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Mineral Commodity Profiles—Gold

By W.C. Butterman and Earle B. Amey III

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Overview

Gold has been treasured since ancient times for its beauty and permanence and remains the decorative metal par excellence while retaining a high standing among all commodities as a long-term store of value. Worldwide, about 90 percent of the gold supplied to the market each year goes into manufactured products, and the remainder goes to private investors and to monetary reserves. Of manufactures, jewelry is by far the most important quantitatively and accounts for 85 percent, by weight, of world gold fabricated each year, or more than three-fourths of the gold supplied to the world market for fabrication, investment, and monetary uses. Gold has a long history of use as money or as a reserve backing for other forms of money, but that role is shrinking as gold is gradually being demonetized in the industrial nations. A host of applications that take advantage of gold's unique physicochemical properties, however, have been developed in the 20th century, thus making gold an industrial metal of great technological importance, especially to the electronics industry.

Gold is mined in 94 countries, of which the United States is the second largest producer, after the Republic of South Africa, and accounts for 335 metric tons (t), or nearly 13 percent of world production in 2001. Worldwide, hundreds of gold-producing mines yield about 2,600 metric tons per year (t/yr) of gold, a quantity that had a market value of about $22 billion in 2001. With the inclusion of secondary (recycled) gold and outflow from above-ground bullion stocks, the world market supply of bullion is nearly 3,900 t/yr, and had an approximate market value in 2001 of $34 billion. In the United States, in 2001, gold was produced at 53 lode mines (including 8 base-metal mines), several large placer mines, and numerous small placer mines. Nearly all the mines are in the contiguous Western States and Alaska. Each year they produce metal valued at about $3.0 billion, employ 9,000 people at mine and mill operations, and indirectly enable the employment of another 85,000 people. Total investment in U.S. gold mines from 1980 through 1997, a period of rapid growth, has been estimated to have been about $16 billion (Thompson, 1998). Production is concentrated among the larger mines—the top 8 mines account for 77 percent of domestic production, and the top 25, for more than 95 percent.

World underground resources are estimated to contain about 89,000 t of gold, of which 15 percent to 20 percent is byproduct gold. South Africa has about 40 percent of the world resources, and Australia and the United States have about 7 percent each. Palladium, platinum, and silver are the principal substitutes for gold, and in most uses, gold is commonly alloyed with these substitutes and with a wide range of base metals.

Descriptive Terms and Units of Measure

Before considering the forms in which gold is used and traded, an introduction to some descriptive terms is in order. Two terms are commonly used to denote the purity of gold or the composition of its alloys. "Fineness" refers to the weight proportion of gold in an alloy or in impure gold, expressed in parts per thousand. For example, gold that contains 90 percent gold and 10 percent alloy metal is referred to as "900 fine." Used by itself, without numerical qualification, as in "fine gold," the reference is to unalloyed, or commercially "pure," gold, as distinguished from coin gold or other gold alloys. The term "karat," like "fineness," refers to purity, but purity expressed in 24ths, rather than parts per thousand; thus 24-karat gold is 1000 fine, or pure gold, and 10-karat gold refers to an alloy of gold and one or more other metals that is $^{10}/_{24}$, or 41.7 percent gold, by weight. Note that

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[1] Retired.

karatage and fineness refer only to the gold content of an alloy and not its nongold components. For this reason, there can be many 10-karat alloys, many 14-karat alloys, etc., that differ from each other in the number, identity, and proportions of their nongold component metals.

As with purity, the quantity of gold is commonly expressed in either of two units—the troy ounce or the kilogram (or one of its decimal equivalents). The troy system of weights, which is said to have originated in the Middle Ages with a weight unit used at the annual trade fair at Troyes in northeastern France, has traditionally been used in the West for gold and other precious metals. It is based on the troy ounce of 480 grains, or 20 pennyweight; 1 troy ounce is equivalent to 1.097 ounces avoirdupois, or 31.10 grams (g). Troy weight is still widely used, especially for prices and especially in English-speaking countries. Système International (SI, or metric units)—grams, kilograms, metric tons—are commonly used also, especially for nonprice statistics. In addition, the baht [14.62 g (0.47 troy ounce)] is used in Thailand, the tola [11.66 g (0.375 troy ounce)] is used in India and in parts of the Middle East, and the tael [37.5 g (1.20337 troy ounces)] is used in China.

