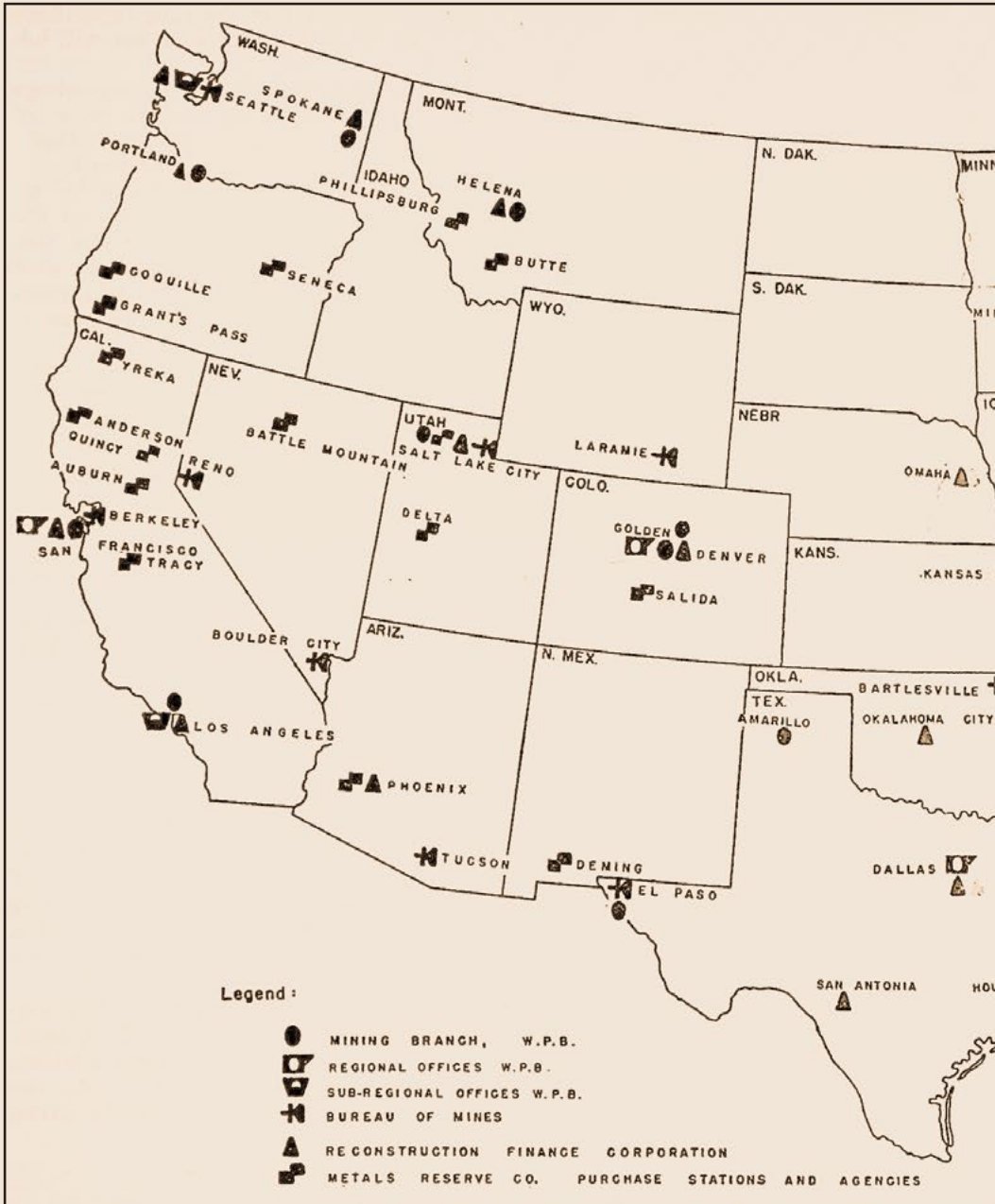


Critical Minerals in Subduction-related Magmatic-Hydrothermal Systems of the United States



Map to show location of War Production Board offices or buying depots and Reconstruction Finance Corporation offices.

Scientific Investigations Report 2023–5082

Cover. Western half of map of buying depots and offices of the War Production Board in 1942 (War Production Board, 1942), one of numerous agencies that controlled, by price guarantees, workforce assignments, and other forms of subsidization, domestic production of tungsten, manganese, antimony, and numerous other mineral commodities during the World War II and Cold War eras (1930s–1990s).

Critical Minerals in Subduction-related Magmatic-Hydrothermal Systems of the United States

By Peter Vikre, David John, Niki E. Wintzer, Fleetwood Koutz, Frederick Graybeal,
Chris Dail, and David C. Annis

Scientific Investigations Report 2023–5082

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

U.S. Geological Survey, Reston, Virginia: 2023

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Suggested citation:

Vikre, P., John, D., Wintzer, N.E., Koutz, F., Graybeal, F., Dail, C., and Annis, D.C., 2023, Critical minerals in subduction-related magmatic-hydrothermal systems of the United States: U.S. Geological Survey Scientific Investigations Report 2023–5082, 110 p., <https://doi.org/10.3133/sir20235082>.

ISSN 2328-0328 (online)

Acknowledgments

Numerous individuals provided information and insight on critical minerals in magmatic-hydrothermal, intrusion-related districts and deposits in Western States: Herb Duerr (Sunnyside, Arizona), Shaun Dykes (CuMo, Idaho), Bill Howald (Tonopah, Nevada), Buster Hunsaker and Mark Barton (McCullough Butte, Nevada), Hamish Martin (Resolution, Arizona), Eric Seedorff (copper-(molybdenum) deposits in Arizona), Ralph Stegen (Mo deposits), and Roger Steininger (Mo deposits). Drill hole analyses of the Pebble porphyry Cu-Mo deposit, Alaska, were provided by James Lang and Karen Kelley. Exploration and mining company websites and annual reports, 43-101 and technical reports, and archived records provided description of deposits and resources and, in some reports, quantification of critical minerals in them. Reviewers Jamie Brainard, Bob Seal, and Al Hofstra offered many relevant suggestions regarding content and presentation, most of which have been incorporated in some form.

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
Mass		
ounce, troy	31.10	gram (g)
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ton, short (2,000 lb)	0.9072	metric ton (t)
Concentration		
troy ounce per short ton	34.285	gram per metric ton (g/t)

International System of Units to U.S. customary units

Multiply	By	To obtain
Length		
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
Mass		
gram (g)	0.03527	ounce, avoirdupois (oz)
gram (g)	0.03215	ounce, troy
metric ton (t)	1.102	ton, short [2,000 lb]
metric ton (t)	0.9842	ton, long [2,240 lb]
Concentration		
gram per metric ton (g/t)	0.02917	troy ounce per short ton

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Abbreviations

Gt	billion metric tons
Gst	billion short tons
DDH	diamond drill hole
g/t	grams per metric ton
IS	intermediate sulfidation
Ma	mega-annum
Mt	million metric tons
Mst	million short tons
MRDS	Mineral Resources Data System
ppb	parts per billion
ppm	parts per million
PGE	platinum-group elements
REE	rare earth elements
RIRG	reduced intrusion-related gold
S-R-V	skarn-replacement-vein
opt	troy ounces per short ton
USBM	U.S. Bureau of Mines
USGS	U.S. Geological Survey
USMIN project	U.S. Mineral Deposit Database
wt %	weight percent

Chemical Symbols

Al	aluminum	Nb	niobium
Sb	antimony	Os	osmium
As	arsenic	O	oxygen
Ba	barium	Pd	palladium
Be	beryllium	P	phosphorus
Bi	bismuth	Pt	platinum
Cd	cadmium	K	potassium
Ca	calcium	Re	rhenium
C	carbon	Rh	rhodium
Ce	cerium	Rb	rubidium
Cs	cesium	Ru	ruthenium
Cr	chromium	Sc	scandium
Co	cobalt	Se	selenium
Cu	copper	Ag	silver
Ga	gallium	Na	sodium
Ge	germanium	Sr	strontium
Au	gold	S	sulfur
Hf	hafnium	Ta	tantalum
In	indium	Te	tellurium
Ir	iridium	Tl	thallium
Fe	iron	Th	thorium
Pb	lead	Sn	tin
La	lanthanum	Ti	titanium
Li	lithium	W	tungsten
Mg	magnesium	U	uranium
Mn	manganese	V	vanadium
Hg	mercury	Zn	zinc
Mo	molybdenum	Zr	zirconium
Ni	nickel		

Critical Minerals in Subduction-related Magmatic-Hydrothermal Systems of the United States

By Peter Vikre,¹ David John,¹ Niki E. Wintzer,¹ Fleetwood Koutz,² Frederick Graybeal,² Chris Dail,³ and David C. Annis⁴

Abstract

During the World War and Cold War eras (1910s–1990s), domestic consumption of numerous mineral commodities relied increasingly on imported supplies. Consumption reliance has since expanded to include 50 “critical minerals” (elements and mineral commodities) that are mostly to entirely imported and subject to curtailment by suppliers or supply chain disruption. New domestic supplies of critical minerals are being pursued by mining companies and by several federal departments and agencies. Information on domestic deposits and resources of critical minerals is being compiled by the U.S. Geological Survey Mineral Resources Program, which has organized investigations by mineral system, deposit type, and commodity.

Production, reserves, resources, and inventories of 21 critical minerals in domestic magmatic-hydrothermal deposits related to subduction-generated magmatism, and in tailings, slag, slimes, and electrolyte from copper concentrators, smelters, and refineries that processed some deposits, are largely restricted to Western States and Alaska. The critical mineral commodities Al, Sb, As, Bi, Co, fluorite, Ga, Ge, In, Mn, Ni, Nb, Pd, Pt, potash, Re, Ta, Te, Sn, W, and V are variably concentrated in porphyry/skarn copper-(molybdenum), skarn-replacement-vein (S-R-V) tungsten, polymetallic sulfide S-R-V intermediate sulfidation (IS), high-sulfidation gold-silver, low-sulfidation gold-silver, and lithocap alunite deposit types. These deposit types occur in porphyry copper-molybdenum-gold, alkalic porphyry, porphyry tin (granite related), and reduced intrusion-related mineral systems.

Production, reserves, and resources of Co, Ni, Nb, Pd, Pt, Ta, Sn, and V in subduction-related deposits in Western States are insignificant to small, mostly equivalent to months to a few years of recent annual domestic consumption (2016–2020). Significant inventories, equivalent to 2 or more years of consumption of aluminum, antimony, potash, and tungsten in unmined S-R-V tungsten, polymetallic sulfide S-R-V-IS, and

lithocap alunite deposits vary from approximately 2 to 8 years. Several decades of consumption of arsenic, bismuth, fluorite, gallium, germanium, and indium exist in some polymetallic sulfide S-R-V-IS and lithocap alunite deposit types.

Based on concentrations of critical minerals in reserves, resources, drill holes, and deposit domains (ore types), and in captive refinery records, the largest domestic inventories of Sb, As, Bi, Re, and Te, and possibly Ga, Ge, In, Sn, and W, are in porphyry copper-molybdenum (Cu-Mo) deposits in Alaska, Idaho, Utah, and Arizona, and in interim products of processing porphyry Cu-Mo deposit ores for recovery of copper and molybdenum. Concentrations of critical minerals in archival specimens and sample collections, although somewhat biased by collection and conservation decisions and categorization, are broadly proportionate to those in reserves, resources, and drill holes. These concentrations imply significant inventories of some critical minerals in deposits for which production, resources, and refinery records are unavailable or incomplete.

Because of the large masses of ores mined and processed annually (hundreds of millions of metric tons) and in reserves and resources (hundreds of millions of metric tons to billions of metric tons), calculated inventories of critical minerals in porphyry Cu-Mo deposits are equivalent to decades and centuries of recent consumption. However, these inventories should not be considered consumable supplies without reserve definition and development of economically viable mining plans and recovery techniques. An expeditious strategy for elimination or reduction of import reliance is recovery, and improved recovery efficiency, of Sb, As, Bi, Re, and Te, and possibly Ga, Ge, In, Ni, Sn, Ti, and W; during concentration and refining of copper and molybdenum minerals in ores of operating porphyry Cu-Mo mines; and in unmined porphyry Cu-Mo resources. These chalcophile, siderophile, and lithophile critical minerals, often undetectable in ore, are concentrated (hundreds of parts per million to percents) in slimes and electrolyte during copper electrorefining or could be recovered, in part, during sulfide concentration and smelting. Other than rhenium (recovered during molybdenum refining) and tellurium, all have been routinely discarded.

Subsidization (for example, commodity price guarantees, tax credits, recovery technology development), political initiative, and (or) sustained market favorability could support new production of critical mineral commodities

¹U.S. Geological Survey.

²Consultant.

³Perpetua Resources.

⁴U.S. Forest Service.

from subduction-related magmatic-hydrothermal deposits in Western States. In addition, insufficient domestic refining capacity could relegate the large inventories of critical minerals in porphyry Cu-Mo reserves and resources (for example, Pebble, Alaska; Resolution and Copper World [Rosemont], Arizona) to exportation in concentrates and importation insecurity, fortifying their present status.

Introduction

Critical minerals are mineral commodities “essential to the economic and national security of the United States” for which “the supply chain... is vulnerable to disruption” (Executive Office of the President, 2017; U.S. Department of Commerce, 2019). The term “critical minerals” refers to elements and minerals that are predominantly imported from various countries, some of which may discontinue exports to the United States because of political disputes or restricted availability of supplies. Presidential Executive Order No. 13817 (Executive Office of the President, 2017) and Secretarial Order No. 3359 (U.S. Department of the Interior, 2017) requested the U.S. Geological Survey (USGS) to determine possible domestic sources of critical minerals that could offset or eliminate import reliance. In 2018 a list of 35 critical minerals was released by the U.S. Department of the Interior (2018) (Fortier and others, 2018); 31 were designated import-reliant because imports provide more than 50 percent of annual domestic consumption. In 2021, zinc and nickel were added to the list, platinum group elements (PGE) and rare earth elements (REE) were individually listed, and several commodities were delisted (Nassar and Fortier, 2021), bringing the current list to 50 critical minerals. In response to the administration orders and first critical minerals list the USGS initiated and reorganized several projects, including the Earth Mineral Resources Initiative; the U.S. Mineral Deposit Database (USMIN) project; and the Systems Approach to Critical Minerals Inventory, Research, and Assessment project, to address domestic critical mineral supplies.

Domestic critical minerals covered in this report have been concentrated into deposits by magmatic and hydrothermal processes associated with plate subduction at convergent and transform plate margins of the Western United States. Subduction-related magmatism has been episodically active since the Early Triassic and is represented by granitic intrusions and volcanic fields in Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, and Washington. These igneous rocks mostly reflect partial melting of the mantle wedge by devolatilization of subducted oceanic crust and lesser pelagic sediments during convergent plate subduction. Basalt magmas generated by partial melting of mantle rocks intruded and partially melted lower and middle crust to form hybridized magmas. Hybridized magmas differentiated, buoyantly ascended, and erupted as andesites and felsic volcanic rocks or crystallized as granitic and porphyritic rocks in the upper crust. Production, resources, and inventories of metals and critical mineral commodities in the Western States were largely derived from, or occur in, deposits in granitic

and porphyritic intrusions, in sedimentary rocks adjacent to intrusions, and in volcanic fields thought to overlie intrusions. Most deposits formed during the Late Cretaceous and Cenozoic. Those in westernmost States formed near the subduction zone during high-angle subduction and slab rollback whereas deposits in the Rocky Mountains States (Colorado, Montana, Wyoming, New Mexico, and parts of Utah) are thought to have formed when oceanic crust was subducted at low angles, thereby heating, and melting by devolatilization lithospheric mantle and lower crust hundreds of kilometers east of the subduction zone. This “flat slab” magmatism generally did not extend further east than the longitude of the Colorado Front Range, thus limiting critical minerals covered in this report to Western States (fig. 1; tables 1, 2).

Other smaller volume magmatism indirectly linked to plate tectonism includes partial melting of (1) lower crust rocks in the central and eastern Great Basin thickened by contraction and in part heated by oceanic crust during flat-slab subduction, (2) depressurized mantle in slab windows of the southern Cascades magmatic arc that were created by late Cenozoic impingement of the Pacific spreading center on the long-lived convergent subduction zone, and (3) depressurized mantle beneath crust in the Great Basin thinned by extension during the late Cenozoic. The small to moderately sized magmatic-hydrothermal deposits (less than 1 to several million metric tons [Mt]) formed during partial melting of tectonically thickened crust contain small masses of critical minerals. None of the deposits in the mostly small-volume volcanic fields of andesite, dacite, and rhyolite, and lesser basalt that represent magmatism of slab windows and extension younger than 17 mega-annum (Ma) contains appreciable quantities of critical minerals relative to recent domestic consumption.

Known and suspected subduction-related magmatic-hydrothermal deposits that contain critical minerals can be classified under four mineral systems and seven deposit types distinguished largely by characteristics of associated igneous rocks, hydrothermal mineral associations, and proportions of mineral commodities (table 1; Hofstra and Kreiner, 2020). Mineral systems evaluated in this report include porphyry copper-molybdenum-gold (Cu-Mo-Au), alkalic porphyry, porphyry tin (granite related), and reduced intrusion-related. Within these mineral systems deposit types represented include porphyry/skarn copper-gold (Cu-Au), skarn-replacement-vein (S-R-V) tungsten, polymetallic sulfide S-R-V intermediate sulfidation (IS), high-sulfidation gold-silver, low-sulfidation gold-silver, and lithocap alunite (aluminum, potash). Assignment of some deposits containing critical minerals to mineral systems and deposit types is problematic because of incomplete descriptions of deposits, especially small deposits, no known spatial or temporal association of deposits with subduction-related igneous rocks, and (or) deposit characteristics that do not easily fit the classification scheme but contain mineral commodities thought to have been concentrated by subduction-related magmatism. Some deposits containing critical minerals are therefore described in the “Unclassified Magmatic-Hydrothermal Deposits” sections.

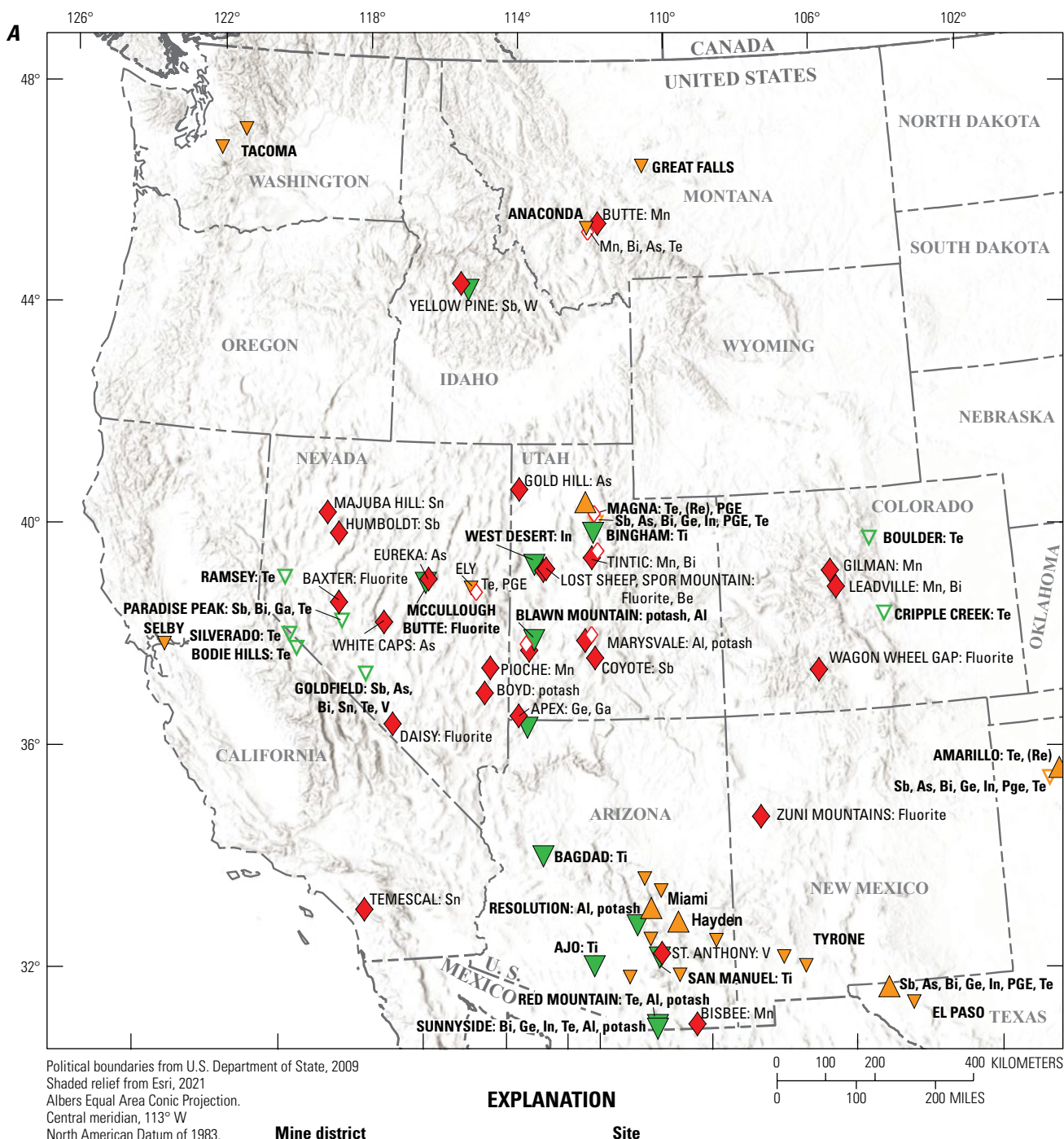
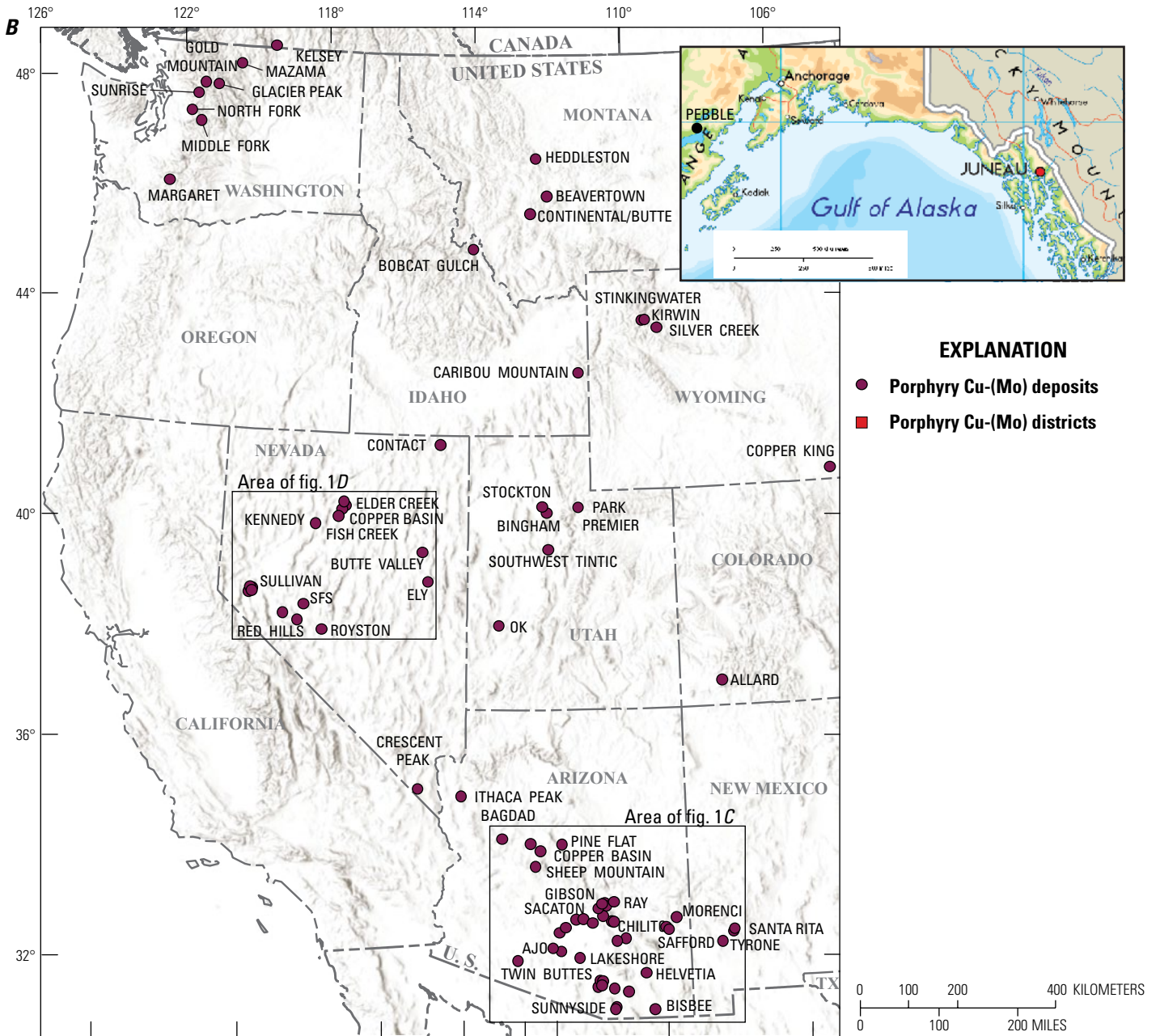


Figure 1. Maps showing locations of deposits and resources of critical minerals in Western States. A, Production (primary product; byproduct), reserves, and resources (including unmined deposits; mine, mill, and copper refinery interim products) of Sb, As, Bi, fluorite, Ga, Ge, In, Mn, potash, Te, Sn, Ti, and V in Western States (table 1). B, Porphyry copper-(molybdenum) (Cu-(Mo)) deposits in Western States. C, Porphyry Cu-Mo deposits and districts in Arizona and New Mexico. D, Porphyry Cu-Mo deposits and districts in Nevada. E, Tungsten deposits and resources in Western States and Alaska described in text and tabulated (open black diamonds; table 2).

4 Critical Minerals in Subduction-related Magmatic-Hydrothermal Systems of the United States



Political boundaries from U.S. Department of State, 2009
 Shaded relief from Esri, 2021; Albers Equal Area Conic Projection.
 Central meridian, 113° W; North American Datum of 1983.

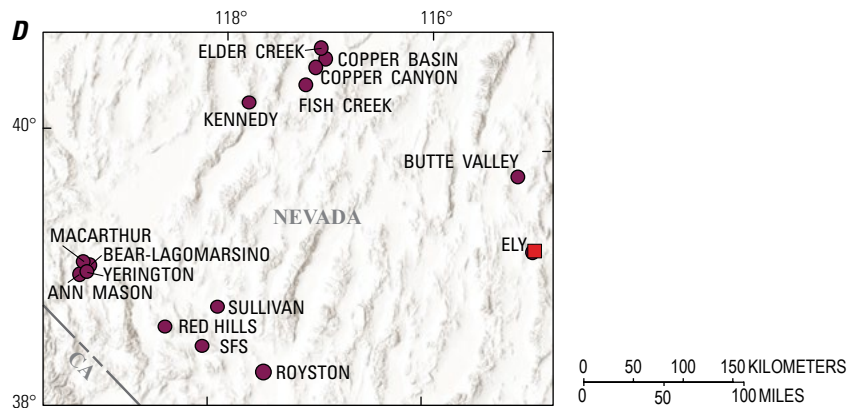
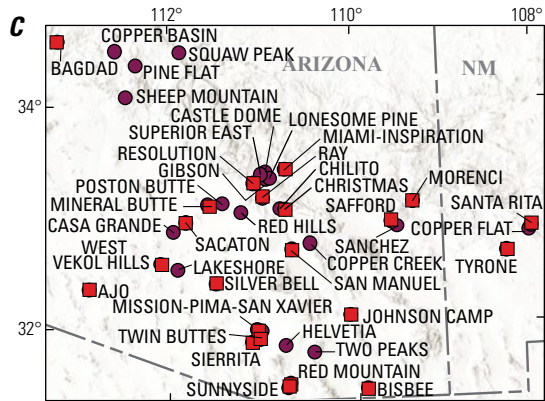


Figure 1.—Continued



Figure 1.—Continued

Porphyry Cu-Mo-Au mineral systems consist of numerous deposit types including Cu-Mo-Au deposits in intrusions (often porphyritic and mostly calc-alkaline) and polymetallic sulfide S-R-V deposits and lithocap alunite deposits in adjacent and overlying sedimentary and volcanic rocks; some include high- and intermediate-sulfidation deposits (Hofstra and Kreiner, 2020). Porphyry Cu-Mo-Au

systems occur within Phanerozoic magmatic arcs adjacent to subduction zones, and supply more than one-half of copper consumed annually worldwide. Critical minerals in porphyry Cu-Mo-Au systems in the Western United States include Al, Sb, As, Bi, Ga, Ge, In, Mn, Ni (designated a critical mineral in 2021), potash (KCl, K₂SO₄ salts; a critical mineral prior to 2021), Re (a critical mineral prior to 2021), Te, Ti, W,

Table 1. Production of critical minerals in districts and deposits of Western States that are related to subduction magmatism, and possible resources of critical minerals where quantified, semi-quantified, or quantifiable.

[Deposits and districts with production of critical minerals as primary products and coproducts are described in Section A; those with byproduct production are described in Section B. Possible significant resources of critical minerals are described in Section C. Assignment of primary products, coproducts, and byproducts in many districts and deposits is uncertain. Mineral systems and deposit types from Hofstra and Kreiner (2020). S-R-V, skarn-replacement-vein; IS, intermediate sulfidation; Cu-Mo-Au, copper-molybdenum-gold; PGE, platinum-group elements; REE, rare earth elements.]

Deposit type	Primary commodities; critical minerals	Production of critical minerals in Western States		Possible significant resources of critical minerals in Western States	
		Primary product, coproduct (chap. A)	Byproduct (chap. B) ¹	Primary product, coproduct (chap. C)	Byproduct (chap. C)
S-R-V tungsten	W, Mo, Cu; <i>W</i>	W: Pine Creek, Calif.	Mo, Cu	W: Andrew Curtis, Calif.	--
		W: Springer/ Nevada Massachusetts, Nev.	--	W: Centennial, Nev.	Au, Ag, Cu
		W: Atolia, Calif	--	W: Sunrise, Wash.	Cu, Mo
		W: Browns Lake, Mont.	--	W: Pilot Mountain, Nev.	Cu, Ag, Zn
Porphyry/skarn copper	Cu, Au, Ag, Mo; PGE, Te, Re, Co, Bi, U	--	--	W: Indian Springs, Nev.	--
		--	Te, PGE: Cu refineries and offsite	Cu refinery, Magna, Utah	Sb, As, Bi, Ge, In, Ni, PGE, Te: Cu refinery slimes ^{2,3}
		--	PGE: Ely, Nev.	Cu refinery, El Paso, Tex.	Sb, As, Bi, Ge, In, Ni, PGE, Te: Cu refinery slimes ^{2,3}
		--	PGE, Te: Bingham, Utah	Cu refinery, Amarillo, Tex.	Sb, As, Bi, Ge, In, Ni, PGE, Te: Cu refinery slimes ^{2,3}
		--	Te: Butte, Mont.	--	In: West Desert, Utah
		--	Te: Amarillo, Tex.	--	Te: Red Mountain, Ariz. ⁴
		--	--	--	Bi, Ge, In, Te: Sunnyside, Ariz. ⁴
		--	--	--	Re, PGE: Pebble, Alaska ⁴
		--	--	--	Ti (rutile): Bingham, Utah
		--	--	--	Ti (rutile): Ajo, San Manuel, Bagdad, Ariz.
Porphyry/skarn copper	Cu, Au, Ag, Mo; PGE, Te, Re, Co, Bi, U	--	--	W: CuMo, Idaho	W: Margerie Glacier, Alaska
		--	Re: Mo refineries	--	--
		--	Re: Bingham, Butte, Sierrita, Morenci, Bagdad, Santa Rita, others	--	Re: Bingham, Butte, Sierrita, Morenci, Bagdad, Santa Rita. Other: Mo refineries
		--	--	--	--

Table 1. Production of critical minerals in districts and deposits of Western States that are related to subduction magmatism, and possible resources of critical minerals where quantified, semi-quantified, or quantifiable.—Continued

[Deposits and districts with production of critical minerals as primary products and coproducts are described in Section A, those with byproduct production are described in Section B. Possible significant resources of critical minerals are described in Section C. Assignment of primary products, coproducts, and byproducts in many districts and deposits is uncertain. Mineral systems and deposit types from Hofstra and Kreiner (2020). S-R-V, skarn-replacement-vein; IS, intermediate sulfidation; Cu-Mo-Au, copper-molybdenum-gold; PGE, platinum-group elements; REE, rare earth elements.]

Deposit type	Primary commodities; critical minerals	Production of critical minerals in Western States		Possible significant resources of critical minerals in Western States	
		Primary product, coproduct (chap. A)	Byproduct (chap. B) ¹	Primary product, coproduct (chap. C)	Byproduct (chap. C)
Porphyry Cu-Mo-Au mineral systems—Continued					
Polymetallic sulfide S-R-V-IS	Cu, Zn, Cd, Pb, Ag, Au; <i>Mn, Ge, Ga, In, Bi, Sb, As, W, Te</i>	V: St. Anthony mine, Mammoth, Ariz. Bi: Leadville, Colo.	Mn, Bi, As, Te: Butte, Mont. Bi, Mn, Sb: Tintic, Utah Bi: Big, Little Cottonwood districts, Utah Bi?: Victoria, Nev. W, As: Gold Hill, Utah As: Eureka, Nev. (speiss) As: Battle Mountain district, Nev.	--	Mn: Hardshell-Alta-Hermosa, Ariz. -- -- -- -- -- --
High-sulfidation gold-silver	Au, Ag, Cu; <i>As, Sb, Te, Bi, Sn, Ga</i>	--	Bi, Mn: Leadville, Colo. Mn: Gilman, Colo. Mn: Pioche-Bristol-Jackrabbit, Nev. Mn: Bisbee, Ariz.	--	Sb, As, Bi, Sn, Te, V: Goldfield, Nev. Bi, Ga, Sb: Paradise Peak, Nev. Sb, As, Bi, Te: Nevada-California districts
Lithoep alunite	Al, K ₂ SO ₄ ; <i>Al, K₂SO₄, Ga</i>	Al, potash: Blawn Mountain, Utah Al, potash: Marysvale, Utah	--	Al, potash: Red Mountain, Ariz. Al, potash: Sunnyside, Ariz. Al, potash: Resolution, Ariz. Al, potash: numerous deposits, Wash.	-- -- -- --

Table 1. Production of critical minerals in districts and deposits of Western States that are related to subduction magmatism, and possible resources of critical minerals where quantified, semi-quantified, or quantifiable.—Continued

[Deposits and districts with production of critical minerals as primary products and coproducts are described in Section A, those with byproduct production are described in Section B. Possible significant resources of critical minerals are described in Section C. Assignment of primary products, coproducts, and byproducts in many districts and deposits is uncertain. Mineral systems and deposit types from Hofstra and Kreiner (2020). S-R-V, skarn-replacement-vein; IS, intermediate sulfidation; Cu-Mo-Au, copper-molybdenum-gold; PGE, platinum-group elements; REE, rare earth elements.]

Deposit type	Primary commodities; critical minerals	Production of critical minerals in Western States		Possible significant resources of critical minerals in Western States	
		Primary product, coproduct (chap. A)	Byproduct (chap. B) ¹	Primary product, coproduct (chap. C)	Byproduct (chap. C)
Polymetallic sulfide S-R-V-IS	Au, Ag, Pb, Zn, Cu; <i>Ge, Ga, In, Bi, Te</i>	--	--	--	Te: Cripple Creek, Colo. Te: Boulder district, Colo.
Alkalic porphyry mineral systems					
Porphyry/skarn Polymetallic sulfide S-R-V-IS	Sn, W, Be; <i>Sn, W, Be, Fluorite</i> Cu, Zn, Pb, Ag, Au; <i>Sn, Mn, Ge, Ga, In, Bi, Sb, As</i>	Cu, Sn: Majuba Hill, Nev.	--	--	--
Porphyry tin (granite-related) mineral systems					
	--	Sn: Taylor Creek, N. Mex.	--	Sn: Taylor Creek, N. Mex.	--

Table 1. Production of critical minerals in districts and deposits of Western States that are related to subduction magmatism, and possible resources of critical minerals where quantified, semi-quantified, or quantifiable.—Continued

[Deposits and districts with production of critical minerals as primary products and coproducts are described in Section A, those with byproduct production are described in Section B. Possible significant resources of critical minerals are described in Section C. Assignment of primary products, coproducts, and byproducts in many districts and deposits is uncertain. Mineral systems and deposit types from Hofstra and Kreiner (2020). S-R-V, skarn-replacement-vein; IS, intermediate sulfidation; Cu-Mo-Au, copper-molybdenum-gold; PGE, platinum-group elements; REE, rare earth elements.]

Deposit type	Primary commodities; <i>critical minerals</i>	Production of critical minerals in Western States		Possible significant resources of critical minerals in Western States	
		Primary product, coproduct (chap. A)	Byproduct (chap. B) ¹	Primary product, coproduct (chap. C)	Byproduct (chap. C)
Polymetallic, monometallic veins	--	Sb: Yellow Pine, Idaho	--	Sb: Yellow Pine, Idaho	As, Bi, W: Yellow Pine, Idaho ⁴
		Sb: numerous districts, Nev.	--	--	--
		Sb: Coyote district, Utah	--	Sb: Coyote district, Utah	--
		Sb, As: White Caps, Nev.	--	--	--
		Be, fluorite: Spor Mountain, Utah	--	--	REE, Spor Mountain, Utah
		Ge, Ga: Apex mine, Utah	--	Ge, Ga: Apex mine, Utah	--
		--	--	Ge, Ga: Apex mine, Utah	--
		Fluorite: Daisy mine, Nev.	--	Ge: Cordero/ McDermitt, Nev.	--
		Fluorite: Baxter mine, Nev.	--	--	--
		Fluorite: Zuni Mountains, N. Mex.	--	--	--
		Fluorite: Lost Sheep mine, Utah	--	--	--
		Fluorite: Wagon Wheel Gap mine, Colo.	--	--	--
		--	--	Fluorite: McCullough Butte, Nev.	--
	--	--	--	Ti, Zr, Sn, White Mountains, Calif.	

¹Mining and (or) recovery enabled in part by subsidization, usually commodity price guarantees.

²Includes mine waste (dumps, tailings, slag) and copper refinery slimes.

³Calculated.

⁴Inventory based on drill holes.

10 Critical Minerals in Subduction-related Magmatic-Hydrothermal Systems of the United States

Table 2. Characteristics of the largest tungsten deposits and resources in Western States.

[Latitude and longitude in decimal degrees north and west. S-R-V, skarn-replacement-vein; t, metric ton, Mt, million metric tons; Mst, million short tons; opt, troy ounces per short ton; ft, feet; USGS, U.S. Geological Survey.]

Deposit name	Alternate name	State	Latitude	Longitude	Owner	Production	Resource/reserve estimate
Andrew Curtis	Andrew Curtis Mine, Andrew Group, Alron #1, Alron #2, Tiffany-Andrew Group, 4 Hi #1, Curtis Claims, Cattle Canyon Placers	Calif.	34.258	117.685	Curtis Tungsten, Inc.	7.55 t WO ₃ concentrate (21–50%) from 1974 to 1982	Reserves: 6,000 t W measured; 17,000 t W indicated; 216,000 t W inferred (Unruh and Graber, 1982)
Pilot Mountain	Desert Scheelite, Aurora district	Nev.	38.379	117.871	Thor Mining PLC	Nominal; “R.C. Armstrong shipped tungsten ore from the Desert Scheelite mine to a custom mill” (Maurer and Wallace, 1956).	18,600 t W indicated, 8,600 t W inferred (Thor Mining PLC, 2018a, b).
Centennial	Mount Hamilton mine, Northeast Seligman mine, Treasure Hill mine	Nev.	39.247	115.558	Mount Hamilton Mining Company	1997, 7.72 Mst at 0.035 opt Au	Reserve: 18,200 t W from a pre-1978 non-43-101 compliant source and unverified data (SRK Consulting, 2009a).
Indian Springs	Gambel Ranch or Ludwig Tunnel	Nev.	41.622	114.251	Utah International, Inc.; Azl Resources Inc.; and Norman Ludwig	Past producer	Resource: 10,900 t W indicated, 9,900 t W inferred (Moran and Stryhas, 2007)
Browns Lake	Ivanhoe, Lost Creek, Lentung, Red Button mine	Mont.	45.521	112.836	American Alloy Metals, Inc and Garrand Corp.	From 1953 to 1958, 567,477 short tons at 0.35 percent WO ₃ ; 1953–58, 19,200 short tons at 0.18 percent WO ₃ (Werner and others, 2014)	14,400 t contained W (Werner and others, 2014)

Table 2. Characteristics of the largest tungsten deposits and resources in Western States.—Continued

[Latitude and longitude in decimal degrees north and west. S-R-V, skarn-replacement-vein; t, metric ton, Mt, million metric tons; Mst, million short tons; opt, troy ounces per short ton; ft, feet; USGS, U.S. Geological Survey.]

Basis of resource/reserve estimate	Deposit type	Ore minerals present	Elements in deposit	CM in resource	CM domestic consumption threshold (2019)	CM inventory besides W (metric tons)	References
“Extensive mapping, sampling and mill recovery tests” (Unruh and Graber, 1982)	W skarn (S-R-V; scheelite concentrated in shear zones)	Scheelite, barite	W, Ba	W, Ba	>2 years at 27,600 t W	No Ba inventory available	Evans and others (1977); Raney (1982); Unruh and Graber (1982); USGS (2010a); Carroll and others (2018)
Drillcore, historic and recent	W skarn (S-R-V)	Scheelite, chalcopyrite, azurite	W, Cu, Ag, An, Au	W	>1 year at 13,800 t W	None	Maurer and Wallace (1956); Cowie (1985); Stager and Tingley (1988); Carroll and others (2018); Thor Mining PLC (2018a, b)
Drill core	W skarn (S-R-V)	Scheelite; chalcopyrite; free gold; sphalerite; galena; pyrite; covellite; bornite; chalcopyrite; bournonite; jamesonite	Cu, Mo, W, Au, Ag, and Sb	W, Sb	>2 years at 27,600 t W but uncertain reliability of resource estimates	No Sb inventory available; Sb classified as a tertiary commodity	USGS (2007); Moran and others (2009); SRK Consulting (2009a, 2012, 2014); Carroll and others (2018)
Drill core	W skarn (S-R-V)	Scheelite, powellite, molybdenite, tetrahedrite, chalcopyrite,	W, Mo, Cu	W	>1 year at 13,800 t W	None	Slack (1972); Moran and Stryhas (2007); USGS (2010b); Carroll and others (2018)
Unspecified	W skarn (S-R-V)	Chalcopyrite, powellite, scheelite, bornite, covellite, malachite, pyrrhotite	W, Cu, Mo	W	>1 year at 13,800 t W	None	USGS (1992); Werner and others (2014); Carroll and others (2018)

12 Critical Minerals in Subduction-related Magmatic-Hydrothermal Systems of the United States

Table 2. Characteristics of the largest tungsten deposits and resources in Western States.—Continued

[Latitude and longitude in decimal degrees north and west. S-R-V, skarn-replacement-vein; t, metric ton, Mt, million metric tons; Mst, million short tons; opt, troy ounces per short ton; ft, feet; USGS, U.S. Geological Survey.]

