Titanium

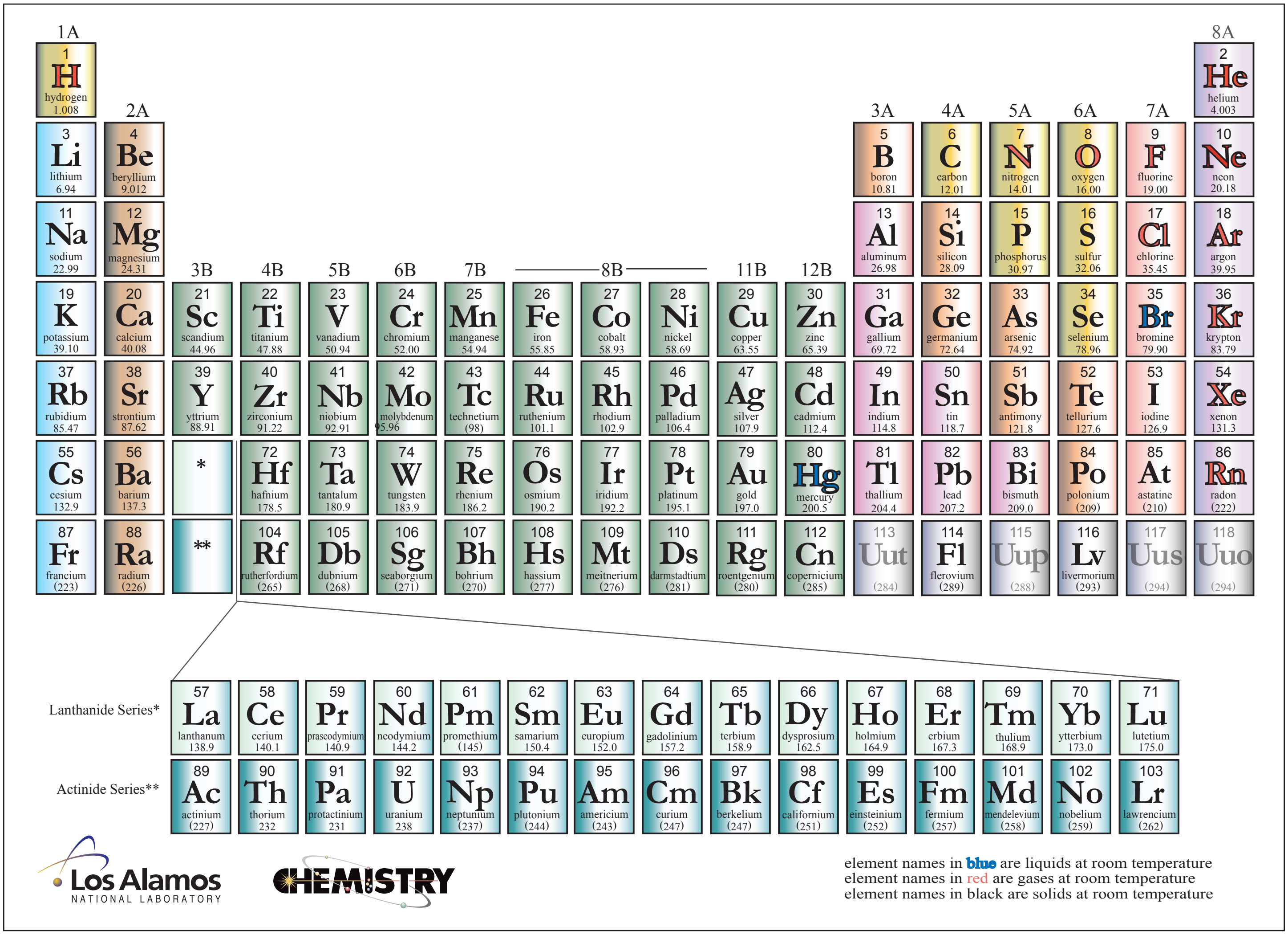
Chapter T of

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

Professional Paper 1802–T

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

Periodic Table of Elements



1A	2A	3B	4B	5B	6B	7B	8B			11B	12B	3A	4A	5A	6A	7A	8A
1 H hydrogen 1.008																	2 He helium 4.003
3 Li lithium 6.94	4 Be beryllium 9.012											5 B boron 10.81	6 C carbon 12.01	7 N nitrogen 14.01	8 O oxygen 16.00	9 F fluorine 19.00	10 Ne neon 20.18
11 Na sodium 22.99	12 Mg magnesium 24.31											13 Al aluminum 26.98	14 Si silicon 28.09	15 P phosphorus 30.97	16 S sulfur 32.06	17 Cl chlorine 35.45	18 Ar argon 39.95
19 K potassium 39.10	20 Ca calcium 40.08	21 Sc scandium 44.96	22 Ti titanium 47.88	23 V vanadium 50.94	24 Cr chromium 52.00	25 Mn manganese 54.94	26 Fe iron 55.85	27 Co cobalt 58.93	28 Ni nickel 58.69	29 Cu copper 63.55	30 Zn zinc 65.39	31 Ga gallium 69.72	32 Ge germanium 72.64	33 As arsenic 74.92	34 Se selenium 78.96	35 Br bromine 79.90	36 Kr krypton 83.79
37 Rb rubidium 85.47	38 Sr strontium 87.62	39 Y yttrium 88.91	40 Zr zirconium 91.22	41 Nb niobium 92.91	42 Mo molybdenum 95.96	43 Tc technetium (98)	44 Ru ruthenium 101.1	45 Rh rhodium 102.9	46 Pd palladium 106.4	47 Ag silver 107.9	48 Cd cadmium 112.4	49 In indium 114.8	50 Sn tin 118.7	51 Sb antimony 121.8	52 Te tellurium 127.6	53 I iodine 126.9	54 Xe xenon 131.3
55 Cs cesium 132.9	56 Ba barium 137.3	*	72 Hf hafnium 178.5	73 Ta tantalum 180.9	74 W tungsten 183.9	75 Re rhenium 186.2	76 Os osmium 190.2	77 Ir iridium 192.2	78 Pt platinum 195.1	79 Au gold 197.0	80 Hg mercury 200.5	81 Tl thallium 204.4	82 Pb lead 207.2	83 Bi bismuth 209.0	84 Po polonium (209)	85 At astatine (210)	86 Rn radon (222)
87 Fr francium (223)	88 Ra radium (226)	**	104 Rf rutherfordium (265)	105 Db dubnium (268)	106 Sg seaborgium (271)	107 Bh bohrium (270)	108 Hs hassium (277)	109 Mt meitnerium (276)	110 Ds darmstadtium (281)	111 Rg roentgenium (280)	112 Cn copernicium (285)	113 Uut (284)	114 Fl flerovium (289)	115 Uup (288)	116 Lv livermorium (293)	117 Uus (294)	118 Uuo (294)

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

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

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

Cover. Upper left, Ilmenite open pit mine at Tellnes, Sokndal, Norway. Photograph courtesy of Mike Norton/CC-BY-SA-3 at https://en.wikipedia.org/wiki/File:Tellnes.jpg. Lower left, open pit mining of heavy mineral sands at the Maxville deposit on Trail Ridge near Starke, Florida. Photograph by Andrew Romeo, The Chemours Co., used with permission. Upper right, because of titanium's high strength-to-weight ratio, it is used for many spacecraft components. For example, the Hubble Space Telescope's primary mirror is made of titanium silicate glass. Photograph courtesy of NASA. Lower right, most of the world's titanium output is refined into titanium dioxide (TiO_2), which is used to give a durable white color to many products, including paint, paper, rubber, and wallboard. Photograph ©2012 Tronox Ltd. All rights reserved.

Titanium

By Laurel G. Woodruff, George M. Bedinger, and Nadine M. Piatak

Chapter T of

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

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

Professional Paper 1802–T

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

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

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

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

Suggested citation:
Woodruff, L.G., Bedinger, G.M., and Piatak, N.M., 2017, Titanium, chap. T *of* Schulz, K.J., DeYoung, J.H., Jr., Seal, R.R., II, and Bradley, D.C., eds., Critical mineral resources of the United States—Economic and environmental geology and prospects for future supply: U.S. Geological Survey Professional Paper 1802, p. T1–T23, https://doi.org/10.3133/pp1802T.

ISSN 2330-7102 (online)

Contents

Figures

Tables

Conversion Factors

International System of Units to Inch/Pound

Multiply	By	To obtain
Length		
angstrom (Å) (0.1 nanometer)	0.003937	microinch
angstrom (Å) (0.1 nanometer)	0.000003937	mil
micrometer (µm) [or micron]	0.03937	mil
millimeter (mm)	0.03937	inch (in.)
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)
kilometer (km)	0.6214	mile (mi)
Area		
hectare (ha)	2.471	acre
square kilometer (km^2)	247.1	acre
square meter (m^2)	10.76	square foot (ft^2)
square centimeter (cm^2)	0.1550	square inch (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
Volume		
milliliter (mL)	0.03381	ounce, fluid (fl. oz)
liter (L)	33.81402	ounce, fluid (fl. oz)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)
cubic meter (m^3)	264.2	gallon (gal)
cubic centimeter (cm^3)	0.06102	cubic inch (in^3)
cubic meter (m^3)	1.308	cubic yard (yd^3)
cubic kilometer (km^3)	0.2399	cubic mile (mi^3)
Mass		
microgram (µg)	0.00000003527	ounce, avoirdupois (oz)
milligram (mg)	0.00003527	ounce, avoirdupois (oz)
gram (g)	0.03527	ounce, avoirdupois (oz)
gram (g)	0.03215075	ounce, troy
kilogram (kg)	32.15075	ounce, troy
kilogram (kg)	2.205	pound avoirdupois (lb)
ton, metric (t)	1.102	ton, short [2,000 lb]
ton, metric (t)	0.9842	ton, long [2,240 lb]
Deposit grade		
gram per metric ton (g/t)	0.0291667	ounce per short ton (2,000 lb) (oz/T)
Pressure		
megapascal (MPa)	10	bar
gigapascal (GPa)	10,000	bar
Density		
gram per cubic centimeter (g/cm^3)	62.4220	pound per cubic foot (lb/ft^3)
milligram per cubic meter (mg/m^3)	0.00000006243	pound per cubic foot (lb/ft^3)
Energy		
joule (J)	0.0000002	kilowatthour (kWh)
joule (J)	6.241×10^{18}	electronvolt (eV)
joule (J)	0.2388	calorie (cal)
kilojoule (kJ)	0.0002388	kilocalorie (kcal)

International System of Units to Inch/Pound—Continued

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

Inch/Pound to International System of Units

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

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

$$°F = (1.8 \times °C) + 32$$

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

$$K = °C + 273.15$$

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

$$°C = (°F - 32) / 1.8$$

Datum

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

Supplemental Information

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

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

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

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

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

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

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

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

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

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

Equivalencies

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

Metric system prefixes

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

Abbreviations and Symbols

°C	degree Celsius
μg/L	microgram per liter
μm	micrometer
EPA	U.S. Environmental Protection Agency
Ga	giga-annum
kg	kilogram
km^2	square kilometer
m	meter
mg/L	milligram per liter
ng/m^3	nanogram per cubic meter
WHO	World Health Organization

Titanium

By Laurel G. Woodruff, George M. Bedinger, and Nadine M. Piatak

Abstract

Titanium is a mineral commodity that is essential to the smooth functioning of modern industrial economies. Most of the titanium produced is refined into titanium dioxide, which has a high refractive index and is thus able to impart a durable white color to paint, paper, plastic, rubber, and wallboard. Because of their high strength-to-weight ratio and corrosion resistance, titanium metal and titanium metal alloys are used in the aerospace industry as well as for welding rod coatings, biological implants, and consumer goods.

Ilmenite and rutile are currently the principal titanium-bearing ore minerals, although other minerals, including anatase, perovskite, and titanomagnetite, could have economic importance in the future. Ilmenite is currently being mined from two large magmatic deposits hosted in rocks of Proterozoic-age anorthosite plutonic suites. Most rutile and nearly one-half of the ilmenite produced are from heavy-mineral alluvial, fluvial, and eolian deposits. Titanium-bearing minerals occur in diverse geologic settings, but many of the known deposits are currently subeconomic for titanium because of complications related to the mineralogy or because of the presence of trace contaminants that can compromise the pigment production process.

Global production of titanium minerals is currently dominated by Australia, Canada, Norway, and South Africa; additional amounts are produced in Brazil, India, Madagascar, Mozambique, Sierra Leone, and Sri Lanka. The United States accounts for about 4 percent of the total world production of titanium minerals and is heavily dependent on imports of titanium mineral concentrates to meet its domestic needs.

Titanium occurs only in silicate or oxide minerals and never in sulfide minerals. Environmental considerations for titanium mining are related to waste rock disposal and the impact of trace constituents on water quality. Because titanium is generally inert in the environment, human health risks from titanium and titanium mining are minimal; however, the processes required to extract titanium from titanium feedstock can produce industrial waste.

Introduction

Titanium is an abundant element that has become an important industrial commodity only within the past 150 years. Ilmenite ($FeTiO_3$) and rutile (which is the most common form of titanium dioxide [TiO_2]) are the two principal minerals that are sources of titanium. Pure titanium metal was first isolated in 1910, but the metal was not commercially available until the development of the Kroll process by William Kroll in 1938. In this process, titanium is produced by reduction of titanium tetrachloride with magnesium. Titanium is now considered essential for modern industrial technology production as well as to meet other needs of modern affluent societies. Many of the uses for titanium in modern industry, including in pigments for paints and paper and in manufacturing by the aerospace industry, are described by Gambogi (2012) and Murphy and Frick (2006). Although the United States is dependent on imports of titanium mineral concentrates and titanium sponge, the United States continues to be a net exporter of TiO_2 pigment and titanium wrought-metal products.

Titanium Commodities

The major titanium commodities and their industrial uses are described in Murphy and Frick (2006). Titanium commodity sources include both titanium-bearing oxide minerals extracted from natural sources and synthetic titanium-bearing materials processed from these minerals. Some 93 percent of the world's titanium resources are accounted for by the mineral ilmenite; the remaining percentage is mainly from rutile and leucoxene. Leucoxene is not a true mineral but is, rather, a finely crystalline aggregate of rutile, anatase, or brookite with greater than 70 percent TiO_2 that is created by the weathering of ilmenite. Rutile, anatase, and brookite are TiO_2 polymorphs; that is, minerals that share the same chemical composition of TiO_2 but have different crystal forms.

Ilmenite, rutile, and leucoxene are processed mainly into titanium-rich slag or synthetic rutile and then further processed for use in pigments and as titanium metal. Titanium slag, which is derived by smelting ilmenite, contains about 75 to 86 percent TiO_2; with further processing by high-pressure acid leaching, titanium slag can be upgraded to about 94.5 percent TiO_2 (Guéguin and Cardarelli, 2007). Synthetic rutile is produced by removing iron from secondary ilmenite feed, which increases its TiO_2 content to about 90 to 95 percent TiO_2 from about 50 to 55 percent TiO_2 (Mackey, 1994). Synthetic rutile can be used as a substitute for natural rutile.