In this report, unless stated otherwise, "ounce" refers to the troy ounce, and "ton" (t) to the metric ton. Three useful equivalence statements are listed below:

1 g = 0.032 ounce
1 metric ton (t) = 10^3 kilograms (kg) = 10^6 g = 32,150.7 ounces
1 gram per metric ton (g/t) = 1 part per million (ppm)

Historical Background

Gold was highly valued by the early peoples who possessed it because of its scarcity, durability, and its characteristic yellow color, reminiscent of the sun, which some of them worshiped as a deity. It was first recovered from streambed gravels, where it occurred in metallic form, and thus required no complicated metallurgical extraction from ores; it was essentially imperishable and was easily worked.

These beautiful and seemingly indestructible nuggets were prized possessions that could be fashioned into bars of different set weights, and into ornaments and items of adornment that also served as portable wealth. At first crude, but increasingly refined and specialized over the years, these manufactured forms eventually diverged, at least partly, into jewelry and money. For more than five millennia, until well into the 20th century, they were the only quantitatively important uses of gold.

During that time, there remained and in some developing countries remains today a functional overlap between jewelry and money; that is, items of gold jewelry have been used as money, and gold money has been made into items of jewelry. Crude forms of jewelry/money appear to have originated soon after the founding of the first cities. Their invention is commonly ascribed to the Mesopotamians or, more specifically, the Sumerians, who lived in what is now southern Iraq. On the long time line, the art of working gold and silver into jewelry/money seems to have arisen in Sumer, Egypt, and Crete at roughly the same time—probably around 3000 B.C. From the beginning, the universal perception of gold as a store of wealth has been implicit in its use as money and jewelry.

Gold in Jewelry and Ornamentation

The native gold recovered from streambed gravels by the ancients was typically 80 percent to 85 percent pure, most of the balance being silver, and could be worked readily. It was so malleable and ductile that it was easily worked into very thin sheets and into wire, which could be woven into chains. The variety of the gold jewelry developed by the Sumerians, Minoans, Mycenaeans, Egyptians, Etruscans, and other Mediterranean peoples is truly impressive. Over time, they mastered fire refining (cupellation), casting, fusion welding, and granulation; the manufacture of wire, gold leaf, and gold chain, some forms of which are still used today; and the formation of intricate shapes from sheet gold by repoussage and chasing. The goldsmith's art advanced steadily and culminated in Egypt between 2100 and 1700 B.C., on Crete around 1500 B.C., and in Etruria around 600 B.C. (Schadt, 1996,

p. 7). The fabrication of jewelry continued into the era of the Roman Empire, but gold was deemphasized in jewelry by the Romans, who tended to use it as the setting for precious stones. In the Americas, the native peoples began working gold as early as about 1200 B.C. and, by the time of the arrival of Europeans, had independently developed many of the same techniques, such as alloying, casting, fusion bonding, and mechanical plating, used by the Mediterranean peoples. Only a tiny fraction of their work survived the melting pots of the Conquistadores. Through most of the Middle Ages, when the supply of gold was small, the few goldsmiths in Europe produced works for kings and for the Catholic Church and lost touch with the jewelry forms of the ancient Mediterranean world. It was not until the Renaissance in southern Europe that the goldsmith's art flourished once more, benefiting from the sudden inflow of gold from the Americas. In the 17th and 18th centuries, gold jewelry survived renewed emphasis on precious stones. In the 19th century, the world supply of gold was augmented by new mine production in Australia, North America, and South Africa. In the 20th century, mass production techniques applied to the manufacture of jewelry made gold jewelry more affordable to large segments of the population; jewelry once more became the largest use of gold, displacing coinage, which had been the largest use for a century or more.

