna volcano in Italy, with a median of 0.39 ppm selenium. Despite these high soil concentrations, selenium is not readily leached from soils. Strong sorption of selenium with soil compounds, such as ferrihydrite, poorly crystalline aluminosilicates, and organic matter, has been cited in volcanic soils from Hawaii, Mount Etna in Italy, and New Zealand (Floor and Román-Ross, 2012).

The strong sorption between selenium and volcanic soils may be site specific, as sorption is highly dependent upon soil chemistry and mineralogy. Whereas groundwater in volcanic aquifers can have low concentrations—often less than 0.1 ppb selenium (Floor and Román-Ross, 2012)—some sites show distinctly higher concentrations. Aiuppa and others (2000) sampled groundwaters near Mount Etna and found a range of 0.6 to 66.8 ppb selenium, with an average of 2.9 ppb selenium. At Mount Vesuvius, Italy, Aiuppa and others (2005) demonstrated that selenium can be one of the most mobile elements during rock weathering.

Plants show elevated concentrations of selenium when grown in soils with high selenium concentration, although the accumulation can vary by more than two orders of magnitude for a given selenium concentration in the soil (Winkel and others 2012, and references therein). Selenium accumulator plants include Astragalus L., as well as Oonopsis (Nutt.) Greene, Oryzopsis Michx., Xylorhiza Nutt., Mentzelia L., and Stanleya Nutt. (Moxon and others, 1938; Trelease and Beath, 1949; Cannon, 1957; Presser, 1999). Cannon (1957) reported that members of Astragalus can display selenium concentrations of several hundreds to a thousand parts per million when grown in soils that contain only 2 ppm selenium. In addition to soil selenium, other factors that affect the plant’s selenium content include the age of the plant, the stage of growth, and the part of the plant analyzed—seed, leaf, or stem (Moxon and others, 1938).

**Mobility in Water and Soils**

The chemical form of selenium (its speciation) determines its behavior and fate in the environment. Selenium is a metalloid that commonly takes an anionic form in oxic to suboxic conditions when dissolved, and its primary species in water are selenite (Se(IV) or SeO₃²⁻), selenate (Se(VI) or SeO₄³⁻), and organo-selenium (org-Se(-II), such as selenomethionine) (Luoma and Presser, 2009). Speciation will also determine whether selenium can be taken up by algae or microbes, or whether it can transform to particulate matter in seawater (seston) or in sediments.

In the sections above, the sources of selenium in the environment have been identified as emissions from volcanoes, biogenic processes, manufacturing and power generation, weathering of marine shale bedrock and overlying soils, and selenium leachate from fly ash and other solid waste materials. Mobilization of selenium from these sources to aquatic environments and pore waters occurs under oxidizing, slightly alkaline weathering conditions and produces soluble selenate and selenite (McNeal and Balistrieri, 1989; Presser and Swain, 1990; Piper and others, 2000).

Once selenium has transformed to aqueous selenate and selenite, it is readily mobile and bioavailable (meaning that it can be taken up by organisms). Selenate predominates in well-aerated surface waters, especially at alkaline pH. Selenite predominates in slow-moving waters, such as lakes and reservoirs. Chemical parameters, such as pH and redox, and microbial respiration, can convert selenate to selenite and organo-selenium. Dissolved selenium can sometimes be predominately organo-selenium, and this species may be seasonally important (Skorupa and others, 2004). The presence of organic carbon, ferric oxyhydroxides, and clays in soils affect the partitioning of these selenium species among water and soil and (or) sediments.

Selenate (Se (VI)) does not form strong adsorption complexes on mineral surfaces. It can be easily desorbed by a change in solution chemistry (for example pH, or ionic strength), and it exchanges readily with SO₄. Ready desorption and exchange are among the reasons for the high solubility of Se(VI), which enhances its mobility (Fukushi and Sverjensky, 2007). In solutions of alkaline pH with high Eh values, Se(VI) is mobile and bioavailable to plants (Winkel and others, 2012). In contrast, selenite (Se(IV)) is stable in solutions of moderate...
to low Eh values, and it is more likely to adsorb irreversibly to iron oxyhydroxides, clay minerals, and organic matter than to selenite. When selenium is tightly held by mineral surfaces and organic matter, it is less mobile and less available for plant uptake (Winkel and others, 2012, and references therein).

In a system where mineral surfaces and organic matter are not present in sufficient concentrations, however, Se(IV) and organo-selenide may be more readily incorporated into biota. When selenium is taken up at the base of the food web by plants and microbes, it is converted to organo-selenide, regardless of whether it was initially present as Se(IV) or Se(VI) (Presser and others, 1994). Organo-selenide is rereleased to water as these cells die or are consumed, and it can be reoxidized to Se(IV). Slow reaction kinetics restrict reoxidation to Se(VI). This means that biologically productive systems will evolve to see a decrease in soluble Se(VI) and an increase in Se(IV) and organo-Se(-II). For example, in streams in the upper part of California’s San Joaquin River watershed, dissolved selenium is almost 100 percent Se(VI), but lower in the watershed and downstream of the delta of the San Joaquin River, Se(VI), Se(IV), and organo-Se(-II) are equal in abundance (Cutter and Cutter, 2004).

Elemental (native) selenium is not soluble in water and is considered unavailable to plants. Some estimates suggest that elemental selenium may account for 30 to 60 percent of the total selenium in sediments (Zhang and others, 2004). It is often found as nanometer-sized spherical particles that are produced from microbiologically mediated reduction of Se(VI) and Se(IV). The extremely small size of these particles enables them to remain in colloidal suspension for weeks, and they may be able to enter cells directly, making the particles more bioavailable. A high surface-to-volume ratio makes them highly reactive, meaning that they may reoxidize to selenite and selenate. Finally, an organic polymer layer of protein that has been observed on the surface of these spherical particles may alter their surface properties and affect the distribution of elemental selenium in the environment (Winkel and others, 2012).

It was noted earlier that selenium exchanges readily with sulfur; this is because selenium and sulfur are both members of Group 6b of the periodic table; hence, they exhibit similar chemical behavior because they have similar ionic radii and can have the same valence. The S(VI) competition with Se(VI) for adsorption sites on mineral surfaces and in biological uptake is a primary mechanism for Se(VI) mobilization. For example, in soils developed on the flanks of Mount Etna, it was observed that selenium is mobilized during rainwater-soil interaction. It was found that aluminum oxides and soil organic matter were the active phases to sequester selenate in soil through adsorption and complexation reactions. When sulfate was introduced from rainwater, however, sulfate exchanged with adsorbed and complexed selenate, transforming it to a soluble and therefore mobile selenium species. Yet when redox conditions allowed for selenium transformation to Se⁴⁺, selenium would not be remobilized by acidic water (Floor and others, 2011).

### Mine Waste Characteristics

Coal deposits and associated mine waste rock are common geologic sources for environmental selenium (fig. Q5). In the Appalachian region, coal mining companies often practice mountaintop mining to access underlying coal seams, and the waste rock is commonly placed in streams and valleys. According to the U.S. Environmental Protection Agency (EPA), an estimated 724 stream miles (1,165 stream kilometers), or 1.2 percent of streams, were covered by more than 6,800 valley fill waste piles from 1985 to 2001 in the States of Kentucky, Tennessee, Virginia, and West Virginia (U.S. Environmental Protection Agency, 2005, p. 4–5). This waste disposal practice serves to increase selenium input into aquatic systems because fresh faces on newly broken rock provide increased surface area for water-rock reaction and selenium transfer into surface waters. Bryant and others (2003) observed that the selenium concentration in Appalachian streams associated with valley fills (<0.3 to 37 ppb selenium) was greater than background concentration (<0.3 ppb selenium), and that the selenium concentrations in holding ponds at the base of valley fills ranged from 24 to 42 ppb selenium. Surface and groundwater pH greatly affect selenium solubility. Unlike other trace elements associated with coal (for example, cadmium, copper, and lead), the oxic forms of selenium are soluble in waters with neutral-to-alkaline pH. This behavior is explained by the difference in adsorption potential among base cations (for example, cadmium, copper, and lead), which adsorb strongly to oxide surfaces at higher pH values, and oxyanion forms of selenate and selenite, which adsorb more strongly at lower pH values (Stumm, 1992; Elzinga and others, 2009).

Although selenium can occur naturally in soils associated with unmined coal seams, mining is known to enhance its solubility in reclaimed and revegetated mine lands, which can potentially result in aquatic contamination and elevation of selenium in plant materials. Sharmasarkar and Vance (1997) analyzed 40 soil samples (ranging in depth from 0 to 200 cm) from native, reclaimed, and abandoned coal mine environments in Wyoming, and observed selenium concentrations of 0.26 to 26.13 ppm selenium, with a mean concentration of 1.73 ppm.

Another source of selenium to natural waters is ash and other waste products produced from coal-fired powerplants. The case study for this selenium pathway was Belews Lake in North Carolina. From 1974 to 1985, lake water was withdrawn and mixed with ash generated by a nearby coal-fired electricity-generating plant. Presser (1999) noted that fly ash may contain even higher levels of soluble selenium than the initial, seleniumiferous coal; that is, 50 to 500 ppm versus 2 to 20 ppm. Solids were allowed to settle from the slurry before the wastewater,
which contained 150 to 200 ppb selenium, was returned to the lake, creating lake water selenium concentrations of 20 ppb. Once this disposal practice was ended, lake water selenium concentrations fell to less than 1 ppb (Lemly, 1997).

High ash content in bone coals (coal with a high ash content) creates another source of environmental selenium. In Pingli County, Shaanxi Province, China, the Badao bone coal contains 41 to 75 ppm of selenium, with a mean concentration of 57.5 ppm. After combustion, the coal ash fraction was found to contain 28 ppm of selenium, indicating that the difference (approximately 30 ppm) is volatilized to the atmosphere. Selenium is also released to the environment through the use of bone coal ash as an agricultural soil amendment. The local environment in Pingli County was found to contain soil with a mean concentration of 7.1 ppm selenium, surface water with concentrations of 0.3 to 1.1 ppm selenium, and agricultural crops with concentrations of 0.57 to 2.75 ppm selenium (Fang and others, 2003).

As discussed previously, selenium is associated with phosphate deposits, and, quite notably, in the United States, with the Meade Peak member of the Permian Phosphoria Formation in Idaho, Montana, Nevada, Utah, and Wyoming. Features of the mined environment include lakes that form in open pit mines after mining has ended, waste rock contoured into hills or emplaced as cross-valley fills, wetlands that form at the base of waste dumps, and vegetation that is reseeded onto the surface of the dumps.

A selenium mass-balance study was conducted for the wetland that formed at the base of the Wooley Valley Unit 4 waste dump in southeastern Idaho (Stillings and Amacher, 2004; Stillings and others, 2007). The waste dump was created in the 1970s from overburden and waste shale that remained after the mining of the upper and lower phosphate zones of the Meade Peak member, and the wetland developed soon thereafter. In 2002, inlet and outlet flow volumes and chemistry were measured continuously from May through September. The calculated influx of selenium was high at the beginning of May (approximately 90 grams per day [g/d] of selenium), but dropped rapidly throughout the month and became zero when the seep dried up at the end of June. The outflux of selenium ranged from approximately 0.05 to 2.0 g/d during the entire season. The mass balance created for this time period showed that although 685 grams (g) of selenium was delivered to the wetland, only 84 g of selenium left the wetland, meaning that 601 g, or 88 percent of the influx, was retained within the wetland. Further work determined that selenium was scavenged from wetland surface waters by adsorption and co-precipitation with iron oxyhydroxides that precipitated on the surface of wetland soils (Stillings and Amacher, 2004; Stillings and others, 2007).

In a related study, selenium concentrations were measured in plants grown on the waste rock dumps at Wooley Valley Units 1, 3, and 4 and compared with concentrations of plants growing on undisturbed areas of the Phosphoria Formation. Vegetation growing in highly disturbed soils, including those on the surface of waste dumps, had the highest tissue selenium concentrations. The mean concentration for legumes was 80 ppm; trees, 52 ppm; grasses, 18 ppm; shrubs, 6 ppm; and forbs, 3 ppm. The grasses collected from the wetland described in the previous paragraph showed a mean selenium concentration of 53 ppm. This second study was used to argue for the removal of legumes from seed mixtures used to revegetate the surfaces of the cross-valley waste dumps, thus decreasing selenium in browse vegetation for herbivores (Mackowiak and others, 2004).