Two main industrial processes—a sulfate process and a chloride process—are currently used to convert the raw materials of ilmenite and rutile into pure white TiO_2 for use in pigment or into titanium metal (Mackey, 1994). The sulfate process is the older of the two processes; it was perfected in 1916 by two Norwegian chemists (Korneliussen and others, 2000a). In the sulfate process, finely ground ilmenite or high-TiO_2 slag is digested with concentrated sulfuric acid. In the chloride process, high titanium-content feedstock, such as natural and synthetic rutile, high-TiO_2 slag, or high-TiO_2 ilmenite sands, is converted into titanium chlorides at high temperature. As of 1992, the sulfate and chloride processes produced about equal amounts of product; however, because it produces a superior TiO_2 pigment product and fewer waste products, the chloride process has largely supplanted the sulfate process. This shift from the sulfate process to the chloride process for TiO_2 pigment production has increased demand for a high-grade titanium feedstock, such as rutile, upgraded titanium-rich slag, and synthetic rutile.

Settings for Titanium Oxide Mineral Occurrences

The diverse types of economic and potentially economic titanium deposits originally categorized by rock type and environment by Force (1991) have been updated in table T1 and are described in the geology section of this chapter. Major deposit types listed in table T1 include (a) magmatic deposits in igneous and related rocks with ilmenite as the primary ore mineral; (b) metamorphic deposits with rutile as the primary ore mineral; (c) rutile in hydrothermal porphyry deposits, and (d) heavy-mineral concentrations in unconsolidated and lithified sand deposits that may include rutile, ilmenite, and alteration products, such as leucoxene. Most deposit types (for example, those in the I–8 and S–4 classes) can be further altered by weathering, at times upgrading the titanium content of the ilmenite, if present.

Ilmenite accounts for about 92 percent of the world's consumption of titanium minerals. The world's two active magmatic titanium mines—the Tellnes Mine in Norway and the Lac Tio Mine in the Province of Quebec, Canada—together produce an estimated 32 percent of the world's titanium (Gross, 1996; Schiellerup and others, 2003). The remaining 68 percent comes from high-grade ilmenite and rutile heavy-mineral deposits in unconsolidated heavy-mineral shoreline and dune deposits, fluvial placers (surface mineral deposits formed by mechanical concentration of minerals from weathered rock), and older lithified equivalents.

Magmatic iron-titanium-oxide-rich deposits are hosted by a complex suite of mafic rocks that includes anorthosite, gabbro, and norite. The principal ore minerals are ilmenite and hemo-ilmenite, which is ilmenite that has extensive hematite (Fe_2O_3) exsolution lamellae, so that hematite occurs as small parallel plates within larger ilmenite crystals. Titaniferous magnetite, which is a complex oxide made up primarily of magnetite (Fe_3O_4) with iron-titanium-oxide exsolution lamellae, can also occur in these rocks in high concentrations, but it is of less economic importance because of its low titanium content.

Heavy-mineral deposits contain concentrations of iron-titanium-oxide minerals that are denser than quartz and so lag behind during erosion and weathering as lighter minerals are more rapidly transported away or broken down. A typical mineral assemblage in heavy-mineral deposits can include rutile and ilmenite (and minerals produced from the weathering of ilmenite, such as anatase, leucoxene, and pseudorutile), as well as other high-density, erosion-resistant minerals, including chromite, garnet, kyanite, monazite, staurolite, tourmaline, and zircon. Heavy-mineral deposits develop when relatively resistant iron-titanium-oxide minerals and other heavy minerals, such as monazite and zircon, are eroded from the parent rocks, transported and sorted, and finally deposited in fluvial, alluvial, or eolian settings. Many productive heavy-mineral provinces, such as the East Coast of the United States, the east and west coasts of South Africa, and the east and west coasts of Australia, are located on passive continental margins that are usually backed by elevated and often highly weathered high-grade metamorphic or mafic igneous hinterlands (Force, 1991).

Uses and Applications

About 93 percent of the world's titanium is refined into TiO_2 for pigment; consequently, trends in the TiO_2 pigment industry exert a large influence on the development of titanium resources (Towner and others, 1988; Murphy and Frick, 2006). Titanium dioxide has properties of whiteness, opacity, and chemical inertness that make it especially suitable for use as pigment to impart a durable white color to paints, paper, plastic, sunscreen, toothpaste, and wallboard (Miller, 1957; Stamper, 1970). The leading uses of TiO_2 pigment in the United States in 2012 were paint (59 percent), plastics (28 percent), paper (9 percent), and other (4 percent) (Bedinger, 2013). Titanium is different than most other metallic elements in that it is mined primarily to satisfy demands for a chemical product (TiO_2 for pigment) rather than for the metal itself (Murphy and Frick, 2006). The high cost of extracting titanium metal from ore curtails broader use of titanium metal and alloys.

About 2.5 percent of the world's titanium is used for the production of corrosion-resistant titanium metal (Murphy and Frick, 2006). Titanium metal alloys are desirable for their high strength-to-weight ratio and corrosion resistance,

Table T1. Classification of selected titanium mineral deposits based on their geologic setting and the processes through which they were formed.

[Modified from Force (1991). The relative economic importance of each deposit type, which is subjective, is indicated as follows: 1, of great current importance; 2, of probable great importance in the near future; 3, of possible importance; 4, of moderate importance; and 5, of minor importance. Locality abbreviations: Ark., Arkansas; Colo., Colorado; Fla., Florida; Md., Maryland; Minn., Minnesota; N.Y., New York; Va., Virginia]

Deposit class	Deposit type[1]	Typical mineralogy	Level of economic importance	Example deposits
Magmatic (igneous and igneous related)				
I–1	Massif anorthosite	Hemo-ilmenite	1	Lac Tio, Quebec; Tellnes, Norway
I–2	Anorthosite-gabbro	Ilmenite, titanomagnetite	2	Sanford Lake district, N.Y.
I–3	Layered mafic intrusion	Ilmenite, titanomagnetite	2	Magpie, Quebec; Panzihuia, China
I–4	Troctolite/ultramafic	Ilmenite, titanomagnetite	3	Longnose, Minn.
I–5	Albititic/metasomatized	Rutile	3	Kragerø, Norway; Roseland, Va. (in part)
I–6	Alkalic/metasomatized	Perovskite, brookite, rutile	3	Iron Hill, Colo.; Magnet Cove, Ark.
I–7	Weathered alkalic rocks	Anatase	2	Catalão, Salitre, and Tapira, Brazil
I–8	Weathered anorthositic rocks	Ilmenite, rutile	4	Roseland, Va. (in part)
Metamorphic				
M–1	Eclogite-hosted	Rutile	2	Engebøfjellet, Norway; Piampaludo, Italy
M–2	Amphibolite-hosted	Rutile	3	Daixian, China
M–3	Greenschist-hosted	Rutile	5	Dinning, Md.
M–4	Contact metasomatized anorthosite	Ilmenite, rutile	4	Roseland, Va. (in part)
M–5	Metasomatized aluminum-rich schist	Rutile	5	Evergreen, Colo.
Hydrothermal (igneous and [or] metamorphic)				
I/M	Hydrothermal porphyry ore deposits	Rutile	3	Bingham, Utah; El Teniente, Chile
Sedimentary-related				
S–1	Fluvial	Rutile, ilmenite	1	Mogbwemo and Sherbo River, Sierra Leone
S–2	Beach (strandline) and (or) coastal dune	Ilmenite, altered ilmenite, rutile, leucoxene	1	North Stradbroke Island, eastern Australia; Richards Bay, South Africa; Trail Ridge, Fla. (in part)
S–3	Lithified paleo-placers (fluvial and [or] beach)	Ilmenite, altered ilmenite, rutile, leucoxene	2	Bothaville, South Africa
S–4	Weathered sedimentary deposits	Altered ilmenite, leucoxene	1	Trail Ridge, Fla. (in part)

[1] Individual deposit types are further classified and described more fully in the text.

and they are used widely in the manufacturing of aircraft. In general, production of titanium mill products precedes aircraft deliveries by about 1 year. In 2010, mill product shipments increased by 62 percent because of increased aircraft build rates and higher inventory levels throughout the titanium supply chain (Gambogi, 2012). The aerospace industry (67 percent) was the leading end user of mill products.

Titanium has other important end uses. For example, titanium is used in welding-rod coatings, where it protects the surfaces of a weld from unwanted reaction with the atmosphere during welding, as well as in the manufacture of mineral fibers; it is used in ceramic components for electronic equipment, and in carbides and other titanium chemicals. Because of titanium's resistance to corrosion in saltwater, it is used in shipbuilding, deep-sea petroleum exploration and production, and geothermal power-generating facilities. A significant quantity of titanium in the form of ferrotitanium, scrap, and sponge (a porous form of titanium created during the first stage of processing) is consumed in the steel and nonferrous metal alloy industries. In the steel industry, titanium is used for deoxidation, grain size control, and controlling and stabilizing carbon and nitrogen content. Titanium-intensive steels include interstitial-free, stainless, and high-strength low-alloy steels. Titanium has the property of osseointegration, which means that it can be structurally accepted by bone, and because titanium is nonreactive, it is increasingly used to make medical devices, such as hip and knee joints, bone screws and plates, and dental implants.

Strategic and Critical Resource Issues

Titanium is considered a critical and strategic mineral because of the unique properties of both titanium metal (and its alloys) and TiO_2 pigment. There are no completely satisfactory substitutes for titanium, especially titanium metal (Towner and others, 1988). Titanium metal's combination of corrosion resistance, excellent weight-to-strength ratio, and very high melting point is not found with other metals. Substitutes for TiO_2 pigment, such as zinc oxide, lithopone (a mixture of barium sulfate and zinc sulfide), and calcium carbonate, generally result in an inferior product and are less environmentally safe. Although lead has similar whitening properties, titanium dioxide pigment replaced lead as a whitener because of public health issues related to lead toxicity.

Consumption of titanium mineral concentrates in the United States exceeds domestic production (Gambogi, 2012). From 2008 to 2012, U.S. consumption of titanium concentrates averaged about 1,400,000 metric tons. The net import reliance for the United States in that same time period, as a percentage of apparent consumption, was between 65 and 78 percent. The primary sources of U.S. imports of titanium mineral concentrates, which include ilmenite, rutile, synthetic rutile, and titanium slag, were Australia, Canada, Mozambique, and South Africa.

The titanium feedstock industry is dominated by a relatively few companies at both ends of the supply chain; consequently, the actions of a few industry leaders can have implications for the entire industry (Murphy and Frick, 2006). Titanium resources are located in relatively few countries, which means that many industrial nations are dependent on titanium imports (Towner and others, 1988). In addition, the influence of China is an important strategic issue for the titanium industry, as increased economic growth in that nation will likely increase its consumption of titanium minerals, pigments, and metal in the long term (Gambogi, 2012). Increasing demand in China for titanium will be paced by increasing demand in the United States as the U.S. economy recovers from the recession that began in 2008 and as aerospace, defense, and industrial uses grow. For example, new lighter and fuel-efficient aircraft and ground vehicles will require significantly more titanium in their structures to reduce weight and increase durability. Global consumption of titanium by the defense industry alone was expected to increase by slightly more than 30 percent between 2010 and 2015 (Gambogi, 2012). Improving global economic conditions resulted in a 7 percent increase in domestic TiO_2 pigment production from 2009 to 2010 (Gambogi, 2012). Thus, the dynamics of the global titanium industry are a complex interdependence of supply and demand, industry activities, and environmental regulations, all of which could be highly influenced by the discovery of new uses for titanium and by technological advances in the extraction and production of titanium metal and TiO_2 pigment.

Geology

Geochemistry

Titanium is the ninth most abundant element in Earth's crust, with an average TiO_2 abundance of 0.7 weight percent (Rudnick and Fountain, 1995). Titanium can be found in nearly all rocks and sediments, often at contents greater than 1 weight percent, and thus, unlike many other elements of economic interest, it is considered to be a major element rather than a trace element. Titanium is a transition element with atomic number 22 and an atomic mass of 47.867 atomic mass units. Titanium's chemistry has similarities to the chemistries of silicon and zirconium. The main oxidation state is Ti^{4+}, although Ti^{2+} and Ti^{3+} are known to exist. Titanium is a lithophile element with a strong affinity for oxygen, and it typically forms oxide minerals. It is not found as a pure metal in nature, and processing is required to produce a low-density, high-strength metal. Titanium metal has excellent corrosion resistance, and it is as strong as steel but 45 percent lighter.

Mineralogy

The most economically important titanium oxides are ilmenite ($FeTiO_3$) and the titanium dioxide (TiO_2) polymorphs rutile, anatase, and brookite. Only some titanium-bearing oxide minerals currently have economic value. Less common, subeconomic minerals include pseudobrookite (Fe_2TiO_5), perovskite ($CaTiO_3$), geikielite ($(Mg,Fe)TiO_3$), pyrophanite ($MnTiO_3$), and titanite or sphene ($CaTiSiO_5$). The titanium content in titanomagnetite ranges between about 2 percent and about 20 percent, and titaniferous magnetite as a group of iron-titanium-oxide ore minerals contains between about 1 percent and about 15 percent titanium (fig. T1; Rose, 1969).

The mineralogy of iron-titanium oxides in magmatic deposits is dependent on several factors, including the initial magma composition, the magma oxygen fugacity, and the cooling history. At magmatic temperatures (>700 degrees Celsius [°C]), iron-titanium-rich liquids are in a single, homogenous phase after which, during cooling, the liquids will separate into two or more oxide minerals. In a high-temperature titanium-rich magma, a small amount of hematite (Fe_2O_3) will separate out of the cooling oxide phase to form thin lamellae within ilmenite crystals. Deposits dominated by the composite mineral hemo-ilmenite (fig. T2*A*) are the largest and most economically important magmatic deposits. In more iron-rich magmas under varying magmatic conditions, a titanium-rich phase (usually ilmenite or ulvöspinel [Fe_2TiO_4]) will separate from magnetite (Fe_3O_4) to form (a) titanomagnetite, which is a complex mixture of iron-titanium oxides with thin exsolution lamellae of ilmenite or ulvöspinel in magnetite, or (b) granular, interlocking discrete grains of ilmenite, ulvöspinel, and magnetite (fig. T2*B*). Titaniferous magnetite is a general mining term applied to low-temperature aggregations of hematite, ilmenite,

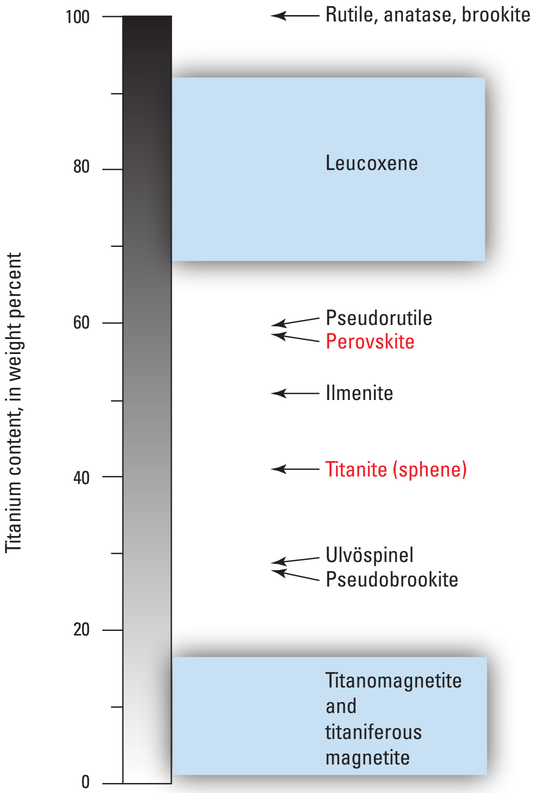


Figure T1. Chart showing common titanium-bearing oxide minerals (black text) and common titanium-bearing silicate minerals (red text) with their approximate titanium content (in weight percent). The blue shaded boxes represent the range of titanium content for the mineral species in the boxes.