The use of gold in the decoration of objects, as distinguished from jewelry, perhaps could be said to have begun with the Egyptians about 3000 B.C. when they developed the art of beating gold into thin sheets that were used as decorative coverings on funerary masks, statuary, temples, and tombs. The process of beating was gradually improved over the ages until, by the early 17th century, the goldbeaters of Paris were able to beat a troy ounce of gold thin enough to cover nearly 10 square meters (m^2). By the early 18th century, they could beat a troy ounce of gold to nearly 14 m^2. Modern methods in France and elsewhere have increased this to about 18 m^2 and sometimes more (Barnes, 1962, p. 11).

Gold in Other Nonmonetary Uses

Gold may have been used in dentistry for as long as 3,000 years. In the seventh century B.C., the Etruscans used gold wire to fasten replacement teeth in place (World Gold Council, 1999§[1]). Although gold leaf probably has been used for filling dental cavities since ancient times, its first documented use came at the beginning of the ninth century A.D. when Caliph Haroun al-Raschid had a cavity packed with gold leaf (Harrer, 1967§). Most of the other nonmonetary, nonjewelry uses have arisen in the 20th century; these included architectural (solar) glass, electrical and electronic circuitry, radioisotope medicine, scientific instrumentation, and radiation shielding and solid lubricants for use in outer space.

Gold as a Monetary Metal

Once gold had become widely acceptable as an item of ornamentation and barter, it was able to fill a larger role as a medium of exchange, or money. From early times, metals, where available, have usually been favored for use as money over such commodities as cattle, cowry shells, or salt, because they are at once durable, portable, and easily divisible. The use of gold as money has been traced back to the fourth millennium B.C. when the Egyptians used gold bars of a set weight as a medium of exchange, as the Sumerians had done somewhat earlier with silver bars. The first gold coins were introduced about 650 B.C. in Lydia (now western Turkey).

From ancient times to the present, gold coins have coexisted with those of silver and base metal, the choice of metal coined in a given region often being determined by the kind of metal deposits available in the region and, after large-volume interregional trade in goods developed, by the tendency for the coins of the dominant trading partners to be preferred for payment for the goods. Until the 19th century, silver remained the dominant coinage in most of Europe, and gold tended to predominate in the Middle East (Green, 1999, p. 6). The value ratio of gold to silver, which is usually referred to simply as the "gold/silver ratio," fluctuated from time to time and place to place. During the thousands of years that both served as the premiere coin metals, however, the ratio stayed in a narrow range, from about 9 to 1 to 16 to 1, until the second half of the 19th century when most of the world adopted the gold standard and silver was largely demonetized; the ratio then increased rapidly. For example, in the United States in the 1990s, the gold/silver ratio ranged from about 53 to 1 to 90 to 1.

With the widespread introduction of national currencies in the 19th and 20th centuries, gold or silver or a combination of the two has often been chosen as the monetary reference metals; that is, the national unit of account—the pound sterling, the franc, the dollar—has been defined in terms of a stated quantity of one of the reference metals or stated quantities of each of the two metals. The United Kingdom went to a de facto gold standard early in the 18th century and made gold its official standard about a century later. By the end of the 19th century, most of the world had gone to the gold standard. Because the gold standard proved to be fragile in unstable times, it had to be suspended during the Napoleonic wars, World War I, World War II and during times of economic crisis, as in the 1930s. During World War II, the International Monetary Fund (IMF) was established, and in 1946, its member nations went on a modified gold standard in which each country set the exchange rate for its currency against the U.S. dollar and against gold at $35 per ounce. The dollar was to substitute for gold in international transactions. The system broke down as the United States experienced currency inflation and ran large balance-of-payments deficits in the 1960s and 1970s. In 1971, the United States ended the convertibility of dollars into gold. The U.S. dollar, which had been devalued in 1934 from $20.67 to $35 per ounce of gold, was devalued again in 1972 to $38 per ounce and yet again in 1973 to $42.22 per ounce. After the IMF broke the link between currencies and gold in mid-1974, a system of managed floating exchange rates evolved that is still in use. As a way of de-emphasizing the role of gold in monetary affairs, the IMF and the United States auctioned off about 1,262 t of bullion stocks on the open market between 1975 and 1980.

