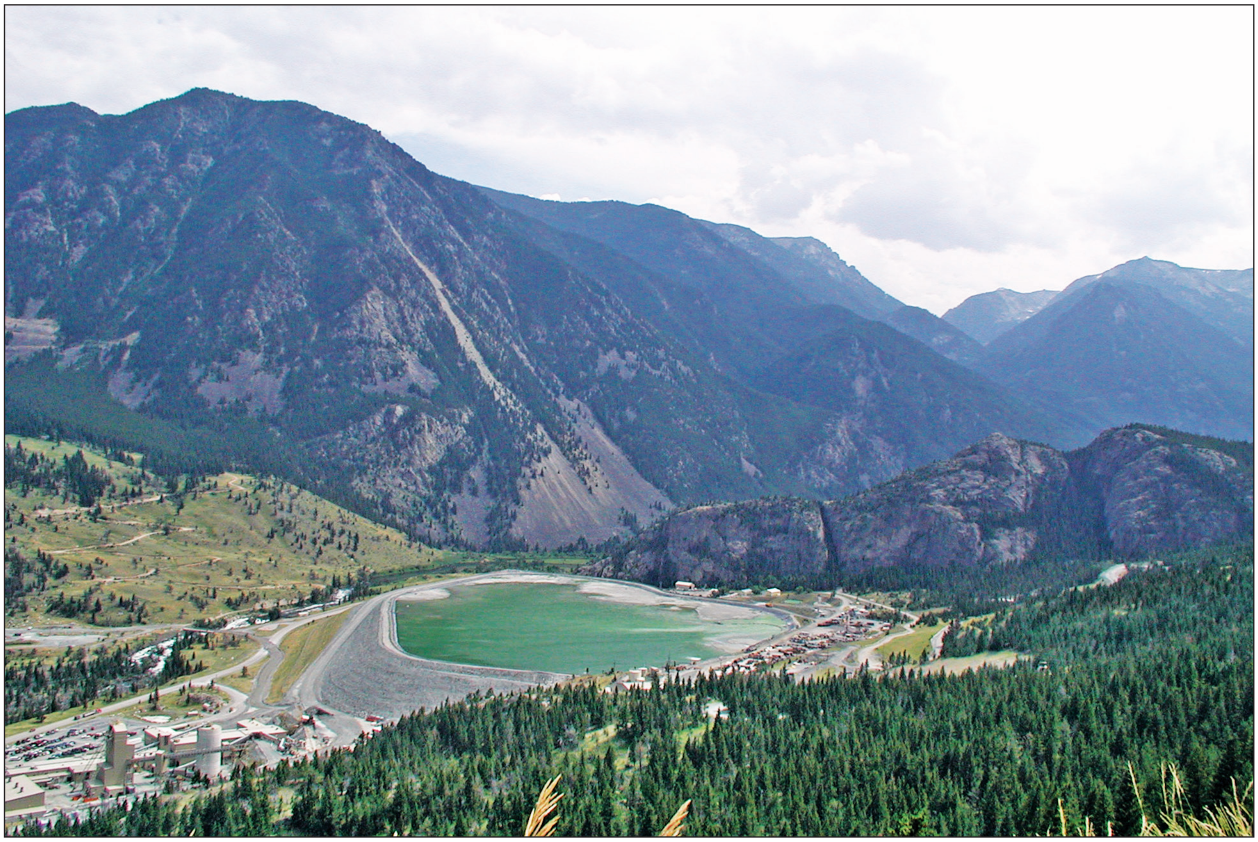
Platinum-Group Elements

Chapter N of

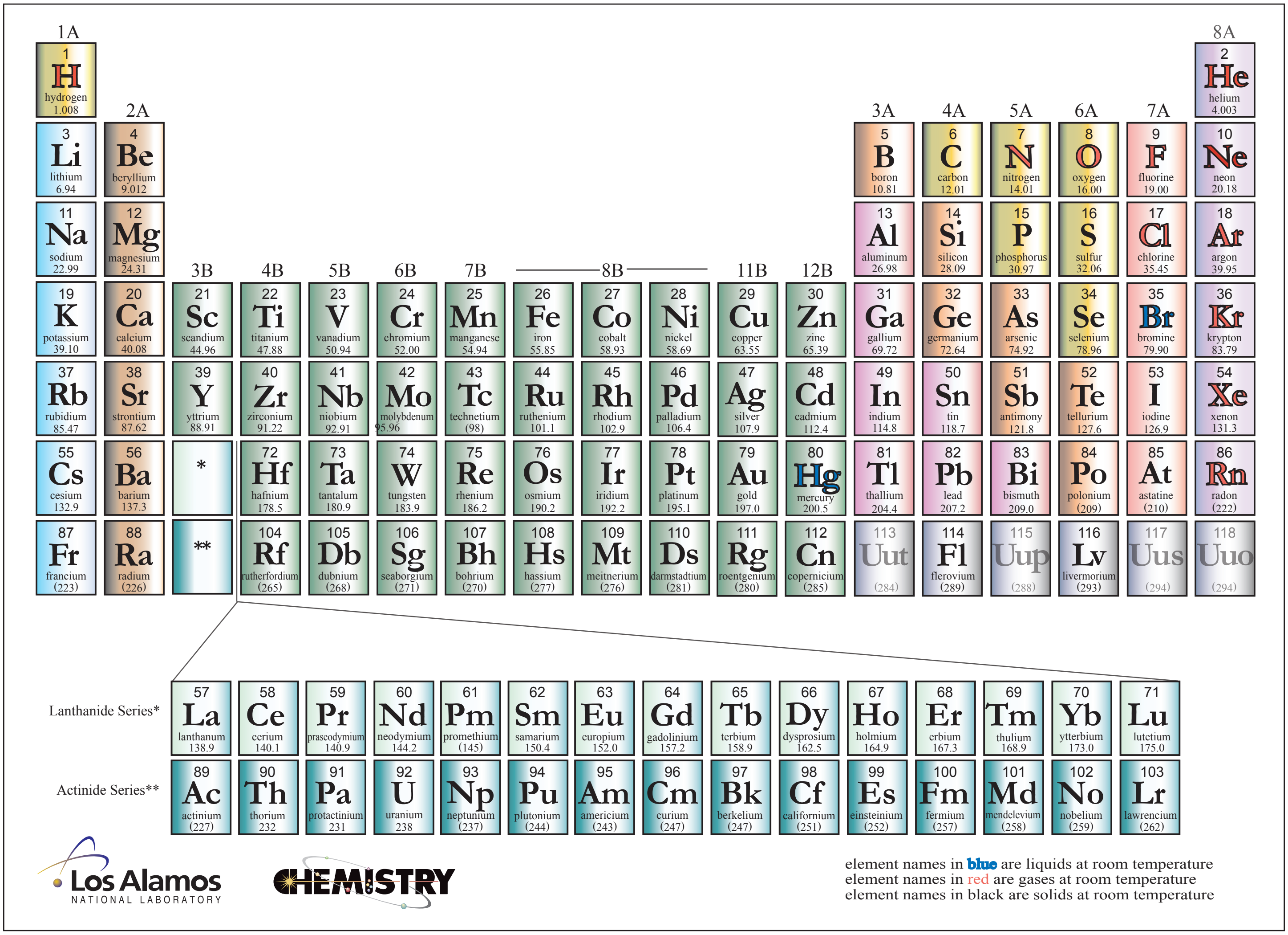
Critical Mineral Resources of the United States—Economic and Environmental Geology and Prospects for Future Supply



Professional Paper 1802–N

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. Stillwater Mine in south-central Montana, looking southeast. The pond is the tailings impoundment. The buildings in the lower left include the shaft, the mill complex, and offices. Photograph by Michael L. Zientek, 2006.

Platinum-Group Elements

By Michael L. Zientek, Patricia J. Loferski, Heather L. Parks, Ruth F. Schulte,
and Robert R. Seal II

Chapter N of

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

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

Professional Paper 1802–N

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

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

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

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

Suggested citation:
Zientek, M.L., Loferski, P.J., Parks, H.L., Schulte, R.F., and Seal, R.R., II, 2017, Platinum-group elements, chap. N *of* Schulz, K.J., DeYoung, J.H., Jr., Seal, R.R., II, and Bradley, D.C., eds., Critical mineral resources of the United States—Economic and environmental geology and prospects for future supply: U.S. Geological Survey Professional Paper 1802, p. N1–N91, https://doi.org/10.3133/pp1802N.

ISSN 2330-7102 (online)

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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

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/t	gram per metric ton
ICP–MS	inductively coupled plasma-mass spectrometry
kg	kilogram
kg $CaCO_3$/t	kilogram of calcium carbonate per metric ton
km	kilometer
km^2	square kilometer
km^3	cubic kilometer
LED	light-emitting diode
LIP	large igneous province
m	meter
Ma	mega-annum
MSS	monosulfide solution
m.y.	million years
PEM	proton exchange membrane
PGE	platinum-group element
PGM	platinum-group metal
ppb	part per billion
ppm	part per million
ppt	part per trillion
USGS	U.S. Geological Survey

Platinum-Group Elements

By Michael L. Zientek, Patricia J. Loferski, Heather L. Parks, Ruth F. Schulte, and Robert R. Seal II

Abstract

The platinum-group elements (PGEs)—platinum, palladium, rhodium, ruthenium, iridium, and osmium—are metals that have similar physical and chemical properties and tend to occur together in nature. PGEs are indispensable to many industrial applications but are mined in only a few places. The availability and accessibility of PGEs could be disrupted by economic, environmental, political, and social events. The United States net import reliance as a percentage of apparent consumption is about 90 percent.

PGEs have many industrial applications. They are used in catalytic converters to reduce carbon monoxide, hydrocarbon, and nitrous oxide emissions in automobile exhaust. The chemical industry requires platinum or platinum-rhodium alloys to manufacture nitric oxide, which is the raw material used to manufacture explosives, fertilizers, and nitric acid. In the petrochemical industry, platinum-supported catalysts are needed to refine crude oil and to produce aromatic compounds and high-octane gasoline. Alloys of PGEs are exceptionally hard and durable, making them the best known coating for industrial crucibles used in the manufacture of chemicals and synthetic materials. PGEs are used by the glass manufacturing industry in the production of fiberglass and flat-panel and liquid crystal displays. In the electronics industry, PGEs are used in computer hard disks, hybridized integrated circuits, and multilayer ceramic capacitors.

Aside from their industrial applications, PGEs are used in such other fields as health, consumer goods, and finance. Platinum, for example, is used in medical implants, such as pacemakers, and PGEs are used in cancer-fighting drugs. Platinum alloys are an ideal choice for jewelry because of their white color, strength, and resistance to tarnish. Platinum, palladium, and rhodium in the form of coins and bars are also used as investment commodities, and various financial instruments based on the value of these PGEs are traded on major exchanges.

PGEs are among the rarest metals; Earth's upper crust contains only about 0.0005 part per million (ppm) platinum. Today, the average grade of PGEs in ores that are mined primarily for their PGE concentrations varies from 5 to 15 ppm, although the concentration of PGEs in hand-picked ore specimens may range from tens to hundreds of parts per million.

More than 100 different minerals have one of the PGEs as an essential component. PGE minerals occur as native metals. They also occur as compounds with other transition metals (copper, iron, mercury, nickel, and silver), post-transition metals (bismuth, lead, and tin), metalloids (antimony, arsenic, and tellurium), and nonmetals (selenium and sulfur).

From 1900 to 2011, approximately 14,200 metric tons of PGEs was produced, and roughly 95 percent of that production (13,500 metric tons) took place between 1960 and 2011. The breakdown of production by country shows that, since 1900, about 90 percent of the production came from South Africa and Russia. The secondary supply of platinum, palladium, and rhodium is obtained through the recycling of catalytic converters from end-of-life vehicles, jewelry, and electronic equipment. Recycled platinum, palladium, and rhodium provide a significant proportion of the world's total supply; these secondary sources are sufficient to close the gap between world mine production and consumption.

Exploration and mining companies report resources of about 104,000 metric tons of PGEs (including minor amounts of gold) in mineral deposits around the world that could be developed. For PGEs, almost all the reported production and identified resources are associated with deposits in three geologic features—the Bushveld Complex, which is a layered mafic to ultramafic intrusion in South Africa; the Great Dyke, which is a layered mafic to ultramafic intrusion in Zimbabwe; and sill-like intrusions associated with flood basalts in the Noril'sk-Talnakh area of Russia.

The metallic forms of PGEs are generally considered to be inert. PGEs pose a risk to human health only in cases where individuals are occupationally exposed to synthetic PGE compounds, especially workers in precious-metal refineries. In the natural environment, background PGE concentrations are low in water, sediment, soil, and plants. Anthropogenic sources of PGEs in the environment include catalytic converters used in modern automobiles, platinum-based chemotherapy drugs, and smelter emissions.

The abundance of sulfide minerals defines the environmental and geologic characteristics of PGE-enriched magmatic sulfide deposits; those deposits with the highest amount of sulfide minerals could have the highest environmental impact. Acid rock drainage from reef-type and contact-type deposits

is unlikely because the ores and their host rocks contain low proportions of sulfide minerals. For some conduit-type orebodies with massive ores, mineral-processing techniques separate and produce concentrates of copper-, iron-, and nickel-bearing sulfide minerals; those with copper and nickel are processed to extract metal, but the iron-sulfide minerals, mainly pyrrhotite, are discarded as waste. This results in waste material with a high acid-generating potential.

The most significant primary source of PGEs in the United States is a deposit in the Stillwater Complex, which is a layered igneous intrusion in Montana. Approximately 305 metric tons of platinum and palladium have been mined from the Stillwater Complex deposit since 1986. Exploration and development drilling indicate that another 2,200 metric tons are present. Mining has progressed to depths of 1,800 meters below the surface, but the bottom of the ore deposit has not been reached; geologic estimates suggest that another 1,000 to 6,200 metric tons of PGEs could be present at depth. In the future, PGEs may be mined from deposits found near the base of the Duluth Complex, which is a group of igneous intrusions in Minnesota.

Introduction

The platinum-group elements (PGEs)—platinum, palladium, rhodium, ruthenium, iridium, and osmium—are chemical elements that have similar physical and chemical properties and tend to occur together in nature. They are transition metals, lying in Group 8B and periods 5 and 6 of the periodic table of elements. Along with gold and silver, they are also precious metals that have high economic value determined not only by their practical uses but also by their role as investment instruments and as a store of value. The PGEs are also known as the platinum-group metals (PGMs).

Pre-Columbian peoples found naturally occurring platinum and platinum-rich alloys in stream deposits in Colombia and Ecuador. In the 1500s, Spanish colonists also found grains of these alloys mingled with gold nuggets they recovered from stream deposits in the same area; they called the metal "platina" (McDonald and Hunt, 1982). At that time, the metal had no known use and was considered worthless. The platinum-rich grains were a nuisance because they could not be separated from gold nuggets by panning. Small samples of platinum-enriched nuggets from South America reached Europe during the 1740s. Platinum was described as a new metal in 1750, followed by iridium and osmium in 1803, palladium and rhodium in 1804, and ruthenium in 1807. The unique properties of the metals were realized later in the 19th century.

PGEs are essential for important industrial applications but are mined in only a limited number of places. Therefore, the availability and accessibility of PGEs could be disrupted by economic, environmental, political, and social events. This is not a new development. During World War I, the United States considered platinum a "vital war material" needed for the production of amplifiers, magnetos, munitions, shell primers, and sulfuric acid, and it was ranked second on the "list of strategic raw material" for which the United States was either entirely or partially dependent on foreign countries (Lael and Killen, 1982). During World War II, these metals had even greater strategic importance to science and industry, and the United States was still dependent on sources in foreign countries (DeMille, 1947; U.S. Bureau of Mines and U.S. Geological Survey, 1947). Security of supply was also a concern during the Cold War (U.S. Congress, Office of Technology Assessment, 1985; Sutphin and Page, 1986). With the dissolution of the Soviet Union and the peaceful transition of government in South Africa in the early 1990s, import vulnerability became less of an immediate concern. The United States net import reliance as a percentage of apparent consumption is still about 90 percent, however, and the main sources of these elements are still limited to a few mineral deposits in South Africa and Russia (Loferski, 2012a, b). The potential restrictions on supplies of critical raw minerals, such as the PGEs, have again become a topic for international concern and discussion (National Research Council of the National Academies, 2008; Buchert and others, 2009; European Commission, 2010; American Physical Society Panel on Public Affairs and Material Research Society, 2011; British Geological Survey, 2012).

This chapter summarizes how the PGEs are used, gives an overview of where PGEs are mined, and summarizes how much mineralized material has been found by mineral exploration companies. The geology of significant deposits is described, and the assessment for undiscovered resources is discussed, as are possible topics for future research. The report also discusses environmental aspects of the PGEs, including their sources and fate in the environment; mine waste characteristics; and human health, ecological, and carbon footprint concerns. Where indicated, data in tables 1 through 9 are taken from data prepared by the authors in table 10 (back of chapter).

Uses, Applications, and Consumption

The PGEs possess excellent catalytic and stable electrical properties. PGEs are also highly resistant to wear, tarnishing, and chemical attack, and can withstand high temperatures, making them indispensable to many industrial applications. Their leading use is as catalysts for oxidation and reduction reactions that decrease hydrocarbon, carbon monoxide, and nitrous oxide emissions in automobile exhaust (fig. N1). The chemical industry requires either platinum or platinum-rhodium alloy to manufacture nitric oxide, which is a raw material used to manufacture explosives, fertilizers, and nitric acid. PGEs are also used in the production of specialty silicones, which, in turn, have many uses, such as in coatings on automobile airbags, water repellent coatings, and adhesives for sticky notes. In the petrochemical industry, platinum-supported catalysts are needed to refine crude oil and to produce high-octane gasoline and aromatic compounds.

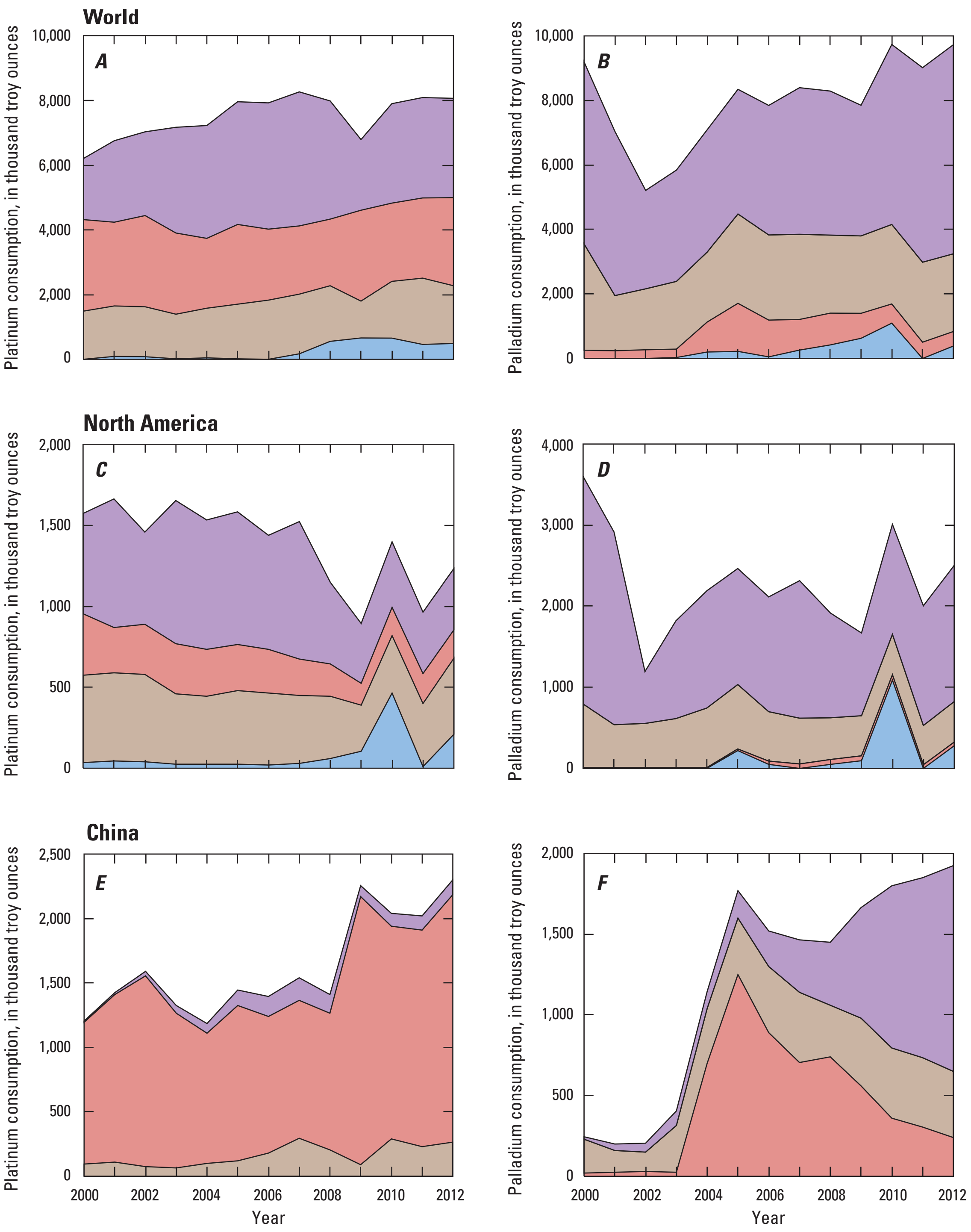


Figure N1. Graphs showing platinum and palladium consumption, by category of use, from 2000 to 2012 for the world (*A* and *B*), North America (*C* and *D*), and China (*E* and *F*). The decrease in platinum consumption for North America is directly related to the decreased production of cars and trucks during the same period (Organisation Internationale des Constructeurs d'Automobiles, 2013). The graphs also illustrate how consumption of platinum jewelry varies by region. In each graph, the layers are placed one above the other, forming a cumulative total. Created from data in Platinum Today (2013c).

EXPLANATION

- 🟪 **Autocatalyst**
- 🟥 **Jewelry**
- 🟫 **Industrial**
- 🟦 **Investment**

Alloys of PGEs are exceptionally hard and durable, making them the best known coating for industrial crucibles used in the manufacture of chemicals and synthetic materials, such as high-purity single crystals used in the production of light-emitting diodes (LEDs). PGEs are used by the glass manufacturing industry in the production of fiberglass and flat-panel and liquid crystal displays. In the electronics industry, PGEs are used in computer hard disks to increase storage capacity, and they are ubiquitous in electronic devices, hybridized integrated circuits, and multilayer ceramic capacitors. Platinum does not corrode inside the body, and allergic reactions to platinum are extremely rare; therefore, it is used in medical implants, such as pacemakers. PGEs are also used in cancer-fighting drugs. Other uses of PGEs include gas sensors in automobiles and homes, spark plug tips, and additives to superalloys (Impala Platinum Holdings Ltd., 2012; Loferski, 2013a; Platinum Today, 2013a).

Their white color, strength, and resistance to tarnish make platinum alloys an ideal choice for jewelry (Platinum Today, 2013b). In parts of Ecuador and Colombia before the Spanish conquest, platinum was used by indigenous peoples for the fabrication of small objects, as well as sintered with gold, and incorporated into bimetallic and platinum-clad articles (fig. N2; Scott and Bray, 1980; Meeks and others, 2002; Noguez and others, 2006). Their masterworks reflect a high degree of technical innovation because the high melting temperature of platinum (1,769 degrees Celsius [ºC]) requires sophisticated manufacturing techniques and craftsmanship. The modern tradition of using platinum for jewelry began in Europe in the 18th century. The works produced by Cartier and Tiffany in the late 19th century and early 20th century created interest in platinum jewelry, particularly in the United States. The Great Depression of the 1930s and the advent of World War II suppressed the platinum jewelry market in the United States. In the 1960s, demand for platinum jewelry in Japan surged, followed by a surge in demand in China in the mid-1990s.

Platinum, palladium, and rhodium are also used for investment in the form of physical or financial assets. Physical assets include platinum and palladium as collectible coins, or as bullion coins, bars, or wafers. Financial assets include stocks, mutual funds, and exchange-traded funds. Financial assets allow investors to own platinum, palladium, and rhodium without the difficulties associated with physically holding the metal.

Figure N2. Photograph of gold mask with platinum highlights, from the period of La Tolita culture, Ecuador. From Museo Nacional del Banco Central del Ecuador collection.

Geology

Geochemistry

All chemical elements heavier than oxygen, including the PGEs, are created by nuclear fusion and nucleosynthesis processes during supernova explosions. The matter derived from supernova explosions is dispersed into the interstellar medium and enriches molecular clouds, which are sites of star and planetary formation. Earth formed from the same cloud of matter as the sun, so the bulk PGE composition of Earth is thought to be similar to that of the solar system. Carbonaceous meteorites of the Ivuna type (carbonaceous chondrites [type 1], or C1 chondrites) are used to estimate solar system abundances (Lodders, 2010). The Orgueil meteorite, which is considered most representative of the C1 chondrites, contains 0.947 part per million (ppm) platinum.

Early in its evolution, Earth differentiated into a metallic core, a silicate mantle, and a silicate crust. The segregation processes affected the distribution of the PGEs and resulted in concentrations progressively decreasing from core to mantle to upper crust. The range of platinum concentration in samples of iron meteorites, which are perhaps the best analogs for the composition of Earth's core, is 2.4 to 16 ppm (Wasson and others, 1989). The average platinum concentrations of samples of the upper mantle vary from about 0.002 to 0.005 ppm (2 to 5 parts per billion [ppb]) (Maier and others, 2012). In contrast, the upper crust is estimated to contain only 0.0005 ppm (0.5 ppb) platinum (Rudnick and Gao, 2003). Today, the average grade of PGEs in ores that are mined primarily for their PGE concentrations ranges from 5 to 15 ppm; however, the concentration of PGEs in hand-picked ore specimens may range from tens to hundreds of parts per million.

Mineralogy

The PGEs can occur as an essential component of the crystal structure of a mineral (a naturally occurring inorganic element or compound having a periodically repeating arrangement of atoms and characteristic chemical composition, resulting in distinctive physical properties). The Commission on New Minerals, Nomenclature and Classification of the International Mineralogical Association has recognized more than 100 different minerals in which at least one of the PGEs is an essential component (Cabri, 2002); they are called platinum-group minerals. Platinum-group minerals include native-metal-minerals and compounds with other transition metals (such as copper, iron, mercury, nickel, and silver), post-transition metals (such as bismuth, lead, and tin), metalloids (such as antimony, arsenic, and tellurium), and nonmetals (such as selenium and sulfur) (table N1). In most rocks, platinum-group minerals are fine-grained and range in size from less than a micron to a few hundred microns in diameter. Most geologists can spend a lifetime working on rocks enriched in PGEs and never see a platinum-group mineral in a hand specimen. Yet the platinum-group minerals are important to characterize because information about their mineralogy is needed to extract metals from their ore minerals effectively and to understand ore-forming processes.

PGEs also occur in solid solution in base-metal sulfides and sulfarsenides. In solid solution, different chemical elements can substitute in specific atomic sites without changing a mineral's crystalline structure. For example, palladium can substitute for nickel in pentlandite (Cabri, 1992); the amount of substitution can be significant and is detectable by several microanalytical techniques. PGEs also occur in solid solution in nickeliferous cobaltite (nickel-iron sulfarsenide) in ores mined at the Copper Cliff North Mine in Sudbury, Ontario, Canada (Szentpéteri and others, 2002). Low-level concentrations of PGEs in solid solution in base-metal sulfide minerals can be assessed using laser-ablation inductively coupled plasma-mass spectrometry (ICP–MS) (for example, Cabri and others, 2003; Godel and others, 2007; Pagé and others, 2012). These studies document that pentlandite is the principal base-metal sulfide mineral that hosts PGEs. Pyrrhotite ($Fe_{1-x}S$) can contain some iridium, osmium, rhodium, and ruthenium, but not palladium or platinum. Chalcopyrite ($CuFeS_2$) does not contain significant amounts of PGEs in solid solution. Platinum and gold do not partition into base-metal sulfide minerals.

Deposit Types

Mineral deposits can be classified into groups or types based on common features and associations that ultimately relate to the underlying geologic processes that formed the ore. Each mineral deposit type has characteristic geometries, distributions of tonnage and grade, and rock and mineral properties that determine the potential value of the deposit. Each deposit type also has specific characteristics that determine how much sampling will be required to delimit the deposit's mineral resources and in what manner the valuable material will be mined and processed. Furthermore, each deposit type exerts a specific impact on the environment, whether through natural weathering processes or the result of mining.

At a basic level, economic geologists recognize the following mineral deposit types: (a) magmatic—formed during the cooling and crystallization of magma, (b) hydrothermal—formed by the interaction of hot water and rock, (c) sedimentary—formed by the precipitation or settling of minerals directly from water in oceans or lakes, (d) residual—formed by the intense weathering of rocks under hot, humid conditions, and (e) placers—formed by the physical concentration of heavy particles of rocks or minerals by the action of moving water. PGE-enriched rocks can be found in each of the deposit types listed above. The following sections describe examples of PGE mineralization found in each of these deposit types. More information is given for magmatic deposits because they are the source of almost all the PGEs recovered by mining. The locations of the world's major and minor PGE deposits are shown in figure N3.

Magmatic Deposits

PGEs are transferred from Earth's mantle to its crust by magnesium-rich magmas that were formed by the melting of a high percentage of mantle material from which magma had not been previously extracted. A high degree of partial melting is needed to release PGEs into the melt from the small quantities of sulfide minerals or alloys that are present in the mantle. Upon emplacement in the crust, the magnesium-rich magmas cool to form mafic and ultramafic igneous rocks.

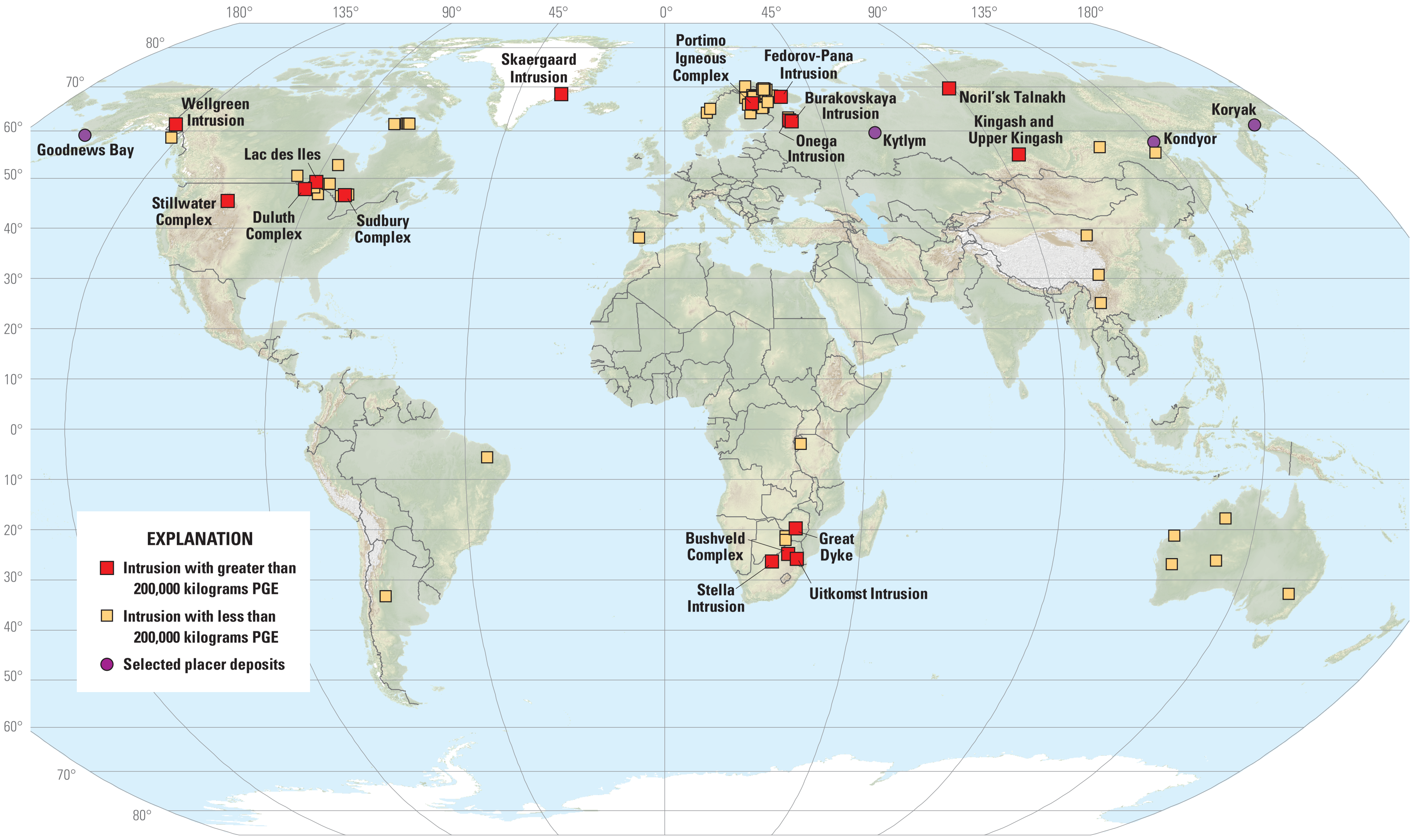
Magmatic deposits are concentrations of metallic oxide or sulfide minerals that formed during the cooling and crystallization of magma. Textural and experimental evidence indicate that PGE-enriched mineralization forms when mafic to ultramafic magma becomes saturated with sulfur and an immiscible sulfide liquid exsolves from the silicate magma (Barnes and others, 2008; Holwell and McDonald, 2010; Naldrett, 2010a). The solubility of sulfur in mafic magmas is affected by changes in the bulk composition of the magma, the fugacity of sulfur and oxygen, temperature, and pressure (Ripley, 1999). Processes that change the solubility of sulfur and may cause an exsolution event include (a) fractional crystallization of the silicate magma, (b) mixing of magmas, (c) assimilation of additional sulfur from sources external to the magma, and (d) modification of the magma composition by bulk contamination, such as changing the silica content of the magma (Mungall, 2005).