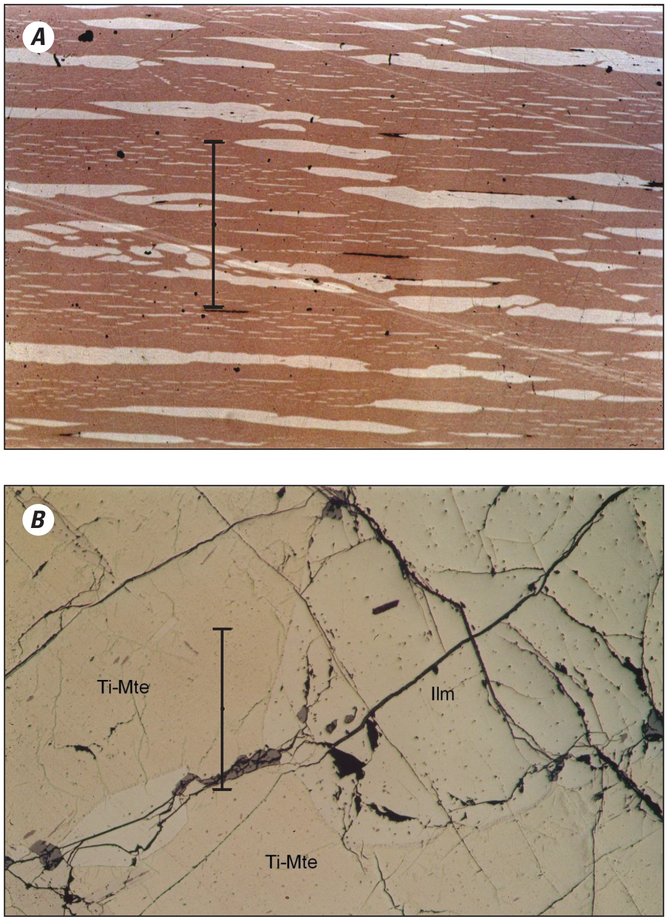


Figure T2. Reflected-light photographs showing *A*, lamellae of hematite (light-pink) in ilmenite (dark pink) in hemo-ilmenite from the magmatic Lac Tio hemo-ilmenite deposit, and *B*, titaniferous magnetite (Ti-Mte) and ilmenite (Ilm) from the magmatic La Blache iron-titanium-oxide deposit. Scale bar is 0.5 millimeters in length. Photographs courtesy of Serge Perreault, SOQUEM, Inc.

magnetite, titanomagnetite, and other intermediate members of the iron-titanium-oxide solid solution series (Rose, 1969). With current technologies, deposits dominated by titaniferous magnetite are generally too high in titanium to mine for iron ore yet too low in titanium to mine for titanium; however, if metallurgical problems with extraction and separation could be resolved, then deposits containing very large resources of titaniferous magnetite could be economically viable for both elements (Rose, 1969). Substitution of aluminum, calcium, chromium, copper, magnesium, manganese, silicon, vanadium, and zinc in the ilmenite crystal structure can lower the quality of ilmenite concentrate, as these elements decrease the TiO_2 grade and may affect pigment color (Chernet, 1999). Ilmenite also is a common detrital mineral, being somewhat resistant to erosion processes. Weathering of ilmenite typically involves progressive leaching of iron from its mineral structure, thereby enriching the altered ilmenite in titanium and potentially forming pseudorutile ($Fe_2Ti_3O_9$), leucoxene, and rutile (fig. T1). Because of this upgrading in titanium content, altered ilmenite is a preferred ore target.

Rutile is the most common of the TiO_2 polymorphs. It has a high index of refraction and thus a high degree of opacity, which accounts for rutile's desirability for use in pigments. Rutile occurs as an accessory mineral in many igneous rocks and in all grades of metamorphic rocks. With increasing metamorphic grade, the breakdown of ilmenite and silicates will release titanium, which then crystallizes into rutile. Rutile is highly stable across most geologic environments, which explains its presence in a wide range of rock types and as a common detrital mineral. Rutile can be a major host mineral for niobium, tantalum, tungsten, uranium, zirconium, and ferric iron. The presence of trace elements is in part dependent on the availability of trace constituents during rutile formation. Anatase and brookite are low-temperature alteration products of ilmenite or titanite.

Deposit Types

Table T1 shows the classification of titanium mineral deposit types. These classifications can have considerable overlap. For example, magmatic concentrations of iron- and titanium-bearing silicates and oxides can be metamorphosed to form rutile, weathered from parent rocks to subsequently reside in place within weathered zones, or transported and sorted by wind or water to form heavy-mineral deposits. A common thread among all the deposit types described in table T1 is their ultimate origin from rocks somewhat enriched in titanium by geologic processes.

The worldwide distribution of titanium deposits is shown in figure T3. The economic value and mining potential of a titanium deposit is highly dependent on its mineralogy rather than its overall titanium content. Although there are very large global resources of ilmenite and rutile combined, there is a worldwide lack of high-grade, high-quality ilmenite deposits as well as of high-quality rutile deposits (Korneliussen and others, 2000a). Mineral assemblage, grain size, morphology, texture, and type and quantity of included trace elements all contribute to the economic potential of a deposit.

Qualitative differences in the approximate TiO_2 content of different deposit types are shown in figure T4. In sedimentary deposits, titanium-bearing minerals have been released from their parent rock; thus, low-grade deposits of this type may be mined if the titanium minerals are of sufficiently high quality, either through alteration of ilmenite or by the presence of rutile. Brooks (1976, p. 149), in postulating that the ultimate “cut-off grade” for each metal is its crustal abundance, acknowledges former U.S. Geological Survey Director Vincent McKelvey for pointing out that the titanium content of ilmenite beach placers mined in Florida is below the crustal abundance of titanium.

The presence or absence of discrete crystals of ilmenite is a key factor that determines the economic value of most magmatic oxide deposits. In magmatic hemo-ilmenite deposits, such as the deposit at Tellnes (Norway), ore has to be mined and crushed and the ilmenite separated from the waste rock; therefore, ore grades in these types of deposits must be high (Korneliussen and others, 2000a). Deposits with unconventional titanium ore minerals, such as Iron Hill (Colorado; also called Powderhorn in the literature), which host perovskite, are currently uneconomic; likewise, the anatase deposits in Brazil (the Catalão, Salitre, and Tapira deposits) are not being exploited for titanium at this time.

Titanium Deposits Related to Igneous Rock

Mafic intrusions of various age and rock types can contain significant iron-titanium-oxide deposits. Deposits dominated by ilmenite and hemo-ilmenite are hosted by discordant and layered bodies in Proterozoic-age massif anorthosite plutonic complexes. These unique rock suites are restricted in time, from about 0.5 to 2.5 Ga (giga-annum, or billion years ago); the majority that contain significant titanium resources were emplaced from about 1.0 to 1.8 Ga (Ashwal, 2010). The plutonic suites are dominated by different and often unusual mafic rock types. These rocks are called, for example, anorthosite, charnockite, jotunite, gabbro, norite, or troctolite. The different names distinguish among rocks with various proportions and compositions of plagioclase and pyroxene. Anorthosite plutonic suites of the Grenville Province in eastern Canada and parts of the Northeastern United States and the Rogaland anorthosite province in Norway contain numerous iron-titanium-oxide deposits (Rose, 1969; Krause and others, 1985; Corriveau and others, 2007). Hemo-ilmenite (with little or no magnetite) is currently being mined at Lac Tio in Quebec Province, Canada, and is hosted by the Allard Lake anorthosite in the Havre-Saint-Pierre anorthosite plutonic suite (Gross, 1996). Hemo-ilmenite is also being mined at Tellnes, which is a hemo-ilmenite-bearing norite lens in the Åna-Sira anorthosite pluton in Norway (Wilmart and others, 1989). A deposit model for titanium deposits hosted by Proterozoic-age massif anorthosite plutonic suites was completed by Woodruff and others (2013).

Deposits dominated by titaniferous magnetite with minor amounts of ilmenite are hosted in layered and massive intrusions of gabbro, leucogabbro (light-colored gabbro), and norite, which can include, but are not restricted to, Proterozoic-age massif anorthosites (Gross, 1996). These types of deposits have somewhat different characteristics than the magmatic deposits typified by Lac Tio or Tellnes, including differences in host rock form, dominant ore mineralogy, and proposed magmatic history. Examples include numerous deposits in layered and discordant anorthosite-norite-gabbro intrusions in the Grenville Province, such as Magpie Mountain and Lac la Blache (Canada) and Sanford Lake district in the Adirondacks (New York), and large layered mafic intrusions of various ages, such as the Bushveld Complex (South Africa), which is currently being exploited for vanadium from titaniferous magnetite. Titanomagnetite and ilmenite are mined for iron, titanium, and vanadium from several deposits in the Permian-age Panzhihua layered mafic intrusion in China (Zhou and others, 2005).

Other magmatic occurrences are somewhat enigmatic. For example, in the Duluth Complex of Minnesota, small bodies of ilmenite and titanomagnetite hosted by ultramafic rocks that cross-cut gabbroic rocks are a significant (but presently subeconomic) titanium resource. The origin of these deposits remains under debate (Hauck and others, 1997). In Finland, the relatively small Koivusaarenneva gabbro intrusion contains layers of ilmenite (with minor amounts of magnetite) that are interpreted as iron-titanium-oxides deposited in a flow-through magmatic system that has created a large resource in a small-volume intrusion (Kärkkäinen and Bornhorst, 2003).

Formation of iron-titanium-oxide deposits in mafic intrusions requires favorable combinations of composition, oxygen fugacity, and crystallization history, which determine if a deposit is dominated by ilmenite or titaniferous magnetite (Woodruff and others, 2013). Massive hemo-ilmenite

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

Figure T3. World map showing global distribution of titanium deposits, by size and type of depost. Deposit types are from table T1 and are described more fully in the text. D, district; S, State; numbers in parentheses indicate the number of deposits included in a single symbol. Deposit size is denoted by the relative size of each circle and descriptive text. QMM stands for QIT Madagascar Minerals, which is a Rio Tinto-Madagascar Government joint venture to extract ilmenite from sands around Fort Dauphin. Deposit information was compiled primarily from Towner and others (1988) and Force (1991).

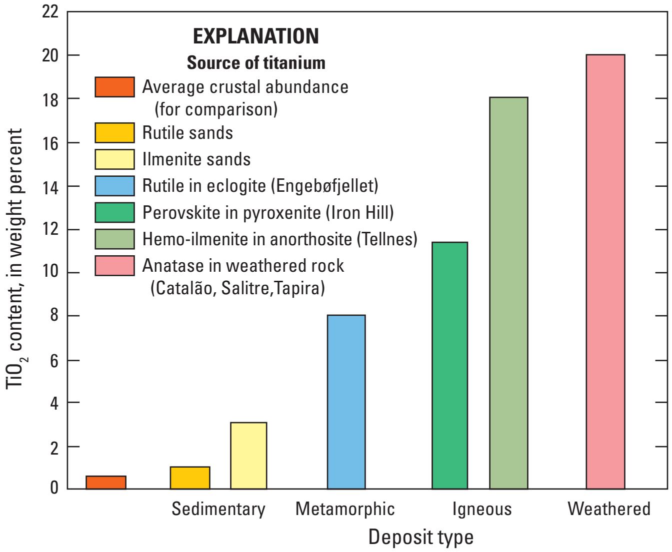


Figure T4. Bar chart comparing approximate titanium dioxide (TiO_2) content in titanium deposits of different deposit types (modified from Korneliussen and others, 2000a). The sources of ore given here as examples are average crustal abundance (Rudnick and Fountain, 1995); average rutile and ilmenite sands (sedimentary) (Force, 1991); rutile in eclogite from the Engebøfjellet deposit in Norway (metamorphic) (Korneliussen and others, 2000a); perovskite in pyroxenite at the Iron Hill (Powderhorn) deposit in Colorado (igneous) (Van Gosen, 2009); hemo-ilmenite in anorthosite at the Tellnes deposit in Norway (igneous) (Korneliussen and others, 2000a); and anatase in weathered rocks from the Catalão, the Salitre, and the Tapira deposits in Brazil (Force, 1991).

deposits, such as those at Lac Tio and Tellnes, are thought to have formed by early magmatic crystallization of ilmenite (Duchesne, 1999; Charlier and others, 2010). Deposits dominated by titaniferous magnetite in layered intrusions may represent late-stage concentrations of iron and titanium in magmatic liquids following extensive silicate crystallization.

When rocks are affected by metasomatism (a process that changes the chemical composition of rocks by the introduction of external fluids), titanium minerals in the host rock may be altered. For example, at the Bamble-Arendal iron-titanium province of Norway, Proterozoic-age mafic rocks were affected by local and regional alkali-metasomatism during which original ilmenite was converted to rutile by the removal of iron (Korneliussen and others, 2000a). In this district, rutile was mined at Kagerø from a rutile-rich vein (Force, 1991). At Roseland, Va., rutile that occurs in metasomatized shear zones along complex contacts of anorthosite/ferrogabbro intrusions and dikes with adjacent country rocks was mined from 1900 to 1949 (Herz and Force, 1987).

Concentrations of titanium minerals also occur in carbonatites (unusual rocks of magmatic or metasomatic origin dominated by carbonate minerals) and alkali igneous rocks. The Iron Hill (Powderhorn) carbonatite complex in Colorado is a series of successively intruded alkali rocks, including such rock types as carbonatite, nepheline, pyroxenite, and syenite (Temple and Grogan, 1965). Mainly because it contains abundant amounts of perovskite (a calcium-titanium oxide), the pyroxenite ranges from 1.9 to 9.6 weight percent TiO_2 (with an average of about 5.3 weight percent TiO_2) and significant amounts of rare-earth elements, thorium, niobium, and vanadium (Van Gosen, 2009).

In another carbonatite-hosted setting, extensive titanium (plus vanadium and niobium) mineralization is related to intrusion of the Magnet Cove carbonatite-alkalic ring dike complex in Arkansas, and accompanying metasomatic events (Fryklund and Holbrook, 1950; Flohr, 1994). At the Magnet Cove deposit, rutile occurs in feldspar-carbonate veins. Other deposits at Magnet Cove that formed by contact metasomatism include the Christy titanium-niobium-vanadium deposit and the Hardy-Walsh prospect. Both deposits contain brookite in novaculite (chert) where country rock was intruded by and reacted with titanium-, vanadium-, and niobium-bearing fluids from adjacent alkali-rich rocks (Erickson and Blade, 1963; Flohr, 1994). Brookite at the Christy deposit can contain exceptionally high amounts of niobium and vanadium (Flohr, 1994).