With the adoption of the gold standard by most countries in the 19th century, national monetary gold stocks became very large. When the United States Mint began buying all the gold offered to it at the sharply higher price of $35 per ounce in 1934, the U.S. stock grew rapidly and continued growing through the 1940s; it reached nearly 22,000 t in 1949 (Butterman, 1980). The flow reversed in the 1960s and 1970s, and by mid-1971, when convertibility of the dollar to gold was suspended, the U.S. stock had declined to about 9,000 t and European stocks had risen to more than 20,000 t. World monetary stocks changed little in total thereafter. In 1999, they were 33,000 t, or about 24 percent of all the gold ever mined.

Production and Supply

In the fourth millennium B.C., gold was recovered as nuggets and flakes from streambed gravels in Asia Minor and Central Asia. At about the same time or possibly a little later, the Egyptians recovered gold along the Nile in Egypt and Nubia (Sudan) and from the plateau east of the Nile near the Red Sea. At the plateau deposits, gold was first extracted from weathered surface materials and later from underground shafts and tunnels that extended as much as 100 meters (m) below the surface. The Egyptians may have also mined for gold elsewhere in Africa and in the Arabian Peninsula. In any case, Egypt was the source of most of the gold in the ancient Mediterranean world before the ascendance of Greece. Although gold had been mined in Macedonia and western Thrace, it was scarce in Greece until Alexander’s conquest of the Persians in 331 B.C. at Susa brought in more than 300 t of gold from the royal treasury there, and he undoubtedly added more at other points along his route of conquest. In their own mining ventures, the Greeks improved the methods of prospecting for gold, diverted streams to obtain adequate water for washing the gold gravels, and used fire setting/quenching to break up hard ore and rock.

About a century later after the second Punic War, the Romans took over the exploitation of Spanish gold and silver deposits from Carthage. They improved underground structures and mining methods, devised better ways of pumping and controlling underground water, improved sluices, and developed a crude monitor (a high-pressure water cannon used to blast apart consolidated gold-bearing gravel terraces). Their improved smelting methods were able to deal with at least some of the complex sulfide and telluride ores. At the start of the Christian era, the Roman Empire’s production of gold, not just from Asia Minor, Central Europe, France, Spain, and Thrace was nearly 8 metric tons per year (t/yr) (Boyle, 1987, p. 630).

Except for itinerant gold washers in the region south of the Urals and in Central Asia and some contract laborers in the Roman era, the miners in ancient times were criminals, war prisoners, and slaves, all of whom were worked mercilessly, sometimes literally worked to death. With such minimal labor costs, the cutoff ore grades were very low; Boyle (1987, p. 632) estimated that in gold-quartz deposits, the cutoff was sometimes less than 1g/t, although in sulfide or telluride ores, from which the gold was harder to extract, the cutoff grade was much higher (closer to 15 g/t). The mines, ore deposits, and the gold produced were usually the exclusive property of a monarch or the city-state in which the mines were located.

During the Dark Ages in the West, precious-metals mining continued but at a greatly reduced rate and in far fewer places. Many of the known placers had been depleted, and inability to control ground water had limited the depth of underground workings. Gold and silver were in short supply in the West; Boyle (1987, p. 630) cited an estimate of 3.1 t/yr for mine production in most of the Middle Ages. This was only 40 percent of the amount mined each year at the beginning of the Christian era. Production expanded in the 14th century, however, as major gold discoveries in Bohemia, Hungary, and Silesia brought it up to about 7.8 t/yr by midcentury. These deposits were rather quickly depleted, and a long “bullion famine” began in Europe toward the end of the century. The 15th century was a time of scarce gold, but the Portugese established a presence in Africa and began shipping gold from Guinea and later from the Gold Coast (Ghana).

After Europeans found the Americas in the 16th century, the situation changed abruptly. Green (1999, p. 14) estimated that the looting of South American gold treasures in the 1530s yielded nearly 8 t of gold. After it established colonies and mines in Mexico and South America, Spain was receiving more than 4 t/yr of gold from them by the 1550s. Authorities differ on how much gold Spain received from its American colonies during the century; Green (1999, p. 14) cited an estimate of 154 t, but Boyle (1987, p. 630) estimated 311 t, or 40 percent of world production during the century.