The silicate magma solidifies first, followed by the sulfide liquid, which solidifies at temperatures in excess of 900 °C. The textures and mineralogy of PGE ores record a prolonged and complex process of solid-state transformation and

Table N1. Chemical formulas for selected platinum-group minerals as well as other common rock-forming minerals mentioned in this chapter.

[Sources: Deer and others (1966); Vaughan and Craig (1978); and Cabri (2002). Elements: Al, aluminum; As, arsenic; Bi, bismuth; C, carbon; Ca, calcium; Cr, chromium; Cu, copper; Fe, iron; Hg, mercury; Ir, iridium; K, potassium; Mg, magnesium; Na, sodium; Ni, nickel; O, oxygen; Os, osmium; Rh, rhodium; Ru, ruthenium; Pb, lead; Pd, palladium; Pt, platinum; S, sulfur; Sb, antimony; Si, silicon; Sn, tin; Te, tellurium]

Mineral name	Chemical formula
PLATINUM-GROUP MINERALS	
Native metals	
Iridium	Ir
Osmium	Os
Palladium	Pd
Platinum	Pt
Rhodium	Rh
Ruthenium	Ru
Compounds with transition metals	
Isoferroplatinum	Pt_3Fe
Potarite	PdHg
Tulameenite	$PtFe_{0.5}Cu_{0.5}$
Compounds with post-transition metals (Bi, Pb, and Sn)	
Atokite	Pd_3Sn
Froodite	$PdBi_2$
Insizwaite	$PtBi_2$
Rustenburgite	Pt_3Sn
Paolovite	Pd_2Sn
Compounds with metalloids	
Genkinite	$(Pt,Pd)_4Sb_3$
Geversite	$PtSb_2$
Isomertieite	$Pd_{11}Sb_2As_2$
Kotulskite	PdTe
Merenskyite	$PdTe_2$
Moncheite	$PtTe_2$
Sperrylite	$PtAs_2$
Stibiopalladinite	$Pd_{5+x}Sb_{2-x}$
Stillwaterite	Pd_8As_3
Sudburyite	PdSb
Compounds with nonmetals	
Braggite	(Pt,Pd)S
Cooperite	PtS
Erlichmanite	OsS_2
Laurite	RuS_2
Vysotskite	PdS
Other	
Hollingworthite	RhAsS
Maslovite	PtBiTe
Michenerite	PdBiTe
Ruarsite	RuAsS
BASE-METAL SULFIDE MINERALS	
Bornite	Cu_5FeS_4
Chalcopyrite	$CuFeS_2$
Covellite	CuS
Cubanite	$CuFe_2S_3$
Marcasite	FeS_2
Mooihoekite	$Cu_9Fe_9S_{16}$
Nickeliferous cobaltite	Co(Ni)AsS
Pentlandite	$(Fe,Ni)_9S_8$
Pyrite	FeS_2
Pyrrhotite	$Fe_{(1-x)}S$
Talnakhite	$Cu_9(Fe, Ni)_8S_{16}$
Troilite	FeS
OTHER ROCK-FORMING MINERALS	
Calcite	$CaCO_3$
Chlorite	$(Mg,Fe)_3(Si,Al)_4O_{10}(OH)_2 \bullet (Mg,Fe)_3(OH)_6$
Chromite	$(Fe,Mg)(Cr,Al)_2O_4$
Goethite	FeO(OH)
Gypsum	$CaSO_4$
Jarosite	$KFe(SO_4)_2(OH)_6$
Magnetite	Fe_3O_4
Native sulfur	S
Olivine	$(Mg,Fe)_2SiO_4$
Plagioclase	$(Ca,Na)(Si,Al)_4O_8$
Pyroxene	$Ca(Mg,Fe)Si_2O_6$ to $Mg_2Si_2O_6$
Serpentine	$(Mg,Fe)_3Si_2O_5(OH)_4$
Talc	$Mg_3Si_4O_{10}(OH)_2$



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 N3. World map showing locations of igneous intrusions and intrusive complexes that contain most of the world's platinum-group-element (PGE) deposits, as well as the placer deposits that are mentioned in the text. On the map, intrusions and intrusive complexes are considered to be major when they contain 200,000 kilograms (kg) or more of PGEs, and minor when they contain less than 200,000 kg of PGEs.

recrystallization after solidification (Barnes and others, 2008; Holwell and McDonald, 2010). At high temperature (about 1,000 °C), osmium, iridium, and ruthenium preferentially partition from the immiscible sulfide liquid into a mineral called monosulfide solid solution (MSS). Platinum, palladium, and gold, on the other hand, behave as incompatible elements with respect to MSS and instead are concentrated in residual copper-rich sulfide liquids and associated with the minerals that crystallize from the residual immiscible sulfide liquid. Upon cooling, some of the PGEs held in sulfide crystal structures are expelled, forming discrete minerals. The final mineral assemblage consists of varied proportions of pyrrhotite, pentlandite, chalcopyrite, and bornite, with platinum and gold occurring primarily in platinum-group minerals.

Magmatic sulfide minerals in mafic to ultramafic igneous rocks do not always contain elevated concentrations of PGEs. The metal content of immiscible sulfide liquids is a function of the (a) amount of metal in the silicate magma; (b) relative affinity for metals to occur in the sulfide or silicate liquid; and (c) relative amounts of the two liquids (Campbell and Naldrett, 1979; Barnes and Maier, 1999). Such elements as copper, nickel, and PGEs originally in the silicate melt preferentially concentrate into the sulfide liquid when it exsolves. Concentration of these metals into the sulfide liquid can, under some circumstances, deplete their concentration in the silicate magma. If there is a large volume of sulfide liquid compared with that of the silicate magma, the sulfide liquids and the resulting ores will have lower concentrations of PGEs. If the sulfide liquid effectively interacts with a large volume of silicate magma, the sulfide liquids become enriched in PGEs, resulting in high-grade ores.

Economic geologists who study magmatic processes expend a lot of effort trying to understand how large mass ratios are achieved. Proposed answers have included mixing of magmas; the migration of interstitial melts (and "fluids") upward through crystal mush; and (or) the streaming of magma over sulfide liquids in a channelized lava flow, sill, or feeder dike (Barnes and Maier, 1999; Mathez, 1999; Naldrett, 2010a).

Tectonic Setting of Magmatic Deposits (Large Igneous Provinces)

As the theory of plate tectonics gained acceptance in the 1960s and its predictive power became evident, geologists, including those working on magmatic ore deposits, tried to understand magmatism and ore genesis in a plate-tectonic context (Hutchison, 1983; Sawkins, 1984). For some mafic and ultramafic rocks that are related to subduction zones and mid-oceanic ridges, this conceptual framework provided insight and clarity; however, for other types of mafic and ultramafic rocks found in intraplate settings, which include rocks that host most of the significant magmatic mineral deposit types, it did not.

Most magmatic copper-nickel-PGE deposits occur with continental flood basalts, aerially extensive mafic dike swarms, sill provinces, and large layered ultramafic-to-mafic intrusions, which are indicative of large igneous provinces (LIPs) (Coffin and Eldholm, 1994). Bryan and Ernst proposed that LIPs are magmatic provinces with areal extents greater than 1×10^5 square kilometers (km^2), igneous volumes greater than 1×10^5 cubic kilometers (km^3) and maximum lifespans of about 50 million years (m.y.) that "have intraplate tectonic settings or geochemical affinities, and are characterized by igneous pulse(s) of short duration" (~1 to 5 m.y.), during which time "a large proportion (>75 percent) of the total igneous volume has been emplaced. [The LIPs] are dominantly mafic, but also can have significant ultramafic and silicic components, and some are dominated by silicic magmatism" (Bryan and Ernst, 2008, p. 175). Unlike the vast majority of igneous rocks that are associated with plate tectonic processes at convergent or divergent tectonic plate margins, LIP-related rocks usually occur in an intraplate tectonic setting; the association of some LIPs with hotspot tracks—for example, the North Atlantic Igneous Province and the Iceland hotspot (Storey and others, 2007) is one reason that LIPs are attributed to mantle plumes.

Types of Magmatic Deposits

Magmatic mined deposits associated with LIP-related igneous intrusions are divided into types based on such criteria as the lithology and form of associated igneous rocks, the depth of emplacement, the abundance of sulfide minerals, the relative proportion of metals, and the position of the ores within the intrusion. In this chapter, we distinguish between conduit-type deposits, which occur in intrusions that are part of sill complexes and dike swarms, and reef-type and contact-type deposits, which occur in layered intrusions (fig. N4). The most significant and representative examples for the world and the United States are the conduit-type deposits of the Noril'sk-Talnakh area (Russia); the reef-type deposits in South Africa (the Merensky Reef and the UG2 Chromitite), Zimbabwe (the Main Sulphide Zone), and Montana (the J–M Reef); and the contact-type deposits in South Africa (the Platreef) and Minnesota (the Duluth Complex).

Conduit-Type Deposits

The conduit-type deposits of the Noril'sk-Talnakh area of Russia are associated with an enormous outpouring of mafic magma that formed the Siberian Traps—the largest continental flood basalt province on Earth (fig. N5). The magmas erupted in a short period of time; the 3.5-kilometer (km)-thick basalt succession at Noril'sk-Talnakh was emplaced between 248.7±0.6 and 250.3±1.1 mega-annum (Ma) (Reichow and others, 2009). The flood basalts crop out on the Siberian craton, covering an area of approximately 2.5 million km^2 (Fedorenko and others, 1996). In addition, flood basalts

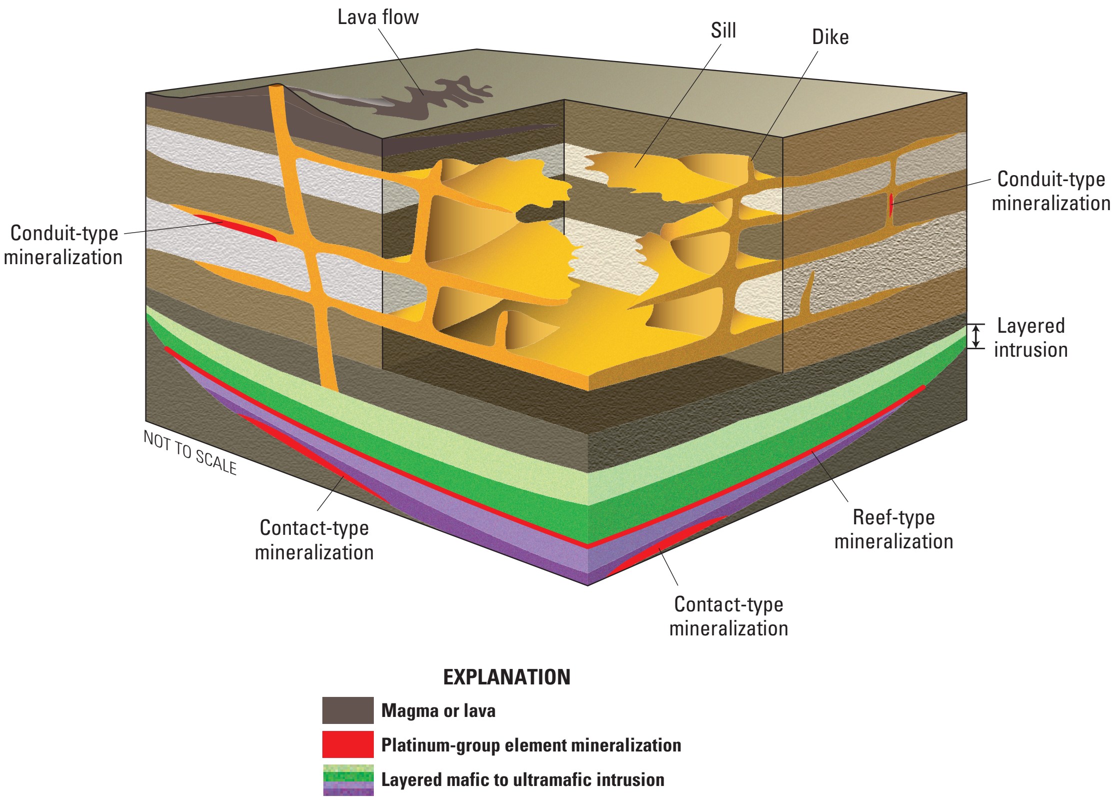


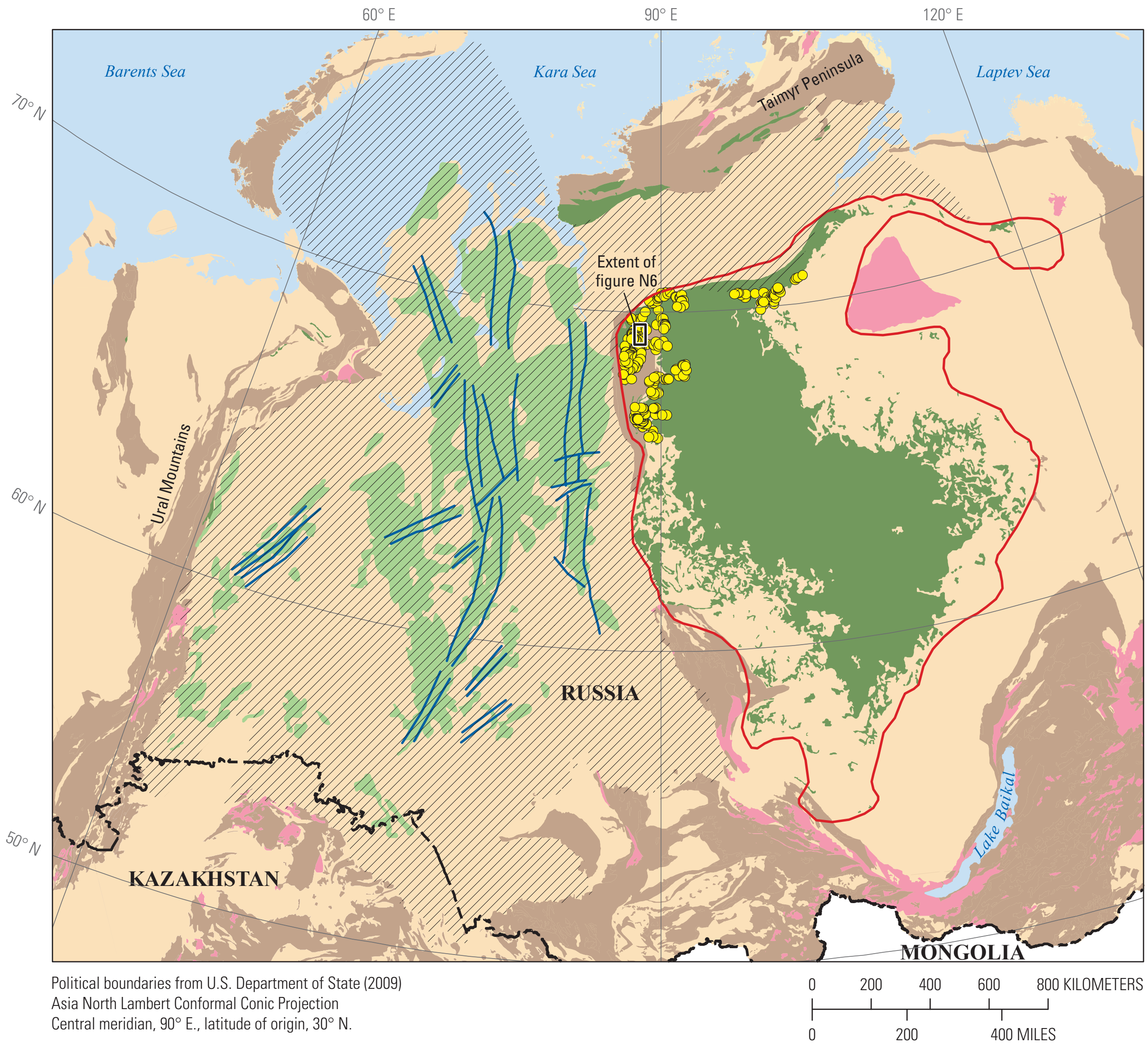
Figure N4. Schematic block diagram showing changes in the form of igneous intrusions with depth and the relative occurrence of conduit-type, contact-type, and reef-type magmatic ore deposits. Layered igneous rocks with reef-type and contact-type deposits occur at depth in large layered intrusions. Sills and dikes provide the conduits or pathways that magma follows as it rises upwards through the crust. Conduit-type magmatic sulfide deposits can be localized in sills or dikes. Modified from Naus-Thijssen (2007).

are also found in the late Mesozoic fold and thrust belt in the Taimyr Peninsula and under the West Siberian Basin (Reichow and others, 2009).

A sill complex lies beneath the thick succession of volcanic flows and is exposed where the flood basalts have been removed by erosion (fig. N5). The sill complex consists of thousands of intrusions that delineate the pathways along which large volumes of magma were transported through the crust (Arndt, 2005). Sills with major nickel-copper-PGE deposits have been identified only in the Noril'sk-Talnakh area; however, copper-nickel sulfide occurrences in sills are distributed over a much larger area (fig. N5). All these occurrences of volcanic rocks and associated sills make up the Siberian Traps LIP (Ernst and Buchan, 2001).

In the Noril'sk-Talnakh area, plateaus covered by flood basalts have been dissected by erosion and exposed the underlying sill complex (fig. N6). More than 300 intrusions have been mapped, but only 33 contain elevated sulfide concentrations. Of these 33 intrusions, 16 contain relatively rich disseminated ore and only 4 contain rich massive sulfide orebodies (Diakov and others, 2002). High sulfur contents coupled with increasing $\delta^{34}S$ values is consistent with the addition of crustally derived ^{34}S-enriched sulfur to the magma of the ore-bearing intrusions (Grinenko, 1985; Li and others, 2003).

The ore-bearing intrusions have an elongate, finger-like shape; they may be up to 1 km wide by 500 meters (m) thick and up to 15 km long. Most of the other sills form sheet-like bodies that are tens of meters thick. Rock textures of sills indicate crystallization and cooling at shallow depth. The ore-bearing intrusions are internally differentiated, with magnesium rocks and minerals concentrated towards the base of the sills; the laterally continuous sills show less internal differentiation.



Political boundaries from U.S. Department of State (2009)
Asia North Lambert Conformal Conic Projection
Central meridian, 90° E., latitude of origin, 30° N.

EXPLANATION

- 🟨 **Undeformed cover of sedimentary rocks**
- ▨ **West Siberian Basin**
- 🟩 **Siberian flood basalts, exposed**
- 🟩 **Siberian flood basalts, covered**
- 🟫 **Orogenic belts**
- 🟪 **Archean and Proterozoic basement rocks**
- — **Extent of sill complex associated with exposed Siberian flood basalts**
- — **Major rift boundary**
- ● **Nickel–copper–platinum-group-element occurrence**

Figure N5. Map showing the geology of the Siberian flood basalt province in Russia, which is the largest flood basalt province in the world. The province includes a large area of exposed lavas and sills. It also includes an equally large area of lavas that are covered by younger deposits that make up the West Siberian Basin. The sill complex associated with the exposed lavas underlies and extends beyond the area of lavas. The deposits of the Noril'sk-Talnakh area, along with many occurrences of magmatic sulfide mineralization, have been found in the northwestern part of the province where the lavas and sills are exposed. Map includes information from Zonenshain and others (1988), Fugro Robertson, Ltd. (2008), and Reichow and others (2009).

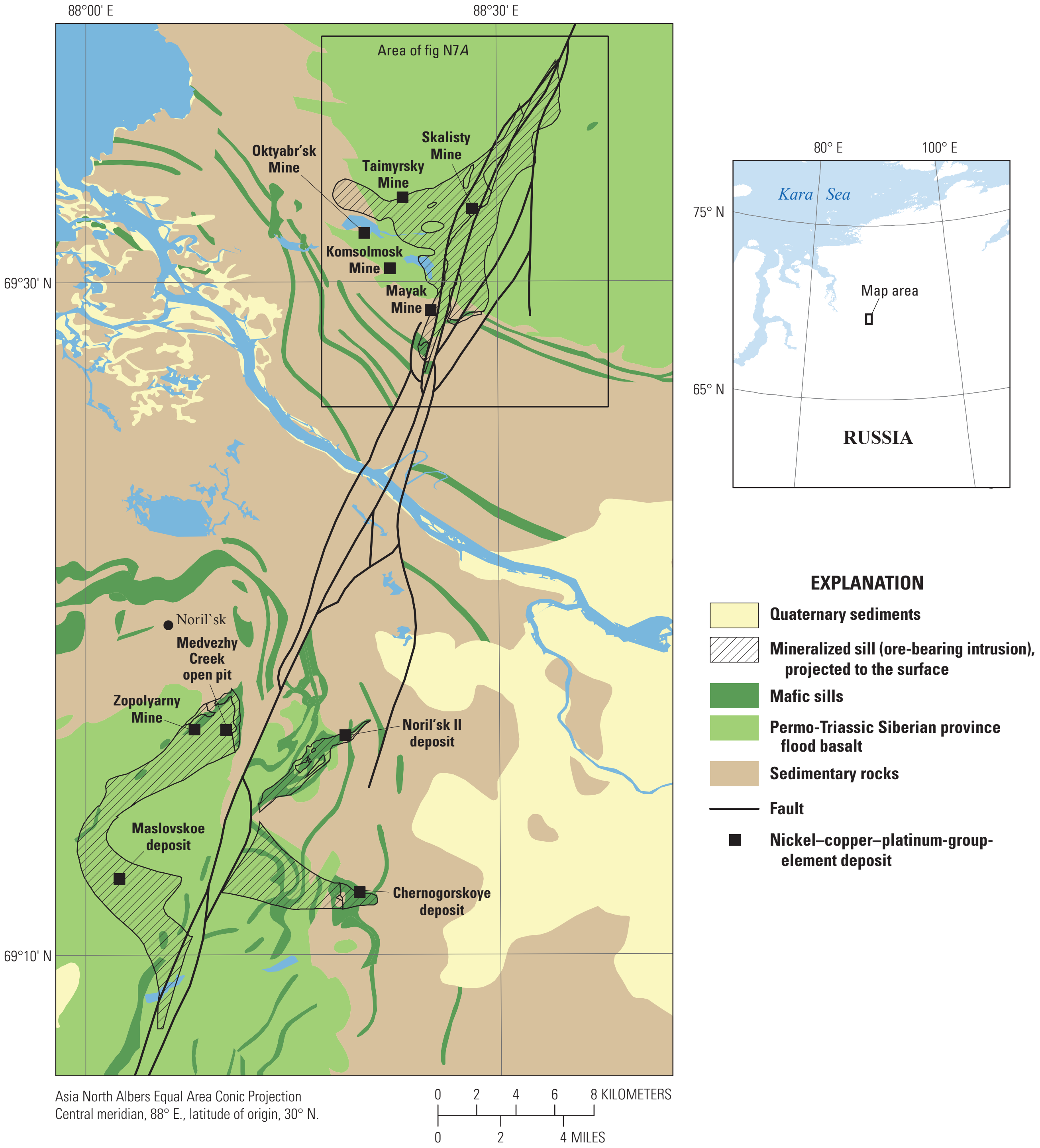


Figure N6. Map showing the geology of the Noril'sk-Talnakh area and the location of nickel–copper–platinum-group-element (Ni-Cu-PGE) deposits. Flood basalts crop out in the northeast and the southeast; in other areas, erosion has removed the lavas and exposed the underlying sills that intrude older sedimentary rocks. The mineralized sills largely underlie the lavas. Their subsurface extent has been projected to the surface. Geology simplified from Sherman and others (1991).

The amount of massive sulfide ores associated with the mineralized intrusions at Talnakh is astounding. The massive sulfide ores, which are up to 45 m thick, underlie most of the intrusions in the Talnakh area (fig. N7*A*; Kunilov, 1994). The ore-bearing sills contain, or are associated with, concentrations of sulfide minerals that exceed the amount of sulfur that could have been dissolved in the volume of magma now in the sills. The sulfide mineralization also contains high concentrations of PGEs, indicating a silicate-to-sulfide ratio that is larger than the observed proportion of silicate minerals to sulfide minerals in the sills. This suggests that at the time of ore formation, the sulfide liquids equilibrated with a much larger volume of magma than is now represented by the igneous rocks in the sill. Field relations indicate lateral movement of immiscible sulfide liquids during and after solidification of the silicate igneous rocks.

In the Talnakh area, fractional crystallization of the immiscible sulfide liquids formed mineralogically and compositionally zoned orebodies (fig. N7*B*). Massive ores formed by early crystallization of sulfides contain less copper and PGEs than ores that formed from sulfide liquid that are the end product of the fractional crystallization process (fig. N8). The copper- and PGE-rich late-stage ores are the likely source of most of the PGE production from the Talnakh deposits (fig. N7*C*). Between 1960 and 2011, Russia (including all the Soviet Union until 1991) produced about 5,000 metric tons of PGEs, most of them from the Noril’sk-Talnakh area (U.S. Bureau of Mines, 1933–96; U.S. Geological Survey, 1997–2016). Mining depths in the Noril’sk-Talnakh area range from 300 to 1,500 m (Kunilov, 1994).

Reef-Type and Contact-Type Deposits

LIP-related layered mafic to ultramafic intrusions contain most of the world’s resources of PGEs. Layered intrusions form by crystallization of magma deep in Earth’s crust and have sheet-like to dike-like shapes. They consist primarily of cumulates, which are rocks that represent accumulations (concentrations) of minerals that crystallize from magmas. Cumulus rock textures are distinctive, as they record nucleation and growth of crystals from the melt, enlargement of crystals to form a touching framework (a crystal mesh), solidification, and subsolidus grain boundary adjustments that minimize grain boundary surface energies (Hunter, 1987). Cumulus rocks are also distinctive in that they do not have the composition of naturally occurring magmas but are instead a mixture of early formed crystals with variable proportions of trapped liquid.

As the magma crystallizes in these intrusions, layering features develop that are recognized by the variations in the modal proportions of the minerals, the rock textures, the grain size, and the mineral compositions. Individual layers range from laminations formed by the orientation of individual crystals that are millimeters in diameter to strata that are tens to hundreds of meters thick and may extend for hundreds of kilometers along strike. The layering features are so pronounced and consistent that stratigraphic principles developed for sedimentary rocks are applied to these igneous rocks. Stratigraphic columns are measured through the sequence of layered igneous rocks to define mappable units; the thickness of the layered rocks in intrusions ranges from hundreds of meters to as much as 10 km.

Layered intrusions have two significant styles of magmatic sulfide mineralization—reef type and contact type. The analogy with sedimentary rocks extends to the terminology used for magmatic deposits in layered intrusions. Some of the magmatic deposits are strata-bound, which means that the deposit is confined to a stratigraphic unit, not to a particular bed. Other magmatic deposits are stratiform, which means that the deposit constitutes one or more of the igneous layers; an example would be the chromium deposits in layered intrusions (which correspond to igneous rock layers that are composed primarily of the mineral chromite). Reef-type and contact-type deposits are strata-bound, as described below.

Reef-type PGE deposits are disseminated copper-, iron-, nickel-, and PGE-bearing minerals that are associated with one or more strata within a layered igneous intrusion (fig. N4). The mineralized rock unit almost always contains disseminated magmatic sulfide minerals, but the rock layers are dominated by silicate minerals or oxide minerals such as chromite or magnetite. The modal abundance of sulfide minerals is usually much less than a few percent. The term “reef” is an Australian and South African mining term for a relatively flat-lying, tabular orebody. Within a layered igneous intrusion, reef-type mineralization is laterally persistent, extending for the strike length of the intrusion, which is typically tens to hundreds of kilometers. The mineralized interval is thin (generally centimeters to meters thick), however, relative to the total stratigraphic thickness of the layers in the intrusion, which can vary from hundreds to thousands of meters.

Copper-nickel-PGE contact-type deposits consist of disseminated magmatic sulfide minerals found near the lower contact or margin of mafic to ultramafic layered intrusions (fig. N4). The host rocks for the disseminated sulfide minerals are the igneous rocks of the intrusion and adjacent contact metamorphosed country rocks. Some igneous lithologies are cumulates, but other mineralized mafic and ultramafic igneous rocks are texturally and lithologically heterogeneous, exhibiting changes in texture and mineral proportions at scales of from centimeters to meters. Textures indicative of chilling or unidirectional growth of silicate minerals may also be present. Inclusions of autoliths and xenoliths are common; they are surrounded by igneous rocks that have textural, mineralogical, and isotopic features suggestive of reaction with the inclusions (Iljina and Lee, 2005).

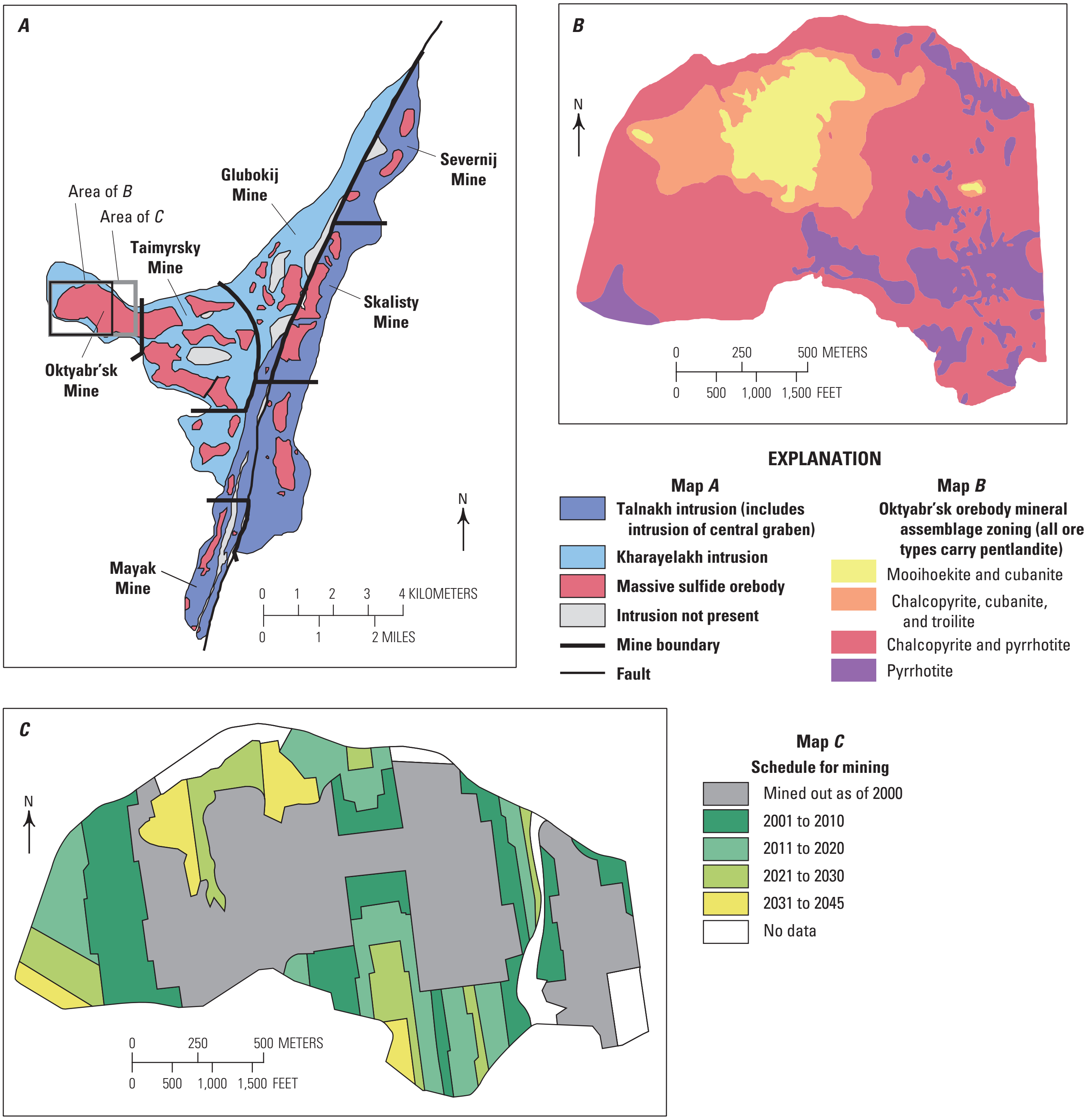


Figure N7. Maps showing nickel–copper–platinum-group-element (Ni-Cu-PGE) deposits in the Talnakh area, Russia. *A,* Extent of two elongate sill-like intrusions (Talnakh and Kharayelakh) and the distribution of massive sulfide ores that underlie them. *B,* Zoning of sulfide minerals in the Oktyabr'sk orebody. The concentric pattern of minerals formed by fractional crystallization of immiscible sulfide melt; the pyrrhotite ($Fe_{1-x}S$) assemblage solidified first, and mooihoekite ($Cu_9Fe_9S_{16}$) and cubanite ($CuFe_2S_3$) solidified last. The copper-rich ore assemblages contain the most PGEs. *C,* Mined-out areas of the Oktyabr'sk orebody and future mine plans to 2045. Most of the copper- and PGE-rich ores have been mined. Maps modified from Zientek and others (1994) and Naldrett (2006).

Figure N8. Photograph of copper-rich massive sulfide ore exposed in a stope in the Oktyabr'sk Mine in the Talnakh area, Russia. The ore consists of several iron-copper-sulfide minerals, such as chalcopyrite ($CuFeS_2$), mooihoekite ($Cu_9Fe_9S_{16}$), and talnakhite ($Cu_9(Fe, Ni)_8S_{16}$). The minerals are brassy to golden yellow, but some develop iridescent blue and maroon colors when exposed to air. These ores represent the end product of the fractional crystallization of immiscible sulfide liquid and can contain tens to hundreds of parts per million platinum-group elements. Photograph by Michael L. Zientek, 1992.