Highly weathered rocks, such as bauxites (white-gray rock dominated by aluminum-rich oxides and hydroxides) and laterites (reddish rock dominated by iron- and aluminum-rich oxides and clays), can contain significant titanium resources. The titanium deposits at Catalão, Salitre, and Tapira (Brazil) formed by weathering of perovskite, magnetite, and titanite in titaniferous carbonatite, resulting in development of anatase in an about 200-meter (m)-thick laterite cap (Gomes and others, 1990; Force, 1991). Significant amounts of rutile and ilmenite occur in saprolite (weathered rock) over mineralized contacts of the ilmenite-bearing Roseland anorthosite pluton (Virginia), with minor transport and accumulation of both minerals in streams that cut through the saprolite (Fish, 1962).

Titanium Deposits Related to Metamorphic Rocks

Rutile is the most economically valuable mineral for titanium, but rutile sand ores are limited in volume, and, given that there are inadequate supplies of high-grade (>55 percent TiO_2) ilmenite sands, much of the recent search for high-grade ore has focused on rutile potential from metamorphic rocks (Korneliussen and others, 2000a). The main exploration focus is on high-grade metamorphic rocks, such as eclogite (a rock composed primarily of garnet and pyroxene, with lesser amounts of rutile, and typically formed under high-pressure conditions). Based on surveys of eclogite in Norway, Korneliussen and others (2000b) state that metamorphism of titanium-rich protoliths (the unmetamorphosed rock from which a metamorphic rock forms) is a requirement to generate sufficient rutile to be of economic interest. Complications for exploitation of eclogite include highly variable rutile concentrations and grain sizes, retrograde alteration of high-grade metamorphic rutile back to ilmenite or titanite, and the possible presence of impurities, such as calcium, magnesium, iron, and aluminum in trace silicates in rutile concentrates (Korneliussen and others, 2000b). For example, in northern Italy, the Piampaludo eclogite has high TiO_2 content (about 6 weight percent), but during later metamorphism, some rutile was replaced by secondary ilmenite and titanite (Liou and others, 1998), making this resource less economically attractive. The only currently active rutile mines in metamorphic rocks are the Daixian rutile deposits in east-central China, which consist of lenses and layers of rutile-bearing high-grade metamorphic rocks that average about 2 weight percent TiO_2 (Shi and others, 2012).

Intense alteration by hydrothermal fluids reacting with large volumes of rock can result in profound changes in the original bulk rock composition, creating aluminum-rich rocks depleted in most other elements. Metamorphism of these hydrothermally altered rocks can create a rock rich in the minerals kyanite (Al_2SiO_5) and quartz and containing trace amounts of rutile (Marsh and Sheridan, 1976; Owens and Pasek, 2007). In addition, metamorphism of deeply weathered rocks, such as laterites and bauxites, can also result in rutile-bearing aluminum-rich rocks. Because these aluminum-rich rocks are stripped of many other elements, they potentially create a low-grade (about 1 percent or less rutile) and commonly low-tonnage but high-quality TiO_2 resource that is generally free of other contaminants (Force, 1991). Rutile in such deposits can be a valuable byproduct of primary industrial commodities, such as alumina, andalusite, kaolinite, or kyanite.

Rutile also commonly occurs in mineralized zones and alteration halos of many hydrothermal and metamorphosed mineral deposits (Czamanske and others, 1981; Force, 1991; Clark and Williams-Jones, 2004). Large bodies of igneous rock that contain disseminated chalcopyrite and other sulfides are known as porphyry copper deposits. In the alteration zones around some porphyry copper deposits, such as Bingham Canyon (United States) or El Teniente (Chile), rutile can form from the breakdown of titanium-bearing silicates and oxides by the introduction of high-temperature hydrothermal fluids into the surrounding rock (Czamanske and others, 1981; Rabbia and others, 2009).

Titanium Deposits Related to Coastal Shorelines and Dunes, and Older Equivalent Rocks

Much of the high-grade ilmenite and rutile used today is extracted from unconsolidated heavy minerals (minerals that typically have a specific gravity higher than 2.85 grams per cubic centimeter) in shoreline beach placers and concentrations in sand dunes. Heavy-mineral sand deposits develop when relatively resistant titanium-bearing minerals and other heavy minerals are eroded from primary parent rocks, then transported and sorted, and finally deposited in fluvial, beach, or eolian settings. In addition to rutile and ilmenite (and minerals produced from weathering of ilmenite, such as anatase, leucoxene, and pseudorutile), other heavy minerals may enhance or detract from a deposit's value. For example, zircon is a valuable commodity for the ceramics industry, whereas monazite (a phosphate mineral that can contain rare-earth elements and thorium) can make a deposit more problematic because of potential radioactivity issues with waste disposal.

Fluvial deposits, as used here, consist of heavy minerals deposited by streams and rivers above sea level, including deltaic deposition in rivers and lakes. Fluvial heavy-mineral deposits in old drainage courses in the Ghangbama district in Sierra Leone (for example, Mogbwemo and Sherbo River) are dominated by rutile, and contain lesser amounts of zircon and ilmenite; the deposits have been eroded from deeply weathered garnet amphibolite and leucocratic garnet granulite highlands (Force, 1991). Many fluvial deposits are small and geologically young and have a heavy-mineral assemblage that closely resembles that of the unaltered source rock (Force, 1991).

The abundance and distribution of heavy minerals in active and older (mostly Pleistocene) beach placer and eolian deposits are related to the area's geology, physiography, and coastal dynamics. Many productive heavy-mineral sand provinces have the following characteristics: (a) deposits are located on passive continental margins that almost always are backed by elevated (typically highly weathered) high-grade metamorphic or mafic igneous hinterlands that supply detritus to the sands; (b) shoreline regions are dominated by sea-level changes and relatively low rates of sedimentation; (c) sands have been repeatedly reworked during marine transgressions and (or) by high-energy waves and littoral drifting; and (d) many sand bodies form topographic highs that represent former barrier island and (or) eolian dunes (Force, 1991; Hamilton, 1995; Roy, 1999; Pirkle and others, 2007; Hou and others, 2017).

Iron-titanium oxides in older, lithified heavy-mineral sand deposits may have undergone extensive post-depositional alteration, which diminishes the proportion of nonheavy minerals and enhances the conversion of ilmenite to leucoxene, causing an upgrade of the titanium content (Force, 1991). Ilmenite-rich layers of the Tertiary Cohansey Formation in New Jersey were mined at the Lakehurst deposit from 1962 until 1978 (Puffer and Cousminer, 1982). The Bothaville deposit in Late Paleozoic sandstones of the Ecca Group in the Karoo basin, South Africa, is a lithified paleo-beach deposit that contains (in order of abundance) ilmenite, rutile, and anatase (Hamilton, 1995). Heavy-mineral placers in shorelines of the Eocene-Pliocene Eucla basin (Hou and others, 2011) and the Pliocene Murray basin (Roy and Whitehouse, 2003) along the southern coast of Australia are major heavy-mineral sand provinces.

A grade-and-tonnage model for shoreline placer titanium was developed by Attanasi and DeYoung (1992). Titanium grade and tonnage data for these deposits were combined with grade and tonnage data for titanium deposits related to both igneous and metamorphic rocks to create figure T5. The data for figure T5 are taken from disparate sources and represent a wide variety of deposit types and settings. Many of the deposits depicted in figure T5 are not economic. The high-grade and low-tonnage igneous deposits are typically characterized by the presence of abundant ilmenite and hemo-ilmenite (for example, Coulombe East and West, Bignel, and Lac Brûlé, all in the Grenville Province, Canada). Low-grade and high-tonnage igneous deposits are dominantly titanomagnetite (for example, Magpie Mountain and Panzhihua). Anatase is the titanium mineral at Salitre and Tapira, and perovskite is the titanium mineral at Iron Hill (Powderhorn), Colorado. Manavalakurichi is a heavy-mineral deposit in the State of Tamil Nadu, India.

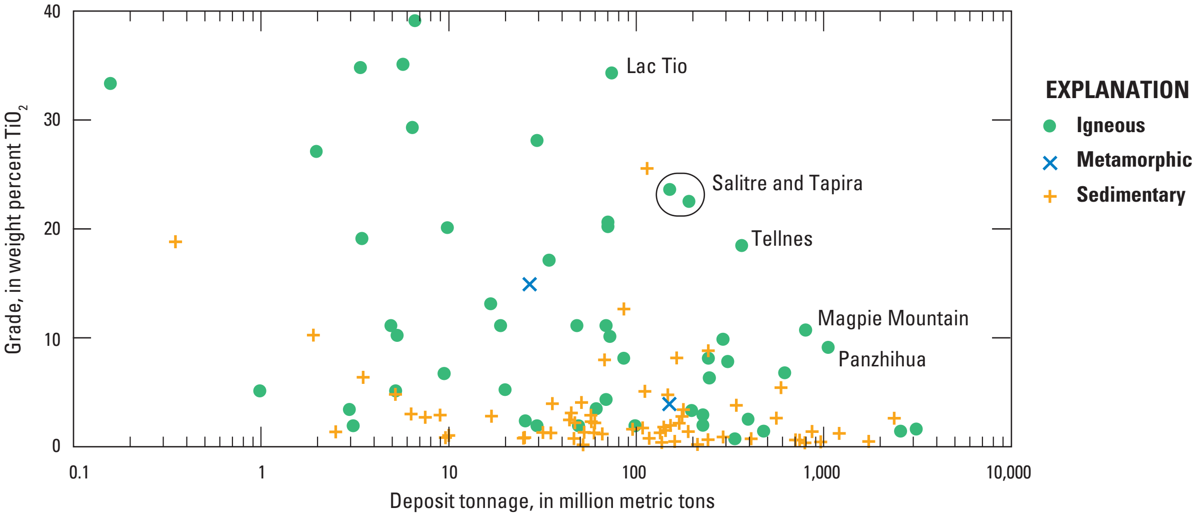


Figure T5. Plot of titanium dioxide grade and tonnage for selected igneous, metamorphic, and sedimentary deposits in the world, by deposit type. Data were compiled from Towner and others (1988), Attanasi and DeYoung (1992), Corriveau and others (2007), and the Fennoscandian Ore Deposit Database (FODD), which is maintained by the Geological Survey of Finland (2013). Deposits extracted from the FODD have titanium, titanium and vanadium, or iron and titanium listed as their main metals. Some of the major deposits discussed in the text are labeled.

Resources and Production

Identified Resources

Figure T6 shows world ilmenite and rutile mine production and reserves for 2012 (based on the data available), which are reported as titanium mineral concentrates by the U.S. Geological Survey (Bedinger, 2013). A major difficulty in quantifying titanium resources is the range of standards that individual countries and companies apply to the categorization of resources (Murphy and Frick, 2006). Resource calculations also depend on complex mineralogical factors, such as ore mineralogy, grain size, and trace element concentrations, which are all critical to a determination of whether a deposit can be mined economically or not. Because of the widespread distribution of titanium minerals in many geologic environments, development of new technologies to extract titanium from nonconventional ore minerals and deposit types has great potential to open up large, currently untapped resources.

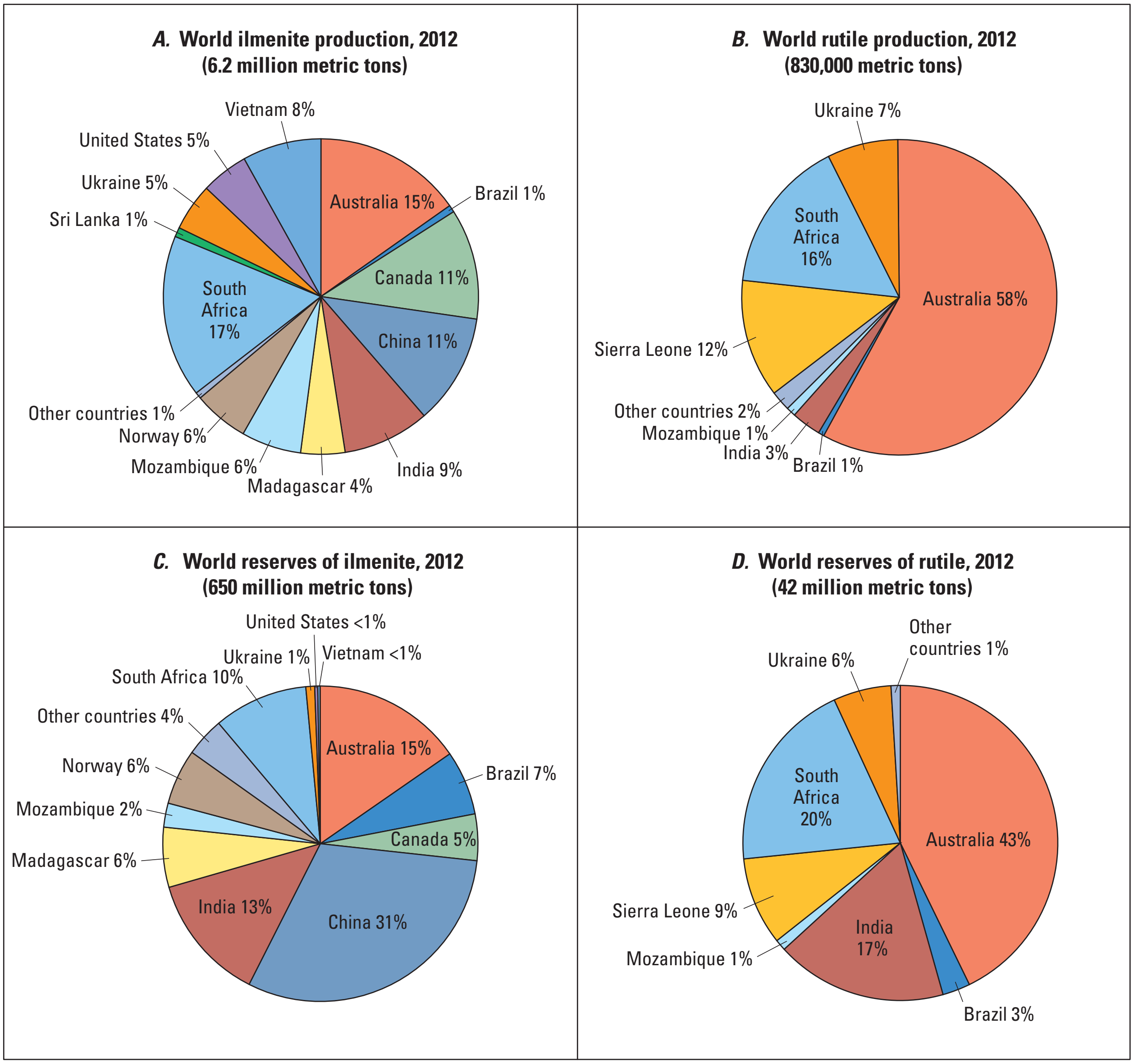


Figure T6. Pie charts showing percentage of estimated 2012 world mine production of *A*, ilmenite, and *B*, rutile, and percentage of global reserves of *C*, ilmenite, and *D*, rutile, by country. Total world mine production and reserves are also shown. Ilmenite data from the United States include rutile to avoid disclosing company proprietary data. Ilmenite reserves for Sri Lanka are not available. Data are from Bedinger (2013). Percentages are rounded and may not add to 100. The term reserves as used here is defined as that part of the reserve base that would be economically extracted or produced at the time of determination (U.S. Bureau of Mines and U.S. Geological Survey, 1980).

