Graphite

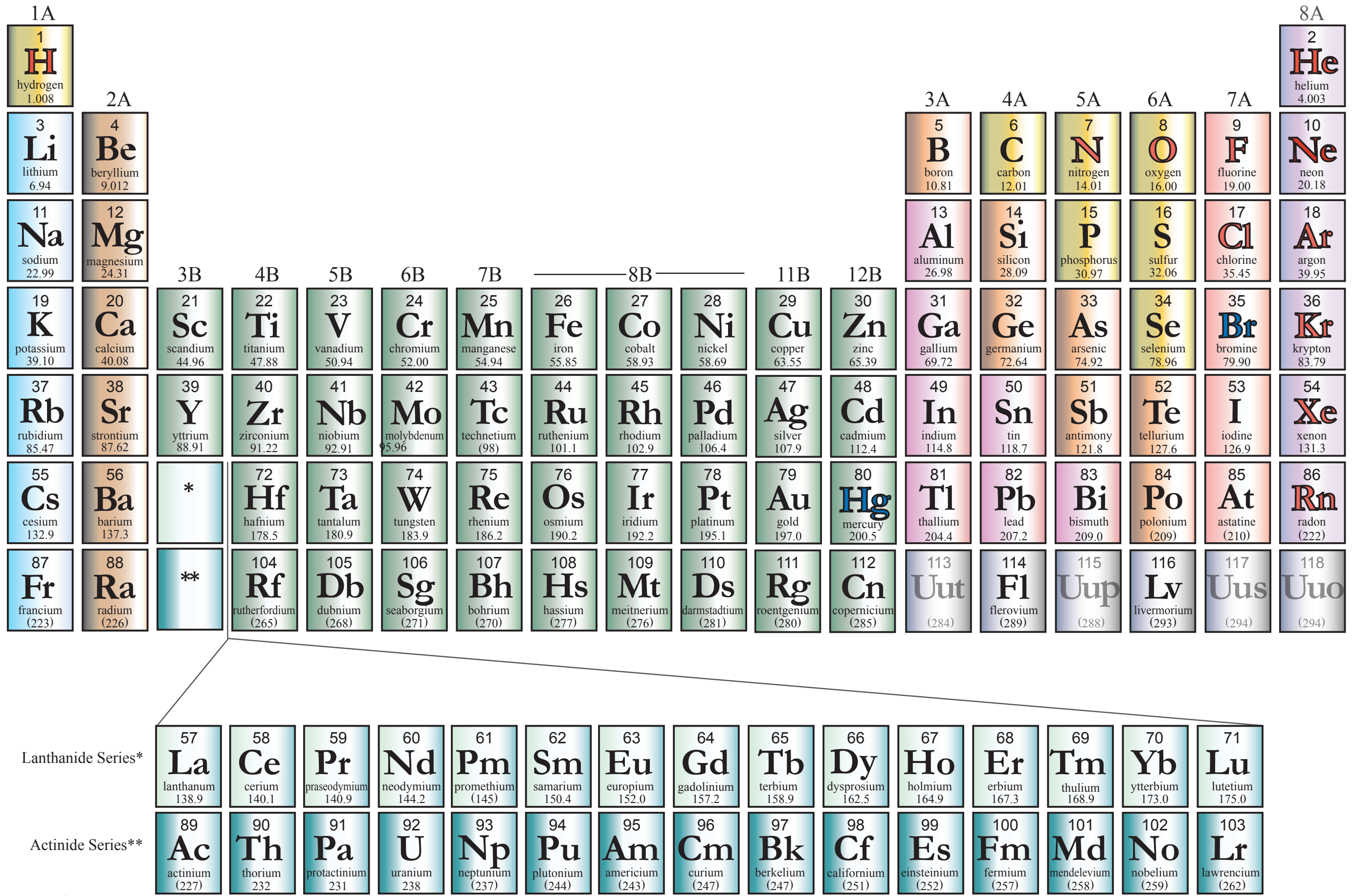
Chapter J of

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

Professional Paper 1802–J

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)

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CHEMISTRY

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

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

Cover. Graphite. U.S. quarter for scale. Mineral collection of Brigham Young University Department of Geology, Provo, Utah. Photograph by Andrew Silver (BYU index 1-1023a).

Graphite

By Gilpin R. Robinson, Jr., Jane M. Hammarstrom, and Donald W. Olson

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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–J

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

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

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

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

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Conversion Factors

International System of Units to Inch/Pound

Multiply	By	To obtain
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
μm	micrometer
cm	centimeter
g/cm^3	gram per cubic centimeter
ISMI	International Strategic Minerals Inventory
kg/cm^2	kilogram per square centimeter
km	kilometer
m	meter
MRDS	Mineral Resources Data System
NIOSH	National Institute for Occupational Safety and Health
TWA	time-weighted average

Graphite

By Gilpin R. Robinson, Jr., Jane M. Hammarstrom, and Donald W. Olson

Abstract

Graphite is a form of pure carbon that normally occurs as black crystal flakes and masses. It has important properties, such as chemical inertness, thermal stability, high electrical conductivity, and lubricity (slipperiness) that make it suitable for many industrial applications, including electronics, lubricants, metallurgy, and steelmaking. For some of these uses, no suitable substitutes are available. Steelmaking and refractory applications in metallurgy use the largest amount of produced graphite; however, emerging technology uses in large-scale fuel cell, battery, and lightweight high-strength composite applications could substantially increase world demand for graphite.

Graphite ores are classified as “amorphous” (microcrystalline), and “crystalline” (“flake” or “lump or chip”) based on the ore’s crystallinity, grain-size, and morphology. All graphite deposits mined today formed from metamorphism of carbonaceous sedimentary rocks, and the ore type is determined by the geologic setting. Thermally metamorphosed coal is the usual source of amorphous graphite. Disseminated crystalline flake graphite is mined from carbonaceous metamorphic rocks, and lump or chip graphite is mined from veins in high-grade metamorphic regions. Because graphite is chemically inert and nontoxic, the main environmental concerns associated with graphite mining are inhalation of fine-grained dusts, including silicate and sulfide mineral particles, and hydrocarbon vapors produced during the mining and processing of ore. Synthetic graphite is manufactured from hydrocarbon sources using high-temperature heat treatment, and it is more expensive to produce than natural graphite.

Production of natural graphite is dominated by China, India, and Brazil, which export graphite worldwide. China provides approximately 67 percent of worldwide output of natural graphite, and, as the dominant exporter, has the ability to set world prices. China has significant graphite reserves, and China’s graphite production is expected to increase, although rising labor costs and some mine production problems are developing. China is expected to continue to be the dominant exporter for the near future. Mexico and Canada export graphite mainly to the United States, which has not had domestic production of natural graphite since the 1950s. Most graphite deposits in the United States are too small, low-grade, or remote to be of commercial value in the near future, and the likelihood of discovering larger, higher-grade, or favorably located domestic deposits is unlikely. The United States is a major producer of synthetic graphite.

Introduction

Graphite, which is a soft form of elemental carbon, is an industrial mineral commodity that is produced only in small amounts globally—worldwide production of approximately 1 million metric tons of graphite concentrate was reported as yearly production from 2010 to 2012 (Olson, 2012, 2013). The word graphite is derived from the Greek word for writing, *graphein*, which reflects the long use of graphite (mixed with clay) for the “lead” in pencils. The unique physical and chemical properties of graphite, particularly coarse crystalline graphite, make it useful for many industrial applications, and for some of those uses, no suitable substitutes are available. Although graphite is widely disseminated in many types of metamorphic and some igneous rocks, most occurrences have no economic importance. The significant deposits of graphite are found in carbonaceous sedimentary rocks that have been subjected to regional or contact metamorphism and in veins precipitated from fluids.

Commercial Classifications of Graphite

Sources of commercial graphite include both natural graphite mined from rock and synthetic graphite manufactured from other carbonaceous materials. For commercial purposes, natural graphite is classified into the following three categories, according to its crystallinity, grain size, and morphology: amorphous, crystalline (flake), and crystalline (lump or chip). These commodity classes differ in the level of purity of the graphite, the proposed industrial use, the price, and the geologic setting in which the graphite occurs (table J1). Descriptions of (a) the graphite commodity classes and their industrial uses, and (b) their associated deposit types, geologic settings, and producing deposit locations are given

Table J1. Characteristics of graphite commodities, deposits, and uses, by commodity type.

[Descriptions of graphite commodity classes and their industrial uses, commodity prices, and classes of associated deposit types and geologic settings are summarized from information in Klar (1958), Weis (1973), Krauss and others (1988), Sutphin (1991a–c), Simandl and Kenan (1997a–c), Taylor (2006), and Olson (2011, 2012, 2013). NA, not applicable; µm, micrometer; cm, centimeter; °C, degree Celsius; m, meter; $, U.S. dollar]

Characteristic	Commodity type			
	Amorphous	Flake	Lump or chip	Synthetic
Deposit type	Amorphous	Disseminated flake	Vein	NA
Crystallinity	Microcrystalline	Crystalline	Crystalline	Microcrystalline to crystalline
Properties (crystallinity, form)	Earthy to compact microcrystalline aggregates; grain size is <4 µm	Well-developed crystal platelets, with grain size between 40 µm and 4 cm (but generally ≤ 1 cm), and 1 to 150 µm thick	Interlocking aggregates of coarse crystals. Available as powders to 10-cm pieces	Available in particle sizes from 2-µm powders to 2-cm pieces
Origin	Contact metamorphism, often by diabasic or granitic intrusions, and (or) regional metamorphism of carbonaceous sediments, often coal	Regional metamorphism of carbonaceous sediments at or exceeding amphibolite facies conditions	Epigenetic veins and lodes formed from metamorphic fluids in high-grade metamorphic rocks, usually granulites	Produced by heat treatment (graphitization) of, or chemical deposition from, hydrocarbon materials above 2,100 °C
Orebody	Layers, seams, and lenses in carbonaceous rock, each a few meters thick and hundreds of meters to several kilometers in length; may be folded and faulted	Strata-bound; tabular or lense form, as much as 33 m thick and thousands of meters long. Irregular in hinge areas of folds. The lenses have variable graphite content internally and between lenses	Vein and fracture-filling within or crosscutting metamorphic structures and rock contacts. Individual veins range from 0.05 to 3 m thick, although usually less than 0.3 m, and extend up to hundreds of meters, although rarely more than tens of meters	NA
Ore grade (percent carbon)	50 to 90 (aggregates may contain nongraphitic carbonaceous material)	Generally 5 to 30, locally higher	40 to 90 (may require hand sorting)	NA
Deposit tonnage (million metric tons)	0.1 to 500	0.1 to 100	Small; no reliable data for individual veins	NA
Mine operations	Surface or underground mines using mechanized and sometimes hand methods	Generally open pit surface mines. Graphite grades and ease of mining enhanced by weathering destruction of gangue minerals	Mines are typically small, labor-intensive, and underground. Mines in Sri Lanka are from 30 to 400 m deep. Ore is hand sorted, washed, and screened	NA
Product grade (percent graphite)	60 to 90	75 to 97	90 to 99.9	99.95
Main uses	Refractories, steel industry, paint, coatings, and batteries	Refractories, brake linings, lubricants, batteries, and expandable graphite applications	Carbon brushes, brake linings, and lubricants	Batteries, carbon brushes, graphite electrodes, nuclear moderator rods (porosity unsuitable for refractory applications)
Prices (per metric ton)	December 2011 prices (80–85 percent graphite) ranged from $600 to $800	December 2011 prices (90% graphite, medium-large flake) ranged from $1,150 to $2,000	Prices in 2011 for Sri Lankan lump and chip graphite (99% graphite) ranged from $1,700 to $2,070. Prices vary by purity, grade, and size	December 2011 prices (99.9 percent graphite) ranged from $7,000 to $20,000, which was about 4 to 7 times that of flake graphite
Major producers and resources (in order of production level)	China, Republic of Korea, Mexico, Austria	China, Brazil, India, Madagascar, Germany, Austria, Norway, Canada, Zimbabwe	Sri Lanka	China, Japan, United States, Germany (Roskill Information Services, Ltd., 2012)

by Klar (1958), Weis (1973), Krauss and others (1988), and Taylor (2006). Descriptive models of the geology and characteristics of the deposit types that produce graphite are given by Sutphin and Bliss (1990), Sutphin (1991a–c), and Simandl and Kenan (1997a–c). A summary of information from these and other sources follows.