Deposit name	Alternate name	State	Latitude	Longitude	Owner	Production	Resource/reserve estimate
Pine Creek	Black Monster, Snow Queen, Union Carbide mine	Calif.	37.362	118.704	Pine Creek Tungsten Mining Llc, Avocet Ventures Inc., and U.S. Tungsten Corp. as of 1995	>10,000 short tons; mine closed in 1986 (Werner and others, 2014)	Resource: 10,000 t W (Werner and others, 2014);
Springer	Stank Hill, Mill City, Nevada Massachusetts	Nev.	40.782	118.133	Americas Bullion Royalty Corp.	~10,800 t	1,400 t W indicated and 6,900 t W inferred (McCandlish and Odell, 2012; SRK Consulting, 2009b)
Atolia	--	Calif.	35.315	117.609	--	~828,339 units WO ₃ (6,568 t W); 94% from veins and 6% from placers; ~54% of total production came from Union mine (developed to depth of 1,021 ft)	“a few thousand tons of 2% ore is in sight in the veins;” mill tailings were being retreated in 1940. Placer deposits contain an estimated 280,000 units WO ₃ (2,200 t W) and small but unquantified amounts of Au.
Margerie Glacier	Leo Mark Anthony, Moneta Porcupine mines, Tarr Inlet	Alaska	59.025	137.091	National Wilderness	None	Resource: 14,500 t W inferred (Brew and others, 1978)
CuMo	CuMo; CuMo Project	Idaho	44.034	115.783	American CuMo Mining Corporation; Mosquito Consolidated Gold Mines Ltd as of 2010; Amax Exploration, Inc. as of 1974 also listed in MRDS	None	Resource: 72,000 t W indicated; 42,000 t W inferred (Jones and others, 2011b)
Sunrise	Brenmac	Wash.	48.008	121.5045	1952: W.E. Oldfield; 1976: Ren Mac Mines, Ltd.	None	31,730 t W in 64.5 Mt grading 0.319% Cu, 0.071% Mo, 0.062% W, 0.002 opt Au, 0.049-0.088 opt Ag

Table 2. Characteristics of the largest tungsten deposits and resources in Western States.—Continued

[Latitude and longitude in decimal degrees north and west. S-R-V, skarn-replacement-vein; t, metric ton, Mt, million metric tons; Mst, million short tons; opt, troy ounces per short ton; ft, feet; USGS, U.S. Geological Survey.]

Basis of resource/reserve estimate	Deposit type	Ore minerals present	Elements in deposit	CM in resource	CM domestic consumption threshold (2019)	CM inventory besides W (metric tons)	References
Drill core	W skarn (S-R-V)	Scheelite, bornite, chalcocite, chalcopyrite, covellite, molybdenite, powellite	W, Cu, Au, Mo, Ag	W	>1 year at 13,800 t W	None	Newberry (1982); USGS (1996); Kurtak (1998); Werner and others (2014); Carroll and others (2018)
Drill core	W skarn (S-R-V)	Scheelite, molybdenite, chalcopyrite, sphalerite	W, Mo, Cu	W	<1 year at 13,800 t W	None	Johnson (1977); McCandlish and Odell (2012); Americas Bullion Royalty Corp (2014); Carroll and others (2018)
Geologic estimation	W vein and W-Au placer	Scheelite	W, Au	W	<1 year at 13,800 t W	None	Lemmon and Dorr (1940); U.S. Bureau of Mines (1943)
Unspecified	Porphyry Cu	Chalcopyrite, pyrrhotite, powellite, scheelite, molybdenite, arsenopyrite, sphalerite	Cu, W, Mo, Ag, Au	W	>1 year at 13,800 t W	None	Brew and others (1978); USGS (1988); Carroll and others (2018)
Diamond drilling	Porphyry Cu+Mo	Molybdenite, chalcopyrite, and scheelite, perhaps microscopic gallite (Cu-GaS ₂)	Cu, Mo, Ag, W, Re, Ga, Pb, and Zn	W, Re, Ga	>2 years at 27,600 t W	Re has reported concentrations from 0.01 to 0.03 ppm in drill core intervals	USGS (2009); Jones and others (2011a, b); Giroux and others (2015); Carroll and others (2018); Hilscher and Dykes (2018)
Drill core and underground workings	W-Cu-Mo breccia	Scheelite, chalcopyrite, molybdenite	W, Cu, Mo, Au, Ag	W; Bi, Re in concentrate	>2 years of recent domestic consumption	none	Derkey and others (1990); Lasmanis (1995); USGS (1997)

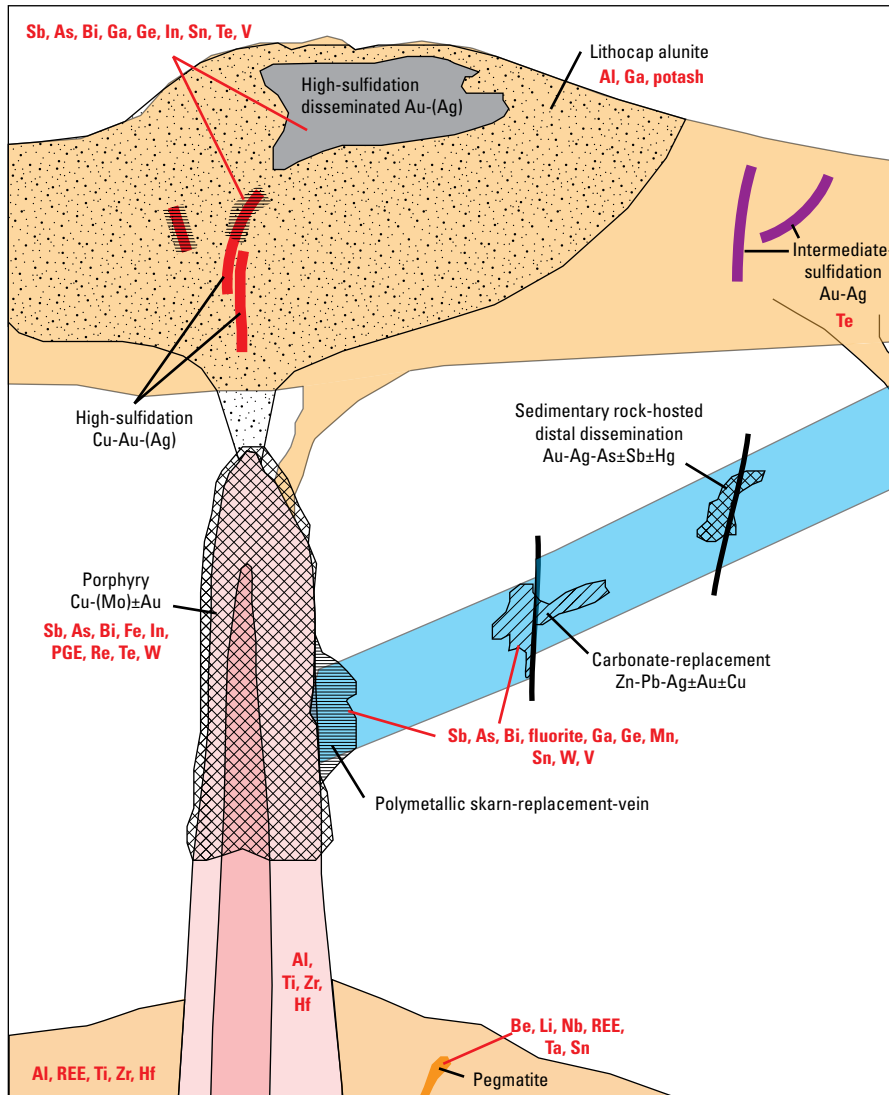


Figure 2. Schematic diagram showing spatial relationships of deposit types (black labels) broadly associated with, in part, porphyry copper-molybdenum-gold (Cu-Mo-Au) mineral systems and critical minerals that have been produced or occur in reserves and resources (red labels). PGE, platinum-group elements; REE, rare earth elements.

and Zn (designated a critical mineral in 2021) that occur in several deposit types. Critical minerals in other deposit types associated subduction-related magmatism include Al, Sb, Be, Bi, fluorite (CaF_2), Li, potash, Ta, Te and Sn in polymetallic sulfide S-R-V-IS deposits, high-sulfidation gold-silver deposits, low-sulfidation gold-silver deposits, lithocap alunite deposits, and in deposits with unclear association with subduction-related magmatism (fig. 2).

Alkalic porphyry mineral systems include Cu-Mo-Au deposits and other deposit types that form in alkalic intrusions, in adjacent sedimentary and volcanic rocks, and in veins in intrusions and in adjacent rocks; they also occur within Phanerozoic magmatic arcs and continental rifts. Deposit types of this system in Western States include low-sulfidation gold deposits that are mined for gold and silver and enriched in tellurium, bismuth, and vanadium and fluor spar deposits (table 1).

Porphyry tin (granite-related) mineral systems include deposits that contain the critical minerals beryllium, lithium, niobium, tin, and tantalum. These deposits occur in or near granitic rocks and in pegmatites that reflect partial melting

of continental crust to form peraluminous magmas. Deposit types represented in Western States are mostly Precambrian pegmatite deposits that have been mined for beryllium, lithium, niobium, REE, tantalum, and tin (table 1). They are not clearly related to subduction magmatism, contain minor amounts of critical minerals relative to recent domestic consumption, and are not covered in this report.

Reduced intrusion-related mineral systems form in continental magmatic arcs in and adjacent to intrusions that assimilated sedimentary strata containing hydrocarbons and pyrite. Deposit types include gold, skarn copper-molybdenum-tungsten (Cu-Mo-W), polymetallic sulfide S-R-V-IS, disseminated gold-silver, intermediate sulfidation, and graphite. In Western States, few unequivocal reduced intrusion-related deposits are known; several have been mined and explored for gold and lesser silver. Critical mineral concentrations and forms in them are largely unquantified.

The 35 critical minerals initially listed by the Department of the Interior, and the recent additions zinc and nickel, are mineral commodities that are produced and marketed as elements (for example, Al, In, Ni, Te, and Zn), compounds

and alloys (for example, GaAs, $\text{Si}_{1-x}\text{Ge}_x$, SbPb, InSb, WC, FeV, and FeMn), oxides and carbonates (for example, SbO_3 , GeO_2 , Li_2CO_3 , and WO_3), and minerals (for example, barite, fluorite, and potash). Critical minerals in Western States that have been produced as primary products, coproducts, and byproducts, and that are known to occur in elevated concentrations in unmined deposits, in interim products of copper concentrators, smelters, and refineries (tailings, slags, slimes, and electrolyte), and in mine dumps, include Al, Sb, As, Be, Bi, fluorite, Ga, Ge, In, Li, Mn, Ni, Nb, Pd, Pt, potash, Re, Ta, Te, Sn, W, V, and Zn.

Descriptions of deposits and resources of the former critical mineral commodities potash and rhenium were completed prior to their delisting and are retained in this report. More recently listed zinc is not covered because of the anticipated time required for evaluation of the large amount of information available. Nickel occurrences in Western States are uncommon, insignificant relative to consumption, and (although in part related to subduction) not related to subduction magmatism. However, nickel in interim products of processing streams of porphyry Cu-Mo-Au ores is potentially recoverable in significant quantities and is correspondingly included where processing information is available.

Elevated concentrations of Al, Sb, As, Bi, Be, Ga, Ge, Mn, potash, and W in some deposits in Western States enabled their production as primary products and coproducts, although most production was small relative to domestic consumption, short lived, and subsidized. Deposits in which critical minerals are primary products are often not distinguishable from coproduct critical minerals because invariably there is insufficient published information to separate them, fluctuating commodity prices can change the relative values of commodities in ore and redefine ore tonnages and grades, and some production was subsidized by guaranteed prices and other federal government policies (for example, War Production Board, 1942; cover image). As used herein, a primary product is a mineral commodity that is essential to the economic viability of a mine (profitability), the basis for exploration, development, and sustained production. A coproduct is one or more mineral commodities produced with other mineral commodities because their combined value is essential for profitable mining. A byproduct is a mineral commodity that is recovered because it adds production value but is not essential to mine profitability.

Production of the primary commodities Cu, Mo, Pb, Zn, Au, and Ag in Western States enabled recovery of most critical minerals, including Sb, As, Bi, Mn, Nb, Pd, Pt, Re, Ta, Te, Sn, W, and V, mostly as byproducts, and in a few deposits as coproducts and primary products. However, many critical minerals in mined deposits occur in low concentrations and small quantities and were never recovered because of unprofitability, and in some cases, no world markets. The porphyry copper-molybdenum (Cu-Mo) deposits in Arizona, New Mexico, Utah, Montana, and Nevada contain small concentrations of critical minerals in ores; however, processing of large tonnages of ore annually for copper and molybdenum recovery concentrates some chalcophile and

siderophile critical minerals (Sb, As, Ge, In, Ni, Re, and Te), several of which are episodically recovered and marketed (Re and Te). Unmined porphyry Cu-Mo resources in Alaska, Idaho, and Arizona similarly contain large inventories of these and other chalcophile and lithophile critical minerals (for example, Al, Ti, and Zr) that theoretically could be recovered during ore processing for copper and molybdenum recovery.

In this report, deposits containing critical minerals are grouped by mined deposits in which critical minerals were primary products and coproducts (chap. A) and byproducts (chap. B), by unmined deposits and interim products of copper production with large critical mineral inventories relative to recent domestic consumption (chap. C), and by deposits with elevated concentrations of critical minerals (greater than crustal abundances) in archival specimens and collection samples (chap. D). Within each chapter, deposits, unmined resources, interim products, and specimens and samples are organized by mineral system and deposit type.

With the exception of the Pebble porphyry Cu-Mo and Margerie Glacier tungsten deposits in Alaska, all critical mineral occurrences described in this report are in conterminous Western States. Locations and descriptions of deposits and resources in Alaska that contain critical minerals are available at the USMIN web site (<https://mrdata.usgs.gov/deposit/>). Deposits and resources containing the critical minerals Be, Li, Nb, PGE, REE, Sn, and Ta as primary products and coproducts, although mostly related to intrusions (for example, Elk Creek niobium, Nebraska; Mountain Pass REE, Calif.; Round Top REE, Tex.; Stillwater Mountains PGE, Mont.; Be-Li-Nb-Sn-Ta pegmatites, N. Mex. and S. Dak.) (USGS and others, 1965, 1975; Bellora and others, 2019; Karl and others, 2021), include deposits in Midwestern States that are not clearly subduction-related and therefore not described below.

This report (1) provides a historical perspective of critical minerals produced from subduction-related magmatic-hydrothermal systems in the Western United States, (2) describes significant inventories of critical minerals in unmined deposits and mine reserves, and (3) tracks critical minerals in interim products of copper refineries where they comprise significant inventories but mostly are not recovered. The report is intended to inform policy makers of the approximate masses of domestic critical minerals that conceivably could become supplies for consumption if economic incentives for their mining and recovery are enabled.

Brief History of Critical Minerals

The concept of critical minerals arose in the early 20th century with the expanded application of alloys and compounds of C, Cr, Fe, Mn, Ni, and W that greatly improved metal durability, machining efficacy, and armament effectiveness (Lovering, 1944; Andrews, 1955; Limbaugh, 2006, 2010; Schmidt, 2012). These ferroalloys and compounds became essential to national defense and industrial competitiveness. Their components, variously

termed critical or strategic minerals, faced supply uncertainty because domestic production since World War I has been insufficient for consumption. Concerns over importation security of tungsten and other commodities crucial for machining and armaments escalated in the 1930s and during World War II. Price guarantees (for example, Sb, As, Mn, and W) (War Production Board, 1942; cover image) and other forms of subsidization by the federal government increased domestic production prior to and during World War II and the Korean War; they were episodically extended into the 1960s through much of the Cold War era. However, peak tungsten production, for example, from domestic mines never exceeded 50 percent of required World War II supplies (approximately equivalent to consumption) (fig. 3; Morgan, 1983); then, as now, importation with trade route protection, as required, secured necessary imports.

Domestic critical mineral deposits, reserves, resources, and inventories described in this report attest to small low-grade deposits and resources of tungsten and other critical minerals, non-recovery of critical minerals at operating and shuttered or demolished refineries, and disincentives to explore for and produce critical minerals in the United States. Many of the largest and highest-grade domestic metal deposits were discovered and mined in the 19th and 20th

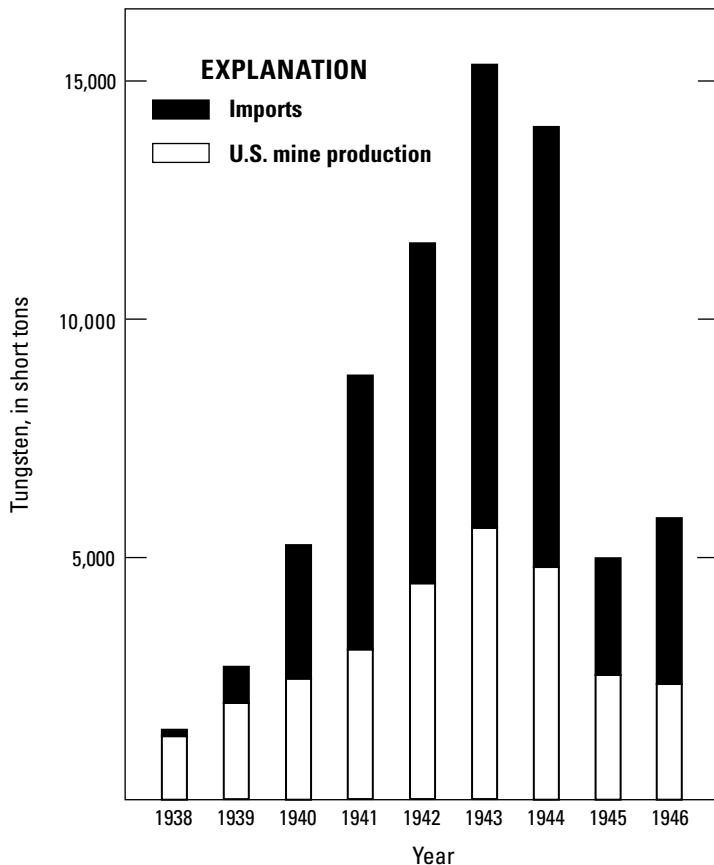


Figure 3. Bar chart of domestic tungsten supplies during World War II and pre- and post-war years derived from U.S. mines and imports (Morgan, 1983).

centuries when there were no or small world markets for commodities subsequently deemed critical or strategic minerals. Comprehensive descriptions of these major deposits and districts (for example, Ridge, 1968) seldom include critical mineral commodities because they had no bearing on production economics and there was no to small demand for many. Imported supplies were generally deemed secure until the vulnerability of oceanic shipping was revealed by World Wars I and II.

Before, during, and after World War II and during the Cold War era, numerous investigations of domestic sources of critical mineral commodities were conducted by the U.S. Bureau of Mines (USBM) and USGS to address wartime shortages and importation vulnerability (USBM, 1941a; Moon, 1950; Foster, 1988). Several “underground stockpiles” of unmined, marginal “ore” were blocked out (measured, indicated, and inferred reserves) by drill holes, surface excavations, underground development, and metallurgical test work. These marginal ores were assumed recoverable, if needed, whereas price guarantees were used to encourage domestic critical mineral production by the mining industry. Some cumulative tonnages of marginal ores defined by USBM investigations are likely too small or scattered or have grades that are too low to mine profitably today without subsidization; for example, 1.380 million short tons (Mst) (1.25 Mt) grading 33 to 53.5 percent fluorite are distributed among 36 deposits, approximately 18 Mst (16.4 Mt) grading 9 to 23.2 percent manganese are distributed among 39 deposits, and 10.6 Mst (9.6 Mt) of alunite in two deposits grading 21 to 31 percent Al_2O_3 (table 1 in Moon, 1950).

Occurrences of many critical minerals associated with subduction-related igneous rocks in Western States are variably described in War Mineral Reports (USBM, 1942–1945), in collaborative reports by the USGS and state geological surveys (for example, USGS and Montana Bureau of Mines and Geology, 1963; USGS and Nevada Bureau of Mines, 1964; USGS and others, 1964, 1965, 1966a, 1969, 1975), and in topical publications by the USGS, most of which stem from World War II and Cold War era supply concerns.

Limitations and Assumptions

Evaluation of critical minerals in this report was conditioned by the quality of published concentrations and brevity of deposit descriptions, by incomplete access to unpublished drill hole records and reserves of mined and unmined deposits, and by general disinterest in critical mineral exploration and recovery. These limitations lead to uncertainty in classification of some deposits and necessitated application of a mass threshold to distinguish significant domestic inventories of critical minerals based on their current consumption.

Quantification of critical minerals is limited by accuracy of published concentrations, especially low concentrations reported in pre-2000 publications. Recovery (free market and subsidized) of some chalcophile, siderophile, and lithophile

critical mineral commodities was usually enabled by average grades and grade ranges of percents to tens of percents (for example, Sb, fluorite, Mn, and W). Production at these grades obtained from published sources is therefore considered reasonably accurate. However, multi-element analyses of critical minerals and other commodities in ores and rocks used in mineral deposit investigations before approximately 2000 had insufficient precision and detection limits to accurately quantify chalcophile and siderophile critical minerals that mostly occur in low concentrations (less than 1 percent; for example, Bi, PGE, and Te) in deposits described in this report. Over the past two decades multi-element analyses with lower detection limits have been increasingly used in mineral deposit exploration programs and reserve delineation of unmined deposits. Concentrations of critical minerals in exploration and deposit delineation drill holes that represent large masses of mineralized rocks are used in this report, as available, to evaluate critical mineral resources and inventories in unmined deposits and resources, in addition to those inventories determined from production and refining records (tables 3–15). Multi-element analyses of archival specimens and collection samples of mineralized rocks also reveal elevated concentrations of critical minerals that portend possibly significant inventories in numerous mining districts in Western States (tables 16–19). Known and suspected sites of critical minerals in deposits, resources, and interim recovery products are listed in table 20 and described in the text.

A subjective threshold is applied in this report to distinguish deposits with relatively large production of a critical mineral, equivalent to 2 years of recent domestic consumption (tabulated in USGS, 2021; table 21), from the myriad of small occurrences that will never materially add to consumable domestic supplies. Deposit descriptions are therefore limited to the largest producers, and for some critical minerals, the only producers of a critical mineral commodity. Descriptions of resources and inventories likewise include only those that contain, or are suspected to contain, substantial proportions of annual domestic consumption. If production, resource, or inventory is equivalent to two or more years of consumption, then it is termed significant (table 22).

Some magmatic-hydrothermal deposits clearly represent deposit types of mineral systems (Hofstra and Kreiner, 2020) whereas others are not closely linked to ore deposit models. Further, some deposits have no known spatial or temporal association with subduction-related intrusions. Some of the unassociated deposits are in Cenozoic sedimentary rocks and Mesozoic granitic rocks (for example, antimony mines in the Coyote [Antimony] district, Utah; gold-silver-antimony-tungsten deposits in the Stibnite-Yellow Pine district, Idaho; fluorite deposits in numerous Western States), whereas other deposits in Paleozoic and Mesozoic sedimentary rocks (for example, Apex germanium-gallium mine, Utah; White Caps gold-antimony-arsenic mine, Nev.) have characteristics of intrusion-related carbonate-replacement deposits but no clear spatial association with igneous rocks. However, the location

and forms of deposits and mineral commodities recovered from these unclassified deposits provisionally associate them with subduction magmatism.

Regarding production and recovery disincentives, many critical minerals in subduction-related magmatic-hydrothermal deposits in Western States are mid- to small-market commodities in which annual domestic consumption is metric tons (t) to several tens of thousands of metric tons (USGS, 2021; table 22). Known domestic deposits of critical minerals are mostly too small to affect cash flows of large mining companies and have not been the focus of exploration programs or recovery technology. Complex and likely expensive recovery processes would be required for recovery or improved recovery efficiency of most small- to mid-market critical mineral commodities. Since curtailment of government price supports and depletion of domestic stockpiles, world market dominance of many critical minerals by China and other exporters with large and (or) high-grade deposits has stifled global competition, which may limit exploration and development of deposits of many critical minerals. Although small exploration and mining companies have identified significant inventories of some critical minerals in recent years, many have minimal cash flows, rely on stock sales for funds, and may be unable to internally fund deposit development costs of deposits, including those containing critical minerals.

Although large inventories of chalcophile and siderophile critical minerals, including Sb, As, Ge, In, Re, and Sn, exist in porphyry Cu-Mo deposits, few have been profitable to recover. In addition to Cu and Mo, Re, Te, and small amounts of Ni and PGE have been episodically recovered from domestic copper refineries since the late 1800s (for example Ely, Nev.; Inspiration, Ariz.) (Hose and others 1976; Phillips, 1980). Other chalcophile, siderophile, and lithophile critical minerals in porphyry Cu-Mo deposits lacked demand and have routinely not been recovered for more than a century. All but three of 20 refineries operating in 1977 (U.S. Environmental Protection Agency, 1977) have been shuttered or demolished; the remaining refineries in El Paso, Tex. (Freeport-McMoRan, Inc., 2020); Amarillo, Tex. (ASARCO); and Magna, Utah (Rio Tinto), occasionally produce tellurium (and rhenium from molybdenite concentrates processed offsite). Because tens of billions of metric tons of Cu-Mo ores have been processed since the early 20th century, substantial masses of chalcophile and some siderophile and lithophile critical minerals, relative to domestic consumption, exist in concentrator tailings and refinery slimes. Concentrations of some of them are tracked in refineries for quality control of cathode copper, the marketed product, and are used in this report to estimate inventories in reserves and unmined domestic porphyry Cu-Mo deposits. The large deposit sizes (up to billions of metric tons) and ore processing rates (tens of thousands of short tons per day) indicate that these inventories could cover annual domestic consumption or lessen import reliance for Sb, As, Ge, In, Re, Te, and Sn supplies if recovery is subsidized.

18 Critical Minerals in Subduction-related Magmatic-Hydrothermal Systems of the United States

Table 3. Element concentrations averaged from multi-element geochemical analyses of drill hole intervals in the Sunnyside porphyry copper-(molybdenum-silver) system, Santa Cruz County, Arizona.

[Data from Granitto and others (2021). ppb, parts per billion; ppm, parts per million; wt %, weight percent; n/a, not available; DDH, diamond drill hole.]

Drill hole	Depth (ft)		Samples	Au (ppb)	Ag	As	Be	Bi	Cu (ppm)	Mn	Mo	Pb
	from	to										
Ridge north of Volcano mine												
BU-1	32	785	8	30.5	2.2	611.4	<5	5.1	3,058.4	--	59.3	156.9
Bucket breccia												
BB-2	40	140	10	46.1	4.4	207.0	--	178.0	4,652.3	19.5	7.0	296.8
BB-3	14	90	8	18.1	4.8	98.1	--	58.8	2,781.6	35.6	12.7	38.5
BB-3	600	720	12	51.9	3.2	157.5	--	10.0	3,369.3	19.2	18.8	24.0
BB-4	12.6	200	19	43.5	3.6	411.3	--	15.3	4,026.3	21.3	8.9	13.4
BB-6	20	120	10	23.2	8.6	476.0	--	108.0	3,595.0	30.0	10.0	31.2
BB-6	300	490	19	49.9	12.8	1,568.4	--	27.9	4,409.1	25.0	25.1	26.2
BB-2 to BB-6 average			78	38.8	6.2	486.4	<5	66.3	3,805.6	25.1	13.8	71.7
Upper Alum Canyon at waterfall												
TM8	176	5,417	19	71.5	6.3	230.0	<5	48.5	3,150.1	--	68.5	90.6
Ridgetop near Volcano mine												
TR10	665	5,448	20	22.0	4.9	185.0	<5	2.2	3,118.2	--	80.4	67.4
TM-13	3,900	4,040	14	23.9	8.5	102.5	0.5	11.4	585.3	3,677.5	97.6	1,197.2
TM-13	190	4,050	45	<104	1.5	17.1	<3	2.1	267.7	1,678.0	10.7	28,308.0
TM-14	540	4,580	95	21.6	0.9	42.3	--	--	105.4	18.6	12.4	14.7
TM-14	n/a	n/a	n/a	17.6	0.9	31.0	--	5.8	149.3	22.1	13.0	13.1
TM-14	n/a	n/a	n/a	16.7	1.8	64.2	--	7.5	578.0	15.8	18.0	11.7
TM-14	n/a	n/a	n/a	12.6	0.7	103.9	--	7.5	381.9	13.2	29.4	8.3
TM-14	n/a	n/a	n/a	14.4	1.6	32.0	--	7.5	802.6	37.5	12.4	62.6
TM-14	4,400	4,580	19	8.3	2.1	63.1	--	17.6	1,132.7	36.9	6.7	61.9
TM-14	540	4,580	114	15.2	1.3	56.1	<5	9.2	525.0	24.0	15.3	28.7
Near Trench mine mill tailings												
TCH-2	4,030	4,050	39	69.3	231.1	21.3	<3	652.4	5,464.2	11,235.1	10.7	18,708.4
	4,653	4,949	--	--	--	--	--	--	--	--	--	--
TCH-2	4,109	5,300	61	<59	40.1	23.7	<9	225.1	2,587.9	10,828.9	68.9	7,826.7
TCH-2A	4,100	4,390	9	10.5	1.7	13.8	0.5	10.0	148.3	4,376.3	25.3	118.8
SU breccia, Flux Canyon												
SU-2	241	802	3	29.7	4.0	1,296.7	<5	4.3	12,010.0	--	138.0	321.7
Ventura breccia, Ventura Canyon												
4 DDH	180	2,735	11	76.7	34.5	210.0	<5	110.9	2,808.7	--	19,841.7	887.2

Table 3. Element concentrations averaged from multi-element geochemical analyses of drill hole intervals in the Sunnyside porphyry copper-(molybdenum-silver) system, Santa Cruz County, Arizona.—Continued

[Data from Granitto and others (2021). ppb, parts per billion; ppm, parts per million; wt %, weight percent; n/a, not available; DDH, diamond drill hole.]

S (wt %)	Sb	V	W	Ga	Ge	In	Li	Ni	Pd	Pt	Sn (ppm)	Re (ppb)	Te	Zn (ppm)
	(ppm)						(ppb)					(ppm)		
Ridge north of Volcano mine														
4.1	88.1	49.3	45.5	20.3	3.6	0.5	<10	64.8	1.0	1.2	15.8	--	--	--
Bucket breccia														
4.1	28.0	1.9	--	--	--	--	--	--	--	--	--	--	--	--
3.8	12.5	1.4	--	--	--	--	--	--	--	--	--	--	--	--
2.5	5.0	2.8	--	--	--	--	--	--	--	--	--	--	--	--
3.0	26.4	2.2	--	--	--	--	--	--	--	--	--	--	--	--
4.7	87.5	1.9	--	--	--	--	--	--	--	--	--	--	--	--
5.0	92.4	1.9	--	--	--	--	--	--	--	--	--	--	--	--
3.8	42.0	2.0	<30	--	--	--	--	--	--	--	--	--	--	--
Upper Alum Canyon at waterfall														
6.5	22.4	39.0	54.8	17.3	2.3	3.2	20.0	11.0	1.0	0.9	9.3	--	--	--
Ridgetop near Volcano mine														
7.7	9.9	57.0	55.5	11.8	2.3	0.4	62.0	21.3	1.8	1.5	8.0	--	--	--
4.5	104.5	98.6	65.4	--	--	--	--	--	--	--	--	--	--	--
1.9	5.2	59.1	13.9	18.5	1	0.2	24.8	22.6	--	--	3.6	36.2	0.7	556.1
3.9	7.5	3.9	--	--	--	--	--	--	--	--	--	--	--	--
5.5	9.4	2.2	--	--	--	--	--	--	--	--	--	--	--	--
3.8	22.5	1.5	--	--	--	--	--	--	--	--	--	--	--	--
4.9	20.4	2.7	--	--	--	--	--	--	--	--	--	--	--	--
3.7	11.1	3.1	--	--	--	--	--	--	--	--	--	--	--	--
4.2	12.7	3.7	--	--	--	--	--	--	--	--	--	--	--	--
4.3	13.9	2.8	<20	--	--	--	--	--	--	--	--	--	--	--
Near Trench mine mill tailings														
5.9	5.4	33.5	61.5	5.4	3.7	5.6	22.9	11.4	--	--	5.2	19.4	29.8	96,282.5
--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
1.4	9.9	243.9	0.4	8.7	1.8	1.5	45.6	19.0	--	--	3.0	43.8	3.2	9,867.0
4.5	5.0	8.8	<30	--	--	--	--	--	--	--	--	--	--	--
SU breccia, Flux Canyon														
17.6	161.3	80.3	61.3	12.0	2.0	<0.2	<10	18.7	1.0	2.0	13.7	--	--	--
Ventura breccia, Ventura Canyon														
10.4	21.1	87.4	123.4	17.9	3.7	2.2	<50	15.3	2.8	12.1	11.9	--	--	--

Table 4. Multi-element analyses of drill hole and surface samples for preparation of standards and bulk metallurgical test samples, Hardshell-Alta-Hermosa silver-manganese-lead-zinc replacement deposit, Santa Cruz County, Arizona.—Continued

[Data from Granitto and others (2021). Determined by WEII-21 (weight of submitted sample), ME-GR21 (multi-element-gold by fire assay and gravimetric finish), ME-MS61 (multi-element-mass spectrometry 61 elements), Hg-CV41 (mercury-cold vapor), Ag-OG62 (silver by hydrofluoric-nitric-perchloric acid digestion with hydrochloric acid leach, inductively coupled plasma-atomic emission spectroscopy or atomic absorption spectroscopy finish),), Pb-OG62 (lead by hydrofluoric-nitric-perchloric acid digestion with hydrochloric acid leach, inductively coupled plasma-atomic emission spectroscopy or atomic absorption spectroscopy finish), and Zn-OG62 (zinc by hydrofluoric-nitric-perchloric acid digestion with hydrochloric acid leach, inductively coupled plasma-atomic emission spectroscopy or atomic absorption spectroscopy finish). ppm, parts per million; wt %, weight percent.]

Sample	Hf	Hg	In	K	La	Li	Mg	Mn	Mn	Mo	Na	Nb	Ni	P	Pb	Rb	Re	S	
	(ppm)	(ppm)	(wt %)	(wt %)	(ppm)	(ppm)	(wt %)	(wt %)	(ppm)	(ppm)	(wt %)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(wt %)	
	ME-MS61																		
	Hg-CV41																		
HDS-1A	6.1	0.24	0.063	3.09	44	15.1	0.34	1,555	--	0.89	0.11	13	2.1	260	1,170	275	<0.002	0.01	
HDS-1B	5.9	0.24	0.062	3.02	42.6	14.7	0.33	1,575	--	0.77	0.1	12.7	2	250	1,160	269	<0.002	0.01	
HDS-1C	6.1	0.24	0.063	3.08	43.9	15.4	0.34	1,595	--	0.87	0.11	13.2	2.4	270	1,190	274	<0.002	0.01	
HDS-2A	1.7	0.21	0.209	1.32	16.1	18.4	0.04	29,000	2.9	4.45	0.02	2.1	2.4	940	>10,000	79.7	0.002	0.08	
HDS-2B	1.7	0.2	0.213	1.27	15.9	18.8	0.04	29,800	3	4.85	0.02	2.5	2.6	940	>10,000	82.2	0.002	0.08	
HDS-2C	1.8	0.19	0.226	1.35	16.6	20	0.04	29,800	3	4.84	0.02	2.7	2.8	950	>10,000	87.8	0.002	0.08	
HDS-3A	1.8	0.39	0.138	1.22	14	21.5	0.05	24,900	2.5	4.22	0.02	2.1	3.2	740	>10,000	84.4	0.002	0.08	
HDS-3B	1.6	0.42	0.119	1.13	12.4	18.7	0.04	24,100	2.4	4.3	0.02	2.2	2.8	720	>10,000	72.1	<0.002	0.08	
HDS-3C	1.7	0.43	0.135	1.17	13.4	21.1	0.04	24,400	2.4	3.63	0.02	1.9	3.1	710	>10,000	79.1	0.002	0.08	
HDS-4A	4.1	0.56	0.195	2.02	34.1	16.5	<0.01	90,500	9.1	5.4	0.03	9	8.8	390	>10,000	149.5	<0.002	0.05	
HDS-4B	4.2	0.56	0.204	1.99	34.4	16	<0.01	90,600	9.1	5.33	0.03	8.8	8.7	390	>10,000	150.5	<0.002	0.05	
HDS-4C	4	0.68	0.2	2	33.9	15.1	<0.01	89,200	8.9	5.4	0.03	8.7	8.1	380	>10,000	148	0.002	0.05	
HDS-5A	1.6	0.68	0.139	0.67	13.4	21	<0.01	95,400	9.5	13.2	0.02	4.9	20.5	260	>10,000	39.3	<0.002	0.06	
HDS-5B	1.3	0.68	0.119	0.67	13.7	19.9	<0.01	97,100	9.7	10.1	0.02	4.3	19.1	260	>10,000	36.2	<0.002	0.06	
HDS-5C	1.3	0.6	0.136	0.68	13.5	21.2	<0.01	97,000	9.7	10.15	0.02	4.7	19.6	270	>10,000	37.2	<0.002	0.06	
Average	--	--	0.1	--	--	18.2	--	48,435.0	--	5.2	--	6.2	7.2	--	1,173.3	124.3	0.0	--	

Table 4. Multi-element analyses of drill hole and surface samples for preparation of standards and bulk metallurgical test samples, Hardshell-Alta-Hermosa silver-manganese-lead-zinc replacement deposit, Santa Cruz County, Arizona.—Continued

[Data from Granitto and others (2021). Determined by WEI-21 (weight of submitted sample), ME-GRA21 (multi-element-gold by fire assay and gravimetric finish), ME-MS61 (multi-element-mass spectrometry 61 elements), Hg-CV41 (mercury-cold vapor), Ag-OG62 (silver by hydrofluoric-nitric-perchloric acid digestion with hydrochloric acid leach, inductively coupled plasma-atomic emission spectroscopy or atomic absorption spectroscopy finish), Pb-OG62 (lead by hydrofluoric-nitric-perchloric acid digestion with hydrochloric acid leach, inductively coupled plasma-atomic emission spectroscopy or atomic absorption spectroscopy finish), and Zn-OG62 (zinc by hydrofluoric-nitric-perchloric acid digestion with hydrochloric acid leach, inductively coupled plasma-atomic emission spectroscopy or atomic absorption spectroscopy finish), ppm, parts per million; wt %, weight percent.]

Sample	(ppm)										(wt %)			(ppm)					(wt %)			
	Sb	Sc	Se	Sn	Sr	Ta	Te	Th	Ti	Ti	U	V	W	Y	Zn	Zr	Ag	Pb	Zn			
											ME-MS61								Ag-OG62		Zn-OG62	
HDS-1A	77.9	5.3	4	2	33.9	0.83	0.2	12.3	0.157	3.01	4.4	17	1.9	31.2	284	164	--	--	--			
HDS-1B	75.7	5	4	1.9	32.3	0.83	0.18	12.1	0.155	2.91	4.2	16	1.9	29.5	281	159.5	--	--	--			
HDS-1C	76.6	5.3	3	2	33.5	0.87	0.18	12.3	0.159	3.05	4.4	16	2	30.6	289	165	--	--	--			
HDS-2A	1,965	3.3	6	2.1	26.7	<0.05	7.31	4.1	0.128	4.45	5.1	38	8.3	11.9	1,900	53.1	152	3.92	--			
HDS-2B	2,040	3.4	6	2.2	27.4	0.05	7.68	4	0.127	4.55	5.2	38	9.4	12.2	1,850	53.6	155	3.86	--			
HDS-2C	2,130	3.5	6	2.2	28.7	0.05	8.05	4.2	0.133	4.84	5.4	39	9.8	12.5	1,880	56.9	149	3.83	--			
HDS-3A	1,590	2.9	4	1.2	35.3	<0.05	2.48	3.6	0.121	5.68	3.9	34	4.2	11.9	3,310	54.1	225	2.15	--			
HDS-3B	1,560	2.5	4	1.1	31.1	<0.05	2.32	3.2	0.116	4.97	3.4	34	4.1	10.4	3,140	47	229	2.19	--			
HDS-3C	1,555	2.7	4	1.2	33.4	<0.05	2.43	3.6	0.119	5.47	3.8	34	4	11.4	3,220	50.9	224	2.17	--			
HDS-4A	457	4	7	2	39.2	0.6	0.98	7.8	0.164	16.15	6.1	48	8.9	25.9	>10,000	113.5	451	1.69	1.07			
HDS-4B	461	4	5	1.9	38.9	0.59	0.82	8.1	0.164	16.95	6.3	48	8.9	23.7	>10,000	102.5	455	1.72	1.08			
HDS-4C	461	4.3	5	1.9	38.6	0.61	0.76	8.2	0.164	16.55	6.4	48	8.7	23.3	>10,000	103	451	1.7	1.08			
HDS-5A	1,275	0.8	4	3.6	102.5	0.37	6.98	2	0.144	28.9	7.7	23	28.5	14	7,750	49.4	1,330	6.91	--			
HDS-5B	1,265	0.6	3	3	102.5	0.31	6.12	2	0.144	28.5	7.6	23	27.6	14.3	7,830	49.8	1,240	6.23	--			
HDS-5C	1,270	1.1	4	3	103.5	0.35	7.4	2.1	0.143	29.6	8	23	27.8	14.6	7,820	40.3	1,230	6.21	--			
Average	1,083.9	--	--	2.1	--	--	3.6	--	--	--	--	31.9	--	--	3,296.2	--	--	--	--			

Table 7. Average concentrations of antimony, arsenic, bismuth, and tungsten in drill hole intervals in and below gold-silver-antimony resources in the Yellow Pine district, Valley County, Idaho, composited for metallurgical recovery testing.

[Data from Midas Gold, Inc. Concentrations determined by ICPMS (inductively coupled plasma mass spectrometry). g/t, grams per metric ton; Mt, million metric tons; DDH, diamond drill holes]

Resource	Mass	Composite	Depth (ft)	(g/t)				
				Sb	As	Bi	W	
Hangar Flats resource	--	8 DDH	3–1,014	10,473.8	27,791.2	5,138.9	317.3	
West End resource	--	9 DDH	85–935	241.4	12,974.9	1,916.5	86.0	
Yellow Pine resource	--	2 DDH	78–392	6,326.9	19,717.6	4,192.9	46.2	
Average concentration	--	--	--	5,681	20,161	3,749	150	
Total resource tonnage¹	104 Mt	--	--	59,082	209,673	38,989	1,560	

¹As of December 2020 (NS Energy, 2021).

Table 8. Rotary, hammer, reverse-circulation, core, blast, drill holes and bulk, grab and cut surface and underground samples (some from historic collections) in the Cripple Creek gold district, Teller County, Colorado.

[Data from Granitto and others (2021). ppb, parts per billion; opt, troy ounces per short ton; ppm, parts per million; wt %, weight percent; MS61, mass spectrometry-61 elements; BLD, below limit of detection.]

Au (ppb)	Au (opt)	F (ppm)	Hg (ppb)	Ag (ppm)	Al (wt %)	As (ppm)	Ba (ppm)	Be (ppm)	Bi (ppm)	Ca (wt %)	Cd (ppm)	Ce (ppm)	Cr (ppm)	Cs (ppm)	Cu (ppm)	
1,155.2	BLD	1,448.3	BLD	BLD	BLD	132.4	BLD	BLD	1.0	BLD	BLD	BLD	9.8	39.7	BLD	35.9
Fe (wt %)	Ga (wt %)	Ge (ppm)	Hf (ppm)	In (wt %)	K (wt %)	La (ppm)	Li (ppm)	Mg (wt %)	Mn (ppm)	Mo (ppm)	Na (wt %)	Nb (ppm)	Ni (ppm)	P (ppm)	Pb (ppm)	Rb (ppm)
BLD	25.6	0.4	BLD	0.1	BLD	BLD	39.6	BLD	1,005.5	47.7	BLD	BLD	28.6	BLD	124.3	167.8
Re (ppm)	S (wt %)	Sb (ppm)	Se (ppm)	Sn (ppm)	Sr (ppm)	Ta (ppm)	Te (ppm)	Th (ppm)	Ti (wt %)	Tl (ppm)	U (ppm)	V (ppm)	W (ppm)	Y (ppm)	Zn (ppm)	Zr (ppm)
BLD	BLD	8.9	BLD	10.7	637.7	BLD	4.8	BLD	0.4	BLD	BLD	118.8	25.0	BLD	206.5	170.3

Table 9. Compositions of anode copper from domestic copper smelters, 1986–2018.