Midway through the 17th century, the world production of nearly 8 t/yr was derived principally from the Americas. Near the end of the century, gold was discovered in eastern Brazil, which led to a gold rush. By the end of the century, world production was about 11 t/yr.

In the first half of the 18th century, gold mine production doubled, mainly owing to Brazilian production and gold from the Ural Mountains in Russia. By midcentury, world production was 23 to 25 t/yr, of which Brazil provided one-third. As the century drew to a close, however, Brazil’s production had declined to as little as one-fourth of the midcentury rate.

The 19th century was an age of gold rushes. The first was in Russia where the Tsar had encouraged exploration for gold with such success that production went from 1.5 t/yr to 5.9 t/yr between 1823 and 1830. By 1846, Russian production had expanded to 25 t, which was more than half of the world production at that time (Del Mar, 1901, p. 389; Green, 1999, p. 20). In 1848, gold was discovered at Sutter’s mill in California; this boosted production in the United States from about 1 t/yr in the 1830s to 16 t/yr in the 1840s (much of it in 1849) and to 83 t/yr for the decade of the 1850s. In 1851, the Australian gold rush began with discoveries in New South Wales and Victoria; production during the next two decades was nearly as large as in California. In 1858, the Comstock Lode in western Nevada was discovered; during its 20-year life, it yielded 265 t of gold and more than 20 times as much silver. In 1886, gold was discovered on the Witwatersrand ridge in South Africa; this discovery would eventually dwarf all other gold discoveries in importance. In 1890, gold was discovered at Cripple Creek, Colorado, a district that to date has yielded more than 620 t. In 1893, another rush started in Kalgoorlie, Western Australia, from which 115 t was produced by the turn of the century. In 1896, placer gold was discovered in the Yukon Territory, northwestern Canada; this led to the Klondike rush, which yielded 62 t from 1897 to 1899. At about the same time, Nome in western Alaska became the center of a rush for placer gold from 1899 to 1903 that quadrupled Alaskan production to 13 t/yr by 1903. In sum, the second half of the 19th century saw the production of more than twice as much gold as had been mined in the 32 centuries that followed the discovery of the Americas (Kettell,1982, p. 31).

The gold mining boom in the second half of the 19th century, which was sustained by the strong demand for gold coinage by nations going onto the gold standard, fostered significant improvements in mining and metallurgical extraction. Improved methods and equipment for the milling and beneficiation of ores and the dewatering of slimes were introduced. The cyanide leaching process, which was patented in 1887 and in use by 1890, made possible the economic extraction of gold from the South African ores as well as from many other refractory ores. Because cyanide extracted a higher percentage of contained gold, it became widely used even on nonrefractory ores, thus displacing amalgamation to some extent and chlorination entirely. Early in the 20th century, the development of froth flotation greatly increased the efficiency of separation of ore minerals and made it possible to treat ores that had once been rejected as too refractory to treat. These developments brought about a great change in the provenance of mined gold from mainly alluvial gravels to mainly quartz veins and cemented Precambrian conglomerates of the Witwatersrand type, as shown in table 1.

Table 1. World gold production, by deposit type
[Expressed as a percentage of world total. ---, zero. Data from Kettel, 1982, p. 31]

Year	Placer, alluvial gravels	Hardrock	
		Quartz veins	Cemented conglomerates
1850-1875	90	10	---
1890	45	47	8
1904	18	60	22
1929	8	39	53

The 20th century has seen rapid, sustained increases in world gold mine production to levels that would have been unimaginable in earlier times. Of all the gold ever mined in the world, more than 80 percent was mined in the 20th century, and half of it in the 42 years from 1959 through 2000 (fig. 1). Many new large gold deposits have been found around the world, and output from those and from existing gold fields has been augmented by developments in mining methods and equipment and particularly in metallurgical extraction, where the widespread adoption of froth flotation in the early part of the century and the development of cyanide heap- leaching processes for low-grade ores in the 1970s were important driving forces that led to a wider selection of economic ores. The 69 percent increase in the price of gold in 1934 (an official U.S. price but a de facto world price) caused a worldwide boom in gold mining that lasted until World War II. After the war, South African production, which dominated the whole century, resumed its steep climb in the 1950s towards its peak production of 1,000 t in 1970 (fig. 2). In the course of learning to mine very hard, tightly cemented ore at depths of as great as 4.5 kilometers, the South Africans pioneered methods and equipment for mine development and for operating under extreme conditions of temperature, humidity, and lithostatic pressure. Production in the U.S.S.R. began a long climb in the mid-1950s towards its peak of 302 t in 1990. Production in most other countries languished for nearly 35 years after World War II but then began to increase sharply around 1980 as high gold prices, strong demand, the commercialization of cyanide heap leaching, which led to the exploitation of low-grade ores, and a renewed interest in Precambrian greenstone gold deposits, especially in Canada, combined to generate a mining boom that lasted the rest of the century. South African production, however, trailed downward after 1970 as inflation drove production costs upward, and new social imperatives raised labor costs sharply. At 402 t in 2001, South Africa was still the world's largest producer by 67 t.