Natural Graphite

Natural graphite is mined from deposits in metamorphic rocks, such as marble, schist, and gneiss, and from accumulations in vein deposits. Natural graphite typically forms as a result of metamorphism (regional or contact) of accumulations of organic matter in sedimentary rocks. Commercial deposits of graphite occur in three types of geologic settings that generally correspond to the following commodity classes (table J1):

a. “Amorphous graphite” is the commercial designation for earthy to compact fine-grained graphite that generally results from thermal metamorphism of coal. Commercial deposits typically contain more than 1 million metric tons of ore that is more than 75 percent carbon. Both the raw ore and the commodity may contain nongraphitic carbonaceous material in addition to graphite.

b. “Flake graphite” is the commercial designation for well-developed crystal platelets of graphite that are between 40 micrometers (µm) and 4 centimeters (cm—but generally less than or equal to 1 cm) in size and that are disseminated in beds of carbonaceous sediments that have been subjected to amphibolite-facies or higher grade regional metamorphism. Commercial deposits generally contain more than 200,000 metric tons of ore that grade greater than 8 percent graphite. Disseminated flake graphite deposits are located in belts of crystalline metamorphic rock that are predominately Archean to late Proterozoic in age.

c. “Lump or chip” is the commercial designation for interlocking aggregates of coarse graphite crystals that occur as veins or fracture-fillings in igneous and crystalline metamorphic rocks that commonly are of Precambrian age. The only commercial deposits occur in Sri Lanka where families of veins that are up to 3 meters (m) thick and which consist of 60 to 95 percent graphite are mined to depths of 30 to 650 m (Touzain and others, 2010). The ore may be hand sorted to provide a product grade that exceeds 90 percent. No reliable data on the tonnages of individual vein deposits are available, but most of the deposits are small and likely do not exceed 100,000 metric tons.

Synthetic Graphite

Most of the graphite used by industries in the United States is synthetic. Synthetic graphite of high purity is produced by heat treatment (graphitization) of, or chemical deposition from, hydrocarbon materials above 2,100 degrees Celsius (°C). High-temperature processing is required to transform the precursor carbon forms to a graphite structure and to vaporize impurities, which include hydrogen, metals, nitrogen, organic compounds, and sulfur in the source materials. As a result of this treatment, synthetic graphite is more than 99.9 percent graphite, but it has slightly higher porosity, lower density, lower electrical conductivity, and a much higher price than natural flake graphite. Synthetic graphite is available in particle sizes ranging from 2-µm powders to 2-cm pieces; the morphology varies from flakey in fine powders to irregular grains and needles in coarser products.

Uses and Applications

Graphite has physical and chemical properties of both metals and nonmetals, which make it ideally suited for many industrial and technology applications. The metallic properties include high thermal and electrical conductivity (table J2). The nonmetallic properties include inertness to most chemical reagents (strong acids, bases, solvents, and fluxes), high thermal resistance, low thermal expansion, and excellent cleavage and lubricity (slipperiness). In a nonoxidizing atmosphere, graphite remains stable to temperatures above 3,000 °C. Graphite has a hardness of 1 to 2 on the Mohs scale and is thus extremely soft.

Table J2. Selected physical properties of graphite.

[Modified from Krauss and others (1988). g/cm^3, gram per cubic centimeter; °C, degree Celsius; watt/cm °C, watt per centimeter per degree Celsius; Ω-cm, ohm-centimeter]

Property	Description
Composition	Carbon
Color	Gray to black, metallic luster
Hardness (Mohs scale)	0.5 to 1
Density (g/cm^3)	2.09 to 2.26
Morphology	Hexagonal system; perfect basal cleavage; usually platy
Melting point	About 3,550 °C in nonoxidizing conditions; decomposes above 600 °C in oxidizing conditions
Miscellaneous	Chemically inert; nontoxic; high thermal and electrical conductivity; high lubricity (natural lubricant)
Thermal conductivity (watt/cm °C)	*a* axis: 4.0 *c* axis: 0.8
Thermal expansion coefficient (1/°C)	*a* axis: 1×10^{-7} *c* axis: 140×10^{-7}
Electrical resistivity ($\Omega\text{-cm}\times10^4$)	*a* axis: 1 to 100 *c* axis: 10,000

Some of the major end uses of graphite are in brake linings, refractories, and steelmaking. Batteries, brushes for electrical motors, foundry materials, fuel cells, and high-temperature lubricants are additional end uses of graphite. Graphite forms intercalation compounds with alkali metal vapors—usually potassium, lithium, rubidium, and cesium—where the metal ions fit between the planar carbon sheets of the graphite structure. These compounds have applications in the energy sector and other technologies. The industrial uses and associated commercial value of natural graphite depend on the characteristics and crystallinity of the mined graphite (table J1).

Fine-grained microcrystalline graphite powder (amorphous graphite) is used extensively in foundry and refractory applications, as a source of carbon in steelmaking, and in other applications where additions of graphite improve the manufacturing process or end product. Coarse-grained crystalline graphite in the form of separate lamellar crystals (flake graphite) has high value and is used in high-temperature lubricants, high-quality foundry and refractory ware, powder metallurgy, coatings, and battery and fuel cell applications. Crystalline flake graphite accounted for about 50 percent of natural graphite usage in the United States in the past decade.

Massive crystalline graphite from vein deposits (lump or chip graphite) has the highest purity and grain size of the natural graphite sold commercially. Because of its purity and crystallinity, many of the highest quality electrical motor brushes and other current-carrying carbon products use formulations of graphite from vein deposits.

Synthetic graphite is used in many applications that require high-purity graphite, including anticorrosion products, batteries, carbon brushes, coatings, conductive fillers, electrodes and electrolytic processes, fuel cell bipolar plates, and nuclear moderator rods. Synthetic graphite is unsuitable for foundry applications because of its increased porosity relative to natural graphite. Synthetic graphite is used in more applications in North America than natural graphite and accounts for a significant share of the graphite market.

Demand and Availability of Supply

No natural graphite was reported to have been mined in the United States in 2010 (Olson, 2012), and the major domestic sources of industrial graphite included imports of natural graphite, mostly from China, Mexico, Canada, Brazil, and Madagascar (in order of tonnage of imports), and synthetic graphite manufactured from carbonaceous materials. In 2010, 65,400 metric tons of natural graphite valued at an estimated $52 million was reported to have been imported into the United States for domestic consumption and 134,000 metric tons of synthetic graphite valued at an estimated $1.07 billion was reported to have been produced in the United States (Olson, 2012).

Graphite Prices and Pricing

Graphite is not traded on any commodity exchange. Commodity prices are subject to negotiation between buyer and seller and depend on carbon content, flake size and distribution (for crystalline flake), and the amount and nature of impurities. China is the dominant global natural graphite producer and has been the world price setter for decades. Four price series for graphite commodities based on production and value data reported by the U.S. Geological Survey (Olson, 2013) and Roskill Information Services, Ltd. (2012) are given in table J1. They are (a) microcrystalline (amorphous) graphite powder (from Mexico), which is currently in a long-term decline in importance because its low-technology end uses are becoming obsolete; (b) crystalline flake, which has become the most important natural graphite commodity in the past few decades and accounts for 80 to 90 percent of the value of U.S. imports of natural graphite; (c) lump graphite from Sri Lanka, which is a specialty product because its relatively high price results in low demand, and (d) synthetic graphite, which is a specialty product used primarily for applications that require high purity; its high price also limits demand. The price of microcrystalline (amorphous) graphite powder (80 to 85 percent carbon) ranged from $600 to $800 per metric ton in 2011; that of flake graphite (90 percent graphite) ranged from $1,150 to $2,000 per metric ton; Sri Lankan lump and chip graphite (99 percent graphite), from $1,700 to $2,070, depending on purity, grade, and particle size; and synthetic graphite (99.9 percent graphite), from $7,000 to $20,000 per metric ton, which is about four to seven times that of flake graphite (table J1).

In 2010, graphite prices increased more rapidly for crystalline flake graphite than for amorphous graphite owing to increased demand for crystalline graphite used in friction material applications, such as brake linings, high-quality refractories, and lubricants, and in the manufacturing of graphite foils and long-life alkaline batteries (Industrial Minerals, 2010).

Substitutes for Natural Graphite

The most common substitutes for natural graphite are other forms of carbon. Manufactured synthetic graphite powders and graphite recovered from discarded foundry and manufactured materials can substitute for natural graphite in some applications, depending on the relative price. In steelmaking and some foundry applications, petroleum coke, anthracite, and synthetic graphite can be used instead of natural graphite. Synthetic graphite and natural graphite powder are commonly substituted for each other, or mixtures containing both kinds are prepared for customers (Taylor, 2006). Crystalline graphite is recovered from some foundry and refractory materials, although its recovery cost makes it noncompetitive relative to natural graphite for some applications (Weis, 1973; Olson, 2013).

Strategic and Critical Resource Issues

Graphite is considered a critical and strategic mineral because of its essential applications in the aerospace and energy sectors (such as refractory and foundry applications in the steel and metal industries and use in high-temperature lubricants, high-strength lightweight composite materials, batteries, modern nuclear reactors, fuel cells, electric motors, and evolving electronic applications that anticipate rapid growth in demand for graphite). The high concentration of resource supply from few countries could increase the commodity's susceptibility to market manipulation or disruption (Krauss and others, 1988; Taylor, 2006; European Commission, 2014). The United States has not produced natural graphite since the 1950s; China, Mexico, and Canada, in order of import supply, are the dominant sources of graphite imports to the United States (Olson, 2013). China has very low labor and production costs, and, with aggressive marketing, it established dominance in the world market in the 1980s (Taylor, 2006; Olson, 2013). China's graphite production is expected to increase and remain dominant in the world graphite market for the near future (Olson, 2013). China's rapidly growing domestic market for graphite may restrict future exports, however, which has raised concerns about possible supply shortages of graphite, particularly crystalline flake graphite, needed for anticipated large-scale fuel cell and battery applications; such applications could dramatically increase world demand for graphite (Taylor, 2006; Olson, 2013; Olson and others, 2016).

Graphite has played an important role in the emerging noncarbon energy sector and is used in several new energy applications. In energy production applications, graphite is used in pebbles for modular nuclear reactors and in high-strength composites for wind, tide, and wave turbines. In energy storage applications, graphite is used in bipolar plates for fuel cells and flow batteries, in anodes for lithium-ion batteries, in electrodes for supercapacitors, in high-strength composites for fly wheels, in phase change heat storage, and in solar boilers. In energy management applications, graphite is used in high-performance thermal insulation and in silicon chip heat-dissipation applications. These new energy applications commonly use specialty graphite products with such properties as extreme purity (>99.9 percent graphite), very large or small (nano) particle size, and perfect crystallinity. Current graphite capacity may not be adequate for the increasing demands of these new energy applications, which, when fully implemented, may require double the current graphite supply, especially of high-purity crystalline flake graphite (O'Driscoll, 2010; Olson and others, 2016).