Sulfide abundance in contact-type PGE deposits is typically about 3 to 5 volume percent, although some net-textured and (or) massive sulfide ores may be present. Erratic variation in the distribution of sulfide minerals is typical, although the concentration of sulfide minerals within the intrusion generally increases towards the contact with adjacent country rocks. The mineralization can be laterally persistent, commonly extending for the entire strike length of the layered igneous intrusion. The interval that can contain magmatic sulfide minerals is generally tens to hundreds of meters in thickness, however. The proportion of sulfide minerals varies within the rock layers that can host ore; during exploration and development, economic cutoff grades are used to define the volume of rock within the igneous rock unit that could be mined. Therefore, low-grade mineralization may occur outside the cutoff limit that defines minable parts of deposits. Examples of major reef-type (a–c) and contact-type (a and d) deposits are discussed below.

(a) Merensky Reef, UG2 Chromitite, and Platreef, Bushveld Complex, South Africa. The Paleoproterozoic Bushveld Complex (2,054.4±1.3 Ma, using the uranium-lead-zircon technique for determining age) is a large mass of igneous rock that underlies an area of approximately 69,000 km^2 in South Africa (fig. N9; Hall, 1932; von Gruenewaldt, 1977; Scoates and Friedman, 2008). It is part of the Bushveld LIP (Ernst and Buchan, 2001), which also includes the Molopo Farms Complex (another large layered mafic to ultramafic intrusion in Botswana and South Africa (Prendergast, 2012); a large complex of sills related to the Bushveld Complex (Sharpe, 1981; Sharpe and Hulbert, 1985); and the Dullstroom basalts in South Africa (Buchanan and others, 1999).

The Bushveld Complex consists of several igneous suites. The most important economically is the Rustenburg Layered Suite, which is an approximately 8-km-thick layered sequence of mafic to ultramafic cumulates (Vermaak and von Gruenewaldt, 1986; Walraven, 1986) that contain world-class deposits of chromium, PGEs, and titanium-vanadium. The cumulates of the Rustenburg Layered Suite are exposed intermittently around the periphery of the Bushveld Complex in areas referred to as limbs. Igneous layering dips gently towards the center of the Bushveld Complex. Seismic surveys trace igneous units exposed at the surface to depths exceeding 6 km (Sargeant, 2001; Campbell, 2011). Gravity modeling indicates that the western and eastern limbs of the Bushveld Complex are connected at depth (fig. N9, cross section *A–A'*; Webb and others, 2004).

Two PGE-enriched reefs, the UG2 Chromitite (fig. N10) and the Merensky Reef (fig. N11; Viljoen, 1999), each occur near the base of different repetitive rock sequences (cyclic units) and can be continuously traced onstrike for the full extent of the eastern and western limbs of the complex. The grade of the UG2 Chromitite deposit is about 5 grams per metric ton (g/t) PGEs and gold; the grade of the Merensky Reef is about 6 g/t in the western part of the complex and about 4.2 g/t in the eastern part.

In the northern limb, varitextured pyroxenite, norite, and gabbro are found near the lower contact of the complex with metasedimentary rocks of the Transvaal Supergroup (van der Merwe, 1976). These igneous rocks host the Bushveld Complex's contact-type copper-nickel-PGE deposits (known as the Platreef). The combined PGE and gold grades for the Platreef deposits range from 0.55 to 3.7 g/t. Since the 1920s, mining has recovered 7,200 metric tons of PGEs from the Bushveld Complex (U.S. Bureau of Mines, 1933–34; 1933–96; U.S. Geological Survey, 1997–2016).

(b) Main Sulphide Zone, Great Dyke, Zimbabwe. The Neoarchean Great Dyke (2575.4±0.7 Ma, age determined from zircon using uranium-lead technique; Oberthür and others, 2002) is a long (about 550 km) and narrow (about 11 km) layered igneous intrusion in Zimbabwe. This intrusion and some subparallel dikes are the geologic features associated with the Great Dyke of Zimbabwe LIP (Ernst and Buchan, 2001). The rock types of the Great Dyke consist of layered mafic to ultramafic cumulates that dip inwards from the sides towards the center of the intrusion (fig. N12). Since the 1980s, mining has recovered 107 metric tons of PGEs from a reef-type PGE deposit within the Great Dyke—the Main Sulphide Zone—which occurs 10 to 50 m below the contact between the ultramafic and mafic sequences. The Main Sulphide Zone is typically 2 to 3 m thick, and the grade of the deposit varies from about 3.5 to 4 g/t PGEs and gold (U.S. Bureau of Mines, 1933–96; Wilson, 1996; U.S. Geological Survey, 1997–2016; Wilson and Prendergast, 2001).

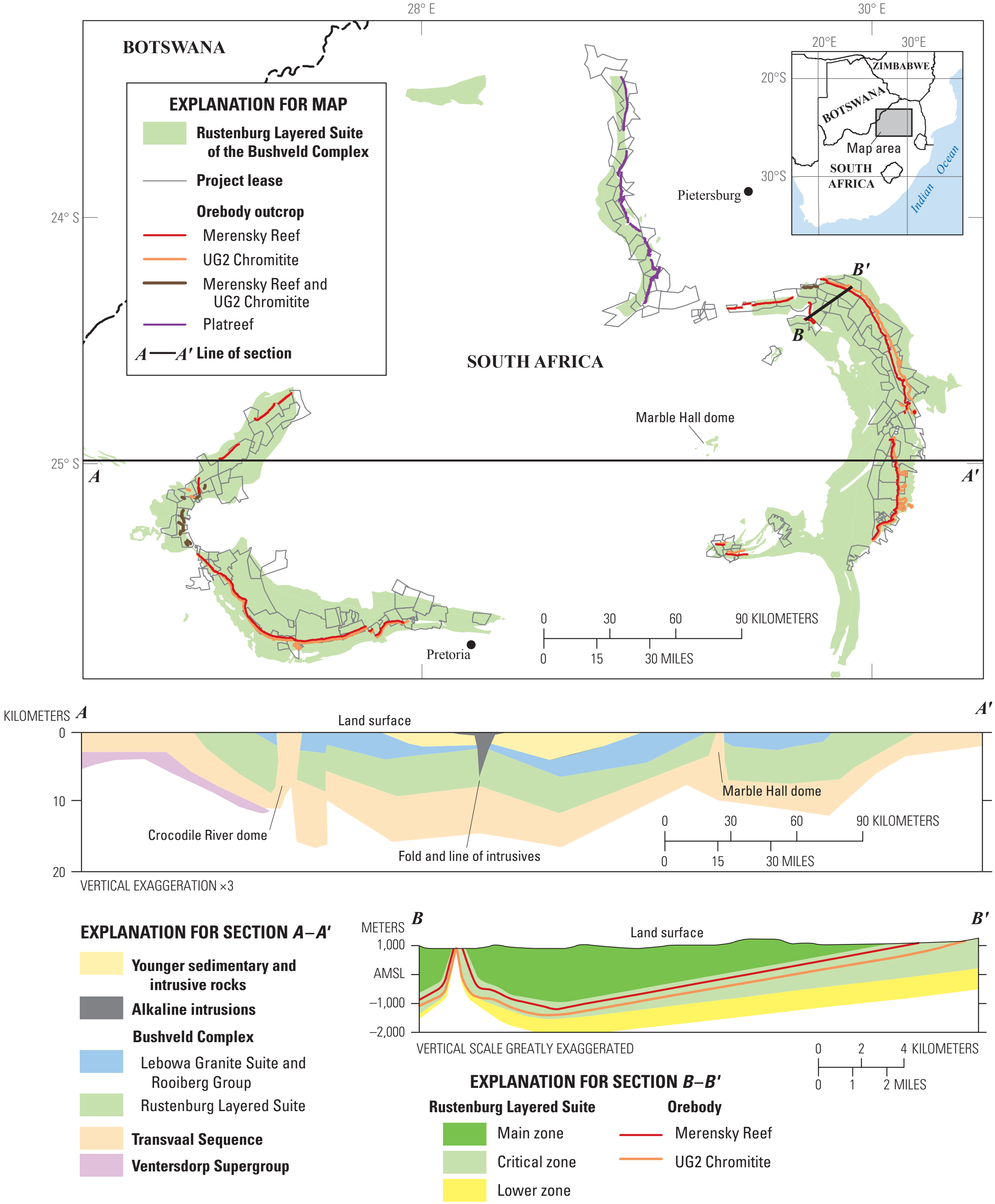


Figure N9. Map showing the Rustenburg Layered Suite of the Bushveld Complex, South Africa, the surface trace of significant orebodies, and cross sections through the central area and northeastern limb. Cross section *A–A′* is based on geophysical modeling and suggests that the mafic and ultramafic rocks that make up the eastern and western portion of the complex are connected at depth. Modified from Webb and others (2004). Cross section *B–B′* shows the remarkable continuity of the layers that host the Merensky Reef and UG2 Chromitite platinum-group-element deposits. Modified from Bauba Platinum (2012). Rustenburg Layered Suite is derived from Martini and others (2001); project leases and orebodies are from Zientek and others (2014).

Figure N10. Photograph of the UG2 Chromitite at the Karee Mine in the western part of the Bushveld Complex, South Africa. The black layer at the base of the exposure is the main layer of the UG2 Chromitite. It has an undulating contact with the underlying, light-colored anorthosite layer. Several thin chromitite seams overlie the main chromitite layer. Most of the exposed rock is brown pyroxenite associated with the UG2 cyclic unit; a sharp contact separates the pyroxenite layer from the overlying light-colored anorthosite layer. Photograph by Wolfgang Maier, University of Cardiff, Wales, United Kingdom.

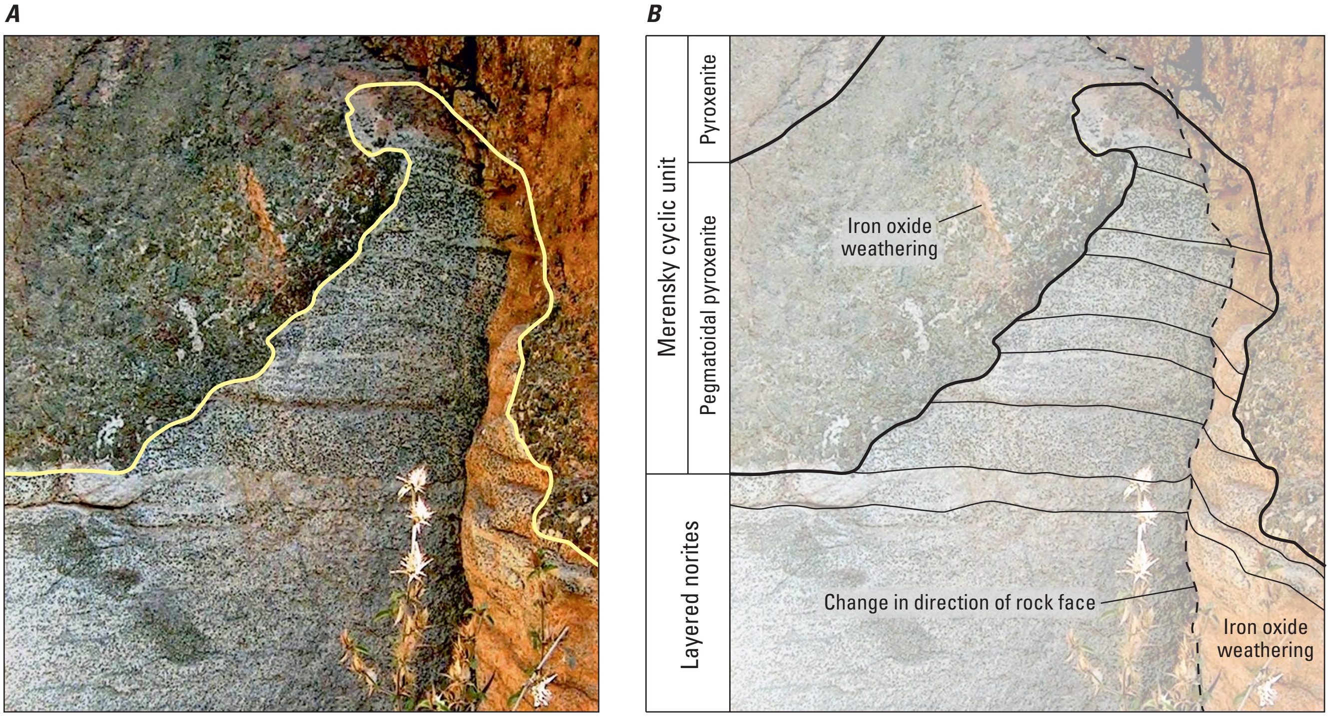


Figure N11. The base of the Merensky cyclic unit, a pegmatoidal pyroxenite, which contains the platinum-group-element-rich Merensky Reef. *A*, Photograph of the base of the Merensky cyclic unit on the Hackney farm property in the eastern part of the Bushveld Complex, South Africa. The basal contact of the cyclic unit is annotated by the yellow line. *B*, Same photograph with an overlay showing major features, including the dark, pegmatoidal pyroxenite cutting layering in the underlying lighter-colored norites. Photograph by Wolfgang Maier, University of Cardiff, Wales, United Kingdom.

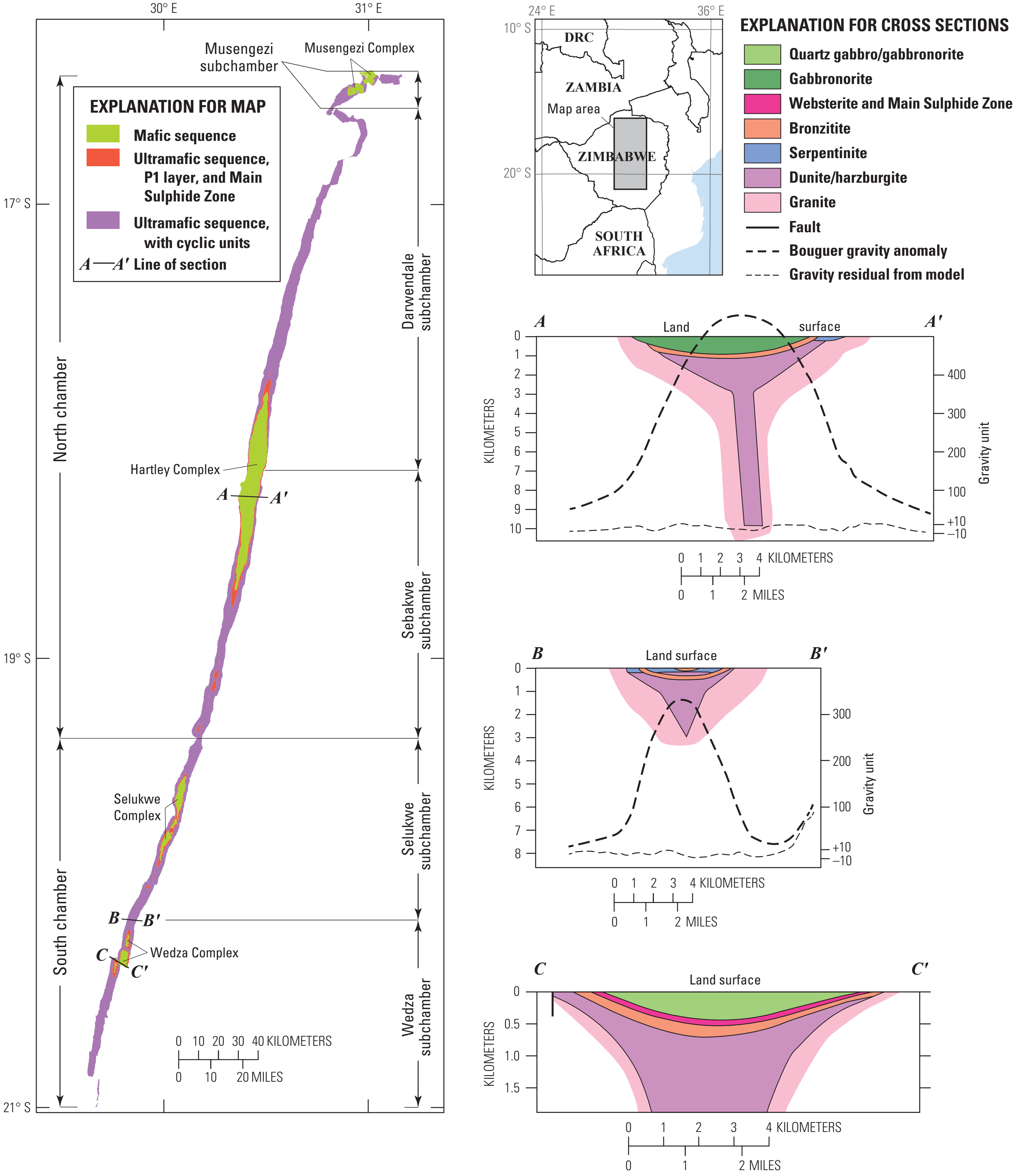


Figure N12. Geologic map and cross sections of the Great Dyke, Zimbabwe. Geologic mapping and geophysical studies show that the intrusion has a dike-like form; however, igneous layering dips gently into the center of the intrusion. The Main Sulphide Zone, which is a reef-type platinum-group-element deposit, is confined to the P1 layer of the ultramafic sequence (as shown on the map) and to the corresponding websterite layer shown on cross section *C–C′*. Geologic map generalized from Worst (1957); geologic sections generalized from Podmore and Wilson (1987).

(c) J–M Reef, Stillwater Complex, Montana. The Neoarchean Stillwater Complex (2,704±5 Ma, using the uranium-lead zircon technique for determining age; Premo and others, 1990) is a mafic to ultramafic layered intrusion exposed in south-central Montana (fig. N13; Zientek and others, 2002). This intrusion is the only feature associated with the Stillwater LIP (Ernst and Buchan, 2001). More than 5,500 m of layered rocks are exposed, which can be traced for 48 km along strike. The J–M Reef, which is a reef-type PGE deposit, consists of 0.5 to 3 volume percent magmatic sulfide minerals that are associated with a distinctive olivine-bearing cyclic unit that can be mapped both on the surface and underground. The actual distribution of sulfide minerals within the cyclic unit is determined by detailed mapping, drilling, and sampling, however. The J–M Reef, which is open at depth, has been traced for 42 km of the 48-km strike length of the complex and at least 2 km down the dip of layering. The J–M Reef is currently the sole source of primary PGE production and reserves in the United States. Since 1986, the Stillwater and East Boulder Mines (fig. N14) have produced roughly 305 metric tons of PGEs from the J–M Reef deposit. The overall deposit grade is about 15 g/t palladium and platinum (U.S. Bureau of Mines, 1933–96; U.S. Geological Survey, 1997–2016; Abbott and others, 2011).

(d) Contact-Type Deposits, Duluth Complex, Minnesota. The Keweenawan LIP resulted from the eruption of lavas and emplacement of igneous intrusions between 1,109 and 1,087 Ma along a linear belt where Earth's crust subsided (the Midcontinent Rift). The rift extends for more than 2,500 km from Kansas northward beneath Lake Superior and then southeast through Michigan (fig. N15); however, exposures of rocks related to the rift are found only in the Lake Superior region. Igneous rocks associated with this LIP cover more than 160,000 km^2 (Ernst and Buchan, 2001). LIP and rift-related igneous rocks exposed in the Lake Superior region include flood basalts, mafic intrusions, and minor rhyolite lava flows. The Mesoproterozoic Duluth Complex in Minnesota is composed of several discrete intrusions formed from mafic to felsic magmas that were emplaced between 1,108 and 1,098 Ma into older rocks, which include Paleoproterozoic sedimentary rocks and Archean granite-greenstone terranes (Peterson and Severson, 2002), and coeval LIP and rift-related flood basalts and hypabyssal (subvolcanic) intrusions.

Contact-type mineralization that includes a few percent sulfide minerals is laterally extensive along the base of some of the intrusions (mainly the South Kawishiwi and the Partridge River intrusions) along the western margin of the Duluth Complex. The mineralized interval of igneous rocks along the contact varies from tens to hundreds of meters in thickness. Mineral exploration studies since the early 1950s indicate that about 4 billion metric tons of mineralized rock containing 0.6 weight percent copper, 0.2 weight percent nickel, and 0.655 g/t PGEs may be present (Listerud and Meineke, 1977; Naldrett, 2010b). Because the proportion of sulfide minerals varies along strike, economic cutoff grades are used to define deposits along the contact zone.

Hydrothermal and Sedimentary Deposits

Anomalous concentrations of PGEs or the presence of platinum-group minerals have been reported in a variety of hydrothermal and sedimentary deposit types (table N2 at back of chapter; Wilde and others, 2003; Wilde, 2005). Hydrothermal mineral deposits form by the interaction of hot water and rock. Water is a good solvent and hot water, called hydrothermal fluid, can efficiently move and deposit materials that occur in some mineral deposits. Sedimentary mineral deposits are economic concentrations of minerals in sedimentary rocks that formed directly from water in oceans, lakes, or in underground reservoirs. Although their occurrence is tantalizing, "a world-class deposit in which the PGE[s] are primary commodities and hydrothermal [processes] were indisputably the primary mechanism of concentration is yet to be discovered" (Wood, 2002, p. 233). Nevertheless, economic deposits of hydrothermal platinum and palladium may exist (Wilde and others, 2003).

Experimental and theoretical investigations by many authors have helped to identify the constraints under which the PGEs can be mobilized by fluids at relatively low temperatures (that is, at approximately 300 °C or less) (Wood and others, 1992; Gammons and Bloom, 1993; Wood, 2002; Hanley, 2005; Colombo and others 2008; Barnes and Liu, 2012; and references cited therein). Significant concentrations of platinum and palladium can dissolve into solution as chloride complexes only under highly oxidizing or highly acidic conditions. Palladium and platinum can be transported as bisulfide complexes in acidic to neutral solutions under reduced and moderate oxidation conditions. Hydroxide, thiosulfate, and organic complexes may be the dominant forms of dissolved platinum and palladium in low-temperature, near-surface environments.

Chloride complexes play a significant role in the mass transfer of PGEs in (a) porphyry copper deposits, especially the porphyry copper-gold subtype with island arc affinities and those associated with alkaline igneous rocks; (b) unconformity-related uranium-gold-platinum-palladium deposits; and (c) sediment-hosted strata-bound copper deposits (Wood, 2002). Bisulfide complexes may be responsible for (a) transporting platinum, palladium, and gold in the footwall copper-nickel-PGE ores at Sudbury, Ontario, and in nickel-molybdenum-PGE-gold enriched black shale deposits; (b) the remobilization of PGEs or recrystallization of platinum-group minerals in ophiolites and other ultramafic rocks during serpentinization and metamorphism; and (c) the remobilization of PGEs from mineralization of primary magmatic origin by deuteric or hydrothermal processes (Wood, 2002).

Manganese crusts that precipitate on the sides of seamounts are the definitive example of a sedimentary deposit enriched in PGEs (table N2). These crusts take millions of years to accumulate; the metals are extracted from seawater by adsorption processes (Halbach and others, 1989).

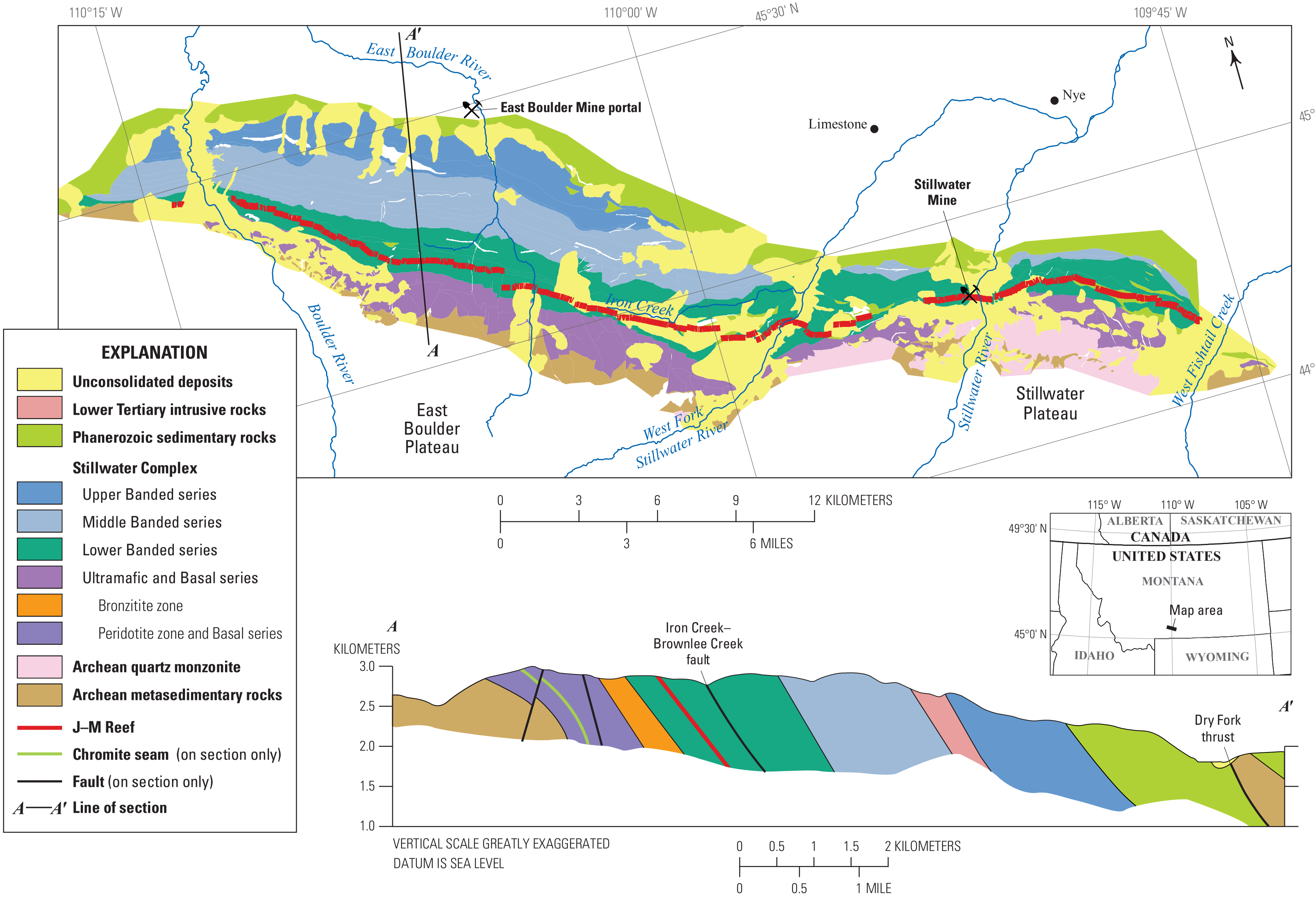


Figure N13. Geologic map and cross section of the Stillwater Complex, Montana. The layered cumulates that make up the complex have been tilted to the north, exposing a section through the entire intrusion, from the ultramafic rocks at its base (Ultramafic and Basal series) to mafic rocks (Lower, Middle, and Upper Banded series) exposed beneath the younger Phanerozoic sedimentary rocks. The platinum-group-element mineralized interval, the J–M Reef, crops out in the Lower Banded series and has been traced for 42 kilometers on strike. Modified from Jones and others (1960) and Zientek and others (2005).

Figure N14. Photograph of the Stillwater Mine in south-central Montana, looking southeast. The pond is the tailings impoundment. The buildings in the lower left include the shaft, the mill complex, and offices. Photograph by Michael L. Zientek, 2006.

Residual Deposits Formed By Weathering and Laterites

In areas with tropical or forested warm to temperate climates, weathered red subsoil rich in secondary oxides forms on ultramafic rocks. These subsoils, or laterites, are a significant source of nickel (the other significant source of nickel is magmatic ore deposits). Laterites contain about 70 percent of the world's nickel resources, have been mined for more than 100 years, and account for about 40 percent of the world's nickel production (Gleeson and others, 2003; Dalvi and others, 2004; Mudd, 2010; Berger and others, 2011).

PGE enrichments are found in some laterites developed on ultramafic rocks, and an ongoing debate among geologists concerns whether this enrichment is related to the mobilization of the PGEs during the laterization process or to the residual accumulation of preexisting platinum-group minerals. Samples of lateritized ophiolitic mantle harzburgite from the Pirogues River area of New Caledonia contain up to 2 ppm (but average 500 ppb) platinum. The continuity of the PGE-enriched laterite layers relative to the discontinuous distribution of PGE-enriched chromitites in the ophiolites initially suggested that the PGEs could be concentrated through the lateritization process (Augé and Legendre, 1994); however, recent work indicates that the PGE-enriched zones are the result of the concentration of residual platinum-group mineral particles that were present in the unweathered ultramafic rock (Traoré and others, 2008). The PGE-enriched saprolitic horizon of the Falcondo nickel-laterite deposit in the Dominican Republic also appears to be a residue of primary platinum-group minerals that were dispersed in ophiolite-related ultramafic rocks (Proenza and others, 2010).

Another PGE-enriched laterite occurrence, the Syerston nickel-cobalt-platinum deposit, overlies the dunitic core of the easternmost of three plugs that make up the Tout Intrusive Complex, which is a Uralian-type intrusion in the Fifield area in New South Wales, Australia (Teluk, 2001). Preferential weathering of the ovoid dunite body formed a slab-like laterite body. The laterite extends to a depth of 40 m and has zones of nickel-cobalt enrichment that average 10 m in thickness in the middle of the weathering profile. An interval of residually concentrated platinum largely coincides with the nickel-cobalt enriched layers. Primary platinum enrichment in the host dunite may explain the distribution of platinum in the Syerston laterite profile, the exceptional grades (commonly in excess of 2.0 g/t platinum), and the coarse grains of the platinum-group minerals. Published resources are 137 million metric tons containing 0.24 g/t platinum; the planned nickel-cobalt open pit area (high-grade goethite zone) accounts for 91.6 million metric tons of the resource and contains 0.70 weight percent nickel and 0.12 weight percent cobalt (Teluk, 2001).

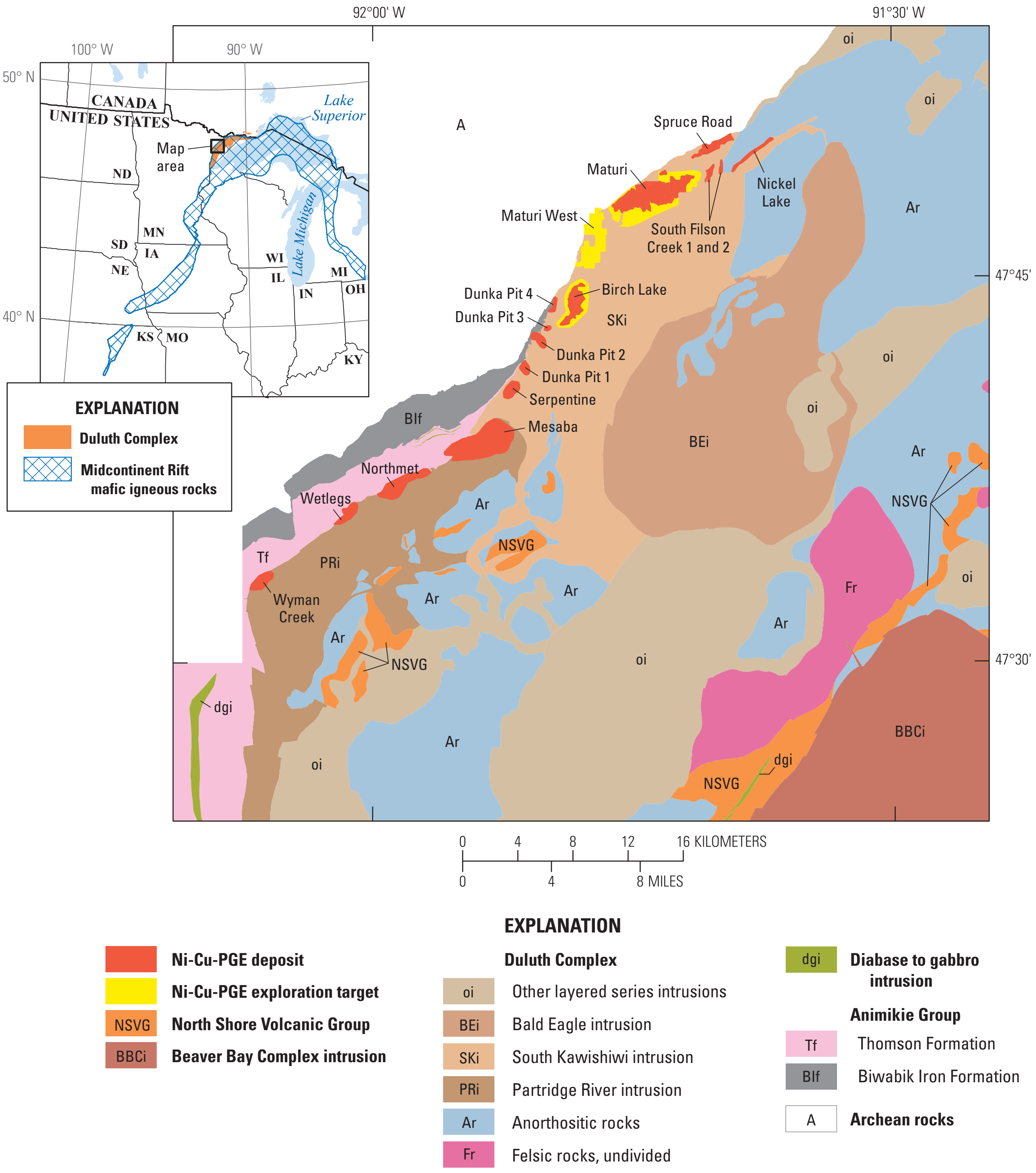


Figure N15. Map showing the geology along the western margin of the Duluth Complex, Minnesota, with the surface projection of nickel–copper–platinum-group-element (Ni-Cu-PGE) deposits and exploration targets. Exploration targets occur along the outer margins of known deposits (Birch Lake and Maturi) or as areas separated from known deposits (Maturi West). The location map shows the exposed and covered areas of the Midcontinent Rift along with the Duluth Complex. Map based on information in Miller and others (2002) and Parker and Eggleston (2012). Geology in the index map is derived from Muehlberger (1997).