The United States has large resources of ilmenite and perovskite, as well as the potential for rutile resources. Table T2 lists the titanium mineral resources (including mineral reserves) of the United States. The East Coast of the United States is part of the eastern North America titanium province, as described by Stanaway (1996). Although deposits in the region include titanium oxides related to anorthosite and gabbro in New York (Sanford Lake district) and Virginia (Piney River [Roseland] anorthosite complex), the bulk of the resource is contained in heavy-mineral concentrations in beach, bar, dune, and stream sands along the Atlantic Coastal Plain and in large parts of the Gulf Coastal Plain (fig. T3; Pirkle and others, 2007). Nonetheless, the estimated amount of more than 100 million metric tons of contained TiO_2 resources in the United States given in table T2 represents less than 10 percent of the world's titanium resources. The low grade of some U.S. resources, the possible presence of unfavorable trace constituents in ore, challenges with mineral separation and beneficiation of such nonconventional ore minerals as titaniferous magnetite and perovskite, anticipated high costs of permitting and production, and competition from foreign sources continue to curtail domestic production.

Total world resources of anatase, ilmenite, and rutile are estimated to be more than 2 billion metric tons (Bedinger, 2013). Compiled world resource estimates given in table T3 total more than this amount but that is because they include hypothetical and speculative resources in addition to identified resources. Rose (1969), Towner and others (1988), and Force (1991) provide detailed geologic and location information for a number of deposits included in the estimates in table T3. Important points from table T3 are (a) the predominance of ilmenite resources versus rutile resources, and (b) the relative proportions of heavy-mineral sand resources compared with igneous and metamorphic sources. Discounting the speculative estimate of greater than 2,000 million metric tons of ilmenite resources in Canada, which is largely based on estimates from Gross (1996), heavy-mineral sand deposits represent the largest resource type for worldwide titanium supplies.

Undiscovered Resources

Undiscovered (hypothetical and speculative) resources of titanium are considered to be very large but difficult to quantify. Ilmenite is a common mineral in mafic and ultramafic rocks, and rutile is a highly stable mineral in metamorphic rocks. Many of the resources identified in table T3 include hypothetical and speculative titanium resources that await technological advances or favorable economics before they are likely to be exploited. For example, Rose (1969) states that high-grade magmatic ilmenite and titaniferous magnetite resources in Canada are measurable in hundreds of millions of tons, whereas low-grade deposits are potentially available in billions of tons. The Alberta oil sands also represent a very large speculative source of titanium (Towner and others, 1988). Although heavy minerals do not occur in large concentrations in these sands, the large quantity of sand processed for hydrocarbons creates a potentially significant titanium resource. The hot-water extraction process that recovers bitumen from the oil sands concentrates heavy minerals in treatment tailings, which contain on average about 11.5 percent TiO_2 (Liu and others, 2006). Attempts to isolate a high-grade titanium concentrate from these tailings have met with only limited success, however (Kaminsky and others, 2008).

About 500 million metric tons of black sands on the North Island of New Zealand contain titanomagnetite (which averages about 23 percent of the raw sand) with a TiO_2 content of 7 to 8 weight percent (Christie and Braithwaite, 1998). The North Island black sands are currently mined for iron with vanadium as a byproduct, but they are not yet considered economic for titanium (Christie and others, 2000). Magmatic iron-titanium-vanadium deposits in layered anorthosite-gabbro rocks that contain abundant titaniferous magnetite but only minor amounts of ilmenite represent another very large potential source of titanium. Among numerous examples are the Magpie Mountain deposits (Canada) (which hosts an estimated 1.5 billion metric tons of titaniferous magnetite ore containing 45.37 weight percent iron and 10.8 weight percent titanium; Gross, 1996) and the large Suwalki district (Poland), which contains significant resources in terms of tonnage that are not economic at this time (Charlier and others, 2009). As with perovskite at Iron Hill (Powderhorn), however, titanium mineralogy rather than the titanium content determines the economic value of the deposit.

Other speculative resources include very large but very low-grade rutile deposits in porphyry copper systems, which Force (1991) suggests have great potential because of the purity and ubiquitous nature of rutile in altered rock. In addition, shallow underwater offshore placers paralleling known exposed coastal placers are sparsely developed and largely unexplored but in some areas are known to contain commercially exploitable heavy minerals. Offshore placers represent large speculative titanium resources (Grosz and others, 1986).

Table T2. Titanium resources of the United States.

[Values are from Force and Lynd (1984) with some updates from Force and Creely (2000), except that the Virginia heavy-mineral sands estimate is from Newton and Romeo (2006). Deposit classes are taken from table T1; —, none reported, or negligible; ?, identification uncertain]

State	District, deposit, or deposit type	Deposit class	Contained titanium dioxide, by primary ore mineral (thousand metric tons)		
			Rutile	Ilmenite	Perovskite
Alabama	Cretaceous sands	S–3	—	100	—
Arizona	Porphyry copper ore	I/M	4,000	100	
Arkansas	Magnet Cove	I–7	200	—	—
California	San Gabriel Mountains	I–2	—	4,800	—
California	Ione placer	S–1	—	4,000	—
California	White Mountains	M–5	300	—	—
Colorado	Iron Hill (Powderhorn)	I–7	—	—	20,000
Colorado	Evergreen	M–5	200	—	—
Florida	Old beach sands	S–2/S–4	1,100	9,700	—
Georgia	Heavy-mineral sands	S–2	500	2,400	—
Maryland	Dinning	M–3?	700	—	—
Minnesota	Duluth Complex	I–2	—	10,000	—
Mississippi	Ship Island	S–2	—	100	—
New Jersey	Lakehurst	S–3	—	10,100	—
New Mexico	Cretaceous sands	S–3	—	700	—
New York	Sanford Lake district	I–2	—	8,600	—
New York	Port Leyden	S–1	—	6,300	—
North Carolina	Yadkin Valley	M–2?	—	200	—
North Carolina	Heavy-mineral sands	S–2	—	400	—
Oklahoma	Wichita Mountains	S–1	—	—	—
South Carolina	Heavy-mineral sands	S–2	200	1,400	—
Tennessee	Cretaceous sands	S–3	1,300	8,400	—
Utah	Porphyry copper ore	I/M	4,000	—	—
Utah	Escalante	S–3	—	200	—
Virginia	Heavy-mineral sands	S–2	150	2,200	—
Virginia	Roseland	I–5/I–8	1,000	5,500	—
Virginia	Willis Mountain kyanite	M–5	300	—	—
Wyoming	Laramie Range	I–2	—	2,700	—
Wyoming	Cretaceous sands	S–3	—	500	—
Total[1]			**14,000**	**77,900**	**20,000**

[1] The U.S. resource total for titanium dioxide contained in the three primary ore minerals (rutile, ilmenite, and perovskite) is about 112 million metric tons of titanium dioxide. Totals have been rounded.

Table T3. Titanium mineral resources of the world (excluding the United States) for ilmenite (including titanomagnetite and leucoxene) and rutile (including anatase and brookite).

[Numbers are estimates. Deposit classes are taken from table T1; S, sedimentary, primarily heavy-mineral sands; I, igneous, primarily ilmenite and (or) titanomagnetite in mafic rocks; M, metamorphic, primarily rutile in eclogite; —, none reported or negligible; ?, amount uncertain; ~, approximately. Values for heavy-mineral sand resources (deposit class S), with the exceptions of New Zealand and Russia, are from Elsner (2010); deposit class S values for New Zealand from Christie and Braithwaite (1998) are for ilmenite on the South Island and do not include titanium in the 500-million-metric-ton titanomagnetite iron sand resources of the North Island; deposit class I values for Brazil, Italy, and Mexico are from Force (1991); deposit class I values for Canada are generalized from Rose (1969); deposit class I values for China are calculated from China Mining Association (2006); deposit class M values for China are from Shi and others (2012); deposit classes I and M values for Norway are from Korneliussen and others (2000a); deposit classes I and S values for Russia are from Bykhovskii and Tigunov (2011)]

Country	Deposit type	Deposit class	Contained titanium dioxide, by primary ore mineral (million metric tons)	
			Rutile	Ilmenite/ titanomagnetite
Australia	Heavy-mineral sands	S	39.9	246
Brazil	Heavy-mineral sands	S	0.1	7
Brazil	Anatase in weathered rock	I	150	—
Cameroon	Heavy-mineral sands	S	2.9	—
Canada	Heavy minerals in oil sands	S	—	183?
Canada	Gabbro/anorthosite	I	—	>2,000
China	Heavy-mineral sands	S	0.7	22
China	Titanomagnetite in layered mafic intrusions	I	—	~52
China	Rutile in anthophyllite	M	6	—
Egypt	Heavy-mineral sands	S	0.5	—
India	Heavy-mineral sands	S	>18.0	>348
Italy	Rutile in eclogite	M	9	—
Kazakhstan	Heavy-mineral sands	S	0.3	~3
Kenya	Heavy-mineral sands	S	3	61
Madagascar	Heavy-mineral sands	S	—	60
Malawi	Heavy-mineral sands	S	>13	190
Malaysia	Heavy-mineral sands	S	—	~10
Mexico	Metasomatized anorthositic rocks	I	—	3
Mozambique	Heavy-mineral sands	S	3.2	237
Namibia	Heavy-mineral sands	S	0.6	36
New Zealand	Heavy-mineral sands	S	—	5
Norway	Gabbro/anorthosite	I	—	238
Norway	Rutile in metamorphic/metasomatic rocks	M	61	—
Russia	Titanomagnetite/ilmenite/titanite	I	—	121
Russia	Heavy-mineral sands	S	2.3	9
Senegal	Heavy-mineral sands	S	0.6	22
Sierra Leone	Rutile/ilmenite in fluvial deposits	S	10.2	5
South Africa	Heavy-mineral sands	S	4.4	82
Sri Lanka	Heavy-mineral sands	S	0.5	~12
Ukraine	Heavy-mineral sands	S	0.5	~14
Vietnam	Heavy-mineral sands	S	—	8
Total[1]			**~325**	**~3,975**

[1] The world resource total for rutile and ilmenite combined is about 4.3 billion metric tons, which includes hypothetical and speculative resources in addition to identified resources.

Exploration for New Deposits

Heavy-mineral analysis is an effective exploration guide for titanium-bearing heavy-mineral concentrations (Hou and others, 2017). In addition to high levels of titanium, geochemical signatures include high levels of zirconium, rare-earth elements, thorium, and uranium (Grosz and Schruben, 1994). For example, data indicating anomalously high levels of hafnium, rare-earth elements, titanium, and zirconium for streambed sediments collected for the U.S. Department of Energy's National Uranium Resource Evaluation program helped locate major heavy-mineral deposits in an area between the Piedmont and the Atlantic Coastal Plain in Virginia and North Carolina (Grosz and Schruben, 1994). Exploration for fluvial placer deposits is best focused on source rock lithology, as many deposits are proximal and reflect the mineralogy of their source rocks (Force, 1991). Thus, a rutile source is more promising than an ilmenite source. More recent exploration for heavy-mineral deposits has relied on increasingly sophisticated radiometric methods and on stratigraphic and sedimentological modeling (Hou and others, 2017). Multichannel gamma-ray spectrometers coupled with geologic and land-use and land-cover data have allowed recognition of anomalies that could be tied to thorium radiation from monazite (Pirkle and others, 2007). In the Eucla basin in southern Australia, high-resolution satellite nighttime thermal imagery and detailed elevation data were combined with geologic data to identify beach-barrier facies and favorable heavy-mineral assemblages (Hou and others 2011, 2017). In most cases, modern beaches or interpreted older beaches must be cored to determine the presence of heavy minerals, and samples have to be characterized by mineralogy, grain size, and titanium content (Pirkle and others, 2007). The large induced polarization response of ilmenite permits exploration for offshore marine heavy-mineral deposits using shipborne geophysical methods (Wynn, 1988). Innovative and modern exploration marine exploration methods, such as induced polarization, could cover a large swath of the continental shelf (Wynn, 1988).

Exploration for magmatic iron-titanium-oxide deposits is not only focused on grade and tonnage, but also on finding ilmenite suitable for pigment processing (for example, chromium- and magnesium-poor ilmenite). Suitable mineralogy and chemistry depend on relationships among magmatic evolution, major- and trace-element chemistry, and low temperature re-equilibration. Geophysical methods have been used for exploration and to extend known deposits. Prospecting for workable and chemically suitable ilmenite resources relies in part on aeromagnetic signatures of iron-titanium-oxides that record ore microtextures that can be related back to ore chemistry (McEnroe and others, 2000). Aeromagnetic maps over favorable terranes may have a spectacular range of positive and negative anomalies because of highly contrasting rocks and possible deposit types (McEnroe and others, 2001). Concentrations of nonmagnetic hemo-ilmenite commonly have distinctive negative magnetic anomalies or mixed patterns of positive and negative magnetic anomalies. Strong positive anomalies related to magnetite content may point toward large titanomagnetite concentrations. Because of contrasting physical properties compared to silicates, iron-titanium-deposits commonly have higher gravity anomalies than surrounding anorthositic, granitic, or gneissic country rock (Gross, 1996).

Exploration for rutile in metamorphic rocks, specifically eclogite, depends on recognition of favorable geologic circumstances that would create high-grade and high-quality rutile concentrations. These favorable circumstances include (a) high-grade metamorphism of large volumes of titanium-bearing gabbroic protoliths; (b) favorable mineralogical factors, such as grain size, mineral intergrowths, modal variations, and degree of retrograde mineral alteration; (c) favorable locations with regard to deposit development, shipping, and waste treatment; and (d) potential byproducts (for example, garnet) that could enhance the economics of a deposit (Korneliussen and others, 2000b).

Environmental Considerations

Sources and Fate in the Environment

The behavior of titanium in the environment is dominated by its low solubility and the limited reactivity of titanium minerals. The main sources of anthropogenic titanium in the environment are from the combustion of fossil fuels and, to a lesser extent, incineration of titanium-containing products (International Programme on Chemical Safety, 1982). The mean concentration of titanium in soils worldwide is 0.33 weight percent titanium (Kabata-Pendias and Mukherjee, 2007); the average and range in titanium concentrations for soils in the conterminous United States are 0.29 weight percent and 0.007 to 2.0 weight percent, respectively (Shacklette and Boerngen, 1984). Titanium in stream waters worldwide ranges from 12 to 926 micrograms per liter (µg/L) (Reimann and de Caritat (1998). River waters in North America contain between 2 and 107 µg/L titanium, and drinking waters in the United States contain from 0.5 to 15 µg/L titanium (International Programme on Chemical Safety, 1982). The average concentration of titanium in suspended sediments in rivers worldwide is 0.44 weight percent (Viers and others, 2009). In the atmosphere, titanium ranges from 0.5 to 2.5 nanograms per cubic meter (ng/m^3) for remote areas and from 15 to 25 ng/m^3 for urban areas (Kabata-Pendias and Mukherjee, 2007). Atmospheric concentrations of titanium in urban areas of the United States are typically below 100 ng/m^3, but values of up to 1,000 ng/m^3 have been reported in some industrial regions (International Programme on Chemical Safety, 1982).