Geology

Geochemistry

Carbon is the fourth most abundant element in the solar system, and in terms of its abundance in Earth's crust, is ranked about 12th to 17th in abundance, with an estimated crustal concentration between 180 and 270 parts per million. The abundance of carbon in Earth's crust is difficult to determine because carbon stores exist and cycle between rock, sediment, atmosphere, biosphere, and ocean reservoirs. The behavior of carbon in its geochemical cycle is influenced by the form in which the carbon occurs. Most of the carbon in Earth's crust (approximately 80 to 90 percent) is contained in carbonate minerals in carbonate rocks. Most of the remaining carbon in the Earth system occurs in living and fossil organic matter and as carbon dioxide (CO_2) in the atmosphere or dissolved in the ocean. These remaining carbon forms dominate the carbon cycle. Graphite makes up only a small proportion of the carbon in Earth's crust, probably less than 0.5 percent, and much of this graphite likely formed by high-temperature thermal alteration of organic matter from biogenic sources deposited in sedimentary rocks and subsurface reservoirs. The mineral graphite is stable and inert in the crustal environment and is unchanged under surface weathering conditions. Burial and thermal metamorphism tends only to recrystallize graphite. Therefore, graphite is largely isolated from the overall carbon cycle.

Mineralogy

Graphite is one of four forms of crystalline elemental carbon; the others are carbon nanotubes, diamond, and fullerenes. Graphite crystallizes in the hexagonal system, with rhombohedral symmetry, commonly forming six-sided tabular crystal flakes. It occurs naturally in metamorphic rocks and in some igneous rocks. Well-crystallized graphite flakes have a black metallic luster, whereas microcrystalline material is black and earthy with an amorphous appearance.

The crystal structure of graphite consists of carbon atoms tightly arranged in parallel-stacked (*c* axis, fig. J1), planar honeycomb-lattice sheets (*a* axis, fig. J1). When the graphite structure is only a 1-atom-thick planar sheet, it is called graphene.

The physical properties of graphite are listed in table J2. Many properties listed in table J2 vary by crystallographic orientation (*a*-axis and *c*-axis values, table J2) because of differences in bonding within (*a* axis, fig. J1) and between lattice sheets (*c* axis, fig. J1). The intraplanar (*a* axis) covalent bonding in graphite sheets is strong, but the electrostatic interlayer (*c* axis) forces holding the sheets together are weak, resulting in delocalized electrons that are free to move between sheets, which separates the sheets and allows them to

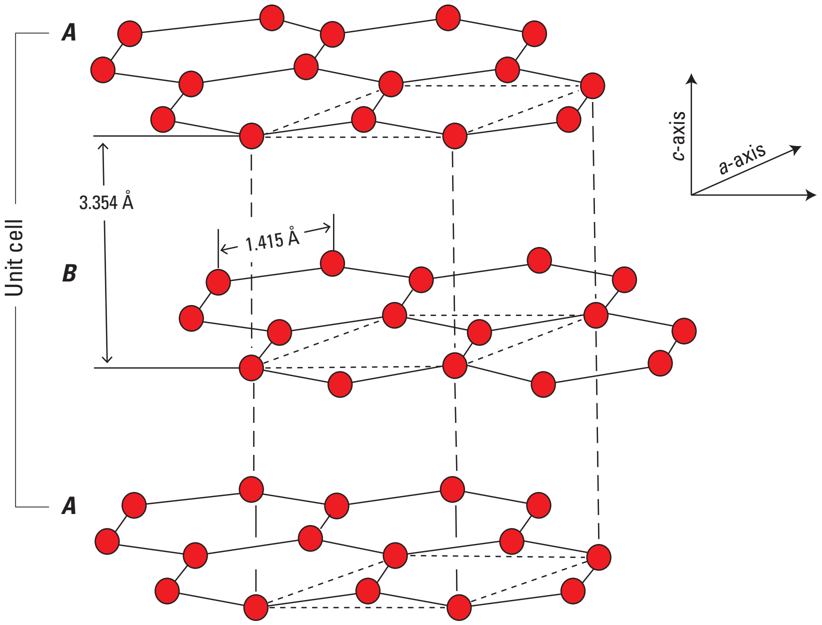


Figure J1. Diagram showing the arrangement of carbon atoms in graphite, which consists of stacks of parallel sheets of carbon atoms (red circles in the figure), with each sheet containing hexagonal arrays of carbon atoms. Each carbon atom within a sheet is connected to its three nearest neighbors by covalent bonds that separate the atoms by a distance of 1.415 angstroms (Å)—an angstrom is one ten-billionth of a meter. The stacked sheets (shown here in their *A* and *B* orientation) are held together by weak intermolecular van der Waals' forces and are separated from each other by a distance of 3.354 Å. The arrangement of atoms defined by the dashed lines portrays one hexagonal (2H) unit cell of graphite. Modified from Kraus and others, 1989.

slide across one another easily. This gives graphite a density of 2.09 to 2.26 grams per cubic centimeter (g/cm^3), perfect basal (one-plane) cleavage, softness (0.5 to 1 on the Mohs scale), a greasy feel, and self-lubricating properties that make it useful as a lubricant. The ratio of force required to induce gliding of graphite sheets relative to compression force is low, resulting in high lubricity. These delocalized interlayer electrons also give graphite its high electrical and thermal conductivity. Graphite is the most electrically and thermally conductive of the nonmetallic elements (*a*-axis values, table J2); however, the intraplanar covalent bonds are very strong and require high energy to break them. These bonding properties make graphite chemically inert and physically stable at high temperatures (refractory). Graphite resists chemical attack by most reagents and is infusible in most common fluxes. Thermal oxidation of graphite in the presence of oxygen begins at about 300 °C, and the rate increases with temperature; however, it is stable in a nonoxidizing atmosphere to above 3,000 °C. Graphite sublimes between 3,300 °C and 3,500 °C at 1.033 kilograms per square centimeter (kg/cm^2) and it melts at approximately 3,550 °C at a triple point under a pressure of 88 kg/cm^2. Graphite is flexible but not elastic. All these properties combined make graphite desirable for many industrial applications.

Deposit Types

Natural graphite is a common constituent of metasedimentary rocks and is mined in three geologic settings: (a) microcrystalline (amorphous) graphite deposits formed by metamorphism of coal, petroleum, or carbon-rich sediments, (b) disseminated flakes in metamorphic rock (flake graphite), and (c) graphite vein deposits (lump or chip graphite). Similar to most industrial mineral commodities, the economics of a deposit depend on its location and transportation costs to markets in addition to deposit grade, size, and mining characteristics. Impurities in the deposit, such as silica, sulfides, or biotite, may limit the economic potential of a deposit.

Amorphous Graphite Deposits

Amorphous graphite deposits, which are formed by thermal metamorphism of coal, petroleum pools, or other highly carbonaceous sedimentary rocks, contain earthy to compact masses of microcrystalline graphite. Deposits may consist of multiple layers, seams, and lenses containing 50 to 90 percent carbon; each deposit is a few meters thick and up to a kilometer in length and lies within clastic metasedimentary rocks. The carbon content of amorphous deposits is dependent on the amount of carbon present in the original sediments, and the grade, tonnage, and purity of the deposit depend upon the characteristics of the precursor coal sequence or carbonaceous material. Deposits in metamorphosed massive coal seams may contain as much as 90 percent graphitic carbon, whereas deposits in other carbonaceous sediments or impure coal sequences commonly range from 25 to 60 percent carbon.

Chemical and isotopic biomarkers found in natural graphite provide evidence of its origin from ancient biological material. Amorphous graphite deposits occur in geologic settings and environments where coal and other organic-rich sedimentary rocks, such as oil shale, occur, including (a) shoreline, fluvial-deltaic, and alluvial fan depositional environments in passive continental margin settings, and (b) lacustrine and shallow inland seas and margins in foreland, continental, sag, or intracontinental rift basin settings. Host rocks include conglomerate, metagraywacke, quartzite, and schist. The thermal metamorphism is commonly caused by crosscutting diabasic or granitic intrusions with associated hornfels alteration of host rocks. Hornfels is a hard metamorphic rock formed by contact metamorphism of sedimentary rocks close to intrusive igneous bodies.

Graphite does not form until temperatures exceed 300 °C to 400 °C (Landis, 1971). The degree of metamorphism controls the degree of graphitization, and the ratio of graphite to nongraphitic carbon varies, but typically increases towards the heat source. Mineral impurities include meta-anthracite, anthracite, quartz, mica, pyrite, and other sulfides. Most currently mined deposits typically contain at least 80 percent carbon in deposits exceeding 1 million metric tons.

The world's main sources of amorphous graphite are the metamorphosed coal deposits in Sonora, Mexico; Siberia, Russia; and the large coal province stretching from China into the Korean peninsula (table J3). The deposits in Sonora, Mexico, are the most significant deposits of amorphous graphite in the Western Hemisphere. They occur in a series of beds in an area 30 kilometers (km) long by 15 km wide located 60 km southeast of Hermosillo. In the district, the orebodies average 3 m in thickness, but deformation can produce seams up to 7 m wide. Grades exceed 75 percent contained graphite and some contain as much as 95 percent. The Moradillas deposit (Lourdes area, Mexico) has been reinterpreted as formed from a graphitized hydrocarbon protolith owing to its vein-like structure and lack of evidence that it is metamorphosed coal (Taylor, 2006). In the United States, small amorphous graphite deposits occur in metamorphosed coal deposits in the Narragansett Basin, Rhode Island, and in deposits in northern Michigan. An additional U.S. example occurs at Raton, New Mexico, where a basalt dike intersects a coal seam.

Deposits of Flake Graphite Disseminated in Metasedimentary Rocks

A large proportion of worldwide graphite production is derived from deposits of disseminated flake graphite found in metamorphic rocks, such as paragneiss (a gneiss derived from sedimentary rock), quartzite, and, sometimes, marble. These deposits formed when preexisting carbonaceous matter in the host sedimentary rock was converted to graphite during regional metamorphic conditions at or exceeding medium-pressure and medium-to-high-temperature conditions (amphibolite facies). These metamorphic conditions are sufficient to crystallize fully ordered graphite (Hoefs and Frey, 1976) and recrystallize the rock matrix. The precursor host rocks of these deposits are interpreted as occurring in depositional settings where organic-rich sediments accumulate and are preserved. These settings include sediment-starved intracratonic and continental margin basins with low-oxygen conditions at depth to accumulate organic sediments, and periods of transgression (compare with, for example, Wilde and others, 1999), when sea level rises relative to land, preserving organic-rich sediments without erosion. The sedimentary rocks that are deposited during transgression may be deposited directly on existing basement rocks of the crust and are termed supracrustal rocks.

The metamorphic conditions sufficient to form these deposits occur in the roots of continental mountain belts formed by deformation of Earth's crust, and significant postmetamorphic uplift and erosion are required to expose deposits in minable settings. Alumina-rich paragneiss, quartzites, and marbles at or near the highest grade of regional metamorphism at medium pressure (granulite facies) are favorable host rocks for flake graphite deposits because of their granular texture, coarse grain size, and low mica content. Supracrustal metasedimentary belts with these metamorphic features are termed crystalline metamorphic basement; their worldwide distribution has been mapped by Chorlton (2007). Most flake graphite deposits are located in Precambrian crystalline metamorphic basement (fig. J2), principally of Neoarchean to Proterozoic eras; however, deposits could occur in crystalline basement of any age. Precambrian supracrustal metamorphic belts appear to be more extensive, and metamorphosed to higher grades, than Phanerozoic belts (Chacko and others, 1987).