[Concentrations of copper and minor elements in copper at several stages of refining (matte, blister, anode) and in electrolytic cell residue (slime, anode mud) and electrolyte, are determined for quantification of precious metals and control of deleterious and beneficial elements. wt %, weight percent; ppm, parts per million; ?, queried as in original source.]

Smelter	Year	Anode copper composition													Source	
		Cu (wt %)	Ag	Au	S	Se	Te	As	Sb	Bi	Pb	Fe	Ni	Sn		O
ASARCO Inc.	2018	99.51	445	1.4	20	509	61	376	82	177	158	657	148	--	1,727	M. Moats, personal commun., 2019
Anodes from smelters at El Paso, Tex., and Hayden, Ariz., some from other smelters, and scrap	2005	99.43	934	2.8	16	640	120	380	260	80	80	40	230	--	1,800	Moats and others (2007)
	2003	99.26	1,545	5.3	18	790	120	490	410	210	140	40	450	--	1,800	Moats and others (2013), Robinson and others (2003)
	1999	--	--	--	--	--	--	390	340	130	110	--	--	--	--	Larouche (2001)
	1998	99.12	2,252	19.5	22	600	100	770	510	200	320	40	990	--	1,600	Davenport and others (1999)
	1994	99.2	1,500	10	14	850	90	460	430	100	280	90	910	--	1,800	Schloen and Davenport (1995)
	1991	99.3	1,200	--	--	600	100	400	550	45	500	--	1,700	--	1,600	Schloen (1991)
	1987	99.3	1,200	--	--	600	100	400	550	45	500	--	1,700	--	1,600	Schloen (1987)
	1986?	98.6–99.4	--	--	10–30	600–700	40–200	300–900	500–800	20–60	300–400	--	400–800	10–50	1,500	Ramachandran and Wildman (1987)
Phelps Dodge/Freeport-McMoRan, El Paso, Tex.	2018	98.9–99.7	160–1,200	1–15	7–30	200–1,000	10–100	70–700	50–300	20–200	10–600	5–100	50–600	--	1,050–2,400	M. Moats, personal commun., 2019
Anodes from smelters at several sites including Miami and Douglas, Ariz.	2005	98.9–99.7	160–1,200	1–15	7–30	200–1,000	10–100	100–3,000	30–500	5–100	10–600	5–100	50–600	--	1,050–2,400	Moats and others (2007)
	2003	99.5–99.7	160–412	5.15–7.2	7–30	200–400	40–85	10–900	<1–60	20–130	50–100	<1–80	50–700	--	1,050–2,400	Moats and others (2013), Robinson and others (2003)
	1998	99.5–99.7	160–412	5.15–7.20	7–30	200–400	40–85	10–900	<1–60	20–130	10–50	<1–80	50–350	--	1,050–2,400	Davenport and others (1999)
	1994	99.5–99.7	60–700	1.7–17	7–60	133–300	20–190	10–900	10–260	20–100	20–400	2–60	100–200	--	1,200–1,600	Schloen and Davenport (1995)
	1991	99.6	200–300	--	--	125–400	20–100	50–300	30–200	10–100	20–200	--	90–800	--	1,200–1,700	Schloen (1991)
	1987	99.5	225–300	--	--	200–450	25–50	25–50	35–50	5–15	15–150	--	100–700	--	1,400–2,800	Schloen (1987)

Table 9. Compositions of anode copper from domestic copper smelters, 1986–2018.—Continued

[Concentrations of copper and minor elements in copper at several stages of refining (matte, blister, anode) and in electrolytic cell residue (slime, anode mud) and electrolyte, are determined for quantification of precious metals and control of deleterious and beneficial elements. wt %, weight percent; ppm, parts per million; ?, queried as in original source.]

Smelter	Year	Anode copper composition											Source			
		Cu (wt %)	Ag	Au	S	Se	Te	As	Sb	Bi	Pb	Fe		Ni	Sn	O
Kennecott/ Rio Tinto Utah Copper	2014	99	430	34	27	614	81	1,966	30	529	2,531	28	316	--	1,555	Moats and others (2014b)
Anodes from smelters at Garfield, Utah, and Magna, Utah (co-sited with copper refinery)	2003	99	462	52	38	784	118	1,113	46	679	2,121	13	271	--	1,709	Moats and others (2007), Robinson and others (2007)
	2003	99	462	52	38	784	118	1,113	46	679	2,121	13	271	--	1,709	Moats and others (2013), Robinson and others (2003)
	1999	--	--	--	--	--	--	1,000– 4,000	100– 125	400– 600	2,500– 4,000	--	215	--	--	Larouche (2001), Davenport and others (2001)
	1998	99.1	500	50	20	600	150	2,000	150	500	3,000	10	250	--	2,200	Davenport and others (1999)
	1994	99.4	500	60	30	500	60	1,000	100	300	2,500	20	300	--	2,100	Schloen and Davenport (1995)
	1991	99.6	538	--	--	500	150	820	80	80	140	--	210	--	1,930	Schloen (1991)
	1987	99.6	403	--	--	500	140	560	60	33	63?	--	220	--	900– 1,200	Schloen (1987)
Cyprus/ Phelps Dodge, Miami, Ariz.	2003	99.5	500	2.5	18	320	12	680	100	12	90	12	600	--	1,350	Robinson and others (2003)
	1999	--	--	--	--	--	--	770	132	13	129	--	514	--	--	Larouche (2001)
	1998	99.5	510	94	10	303	25	90	270	20	127	12	377	--	1,500	Davenport and others (1999)
	1994	95.5	510	24	10	303	25	90	270	20	127	12	377	--	1,500	Schloen and Davenport (1995)
	1991	99.5	400	--	--	300	20	80	150	12	100	--	600	--	1,600	Schloen (1991)

Table 9. Compositions of anode copper from domestic copper smelters, 1986–2018.—Continued

[Concentrations of copper and minor elements in copper at several stages of refining (matte, blister, anode) and in electrolytic cell residue (slime, anode mud) and electrolyte, are determined for quantification of precious metals and control of deleterious and beneficial elements. wt %, weight percent; ppm, parts per million; ?, queried as in original source.]

Smelter	Year	Anode copper composition														Source
		Cu (wt %)	Ag	Au	S	Se	Te	As	Sb	Bi	Pb	Fe	Ni	Sn	O	
White Pine Copper	2003	99.55	550	25	15–45	400– 600	50– 100	350– 400	20–30	10–20	150– 450	50–150	50–150	--	1,200– 1,800	Moats and others (2007)
	2003	99.55	550	25	15–45	400– 600	50– 100	350– 400	20–30	10–20	150– 450	50–150	50–150	--	1,200– 1,800	Robinson and others (2003)
Range Co./ BHP, White Pine, Mich.	1998	99.5	--	--	40	350	100	300	30	20	150	50	50	--	1,600	Davenport and others (1999)
	1994	99.6	700	3.5	6	250	30	250	25	50	15	35	110	--	1,500	Schloen and Davenport (1995)
	1991	99.5– 99.8	700	--	--	25–100	10–60	150	25	5	30	--	40	--	1,500– 2,000	Schloen (1991)
	1987	99.5– 99.8	700	--	--	25	--	200	50	5	80	--	150	--	1,000– 1,500	Schloen (1987)
Magma Metals Co./BHP,	1998	99.7	302	21.3	18	410	29	616	39	59	31	14	87	--	1,306	Davenport and others (1999)
San Manuel, Ariz.	1994	99.7	375	8	20	450	40	320	70	70	50	15	120	--	1,400	Schloen and Davenport (1995)
	1991	99.8	217	--	--	439	12	196	68	19	35	--	68	--	1,483	Schloen (1991)
	1987	99.78	175	--	--	415	6	24	73	3	63	--	121	--	900– 1,200	Schloen (1987)

Table 10. Compositions of tank house slimes from domestic copper refineries, 1986-2018.

[Concentrations of copper and minor elements in copper at several stages of refining (matte, blister, anode) and in electrolytic cell residue (slime, anode mud) and electrolyte, are determined for quantification of precious metals and control of deleterious and beneficial elements. kg, kilogram; t, metric ton; wt %, weight percent; NR, not recorded.]

Refinery	kg slimes/ t anode	Slimes composition (wt %)														Source	
		Cu	Ag	Au	Pt	Pd	S	Se	Te	As	Sb	Bi	Pb	Fe	Ni		
ASARCO Inc., Amarillo and El Paso, Tex., Hayden, Ariz.; Amarillo, Tex.	2.01	2.2	16.8	0.07	--	--	--	23.2	0.8	3.4	2.0	2.0	6.8	7.6	--	--	M. Moats, personal commun., 2019
Notes: refined anodes from ASARCO smelters at El Paso, Tex., and Hayden, Ariz.; also refines blister from other smelters, and #2 scrap	2.2	19.6	18.6	0.12	--	--	--	14.1	1.45	2.91	2.86	0.44	0.15	--	0.74	--	Moats and others (2007)
	4.3	4.63	48.12	0.18	--	--	--	28.13	2.25	2.73	4.05	0.87	0.53	--	--	--	Moats and others (2013), Robinson and others (2003)
	7.42	3.7	38.4	0.29	--	--	--	16.5	1	2.1	4.4	0.8	9.1	--	1.7	--	Davenport and others (1999)
	6	NO SLIME ANALYSES REPORTED; COULD BE CALCULATED FROM REPORTED CATHODE ANALYSES															Schloen and Davenport (1995)
	5	NO SLIME ANALYSES REPORTED; COULD BE CALCULATED FROM REPORTED CATHODE ANALYSES															Schloen (1991)
	5	NO SLIME ANALYSES REPORTED; COULD BE CALCULATED FROM REPORTED CATHODE ANALYSES															Schloen (1987)
	NR	NO SLIME ANALYSES REPORTED; COULD BE CALCULATED FROM REPORTED CATHODE ANALYSES															Ramachandran and Wildman (1987)
Phelps Dodge/ Freeport-McMoRan, El Paso, Tex.	0.9-1.8	1	18	0.2	--	--	12	19	0.4	3	5	0.7	5	0	0.1	--	M. Moats, personal commun., 2019
	2.2-4.4	27.1	12.2	0.12	0.0007	0.006	--	8.8	3.1	1.7	0.66	--	4.65	0.08	0.64	--	Hait and others (2009)
	4-6	1	22	0.2	--	--	12	20	0.4	2	4	0.7	5	0.04	0.05	--	Moats and others (2007)
	4.4-6.4	25	17	0.2	--	--	12	10	2	2	1.7	1.7	3	<1	<1	--	Moats and others (2013), Robinson and others (2003)
	2.2-4.4	25	17	0.2	--	--	12	12	2	2	1.7	1.7	3	<1	<1	--	Davenport and others (1999)
	2.2-4.4	NO SLIME ANALYSES REPORTED; COULD BE CALCULATED FROM REPORTED CATHODE ANALYSES															Schloen and Davenport (1995)
	1.5	NO SLIME ANALYSES REPORTED; COULD BE CALCULATED FROM REPORTED CATHODE ANALYSES															Schloen (1991)
	1.75	NO SLIME ANALYSES REPORTED; COULD BE CALCULATED FROM REPORTED CATHODE ANALYSES															Schloen (1987)

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Table 11. Copper and minor element concentrations in matte and blister copper and tank house slimes of domestic copper refineries, 1897–1973.

[Concentrations of copper and minor elements in copper at several stages of refining (matte, blister, anode) and in electrolytic cell residue (slime, anode mud) and electrolyte, are determined for quantification of precious metals and control of deleterious and beneficial elements. wt %, weight percent; ppm, parts per million; opt, troy ounces per short ton.]

Year	Sample source	Refinery location	Sample analyzed	Cu (wt %)	Au (wt %)	Au (ppm)	Au (opt)	Ag (wt %)	Ag (ppm)	Ag (opt)	Au+Ag (ppm)
1897	Not provided	Not provided	Blister Cu ¹ [Subsample: bottom-center- top of “ingot block”]	--	--	0.68- 10.9- 0.89	--	--	2,480- 6,410- 4,540	--	--
1899	Copper Queen mine, Bisbee district, Ariz.	Douglas, Ariz.?	Matte Cu ²	50.5–98.9	--	--	--	--	--	--	--
1911	Copper Queen mine, Bisbee district, Ariz.	Douglas, Ariz.?	Matte Cu ²	--	0.0035	35	--	0.02	200	--	--
	Butte district, Mont.	Great Falls re- duction plant, Mont.	Matte Cu	--	0.0003	0.3	--	0.05	500	--	--
			Anode mud	--	0.05–1	500– 10,000	--	23	230,000	--	--
1914	Mostly Bingham, Utah, Cu ore	Garfield, Utah	5,000 short tons blister Cu ³	--	--	--	2.88	--	--	34.80	--
	Ely, Nev., Cu ore	Ely (Steptoe), Nev.	3,000 short tons blister Cu ³	--	--	--	1.69	--	--	5.50	--
	Cu-Pb mattes from several Pb-Ag refineries	Omaha, Nebr.	800 short tons blister Cu ³	--	--	--	3.50	--	--	230.90	--
	Not provided	Mountain, Calif.	150 short tons blister Cu ³	--	--	--	14.18	--	--	109.90	--
	Pacific coast and Alaska Cu ores	Tacoma, Wash.	800 short tons blister Cu ³	--	--	--	21.67	--	--	67.10	--
1914	Butte, primarily; in mid-1950s ~30,000	Great Falls re- duction plant, Mont.	Anode Cu ⁴	99.13	--	--	--	--	--	--	1,380
1926	short tons per year		Anode Cu ⁴	99.28	--	--	--	--	--	--	2,410
1929	cement Cu from		Anode Cu ⁴	99.30	--	--	--	--	--	--	2,130
1957	Yerington, Nev., were refined; small amounts of matte Cu and speiss received from International Smelting and Refining at Tooele, Utah; increased Se (1957) from Tooele products; Sb varied with converter used		Anode Cu ⁴	99.55	--	--	--	--	--	--	960
1934	Not provided	Raritan Copper Works, Perth Amboy, N.J.	Raw slime	18.10	--	--	101.52	--	--	5,131	--
			Treated slime ⁵	1.74	--	--	146.2	--	--	7,684	--
1954	Baltimore, Md.	Baltimore, Md.	--	99.43	--	1.41	--	--	18.7	--	--
	Raritan, N.J.	Perth-Amboy, N.J.	--	99+	--	1.5	--	--	55	--	--
	Tacoma, Wash.	Tacoma, Wash.	--	98.08	--	3.59	--	--	90.2	--	--
	Anaconda, Mont.	Great Falls, Mont.	--	99.45	--	0.32	--	--	46.72	--	--
1973	Bingham, Utah, Cu ore	Magna, Utah	Anode mud	30	--	--	290	--	--	2,900	--

¹Blister Cu (~98%) is produced from matte by air oxidation of Cu and Fe sulfide minerals and separation from Fe oxide slag; it has characteristic nodular surfaces from quenched SO₂ bubbles.

²Matte Cu (30–70%) is produced by initial melting of concentrate and gravitational removal of silicate slag.

Table 11. Copper and minor element concentrations in matte and blister copper and tank house slimes of domestic copper refineries, 1897–1973.—Continued

[Concentrations of copper and minor elements in copper at several stages of refining (matte, blister, anode) and in electrolytic cell residue (slime, anode mud) and electrolyte, are determined for quantification of precious metals and control of deleterious and beneficial elements. wt %, weight percent; ppm, parts per million; opt, troy ounces per short ton.]

Pt (opt)	Pd (opt)	Te (wt %)	Te (ppm)	Se (wt %)	Se (ppm)	Se+Te (ppm)	Bi (wt %)	Bi (ppm)	As (wt %)	As (ppm)	Sb (wt %)	Sb (ppm)	Source
--	--	--	50- 270- 190	--	--	--	--	50- 550- 240	--	340- 1,080- 740	--	480- 1,570- 990	Keller, 1897
--	--	--	--	--	--	150–500	--	--	--	140–500	--	100–330	Douglas, 1899
--	--	0.0088	88	0.0113	--	--	0.0044	44	--	--	--	--	Sharwood, 1911
--	--	0.001– 0.01	10–100	0.001– 0.01	--	--	0.03– 0.05	300–500	--	--	--	--	
--	--	2–3	20,000– 30,000	2–3	--	--	2–3	20,000– 30,000	--	--	--	--	
0.0034	0.0118	0.0028	2.8	0.028	--	--	0.0031	31	--	--	--	--	Eiler, 1913
0.0102	0.044	0	0	0.0551	--	--	0.0002	2	--	--	--	--	
0.0133	0.0649	0.0336	33.6	0.0133	--	--	0.0094	94	--	--	--	--	
0.0132	0.0061	0.0017	1.7	0.018	--	--	0.0137	137	--	--	--	--	
0.0071	0.0333	0	0	0.021	--	--	0.0029	29	--	--	--	--	
--	--	--	170	--	90	--	--	38	--	1,180	--	530	Lapee, 1962
--	--	--	1,030	--	110	--	--	25	--	810	--	420	
--	--	--	840	--	120	--	--	57	--	880	--	730	
--	--	--	230	--	200	--	--	33	--	640	--	220	
--	--	5.14	--	5.31	--	--	--	--	--	56,300	--	46,600	Mosher, 1934
--	--	3.49	--	4.51	--	--	--	--	--	36,000	--	139,700	
--	--	0.045	--	0.061	--	--	0.008	--	0.064	--	0.031	--	Schloen and Elkin, 1954
--	--	0.02	--	0.07	--	--	0.002	--	0.06	--	0.1	--	
--	--	--	--	0.051	--	--	0.007	--	0.06	--	0.198	--	
--	--	0.024	--	0.012	--	--	0.003	--	0.059	--	0.027	--	
0.2	2.3	3	--	12	--	--	--	--	2	--	0.5	--	Leigh, 1973

³Element concentrations calculated from tabulated bulk analyses.

⁴Anode Cu (99%) is produced by removing remaining S, Fe, and O from blister Cu; it is cast into sheets for further purification (to cathode Cu) by electrolysis.

⁵Boiled, washed, and filtered.

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Table 12. Critical mineral concentrations in porphyry copper-(molybdenum) deposits based on average concentrations in drill hole intervals, deposit domains, mineralogical investigations, and resource and reserve tonnages.

[Cu-(Mo), copper-(molybdenum); Mt, million metric tons; wt %, weight percent; ppm, parts per million; gd, granodiorite; cpy, chalcopyrite; bn, bornite; cc, chalcocite; en, enargite; tn, tennantite; NR, not reported; est., estimated; USGS, U.S. Geological Survey.]

Porphyry Cu-(Mo) system	Deposit domain	Resource (Mt)	Reserve (Mt)	Number of analyses	Concentrations of primary, coproduct, and byproduct commodities						
					Cu	Mo	Pb	Zn	Au	Ag	Mn
					(wt %)			(ppm)		(wt %)	
Pebble, Alaska	Cu-Mo-Ag-Au-mineralized gd	7,510	--	7,520	0.41	0.024	0.002	NR	0.33	1.3	--
CuMo, Idaho (>0.1 wt % Cu)	Cu-Mo-Ag-mineralized rocks	~2,270	--	10,930	0.16	0.03	--	--	--	5.7	--
Red Mountain, Ariz.	Deep cpy-bn porphyry	385	--	300	0.58	0.009	--	--	0.004	0.12	--
	Near surface cc-en	100–150	--		0.31	0.02	--	--	--	--	--
Sunnyside, Ariz.	Deep cpy porphyry	1,500	--	95	0.33	0.011	--	--	<0.002	0.16	--
	Near-surface cc-en-tn	800	--	97	0.175	<0.01	--	--	<0.07	0.23	--
	Deep polymetallic replacement	NR	--	100	0.4	<0.01	13.3	5.3	0.07	136.5	0.44
Hardshell-Alta-Hermosa, Ariz.	Polymetallic replacement	--	--	15	0.12	0.05	0.12	0.03	<0.26	347	4.84
	Clark deposit	33	--	--	--	--	--	2.31	--	78	9.08
Ventura, Ariz.	Mo-Cu breccia pipe	3.6	--	11	2.4	2.4	0.89	NR	0.080	35	--
Bingham, Utah	Cu-Mo porphyry	--	552	--	0.44	0.031	--	--	0.16	2.11	--
	Cu-Mo porphyry	285	--	--	0.38	0.017	--	--	0.2	1.79	--
	North Rim skarn	20	--	--	3.65	--	--	--	1.62	20.95	--
	Cu-Mo ore	285	552	--	0.69	0.106	--	--	0.41	4.9	--
	Mo core	--	--	--	0.14	0.096	--	--	0.13	0.9	--
	Barren core	--	--	--	0.06	0.012	--	--	0.14	0.6	--
	Ore stockpile	--	0.2	90	--	--	--	--	--	--	--
Yerington, Nev.	Ann Mason Cu porphyry	2,219	--	30	0.29	Est. 0.007	--	--	--	0.66	--
	MacArthur Cu porphyry	159	--	1,000	0.21	--	--	--	--	--	--

Table 12. Critical mineral concentrations in porphyry copper-(molybdenum) deposits based on average concentrations in drill hole intervals, deposit domains, mineralogical investigations, and resource and reserve tonnages.—Continued

[Cu-(Mo), copper-(molybdenum); Mt, million metric tons; wt %, weight percent; ppm, parts per million; gd, granodiorite; cpy, chalcopyrite; bn, bornite; cc, chalcocite; en, enargite; tn, tennantite; NR, not reported; est., estimated; USGS, U.S. Geological Survey.]

Concentrations of critical minerals (value used for inventory in table 13) ¹										Data source; references
Sb	As	Bi	Ge	In	PGE	Re	Sn	Te	W	
(ppm)										
4	41	1	<1	<1	<0.02	<1	2	<1	13	Table 5; USGS (2013a)
1	6	3	<1	<1	NR	<1	7	<1	61	Table 6; SRK Consulting (2020)
12	27	<10	NR	NR	NR	NR	2	34	9	Table 7; Vikre and others (2014), Chaffee (2019)
--	--	--	--	--	--	--	--	--	--	
14–105 (60)	17–183 (100)	2–11 (6)	1–2 (1.5)	<1	<0.002	36	4–8 (6)	<1	14–65 (40)	Table 3; Vikre and others (2014)
22–88 (55)	230–611 (420)	5–66 (35)	2–4 (3)	1–3 (2)	0.001	NR	9–16 (13)	NR	46–55 (50)	--
7.7	22.5	438.8	2.8	3.6	NR	31.6	4.1	16.5	31	--
1,082	914	1	0.2	0.1	NR	0	2	4	10	Table 4; South32 Limited (2020)
--	--	--	--	--	--	--	--	--	--	South32 Limited (2020)
21	210	111	4	2	<0.012	NR	12	NR	123	Table 3; Vikre and others (2014)
--	--	<5.4	--	0.07	0.014	0.04–0.27	6.9	0.34–4.8	--	Table 4
--	--	--	--	--	--	--	--	--	--	--
--	--	--	--	--	--	--	--	--	--	--
1.8	8.7	5.4	<1	<1	NR	0.55	6.9	4.8	21	Austin and Ballantyne (2010)
3.7	10.7	0.9	<1	<1	NR	0.09	1.3	<1	12	--
6.6	8.8	0.7	<1	NR	NR	NR	0.5	<1	1	--
20.4	1,579	--	--	--	--	--	--	--	--	Gunter and Austin (1997)
<1	5.2	<1	--	<1	--	<1	1.5	<1	2.9	Cohen (2011), Hudbay Minerals, Inc. (2021); J. Dilles, Oregon State University, written commun., 2021
--	--	--	--	--	--	--	--	2.4	--	Table 12; Lori (2010)

¹Values in parentheses are average concentrations.

Table 13. Critical mineral inventories in porphyry copper-(molybdenum) deposits based on average concentrations in drill hole intervals, deposit domains, mineralogical investigations, and resource/reserve tonnages.

[Cu-(Mo), copper-(molybdenum); Mt, million metric tons; t, metric tons; est., estimated; USGS, U.S. Geological Survey.]

Porphyry Cu-(Mo) system	Resource (Mt)	Reserve (Mt)	Critical mineral inventories (t)											Data source; references	
			Sb	As	Bi	Ge	In	PGE	Re	Sn	Te	W			
Pebble, Alaska	7,510	--	30,040	307,910	7,510	--	--	--	--	--	15,020	--	--	97,630	Table 5; USGS (2013a)
CuMo, Idaho (>0.1 wt % Cu)	~2,270	--	2,270	13,620	6,810	--	--	--	--	--	15,898	--	--	138,470	Table 6; SRK Consulting (2020)
Red Mountain, Ariz.	385 100-150	--	4,620	10,395	--	--	--	--	--	--	--	13,090	--	3,465	Table 7; Vikre and others (2014); Chaffee (2019)
Sunnyside, Ariz.	1,500 800	--	90,000 44,000	150,000 336,000	9,000 28,000	2,350 2,400	--	--	--	54,000	9,000 10,400	--	--	60,000 24,800	Table 3; Vikre and others (2014)
Hardshell-Alta-Hermosa, Ariz.	1 ¹ Est. 20 2 ² Est. 33	--	154 35,706	450 3,016	8,776 33	56	72	--	--	632	82	330	132	620 330	Table 4; South32 Limited, 2020
Ventura, Ariz.	3.6	--	75.6	756	399.6	14.4	7.2	--	--	--	43.2	--	--	442.8	Table 3; Vikre and others (2014)
Bingham, Utah	-- 285 20 285	552	--	--	4,200	--	60	12	36-228	5,800	285-4,000	--	--	--	Table 4
Yerington, Nev.	2,219	--	--	11,539	--	--	--	--	--	157; 304	1,682; 3,809	1,368; 2,650	--	5,985; 11,592	Gunter and Austin (1997); Austin and Ballantyne (2010); Rio Tinto (2021b)
														29; 55	
														6,624	
														29; 55	
														6,435	Cohen (2011); Hudbay Minerals, Inc. (2021); J. Dilles, Oregon State University, written commun., 2021
														--	Table 8; Lori (2010); Independent Mining Consultants, Inc. (2022)

¹Critical mineral resources calculated using concentrations in diamond drill hole intercepts and an estimated tonnage.²Critical mineral resources calculated from separate concentrations in metallurgical composites and resource tonnage (South32 Limited, 2020).

Table 14. Critical mineral inventories of porphyry copper-(molybdenum) deposits based on concentrations in anode copper and reserve tonnages.

[Mt, million metric tons; wt %, weight percent; ppm, parts per million; t, metric tons; est., estimated; USGS, U.S. Geological Survey.]

Cu refinery (operator)	Ore source	Reserve/ production (Mft)	Years	Range of concentrations of Cu, monitored elements, and critical minerals in anode Cu (ppm)									
				Cu (wt %)	Ag	Au	S	Se	Sb	As	Bi	Fe	
Amarillo, Tex. (ASARCO)	ASARCO mines, Ariz.	Est. 700	1986/ 2018	98.6–99.51	445–1,500	NR–19.5	10–30	509–850	82–800	300–900	45–210	40–657	
Magna, Utah (Kennecott/ Rio Tinto)	Bingham mine, Utah	552	1987/ 2014	99–99.6	403–500	34–60	20–38	500–784	30–150	560–4,000	33–679	10–28	
El Paso, Tex. (Phelps Dodge/ Freeport-McMoRan)	Freeport-McMoRan mines, Ariz.	11,254	1987/ 2018	98.9–99.7	60–1,200	1–17	7–60	133–1,000	1–500	10–3,000	5–200	1–100	
Miami, Ariz. (Cyrus/ Phelps Dodge)	Globe-Miami district mines, Ariz.	Unquantified refinery interim products	1991/ 2003	99.5	400–510	2.5–94	10–18	300–320	100–270	80–770	12–20	12	
San Manuel, Ariz. (Magma Metals Co./ BHP)	San Manuel/ Kalamazoo mine, Ariz.	797	1987/ 1998	99.7–99.8	175–375	8–21.3	18–20	410–450	39–73	24–616	3–70	14–15	

Cu refinery (operator)	Ore source	Range of concentrations of Cu, monitored elements, and critical minerals in anode Cu (ppm)										Data source; references
		Ni	Pb	Sn	Te	Sb	As	Bi	Ni	Sn	Te	
Amarillo, Tex. (ASARCO)	ASARCO mines, Ariz.	148–1,700	80–500	10–50 (1,986)	61–200	57,400–560,000	210,000–630,000	31,500–147,000	103,600–1,190,000	7,000–30,000	42,700–140,000	Tables 9–11
Magna, Utah (Kennecott/ Rio Tinto)	Bingham mine, Utah	210–316	140–4,000	NR	60–150	16,560–82,800	309,120–2,208,000	18,216–374,800	115,920–174,432	--	33,120–82,800	Tables 9–11
El Paso, Tex. (Phelps Dodge/ Freeport-McMoRan)	Freeport-McMoRan mines, Ariz.	50–800	10–600		10–190	11,254–5,627,000	112,540–33,762,000	562,700–2,250,800	562,700–9,003,200	--	112,540–2,138,260	Tables 9–11
Miami, Ariz. (Cyrus/ Phelps Dodge)	Globe-Miami district mines, Ariz.	377–600	90–129		12–25	--	--	--	--	--	--	Tables 9–11
San Manuel, Ariz. (Magma Metals Co./ BHP)	San Manuel/ Kalamazoo mine, Ariz.	68–121	31–63		6–40	31,083–58,181	19,128–490,952	2,391–55,790	54,196–96,437	--	4,782–31,880	Tables 9–11; USGS (2013b)

Table 15. Estimated annual masses of critical minerals predicted in anode copper at operating copper refineries and not recovered (wasted) during production of anode copper at shuttered or demolished copper refineries, based on concentrations in anode copper, reserve tonnages, and mine life.

[Mt, million metric tons; wt %, weight percent; yr, year; est, estimated; t, metric tons; %, percent; NR, not reported; USGS, U.S. Geological Survey.]

Cu refinery (operator)	Ore source	Reserve (Mt)	Production (Mt)	Cu (wt %)	Mine life (yr)	Mine reserves and forecasted production		
						Total Cu (reserves, production) (Mt)	Est. Cu/yr (t)	Est. % Cu production/yr
Predicted								
Amarillo, Tex. (ASARCO)	Mission complex (2016)	303.4	--	0.42	12	1,274,280	106,190	52
	Ray (2018; sulfide, mill ore)	444.7	--	0.514	23	2,285,758	99,381	48
	Silver Bell (2009)	141.4	--	0.33	--	466,620	--	--
Magna, Utah (Kennecott/Rio Tinto)	Bingham mine, Utah	552	--	0.44	11	2,428,800	220,800	--
El Paso, Tex. (Phelps Dodge/Freepport-McMoRan)	North America: Morenci, Bagdad, Safford, Sierrita, Miami, Ariz.; Chino, Tyrone, N.Mex.	11,254	--	--	¹ Est. 16.6	23,550	11,418,000	--
	Morenci	4,300	--	0.23	--	6,500	--	--
	Sierrita	3,240	--	0.22	--	6,000	--	--
	Bagdad	2,591	--	0.31	--	6,909	--	--
	Safford+Lone Star	777	--	0.45	--	2,591	--	--
	Chino+Cobre	313	--	0.44	--	1,136	--	--
	Tyrone	33	--	0.27	--	0.05	--	--
	Miami	--	--	NR	--	0.025	--	--
Wasted								
Miami-Inspiration, Ariz. (Cyprus/ Phelps Dodge)	Bluebird, Copper Cities, Globe, Van Dyke, Live Oak, Inspiration mines	--	1,591	0.63	--	10,023,300	--	--
San Manuel, Ariz. (Magma Metals Co./ BHP)	San Manuel, Kalamazoo deposits	--	797	0.64	44	1,811,000	41,159	--

Table 15. Estimated annual masses of critical minerals predicted in anode copper at operating copper refineries and not recovered (wasted) during production of anode copper at shuttered or demolished copper refineries, based on concentrations in anode copper, reserve tonnages, and mine life.—Continued

[Mt, million metric tons; wt %, weight percent; yr, year; est, estimated; t, metric tons; %, percent; NR, not reported; USGS, U.S. Geological Survey.]

Cu refinery (operator)	Ore source	Annual masses of critical minerals in anode Cu (predicted; slimes)								Data source; references
		Sb	As	Bi	Ni	Sn	Te			
Predicted										
Amarillo, Tex. (ASARCO)	Mission complex (2016)	2,487–24,667	9,100–27,300	1,365–6,370	4,459–51,567	303–1,300	1,850–6,067	Baxter (2016)		
	Ray (2018; sulfide, mill ore)	1,223–11,687	4,383–13,148	657–3,068	2,150–24,835	146–626	891–2,922	Mining Data Solutions (2019)		
	Silver Bell (2009)	--	--	--	--	--	--	USGS (2010c)		
Magna, Utah (Kennecott/Rio Tinto)	Bingham mine, Utah	1,507–7,527	28,102–200,727	1,656–34,073	10,538–15,857		3,010–7,527	Rio Tinto (2021a)		
El Paso, Tex. (Phelps Dodge/Freeport-McMoRan)	North America: Morenci, Bagdad, Safford, Sierrita, Miami, Ariz.; Chimo, Tyrone, N.Mex.	--	--	--	--	--	--	Freeport-McMoRan, Inc. (2020)		
	Morenci	--	--	--	--	--	--			
	Sierrita	--	--	--	--	--	--			
	Bagdad	--	--	--	--	--	--			
	Safford+Lone Star	--	--	--	--	--	--			
	Chimo+Cobre	--	--	--	--	--	--			
	Tyrone	--	--	--	--	--	--			
	Miami	--	--	--	--	--	--			
Wasted										
Miami-Inspiration, Ariz. (Cyprus/ Phelps Dodge)	Bluebird, Copper Cities, Globe, Van Dyke, Live Oak, Inspiration mines	--	--	--	--	--	--	USGS (2002)		
San Manuel, Ariz. (Magma Metals Co./ BHP)	San Manuel, Kalamazoo deposits	706–1,322	435–11,158	54–1,268	1,232–2,192	--	109–725	Briggs, 2014		

¹Estimated mine life based on Cu reserves and 2020 production of 1,418 Mt-Cu from North American mines.

Table 16. Average concentrations of produced commodities (Cu, Mo, Pb, Zn, Ag) and some critical minerals (Sb, As, Bi, Ge, In, Te, Sn, W) in archival specimens of porphyry copper (molybdenum) deposits and associated polymetallic skarn, carbonate-replacement, and vein deposits, and crustal abundances of critical minerals.

[Data from Granitto and others (2020, 2021). Concentrations determined by AES-ST (atomic emission spectroscopy) and MS-ST (mass spectrometry). ppm, parts per million, wt %, weight percent; max, maximum; BLD, below limit of detection; NR, not reported.]

District/mine	State	Note (number of analyses)	Porphyry Cu-(Mo) deposits (ppm)											
			Cu AES-ST	Mo MS-ST	Pb MS-ST	Zn AES-ST	Ag MS-ST	As MS-ST	Bi MS-ST	Ge MS-ST	In MS-ST	Sb MS-ST	Sn MS-ST	Te MS-ST
Wallapai/ Mineral Park porphyry	Ariz.	AVE (6)	14,906.9	59.3	<2,660	10,357.8	<5,490	<5,870	31.7	3.5	7.9	<1,000	24.7	--
		COMMENT	--	--	Some BLD	--	Some BLD	Some BLD	--	--	--	Some BLD	--	--
Bisbee porphyry	Ariz.	AVE (32)	56,145.6	6.3	2,626.7	3,705.4	Max 1,080	82.4	81.4	3.0	29.1	9.5	66.9	<45; most NR
		COMMENT	5.6 wt %	Some BLD	Several very high values	Several very high values	Many BLD	Many BLD	Some BLD	--	--	I high value	--	--
Ajo porphyry	Ariz.	AVE (4)	17,500	56.25	Max 60	72.5	<20	--	5.85	1.25	--	--	<4	--
		COMMENT	1.75 wt %	Most BLD	Most BLD	All BLD	All BLD	All BLD	All BLD	All BLD	All BLD	All BLD	All BLD	All BLD
Christmas porphyry/ skarn	Ariz.	AVE (6)	15,385.5	Max 79	Max 136	1,075.7	Max 10	Max 60	<33	<6	<3.6	Max 2	<23	--
		COMMENT	1.5 wt %	Some BLD	Most BLD	Some BLD	Most BLD	Most BLD	Most BLD	--	--	Many BLD	Many BLD	Many BLD
Morenci district	Ariz.	AVE (14)	37,816.0	755.2	4,748.3	422.7	--	--	71.2	1.6	0.9	7.4	10.5	--
		COMMENT	>3.7 wt %	I very high value	Many BLD; highly variable	--	Most BLD	Most BLD	Highly variable	Most BLD	Most BLD	Most BLD	Many BLD	--
Bagdad porphyry	Ariz.	AVE (17)	40,579.1	725.1	3,519.9	3,736.2	--	--	53.9	3.0	--	60.6	9.6	0.8
		COMMENT	>4.0 wt %	3 very high values	Many BLD; highly variable	--	Many BLD	Many BLD	Highly variable	Some BLD	Some BLD	Some BLD	Some BLD	--
Globe-Miami district porphyry	Ariz.	AVE (19)	48,982.3	673.8	--	10,215.2	<110	Highly variable	Highly variable	2.2	1.9	Highly variable	10.5	0.9
		COMMENT	>4.9 wt %	3 very high values	Most BLD; highly variable	--	Most BLD	Most BLD	Many BLD	Many BLD	Many BLD	Many BLD	Many BLD	--
Ray mine porphyry	Ariz.	AVE (8)	16,163.8	1,326.6	51.3	570.9	<30	--	1.8	2.0	0.4	1.8	6.4	--
		COMMENT	>1.6 wt %	2 very high values	Most BLD; highly variable	--	Most BLD	All BLD	All BLD	--	--	Many BLD	Most BLD	--

Table 16. Average concentrations of produced commodities (Cu, Mo, Pb, Zn, Ag) and some critical minerals (Sb, As, Bi, Ge, In, Te, Sn, W) in archival specimens of porphyry copper-(molybdenum) deposits and associated polymetallic skarn, carbonate-replacement, and vein deposits, and crustal abundances of critical minerals.

[Data from Granitto and others (2020, 2021). Concentrations determined by AES-ST (atomic emission spectroscopy) and MS-ST (mass spectrometry). ppm, parts per million, wt %, weight percent; max, maximum; BLD, below limit of detection; NR, not reported.]

District/mine	W	Be	Ce	Co	Cr	Ga	Li	Nb	Ni	Se	Ta	V	Rb	Sc	
	MS-ST	AES-ST	MS-ST	MS-ST	AES-ST	MS-ST	AES-ST	MS-ST	AES-ST	MS-ST	MS-ST	AES-ST	MS-ST	AES-ST	
Porphyry Cu-(Mo) deposits (ppm)															
Wallapai/ Mineral Park porphyry	15.8	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Bisbee porphyry	63.1	--	--	--	--	6.8	<13	<17; most NR	24.6	<1	<1	72.4	44.2	<176	
<i>I high value</i>	--	--	--	--	--	<i>Many BLD</i>	<i>Most BLD</i>	--	--	<i>Most BLD</i>	--	--	--	<i>Most BLD</i>	
Ajo porphyry	2.25	--	--	--	--	<30	6.8	26.25	--	--	--	69.75	80.2	Max 8	
Christmas porphyry/skarn	<39	--	--	--	--	<40	7.7	27.8	--	Max 1.6	<i>Most BLD</i>	80.8	40.8	Max 20	
Morenci district	14.3	--	--	--	--	<30	9.5	23.9	--	--	<i>Most BLD</i>	43.3	60.4	Max 18	
Bagdad porphyry	46.3	--	--	--	--	--	5.8	15.5	25.2	0.3	57.2	112.9	--	Max 18	
<i>I high value</i>	--	--	--	--	--	--	<i>Some BLD</i>	--	<i>Highly variable</i>	<i>Most BLD</i>	--	--	--	<i>Many BLD</i>	
Globe-Miami district porphyry	15.2	--	--	--	--	7.0	10.2	17.9	23.4	0.6	58.9	117.8	--	Max 19	
Ray mine porphyry	20.8	--	--	--	--	<i>Many BLD</i>	6.6	25.6	<i>Few analyses</i>	-0.1	193.8	106.3	--	18.4	
Sierrita porphyry	17.6	--	--	--	--	<30	9.2	35.4	--	--	<i>Some BLD</i>	53.9	212.6	Max 18	
San Manuel porphyry	24.0	--	--	--	--	<i>Most BLD</i>	8.0	43.2	8.2	<1.5	<i>Some BLD</i>	110.2	82.7	Max 11.0	
	--	--	--	--	--	--	--	--	--	<i>Most BLD</i>	--	--	--	--	

Table 16. Average concentrations of produced commodities (Cu, Mo, Pb, Zn, Ag) and some critical minerals (Sb, As, Bi, Ge, In, Te, Sn, W) in archival specimens of porphyry copper-(molybdenum) deposits and associated polymetallic skarn, carbonate-replacement, and vein deposits, and crustal abundances of critical minerals.

[Data from Granitto and others (2020, 2021). Concentrations determined by AES-ST (atomic emission spectroscopy) and MS-ST (mass spectrometry). ppm, parts per million, wt %, weight percent; max, maximum; BLD, below limit of detection; NR, not reported.]

District/mine	W	Be	Ce	Co	Cr	Ga	Li	Nb	Ni	Se	Ta	V	Rb	Sc
	MS-ST	AES-ST	MS-ST	MS-ST	AES-ST	MS-ST	AES-ST	MS-ST	AES-ST	MS-ST	MS-ST	AES-ST	MS-ST	AES-ST
Silver Bell porphyry	26.5	--	--	--	--	--	<90	6.6	11.0	--	<1.5	41.3	98.3	Max 7
	--	--	--	--	--	--	Many BLD	--	--	--	Many BLD	--	--	Most BLD
Vekol Hills porphyry	<4	--	--	--	--	--	25.0	6.5	12.1	--	<0.8	199.2	64.6	Max 58
	Most BLD	--	--	--	--	--	--	--	--	--	Some BLD	--	--	Some BLD
Tyrone porphyry	19.5	--	--	--	--	--	<77	2.1	<39	<16	<0.5	25.3	64.5	Max 6
	--	--	--	--	--	--	Some BLD	--	--	--	All BLD	--	--	Most BLD
Santa Rita/ Chino porphyry	12.2	--	--	--	--	--	<30	5.6	39.6	<35	<1.7	68.5	59.6	Max 16
	--	--	--	--	--	--	Many BLD	Some BLD	Some BLD	Some BLD	Some BLD	--	--	Most BLD
Yerington porphyry	3.1	<2.4	25.6	45.4	30.3	19.1	--	2.5	37.2	--	--	75.3	42.7	<2.3
	--	Many BLD	--	I very high value	Many BLD	--	All BLD	--	I high value	Few analyses	All BLD	--	--	Most BLD
Bingham porphyry	55.4	All BLD	111.6	13.1	78.2	17.4	<2.8	9.6	49.6	6.6	<0.3	101.1	158.6	4.9
	I high value	--	--	--	--	--	Most BLD	--	Many BLD	Many BLD	Most BLD	--	--	Many BLD
Copper Creek breccia pipe	26.2	--	--	--	--	--	<80	--	9.9	--	--	43.9	74.8	Max 8
	--	--	--	--	--	--	Some BLD	--	Some BLD	--	--	--	--	Some BLD
Associated polymetallic skarn, carbonate replacement, and vein deposits														
Bisbee polymetallic replacement	73.0	--	--	--	--	--	Max 130	<15	2.1	<72; most NR	<0.5	82.0	8.2	Max 53
	Highly variable	--	--	--	--	--	Many BLD	Most BLD	--	--	All BLD	--	--	Many BLD
Johnson Camp polymetallic replacement	926.1	--	--	--	--	--	33.0	7.0	4.7	49.0	--	23.3	49.9	Max 12
	--	--	--	--	--	--	--	--	Some BLD	--	--	--	--	Many BLD
Pima mine polymetallic vein	208.0	--	--	--	--	--	<80	3.3	24.2	--	--	48.3	110.6	Max 10
	--	--	--	--	--	--	Some BLD	Some BLD	--	--	Most BLD	--	--	Most BLD

Table 16. Average concentrations of produced commodities (Cu, Mo, Pb, Zn, Ag) and some critical minerals (Sb, As, Bi, Ge, In, Te, Sn, W) in archival specimens of porphyry copper-(molybdenum) deposits and associated polymetallic skarn, carbonate-replacement, and vein deposits, and crustal abundances of critical minerals.