Platinum Placer Deposits

Erosion and weathering of rocks can form surficial mineral deposits. Placer deposits form when heavy particles of rocks or minerals are physically concentrated by the action of moving water. Placer deposits can form in active streams or rivers or along the shoreline of oceans or lakes. In 1824, placer platinum deposits were discovered on the Orulikha River, north of the Nizhny Tagil Massif in the central Ural Mountains (Urals) of Russia (table N3; fig. N16; Duparc and Tikonowitch, 1920; Pushkarev, 2001). From then until 1922, approximately 330 metric tons of metal was recovered from placer deposits in the Urals. At least one company is still exploring for paleoplacers that are buried beneath younger deposits of sediment and for placers that may be on river terraces along the Tylay and Kos'va Rivers in the Urals (Eurasia Mining plc, 2012). So far, the company has delineated resources in placers that contain 0.6 metric tons of platinum; average grades range from 0.303 to 0.363 gram per cubic meter (Eurasia Mining plc, 2011).

In the second half of the 20th century, platinum placer deposits were discovered at Kondyor in eastern Siberia (fig. N17; Shcheka and others, 2004) and in the Koryak area at the northern end of the Kamchatka Peninsula in eastern Russia (Tolstykh and others, 2004). The Kondyor placer deposits produced about 85 metric tons of platinum from 1984 to 2011. After a decade of mining, approximately 45 metric tons of platinum was recovered in the Koryak area (Hurst, 2005).

The detrital platinum minerals in the placer deposits in Russia are clearly derived from small mafic to ultramafic plutons. The drainages surrounding the Nizhny Tagil Massif contained some of the most productive placer deposits in the Urals (fig. N16*B*). Placer mining near Nizhny Tagil began around 1839. Platinum in bedrock was first discovered in 1892 at a deposit called Krutoy Log in the Nizhny Tagil Massif (fig. N16*B*; Anikina and others, 2014). These plutons, which are the sources of platinum placer deposits, are circular or elliptical in plan view, pipe-like when viewed in profile (that is, in a cross-sectional view), and generally range in areal extent from about 10 to 40 km^2 (Johan, 2002). The rocks that make up the plutons are a core of dunite that is concentrically surrounded by borders of clinopyroxenite, hornblendite, and gabbroic rocks. The zoned ultramafic complexes have rock textures that are consistent with (a) crystallization from magma at depth; (b) deformation, recrystallization, and annealing at high temperature; and (c) metasomatic alteration (Burg and others, 2009; Shmelev and Filippova, 2010). Rocks in these small mafic to ultramafic plutons make up a distinct rock association called Uralian-type complexes. These complexes are enigmatic because lode occurrences of platinum mineralization found in the plutons are inconsequential compared with the amount of placer platinum minerals found in the streams draining from the plutons.

Platinum mineralization in Uralian-type complexes is closely associated with chromitite pods, vein-like bodies, or schlieren within the dunite core of the plutons. In the Nizhny Tagil Massif, more than 1,600 chromitite occurrences have been mapped; most do not exceed 50 centimeters (cm) in length and a few centimeters in thickness. Two types of chromitite are distinguished: (a) massive chromitite that grades into disseminated chromite in the dunite host, and (b) chromitite marked by serpentine rims that has a sharp boundary with the dunite host rock. The second type of chromitite is exceptionally enriched in platinum (Pushkarev and Anikina, 2002). Although the chromitites are small, the abundance of platinum can be quite high. For example, at the Krutoy Log deposit, chromite-platinum ore at the top of the orebody extended for a distance of 2 m in one adit. From this small volume of rock, about 30 kilograms (reported as 965 troy ounces) of native platinum metals was recovered (Mertie, 1969).

The platinum-group minerals in the placer deposits provide clues about the rocks from which they are derived. The platinum-group minerals are dominated by platinum-iron alloys but also contain some iridium and osmium alloys; few minerals with palladium or rhodium are found. The platinum nuggets in the placer deposits can be quite large (more than 10 cm in diameter and weighing up to several kilograms); by comparison, in most contact- and reef-type PGE ore deposits, the platinum-group minerals rarely exceed a few hundred microns in diameter (1 micron equals 0.0001 cm) and weigh less than 0.0000001 kilograms. Some of the detrital platinum-group minerals have crystal faces that reflect their internal crystalline structure (figs. N18*A* and N18*B*). Minerals that display crystal faces usually grow from a liquid or a vapor. Many nuggets contain inclusions of chromite and olivine (fig. N18*C*), or in some cases, form a matrix interstitial to these minerals. These textures suggest that platinum-iron alloys formed from magmas that were crystallizing chromite and olivine. Collectively, these observations indicate that the platinum nuggets are not derived from concentrations of magmatic sulfide minerals; rather, it appears that the nuggets were crystallized directly from silicate melt or a magmatic vapor.

Platinum placers are derived from similar ultramafic plutons in Alaska; British Columbia, Canada; Colombia; Ethiopia; and New South Wales, Australia (table N3). The largest alluvial PGE resource in the United States occurs south of Goodnews Bay in Alaska (fig. N19). The Goodnews Bay placer deposits were discovered in 1926 and mined between 1927 and 1975. Approximately 18 metric tons of platinum was recovered from the Salmon River and its tributaries (Johnston, 1962; Mertie, 1976; Barker, 1986; Tolstykh and others, 2002). Significant placer resources may remain in the unmined, deeply buried ground of the lower Salmon River Valley as well as in waste material (tailings) from previous dredging operations (Southworth and Foley, 1986).

Table N3. Areas with significant placer platinum production, and estimates of cumulative production and grades.

[g/m^3, gram per cubic meter; km, kilometer; n.d., no data; PGE, platinum-group element]

Location	Cumulative production (metric tons)	Dates	Grade(s)	Reference(s)
Ural Mountains, Russia	330 to 435	1824 to present	Initial tenors of placers in the Martian, Syssim, Tschauch, and Wyssim Rivers, which drain the Nizhniy Tagil area, were about 400 g/m^3; by World War I, the grades of placers in these rivers were 0.41 to 35 g/m^3. The average grade of the placers in the Nizhniy Tagil district early in its history is estimated to be about 20 g/m^3. Grades currently estimated for the West Kitlim placer deposit are 0.303 to 0.363 g/m^3.	Lumb (1920); Eurasia Mining plc (2011); Malitch and Thalhammer (2002); Pushkarev and Anikina (2002); Pushkarev (2001); Teluk (2001)
San Juan and Atrato Rivers districts, Colombia	107	1778 to 1965	n.d.	Mertie (1969)
Kondyor, Russia	85	1984 to 2011	Average grade of the placer deposit is 1.6 g/m^3 PGEs. Drainages within the intrusive body have grades of 4 g/m^3. The grades 50 km downstream are about 0.5 g/m^3.	Russian Platinum (2011a); Shcheka and others (2004)
Kamchatka, Russia	45	Approximately 10 years of mining beginning after 1991	The average mined grade is 0.28 g/m^3 platinum.	Hurst (2005)
Goodnews Bay, Alaska	19 to 22	1927 to 1975	At Squirrel Creek, high-grade placers contained 4.1 g/m^3, with an average tenor of 1.2 g/m^3. At Clara Creek, early small-scale mining of placers with a grade of 3.25 g/m^3, with an average tenor of 0.81 g/m^3. A cleanup a short distance from the mouth of Fox Gulch indicated grades of 0.81 to 1.2 g/m^3. Average grade of 470 samples is 0.192 g/m^3, with a maximum value of 1.6 g/m^3.	Johnston (1962); Mertie (1976); Barker (1986); Southworth and Foley (1986); Pacific North West Capital Corp. (2006); Chatterjee and Bandopadhyay (2011)
Yubdo, Ethiopia	2.0	1926 to 1956	Eluvium—Grades were initially 0.3 to 0.5 g/m^3 but decreased to 0.11 g/m^3 as mining moved away from the core of the intrusion. Alluvium—Grades were 0.25 to 0.83 g/m^3 in test pits.	Molly (1959)
Tulameen district, British Columbia, Canada	0.6	1885 to 1932	n.d.	Mertie (1969)
Fifield district, New South Wales, Australia	0.6	1893 to mid-1960s; most production from first few years of operation	n.d.	Mertie (1969); Platina Resources Ltd. (2006)

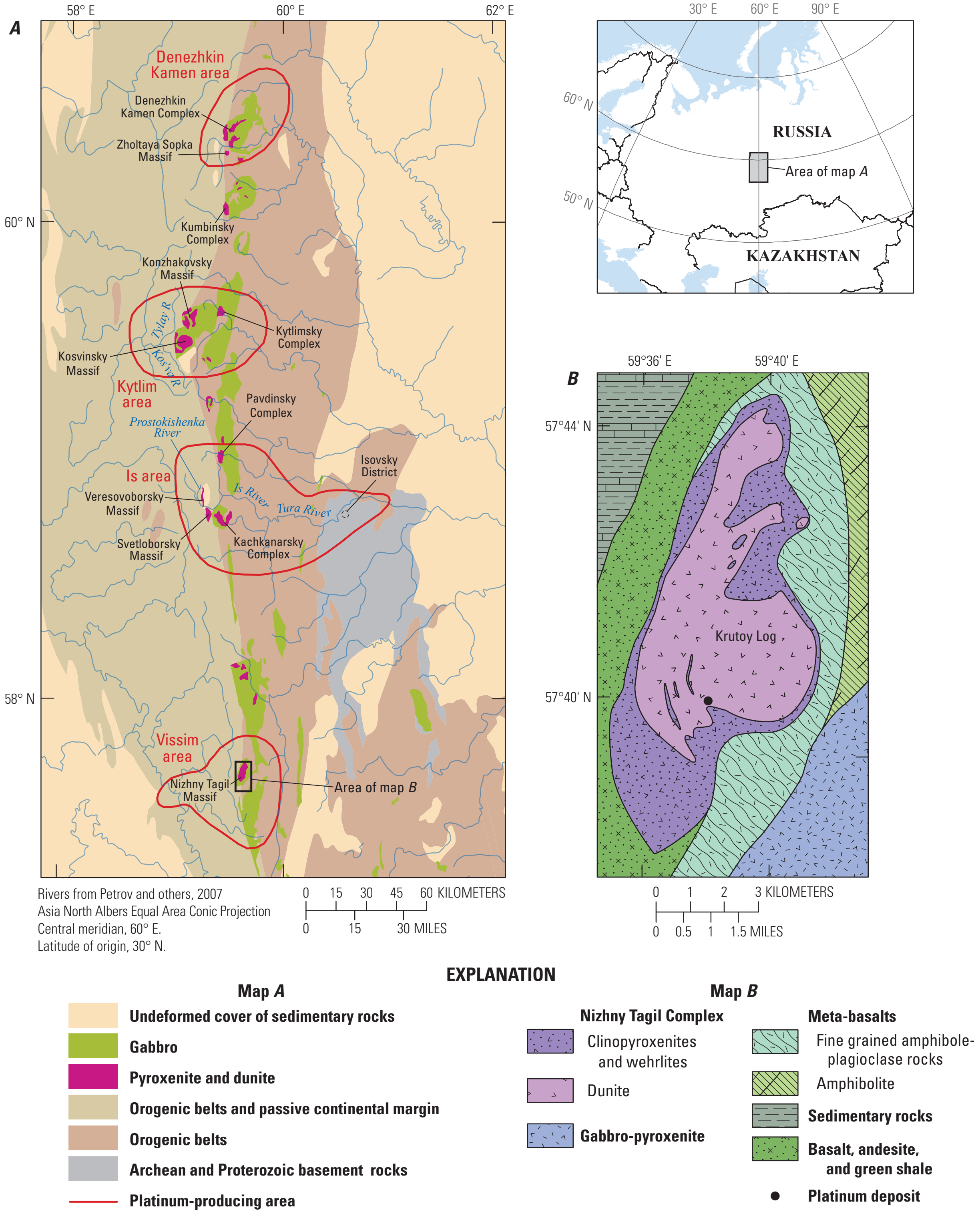


Figure N16. Maps illustrating the distribution of platinum deposits in the Ural Mountains, Russia. *A,* Generalized geology, location of platinum placer districts, and platinum-producing areas in the Ural Mountains, Russia. Placer platinum deposits are derived from pyroxenitic and dunitic intrusions; the platinum-iron alloy derived from the Veresovoborsky Massif and the Svetloborsky Massif occurs in placer deposits that extend about 100 kilometers downstream along the Is and Tura Rivers. Modified from Zonenshain and others (1988), Anderson and Martineau (2002), and Petrov and others (2007). *B,* Geology of the Uralian-type Nizhny Tagil Massif and the location of the Krutoy Log, where the first bedrock source of the platinum deposit was discovered. Platinum minerals were concentrated in chromitites that occur in the dunitic core of the lithologically zoned pluton. Modified from Levin and others (2010).

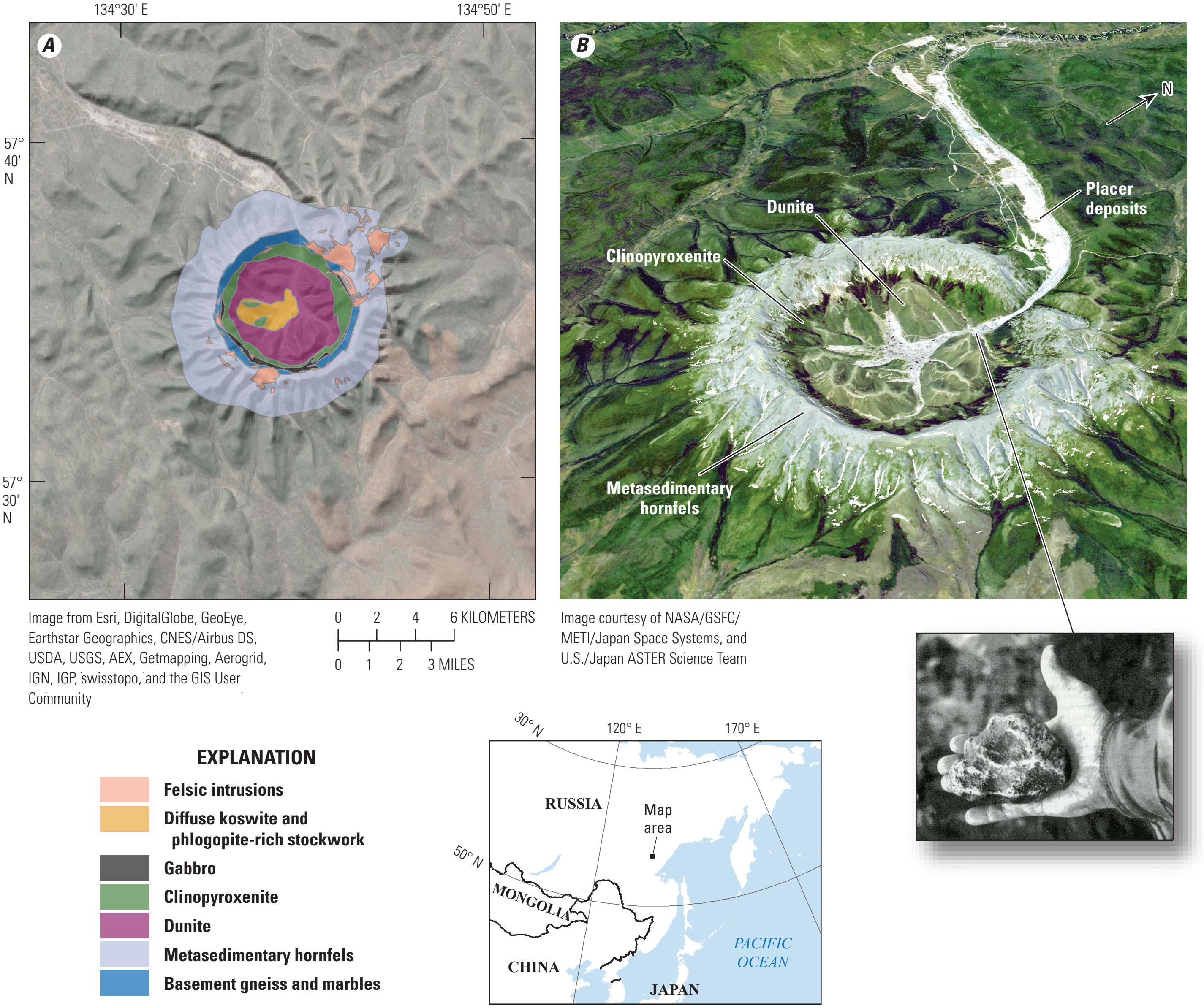


Image from Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Image courtesy of NASA/GSFC/METI/Japan Space Systems, and U.S./Japan ASTER Science Team

Figure N17. Geology and imagery of the Uralian-type Kondyor Massif, which is located in eastern Siberia, Russia, north of the city of Khabarovsk. *A,* Geologic map of the massif, showing that the circular pluton consists of a central core of dunite, which is surrounded by clinopyroxenite and gabbro. Emplacement of the pluton metamorphosed the surrounding sedimentary rocks, forming hornfels. Geology simplified from Burg and others (2009). *B,* Oblique view of the Kondyor Massif showing the core of dunite surrounded by clinopyroxenites. This circular intrusion is about 10 kilometers in diameter; the prominent topographic ridge, which is up to 600 meters high, is underlain by contact metamorphosed rocks that surround the intrusion. The intrusion is the source of coarse crystals of platinum-iron alloy coated with gold that are recovered in streams that drain from the complex. An example of a coarse platinum nugget recovered from the Kondyor Massif is shown in the black-and-white picture. This view was created by draping a simulated natural color Advanced Spaceborne Thermal Emission and Reflection Radiometer ASTER composite image over an ASTER-derived digital elevation model; the image was acquired on June 10, 2006. Photograph courtesy of NASA/GSFC/METI/Japan Space Systems, and U.S./Japan ASTER Science Team. The image of the platinum nugget is from Malitch (1999).

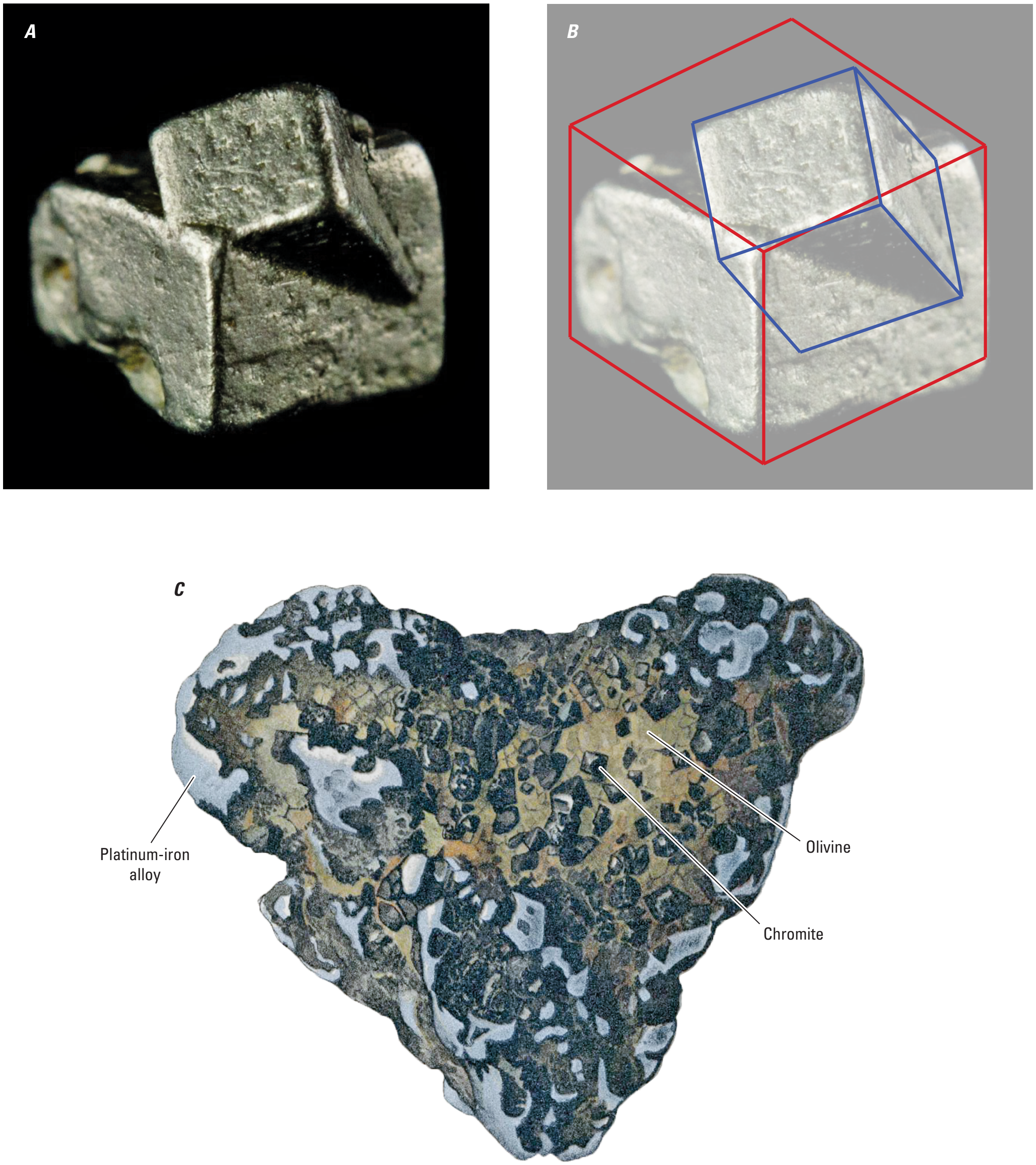


Figure N18. Photograph and lithograph showing the morphology of platinum-iron-alloy nuggets derived from Uralian-type intrusions. *A*, Photograph of silvery-gray nugget of isoferroplatinum from the Kondyor Massif, Russia. The nugget, which is about 4 millimeters (mm) long, consists of two intergrown crystals of isoferroplatinum; each crystal forms a cube with smooth crystal faces and sharp edges and corners (Photograph courtesy of TreasureMountainMining.com). *B*, Sketch of the isoferroplatinum nugget illustrating the cube-shaped crystals. *C*, Lithograph of a platinum nugget with olivine and octahedral chromite, from the Tulameen district, British Columbia, Canada. The longest dimension on the nugget is about 10 mm. In this nugget, platinum-iron alloy occurs interstitial to (in between) magmatic crystals of olivine and chromite. The texture implies that the platinum-iron alloy grew slightly later than the earlier formed olivine and chromite. Image is from Kemp (1902).

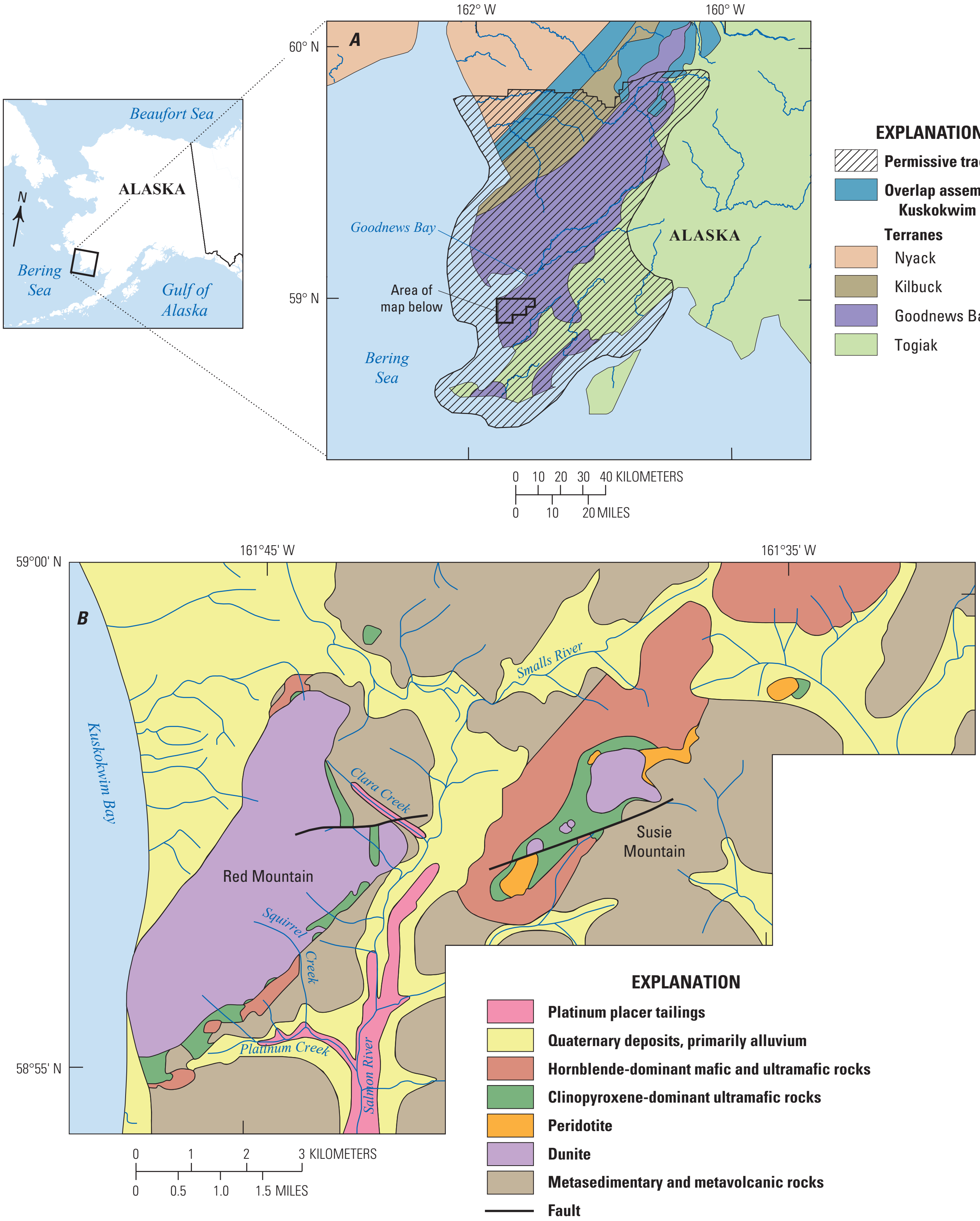


Figure N19. Maps illustrating platinum-group-element (PGE) resources in southeastern Alaska. *A*, Location of the permissive tract assessed for undiscovered placer platinum resources and the major geologic provinces (terranes) it encompasses. The permissive tract is the area where undiscovered PGE resources could be present (Schmidt and others, 2007). *B*, Geologic map of the Goodnews Bay area showing where platinum placer deposits have been mined (platinum placer tailings). The placer platinum deposits can be followed upstream to the Red Mountain pluton, a Uralian-type intrusion that could be the bedrock source of the platinum minerals found in the placers. Modified from Tolstykh and others (2002).

Resources and Production

Discovered mineral resources include the total amount of identified mineral resources that are in the ground as well as the cumulative past production (U.S. Geological Survey National Mineral Resource Assessment Team, 2000). This section begins with an overview of historic and current primary and secondary production of PGEs. Primary production is when metal that occurs in rocks is mined and transferred to above-ground material stock; secondary production is from recycled material or scrap. The section also includes a discussion of the identified mineral resources of PGEs. Identified mineral resources refer to the mineralized material in the ground whose location, grade, quality, and quantity are known or can be estimated from specific geologic evidence (U.S. Bureau of Mines and U.S. Geological Survey, 1980). Identified mineral resources represent the current stock of material in the ground (mineral inventory) that might be mined. The amounts of identified resources discussed this chapter were current as of 2012.

Production

Up to 1920, almost all of the world's PGE production came from placer deposits in Russia and Colombia. The discovery of nickel deposits in solid rock in the Sudbury area of Ontario, Canada, in the 1800s (Giblin, 1984) roughly coincided with technological innovations that used nickel to strengthen traditional steels. This technological innovation led to extensive development of the Sudbury deposits; in the first half of the 20th century, Sudbury produced approximately 80 percent of the world's nickel (Prevec, 1997). PGEs were recovered as a byproduct of nickel mining in Sudbury; by 1934, Canada had become became the world's leading producer of PGEs.

Most of the PGEs produced today are from mineral deposits that were discovered in the Noril'sk-Talnakh area of Russia in 1919 (Kunilov, 1994; Likhachev, 1994) and in South Africa in the 1920s (Wagner, 1929). Significant development of these deposits did not begin until the 1960s when industrial demands for PGEs increased. About the same time that new and extraordinarily PGE-enriched deposits were discovered in the Noril'sk-Talnakh area in Russia (Kunilov, 1994), Anglo American Platinum Ltd. gained a controlling stake in the PGE industry in South Africa (Mattera, 2008) and South Africa had an economic boom (Rouillard, 1997). As a result, beginning in the 1960s, PGE production increased in South Africa and the Soviet Union (Russia), such that South Africa became, and still is, the leading producer of platinum and rhodium, and Russia was and is the world's leading producer of palladium (fig. N20).

Approximately 14,200 metric tons of PGEs was produced from 1900 to 2011, and roughly 95 percent of that amount (about 13,500 metric tons) was produced from 1960 onward. The breakdown of production by country shows that about 90 percent of production since 1900 has come from South Africa and Russia; Canada, the United States, and Zimbabwe accounted for 5 percent, 2 percent, and 1 percent of production, respectively (fig. N21).

A secondary supply of platinum, palladium, and rhodium is obtained through the recycling of catalytic converters from end-of-life vehicles, jewelry, and electronic equipment. Recycling volumes are sensitive to PGE prices; higher prices typically lead to higher recycling volumes owing to the greater incentive to recycle. Recycled platinum, palladium, and rhodium provide a significant proportion of the total supply and are sufficient to close the gap between mine production and consumption. For example, in 2011, about 24 percent

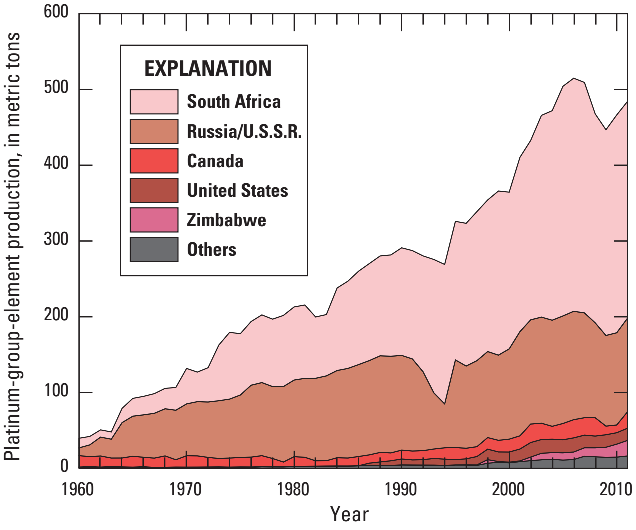


Figure N20. Graph showing world platinum-group-element production, by country and year, from 1960 to 2011. The layers of the graph are placed one above the other, forming a cumulative total. Data are from U.S. Bureau of Mines (1933–34, 1933–96) and U.S. Geological Survey (1997–2016).

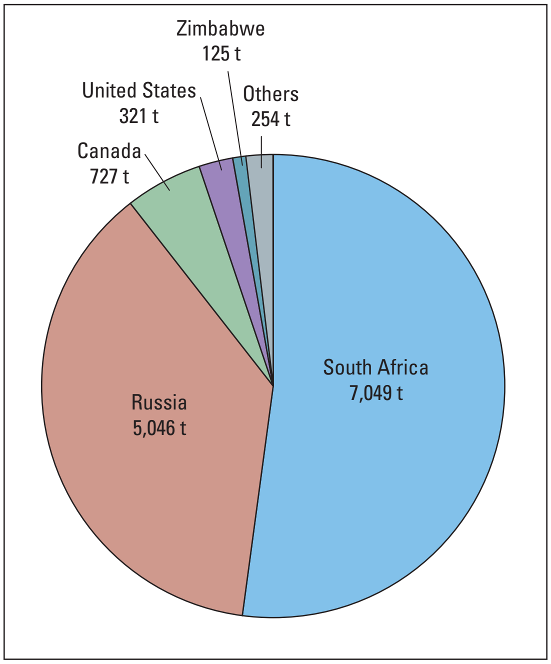


Figure N21. Pie chart showing world platinum-group-element (PGE) production from 1960 to 2011, by country and amount (in metric tons [t]) . Data are from U.S. Bureau of Mines (1933–34,1933–96) and U.S. Geological Survey (1997–2016).

of the total supply of platinum and palladium and about 27 percent of the total supply of rhodium were obtained through recycling (Butler, 2012).

Identified Resources

Exploration and mining companies have delineated approximately 100,000 metric tons of PGE (and minor amounts of gold) resources in mineral deposits around the world that remain to be developed (table N4). This estimate was derived by compiling mineral inventory information about in situ estimates of the tonnage and grade of mineralized rock with “realistic prospects of eventual economic extraction” (Weatherstone, 2008) published by exploration and mining companies and geological surveys. To be considered an identified resource for this compilation, the evaluation of tonnage and grade of mineralized rock must be based on (a) direct sampling of the ore, and (b) industry standard resource estimation practices. The estimate of 100,000 metric tons is comparable to the 91,000 metric tons recently reported by Mudd (2012) (table N4). Most of the difference is accounted for by the larger estimate for the Platreef deposit of the Bushveld Complex in this chapter. For context, the total net consumption of PGEs in 2012 was approximately 460 metric tons (Platinum Today, 2013c).

Table N4. Identified platinum-group-element and gold resources, summarized by deposit type and location.