The principal flake graphite deposits occur as stratabound lenses or layers; individual lenses in deposits are as much as tens of meters thick and hundreds of meters long. The lenses have variable graphite content, both within themselves and from one lens to another. The graphite content of a typical deposit varies from about 8 to 15 percent carbon, but the grade can vary from as low as 3 percent to about 60 percent carbon locally in individual deposits and between deposits. In Madagascar, one rich lens was reported to contain 60 percent graphite, and grades in the Kigluaik Mountains graphite district, Alaska, exceed 50 percent graphite in some areas (Coats, 1944). In paragneiss-hosted deposits, gangue (non-ore) minerals include in order of general abundance, feldspar, biotite, pyroxene, garnet, and sulfide minerals. Gangue minerals in carbonate-hosted deposits include calcite, pyroxene, feldspar, garnet, and sulfides. Flake graphite in crushed ore is separated from mineral impurities using washing, screening, flotation, and, sometimes, leach methods.

The highest graphite grades commonly are associated with rock contacts between marble and paragneiss or quartzite, lenses in fault zones, in segregations within fold crests, and in structures that acted as channels for metamorphic fluids, all suggesting structural control of mineralization. Although most carbon in these deposits is thought to be present in the original sedimentary rocks, some carbon enrichment may be caused by processes involving internal or external buffering or mixing of metamorphic fluids (Lamb and Valley, 1984; Newton, 1986).

Crystals in each deposit vary from a fraction of a millimeter to a few centimeters in size, usually reflecting the grain size in the parent rock. Most currently mined flake graphite deposits typically contain at least 8 to 12 percent graphitic carbon in deposits exceeding 0.5 million metric tons. Graphite is stable in the weathering environment; deposit grades and ease of mining are enhanced by weathering destruction of other minerals. Some deposits become so weathered that they can be mined with shovels and other hand tools.

Table J3. Location, grade, tonnage and other data for selected graphite deposits and districts of the world.

[The names, locations, and descriptions of most of the deposits are taken from the International Strategic Minerals Inventory (ISMI) graphite inventory (Krauss and others, 1988) and the U.S. Geological Survey Mineral Resources Data System (MRDS; U.S. Geological Survey, 2012). Identification number is keyed to the deposits shown in figure J2. Negative values for latitude indicate that the deposit is in the Southern Hemisphere; negative values for longitude indicate that the deposit is in the Western Hemisphere. Record types are from the MRDS. Ore type is characterized as amorphous, crystalline, flake, or lump (includes chip), as defined in table J1. "Weathering" indicates surface ores that have been deeply weathered, which lowers mining costs. Development status of the deposit is given as follows: Current, current or recent mine activity; Past, past producer with no current mining; Prospect, an unmined deposit with characterized resources; Occurrence, an unmined deposit with uncharacterized resources. Tonnage of ore has been updated from the values in the MRDS and is given in metric tons or, alternatively, is categorized as large (likely exceeds 1 million metric tons but is not well characterized) or small (likely is less than 100,000 metric tons). %, percent; —, unknown; WGS 84, World Geodetic System of 1984]

Identification number	Name	Country	State/Province	Latitude	Longitude
				Decimal degrees WGS 84	
1	Quebrada Del Gato	Argentina	San Juan	–31.43	–68.13
2	Undercliff	Australia	New South Wales	–28.66	152.21
3	Jack's Creek	Australia	Queensland	–20.67	147.87
4	Koppio-Uley mines	Australia	South Australia	–34.80	135.71
5	Munglinup River	Australia	Western Australia	–33.50	120.85
6	Doppl-Muehldorf-Zettlitz	Austria	Niederosterreich	48.38	15.45
7	Kaisersberg-Trieben	Austria	Steiermark	47.35	15.07
8	Itanhem	Brazil	Bahia	–17.10	–40.35
9	Itapacerica	Brazil	Minas Gerais	–20.43	–45.13
10	Pedra Azul	Brazil	Minas Gerais	–15.88	–45.13
11	Bisset Creek	Canada	Ontario	46.23	–78.07
12	Coronation	Canada	Ontario	45.29	–77.94
13	Graphite Lake-Ryerson-Todd area	Canada	Ontario	45.73	–79.08
14	Kirkham-Portland-Timmins area	Canada	Ontario	44.56	–76.57
15	Tagliamonte	Canada	Ontario	46.23	–78.07
16	Graphex-Graphico-Orwell Mines	Canada	Quebec	46.14	–75.55
17	North American Mine	Canada	Quebec	45.52	–75.55
18	St-Amime-Lac Des Iles	Canada	Quebec	46.25	–75.53
19	Lac Knife	Canada	Quebec	52.55	–61.18
20	Pollon Lake area	Canada	Saskatchewan	56.38	–103.13
21	Haikou	China	Hainan	20.08	110.42
22	Heling	China	Heilongjiang [Heilungkiang]	46.31	129.55
23	Jixi (Liu Mao)	China	Heilongjiang [Heilungkiang]	45.28	131.00
24	Liu Mao	China	Heilongjiang [Heilungkiang]	45.30	131.07
25	Honan deposits	China	Henan [Honan]	32.50	113.88
26	Hunan	China	Hunan	26.00	113.00
27	Panshi	China	Jilin [Kirin]	42.93	125.97
28	Hohot	China	Nei Mongol (Inner Mongolia)	40.81	111.62
29	Shandong Peninsula	China	Shandong [Shantung]	37.03	120.32
30	Xing He	China	—	40.88	113.88
31	Kolledeye	Czech Republic	—	49.22	14.45
32	Velke Vbrno-Konstantin Vvk	Czech Republic	—	50.13	17.33
33	Kropfmühl-Cesky Krumlov	Germany and Czech Republic	Bayern [Bavaria, Germany]	48.80	14.32

Table J3. Location, grade, tonnage and other data for selected graphite deposits and districts of the world.—Continued

[The names, locations, and descriptions of most of the deposits are taken from the International Strategic Minerals Inventory (ISMI) graphite inventory (Krauss and others, 1988) and the U.S. Geological Survey Mineral Resources Data System (MRDS; U.S. Geological Survey, 2012). Identification number is keyed to the deposits shown in figure J2. Negative values for latitude indicate that the deposit is in the Southern Hemisphere; negative values for longitude indicate that the deposit is in the Western Hemisphere. Record types are from the MRDS. Ore type is characterized as amorphous, crystalline, flake, or lump (includes chip), as defined in table J1. "Weathering" indicates surface ores that have been deeply weathered, which lowers mining costs. Development status of the deposit is given as follows: Current, current or recent mine activity; Past, past producer with no current mining; Prospect, an unmined deposit with characterized resources; Occurrence, an unmined deposit with uncharacterized resources. Tonnage of ore has been updated from the values in the MRDS and is given in metric tons or, alternatively, is categorized as large (likely exceeds 1 million metric tons but is not well characterized) or small (likely is less than 100,000 metric tons). %, percent; —, unknown; WGS 84, World Geodetic System of 1984]

Identification number	Record type	Ore type	Operation	Development status	Tonnage	Grade (% of carbon)
1	District	Crystalline (flake or lump?)	Unknown	Producer	—	—
2	Site	Amorphous	Surface	Past producer	793	32
3	Site	Amorphous	Surface,underground	Past producer	2,200	61
4	District	Flake, weathering	Surface,underground	Past producer	35,030	15
5	District	Flake	Surface,underground	Past producer	30,000	25
6	District	Flake	Surface	Producer	1,000,000	10
7	District	Amorphous	Underground	Producer	1,000,000	85
8	Site	Lump	Surface	Producer	2,778	40
9	Site	Flake, weathering	Surface	Producer	383,000	15.7
10	Site	Flake, weathering	Surface	Producer	26,800,000	11.9
11	Site	Flake	Surface	Prospect	4,938,000	15.58
12	Site	Flake	Unknown	Occurrence	—	—
13	District	Flake	Surface	Producer	Large	—
14	District	Flake	Surface	Producer	478,000	9
15	Site	Flake	Surface	Prospect	—	—
16	District	Flake	Surface	Producer	2,200,000	10
17	Site	Flake	Unknown	Past producer	—	—
18	Site	Flake	Surface	Producer	—	—
19	Site	Flake	Surface	Prospect	4,900,000	15.8
20	District	Flake	Unknown	Past producer	1,663,000	10.3
21	Site	Flake	Surface	Producer	5,000,000	3.7
22	Site	Amorphous	Unknown	Producer	—	—
23	Site	Amorphous	Surface	Past producer	300,000,000	85
24	Site	Flake	Unknown	Producer	3,000,000	18.5
25	District	Unknown	Unknown	Producer	—	—
26	District	Amorphous	Underground	Producer	—	—
27	Site	Amorphous	Underground	Producer	—	—
28	District	Crystalline (flake or lump?)	Surface	Producer	—	—
29	District	Flake	Surface	Producer	5,900,000	5
30	Site	Flake	Unknown	Producer	—	—
31	District	Flake	Surface,underground	Prospect	—	—
32	Site	Amorphous	Surface	Producer	200,000	50
33	District	Flake	Underground	Producer	—	16

Table J3. Location, grade, tonnage and other data for selected graphite deposits and districts of the world.—Continued

[The names, locations, and descriptions of most of the deposits are taken from the International Strategic Minerals Inventory (ISMI) graphite inventory (Krauss and others, 1988) and the U.S. Geological Survey Mineral Resources Data System (MRDS; U.S. Geological Survey, 2012). Identification number is keyed to the deposits shown in figure J2. Negative values for latitude indicate that the deposit is in the Southern Hemisphere; negative values for longitude indicate that the deposit is in the Western Hemisphere. Record types are from the MRDS. Ore type is characterized as amorphous, crystalline, flake, or lump (includes chip), as defined in table J1. "Weathering" indicates surface ores that have been deeply weathered, which lowers mining costs. Development status of the deposit is given as follows: Current, current or recent mine activity; Past, past producer with no current mining; Prospect, an unmined deposit with characterized resources; Occurrence, an unmined deposit with uncharacterized resources. Tonnage of ore has been updated from the values in the MRDS and is given in metric tons or, alternatively, is categorized as large (likely exceeds 1 million metric tons but is not well characterized) or small (likely is less than 100,000 metric tons). %, percent; —, unknown; WGS 84, World Geodetic System of 1984]

Identification number	Name	Country	State/Province	Latitude	Longitude
				Decimal degrees WGS 84	
34	East Godavari	India	Andhra Pradesh	17.38	81.85
35	Khammam	India	Andhra Pradesh	17.38	81.33
36	Srikakulam	India	Andhra Pradesh	18.33	83.10
37	Visakhapatnam	India	Andhra Pradesh	18.02	82.93
38	Khamdih	India	Bihar	23.97	84.22
39	Sokra	India	Bihar	23.97	84.13
40	Dandatapa area	India	Odisha	20.80	84.60
41	Sargipali area	India	Odisha	20.90	83.08
42	Titlagarh area	India	Odisha	20.20	83.37
43	Tumdibandh-Phulbani area	India	Odisha	19.83	83.63
44	Tamatia mines	India	Rajasthan	23.62	74.50
45	Madurai	India	Tamil Nadu [Madras]	10.07	77.83
46	Chawia	Kenya	—	–3.46	38.38
47	Oldoinyo-Nyiro	Kenya	—	0.75	37.00
48	Yonghung-Kaechon area	Korea, North	Hamgyong-Namdo	39.83	127.43
49	Songjin deposits	Korea, North	Hwanghae-Namdo	40.67	129.20
50	Wolmyong-Kaerim-Pongmyong	Korea, Republic of	Ch'Ungch'Ong-Bukto	36.41	127.75
51	Yongwon-GunJa-Pyongtack-Shihung	Korea, Republic of	Ch'Ungch'Ong-Namdo	36.91	127.67
52	Ampangadiatany	Madagascar	Toamasina	–19.41	48.89
53	Ambatomitamba Sahanovo area	Madagascar	Toamasina	–18.35	49.10
54	Perinet-Ambatovy area	Madagascar	—	–18.93	48.45
55	Vatomandry area	Madagascar	—	–19.34	48.94
56	Telixtlahuaca	Mexico	Oaxaca	17.33	–96.86
57	Las Trincheras	Mexico	Sonora	30.40	–111.53
58	Lourdes area	Mexico	Sonora	28.60	–110.50
59	Tonichi	Mexico	Sonora	28.58	–109.57
60	Skaland-Senja	Norway	—	69.45	17.29
61	La Galgada-La Limena-San Carlos Mines	Peru	Ancash	–8.46	–78.13
62	Baia De Fier	Romania	—	45.23	23.75
63	Botogolsk	Russia	Buryatiya	52.46	100.75
64	Boyarsk	Russia	Buryatiya	51.85	106.10
65	Kureyka	Russia	Krasnodarskiy Kray	66.48	87.17
66	Noginskoje	Russia	Krasnodarskiy Kray	64.50	91.25
67	Soyusnoye	Russia	—	47.91	130.93
68	Tayginsk	Russia	—	55.63	60.65
69	Gumbu graphite mine	South Africa	—	–22.32	30.67
70	Malonga graphite mine	South Africa	—	–22.65	30.88
71	Kahatagaha-Kolongaha mines	Sri Lanka	—	7.57	80.53