A significant amount of the titanium manufactured as a metal is recycled. For TiO_2 used for pigment, however, there is no role for recycling because the compound is so profoundly incorporated into the end product that it cannot be recovered with today's technology (Murphy and Frick, 2006). Because the bulk of the world's titanium is used for pigment, recycling currently plays little or no role in titanium consumption or pricing trends.

Mine Waste Characteristics

Magmatic ilmenite and sedimentary-related titanium deposits produce very different volumes and types of mine waste. The open pit methods used to extract ore from massive magmatic ilmenite deposits produce large volumes of waste rock and tailings. The Storgangen Mine (Norway), which operated from 1917 to 1965, produced more than 10 million metric tons of ore (Schiellerup and others, 2003) and more than 8 million metric tons of tailings (Ettner, 1999). Annual production (1999) from the Tellnes open pit mine (Norway) is about 2 million metric tons of ore and 1.6 million metric tons of waste rock (Norges Geologiske Undersøkelse, 2012). Tailings from the Tellnes Mine are composed predominantly of feldspar, ilmenite, and pyroxene with a size range of 10 to 200 micrometers (µm) (Olsgard and Hasle, 1993). Mining of the Lac Tio deposit (Quebec, Canada) began in the early 1950s. Waste-rock piles at Lac Tio are estimated to be more than 72 million metric tons and to cover approximately 100 hectares of land, and they are between 20 and 80 m in height (Pepin and others, 2008). Waste rock at Lac Tio is dominantly plagioclase, followed by lesser amounts of hemo-ilmenite and trace sulfides (Pepin and others, 2008). Pyrite is the main sulfide (1 to 2 weight percent) in waste rock with only trace amounts (<1 weight percent) of chalcopyrite (Plante and others, 2011). Laboratory tests on the Lac Tio Mine waste to approximate weathering produced neutral to slightly alkaline leachate (pH 6.5 to 9.0), which is consistent with the near-neutral natural drainage from the waste piles (Plante and others, 2011). Field monitoring of experimental mine-waste cells produced drainage with a pH of between 4 and 8, which mimicked the pH of rain water (Pepin and others, 2008). Thus, any acid generated by sulfides in mine waste from the Lac Tio Mine is neutralized by silicates; the net neutralization potentials range from –6.0 to 3.1 kilograms (kg) of calcium carbonate ($CaCO_3$) per metric ton of ore, all within the uncertainty zone of ±20 kg of $CaCO_3$ per metric ton of ore for the test method (Plante and others, 2011).

Mining and milling methods for heavy-mineral sand deposits involve physical separation of a bulk concentrate and quartz-rich tailings by mechanical means, typically magnetic or electrostatic methods or density separation. During further concentration, the mineral-bearing sand fraction is separated from finer textured slimes (clays, silts, very fine sand), which is mixed with a flocculent to aid settling, and then pumped back as a slurry into a reclamation pit (Daniels and others, 2003).

The average grain size of heavy minerals and the percentage of slimes in a deposit are variable, which results in different amounts and types of waste material. For example, two mineral-sand blocks in India (Kuttam and Sattankulam) contain up to 10 percent heavy minerals and 15 percent slimes (Murty and others, 2007). The sands in these blocks are very homogeneous—85 percent of the sands range from <2 millimeters to 63 µm in size. Heavy-mineral sands on the northeastern coast of Sri Lanka (Pulmoddai sands) are very high grade; 71 percent of the beach sands are smaller than 355 µm, and more than 99 percent of the titanium content is in this size fraction (Premaratne and Rowson, 2003). The two blocks in India cover approximately 120 square kilometers (km^2) and contain an estimated 400 million metric tons of raw sand and 30 million metric tons of ilmenite (Murty and others, 2007). Pulmoddai sands cover an area of only 3.2 km^2 with an even thickness of 6 m (Premaratne and Rowson, 2003); thus, the amount and type of waste generated by the two deposits in India would be very different than the waste generated at Pulmoddai.

Human Health Concerns

Human health concerns related to titanium are minimal. Titanium can enter the human body by ingestion or inhalation, but most ingested titanium is eliminated unabsorbed. An exception to this is some industrial inhalation exposures to high amounts of dust during titanium processing (Kabata-Pendias and Mukherjee, 2007). Mining processes conducted on ilmenite ore or heavy-mineral sands may create high amounts of airborne dust, and control measures are needed to reduce workers' exposure. The U.S. Environmental Protection Agency (EPA) has not found any human or animal studies that are useful for developing toxicity values for titanium (U.S. Environmental Protection Agency, 2010).

The processing of heavy-mineral sands at mine sites may expose workers to minor amounts of radiation. The radiation levels in heavy-mineral concentrates are usually too low to be classified as radioactive; however, when radioactive minerals, such as monazite or xenotime, are separated at the dry processing stage, precautions may need to be taken to protect employees from low levels of ionizing radiation (Abuodha, 2002).

The EPA and the World Health Organization (WHO) have not established drinking water guidelines for titanium nor has the EPA established soil screening levels for industrial or residential land use for remediation purposes. In fact, TiO_2 replaced lead carbonate and lead oxide as the whiteners in paints in the United States because of its low toxicity to humans.

Ecological Health Concerns

The EPA also has not established water-quality criteria for the protection of aquatic life for titanium because titanium minerals are generally insoluble and not bioaccessible.

Recent findings do suggest that TiO_2 nanoparticles, commonly defined as particles smaller than 100 nanometers in at least two dimensions, may be toxic to some aquatic and terrestrial organisms (Federici and others, 2007; Wang and others, 2008; Sharma, 2009). Titanium dioxide nanoparticles are used in a range of products, including sunscreen, cosmetics, paint, and building materials, and have been shown to behave differently in the environment than larger particles of the same composition (Sharma, 2009). Applications for nanoparticles are increasing and, consequently, this form of titanium may be of increasing environmental concern in the future.

Titanium deposits and related waste products are usually sulfide-poor and generally generate near-neutral pH drainage after interacting with rain, surface water, or groundwater. Therefore, acid mine drainage, which is a common potential problem for many types of ore deposits, is not a significant concern at titanium mines. Although titanium may not be an environmental concern, other metals found in trace sulfides may be deleterious to the environment. Some metals, such as cobalt, nickel, and zinc, will remain in solution even at neutral pH. Drainage water with near-neutral pH and some quantity of dissolved metals is termed “contaminated neutral drainage.” Nickel values greater than 0.5 milligram per liter (mg/L) have been reported from waters draining waste piles at the Lac Tio Mine, at times exceeding U.S. and Canadian water-quality guidelines for the protection of aquatic life (Plante and others, 2010). Initially, nickel was adsorbed by residual ilmenite and plagioclase in fresh waste rock, but as mine waste weathered, adsorption sites filled and a lowered adsorptive capacity resulted in increased nickel in drainage waters, creating contaminated neutral drainage (Plante and others, 2010). This interpretation is consistent with field observations on mine waste experimental cells at Lac Tio that produced drainage with higher concentrations of nickel (0.1 to 0.4 mg/L) from approximately 25-year-old mine waste compared with drainage concentrations of nickel (<0.05 mg/L) from freshly blasted waste rock (Pepin and others, 2008). These studies suggest that ecosystem health concerns from high nickel concentrations in mine drainage waters may increase as mine wastes weather.

Approximately 750,000 cubic meters of water drains annually from a tailings impoundment for the closed Storgangen Mine (Norway) (Ettner, 2007). Runoff from the former mine that subsequently reaches the North Sea at a distance of about 5 kilometers downstream has a neutral pH and nickel concentrations of up to 6 mg/L (Ettner, 2007). An anaerobic passive treatment system was installed in 2003 to remove nickel, and initially it had variable efficacy because of the immaturity of the system and extreme rain storms; since 2007, however, the system has successfully removed nickel from the tailings runoff (Ettner, 2007).

Mine tailings from Tellnes are almost inert and are nontoxic to marine life (Olsgard and Hasle, 1993). Disposal of tailings underwater can lead to increased water turbidity, however, and, depending on the sedimentation rate, to the smothering of organisms living in bottom sediment. At Tellnes, about 2 million metric tons per year of tailings were deposited into a local fjord throughout the 1980s, which resulted in the reduction in number and diversity of species. After underwater tailings deposition ceased in 1994, bottom fauna in the fjord began to recover. Although there was a reduction in species richness compared with that of unaffected background locations for several years after tailings deposition ceased, within 4 years, all the main macrobenthic phyla were represented (Olsgard and Hasle, 1993). Some of the waste rock at the Lac Tio Mine is adjacent to a water body called Lac Petit Pas. A study by the operating company of the Lac Tio Mine showed that there were elevated concentrations of some metals in the first several centimeters of sediment within the lake but concluded that the sediments act as a retention medium (Rio Tinto, 2009).

Mine Closure

The post-mining landscape at titanium mines depends on the type of deposit exploited and the mining methods employed. Pit lakes remaining from open pit magmatic titanium deposits could contain low concentrations of trace elements typically found in ores, such as cobalt, chromium, nickel, vanadium, and zinc. In the Sanford Lake district of New York, the pit lake at the McIntyre Mine, which was closed in 1982, has a neutral pH of 8 and low to nondetectable concentrations of trace elements (Woodruff and others, 2013; S. Hollmeyer, undergraduate student, University of Vermont, unpub. data, December 2003).

Titanium minerals from heavy-mineral sand deposits are most commonly mined using surface methods, including wet dredging and dry mining techniques. Pits are backfilled with tailings and slimes. Commonly, topsoil initially removed at a site is stored during active mining and later mixed with tailings and slimes to facilitate the return of vegetation. Daniels and others (2003) examined soil profiles within reclamation pits at the Old Hickory Mine site (Virginia). Soils were a mixture of dewatered slimes and tailings with added soil amendments, such as biosolids, fertilizer, and lime. Amended surface soils from reclaimed pits had near neutral pH values and up to 1.5 percent organic matter. Reclaimed mine soils from the Green Cove Springs Mine in Florida are similar, with organic-rich topsoil-amended surface layers and quartz-rich tailings in the subsurface (Daniels and others, 1992).

Surface mining of mineral sands has the potential to disturb prime agricultural farmlands along the eastern coast of the United States (Daniels and others, 1992). Orndorff and others (2011) and Zimmerman and others (2008), however, suggest that disturbed lands around such sites could be successfully returned to local regional agricultural levels if best agricultural and science-based practices, such as replacement of topsoil, pH adjustments with lime, and addition of fertilizers and biosolids, are applied.

Problems and Future Research

Titanium is an abundant element; it is found at concentrations higher than 20 percent in many minerals (see fig. T1). It is currently not possible to extract a high-grade titanium product from titanite and perovskite, however, and large-scale recovery of titanium from low-titanium oxides, such as titanomagnetite, is mainly in the research stage. A role for future research for titanium resources revolves around the ability to develop cost-effective extraction methods for titanium minerals other than anatase, brookite, ilmenite, and rutile. Depletion of rutile resources and the shift from the sulfate process to the chloride process, which requires higher-grade TiO_2 feedstock compared with the older sulfate process, increases the need to develop low-cost, energy-efficient hydrometallurgical processes to, in effect, upgrade the more abundant ilmenite (Zhang and others, 2011). If these issues of mineralogy could be resolved, there are many large titanium resources—some of which are in advanced stages of exploration—that could become economic.

Rutile is in high demand, so the search for additional resources is likely to focus on exploration for large, high-grade domestic rutile resources. Increased examination of the myriad geologic environments where rutile occurs (see, for example, Meinhold, 2010) might make it possible to discover previously unrecognized or underutilized rutile sources, such as porphyry systems, metamorphic terranes, or highly weathered rock. Rutile as a magmatic mineral is described for some massif anorthosite ilmenite deposits in the Saint-Urbain and Lac Allard anorthosite plutonic suites (Quebec). Morisset and others (2010) attribute this occurrence to an exceptionally high alumina content of parent magmas and the subsequent oxide crystallization path. Rutile also occurs along the metasomatized margins of the Roseland anorthosite (Virginia) and in the Pluma Hidalgo anorthosite district (Mexico), where swarms of anorthosite dikes and sills cut country rock (Force, 1991). In these two deposits, anorthosite has a more alkali composition than is typical for most other anorthosite-hosted magmatic deposits, which Force (1991) links to the relative abundance of rutile. Thus, research into a possible relation between host anorthosite chemistry and occurrences of abundant rutile with ilmenite in magmatic deposits could result in delineation and identification of favorable environments for higher grade rutile-bearing magmatic deposits.

Recent research in anorthosite plutonic terranes that host ilmenite-dominated magmatic systems, such as Lac Tio and Tellnes, has led to recognition of the role that magmatic processes, such as contamination, mineral fractionation, and flow dynamics, play in the development of world-class titanium orebodies (Wilmart and others, 1989; Charlier and others, 2010). An updated deposit model for the formation of these types of titanium deposits (Woodruff and others, 2013) could guide exploration for this type of mineralization as either a direct source or as protoliths for weathered ore deposits.

References Cited

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

Abuodha, J.O.Z., 2002, Environmental impact assessment of the proposed titanium mining project in Kwale district, Kenya: Marine Georesources and Geotechnology, v. 20, no. 3, p. 199–207. [Also available at http://dx.doi.org/10.1080/03608860290051895.]

Ashwal, L.D., 2010, The temporality of anorthosites: Canadian Mineralogist, v. 48, no. 4, p. 711–728. [Also available at http://dx.doi.org/10.3749/canmin.48.4.711.]

Attanasi, E.D., and DeYoung, J.H., Jr., 1992, Grade and tonnage model of shoreline placer Ti—Model 39c, *in* Cox, D.P., and Singer, D.A., eds., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 270–273. [Also available at https://pubs.er.usgs.gov/publication/b1693/.]

Bedinger, G.M., 2013, Titanium mineral concentrates: U.S. Geological Survey Mineral Commodity Summaries 2013, p. 174–175, accessed March 15, 2013, at https://minerals.usgs.gov/minerals/pubs/commodity/titanium/mcs-2013-timin.pdf.

Brooks, D.B., 1976, Mineral supply as a stock, *in* Vogely, W.A., ed., Economics of the mineral industries: New York, N.Y., American Institute of Mining, Metal, and Petroleum Engineers, p. 127–207.

Bykhovskii, L.Z., and Tigunov, L.P., 2011, Titanium raw materials of Russia: Russian Journal of General Chemistry, v. 81, no. 6, p. 1328–1344. [Also available at http://dx.doi.org/10.1134/S1070363211060387.]

Charlier, Bernard, Namur, Olivier, Duchesne, Jean-Clair, Wiszniewska, Janina, Parecki, Antonia, and Vander Auwera, Jacqueline, 2009, Cumulate origin and polybaric crystallization of Fe-Ti oxide ores in the Suwalki anorthosite, northeastern Poland: Economic Geology, v. 104, p. 205–221. [Also available at http://dx.doi.org/10.2113/gsecongeo.104.2.205.]