Roll-front uranium deposits in the Western United States are another deposit type known to contain selenium; hence, selenium is likely to be present in these mine wastes as well. When uranium is mined with in situ methods (which are commonly used with roll-front deposits), the overlying rock is not disturbed and thus not exposed to oxidizing conditions at Earth’s surface; however, the in situ mining methods used rely on injections of lixiviant (an oxidizing agent—either oxygen or hydrogen peroxide) into the uranium deposit to oxidize and extract the uranium ore. This fluid can leach selenium into the surrounding groundwater by oxidizing organic matter that contains selenium, and by converting insoluble organic selenides to soluble selenate and selenite. Selenium concentrations can exceed 1,000 ppm in areas that have been mined for uranium (Naftz and Rice, 1989, and references therein).

Both groundwater and surface water in areas near copper mines and processing facilities may show elevated selenium concentrations because of selenium’s association with sulfide minerals. Elevated selenium concentrations (>10 ppm) have been found in groundwater under the copper smelter and refinery facility near the Great Salt Lake, Utah. The facility is located within 1.5 km of the southern shore of the lake, and there is some concern that a portion of this plume could discharge into the lake (Naftz and others, 2009, p. 35, and references therein). In 2001, the facility was selected for an EPA selenium treatment/demonstration project, which field-tested three technologies for removing selenium from the Garfield Wetlands-Kessler Springs site. At the start of this project (in May 1999), the Garfield Wetlands-Kessler Springs water contained approximately 2,000 ppm selenium (MSE Technology Applications, Inc., 2001, p. 1).

Soils near a lead-zinc smelter in Kabwe, Zambia, show contamination from atmospheric dust fallout from smelting activities. Kříbek and others (2010) sampled contaminated topsoil and a reference (background) subsoil horizon at 80 to 90 cm depth. The topsoil had a maximum selenium concentration of 0.01 percent (100 ppm), which was significantly higher than the concentrations of trace metals in the subsurface soil.

There are limited reports of selenium in leachate from mine waste associated with banded iron formations in the Upper Peninsula of Michigan. In 2008, the Michigan Department of Environmental Quality (MDEQ) began to assess selenium concentrations and water quality impacts in the vicinity of the Empire Mine and the Tilden Mine in the Marquette Iron Range near Palmer, Michigan. Results of the MDEQ
assessments showed that selenium concentration in water at many lakes near the mine sites were less than 5 ppb, which is the chronic selenium water quality standard for Michigan. Two streams that flowed through mine waste facilities carried mean values of 9.3 and 11 ppb selenium, however, and a popular fishing site, Goose Lake, exhibited 8.8 to 10 ppb selenium. Small streams and springs buried by waste rock piles showed selenium concentrations that ranged from 15 to 68 ppb. Sediments from streams and lakes ranged from less than 5 ppm to between 27 and 39 ppm selenium in Goose Lake (Selenium Monitoring Work Group, 2009, p. ii). Biological samples from Goose Lake Outlet showed a mean value of 8.0 to 17.35 ppm selenium in brook trout (Salvelinus fontinalis [Mitchill, 1814]), white suckers (Catostomus commersonii [Lacepède, 1803]), fathead minnows (Pimephales promelas [Rafinesque, 1820]), and creek chubs (Semotilus [Rafinesque, 1820]) and 22.3 ppm selenium (composite sample of northern caddisfly [Limnephilidae] [Kolenati, 1848]) tissue. Selenium was present in lower levels in benthic macroinvertebrates, such as leeches, snails, mayflies, and odonates (Selenium Monitoring Work Group, 2009, p. 7–8).

Human Health Concerns

Dietary selenium plays a critical role in human health owing to its importance to thyroid hormone metabolism, antioxidant defense mechanisms, and immune functions (Rayman, 2000). Insufficient selenium is associated with growth retardation, impaired bone metabolism, and abnormalities in thyroid function (Stone, 2009). Human populations with insufficient selenium in their diet can be found living in geographic areas with low selenium contents in local bedrock and soils. One example is a northeast-southwest-trending belt in China and an area of southeastern Siberia where populations are at risk for Keshan disease (which causes cardiomyopathy) and Kashin Beck disease (a chronic degenerative osteoarthritis); both are caused by a deficiency of selenium.

Keshan disease was described in Chinese medical literature 100 years ago, but it was not until the mid-1970s that selenium deficiency was identified as its primary cause. After a widespread outbreak in 1935, it was determined to be endemic in children aged 2 to 10 years and in women of child-bearing age. Symptoms are fatigue after light exercise, cardiac arrhythmia and palpitations, loss of appetite, cardiac insufficiency, cardiomegaly, and congestive heart failure (World Health Organization and Food and Agricultural Organization of the United Nations, 2004). Kashin Beck disease was also detected in Chinese children aged 5 to 13 years and in southeastern Siberia. The disease causes joint necrosis in the form of degeneration of the arm and leg joints, which results in structural shortening of bones and leads to growth retardation and stunting (World Health Organization and Food and Agricultural Organization of the United Nations, 2004).

In Finland, blood serum levels of less than 45 ppb selenium were believed to increase the risk of cardiovascular disease and cancer. Because of this, sodium selenite has been added to agricultural fertilizers since 1985 in order to increase the dietary intake. This practice has caused selenium dietary intake to increase from a base of 30 to 40 micrograms per day (µg/d) to greater than 100 µg/d by the early 1990s, and the daily intake is now considered safe and adequate (Varo and others, 1994). It should be noted, however, that some research recommends lower levels of dietary intake, and finds that doses of selenium greater than 75 µg/d, can be mildly toxic and related to an increased risk of diabetes (Winkel and others, 2012, and references therein).

Somewhat analogously, human populations living in geographic areas with high levels of selenium in local foods may suffer from selenium toxicity. This has been observed in humans and animals in the Hubei and Shaanxi Provinces in China, and in Punjab, India, where selenium levels in local foods are high and dietary intake per person is between 750 and 4,990 µg/d. In Punjab, the high dietary selenium values are the result of agricultural irrigation practices and high evaporation rates, which serve to concentrate selenium into irrigated soils and food crops. At doses of greater than 400 µg/d, selenium is acutely toxic and may lead to acute respiratory distress, cardiac failure, facial flushing, hair loss, kidney failure, light headedness, muscle tenderness, myocardial infarction, severe gastrointestinal and neurological symptoms, tremors, and, in rare cases, death (National Institutes of Health, 2013, and references therein). Chronic exposure to subacute levels leads to brittle hair and nails, skin lesions, and neurological disturbances (Winkel and others, 2012, and references therein).

One outcome of modern research into selenium and human health is a better understanding of its role in the immune system. It has been found that the cardiac lesions of Keshan disease are not the result solely of selenium deficiency, but are also related to infection by the coxsackie virus, which is initially nonvirulent, but which becomes virulent and myopathogenic in individuals with selenium deficiency. This process is not unique to the coxsackie virus. It has been determined that the early preclinical stages of human immunodeficiency virus (HIV) infection are marked by a significant decrease in blood plasma selenium concentrations, and that the magnitude of this decrease is linked to the rates of development of acquired immunodeficiency syndrome (AIDS) and to mortality rates associated with AIDS (World Health Organization and Food and Agricultural Organization of the United Nations, 2004). Finally, selenium deficiency has been linked to an increase in mercury toxicity (Berry and Ralston, 2008). Because of the high binding affinity between mercury and selenium, it is thought that selenium can function to chelate mercury and reduce its toxicity; if the molar ratio of mercury to selenium is high, however (that is, greater than 1:1), then the concentration of selenium is insufficient to provide this protective effect.
Pathways for Selenium Ingestion in Humans

Plant foods are the main dietary sources of selenium in most countries, followed by meats and seafood (National Institutes of Health, 2013). In all cases, the selenium content of food is derived from soils and the feed for livestock (World Health Organization, 2011). Although soil selenium is the source of selenium, it is important to note that total selenium concentration is not what controls selenium levels in food crops; rather, it is the concentration of bioavailable selenium that controls the levels. For example, the classical definition of selenium-deficient soils is when concentrations are less than 0.1 ppm selenium, whereas selenium-rich soils have greater than 0.5 ppm selenium. These concentrations refer to total selenium. Soils in areas of China where Keshan disease has occurred have an average concentration of 0.15 ppm selenium, which would not be classified as selenium deficient; however, these soils are selenium deficient because the bioavailable selenium is low. High content of organic matter is the cause of the low bioavailable selenium concentration because it immobilizes selenium by adsorption and biochemical reduction, making it unavailable for uptake by food crops.

The dietary intake of selenium varies somewhat across the United States and Canada because of differences in local soils and food; however, most Americans consume adequate amounts of selenium. The average daily selenium intake in Americans over 2 years in age is 108.5 micrograms from food alone, and if supplements are included, this value increases to 120.8 µg/d (National Institutes of Health, 2013).

Related Diseases, Cancers, and Human Health Effects From Industrial Exposures

Little has been reported regarding selenium health effects from human industrial exposures, and it is selenium deficiency from an inadequate diet that is the greatest human health concern. Selenium concentrations in gas emissions from coal combustion could be one potential cause of industrial exposure, as could exposure in industries with a significant occupational metals exposure risk, such as metals recovery (Fairweather-Tait and others, 2011). The manufacturing process for modern products, such as solar panels, might represent a potential risk if selenium is present in a bioavailable form. Manufactured nanomaterials may also pose health effects, because selenium is a key component in CdSe and PbSe quantum dots, which are nano-sized semiconductors used in light-emitting diodes and photovoltaics. Emergent properties of these materials could elicit toxic responses that may be different from those current selenium sources (Young and others, 2010).

Human Health Guidelines

Although water is not usually a major source of selenium to the human population (Fairweather-Tait and others, 2011), the World Health Organization (WHO) has set a provisional guideline value for selenium in drinking water. The WHO recommendation is that when selenium intake from dietary sources is unknown, then 40 ppb should be the upper limit of selenium in drinking water (World Health Organization, 2011). In Canada, the Government has set this level at 10 ppb, although the Canadian Government is revisiting the criterion and proposing a new maximum acceptable concentration for human consumption of 50 ppb in response to a review of current scientific studies and an understanding of chronic selenosis (Health Canada, 2013). In the United States, the EPA has set the maximum contaminant level for selenium in drinking water at 50 ppb (U.S. Environmental Protection Agency 2014a).

Because there is a narrow concentration range between dietary deficiency (< 40 µg/d) and highly toxic levels (> 400 µg/d) (Winkel and others, 2012), the WHO recommends dietary intakes of 15 µg/d for infants from birth to 6 months, 30 µg/d for children aged 4 to 8 years, and 55 µg/d for older children and adults (World Health Organization, 2011). Older recommendations were 0.05 to 2 milligrams per day (mg/d) for adults, with lower ranges for children (Health Canada, 1992). In the United States, the National Institutes of Health has published recommended daily allowances (RDAs) for humans; these RDAs are similar to those recommended by the WHO, and range from an adequate intake of 15 µg/d for infants from birth to 6 months, to 55 µg/d for older children and adults (table Q7). Pregnant and breast-feeding women have RDAs of 60 and 79 µg/d, respectively (table Q7; National Institutes of Health, 2013).

Ecological Health Concerns

Research on selenium in the environment began in the 1930s when livestock in the Great Plains and Western United States were found with the symptoms of “alkali disease,” including emaciation, loss of hair, deformation and shedding of hooves, loss of vitality, and erosion of joints in long bones (Science Dictionary, 2015). It became recognized that livestock poisoning was occurring because the livestock were browsing on selenium accumulator plants of the genus Aastragalus; these plants grow in saline soils derived from marine Cretaceous sedimentary rocks exposed in more than 830,000 square kilometers of the Western United States (Trelease and Beath, 1949).

Once the cause of selenium poisoning was recognized, efforts were made to prevent and control the exposure of livestock to seleniferous plants using range management techniques. In 1957, however, it was learned that selenium is an essential trace element (or micronutrient) in mammals. It is an essential component of bacterial and mammalian enzyme systems, and that without it, selenium deficiency disorders, such as white muscle disease (in sheep) and mulberry heart disease (in pigs), could occur (Young and others, 2010, and references therein).
In 1976, the sudden disappearance of popular game fish from Belews Lake, North Carolina, was attributed to selenium poisoning. It was learned that the manmade reservoir was fed by water from a coal-ash settling basin that had created lake waters with selenium concentrations of 20 ppb. This level of selenium caused chronic selenium poisoning in the Belews Lake fish populations, where the most serious symptom was reproductive failure and post-hatch mortality. As a result of the selenium toxicity, 19 of 20 species of fish in Belews Lake were eradicated (Lemly, 2002).