Table J3. Location, grade, tonnage and other data for selected graphite deposits and districts of the world.—Continued

[The names, locations, and descriptions of most of the deposits are taken from the International Strategic Minerals Inventory (ISMI) graphite inventory (Krauss and others, 1988) and the U.S. Geological Survey Mineral Resources Data System (MRDS; U.S. Geological Survey, 2012). Identification number is keyed to the deposits shown in figure J2. Negative values for latitude indicate that the deposit is in the Southern Hemisphere; negative values for longitude indicate that the deposit is in the Western Hemisphere. Record types are from the MRDS. Ore type is characterized as amorphous, crystalline, flake, or lump (includes chip), as defined in table J1. "Weathering" indicates surface ores that have been deeply weathered, which lowers mining costs. Development status of the deposit is given as follows: Current, current or recent mine activity; Past, past producer with no current mining; Prospect, an unmined deposit with characterized resources; Occurrence, an unmined deposit with uncharacterized resources. Tonnage of ore has been updated from the values in the MRDS and is given in metric tons or, alternatively, is categorized as large (likely exceeds 1 million metric tons but is not well characterized) or small (likely is less than 100,000 metric tons). %, percent; —, unknown; WGS 84, World Geodetic System of 1984]

Identification number	Record type	Ore type	Operation	Development status	Tonnage	Grade (% of carbon)
34	District	Flake, lump	Surface	Producer	—	—
35	District	Flake, lump	Surface,underground	Producer	—	—
36	District	Flake, lump	Unknown	Producer	—	—
37	District	Flake, lump	Surface	Producer	—	—
38	District	Flake, lump	Surface	Producer	—	—
39	District	Flake, lump	Surface	Producer	—	—
40	District	Flake, lump	Surface	Producer	—	—
41	District	Flake, lump	Surface	Producer	—	—
42	District	Flake, lump	Surface	Producer	—	—
43	District	Flake, lump	Surface	Producer	—	—
44	District	Flake	Surface	Producer	1,120,000	14.1
45	District	Flake, lump	Surface	Producer	130,000	19.5
46	District	Flake, weathering	Surface	Past producer	—	—
47	Site	Flake, weathering	Surface	Prospect	1,200,000	13
48	District	Amorphous	Surface,underground	Producer	—	—
49	District	Flake	Unknown	Producer	—	—
50	District	Amorphous	Underground	Producer	12,000,000	80
51	District	Flake, weathering	Surface	Producer	1,400,000	3.5
52	Site	Flake, weathering	Surface	Past producer	—	—
53	District	Flake, weathering	Surface	Producer	2,000,000	9
54	District	Flake, weathering	Surface	Producer	—	—
55	District	Flake, weathering	Surface	Producer	2,000,000	7
56	Site	Flake, weathering	Surface	Producer	13,400,000	4
57	Site	Amorphous	Underground	Producer	—	—
58	District	Amorphous	Underground	Producer	2,000,000	80
59	Site	Amorphous	Unknown	Producer	2,000,000	75
60	Site	Flake	Underground	Producer	2,000,000	30
61	District	Amorphous	Unknown	Past producer	—	—
62	Site	Amorphous	Surface,underground	Past producer	58,000	70
63	Site	Lump, flake	Underground	Producer	Small	—
64	District	Flake	Unknown	Past producer	Large	5
65	Site	Amorphous	Surface,underground	Producer	87,000,000	88
66	Site	Amorphous	Underground	Producer	10,000,000	85
67	Site	Flake	Surface	Producer	8,200,000	18
68	Site	Flake	Surface	Producer	1,116,000	3
69	Site	Flake	Unknown	Past producer	—	—
70	Site	Amorphous	Surface	Past producer	20,000,000	63.5
71	District	Lump	Underground	Producer	100,000	60

Table J3. Location, grade, tonnage and other data for selected graphite deposits and districts of the world.—Continued

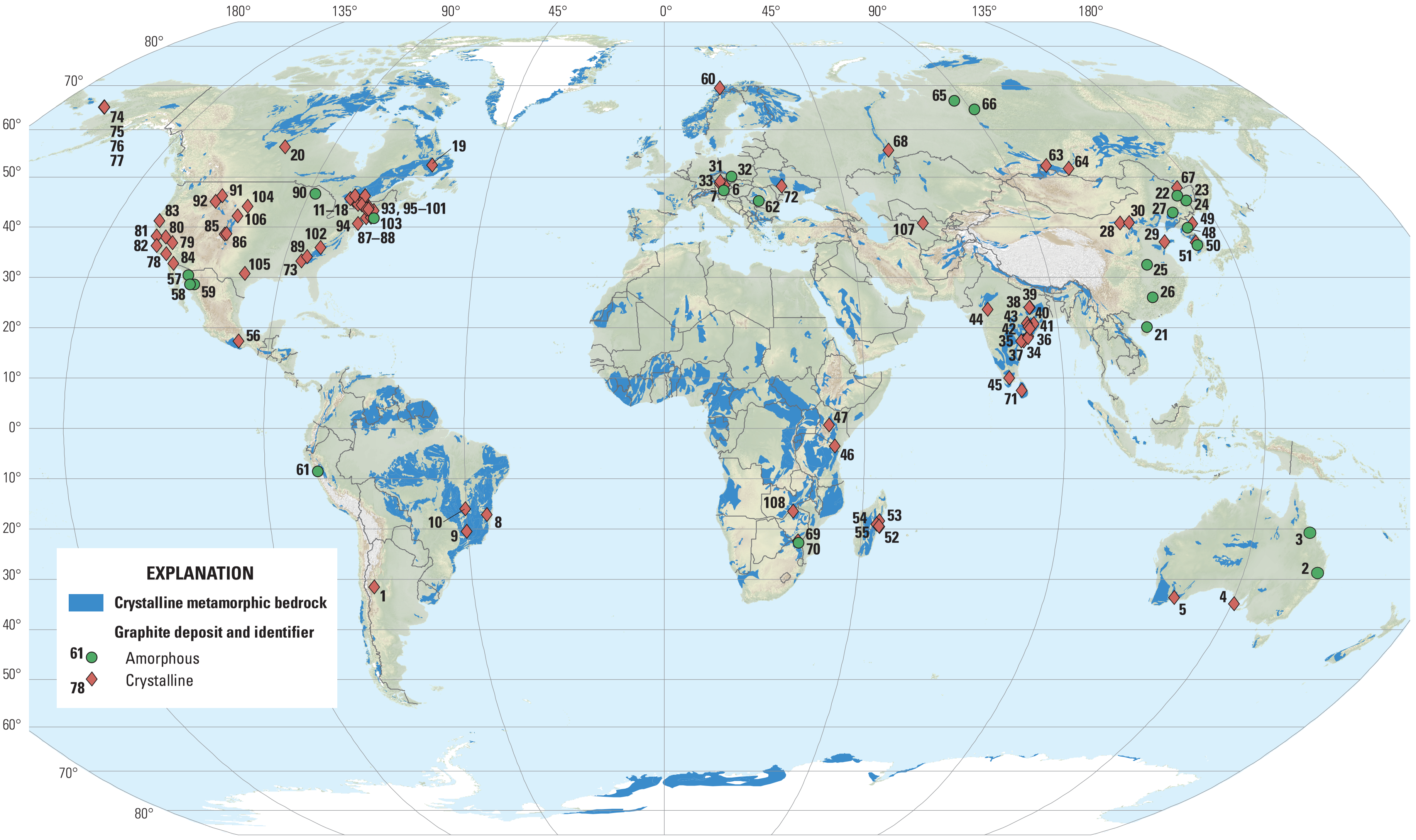
[The names, locations, and descriptions of most of the deposits are taken from the International Strategic Minerals Inventory (ISMI) graphite inventory (Krauss and others, 1988) and the U.S. Geological Survey Mineral Resources Data System (MRDS; U.S. Geological Survey, 2012). Identification number is keyed to the deposits shown in figure J2. Negative values for latitude indicate that the deposit is in the Southern Hemisphere; negative values for longitude indicate that the deposit is in the Western Hemisphere. Record types are from the MRDS. Ore type is characterized as amorphous, crystalline, flake, or lump (includes chip), as defined in table J1. "Weathering" indicates surface ores that have been deeply weathered, which lowers mining costs. Development status of the deposit is given as follows: Current, current or recent mine activity; Past, past producer with no current mining; Prospect, an unmined deposit with characterized resources; Occurrence, an unmined deposit with uncharacterized resources. Tonnage of ore has been updated from the values in the MRDS and is given in metric tons or, alternatively, is categorized as large (likely exceeds 1 million metric tons but is not well characterized) or small (likely is less than 100,000 metric tons). %, percent; —, unknown; WGS 84, World Geodetic System of 1984]

Identification number	Name	Country	State/Province	Latitude	Longitude
				Decimal degrees WGS 84	
72	Zavalyevskiy	Ukraine	—	48.20	30.03
73	Clay-Coosa-Chilton graphite district	United States	Alabama	33.28	–85.84
74	Christophosen Creek	United States	Alaska	65.03	–165.63
75	Graphite Creek	United States	Alaska	65.04	–165.54
76	Imuruk Basin Graphite	United States	Alaska	65.04	–165.55
77	Kigluaik Mountains graphite district	United States	Alaska	65.04	–165.54
78	Southern California area	United States	California	34.65	–118.47
79	Black Lady Nos. 1 and 2	United States	California	36.90	–118.07
80	Eureka Plumbago-Morgan mines	United States	California	38.02	–120.38
81	Skinner Ranch	United States	California	38.19	–122.59
82	Unnamed	United States	California	36.28	–121.56
83	Unnamed	United States	California	41.21	–123.77
84	Wedge	United States	California	32.80	–115.98
85	Graphite Basin	United States	Colorado	38.59	–106.38
86	Unnamed graphite deposit	United States	Colorado	38.67	–105.98
87	Graphite mines	United States	Connecticut	41.86	–73.37
88	Lead Hill Mine graphite deposits	United States	Connecticut	41.94	–72.18
89	Unnamed graphite mine	United States	Georgia	34.12	–84.74
90	Detroit-Northern Graphite quarries	United States	Michigan	46.63	–88.35
91	Black Diamond Carbon Graphite	United States	Montana	46.32	–111.63
92	Crystal Graphite Mine	United States	Montana	45.10	–112.51
93	Boston-Goshen-Osgood Mines area	United States	New Hampshire	43.27	–72.10
94	Stone Mills Graphite Mine	United States	New Jersey	40.68	–74.88
95	Adirondack Mining & Milling Mine	United States	New York	43.56	–73.46
96	Essex-Warren area	United States	New York	43.90	–73.47
97	Champlain Graphite Mine	United States	New York	43.54	–73.48
98	M. B. Hooper Graphite Mine	United States	New York	43.55	–73.50
99	Pope Mills-Rossie deposits	United States	New York	44.47	–75.55
100	Rowland Graphite Mine area	United States	New York	43.60	–73.97
101	Silver Leaf Graphite Co. Mine	United States	New York	43.59	–73.43
102	Dillinger Mine and mill	United States	North Carolina	35.90	–82.18
103	Cranston-Penners Ledge Mines	United States	Rhode Island	41.77	–71.46
104	Copper Cliff Mine	United States	South Dakota	44.12	–103.84
105	Burnet-Llano district	United States	Texas	30.78	–98.36
106	Rabbit Creek area	United States	Wyoming	42.21	–105.23
107	Taskazgan	Uzbekistan	—	40.81	63.38
108	Lynx Mine	Zimbabwe	—	–16.43	29.30