[Data from Granitto and others (2020, 2021). Concentrations determined by AES-ST (atomic emission spectroscopy) and MS-ST (mass spectrometry). ppm, parts per million, wt %, weight percent; max, maximum; BLD, below limit of detection; NR, not reported.]

District/mine	W	Be	Ce	Co	Cr	Ga	Li	Nb	Ni	Se	Ta	V	Rb	Sc	
	MS-ST	AES-ST	MS-ST	MS-ST	AES-ST	MS-ST	AES-ST	MS-ST	AES-ST	MS-ST	MS-ST	AES-ST	MS-ST	AES-ST	
Associated polymetallic skarn, carbonate replacement, and vein deposits—Continued															
San Xavier porphyry/skarn	213.9	--	--	--	--	--	<50	-0.3	4.0	--	-0.5	43.3	Max 2.7		
	--	--	--	--	--	--	Most BLD	--	--	--	Some BLD	--	Some BLD	All BLD	
Mission porphyry/skarn	167.3	--	--	--	--	--	<130	4.6	20.7	--	--	29.2	108.0	Max 15	
	<i>I high value</i>	--	--	--	--	--	--	--	--	--	Some BLD	--	--	Most BLD	
Twin Buttes porphyry/skarn	62.6	--	--	--	--	--	14.0	5.6	11.2	--	--	49.2	131.4	--	
	--	--	--	--	--	--	--	--	--	--	Most BLD	--	--	All BLD	
Magma polymetallic vein	33.6	--	--	--	--	--	--	--	--	16.0	--	26.4	2.2	Max 16	
	--	--	--	--	--	--	Most BLD	Most BLD	Many BLD	2 analyses	All BLD	--	--	Most BLD	
Butte polymetallic veins	500.1	--	--	--	--	--	<20	<9	7.6	29.0	<0.5	124.6	14.0	Max 19	
	<i>Highly variable</i>	--	--	--	--	--	--	Most BLD	--	--	All BLD	Variable	--	Most BLD	
Central district Polymetallic I	24.0	--	--	--	--	--	<27	5.0	31.4	<46	<1.1	46.4	4.0	Max 15	
	--	--	--	--	--	--	Most BLD	--	--	Most BLD	Most BLD	--	--	Most BLD	
Central district Groundhog polymetallic	8.4	--	--	--	--	--	<20	<5.8	<11	<111	-0.5	13.3	22.4	--	
	--	--	--	--	--	--	Many BLD	Most BLD	Some BLD	Many BLD	All BLD	--	--	All BLD	
Central district polymetallic II	15.7	--	--	--	--	--	<44	<15	<42	<6	<1.2	51.1	178.4	Max 10	
	--	--	--	--	--	--	Some BLD	Most BLD	Some BLD	Most BLD	Most BLD	--	--	Most BLD	
Bingham skarn/replacement	21.6	All BLD	8.9	21.7	11.0	--	<4.7	<0.4	20.7	13.5	All BLD	29	7.5	All BLD	
	--	--	--	--	Some BLD	--	Most BLD	Most BLD	Some BLD	--	--	--	--	--	
Crustal abundance	1.25	2.8	66.5	25	102	19	20	20	84	0.05	2	120	90	22	

Table 17. Average concentrations of produced commodities (Cu, Au, Ag, Pb, Zn) and some critical minerals (Sb, As, Bi, In, Pd, Pt, Te, Sn, Zn) in mineralized samples from mine dumps of carbonate-replacement deposits and vein deposits in Nevada and Idaho, and crustal abundances of critical minerals.

[Data from Granitto and others (2020, 2021). Concentrations determined by FA (fire assay), ICPAES (inductively coupled plasma atomic emission spectroscopy), and NIS-FA-INAA-PGE (nickel sulfide-fire assay-instrumental neutron activation analysis-platinum group elements). ppm, parts per million; ppb, parts per billion.]

District	Number of analyses	Au	Ag	Cu	Pb	Zn	Pd	Pt	Ir	Os	Rh	Ru	As
		(ppb)	(ppm)				(ppb)		(ppb)				
		C-Au-Pt-Pd FA	C-ICPAES-MS-42				C-Au-Pt-Pd FA		C-NIS-FA-INAA-PGE				
Eureka, Nev. I	9	3,100	200	822	11,283	4,376	<6	0.011	--	--	--	--	1,880
Eureka, Nev. II	14	6,720	1,525	1,095	35,692	15,187	2	--	--	--	--	--	26,480
Pioche, Nev. I	4	2,590	272	902	35,750	47,800	<6	0.011	--	--	--	--	999
Pioche, Nev. II	16	1,147	583	5,710	56,685	99,176	1.9	--	--	--	--	--	846
Goodsprings, Nev. I	12	520	145	5,490	11,443	4,931	<6	<5	--	--	--	--	496
Goodsprings, Nev. II	20	1,575	545	2,804	30,171	34,294	1.9	0.0	--	--	--	--	6,140
Goodsprings, Nev. III	5	8,644	34	36,109	364	601	3,719.2	1,195.2	95.8	12.3	23.5	9.4	249
Merrimac, Nev.	9	60	70	5,596	175	9,237	<6	<19	--	--	--	--	859
Rochester, Nev.	5	400	346	4,982	13,678	2,453	<6	<18	--	--	--	--	236
Monitor, Calif.	7	33,500	134	1,998	6,795	4,093	<6	<17	--	--	--	--	1,439
Silver City, Idaho	3	3,300	163	187	<180	81	<6	<3	--	--	--	--	59
Crustal abundance		1.2	0.075	60	14	70	--	--	--	--	--	--	1.8

Table 18. Average concentrations of produced commodities (Cu, Au, Ag, Pb, Zn) and some critical minerals (Sb, As, Bi, In, Pd, Pt, Te, Sn, Zn) in mineralized samples from mine dumps in the Goldfield district, Nevada, and crustal abundances of elements.

[Data from Granitto and others (2020, 2021). Concentrations determined by NIS-FA-INAA-PGE (nickel sulfide-fire assay-instrumental neutron activation analysis-platinum group element), ICPOES (inductively coupled plasma optical emission spectroscopy), FA (fire assay), CVAAS-HG, (cold vapor atomic emission spectroscopy-mercury). ppb, parts per billion; ppm, parts per million.]

Dataset	Number of analyses	Au	Ag	Cu	Pd	Pt	Ir	Os	Rh	Ru	As	Bi	In
		(ppb)	(ppm)	(ppm)	(ppb)	(ppb)	(ppb)				(ppm)		
		C-NIS-FA-INAA-PGE	C-ICPOES-MS-49	C-NIS-FA-INAA-PGE	C-Au-Pd-Pt FA	C-NIS-FA-INAA-PGE				C-ICPOES-MS-49	C-CVAAS-HG		
I; samples analyzed 2011–2020	33	9,897	53	6,733	<2	<8	<3	<10	<0.01	<98	1,659	121	2
II; samples analyzed 2011–2020	15	21,915	114	32,937	4	5	--	--	15	4	7,125	2,243	4
III; samples analyzed 1987–1994	63	4,401	73	857	--	--	--	--	--	--	1,735	226	--
Crustal abundance		1.2	0.075	60	--	--	--	--	--	--	1.8	0.0085	0.25

Table 17. Average concentrations of produced commodities (Cu, Au, Ag, Pb, Zn) and some critical minerals (Sb, As, Bi, In, Pd, Pt, Te, Sn, Zn) in mineralized samples from mine dumps of carbonate-replacement deposits and vein deposits in Nevada and Idaho, and crustal abundances of critical minerals.—Continued

[Data from Granitto and others (2020, 2021). Concentrations determined by FA (fire assay), ICPAES (inductively coupled plasma atomic emission spectroscopy), and NIS-FA-INAA-PGE (nickel sulfide-fire assay-instrumental neutron activation analysis-platinum group elements). ppm, parts per million; ppb, parts per billion.]

Bi	In	Sb	Sn	Te	W	Be	Ce	Co	Cr	Ga	Li	Nb	Ni	Sc	Sr	V
(ppm)																
C-ICPAES-MS-42																
73	7	1,719	163	19	24	<0.3	7	3	<20	8	<9	<2.7	<5	<1.6	46	8
219	2	5,467	207	47	137	1	15	41	10	6	4	6	6	2	71	14
2	19	584	43	<0.6	161	<0.4	4	1	8	8	3	0	<3.3	1	17	<15
23	40	596	79	16	54	1	9	28	9	58	6	1	4	2	211	32
69	2	199	2	<0.3	4	<3.1	10	116	11	10	<25	<15	39	2	136	43
77	14	1,713	99	28	76	1	9	38	10	18	4	2	16	2	96	24
155	14	109	10	0	2	13	1	50	14	512	3	32	79	15	26	23
152	<6	199	36	<18	5	<1.5	25	5	14	5	20	4	11	4	138	36
2	0	383	4	<0.1	4	1	46	3	6	12	7	3	<11	3	13	17
12	0	1,777	33	55	4	1	34	9	37	12	31	1	<59	1	758	42
21	<0.05	33	1	3	2	1	9	1	7	5	61	1	<0.6	1	72	5
0.0085	0.25	0.2	2.3	0.001	1.25	2.8	66.5	25	102	19	20	20	84	22	370	120

Table 18. Average concentrations of produced commodities (Cu, Au, Ag, Pb, Zn) and some critical minerals (Sb, As, Bi, In, Pd, Pt, Te, Sn, Zn) in mineralized samples from mine dumps in the Goldfield district, Nevada, and crustal abundances of elements.—Continued

[Data from Granitto and others (2020, 2021). Concentrations determined by NIS-FA-INAA-PGE (nickel sulfide-fire assay-instrumental neutron activation analysis-platinum group element), ICPOES (inductively coupled plasma optical emission spectroscopy), FA (fire assay), CVAAS-HG, (cold vapor atomic emission spectroscopy-mercury). ppb, parts per billion; ppm, parts per million.]

Sb	Sn	Te	Be	Ce	Co	Cr	Ga	Li	Nb	Ni	Rb	Sc	Sr	V	W	Zn	Mo	Pb
(ppm)																		
C-ICPOES-MS-49																		
1,418	119	60	<3	50	6	23	15	13	8	<11	14	3	677	74	5	38	--	378
5,163	667	385	0	30	12	16	20	26	3	25	6	2	646	62	3	8,429	7	486
1,617	377	187	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	511
0.2	2.3	0.001	2.8	66.5	25	102	19	20	20	84	--	22	370	120	1.25	70	1.2	14

Table 19. Average concentrations of produced commodities (Cu, Au, Ag, Pb, Zn) and some critical minerals (Sb, As, Bi, In, Pd, Pt, Te, Sn, Zn) in mineralized samples from mine dumps in the Tonopah district, Nevada, and crustal abundances of elements.

[Data from Granitto and others (2020, 2021). Concentrations determined by FA (fire assay) and ICPAES (inductively coupled plasma atomic emission spectroscopy), ppm, parts per million.]

Dataset	Number of analyses	Au	Ag	Pt			As			Bi	Ce	Co	Cr	Ga	In
		(ppb)	(ppm)	Pd	Pt	FA	As	Bi	Ce	Co	Cr	Ga	In		
		C-Au-Pt-Pd FA	C-ICPAES-MS-42	C-Au-Pt-Pd FA	C-Au-Pt-Pd FA	As	Bi	Ce	Co	Cr	Ga	In			
I	10	6,243	457	<2	<12	81	1	22	4	10	8	0			
II	5	3,670	215	--	--	46	0	7	6	4	4	0			
Crustal abundance		1.2	0.075	--	--	1.8	0.0085	66.5	25	102	19	0.25			
Dataset	Number of analyses	Li	Nb	Ni	Sb	Sn	Te	W	Zn	Cu	Mo	Pb			
		(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)			
		C-Au-Pt-Pd FA	C-ICPAES-MS-42	C-Au-Pt-Pd FA	C-Au-Pt-Pd FA	C-ICPAES-MS-42	C-ICPAES-MS-42	C-ICPAES-MS-42	C-ICPAES-MS-42	C-ICPAES-MS-42	C-ICPAES-MS-42	C-ICPAES-MS-42			
I	10	66	14	4	29	1	30	3	1,168	232	184	1,150			
II	5	72	0	2	402	BLD	2	2	1,688	128	37	--			
Crustal abundance		20	20	84	0.2	2.3	0.001	1.25	70	60	1.2	14			

Table 20. Minerals containing and comprising critical minerals in subduction-related magmatic-hydrothermal deposits.

[wt %, weight percent; ppm, parts per million; est. estimated.]

Critical mineral commodity	Critical mineral or contained critical mineral(s)	Formula	Concentrations of critical mineral	References
Al, potash	Alumite	$KAl_3(SO_4)_2(OH)_6$	Al 19.54 wt %; K 9.44 wt %; SO_4 ~42.5 wt %	http://webmineral.com/data/Alumite.shtml
Sb	Stibnite	Sb_2S_3	71.7 wt % Sb in stibnite	http://webmineral.com/data/Stibnite.shtml
	Polybasite	Cu-Pb-Sb-As-S minerals	7.07 wt % Sb, 2.61 wt % As in polybasite	http://webmineral.com/data/Polybasite.shtml
Cu refinery slimes	Sb oxides		1–4 wt % ¹ Sb in slimes	Chen and Dutrizac (2005), Hait and others (2009)
	$SbAsO_4$			Hait and others (2009)
As	Arsenopyrite	FeAsS	46.01 wt % As in arsenopyrite	http://webmineral.com/data/Arsenopyrite.shtml
	Enargite-famatinite; tennantite-tetrahedrite	Cu-Sb-As-S minerals	19.02 wt % As in enargite	http://webmineral.com/data/Enargite.shtml
Cu refinery slimes	As oxides		2–5 wt % ¹ As in slimes	Chen and Dutrizac (2005), Hait and others (2009)
	$SbAsO_4$			Hait and others (2009)
Be	Beryl	$Be_3Al_2Si_6O_{18}$	5.02 wt % Be in beryl	http://webmineral.com/data/Beryl.shtml
Al			10.04 wt % Al in beryl	
Bi	Bismuthinite	Bi_2S_3	81.3 wt %	http://webmineral.com/data/Bismuthinite.shtml
Wittichenite, others			--	http://webmineral.com/data/Wittichenite.shtml
	Cu refinery slimes	Bi oxides	0.44–3 wt % ¹	Chen and Dutrizac (2005), Hait and others (2009)
Fluorite	Fluorspar	CaF_2	Ca 51.33 wt %; F 48.67 wt %	http://webmineral.com/data/Fluorite.shtml
Ge	Sphalerite	--	--	https://mrdata.usgs.gov/deposit/metadata/USGS_Germanium_US_Metadata.html
Ga	Sphalerite; Al refinery product	--	--	https://www.usgs.gov/data/gallium-deposits-united-states
Ga	Alumite	$KAl_3(SO_4)_2(OH)_6$	Mostly tens of parts per million	Ryuba and others (2003)
In	Cu-In-S	--	--	Observed in near-surface chalcocite-enargite-tetrahedrite resource, Sunnyside PCS, Ariz.
In	Chalcopyrite	--	--	--
K salts	Potash	--	--	--
Sylvite	Sylvite	KCl	K 52.45 wt %; Cl 47.55 wt %	http://webmineral.com/data/Sylvite.shtml
Alum, Al	--	$KAl(SO_4)_2 \cdot 12(H_2O)$	K 8.24 wt %; Al 5.69 wt %	http://webmineral.com/data/Alum-(K).shtml
Li, Al	Spodumene	$LiAlSi_3O_6$	Li 3.76 wt %; Al 14.5 wt %	http://webmineral.com/data/Spodumene.shtml
Li, Al	Lepidolite	$K(Li,Al)_3(Si,Al)_4O_{10}(F,OH)_2$	Li 3.58 wt %; Al 6.95 wt %	http://webmineral.com/data/Lepidolite.shtml

Table 20. Minerals containing and comprising critical minerals in subduction-related magmatic-hydrothermal deposits.—Continued

[wt %, weight percent; ppm, parts per million; est. estimated.]

Critical mineral commodity	Critical mineral or contained critical mineral(s)	Formula	Concentrations of critical mineral	References
Mn	Rhodochrosite	MnCO ₃	47.8 wt % Mn in rhodochrosite	http://www.webmineral.com/data/Rhodochrosite.shtml
	Psilomelane	(Ba,H ₂ O) ₂ Mn ₅ O ₁₀	46.6 wt % Mn in psilomelane	http://webmineral.com/data/Psilomelane.shtml
	Pyrolusite	MnO ₂	63.2 wt % Mn in pyrolusite	http://webmineral.com/data/Pyrolusite.shtml
Nb	Columbite	Fe ²⁺ Nb ₂ O ₆	55.0 wt % Nb in columbite	http://webmineral.com/data/Columbite-(Fe).shtml
Pd	Merenskyite; tellurides	(Pd,Pt)(Te,Bi) ₂	59.39 wt % Te, 24.76 wt % Pd in merenskyite	http://webmineral.com/data/Merenskyite.shtml
Pt, Pd	--	Cu refinery anode slimes	Est. parts per trillion Pt, Pd in slimes	--
Re	Molybdenite	MoS ₂	<10 to 2,000 ppm in molybdenite	John and Taylor (2016)
Sn	Cassiterite	SnO ₂	78.38 wt % Sn in cassiterite	http://webmineral.com/data/Cassiterite.shtml
Sn	Stannite	Cu ₂ FeSn ₄	27.6 wt % Sn in stannite	http://webmineral.com/data/Stannite.shtml
Sn, V, Ge, As, Sb	Colusite	Cu ₁₂₋₁₃ V(As,Sb,Sn,Ge) ₃ S ₁₆	V 3.04 wt %; Sn 4.26 wt %; Ge 1.30 wt %; As 6.72 wt %; Sb 6.55 wt % in colusite	http://webmineral.com/data/Colusite.shtml
Ta	Microcline	(Na,Ca) ₂ Ta ₂ O ₆ (OH,F)	68.4 wt % Ta in microcline	http://webmineral.com/data/Microcline.shtml
	Tantalite	MnTa ₂ O ₆	70.6 wt % Ta in tantalite	http://webmineral.com/data/Tantalite-(Mn).shtml
Te	Chalcopyrite	CuFeS ₂	Est. parts per billion in chalcopyrite	Ballantyne and others (1997)
	Hessite	Ag ₂ Te	37.2 wt % Te in hessite	http://webmineral.com/data/Hessite.shtml ; Hait and others (2009)
	Petzite	Ag ₃ AuTe ₂	32.9 wt % Te in petzite	http://webmineral.com/data/Petzite.shtml
	Calaverite	AuTe ₂	56.4 wt % Te in calaverite	http://webmineral.com/data/Calaverite.shtml
	Wehrlite	Bi ₃ Te ₂	--	Ballantyne and others (1997), Kocher (2017), Brodbeck and others (2020), http://webmineral.com/data/Merenskyite.shtml
	Merenskyite	(Pd,Pt)(Te,Bi) ₂	59.39 wt % Te in merenskyite	
	Cu refinery slimes	Au, Ag tellurides; Cu-Se-Te	0.4–1.45 wt % ¹ Te in slimes	Chen and Dutrizac (2005), Hait and others (2009)
V	Vanadinite	Pb ₅ (VO ₄) ₃ Cl	10.8 wt % V in vanadinite	http://webmineral.com/data/Vanadinite.shtml
V, Sn, Ge, As, Sb	Colusite	Cu ₁₂₋₁₃ V(As,Sb,Sn,Ge) ₃ S ₁₆	V 3.04 wt %; Sn 4.26 wt %; Ge 1.30 wt %; As 6.72 wt %; Sb 6.55 wt % in colusite	http://webmineral.com/data/Colusite.shtml
W	Scheelite	CaWO ₄	63.9 wt % W in scheelite	http://webmineral.com/data/Scheelite.shtml
	Wolframite	(Fe,Mn)WO ₄	60.6 wt % W in wolframite	http://webmineral.com/data/Wolframite.shtml
	Ferberite	FeWO ₄	60.5 wt % W in ferberite	http://webmineral.com/data/Ferberite.shtml

¹Domestic copper refineries only (Amarillo, Tex.; El Paso, Tex.; Magna, Utah).

Table 21. Apparent annual domestic consumption and import reliance of critical mineral commodities described in this report.

[Data from from U.S. Geological Survey (2021). est., estimated; REE, rare earth elements; t, metric tons; %, percent; PGE, platinum-group elements.]

Critical mineral commodity	Units	Consumption					Net import reliance as percentage of consumption	Domestic production, consumption, import, and export notes
		2016	2017	2018	2019	2020		
Al	Thousand metric tons	5,090	5,680	4,900	4,940	2,870	13–59	Domestic production from imports and scrap, ~20% exported
Sb	Metric tons	25,900	27,400	27,700	26,400	22,000	81–84	Domestic production from lead-acid batteries and imported feedstock were ~18% of consumption; exports and imports include ore, concentrate, oxide, powder, and scrap
As (est.)	Metric tons	6,120	6,920	6,470	7,480	10,500	100	Exported As products were <1 to 29% of imports
Bi	Metric tons	1,780	2,530	2,080	1,650	1,400	94–97	Small production from scrap; exports included metal, alloys, and scrap
Co	Metric tons	10,300	11,500	8,920	7,580	12,400	64–78	Primary and secondary domestic production ~34–43% of consumption; some Co products exported
Fluorite	Thousand metric tons	371	390	450	368	380	100	Imports included acid and metallurgical grade fluorspar, HF acid, AlF ₃ , and cryolite
Ga	Metric tons	18.1	17.9	15.0	17.9	15.0	100	Minor domestic production from impure Ga and scrap
Ge (est.)	Metric tons	30	30	30	30	30	>50	Imports included metal and GeO ₂ ; domestic Zn concentrates containing Ge were exported; ~16–31% of imports were exported as products or equivalents in Zn concentrates
In (est.)	Metric tons	160	127	125	95	100	100	Undisclosed tonnages were exported as alloys, metal, and solders
Mn	Thousand metric tons	545	714	793	790	520	100	Imports included ores, concentrates, ferromanganese, and silicomanganese
Ni	Thousand metric tons	235	273	259	217	200	44–52	Consumption included metal and scrap; domestic mine concentrate was shipped abroad for processing; by-product from Stillwater PGE mines; ~40–67% of imports were exported in various forms including Ni equivalents in concentrates
Potash (K₂O equivalent)	Thousand metric tons	5,100	6,200	6,100	5,300	5,500	88–92	Domestic production from New Mexico and Utah hard rock and solution mining
Re	Metric tons	40.3	42.7	47.6	52.6	32	76–84	Domestic production included byproduct of refined Mo concentrates, scrap, and waste
REE	Metric tons	10,500	9,060	6,520	11,700	7,800	100	Domestic production exported for processing
Te	Metric tons	withheld	withheld	withheld	withheld	withheld	>95	Consumption estimated from net import reliance and imports was ~60–200 t from 2016 to 2019
Ti mineral concentrates	Thousand metric tons	1,100	1,300	1,200	1.3	900	88–92	Domestic production included ilmenite and rutile from Georgia, Florida, and South Carolina

Table 21. Apparent annual domestic consumption and import reliance of critical mineral commodities described in this report.—Continued

[Data from from U.S. Geological Survey (2021). est., estimated; REE, rare earth elements; t, metric tons; %, percent; PGE, platinum-group elements.]

Critical mineral commodity	Units	Consumption					Net import reliance as percentage of consumption	Domestic production, consumption, import, and export notes
		2016	2017	2018	2019	2020		
Ti	Metric tons	54,100	37,400	35,200	withheld	withheld	45–88	Consumption included metal and TiO ₂ pigment
TiO ₂	Metric tons	840,000	870,000	893,000	965,000	900,000	Net exportation	
W	Metric tons	withheld	withheld	withheld	withheld	withheld	>25 to >50	Consumption estimated from net import reliance and imports was ~10,000–14,500 t

Table 22. Significant domestic reserves and resources, exclusive of porphyry copper-molybdenum deposits (fig. 6; tables 13–15), of some critical minerals that comprise 2 years or more of recent (2016–2020) apparent annual domestic consumption.

[Data from U.S. Geological Survey (2021). Sites with unquantified but potentially large masses and that may represent more than 2 years of recent consumption are described in the text. Market volume: very large market, annual domestic consumption of more than 1 million metric tons (Mt); large market, consumption of hundreds of thousands of metric tons; mid-market, consumption of tens of thousands of metric tons; small market, consumption of several thousand metric tons; very small market, consumption of tens to hundreds of metric tons. REE, rare earth elements; kt, thousand metric tons; t, metric tons.]

Critical mineral commodity	Relative market volume	Apparent annual domestic consumption (2016–2020)	Domestic reserve/resource site	Estimated mass (metric tons critical mineral)	Approximate equivalent consumption (years)	Reserves and resources references	New domestic supply barriers
Al	Very large market	2.87–5.68 Mt	Blawn Mountain, Utah Red Mountain, Ariz. Sunnyside, Ariz. San Gabriel Mountains, Calif.	2.45 Mt 18 Mt 7 Mt Potentially large	6–0.5	See text North American Potash Developments, Inc. (2012) Table 3 Carter (1982)	World market competition
Sb	Mid-market	22,000–27,700 t	Coyote district, Utah Yellow Pine, Idaho	95,455 t 59,000–112,000 t	4.8–3.8 5.1–2.1	Palladine (1941); Mills and Rupke (2020) Becker and others (2019); NS Energy (2021)	-- Possible byproduct
As	Mid-market	est. 6,120–10,500 t	Yellow Pine, Idaho	209,673 t	34–20	Table 8	Possible byproduct
Bi	Small market	1,400–2,530 t	Yellow Pine, Idaho	38,989 t	28–15	Table 8	Possible byproduct
Co	Mid-market	7,580–12,400 t	none	--	--	--	--
Fluorite	Large market	368–450 kt	McCullough Butte, Nev. New Mexico, Utah, Nevada	>8,000 kt >1 Mt	22–18 Several	Tertiary Minerals PLC, 2020 U.S. Geological Survey and others (1965), Bullock (1976, 1981), Papke (1979)	Grades are uncompetitive in world markets
Ga	Very small market	15–18.1 t	Apex mine, Utah	300 t	20–17	Dutrizac and others (1986); Mills and Rupke (2020)	Very small market sensitive to new supply
Ge	Very small market	est. 30 t	Apex mine, Utah	773 t	26	Dutrizac and others (1986); Mills and Rupke (2020)	Very small market sensitive to new supply
In	Very small market	est. 95–160 t	Fish Springs, Utah	1,474–2,077 t	22–9	Dyer and others (2014)	Very small market sensitive to new supply
Mn	Large market	520–793 kt	Hardshell-Alta-Hermosa, Arizona (Clark deposit)	5 Mt	6.6	South32 Limited, 2021	World market competition
Ni	Large market	200–273 kt	none	--	--	--	--

Table 22. Significant domestic reserves and resources, exclusive of porphyry copper-molybdenum deposits (fig. 6; tables 13–15), of some critical minerals that comprise 2 years or more of recent (2016–2020) apparent annual domestic consumption.—Continued

[Data from U.S. Geological Survey (2021). Sites with unquantified but potentially large masses and that may represent more than 2 years of recent consumption are described in the text. Market volume: very large market, annual domestic consumption of more than 1 million metric tons (Mt); large market, consumption of hundreds of thousands of metric tons; mid-market, consumption of tens of thousands of metric tons; small market, consumption of several thousand metric tons; very small market, consumption of tens to hundreds of metric tons. REE, rare earth elements; kt, thousand metric tons; t, metric tons.]

Critical mineral commodity	Relative market volume	Apparent annual domestic consumption (2016–2020)	Domestic reserve/resource site	Estimated mass (metric tons critical mineral)	Approximate equivalent consumption (years)	Reserves and resources references	New domestic supply barriers
Potash	Very large market	5.2–6.2 Mt	Blawn Mountain, Utah	10.6–32 Mt	8–4	SOPerior Fertilizer Corp. (2021)	World market competition
			Red Mountain, Ariz.	42 Mt		See text	
			Sunnyside, Ariz.	27 Mt		See text	
Re	Very small market	32–53 t	None	Potentially large	Potentially many	Figs. 44–D, 6; tables 3–6	Very small market sensitive to new supply
REE	Small-mid-market	7,800–11,700 t	San Gabriel Mountains, Calif.	Est. 1.8 Mt	Potentially many	Carter (1982)	Semi-quantified; location; recovery; world market competition
Te	Very small market	Est. 160 t	Boulder County, Colo.	<60 t	<3	Kelly and Goddard (1969)	Unquantified; very small market sensitive to new supply
			Cripple Creek, Colo.	Potentially large	Potentially many	Table 8	
			Goldfield, Nev.	Potentially large	Potentially many	Table 18	
			Paradise Peak, Nev.	Potentially large	Potentially many	Table 18	
Ti mineral concentrates	Large market	900–1,300 kt	San Gabriel Mountains, Calif.; Wyoming	Potentially large	Potentially many	Carter (1982)	Semi-quantified; location; recovery; world market competition
Ti	Mid-market	35,200–54,100 t					
Ti (TiO₂)	Large market	840–965 kt					
W	Mid-market	Est. 11,000–14,450 t	Pilot Mountain, Nev.	27,200 t	2–4	Thor Mining PLC (2018a, b)	World market competition
			Andrew Curtis, Calif.	42,000 t		Annis (2020a, b)	
			Centennial, Nev.	32,200 t		SRK Consulting (2014)	
			Sunrise, Wash.	31,700 t		Derkey and others (1990)	
			Indian springs, Nev.	20,800 t		Moran and Stryhas (2007)	

Chapter A



Rare Metals Corporation roadside advertisement for tungsten concentrates mined and milled under 1940s–1950s price supports near Lovelock, Nevada.

Chapter A. Primary Product and Coproduct Production of Critical Minerals

In this chapter, the largest, subduction-related deposits from which the critical minerals Al, Sb, As, Be, Bi, fluorite, Ga, Ge, Mn, Sn, W, and V were produced as primary products and coproducts are described (fig. 1A, E; tables 1, 2) and production compared to recent domestic consumption (tables 21, 22). Deposits described are mostly those with production ranging from percents to tens of percents or more of recent consumption. There are numerous small deposits of tungsten, antimony, fluorite, and manganese in Western States in which these critical minerals were primary products. For example, there are approximately 285 tungsten deposits and production sites in Western States (Kerr, 1946) and 184 antimony deposits in Nevada alone (Lawrence, 1963), many of which produced tens to several hundred metric tons of tungsten and antimony as primary products under war-era price supports (Limbaugh, 2006, 2010; Karl and others, 2020). These and other primary commodity deposits that individually represent very small proportions of recent consumption are not described. However, descriptions of several small critical mineral deposits are included below if they represent the few or only primary production sites (for example, Al, Bi, potash, Sn, and V).

Mineral System—Porphyry Cu-Mo-Au

Deposit type—Polymetallic Sulfide Skarn, Replacement, Vein

Arsenic (As)

Arsenic was produced for short periods during the World Wars (mostly 1918–1919 and 1943–1945) from arsenopyrite in vein and replacement deposits in the Gold Hill district, Tooele County, Utah. Production estimates vary from 24,000 to 100,000 short tons (21,820 to 90,910 metric tons [t]) of arsenic (Huntoon, 1919; El-Shatory and Whelan, 1970; Robinson and others, 1993; Robinson, 2006; Mills and Rupke, 2020). Small amounts of arsenic (approximately 1,504 short tons [1,367 t]) were recovered from realgar and orpiment in carbonate-replacement ores mined intermittently for gold, antimony, and arsenic at the White Caps mine, Nye County, Nev. (Williams, 1932; Kleinhampl and Ziony, 1984). An unquantified amount of arsenic was produced from quartz veins in Paleozoic strata in the Battle Mountain district, Lander County, Nev. (Stewart and others, 1977). Small but unquantified amounts of arsenic were recovered from speiss, a product of smelting lead-zinc-silver-gold carbonate-replacement and vein deposits in the Eureka district, Eureka County, Nev. (Roberts and others, 1967).

Annual domestic consumption of arsenic from 2016 to 2020 varied from 6,120 to 10,500 t and net imports provided 100 percent of consumption (table 21; U.S. Geological Survey [USGS], 2021). Total recorded production of

arsenic from subduction-related deposits in Western States was equivalent to approximately 2.2 to 15 years of recent domestic consumption.

Bismuth (Bi)

Bismuth has been recovered mostly as a byproduct in numerous vein, skarn, and carbonate-replacement deposits in Western States that were mined primarily for Cu, Pb, Zn, Ag, and Au (USGS and Montana Bureau of Mines and Geology, 1963; USGS and Nevada Bureau of Mines, 1964; USGS and others, 1964, 1965, 1969). In a few deposits bismuth apparently was a coproduct, although production statistics that include bismuth concentrations in ores are seldom available, and the economics of mining are infrequently described. Tonnages and years of production are sporadically listed in annual reports of mining companies. In the Leadville district, Lake County, Colo., carbonate and oxide ores containing 5 to 16 weight percent bismuth and approximately 1 troy ounce per short ton (31.1 grams per metric ton [g/t]) of gold were episodically mined on Breece Hill from deposits in the Lilian, Ballard, Big Six, Penn, and other mines (Henderson, 1926; Emmons and others, 1927; Tweto, 1968); bismuth may have been the primary commodity during some years of mine operation. An estimated 1,000 short tons (909 t) of bismuth carbonate minerals were shipped in 1901 for bismuth recovery, apparently to St. Louis, Missouri, and Liverpool, England. An unquantified amount of bismuth was recovered at the Arkansas Valley smelter that processed Leadville-district ores.

In the Tintic and Little and Big Cottonwood districts, Utah County and Salt Lake County, respectively, Utah, small amounts of bismuth recovered from polymetallic carbonate-replacement deposits may have been a coproduct in some ores (Hess, 1919; Kasteler and Hild, 1948; Krahulec and Briggs, 2006). At Tintic, approximately 6.24 short tons (5.67 t) of bismuth were produced from the Iron Blossom mine prior to 1938 acquisition of the mine by the Tintic Standard Mining Company (Tintic Standard Mining Company, 1938). In the Little and Big Cottonwood districts, small amounts of copper-silver-gold ore produced in 1936 contained approximately 3 percent bismuth (Alta United Mines Company, 1936).

Annual domestic consumption of bismuth from 2016 to 2020 varied from 1,400 to 2,530 t and net imports provided 94 to 96 percent of consumption (table 21; USGS, 2021). Total primary and coproduct production of bismuth from subduction-related deposits in Western States is unknown but likely represents a few years at most of recent domestic consumption.

Manganese (Mn)

Production of manganese in the Butte district, Silver Bow County, Mont., began in 1917 and by 1973 constituted approximately 1.85 million short tons (Mst) (1.68 Mt); manganese was largely recovered from rhodochrosite in Cu-Au-Ag-Pb-Zn vein deposits (Anaconda Copper Mining Company, 1915–1955; Meyer and others, 1968; Miller, 1973) and shipped to steel mills. In the Bisbee district, Cochise County, Ariz., manganese oxides were produced during World

War I (1916–1918), from 1925 to 1930, during World War II (1941–1943) (4,545 t of manganese) and in subsequent years under price supports (Farnham and others, 1961; Graeme, 1981). Production of manganese ore and concentrate containing approximately 40 percent manganese is estimated at 35,000 short tons (31,818 t) (Farnham and others, 1961). The vein-like and fissure-filling deposits occur in Paleozoic carbonate rocks (Jones and Ransome, 1920). Manganese oxide minerals were derived from weathering of rhodochrosite and rhodochrosite (Schumer, 2017). In the Globe district, Gila County, Ariz., more than 25,000 t of manganese ore and concentrate containing less than 25 to more than 38 percent manganese were produced from mines in the vicinity of the town of Globe. The manganese-oxide deposits, many containing recoverable silver, occur in faults and fracture zones in Paleozoic quartzite and diabase adjacent to Cretaceous felsic intrusions (Jones and Ransome, 1920; Farnham and others, 1961). In the adjacent Superior district, Pinal County, Ariz., approximately 35,000 t of manganese-oxide ore and concentrate containing approximately 28 percent manganese were mined from faults and replacement deposits in Paleozoic limestone and quartzite, mostly under wartime and 1950s price supports (Farnham and others, 1961). At Tombstone, Cochise County, Ariz., small tonnages of manganese-silver oxide ore were mined from near-surface, pipe-like deposits in Paleozoic and Mesozoic carbonate rocks adjacent to Cretaceous felsic intrusions (Jones and Ransome, 1920; Butler and others, 1938). Production, mostly during wartime and enabled in part by silver content, was approximately 13,000 short tons (11,818 t) grading approximately 35 percent manganese (Farnham and others, 1961).

In the Leadville district, Colo., approximately 3.2 Mt of metallurgical and flux grade (approximately 15–45 percent manganese) manganese-oxide ore and larger tonnages of lower grade manganese-iron-silver-silica (SiO_2) oxide ore were mined from oxidized zones of Pb-Zn-Cu-Au-Ag replacement and vein deposits in Paleozoic carbonate rocks, in part under wartime price guarantees. These oxide ores were used locally for smelting low-grade lead-silver ores and in steel manufacturing in Pueblo, Colo., and eastern facilities (Emmons and others, 1927; Hedges, 1940; Tweto, 1968). In the Gilman district, Eagle County, Colo., 0.21 Mst (0.19 t) of manganese-oxide ore averaging 15 percent manganese were mined from the oxidized zones of Cu-Ag-Zn-Pb-Au manto and chimney replacement deposits in Paleozoic carbonate rocks (Radabaugh and others, 1968). More than 1.1 Mst (1 Mt) of manganese-oxide ore were produced from Pb-Zn-Cu-Ag-Au replacement, vein, and pipe-like deposits in Paleozoic sedimentary rocks in the Pioche, Bristol, and Jackrabbit districts, Lincoln County, Nev. (Tschanz and Pampeyan, 1970). In the Tintic district, Utah, approximately 735 short tons (668 t) of manganese were produced in 1931 (Chief Consolidated Mining Company, 1931), with manganese production likely in previous and subsequent years. Manganese oxide was reportedly shipped to steel mills from Tintic mines (James, 1984; Krahulec and Briggs, 2006); tonnages and years are intermittently listed in annual

reports of Tintic mining companies. At Leadville, Gilman, and Pioche the manganese-oxide ores consist primarily of manganosiderite or were derived from weathering of manganosiderite; some manganese ores contained small to significant amounts of Ag, Au, Zn, Pb, Cu, and Bi. At Leadville, manganosiderite comprised “haloes” around lead-zinc sulfide deposits (Hedges, 1940). Most manganese oxides were produced in these districts under price guarantees during World War II.

Annual domestic consumption of manganese from 2016 to 2020 varied from 530,000 to 794,000 t and net imports provided 100 percent of consumption (table 21; USGS, 2021). The estimated total primary and coproduct production of manganese from subduction-related deposits in Western States, for the same time period, is approximately equivalent to 20 years of recent domestic consumption, although total mined tonnages of manganese cannot be precisely calculated because some production is reported as manganese-oxide ores with unquantified or a range of manganese grades.

Vanadium (V)

At the St. Anthony mine, Mammoth district, Pinal County, Ariz., Pb, Zn, Au, V, and lesser Cu, Mo, and Ag were recovered from vein deposits in Laramide(?) age quartz monzonite and Cenozoic rhyolite. Approximately 710 short tons (645 t) of vanadium (2,540,842 pounds of vanadium oxide) were produced from 1934 to 1944 possibly as a coproduct; vanadium occurred primarily in vanadinite. In 1938, mill concentrate contained 0.4–0.5 percent WO_3 ; tungsten is contained in wulfenite and vanadinite (Creasey, 1950; Creasey and Pelletier, 1965). Mill tailings analyzed during World War II contained approximately 560 parts per million (ppm) vanadium (Kaiser and others, 1954), indicating that elevated concentrations of tungsten and vanadium may remain in tailings. Small amounts of vanadium in vanadate minerals were produced as byproducts from several porphyry Cu-Mo and polymetallic carbonate-replacement deposits in Arizona, New Mexico, Nevada, and California (Fischer, 1975).

Annual domestic consumption of vanadium from 2016 to 2020 varied from 4,800 to 9,980 t and net imports provided 94 to 100 percent of consumption (table 21; USGS, 2021). Coproduct vanadium production from the St. Anthony mine represents less than 1 year of recent domestic consumption.

Deposit type—Skarn-Replacement-Vein (S-R-V) Tungsten

Tungsten (W)

The tungsten-skarn deposits near Bishop, Inyo County, Calif., were the largest domestic source of tungsten with production of 24,878 t of tungsten, 7,760 t of molybdenum, and 8,910 t of copper from 1916 to 1965 (Gray and others, 1968; Werner and others, 2014; table 1). Most of the approximately 6 Mt processed were produced by the Pine Creek mine where ore was extracted from five irregular

bodies that averaged 0.7 percent WO_3 (Dixon, 1979) and less than 1 percent molybdenum and copper. Oxide and sulfide minerals in ore included scheelite, bornite, chalcocite, chalcopyrite, covellite, molybdenite, powellite, and small amounts of bismuthinite which were variably concentrated in skarn consisting of garnet, pyroxene, and lesser quartz, calcite, orthoclase, idocrase, and plagioclase. Tactites formed along the contact between Early Cambrian to Late Triassic metasedimentary rocks and sills of middle Cretaceous Morgan Creek quartz monzonite (Bateman, 1956; Gray and others, 1968; Newberry, 1982; Karl and others, 2020). Scheelite was later remobilized during hydrosilicate alteration during which wollastonite and idocrase were replaced by calcite-quartz-z-epidote-chlorite-fluorite assemblages (Newberry, 1982). Additional attributes of the Pine Creek tungsten deposits, other tungsten deposits with relatively large production described below, and deposits with significant tungsten resources described in chapter C, are compiled in [table 2](#).

The Springer mine (also known as Nevada-Massachusetts), Pershing County, Nev., and nearby mines produced approximately 10,810 t of tungsten from deposits in Late Triassic marine sedimentary rocks adjacent to Cretaceous granodiorite of the Springer, Uncle Sam, and Olsen stocks (Johnson, 1977; Associated Geosciences, Ltd., 2012). Average grade during production years (1918–1958) was 0.875 percent WO_3 . Production was episodic because of high wartime demand and intervening periods of unsupported tungsten prices. Tailings were reprocessed several times during periods of guaranteed prices. Ore occurs in masses of skarn hundreds to more than 1,000 feet (ft) (330 meters [m]) in lateral dimension and 3 to 6 ft (1–2 m) wide that consist of quartz, garnet, epidote and scheelite from which tungsten was recovered (Johnson, 1977). Later remobilization formed coarse-grained scheelite aggregates and fine- to medium-grained euhedral scheelite crystals (Associated Geosciences, Ltd., 2012). In addition to tungsten in scheelite, ore contained molybdenum and copper in molybdenite and chalcopyrite, respectively, that apparently were not recovered (McCandlish and Odell, 2012).

In the Atolia district, San Bernardino and Kern Counties, Calif., relatively high-grade, steeply dipping, scheelite-quartz-carbonate veins (3.5 to 8.5 weight percent WO_3) were mined in and adjacent to the Cretaceous Atolia Quartz Monzonite intrusion. At least 6,568 t of tungsten were produced from vein ores and lesser placer deposits (Lemmon and Dorr, 1940; USBM, 1943; Bateman and Irwin, 1954; Gavryliv, 2020). Production, which included tailings reprocessing, spanned 1905–1950 and was episodic, as at other domestic tungsten mines, because of fluctuating demand and sporadic price supports.