[Data are from table N10 at the end of this chapter. Numbers may not add to totals because of rounding]

Deposit type	Deposit	PGE and gold resources compiled for this chapter (metric tons)	PGE and gold resources compiled by Mudd, 2012 (metric tons)
Reef	Merensky Reef and UG2 Chromitite, Bushveld Complex, South Africa	58,000	56,000
	Main Sulphide Zone, Great Dyke, Zimbabwe	8,200	8,700
	J–M Reef, Stillwater Complex, Montana	2,200	620
	Other areas	2,700	1,700
	Total, reef-type deposits	**71,000**	**67,000**
Contact	Platreef, Bushveld Complex, South Africa	17,000	7,700
	Other areas	3,100	1,600
	Total, contact-type deposits	**20,000**	**9,300**
Conduit	Noril’sk-Talnakh area, Russia	10,000	11,000
	Other areas	1,200	2,100
	Total, conduit-type deposits	**11,000**	**13,000**
Other	All other areas	990	1,200
	Grand total, all three types of deposits	**100,000**	**91,000**

Tonnage and Grade Relations for Magmatic Ore Deposits

Tonnage and total PGE and gold grade relations for identified resources in magmatic deposits are shown in figure N22. Estimates of total PGE and gold grade can vary over about three orders of magnitude, whereas tonnage can vary over five orders of magnitude. Tonnage and grade are not strongly correlated, which is typical for mineral deposits of a given type. Some conduit-type deposits have lower PGE and gold grades than reef-type deposits because conduit-type deposits are polymetallic deposits in which copper, nickel, PGEs, and gold all contribute to the value of the ore. In reef-type deposits, the value of the ore is primarily in the PGE and gold concentrations. In terms of contained metal, most deposits contain more than 1 metric ton of PGEs and gold. For any values less than 1 metric ton, it simply is not economic to determine the tonnage and grade. In 2012, world mine production was about 450 metric tons of PGEs and world usage was about 615 metric tons (Loferski, 2013b). The shaded area in figure N22 highlights those deposits that have more than 1 year's worth of contained PGEs, given current rates of production and usage. Only a fraction of the deposits in the world have enough contained metal to satisfy multiple years of world demand.

Mineral deposits occur rarely in Earth's crust, and large ones are especially uncommon (Singer, 1995). Most of the known metal for many mineral commodities is contained in a few, very large deposits (Singer and DeYoung, 1980). For most types of mineral deposits, the grade of the ore varies by about one order of magnitude and the tonnage varies by several orders of magnitude among deposits. As a result, contained metal correlates strongly with tonnage. For porphyry copper deposits (which are the world's leading source of copper), for example, 10 percent of the deposits accounts for approximately 60 percent of the identified copper resource whereas the bottom 50 percent of the deposits accounts for less than 5 percent of the identified copper resources (fig. N23*A*). For the PGEs, this correlation is more pronounced. Ten percent of PGE deposits account for more than 80 percent of identified PGE resources whereas the bottom 50 percent of the PGE deposits accounts for less than 1 percent of identified PGE resources. Thirty percent of PGE deposits contain more than 97 percent of the world's identified PGE resources, and almost all these deposits are associated with three areas—the Bushveld Complex in South Africa, the Great Dyke in Zimbabwe, and the Noril'sk-Talnakh area in Russia (fig. N23*B*).

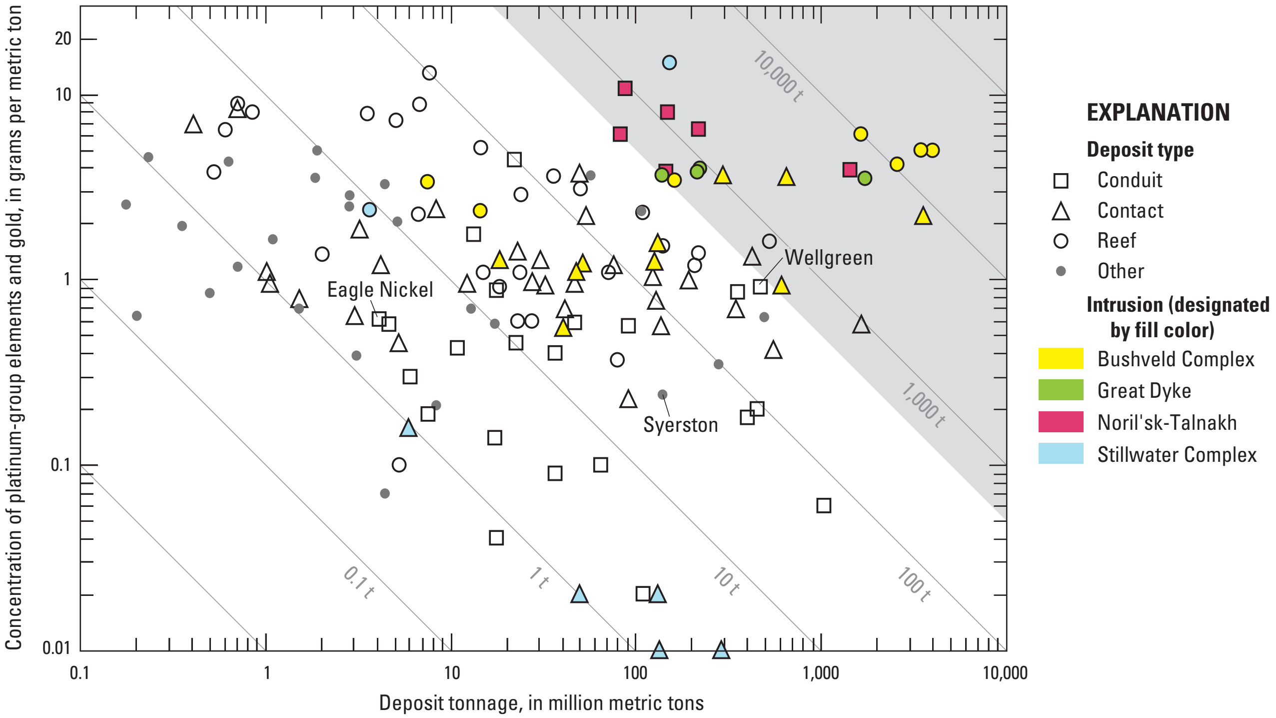


Figure N22. Plot showing the relation between tonnage and grade of remaining resources for conduit-type, reef-type, and other types of deposits enriched in platinum-group elements (PGEs). Diagonal lines are isolines that show amounts of contained PGEs and gold in the deposits, in metric tons (t). Annual world production and usage of PGEs, as of 2012, was about 450 metric tons. The shaded area on the figure highlights those deposits that are large enough to contain more than 1 year's worth of the world's PGE needs.

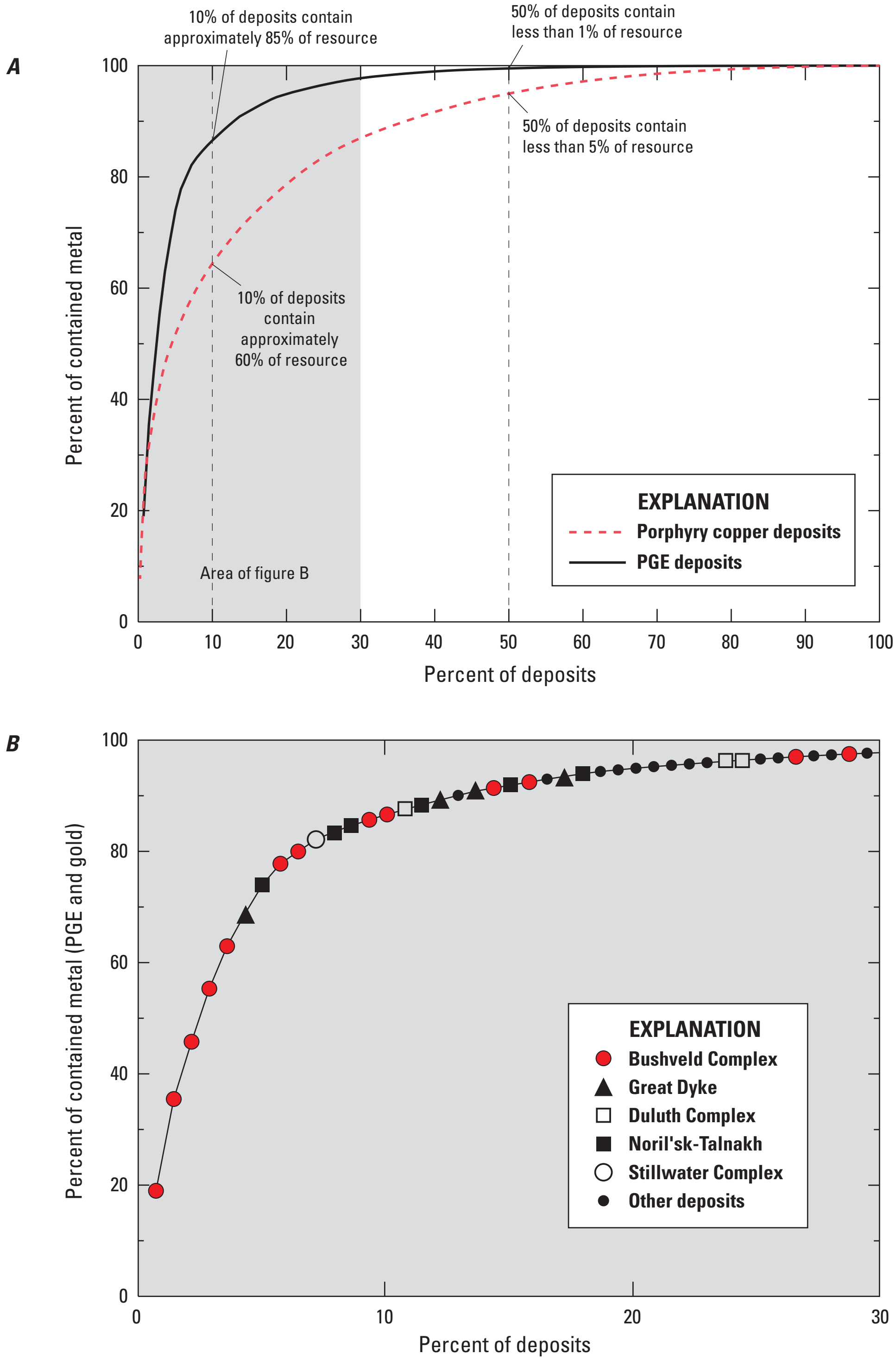


Figure N23. Graphs showing the percent of contained metal against percent of deposits for *A*, the world's platinum-group-element (PGE) and porphyry copper deposits, and *B*, the top 30 percent of the world's PGE deposits. In *A*, the curves are derived from compilations of known deposits and show that most of the contained metal in a given deposit type is associated with a small percentage of very large deposits. Both deposit types show the effect, but it is more pronounced for PGE deposits. In *B*, the curve focuses on the largest deposits, showing the data points and the name of the igneous intrusion hosting the deposit. Most of the large deposits are associated with the Bushveld Complex in South Africa, the Great Dyke in Zimbabwe, and sills in the Noril'sk-Talnakh area of Russia. Data for porphyry copper are from Singer and others (2008). PGE data are from table N10 at the end of this chapter.

Seventy-two percent of the world's PGE resources are found in reef-type and contact-type deposits in the Bushveld Complex, South Africa (table N4). The conduit-type magmatic deposits in the Noril'sk-Talnakh area, Russia, account for 10 percent of the world's identified PGE resources. Eight percent of the world's identified PGE resources are in the Great Dyke, Zimbabwe. In fact, more than 97 percent of all the world's identified PGE resources are contained in only 14 intrusions or intrusive complexes (table N5 at back of chapter).

When considered by deposit type alone, 69 percent of identified PGE resources are associated with reef-type deposits, 20 percent are associated with contact-type deposits, and 11 percent are associated with conduit-type deposits (table N4). For reef-type deposits, 81 percent of identified resources have been delineated in the Bushveld Complex (South Africa); 12 percent in the Great Dyke (Zimbabwe); and 3 percent in the Stillwater Complex (Alaska). For contact-type deposits, 85 percent of the world's identified resources are found in the Bushveld Complex. For conduit-type deposits, about 90 percent of the identified resources are found in the Noril'sk-Talnakh area of Russia.

For simplicity, the previous discussion has focused on total PGE production and resources; however, individual PGEs do have different values and uses. For example, platinum and rhodium are more valuable economically than palladium, and the iridium market is much smaller than the markets for platinum and palladium. The proportions of the PGEs differ among deposits, however (fig. N24). The deposits in South Africa and Zimbabwe have a higher proportion of platinum than any other major deposit in the world. The proportion of palladium is much higher in the deposits in the Noril'sk-Talnakh area in Russia.

Undiscovered (Hypothetical and Speculative) Resources (United States and Global)

In addition to the resources of PGEs that have been discovered (identified), additional PGEs may be present as undiscovered resources in areas adjacent to identified magmatic deposits and in deposits that remain to be discovered.

Extensions to Identified Deposits

Additional PGE resources may be present in areas adjacent to or near deposits that now dominate world supply. Although resources for reef-type and contact-type PGE deposits are formally delineated in advance of mining, the extent of the deposits is never completely delineated because the upfront costs would be too great. Instead, mining companies conduct enough research and work to ensure that the deposit contains adequate resources to justify mine development. It is possible, therefore, that some deposits are larger than previously thought.

In the Bushveld Complex, South Africa, relatively unexplored extensions of the Merensky Reef and the UG2 Chromitite deposits could contain an additional 33,000 metric tons of platinum and 32,000 metric tons of palladium to a depth of 3 km (Zientek and others, 2014). These reef-type PGE deposits are in the form of vast sheet-like orebodies. Mining has started at the surface and has progressed to depths of 2 km in some regions (fig. N25). Likewise, the Platreef in the Bushveld Complex could contain an estimated 1,100 metric tons of platinum and nearly 1,400 metric tons of palladium (based on a mean estimate to a depth of 1 km). The Great Dyke of Zimbabwe

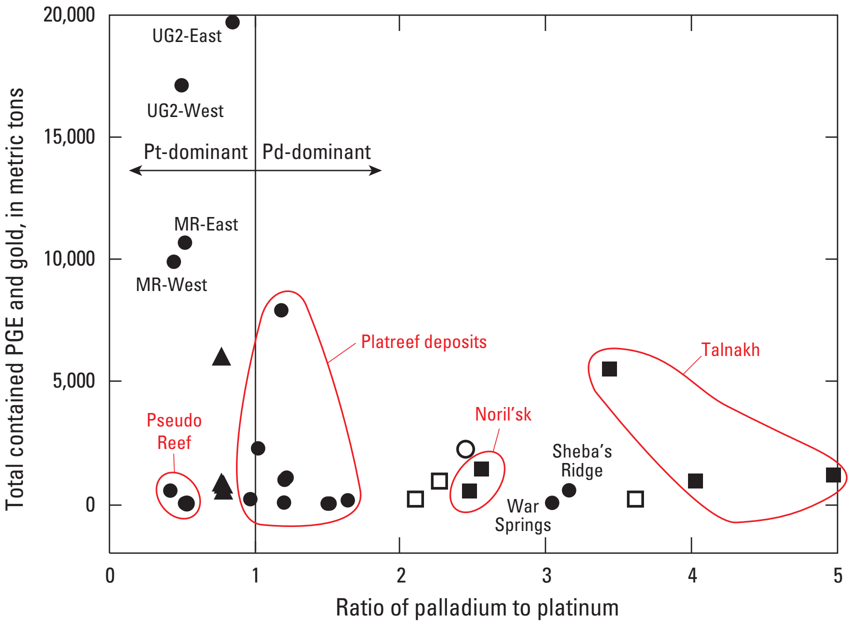


Figure N24. Graph showing contained platinum-group element (PGE) and gold metal against the ratio of palladium to platinum for the major PGE deposits of the world. The only identified deposits in which platinum is the dominant metal are associated with the Bushveld Complex in South Africa and the Great Dyke in Zimbabwe. PGE data are from table N10 at the end of this chapter. MR, Merensky Reef; Pd, palladium; Pt, platinum, UG2, UG2 Chromitite

EXPLANATION

Intrusion or area

● Bushveld Complex	■ Noril'sk Talnakh
□ Duluth Complex	○ Stillwater Complex
▲ Great Dyke	

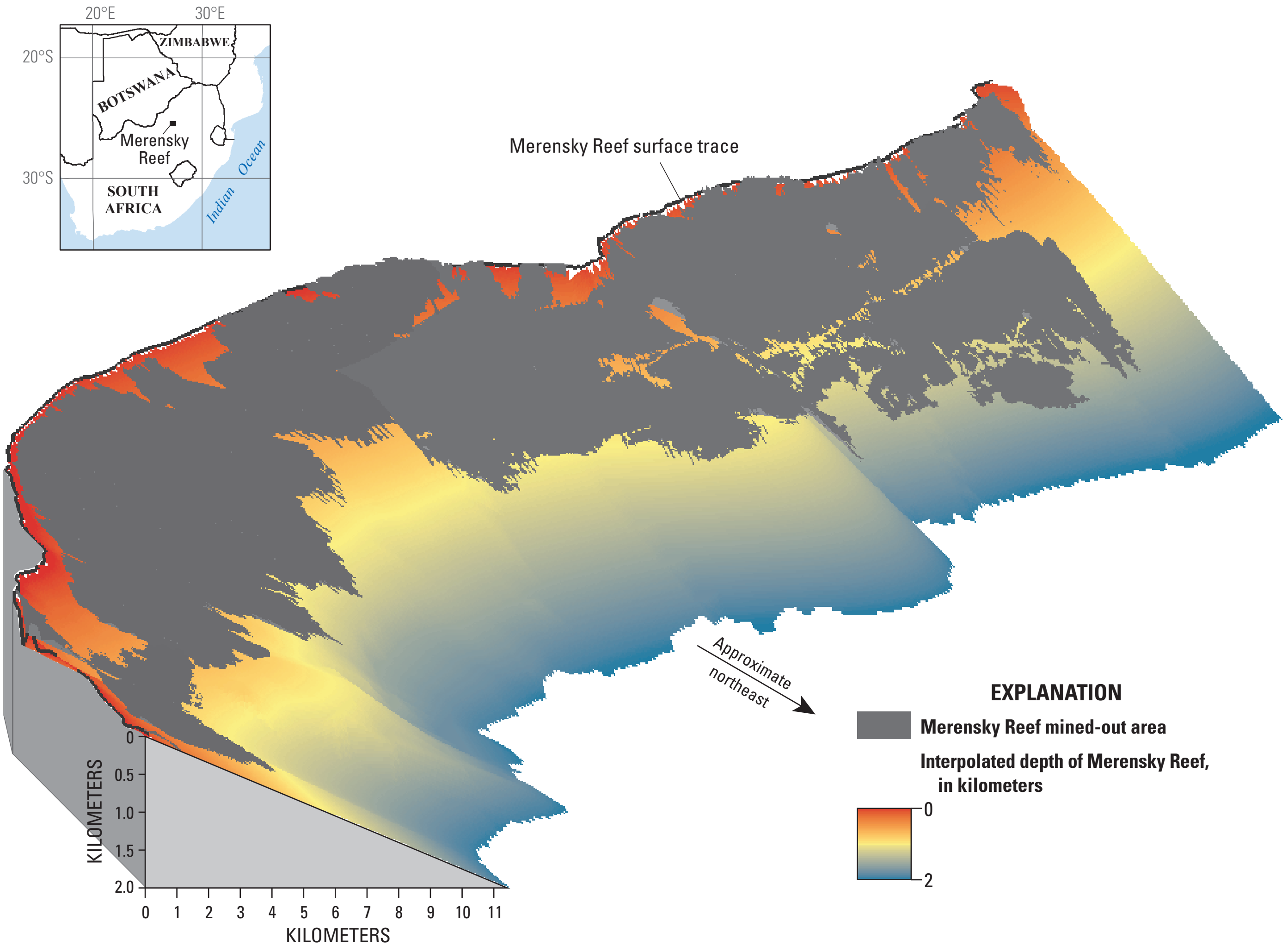


Figure N25. Three-dimensional block diagram showing the Merensky Reef interpolated down to 2 kilometers in the southern area of the western limb of the Bushveld Complex, South Africa. Mined out areas are shown in gray, and the Merensky Reef trace is shown as a black line. The Merensky Reef continues at depth beyond what is shown in this illustration.

could contain up to 6,900 metric tons of undiscovered platinum, palladium, and rhodium (Zientek and others, 2014).

Additional PGE resources in the Noril'sk-Talnakh area in Russia are difficult to assess. The extent of the orebodies for which resources are reported is not revealed in publicly accessible technical information released by the mining company. The northernmost mine in the Talnakh area, the Skalisty Mine, appears to be midway along the axis of the intrusion that hosts the massive sulfide orebodies (fig. N7*A*). If existing maps, similar to the one shown in figure N7*A*, are approximately correct, additional resources associated with massive sulfide orebodies in the Talnakh area could be present.

Roughly 305 metric tons of platinum and palladium have been produced from the J–M Reef in the Stillwater Complex in Montana, and drill-based estimates indicate that another 2,200 metric tons are present (U.S. Bureau of Mines, 1933–96; U.S. Geological Survey, 1997–2016; Abbott and others, 2011). Mining has progressed to depths of 1,800 m below the surface, but the bottom of the ore deposit has not been reached. Rough geologic estimates suggest that another 1,000 to 6,200 metric tons of platinum and palladium could be present at depth (Zientek, 1993; Zientek and others, 2002). As with the Bushveld Complex, the J–M Reef has been traced for longer distances along strike than down dip. The downdip projection of the J–M Reef is complicated by structural deformation associated with the uplift of the Beartooth Mountains. Gravity anomalies and inclusion suites in younger, cross-cutting intrusions, however, demonstrate that a portion of the complex is concealed at depth (Brozdowski, 1985; Kleinkopf, 1985). As a result, structural and geophysical models would be needed to constrain what rocks may be present at depth.

Undiscovered Reef-Type and Contact-Type Deposits

Based on literature research, there are at least 200 layered intrusions in the world, although the actual number could be two to three times higher. An intrusion does not have to be large to have a reef-type deposit; intrusions as small as a few tens of kilometers in length with as little as 500 m of layered cumulates are known to host reef-type mineralization (table N6 at back of chapter; fig. N26). Well-explored intrusions have at the most 1- or 2-m-thick reef-type deposits (and several subeconomic occurrences) that occur in thousands of meters of layered rock. Many small intrusions could be evaluated for their reef-type potential to assess whether an economic deposit could be present.

For example, the identified PGE resources in Finland are 91 metric tons of platinum and 237 metric tons of palladium in seven reef-type and contact-type deposits. An assessment by the Geological Survey of Finland estimates that a mean number of 29 and 23 contact-type and reef-type deposits, respectively, occur in Finland. They estimate that the median contained metal contents would be 5,500 metric tons of platinum and 12,000 metric tons of palladium in the undiscovered contact-type and reef-type deposits (Rasilainen and others, 2010).

Undiscovered magmatic mineral deposits could be present in many areas of the United States and the world. The intrusions of the Duluth Complex, United States, and other smaller intrusive complexes of the Midcontinent Rift in the Lake Superior region have high potential to contain undiscovered copper-nickel-PGE sulfide deposits (fig. N15; Miller and others, 2002). In fact, recent exploration has dramatically expanded the mineral resource inventory of contact-type deposits along the western margin of the Duluth Complex. Exploration results have led to new exploration models, which indicate additional areas that may have the potential for undiscovered deposits. Furthermore, the Duluth Complex has many large layered intrusions that may have the potential to host reef-type PGE deposits. New models, new data, and tools for integration and visualization could result in discoveries of mineralized rocks.

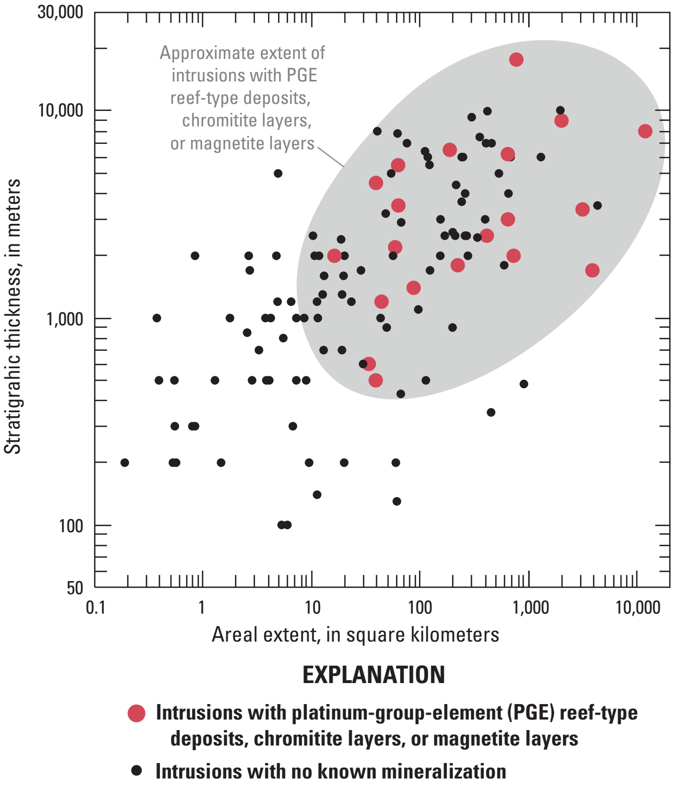


Figure N26. Graph illustrating the exposed area and stratigraphic thickness of cumulates in more than 200 intrusions from around the world.

Ernst and Buchan (2001) cataloged more than 300 LIP events worldwide; they determined that more than 100 LIP events have associated sill complexes or layered intrusions. All are prospective for the occurrence of magmatic mineral deposits. In the United States, Ernst and Buchan identified about 25 LIP events, of which several have sill complexes and layered intrusions. The obvious exploration targets for reef-type deposits in the United States are the Stillwater Complex in Montana and the dozens of intrusions that make up the Duluth Complex in Minnesota and associated rocks of the Keweenawan LIP. Other layered mafic intrusions with reef-type potential occur in the Wichita Mountains of Oklahoma, which are part of a Cambrian LIP. The Lake Owens Complex in Wyoming, which is a small layered intrusion, is also reported to have reef-type mineralization (Loucks, 1991). Other large layered intrusions are known from subsurface oil and gas exploration in west Texas and New Mexico; at present, they are too deep to be targets for mineral exploration (Keller and others, 1989; Kargi and Barnes, 1995; Adams and others, 1997).

To have a significant effect on global supply, a large-tonnage deposit would first have to be discovered. Large-tonnage reef-type deposits can occur only in large layered intrusions. A survey of the literature shows there are several large intrusions that do not have identified reef-type mineralization (such as the Tete Complex, the Dufek intrusion, the Molopo Farms Complex, the Windimurra Complex, and so on) (table N6). Some of the intrusions are poorly exposed and others have been intensely deformed and metamorphosed, which makes them difficult to explore for deposits. The economic risk associated with exploring these intrusions would be relatively high compared with identifying additional resources in extensions of known reef-type deposits.

Undiscovered Conduit-Type Deposits in the United States—Nikolai Greenstone and Eastern Wrangellia

Several LIPs with sill complexes occur in the United States (Ernst and Buchan, 2001); however, one in particular stands out for its potential for undiscovered conduit-type nickel-copper-PGE mineralization (Hulbert, 1997; Hulbert and Stone, 2006; Schmidt and Rogers, 2007). The Wrangellia LIP is known from extensive flood basalts and related rocks of the Middle to Late Triassic Nikolai Greenstone that is part of the Wrangellia terrane accreted to the western margin of North America (Berg and others, 1972; Jones and others, 1972; Berg and others, 1978; Nokleberg and others, 1994; Plafker and Berg, 1994). The Wrangellia terrane can be traced discontinuously for more than 2,000 km from the Wrangell and Amphitheater Mountains in southern Alaska through Canada's southwestern Yukon Territory, to the Queen Charlotte and Vancouver Islands in British Columbia, Canada.

Sill-like mafic to ultramafic intrusive complexes in Wrangellia are the remnants of subvolcanic magma chambers that fed the thick, overlying flood basalts and picritic pyroclastics of the Nikolai Greenstone. A conduit-type deposit in the Wellgreen intrusion, Yukon Territory, contains a resource of 461 million metric tons grading 0.32 weight percent nickel, 0.26 weight percent copper, 0.4 ppm platinum, 0.34 ppm palladium, and 0.17 ppm gold (McCracken, 2011; Carter and others, 2012).

Alaska's Amphitheater Mountains and the area of south-central Alaska are also underlain by several mafic to ultramafic complexes that are part of the Nikolai LIP (fig. N27; Schmidt and Rogers, 2007; Glen and others, 2011). The largest and most exposed mafic to ultramafic sills include the Fish Lake and Tangle (FL–T) Complexes, which occur along the flanks of the Amphitheater Mountains synform. Smaller mafic to ultramafic complexes include Canwell, Eureka, and Rainy. The occurrence of picritic volcanic rocks (high-magnesium olivine basalt) near some of the larger mineralized ultramafic bodies is consistent with mineralized occurrences that have high nickel-to-copper ratios and elevated PGE concentrations. Grab samples from three different mafic to ultramafic complexes have extremely high metal concentrations, as follows: 2.0 weight percent nickel, 1.3 weight percent copper, and 7.9 g/t PGE+gold+silver from Rainy; 13.6 weight percent nickel, 2.9 weight percent copper, and 26.0 g/t PGEs from Canwell; and 6.7 weight percent nickel, 1.0 weight percent copper, and 1.5 g/t PGEs from Alpha (same as Fish Lake) (Pure Nickel, Inc., 2013).

Undiscovered Platinum Placer Deposits in Alaska

Undiscovered marine placer deposits could be associated with paleochannels or beach deposits in the Goodnews Bay region in Alaska. A geophysical survey indicates the presence of ultramafic rocks offshore, which could be a source of placer platinum (Barker and others, 1988; Barker and Lamal, 1989). Seismic analysis indicates that the bottoms of the paleochannels that drained these now-offshore ultramafic rocks are about 20 to 40 m deep and covered with modern sediments (Oommen, 2006; Oommen and others, 2008). Platinum may have accumulated in marine sand bars that are aligned parallel or subparallel to the current Alaskan coastline (Oommen, 2006; Oommen and others, 2008). Assuming that the sand bars represent submerged paleobeaches exposed during periods of glaciation in the Pleistocene Epoch, intensified wave sorting and concentration of heavy minerals (including entrained platinum grains) may have taken place. Spatial distribution patterns of platinum and sediments offshore of the Goodnews Bay Complex suggest relatively high platinum concentrations near Goodnews Bay and Carter Bay (Oommen, 2006; Oommen and others, 2008).

Schmidt and others (2007) delineated a permissive tract (fig. N19*A*) for placer PGE-gold deposits hosted in Quaternary unconsolidated alluvial and marine sediments that includes onshore regions and areas up to 10 km offshore that are downstream of known mafic to ultramafic complexes within the Goodnews Bay and Togiak terranes (Hoare and Coonrad, 1978; Decker and others, 1994). They estimate that the tract has a 90 percent probability of containing at least 1 metric ton of platinum and a 10 percent probability of containing at least 17 metric tons; the mean and median estimates are 5 and 7 metric tons, respectively.

Metals in Stored Waste Products

PGEs may also be present in material discarded during the mining and beneficiation of magmatic ore deposits. When ore materials are processed to recover the PGEs, some losses always occur; in other words, it is impossible to recover 100 percent of the metal in the mined material. For example, tailings derived from processing ores from the Noril'sk-Talnakh area in Russia may contain 800 to 1,000 metric tons of PGEs; an additional 100 metric tons of PGEs may be present in stored pyrrhotite concentrates and iron cakes (Petrov and others, 2013). Some of the metals in stored waste products could be recovered if appropriate technologies are developed. For example, ultrafine grinding techniques are currently being used to reprocess tailings from the Merensky Reef mines in South Africa (Buys and others, 2013).

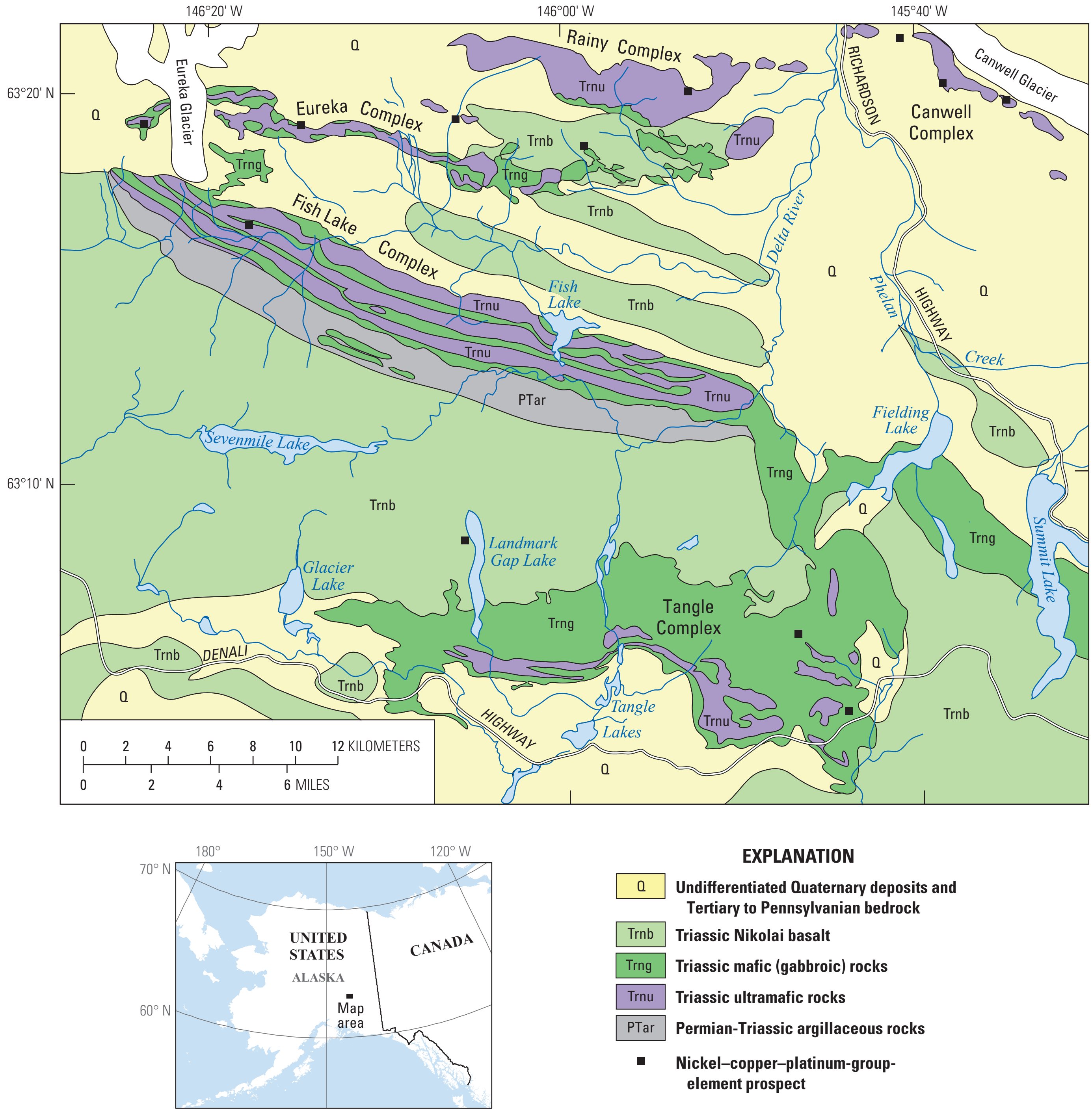


Figure N27. Geologic map of the Amphitheater Mountains and south-central Alaska showing the location and names of mafic-ultramafic complexes that are part of the Nikolai large igneous province (Schmidt and Rogers, 2007).