Soon after this, in 1983, another extinction of fish populations was discovered. This time it was at the Kesterson Reservoir in San Joaquin Valley, Calif., which is a wetland area fed by agricultural drainage from the San Joaquin Valley. Massive numbers of dead and deformed bird embryos and chicks were found to accompany the fish extinction, and the cause was determined to be selenium poisoning from bioaccumulation in the food chain (Ohlendorf, 2002). After this discovery, deformities of aquatic birds from selenium toxicosis began to be observed in similar environments; that is, wetland basins that received waters draining seleniferous soils, such as the Tulare Lake Bed Area, Calif.; the Middle Green River Basin, Utah; the Kendrick Reclamation Project Area, Wyoming; the Sun River Basin, Montana; and the Stillwater Wildlife Management Area, Nevada. Most of these study areas had climate, geology, and hydrology similar to that of the San Joaquin Valley. Results indicated that bioaccumulation of selenium was occurring in most of the wetland areas, and these data marked the initial elucidation of a biogeochemical pathway for selenium from geologic source to aquatic wildlife (Presser and others, 1994).

Pathways for Selenium Ingestion in Aquatic and Terrestrial Organisms

Just as in human health, the main pathway for selenium entry into aquatic and terrestrial organisms is through diet, and speciation is an important factor in determining the amount of selenium that enters the food chain. The primary step by which selenium accumulates in aquatic systems is found at the base of the food chain where algae and other microorganisms (trophic level 1) accumulate selenium from water by factors of up to 1 million times the aqueous concentration. Selenate (Se(VI)) is slow to be taken up by these organisms, especially in the presence of sulfate, which is more competitive. Selenite (Se(IV)) and organo-selenides are taken up more quickly. Once selenium has been accumulated by an organism, the selenium is reduced to selenide (Se(-II)) and ultimately incorporated into amino acids, primarily selenomethionine, which is the organo-selenide that bioaccumulates in food webs and produces toxicity (Luoma and Presser, 2009).

The algae and microbes, together with abiotic particle-sorbed selenium, constitute the particulate selenium fraction in the water column. Particulate matter is ingested by aquatic primary consumers, such as zooplankton, insect larvae, larval fish, and bivalves (trophic level 2), thus transferring selenomethionine (a naturally occurring amino acid) up the food chain. Abiotic selenium, which may be ingested with particulate matter, is transformed to selenomethionine by the primary consumers, which may, in turn, be consumed by predators, such as fish and birds (trophic level 3 and above). In this manner, selenium continues to accumulate, and its concentrations magnify as it is transferred to higher trophic levels. The accumulated concentration determines whether toxicity is manifested (Luoma and Presser, 2009; Young and others, 2010; U.S. Environmental Protection Agency, 2014b).

Recycling of selenium in the aquatic environment occurs when organo-selenide, mostly in the form of selenomethionine, is returned to the water upon the death and decay of aquatic organisms. Some organo-selenide may be oxidized to Se(IV), but neither organo-selenide nor Se(IV) will be converted to Se(VI) because the reaction is very slow, with a half-life of hundreds of years. The net outcome of recycling in a watershed is an evolution of selenium from Se(VI), which is the primary form of selenium from natural and anthropogenic sources, to Se(IV) and organo-selenide (Se-II), which are the more bioavailable species (Young and others, 2010).

Selenium enters terrestrial organisms by a similar pathway. Accumulator plants take up selenium from soil water, usually as Se(VI) or Se(IV), and transform it primarily into the amino acid selenomethionine. These accumulators are able to incorporate large amounts of selenium—some as high as 15,000 ppm (Trelease and Beath, 1949). Livestock grazing on these plants accumulate selenomethionine, with potentially fatal results.

### Table Q7.
National Institutes of Health recommended dietary reference intakes (DRIs) for selenium.

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>Recommended daily allowance (µg/d)</th>
<th>Tolerable upper intake level (µg/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 0.5</td>
<td>15</td>
<td>45</td>
</tr>
<tr>
<td>0.5 to 1</td>
<td>20</td>
<td>60</td>
</tr>
<tr>
<td>1 to 3</td>
<td>20</td>
<td>90</td>
</tr>
<tr>
<td>4 to 8</td>
<td>30</td>
<td>150</td>
</tr>
<tr>
<td>9 to 13</td>
<td>40</td>
<td>280</td>
</tr>
<tr>
<td>14 to 18</td>
<td>55</td>
<td>400</td>
</tr>
<tr>
<td>19 to 50</td>
<td>55</td>
<td>400</td>
</tr>
<tr>
<td>51+</td>
<td>55</td>
<td>400</td>
</tr>
</tbody>
</table>

1This level is called the adequate intake (AI) level because evidence is insufficient to develop a recommended daily allowance.
Aquatic Toxicity and Aquatic Ecosystem Health Guidelines

Selenium is bioaccumulative, meaning that fish and other aquatic life can contain concentrations greater than the surrounding water. The primary source of selenium to aquatic life is dietary, and toxicity primarily occurs through transfer to eggs and subsequent reproductive effects. Because selenium bioaccumulation rates may vary among aquatic environments, the EPA has proposed a four-part freshwater criterion that includes elements for (1) fish eggs and ovaries, set at 15.2 ppm selenium dry weight; (2) whole fish body tissue not to exceed 8.1 ppm dry weight, or muscle tissue not to exceed 11.8 ppm dry weight; (3) a 30-day average selenium concentration not to exceed 4.8 ppb selenium in lotic (flowing) waters or 1.3 ppb selenium in lentic (standing) waters, more than 1 time in 3 years, on average; and (4) repeated short-term exposures where the intermittent water quality concentration for both lentic and lotic waters is calculated from the 30-day concentration; the background selenium concentration; and the fraction of time (over the 30-day period) during which elevated selenium concentrations occur. The purpose of this criterion with two fish-tissue-based and two water-based elements is to protect against adverse reproductive effects of selenium on aquatic life, and the criterion apply to total selenium concentrations; that is, the sum of all forms of selenium (selenate, selenite, organic selenium, and any other forms) (U.S. Environmental Protection Agency, 2014a).

Previous to this four-part criterion, the EPA freshwater criterion for protection of aquatic life was 5 ppb selenium with a lower criterion of 2 ppb selenium for some wetland environments in California (Luoma and Presser, 2009). In marine waters, the maximum allowable concentration is 290 ppb selenium, whereas the continuous concentration is 71 ppb selenium (U.S. Environmental Protection Agency, 2014c). It should be noted that there is no international agreement on these guidelines. In Canada, the marine and freshwater guidelines are 2 ppb selenium, and in Europe, selenium is not considered an ecological threat and is not subject to environmental quality standards (Luoma and Presser, 2009; European Commission Joint Research Centre Institute for Health and Consumer Protection, 2011).

Problems and Future Research

There is no “free lunch.” Selenium extraction from mineral resources has led to technological development and has greatly benefited our society. At the same time, there are environmental consequences of mining that must be recognized and evaluated for every mining project. This chapter provides an overview of the selenium life cycle. Although the main focus is selenium as a mineral resource and commodity, these selenium topics cannot be presented without acknowledging the environmental concerns that accompany the presence of selenium in the environment.

Challenges abound for new research on selenium in the 21st century. Extraction of selenium from the waste products (anode slimes) of copper ore processing has been a proven technology for many decades, but changes in processing technology will affect selenium recovery. Will it be possible to recover selenium from other sources economically? Coal and other organic carbon sources come immediately to mind; these technologies exist but are not economically favorable at present. High-grade but low-tonnage deposits with selenide minerals may be another source for selenium extraction, contingent upon available technology and favorable economics.

Other research directions would contribute to the scientific understanding of the selenium elemental cycle in Earth’s crust. A very basic question concerns the amount of selenium in the crust. The current estimate of 0.05 ppm selenium in the continental crust dates to 1961. Could this estimate be updated and revised, given our current knowledge of selenium concentrations in various crustal reservoirs? Next, can selenium concentrations and isotopic composition be used as an exploration tool for the discovery of concealed deposits? Finally, to thoroughly understand the elemental cycle of selenium in the earth, it would be useful to compare and contrast the magmatic selenium pathway from volcanoes to enriched ore deposits, to the sedimentary selenium pathway that involves selenium uptake by algae and bacteria in productive marine basins and deposition in organic-rich sediments. Are there connections between these two pathways and does selenium cycle between them?

Research opportunities exist under the topic of selenium environmental concerns as well. Some of the most pressing topics involve the bioavailability of selenium and its incorporation into the food web and whether the understanding of this cycle can translate into ecosystem and human health guidelines. The newly proposed tissue-based criterion for selenium in aquatic systems is a direct result of years of focused scientific study. Other research might target methods to redirect or disrupt the process that transfers selenium from rock to biota. Studies that amend selenium-rich soil with sulfur, or plant non-selenium-accumulating plants on mine waste, are creative attempts to break the rock-biota selenium connection. Studies to limit selenium solubility from nanoparticles would aid in keeping new technologies environmentally safe. Regardless of the focus, research into the elemental cycle of selenium, including the manufacture and disposal of selenium-containing commodities, will continue to increase understanding of Earth processes.

Acknowledgments

The author thanks technical reviewers John DeYoung, Daniel Edelstein, Micheal George, Sandy Neuzil, Theresa Presser, Klaus Schulz, Bob Seal, and Michael Magyar for improving this manuscript with their gifts of time and insight. Bob Seal is especially commended for reminding the author that this
chapter is part of a volume on mineral resources, not environmental processes. The USGS publications staff is gratefully acknowledged for gentle correction of the author’s mistakes and poor writing habits. Keith Labay helped create the deposit location maps, and Suzanne Nicholson provided additional editorial comments after the technical review was complete.

References Cited

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


Aiuppa, Alessandro, Allard, Patrick, D’Alessandro, Walter, Michel, Agnes, Parello, Francesco, Treuil, Michel, and Valenza, Mariano, 2000, Mobility and fluxes of major, minor and trace metals during basalt weathering and groundwater transport at Mt. Etna volcano (Sicily): Geo- chimica et Cosmochimica Acta, v. 64, no. 11, p. 1827–1841. [Also available at http://dx.doi.org/10.1016/S0016- 7037(00)00345-8.]


Bindi, Luca, and Pratesi, Giovanni, 2005, Selenoalpalite, Ag,CuSe₂, a new mineral species from the Skrikerum Cu-Ag-Tl selenide deposit, Småland, southeastern Sweden: The Canadian Mineralogist, v. 43, no. 4, p. 1373–1377. [Also available at http://dx.doi.org/10.2113/gsecongeo.43.4.1373.]


Floor, G.H., Calabrese, S., Román-Ross, G., D’Alessandro, W., and Aiuppa, A., 2011, Selenium mobilization in soils due to volcanic derived acid rain—An example from Mt Etna volcano, Sicily: Chemical Geology, v. 289, nos. 3–4, p. 235–244. [Also available at http://dx.doi.org/10.1016/j.chemgeo.2011.08.004.]


Hawley, J.E., and Nichol, Ian, 1959, Selenium in some Canadian sulfides: Economic Geology, v. 54, p. 608–628. [Also available at http://dx.doi.org/10.2113/econgeo.54.3.608.]


Piper, D.Z., 1994, Seawater as the source of minor elements in black shales, phosphorites, and other sedimentary rocks: Chemical Geology, v. 114, nos. 1–2, p. 95–114. [Also available at http://dx.doi.org/10.1016/0009-2541(94)90044-2.]


Q40  Critical Mineral Resources of the United States—Selenium


Trelease, S.F., and Beath, O.A., 1949, Selenium—Its geo-


Tables Q1 and Q2
Table Q1. Selenium minerals recognized by the International Mineralogical Association.