The tungsten-skarn deposit at Browns Lake, Beaverhead County, Mont., produced 567,477 t grading 0.35 percent WO_3 from 1953 to 1958 (approximately 1,432 t of tungsten) (Werner and others, 2014), and 19,200 short tons (17,455 t)

grading 0.18 percent WO_3 were mined from 1952 to 1956. From 1970 to 1975, approximately 12,500 short tons (11,364 t) were mined that yielded about 14 units WO_3 (Stager and Tingley, 1988). The deposit is enriched in copper and molybdenum (Pattee, 1960; Karl and others, 2020), but apparently neither was recovered. Rocks that host ore are the Pennsylvanian Amsden Formation (Geach, 1972) and quartz monzonite of the Late Cretaceous to Paleocene Mount Torrey batholith (Peters, 1971). Primary oxide and sulfide minerals are scheelite, chalcopyrite, bornite, covellite, and powellite (Pattee, 1960; Karl and others, 2020), and skarn minerals include garnet, limonite, specular hematite, and epidote (Peters, 1971).

Although annual domestic production and consumption of tungsten from 2016 to 2020 have not been quantified, imports for consumption varied from 11,000 to 14,450 t, and net imports provided more than 25 percent of consumption ([table 21](#); USGS, 2021). If imports for consumption approximate consumption, then tungsten production from deposits at Pine Creek, Springer, Atolia, and Browns Lake is each equivalent to approximately 2 to less than 1 year of recent domestic consumption.

Deposit type—Lithocap Alunite

Aluminum (Al) and Potash (KCl, K_2SO_4 , KNO_3)

In Utah, small amounts of high-grade alunite (approximately 0.31 Mt) were mined from vein and lesser replacement deposits in Cenozoic volcanic rocks near Marysvale (Piute, Sevier, and Beaver Counties) and at Blawn Mountain (Beaver County) where it was processed for aluminum and potash fertilizer during World Wars I and II (Thoenen, 1941; Hild, 1946; USGS and others, 1964; Hall, 1978; Lowe and others, 1985; Mills and Rupke, 2020; SOPerior Fertilizer Corp., 2021). In Nevada, three “carloads” of alunite were shipped from a lens of impure alunite in Cenozoic volcanic rocks near Boyd, Lincoln County, Nev., for use as fertilizer (Tschanz and Pampeyan, 1970; Lowe and others, 1985). At Sulfur, Humboldt County, Nev., an estimated 500 short tons (455 t) of alunite were mined from several high-angle veins (Vanderburg, 1938); small alunite resources may exist in resistant quartz-alunite knobs and ridges to the west of Sulfur. Other explored alunite deposits in Arizona, Colorado, Nevada, and Utah have small to no recorded production.

Annual domestic consumption of aluminum from 2016 to 2020 varied from 2.87 to 5.68 Mt and net imports provided 13 to 59 percent of consumption ([table 21](#); USGS, 2021). Annual domestic consumption of potash from 2016 to 2020 varied from 5.1 to 6.2 Mt and net imports provided 88 to 92 percent of consumption ([table 21](#); USGS, 2021). Production of aluminum and potash from subduction-related alunite deposits in Western States was miniscule relative to recent consumption.

Mineral System—Porphyry Tin (Granite Related)

Deposit Type—Porphyry/Skarn

Tin (Sn)

In California, approximately 130 t of tin were recovered from quartz-tourmaline-cassiterite veins and pipes in the Temescal district (Riverside County) (Bedford and Johnson, 1946; USGS and others, 1966a). Veins are in Cretaceous hornblende-biotite quartz monzonite.

The Majuba Hill copper-(tin, silver, gold) deposit (Pershing County, Nev.) consists of breccias and veins in nested and juxtaposed Oligocene rhyolite domes and sub-volcanic intrusions with varietal textures and compositions. The rhyolites intruded Mesozoic argillite and siltstone. From 1906 to 1951, Majuba Hill area mines produced approximately 1,100 short tons (1,000 t) of copper; 184,000 troy ounces (5.7 t) of silver; 440 short tons (400 t) of lead; less than 5,253 troy ounces (0.16 t) of gold, minor zinc, and approximately 10 to 15 short tons (9.1–13.6 t) of tin. Production was primarily based on copper concentrations (chalcopyrite). Recovery of tin, which occurred in a separate deposit of cassiterite, was apparently feasible because of mine development for copper extraction (Smith and Gianella, 1942; Trites and Thurston, 1958; Wenrich and others, 1986; Bookstrom and MacKenzie, 1978; Holmwood and others, 2021), and was likely a short-lived coproduct. Elevated tin and copper concentrations of up to 95.4 and 31,800 ppm, respectively, occur among 994 soil samples adjacent to the rhyolite intrusions to the south and west, although concentrations in part may reflect windblown tailings from a dismantled recovery plant (Morris, 2017).

Minor tin deposits, with very small production relative to recent annual domestic consumption, occur in the Taylor Creek district, N. Mex., and in the Thomas Range and Wah Wah Range, Utah (Volin and others, 1947; USGS and others, 1965; Eggleston and Norman, 1986; Maxwell and others, 1986; Duffield and others, 1990, 1995).

Annual domestic consumption of tin from 2016 to 2020 varied from 32,000 to 36,800 t and net imports provided 75 to 77 percent of consumption (table 21; USGS, 2021). Total primary and coproduct production of tin from subduction-related deposits in Western States was miniscule relative to recent consumption.

Unclassified Magmatic-Hydrothermal Deposits

Antimony (Sb), Arsenic (As), and Tungsten (W)

Deposits mined for antimony are widespread in Western States (USGS and Montana Bureau of Mines and Geology, 1963; USGS and Nevada Bureau of Mines, 1964; USGS and others, 1964, 1965, 1969). The few deposits with relatively large production (more than 100 short tons [91 t] of antimony) are mostly in Idaho, Nevada, and Utah. Numerous smaller antimony deposits were mined primarily during World War II under government price support programs.

In the Stibnite-Yellow Pine district, Valley County, Idaho, approximately 44,000 short tons (40,000 t) of antimony, approximately 1 million troy ounces (31.1 t) of gold, 2.1 million troy ounces (65.3 t) of silver, and 0.86 million units of tungsten (approximately 6,200 t) were produced from two fault zones (tens of meters wide) in Cretaceous granitic plutons of the Idaho batholith and in a pendant of late Proterozoic–early Paleozoic siliciclastic and carbonate strata. Largely cospatial and juxtaposed deposits of gold, silver, antimony, and tungsten in the Meadow Creek fault zone represent several hydrothermal events in which stibnite, the source of recovered antimony, is among the youngest epigenetic minerals. Stibnite and other recovered commodities (gold and silver minerals, scheelite) occur with quartz, potassium-feldspar, muscovite, and carbonate minerals in breccia fragments, breccia matrices, and veins that comprise the Meadow Creek fault zone (Perpetua Resources, 2021; Vikre and others, in press).

In Nevada, the fifteen deposits which each produced 100 or more short tons (91 or more t) of antimony (reported production varies somewhat by source) are mostly in the Humboldt, South Humboldt, Trinity, and Clan Alpine ranges in Pershing, Churchill, and Lander Counties. The deposits occur in Mesozoic limestone, calcareous shale, and lesser siliciclastic and volcanic rocks; some are in or adjacent to Cretaceous granitic intrusions (Lawrence, 1963; Johnson, 1977; Vikre, 1977). The antimony-only vein deposits of the Humboldt Range and South Humboldt Range include the Bloody Canyon mine which produced approximately 1,200 short tons (1,090 t) of antimony (Lawrence, 1963) (100 short tons [91 t] according to Lowe and others, 1985). Mined veins were up to 10 ft (3 m) wide, consist primarily of quartz, stibnite, and lesser pyrite, and occur in Early Triassic rhyolites of the Koipato Group (Vikre, 1977, 2014). Several hundred to more than 1,000 short tons of antimony recovered from other vein deposits in these ranges occur in Triassic and Jurassic carbonate and siliciclastic strata (Lowe and others, 1985). The largest of these deposits, the Sutherland mine, produced 1,542 short tons (1,402 t) of antimony (Lowe and others, 1985). The broadly elliptical distribution and ages of antimony, mercury, tungsten, and gold deposits in the Humboldt Range have been attributed to thermal zoning around Cretaceous intrusions (Vikre and McKee, 1985; Vikre, 2014). Antimony was likely a coproduct in contact deposits adjacent to granitic intrusions (for example, Arabia district) from which appreciable silver and lead were recovered. The cluster of quartz-stibnite-sulfide vein deposits mined for antimony in the Bernice Canyon area (Churchill County), with production of tens to more than 100 short tons (91 t) of antimony, are also in Mesozoic sedimentary rocks, some near highly altered dikes. The Bray-Beulah and Antimony King mines in the Toiyabe Range (Lander County) produced more than 908 and 450 short tons (825 and 409 t) of antimony, respectively, from quartz-stibnite veins in Paleozoic siliciclastic rocks (Lawrence, 1963; Lowe and others, 1985). In all deposits antimony was

recovered mostly from stibnite and antimony-oxide minerals formed by weathering; minor amounts of antimony were recovered from Pb-Sb-Fe-Ag-S minerals.

In the Coyote (Antimony) district, Piute County, Utah, antimony was recovered from horizontal lenses consisting of fractured sandstone, veins, and small masses of stibnite and antimony oxides within a sequence of Paleocene conglomerate, sandstone, and shale exposed in Antimony Canyon (Traver, 1949; USGS and others, 1964; Callaghan, 1973; Mills and Rupke, 2020). The extent of stopes and mine dumps implies modest production, but tonnages have not been published. Using an estimated value of production (\$100,000) (Traver, 1949) and an average price of antimony from 1900 to 1920 (\$0.115 per pound [lb]) (Carlin, 2013), approximately 395 t of antimony were produced.

At the White Caps mine, Nye County, Nev., gold, antimony, and arsenic were recovered from pipe-like and stratiform replacement deposits consisting of quartz, calcite, fine-grained gold, stibnite, realgar, orpiment, and other sulfide minerals; deposits are mostly in the Cambrian White Caps Limestone Member of the Gold Hill Formation (Kral, 1951; Lawrence, 1963; Kleinhampl and Ziony, 1984). Apparently, no igneous rocks occur in the immediate vicinity of the deposits. Gold, antimony, and arsenic were produced both simultaneously and separately from approximately 1912 through at least 1967. Simultaneous production from 1931 to 1940 was approximately 34,000 short tons (30,909 t) with estimated average gold grade between 1 and 2 troy ounces per short ton (32 and 54 g/t), antimony between 1 and 2 weight percent, and arsenic between 2 and 3 weight percent (Williams, 1932). An earlier shipment (circa 1920) of arsenic-gold ore contained approximately 335 short tons (305 t) of arsenic (Kral, 1951). Small amounts of ore cumulatively containing several tens of short tons antimony were shipped to smelters and processing facilities until 1958 (Lawrence, 1963). Total ore production to 1967 was approximately 152,000 short tons (138,182 t) and included approximately 142 short tons (129 t) of antimony and approximately 1,504 short tons (1,367 t) of arsenic, presumably all produced from the White Caps mine (Williams, 1932; Couch and Carpenter, 1943; Kleinhampl and Ziony, 1984).

Annual domestic consumption of antimony from 2016 to 2020 varied from 22,000 to 27,700 t and net imports provided 81 to 84 percent of consumption (table 21; USGS, 2021). Total primary and coproduct production of antimony from the largest deposits in Western States relative to recent domestic consumption cannot be calculated because of incomplete records but may be approximately equivalent to 2 to 5 years of recent annual consumption (table 22). Tungsten produced in the Yellow Pine district during World War II, and arsenic produced from the White Caps mine, represent about one half year and several months, respectively, of recent consumption.

Beryllium (Be)

At the Spor Mountain mine, Juab County, Utah, beryllium occurs in Paleozoic carbonate clasts (~25 mega-annum [Ma]); the clasts have been replaced by bertrandite ($\text{Be}_4\text{Si}_2\text{O}_7(\text{OH})_2$), fluorite, calcite, and silica. Beryllium is thought to have

been sourced by hydrothermal leaching of volcanic glass in overlying topaz rhyolite. Pegmatite and non-pegmatite beryllium deposits occur near and west of the Spor Mountain mine (Mills and Rupke, 2020). Annual production of beryllium since 1970 has varied from approximately 65 to 260 short tons (59 to 236 t) (Mills and Rupke, 2020). Annual domestic consumption of beryllium from 2016 to 2020 varied from 179 to 202 t and net imports provided 4 to 18 percent of consumption (table 21; USGS, 2021). The annual beryllium production of the Spor Mountain mine is broadly equivalent to annual domestic consumption.

Fluorite (CaF_2)

Fluorite has been mined in numerous Western States from widely distributed vein, breccia, and carbonate-replacement deposits (USGS and Montana Bureau of Mines and Geology, 1963; USGS and Nevada Bureau of Mines, 1964; USGS and others, 1964, 1965, 1969). Most deposits produced hundreds to several tens of thousands of short tons of fluorite ore in three grades (acid [more than 97 percent fluorite], flux, and metallurgical [60–85 percent fluorite]); a few had larger production. Some deposits contained small amounts of beryllium and REE.

In Nevada, fluorite was recovered from many vein, breccia, and replacement deposits, two of which produced more than 100,000 short tons (90,909 t) of fluorite. At the Daisy mine (Nye County) approximately 200,000 short tons (181,818 t) of fluorite were produced from replacement deposits in low-calcium dolomite with no megascopic alteration. Minor montmorillonite occurred with fluorite, most of which was hand-sorted to acid-grade (≤ 1.5 weight percent silica and other impurities). At the Baxter mine (Mineral County) approximately 182,000 short tons (165,455 t) of fluorite were produced from veins and a fault zone in Cenozoic andesite and tuff weakly altered to quartz, montmorillonite, and lesser sericite (Papke, 1979).

In Utah, approximately 350,000 short tons (319,182 t) of 60- to 90-percent fluorite ore, some containing beryllium, have been produced in the Spor Mountain district from breccia pipes and lesser vein and disseminated deposits in Paleozoic dolomites. The largest single producer at approximately 110,000 short tons (100,000 t) is the Lost Sheep mine where fluorite was mined from pipe-like replacement deposits; new production commenced in 2018 (Bullock, 1976, 1981; Mills and Rupke, 2020; Ares Strategic Mining, Inc., 2021).

In New Mexico, fluorite was mined from many vein, breccia, and replacement deposits in Cenozoic igneous and eruptive rocks, in Precambrian granitic rocks, and in Paleozoic sedimentary rocks. Deposits in Precambrian rocks are spatially associated with Cretaceous and Tertiary intrusions. Production of nearly all individual deposits is tens to tens of thousands of short tons. Deposits in the Zuni Mountains (Valencia County) produced approximately 182,000 short tons (165,455 t) of “crude fluorspar ore,” most of which was recovered from vein deposits in Precambrian granitic rocks (No. 21 and No. 27 mines; McAnulty, 1978).

In Colorado, approximately 190,000 short tons (172,727 t) of fluorite were produced from the Wagon Wheel Gap mine (Mineral County) from 1913 to 1948 (Steven, 1968; Steven and Lipman, 1973). The deposit consists of veins and fluorite-filled fractures in Cenozoic volcanic rocks of the Creede caldera and also contains pyrite, quartz, barite, calcite, and halloysite.

Annual domestic consumption of fluorite from 2016 to 2020 varied from 368,000 to 450,000 t, and imports provided 100 percent of consumption (table 21; USGS, 2021). Total primary production of fluorite from fluorite deposits in Western States cannot be precisely calculated because some production is reported as fluor spar ore with unquantified grades. Recorded production is apparently equivalent to a few years at most of annual domestic consumption.

Germanium (Ge) and Gallium (Ga)

The Apex mine, Washington County, Utah, produced approximately 7,000 t of copper, 400 t of lead, 180,000 troy ounces (5.6 t) of silver, and minor zinc and gold (Bernstein, 1986; Foster, 1991) under two operators between 1884 and 1992. From 1985 through the early 1990s, the mine also produced germanium and gallium which occur at grades of

0.5 to 0.7 weight percent in aggregates of iron and copper oxide, carbonate, and sulfate minerals. Most germanium was recovered from goethite and most gallium from jarosite. The germanium-gallium ore remained from earlier mining of copper-lead-silver-oxide minerals in chimney-like deposits within subparallel fault zones in Pennsylvanian Callville Limestone (Bernstein, 1986). Remnant pyrite, galena, sphalerite, and chalcocopyrite suggest germanium and gallium were enriched by weathering of these and possibly other sulfide minerals. Deposit characteristics (host rock, form, and mineralogy) are similar to intrusion-related carbonate-replacement deposits, although nearby igneous rocks have not been described. Alternatively, the deposit has been interpreted as a solution-collapse breccia pipe (Wenrich and Verbeek, 2014).

Annual domestic consumption of germanium from 2016 to 2020 is estimated at 30 t, and imports provided more than 50 percent of consumption (table 21; USGS, 2021). Annual domestic consumption of gallium from 2016 to 2020 varied from 14.9 to 17.9 t, and imports provided 100 percent of consumption (table 21; USGS, 2021). Because germanium and gallium production from the Apex mine has not been reported, it cannot be compared to annual domestic consumption.

Chapter B



Photograph showing marketed forms of high-purity critical minerals bismuth, zinc, and tin.

Chapter B. Byproduct Production of Critical Minerals

Deposits in which the critical minerals Sb, As, Bi, fluorite, Mn, Ni, Nb, platinum-group elements (PGE [Pd, Pt]), Re, Ta, Te, Sn, W, and V were produced as byproducts are listed on [table 1](#) and shown on [figure 1A](#). Most have been recovered where economically feasible from deposits in which Cu, Pb, Zn, Au, and Ag were the primary and coproduct commodities. Byproduct commodity recovery was enabled by (1) elevated concentrations in Cu-Pb-Zn-Au-Ag ores, (2) available recovery techniques, (3) existing world markets, and (4) processing capacity. Processes that recover copper and molybdenum from the large masses of porphyry copper-molybdenum (Cu-Mo) deposit ores mined daily (tens of thousands of metric tons [t]) simultaneously concentrate by factors of 10^3 or more some chalcophile and siderophile elements (including Sb, As, Bi, Ni, PGE, Re, and Te) with very low concentrations in ores.

Mineral System—Porphyry Cu-Mo-Au

Deposit type—Porphyry/skarn Copper

Antimony (Sb), Bismuth (Bi), Nickel (Ni), Platinum-Group Elements (PGE), Rhenium (Re), and Tellurium (Te)

Small but mostly unquantified amounts of Sb, Bi, In, Ni, PGE, Re, and Te have been recovered during refining of ores from porphyry Cu-Mo deposits in Nevada, Utah, Arizona, and other Western States (Eiler, 1913; Hess, 1919; Hose and others, 1976; Parker, 1978; Phillips, 1980; Foster, 1991; Peterson, 1993; chap. C). The critical minerals Sb, Bi, In, Ni, PGE, and Te have been episodically recovered at copper refineries in Amarillo and El Paso, Texas; Magna, Utah; Miami, Arizona; and Great Falls, Montana (Foster, 1991). Rhenium is currently recovered at molybdenum processing facilities in Arizona and other locations. Tellurium has been recently sold by the copper refinery in Amarillo (ASARCO, 2021), and annual tellurium recovery of 20 t is planned for Magna (Rio Tinto, 2021a). Tellurium and other critical minerals (Sb, As, Bi, Co, Ge, In, Ni, and Sn) also have been episodically recovered at lead and zinc refineries in numerous States (including Utah, Washington, Idaho, Montana, Nebraska, Missouri, Texas, and Tennessee); nearly all the refineries that were in operation in the 1970s and 1980s (Parker, 1979; Foster, 1991) are shuttered or demolished.

In addition to the large production of copper, molybdenum, gold, and silver from deposits that comprise the Bingham Canyon porphyry Cu-Mo deposit, PGE (Pd, Pt), rhenium, and tellurium have been episodically produced (John and Taylor, 2016; Nexhip, 2016; Krahulec, 2018; Rio Tinto, 2021b). These byproducts were recovered at the nearby refinery in Magna, Salt Lake County, Utah, other earlier facilities (Garfield copper refinery), and offsite, although production data for PGE, rhenium, and tellurium have not

been routinely published. The Bingham porphyry Cu-Mo deposits include the Bingham porphyry Cu-Mo deposit (Bingham Canyon mine), Ag-Pb-Zn carbonate replacement deposits (Lark and U.S. mines), Cu-Au skarn deposits (Highland Boy and Carr Fork mines and North Rim skarn) (Cameron and Garmoe, 1987), copper-rich massive sulfide, manto-like siliceous replacement deposits, polymetallic (Pb-Zn-Cu-Ag-Au) veins (Tomlinson and others, 2021), and distal disseminated silver deposits (Barneys Canyon and Melco mines) (Presnell and Parry, 1996; Gunter and Austin, 1997). PGE, rhenium, and tellurium, recovered in recent decades as world markets developed and expanded, were apparently derived from the porphyry Cu-Mo deposit as the carbonate-replacement, skarn, vein, and distal disseminated deposits have not been mined since 2001. At Magna, these critical minerals are mostly concentrated in electrorefining slimes. Approximately 1 short ton per year rhenium is recovered from smelter gases (Nexhip, 2016).

Compared to other porphyry Cu-Mo deposits, the sites, distribution, and concentrations of PGE, rhenium, and tellurium in the Bingham porphyry Cu-Mo deposit are relatively well-documented. Whole-rock samples, including those with more than 2,000 parts per million (ppm) copper and 0.13 to 0.14 grams per metric ton (g/t) gold, average 8 to 12 parts per billion (ppb) palladium and 2 ppb platinum (Kocher, 2017; Sinclair and Jonasson, 2020), concentrations that are comparable to the palladium-platinum contents of unaltered mafic alkaline rocks in the Bingham district (Maughan and others, 2002). PGE are recovered from tellurides in refinery slimes (Nexhip, 2016).

Tellurium contents of copper-iron (Cu-Fe) sulfide minerals analyzed by laser ablation-inductively coupled plasma-mass spectroscopy are mostly less than 10 ppm (Brodbeck and others, 2020). Whole-rock tellurium concentrations averaging 4.8 ppm in Cu-Mo ore and 0.1 ppm in molybdenum-only ore are reported by Austin and Ballantyne (2010). Tellurium mostly occurs in telluride inclusions in, or intergrown with, sulfide minerals (Ballantyne and others, 1997; Kocher, 2017; Brodbeck and others, 2020). Telluride minerals in Cu-Mo ores include, in addition to hessite (Ag_2Te), wehrlite (Bi_3Te_2) in Cu-Fe sulfide minerals and merenskyite (Pd_2Te) in molybdenite.

Rhenium concentrations in molybdenite in porphyry Cu-Mo ore, which range from less than 10 to 2,000 ppm (Giles and Schilling, 1972; John and Taylor, 2016; Kocher, 2017), correlate with the abundance and type of molybdenite (Austin and Ballantyne, 2010; Kocher, 2017). Disseminated molybdenite and molybdenite in early, deep, and more centrally located quartz veins generally have lower rhenium contents than molybdenite in later, shallower, and more distal quartz veins (Kocher, 2017).

Production of byproduct nickel, PGE, rhenium, and tellurium from Bingham and other porphyry Cu-Mo deposits has not been routinely published and only compiled occasionally in refinery surveys (for example, Foster, 1991; Wang, 2011). Inventories of nickel, PGE, rhenium, tellurium, and other critical minerals in the Bingham and other porphyry

Cu-Mo systems, determined from drill holes, mineral domains in mines, and compositions of anode copper in refineries, are described and compared in chapter C.

Deposit type—Polymetallic Sulfide Skarn, Replacement, Vein

Antimony (Sb)

In the Tintic district, Utah, an unquantified amount of antimony was reportedly recovered during processing of complex Pb-Zn-Cu-Au-Ag carbonate-replacement ores (James, 1984).

Arsenic (As)

In the Butte district, Mont., approximately 150,117 short tons (136,470 t) of arsenic compounds were recovered mostly from vein ores mined from 1880 to 1964 for Cu, Au, Ag, Pb, Zn, and Mn (primary and coproducts; Anaconda Copper Mining Company, 1915–1955; Meyer and others, 1968). Arsenic production at Butte, which began in 1921, represents approximately 14 to 25 years of recent annual domestic consumption (2016–2020) (table 21).

Bismuth (Bi)

Bismuth has been recovered as a byproduct in numerous skarn, replacement, and vein deposits in Montana, Idaho, Utah, and Nevada that were mined primarily for Cu-Pb-Zn-Au-Ag (USGS and Montana Bureau of Mines and Geology, 1963; USGS and Nevada Bureau of Mines, 1964; USGS and others, 1964, 1965, 1969; table 1).

In the Butte district, Mont. approximately 2,021 short tons (1,887 t) of bismuth were recovered from vein ores mined for Cu, Au, Ag, Pb, Zn, and Mn (Meyer and others, 1968; Miller, 1973); bismuth recovery apparently began during World War II (Anaconda Copper Mining Company, 1915–1955). At the Victoria mine, Elko County, Nev., approximately 8,000 short tons (4,545 t) of copper and approximately 40,000 troy ounces (1.2 t) of silver were produced between 1975 and 1981 from a breccia pipe in Permian limestone and sandstone adjacent to a Late Jurassic quartz monzonite intrusion (Atkinson and others, 1982; Lowe and others, 1985; Lapointe, and others, 1991). The initial reserve of 3.45 million short tons (Mst) (3.14 Mt) grading 2.45 weight percent copper and approximately 0.6 troy ounces of silver per short ton (19.2 g/t), also contained 0.05 weight percent bismuth. Based on largely cospatial elevated concentrations of copper (chalcopyrite) and bismuth (bismuthinite) (figs. 14, 15 in Atkinson and others, 1982), copper concentrates may have contained 1,725 short tons (1,568 t) of bismuth. This bismuth could have been recovered at the Kennecott copper refinery in McGill, Nev., and (or) the Anaconda copper refinery in Great Falls, Mont. (both since demolished), or remain in tailings, slag, and slimes discarded at those sites. At Victoria, bismuth sulfide minerals (bismuthinite; wittichenite [Cu₃BiS₃]) are present in dump rocks.

Byproduct production of bismuth from Butte district mines, the Victoria mine, and other domestic deposits is incompletely known. Combined primary, coproduct (chap. A),

and byproduct production of bismuth in Western States apparently represents at most a few years of recent domestic consumption (table 21).

Gallium (Ga), Indium (In), Nickel (Ni), Palladium (Pd), Platinum (Pt), Tin (Sn), and Vanadium (V)

Unquantified amounts of Ga, In, Ni (Ni sulfate), PGE, Sn, and V, in addition to As, Bi, Mn, and Te, were episodically produced during the vein mining era in the Butte district, Mont. The earliest reported recovery of these critical mineral commodities was 1926, with annual recovery reported during and after World War II (1941–1951) (Anaconda Copper Mining Company, 1915–1955). It is unknown if these commodities were derived from Butte district ores, tolled ores and concentrate, or both, as 15 percent or more of copper produced from 1915 to 1955 was derived from external sources. The large nickel-sulfate production (for example, 200,600 short tons [182,364 t] in 1932 and 145,935 short tons [132,668 t] in 1937) and chromium and vanadium production during World War II (Anaconda Copper Mining Company, 1915–1955) suggest nickel, chromium, and other critical minerals were recovered from external ores (outside of the Butte district), in part because of wartime demand.

Manganese (Mn)

The relatively large carbonate-replacement and vein deposits that produced thousands to more than 1 million short tons (909,090 t) of manganese as primary and coproducts (Butte, Mont.; Bisbee, Ariz.; Leadville and Gilman, Colo.; Pioche, Nev.; and Tintic, Utah, districts) are described above in chapter A. Lesser amounts of manganese (relative to annual domestic consumption) have been recovered from numerous smaller Cu-Pb-Zn-Au-Ag replacement and vein deposits as byproducts (Butler and others, 1938; USGS and Nevada Bureau of Mines, 1964; USGS and others, 1964, 1965, 1966a; Mills and Rupke, 2020). In many magmatic-hydrothermal deposits, manganese, a historically low-unit-value commodity, was produced where it had been enriched by weathering of carbonate minerals or under wartime price supports.

Tellurium (Te)

In the Butte district, Mont., approximately 119 short tons (108 t) of tellurium were recovered from vein ores mined for Cu, Au, Ag, Pb, Zn, and Mn (Meyer and others, 1968; Miller, 1973). This production represents approximately 1.2 years of recent consumption (table 21).

Tungsten (W)

Some skarn, replacement, and vein deposits mined for Cu-Pb-Zn-Au-Ag contained enough tungsten, as scheelite and wolframite, for recovery. This coproduct and byproduct tungsten production was invariably smaller than production from deposits in which tungsten was the principal commodity, the largest of which are described in chapter A (USGS and Nevada Bureau of Mines, 1964; USGS and others, 1964, 1965, 1966a; Mills and Rupke, 2020).

Chapter C



Photograph showing a souvenir copper cathode, ASARCO Copper Refinery, Amarillo, Texas.

Chapter C. Inventories, Reserves, and Resources of Critical Minerals in Porphyry Copper-Molybdenum-Gold (Cu-Mo-Au) and Other Mineral Systems

In this chapter, mine reserves and unmined resources in porphyry copper-molybdenum (Cu-Mo) deposits and in deposits of other mineral systems that could contain significant resources of Al, Sb, As, Bi, Co, fluorite, Ge, In, Mn, Ni, Nb, platinum-group elements (PGE [Pd, Pt]), potash, Re, Ta, Te, Sn, W, and V are described. Inventories are quantified where critical mineral concentrations and reserve and resource tonnages have been measured or estimated, mainly from drill holes, and semi-quantified from mine site and exploration drill hole analyses and copper refinery records (fig. 1A–E; tables 3–15). Some chalcophile and siderophile critical minerals have been episodically recovered as byproducts from refinery slimes and electrolyte (Cu₂SO₄ and H₂SO₄) generated during processing of copper ores from large tonnage (hundreds to more than 1 billion short tons [Gst] or 0.91 billion metric tons [Gt]) porphyry Cu-Mo deposits (for example, Sb, Bi, In, Ni, PGE, Re, and Te; described in chap. B); these and other critical minerals also have been historically discarded because of low to no demand or unprofitable recovery. During copper refining Sb, As, Bi, Ni, PGE, Te, and possibly other critical minerals are concentrated in tank house slimes that remain from electrorefining copper anodes to copper cathodes, the marketable form of copper. Concentrations of these elements are monitored for quality control of cathodes and marketability (tables 9–11). Calculated inventories of critical minerals in reserves and resources based on concentrations in processing streams of copper refineries are also described below.

For other deposit types, including skarn-replacement-vein tungsten, lithocap alunite, and unclassified magmatic-hydrothermal deposits, inventories of critical minerals are based on analyses of drill hole intervals and mine and metallurgical samples (figs. 4–6; tables 3–8). Many critical mineral concentrations are included in multi-element analyses, determined within the past two decades, for exploration and mine-expansion drill holes, in part from conserved cores of holes drilled prior to 2000. Some critical mineral concentrations have been published; others are, or were, available on websites, as referenced. Small known and suspected resources, including mine dumps and mill tailings, are described for several mineral commodities that occur in few domestic deposits as primary products and coproducts or are heavily imported (for example, Bi, Te, and Sn).

Concentrations and Inventories of Critical Minerals in Porphyry Cu-Mo Deposits Systems Based on Drill Holes and Mineral Zones

Mineral System—Porphyry Cu-Mo-Au

Deposit type—Porphyry/Skarn Copper

Drill holes used to define reserves and resources of large tonnage, unmined porphyry Cu-Mo deposits and associated replacement, skarn, vein, and breccia deposits in Alaska, Arizona, and Idaho, have been analyzed for numerous elements in addition to the primary, coproduct, and byproduct commodities copper, molybdenum, gold, and silver. Analyses of approximately 19,000 core hole intervals in the Pebble, Alaska; Red Mountain and Sunnyside, Ariz.; and CuMo, Idaho, porphyry deposits, and in the Ventura molybdenum-copper (Mo-Cu) breccia deposit, Ariz., were obtained from websites and provided by coauthors and associates (tables 3–8). Inventories of critical minerals in these deposits were calculated using reserve and resource tonnages, where published or estimated, and average concentrations in drill holes. The calculated inventories (critical mineral metric tons) were obtained by multiplying reserve and resource tonnages by critical mineral concentrations. Concentrations of critical minerals in mineral zones of the porphyry Cu-Mo deposit at Bingham, Utah, were used to estimate inventories in reserves and resources for which tonnages have been publicized. Analyses of drill hole and mine samples from the Yerington, Nevada, copper district are relatively limited in number and provide qualified inventories of several critical minerals (figs. 6–8; tables 3–8, 12–15).

Antimony (Sb), Arsenic (As), Bismuth (Bi), Germanium (Ge), Indium (In), Platinum-Group Elements (PGE), Rhenium (Re), Tin (Sn), Tellurium (Te), and Tungsten (W)

Concentrations of critical minerals in the unmined Pebble, Alaska, porphyry Cu-Mo deposit are included in multi-element analyses of drill holes used to define a reserve (figs. 4A–D, 6; table 5; Granitto and others, 2020, 2021). The Pebble deposit consists of 7.51 Gt grading 0.416 weight percent copper, 0.024 weight percent molybdenum, and 0.33 grams per metric ton (g/t) gold that comprise the coeval West and East zones. The near-surface West zone (0–500 m depth) consists of mineralized approximately 90 mega-annum (Ma) granodiorite, sedimentary rocks, and other igneous intrusions and breccias. The deeper and higher-grade East zone extends to 1,700-m depth. Deposits are associated with numerous alteration types including sodic-calcic, potassic,

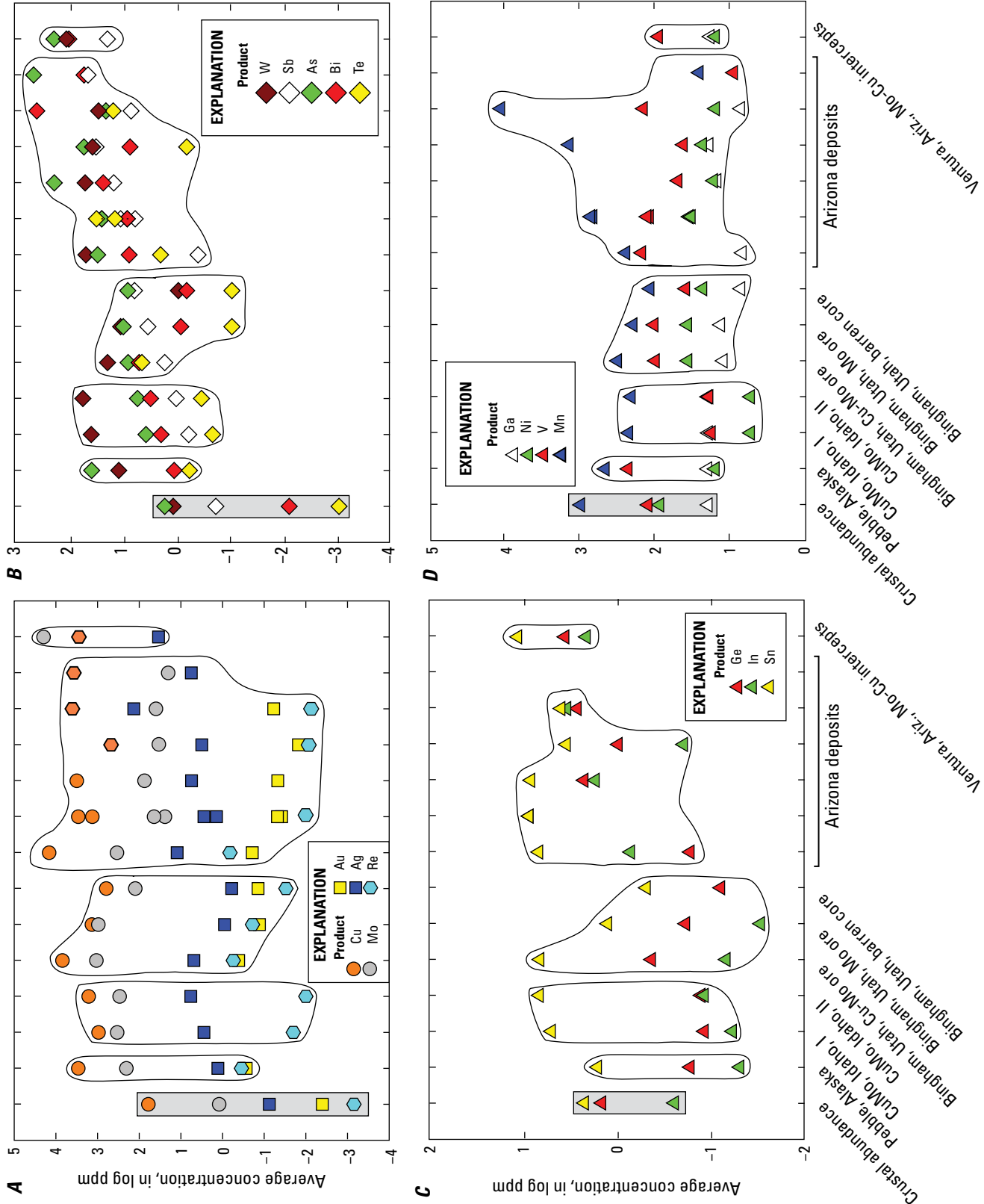


Figure 4. Plots of average concentrations of primary products, coproducts, and byproducts (Cu, Mo, Au, Ag, and Re) and selected critical minerals in groups of domestic porphyry copper-molybdenum (Cu-Mo) deposits and resources (thin line unshaded enclosures), based on averages of drill core intervals and mineral domains (tables 3–8), compared to crustal abundances (gray rectangles). In most deposits copper is the primary product; in some molybdenum and other elements, including gold, silver, and rhenium, where recovered, are coproducts and byproducts. A, Cu, Mo, Au, Ag, and Re. B, W, Sb, As, Bi, and Te. C, Ge, In, and Sn. D, Ga, Ni, V, and Mn. Crustal abundances from Haynes (2016). Deposits and resources in Arizona are grouped to disguise proprietary data. ppm, parts per million.

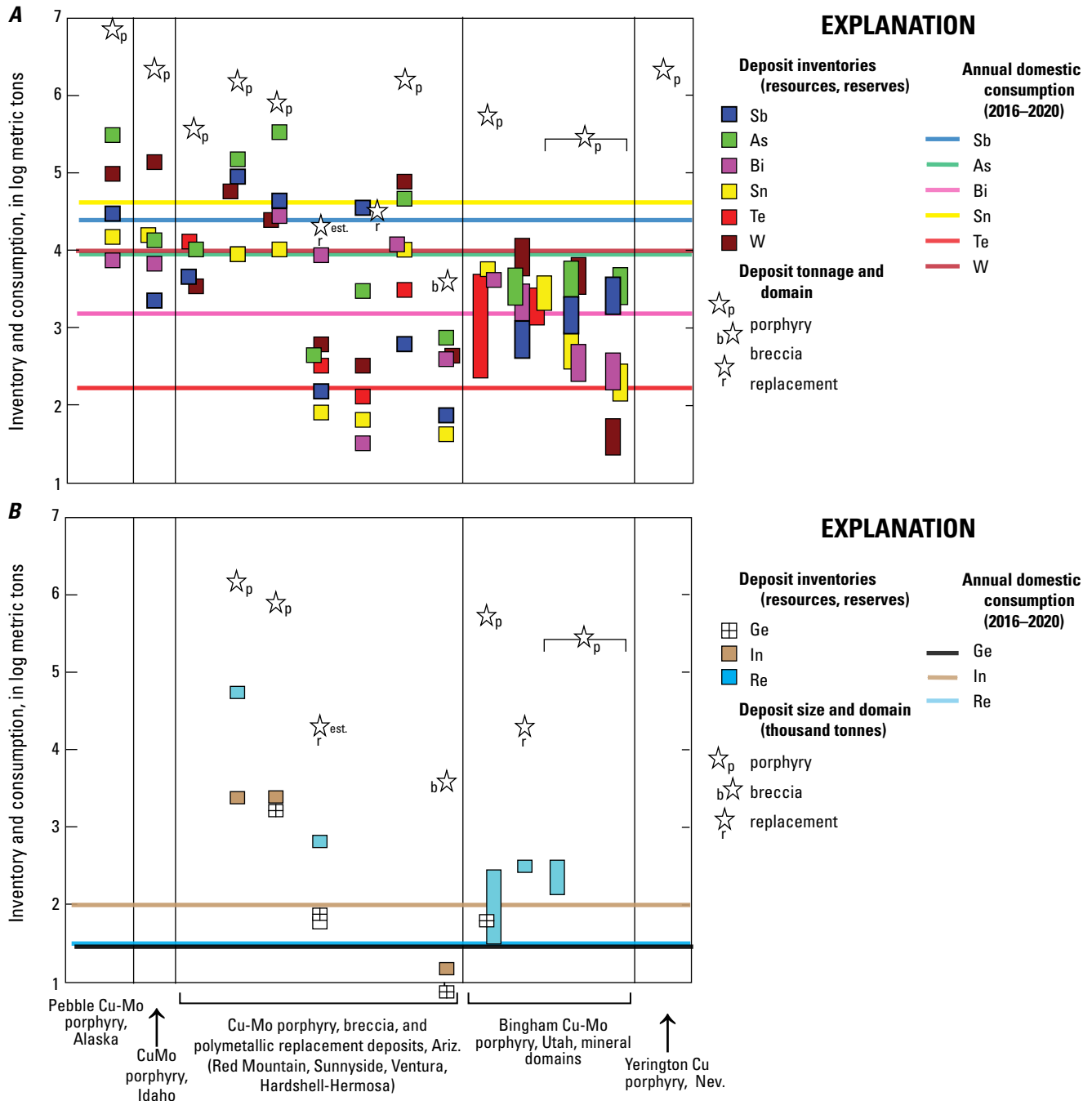


Figure 5. Plots of inventories, consumption, and concentrations of critical minerals in porphyry copper-molybdenum (Cu-Mo) deposits. Inventories of Sb, As, Bi, Sn, Te, and W (A) and Ge, In, and Re (B) in porphyry Cu-Mo deposits (porphyry, breccia, and replacement tonnages and domains) in Alaska, Idaho, Arizona, Utah, and Nevada based on drill holes (tables 3–8) and published sources, compared to average annual domestic consumption of recent years (2016-2020). C, Element concentrations in drill hole intervals used to define the CuMo Cu-Mo resource (tables 3–8), Idaho, relative to crustal abundances. D, Comparison of molybdenum concentrations and rhenium concentrations in intervals of drill holes in the CuMo resource (tables 3–8). Limitations of calculated inventories are described in the text.