Exploration for New Deposits

The methods of locating PGE deposits can vary. In very rare cases, PGE-enriched sulfide mineralization has been found by panning. For example, the Merensky Reef of the Bushveld Complex, South Africa (fig. N9), was discovered in 1924 as the result of panning in a dry river bed and finding platinum minerals in the concentrate (Cawthorn, 1999). In most cases, chemical analysis of samples is required to identify PGE-enriched rocks. Because of the refractory nature of PGEs and their low concentration in most materials, an analytical technique that preconcentrates PGEs before analysis and ensures complete digestion of the sample is required. The preferred method to analyze for PGEs is fire assay.

A practical and effective exploration approach is to look for anomalous concentrations of copper, platinum, and palladium in residual or transported material derived from a larger volume of rock, such as soil, stream sediments, and talus fines (Cameron and Hattori, 2005). Soil chemistry has been used to delineate mineralized rocks in the Platreef of the Bushveld Complex (Frick, 1985). The J–M Reef of the Stillwater Complex (fig. N13) was discovered in 1974 by analyzing soil and talus fines for platinum and palladium (Conn, 1979; Zientek and others, 2005). Contact-type mineralization in the Duluth Complex (fig. N15) is currently being explored using regional geochemical surveys of glacial till (Duluth Metals Ltd., 2011).

Surface-water geochemistry led to the discovery of the ore deposits in the Noril'sk-Talnakh area in Russia (figs. N3 and N6; Kunilov, 1994). A surface water geochemical survey showed elevated concentrations of SO_4^{2-} in samples from the Talnakh River. This led to the discovery of mineralized boulders in the area, which were traced to the base of the Kharayelakh Mountains. A study of talus along the slope of Otdel'naya Mountain led to the discovery of mineralized outcrops.

Geophysical methods used in PGE exploration map physical property contrasts, which primarily indicate the presence of magnetite, silicate minerals, and sulfide minerals that may be associated with PGE mineralization (Balch, 2005). If the PGEs are associated with base-metal sulfide minerals that have some degree of interconnection in the rock (and are electrically conductive), airborne and ground electromagnetics and induced polarization surveys can be used to detect mineralized rocks. High-resolution aeromagnetic surveys can be used to map igneous layering and tectonic structures (Campbell, 2006) but generally do not give direct indication of mineralized rock. Gravity studies are used to determine the subsurface extent of rocks with variable density and are particularly well suited to map and model the extent and volume of mafic and ultramafic igneous rocks (Webb and others, 2004). Once a rock layer that contains reef-type mineralization has been identified, seismic studies can be used to map the subsurface extent of the rocks (Davison and Chunnett, 1999; Chunnett and Rompel, 2004).

Lithogeochemical studies can be used to focus exploration activities (Maier and Barnes, 2005). For example, changes in the ratio of PGEs to sulfur or copper in rocks can be used to target specific intervals in cumulate stratigraphy where reef-type PGE mineralization could be present. In layered intrusions, nickel depletion in olivine is thought to indicate indirectly the presence of magmatic sulfide mineralization. Metal depletion in lavas flows is thought to indicate the presence of sulfide mineralization in the sills and dikes that served as feeders to the flows.

High-density drilling and sampling are required to delineate mineral resources and reserves in PGE deposits. For the J–M Reef, drilling on 15-m spacing is used to define proven mineral reserves; probable mineral reserves are delineated by projecting data 300 m from drill holes (Abbott and others, 2011). In the reef-type deposits in the Bushveld Complex, South Africa, measured mineral resources are defined with holes spaced 250 to 300 m apart, indicated resources are defined with holes spaced 500 to 600 m apart, and inferred mineral resources are defined with holes spaced 800 to 2,000 m apart. By comparison, massive sulfide ores in the Noril'sk-Talnakh area, Russia, are explored on a 32- by 60-m rectangular grid (Kunilov, 1994).

Environmental Considerations

The mineralogy of the ore and waste material associated with reef-type, contact-type, and conduit-type deposits are similar. Common sulfide minerals include chalcopyrite, pentlandite, and pyrrhotite. Secondary phases that typically form from primary sulfide minerals include covellite, goethite, gypsum, jarosite, marcasite, native sulfur, and pyrite (McGregor and others, 1998; Johnson and others, 2000). Common primary gangue minerals include chromite, olivine, plagioclase, and pyroxene. Alteration products include chlorite, magnetite, serpentine, talc, and minor amounts of carbonate and clay minerals.

The abundance of sulfide minerals defines the environmental and geologic characteristics of PGE-enriched magmatic sulfide deposits. The high proportion of sulfide minerals distinguishes some conduit-type deposits from reef- and contact-type deposits. The overall pyrrhotite content of ore, waste rock, and tailings determines their acid-generating potential. Acid generated by the oxidative weathering of pyrrhotite can attack associated ore sulfide minerals and gangue silicate minerals, releasing a variety of potentially toxic elements—particularly cobalt, copper, iron, manganese, nickel, and, to a lesser extent, aluminum, cadmium, chromium, lead, and zinc to solution or to secondary solid phases (McGregor and others, 1998; Johnson and others, 2000). Massive ores characteristic of some conduit-type deposits have greater than 50 volume percent sulfide minerals and pose a greater challenge for mining and processing the ores without causing environmental problems. Both the low-sulfide reef-type and contact-type deposits have significantly lower sulfide contents, usually less than a few volume percent. Therefore, acid generation in mine wastes is less of a challenge to manage.

Sources and Fate in the Environment

The abundance of PGEs in the upper continental crust ranges from tens to hundreds of parts per trillion (ppt); platinum is the most abundant, followed by palladium, osmium, ruthenium, iridium, and rhodium (table N7; Taylor and McLennan, 1995; Park and others, 2012). Background PGE concentrations are also low in other environmental media, such as water, sediment, soil, and plants.

Experimental studies suggest that the maximum solubility of platinum in water at room temperature (25 °C) under oxygenated conditions ranges between 0.02 and 195 ppb, depending upon the pH of the water (Wood, 1991; Azaroual and others, 2001). The solubility of palladium in water at room temperature (25 °C) under oxygenated conditions ranges between 1 and 3,400 ppb, depending upon the pH of the water (Wood, 1991). Because of its greater solubility, palladium is more mobile in the environment than platinum.

PGE concentrations in water are generally in the 10^{-2} ppt range. Rhodium (0.082 ppt) has the highest mean concentration in seawater, followed by palladium (0.062 ppt), platinum (0.026 ppt), and osmium (0.005 ppt); ruthenium and iridium are present well below the ppt range (Bruland and Lohan, 2003). Platinum concentrations range from 0.22 to 78,000 ppt in surface water and from 3 to 38 ppt in groundwater (Ravindra and others, 2004).

Environmental baseline studies generally show low concentrations of PGEs and trace elements in water near undeveloped deposits. In the vicinity of the contact-type NorthMet deposit in northern Minnesota, surface water downstream of the deposit in the Partridge River watershed has neutral pH (7.0), a low dissolved sulfate concentration (7.2 ppm), and moderate alkalinity (31 ppm calcium carbonate [$CaCO_3$]) and hardness (30.3 ppm $CaCO_3$). Dissolved platinum and palladium concentration are below the detection limit (<25 ppb), and the concentrations of other trace elements are low (table N8 at back of chapter; Minnesota Department of Natural Resources and the U.S. Army Corps of Engineers, 2009). Near the buried Eagle deposit, which is a conduit-type deposit in northern Michigan, maximum concentrations of iron (190 ppb), nickel (59 ppb), and zinc (88 ppb) in groundwater near the deposit reflect the presence of the orebody, whereas maximum concentrations of copper (<5 ppb) and cobalt (<10 ppb) are below their detection limits. In contrast, the concentrations of copper, nickel, and other trace elements in surface waters over the buried deposit are indistinguishable from those from regional water samples (Kennecott Eagle Minerals Co., 2006).

In fluvial and pelagic-marine sediment away from any known deposits, total PGE concentrations are less than a few tens of ppb (table N7). Platinum and palladium are found in higher concentrations than are (in decreasing order of abundance) ruthenium, iridium, osmium, and rhodium.

Fuchs and Rose (1974) investigated the geochemical behavior of platinum and palladium in the weathering cycle in soils around the Stillwater Complex in Montana. They found that palladium was depleted in the surface soil horizons but was concentrated at depth, reaching a maximum concentration of approximately 40 ppb. Platinum did not show systematic trends with depth; a maximum concentration of approximately 180 ppb was recorded. The differences in the behavior of palladium and platinum in soils reflects the higher solubility of palladium in water compared with that of platinum in water (Fuchs and Rose, 1974).

Table N7. Platinum-group-element concentrations in samples of upper crust, loess, river sediment, and marine pelagic sediment.

[n.d., no data]

Material	Platinum	Palladium	Ruthenium	Iridium	Osmium	Rhodium	Reference(s)
	(part per billion)						
Upper continental crust	0.599	0.526	0.03	0.022	0.05	0.018	Taylor and McLennan (1995); Park and others (2012)
Loess (China)	0.751	0.546	0.03	0.023	n.d.	0.018	Park and others (2012)
River sediment (Mölndal River, Sweden, and Stour River, England)	<0.29 to 53.9	0.08 to 38.7	<0.15 to 3.73	<0.03 to 2.69	n.d.	<0.11 to 9.4	Ravindra and others (2004); Moldovan and others (2001); de Vos and others (2002)
Marine pelagic sediment	0.4 to 21.9	1.2 to 9.4	< 0.2 to 2.2	<0.2 to 1.2	<0.05 to 0.81	n.d.	Goldberg and Koide (1990)

The results of an exploration program illustrate the natural background variation of platinum and palladium in a layered intrusion that hosts a major reef-type deposit. Following the studies by Fuchs and Rose, more than 10,900 samples of soil and talus fines were collected and analyzed for platinum and palladium as part of the exploration program that led to the discovery of the J–M Reef at the Stillwater Complex (Conn, 1979; Zientek and others, 2005). Palladium was below the detection limit for 14 percent of the locations; almost one-half of the samples had platinum concentrations that were below the detection limit. For most of these samples, the detection limit for palladium and platinum was 2 ppb and 20 ppb, respectively. The median values for samples in the study above the detection limit were 8 ppb and 20 ppb for palladium and platinum, respectively. Maximum values measured for palladium and platinum were 6.4 ppm and 5.76 ppm, respectively.

Platinum and palladium data are characterized by positive-skewed, multimodal distributions. More than 95 percent of the samples belong to a population consisting of unmineralized material with less than 30 to 40 ppb palladium and less than 40 to 50 ppb platinum. The remaining approximately 460 samples appear to be made up of two populations. The range of values for the largest population in the remaining 5 percent varies from about 40 ppb to 200 ppb palladium and about 50 to about 200 ppb platinum. About 50 samples make up the third population and consist of material with more than 200 ppb platinum or palladium.

Biogeochemical surveys show that platinum and palladium can concentrate in plants near mineralized outcrops. Riese and Arp (1983) conducted a geochemical orientation survey of the J–M Reef in the Stillwater Complex and found accumulations of platinum in stems of Douglas-fir (*Pseudotsuga menziesii*) up to thousands of parts per billion in ashed samples. In the northern forests of Saskatchewan, Canada, platinum and palladium tend to be concentrated in the twigs and trunks of black spruce (*Picea mariana*) and jack pine (*Pinus banksiana*) and in the stems of Labrador tea (*Rhododendron groenlandicum*). Spruce was sampled close to a worked-out nickel-copper deposit in northern Saskatchewan that contained 3,000 ppb platinum and 6,000 ppb palladium. The ashed twigs yielded up to 880 ppb platinum and 1,350 ppb palladium compared with background levels of below 10 ppb platinum and 2 ppb palladium (Dunn, 1986). Coker and others (1991) found greater enrichment of palladium than of platinum in vegetation around several PGE deposits in Canada—some that had been mined and some that had not been mined.

Anthropogenic sources of PGEs in the environment include catalytic converters used in modern automobiles (Ek and others, 2004; Ravindra and others, 2004; Wiseman and Zereini, 2009), platinum-based chemotherapy drugs (Ravindra and others, 2004), and smelter emissions (Chen and others, 2009). During the release of exhaust gases from automobile engines, the catalytic converters are chemically and physically stressed and release PGE-containing particulate matter. Most of the PGEs in the particles are in the metallic state, but about 1 percent is in an oxidized form that could be bioavailable (Ravindra and others, 2004). Concentrations of PGE particles are found in roadside dust, soils, and water. In platinum-bearing drugs that are used to treat cancer, the platinum is excreted by the patients following treatment and ends up in the hospital sewage. The contribution of PGEs to the environment through this method is minor, however, compared with that from catalytic converters (Ravindra and others, 2004). Tiny amounts of osmium (0.25 to 23 femtograms per gram of water; 1 femtogram is 10^{-15} grams) are found in rainwater and snow from around the world (Chen and others, 2009). The most likely sources of this metal are smelters that process PGE ores. The osmium concentrations are so low that they are difficult to analyze; however, it is possible that the global appearance of osmium could someday be used as an environmental tracer.

Platinum-Group-Element Mining and Mineral-Processing Methods

Selective underground mining techniques are used for PGE deposits that occur in narrow reefs, such as those in the Bushveld Complex (South Africa) and the Stillwater Complex (Montana). The underground mining is performed by using either handheld pneumatic drills or mechanized drills to bore holes in the ore horizon, which are then filled with explosives. After blasting, the ore is removed from the mining stope and transported to the surface for further processing. Open pit mining is used for deposits in which the PGEs occur in greater thicknesses and at shallow depth, such as in the Lac des Iles Mine in Canada and the Platreef of the Bushveld Complex.

After ore is removed from the mines, it is crushed and ground to reduce the particle size and free the PGE-containing minerals from the rock matrix. The ore is then concentrated by using froth flotation circuits. For flotation, the ground rock particles are mixed with water and various reagents and air is pumped through the liquid, creating bubbles to which the PGE-containing minerals adhere. These bubbles float to the surface of the flotation vats and are removed as froth. The material is reground and refloated to produce a concentrate of nickel-iron-copper-PGE sulfide minerals for further processing. The greatest losses of PGEs occur in the early stages of processing, including crushing, milling, and froth flotation, owing to the diversity of PGE mineralogy. Much research is devoted to increasing PGE recovery rates in these early stages.

The concentrate is dried and then smelted in an electric arc furnace at temperatures that can exceed 1,500 ºC. During smelting, the concentrate forms a liquid, which separates into two layers. A matte containing the valuable metals is separated from a silicate- and oxide-rich slag, which is discarded. At the Stillwater Mining Co. smelter, the gases released from smelting operations undergo a gas-to-liquid scrubbing process, which removes approximately 99.8 percent of the sulfur dioxide. The sulfur dioxide is converted to gypsum, which is sold to local farmers for use as a soil amendment.

After smelting, the PGE-rich matte is transferred to converters, through which air is blown to remove iron and sulfur. The converter matte is processed at the base-metals refinery to separate the base metals from the PGEs by selective leach processing. The final stage is PGE refining by various hydrometallurgical techniques, including solvent extraction, precipitation, and dissolution using chloride solutions, in which the six PGEs are separated from each other to a purity of more than 99.99 percent. The refined PGEs can be produced in various forms, including as ingots, grains, or a fine powder known as “sponge.”

The chromium-rich ores of the Bushveld Complex’s UG2 Chromitite present special difficulties for beneficiation. The high chromium content of the ores requires especially high temperatures for smelting, and the low sulfide content both increases the matte viscosity and lowers the amount of matte formed. A processing technique, known as ConRoast, has been employed by some Bushveld processors specifically for use with high-chromium PGE ores. The ConRoast technique removes sulfur from the concentrate by roasting the ore at high temperatures in oxidizing conditions followed by smelting in a direct-current arc furnace in reducing conditions, which uses an iron-based alloy as a collector of cobalt, copper, nickel, and PGEs. The ConRoast technique can be used for concentrates containing any amount of chromite (Jones, 2002).

Ores from the Duluth Complex (Minnesota) present another challenging processing problem. Their low-grade nature makes smelting inefficient and uneconomic. A high-temperature chloride-assisted pressure-leaching process, known as PLATSOL™, has been developed to process the Duluth ores. The PLATSOL™ process is an alternative to smelting and is capable of processing low-grade PGE ores. The nickel-copper-PGE ore concentrates are processed in an autoclave in an oxidizing environment in which PGEs, as well as gold, are solubilized and can be recovered directly after leaching by adsorption or precipitation with sulfide ions. Finally, base-metal sulfides are recovered either by precipitation, ion exchange, or solvent extraction-electrowinning (Baxter and others, 2005).

Mine Waste Characteristics

The majority of solid mine waste includes waste rock, mill tailings, slag, and smelter dust. Waste rock is uneconomic rock that must be removed to access the ore and is disposed of on site. It can also be used for construction on site if tests determine that it will not generate acid-rock drainage when it is exposed to the atmosphere and water. Tailings, which is the waste material from processing ore, can be pumped as slurry or trucked dry to a tailings storage facility on site. Tailings storage facilities are typically impoundments surrounded by a retaining dam. Tailings can also be disposed of underground in mined-out portions of the mine. The crushing and milling process increases the porosity of the solid waste and thus its volume by a factor of approximately two, which means that only about one-half of the waste from ore processing can be returned underground. Smelter slag, which is glassy waste matter separated from metals during the refining of ore, also has both physical and chemical characteristics of environmental concern and is typically held in storage facilities. Slag is also used in some mining and construction applications. Smelters produce gaseous emissions that may contain particulate material (smelter dust). If the emissions are not treated before the gases are vented to the atmosphere, the particulate material will settle near the smelter. For most modern smelting facilities, the gaseous emissions are treated to remove particulates, which are reprocessed to recover metals or put into a storage system.

Waste rock and tailings are usually found at all mines, but their proportions vary based on the mining method. The amount of waste rock is significantly greater at open pit mines than at underground mines. Reef-type deposits are generally mined by underground methods because of the narrow width of the ore horizon. Contact-type and conduit-type ores are mined by either open pit or underground methods, depending upon the geometry and depth of the orebodies.

Acid-Base Accounts

Metals and many other trace elements tend to be more soluble at low pH than at neutral or high pH. Therefore, the acid-generating or acid-neutralizing potentials of waste rock, tailings, and other solid waste material help determine the possible environmental risk of mineral resource development. The balance between the acid-generating and the acid-neutralizing potential of rocks and mine waste is expressed as an “acid-base account” (Price, 2009; International Network for Acid Prevention, 2011). The release of acid is primarily related to the presence of pyrrhotite in the rocks and waste. The presence of carbonate minerals, such as calcite, and some silicate minerals, such as feldspar, olivine, or pyroxene, in rocks and wastes can neutralize acidic solutions. Acid-base accounting values are commonly expressed in terms of kilograms of calcium carbonate per metric ton (kg $CaCO_3$/t) of waste material.

Acid-Base Accounts for Reef-Type and Contact-Type Deposits

Acid rock drainage from reef-type and contact-type deposits is unlikely because the ores and their host rocks contain low proportions of sulfide minerals. Jambor and others (2000) proposed a threshold of 0.3 weight percent sulfur present in sulfide minerals for acid generation. The sulfur content of ore in the J–M Reef at the Stillwater Complex in Montana ranges from 0.13 to 0.49 weight percent, with concentrations in tailings ranging from 0.05 to 0.08 weight percent. The sulfur content of the waste rock ranges from 0.01 to 0.04 weight percent (table N9 at back of chapter). Similarly, the ores and host rocks for the UG2 Chromitite, the Merensky Reef, and the Platreef deposits have low sulfur concentrations (Wilson and Chunnett, 2006; Naldrett and others, 2009). Acid-base accounting studies, leach tests, and site monitoring demonstrate that there is limited potential for the generation of hazardous metal leachates from ores, waste rocks, or tailings from most reef-type and contact-type deposits (table N9).

Acid-Base Accounts for Conduit-Type Deposits

For some conduit-type deposits with massive ores, the ore is processed to separate out and produce concentrates of iron-, copper-, and nickel-bearing sulfide minerals; the concentrated material is then further processed to extract the copper and nickel metals, and the iron-bearing sulfide minerals, mainly pyrrhotite, are discarded as waste. This process results in waste material with high acid-generating potential; the presence of minor amounts of carbonate minerals in the ore assemblage and the lower reactivity of the neutralizing minerals, such as olivine and pyroxene, offer minimal short-term acid-neutralizing potential. The Eagle deposit in northern Michigan has the potential to generate acid leachate similar to that found in mineralogically similar tailings from Sudbury, Ontario, Canada (McGregor and others, 1998; Johnson and others, 2000). Johnson and others (2000) documented the generation of low pH (down to 3) waters with high dissolved concentrations of iron (up to 9,800 ppm), sulfate (up to 2,400 ppm), aluminum (up to 1,130 ppm), and nickel (up to 698 ppm) in groundwater in the tailings pile at the Nickel Rim Mine at Sudbury, Ontario, Canada. Copper (up to 3.5 ppm) and cobalt (up to 2.5 ppm) were also significant constituents.

Air Quality Assessments

An air quality assessment of the heavily industrialized western part of the Bushveld Complex, where the Merensky Reef and the UG2 Chromitite are mined, found that sulfur dioxide, nitrous oxide, and carbon monoxide concentrations are at acceptable levels using South African and European air quality standards (Venter and others, 2012). The major contributing sources were high-stack industry emissions for sulfur dioxide (metallurgical complexes and smelters), and household combustion for nitrous oxide and carbon monoxide. The levels of ozone and PM_{10} frequently exceeded standards (PM_{10} refers to the total mass concentration of particulate matter up to 10 micrometers [μm] in size). Ozone is related to regional sources (wildfires, and coal and wood combustion for cooking and heating). The source of PM_{10} was identified as local household combustion (Hirsikko and others, 2012; Venter and others, 2012).

Mining operations in the Noril'sk-Talnakh area of Russia emit large amounts of sulfur dioxide and nickel and other metals (Council on Ethics, 2009; Bellona Foundation, 2010). According to the Norwegian Government's Council on Ethics for the Government Pension Fund-Global, atmospheric emissions of sulfur dioxide, which lead to acid rain, are about 2,000,000 metric tons per year, and atmospheric emissions of copper, nickel, and cobalt are conservatively estimated to be about 500, 450, and 50 metric tons per year, respectively. Smelting operations release metals into the atmosphere in the form of dust or particulates. Smelter emissions have been shown to cause death or significant damage to vegetation up to 200 km from the mining operations.

Human Health Concerns

The metallic forms of PGEs are generally considered to be inert. Health hazards specifically related to PGEs affect only individuals who are occupationally exposed to manmade PGE compounds, especially workers in precious-metal refineries. Platinum-based drugs, such as cisplatin and carboplatin, are used in cancer treatment. Broader human health effects of PGEs appear to be limited because of the low concentrations of PGEs in the environment (Hoppstock and Sures, 2004). Ravindra and others (2004) and Hoppstock and Sures (2004) reviewed human health risks associated with PGEs, and Kielhorn and others (2002) reviewed the human health effects of palladium specifically. The more significant human health risks associated with PGE mining are related to the trace elements associated with PGE deposits.

As discussed in a previous section, the mining operations at the Noril'sk-Talnakh area in Russia affect air quality; surface and groundwater are also affected by the industrial activities. Respiratory diseases and various forms of cancer have been shown to be more prevalent in the local population of the Noril'sk-Talnakh area than in other regions of Russia (Council on Ethics, 2009). Industrial activity in this area has been shown to be related to increased incidences of acute respiratory illness and a higher prevalence of oncological disease, particularly lung cancer, and may be related to other possible negative health effects, such as weakening of the immune system, reproductive health issues, an increase in the rate of disease in children, and reduced life expectancy (Council on Ethics, 2009).

Ecological Health Concerns

The risks to the ecosystem from mining PGEs and associated minerals are mainly those related to acid mine drainage, which primarily affects aquatic environments. The surface water chemistry downstream from platinum mine waste dumps in Zimbabwe was investigated by Meck and others (2006). The surface water in the vicinity of platinum dumps was found to be near neutral or to have slightly alkaline pH and to contain concentrations of chromium, cobalt, copper, lead, and nickel that exceeded chronic surface-water criteria established by the U.S. Environmental Protection Agency (Suter, 1996; U.S. Environmental Protection Agency, 2009). Differences between upstream and downstream sample sites were most noticeable for nickel and approached a difference of 500 ppb.

Ecological risks can also be associated with soils and mill tailings. The toxicity of rehabilitated and nonrehabilitated mill tailings from reef-type deposits in South Africa to earthworms (*Eisenia fetdia*) was investigated by Jubileus (2008) and Maboeta and others (2008) using laboratory bioassay techniques. Sublethal impairment of earthworms (that is, effects on the growth and hatching success of cocoons) in soil samples decreased with distance from the tailing storage facilities. Anomalous concentrations of chromium, copper, nickel, and zinc were found in the tailings relative to the regional background soils. Wahl and others (2012) reached similar conclusions based on mesofauna surveys from the same tailing storage facilities.

Studies of soil and grass show anthropogenic platinum enrichment near mines in the Bushveld Complex. Thousands of soil and stream sediment samples collected at the Bushveld Complex show anomalous concentrations of precious metals related to bedrock sources and mining areas (Wilhelm and others, 1997). The results of the soil and stream sediment surveys mapped two bedrock sources of PGEs that are concordant to magmatic layering in the Bushveld Complex. The survey also mapped large anomalies near the locations of the large PGE mines in the western part of the Bushveld Complex; anomalies near the mines exceed 200 ppb PGEs. Rauch and Fatoki (2013) found about 700 ppb platinum in soils at a smelter. The maximum concentration in grass was 256 ppb platinum, again found at the smelter.

Carbon Footprint

The PGEs and their mining have several links to carbon cycling in the environment. One of the most important uses of PGEs is in catalytic converters (Loferski, 2012a, b), which help to limit the amount of carbon and nitrogen gases and other air pollutants that enter the environment through vehicle exhaust. Fuel cells are an emerging energy technology. Proton exchange membrane (PEM) fuel cells use hydrogen as fuel, combining it with oxygen to form water; these fuel cells rely on platinum catalysts (Mehta and Cooper, 2003).

The trend towards the mining of lower grade ore in existing mines is expected to have a negative effect on greenhouse gas emissions. Lower grade ores require more energy to produce a unit of PGEs than do higher grade ores. The trend towards increased greenhouse gas emissions per unit of PGEs produced (measured in tons of carbon dioxide [CO_2] per kilogram of PGEs) over time is evident in data from South Africa that date back to 2002 (Glaister and Mudd, 2010). In 2002, unit greenhouse gas emissions varied from about 20 to 40 metric tons for different mine properties. In 2008, the range of values increased to about 30 to 65 metric tons.

The calcium- and magnesium-rich silicate minerals common in mine wastes from PGE deposits represent an important sink for atmospheric carbon dioxide because these minerals react fairly readily with this greenhouse gas. The potential for mineral carbonation of PGE tailings was evaluated by Vogeli and others (2011). They ranked South African PGE tailings in terms of their carbonation potential on the basis of their mineralogy and the grain size and found that finer-grained, more olivine-rich, and plagioclase-poor tailings would be best for mineral carbonation. Although the mass of PGE tailings globally is inadequate to reduce global atmospheric carbon dioxide concentrations significantly, the carbonation of calcium- and magnesium-rich tailings can contribute to reducing the carbon footprint of individual mining operations.

Mine Closure

The procedures used to close PGE mines depends primarily on the method of mining and the character of the waste material. Reef-type deposits are typically developed using underground methods. Contact-type and conduit-type deposits can be developed by underground or open pit methods, depending upon the geometry of the orebody. For all these deposit types, open pit mining results in at least three different features after mining: the open pit, waste rock piles, and tailings storage facilities. Because of the scale of typical PGE mining activities, backfilling open pits is usually not practical. If the water table is above the bottom of the pit, the pit will fill with water and form a lake. The water quality of the lake will depend upon a number of factors, including the nature of the wall rock, the extent of interconnected underground mine workings that open to the pit, the water level in the pit, the local hydrology, and the climate, among others (Castendyk and Eary, 2009).

The long-term fate of tailing storage facilities depends upon the nature of the tailings and the method of construction of the facility. Some facilities can be regraded, capped, and revegetated. Others are designed to have a water cover in perpetuity to limit sulfide oxidation. Either type may have seepage that may require some form of water treatment.

The long-term fate of waste rock piles may include regrading, capping, and revegetation. Depending upon the acid-generating potential of the material, some piles may require some form of water treatment. An emerging issue for historical PGE tailings and piles is that older ore-processing techniques were not as efficient as those used today. As a consequence, historical tailings and waste piles can carry significant PGE grades.

Problems and Future Research

The supply of PGE from primary and secondary sources currently meets society's demand for these metals. Even if demand increases (as it assuredly will), the in-ground identified mineral resources appear to be sufficient to supply the world's needs for several decades. The location of most of the in-ground resources in a few big deposits in a few places makes the primary production of PGE susceptible to supply disruption, however. The following section discusses this problem in more detail.

Future Demand and Possible Risks to Supply

The demand for PGEs continues to increase. PGE use in automobile catalytic converters is expected to increase as more-stringent automobile emission standards are adopted worldwide. An emerging industrial use for platinum is in fuel cells that provide electricity for automobiles, homes, and businesses. Fuel cells produce electricity through electrochemical reactions by combining oxygen with a hydrogen-bearing fuel over a catalyst, such as platinum, and produce only water and carbon dioxide as emissions.

Various studies have compared anticipated demand for the PGEs with the amount of PGE ore that has been positively identified by mineral exploration. Along with the anticipated supply of PGEs by recycling, the studies suggest that there are sufficient PGE resources in the ground to meet projected platinum demand well into the middle of the 21st century (Tiax LLC, 2003; Wilburn and Bleiwas, 2004; Mudd, 2012; Wilburn, 2012). Mineral reserves in the Bushveld Complex would be sufficient to meet global platinum demand until 2040 (assuming an annual increase in platinum consumption of 2 percent). The much larger volume of mineralized rock that has been classified as mineral resources, coupled with the potential for additional undiscovered resources to be found, indicates that the potential amount of PGEs that could be mined will not be a constraint to PGE supply for many decades. Disruptions to the PGE supply are more likely to be affected by social, environmental, political, and economic factors rather than geologic issues or resource depletion (Mudd, 2012).

Variations in the annual average prices of the PGEs during the past 40 years illustrate the types of events and policies that could affect global supply and demand for mineral commodities (fig. N28). Some events, such as the oil embargo in the mid-1970s and the global recession that began in 2008, affected all metal prices (not just the prices of PGEs). Other effects can be specifically related to legislation passed by one or more Governments; for example, in the mid-1970s, catalytic converters, which use PGEs as the catalyst, were installed in automobiles to meet air standards set in the Clean Air Act Amendments of 1970 (84 Stat. 1705, P.L. 91–604; Gerard and Lave, 2005; McCarthy and others, 2011). Catalytic converters reduce harmful emissions from automobiles; the widespread adoption of catalytic converters, first in the United States in the 1970s, then in the European Union and Japan, increased demand for PGEs. Palladium supply was disrupted in 1999 and 2000 because Russian Government legislation temporarily blocked export of this metal (United Nations Conference on Trade and Development, undated). Other effects are related to problems with mineral production; for example, problems with a refinery in Rustenburg, South Africa, in 1989 caused a decrease in the world supply of rhodium. The PGE supply was also affected by work stoppages and miners' strikes in South Africa in 1986, 2011, and 2012 (Yager and others, 2012).

Production of PGEs requires power and water, both of which are in short supply in southern Africa. Africa depends on imports of oil and on production of synthetic fuels from coal to meet its fuel requirements (United Nations Conference on Trade and Development Secretariat, 1995). In January 2008, the South African mining industry briefly shut down almost all its operations because of the unpredictability of the power supply. Roughly one-quarter of the installed generating capacity was not available owing to system faults, planned maintenance, and a shortage of the coal used in power stations. The country was subject to short-notice blackouts, which made mining unsafe (Platinum Today, 2008). Expanding the mining capacity at the Bushveld Complex in South Africa is constrained by the power supply. Water is required to mine, process ore, and refine metals; if the water supply is restricted, then production is affected. In any country that is water-stressed, mining companies must strive to manage the supply and use of water to ensure continuation of operations (Anglo American Platinum Ltd., 2012).