[Data are from Mindat.org (2015) and the International Mineralogical Association (IMA) (2014). ?, uncertain according to the IMA; NA, not available]

<table>
<thead>
<tr>
<th>Mineral name</th>
<th>Chemical formula</th>
<th>Date of discovery or IMA approval</th>
<th>Geologic setting and (or) first recorded locality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Achavalite</td>
<td>(Fe,Cu)Se</td>
<td>1939</td>
<td>Selenide deposit, Mendoza, Argentina</td>
</tr>
<tr>
<td>Aguilarite</td>
<td>Ag₅SeS</td>
<td>1891</td>
<td>Low-temperature hydrothermal deposits with silver and selenium but low amount of sulfur, Guanajuato, Mexico</td>
</tr>
<tr>
<td>Ahlfeldite</td>
<td>(Ni,Co)SeO₆ • 2H₂O</td>
<td>1935</td>
<td>Alteration product of nickel sulfides and selenides, Pacajake Mine, Potosí Department, Bolivia</td>
</tr>
<tr>
<td>Allochalcoselite</td>
<td>Cu⁺ PbCu⁺⁺ (SeO₃)Cl₂O₂</td>
<td>2004</td>
<td>Scoria cone, Tolbachik volcano, Far Eastern Region, Russia</td>
</tr>
<tr>
<td>Antimonselite</td>
<td>Sb₂Se₃</td>
<td>1993</td>
<td>Uranium deposit No. 504, Guizhou Province, China</td>
</tr>
<tr>
<td>Athabascaite</td>
<td>Cu₅Se₄</td>
<td>1970</td>
<td>Inclusions in and replacements of umangite, as well as stringers and veinlets in carbonate veins cutting basalt, Martin Lake Mine, Saskatchewan, Canada</td>
</tr>
<tr>
<td>Babkinite</td>
<td>Pb₂Bi₂ (S,Se)₃</td>
<td>1994</td>
<td>Hydrothermal deposit in sediments, near contact with granite intrusion, Neveskoe tungsten-tin deposit, Far Eastern Region, Russia</td>
</tr>
<tr>
<td>Bambollaite</td>
<td>Cu(Se,Te)</td>
<td>1972</td>
<td>Oxidized gold-tellurium ore, Moctezuma Mine, Sonora, Mexico</td>
</tr>
<tr>
<td>Bellidoite</td>
<td>Cu₂Se</td>
<td>1975</td>
<td>Low-to-moderate temperature hydrothermal deposits, Habr Mine, Moravia, Czech Republic</td>
</tr>
<tr>
<td>Berzelianite</td>
<td>Cu₂Se</td>
<td>1850</td>
<td>Hydrothermal veins, Skrikerum Mine, Östergötland, Sweden</td>
</tr>
<tr>
<td>Bohdanowiczite</td>
<td>AgBiSe₂</td>
<td>1967</td>
<td>Fluorite and quartz veins near magnetite skarn, Kletno, Lower Silesia, Poland</td>
</tr>
<tr>
<td>Bornhardtite</td>
<td>Co²⁺ Co⁺⁺⁺ Se₄</td>
<td>1955</td>
<td>Hydrothermal deposits, Trogtal Quarries, Lower Saxony, Germany</td>
</tr>
<tr>
<td>Brodkorbite</td>
<td>Cu₂HgSe₂</td>
<td>1999</td>
<td>Telethermal selenide vein-type assemblage, Tumiñico Mine, La Rioja Province, Argentina</td>
</tr>
<tr>
<td>Bukovite</td>
<td>Tl₂(Cu,Fe)₅Se₄</td>
<td>1971</td>
<td>Calcite veins of hydrothermal origin, Bukov Mine, Moravia, Czech Republic</td>
</tr>
<tr>
<td>Burnsite</td>
<td>KCdCu⁺⁺⁺(SeO₃)₂Cl₆</td>
<td>2000</td>
<td>Scoria cone, Tolbachik volcano, Far Eastern Region, Russia</td>
</tr>
<tr>
<td>Cadmoselite</td>
<td>CdSe</td>
<td>1957</td>
<td>Sedimentary rocks in an alkaline, reducing environment, Ust’ Uyok deposit, eastern Siberia, Russia</td>
</tr>
<tr>
<td>Carolruizite</td>
<td>K₄(Na,K)Na₂Mg₄(SeO₃)₁₂(10H₂O)₁₂ • 12H₂O</td>
<td>1994</td>
<td>Zapiga, Tarapacá Region, Chile</td>
</tr>
<tr>
<td>Chalcomenite</td>
<td>CuSeO₃ • 2H₂O</td>
<td>1881</td>
<td>Secondary mineral in copper-selenium deposits, Cerro de Cacheuta, Mendoza, Argentina</td>
</tr>
<tr>
<td>Chaméanite</td>
<td>(Cu,Fe)₂As(Se,S)₄</td>
<td>1980</td>
<td>Late-stage deposits cutting granites, Chaméane uranium deposit, Auvergne, France</td>
</tr>
<tr>
<td>Chloromenite</td>
<td>Cu₈(SeO₃)₂OCl₈</td>
<td>1996</td>
<td>Novaya fumarole, Tolbachik volcano, Far Eastern Region, Russia</td>
</tr>
<tr>
<td>Christanleyite</td>
<td>Ag₂Pd₅Se₄</td>
<td>1996</td>
<td>Gold-bearing veins, Hope’s Nose, Devon, England</td>
</tr>
<tr>
<td>Clausthalite</td>
<td>PbSe</td>
<td>1832</td>
<td>Selenium-bearing, low-sulfur hydrothermal deposits, St. Lorenz Mine, Lower Saxony, Germany</td>
</tr>
<tr>
<td>Cobaltomenite</td>
<td>CoSeO₃ • 2H₂O</td>
<td>1882</td>
<td>Cerro de Cacheuta, Mendoza, Argentina</td>
</tr>
<tr>
<td>Crerarite</td>
<td>Pt₁₋₂(Bi,Pb)₁(S,Se)₁₁</td>
<td>1994</td>
<td>Copper–nickel–platinum-group-element deposit, Lac Sheen, Quebec, Canada</td>
</tr>
<tr>
<td>Crookesite</td>
<td>Cu₃(Tl,Ag)Se₄</td>
<td>1866</td>
<td>Copper-silver-lead-selenium hydrothermal deposits, Skrikerum Mine, Östergötland, Sweden</td>
</tr>
<tr>
<td>Demesmaekerite</td>
<td>Pb₄Cu₃(SeO₃)₂(OH)₂ • 2H₂O</td>
<td>1965</td>
<td>Copper-cobalt-manganese-uranium deposit, Musonoi Mine, Democratic Republic of the Congo [Kinshasa]</td>
</tr>
<tr>
<td>Derriksite</td>
<td>Cu₅(UO₃)₃(SeO₃)₂(OH) • H₂O</td>
<td>1971</td>
<td>Copper-cobalt-manganese-uranium deposit, Musonoi Mine, Democratic Republic of the Congo [Kinshasa]</td>
</tr>
</tbody>
</table>
Table Q1 | Selenium minerals recognized by the International Mineralogical Association.—Continued

[Data are from Mindat.org (2015) and the International Mineralogical Association (IMA) (2014). ?, uncertain according to the IMA; NA, not available]