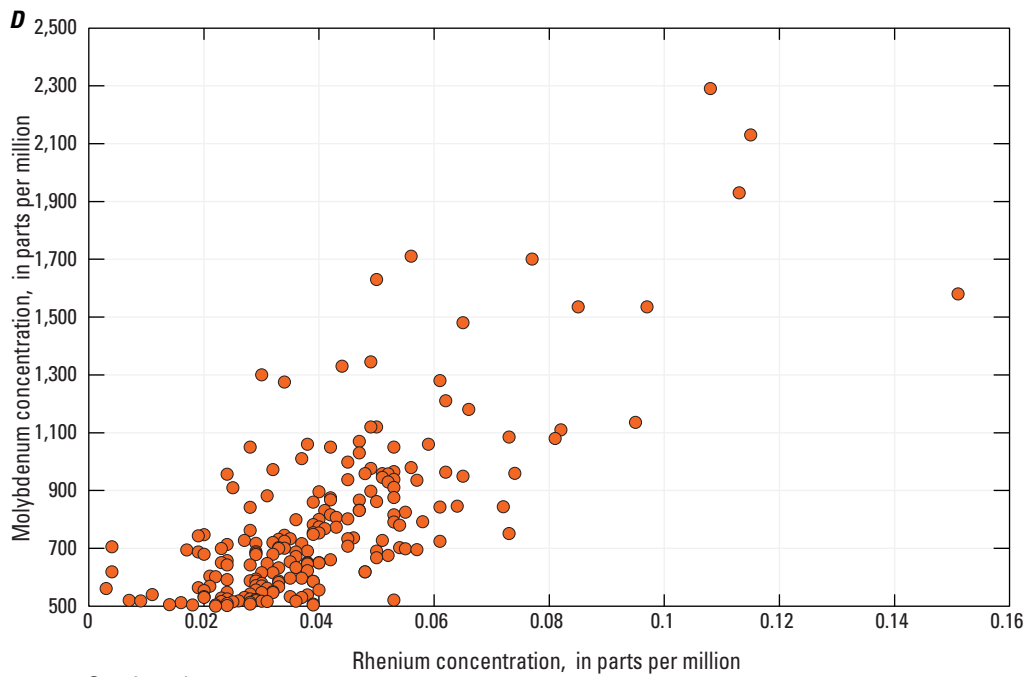
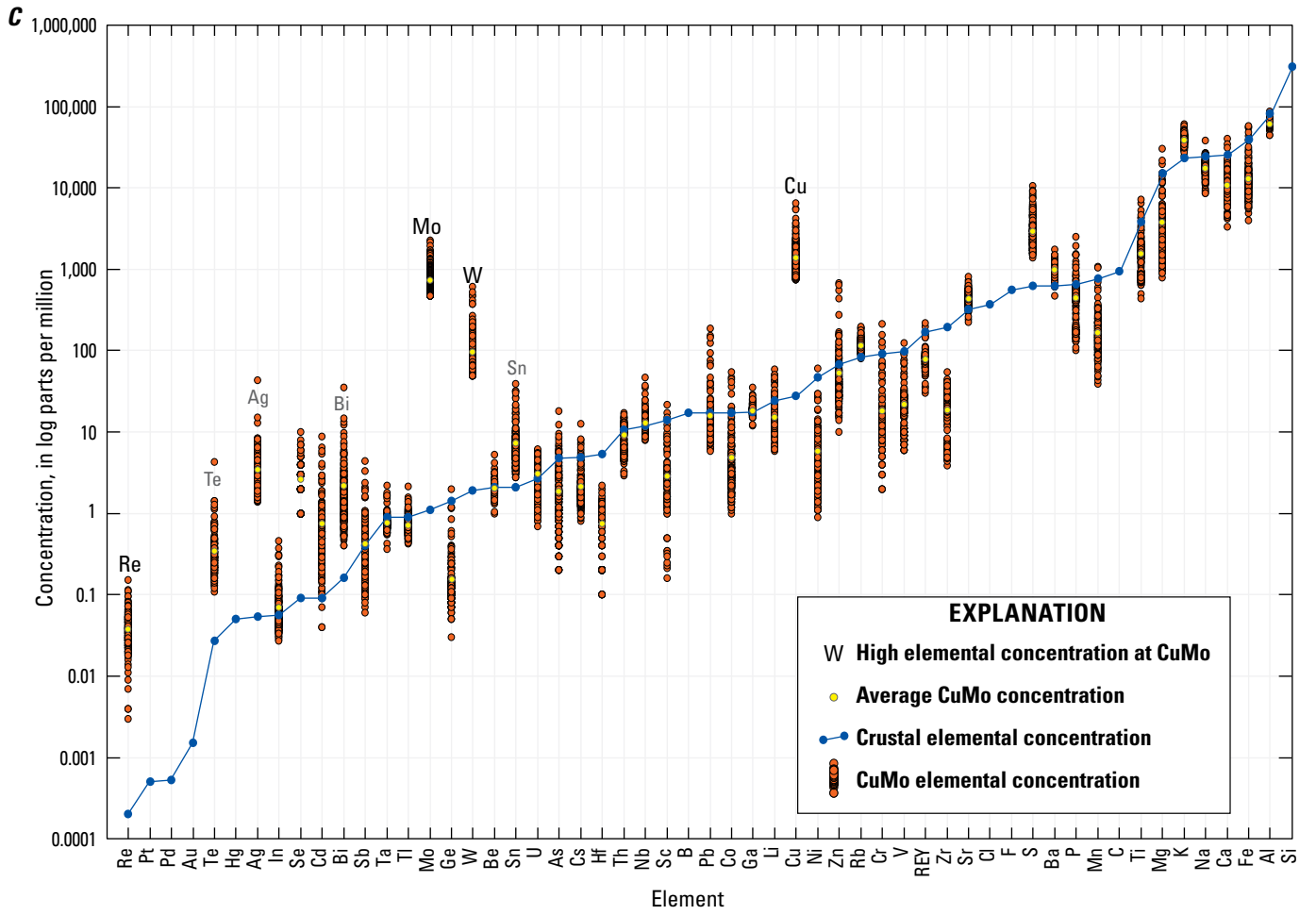
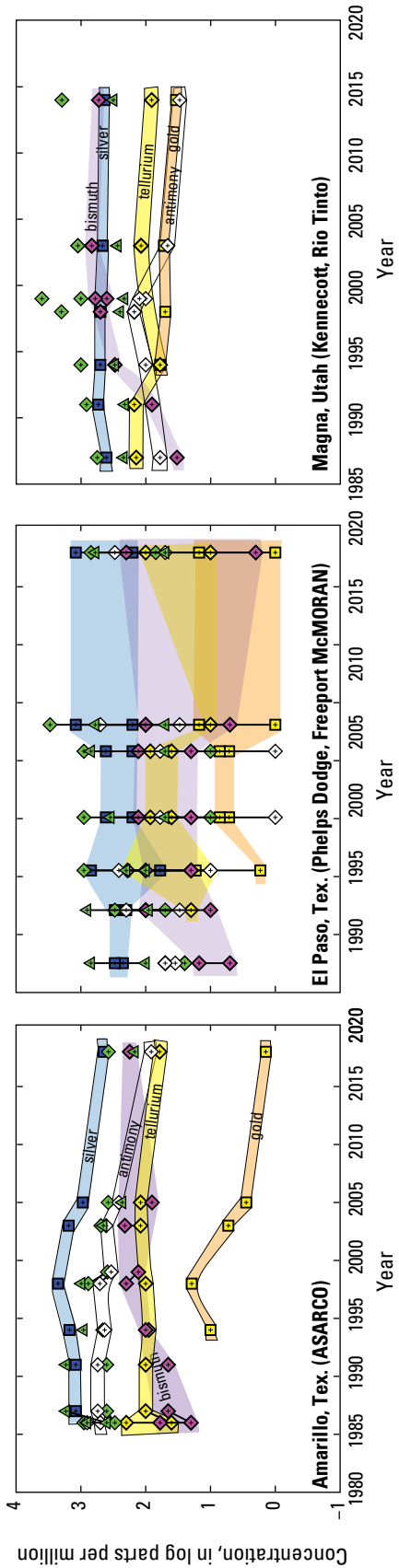


Figure 5.—Continued

A. Critical minerals in anode copper in operating refineries



B. Critical minerals in anode copper in shuttered or demolished refineries

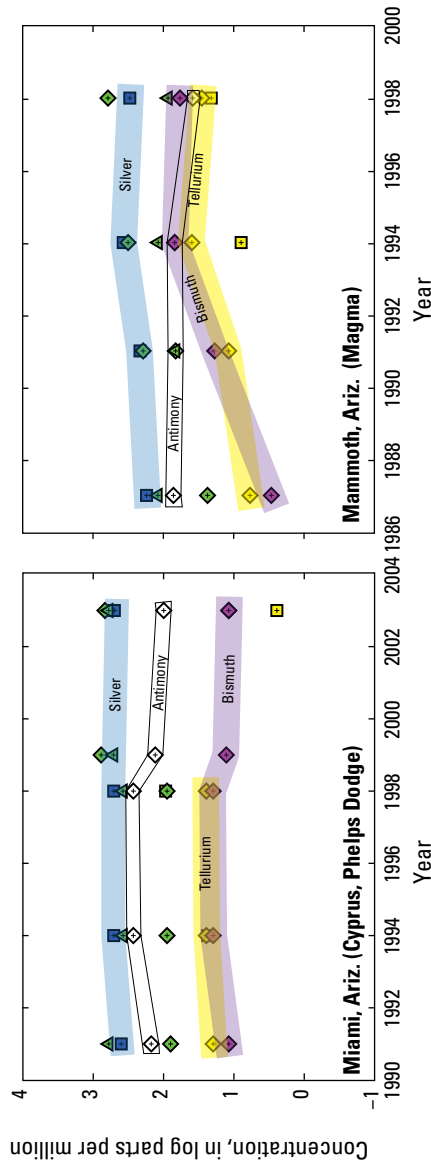
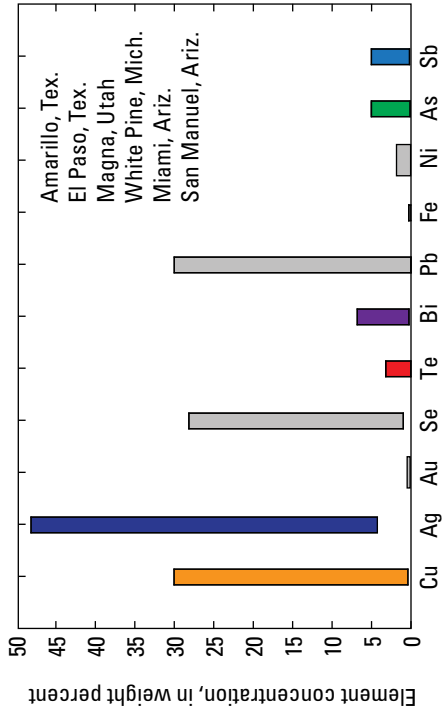


Figure 6. Plots of concentrations of critical minerals in anode copper in operating and shuttered or demolished refineries and in tank house slimes and partitioning of critical minerals during copper processing. *A.* Ag, Au, Te, As, Sb, Bi, and Ni concentrations in anode copper in operating refineries (2021). *B.* Ag, Au, Te, As, Sb, Bi, and Ni concentrations in anode copper in shuttered or demolished refineries. *C.* Cu, Ag, Au, Se, Te, Bi, Pb, Fe, Ni, As, and Sb concentrations ranges in tank house slimes from Amarillo and El Paso, Texas; Magna, Utah; White Pine, Michigan; and Miami and San Manuel, Arizona, refineries (table 11). *D.* Diagram showing partitioning of critical minerals (CM) during mining and processing of copper-(molybdenum) ores for copper, molybdenum, rhenium, and tellurium recovery (marketed critical minerals). Gold and silver have been routinely recovered from electrorefinery slimes for marketing.

C. Combined concentrations of critical minerals and other elements in copper refinery slimes (1998–2018)



D. Critical Minerals deployment during copper refining

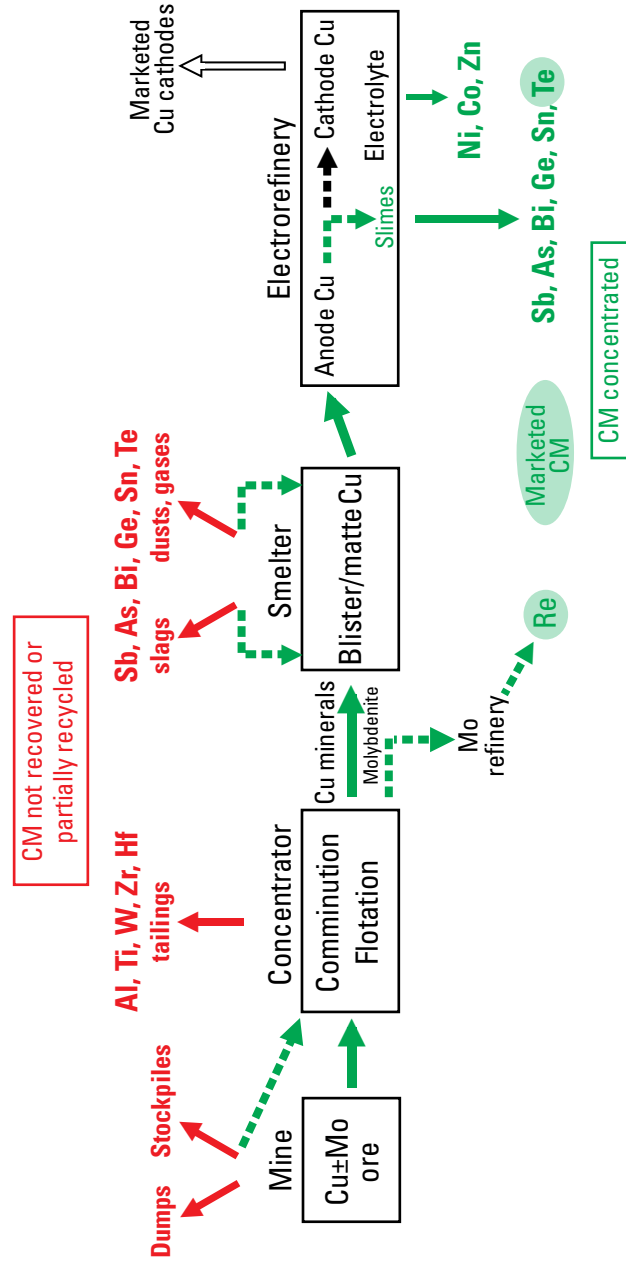
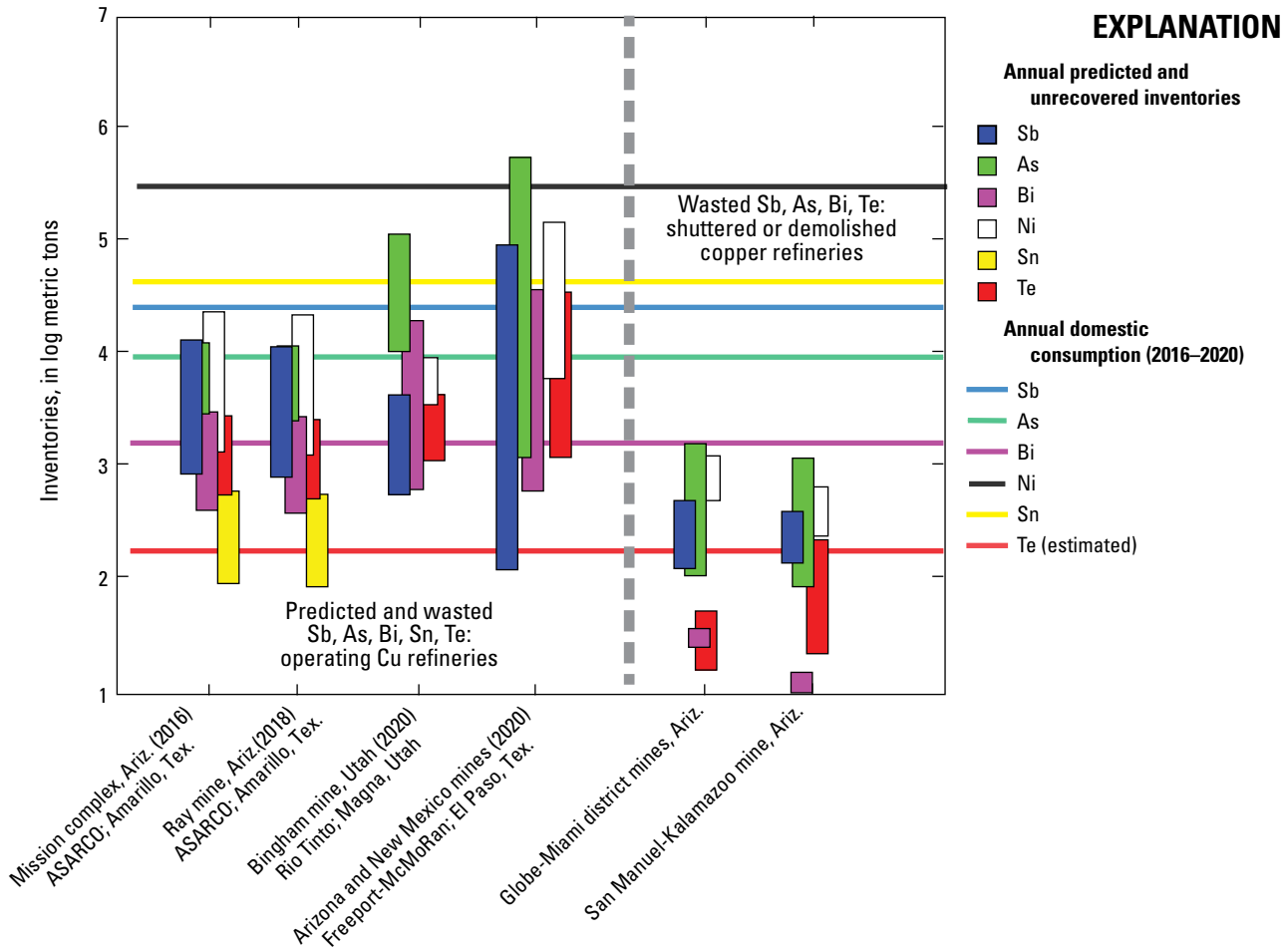


Figure 6.—Continued

A. Critical mineral inventories based on anode copper in copper refineries



B. Critical mineral inventories in resources and reserves predicted from mineral domains and anode copper at Bingham, Utah

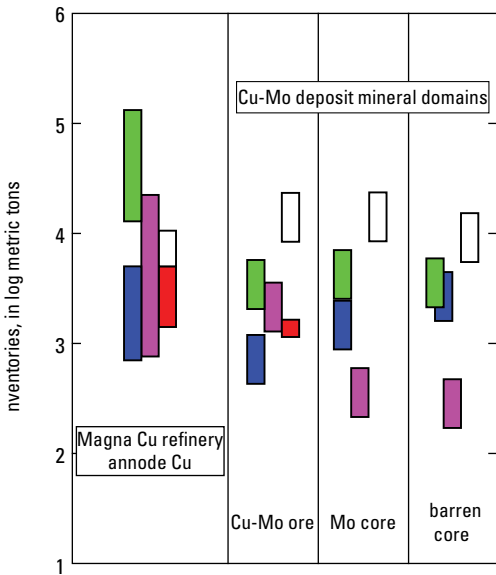


Figure 7. Plots of predicted and unrecovered inventories of critical minerals in refineries and resources. *A*, Annual predicted inventories of Sb, As, Bi, Ni, Sn, and Te in anode copper in copper refineries (1986–2018) (tables 9–15) and recent annual domestic consumption (2016–2020). *B*, Comparison of predicted Sb, As, Ni, and Te inventories in resources and reserves of the Bingham porphyry copper-molybdenum (Cu-Mo) deposit, calculated from concentrations in mineral domains to inventories in anode copper of the captive Magna copper refinery (tables 9–15).

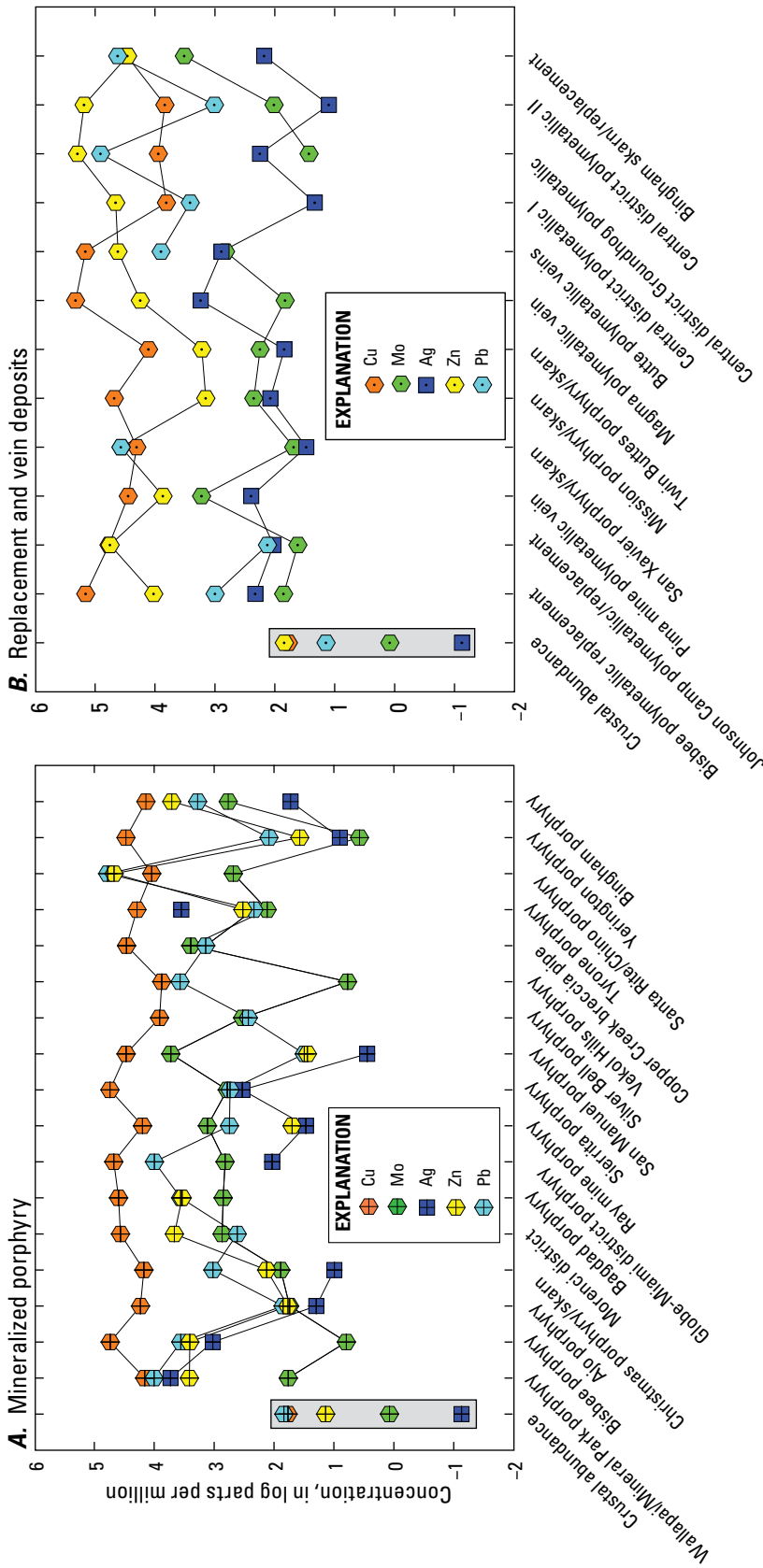


Figure 8. Average concentrations of primary products, coproducts, and selected critical minerals in domestic copper-(molybdenum) deposits and associated replacement and vein deposits, based on average concentrations of archival specimens and collection samples (tables 16–19), compared to crustal abundances (gray rectangles). In most deposits Cu, Mo, Zn, and Pb are primary and coproducts and Au and Ag, where recovered. A, Cu, Mo, Ag, Zn, and Pb in mineralized porphyry copper-molybdenum (Cu-Mo) deposits. B, Cu, Mo, Ag, Zn, and Pb in replacement and vein deposits, where distinguishable from descriptions in datasets. C, Sb, As, Bi, Te, and W in mineralized porphyry deposits. D, Sb, As, Bi, Te, and W in replacement and vein deposits, where distinguishable from descriptions in datasets. E, Sn, Ge, and In in mineralized porphyry deposits. F, Sn, Ge, and In in replacement and vein deposits, where distinguishable from descriptions in datasets. G, Ni, V, Rb, and Nb in mineralized porphyry deposits. H, Ni, V, Rb, and Nb in replacement and vein deposits, where distinguishable from descriptions in datasets.

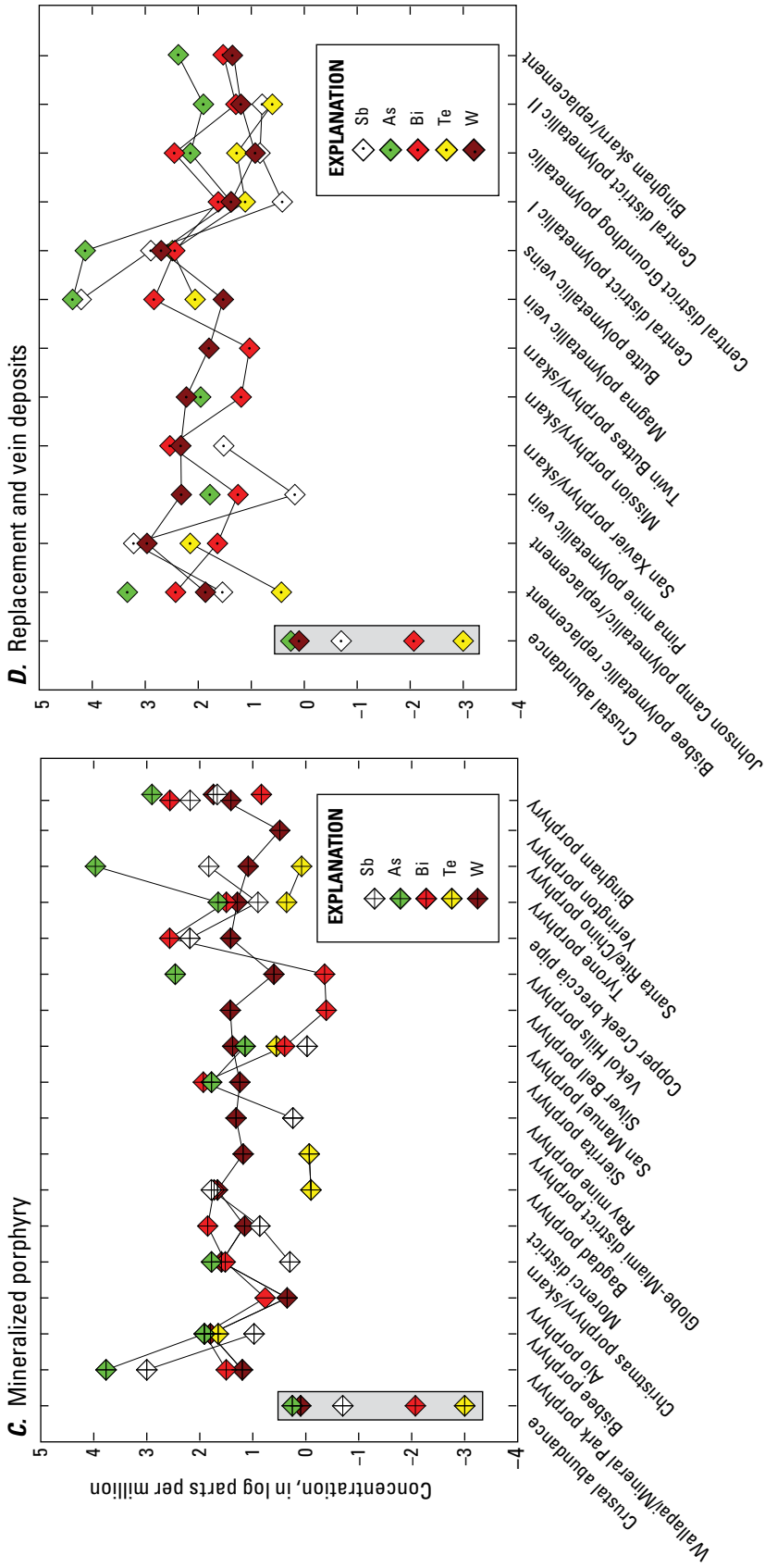


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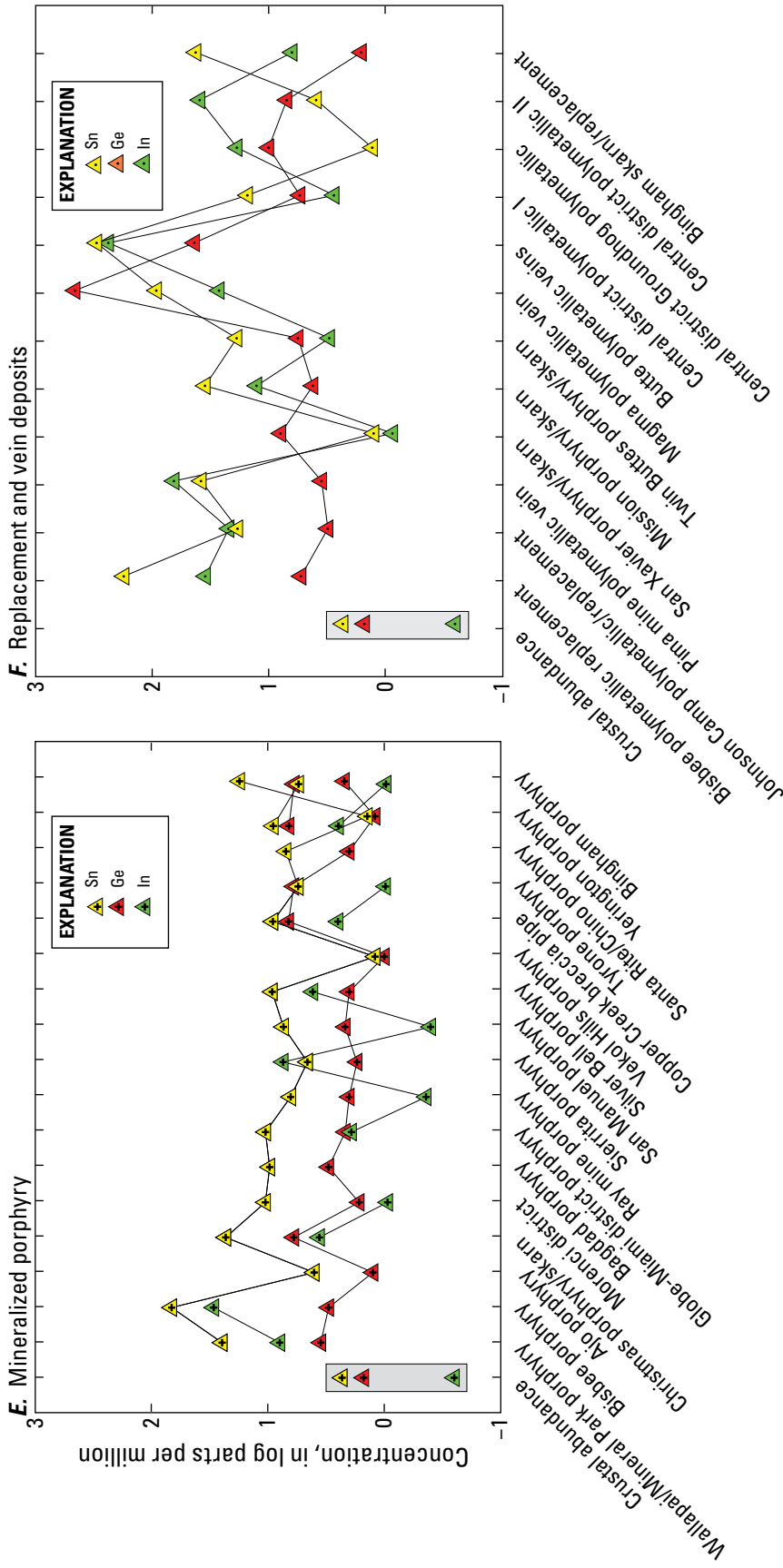


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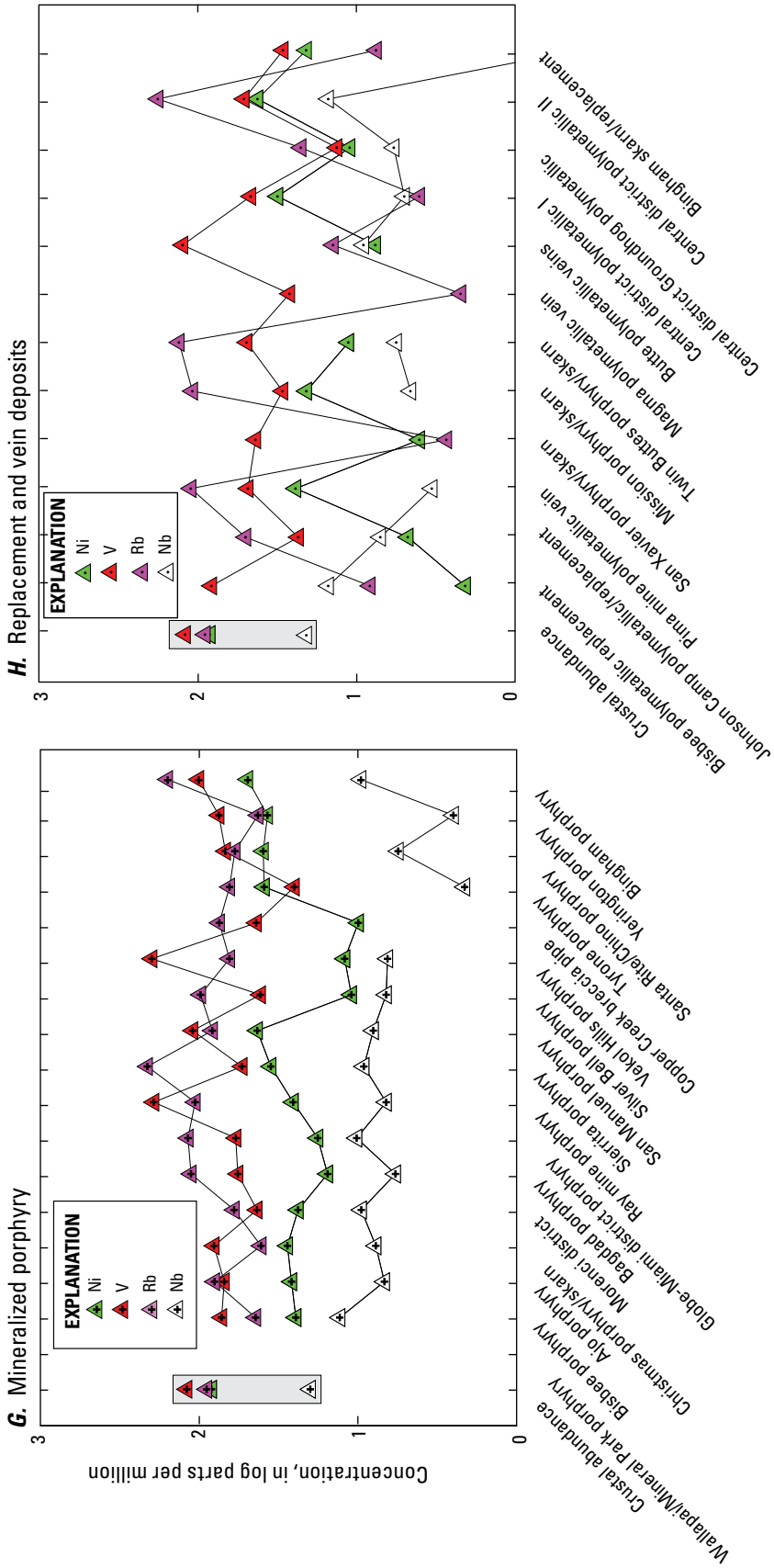


Figure 8.—Continued

sodic-potassic, illitic, advanced argillic, quartz-sericite-pyrite, and propylitic. Ore minerals include chalcocite/digenite/covellite, chalcopyrite, molybdenite, and gold (Lang and others, 2013; U.S. Geological Survey [USGS], 2013a). Inventories of thousands to more than 300,000 metric tons (t) of Sb, As, Bi, Sn, and W occur in the deposit based on bulk analysis of drill hole intervals and the reserve tonnage (figs. 4, 6; table 5). Concentrations of other critical minerals in ores and some sulfide minerals have been determined. Combined concentrations of palladium and platinum (Pd+Pt) in ore of approximately 7 ppb are reported by Sinclair and Jonasson (2014, 2020). Pyrite in propylitically altered rocks contains up to 3 parts per million (ppm) palladium. The average rhenium concentration in molybdenite is 906 ppm (Lang and others, 2013; USGS, 2013a).

Resources of the unmined Red Mountain porphyry Cu-Mo deposits, Santa Cruz County, Ariz. (figs. 1, 4A–D, 5, 6; tables 3, 12–15), include 100 to 150 million short tons (Mst) (90.9–136.4 million metric tons [Mt]) grading 0.31 weight percent copper and 0.02 weight percent molybdenum that comprise a near-surface chalcocite-enargite deposit, and approximately 435 Mst (395 Mt) grading more than 0.6 weight percent copper, 0.01 weight percent molybdenum, and more than 0.1 troy ounce per ton silver that comprise a deep chalcopyrite-bornite deposit. Mineralized rocks of the deposits are centered on 62 Ma granodiorite and include 73 to 68 Ma volcanic rocks (rhyolite, trachyandesite, and biotite latite; Vikre and others, 2014). Elevated concentrations of tellurium (up to 3 ppm) and arsenic (several hundred ppm), and slightly elevated concentrations of tungsten (tens of ppm) occur in and above the deep chalcopyrite-bornite deposit, based on analyses of drill hole and surface rock and soil samples (Chaffee, 2019). The greatest tellurium and some of the greatest arsenic concentrations correspond spatially to a near-surface zone of quartz-alunite-kaolinite-pyrophyllite-altered rocks that includes the chalcocite-enargite deposit. Other elevated arsenic concentrations are partly cospatial with the deep chalcopyrite-bornite deposit. Most concentrations were determined by semi-quantitative emission spectrography and reflect generalized distributions of elements. However, because of the large deposit tonnage, elevated concentrations of arsenic, tellurium, tungsten, and other critical minerals present in low concentrations that spatially coincide with ore-grade copper concentrations comprise large inventories that are possibly recoverable if the deposits are mined for copper (fig. 4A–D). Inventories of thousands to more than 10,000 t of antimony, arsenic, tellurium, and tungsten in the entire deposit (near-surface chalcocite-enargite and deep chalcopyrite-bornite) were calculated from drill hole intervals and published resources (figs. 4, 6; tables 3, 12–15).

Elevated concentrations of bismuth, germanium, indium, and tellurium occur with calc-silicate and copper-lead-zinc-silver sulfide minerals in Paleozoic and Mesozoic carbonate rocks adjacent to the unmined Sunnyside porphyry Cu-Mo deposits (Santa Cruz County, Ariz.; figs. 1, 4A–D, 5, 6; tables 3, 12–15; Granitto and others, 2021),

approximately 4 km (2.5 mi) south of the Red Mountain porphyry Cu-Mo deposit. Much lower concentrations, but large inventories of these and other critical minerals occur in two 61 to 59 Ma porphyry deposits. Resources in porphyry deposits include approximately 800 Mst (727 Mt) grading 0.175 weight percent copper, 0.011 weight percent molybdenum, 0.23 troy ounces of silver per short ton, and small amounts of lead and zinc that comprise a near-surface chalcocite-enargite-tennantite deposit, and approximately 1.5 Gst (1.4 Gt) grading 0.33 weight percent copper, 0.011 weight percent molybdenum, and 0.16 troy ounces of silver per short ton that comprise a deep chalcopyrite deposit (Turner, 2012, 2017; Vikre and others, 2014). A resource for the zinc-lead-silver-copper sulfide deposit in carbonate rocks has not been determined. Vertical thicknesses of mineralized drill hole intercepts (up to 300 ft [91 m]; table 3) imply tens of millions of short tons. Drill hole intercepts average 1.9 weight percent Pb, 9.6 weight percent Zn, 231 ppm Ag, 0.55 weight percent Cu, 624 ppm Bi, 3.7 ppm Ge, 5.6 ppm In, and 29.8 ppm Te. Significant inventories of bismuth, germanium, indium, and tellurium may reside in this skarn/replacement deposit. A zinc-lead-silver-manganese resource in the same strata east of Sunnyside has been identified by drill holes in the vicinity of the Hardshell, Alta, and Hermosa mines (South32 Limited, 2021). This resource, approximately 33 Mt grading 2.3 to 3.4 weight percent zinc, 3.7 weight percent lead, 69 to 78 g/t silver, and 9.1 weight percent manganese, contains elevated concentrations of arsenic and antimony (table 4) that may be recoverable. Calculated inventories of critical minerals in the Sunnyside and Hardshell-Alta-Hermosa resources (figs. 4, 6; tables 3, 4, 12–15) largely correlate in mass with tonnage estimates of the resources. Inventories of more than 1,000 to more than 100,000 t of Sb, As, Bi, Ge, In, Re, Sn, and W were calculated for the near-surface chalcocite-enargite-tennantite and deep chalcopyrite deposits from drill hole intervals. Inventories of Sb, As, Bi, Ge, In, Re, Te, Sn, and W (mostly tens to a few thousand metric tons) were calculated from drill holes in the sulfide deposit in carbonate rocks and for the Hardshell-Alta-Hermosa resource. The relatively small inventories of critical minerals in carbonate rocks correlate with estimated deposit sizes of 20 and 33 Mt, respectively (figs. 4, 6; tables 3, 4, 12–15).

The unmined Ventura Mo-Cu breccia deposit, approximately 1.6 km (1 mi) west of the Sunnyside deposits (figs. 1, 4A–D, 5, 6; tables 4, 12–15; Granitto and others, 2021), consists of approximately 3.6 Mst (3.3 Mt) grading 0.24 weight percent molybdenum and 0.24 weight percent copper. Mineralized rocks include fragments of Jurassic granite and lesser Mesozoic volcanic and sedimentary rocks cemented by coarse-grained matrices of quartz, biotite, muscovite, molybdenite, chalcopyrite, and kaolinite (Vikre and others, 2014). Inventories of tens to hundreds of metric tons of Sb, As, Bi, Ge, In, Sn, and W, calculated from drill hole intervals, are relatively small because of small deposit tonnage.

Concentrations of numerous critical minerals in the CuMo porphyry Cu-Mo deposit, Boise County, Idaho (figs. 1, 4A–D, 5, 6; tables 6, 7), are included in multi-element analyses of drill holes used to define resources. Measured and indicated resources are 2.27 Gst (2.06 Gt; at \$5 copper value cutoff) grading 0.08 weight percent copper, approximately 0.045 weight percent molybdenum, and 0.07 troy ounces of silver per short ton (approximately 2.4 ppm) (SRK Consulting, 2020). The deposit consists of copper-molybdenum-silver mineralized veins, fractures, and stockwork veins, ranging from millimeters to tens of centimeters wide, in Cenozoic quartz monzonite and rhyolite porphyry that intruded granitic rocks of the Idaho batholith (~95 to 70 Ma). Copper occurs primarily in chalcopyrite, molybdenum in molybdenite, and the critical minerals rhenium in molybdenite, tungsten in scheelite, and gallium in gallite (CuGaS₂) (Hilscher and Dykes, 2018). Hydrothermal biotite and chlorite-epidote-magnetite-(pyrite) alteration assemblages are associated with earlier and shallower chalcopyrite, whereas mostly deeper molybdenite and scheelite are associated with potassium-feldspar alteration (potassium-feldspar and hydrothermal biotite). Late chlorite-smectite-calcite-(kaolinite) alteration is distributed throughout the deposit. Scheelite is largely cospatial with molybdenite. Somewhat elevated concentrations of tungsten, rhenium (average grade 0.021 ppm), and gallium exist in the resources (fig. 5). Indicated and inferred resources are approximately 125,000 short tons (approximately 113,000 t) of tungsten and 79.7 t of rhenium at \$5 recovered metal values with molybdenum oxide at \$10 per pound, copper at \$3 per pound, and silver at \$12.50 per troy ounce (SRK Consulting, 2020; Hilscher and Dykes, 2018; table 6). A gallium resource has not been reported. In addition to publicized tungsten and rhenium inventories, inventories of thousands to more than 10,000 t of antimony, arsenic, bismuth, and tin were calculated from drill hole intervals (figs. 4, 6; table 6). The somewhat larger calculated tungsten inventory (138,470 t; table 6) may reflect different copper grade restrictions applied.

Concentrations of critical minerals in the Bingham porphyry Cu-Mo deposit (figs. 1, 4, 6; tables 12–15) are included in multi-element analyses of mineral domains and other sources described in chapter B. Reserves at the end of 2020 were 552 Mt containing 0.44 percent copper, 0.031 percent molybdenum, 0.16 ppm gold, and 2.11 ppm silver; resources comprise 285 Mt containing 0.38 percent copper, 0.017 percent molybdenum, 0.20 ppm gold, and 1.79 ppm silver (Rio Tinto, 2021b). A resource of approximately 20 Mt grading 3.65 percent copper, 1.62 ppm gold, and 20.95 ppm silver has been determined for the North Rim skarn deposit. Inventories of Sb, As, Bi, PGE, Re, Te, Sn, and W calculated from element concentrations in mineral domains and reserve and resource tonnages vary mostly from tens to thousands of metric tons (figs. 4, 6; tables 12–15).