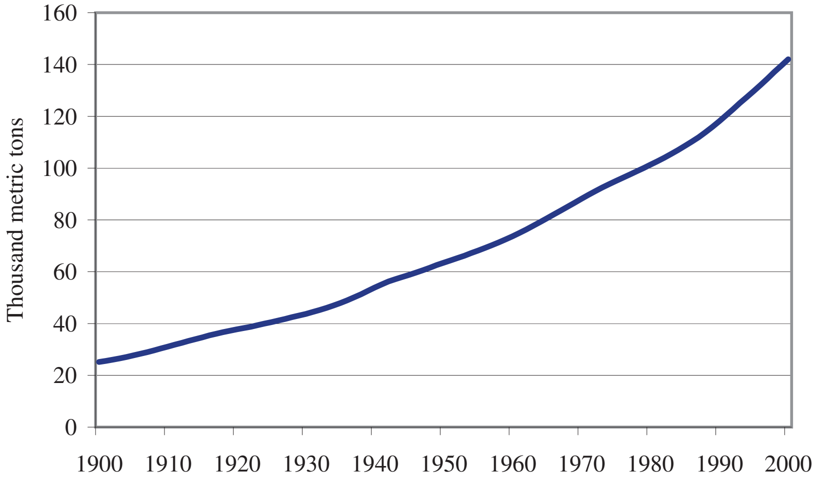

Figure 1. Cumulative world gold mine production. Pre-1900 total is a U.S. Geological Survey estimate based on several sources, including Del Mar, 1901, p. 389; Ridgway, 1929, p. 12-13; Kettell, 1982, p. 31; Boyle, 1987, p. 630; and Green, 1999, p. 14. Data for 1900-2000 are based on data from U.S. Geological Survey, 1879-1923, 1996-2000; and U.S. Bureau of Mines, 1924-1931, 1932-1995.

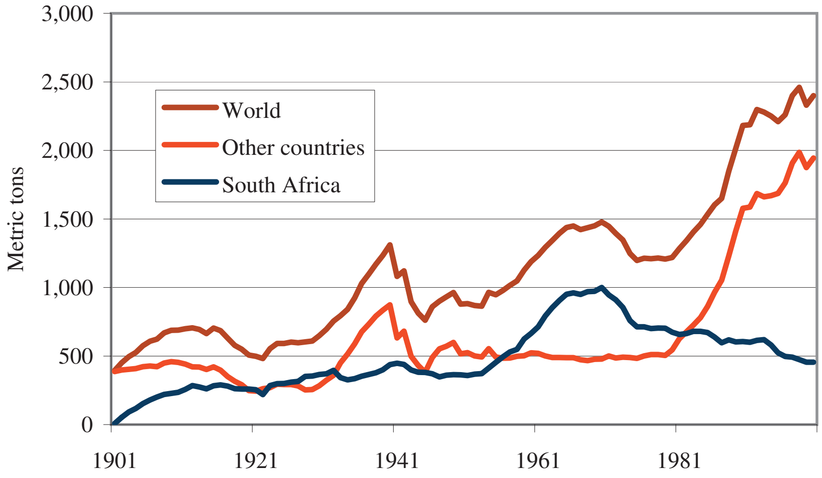

Figure 2. Annual gold mine production. Data from U.S. Geological Survey, 1879-1923, 1996-1999; U.S. Bureau of Mines, 1924-1931, 1932-1995; and Ridgway, 1929, p. 12-13.