Table J3. Location, grade, tonnage and other data for selected graphite deposits and districts of the world.—Continued

[The names, locations, and descriptions of most of the deposits are taken from the International Strategic Minerals Inventory (ISMI) graphite inventory (Krauss and others, 1988) and the U.S. Geological Survey Mineral Resources Data System (MRDS; U.S. Geological Survey, 2012). Identification number is keyed to the deposits shown in figure J2. Negative values for latitude indicate that the deposit is in the Southern Hemisphere; negative values for longitude indicate that the deposit is in the Western Hemisphere. Record types are from the MRDS. Ore type is characterized as amorphous, crystalline, flake, or lump (includes chip), as defined in table J1. "Weathering" indicates surface ores that have been deeply weathered, which lowers mining costs. Development status of the deposit is given as follows: Current, current or recent mine activity; Past, past producer with no current mining; Prospect, an unmined deposit with characterized resources; Occurrence, an unmined deposit with uncharacterized resources. Tonnage of ore has been updated from the values in the MRDS and is given in metric tons or, alternatively, is categorized as large (likely exceeds 1 million metric tons but is not well characterized) or small (likely is less than 100,000 metric tons). %, percent; —, unknown; WGS 84, World Geodetic System of 1984]

Identification number	Record type	Ore type	Operation	Development status	Tonnage	Grade (% of carbon)
72	Site	Flake, weathering	Surface	Producer	100,000,000	5.5
73	District	Flake	Unknown	Past producer	300,000	10
74	Site	Flake	Unknown	Past producer	65,000	52
75	Site	Flake	Unknown	Past producer	—	—
76	Site	Flake	Surface	Past producer	—	—
77	District	Flake	Unknown	Past producer	10,000,000	10
78	District	Flake	Surface	Past producer	—	—
79	Site	Flake	Surface	Past producer	—	—
80	District	Flake	Unknown	Past producer	—	—
81	Site	Flake	Surface	Past producer	—	—
82	Site	Flake	Unknown	Past producer	—	—
83	Site	Flake	Unknown	Past producer	—	—
84	Site	Flake	Unknown	Past producer	—	—
85	District	Flake	Underground	Past producer	—	—
86	Site	Flake	Unknown	Past producer	—	—
87	Site	Lump or flake	Surface	Past producer	Small	—
88	Site	Lump or flake	Surface	Past producer	Small	—
89	Site	Flake	Surface	Past producer	—	—
90	Site	Amorphous	Surface	Past producer	—	—
91	Site	Flake	Surface	Past producer	—	—
92	Site	Lump or flake	Unknown	Past producer	—	—
93	District	Lump or flake	Surface	Past producer	—	—
94	Site	Lump or flake	Unknown	Past producer	—	—
95	Site	Lump or flake	Surface	Past producer	—	—
96	District	Lump or flake	Surface-Underground	Past producer	—	—
97	Site	Lump or flake	Surface	Past producer	—	—
98	Site	Lump or flake	Underground	Past producer	—	—
99	District	Lump or flake	Underground	Past producer	—	—
100	District	Lump or flake	Surface-Underground	Past producer	—	—
101	Site	Lump or flake	Surface	Past producer	—	—
102	Site	Flake	Surface	Past producer	—	—
103	District	Amorphous	Unknown	Past producer	—	—
104	Site	Flake	Unknown	Past producer	—	—
105	District	Flake	Unknown	Past producer	400,000	5
106	Site	Flake	Underground	Past producer	—	—
107	Site	Flake	Surface	Producer	2,300,000	15
108	Site	Flake	Underground	Producer?	6,700,000	26.2



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 J2. World map showing locations of major graphite deposits and districts in the world, by commodity type. Numbers refer to the identifier number in table J3. Distribution of crystalline metamorphic basement is from Chorlton (2007).

The world's main sources of crystalline flake graphite are the deposits in Brazil, Canada, China, India, and Madagascar. Probably the largest resources of high-grade crystalline flake graphite in the world are in China (Jixi district) and the island country of Madagascar. The deposits in both areas occur in belts of Neoarchean to late Proterozoic micaceous gneiss and schist that are interpreted to be associated with a series of mountain-building events related to the formation of the Gondwana supercontinent about 600 million years ago (Wilde and others, 1999), named the Pan-African orogeny. Pan-African age supracrustal metamorphic belts also occur in areas in Western Australia, eastern India, and Sri Lanka; these areas also host significant flake graphite deposits located in the most productive graphite-bearing regions of the world (fig. J2).

Graphite-rich horizons in Madagascar occur over a distance of more than 800 km in the eastern half of the island. Individual deposits are graphite-rich layers that range from 3 m to more than 35 m in thickness and extend up to a few kilometers. Ore grades average 4 to 10 percent graphite, but grades are reported to be as high as 60 percent in some areas. The flake graphite deposits in the State of Minas Gerais, Brazil, are mined from graphite-bearing soils overlying extensively weathered host rock with grades of 12 to 16 percent graphite; the ore is mined by front-end loader or shovel. Shandong Province in China is a major flake graphite producer. The flake graphite deposits in the vicinity of Jixi, China, are mined from deformed lenses and discordant layers of graphite schist and gneiss in paragneiss; graphite content ranges from 15 percent in the gneiss to up to 45 percent in the schists, with local flake graphite resources exceeding 360 million metric tons (Wilde and others, 1999). Little is known about the deposits in Russia and India.

Large disseminated flake graphite deposits occur at a number of places in the Grenville Province metamorphic belt in Canada's Quebec and southeastern Ontario Provinces, and small deposits associated with Grenville series marble, gneiss, and pegmatites also occur in the Adirondack Mountains west and northwest of Ticonderoga, New York (Alling, 1918). The Grenville Province is a southwest-trending belt of deformed high-grade supracrustal metamorphic rocks of Mesoproterozoic age that is exposed across 2,000 km from Labrador, through Quebec, into southeastern Ontario, and continues in the subsurface a further 3,000 km to Texas and Mexico. The Lac Knife graphite deposit at Fermont, Quebec, has high-grade ore hosted by migmatized quartz-feldspar (biotite) gneiss. The host rock is the southern extension of carbonaceous shales and sandstones that have been deformed and metamorphosed in the crosscutting Grenville Province metamorphic belt.

Deposits of flake graphite in the United States have been mined in Alabama, Alaska, and Texas. The deposits of the Clay-Coosa-Chilton graphite district, Alabama, occur in two parallel layers and lenses in the Ashland quartz-mica schist that contain 1 to 5 percent disseminated flake graphite (Pallister and Thoenin, 1948). The layers and lenses range from 6 m to more than 35 m in thickness, dip gently, and occur in a northeast-trending 1- to 3-km-wide belt that extends for more than 90 km. The deposits are weathered to depths of 35 m. The deposits in the Burnet-Llano district, Texas, occur in the Precambrian Packsaddle schist and show a wide range of graphite content and flake size (Needham, 1946). The graphite flake deposits in the Kigluaik Mountains graphite district, Alaska (Coats, 1944) represent the largest known domestic graphite resource, but are located in a rugged and remote area with high mining costs.

Vein Deposits Containing Lump or Chip Graphite

Crystalline graphite of the lump or chip commodity type is generally found in well-defined veins composed almost entirely of graphite that cut high-grade metamorphic rocks or as accumulations along intrusive contacts of pegmatites with marbles or paragneiss. The veins form in high-grade regional metamorphic environments where metasedimentary belts are invaded by igneous rocks. In some areas, the veins are localized in granulite-facies domains within the broader regional metamorphic belt (Chamberlain and Rumble, 1988).

Graphite-bearing veins form within or crosscut metamorphic structures, rock contacts, and folds. The veins range from thin films to massive bodies that are more than 3 m thick and may extend for hundreds of meters, although they usually extend for less than tens of meters. The veins consist largely of coarse, platy, or needlelike interlocking crystals of graphite. Mineral impurities depend largely upon the host rock; quartz, feldspar, pyroxene, and calcite are common. Ore grades range from 40 to more than 90 percent graphitic carbon; the percentage largely depends on the amount of wallrock contained with the ore material. Hand sorting may be required to provide lump concentrates of high purity.

Graphite vein deposits are found in similar settings as disseminated flake graphite deposits, and they may be spatially associated with them. The Sri Lankan graphite deposits, which are the only economically significant examples of the vein-type deposits, occur in high-grade metamorphic rocks of Neoarchean to Proterozoic age. Most vein deposits and prospects occur in crystalline metamorphic basement rocks of Neoarchean to late Proterozoic age, although deposits may be of any age. The graphite in these deposits occurs as veins in fractures and structures that are emplaced near or after peak metamorphic conditions.

It is clear that the carbon in the vein deposits has been transported by metamorphic or replacement processes, presumably aided by metamorphic or other fluids; however, the nature of the processes responsible for the precipitation of graphite in the veins is uncertain and controversial, and may vary between deposits. Most veins are hosted in high-grade metamorphic rocks; however, graphite precipitation may take place after the most intense deformation and thermal conditions of regional metamorphism have been achieved, as suggested by the localization of veins in brittle structures that are not disturbed by penetrative deformation associated with metamorphism and veins that crosscut syntectonic intrusives

(Rumble and Hoering, 1986; Rumble and others, 1986). In some veins, low-temperature minerals, such as prehnite, occur with graphite. Textural evidence and age determinations on zircon inclusion rims in graphite (Zeitler and others, 1990), however, indicate that some veins were emplaced during or soon after peak metamorphic conditions and that the hydrothermal systems responsible for vein formation may also be responsible for the high-grade metamorphic conditions found in their immediate vicinity (Chamberlain and Rumble, 1988). Carbon isotope studies of the vein deposits show a wide range in isotopic composition between and within districts; this variation may be explained by varying carbon sources from two crustal reservoirs: (a) reduced biogenic carbon, and (b) carbonate minerals (Rumble and Hoering, 1986). The most probable processes resulting in graphite precipitation in veins likely include rock-fluid redox reactions, such as oxidation of methane (CH_4)-bearing fluids or reduction of CO_2-bearing fluids by wall rock (internal or external buffering), cooling of hot fluids saturated with respect to graphite, and mixing of fluids with differing CH_4 and CO_2 contents (Rumble and others, 1986).

The United States has small graphite vein deposits in New Hampshire, Connecticut, the Adirondacks of New York, and Montana; these deposits are largely of only scientific interest. The Crystal Graphite Mine near Dillon, Montana, is the largest known graphite vein deposit in the United States. At this deposit, veins up to 60 cm thick and 15 m long occur in fractures in gneiss and pegmatite (Bastin, 1912); the fractures and veins formed after the peak of metamorphism in these rocks (Ford, 1954).