Charlier, Bernard, Namur, Olivier, Malpas, Simon, de Marneffe, Cedric, Duchesne, Jean-Clair, Vander Auwera, Jacqueline, and Bolle, Olivier, 2010, Origin of the giant Allard Lake ilmenite ore deposit (Canada) by fractional crystallization, multiple magma pulses and mixing: Lithos, v. 117, June, p. 119–134. [Also available at http://dx.doi.org/10.1016/j.lithos.2010.02.009.]

Chernet, T., 1999, Effect of mineralogy and texture in the TiO_2 pigment production process of the Tellnes ilmenite concentrate: Mineralogy and Petrology, v. 67, nos. 1–2, p. 21–32. [Also available at http://dx.doi.org/10.1007/BF01165113.]

China Mining Association, 2006, Metallic mineral resources—Section 3.5 titanium: China Mining Association, accessed November 13, 2012, at http://www.chinamining.org/Facts/index-64.html.

Christie, A.B., and Braithwaite, R.L., 1998, Mineral commodity report 16—Titanium: New Zealand Mining, v. 23, p. 15–25.

Christie, Tony, Douch, Colin, Winfield, Barry, and Thompson, Bruce, 2000, Industrial minerals in New Zealand: New Zealand Mining, v. 27, p. 14–25, accessed March 28, 2014, at http://www.nzpam.govt.nz/cms/pdf-library/minerals/publications/Commodity Reports/report20a_indmins.pdf/view/.

Clark, J.R., and Williams-Jones, A.E., 2004, Rutile as a potential indicator mineral for metamorphosed metallic ore deposits: Montreal, Quebec, Canada, DIVEX, Rapport Final Sous-project SC2, 17 p. [Also available at http://www.divex.ca/projets/doc/SC2-Williams-Jones-2004.pdf.]

Corriveau, Louise, Perreault, Serge, and Davidson, Anthony, 2007, Prospective metallogenic settings of the Grenville Province, *in* Goodfellow W.D., ed., Mineral deposits of Canada—A synthesis of major deposit-types, district metallogeny, the evolution of geological provinces, and exploration methods: Geological Association of Canada Special Publication no. 5, p. 819–848.

Czamanske, G.K., Force, E.R., and Moore, W.J., 1981, Some geologic and potential resource aspects of rutile in porphyry copper deposits: Economic Geology, v. 76, p. 2240–2256. [Also available at http://dx.doi.org/10.2113/gsecongeo.76.8.2240.]

Daniels, W.L., Genthner, M.H., and Hodges, R.L., 1992, Soil development in sandy tailings derived from mineral sands mining in Florida, *in* Achieving land use potential through reclamation—Proceedings of the 9th Annual Meeting of the American Society for Surface Mining and Reclamation, Duluth, Minn., June 14–18, 1992: Princeton, W. Va., American Society for Surface Mining and Reclamation, p. 37–47. [Also available at http://www.asmr.us/Portals/0/Documents/Conference-Proceedings/1992/0037-Daniels.pdf.]

Daniels, W.L., Orndorff, Z.W., and Schroeder, P.D., 2003, Chemical and physical properties of mineral sands mine soils in southeastern Virginia, *in* Barnhisel, R.I., ed., Working together for innovative reclamation—Proceedings of a Joint Conference of [the] 9th Billings Land Reclamation Symposium and American Society of Mining and Reclamation 20th Annual National Conference, Billings, Mont., June 3–6, 2003: Lexington, Ky., American Society of Mining and Reclamation, p. 209–228. [Also available at http://www.asmr.us/Publications/Conference Proceedings/2003/0209-Daniels.pdf.]

Duchesne, J.-C., 1999, Fe-Ti deposits in Rogaland anorthosites (south Norway)—Geochemical characteristics and problems of interpretation: Mineralium Deposita, v. 34, p. 182–198. [Also available at http://dx.doi.org/10.1007/s001260050195.]

Elsner, Harald, 2010, Heavy minerals of economic importance—Assessment manual: Hanover, Germany, Bundesanstalt für Geowissenschaften und Rohstoffe, 218 p.. [Also available at http://www.bgr.bund.de/DE/Themen/Min_rohstoffe/Downloads/heavy-minerals-economic-importance.pdf?__blob=publicationFile&v=5.]

Erickson, R.L., and Blade, L.V., 1963, Geochemistry and petrology of the alkalic igneous complex at Magnet Cove, Arkansas: U.S. Geological Survey Professional Paper 425, 95 p. [Also available at http://pubs.usgs.gov/pp/0425/report.pdf.]

Ettner, D.C., 1999, Pilot scale constructed wetland for the removal of nickel from tailings drainage, southern Norway, *in* Mine, Water & Environment, 1999 International Mine Water Association (IMWA) Congress, Sevilla, Spain, Proceedings: Wendelstein, Germany, International Mine Water Association, p. 207–211. [Also available at http://www.mwen.info/docs/imwa_1999/IMWA1999_Ettner_207.pdf.]

Ettner, D.C., 2007, Passive mine water treatment in Norway, *in* Cidu, R., and Frau, F., eds., Water in mining environments—International Mine Water Association (IMWA) Symposium 2007, Cagliari, Italy, May 27–31, 2007: Wendelstein, Germany, International Mine Water Association, 5 p., accessed January 28, 2012, at http://www.imwa.info/docs/imwa_2007/IMWA2007_Ettner.pdf.

Federici, Gillian, Shaw, B.J., and Handy, R.D., 2007, Toxicity of titanium dioxide nanoparticles to rainbow trout (*Oncorhynchus mykiss*); gill injury, oxidative stress, and other physiological effects: Aquatic Toxicology, v. 84, no. 4, p. 415–430. [Also available at http://dx.doi.org/10.1016/j.aquatox.2007.07.009.]

Fish, G.E., 1962, Titanium resources of Nelson and Amherst Counties, Virginia (in two parts)—Part 1—Saprolite ores: U.S. Bureau of Mines Report of Investigations 6429, 25 p.

Flohr, M.J.K., 1994, Titanium, vanadium, and niobium mineralization and alkali metasomatism from the Magnet Cove Complex, Arkansas: Economic Geology, v. 89, p. 105–130. [Also available at http://dx.doi.org/10.2113/gsecongeo.89.1.105.]

Force, E.R., 1991, Geology of titanium-mineral deposits: Geological Society of America Special Paper 259, 112 p. [Also available at http://dx.doi.org/10.1130/SPE259-p1.]

Force, E.R., and Creely, Scott, 2000, Titanium mineral resources of the Western U.S.—An update: U.S. Geological Survey Open-File Report 00–442, 37 p.

Force, E.R., and Lynd, L.E., 1984, Titanium mineral resources of the United States—Definitions and documentation: U.S. Geological Survey Bulletin 1558–B, p. B1–B11. [Also available at http://pubs.usgs.gov/bul/1558a-b/report.pdf.]

Fryklund, V.C., and Holbrook, D.F., 1950, Titanium ore deposits of Hot Spring County, Arkansas: Arkansas Resources and Development Commission Division of Geology Bulletin no. 16, 173 p.

Gambogi, Joseph, 2012, Titanium, *in* Metals and minerals: U.S. Geological Survey Minerals Yearbook 2010, v. I, p. 78.1–78.17. [Also available at http://minerals.usgs.gov/minerals/pubs/commodity/titanium/myb1-2010-titan.pdf.]

Geological Survey of Finland, 2013, Fennoscandian Ore Deposit Database (FODD): Geological Survey of Finland, accessed April 17, 2013, at http://en.gtk.fi/informationservices/databases/fodd/index.html.

Gomes, C.B., Ruperti, E., and Morbidelli, Lucio, 1990, Carbonatite complexes from Brazil—A review: Journal of South American Earth Sciences, v. 3, no. 1, p. 51–63. [Also available at http://dx.doi.org/10.1016/0895-9811(90)90017-U.]

Gross, G.A., 1996, Mafic intrusion-hosted titanium-iron, *in* Eckstrand, O.R., Sinclair, W.D., and Thorpe, R.I., eds., Geology of Canadian mineral deposit types: Geological Survey of Canada Geology of Canada series, no. 8, p. 573–582. [Also available at http://publications.gc.ca/collections/collection_2016/rncan-nrcan/M40-49-8-31-eng.pdf.]

Grosz, A.E., and Schruben, P.G., 1994, NURE geochemical and geophysical surveys—Defining prospective terranes for United States placer exploration: U.S. Geological Survey Bulletin 2097, 9 p., available at http://pubs.usgs.gov/bul/2097/report.pdf.

Grosz, A.E., Hathaway, J.C., and Escowitz, E.C., 1986, Placer deposits of heavy minerals in Atlantic Continental Shelf sediments, *in* Proceedings of the 17th Offshore Technology Conference, Houston, Texas, May 5–8, 1985: Richardson, Texas, Offshore Technology Conference, p. 387–394. [Also available at http://dx.doi.org/10.4043/5198-MS.]

Guéguin, Michel, and Cardarelli, François, 2007, Chemistry and mineralogy of titania-rich slags, Part 1—Hemoilmenite, sulphate, and upgraded titania slags: Mineral Processing and Extractive Metallurgy Review, v. 28, no. 1, p. 1–58. [Also available at http://dx.doi.org/10.1080/08827500600564242.]

Hamilton, N.T.M., 1995, Controls on the global distribution of coastal titanium-zirconium placers: International Geology Review, v. 37, no. 9, p. 755–779. [Also available at http://dx.doi.org/10.1080/00206819509465426.]

Hauck, S.A., Severson, M.J., Zanko, L.M., Barnes, Sarah-Jane, Morton, Penelope, Alminas, H.V., Foord, E.E., and Dahlberg, E.H., 1997, An overview of the geology and oxide, sulfide, and platinum-group element mineralization along the western and northern contacts of the Duluth Complex, *in* Ojakangas, R.W., Dickas, A.B., and Green, J.C., eds., Middle Proterozoic to Cambrian rifting, central North America: Geological Society of America Special Paper 312, p. 137–185. [Also available at http://dx.doi.org/10.1130/0-8137-2312-4.137.]

Herz, Norman, and Force, E.R., 1987, Geology and mineral deposits of the Roseland district of central Virginia: U.S. Geological Survey Professional Paper 1371, 56 p. [Also available at http://pubs.er.usgs.gov/publication/pp1371/.]

Hou, Baohong, Keeling, John, Reid, Anthony, Fairclough, Martin, Warland, Ian, Belousova, Elena, Frakes, Larry, and Hocking, Roger, 2011, Heavy mineral sands in the Eucla basin, southern Australia—Deposition and province-scale prospectivity: Economic Geology, v. 106, p. 687–712. [Also available at http://dx.doi.org/10.2113/econgeo.106.4.687.]

Hou, Baohong, Keeling, John, and Van Gosen, B.S., 2017, Geological and exploration models of beach placer deposits, integrated from case-studies of southern Australia: Ore Geology Reviews, v. 80, p. 437–459. [Also available at http://dx.doi.org/10.1016/j.oregeorev.2016.07.016.]

International Programme on Chemical Safety, 1982, Environmental Health Criteria 24—Titanium: World Health Organization, accessed January 9, 2013, at http://www.inchem.org/documents/ehc/ehc/ehc24.htm.

Kabata-Pendias, Alina, and Mukherjee, A.B., 2007, Trace elements from soil to human: Berlin, Germany, Springer-Verlag, 550 p.

Kaminsky, H.A.W., Etsell, T.H., Ivey, D.G., and Omotoso, Oladipo, 2008, Characterization of heavy minerals in the Athabasca oil sands: Minerals Engineering, v. 21, no. 4, p. 264–271. [Also available at http://dx.doi.org/10.1016/j.mineng.2007.09.011.]

Kärkkäinen, N.K., and Bornhorst, T.J., 2003, The Svecofennian gabbro-hosted Koivusaarenneva magmatic ilmenite deposit, Kälviä, Finland: Mineralium Deposita, v. 38, no. 2, p. 169–184. [Also available at http://link.springer.com/article/10.1007%2Fs00126-002-0297-0.)

Korneliussen, Are, McEnroe, S.A., Nilsson, L.P., Schiellerup, Henrik, Gautneb, Håvard, Meyer, G.B., and Størseth, L.R., 2000a, An overview of titanium deposits in Norway: Norges Geologiske Underskøleske Bulletin 436, p. 27–38. [Also available at http://www.ngu.no/FileArchive/102/Bulletin436_3.pdf.]

Korneliussen, Are, McLimans, Roger, Braathen, Alvar, Erambert, Muriel, Lutro, Ole, and Ragnhildstveit, Jomar, 2000b, Rutile in eclogites as a mineral resource in the Sunnfjord region, western Norway: Norges Geologiske Underskøleske Bulletin 436, p. 39–47, available at http://www.ngu.no/FileArchive/102/Bulletin436_4.pdf.

Krause, H., Gierth, E., and Schott, W., 1985, Fe-Ti deposits in the South Rogaland igneous complex, with special reference to the Åna-Sira anorthosite massif: Norges Geologiske Underskøleske Bulletin 402, p. 25–37.

Liou, J.G., Zhang, Ruyuan, Ernst, W.G., Liu, Jun, and McLimans, Roger, 1998, Mineral paragenesis in the Piampaludo eclogitic body, Gruppo di Voltri, Western Ligurian Alps: Schweizerische Mineralogische und Petrographische Mitteilungen—Bulletin Suisse de Mineralogie et Petrographie, v. 78, no. 2, p. 317–335.

Liu, Qi, Cui, Z., and Etsell, T.H., 2006, Characterization of Athabasca oil sands froth treatment tailings for heavy mineral recovery: Fuel, v. 85, nos. 5–6, p. 807–814. [Also available at http://dx.doi.org/10.1016/j.fuel.2005.08.032.]

Mackey, T.S., 1994, Upgrading ilmenite into a high-grade synthetic rutile: Journal of Metals, v. 46, no. 4, p. 59–64. [Also available at http://dx.doi.org/10.1007/BF03220676.]

Marsh, S.P., and Sheridan, D.M., 1976, Rutile in Precambrian sillimanite-quartz gneiss and related rocks, east-central Front Range, Colorado: U.S. Geological Survey Professional Paper 959–G, 17 p. [Also available at http://pubs.er.usgs.gov/publication/pp959G.]

McEnroe, S.A., Robinson, P., and Panish, P.T., 2000, Chemical and petrographic characterization of ilmenite and magnetite in oxide-rich cumulates of the Sokndal region, Rogaland, Norway: Norges Geologiske Undersøkelse Bulletin 436, p. 49–56. [Also available at http://www.ngu.no/FileArchive/102/Bulletin436_5.pdf.]

McEnroe, S.A., Robinson, Peter, and Panish, P.T., 2001, Aeromagnetic anomalies, magnetic petrology, and rock magnetism of hemo-ilmenite- and magnetite-rich cumulate rocks from the Sokndal region, South Rogaland, Norway: American Mineralogist, v. 86, p. 1447–1468. [Also available at http://ammin.geoscienceworld.org/content/86/11-12/1447.full.]