Concentrations of PGE, rhenium, and tellurium at Bingham have been determined by mineralogical investigations (chap. B). Using an average concentration of

14 ppb Pd+Pt and 837 Mt of reserves and resources, porphyry ores contain about 12 t of Pd+Pt. If the North Rim skarn deposit has similar Pd+Pt concentrations, then it contains approximately 3.8 to 20 t of Pd+Pt. Somewhat greater Pd+Pt concentrations of 0.006 to 0.034 troy ounces per short ton (approximately 0.19 to 1 ppm), are reported in gold-rich skarn at the Carr Fork mine (Cameron and Garmoe, 1987). In copper ore from unspecified sites but possibly skarn/replacement ores mined prior to open-pit mining of porphyry ore, calculated platinum and palladium concentrations are approximately 2 and 6 ppm, respectively, according to analyses of blister copper in the Garfield copper refinery (predecessor to the Magna copper refinery) (Eiler, 1913). If these analyses and assumptions are correct, then skarn resources could contain tens of metric tons or more of PGE. Using an average molybdenite rhenium concentration of 100 ppm (Kocher, 2017) and average molybdenum grade, approximately 36 t of rhenium are contained in the porphyry Cu-Mo deposit reserves and resources. Tellurium inventories in the porphyry Cu-Mo deposit, calculated from averages of Cu-Mo-rich whole-rock samples, range from 285 to 4,000 t (tables 12–15).

Concentrations of critical minerals in the Yerington porphyry Cu-Mo district, Lyon County, Nev. (figs. 1, 4A–D, 5, 6), are incompletely known as only a few are published for the Mason (formerly Ann Mason) and MacArthur deposits (Lori, 2010; Cohen, 2011; Aird and others, 2021; Hudbay Minerals, Inc., 2021; Independent Mining Consultants, Inc., 2022; John Dilles, Oregon State University, written commun., 2021; tables 12–15). The Yerington district includes four porphyry copper deposits and small iron-oxide-copper-gold skarn deposits in Jurassic granitic and volcanic rocks altered to garnet-pyroxene hornfels and endoskarn, and later copper-andradite skarn (Dilles and others, 2000). Although the concentrations of critical minerals in copper-mineralized samples are a few parts per million or less, as in most porphyry Cu-Mo deposits, the combined reserve tonnage of the Mason and MacArthur deposits (approximately 2.24 Gt) portends large inventories that could conceivably be recovered (figs. 1, 4, 6; tables 12–15). Qualified inventories of thousands to more than 10,000 t of arsenic, tin, and tungsten were calculated from available analyses.

Comparisons Among Critical Mineral Concentrations and Inventories in Porphyry Cu-Mo Deposits

Concentrations of primary commodities in porphyry Cu-Mo and breccia Mo-Cu deposit reserves that dictate exploration, development, and production (Cu and Mo), and of coproduct, and byproduct commodities (Au, Ag, Re, and Te) that can increase profitability, are mostly one to approximately three orders of magnitude greater than crustal abundances in the deposits investigated (fig. 4A). Concentrations of the critical minerals Sb, As, Bi, Te, and W are one to more than two orders of magnitude greater than crustal abundances (Haynes, 2016); tellurium and bismuth concentrations are as much as 4.5 orders of magnitude greater (fig. 4B). Concentrations of the critical minerals germanium, indium,

and tin vary considerably. They are slightly to markedly elevated relative to crustal abundance in some reserves and resources and relatively depleted (less than one order of magnitude) or approximately equal to crustal abundance in others (fig. 4C). Concentrations of the critical minerals gallium, nickel, manganese, and vanadium are mostly lower than or approximately equal to crust (fig. 4B), with the exception of the Sunnyside and Hardshell-Alta-Hermosa replacement deposits in which manganese concentrations are greater than 10 times crustal abundance. Small amounts of manganese were recovered in conjunction with lead and silver in more distal replacement and vein deposits of the Sunnyside porphyry copper system, including the Hardshell, Mowry, and Trench mines (Farnham and others, 1961; Koutz, 1984; Vikre and others, 2014). In these mines manganese occurs in manganese oxide minerals and lesser alabandite, rhodochrosite, and rhodonite-group minerals.

Concentrations of primary, coproduct, and byproduct commodities, and of critical minerals, vary somewhat geographically among deposits (fig. 4A–D). Molybdenum and gold concentrations in Arizona deposits, except for Mo in the Ventura Mo-Cu breccia deposit, are distinctly lower than in other deposits, whereas silver concentrations in Arizona deposits are the same as or greater than in other deposits. Concentrations of the critical minerals Sb, As, Bi, Ge, In, and Te also are generally greater in Arizona deposits than in other deposits. Consequently, porphyry Cu-Mo deposits in Arizona, and in Alaska and Idaho, have somewhat larger inventories (per reserve and resources tonnages) of Sb, As, Bi, Sn, and possibly Re than Bingham deposits in Utah (figs. 4A, B, 6), although some critical minerals (Ge, In, Re, and Te) are not reported for all deposits.

Inventories of critical minerals in reserves and resources of porphyry Cu-Mo deposits, including porphyry, breccia, and polymetallic replacement deposits, broadly correspond to deposit size with the largest deposits containing the largest inventories of critical minerals (fig. 4A, B). Relatively small tonnage polymetallic replacement and breccia deposits (r and b, respectively, in fig. 5A, B) have much smaller inventories, although higher concentrations, of most critical minerals.

Relative to recent annual domestic consumption (table 21), Sb, As, Bi, Te, and W inventories in Alaska, Idaho, and Arizona porphyry Cu-Mo deposits are less than 1 to several orders of magnitude greater than consumption whereas tin inventories are lower than consumption. Inventories of Sb, As, Bi, and Sn in Bingham deposits are lower than those of other porphyry deposits. Although inventories of Ge, In, and Re are incompletely known, they are up to several orders of magnitude greater than consumption in Arizona and Bingham deposits (fig. 6B). Conceivably, simultaneous or sequential recovery of Sb, As, Bi, W, and possibly Ge, In, and PGE during recovery of primary, coproduct, and byproduct commodities (Cu, Mo, Au, Ag, Re, and Te) when these reserves and resources are mined could supply domestic consumption for years to many decades. Staged recovery from staggered development of unmined deposits would

provide lower proportions of annual consumption. These new prospective supplies would likely require subsidization such as sustained price guarantees and tax reductions, and assistance in development of recovery processes. The relatively small inventories of Sn, relative to consumption, would not provide appreciable long-term supplies but could lessen importation reliance. The recovery of rutile and zircon in igneous rocks in porphyry Cu-Mo deposits would hinge on a marketable product form, and costs of concentrator modifications and operation at mines and copper refineries.

Forms of Sb, As, Bi, Ge, In, Re, Te, and Sn in Porphyry Cu-Mo Deposits

Chalcophile critical minerals in porphyry Cu-Mo deposits, including Sb, As, Bi, Ge, In, Re, Te, and Sn, are often undetectable in bulk ore. The highest concentrations of Sb, As, and Mn occur in sulfide and carbonate minerals (tetrahedrite-tennantite [(Cu,Fe)₁₂Sb₄S₁₃–(Cu,Fe)₁₂As₄S₁₃], arsenopyrite [FeAsS], and rhodochrosite [(Mn,Fe,Mg,Ca)CO₃]) (table 20) that are relatively abundant in some deposit types (skarn, replacement, and vein) with higher total sulfide concentrations than porphyry Cu-Mo ores, whereas these and other critical minerals also occur in cryptic forms or in relatively uncommon minerals mostly observed in skarn, replacement, and vein deposits (tables 3–19). Minerals that contain critical minerals have been identified in some districts and deposits.

In replacement deposits in the Bisbee district, Ariz., Sb, As, Bi, Mn, Sn, W, and V occur in many minerals including tetrahedrite ((Cu,Fe)₁₂Sb₄S₁₃–(Cu,Fe)₁₂As₄S₁₃), wittichenite (Cu₃BiS₃), colusite (Cu_{12–13}V(As,Sb,Sn,Ge)₃S₁₆), stannite (Cu₂FeSnS₄), mawsonite (Cu₆Fe₂SnS₈), and numerous rare Cu-Bi-Ag-Pb-Sb-In-Sn-W-S minerals; tellurium occurs in goldfieldite (Cu₁₂(Te,Sb,As)₄S₁₃), and lesser hessite (Ag₂Te), and petzite (Ag₃AuTe₂) (Bryant and Metz, 1966; Graeme, 1993; Schumer, 2017). At the Magma mine, Superior district, a large polymetallic vein and replacement deposit in Arizona, Sb, As, Bi, Te, Sn, W, and V occur in tetrahedrite-tennantite, enargite (Cu₃AsS₄), wulfenite (PbMoS₄), cassiterite (SnO₂), telluride minerals, colusite, and wittichenite (Gustafson, 1962; Hammer and Peterson, 1968; Frieauff, 1998). At Butte, Montana, bismuth, manganese (wittichenite, rhodochrosite, rhodonite [MnSiO₃]), and tungsten (scheelite and hubnerite [MnWO₄]) occurred in mined veins, along with uncommon copper-vanadium-sulfur minerals (Meyer and others, 1968; Czehura, 2006). Wittichenite is at least one source of recovered bismuth, and rhodochrosite and rhodonite, along with manganese-oxide minerals, were sources of recovered manganese (described in chaps. A, B).

At Bingham, Utah, the critical minerals rhenium, palladium, platinum, and tellurium have been episodically produced (Krahulec, 2018). Rhenium occurs in molybdenite and tellurium occurs in hessite and other telluride minerals and a gold-bismuth tellurite (Ballantyne and others, 1997), but palladium and platinum have not been linked to specific minerals. In the Ely (Robinson) district, White Pine County,

Nev., ores mined for copper contained unquantified amounts of Bi, Ni, PGE, Te, and W (scheelite) in unknown forms that were mostly not recovered (Hose and others, 1976; Gott and McCarthy, 1966; Watterson and others, 1977). In the Copper Canyon district, Lander County, Nev., elevated concentrations of tellurium are widely distributed in rocks (Theodore and Blake, 1975), but tellurium was not recovered during mining operations and forms of tellurium in deposits have not been determined. In the carbonate-replacement and vein deposits of the Tintic district, Utah, Sb, As, Bi, Mn, Zn, and other elements in ores were either not recovered or recovered from weathered deposits and slag only, in part because of complex mineralogy (James, 1984). Non-contiguous drill hole intervals in the center of the southwest porphyry copper system at Tintic contain approximately 1 to more than 2 ppm tellurium (Krahulec, 1996) in unreported sites. Skarn, replacement, and vein ores mined in other porphyry copper districts apparently contained variably elevated concentrations of chalcophile critical minerals according to analyses of archival specimens and samples from collections (tables 16–19), as described below.

Deposit Type—Porphyry/Skarn-Replacement-Vein Bismuth (Bi), Fluorite, Indium (In), and Tungsten (W)

Tungsten (W)

Unmined tungsten resources in California, Nevada, and Montana with inventories that approach or exceed 2 years of recent annual domestic consumption, the threshold for significant inventories used herein, are mostly in the vicinity of small tungsten skarn deposits. Several are adjacent to relatively large, mined deposits that have been described in chapter A (table 2).

The tungsten deposit known as Andrew Curtis, Los Angeles County, Calif., consists of scheelite-quartz veins and stockwork veins in shear zones, and alluvial and placer scheelite and lesser barite deposits that originated from the veins (Evans and others, 1977; USGS, 2010a; Unruh and Graber, 1982; Annis, 2020a; table 2). Small amounts of tungsten have been produced from the deposits including several metric tons of scheelite concentrate shipped from 1978 to 1982 (USGS, 2010a). Two of the veins are 1 to 10 inches wide and traceable for a slope distance of up to 300 ft (Unruh and Graber, 1982). Veins are in layered gneiss of the Proterozoic Tujunga terrane, quartz monzonite of the Triassic Mount Lowe intrusive suite, and Cretaceous Mount San Antonio hornblende-biotite quartz diorite (Annis, 2020a). The “west vein” is the principal vein deposit in Cattle Canyon where the Andrew Curtis mine claims were staked and intermittently worked until forfeited in 2018. The “west vein” complex contains an indicated resource of approximately 3,200 t grading 0.75 percent WO_3 , or approximately 19 t of tungsten (Annis, 2020b). The Cattle Canyon alluvial deposit was the focus of a Forest Service Validity Examination in 2020 that determined a measured resource of 3.9 million cubic yards with an average grade of 0.0023 percent WO_3 or 67.34 cubic meters of tungsten (90 t of tungsten) (Annis, 2020b). Earlier, unverified resource

estimates of all deposit types include approximately 6,000 t of tungsten measured, approximately 17,000 t of tungsten indicated, and 215,000 t of tungsten inferred (Unruh and Graber, 1982; Ridenour and others, 1982).

The Centennial (also known as Mount Hamilton) tungsten-gold-silver deposit, White Pine County, Nev., consists of scheelite, gold, and sulfide minerals in hornfels and skarn (diopside-quartz-potassium feldspar-biotite) that selectively replaced thin-bedded Cambrian Secret Canyon Shale and overlying dolomite and shale of the Dunderberg Shale. The large masses of mineralized hornfels and skarn are adjacent to the Cretaceous (~105 Ma) Seligman hornblende-biotite granodiorite stocks (Myers, and others, 1991; SRK Consulting, 2009a, 2014; table 2). There is no recorded tungsten production. Exploration over the past several decades has identified resources that contain, in addition to W in scheelite, Sb (stibnite; bournonite; and jamesonite), Au and Ag (electrum), Cu (chalcopyrite; covellite; bornite), and Mo (molybdenite; USGS, 2007; SRK Consulting, 2012, 2014). Tungsten resources based on 100,000 ft of drilling by Phillips Petroleum Company from 1968 to 1982 are 4.2 Mst (3.8 Mt) grading 0.42 percent WO_3 and 6.2 Mst (5.6 Mt) grading 0.37 percent WO_3 (SRK Consulting, 2012), or approximately 32,200 t of tungsten. A gold-silver resource that contained an estimated 0.55 million troy ounces (17.1 t) of gold and 4.5 million troy ounces (140 t) of silver (proven and probable; SRK Consulting, 2014) was partially mined (NE Seligman mine) from 1994 to 1997 with production of 0.124 million troy ounces (3.9 t) of gold and 0.31 million troy ounces (9.6 t) of silver (SRK Consulting, 2014).

The Sunrise copper-molybdenum-tungsten deposit, Snohomish County, Washington, is in a steeply plunging pipe-like breccia that consists of multi-generational, hornfelsed quartz diorite fragments cemented by matrices containing chalcopyrite and molybdenite (table 2). These sulfide minerals are also disseminated in breccia fragments and fill fractures in Jurassic greenstone and siliciclastic strata that enclose the deposit. Diorite fragments in the pipe increase in abundance with depths and may be related to nearby Oligocene intrusions. The deposit contains a resource (measured, indicated, and inferred) of 64.5 Mt grading 0.319 percent copper, 0.071 percent MoS_2 , 0.062 percent WO_3 (approximately 31,730 t of tungsten), 0.002 to 0.006 troy ounces of gold per short ton, and 0.049 to 0.088 troy ounces of silver per short ton (Derkey and others, 1990; Lasmanis, 1995; USGS, 1997).

At Pilot Mountain, Mineral County, Nev., minor amounts of tungsten in scheelite were recovered from skarn, replacement, and vein deposits (Maurer and Wallace, 1956; Nash and others, 1985; Cowie, 1985; table 2). The Pilot Mountain group of deposits (Desert Scheelite, Gun Metal, Garnet, and Good Hope) also contain copper (chalcopyrite, azurite), silver, and zinc (sphalerite; Karl and others, 2020) but there is no recorded production of metals other than tungsten. The deposits occur in carbonate beds of the lower to middle members and the upper carbonate member of the Triassic Luning Formation adjacent to a Cretaceous biotite

quartz monzonite intrusion (Godfrey, 2018). Drill-defined resources (indicated and [or] inferred) include 9.01 Mt grading 0.26 weight percent WO_3 (Desert Scheelite) and 1.83 Mt grading 0.36 weight percent WO_3 (garnet) (Thor Mining PLC, 2018a, b), or 27,200 t of tungsten. Copper (16,000 t), silver (approximately 0.67 million troy ounces [20.8 t]), and zinc (40,300 t) may be recovered (coproducts or byproducts) if the tungsten resources are mined. Based on recent exploration and a scoping study, an open pit mine with a 12-year mine life and annual production of 1,000 t of scheelite concentrate is proposed. Copper, silver, and zinc also may be recovered (Thor Mining PLC, 2018a, b).

The tungsten skarn deposit at Indian Springs, Elko County, Nev., consists of scheelite-quartz-sulfide veins in calcareous feldspathic medium-grained sandstone of the Permian Pequop Formation and in the Early Cretaceous (~135 Ma) Indian Springs stock (Slack, 1972; SRK Consulting, 2007; [table 2](#)). Three of the four generations of hydrothermal activity produced scheelite-bearing veins: (1) (oldest) pneumatolytic scheelite-powellite-quartz vein stockworks; (2) pyrite and molybdenite in quartz veins and disseminations; and (3) chalcopyrite-tetrahedrite-quartz veins. Argillization, sericitization, and silicification are associated with tungsten mineralization (Slack, 1972; SRK Consulting, 2007). A minor amount of tungsten (12,500 short tons [11,364 t]) of tungsten grading 0.25 weight percent WO_3 , yielding 14 units of WO_3 was produced in 1974 and 1975 by Union Carbide (USGS, 2010b). The deposit contains estimated resources of 10.7 Mt of WO_3 grading 0.171 percent (indicated), and 8.2 Mt grading 0.167 percent WO_3 (inferred; Moran and Stryhas, 2007), or approximately 20,800 t of tungsten.

The Browns Lake tungsten skarn deposit, Beaverhead County, Mont. (described in chap. A; [table 2](#)), contains an estimated resource of 14,400 t of tungsten (Werner and others, 2014). The Pine Creek tungsten skarn mine, Inyo County, Calif. (described in chap. A; [table 2](#)), contains a resource estimated to exceed 10,000 short tons (9,090 t) of tungsten. The Springer (also known as Nevada-Massachusetts) tungsten skarn mine, Humboldt County, Nev. (described in chap. A; [table 2](#)), contains indicated and inferred resources in three deposits of 1,400 and 6,900 t of tungsten, respectively (8,300 t of tungsten combined). Placer deposits in the Atolia district, San Bernardino and Kern Counties, Calif. (described in chap. A; [table 2](#)) contain an estimated 280,000 units WO_3 (2,200 t of tungsten) and small but unquantified amounts of gold.

Tungsten resources at Andrew Curtis, Centennial, Sunrise, Pilot Mountain, and Indian Springs are each equivalent to approximately 2 to 4 years of recent annual consumption. Those at Browns Lake, Pine Creek, and Springer are each equivalent to approximately 1 year or less of consumption (described in chap. A; [tables 2, 21, 22](#))

Bismuth (Bi)

A resource of 20,000 short tons (18,182 t) grading 0.84 percent bismuth (approximately 1,680 short tons [1,527 t]) and 0.26 percent tungsten (approximately 520 short

tons [473 t]) was identified in the Little Cottonwood district, Salt Lake County, Utah (Kasteler and Hild, 1948; Moon, 1950). At the Victoria mine, Elko County, Nev., reserves remaining after 1981 were 1.4 Mst (1.27 Mt) grading 2.15 weight percent copper and 0.35 troy ounces of silver per short ton, according to Lapointe and others (1991) and 1.49 Mst (1.35 Mt) grading 2.34 weight percent copper according to Lowe and others (1985). If the reserve of Lapointe and others (1991) has the same bismuth grade as ore, then the bismuth resource at the Victoria mine is approximately 700 short tons (636 t). These bismuth resources are equivalent to less than 1 year of recent domestic consumption ([tables 21, 22](#)).

Fluorite (CaF_2)

At McCullough Butte, Eureka County, Nev., a resource of more than 80 Mt grading approximately 11 percent fluorite (more than 8 Mt fluorite) has been estimated from drill holes (Tertiary Minerals PLC, 2020). In addition, elevated but unquantified concentrations of Be, Mo, Sn, W, and Zn are distributed in the fluorite resource. The resource occurs in porphyry felsite dikes (~84 Ma) and aplite, and Paleozoic limestone, dolomite, and quartzite altered to greisen/quartz veins, tremolite, phlogopite, and calcite. Six vein types in the resource contain variable amounts of quartz, feldspar, garnet, epidote, feldspar, fluorite, pyrite, muscovite, sphalerite, molybdenite, zoisite, beryl, barite, and antimony sulfosalts (Barton 1982, 1987). Minor amounts of fluorite and beryllium were produced at the nearby Reese and Berry mine (Roberts and others, 1967). Based on recent annual domestic consumption of fluorite ([table 21](#)), a large-market commodity, the fluorite resource at McCullough Butte is approximately equivalent to 18 to 22 years of consumption ([table 22](#)). However, the fluorite grade at McCullough Butte is much lower than grades of imported fluorite.

Indium (In)

In the Fish Springs district, Juab County, Utah, a drill-defined resource (indicated and inferred) of approximately 67 Mt grading 5 to 6 percent zinc, 0.2 percent copper, and 22 to 31 ppm indium occurs in magnetite-sphalerite skarn deposits that formed in Paleozoic carbonate and siliciclastic rocks adjacent to Eocene felsic intrusions (Dyer and others, 2014). The indium inventory is 1,474 to 2,077 t. Based on recent annual domestic consumption of indium ([table 21](#)), a small-market commodity, the indium resource at Fish Springs is equivalent to approximately 9 to 22 years of recent domestic consumption ([table 22](#)).

Manganese (Mn)

The Hardshell-Alta-Hermosa zinc-lead-silver-manganese resource, Santa Cruz County, Ariz., includes approximately 5 Mt of manganese in the Taylor deposit (South32 Limited, 2021) that may be recovered as a coproduct with zinc, lead, and silver. Based on recent annual domestic consumption of

manganese, a large market commodity, the Taylor manganese resource is equivalent to approximately 6.6 years of recent domestic consumption (table 22).

Deposit Type—Lithocap Alunite

Aluminum (Al), Potash (KCl, K_2SO_4 , KNO_3)

Large tonnage alunite resources exist in Utah, Arizona, Nevada, and Colorado. Some were encountered in holes drilled for Cu-Mo resources; several are potentially minable for aluminum and potash. At Blawn Mountain (Wah Wah Range, Beaver County, Utah), where small tonnages of alunite were processed during World War II for aluminum and potash (fertilizer; described in chap. A), the SOPerior Fertilizer Corporation (formerly Potash Ridge) is developing a reserve of approximately 10.6 Mst (9.6 Mt) of potassium sulfate that is within an indicated resource of approximately 32 Mst (29 Mt). Assuming alunite contains 19.5 weight percent aluminum, 76 weight percent K_2SO_4 , 4.5 weight percent H_2O and no sodium or calcium, the aluminum resource in the potash reserve at Blawn Mountain is approximately 2.56 Mst (2.33 Mt). Vein reserves at Marysvale, Utah, were estimated in 1941 at approximately 1.4 to 3 Mst (1.3 to 2.7 Mt) grading 87 percent or more alunite; replacement deposit resources comprise a much larger aggregate tonnage, but deposits are lower grade (Thoenen, 1941). Other alunite vein and replacement deposits in southwestern Utah (Beaver, Piute, Siever, and Iron Counties) constitute possible aluminum and potash resources (Mills and Rupke, 2020). In 1941, estimated resources in Utah varied from hundreds of thousands to 6 Mst (hundreds of thousands to 5.5 Mt) containing 6 to more than 55 percent alunite (Thoenen, 1941).

At Red Mountain, Santa Cruz County, Ariz., quartz-alunite-kaolinite-pyrophyllite-altered rocks overlie two copper-(molybdenum-silver) resources that constitute the Red Mountain porphyry copper deposit (Lecumberri-Sanchez and others, 2013; Vikre and others, 2014). Holes drilled in the 1970s outlined a prospective resource of more than 300 Mst (273 Mt) grading 30 percent alunite (91 Mst [83 Mt] of alunite; North American Potash Developments, Inc., 2012). Assuming alunite contains 19.5 weight percent aluminum, 76 weight percent K_2SO_4 , 4.5 weight percent H_2O , and no sodium or calcium, the aluminum and potash resources at Red Mountain are approximately 18 and 42 Mst (16 and 38 Mt), respectively.

At Sunnyside, Santa Cruz County, Ariz., quartz-alunite e-kaolinite-pyrophyllite-topaz-zunyite-altered rocks overlie two copper-(molybdenum-silver) resources that constitute the Sunnyside porphyry copper deposit and extend northwest to the 3R mine and south to the Thunder mine (Berger and others, 2003; Vikre and others, 2014). An estimated mass of 180 Mst (164 Mt) grading 20 percent alunite (includes internal waste; approximately 36 Mst [33 Mt] alunite) from the surface to a depth of 500 ft (152 m) occurs in the vicinity of these resources and mines. This mass could contain approximately 7 Mst (6.4 Mt) aluminum and approximately 27 Mst (24.5 Mt) potash.

Numerous alunite deposits occur in quartz-alunite-altered Cenozoic andesite and andesite tuffs in Pierce County, Wash. They comprise a resource estimated at 1 to 2 Mst (0.91 to 1.82 Mt) grading 20 to 30 or more weight percent alunite (USGS and others, 1966b). In King County, Wash., resources of approximately 1.2 Mst (1.1 Mt) grading approximately 30 to 80 percent alunite occur in quartz-alunite-altered volcanic rocks (Thoenen, 1941). Although no alunite production is reported, high-purity silica in or near some alunite resources has been mined for flux and wall-board products (John and others, 2003). A reportedly large but incompletely quantified and described alunite resource (estimated at more than 70 Mt) occurs in dacite intrusions and breccias (~23 Ma) on Red Mountain near Lake City, Colo. (Bove and Hon, 1990).

Based on recent annual domestic consumption of aluminum (table 21), a very large market commodity, the aluminum resources at Blawn Mountain, Red Mountain, and Sunnyside are equivalent to approximately 1 to 6 years of the lowest consumption (2.87 Mt) and approximately 0.5 to 3 years of the highest consumption (5.68 Mt; table 22). Based on recent annual domestic consumption of potash (table 21), a very large-market commodity, the potash resources at Blawn Mountain, Red Mountain, and Sunnyside are equivalent to approximately 5 to 8 years of the lowest consumption (5.2 Mt) and approximately 4 to 7 years of the highest consumption (6.2 Mt; table 22).

Unclassified Magmatic-Hydrothermal Deposits

Antimony (Sb)

No production figures for the Coyote (Antimony) district, Utah (described in chap. A), have been published but a significant resource may remain in the district. Lateral and vertical dimensions of unmined lenses or stratiform masses of stockwork veins and small masses of stibnite and antimony oxides are up to several hundreds of ft in length and several tens of ft thick (Traver, 1949; Callaghan, 1973). Based on these and other dimensions of mineralized zones, and on distribution of mined deposits, a resource of 1.5 Mst (1.3 Mt) grading 6 to 7 percent antimony, or approximately 90,000 to 105,000 short tons (81,818–95,455 t) of antimony, was estimated in 1941 (Palladine, 1941). Callaghan (1973) estimated lower grades of unmined lenses, 0.5 to less than 3 weight percent antimony, but provided no resource tonnage. According to Mills and Rupke (2020), 105,000 short tons (95,455 t) of antimony may remain in the district, an estimate identical to and perhaps derived from Palladine (1941). However, this tonnage is inordinately large relative to production estimated from antimony value during mining (approximately 395 t). Based on recent annual domestic consumption of antimony (table 21), a mid-market commodity, a 105,000-short-ton antimony resource in the Coyote district is equivalent to approximately 4.8 years of the lowest consumption (22,000 t) and approximately 3.8 years of the highest consumption (27,700 t; table 22).

Antimony (Sb), Arsenic (As), Bismuth (Bi), and Tungsten (W)

In the Yellow Pine district, Valley County, Idaho (described in chap. A), composited analyses of diamond drill holes (DDH) used to define the Yellow Pine, Hangar Flats, and West End gold-silver-(antimony) resources include markedly elevated concentrations of As, Bi, and W in addition to Au, Ag, and Sb (table 7). The resources contain approximately 5.63 million troy ounces (175 t) of gold, 8.68 million troy ounces (270 t) of silver, and approximately 74,000 t of antimony (Huss and others, 2014; Becker and others, 2019; NS Energy, 2021) which represents the largest unmined domestic antimony reserve. Using a total resource tonnage of 104 Mt and composited analyses from 19 DDH (table 7), approximately 59,082 t of antimony, 209,673 t of arsenic, 38,989 t of bismuth, and 1,560 t of tungsten occur in the currently defined reserve. The conflicting antimony tonnages suggest the DDH composites do not accurately represent the established reserve; however, the DDH composites indicate that there is substantial bismuth in the reserve.

Based on recent annual domestic consumption of antimony, arsenic, bismuth, and tungsten (table 21), mid- and small-market commodities, and the DDH composites, the estimated antimony resources at Yellow Pine are equivalent to approximately 3 to 5 years of the lowest consumption (22,000 t) and approximately 0.5 to 4 years of the highest consumption (27,700 t; table 22). The estimated arsenic resource is equivalent to approximately 34 years of the lowest consumption (6,120 t) and approximately 20 years of the highest consumption (10,500 t; table 22). The estimated bismuth resource is equivalent to approximately 27.8 years of the lowest consumption (1,400 t) and approximately 15.4 years of the highest recent consumption (2,530 t; table 22). The tungsten resource is very small relative to recent annual domestic consumption and comprises less than 1 year supply.

Fluorite (CaF₂)

Modest tonnage deposits of relatively low-grade fluorite exist in New Mexico, Utah, and Nevada. Estimated fluorite resources in New Mexico are estimated at 1.4 Mst (1.3 Mt) grading 35 weight percent or more fluorite (USGS and others, 1965). Large but incompletely quantified resources of fluorite also occur in and near the Spor Mountain, Utah, beryllium deposits (Bullock, 1976, 1981); these deposits have not been successfully marketed because of the low grade and fine grain size of fluorite and other factors.

Gallium (Ga) and Germanium (Ge)

At the Apex mine, Washington County, Utah (described in chap. A), a resource of 850 short tons (773 t) of germanium, 330 short tons (300 t) of gallium, and 18,000 short tons (16,364 t) of copper remains in the reclaimed mine (Dutrizac and others, 1986; Mills and Rupke, 2020). Based on recent annual domestic consumption of gallium and germanium

(table 21), both very small market commodities, the gallium resource at the Apex mine is equivalent to approximately 20 years of the lowest consumption and approximately 17 years of the highest consumption (table 22); the germanium resource is equivalent to approximately 26 years of consumption (estimated 30 t; table 22).

Inventories of Critical Minerals in Unmined Porphyry Cu-Mo Deposits Based on Anode Copper

Concentrations of Cu, Mo, Au, Ag, Sb, As, Bi, Fe, Pb, Ni, O, PGE, Re, Se, S, Te, and Sn have been variably tracked during processing of ores from porphyry copper-(molybdenum) (Cu-(Mo)) and other deposits for recovery of copper and molybdenum (tables 9–11). In the three operating domestic copper refineries and allied facilities, Cu and Mo are concentrated to marketable purity, and Au, Ag, Re, and Te are recovered when profitable. These primary products and byproducts were also concentrated in numerous other copper refineries since shuttered or demolished. In addition to the critical minerals Re and Te, small amounts of other critical minerals, including Sb, Bi, Ni, and PGE have been episodically recovered at operating and shuttered or demolished copper refineries that processed porphyry Cu-Mo deposit ores (described in chap. B and previously in chap. C). Whereas Cu and Mo production is quantified and recorded annually, quantification of Sb, Bi, Ni, PGE, and other critical minerals, including As, In, Sn and often Re and Te, is seldom reported even when recovered (for example, Anaconda Copper Mining Company, 1915–1955; ASARCO, 2021).

Apparently, most critical minerals have been routinely discarded in tailings, slags, slimes, and electrolyte or disposed of in storage sites. Owing to the large scale of mining of porphyry Cu-Mo deposits (tens of thousands of metric tons of ore per day) and episodic recovery of critical minerals, slimes and electrolyte at operating copper refineries and allied facilities (and stored at shuttered or demolished refineries or other sites) could contain large inventories of Sb, As, Bi, Ni, Te, and Sn and possibly other critical minerals (fig. 6D), and concentrator tailings could contain large inventories of Al, Ti, W, and Zr. The concentrations of critical minerals in concentrator tailings have not been published and tailings inventories cannot be calculated. However, concentrations of critical minerals in anode copper, a partially refined form of copper, have been episodically compiled and can be used to semi-quantify inventories of critical minerals in (1) refinery slimes, and (2) unmined resources and mine reserves and resources. The following evaluation is concerned only with critical mineral inventories of unmined resources and mine reserves and resources.

Refining of Cu-Mo ores to marketable copper and molybdenum involves three stages: (1) concentration of copper and molybdenum sulfide minerals by separation from valueless silicate, carbonate, oxide, and other sulfide

minerals; molybdenum sulfide minerals (nearly exclusively molybdenite) are then sent to separate allied facilities for molybdenum recovery, (2) smelting of copper sulfide mineral concentrate to remove iron, sulfur, and oxygen and silicate impurities, and (3) electrorefining of smelted copper with 1 to 2 percent remaining impurities, known as anode copper, to cathode copper containing a few tens of parts per million or less of impurities (fig. 6D). During electrorefining, anode copper is dissolved in electrolyte, transferred to cathodes where it precipitates as 99.9 weight percent or more copper, and cast into fabricator products (ingots, wirebar) (for example, Anaconda Copper Mining Company, 1937). The very fine grained impurities in anode copper settle in electrolyte tanks and are known as slimes or tank house slimes. Slimes contain elevated concentrations of gold, silver, and other chalcophile critical minerals (Sb, As, Bi, Te, and Sn), whereas electrolyte contains elevated concentrations of the siderophile critical minerals Co, Ni, and Zn.

In operating (and shuttered or demolished) copper refineries, Cu, Au, Ag, Sb, As, Bi, Fe, Pb, Ni, O, Se, S, Te, and Sn are monitored (tables 9, 10) because (1) some elements, including the critical minerals Sb and As, affect electrical conductivity, malleability, and ductility, the properties essential to copper fabricators (Lane and others, 2016; Moats and others, 2012, 2014a, b, 2016; Artzer and others, 2018), (2) recovery of copper and the marketable critical mineral tellurium can be increased by recycling slag and effluent (dusts; gases), (3) some elements can be profitably recovered as byproducts (Au, Ag, and Te), and (4) many elements are subject to emission control regulations (for example, As, Pb, Se, S; fig. 6D). Concentrations of some critical minerals in porphyry Cu-Mo ores (for example, PGE, Re, and Te) are very low, often below detection limits, and measurable only in concentrates (Tarkian and Stribny, 1999), interim products (slags, dusts, and gases) (Tylecote and others, 1977; Schwitzgebel and others, 1978; Mauser, 1982; Foster, 1991; Wong and others, 2006), anode copper, and electrorefining slimes (table 12–15). However, because thousands to tens of thousands of metric tons of ore are processed daily for copper, molybdenum, and byproduct recovery, concentrations of critical minerals and other monitored elements in anode copper are often tens to hundreds of parts per million and in slimes and electrolyte several weight percent (tables 9–15; Anaconda Copper Mining Company, 1937; Broadhurst and others, 2007; Hait and others, 2009; Dupont and others, 2016). Cathode copper, the marketable form, typically contains less than 1 to several tens of parts per million Au, Ag, Sb, As, Bi, Te, and Sn (Anaconda Copper Mining Company, 1937; Parker, 1978; Ramachandran and Wildman, 1987; Moats and others, 2013), indicating that chalcophile and siderophile critical minerals in anode copper are largely partitioned to slimes during electrorefining. Sb, As, and Bi in anodes and slimes occur in various oxide minerals whereas Te and PGE apparently occur in gold-silver tellurides (Parker, 1978; Chen and Dutrizac, 2005; Hait and others, 2009) and likely in copper and other telluride minerals.

Metallurgical Accounting of Critical Minerals During Copper Recovery

Metallurgical accounting of critical minerals in copper refineries, operating and shuttered or demolished, is notoriously difficult to balance. The quantities of critical minerals not recovered during concentration of copper and molybdenum minerals (concentrator tailings; [1] above), and during smelting of copper minerals (slags, dusts, and gases; no. 2 above) (fig. 6D) are seldom published (Miller and others, 1976; Mauser, 1982; Foster, 1991; Goonan, 2004; Chen and others, 2012; Xiao and others, 2012; Avarmaa and others, 2016). Partitioning of critical minerals and other elements between impure forms of copper (matte, blister, anode) and interim products (concentrator tailings, slags/speiss, and dusts) also have been infrequently reported, in part because concentrates and slimes have been processed at different facilities or exported and are difficult to track (Parker, 1978; Foster, 1991). In addition, although Sb, Bi, Ni, PGE, and Te episodically recovered at copper refineries were derived predominantly from captive porphyry Cu-Mo deposits, smelters, and refineries regularly to periodically processed tolled concentrates and ores, some imported, from other deposit types and scrap.

The variable concentrations of critical minerals in anode copper, slimes, and electrolyte (fig. 7A, B) also reflect deposit zoning, as ore depths increased over time, and processing refinements (for example, Foster, 1991; Newman and others, 1999). Prior to 1990, at least, interim products at some refineries contained tens of weight percent, Au, Ag, As, Se, and Te that in part correlated with ore type and processing techniques (for example, Foster, 1991). Interim products are now mostly recycled (reprocessed) to lessen marketable commodity loss (Cu, Au, Ag, and Te) and comply with regulatory emission requirements (fig. 6D; see Arthur D. Little, Inc., 1974; Malcolm Pirnie, Inc, 2010; Nexhip, 2016).

Other uncertainties in metallurgical accounting arise from exported copper concentrate and unquantified deportment of critical minerals in low-grade porphyry copper ores that are processed by heap leaching, pressure leaching, and other hydrometallurgical techniques. Regarding hydrometallurgy, since 2001 copper production at Morenci, Ariz., which approaches 400,000 t annually, largely derives from leaching and electrowinning (Dresher, 2001) during which critical minerals are apparently not tracked or recovered. In addition, domestic copper mine production has occasionally exceeded refinery capacity, necessitating shipment of concentrates to refineries abroad. New production from mines in Nevada (for example, Pumpkin Hollow) and Arizona (Copper World [Rosemont]; Resolution) will further tax domestic copper refinery capacity (DeMull and others, 2018), making tracking of critical minerals in domestic porphyry Cu-Mo deposits more difficult.

Low-grade stockpiles and dumps not included in reserves or resources that are processed for copper recovery (leaching and milling, when profitable) can further imbalance

critical mineral accounting. The small amounts of primary commodities and critical minerals that remain in mine dumps and mill tailings, and their recovery, are the subjects of recent investigations and operations (for example, Bian and others, 2012; Reck and Graedel, 2012; Zhang and others, 2020; Tabelin and others, 2021). For example, a heap leach facility at the Sacaton copper mine, Ariz., is being permitted and developed to recover copper from dumps from earlier mining operations (1970s–90s) (Sexauer and others, 2021; Arizona Sonoran Copper Company, 2021). However, the department of critical minerals during reprocessing at Sacaton has apparently not been addressed.

Critical mineral concentrations in anode copper, compiled from records that span decades, are used with reserve and resource tonnages, to calculate inventories in the following section. Based on the caveats and forecasts described above, these inventories may not accurately reflect concentrations in ores of captive mines. However, the masses of Sb, As, Bi, Te, Sn, and other critical minerals (Ni, PGE) that are transferred from anode copper to slimes during electrorefining represent significant inventories that have been mostly sent offsite for disposal and additional processing or exported. They are potentially recoverable or more effectively recovered in operating domestic copper refineries (for example, tellurium) (fig. 5; Wang, 2011; Dupont and others, 2016; Rio Tinto, 2021a). The production of approximately 1,100 short tons per year (1,000 t per year) of antimony from anode slimes between 1978 and 1986 at ASARCO's El Paso refinery (shuttered in 1999) (Yuan, 2007; ASARCO, 2021), or approximately 5 percent of recent domestic consumption (table 21), attests to the masses of critical minerals in slimes that are largely unrecovered in operating refineries (table 12–15).

Calculated Critical Mineral Inventories Based on Concentrations in Anode Copper and Slimes

Concentrations of the critical minerals monitored in domestic copper refineries have been episodically compiled since 1978, and with regularity from 1986 to 2018 (Parker, 1978; fig. 7A, B; tables 9–11). In the 1970s there were approximately 20 operating copper smelters and refineries; in 1995 seven remained (Parker, 1978; Eastern Research Group, Inc., 1998). As of 2022, there are three operating domestic refineries. The Rio Tinto refinery in Magna, Utah, processes Cu-Mo ores from the nearby Bingham district mines; the ASARCO smelter in Hayden, Ariz., and refinery in Amarillo, Tex., process Cu-Mo ores primarily from the Ray, Mission, and Silver Bell mines, Ariz.; and the Freeport-McMoRan smelter in Miami, Ariz., and refinery in El Paso, Tex., process ores, steadily to episodically, from the Morenci, Bagdad, Safford, Miami, and Sierrita mines, Ariz., and Chino and Tyrone mines, N. Mex. (fig. 7A). Shuttered or demolished domestic copper refineries for which anode copper and slime concentrations have been published include those at San Manuel and Miami, Ariz. (fig. 7B; tables 9–11).

The concentrations of Sb, As, Bi, Te, and Sn in anode copper and slimes can be used to semi-quantify inventories in operating porphyry Cu-(Mo) mine reserves and in unmined Cu-(Mo) reserves and resources (fig. 8A; tables 12–15). Predicted and annual inventories of Sb, As, Bi, Ni, Te, and Sn have been estimated from reserve and resource tonnages for mines that feed or fed operating and shuttered or demolished domestic copper refineries, concentrations of critical minerals in anode copper, and terms (years) of refinery operation (estimated in part) and (or) refinery records (fig. 8A; tables 12–15). Annual inventories were calculated by multiplying metric tons of ore processed by 0.5 weight percent copper (assumed average grade), then by 200 (concentration factor of critical minerals in anode copper), and then by the concentration of critical minerals (in parts per million or weight percent) in anode copper. Mine reserve inventories and inventories in unmined reserves and resources were obtained by multiplying annual inventories by mine life (years of reserves), or by using total reserve and resource tonnages.

In operating refineries, the annual inventories of critical minerals that are mostly in disposal sites, but which could constitute domestic supplies if recovered, are both larger and smaller than recent annual domestic consumption of these commodities. The range of arsenic, bismuth, and tellurium inventories per refinery (in metric tons per year) spans or exceeds annual consumption (fig. 8A); combined inventories exceed consumption. Tin has been too infrequently tracked for trend recognition, but the small annual inventories of tin potentially available are unlikely to comprise a significant proportion of annual consumption. This prediction is also supported by the relatively small inventories of tin in porphyry Cu-Mo deposits estimated from drill holes and mineral zones, described previously in chapter C. Likewise, annual nickel inventories per refinery are lower than consumption; however, combined inventories could conceivably approach consumption.

From estimated production tonnages of mines that fed two shuttered or demolished domestic copper refineries, and estimated terms (in years) of refinery operation, calculated inventories of Sb, As, Bi, Ni, and Te are considerably lower than for operating refineries (fig. 8A; tables 12–15). Because of imprecise production records and mine consolidation in the Globe-Miami district, Ariz., production tonnages, and critical mineral inventories calculated from them may not be accurately separated by mine production, production years, and assigned critical mineral concentrations in anode copper.

The two methods of critical mineral inventory estimation—one based on reserve and resource tonnages and concentrations in drill holes and mineral zones, and the second based on reserve and resource tonnages and concentrations in anode copper—can be compared for the Bingham porphyry Cu-Mo deposit where both methods were applied (fig. 8B). At Bingham, the calculated ranges of inventories of antimony, bismuth, nickel, and tellurium in anode copper are within, all or in part, inventories in Cu-Mo ore and other mineral zones (fig. 7B). The calculated inventory range (reserve and

resource) of arsenic in anode copper is considerably greater than that of Cu-Mo ore and mineral zones (for unknown reasons). However, the close correspondence of most comparable critical mineral inventories (Sb, Bi, Ni, and Te) implies that inventories determined by both methods are broadly valid.