The ultimate constraint on the development of PGE mineral resources may not be the presence of mineralized rock but rather the rock temperature. For example, the contact between the Main zone and the Lower Critical subzone in the Bushveld Complex can be traced to depths of 6 km in seismic surveys (Sargeant, 2001; Campbell, 2011), which indicates that mineralization associated with the Merensky Reef and the UG2 Chromitite may also be present at those depths (Cawthorn, 2010). These reefs are currently being mined at depths exceeding 2 km at the Northam Mine, where virgin rock temperatures of 70 °C are measured at a depth of 2,176 m (Northam Platinum Ltd., 2008). Anglo American Platinum Ltd., whose operations include several mines in the Bushveld Complex, considers a virgin rock temperature of 75 °C to be the limit of mining based on the anticipated technology, metal prices, and energy costs (Anglo American Platinum Ltd., 2011). By comparison, rock temperatures within the ore-bearing intrusions at the Talnakh area of Russia are up to 35 ºC in the Taimyrsky Mine, 27 to 30 ºC in the Skalisty Mine, and are anticipated to be 43 to 47 ºC in the area that will be developed by the Gluboky Mine (Kunilov, 1994). The massive sulfide ores in these Russian mines are highly reactive, however, and are prone to oxidation and spontaneous combustion.

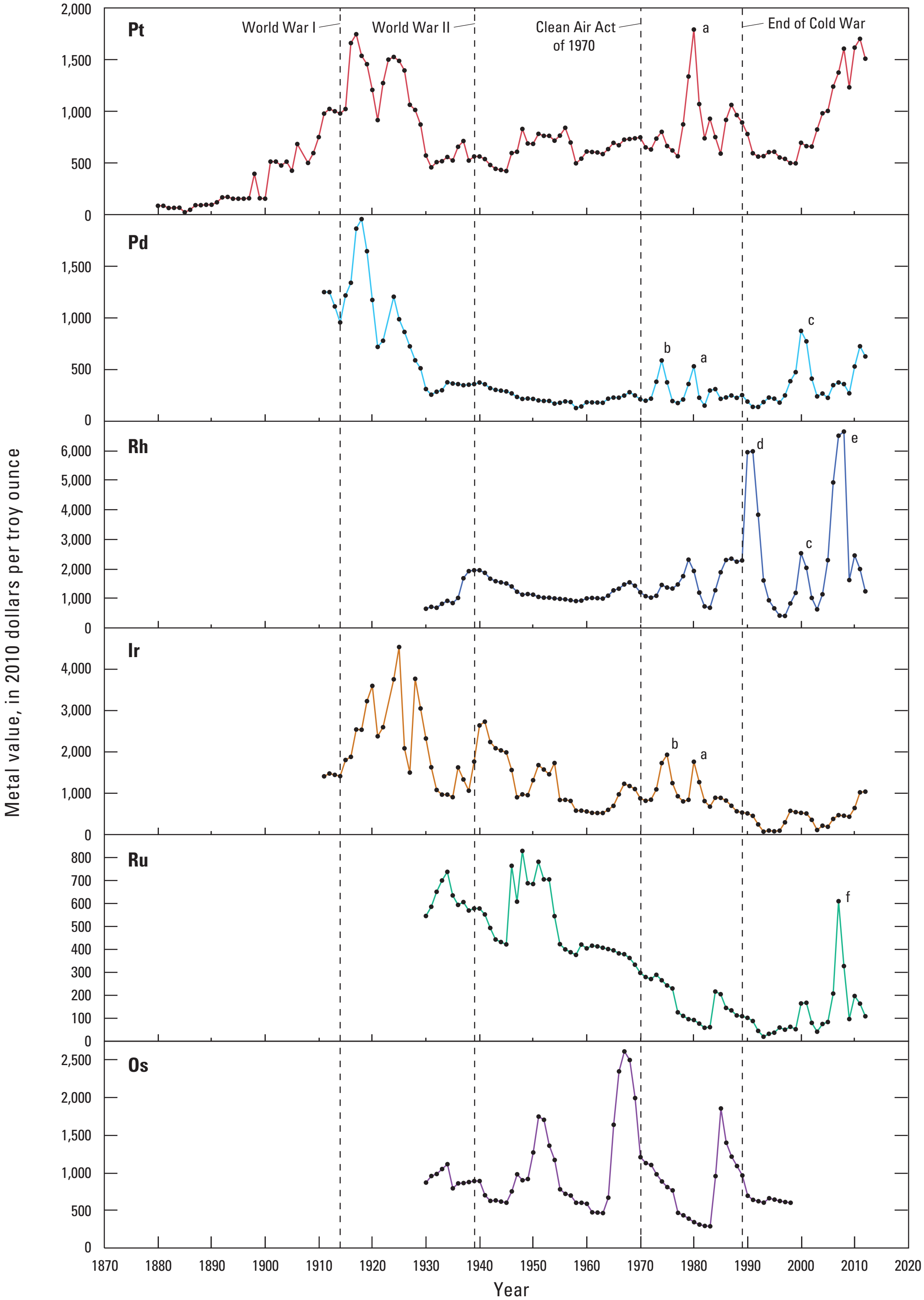


Figure N28. Graphs showing platinum-group-element prices (in constant U.S. dollars referenced to 2010) for platinum (Pt), palladium (Pd), rhodium (Rh), iridium (Ir), ruthenium (Ru), and osmium (Os) from 1880 to 2013. Major world events affecting pricing are shown as vertical dashed lines. Other major events shown are (a) investor speculation, (b) catalytic converter use begins and the Arab oil embargo, (c) shortfall of supplies of palladium from Russia, (d) disruption of supply because of problems at the Rustenburg refinery in South Africa, (e) increased demand for autocatalysts in Asian markets, and (f) increased ruthenium usage in electronics, especially in computer hard disk drives. National deflators are from the California Department of Finance (2012). Price data are from Plunkert and Jones (1999); Reese (1996); Hilliard (1998, 2000, 2004); Loferski (2012b, 2013c); and Platinum Today (2012).

Research Directions

Successful exploration strategies for PGEs have been based on the magmatic deposit paradigm. This approach has proven highly successful and will likely result in additional discoveries. Its utility has a down side, however, in that other geologic settings in which PGEs may be concentrated have not been studied. Models strongly influence the observations made in both research and mineral exploration. For example, most economic geologists would not look for world-class PGE deposits in ophiolites. The most common magmatic ore type in ophiolites are chromitite deposits; all contain PGEs but are enriched in iridium relative to platinum (Mungall, 2002; Finnigan and others, 2008). There are a few examples of platinum-enriched chromitites in ophiolites, but these are too small to be of any economic consequence. Therefore, mineral exploration geologists have not searched for concentrations of magmatic sulfide minerals in ophiolites; however, a small magmatic sulfide deposit in the Acoje ophiolite, Philippines (Bacuta and others, 1990; Yumul, 2001), and occurrences in cumulates of the Shetland Ophiolite Complex, United Kingdom (Prichard and Lord, 1993), are examples that indicate that sulfide exsolution and PGE enrichment can take place in ophiolites. The examples of hydrothermal ore deposits with elevated PGEs are other reminders that an economic PGE deposit may be present in rocks that have not been explored.

Most researchers in the field of economic geology can supply a list of research topics that could be undertaken to alleviate concerns about the global availability of PGEs. One approach to addressing concerns is to find more deposits, but finding small deposits will not solve the problem. The deposits must be large (like one or more of the giants that currently dominate supply). Research to find new deposits can be basic, in which known deposits are mapped and characterized in order to understand how they form. The research can also be applied, in which the search for PGE deposits is extended into geologic settings where the deposits would be highly weathered, highly metamorphosed, or largely concealed. Additionally, research can focus on new ways to understand and integrate information so that new hypotheses can be proposed and tested. Research will be most effective if basic and applied research is integrated. It will also be more fruitful if expertise from many disciplines is involved in solving the problem.

Acknowledgments

Technical reviews by Art Bookstrom, Niki Wintzer, and Ennis Geraghty (Stillwater Mining Co.) greatly improved this chapter. Constructive comments were provided by Klaus Schulz and Dwight Bradley on an early version of the manuscript; John DeYoung and Suzanne Nicholson carefully looked through the document after the technical review was complete. Keith Labay helped create the world map, and Heather Parks constructed the first draft of the illustrations.

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Tables N2, N5, N6, and N8–N10

Table N2. Examples of rocks and ores with anomalous platinum-group-element concentrations that are not associated with magmatic deposits, by deposit type.

[Units of measure: g/t, gram per metric ton; Mt, million metric tons; ppb, part per billion; ppm, part per million. Elements: Au, gold; Co, cobalt; Cu, copper; Fe, iron; Mo, molybdenum; Ni, nickel; Pd, palladium; PGE, platinum-group element; Pt, platinum; U, uranium; V, vanadium; Zn, zinc. n.d., no data; %, percent]

Deposit type	Site name and (or) location	Comments	Number of samples	Platinum (ppm)	Palladium (ppm)	Gold (ppm)	Other metals	Reference(s)
Black shale	Jiangxi, China	None	1	0.01	0.02	0.16	0.055% Mo; 0.01% Ni; 1.12% V	Wilde (2005)
	Woodford Shale, Oklahoma	Maximum value	n.d.	0.048	n.d.	0.018	n.d.	Orth and others (1988)
	Upper Woodford Shale, Indiana	Range of values	4	0.026 to 0.063	0.008 to 0.016	n.d.	n.d.	Lechler and Hsu (1989)
Brecciated quartz veins in fault zone	Waterberg deposit, South Africa	Sample cuts across ore zone; range of values	4	184 to 1,747	n.d.	n.d.	n.d.	Wagner (1929); Armitage and others (2007)
		Picked samples; range of values	2	5,565 to 5,735	n.d.	n.d.	n.d.	Wagner (1929); Armitage and others (2007)
Copper skarn	Carr Fork, Utah	Upper Parnell Cu-Au skarn	3	n.d.	0.068 to 0.210	0.450 to 0.960	n.d.	Cameron and Garmoe (1987)
		Au-pyrite-quartz ore shoot	6	n.d.	0.069 to 0.340	0.100 to 0.270	n.d.	Cameron and Garmoe (1987)
Gold–PGE mineralization associated with reduced-facies sediment-hosted strata-bound copper mineralization	Ruwe Hill Mine, Katangan copperbelt, (Mutoshi Mine), Democratic Republic of the Congo	Samples from 60-meter gallery	56	10.29	3.72	4.68	n.d.	Jebwab (2003) citing Buttgenbach (1908); Ball and Shaler (1914)
		None	n.d.	12	n.d.	9	n.d.	Stevens (1905)
High-grade hydrothermal manganese ore	Gibellini Mine, Nevada	Range of values	6	0.167 to 0.626	0.018 to 0.045	n.d.	n.d.	Lechler and others (1988)
Homestake-type gold deposits	Dome Mine, Ontario, Cananda	None	16	n.d.	0.020 to 0.262	0.12 to 9.5	n.d.	Fryer and others (1979)

Table N2. Examples of rocks and ores with anomalous platinum-group-element concentrations that are not associated with magmatic deposits, by deposit type.—Continued

[Units of measure: g/t, gram per metric ton; Mt, million metric tons; ppb, part per billion; ppm, part per million. Elements: Au, gold; Co, cobalt; Cu, copper; Fe, iron; Mo, molybdenum; Ni, nickel; Pd, palladium; PGE, platinum-group element; Pt, platinum; U, uranium; V, vanadium; Zn, zinc. n.d., no data; %, percent]

Deposit type	Site name and (or) location	Comments	Number of samples	Platinum (ppm)	Palladium (ppm)	Gold (ppm)	Other metals	Reference(s)
Hydrogeneous iron-manganese crusts on seamounts	Central Pacific	Range of values; mean value in parentheses	34	0.14 to 1.02 (0.51)	n.d.	n.d.	n.d.	Halbach and others (1989)
	Federated States of Micronesia-Palau	Mean value	32	0.239	0.002	n.d.	n.d.	Hein and others (2000)
	Marshall Islands	Mean value	77	0.634	0.003	n.d.	n.d.	Hein and others (2000)
	Northwest of Marshall Islands	Mean value	19	0.501	<0.0054	n.d.	n.d.	Hein and others (2000)
	Johnston Island	Mean value	99	0.244	n.d.	n.d.	n.d.	Hein and others (2000)
	California borderlands	Mean value	60	0.082	n.d.	n.d.	n.d.	Hein and others (2000)
	Northwest Pacific	Mean value	113	0.777	n.d.	n.d.	n.d.	Hein and others (2000)
	Hawaii	Mean value	25	0.174	0.003	n.d.	n.d.	Hein and others (2000)
	West Pacific	Range of values	20	0.04282 to 0.50062	0.00051 to 0.00199	0.0006 to >1.5	n.d.	Xue and others (2005)
	Afanasiy-Nikitin seamount	Range of values	9	0.101 to 0.78	0.004 to 0.02	0.0025 to 0.19	n.d.	Banakar and others (2007)
Hydrothermal copper vein	New Rambler, Wyoming	Quartz-pyrite-chalcopyrite veins associated with shears in mafic complex; Approximately 19.3 kilograms of PGEs produced	Average of 87 samples	4	75	n.d.	n.d.	McCallum and others (1976)
Limestone	Welden Limestone, Oklahoma	Maximum value	n.d.	0.05	n.d.	0.014	n.d.	Orth and others (1988)
Near-surface bonanza ore from sulfur-deficient hydrothermal system	Serra Pelada, Brazil	43-meter interval in drill core	n.d.	204	1,174	4,709	n.d.	Cabral and others (2002)

Table N2. Examples of rocks and ores with anomalous platinum-group-element concentrations that are not associated with magmatic deposits, by deposit type.—Continued

[Units of measure: g/t, gram per metric ton; Mt, million metric tons; ppb, part per billion; ppm, part per million. Elements: Au, gold; Co, cobalt; Cu, copper; Fe, iron; Mo, molybdenum; Ni, nickel; Pd, palladium; PGE, platinum-group element; Pt, platinum; U, uranium; V, vanadium; Zn, zinc. n.d., no data; %, percent]

Deposit type	Site name and (or) location	Comments	Number of samples	Platinum (ppm)	Palladium (ppm)	Gold (ppm)	Other metals	Reference(s)
Porphyry copper, copper-gold type	St. Tomas II, Philippines	Mean value	5	0.038	0.16	1.8	n.d.	Tarkian and Koopmann (1995)
	Afton, British Columbia, Canada	Range of values	10	0.0026 to 0.143	0.0193 to 1.179	1.226 to 7.764	n.d.	Nixon (2003)
	Skouries, Greece	Deposit has 206 Mt at 0.5% Cu, 75 ppb Pd, and 17 ppb Pt	n.d.	0.017	0.075	n.d.	n.d.	Kiousis and others (2005)
Porphyry copper, copper-molybdenum type	Aksug, Sora, and Zhireken, Russia; Erdenetuin-Obo, Mongolia	Range of values	31	<0.010 to 0.028	0.013 to 0.018	0.017 to 0.061	n.d.	Sotnikov and others (2001)
Reduced-facies sediment-hosted strata-bound copper	Kalahari copperbelt, Namibia	Range of values	3	0.034 to 0.12	0.0 to 0.008	0.007 to 0.046	2.5 to 3.3%	Borg and others (1987)
Secondary oxidized system developed on reduced-facies sediment-hosted strata-bound copper mineralization	Lubin area, Poland	Red Kupferschiefer deposit; range of values for palladium and platinum; average for gold	6	0.163 to 0.75	0.250 to 1.759	15.419 (average)	n.d.	Pieczonka and others (2008)
Sediment-hosted gold-arsenic deposits	Sukhoi Log, Siberia, Russia	Altered carbonaceous and pyritic meta-siltstone of the Khomolkho Formation	22	0.01	0.002	18.056	n.d.	Wilde (2005)

Table N2. Examples of rocks and ores with anomalous platinum-group-element concentrations that are not associated with magmatic deposits, by deposit type.—Continued

[Units of measure: g/t, gram per metric ton; Mt, million metric tons; ppb, part per billion; ppm, part per million. Elements: Au, gold; Co, cobalt; Cu, copper; Fe, iron; Mo, molybdenum; Ni, nickel; Pd, palladium; PGE, platinum-group element; Pt, platinum; U, uranium; V, vanadium; Zn, zinc. n.d., no data; %, percent]

Deposit type	Site name and (or) location	Comments	Number of samples	Platinum (ppm)	Palladium (ppm)	Gold (ppm)	Other metals	Reference(s)
Sediment-hosted nickel-molybdenum	Kuusilampi and Kolmisoppi orebodies, Talvivaara deposit, Finland	15 to 25% sulfide in intensively folded black schists; samples with Ni≥0.1%; deposit has 2.052 billion metric tons containing 0.22% Ni, 0.02% Co, 0.13% Cu, 0.05% Zn, and 0.0017% U; range of values. Mean value in parentheses	27	0.002 to 0.027 (0.008)	0.006 to 0.073 (0.12)	<0.005 to 0.0159 (0.0023)	0.13% Cu; 0.22% Ni; 0.05% Zn	Loukola-Ruskeeniemi (1991); Loukola-Ruskeeniemi and Heino (1996); Talvivaara Mining Company plc (2013)
	Huangjiawan Mine; Lower Cambrian Niutitang Formation, southern China	Polymetallic sulfide layers; mean value	7	0.295	0.3	0.334	3.0% Mo; 2.6% Ni	Mao and others (2002)
	Lower Cambrian Niutitang Formation, southern China	Polymetallic sulfide layers	n.d.	0.405	0.38	0.32	5.7% Mo; 3.6% Ni	Mao and others (2002)
	Guizhou, southern China	Polymetallic sulfide layers	8	0.19	0.24	0.17	3.23% Mo; 3.55% Ni	Wilde (2005)
	Nick, Yukon Territory, Canada	Representative mineralized samples	9	0.41	0.214	0.086	0.24% Mo; 5.24% Ni	Hulbert and others (1992)
	Western Hunan, China	Polymetallic sulfide layers	1	0.3	0.33	0.249	18.28% Mo; 5.15% Ni	Wilde (2005)
Unconformity uranium	Jabiluka uranium–gold–palladium ore, Northern Territory, Australia	Uranium ore, graphitic schist	27	n.d.	0.29	2.63	n.d.	Wilde (2005)
	Coronation Hill, Northern Territory, Australia	Deposit has 4.85 Mt containg 4.85 g/t Au, 0.19 g/t Pt, and 0.65 g/t Pd	n.d.	0.19	0.65	4.85	n.d.	Carville and others (1990)
Uranium–gold–PGE mineralization in carbonate-hematite-pitchblende shear and fracture zone	Nicholson No. 2 zone, Saskatchewan, Canada	None	n.d.	13.8	17.3	136	n.d.	Hulbert and others (1988)

Table N5. Igneous intrusions and intrusive complexes that contain more than 97 percent of the world's identified platinum-group-element (PGE) and gold resources, in order of total contained PGEs.

[Data are from table N10 at the end of this chapter. Ma, mega-annum (10^6 years ago); PGE, platinum-group element; Ti-V, titaniferous-vanadiferous; n.d., no data]

Igneous intrusion and country	Age (Ma)	Age reference	Deposit types	Names of deposits included in tally	Resources (million metric tons)	PGE and gold grade (grams per metric ton)	Total contained PGEs (kilograms)	Proportion of total resources, (percent)	Active PGE production
Bushveld Complex, South Africa	2,054.4 ± 1.3	Scoates and Friedman (2008)	Contact and reef	Merensky Reef, UG2 Chromitite, Platreef, and Sheba's Ridge deposits	21,700	3.46	75,200,000	73	Yes, for PGE
Noril'sk-Talnakh area, Russia	290 ± 2.8 to 226.7 ± 0.9	Malitch and others (2012)	Conduit	Talnakh, Noril'sk 1, Maslovskoe, and Chernogorskoye deposits	2,080	4.84	10,100,000	10	Yes, as a byproduct
Great Dyke, Zimbabwe	2,575.4 ± 0.7	Oberthür and others (2002)	Reef (sulfide)	Main Sulphide Zone, all properties	2,260	3.63	8,190,000	7.9	Yes, for PGE
Stillwater Complex, Montana	2,704 ± 4	Premo and others (1990)	Reef (sulfide)	J–M Reef, Stillwater, and East Boulder Mines	149	15.0	2,240,000	2.2	Yes, for PGE
Duluth Complex, Minnesota	1,095.94 ± 0.18	Hoaglund (2010)	Contact	Northmet, Birch Lake, and Maturi (deposits with PGEs reported)	2,490	0.560	1,390,000	1.3	No
Onega intrusion, Russia	2,050 ± 70	Geological Survey of Finland (2010)	Reef (Ti-V layers)	Pudozhgorskoe deposit	517	1.62	837,000	0.81	No
Fedorov-Pana intrusion, Russia	2,5326 ± 6; 2,496 ± 7	Nitkina (2006)	Contact and reef	All deposits	458	1.70	780,000	0.75	No
Burakovskaya intrusion, Russia	2,433 ± 4; 2,430 ± 5	Bailly and others (2009)	Reef	All deposits	587	1.10	645,000	0.62	No
Portimo Igneous Complex, Finland	n.d.	n.d.	Contact and reef	All deposits	382	1.37	524,000	0.51	No
Wellgreen intrusion, Canada	232.3 ± 1	Mortensen and Hulbert (1992)	Conduit	n.d.	461	0.91	421,000	0.41	No
Sudbury Complex, Canada	1,850 ± 1	Corfu and Lightfoot (1996)	Sudbury	Vale properties (PGEs reported)	105	2.36	249,000	0.24	Yes, as a byproduct
Skaergaard intrusion, Greenland	55.59 ± 0.13	Hamilton and Brooks (2004)	Reef (sulfide)	Pd5 layer	104	2.18	227,000	0.22	No
Stella intrusion, South Africa	3,033.5 ± 0.3	Maier and others (2003)	Reef (Ti-V layers)	Kalplats project	137	1.53	210,000	0.20	No
Lac des Iles, Canada	2,689 ± 1	Baker and others (2003)	Atypical; pipe-like orebodies?	n.d.	56	3.68	207,000	0.20	Yes, for PGE

	Proportion of total (percent)	Total contained PGEs (kilograms)
Subtotal for first four intrusions in this list	**92.3**	**95,700,000**
Subtotal for all intrusions in this list	**97.6**	**101,000,000**
Total inventory identified in table N10 of this chapter	**100**	**104,000,000**

Table N6. Areal extent and stratigraphic thickness of layered intrusions with reef-type platinum-group-element deposits and some examples of large intrusions with no known deposits, in order of areal extent.

[Areal extent in parentheses is inferred from geophysical interpretations; —, no identified deposits or occurrences]

Intrusion	Country or U.S. State	Areal extent (square kilometers)	Stratigraphic thickness of cumulates (meters)	Name of reef deposits and occurrences	Comments	Reference(s)
Bushveld Complex (Rustenburg Layered Suite)	South Africa	12,000 (69,000)	8,000	Merensky Reef, UG2 Chromitite, Pseudo Reef	None	Vermaak and von Gruenewaldt (1986); Walraven (1986); Martini and others (2001); Barnes and Maier (2002); Cawthorn and others (2002)
Tete Complex	Mozambique/ Malawi	5,500	Unknown	—	None	Instituto Nacional de Geologica (1987); Maier and others (2001)
Dufek intrusion	Antarctica	4,300 (7,700)	3,500 exposed, up to 9,000 inferred	—	Largely covered by ice; only 145 square kilometers of rock is exposed	Ford (1976); Ford, Schmidt, and Boyd (1978); Ford, Schmidt, Boyd, and Nelson (1978); Ferris and others (1998; 2003)
Molopo Farms Complex	South Africa	3,900 (14,000)	3,200	—	None	von Gruenewaldt and others (1989); Walker and others (2010); Prendergast (2012)
Great Dyke	Zimbabwe	3,100	3,350	Main Sulphide Zone, Boehmke Reef	None	Worst (1957); Prendergast and Wilson (1989); Wilson and Tredoux (1990); Evans and others (1996); Wilson and Prendergast (1989, 2001); Armstrong and Wilson (2000); Oberthuer (2002)
Windimurra igneous complex	Australia	2,500	~10,000	—	None	Parks and Hill (1986); Mathison and Ahmat (1996); Ivanic and others (2013)
Barro Alto Complex	Brazil	2,000	10,100	—	Granulite facies metamorphism	Schobbenhaus and others (2004); Pimentel and others (2006); Ferreira-Filho and others (2010)
Fraser Range Metamorphics (Fraser Complex)	Australia	1,000	>16,000	—	Metamorphosed and deformed	Meyers (1985); Spaggiari and others (2009)
Niquelândia layered complex	Brazil	770	17,750	—	Intense deformation and amphibolite to granulate facies metamorphism	Schobbenhaus and others (2004); Pimentel and others (2006); Ferreira-Filho and others (2010)
Fiskenaesset intrusion	Greenland	730	550	Ghisler Reef	Deformed with amphibolite to granulate facies metamorphism	Myers (1976, 1985); Allaart (1998); Appel and others (2011)
Rincon del Tigre Complex	Bolivia	640	4,600	Precious Metals Zone	None	Mitchell (1983); Montemurro (1984); Prendergast (2000)
Aganozero-Burakovsky intrusion	Russia	640	6,200	Aganozero, Platinometal horizon “A,” Shalozerskoe (Kuk Ruchi Zone)	None	Grokhovskaya and others (2005); Bailly and others (2009)

Table N6. Areal extent and stratigraphic thickness of layered intrusions with reef-type platinum-group-element deposits and some examples of large intrusions with no known deposits, in order of areal extent.—Continued

[Areal extent in parentheses is inferred from geophysical interpretations; —, no identified deposits or occurrences]

Intrusion	Country or U.S. State	Areal extent (square kilometers)	Stratigraphic thickness of cumulates (meters)	Name of reef deposits and occurrences	Comments	Reference(s)
Pedra Branca Unit–Ceará and Tróia Complexes	Brazil	530	unknown	Pedra Branca	Intense deformation and amphibolite to granulate facies metamorphism	Angeli (2005); Barrueto and Hunt (2010)
Coldwell Complex	Canada	410	<2,500	Skipper Lake	None	Barrie and others (2002)
Fedorov Pana intrusion	Fennoscandia	340	3,750	Vostochno (eastern) Panskoe; Western Panskoe	None	Alapieti and Lahtinen (2002); Mitrofanov and others (2005)
Stillwater Complex	Montana	190 (2,300)	6,500	J–M Reef, A–B chromitite	None	McCallum and others (1980); Segerstrom and Carlson (1982); Raedeke and McCallum (1984); Kleinkopf (1985); Zientek and others (2002)
Weld Range Complex	Australia	77	8,500	Parks Reef	None	Parks (1998); Geological Survey of Western Australia (2004)
Skaergaard intrusion	Greenland	63	3,500	Platinova Reef	None	McBirney (1989); Nielsen and others (2005)
Munni Munni intrusion	Australia	63	5,450	Ferguson Reef	None	Barnes and others (1990); Geological Survey of Western Australia (2004)
Penikat intrusion	Finland	59	2,200	Sompujärvi, Ala-Pennika, and Paasivaara Reefs	None	Alapieti and Lahtinen (2002); Rasilainen and others (2010)
Sonju Lake intrusion	Minnesota	44	1,200	Sonju Lake Reef	None	Miller (1999); Miller and others (2002)
Lake Owen intrusion	Wisconsin	39	4,500	Unnamed occurrence	None	Houston and Orback (1976); Loucks and Glasscock (1989); Shive and others (1990); Loucks (1991); Green and Drouillard (1994)
Portimo Complex	Finland	39	900	Siika-Kämä Reef, Rytikangas Reef	None	Alapieti and Lahtinen (2002); Rasilainen and others (2010)
Stella intrusion	South Africa	16	1,000	Main Reef	None	Maier and others (2003); Carroll (2005); Lewins and others (2008); African Rainbow Minerals Ltd. (2010)
Panton intrusion	Australia	13	1,600	Top and Middle Reefs	None	Perring and Vogt (1991); Hoatson and Blake (2000)

Table N8. Trace element geochemistry of waters from selected reef-type, contact-type, and conduit-type deposits.

[Elements: Cd, cadmium; Co, cobalt; Cr, chromium; Cu, copper, Fe, iron; Mn, manganese; Ni, nickel; Pb, lead; Sb, antimony; Zn, zinc. n.d., no data]

Area or subject	Media or material	pH	Cd	Co	Cr	Cu	Fe	Mn	Ni	Pb	Sb	Zn	Reference(s)
			(part per billion)										
Reef-type deposits													
Pilanesberg Platinum Mines, Zimbabwe	Surface water downstream of waste dumps	Near neutral to slightly alkaline	60	260	2,370	60	n.d.	n.d.	820	110	910	70	Meck and others (2006)
UG2 Chromitite, Bushveld Complex, South Africa	Leachate from leach test	5.1	<5	<25	370	<25	1.53	74	50	<20	n.d.	50	Bolton (2013)
Merensky Reef, Bushveld Complex, South Africa	Leachate from leach test	5.1	<5	<25	<25	<25	1.45	1,220	430	<20	n.d.	30	Bolton (2013)
Stillwater Mine, Montana, J–M Reef ore	Leachate from leach test	n.d.	<0.0001 to <0.1	n.d.	<0.01 to <0.5	<0.01 to <0.5	n.d.	n.d.	<0.1 to <0.5	0.0004 to <0.5	n.d.	0.01 to <0.5	Kirk and others (2006); Montana Department of Environmental Quality (2012b)
East Boulder Mine, Montana, J–M Reef ore	Leachate from leach test	n.d.	<0.0001	n.d.	<0.01	<0.01	n.d.	n.d.	<0.01	<0.0001	n.d.	<0.01	Kirk and others (2006); Montana Department of Environmental Quality (2012b)
Stillwater Mine, Montana, waste rock	Leachate from leach test	n.d.	<0.0001	n.d.	<0.01	<0.01	n.d.	n.d.	<0.01	0.0007	n.d.	0.01	Kirk and others (2006); Montana Department of Environmental Quality (2012b)
East Boulder Mine, Montana, waste rock	Leachate from leach test	n.d.	<0.0001	n.d.	<0.01	<0.01	n.d.	n.d.	<0.01	0.0002	n.d.	0.02	Kirk and others (2006); Montana Department of Environmental Quality (2012b)
Stillwater Mine, Montana, tailings	Leachate from leach test	n.d.	<0.0001	n.d.	<0.01	<0.01	n.d.	n.d.	<0.01	0.0002	n.d.	0.01	Kirk and others (2006); Montana Department of Environmental Quality (2012b)

Table N8. Trace element geochemistry of waters from selected reef-type, contact-type, and conduit-type deposits.—Continued

[Elements: Cd, cadmium; Co, cobalt; Cr, chromium; Cu, copper, Fe, iron; Mn, manganese; Ni, nickel; Pb, lead; Sb, antimony; Zn, zinc. n.d., no data]

Area or subject	Media or material	pH	Cd	Co	Cr	Cu	Fe	Mn	Ni	Pb	Sb	Zn	Reference(s)
			(part per billion)										
Reef-type deposits—Continued													
East Boulder Mine, Montana, tailings	Leachate from leach test	n.d.	<0.0001	n.d.	<0.01	<0.01	n.d.	n.d.	<0.01	<0.0001	n.d.	0.01	Kirk and others (2006); Montana Department of Environmental Quality (2012b)
East Boulder Mine, Montana, tailings water	Operational wastewater	n.d.	<0.0001	n.d.	<0.001	0.002	0.025	0.005	<0.02	<0.002	n.d.	<0.01	Kirk and others (2006); Montana Department of Environmental Quality (2012b)
Stillwater Mine, Montana, tailings water	Operational wastewater	n.d.	<0.0001	n.d.	<0.01	0.003	0.025	<0.003	n.d.	<0.003	<0.01	n.d.	Kirk and others (2006); Montana Department of Environmental Quality (2012b)
Contact-type deposits													
Northmet deposit, Minnesota	Surface water downstream of the deposit	7.0	<0.2	<1	2	n.d.	0.89	80	<5	<1	n.d.	<10	Minnesota Department of Natural Resources, and the U.S. Army Corps of Engineers (2009)
Conduit-type deposits													
Eagle Mine, Michigan	Groundwater near the the deposit	8.7	<0.5	<10	<5	<5	0.19	220	59	<1	<6	88	Kennecott Eagle Minerals Co. (2006)
Water-quality criteria													
Groundwater criteria (State of Montana)	Standard	n.d.	0.005	n.d.	0.100	1.3	0.300	0.050	0.1	0.015	n.d.	2.0	Montana Department of Environmental Quality (2012a)
Chronic surface-water criteria (U.S. Government)	Standard	n.d.	n.d.	n.d.	n.d.	1.3	n.d.	0.50	0.610	n.d.	n.d.	7.4	Suter (1996); U.S. Environmental Protection Agency (2009)
Drinking water criteria (World Health Organization)	Standard	n.d.	0.003	n.d.	0.05	0.002	n.d.	n.d.	0.07	0.01	0.02	n.d.	World Health Organization (2008)

Table N9. Acid-base accounting for selected reef-type, contact-type, and conduit-type deposits.