Mining and Beneficiation Methods

Natural graphite is mined from both open pit and underground mine operations (table J3). Production from open pit operations is less expensive and is preferred where the overburden can be removed economically. Most crystalline flake deposits are mined using open pit methods; the exception is some steeply dipping bodies with high-grade minable lenses containing 15 percent or more contained carbon (table J3). Graphite is stable in the weathering environment, and intensely weathered crystalline flake deposits, such as those in Brazil, Kenya, Madagascar, and Oaxaca, Mexico, can be easily and profitably mined using open pit methods. Underground mining methods are used in some amorphous deposits in China, Europe, the Republic of Korea, and Mexico, and vein deposits in Sri Lanka, where the ore intervals are deep and of high grade (>80 percent contained carbon). Beneficiation processes for graphite vary from simple hand sorting and screening of high-grade ore at some amorphous graphite deposits and at the Sri Lankan vein operations to multistage crushing, screening, washing, and flotation cycles required to produce high-quality and high-purity graphite flake and powder products. No refining of amorphous graphite ore is needed for most uses.

Resources and Production

Distribution of Graphite Deposits and Districts

The world map in figure J2 shows the location of 108 natural graphite deposits and districts characterized as: (a) amorphous deposits that result from thermal or contact metamorphism of highly carbonaceous sediments, usually graphitized coal beds, or (b) crystalline deposits of either disseminated flake graphite, which have resulted from regional metamorphism of carbonaceous sediments under conditions exceeding amphibolite facies, or coarse graphite aggregates (lump or chip) in fracture-filling veins cutting igneous and metamorphic rocks. Both of the crystalline deposit types (flake, or lump and chip) are mostly located in crystalline metamorphic bedrock (fig. J2), consisting primarily of coarse-grained quartzofeldspathic metasedimentary rocks at high metamorphic grades (Chorlton, 2007).

Table J3 describes the features of the 108 natural graphite deposits and districts shown in figure J2 that are known to have produced graphite or are significant prospects with potential for future development. A number of deposits and districts with past production, particularly those in the United States, have grade and tonnage characteristics that render the deposits subeconomic under current conditions; these are included to identify broad areas and regions that may be future sources of graphite production or may contain undiscovered deposits. The names, locations, and descriptions of most of the deposits in table J3 are taken from the International Strategic Minerals Inventory (ISMI) graphite inventory (Krauss and others, 1988) and the U.S. Geological Survey Mineral Resources Data System (MRDS) (U.S. Geological Survey, 2012). Figure J3 shows the deposit grade (percent carbon) and tonnage reported for some of the deposits in table J3, characterized by deposit type. The lowest tonnage and grade deposits in figure J3 are

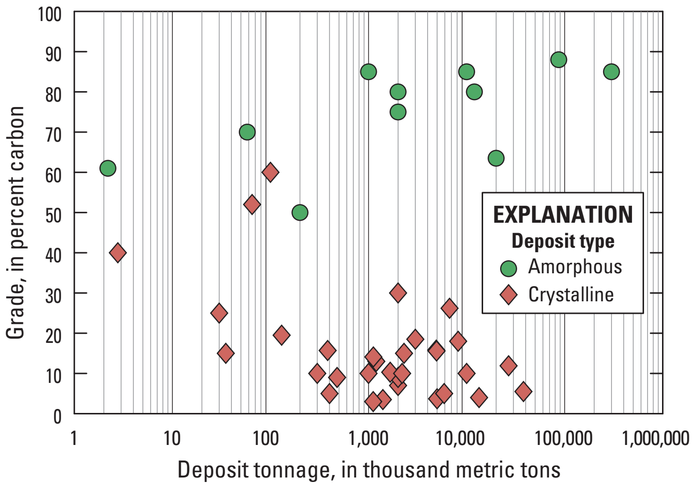


Figure J3. Plot of grade (carbon) and tonnage for some of the amorphous and crystalline graphite deposits listed in table J3, by deposit type. The table also gives additional resource data, and sources.

subeconomic under current market conditions; typical ranges of commercial grades and deposit tonnage, by commodity type, are given in table J1.

World Graphite Production and Resources

Natural graphite is produced by more than 20 nations, but world production is dominated by China, India, and Brazil. Figure J4 shows the average level and amounts of natural graphite produced worldwide by area from 2006 to 2010, based on data from Olson (2011). During this period, China accounted for approximately 67 percent of worldwide production of natural graphite, and established itself as the dominant exporter with the ability to set world prices. China became a major global supplier of graphite in the 1980s owing in part to very low production costs and aggressive marketing. India and Brazil are significant worldwide exporters of graphite whereas Mexico and Canada export mainly to the United States.

Global graphite resources are large relative to annual global consumption, and undoubtedly extensive, but their extent is poorly known because resources of industrial mineral commodities typically are not fully delineated and reported far in advance of development. Complete estimates of graphite resources are likely not available for any single major graphite district in the world. Table J4 tabulates conservative estimates for recoverable graphite resources for a number of major graphite-producing nations. Reserves of natural graphite (that is, the identified, delineated, and reported world resources that are considered to warrant economic exploitation at the time of reserve determination) are equivalent to 81 million metric tons. Approximately 26 percent of reserves are crystalline (flake and vein type [lump or chip]) graphite materials for which demand is increasing. Other identified resources beyond reserves ("Other identified resources" in table J4) are about an additional 1.4 billion metric tons, leading to an estimate of total identified graphite resources of approximately 1.5 billion metric tons worldwide. Approximately one-half of this total resource estimate is flake graphite. Future exploration is likely to result in the discovery of world resources that are many times this estimate; however, many new discoveries are likely to be located in remote areas with high mining costs and limited access to infrastructure and industrial markets that use graphite. The Lac Knife deposit in Quebec, Canada, is an example of a relatively recent discovery in a remote setting (Bonneau and Raby, 1990).

Future discoveries of amorphous and flake graphite deposits in the conterminous United States are likely to be limited by favorable geology and preexisting exploration coverage. The coal fields of the United States are well explored and delineated, and past igneous activity in the coalfields is either absent or of such limited scale that the chance of finding amorphous graphite deposits of commercial size and grade is negligible. Furthermore, with the exception of Alaska, crystalline metamorphic rocks that could potentially host flake and vein (lump or chip) graphite deposits have limited extent and exposure in the United States, and most of the crystalline basement that is present is well characterized. The identified flake graphite deposits in the Kigluaik Mountains of Alaska indicate potential for additional deposits in surrounding areas; however, these are likely to occur in remote areas with rugged terrain and limited infrastructure, and such deposits would be a great distance from graphite markets and have high mining costs. The weathered low-grade crystalline flake deposit districts in Alabama and Texas may provide future domestic sources of graphite if flake graphite prices increase, because of the ease of mining the deposits and their proximity to markets.

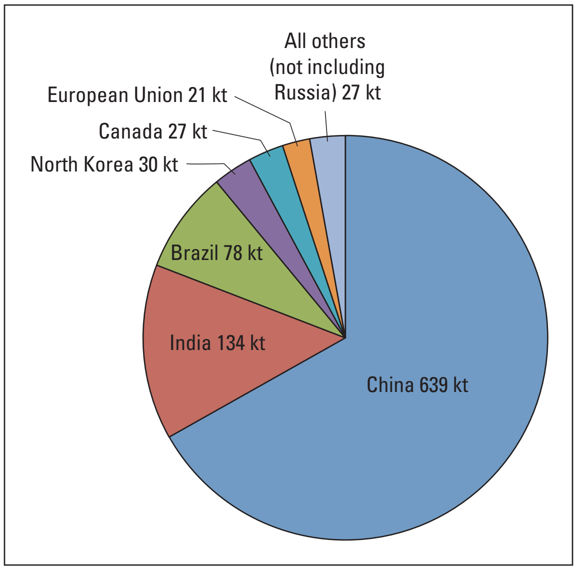


Figure J4. Pie chart showing average annual natural graphite production for the period 2006–10, by country or region and amount (in thousand metric tons [kt]). The tonnages are estimated based on data reported in Olson (2011).

Table J4. Estimates of world graphite resources, by country, commodity type, and resource category, in thousand metric tons of recoverable graphite.

[Resources reported for recoverable amorphous, flake, or crystalline (vein-type) commodity categories. Resource categories: (a) Reserves are demonstrated resources of recoverable natural graphite considered to warrant economic exploitation at the time of reserve determination; (b) Other identified resources are estimates of characterized recoverable resources beyond those reported as reserves; only part of this estimate would be economic; and, (c) Total identified resources includes reserves and other identified resources. Data are adapted from Olson (2013) and Taylor (2006) and rounded to two significant figures. NA, not available]

Country	Type	Reserves	Other identified resources	Total identified resources[1]
Austria	Amorphous	50	1,100	1,200
Brazil	Flake	360	3,400	3,800
Canada	Flake	1,500	4,200	5,700
China	Amorphous	55,000	NA	NA
	Flake	6,000	350,000	360,000
Czech Republic	Flake	900	12,000	13,000
Germany	Flake	130	690	820
India	Flake	735	13,000	14,000
Madagascar	Flake	940	180,000	180,000
Mexico	Amorphous	3,100	10,000	13,000
	Flake	106	320	430
North Korea	Amorphous	1,000	30,000	31,000
	Flake	700	1,400	2,100
Norway	Flake	200	260	460
Republic of Korea	Amorphous	20	2,100	2,100
	Flake	6	74	80
Romania	Amorphous	300	NA	300
Russia, with Ukraine	Amorphous	1,000	560,000	560,000
	Flake	6,400	94,000	100,000
Sri Lanka	Crystalline, vein	50	400	450
	Flake	1,800	7,000	8,800
United States[2]	Amorphous	0	5,900	5,900
	Flake	0	280	280
Zimbabwe	Flake	600	1,200	1,800
Other	Flake	280	920	1,200
Total	**Amorphous**	**60,000**	**750,000**	**810,000**
Total	**Flake**	**21,000**	**670,000**	**690,000**
Total	**Crystalline, vein**	**50**	**400**	**450**
Total	**By resource category**	**81,000**	**1,400,000**	**1,500,000**

[1] Total identified resources includes reserves and other identified resources.

[2] Other identified resources includes Alabama, Alaska, and New York.

Exploration for New Deposits

Prospecting for graphite deposits consists primarily of outcrop examination, trenching, and sampling, usually followed by drilling. Because of its chemical inertness, graphite resists weathering, and outcrops containing graphite and residual soils containing conspicuous graphite flakes may be evident. Knowledge of areal geology and the geologic features and settings of different graphite deposit types and associated deposits, such as coal, can be used to identify promising exploration targets. The Lac Knife flake graphite deposit was initially discovered during routine geologic mapping. When interest developed, the prospect was trenched by shovel, followed by further surface excavation, and later systematically characterized at depth by more than 99 drill holes. All this activity occurred during a more than 30-year time period (Bonneau and Raby, 1990).

Because of the high electrical conductivity of graphite (in deposits where individual graphite flakes are touching), a variety of electromagnetic methods have been used to search for deposits, principally flake graphite deposits. Electro-magnetic geophysical methods measure variations in the electrical conductivity of the ground caused by changes in mineral content, properties, or subsurface features. The methods rely on the process of electromagnetic induction that describes how a conductive material, such as graphite, will interact with a magnetic field. Surveys are conducted by using either surface or airborne methods; all methods use a transmitter and receiver coil spaced in standard configurations. The different methods use different operating frequencies to provide a range of depth penetrations and resolution needed for different applications. High-frequency electromagnetic systems are best for locating small shallow targets; lower frequency systems are used to investigate deeper subsurface conditions or define regional targets. The relative merits of various geophysical techniques in detecting graphite deposits are discussed by Goosens (1982, p. 136).