<table>
<thead>
<tr>
<th>Mineral name</th>
<th>Chemical formula</th>
<th>Date of discovery or IMA approval</th>
<th>Geologic setting and (or) first recorded locality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downeyite</td>
<td>SeO₂</td>
<td>1971</td>
<td>Burning anthracite coal deposits, Pennsylvania, United States</td>
</tr>
<tr>
<td>Drysdallite</td>
<td>Mo(Se,S)₄</td>
<td>1973</td>
<td>Oxidation zone of uranium deposits, Kampijimpanga, North-Western Province, Zambia</td>
</tr>
<tr>
<td>Dzharkenite</td>
<td>FeSe₃</td>
<td>1995</td>
<td>Suluchekinskoye selenium-uranium deposit, Almaty Province, Kazakhstan</td>
</tr>
<tr>
<td>Eldragenite</td>
<td>CuₙBiSe₄(Se₂)</td>
<td>2011</td>
<td>Hydrothermal veins with selenium &gt; sulfur, El Dragón Mine, Potosí Department, Bolivia</td>
</tr>
<tr>
<td>Eskebornite</td>
<td>CuFeSe₂</td>
<td>1949</td>
<td>Low-temperature hydrothermal deposits, Eskaborn Adit, Saxony-Anhalt, Germany</td>
</tr>
<tr>
<td>Eucairite</td>
<td>AgCuSe</td>
<td>1818</td>
<td>Copper-silver-lead-selenium hydrothermal deposits, Skrikerum Mine, Östergötland, Sweden</td>
</tr>
<tr>
<td>Favreauite</td>
<td>PbBiCu₈O₄(SeO₃)₄(OH)•H₂O</td>
<td>2014</td>
<td>Hydrothermal veins with selenium &gt; sulfur, El Dragón Mine, Potosí Department, Bolivia</td>
</tr>
<tr>
<td>Ferroselite</td>
<td>FeSe₂</td>
<td>1955</td>
<td>Red bed deposits of Colorado plateau type, Ust' Uyok deposit, eastern Siberia, Russia</td>
</tr>
<tr>
<td>Fischesserite</td>
<td>Ag₃AuSe₂</td>
<td>1971</td>
<td>Carbonate vein in epithermal hydrothermal gold-uranium-selenium deposit, Předbořice, Bohemia, Czech Republic</td>
</tr>
<tr>
<td>Francisite</td>
<td>Cu₁Bi(SeO₃)₂O₂Cl</td>
<td>1990</td>
<td>Iron Mine, Iron Monarch open cut, South Australia, Australia</td>
</tr>
<tr>
<td>Freboldite</td>
<td>CoSe</td>
<td>1957</td>
<td>Dolomite veinlets, Trogtal Quarries, Lower Saxony, Germany</td>
</tr>
<tr>
<td>Geffroyite</td>
<td>(Cu,Fe,Ag)₃(Se,S)₃</td>
<td>1982</td>
<td>Late-stage veins cutting granite, Chaméane uranium deposit, Auvergne, France</td>
</tr>
<tr>
<td>Georgbokiite</td>
<td>Cu₃(SeO₃)₂O₂Cl₂</td>
<td>1996</td>
<td>Scoria cone, Great Fissure eruption, Far Eastern Region, Russia</td>
</tr>
<tr>
<td>Giraudite</td>
<td>Cu₁(Cu₄Fe,Zn)₂As₅Se₁₃</td>
<td>1982</td>
<td>Late-stage veins cutting granite, Chaméane uranium deposit, Auvergne, France</td>
</tr>
<tr>
<td>Guanajuatite</td>
<td>Bi₃Se₃</td>
<td>1873</td>
<td>Low- to moderate-temperature hydrothermal deposits, Santa Catarina Mine, Guanajuato, Mexico</td>
</tr>
<tr>
<td>Guilleminite</td>
<td>Ba(UO₂)₆(SeO₃)₄(OH)₄•3H₂O</td>
<td>1965</td>
<td>Oxidized zone of a copper-cobalt-manganese-uranium deposit, Musonoi Mine, Democratic Republic of the Congo (Congo [Kinshasa])</td>
</tr>
<tr>
<td>Hakite</td>
<td>Cu₉(Cu₄Hg)₃(Sb₂Se₁₃</td>
<td>1970</td>
<td>In epithermal calcite veins, Předbořice, Bohemia, Czech Republic</td>
</tr>
<tr>
<td>Haynesite</td>
<td>(UO₂)₃(SeO₃)₄(OH)₄•5H₂O</td>
<td>1991</td>
<td>Oxidized uranium deposits, Repete Mine, Utah, United States</td>
</tr>
<tr>
<td>Ikunolite¹</td>
<td>Bi₃(S,Se)₃</td>
<td>1959</td>
<td>Xenothermal veins with silver-gold-copper-lead-tin-tungsten-zinc, Ikuno Mine, Honshu Island, Japan</td>
</tr>
<tr>
<td>Ilinskite</td>
<td>(Na,K)Cu₆(SeO₃)₂O₂Cl₃</td>
<td>1996</td>
<td>Scoria cone, Tolbachik volcano, Far Eastern Region, Russia</td>
</tr>
<tr>
<td>Jacutingaite</td>
<td>Pt₃HgSe₄</td>
<td>2011</td>
<td>Iron-gold-palladium deposit, Cauê Mine, Minas Gerais, Brazil</td>
</tr>
<tr>
<td>Jagüeite</td>
<td>Cu₂Pd₂Se₄</td>
<td>2002</td>
<td>Telethermal selenide vein-type deposit, El Chire prospect, La Rioja Province, Argentina</td>
</tr>
<tr>
<td>Jolliffeite</td>
<td>NiAsSe</td>
<td>1991</td>
<td>Uraninite vein, Fish Hook Bay, Saskatchewan, Canada</td>
</tr>
<tr>
<td>Junoite</td>
<td>Cu₄Pb₂Bi₄(S,Se)₁₆</td>
<td>1975</td>
<td>Gold-copper-bismuth deposit, Juno Mine, Northern Territory, Australia</td>
</tr>
<tr>
<td>Kalungaite</td>
<td>PdAsSe</td>
<td>2004</td>
<td>Gold deposit, related to a peraluminous granite, Buraco do Ouro Mine, Goiás, Brazil</td>
</tr>
<tr>
<td>Kawazulite</td>
<td>Bi₅Te₅Se</td>
<td>1970</td>
<td>Epithermal gold-silver-tellurium-manganese veins, Kawazu Mine, Honshu Island, Japan</td>
</tr>
<tr>
<td>Kitkaite</td>
<td>NiTeSe</td>
<td>1961</td>
<td>Low-grade uranium and selenium mineralization in carbonate-bearing veinlets, Kitka River Valley, northern Finland</td>
</tr>
<tr>
<td>Mineral name</td>
<td>Chemical formula</td>
<td>Date of discovery or IMA approval</td>
<td>Geologic setting and (or) first recorded locality</td>
</tr>
<tr>
<td>-------------</td>
<td>------------------</td>
<td>----------------------------------</td>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td>Klockmannite</td>
<td>CuSe</td>
<td>1928</td>
<td>Silver-copper-selenium deposit, Las Asperezas Mine, La Rioja Province, Argentina</td>
</tr>
<tr>
<td>Krut’aite</td>
<td>CuSe₂</td>
<td>1972</td>
<td>Uranium deposit, Petrovice, Moravia, Czech Republic</td>
</tr>
<tr>
<td>Kullerudite</td>
<td>NiSe₂</td>
<td>1964</td>
<td>Alteration of wilkmanite in low-grade uranium and selenium mineralization, Kitka River Valley, northern Finland</td>
</tr>
<tr>
<td>Kurilite</td>
<td>Ag₆Te₂Se</td>
<td>2009</td>
<td>Kuril islands gold deposit, Prasolovskoe gold deposit, Far Eastern Region, Russia</td>
</tr>
<tr>
<td>Laitakarite</td>
<td>Bi₂Se₃S</td>
<td>1959</td>
<td>Copper-gold deposit, Orijárvi, southwestern Finland</td>
</tr>
<tr>
<td>Laphamite</td>
<td>As₄(Se,S)</td>
<td>1985</td>
<td>Burning anthracite coal deposit, Burnside, Pennsylvania, United States</td>
</tr>
<tr>
<td>Larisaite</td>
<td>Na₃(UO₂)₃(Se⁴⁺O₃)O₄·4H₂O</td>
<td>2002</td>
<td>Uranium deposit, Repete Mine, Blanding, San Juan County, Utah, United States</td>
</tr>
<tr>
<td>Litochlebite</td>
<td>Ag₆PbBi₃Se₈</td>
<td>2009</td>
<td>Quartz-uranium-carbonate deposit, Zálesi, Moravia, Czech Republic</td>
</tr>
<tr>
<td>Luberoite</td>
<td>Pt₄Se₄</td>
<td>1992</td>
<td>Lubero region, Kivu, Democratic Republic of the Congo (Congo [Kinshasa])</td>
</tr>
<tr>
<td>Mäkinenite</td>
<td>γ-NiSe</td>
<td>1967</td>
<td>Low-grade uranium and selenium mineralization, Kitka River Valley, northern Finland</td>
</tr>
<tr>
<td>Mandarinoite</td>
<td>Fe₃⁺(Se⁴⁺O₃)₂·6H₂O</td>
<td>1978</td>
<td>Oxidation product of penroseite and pyrite, Virgen de Surumi Mine (Pacajake Mine), Potosí Department, Bolivia</td>
</tr>
<tr>
<td>Marthozite</td>
<td>Cu(UO₂)₃(SeO₄)₂(OH)₄·8H₂O</td>
<td>1969</td>
<td>Copper-cobalt-manganese-uranium deposit, Musonoi Mine, Katanga, Democratic Republic of the Congo (Congo [Kinshasa])</td>
</tr>
<tr>
<td>Mgréite</td>
<td>Cu₃AsSe₃</td>
<td>1982</td>
<td>Silver-uranium deposit, Schlema-Hartenstein District, Saxony, Germany</td>
</tr>
<tr>
<td>Miessiite</td>
<td>Pd$_{11}$Te₂Se₂</td>
<td>2006</td>
<td>Placer deposits, Miessijoki River, Lapland Region, Finland</td>
</tr>
<tr>
<td>Milotaite</td>
<td>PdSbSe</td>
<td>2003</td>
<td>Gold-uranium-selenium deposit, Redbořice, Bohemia, Czech Republic</td>
</tr>
<tr>
<td>Molybdonite</td>
<td>PbSeO₄</td>
<td>1882</td>
<td>Cacheuta Mine, Mendoza, Argentina</td>
</tr>
<tr>
<td>Mozgovaite</td>
<td>PbBi₃(S,Se)₅</td>
<td>1998</td>
<td>Magmatic-hydrothermal system, La Fossa crater, Vulcano Island, Sicily, Italy</td>
</tr>
<tr>
<td>Munakataite</td>
<td>Pb₃Cu₂(Se⁴⁺O₃)⁵(SO₄)⁴(OH)₄</td>
<td>2007</td>
<td>Oxide zone of aguilarite-bearing lead-zinc-gold-silver ores, Kato Mine, Kyushu Region, Japan</td>
</tr>
<tr>
<td>Naumannite</td>
<td>Ag$_{2}$Se</td>
<td>1828</td>
<td>Selenium mineralization in hematite mine, Tilkerode, Saxony-Anhalt, Germany</td>
</tr>
<tr>
<td>Nestolaite</td>
<td>CaSeO₄·H₂O</td>
<td>2013</td>
<td>In sandstone host, Little Eva Mine, Utah, United States</td>
</tr>
<tr>
<td>Nevskite</td>
<td>Bi(Se,S)</td>
<td>1984</td>
<td>Nevskoe tungsten-tin deposit, Far Eastern Region, Russia</td>
</tr>
<tr>
<td>Nicksobelevite</td>
<td>Cu₃(SeO₄)₃Cl₄</td>
<td>2013</td>
<td>Scoria cone, Tolbachik volcano, Far Eastern Region, Russia</td>
</tr>
<tr>
<td>Nordströmite³</td>
<td>CuPbBi₃(Se₂S₁₀)₅</td>
<td>1978</td>
<td>Copper-gold-silver-lead-zinc deposit, Falun Mine, Falun, Dalarna, Sweden</td>
</tr>
<tr>
<td>Olsacherite</td>
<td>Pb₃(SeO₄)₅(SO₄)⁵</td>
<td>1969</td>
<td>Silver-selenium deposit, Virgen de Surumi Mine (Pacajake Mine), Potosí Department, Bolivia</td>
</tr>
<tr>
<td>Oosterboschite</td>
<td>(Pd,Cu)₃Se₅</td>
<td>1970</td>
<td>Copper-cobalt-manganese-uranium deposit, Musonoi Mine, Katanga, Democratic Republic of the Congo (Congo [Kinshasa])</td>
</tr>
<tr>
<td>Orlandiite</td>
<td>Pb₃(SeO₄)₅O₇Cl₄·H₂O</td>
<td>1998</td>
<td>Galena-arsenopyrite deposit, Baccu Locci Mine, Sardinia, Italy</td>
</tr>
<tr>
<td>Mineral name</td>
<td>Chemical formula</td>
<td>Date of discovery or IMA approval</td>
<td>Geologic setting and (or) first recorded locality</td>
</tr>
<tr>
<td>------------------</td>
<td>------------------</td>
<td>-----------------------------------</td>
<td>---------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Padmaite</td>
<td>PdBiSe</td>
<td>1991</td>
<td>Uranium-vanadium deposit, Srednyaya Padma Mine, Northern Region, Russia</td>
</tr>
<tr>
<td>Palladseite</td>
<td>Pd&lt;sub&gt;7&lt;/sub&gt;S&lt;sub&gt;e&lt;/sub&gt;&lt;sub&gt;15&lt;/sub&gt;</td>
<td>1977</td>
<td>Itabira, Iron Quadrangle, Minas Gerais, Brazil</td>
</tr>
<tr>
<td>Parageorgbokiite</td>
<td>Cu&lt;sub&gt;2&lt;/sub&gt;(SeO&lt;sub&gt;4&lt;/sub&gt;)&lt;sub&gt;2&lt;/sub&gt;OCl&lt;sub&gt;2&lt;/sub&gt;</td>
<td>2006</td>
<td>Scoria cone, Tolbachik volcano, Far Eastern Region, Russia</td>
</tr>
<tr>
<td>Paraguanaujaitite</td>
<td>Bi&lt;sub&gt;2&lt;/sub&gt;S&lt;sub&gt;e&lt;/sub&gt;</td>
<td>1948</td>
<td>Gold-sulfur deposit, Santa Catarina Mine, Guanajuato, Mexico</td>
</tr>
<tr>
<td>Pekoite&lt;sup&gt;1&lt;/sup&gt;</td>
<td>PbCuBi&lt;sub&gt;1&lt;/sub&gt;(S,Se)&lt;sub&gt;18&lt;/sub&gt;</td>
<td>1975</td>
<td>Gold-copper-bismuth deposit, Juno Mine, Northern Territory, Australia</td>
</tr>
<tr>
<td>Penroseite</td>
<td>(Ni,Co,Cu)Se&lt;sub&gt;2&lt;/sub&gt;</td>
<td>1926</td>
<td>Silver-selenium deposit, Virgen de Surumi Mine (Pacajake Mine), Potosí Department, Bolivia</td>
</tr>
<tr>
<td>Penzhinite</td>
<td>(Ag,Cu)&lt;sub&gt;4&lt;/sub&gt;Au(S,Se)&lt;sub&gt;4&lt;/sub&gt;</td>
<td>1984</td>
<td>Sergeevskoye gold-silver occurrence, Far Eastern Region, Russia</td>
</tr>
<tr>
<td>Permiffavitite</td>
<td>Cu&lt;sub&gt;2&lt;/sub&gt;SbSe&lt;sub&gt;4&lt;/sub&gt;</td>
<td>1971</td>
<td>Gold-uranium-selenium deposit, Předbořice, Bohemia, Czech Republic</td>
</tr>
<tr>
<td>Petrovicite</td>
<td>Cu&lt;sub&gt;2&lt;/sub&gt;HgPbBiSe&lt;sub&gt;5&lt;/sub&gt;</td>
<td>1976</td>
<td>Uranium deposit, Petrovice, Moravia, Czech Republic</td>
</tr>
<tr>
<td>Petrovskaite&lt;sup&gt;1&lt;/sup&gt;</td>
<td>AuAg(S,Se)</td>
<td>1984</td>
<td>Maikain gold deposit, Pavlodar Province, Kazakhstan</td>
</tr>
<tr>
<td>Piretite</td>
<td>Ca(UO&lt;sub&gt;2&lt;/sub&gt;)(SeO&lt;sub&gt;4&lt;/sub&gt;)(OH)&lt;sub&gt;4&lt;/sub&gt;·4H&lt;sub&gt;2&lt;/sub&gt;O</td>
<td>1996</td>
<td>Copper-cobalt-nickel-uranium deposit, Shinkolobwe Mine, Katanga, Democratic Republic of the Congo (Congo [Kinshasa])</td>
</tr>
<tr>
<td>Plumboselite</td>
<td>PbO&lt;sub&gt;3&lt;/sub&gt;(SeO&lt;sub&gt;4&lt;/sub&gt;)</td>
<td>2010</td>
<td>Copper-lead-zinc-silver-germanium-cadmium deposit in dolomite, Tsumeb Mine, Ojikoto Region, Namibia</td>
</tr>
<tr>
<td>Poubaite</td>
<td>PbBi&lt;sub&gt;1&lt;/sub&gt;(Te,Se,S)&lt;sub&gt;4&lt;/sub&gt;</td>
<td>1978</td>
<td>Uraninite deposit with sulfur-selenium, Oldřichov, Bohemia, Czech Republic</td>
</tr>
<tr>
<td>Prewittite</td>
<td>KPb&lt;sub&gt;1.5&lt;/sub&gt;ZnCu&lt;sub&gt;2&lt;/sub&gt;(SeO&lt;sub&gt;4&lt;/sub&gt;)&lt;sub&gt;2&lt;/sub&gt;OCl&lt;sub&gt;10&lt;/sub&gt;</td>
<td>2002</td>
<td>In fumarole field, Tolbachik volcano, Far Eastern Region, Russia</td>
</tr>
<tr>
<td>Proudite</td>
<td>CuPb&lt;sub&gt;2&lt;/sub&gt;Bi&lt;sub&gt;4.3&lt;/sub&gt;(S,Se)&lt;sub&gt;22&lt;/sub&gt;</td>
<td>1975</td>
<td>Gold-copper-bismuth deposit, Juno Mine, Northern Territory, Australia</td>
</tr>
<tr>
<td>Sabatierite</td>
<td>Cu&lt;sub&gt;2&lt;/sub&gt;TlSe&lt;sub&gt;4&lt;/sub&gt;</td>
<td>1976</td>
<td>Uranium deposit, Bukov Mine, Moravia, Czech Republic</td>
</tr>
<tr>
<td>Sarrabosite</td>
<td>Pb&lt;sub&gt;2&lt;/sub&gt;CuCl&lt;sub&gt;2&lt;/sub&gt;(SeO&lt;sub&gt;4&lt;/sub&gt;)&lt;sub&gt;4&lt;/sub&gt;</td>
<td>1997</td>
<td>Galena-arsenopyrite deposit, Baccu Locci Mine, Sardinia, Italy</td>
</tr>
<tr>
<td>Schlemaite&lt;sup&gt;1&lt;/sup&gt;</td>
<td>(Cu,□)&lt;sub&gt;6&lt;/sub&gt;(Pb,Bi)Se&lt;sub&gt;4&lt;/sub&gt;</td>
<td>2003</td>
<td>Hydrothermal selenium-bearing dolomite-ankerite vein, Schlema-Hartenstein District, Saxony, Germany</td>
</tr>
<tr>
<td>Schmiederite</td>
<td>Pb&lt;sub&gt;2&lt;/sub&gt;Cu(S&lt;sub&gt;2&lt;/sub&gt;Se&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;4&lt;/sub&gt;)(Se&lt;sub&gt;2&lt;/sub&gt;Se&lt;sub&gt;3&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;)(OH)&lt;sub&gt;4&lt;/sub&gt;</td>
<td>1962</td>
<td>Hydrothermal veinlets in sedimentary host, selenium &gt; sulfur, El Cóndor Mine, Los Llanentes district, La Rioja Province, Argentina</td>
</tr>
<tr>
<td>Sederholmite</td>
<td>β-NiSe</td>
<td>1964</td>
<td>In calcite veins with nickel selenides associated with low-grade uranium mineralization, Kitka River Valley, northern Finland</td>
</tr>
<tr>
<td>Selenium</td>
<td>Se</td>
<td>1828&lt;sup&gt;2&lt;/sup&gt;</td>
<td>NA</td>
</tr>
<tr>
<td>Selenojalpaite</td>
<td>Ag&lt;sub&gt;2&lt;/sub&gt;CuSe&lt;sub&gt;2&lt;/sub&gt;</td>
<td>2004</td>
<td>Copper-silver-lead-selenium hydrothermal deposits, Skríkerum Mine, Östergötland, Sweden</td>
</tr>
<tr>
<td>Selenopolybasite</td>
<td>[(Ag,Cu),(Sb,As),(S,Se)&lt;sub&gt;t&lt;/sub&gt;]&lt;sub&gt;2&lt;/sub&gt;[(Ag,Cu,S,Se)&lt;sub&gt;2&lt;/sub&gt;]&lt;sub&gt;s&lt;/sub&gt;</td>
<td>2006</td>
<td>Silver deposit, De Lamar Mine, Idaho, United States</td>
</tr>
<tr>
<td>Selenostephanite</td>
<td>Ag&lt;sub&gt;5&lt;/sub&gt;Sb(Se,S)&lt;sub&gt;4&lt;/sub&gt;</td>
<td>1985</td>
<td>Volcanogenic silver-gold deposit, Rudnaya Sopka, Far Eastern Region, Russia</td>
</tr>
<tr>
<td>Skippenite</td>
<td>Bi&lt;sub&gt;2&lt;/sub&gt;TeSe&lt;sub&gt;3&lt;/sub&gt;</td>
<td>1987</td>
<td>Otish Mountains uranium deposit, Quebec, Canada</td>
</tr>
<tr>
<td>Sofiite</td>
<td>Zn&lt;sub&gt;2&lt;/sub&gt;(SeO&lt;sub&gt;4&lt;/sub&gt;)Cl&lt;sub&gt;2&lt;/sub&gt;</td>
<td>1989</td>
<td>Scoria cone, Tolbachik volcano, Far Eastern Region, Russia</td>
</tr>
<tr>
<td>Součekite</td>
<td>PbCuBi(S,Se)&lt;sub&gt;9&lt;/sub&gt;</td>
<td>1979</td>
<td>Uranium deposit with sulfur-selenium, Oldřichov, Bohemia, Czech Republic</td>
</tr>
</tbody>
</table>
Table Q1. Selenium minerals recognized by the International Mineralogical Association.—Continued