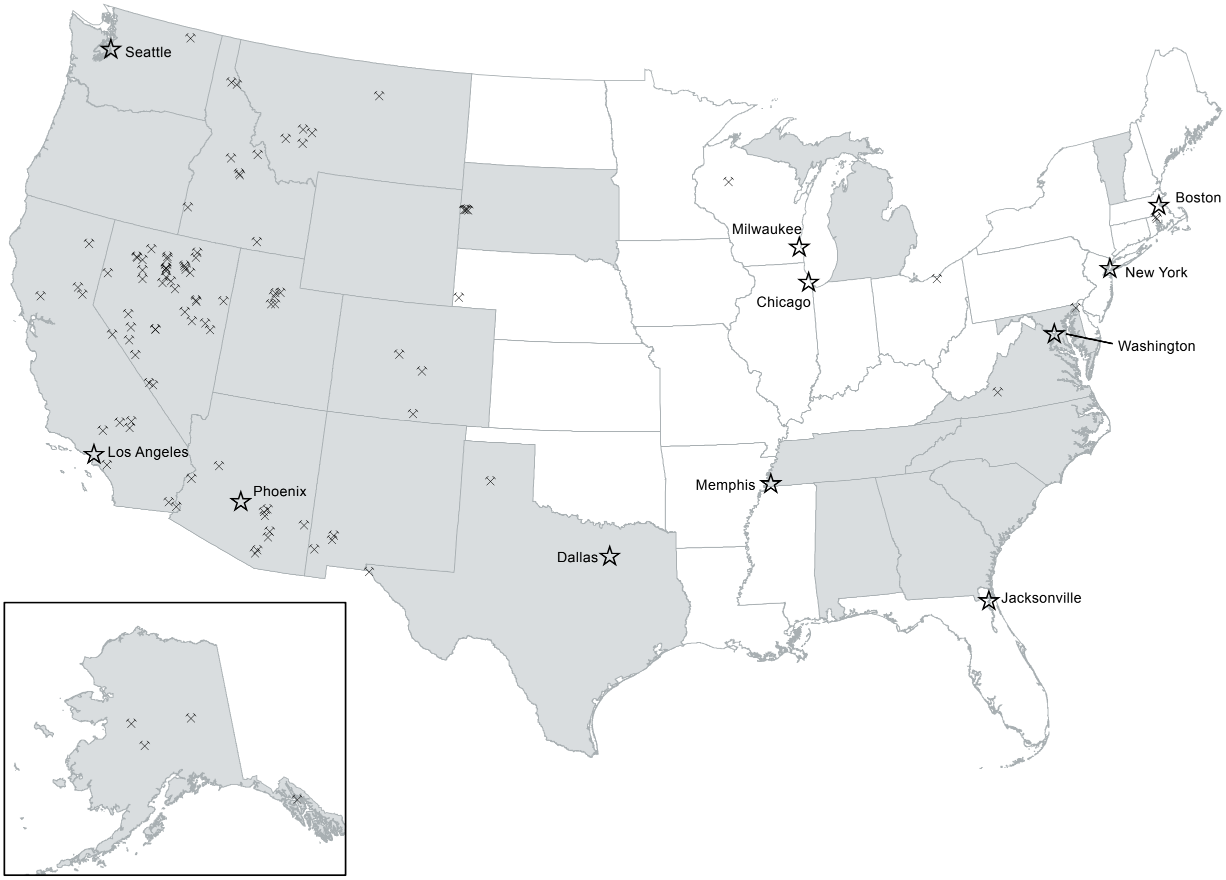

Figure 3. Gold mines operating in the United States in 2000 and States from which, historically, at least 100 kilograms of gold has been mined. Data from the U.S. Geological Survey.

Total world gold production from its beginnings in prehistory through 2000 was conservatively estimated to be 142,000 t (fig. 1). This cumulative production is equivalent to a cube of gold 19.4 m on a side. More than two-thirds of the gold has come from only five countries—South Africa, 34 percent; the U.S.S.R. (or the group of its member states), 11 percent; the United States, 10 percent; Australia, 7 percent; and Canada, 6 percent; but nearly 100 countries have reported at least some production of gold. How much of this gold remains above ground is a matter of conjecture. Estimates published in 1999 range from about 85 percent to 99 percent (More information can be found in the section entitled "Supply and Demand").