Graphite flakes may be found in stream sediment samples collected during exploration geochemical surveys. The presence of sulfides and vanadium-bearing garnet (goldmanite) may also be an indicator. There is a positive correlation between carbon, uranium, and vanadium contents in some deposits (Li and others, 1985), and positive vanadium, nickel, and (or) uranium anomalies in soil associated with graphite beds were reported by Tichy and Turnovec (1978) and may be considered a geochemical indicator of graphite deposits. These geochemical features probably relate to the depositional environment and trace element content of the protolith and likely vary among deposits. Therefore, it may be difficult to use these features effectively in grassroots exploration for graphite deposits.

Environmental Considerations

Because of the chemically inert, nontoxic nature of graphite, the main environmental concerns associated with graphite mining are (a) the presence of other minerals that can occur with graphite, and (b) inhalation of graphite particles or fine-grained silica minerals in graphite during mining and processing. For example, the iron sulfide minerals pyrite and pyrrhotite are present in amounts ranging from a trace to several percent in some graphite deposits. These minerals can cause acid-rock drainage if exposed to air and water in waste rock or tailings. Graphite in soils and stream or river sediments is inert and poses no known terrestrial or aquatic risks.

Mine Waste Characteristics

The volumes and mineralogical characteristics of mine wastes depend on the size and type of deposit, as well as the mining and processing practices employed. For open pit mines, the amount of overburden that must be stripped prior to the onset of mining contributes to the mine waste. Ore processing for disseminated flake graphite typically includes milling, flotation, screening, and drying. The resulting mine waste and flotation tailings are composed of the minerals that make up the host rocks, typically schists and gneisses composed mainly of quartz and feldspars. Other silicate minerals in these rocks include pyroxenes, amphiboles, micas, garnet, and sillimanite. These are all moderate- or slow-weathering minerals (Jambor, 2003). Quartz persists in the environment, whereas feldspars weather to clays. Fast-weathering, potentially acid-producing sulfide minerals, such as pyrite and pyrrhotite, are reported at some deposits. The yellow iron sulfate mineral jarosite, which is an indicator of acidic conditions, is a common weathering product of pyritic, gneiss-hosted graphite deposits (Simandl and Kenan, 1997b). Calcite and other carbonate minerals may be present in gangue and can provide acid neutralization if present in sufficient amounts.

The largest known flake graphite deposit, the Zavalyevskiy deposit in Ukraine, has total resources on the order of 100 million metric tons with reserves of 6.4 million metric tons containing 5 to 7 percent graphite (Zavalyevskiy Graphite Ltd., 2013). The ore is kaolinized gneiss that contains garnet, biotite, chlorite, pyroxene, quartz, and sillimanite. Both garnet and crushed stone products are recovered from the ore. The graphite ore is processed by flotation to produce a high-purity graphite concentrate (86 to 97 percent graphite) and ash (10 to 13 percent graphite). Graphite orebodies in graphite schist at the Liu Mao Mine in China are elevated in vanadium (0.2 percent vanadium pentoxide [V_2O_5]), titanium (0.5 percent titanium dioxide [TiO_2]), and uranium (0.004 percent U). These elemental concentrations are attributed to garnet intergrown with graphite in the deposit (Wilde and others, 1999). In Canada, a composite grab sample for metallurgical testing at the Trout Lake (also known as Treelined Lake) graphite prospect in southern Ontario contains 1.8 percent sulfur, which is attributed to 4.5 percent pyrrhotite in the sample; the preliminary test indicated that pyrrhotite removal by screening and flotation would be required to obtain a salable graphite product (Kuehnbaum and Zebruck, 2002). At the Bissett Creek flake graphite deposit in Ontario, both ore and waste rock are recognized as potential acid generators (Systèmes Gèostat International Inc., 2007). The graphite occurs in a calcareous biotite-amphibole-quartzofeldspathic gneiss with disseminated graphite, pyrite, pyrrhotite, and trace chalcopyrite. Graphite concentrations range from about 1 to 10 percent; the sulfide minerals constitute 1 to 5 percent of the rock. Mine plans call for underwater tailings storage and the addition of carbonate-bearing material to the waste dump to neutralize acid potential. In contrast, at the Eagle deposit in British Columbia, high-purity flake graphite is quarried from quartz-rich sands, and slightly alkaline sand and aggregate byproducts are marketed as construction materials.

Amorphous graphite deposits range from about 300 to 800 million metric tons of ore and have higher average graphite grades than other types of graphite deposits (table J1). The ore is essentially the entire graphitized unit. The associated waste primarily is any overburden that must be removed to access the deposit. Mineral impurities in amorphous graphite deposits reflect the compositions of the protolith coal or sediment (Simandl and Kenan, 1997a). In the Bohemia region of the Czech Republic, elevated concentrations of vanadium and nickel anomalies are associated with amorphous graphite deposits (Tichy and Turnovec, 1978). Waste material described as graphite gangue at the Jixi deposit in China contains zinc, nickel, and mercury (Liu and Man, 2007).

Vein graphite from Sri Lanka, which is significant for its purity and high degree of crystallinity, is mined underground at the Bogala Mine (370 m deep) and Kahatagaha-Kolongaha Mine (650 m deep). Total inferred reserves for these two mines are about 400,000 metric tons. At these mines, graphite veins are blasted with dynamite. When the fumes clear, the ore is hauled to the surface and then hand cobbed and graded; no further processing is required, so no tailings or large waste piles are produced (Ranasinha and Uragoda, 1972). Hydrothermal minerals associated with the graphite from Sri Lanka include apatite, biotite, calcite, chalcopyrite, pyrite, and quartz. The average chemical contents reported for different vein graphite morphologies from the Bogala and the Kahatagaha-Kolongaha Mines reported by Touzain and others (2010) are as follows: 93 to 99 percent carbon, 0.06 to 1.06 percent iron oxide (Fe_2O_3), 0.05 to 0.45 percent silicon dioxide (SiO_2), 0.01 to 0.19 percent sulfur, and 0.004 to 0.82 percent calcium oxide (CaO).

Human Health Concerns

The primary human health concern associated with graphite mining is inhalation of dust and fumes generated during mining and processing. Graphite is not considered to be toxic and is not a listed carcinogen, although crystalline silica (a common impurity in graphite) is considered to be carcinogenic. Graphite is considered a nuisance dust. The time-weighted average (TWA) recommended exposure level set by the U.S. National Institute for Occupational Safety and Health (NIOSH) is 2.5 milligrams per cubic meter.

Chronic exposure to graphite dust is associated with pneumoconiosis, a group of lung diseases associated with chronic exposure to mineral and metallic dusts. Graphite pneumoconiosis was recognized in the 1940s in graphite workers in Sri Lanka based on similarities to pneumoconiosis in coal miners (Uragoda, 1997). The fact that graphite always contains some quartz (typically about 2 percent but up to 10 percent) raised concerns that graphite pneumoconiosis was actually a slow developing form of silicosis (Ranasinha and Uragoda, 1972). A review of 605 cases of graphite pneumoconiosis reported in the literature and experimental studies on animals concluded that although many years of occupational exposure to pure graphite may cause disease, most studies indicate that mixed-dust inhalation is a more likely cause of lung disease (Hanoa, 1983). Implementation of dust abatement protocols in mining and processing has resulted in decreased incidence of lung disease in graphite workers since the 1970s.

Ecological Health Concerns

The environmental fate and effects of dispersed graphite flakes were addressed in a study of the use of graphite flakes in a dust cloud to obscure visual and electromagnetic observation of military operations under battlefield conditions (Driver and others, 1993). Graphite mixed with fog oil and dispersed as an aerosol provides a chemically inert obscurant used to protect movements of troops and equipment. Dispersion of airborne plumes of these mixtures can deposit graphite on soil, vegetation, and water surfaces or pose inhalation risks to wildlife. Although obscurant releases are short-term events (~30 minutes), airborne distribution and surface deposition of flake graphite can occur many kilometers downwind of the release site. Deposited graphite persists in the environment, so the repeated use on military training sites warranted an evaluation of potential ecological impacts. These studies are not directly applicable to graphite mining and processing, but they do demonstrate that graphite flakes likely pose little or no chemical risk to the environment. The series of experiments described by Driver and others (1993) showed that (a) graphite flakes are not toxic to soil invertebrates (*oligochaeta*, or earthworms), (b) no adverse effects on terrestrial plants (corn and cucumber) were noted in soils amended with graphite flakes in concentrations up to 0.5 percent, by weight, and (c) a 48-hour acute aquatic toxicity test toward *daphnia* (water fleas) using graphite suspensions was toxic; however, iron contaminants in the graphite may explain the toxicity. The long-term effects of obscurant flake graphite on exposed avian and mammalian wildlife are unknown.

Carbon Footprint

The term "carbon footprint" refers to the amount of carbon dioxide (CO_2) emitted in a 1-year period. According to GrafTech International Holdings, Inc. (2013), natural graphite has a substantially lower carbon footprint for both CO_2 emissions and energy consumption during mining and processing than other mineral commodities for which data are available, such as aluminum or copper, on an equivalent mass, volume, or yearly production basis. Cost- and energy-efficient technologies that could reduce CO_2 to synthetic graphite could lower CO_2 emissions and produce inert graphite, providing an industrial option to sequester carbon from the atmosphere (Xu and others, 2005).

Regulatory and Environmental Considerations

The environmental requirements for natural graphite, which is an inert, nontoxic substance, are limited to dust control and control of organic vapors that may arise during mining or processing of graphite ores or the fabrication of graphite products. Given the current and likely future absence of graphite mining in the United States, no other domestic regulatory or environmental requirements are anticipated.

Problems and Future Research

Major shifts in U.S. consumption of natural graphite by end use are underway and include a long-term decrease in the use of amorphous graphite for refractory and other applications and an increase in the use of flake graphite, particularly for emerging energy and high-technology applications (Taylor, 2006). In addition, shifts in the global graphite supply and exports are anticipated as China's rapidly growing domestic market for graphite, coupled with their developing mine production problems and rising labor costs, may serve to limit Chinese exports in the future, particularly of crystalline flake graphite; meanwhile, anticipated large-scale fuel cell and battery applications could dramatically increase world demand for graphite (Taylor, 2006; Olson, 2013; Olson and others, 2016). For the near future, however, China's graphite production is expected to increase and its dominance of world production to continue (Olson, 2013). Possible disruptions to global supplies are likely to be temporary or sporadic because identified reserves in China are sufficient to support new mines and additional production. In addition, exploration for new flake graphite deposits is ongoing, and additional deposits are near development in Canada and elsewhere (Olson, 2013; Olson and others, 2016).

Other than scientific studies on some vein graphite deposits of scientific (not commercial) interest, little recent geologic characterization and study has been undertaken on graphite deposits in the United States, and exploration for new deposits has not taken place. The lack of exploration is chiefly because known deposits are considered noncommercial, large areas of the country lack the geologic conditions and settings thought necessary to form economic graphite deposits, graphite supplies have been reliably available from foreign sources for many years, and synthetic graphite is increasingly used for many applications. As earlier noted by Weis (1973), research and development of better techniques to beneficiate low-grade flake graphite ores would be needed to support a viable domestic industry.

Studies on the temporal variation of carbon deposition and preservation and the behavior of organic matter and graphite under metamorphic and hydrothermal conditions might provide additional insights into the occurrence and distribution of high-grade flake graphite deposits. Many of the important flake graphite deposits worldwide occur in Precambrian crystalline metamorphic rocks, and most of these occur in Pan-African age supracrustal metamorphic belts. In addition, many of these deposits have grades exceeding 15 percent contained carbon, which exceeds the typical carbon content range of organic-bearing shales (Vine and Tourtelot, 1970). It is not known whether these deposits represent unusual protoliths—for example, saprolitic alginate (oil-shale), unusual periods or regions of biological productivity and preservation of organic matter, or if they record some carbon enrichment owing to mechanical deformation or precipitation of graphite by processes involving internal or external buffering or mixing of metamorphic fluids.

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