<table>
<thead>
<tr>
<th>Mineral name</th>
<th>Chemical formula</th>
<th>Date of discovery or IMA approval</th>
<th>Geologic setting and (or) first recorded locality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stilleite</td>
<td>ZnSe</td>
<td>1956</td>
<td>Uranium deposit with copper, cobalt, and nickel, Shinkolobwe Mine, Katanga, Democratic Republic of the Congo (Congo [Kinshasa])</td>
</tr>
<tr>
<td>Sudovikovite</td>
<td>PtSe₂</td>
<td>1995</td>
<td>Uranium-vanadium deposit, Srednyaya Padma Mine, Northern Region, Russia</td>
</tr>
<tr>
<td>Telluronevskite</td>
<td>Bi₅TeSe₃</td>
<td>1993</td>
<td>Selenium and tellurium mineralization in hydrothermal veins, in argillic andesite host, Poruba pod Vihorlatom, Michalovce County, Košice Region, Slovakia</td>
</tr>
<tr>
<td>Tiemannite</td>
<td>HgSe</td>
<td>1855</td>
<td>Ancient lead and zinc mine, working veins of the Burgstadt vein system, St. Lorenz Mine, Lower Saxony, Germany</td>
</tr>
<tr>
<td>Tischendorfite</td>
<td>Pd₃Hg₃Se₄</td>
<td>2001</td>
<td>Selenium mineralization in hematite mine, Eskaborn Adit, Tilkerode, Saxony-Anhalt, Germany</td>
</tr>
<tr>
<td>Trogtalite</td>
<td>CoSe₂</td>
<td>1955</td>
<td>Abandoned greywacke quarries, Trogtal Quarries, Lower Saxony, Germany</td>
</tr>
<tr>
<td>Trüstedtite</td>
<td>Ni₅Se₄</td>
<td>1967</td>
<td>Low-grade uranium and selenium mineralization in an albite diabase, Kitka River Valley, northern Finland</td>
</tr>
<tr>
<td>Tsnigriite</td>
<td>Ag₅SbTe₃(S,Se)₃</td>
<td>1991</td>
<td>Black-shale-hosted Vysokovol’tnoye silver-gold deposit, Bel’tau Mountains, Kyzylkum Desert, Uzbekistan</td>
</tr>
<tr>
<td>Tyrrellite</td>
<td>Cu(Co³⁺,Ni³⁺)Se₄</td>
<td>1952</td>
<td>Ato Bay, Beaverlodge Lake, Goldfields District, Beaverlodge Region, Saskatchewan, Canada; and Eagle Claims uranium-copper-selenium occurrence, Eagle shaft area, Melville Lake, Goldfields District, Beaverlodge Region, Saskatchewan, Canada</td>
</tr>
<tr>
<td>Umangite</td>
<td>Cu₃Se₂</td>
<td>1891</td>
<td>Las Asperezas silver mine (Sarmiento deposit, Veta Sarmiento), Sierra de Cacho, Villa Castelli, General Lamadrid Department, La Rioja Province, Argentina; and abandoned greywacke quarries, Trogtal Quarries, Lautenthal, Harz, Lower Saxony, Germany</td>
</tr>
<tr>
<td>Verbeekite</td>
<td>PdSe₂</td>
<td>2001</td>
<td>Copper-cobalt-manganese-uranium deposit. Known for rare assemblage of uranyl selenites, Musonoi Mine, Kolwezi, Kolwezi District, Katanga Copper Crescent, Katanga (Shaba), Democratic Republic of the Congo (Congo [Kinshasa])</td>
</tr>
<tr>
<td>Vihorlatite</td>
<td>Bi₄Se₁₁Te₄</td>
<td>1988</td>
<td>Poruba pod Vihorlatom, Michalovce County, Košice Region, Slovakia</td>
</tr>
<tr>
<td>Watkinsonite</td>
<td>Cu₂PbBi₃(Se,S,Te)₄</td>
<td>1985</td>
<td>Otish Mountains uranium deposit, Otish Mountains, Baie-James, Nord-du-Québec, Quebec, Canada</td>
</tr>
<tr>
<td>Weibullite</td>
<td>Pb₃Bi₃Se₇S₁₁</td>
<td>1910</td>
<td>Copper mine with minor amount of gold, Falun Mine, Falun, Dalarna, Sweden</td>
</tr>
<tr>
<td>Wilkmanite</td>
<td>Ni₅Se₄</td>
<td>1964</td>
<td>Low-grade uranium and selenium mineralization in an albite diabase, Kitka River Valley, Kuusamo, northern Finland</td>
</tr>
<tr>
<td>Wittite</td>
<td>Pb₃Bi₃(S,Se)₂₃</td>
<td>1924</td>
<td>Falun Mine, Falun, Dalarna, Sweden</td>
</tr>
<tr>
<td>Zincomenite</td>
<td>ZnSeO₃</td>
<td>2014</td>
<td>Northern fumarole field, first scoria cone, Northern Breakthrough (North Breach), and Great Fissure eruption (Main Fracture), Tolbachik volcano, Far Eastern Region, Russia</td>
</tr>
</tbody>
</table>

¹The IMA chemical formula does not show selenium substitution for sulfur.
²The IMA chemical formula is $\text{Pb}_5\text{CuBi}_3(S,\text{Se})_{12}$.
³The symbol □ in the chemical formula denotes an empty atomic site that can be filled (or not), depending upon compositional variation.
### Table Q2.  A summary of selenium concentrations in various selenides and sulfides from deposits around the world.

[Avg, average; b.d.l., below detection limit; Do., do., ditto; IOCG, iron oxide-copper-gold; n.d., not detected; n.r., not reported; ppm, part per million; wt. %, weight percent; —, none. Abbreviations for elements: Ag, silver; As, arsenic; Au, gold; Bi, bismuth; Co, cobalt; Cu, copper; Fe, iron; Hg, mercury; Mo, molybdenum; Ni, nickel; Pb, lead; Pd, palladium; PGE, platinum-group element; Pt, platinum; S, sulfur; Se, selenium; Te, tellurium; Ti, titanium; Tl, thallium; U, uranium; Zn, zinc.]

<table>
<thead>
<tr>
<th>Deposit type and (or) chemistry</th>
<th>Mine/deposit name</th>
<th>Mineral phases</th>
<th>Selenium concentration</th>
<th>Notes</th>
<th>Reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Australia, eastern</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volcanic-hosted massive sulfide</td>
<td>Agincourt deposit</td>
<td>Pyrite</td>
<td>&lt;6 to 9 ppm</td>
<td>—</td>
<td>Huston and others (1995)</td>
</tr>
<tr>
<td>Do. Dry River South deposit</td>
<td>do.</td>
<td>do.</td>
<td>&lt;6 to 760 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do. Mount Chalmers deposit</td>
<td>do.</td>
<td>do.</td>
<td>&lt;5 to 200 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do. Rosebery deposit</td>
<td>do.</td>
<td>do.</td>
<td>&lt;6 to 33 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do. Waterloo deposit</td>
<td>do.</td>
<td>do.</td>
<td>&lt;6 to 180 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td><strong>Australia, southern</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Protozoic Olympic Dam IOCG</td>
<td>Olympic Dam</td>
<td>Bornite</td>
<td>18.8 ppm</td>
<td>—</td>
<td>Cook and others (2011)</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Chalcopyrite</td>
<td>8.7 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td><strong>Australia, western</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Au-Ag-PGE-Hg-Se polymetallic veins</td>
<td>Pilbara region, Copper Hills</td>
<td>Chalcopyrite</td>
<td>3.5 wt. %</td>
<td>—</td>
<td>Nickel (2002)</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Cu-chalcopyrite (Cu,Pd,Se)</td>
<td>41.33 wt. %</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Naumannite (Ag,Se)</td>
<td>28.8 wt. %</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Oosterboschite (Pd,Cu,Se)</td>
<td>45 wt. %</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Umanite (Cu,Se)</td>
<td>13.7 wt. %</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td><strong>Brazil, northern</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Au-Pd-Pt</td>
<td>Serra Pelada</td>
<td>Bulk rock of bonanza grade Au-Pd-Pt</td>
<td>21 to 36 ppm</td>
<td>Disaggregated, clayey material</td>
<td>Cabral and others (2002)</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Palladseite (Pd,Se)</td>
<td>n.r.</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Sudovikovite (Pd,Se)</td>
<td>11.5 to 12.2 wt. %</td>
<td>Pd-Pt-Se inclusions in palladian gold aggregates</td>
<td>Do.</td>
</tr>
<tr>
<td><strong>Canada, British Columbia</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Au-pyrite quartz veins</td>
<td>Caribooa</td>
<td>Pyrite</td>
<td>&lt;15 ppm</td>
<td>Low to negligible Se content of Au-quartz deposits is attributed to Se-poor mafic rocks and (or) wall rocks.</td>
<td>Hawley and Nichol (1959)</td>
</tr>
<tr>
<td><strong>Canada, Manitoba</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Massive Cu-Fe-(Zn)-S replacement</td>
<td>Flin Flon</td>
<td>Chalcopyrite</td>
<td>145 to 470 ppm</td>
<td>Major concentration of Se found in the Canadian Precambrian deposits occurs in the massive Cu, Fe S replacement types of deposits, hydrothermal in origin.</td>
<td>Hawley and Nichol (1959)</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Pyrite</td>
<td>&lt;15 to 220 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Pyrrhotite</td>
<td>375 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td><strong>Canada, New Brunswick</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu-Fe-Zn-S banded ores</td>
<td>Heath Steele</td>
<td>Pyrite</td>
<td>20 ppm</td>
<td>—</td>
<td>Hawley and Nichol (1959)</td>
</tr>
<tr>
<td>Massive Cu-Fe-(Zn)-S replacement, banded</td>
<td>do.</td>
<td>Pyrrhotite</td>
<td>21 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td><strong>Canada, Newfoundland and Labrador</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ni-Cu-Co</td>
<td>Nain Plutonic Suite, Voisey’s Bay, Ovid ore zone</td>
<td>Chalcopyrite</td>
<td>38 to 70 ppm</td>
<td>—</td>
<td>Ripley and others (2002)</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Pentlandite</td>
<td>53 to 93 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
</tbody>
</table>
### Critical Mineral Resources of the United States—Selenium