Meinhold, Guido, 2010, Rutile and its applications in earth sciences: Earth-Science Reviews, v. 102, p. 1–28. [Correction to incorrect formula published as Meinhold, Guido, 2013, Erratum to “Rutile and its applications in earth sciences” (Earth-Science Reviews 102 (2010) 1–28): Earth-Science Reviews, v. 116, p. 211.]

Miller, J.A., 1957, Titanium—A materials survey: U.S. Bureau of Mines Information Circular 7791, 202 p.

Morisset, Caroline-Emmanuelle, Scoates, J.S., Weis, Dominique, Suavé, Martin, and Stanaway, K.J., 2010, Rutile-bearing ilmenite deposits associated with the Proterozoic Saint-Urbain and Lac Allard anorthosite massifs, Grenville Province, Quebec: Canadian Mineralogist, v. 48, no. 4, p. 821–849. [Also available at http://dx.doi.org/10.3749/canmin.48.4.821.]

Murphy, Philip, and Frick, Louise, 2006, Titanium, *in* Kogel, J.E., Trivedi, N.C., Barker, J.M., and Krukowski, S.T., eds., Industrial minerals and rocks (7th ed.): Littleton, Colo., Society for Mining, Metallurgy, and Exploration, Inc., p. 987–1003.

Murty, Ch.V.G.K., Gurung, R., Upadhyay, R., and Asokan, S., 2007, Tata Steel’s Titania project—Challenges in slimes disposal, *in* Heavy minerals conference—Back to basics, 6th, Zulu Nyala, Hluhluwe, South Africa, September 10–14, 2007: Johannesburg, South Africa, Southern African Institute of Mining and Metallurgy, Symposium Series, v. 48, p. 111–118. [Also available at http://www.saimm.co.za/Conferences/HMC2007/111-118_Murty.pdf.]

Natural Earth, 2014, Small scale data—Natural Earth map dataset, scale 1:110,000,000, accessed June 23, 2014, at http://www.naturalearthdata.com.

Newton, M.C., III, and Romeo, A.J., 2006, Geology of the Old Hickory mineral sand deposit, Dinwiddie and Sussex Counties, Virginia, *in* Reid, J.C., ed., Proceedings of the 42nd Forum on the Geology of Industrial Minerals, Asheville, North Carolina, May 7–13, 2006: North Carolina Geological Survey Information Circular 34, p. 464–480.

Norges Geologiske Undersøkelse, 2012, Deposit area—Tellnes, *in* The ore database: Norges Geologiske Undersøkelse database, accessed January 8, 2013, at http://aps.ngu.no/pls/oradb/minres_deposit_fakta.Main?p_objid=4998&p_spraak=E.

Olsgard, Frode, and Hasle, J.R., 1993, Impact of waste from titanium mining on benthic fauna: Journal of Experimental Marine Biology and Ecology, v. 172, nos. 1–2, p. 185–213. [Also available at http://dx.doi.org/10.1016/0022-0981(93)90097-8.]

Orndorff, Z.W., Daniels, W.L., Meredith, K.R., Alley, M.M., and Wick, A.F., 2011, Effects of prime farmland soil reconstruction methods on post-mining productivity of mineral sands mine soils in Virginia, *in* Barnhisel, R.I., ed., Reclamation—Sciences leading to success, Proceedings of the 28th Annual National Conference of the American Society of Mining and Reclamation, Bismarck, North Dakota, June 11–16, 2011: Lexington, Ky., American Society of Mining and Reclamation, p. 504–518. [Also available at http://landrehab.org/UserFiles/DataItems/7A5A5650564671794835553D/Orndorff%20et%20al.,%202011%20ASMR%20Effects%20of%20prime%20farmland.pdf.]

Owens, B.E., and Pasek, M.A., 2007, Kyanite quartzites in the Piedmont province of Virginia—Evidence for a possible high-sulfidation system: Economic Geology, v. 102, p. 495–509. [Also available at http://dx.doi.org/10.2113/gsecongeo.102.3.495.]

Pepin, Geneviève, Bussière, Bruno, Aubertin, Michel, Benzaazoua, Mostafa, Plante, Benoît, Laflamme, Donald, and Zagury, G.J., 2008, Field experimental cells to evaluate the generation of contaminated neutral drainage by waste rock at the Tio Mine, Quebec, Canada, *in* Rapantova, N., and Hrkal, Z., eds., Proceedings of the 10th International Mine Water Association (IMWA) Congress on Mine Water and the Environment, Karlsbad, Czech Republic. June 2–5, 2008: International Mine Water Association, p. 309–312, accessed January 14, 2013, at http://www.imwa.info/docs/imwa_2008/IMWA2008_136_Pepin.pdf.

Pirkle, F.L., Pirkle, W.A., and Pirkle, E.C., 2007, Heavy-mineral sands of the Atlantic and Gulf coastal plains, USA, chap. 45 *of* Mange, M.A., and Wright, D.T., eds., Heavy minerals in use: Boston, Mass., Elsevier Developments in Sedimentology Series, v. 58, p. 1145–1232. [Also available at http://dx.doi.org/10.1016/S0070-4571(07)58045-3.]

Plante, B., Benzaazoua, M., and Bussière, B., 2011, Predicting geochemical behavior of waste rock with low acid generating potential using laboratory kinetic tests: Mine Water and the Environment, v. 30, no. 1, p. 2–21. [Also available at http://dx.doi.org/10.1007/s10230-010-0127-z.]

Plante, B., Benzaazoua, M., Bussière, B., Biesinger, M.C., and Pratt, A.R., 2010, Study of Ni sorption onto Tio Mine waste rock surfaces: Applied Geochemistry, v. 25, no. 12, p. 1830–1844. [Also available at http://dx.doi.org/10.1016/j.apgeochem.2010.09.010.]

Premaratne, W.A.P.J., and Rowson, N.A., 2003, The processing of beach sand from Sri Lanka for the recovery of titanium using magnetic separation: Physical Separation in Science and Engineering, v. 12, no. 1, p. 13–22. [Also available at http://dx.doi.org/10.1080/1478647031000101232.]

Puffer, J.H., and Cousminer, H.L., 1982, Factors controlling the accumulation of titanium-iron oxide-rich sands in the Cohansey Formation, Lakehurst area, New Jersey: Economic Geology, v. 77, p. 379–391. [Also available at http://dx.doi.org/10.2113/gsecongeo.77.2.379.]

Rabbia, O.M., Hernández, L.B., French, D.H., King, R.W., and Ayers, J.C., 2009, The El Teniente porphyry Cu-Mo deposit from a hydrothermal rutile perspective: Mineralium Deposita, v. 44, no. 8, p. 849–866. [Also available at http://dx.doi.org/10.1007/s00126-009-0252-4.]

Reimann, Clemens, and de Caritat, Patrice, 1998, Chemical elements in the environment: Berlin, Germany, Springer-Verlag, 398 p.

Rio Tinto, 2009, Health, safety and environment, chap. 3 *of* Adaptation sustanaible [sic] development report: Sorel-Tracy, Quebec, Canada, Rio Tinto Fer et Titane, p. 13–25, accessed January 8, 2013, at http://www.riotinto.com/documents/ReportsPublications/RTFT_SD09_eng.pdf.

Rose, E.R., 1969, Geology of titanium and titaniferous deposits of Canada: Geological Survey of Canada, Economic Geology Report no. 25, 177 p.

Roy, P.S., 1999, Heavy mineral beach placers in southeastern Australia—Their nature and genesis: Economic Geology, v. 94, p. 567–588. [Also available at http://dx.doi.org/10.2113/gsecongeo.94.4.567.]

Roy, P.S., and Whitehouse, John, 2003, Changing Pliocene sea levels and the formation of heavy minerals beach placers in the Murray basin, southeastern Australia: Economic Geology, v. 98, p. 975–983. [Also available at http://dx.doi.org/10.2113/gsecongeo.98.5.975.]

Rudnick, R.L., and Fountain, D.M., 1995, Nature and composition of the continental crust—A lower crustal perspective: Reviews of Geophysics, v. 33, no. 3, p. 267–309. [Also available at http://dx.doi.org/10.1029/95RG01302.]

Schiellerup, Henrik, Korneliussen, Are, Heldal, Tom, Marker, Mogens, Bjerkgård, Terje, and Nilsson, Lars-Petter, 2003, Mineral resources in the Rogaland Anorthosite Province, south Norway: Origins, history and recent developments, *in* Duchesne, Jean-Clair, and Korneliussen, Are, eds., Ilmenite deposits and their geological environment: Norges Geologiske Undersøkelse Special Publication 9, p. 117–135.

Shacklette, H.T., and Boerngen, J.G., 1984, Element concentrations in soils and other surficial materials of the conterminous United States: U.S. Geological Survey Professional Paper 1270, 105 p. [Also available at http://pubs.usgs.gov/pp/1270/.]

Sharma, V.K., 2009, Aggregation and toxicity of titanium dioxide nanoparticles in aquatic environment—A review: Journal of Environmental Science and Health Part A, v. 44, no. 14, p. 1485–1495. [Also available at http://dx.doi.org/10.1080/10934520903263231.]

Shi, Guanghai, Li, Xianhua, Li, Qiuli, Chen, Zhenyu, Deng, Jun, Liu, Yingxin, Kang, Zhujuan, Pang, Ercheng, Xu, Yongjin, and Jia, Xiuming, 2012, Ion microprobe U-Pb age and Zr-in-rutile thermometry of rutiles from the Daixian rutile deposit in the Hengshan Mountains, Shanxi Province, China: Economic Geology, v. 107, p. 525–535. [Also available at http://dx.doi.org/10.2113/econgeo.107.3.525.]

Stamper, J.W., 1970, Titanium, *in* Mineral facts and problems 1970: U.S. Bureau of Mines Bulletin 650, p. 773–794.

Stanaway, Kerry, 1996, The Eastern North America titanium province—A review: Lithology and Mineral Resources, v. 32, p. 509–517.

Temple, A.K., and Grogan, R.M., 1965, Carbonatite and related alkalic rocks at Powderhorn, Colorado: Economic Geology, v. 60, p. 672–692. [Also available at http://dx.doi.org/10.2113/gsecongeo.60.4.672.]

Towner, R.R., Gray, J.M., and Porter, L.M., 1988, International Strategic Minerals Inventory summary report—Titanium: U.S. Geological Survey Circular 930–G, 59 p. [Also available at http://pubs.er.usgs.gov/publication/cir930G.]

U.S. Bureau of Mines and U.S. Geological Survey, 1980, Principles of a resource/reserve classification for minerals: U.S. Geological Survey Circular 831, 5 p. [Also available at http://pubs.er.usgs.gov/publication/cir831.

U.S. Environmental Protection Agency, 2010, Provisional peer-reviewed toxicity values for titanium: U.S. Environmental Protection Agency Chemical Assessment Summary, CASRN 7440–32–6, accessed January 9, 2013, at http://hhpprtv.ornl.gov/issue_papers/Titanium.pdf.

U.S. Geological Survey, 1996, Global 30 arc-second elevation (GTOPO30): Reston, Va., U.S Geological Survey dataset (digital elevation model), accessed June 23, 2014, at https://lta.cr.usgs.gov/GTOPO30.

Van Gosen, B.S., 2009, The Iron Hill (Powderhorn) carbonatite complex, Gunnison County, Colorado—A potential source of several uncommon mineral resources: U.S. Geological Survey Open-File Report 2009–1005, 28 p. [Also available at http://pubs.usgs.gov/of/2009/1005/.]

Viers, Jérôme, Dupré, Bernard, and Gaillardet, Jérôme, 2009, Chemical composition of suspended sediments in the world rivers—New insights from a new database: Science of the Total Environment, v. 407, no. 2, p. 853–868. [Also available at http://dx.doi.org/10.1016/j.scitotenv.2008.09.053.]

Wang, Jiangxue, Liu, Ying, Jiao, Fang, Lao, Fang, Li, Wei, Gu, Yiqun, Li, Yufeng, Ge, Cuicui, Zhou, Guoqiang, Li, Bai, Zhao, Yuliang, Chai, Zhifang, and Chen, Chunying, 2008, Time-dependent translocation and potential impairment on central nervous system by intranasally instilled TiO_2 nanoparticles: Toxicology, v. 254, nos. 1–2, p. 82–90. [Also available at http://dx.doi.org/10.1016/j.tox.2008.09.014.]

Wilmart, E., Demaiffe, D., and Duchesne, J.-C., 1989, Geochemical constraints on the genesis of the Tellnes ilmenite deposit, southwest Norway: Economic Geology, v. 84, p. 1047–1056. [Also available at http://dx.doi.org/10.2113/gsecongeo.84.5.1047.]

Woodruff, L.G., Nicholson, S.W., and Fey, D.L., 2013, A deposit model for magmatic iron-titanium-oxide deposits related to Proterozoic massif anorthosite plutonic suites: U.S. Geological Survey Scientific Investigations Report 2010–5070–K, 47 p. [This USGS publication supersedes Scientific Investigations Report 2013–5091; also available at http://pubs.usgs.gov/sir/2010/5070/k/]

Wynn, J.C., 1988, Titanium geophysics—The application of induced polarization to sea-floor mineral exploration: Geophysics, v. 53, no. 3, p. 386–401. [Also available at http://dx.doi.org/10.1190/1.1442472.]

Zhang, Weinsheng, Zhu, Zhaowu, and Cheng, C.Y., 2011, A literature review of titanium metallurgical processes: Hydrometallurgy, v. 108, nos. 3–4, p. 177–188. [Also available at http://dx.doi.org/10.1016/j.hydromet.2011.04.005.]

Zhou, M.F., Robinson, P.T., Lesher, C.M., Keays, R.R., Zhang, C.-J., and Malpas, John, 2005, Geochemistry, petrogenesis and metallogenesis of the Panzhihua gabbroic layered intrusion and associated Fe-Ti-V oxide deposits, Sichuan Province, SW China: Journal of Petrology, v. 46, no. 11, p. 2253–2280. [Also available at http://dx.doi.org/10.1093/petrology/egi054.]

Zimmerman, Clint, Stilson, Chuck, and Daniels, W.L., 2008, Reclamation of mineral sands mine and topsoil replacement study, *in* Proceedings of the 25th Annual Meeting of the American Society of Mining and Reclamation and 10th meeting of the IALR, Richmond, VA, June 14–19, 2008: Lexington, Ky., American Society of Mining and Reclamation, p. 1429–1444. [Also available at http://landrehab.org/UserFiles/DataItems/61326B4E366357773754493D/Zimmerman%20et%20al.,%202008%20ASMR%20Reclamation%20of%20Mineral-VA.pdf.]

For more information concerning this report,
please contact:

Mineral Resources Program Coordinator

U.S. Geological Survey

913 National Center

Reston, VA 20192

Telephone: 703–648–6100

Fax: 703–648–6057

Email: minerals@usgs.gov

Home page: https://minerals.usgs.gov

Prepared by the USGS Science Publishing Network
Reston Publishing Service Center
Edited by J.C. Ishee
Illustrations by Caryl J. Wipperfurth
Layout by Caryl J. Wipperfurth and Cathy Y. Knutson
Posting by Angela E. Hall

Woodruff and others—**Critical Mineral Resources of the United States—Titanium**—Professional Paper 1802–T

ISSN 2330-7102 (online)
https://doi.org/10.3133/pp1802T