[Net neutralizing potential is the difference between the acid-generating and the acid-neutralizing potentials. A negative value indicates excess acid-generating potential and a positive value indicates excess acid-neutralizing potential. kg $CaCO_3$/t, kilograms of calcium carbonate per metric ton; ?, identification uncertain; n.d., no data]

Deposit and area	Material	Sulfur content (weight percent)	Acid-generating potential	Acid-neutralizing potential	Net neutralizing potential	Reference(s)
			(kg $CaCO_3$/t)			
Reef-type deposits						
J–M Reef, Stillwater Complex, Montana	Waste rock	<0.05	Low (<1)	20 to 70	n.d.	Kirk and others (2006)
Merensky Reef, Pilanesberg Platinum Mine, Bushveld Complex, South Africa	Ore	<0.07	2.07	15.12	7.29	Bolton (2013)
UG2 Chromitite, Pilanesberg Platinum Mine, Bushveld Complex, South Africa	Ore?	<0.01	0.31	10.21	32.66	Bolton (2013)
Contact-type deposits						
Babbit deposit, Duluth Complex, Minnesota	Waste rock	n.d.	19.7 to 44.1	0.6 to 2.1	Slight excess of acid-generating potential	Lapakko (1994)
Duluth Complex, Minnesota	Tailings from metallurgical testing of Duluth Complex ores	n.d.	6.2 to 8.1	14	Slight excess of acid–neutralizing potential	Lapakko and Berndt (2009); Minnesota Department of Natural Resources, and the U.S. Army Corps of Engineers (2009)
Northmet deposit, Duluth Complex, Minnesota	Nonreactive waste rock	n.d.	0.9	n.d.	n.d.	Minnesota Department of Natural Resources, and the U.S. Army Corps of Engineers (2009)
	Reactive waste rock	n.d.	14.1	n.d.	n.d.	
Turfspruit deposit, Platreef, Bushveld Complex, South Africa	Ore	0.3 to 0.5	n.d.	n.d.	–5.56 to 2.8	Lishman (2009)
	Waste rock	0.27 to 0.67	n.d.	n.d.	–11.21 to 0.78	
	Tailings	0.03 to 0.05	n.d.	n.d.	12.6 to 13.44	
Conduit-type deposits						
Eagle deposit, Michigan	Massive ore	35.66	1,111	0	–1,111	Kennecott Eagle Minerals Co. (2006)
	Semimassive ore	13.43	419	41	–378	
	Peridotite	1.57	49	44	–5	
	Pyroxenite	1.30	40	34	–6	
	Siltstone	1.03	32	19	–12	
	Sandstone	0.33	10	38	28	
	Hornfels	8.91	49	18	–31	

Table N10. Grade and tonnage of mineralized rock remaining in platinum-group-element-bearing mineral deposits.

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Deposit name	Deposit type	Intrusion	Country	Latitude	Longitude	Ore (Mt)	Ni (percent)	Cu (percent)	Pt (g/t)	Pd (g/t)	Au (g/t)	PGE and Au (g/t)	Reference(s)
				Decimal degrees WGS 84									
A–B chromitite, West Fork area	Reef	Stillwater Complex	United States	45.38	–110.01	3.6	n.d.	n.d.	0.685	1.71	n.d.	2.40	Zientek (1993)
Aganozero	Reef (chromitite)	Burakovskaya intrusion	Russia	62.20	36.52	200	n.d.	n.d.	n.d.	n.d.	8.9	1.20	Geological Survey of Finland (2011)
Aguablanca	Synorogenic	Aguablanca intrusion	Spain	37.85	–6.18	17	0.51	0.43	0.241	0.217	0.121	0.579	Alvarez and others (2009)
Ahmavaara	Contact	Portimo	Finland	66.10	26.04	190	0.09	0.17	0.17	0.82	0.1	0.990	Geological Survey of Finland (2011)
Akanani (P1 and P2)	Contact	Bushveld	South Africa	–23.97	28.85	290	0.22	0.12	1.57	1.91	0.219	3.70	Lonmin plc (2011)
Akanvaara LC	Reef (chromitite)	Akanvaara	Finland	67.20	28.20	27	n.d.	n.d.	0.52	0.08	n.d.	0.600	Geological Survey of Finland (2011)
Akanvaara UC	Reef (chromitite)	Akanvaara	Finland	67.18	28.20	18	n.d.	n.d.	n.d.	0.92	n.d.	0.920	Geological Survey of Finland (2011)
Ala-Penikkavaara (AP Reef)	Reef	Penikat intrusion	Finland	65.82	25.01	3.5	n.d.	0.21	1.68	6.16	0.28	7.95	Geological Survey of Finland (2011)
Benbow	Contact	Stillwater	United States	45.36	–109.81	130	0.22	0.22	0.0068	0.0106	n.d.	0.0174	Zientek (1993)
Birch Lake (Twin Metals)	Contact	Duluth	United States	47.73	–91.80	340	0.15	0.48	0.196	0.411	0.0949	0.702	Parker and Eggleston (2012)
Bird River (Page Zone and Ore Fault Zone)	Contact	Bird River Sill	Canada	50.48	–95.51	5.2	0.34	0.18	0.088	0.352	0.0151	0.456	Ewert and others (2008)
Boikgantsho Project	Contact	Bushveld	South Africa	–23.90	28.88	130	0.11	0.08	0.767	0.743	0.0724	1.58	Ferreira and Bisnath (2012)
Bokai and Unki East (Main Sulphide Zone)	Reef (sulfide)	Great Dyke	Zimbabwe	–19.74	30.04	210	0.21	0.17	1.88	1.48	0.332	3.85	Central African Mining & Exploration Company Plc (2009); Anglo American Platinum Ltd. (2011)
Brattbakken	Hydrothermal or remobilized? (stockwork)	n.d.	Norway	63.94	12.34	1.5	1	0.8	0.7	n.d.	n.d.	0.700	Geological Survey of Finland (2011)

Table N10. Grade and tonnage of mineralized rock remaining in platinum-group-element-bearing mineral deposits.—Continued

[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. WGS 84, World Geodetic System of 1984. Elements: Au, gold; Cu, copper; Ni, nickel; Pd, palladium; PGE, platinum-group element(s); Pt, platinum. Abbreviations: Mt, million metric tons; g/t, gram per metric ton; LC, lower chromitite; LG, lower grade reef; LM, lower main reef; MMW, mid-main waste zone; MMZ, main mineralized zone; MR, mid reef; PCMZ, peridotite chromititic mineralized zone; Ti-V, titaniferous-vanadiferous; UC, upper chromitite; UM, upper main reef; UUM, post reef hanging wall; n.d., no data; ?, identification uncertain]

Deposit name	Deposit type	Intrusion	Country	Latitude	Longitude	Ore (Mt)	Ni (percent)	Cu (percent)	Pt (g/t)	Pd (g/t)	Au (g/t)	PGE and Au (g/t)	Reference(s)
				Decimal degrees WGS 84									
Broken Hammer (Sudbury area)	Offset type deposit	Sudbury	Canada	46.77	–81.04	0.23	0.1	0.92	2.01	1.9	0.71	4.62	Doran and others (2012)
Bystrinskoe	Conduit	Pechenga greenstone belt	Russia	69.40	30.73	36	0.49	0.26	n.d.	n.d.	0.008	0.0860	Geological Survey of Finland (2011)
Camp deposit	Contact	Stillwater	United States	45.41	–110.08	5.9	0.42	0.23	0.018	0.139	n.d.	0.157	Zientek (1993)
Chernogorskoye deposit	Conduit	Noril'sk Talnakh	Russia	69.15	88.27	140	0.22	0.29	n.d.	n.d.	n.d.	3.90	Russian Platinum (2011b)
Chinei intrusion. all deposits (reserves only)	Contact	Chinei	Russia	56.48	118.58	23	0.05	0.65	0.23	1.04	0.17	1.44	Vladimir Chechetkin, Research Geologist (retired), written comm., 2009
Dikolati Nickel project	Contact	n.d.	Botswana	–22.03	27.74	4.1	0.7	0.5	n.d.	n.d.	n.d.	1.20	Discovery Metals Ltd. (2013)
Eagle Nickel	Conduit	Eagle Intrusion	United States	46.75	–87.89	4.1	3.6	2.9	0.73	0.47	0.28	0.617	Rossell and Coombes (2005)
Eagle's Nest	Conduit	Double Eagle Complex	Canada	52.74	–86.31	22	1.4	0.98	1	3.22	0.23	4.44	Burgess and others (2012)
Expo	Komatiitic	n.d.	Canada	61.56	–73.45	5.1	0.85	0.86	0.372	1.6	0.1	2.07	Puritch and others (2006)
Fedorovo	Contact	Imandra-Varzuga greenstone belt	Russia	67.51	35.00	410	0.09	0.15	0.311	0.933	0.084	1.33	Barrick Gold Corp. (2008); Schissel and others (2002); Mitrofanov and others (2007); Rasilainen and others (2010)
Geordie Lake	Contact	Coldwell Complex	Canada	48.82	–86.49	40	n.d.	0.37	0.038	0.611	0.048	0.697	Drennan and Fell (2010)
Gold-platinum horizon "B" Burakovka intrusion	Reef	Burakovskaya intrusion	Russia	62.07	36.45	23	n.d.	n.d.	n.d.	n.d.	2.49	0.600	Geological Survey of Finland (2011)

Table N10. Grade and tonnage of mineralized rock remaining in platinum-group-element-bearing mineral deposits.—Continued

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Deposit name	Deposit type	Intrusion	Country	Latitude	Longitude	Ore (Mt)	Ni (percent)	Cu (percent)	Pt (g/t)	Pd (g/t)	Au (g/t)	PGE and Au (g/t)	Reference(s)
				Decimal degrees WGS 84									
Gold zone	Reef (sulfide)	Skaergaard	Greenland	68.19	–31.67	110	n.d.	n.d.	0.05	0.59	1.68	2.32	Secher and others (2007)
Great Lakes Nickel	Contact	Crystal Lake gabbro	Canada	48.08	–89.63	46	0.18	0.33	0.206	0.686	0.0686	0.960	Postle and others (1986); Lightfoot and Lavigne (1995)
Haukiaho	Contact	Koilismaa	Finland	65.85	28.06	27	0.24	0.36	0.209	0.549	0.216	0.974	Iljina and others (2005)
Hietaharju	Komatiitic	Kuhmo	Finland	65.15	29.08	1.1	0.8	0.4	0.49	1.17	n.d.	1.66	Geological Survey of Finland (2011)
Hitura	Synorogenic	Hitura	Finland	63.84	25.05	4.4	0.52	0.18	0.03	0.04	n.d.	0.0700	Geological Survey of Finland (2011)
Horizon of banded subzone of Agano zero and Shalozero blocks	Reef	Burakovskaya intrusion	Russia	62.07	36.45	23	n.d.	n.d.	n.d.	n.d.	1.3	1.10	Geological Survey of Finland (2011)
Ikenskoe	Conduit	Kun-Manie Massif	Russia	55.33	132.53	36	0.45	0.13	0.2	0.2	n.d.	0.400	Armitage (2007)
Ivakkak	Komatiitic	n.d.	Canada	61.44	–77.17	0.63	1.6	2	0.782	3.42	0.168	4.37	Puritch and others (2006)
Ivanhoe (Turfspruit, Rietfontein, Macalacaskop)—selective underground	Contact	Bushveld	South Africa	–24.10	28.98	630	0.33	0.17	1.61	1.64	0.267	3.60	Ivanplats (Pty) Ltd. (2013)
Jinbasoshan	Conduit	Jinbaoshan intrusion	China	25.01	100.76	13	0.18	0.19	1.09	0.669	n.d.	1.76	Jinshan Gold Mines (2004)
Jinchuan, Baijiazuizi	Conduit	Jinchuan intrusion	China	38.47	102.17	440	1	0.66	0.11	0.082	n.d.	0.197	Yonglin (2005)
Kabanga	Conduit	Kabanga	Tanzania	–2.87	30.58	46	2.7	0.38	0.252	0.256	0.0873	0.595	Xstrata plc (2007)
Kalplats Project (Main Reef+LG+UM+UUM+LM+MR+MMW)	Reef (Ti-V layers)	Amalia-Kraaipan greenstone belt	South Africa	–26.31	24.86	140	n.d.	n.d.	0.696	0.788	0.0433	1.53	Lewins and others (2008); African Rainbow Minerals Ltd. (2011)
Karenhaugen	Hydrothermal or remobilized?	n.d.	Norway	70.03	25.22	0.7	n.d.	0.57	0.31	0.87	n.d.	1.18	Geological Survey of Finland (2011)

Table N10. Grade and tonnage of mineralized rock remaining in platinum-group-element-bearing mineral deposits.—Continued

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Deposit name	Deposit type	Intrusion	Country	Latitude	Longitude	Ore (Mt)	Ni (percent)	Cu (percent)	Pt (g/t)	Pd (g/t)	Au (g/t)	PGE and Au (g/t)	Reference(s)
				Decimal degrees WGS 84									
Karhunjupukka	Reef (Ti-V layers)	Pajala-Kolari	Finland	67.29	24.48	5.2	n.d.	0.03	n.d.	0.1	n.d.	0.100	Geological Survey of Finland (2011)
Karikjavr	Conduit	Pechenga greenstone belt	Russia	69.30	31.43	22	0.63	0.5	n.d.	n.d.	n.d.	0.464	Geological Survey of Finland (2011)
Kaukua	Contact	Koilismaa	Finland	65.94	28.18	12	0.1	0.15	0.25	0.71	0.08	0.960	Geological Survey of Finland (2011)
Kevitsa	Atypical; pipe-like ore-bodies?	n.d.	Finland	67.70	29.97	270	0.3	0.41	0.2	0.15	0.11	0.350	Geological Survey of Finland (2011)
Kilvenjärvi	Contact	Portimo	Finland	66.24	26.17	0.7	n.d.	2.7	1.12	7.27	0.8	8.39	Geological Survey of Finland (2011)
Kilvenjoki	Offset type contact deposit	Portimo	Finland	66.26	26.17	0.18	0.28	6.1	0.06	2.5	0.84	2.56	Geological Survey of Finland (2011)
Kilvenlatvalampi	Contact	Portimo	Finland	66.25	26.27	3.2	n.d.	0.5	0.5	1.4	n.d.	1.90	Geological Survey of Finland (2011)
Kingashskoe and Verkhnekin-gashskoye	Komatiitic	n.d.	Russia	54.92	95.36	480	0.45	0.21	n.d.	n.d.	n.d.	0.630	OJSC MMC Norilsk Nickel (2009)
Koitelainen LC	Reef (chromitite)	Koitelainen	Finland	67.80	27.10	2	n.d.	n.d.	0.48	0.9	n.d.	1.38	Geological Survey of Finland (2011)
Koitelainen UC	Reef (chromitite)	Koitelainen	Finland	67.83	27.32	70	n.d.	n.d.	n.d.	n.d.	n.d.	1.10	Geological Survey of Finland (2011)
Koivukivalonaapa	Reef?	Portimo	Finland	66.25	26.20	0.84	n.d.	0.1	2.1	6	0.17	8.10	Geological Survey of Finland (2011)
Konttijärvi	Contact	Portimo	Finland	66.12	25.98	75	0.05	0.1	0.27	0.95	0.07	1.22	Geological Survey of Finland (2011)
Kootsel'vaara-Kammikivi	Conduit	Pechenga greenstone belt	Russia	69.40	30.33	7.5	1.2	0.64	n.d.	n.d.	n.d.	0.185	Geological Survey of Finland (2011)
Lac des Iles	Atypical; pipe-like ore-bodies?	Lac des Iles	Canada	49.17	–89.62	56	0.09	0.06	0.258	3.2	0.222	3.68	North American Palladium Ltd. (2012)

Table N10. Grade and tonnage of mineralized rock remaining in platinum-group-element-bearing mineral deposits.—Continued

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Deposit name	Deposit type	Intrusion	Country	Latitude	Longitude	Ore (Mt)	Ni (percent)	Cu (percent)	Pt (g/t)	Pd (g/t)	Au (g/t)	PGE and Au (g/t)	Reference(s)
				Decimal degrees WGS 84									
Las Aguilas	Conduit	n.d.	Argentina	–33.11	–66.13	4.6	0.41	0.41	0.123	0.145	0.311	0.579	Carter and othrers (2012)
Lavotta	Contact	Koilismaa	Finland	65.80	28.14	3	0.21	0.26	0.18	0.26	0.2	0.640	Mattila and others (1976); Lahtinen (1983)
Lomalampi	Komatiitic	n.d.	Finland	67.91	26.92	3.1	0.17	0.06	0.269	0.122	0.074	0.391	Geological Survey of Finland (2011)
Lower Pseudo Reef	Reef (sulfide)	Bushveld	South Africa	–25.18	26.97	14	0.14	0.03	1.41	0.733	0.127	2.37	Harper and de Wit (2009); Platinum Australia Ltd. (2012)
Lukkulaisvaara—total resources	Contacts of macrodike and reef	Olanga	Russia	66.32	30.87	2.8	0.06	0.12	0.6	2.13	0.14	2.87	Zarubezhtsvetmet Austrasia pty Ltd. (2009)
Main sulfide layer (Ferguson Reef)	Reef (sulfide)	Munni Munni	Australia	–21.14	116.84	24	0.09	0.15	1.1	1.5	0.2	2.90	Platina Resources Ltd. (2010)
Marathon	Contact	Coldwell Complex	Canada	48.79	–86.32	120	n.d.	0.24	0.222	0.751	0.072	1.05	Murahwi and others (2011)
Maslovskoe deposit	Conduit	Noril'sk Talnakh	Russia	69.20	88.04	220	0.33	0.51	1.78	4.56	0.19	6.53	OJSC MMC Norilsk Nickel (2012)
Maturi (Nokomis) (Twin Metals)	Contact	Duluth	United States	47.81	–91.73	1,600	0.18	0.56	0.151	0.344	0.0806	0.576	Parker and Eggleston (2012)
Mequillon	Komatiitic	n.d.	Canada	61.51	–73.75	4.4	0.7	0.9	0.7	2.4	0.2	3.30	Puritch and others (2006)
Merensky Reef—eastern limb	Reef (sulfide)	Bushveld	South Africa	–24.60	30.00	2,500	0.16	0.09	2.51	1.3	0.288	4.23	Zientek and others (2014)
Merensky Reef—western limb	Reef (sulfide)	Bushveld	South Africa	–25.30	27.30	1,600	0.2	0.08	3.88	1.72	0.269	6.16	Zientek and others (2014)
Merensky Reef, Pseudo Reef, UG2	Reef	Bushveld	South Africa	–25.14	27.00	160	0.09	0.02	2.19	0.918	0.109	3.47	Platinum Australia Ltd. (2011, 2012); Platmin Ltd. (2011); Realm Resources Ltd. (2011)
Mesamax	Komatiitic	n.d.	Canada	61.58	–73.26	1.9	2.1	2.6	0.994	3.83	0.198	5.02	Puritch and others (2006)

Table N10. Grade and tonnage of mineralized rock remaining in platinum-group-element-bearing mineral deposits.—Continued

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				Decimal degrees WGS 84									
Mimosa (Main Sulphide Zone)	Reef (sulfide)	Great Dyke	Zimbabwe	–20.30	29.81	140	0.14	0.11	1.81	1.41	0.318	3.70	Aquarius Platinum Ltd. (2011); Impala Platinum Holdings Ltd. (2011)
Mogalakwena Mine	Contact	Bushveld	South Africa	–24.00	28.92	3,500	n.d.	n.d.	0.976	1.15	0.126	2.25	Anglo American Platinum Ltd. (2011)
Mokopane	Contact	Bushveld	South Africa	–24.14	29.00	40	0.15	0.09	0.22	0.33	n.d.	0.550	Blackthorn Resources Ltd. (2009)
Monchetundorvskoe	Contact	Imandra-Varzuga greenstone belt	Russia	67.88	32.75	48	n.d.	n.d.	n.d.	n.d.	n.d.	3.81	Geological Survey of Finland (2011)
Mouat	Contact	Stillwater	United States	45.38	–109.90	130	0.31	0.29	0.0039	0.0105	n.d.	0.0144	Zientek (1993)
Mt. General'skaya	Contact	Mt. General'skaya	Russia	69.42	31.08	53	0.27	0.46	0.2	2.05	n.d.	2.25	Geological Survey of Finland (2011)
Nadezhda	Contacts of macrodike	Olanga	Russia	66.32	30.87	1.8	n.d.		n.d.	n.d.	n.d.	3.57	Zarubezhtsvetmet Austrasia pty Ltd. (2009)
Nebo-Babel	Conduit	Giles Complex	Australia	–26.10	127.71	390	0.3	0.3	n.d.	n.d.	n.d.	0.180	Western Mining Corp. (2005)
Niittylampi	Contact	Portimo	Finland	66.10	26.20	1	0.67	0.49	0.27	0.68	n.d.	0.950	Geological Survey of Finland (2011)
Nkomati Mine (MMZ and PCMZ)	Conduit	Uitkomst intrusion	South Africa	–25.73	30.60	340	0.34	0.13	0.23	0.597	0.0125	0.861	African Rainbow Minerals Ltd. (2006, 2011)
Noril'sk-1 deposit, all resource categories	Conduit	Noril'sk Talnakh	Russia	69.23	88.18	81	0.32	0.44	1.68	4.17	0.172	6.19	OJSC MMC Norilsk Nickel (2011)
Northern Limb projects—Aurora and Hacra	Contact	Bushveld	South Africa	–23.50	28.90	120	0.04	0.05	0.478	0.782	n.d.	1.26	McConnachie and others (2011)

Table N10. Grade and tonnage of mineralized rock remaining in platinum-group-element-bearing mineral deposits.—Continued

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Deposit name	Deposit type	Intrusion	Country	Latitude	Longitude	Ore (Mt)	Ni (percent)	Cu (percent)	Pt (g/t)	Pd (g/t)	Au (g/t)	PGE and Au (g/t)	Reference(s)
				Decimal degrees WGS 84									
Northmet (Polymet)	Contact	Duluth	United States	47.62	–91.97	550	0.09	0.33	0.0823	0.298	0.0418	0.422	Desautels and Zurowski (2012)
Nunatak-Brady Glacier	Contact	La Perouse	United States	58.55	–136.93	90	0.53	0.33	0.116	0.113	n.d.	0.229	U.S. Bureau of Mines (1991); Czamanske and others (1981); Himmelberg and Loney (1981)
Nutturalampi	Contact	Portimo	Finland	66.26	26.31	0.4	n.d.	0.09	1.5	5.5	0.15	7.00	Geological Survey of Finland (2011)
Nye Basin	Contact	Stillwater	United States	45.37	–109.84	280	0.22	0.25	0.0032	0.0087	n.d.	0.0119	Zientek (1993)
Owendale (includes Owendale North, Cincinnati, and Milverton)	Uralian	Fifield	Australia	–32.69	147.46	13	n.d.	n.d.	0.7	n.d.	n.d.	0.700	Platina Resources Ltd. (2013)
Paasivaara Reef (PV Reef)	Reef (sulfide)	Penikat intrusion	Finland	65.81	24.98	5	n.d.	0.28	4.04	2.58	0.61	7.31	Geological Survey of Finland (2011)
Parkin (Sudbury area)	Offset type deposit	Sudbury	Canada	46.83	–80.85	0.35	0.59	0.7	0.764	0.874	0.322	1.96	Bailey (2012)
Parks Reef	Reef (sulfide)	Weld Range	Australia	–26.84	117.75	15	n.d.	n.d.	0.6	0.5	n.d.	1.10	Parks (1998)
Pazhskoe	Hydrothermal (vein swarm)	Onega	Russia	62.71	35.76	2.8	n.d.	n.d.	2.5	n.d.	n.d.	2.50	Geological Survey of Finland (2011)
Pedra Branca	Reef (chromitite)	Troia Unit of the Cruzeta Complex	Brazil	–5.60	–39.96	6.6	0.23	0.03	n.d.	n.d.	n.d.	2.27	Anglo American Platinum Ltd. (2009)
Peura-aho	Komatiitic	Kuhmo	Finland	65.20	29.12	0.49	0.6	0.27	0.27	0.58	n.d.	0.850	Geological Survey of Finland (2011)
Platinometal horizon “A”	Reef (chromitite)	Burakovskaya intrusion	Russia	62.07	36.45	210	n.d.	n.d.	n.d.	n.d.	n.d.	1.40	Geological Survey of Finland (2011)
Pudozhgorskoe	Reef (Ti-V layers)	Onega	Russia	62.28	35.90	520	n.d.	0.13	n.d.	n.d.	0.21	1.62	Geological Survey of Finland (2011)
River Valley	Contact	River Valley intrusion	Canada	46.69	–80.26	130	0.02	0.06	0.197	0.518	0.0372	0.772	McCracken (2012)

Table N10. Grade and tonnage of mineralized rock remaining in platinum-group-element-bearing mineral deposits.—Continued

[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. WGS 84, World Geodetic System of 1984. Elements: Au, gold; Cu, copper; Ni, nickel; Pd, palladium; PGE, platinum-group element(s); Pt, platinum. Abbreviations: Mt, million metric tons; g/t, gram per metric ton; LC, lower chromitite; LG, lower grade reef; LM, lower main reef; MMW, mid-main waste zone; MMZ, main mineralized zone; MR, mid reef; PCMZ, peridotite chromititic mineralized zone; Ti-V, titaniferous-vanadiferous; UC, upper chromitite; UM, upper main reef; UUM, post reef hanging wall; n.d., no data; ?, identification uncertain]

Deposit name	Deposit type	Intrusion	Country	Latitude	Longitude	Ore (Mt)	Ni (percent)	Cu (percent)	Pt (g/t)	Pd (g/t)	Au (g/t)	PGE and Au (g/t)	Reference(s)
				Decimal degrees WGS 84									
Rocky Claim Group (Chrome Lake)	Contact	Stillwater	United States	45.35	–109.80	49	0.28	0.26	0.0052	0.0107	n.d.	0.0159	Zientek (1993)
Rooiport	Contact	Bushveld	South Africa	–24.27	29.01	18	0.19	0.11	0.474	0.717	0.0896	1.28	Verbeek and Lomberg (2005)
Rusamo	Contact	Koilismaa	Finland	65.78	27.95	1.5	0.24	0.39	0.266	0.384	0.15	0.800	Lahtinen (1983)
Selkirk	Contact	n.d.	Botswana	–21.21	27.77	140	0.23	0.27	n.d.	n.d.	n.d.	0.569	OJSC MMC Norilsk Nickel (2011)
Semiletka	Conduit	Pechenga greenstone belt	Russia	69.38	30.33	17	0.65	0.35	n.d.	n.d.	0.036	0.140	Geological Survey of Finland (2011)
Shakespeare	Conduit	Nipissing Suite sill	Canada	46.35	–81.83	17	0.33	0.36	0.333	0.362	0.187	0.883	Carter and others (2012)
Shalozerskoe (Kuk Ruchi Zone)	Reef (chromitite)	Burakovskaya intrusion	Russia	62.10	36.47	78	0.07	0.05	0.17	0.175	0.0245	0.369	Fletcher (2009)
Sheba's Ridge	Contact	Bushveld	South Africa	–25.32	29.36	610	0.19	0.08	0.209	0.659	0.0637	0.932	Aquarius Platinum Ltd. (2011)
Showing №15 (massif Lukkulaisvaara)	Reef?	Olanga	Russia	66.32	30.87	0.6	n.d.	n.d.	2.5	4	n.d.	6.50	Geological Survey of Finland (2011)
Showing №2 (massif Lukkulaisvaara)	Reef?	Olanga	Russia	66.32	30.87	0.7	n.d.	n.d.	3	6	n.d.	9.00	Geological Survey of Finland (2011)
Siika-Kämä (SK Reef)	Reef (sulfide)	Portimo	Finland	66.22	26.48	49	0.08	0.1	0.67	2.45	0.07	3.12	Geological Survey of Finland (2011)
Sompujärvi (SJ Reef)	Reef (sulfide)	Penikat intrusion	Finland	65.94	25.14	6.7	n.d.	n.d.	3.08	5.36	0.1	8.92	Geological Survey of Finland (2011)
Sputnik	Conduit	Pechenga greenstone belt	Russia	69.40	30.67	17	1.4	0.77	n.d.	n.d.	0.01	0.0350	Geological Survey of Finland (2011)
Stillwater and East Boulder	Reef (sulfide)	Stillwater	United States	45.39	–109.88	150	n.d.	n.d.	4.35	10.7	n.d.	15.0	Abbott and others (2011)
Stormyrplutten	Synvolcanic gabbroic body	n.d.	Norway	64.78	13.47	0.2	0.08	0.5	0.331	0.313	n.d.	0.644	Geological Survey of Finland (2011)
Sudbury-Vale	Sudbury	Sudbury	Canada	46.54	–81.00	110	1.2	1.5	0.916	1.06	0.387	2.36	Vale S.A. (2012)

Table N10. Grade and tonnage of mineralized rock remaining in platinum-group-element-bearing mineral deposits.—Continued

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Deposit name	Deposit type	Intrusion	Country	Latitude	Longitude	Ore (Mt)	Ni (percent)	Cu (percent)	Pt (g/t)	Pd (g/t)	Au (g/t)	PGE and Au (g/t)	Reference(s)
				Decimal degrees WGS 84									
Suhanko	Contact	Portimo	Finland	66.10	26.09	1	0.2	0.31	0.2	0.9	0.03	1.10	Geological Survey of Finland (2011)
Syerston	Laterite	Fifield	Australia	n.d	n.d	140	n.d.	n.d.	0.24	n.d.	n.d.	0.240	Teluk (2001)
Talnakh ore field—cuprous	Conduit	Noril'sk Talnakh	Russia	69.53	88.45	85	0.89	3.8	2.11	8.49	0.614	10.8	OJSC MMC Norilsk Nickel (2011)
Talnakh ore field—disseminated	Conduit	Noril'sk Talnakh	Russia	69.53	88.45	1,400	0.51	1	0.842	2.9	0.19	3.91	OJSC MMC Norilsk Nickel (2011)
Talnakh ore field—rich	Conduit	Noril'sk Talnakh	Russia	69.53	88.45	150	2.8	3.3	1.26	6.28	0.195	8.04	OJSC MMC Norilsk Nickel (2011)
Thunder Bay North project	Contact	n.d.	Canada	48.75	–88.90	8.2	0.21	0.29	1.22	1.15	0.0756	2.45	Cole and El-Rassi (2009)
Top and Middle Reefs	Reef (chromitite)	Panton Sill	Australia	–17.77	127.83	14	0.27	0.08	2.19	2.39	0.31	5.20	Platinum Australia Ltd. (2003, 2011)
Tundrovskoe	Conduit	Pechenga greenstone belt	Russia	69.40	30.67	110	0.51	0.26	n.d.	n.d.	0.008	0.0220	Geological Survey of Finland (2011)
UG2—eastern limb	Reef (chromitite)	Bushveld	South Africa	–24.60	30.00	3,900	0.11	0.04	2.44	2.06	0.0779	5.03	Zientek and others (2014)
UG2—western limb	Reef (chromitite)	Bushveld	South Africa	–25.30	27.30	3,400	0.12	n.d.	2.98	1.48	0.0333	5.05	Zientek and others (2014)
Upper Pseudo Reef	Reef (sulfide)	Bushveld	South Africa	–25.18	26.97	7.4	0.17	0.04	2.02	1.07	0.128	3.40	Harper and de Wit (2009); Platinum Australia Ltd. (2012)
Vaara	Komatiitic	Kuhmo	Finland	65.28	29.29	8.2	0.32	0.02	0.07	0.14	n.d.	0.210	Geological Survey of Finland (2011)
Vaaralampi	Contact	Portimo	Finland	66.10	26.18	32	0.31	0.2	0.25	0.68	0.07	0.930	Geological Survey of Finland (2011)
Verkhnee	Conduit	Pechenga greenstone belt	Russia	69.40	30.63	63	0.5	0.24	n.d.	n.d.	0.02	0.099	Geological Survey of Finland (2011)
Vodorazdelny	Conduit	Kun-Manie Massif	Russia	55.35	132.44	5.9	0.71	0.2	0.2	0.2	n.d.	0.300	Armitage (2007)
Volspruit project—North Pit Mines	Contact	Bushveld	South Africa	–24.35	28.95	51	0.14	0.04	0.556	0.667	0.0222	1.24	Clay and others (2010)

Table N10. Grade and tonnage of mineralized rock remaining in platinum-group-element-bearing mineral deposits.—Continued

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Deposit name	Deposit type	Intrusion	Country	Latitude	Longitude	Ore (Mt)	Ni (percent)	Cu (percent)	Pt (g/t)	Pd (g/t)	Au (g/t)	PGE and Au (g/t)	Reference(s)
				Decimal degrees WGS 84									
Vostochno (eastern) Panskoe	Reef (sulfide)	Imandra-Varzuga greenstone belt	Russia	67.40	35.95	7.6	0.23	0.17	n.d.	n.d.	n.d.	13.2	Geological Survey of Finland (2011)
Vostochnoe—critical zone	Reef?	Olanga	Russia	66.32	30.90	0.52	n.d.	n.d.	3.77	0.07	n.d.	3.84	Geological Survey of Finland (2011)
War Springs	Contact	Bushveld	South Africa	–24.22	29.05	47	n.d.	n.d.	0.255	0.777	0.0777	1.11	Platmin Ltd. (2011)
Wellgreen (indicated and inferred pitshell)	Conduit	Wellgreen	Canada	61.47	–139.52	460	0.32	0.26	0.399	0.343	0.171	0.913	McCracken (2011); Carter and others (2012)
Western Panskoe	Reef (sulfide)	Imandra-Varzuga greenstone belt	Russia	67.53	35.27	35	0.1	0.25	n.d.	n.d.	n.d.	3.65	Geological Survey of Finland (2011)
Yangliuping deposit	Conduit	Yangliuping Sill	China	30.70	101.90	90	0.44	0.26	0.23	0.3	n.d.	0.563	Yao and others (2001); Song, Zhou, Cao, and others (2003); Song, Zhou, and Cao (2004)
Yli-Portimo	Contact	Portimo	Finland	66.13	26.17	30	n.d.	n.d.	0.18	1.12	0.11	1.30	Geological Survey of Finland (2011)
Zapolyarnoe	Conduit	Pechenga greenstone belt	Russia	69.40	30.75	11	2.3	1.2	n.d.	n.d.	0.008	0.430	Geological Survey of Finland (2011)
Zhdanovskoe	Conduit	Pechenga greenstone belt	Russia	69.44	30.67	1,000	0.57	0.25	n.d.	n.d.	0.008	0.0580	Geological Survey of Finland (2011)
Zimplats Hartley Mine (Main Sulphide Zone)	Reef (sulfide)	Great Dyke	Zimbabwe	–17.99	30.45	220	n.d.	n.d.	2	1.55	0.297	4.02	Impala Platinum Holdings Ltd. (2011)
Zimplats Ngezi Mine (Main Sulphide Zone)	Reef (sulfide)	Great Dyke	Zimbabwe	–18.42	30.41	1,700	n.d.	n.d.	1.77	1.37	0.262	3.55	Impala Platinum Holdings Ltd. (2011)

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

Zientek and others—**Critical Mineral Resources of the United States—Platinum-Group Elements**—Professional Paper 1802–N

ISSN 2330-7102 (online)
https://doi.org/10.3133/pp1802N