Table Q2. A summary of selenium concentrations in various selenides and sulfides from deposits around the world.—Continued

[avg, average; b.d.l., below detection limit; Do., do., ditto; IOCG, iron oxide-copper-gold; n.d., not detected; n.r., not reported; ppm, part per million; wt. %, weight percent; —, none. Abbreviations for elements: Ag, silver; As, arsenic; Au, gold; Bi, bismuth; Co, cobalt; Cu, copper; Fe, iron; Hg, mercury; Mo, molybdenum; Ni, nickel; Pb, lead; Pd, palladium; PGE, platinum-group element; Pt, platinum; S, sulfur; Se, selenium; Te, tellurium; Ti, titanium; Tl, thallium; U, uranium; Zn, zinc]

<table>
<thead>
<tr>
<th>Deposit type and (or) chemistry</th>
<th>Mine/deposit name</th>
<th>Mineral phases</th>
<th>Selenium concentration</th>
<th>Notes</th>
<th>Reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au-pyrite quartz veins</td>
<td>Yellowknife, Discovery Mine</td>
<td>Pyrrhotite</td>
<td>26 to 30 ppm</td>
<td>—</td>
<td>Hawley and Nichol (1959)</td>
</tr>
<tr>
<td>Au-pyrite quartz veins</td>
<td>Cathroy-Larder, Hardrock, Howey-Hasaga (Red Lake), Renabi</td>
<td>Pyrite</td>
<td>&lt;15 ppm</td>
<td>Low to negligible Se content of Au-quartz deposits is attributed to Se-poor mafic sources and (or) wall rocks.</td>
<td>Hawley and Nichol (1959)</td>
</tr>
<tr>
<td>Do.</td>
<td>Hollinger</td>
<td>Chalcopyrite</td>
<td>23 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>McIntyre Mine</td>
<td>High-temperature pyrite</td>
<td>&lt;15 to 83 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>McIntyre Mine</td>
<td>Low-temperature pyrite</td>
<td>&lt;15 to 110 ppm</td>
<td>In the McIntyre Mine, the authors identified low-temperature pyrite with a higher range of Se concentrations than high-temperature pyrite.</td>
<td>Do.</td>
</tr>
<tr>
<td>Banded siderite-pyrite</td>
<td>Michipicoten Iron Formation, Rand No. 2 Mine</td>
<td>Pyrrhotite</td>
<td>&lt;15 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>Michipicoten Iron Frm, Rand No. 2 Mine</td>
<td>Pyrite</td>
<td>&lt;15 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Diabase dikes</td>
<td>Algoma U district, Can-Met Mine</td>
<td>Pyrrhotite</td>
<td>&lt;15 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Magnetite (replacement)</td>
<td>Marmora</td>
<td>Pyrite</td>
<td>&lt;15 ppm</td>
<td>Author noted that Se showed no order of preference among individual sulfide phases, but showed a tendency for progressive concentration of Se with the order of crystallization.</td>
<td>Do.</td>
</tr>
<tr>
<td>Massive Cu-Fe-(Zn)-S replacement</td>
<td>Manitouwadge, Geco Mine,</td>
<td>Chalcopyrite</td>
<td>130 to 540 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Ni-Cu-S ore</td>
<td>Porcupine, Alexo Mine</td>
<td>do.</td>
<td>17 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>Sudbury Complex</td>
<td>Chalcopyrite</td>
<td>11 to 165 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>Sudbury Complex</td>
<td>Pentlandite</td>
<td>30 to 160 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>Sudbury Complex</td>
<td>Pyrite</td>
<td>25 to 130 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>Sudbury Complex</td>
<td>Pyrrhotite</td>
<td>17 to 230 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Pyritiferous U banded or bedded deposits</td>
<td>Algoma, Blind River area</td>
<td>Pyrite</td>
<td>&lt;15 to 79 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
</tbody>
</table>
Table Q2. A summary of selenium concentrations in various selenides and sulfides from deposits around the world.—Continued

(avg, average; b.d.l., below detection limit; Do., do., ditto; IOCG, iron oxide-copper-gold; n.d., not detected; n.r., not reported; ppm, part per million; wt. %, weight percent; —, none. Abbreviations for elements: Ag, silver; As, arsenic; Au, gold; Bi, bismuth; Co, cobalt; Cu, copper; Fe, iron; Hg, mercury; Mo, molybdenum; Ni, nickel; Pb, lead; Pd, palladium; PGE, platinum-group element; Pt, platinum; S, sulfur; Se, selenium; Te, tellurium; Ti, titanium; Tl, thallium; U, uranium; Zn, zinc)

<table>
<thead>
<tr>
<th>Deposit type and (or) chemistry</th>
<th>Mine/deposit name</th>
<th>Mineral phases</th>
<th>Selenium concentration</th>
<th>Notes</th>
<th>Reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Canada, Quebec</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Au-pyrite quartz veins</td>
<td>Granada</td>
<td>Pyrite</td>
<td>&lt;15 ppm</td>
<td>Low to negligible Se content of Au-quartz deposits is attributed to Se-poor magmatic sources and (or) wall rocks.</td>
<td>Hawley and Nichol (1959)</td>
</tr>
<tr>
<td>Do.</td>
<td>Powell Rouyn</td>
<td>do.</td>
<td>23 to 24 ppm</td>
<td></td>
<td>Do.</td>
</tr>
<tr>
<td>Cu-Fe-Zn-S banded</td>
<td>Suffield</td>
<td>do.</td>
<td>&lt;15 ppm</td>
<td></td>
<td>Do.</td>
</tr>
<tr>
<td>Massive Cu-Fe-(Zn)-S replacement</td>
<td>Aldermac</td>
<td>Chalcopyrite</td>
<td>135 ppm</td>
<td></td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Pyrite</td>
<td>56 ppm</td>
<td></td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Pyrrhotite</td>
<td>74 ppm</td>
<td></td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>Campbell-Chibougamau</td>
<td>Chalcopyrite</td>
<td>25 to 94 ppm</td>
<td></td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Pyrite</td>
<td>51 ppm</td>
<td>In pyrite, pyrrhotite, and chalcopyrite, the Se content is greatest when the mineral phase is located in a massive Cu-S replacement body.</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Pyrrhotite</td>
<td>&lt;15 to 82 ppm</td>
<td></td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>Noranda</td>
<td>Chalcopyrite</td>
<td>360 to 535 ppm</td>
<td></td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Pyrite</td>
<td>33 to 1,000 ppm</td>
<td></td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Pyrrhotite</td>
<td>36 to 555 ppm</td>
<td></td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>Normetal</td>
<td>Chalcopyrite</td>
<td>23 to 260 ppm</td>
<td></td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Pyrite</td>
<td>&lt;15 to 320 ppm</td>
<td></td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Pyrrhotite</td>
<td>15 to 235 ppm</td>
<td></td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>Quemont</td>
<td>Chalcopyrite</td>
<td>40 to 280 ppm</td>
<td></td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Pyrite</td>
<td>10 to 250 ppm</td>
<td></td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Pyrrhotite</td>
<td>54 to 425 ppm</td>
<td></td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>Waite Amulet</td>
<td>Chalcopyrite</td>
<td>395 ppm</td>
<td></td>
<td>Do.</td>
</tr>
<tr>
<td><strong>Canada, Saskatchewan</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Au-pyrite quartz veins</td>
<td>Foudulac, Algold</td>
<td>Pyrite</td>
<td>23 to 24 ppm</td>
<td></td>
<td>Hawley and Nichol (1959)</td>
</tr>
<tr>
<td><strong>Chile, northern</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High sulfidation, epithermal Au-Ag-Cu</td>
<td>Pascua deposit</td>
<td>Main stage pyrite</td>
<td>0.01 to 0.06 wt. %</td>
<td></td>
<td>Chouinard and others (2005)</td>
</tr>
<tr>
<td>Volcanic-hosted strata-bound Cu deposit</td>
<td>Mantos Blancos</td>
<td>Chalcopyrite</td>
<td>0.34 to 4.76 ppm</td>
<td></td>
<td>Reich and others (2013)</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Bornite</td>
<td>0.16 to 5.11 ppm</td>
<td></td>
<td>Do.</td>
</tr>
<tr>
<td><strong>Democratic Republic of the Congo (Congo [Kinshasa])</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U-Cu-Co</td>
<td>Katanga Copperbelt, Musonoi Mine</td>
<td>Berzelianite (Cu₅Se₄)</td>
<td>28.65 to 40.40 wt. %</td>
<td></td>
<td>Pirard and Hater (2008)</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Digenite (Cu₁₈S₈)</td>
<td>0.63 to 19.05 wt. %</td>
<td></td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Athabascaite (Cu₇Se₄)</td>
<td>12.48 to 34.37 wt. %</td>
<td></td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Trogtalite (CoSe₂)</td>
<td>69.43 to 70.23 wt. %</td>
<td></td>
<td>Do.</td>
</tr>
</tbody>
</table>
Critical Mineral Resources of the United States—Selenium

Table Q2. A summary of selenium concentrations in various selenides and sulfides from deposits around the world.—Continued