It should be cautioned that the concentrations and calculated inventories of critical minerals in porphyry Cu-Mo reserves and resources, based on concentrations in drill holes, mineral zones, and anode copper (figs. 4–8; tables 3–15), are estimates only and should not be considered domestic supply forecasts for these critical minerals. The calculated inventories are conditioned by numerous limitations:

- Published concentrations of critical minerals in anode copper vary considerably over time, and reserve and resource tonnages from which critical mineral inventories were calculated also vary by published source. In addition, reserve tonnage and mine life may change with fluctuation in copper prices and by reserve expansion through exploration at mine sites.
- Most critical mineral concentrations in drill holes used to calculate inventories are averages, and concentrations in actual reserves and resources may or may not be fully represented by the drill holes or averaging. Further, the number and spatial distribution of drill holes and intervals analyzed are unknown for some deposits, reserves, and resources.
- Elevated concentrations of critical minerals may not correspond spatially to those of principal commodities for which mine plans are developed (for example, copper and molybdenum), and that will condition reserve definition and new deposit development. Critical mineral recovery from mined Cu-Mo ore may be smaller or larger than deposit inventories calculated from drill holes, mineral domains, and anode copper.
- Inventories calculated by the copper anode method assume that critical minerals were largely to entirely sourced from captive mines and smelters (mines and processing facilities owned by the same company; for example, Anaconda Copper Mining Company, 1915–1955). Average concentrations and tonnages used in inventory calculations disguise the variable critical mineral concentrations in (A) anode copper (resulting from changes in processing techniques), (B) ores from different mineral zones in deposits, and (C) ores from different deposits. Anode copper compositions may also reflect tolled concentrates and processed scrap. Further, some copper is recovered by leaching and electrowinning, as at Morenci, Ariz., rather than by smelting and electrorefining. The partitioning of critical minerals during leaching-electrowinning and other hydrometallurgical processes is unknown. However, copper produced by hydrometallurgy is included in total copper production used in inventory

calculations, whereas unknown critical mineral concentrations in leach lixiviant and waste are not used, thereby potentially inflating inventories.

- During copper concentration, smelting, and electrorefining, variable amounts of critical minerals are partitioned to interim products (concentrator tailings, flue dusts, and slags) (for example, Parker, 1978). Although recycling of these interim products to improve recovery and comply with emissions regulations has increasingly characterized refinery performance over the past several decades, large quantities of some lithophile critical minerals (Al, Ti, W, and Zr) could remain in concentrator tailings, and small unquantified amounts of chalcophile critical minerals (Sb, As, Bi, Ge, Te, and Sn; fig. 6D) could remain in interim products that are eventually discarded.
- Predicted inventories are not necessarily recoverable supplies as techniques for recovery of Sb, As, Bi, Ni, and Sn may not have been developed and recovery efficiencies are therefore unknown. Recovery of critical minerals may require subsidization, especially for low concentrations (tens of parts per million or less) and for some high concentrations.
- New and (or) increased recovery of small- (for example, Ge, In, Re, and Te) and mid-market (for example, Sb, As, and Sn) commodities (table 22) at copper refineries, without commensurate increase in demand, would undoubtedly lower market prices and necessitate adjustment of production subsidies and scheduling.

Semi- and Unquantified Inventories of Critical Minerals in Porphyry Cu-Mo and Other Deposit Types, and in Mill Tailings

Deposits and mill tailings with potential for significant inventories of critical minerals that have not been quantified, or are semi-quantified, are represented by several deposit types (porphyry Cu-Mo-Au, lithocap alunite, porphyry/skarn tin, low sulfidation, and high sulfidation). Critical mineral concentrations are based on elevated concentrations with variable analytical precision, and more precise analyses are needed to assess inventory significance.

Mineral System—Porphyry Cu-Mo-Au

Deposit type—Porphyry/Skarn Copper

Antimony (Sb), Arsenic (As), Bismuth (Bi), Cobalt (Co), Indium (In), Nickel (Ni), PGE, Tellurium (Te), Tin (Sn), and Vanadium (V)

Variably elevated concentrations (tens to more than 100 ppm) of Sb, As, Bi, Co, In, Ni, PGE, Te, Sn, and V occur in rocks in and near copper and gold deposits in the Battle Mountain district, Lander County, Nev. (Theodore and Blake, 1975; Page and others, 1978), in sphalerite in

Au-Ag-Pb-Zn-Cu-U deposits of the Central City district, Colo. (Sims and others, 1961), in sphalerite and chalcopyrite in polymetallic skarn, replacement and vein deposits of the Central district, N. Mex. (Rose, 1967; Briskey, 2005), and in several minerals in replacement deposits at Darwin, California (Carlisle and others, 1954; Czamanske and Hall, 1975; Foord and Shawe, 1989; Dunning and others, 2006). Deposits in the Battle Mountain and Central districts are spatially and temporally associated with Cu-Mo-mineralized intrusions, whereas deposits in the Central City and Darwin districts have unknown association with mineralized porphyritic intrusions. Critical mineral concentrations in these deposits were determined mostly by semi-quantitative spectrographic methods with relatively low precision and high detection limits, but elevated concentrations may be semi-quantitatively valid.

Elevated PGE and tellurium concentrations occur in other deposits in Nevada that are in or related to intrusions. Lechler (1988) reported elevated concentration of Pt (up to 53.4 troy ounces per short ton), Pd, Rh, Ru, Ir, and Os+Ir in selected samples from a vein deposit in a Mesozoic granitic intrusion on Crescent Peak, Clark County, Nev.; the samples also contained up to 10 troy ounces of gold per short ton and 54 troy ounces of silver per short ton. Elevated concentrations of tellurium occur in jasperoid and gossan in the Ely (Robinson) district, Nev. (Gott and McCarthy, 1966; Watterson and others, 1977), and at Tintic and Bingham, Utah (Lovering and others, 1966). Elevated concentrations of tellurium occur in gold- and silver-mineralized rocks that comprise the Gold Jackpot project, Elko County, Nev. (CAT Strategic Metals Corp., 2021).

Titanium (Ti)

Approximately 4 Mt of rutile are contained in igneous rocks of the Bagdad, San Manuel, and Ajo porphyry copper deposits, Ariz., and 4 Mt of rutile are contained in igneous rocks of the Bingham porphyry copper deposit, Utah (Czamanske and others, 1981; Chaffee, 1982; Force and Lynd, 1984). Annual domestic consumption of TiO₂ from 2016 to 2020 averaged more than 1 Mt and varied by product form with most TiO₂ consumption for pigment applications (USGS, 2021). Porphyry Cu-Mo deposits could theoretically provide several years of annual domestic consumption if a marketable form of titanium could be produced.

Deposit Type—Porphyry/Skarn-Tungsten

Tungsten (W)

Margerie Glacier is a porphyry Cu-Mo deposit in southeastern Alaska about 100 mi (167 km) northwest of Juneau, Alaska (table 2). It contains elevated concentrations of tungsten, molybdenum, gold, and silver attributed, at least in part, to quartz-chalcopyrite-arsenopyrite-scheelite-powellite veins up to 1.7 ft (0.5 m) wide in Tertiary porphyry quartz monzodiorite and sedimentary and marine volcanic rocks (Brew and others, 1978; Kurtak, 1985; Carroll and others,

2018). Plagioclase and potassium feldspar that comprise much of the quartz monzodiorite have been altered to sericite, and biotite has been altered to chlorite. Brew and others (1978) report a tungsten resource of 145 Mt grading 0.01 percent tungsten (14,500 t). This resource is equivalent to approximately 1 year or more of recent annual domestic consumption (tables 21, 22).

Deposit Type—Lithocap Alunite

Aluminum (Al) and Potash (KCl, K₂SO₄, KNO₃)

The upper part of the Resolution porphyry copper deposit near Superior, Ariz., consists of a large mass of rock altered to dickite (Al₂Si₂O₅(OH)₆), topaz (Al₂SiO₄(F,OH)₂), quartz, and lesser pyrite, alunite, zunyite (Al₁₃Si₅O₂₀), and woodhouseite (CaAl₃PO₄SO₄(OH)₆) that is within and overlying a 1.66-Gst (1.51 Gt) Cu-Mo inferred resource (Troutman, 2001; Martin, 2019; Cooke and others, 2020). The mass was identified in holes drilled for Cu-Mo resources, but no alunite resource has been published. Other unquantified alunite resources occur in altered rocks overlying and adjacent to gold-silver-(copper) deposits in the Goldfield and National districts, Nev. (Vikre, 2007), in quartz-alunite alteration cells in the Walker Lane, Nev. and Calif. (Vikre and Henry, 2011), in Pliocene volcanic rocks in the Sweetwater Mountains, Calif. and Nev. (Balogh and others, 2021), and in the western San Juan Mountains, Colo. (Hall, 1978; Lowe and others, 1985). A low-grade alunite deposit (estimated 3.5 percent) at Sugarloaf Butte, Yuma County, Ariz., consisting of veins in schistose porphyry dacite and sericite schist, comprises at least 10 Mt (USGS and others, 1969); the relationship of this occurrence relative to subduction-related intrusions is unknown. The suspected low quality and (or) small size of these alunite occurrences portends relatively small inventories of aluminum and potash relative to recent annual domestic consumption.

Mineral System—Porphyry Tin (granite-related)

Deposit Type—Porphyry/Skarn Tin

Tin (Sn)

At Taylor Creek, Catron and Sierra Counties, N. Mex., estimated tin reserves in 1941 were approximately 7,603 t in a five-acre area of altered rhyolite, and approximately 49 t in derivative placer deposits (U.S. Bureau of Mines, 1941b). It is unknown if these reserves were verified and mined. They comprise approximately 22 percent of recent annual domestic consumption (table 21).

Several areas in Nevada contain small tin deposits (Majuba Hill, described in chap. A) and widespread tin occurrences. Tin occurs in the Trinity silver mine and in altered rhyolites in the Trinity Range south of Majuba Hill. Small amounts of cassiterite, scheelite, and cinnabar were recovered with gold from placer deposits intermittently mined from the 1870s to the 1940s in the Kamma Mountains north and northwest of Majuba Hill (Rabbit Hole district;

Rosebud Canyon) (Vanderburg, 1936; Smith and Gianella, 1942; Trites and Thurston, 1958; Stevens, 1971; MacKenzie and Bookstrom, 1976; Johnson, 1977; Wenrich and others, 1986; Castor and Ferdock, 2003; Whateley and others, 2006; Coolbaugh, 2014). Minor amounts of “wood tin” occur in Miocene volcanic rocks northwest of Battle Mountain (Fries, 1942). Small amounts of tin (in stannite) occur with numerous Cu-Mo-Au-Bi-Pb-Zn-Ag minerals in contact zones of Eocene intrusions and Paleozoic siliciclastic strata in the Tenabo district and with carbonate-replacement deposits mined for lead in the Delano district (Kelson and others, 2008; Mankins and Muntean, 2021; Hewitt, 1968; Lapointe and others, 1991). Tin is reported in the McCullough Butte fluorite deposit (described previously in chap. C). Like tin deposits in felsic rocks elsewhere, the tin deposits and occurrences in Nevada may be associated with reduced, peraluminous intrusions (Holmwood and others, 2021). Relative to recent consumption, none of the tin deposits and occurrences in Nevada are likely to comprise significant inventories.

Mineral System—Alkalic porphyry

Deposit Type—Low Sulfidation

Tellurium (Te) and Vanadium (V)

Approximately 1,700 analyses of mineralized samples from drill holes, mine workings, and surface exposures in the Cripple Creek district, Teller County, Colo., average more than 1 ppm gold and approximately 4.8 ppm tellurium in oxide minerals (table 8). These analyses imply a large in situ inventory of tellurium that could be recovered if ores were treated by milling rather than heap leaching which does not recover tellurium from oxide minerals. Mill tailings from recovery of gold mined at much higher grades from 1891 to 1944—the period of most district production (approximately 18.5 million troy ounces [575 t] of silver; 2.1 million troy ounces [65 t] of gold) (Vanderwilt, 1947)—could constitute a second large tellurium inventory; tailings reside at numerous mill sites in the vicinity of Colorado Springs, Old Colorado City, Florence, and Pueblo. If gold was recovered primarily from the gold-silver-tellurium minerals calaverite (AuTe_2) and sylvanite ($(\text{Au, Ag})\text{Te}_2$), then approximately 0.6 ounces per short ton of tellurium, or approximately 345 t of tellurium, may reside in tailings. In addition, elevated concentrations of vanadium (approximately 560–3,360 ppm) occur in concentrate and slag of the Golden Cycle mill at Cripple Creek (Kaiser and others, 1954). However, some gold-silver telluride ores were roasted prior to cyanidation to eliminate tellurium, some ores contained tellurium oxide minerals, and some mill tailings have been moved and repurposed. Significant masses of tellurium and vanadium may exist in mine and processing tailings and in unmined gold resources (approximately 270 Mst [245 Mt]) (Newmont Corporation, 2019), although at widely separated sites.

Based on production of gold and silver from the telluride vein deposits of Boulder County, Colo., less than 60 short tons (55 t) of tellurium are estimated to have been mined

(Kelly and Goddard, 1969), but there is no record of tellurium production. Other districts in Colorado in which appreciable amounts of telluride minerals were processed for gold and silver but not tellurium recovery include La Plata and Lake City (Henderson, 1926; Eckel and others, 1949; Werle and others, 1984).

In the Tonopah district, Nye County, Nev., elevated concentrations of tellurium (average 30 and 36 ppm by different analytical techniques) in selected mineralized samples from mine dumps (table 19) represent an improbable source of tellurium because dumps, although large (aggregate of several million short tons) and undisturbed, are mostly unmineralized wall rocks. About 8.1 Mst (7.4 Mt) of vein ore were produced from 1901 to 1950 and milled at several sites in and near Tonopah (Carpenter and others, 1953; Bonham and Garside, 1979). Concentrations of tellurium and other critical minerals in Slime Wash, the largest mass of mill tailings, and at Millers, the site of numerous mills approximately 13 mi northwest of Tonopah, have not been quantified. The concentrations of gold, silver, and other elements in mill tailings may warrant recovery if additional vein resources are developed (W. Howald, Blackrock Silver, oral commun., 2021).

Deposit Type—High Sulfidation

Antimony (Sb), Arsenic (As), Bismuth (Bi), Germanium (Ge), Indium (In), Tellurium (Te), Tin (Sn), and Vanadium (V)

Sb, As, Bi, Ge, In, Te, Sn, and V are major to minor components of chalcogenide minerals that comprise some ores in the Goldfield district, Esmeralda County, Nev. (Granitto and others 2020, 2021; Vikre and others, in press). Elevated concentrations but small masses of these critical minerals reside in mine dumps (table 18) in the main district and may reside in tailings adjacent to foundations of the demolished Goldfield Consolidated Mining Company mill. Since the 1990s, most mine dumps have been moved, all or in part, to heap leach pads for gold recovery. Mill tailings were reprocessed, all or in part, from 1920 to 1929 and from 1970 to 1995 for gold recovery. The masses of critical minerals, relative to annual domestic consumption, may be significant, but the low concentration of gold remaining in tailings and mine dumps (estimated <1 ppm), could preclude recovery of Sb, As, Bi, Ge, In, Te, Sn, and V unless subsidized. Elevated concentrations of these critical minerals are also likely in unmined gold resources (Gemfield, McMahan Ridge, and Goldfield main) (Centerra Gold, 2022) but have not been quantified and may not be recoverable if gold is recovered by heap-leaching and cyanidation.

At the Paradise Peak mine, Mineral County, Nev., tailings generated from recovery of 1.6 million troy ounces (49.8 t) of gold may be enriched in antimony and bismuth. Three vertical pre-mine drill holes in the deposit averaged 331, 1,269, and 1,500 ppm antimony and 244, 469, and 1,009 ppm bismuth, over 80, 88, and 128 m, respectively, (John and others, 1991; Sillitoe and Lorson, 1994); antimony and bismuth were not recovered from the 8.1 Mt of ore processed. If tailings contain

200 ppm each antimony and bismuth, then approximately 1,620 t of each may remain. Gallium in rocks altered to alunite that overlay the gold-silver deposit averaged 30 to 35 ppm over 25 m in two drill holes through the center of the deposit (Rytuba and others, 2003). Remaining gold in dumps and tailings may enable simultaneous recovery of these critical minerals. However, the apparent small masses of antimony and bismuth relative to annual domestic consumption and low gallium concentrations (near crustal abundance) may preclude their recovery or require subsidized recovery.

At Washington Hill, Storey County, Nev., large but unquantified masses of Miocene volcanic rocks have been pervasively altered to quartz, alunite, pyrite, and other epigenetic minerals. Surface samples and numerous drill hole intervals contain tens to hundreds of parts per million Sb, As, Bi, Te, and Sn (Albino, 1991; Diner, 1989) which conceivably could be recovered if minable quantities of other commodities such as copper and molybdenum are identified.

Based on elevated concentrations in mineralized rocks, tellurium and other critical minerals may exist in mine dumps and mill tailings in the Battle Mountain district, Nev., (Theodore and Blake, 1975), in gold-silver districts in the Walker Lane in addition to those described above (for example, Ramsey district, Nev.; Bodie Hills districts, Calif. and Nev.) (Vikre and Henry, 2011; Vikre and others, 2015; Balogh and others, 2021), and in precious metal and polymetallic districts in Colorado, Montana, and New Mexico (Henderson, 1926; Rose, 1967; Briskey, 2005). Masses of critical minerals in mine dumps and mill tailings of these and other districts in Western States may be too small to warrant recovery, even with subsidization, but apparently no attempt has been made to quantify them.

Unclassified Magmatic Deposits

Aluminum (Al), Rare Earth Elements (REE), Titanium (Ti), Zircon ($ZrSiO_4$), and Tin (Sn)

Anorthosite in the San Gabriel Mountains, Los Angeles and San Bernardino Counties, Calif., has been evaluated for aluminum resources and mined on a small scale for clay for cement manufacturing. The anorthosite comprises a partially quantified “enormous reserve” of approximately 27 weight percent Al_2O_3 (USGS and others, 1966a; Carter, 1982). Ilmenite-magnetite-apatite-rich cumulate in the anorthosite also constitutes a low-grade REE resource of approximately 2 Mst (1.8 Mt) grading 0.17 weight percent RE_2O_3 , (approximately 16 percent of which is yttrium), and a larger titanium resource (approximately 1.2 Gst [1.1 Gt] grading 6.2 weight percent TiO_2) (Carter, 1982). Other felsic intrusions in Arizona, California, and Wyoming contain modest to large inventories of titanium (mostly in rutile) and zirconium (in zircon) (Force and Lynd, 1984; Osterwald and others, 1966). Titanium, zirconium, and tin minerals (cassiterite) have been recovered in small quantities from placer deposits generated by weathering of the San Gabriel Mountains anorthosite and other granitic intrusions, mostly anorthosites. Although the San Gabriel Mountains and other anorthosites are Precambrian and external to the scope

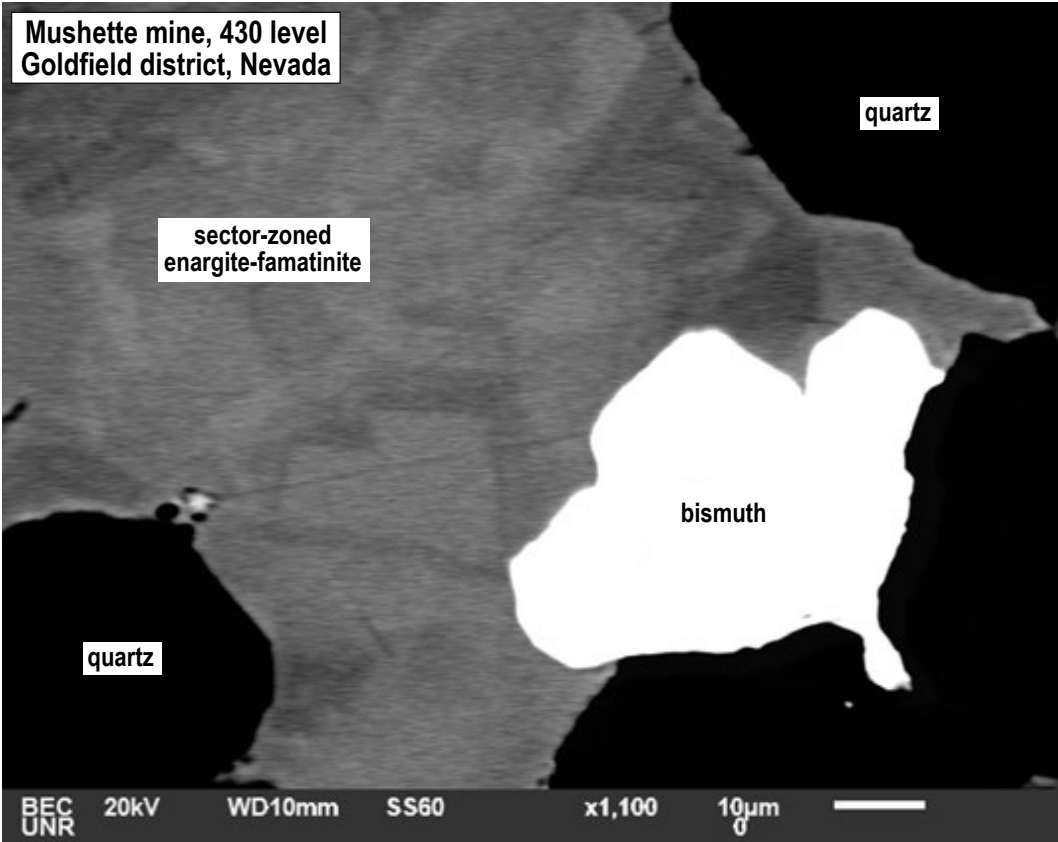
of this report, they exemplify the potentially large inventories of titanium, zirconium, and possibly tin contained in felsic intrusions related to subduction and in derivative colluvial and alluvial deposits. Some felsic intrusions are being mined for copper and molybdenum (porphyry Cu-Mo deposits) and large dumps (tens to hundreds of millions of metric tons) consisting of felsic granitic rocks exist at operating and shuttered mines. Since Cu-Mo ores are finely crushed for separation of copper and molybdenum minerals, rutile and zircon could conceivably be recovered from heretofore valueless silicate minerals discarded as concentrator tailings (fig. 6D).

Mineral System—Reduced Intrusion-Related

One operating gold mine and several gold resources in Nevada have characteristics of reduced intrusion-related gold (RIRG) deposits. These deposits largely consist of several to numerous closely spaced vein sets and skarns that are or may be bulk minable for gold. Critical mineral concentrations in the gold mine and resources are incompletely known.

Critical mineral concentrations in drill holes in the Bald Mountain gold mine, White Pine County, Nev., have been geochemically correlated (Pace, 2009) but absolute concentrations are not available (Dan Pace, written commun., 2021). However, the reserve of 204.5 Mt grading 0.016 troy ounces of gold per short ton (measured and indicated) (Kinross Gold Corporation, 2020) is large enough to contain significant inventories of some critical minerals. At Spring Valley, Pershing County, critical mineral concentrations (Co, Ga, Ni, Nb, Ta, Sn, W, and V) in 10 samples representative of alteration zones within the gold resource (202.4 Mt grading 0.019 troy ounces of gold per short ton) are mostly at or below crustal abundances (Crosby, 2012; Muntean and others, 2020), implying low potential for critical mineral recovery if gold is mined. At Buffalo Canyon, Nye County, critical mineral concentrations (Sb, As, Bi, Co, Ga, Ge, In, Ni, Nb, Re, Ta, Te, Sn, W, and Zn) in 120 samples of vein types that comprise the gold resource (23.1 Mt grading 0.0125 troy ounces of gold per short ton) are mostly at or below crustal abundances (Quillen, 2017; Orogen, 2021). Some Sb, As, Bi, Te, and Sn concentrations slightly to greatly exceed crustal abundance in vein types on which the gold resource is based, but the small masses conceivably present may not warrant recovery. At Robertson, Lander County (Bullion district), Au is associated with elevated concentrations of As, Bi, Te, and Sn which occur in arsenopyrite, loellingite, bismuth tellurides, and bismuth (Kelson and others, 2008; Mankins and Muntean, 2021; Mankins and others, 2022). No resource has been publicized and arsenic, bismuth, tellurium, and tin inventories cannot be estimated. The nearby McCoy and Cove gold-silver deposits and resources, Lander County, Nev., also have characteristics of RIRG deposits (Johnson, 2003; Bonner, 2019), but critical minerals have not been quantified. Although tonnages of several RIRG resources are moderately large, average concentrations of critical minerals are mostly at or below crustal abundances, and likely constitute small inventories that portend costly recovery.

Chapter D



Back-scattered electron image of bismuth, enargite-famatinite, and quartz from Mushette mine, Goldfield district, Nevada.

Chapter D. Critical Minerals in Archival Specimens and Collection Samples

Element concentrations in archival specimens from museums and samples from collections of authors and associates have been obtained or collected and analyzed over several decades by several methods (Granitto and others, 2020, 2021; tables 16–19). The specimens and samples summarized in this chapter are from domestic porphyry copper-molybdenum (Cu-Mo) and precious metal districts; deposit types represented are porphyry/skarn copper, polymetallic sulfide skarn replacement-vein-intermediate sulfidation, high-sulfidation gold-silver, and low-sulfidation gold-silver. Mineralized specimens from porphyry Cu-Mo districts and deposits for which critical mineral and other element concentrations were determined are: Mineral Park, Bisbee, Ajo, Christmas, Morenci, Bagdad, Globe-Miami, Ray, Sierrita, San Manuel, Silver Bell, and Vekol Hills, Arizona; Yerington, Nevada; and Bingham, Utah. Mineralized specimens of skarn, replacement and vein deposits associated with mineralized porphyry deposits, where separable, for which critical mineral and other element concentrations were determined are Bisbee, Johnson Camp, Mission-Pima-San Xavier, Twin Buttes, and Superior (Magma mine polymetallic veins) districts, Ariz.; the Butte district, Montana; the Bingham district, Utah; and the Central district, New Mexico (figs. 1A, 8A–H; tables 16, 17). Deposit types represented by collection samples are polymetallic sulfide skarn-replacement-vein (S-R-V) intermediate sulfidation (IS), high-sulfidation gold-silver, and low-sulfidation gold-silver. Districts and deposits for which critical minerals and other elements were analyzed are Eureka, Pioche, Goodsprings, Goldfield, Tonopah, Paradise Peak, Merrimac, and Pyramid, Nev.; Monitor, California; and Silver City, Idaho (figs. 1A, 9A, B; tables 18, 19).

Primary products of the deposits from which the analyzed archival specimens and collection samples were derived include Cu, Au, Ag, Pb, and Zn. In some deposits, gold, silver, and molybdenum were coproducts that influenced production decisions. Critical minerals were produced from some deposits (or districts in which production is aggregated or generalized), and in porphyry Cu-Mo resources comprise significant inventories because of the large scales of mining and processing, as described in chapters A–C.

Specimen and Sample Representativeness

The average and range of critical mineral concentrations in archival specimens and collection samples summarized below (figs. 7A, B, 8A–H; tables 4A–D) are organized by the deposit type in the source datasets (Granitto and others, 2020, 2021). However, average concentrations of porphyry/skarn Cu-Mo deposit type specimens and polymetallic sulfide S-R-V-IS deposits type specimens may include mixtures of deposit types where deposit type designations are unclear

or incorrect. In general, S-R-V deposits have higher copper, lead, and zinc concentrations than associated porphyry Cu-Mo deposits; average copper, lead, and zinc concentrations that exceed 1 weight percent could reflect mixtures of deposit types.

In addition, there is a wide range of concentrations of individual critical minerals within deposits and districts, and concentrations of primary commodities are often considerably greater than crustal abundances. Many to most archival specimens were apparently collected for appearance and weight. Thus, while averaging concentrations may deemphasize high-grade specimens and collected samples, average concentrations of primary product and coproduct commodities (Cu, Pb, Zn, Au, Ag, and Mo; fig. 8A, B) often exceed production grades. Therefore, average concentrations of critical minerals in specimens and samples are not necessarily representative of resources or inventories.

Another consequence of preferential high-grade specimen and sample conservation is that very high concentrations could not be quantified by the analytical method used, thus lowering average concentrations that include analytical maximum concentrations. Similarly, concentrations below detection, when included in averages, inflate the averages, disqualifying their use for resource and inventorying calculation.

Aside from limitations imposed by high-grade and appearance selectivity of specimens and samples, and by analytical techniques, some deductions can be made regarding the concentrations of critical minerals relative to crust concentrations and relative to primary and coproduct commodity concentrations. Concentrations and proportions of critical minerals in deposits and resources will influence the processes and costs of recovering them as coproducts or byproducts. Specimen and sample concentrations provide default guidance to critical mineral potential in the absence of more representative quantification.

Critical Minerals Enriched in Porphyry Cu-Mo Deposits

Average concentrations of some critical minerals in both deposit types (porphyry and S-R-V deposits), including Sb, As, Bi, Te, and W, are routinely greater than crustal abundances (fig. 8C, D). Germanium, indium, and tin concentrations also exceed crustal abundances in some deposits of both types (fig. 8E, F), although averaging of most of these critical minerals is hindered by concentrations below detection in many specimens and samples. Based on elevated concentrations of these critical minerals in large drill hole datasets (described in chap. C; tables 3–8), the average concentrations in the specimen and sample datasets, although equivocal, broadly show enrichment of these critical minerals relative to their average concentrations in crust.

Antimony concentrations in both deposit types are highly variable and few averages can be calculated because many concentrations are below detection. Numerous concentrations of individual specimens and samples exceed crustal abundance

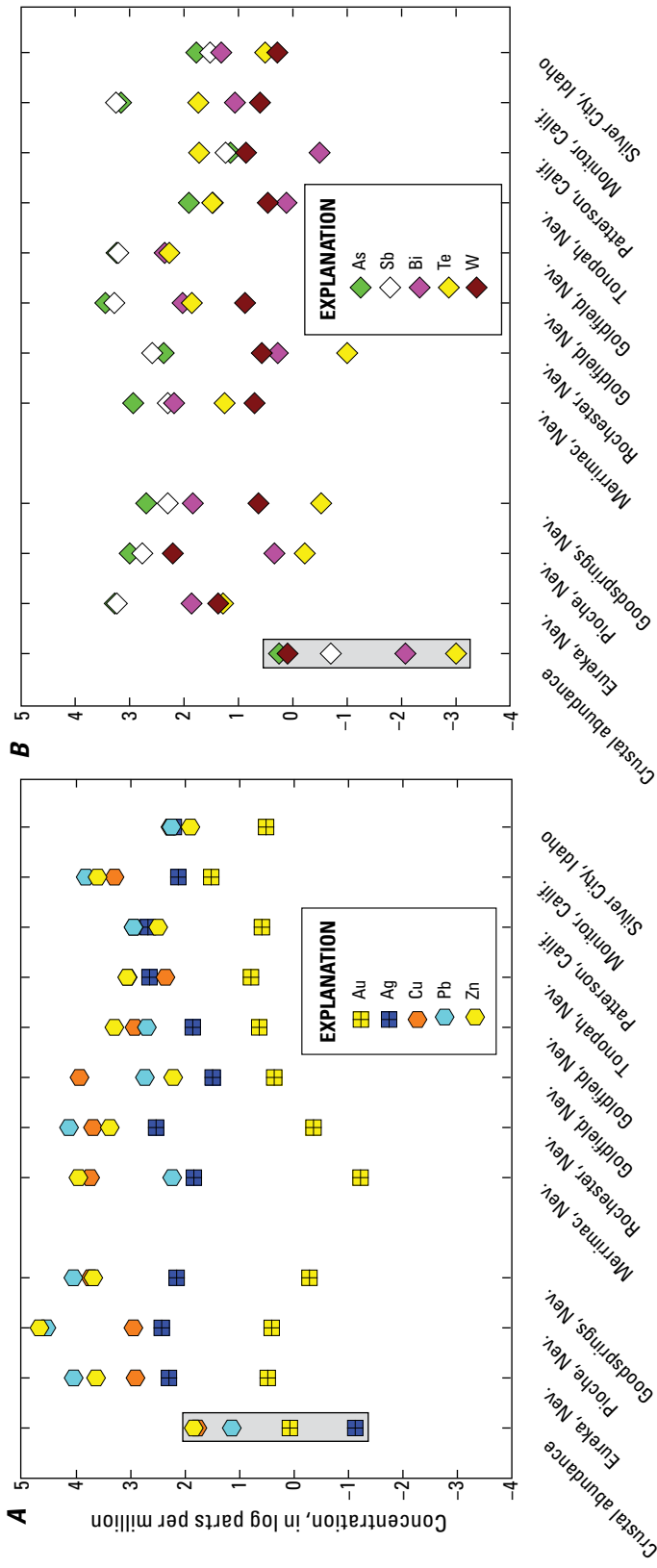


Figure 9. Concentrations of minerals relative to crustal abundances in carbonate-replacement deposits (Eureka, Pioche, and Goodsprings, Nevada) and vein deposits (Merrimac, Rochester, Goldfield, and Tonopah, Nevada; Patterson and Monitor, California; and Silver City, Idaho; tables 16–19). A: Au, Ag, Cu, Pb, and Zn. B: As, Sb, Bi, Te, and W.

(0.2 parts per million [ppm]), with the highest concentrations, some more than 100 ppm, in polymetallic sulfide S-R-V-IS deposits. Average arsenic and bismuth concentrations in both deposit types, also variable, exceed crustal abundances of 1.8 ppm and 0.0085 ppm, respectively, and are generally higher in replacement and vein deposits than in porphyry deposits. Average bismuth concentrations in many deposits are 3 to more than 4 orders of magnitude greater than crustal abundance (fig. 8C, D); bismuth, silver, and tellurium are the most highly enriched elements in both deposit types based on specimens and samples analyzed. However, antimony, arsenic, and bismuth are concentrated during copper refining, and porphyry deposits contain significant inventories of these critical minerals (figs. 4–6).

Few average tellurium concentrations are calculable because of the small number of analyses reported. All reported concentrations exceed crustal abundance (0.001 ppm) and some tellurium concentrations in polymetallic sulfide S-R-V-IS deposits exceed 100 ppm. However, tellurium, like antimony and tin, is concentrated during copper electrorefining, and significant inventories of tellurium exist in reserves and resources of both deposit types because of the scales of mining (tens of thousands to millions of metric tons of ore per year). Tellurium has been episodically recovered at the copper refineries at Magna, Utah (Rio Tinto), and at Amarillo, Texas (ASARCO).

Average tungsten concentrations in porphyry/skarn copper deposits, where calculable, are mostly several tens of parts per million. Average tungsten concentrations in associated polymetallic sulfide S-R-V-IS deposits are tens to hundreds of parts per million. Tungsten concentrations in both deposit types are greater than crustal abundance (1.25 ppm). Large inventories of tungsten exist in these deposit types (figs. 4–6) but tungsten has not been recovered from any of them.

Average germanium concentrations are the same as to approximately two times greater than crustal abundance (1.5 ppm) in porphyry/skarn copper deposits, and approximately three to four times greater than crustal abundance in polymetallic sulfide S-R-V-IS deposits. There are very few elevated concentrations (tens to more than 100 ppm). However, germanium is concentrated during zinc refining, and possibly during copper refining, and these deposits represent potentially significant inventories of germanium because of large tonnages of ore that are mined and processed annually, large-tonnage unmined resources, and the very small market volume of germanium.

Average indium concentrations in most specimens from porphyry copper deposits are below detection, with few concentrations exceeding crustal abundance (0.25 ppm). In polymetallic sulfide S-R-V-IS deposits, indium concentrations are considerably higher with numerous specimens more than 10 ppm. While average indium concentrations cannot be calculated because many concentrations are below detection, indium may be concentrated during copper and zinc

refining, and significant inventories of indium could exist in unmined large-tonnage polymetallic sulfide S-R-V-IS deposits associated with porphyry Cu-Mo deposits (for example, Bingham, Utah; Sunnyside, Ariz.), several of which are currently mined (Mission and Twin Buttes mines, Ariz.).

Average tin concentrations in porphyry/skarn copper deposits are generally several times greater than crustal abundance (2.3 ppm) and ten times or more crustal abundance in polymetallic sulfide S-R-V-IS deposits. Tin, like other chalcophile and siderophile critical minerals, is potentially recoverable during processing of large tonnage deposits.

Concentrations of critical minerals in samples collected by authors and associates in polymetallic sulfide S-R-V-IS districts in Nevada (Eureka, Pioche, and Goodsprings districts; table 18) were analyzed at different times (circa 1990–2021) by different techniques for a large array of element concentrations. Deposits in these districts were mined for Pb, Zn, and Ag, with lesser production of Cu, Au, Pt, and Pd (Vikre 1998; Vikre and Browne, 1999; Vikre and others, 2011). In general, average Sb, As, Bi, In, Sn, and W concentrations are mostly tens to thousands of times greater than crustal abundances, whereas average Be, Ce, Cr, Co, Ga, Li, Ni, Nb, Sc, Sr, and V concentrations are less than one half crustal abundances. Unmined deposits and mine dumps and tailings in these districts are much smaller masses (several millions of short tons) than in porphyry Cu-Mo districts, and unlikely to contain large inventories of critical minerals.

Critical Minerals Unenriched or Depleted in Porphyry Cu-Mo Deposits

Concentrations of many critical minerals, including Be, Ce, Cr, Co, Ga, Li, Ni, Nb, Rb, Sc, Ta, and V in archival specimens and samples of porphyry/skarn copper-(molybdenum) deposits and polymetallic sulfide S-R-V-IS deposits are at or below crustal abundances. Regardless of averaging discrepancies, these critical minerals have low potential for recovery. Average concentrations of beryllium, cerium, and chromium are entirely near and below crustal abundances of 2.8, 66.5, and 102 ppm, respectively (tables 3, 16–19). Average rubidium concentrations vary from approximately one half to twice crustal abundance (90 ppm) in both deposit types; rubidium in some polymetallic sulfide S-R-V-IS deposits is less than 10 ppm. Average scandium concentrations in both deposit types are mostly below detection. Average scandium concentrations in two porphyry/skarn copper deposits are 18 and 10 ppm, approximately the same as maximum concentrations in other porphyry/skarn copper and polymetallic sulfide S-R-V-IS deposits and near crustal abundance of 22 ppm. Separation of Be, Ce, Cr, Rb and Sc from ores (and waste) of these deposit types is unlikely, based on the highest concentrations that seldom exceed crustal abundances and on the economics of Rb and Sc production from other deposit types with much higher concentrations.

Average cobalt and gallium concentrations are near or below crustal abundance (66.5 ppm and 19 ppm, respectively) in both deposit types. The very small number of concentrations greater than crustal abundance do not portend significant cobalt and gallium inventories in these deposit types based on the specimen and collection datasets. Average lithium concentrations in both deposit types are incalculable because many concentrations are below detection. The crustal abundance of lithium is 20 ppm, and there are few deposits with concentrations more than 100 ppm. All lithium concentrations are far lower than those of domestic hard rock lithium resources (more than 3,000 ppm; for example, Lithium Americas, 2021) being developed for production. Average nickel, niobium, and tantalum concentrations, where calculable, are below crustal abundances (84, 20, and 2 ppm, respectively; [fig. 8G, H](#)) in specimens and samples from all districts and deposits; many to most concentrations are below detection and there are few concentrations that exceed crustal abundances. Average vanadium concentrations in both deposit types are mostly below crustal abundance (120 ppm; [fig. 8G, H](#)); several are slightly greater than crustal abundance. Separation of these critical minerals from ores (and waste) of porphyry/skarn copper and polymetallic sulfide S-R-V-IS deposits is considered infeasible, based the economics of nickel, niobium, tantalum, and vanadium production from other deposit types with much higher concentrations.

Critical Minerals Enriched in High-Sulfidation and Low-Sulfidation Gold-Silver Veins

Relatively small multi-element geochemical datasets were obtained from analysis of samples collected by authors and associates in the Goldfield and Tonopah districts, Nev.; districts in the Bodie Hills, Calif. and Nev. (Vikre and others, 2015); and at Paradise Peak, Nev. (John and others, 1991; [figs. 1A, 9; tables 18, 19](#)). Some critical minerals at Goldfield and Paradise Peak are described by deposit type above (chap. C). Deposits in these districts were mined for gold and silver; and small amounts of copper and mercury were also recovered. In general, average Be, Ce, Co, Cr, Ga, Li, Ni, Nb, Sc, and V concentrations are approximately equal to or less than one half crustal abundances; strontium is double crustal abundance. In Goldfield district samples, average Sb, As, Bi, In, Te, Sn, and W concentrations are mostly tens to tens of thousands of times greater than crustal abundances; average Sb, Bi, and Te concentrations exceed crustal abundances by factors more than 10^4 . In Tonopah district samples, average Li concentrations are approximately three times crustal abundance, whereas Sb, As, Bi, In, Sn, and W concentrations are mostly less than ten times crustal abundances. Tellurium concentrations vary highly from below detection to 127 ppm and are not closely correlated with silver and gold concentrations. Unmined deposits and processed ore in these districts are much smaller masses (several million short tons) than in porphyry Cu-Mo districts, and unlikely to contain large inventories of critical minerals.

Conclusions

1. In the western U.S., the critical mineral commodities Al, Sb, As, Bi, Co, fluorite, Ga, Ge, In, Mn, Ni, Nb, Pd, Pt, potash, Re, Ta, Te, Sn, W, and V are variably concentrated in magmatic-hydrothermal deposits related to subduction. These deposits include porphyry/skarn copper-gold, skarn-replacement-vein (S-R-V) tungsten, polymetallic sulfide S-R-V intermediate sulfidation, high-sulfidation gold-silver, low-sulfidation gold-silver, and lithocap alunite deposits, which occur in porphyry copper-molybdenum-gold, alkalic porphyry, porphyry tin (granite-related), and reduced intrusion-related mineral systems.
2. Production of critical minerals in these deposit types as primary products, coproducts, and byproducts varies from none to mostly small relative to recent domestic consumption, even with sustained to ephemeral subsidization of antimony, manganese, and tungsten, and numerous other mineral commodities during the World War and Cold War decades of the 1910s to 1990s.
3. Reserves, resources, and significant inventories that comprise 2 or more years of recent annual domestic consumption exist for the mostly very small- to mid-market commodities including Sb, As, Ga, Ge, In, Re, Te, and W. Very large inventories, equivalent to decades or more of consumption, of Sb, As, Re, and Te cumulatively reside in porphyry copper-molybdenum (Cu-Mo) deposits, commensurate with large tonnages of those deposits, and are tracked for quality control and episodic sale (Re and Te). Inventories in porphyry Cu-Mo deposits, reserves, and resources may or may not equate to consumable supplies because of recovery economics and techniques, spatial relationships to primary commodities (copper, molybdenum) on which mine plans are based, and insufficient quantification.
4. Importation reliance for supplies of very small- to large-market chalcophile and siderophile commodities, including Sb, As, Bi, Ge, In, Ni, platinum-group elements (PGE), Te, and Sn, could be reduced or eliminated by recovery or more efficient recovery during copper refining, and by production from porphyry Cu-Mo reserves and resources (unmined deposits). Mid- to large-market lithophile commodities, including aluminum, titanium, tungsten, and zircon, conceivably could be recovered at copper concentrators.
5. Significant inventories of large- and very large market commodities, including aluminum, fluorite, potash, and titanium, have been known for decades. Subsidization or other regulatory policies could enable production, but inventories will likely remain subeconomic at current world market conditions because of low concentrations, small masses, and (or) geographic location.

6. Broadly, new production of critical mineral commodities from subduction-related magmatic-hydrothermal deposits in Western States could be supported through options such as subsidization (for example, commodity price supports, lower taxation, recovery technique development), political incentives, and (or) sustained increases in demand. An impediment to production of critical minerals from unmined porphyry Cu-Mo deposits with known or suspected large critical mineral inventories (Pebble, Alaska; Resolution, Copper World [Rosemont], Red Mountain, and Sunnyside, Arizona) is insufficient domestic refining capacity, subjecting critical minerals exported in copper concentrates to the importation insecurity that got them listed.

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