<table>
<thead>
<tr>
<th>Deposit type and (or) chemistry</th>
<th>Mine/deposit name</th>
<th>Mineral phases</th>
<th>Selenium concentration</th>
<th>Notes</th>
<th>Reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Europe, southeastern</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cretaceous skarn, epithermal and porphyry deposits</td>
<td>Baita Bihor, Chelopeck, Elasite, Ocna de Fier, Radka, Sasea Montana; Banatitic magmatic and metallogenic belt (BMMB)</td>
<td>Bornite</td>
<td>1.5 to 1,046 ppm</td>
<td>—</td>
<td>Cook and others (2011)</td>
</tr>
<tr>
<td>Do. Baita Bihor, Ocna de Fier; Banatitic magmatic and metallogenic belt (BMMB)</td>
<td>Chalcopyrite</td>
<td>8.7 to 538 ppm</td>
<td>—</td>
<td>Do.</td>
<td></td>
</tr>
<tr>
<td>Do. do. Cu, S sulfides</td>
<td>151 to 383 ppm</td>
<td>—</td>
<td>Do.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Italy, Sardinia</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pb-As</td>
<td>Baccu Locci Mine</td>
<td>Cupropavonite</td>
<td>0.26 wt. %</td>
<td>—</td>
<td>Pirri (2002)</td>
</tr>
<tr>
<td>Do. do.</td>
<td>Galena</td>
<td>0.64 wt. %</td>
<td>—</td>
<td>Do.</td>
<td></td>
</tr>
<tr>
<td>Do. do.</td>
<td>Greenockite</td>
<td>0.13 wt. %</td>
<td>—</td>
<td>Do.</td>
<td></td>
</tr>
<tr>
<td>Do. do.</td>
<td>Se-rich galena (clausthalite?)</td>
<td>12.99 wt. %</td>
<td>—</td>
<td>Do.</td>
<td></td>
</tr>
<tr>
<td>Do. do.</td>
<td>Sphalerite</td>
<td>0.12 wt. %</td>
<td>—</td>
<td>Do.</td>
<td></td>
</tr>
<tr>
<td>Do. do.</td>
<td>Wittichenite</td>
<td>0.22 wt. %</td>
<td>—</td>
<td>Do.</td>
<td></td>
</tr>
<tr>
<td><strong>Japan, Hokkaido</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ag-Bi-Te-Se-S</td>
<td>Suttsu Mine</td>
<td>Kawazulite (Bi$<em>{1.26}$ (Te$</em>{0.42}$ Se$<em>{1.3}$)$</em>{1.39}$)</td>
<td>12.9 wt. %</td>
<td>Shimizu and others (1995)</td>
<td></td>
</tr>
<tr>
<td>Do. do.</td>
<td>Selenian bismuthinite (Bi$<em>{2.80}$ (S$</em>{1.1}$ Se$<em>{1.3}$)$</em>{1.39}$)</td>
<td>3.7 wt. %</td>
<td>—</td>
<td>Do.</td>
<td></td>
</tr>
<tr>
<td>Do. do.</td>
<td>Selenian pavonite (Ag$<em>{0.9}$ (Bi$</em>{2.80}$ (Te$<em>{0.42}$ Se$</em>{1.3}$)$_{1.39}$)</td>
<td>11.1 wt. %</td>
<td>—</td>
<td>Do.</td>
<td></td>
</tr>
<tr>
<td>Do. do.</td>
<td>Unnamed (Bi$<em>{4}$ (Te, Se, S)$</em>{4}$)</td>
<td>9.5±4 wt. %</td>
<td>—</td>
<td>Do.</td>
<td></td>
</tr>
<tr>
<td><strong>Kazakhstan</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Porphyry Cu-Mo</td>
<td>Boshchekul’ deposit</td>
<td>Chalcopyrite II</td>
<td>64 to 123.7 ppm</td>
<td>—</td>
<td>Filimonova (1972)</td>
</tr>
<tr>
<td>Do. do.</td>
<td>Chalcopyrite III</td>
<td>111 to 225 ppm</td>
<td>—</td>
<td>Do.</td>
<td></td>
</tr>
<tr>
<td>Do. do.</td>
<td>Chalcopyrite IV</td>
<td>20.6 to 44.4 ppm</td>
<td>—</td>
<td>Do.</td>
<td></td>
</tr>
<tr>
<td>Do. do.</td>
<td>Magnetite</td>
<td>5 to 7 ppm</td>
<td>—</td>
<td>Do.</td>
<td></td>
</tr>
<tr>
<td>Do. do.</td>
<td>Molybdenite I</td>
<td>120 to 781 ppm</td>
<td>—</td>
<td>Do.</td>
<td></td>
</tr>
<tr>
<td>Do. do.</td>
<td>Molybdenite II</td>
<td>235 to 800 ppm</td>
<td>—</td>
<td>Do.</td>
<td></td>
</tr>
<tr>
<td>Do. do.</td>
<td>Pyrite I</td>
<td>42 to 105 ppm</td>
<td>—</td>
<td>Do.</td>
<td></td>
</tr>
<tr>
<td>Do. do.</td>
<td>Pyrite III</td>
<td>50 to 203 ppm</td>
<td>—</td>
<td>Do.</td>
<td></td>
</tr>
<tr>
<td>Do. do.</td>
<td>Pyrite IV</td>
<td>16 to 100 ppm</td>
<td>—</td>
<td>Do.</td>
<td></td>
</tr>
<tr>
<td>Do. do.</td>
<td>Sphalerite</td>
<td>29.5 ppm</td>
<td>—</td>
<td>Do.</td>
<td></td>
</tr>
</tbody>
</table>
Table Q2. A summary of selenium concentrations in various selenides and sulfides from deposits around the world.—Continued

<table>
<thead>
<tr>
<th>Deposit type and (or) chemistry</th>
<th>Mine/deposit name</th>
<th>Mineral phases</th>
<th>Selenium concentration</th>
<th>Notes</th>
<th>Reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pacific Ocean, 13° North, East Pacific Rise</td>
<td>Cu sulfides, Black smoker active chimneys</td>
<td>Hi-T hydrothermal sulfide deposits: axial graben</td>
<td>Chalcopyrite</td>
<td>100 to 2,000 ppm</td>
<td>High Se values occur in high-temperature mineral assemblages, found in the inner part of the deposit in equilibrium with pure, unmixed hydrothermal water; lowest Se values in outer part of deposit, influenced by mixing of hydrothermal waters and seawater.</td>
</tr>
<tr>
<td></td>
<td>Fe-Cu massive sulfides, mature hydrothermal edifice</td>
<td>Off-axis seamounts</td>
<td>Chalcopyrite</td>
<td>0 to 2,500 ppm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0 to 1,500 ppm</td>
<td></td>
</tr>
<tr>
<td>Portugal</td>
<td>Cu-Zn ore</td>
<td>Neves Corvo deposit, Lombador orebody</td>
<td>Se-galena, up to 30% of clausthalite (PbSe), and junoite (Pb, Cu, Bi[S,Se])</td>
<td>2,560 ppm (avg)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pb-Zn ore</td>
<td>Neves Corvo deposit, Zambugal orebody</td>
<td>do.</td>
<td>3,220 ppm (avg)</td>
<td></td>
</tr>
<tr>
<td>Russia, Siberia</td>
<td>Cu-Ni-PGE</td>
<td>Noril’sk, Oktyabr deposit</td>
<td>Chalcopyrite</td>
<td>44 to 148 ppm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>92 to 94 ppm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>496 ppm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>94 ppm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>56 to 213 ppm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>50 to 98 ppm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>87 ppm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>69 to 152 ppm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>85 to 181 ppm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>139 to 190 ppm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>70 to 74 ppm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>115 to 190 ppm</td>
<td></td>
</tr>
<tr>
<td>Russia, Ural Mountains</td>
<td>Cu-S</td>
<td>Karabash group</td>
<td>Bornite</td>
<td>18 ppm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.8 to 216 ppm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>11 to 16 ppm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>81 ppm</td>
<td></td>
</tr>
</tbody>
</table>
Table Q2. A summary of selenium concentrations in various selenides and sulfides from deposits around the world.—Continued

<table>
<thead>
<tr>
<th>Deposit type and (or) chemistry</th>
<th>Mine/deposit name</th>
<th>Mineral phases</th>
<th>Selenium concentration</th>
<th>Notes</th>
<th>Reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu-S</td>
<td>Karabash group</td>
<td>Tetrahedrite-tennantite (from quartz-carbonate veins and veinlets)</td>
<td>45 to 100 ppm</td>
<td>—</td>
<td>Yushoko-Zakharova and others (1978)</td>
</tr>
<tr>
<td>Do.</td>
<td>Mauk deposit</td>
<td>Chalcopyrite (from Cu-pyrrhotite ores)</td>
<td>180 to 325 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Pyrite</td>
<td>n.d. to 119 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Pyrrhotite</td>
<td>21 to 145 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Sphalerite</td>
<td>140 to 187 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Cu-Zn-S</td>
<td>Gay deposit</td>
<td>Bornite</td>
<td>10 to 120 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Chalcopyrite (from Cu sphalerite ores)</td>
<td>5 to 150 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Galena</td>
<td>30 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Pyrite</td>
<td>5 to 550 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Sphalerite</td>
<td>8 to 84 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Tetrahedrite-tennantite (from cupreous pyrite)</td>
<td>10 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>III Internatsional deposit</td>
<td>Bornite</td>
<td>Trace to 10 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Chalcocite</td>
<td>n.d. to 200 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Chalcopyrite (from Cu sphalerite ores)</td>
<td>33 to 220 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Chalcopyrite (from late quartz-carbonate veinlets)</td>
<td>Trace to 30 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Pyrite</td>
<td>Trace to 146 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Sphalerite</td>
<td>2 to 16 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Tetrahedrite-tennantite (from cupreous pyrite)</td>
<td>9 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>Levikha XIV deposit</td>
<td>Chalcopyrite (from Cu sphalerite ores)</td>
<td>5 to 210 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Tetrahedrite-tennantite (from quartz-carbonate veins and veinlets)</td>
<td>13 to 20 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>Sibay deposit</td>
<td>Chalcopyrite (from Cu pyrrhotite ores)</td>
<td>80 to 265 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Chalcopyrite (from Cu sphalerite ores)</td>
<td>10 to 130 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Pyrite</td>
<td>1 to 88 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Pyrrhotite</td>
<td>53 to 126 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Sphalerite</td>
<td>0.5 to 13 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>FeS2</td>
<td>Zyyuzel’skoye deposit</td>
<td>Chalcopyrite (from Cu sphalerite ores)</td>
<td>160 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Chalcopyrite (from late quartz-carbonate veinlets)</td>
<td>Trace to 54 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Pyrite</td>
<td>Trace to 495 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
</tbody>
</table>
Table Q2. A summary of selenium concentrations in various selenides and sulfides from deposits around the world.—Continued

[avg, average; b.d.l., below detection limit; Do., do., ditto; IOCG, iron oxide-copper-gold; n.d., not detected; n.r., not reported; ppm, part per million; wt. %, weight percent; —, none. Abbreviations for elements: Ag, silver; As, arsenic; Au, gold; Bi, bismuth; Co, cobalt; Cu, copper; Fe, iron; Hg, mercury; Mo, molybdenum; Ni, nickel; Pb, lead; Pd, palladium; PGE, platinum-group element; Pt, platinum; S, sulfur; Se, selenium; Te, tellurium; Ti, titanium; Tl, thallium; U, uranium; Zn, zinc]

<table>
<thead>
<tr>
<th>Deposit type and (or) chemistry</th>
<th>Mine/deposit name</th>
<th>Mineral phases</th>
<th>Selenium concentration</th>
<th>Notes</th>
<th>Reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Late Proterozoic metamorphic Cu-vein systems</td>
<td>Glava, Grusen, Moberg, Tinnsjå, Tjøstolfatten</td>
<td>Bornite</td>
<td>2.8 to 4,617 ppm</td>
<td>Se concentrations in bornite show promise as a vector for exploration and may be able to track proximal to distal zonation.</td>
<td>Cook and others (2011)</td>
</tr>
<tr>
<td>Do.</td>
<td>Tinnsjå</td>
<td>Chalcopyrite</td>
<td>20.7 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>Grusen, Moberg, Tinnsjå</td>
<td>Cu₂₅₅ S sulfides</td>
<td>b.d.l. to 1,291 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Sweden and Norway</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu-Ag-Ti-Se</td>
<td>Skrikerum deposit, Småland</td>
<td>Selenojalpaite (Ag,CuSe₂)</td>
<td>29.01 wt. %</td>
<td>—</td>
<td>Bindi and Pratesi (2005)</td>
</tr>
<tr>
<td>Spain</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbonate-hosted epithermal gold</td>
<td>Providencia Mine, Leon</td>
<td>Villamaninite (Cu,Ni,Co,Fe) (S,Se,Te)</td>
<td>1.89 to 9.12 wt. %</td>
<td>—</td>
<td>Paniagua (1995)</td>
</tr>
<tr>
<td>Turkey, northeastern</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu</td>
<td>Murgul deposit</td>
<td>Aikinite Pb₉₆Cu₂₉₈₆Bi₁₀₄S₂₅₇Se₂₀₂Te₀₃₃</td>
<td>2.75 wt. %</td>
<td>—</td>
<td>Willgallis and others (1990)</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Galena (Pb₉₆Ag₂₉₈₆Bi₁₀₄S₂₅₇Se₂₀₂Te₀₃₃)</td>
<td>1 wt. %</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Tennantite (Cu₄₆Zn₁₄₃₂S₄₀₄Te₀₃₃)</td>
<td>0.05 and 0.36 wt. %</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Tetradymite (Bi₁₀₄Pb₂₉₈₆Cu₁₂₆Te₁₄₆S₁₆₄Se₁₆₄)</td>
<td>6.33 wt. %</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>United States, Alaska</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Porphyry Cu-Au-Mo deposit</td>
<td>Bristol Bay, Pebble deposit</td>
<td>Sample pyrite-4</td>
<td>142 ppm</td>
<td>—</td>
<td>Gregory and others (2013)</td>
</tr>
<tr>
<td>Pb-Zn</td>
<td>Southern Brooks Range, Red Dog</td>
<td>Galena and sphalerite (ore minerals), and associated pyrite</td>
<td>&lt;1 ppm</td>
<td>Se distributed evenly among these mineral phases</td>
<td>Baker and others (2000)</td>
</tr>
<tr>
<td>United States, Minnesota</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu-Ni-PGE</td>
<td>Duluth Complex, Babbitt deposit</td>
<td>Cubanite</td>
<td>6 to 157 ppm</td>
<td>—</td>
<td>Ripley (1990)</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Pentlandite</td>
<td>24 to 363 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Pyrrhotite</td>
<td>24 to 169 ppm</td>
<td>—</td>
<td>Do.</td>
</tr>
<tr>
<td>United States, Nevada</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Au-Ag veins</td>
<td>Humboldt County, National District, Buckskin Mountain</td>
<td>HgSeSCl phases</td>
<td>2.12 to 21.91 wt. %</td>
<td>—</td>
<td>Vikre (2007)</td>
</tr>
<tr>
<td>Do.</td>
<td>do.</td>
<td>Stibnite</td>
<td>0.10 to 3.62 wt. %</td>
<td>—</td>
<td>Do.</td>
</tr>
</tbody>
</table>