Mining in the United States

The first domestic gold mining took place in the last decade of the 18th century in North Carolina. Georgia followed in 1829, and Alabama, in 1830; then in a few years Tennessee, Virginia, and later New Mexico became producers as prospectors moved west. Because of its influence on the development of the West and the large amount of gold produced in the region, the most important gold discovery was at Sutter's mill in California in 1848. Discoveries were made later in most of the other Western States and territories. Through 2001, gold had been mined in at least 24 of the 50 States (fig. 3; Craig and Rimstidt, 1998, p. 407).

Early mining was done largely by means of placer methods in which a multitude of miners worked stream deposits (placers) by various hydraulic techniques. The gold was recovered by gravity separation and/or by amalgamation with mercury. In the 1860s, the more-difficult underground mining of lode deposits—the sources of the placers—became important. Quartz-gold ore was crushed in stamp mills, and the gold was removed from the pulverized ore by amalgamation with mercury. Cyanidation, which is a wet chemical process for extracting gold from pulverized ores, was introduced in about 1890. This process extracted substantially more gold from ores and made the economic recovery of gold possible from lower grade ores, which greatly expanded the world's gold reserves and generated a tremendous increase in world gold production. The concentration of finely ground ores by selective adherence of mineral particles to rising bubbles—the flotation process—was first used for gold ores in around 1900 and came into general use about 30 years later. It, too, greatly extended the range of mineralized assemblages that could be classified as ore.

U.S. cumulative production through 2001 totaled about 15,200 t, of which 90 percent was mined in 7 Western States; the balance came from 17 other States (table 2), 1998, p. 412-423).

Table 2. Gold mined in the United States through 2001
[Data from U.S. Geological Survey, 1882-1923, 1996-2002; U.S. Bureau of Mines, 1924-1931, 1932-1995; Ridgway, 1929, p. 18-19; Bonham, 1969, p. 103; Craig and Rimstidt, 1998, p. 412-423. Total is rounded to no more than three significant digits]

State	Quantity (metric tons)	Percentage of U.S. total
Nevada	3,700	26
California	3,670	25
South Dakota	1,430	10
Colorado	1,360	9
Alaska	1,090	8
Utah	1,010	7
Montana	730	5
Other	1,480	10
Total	14,500	100

Table 3. The 10 largest U.S. gold deposits in terms of past production through 1996
[In metric tons. Source: Long, DeYoung, and Ludington, 2000, p. 635. Do, ditto]

Deposit	State	Production
Homestake	South Dakota	1,240
Bingham Canyon copper district	Utah	750
Cripple Creek	Colorado	605
Goldstrike-Post-Meikle	Nevada	307
Comstock	do.	258
Gold Quarry-Maggie Creek	do.	258
Fairbanks	Alaska	250
Empire-North Star	California	196
Hammonton	do.	160
Nome	Alaska	152

Until late in the 19th century, most of the world's gold was mined from alluvial deposits, and most of the rest, from quartz veins (table 1). In contrast, about 72 percent of the gold mined in the United States in the 20th century through 1998 came from precious metal lodes, 14 percent came from placer deposits, and 14 percent was a byproduct of base-metal mining. The country's oldest operating mine, Homestake in South Dakota, was in operation from 1876 through yearend 2001, when it was scheduled for closure. Through 1996, it had yielded more than 1,240 t of gold and accounted for nearly 9 percent of cumulative U.S. production. Homestake and other major sources of past production are shown in table 3.

Production from deposits of disseminated gold, especially in Nevada, has grown in importance since the mid-1960s; these deposits have accounted for more than one-half of domestic gold mine production each year since 1985 and for about three-fourths of production in 1999. Because of the dominance of the disseminated-gold ores, 93 percent of domestic gold mine production now comes from precious-metal ores, another 6 percent is a byproduct of base-metals mining, and only 1 percent comes from placers.

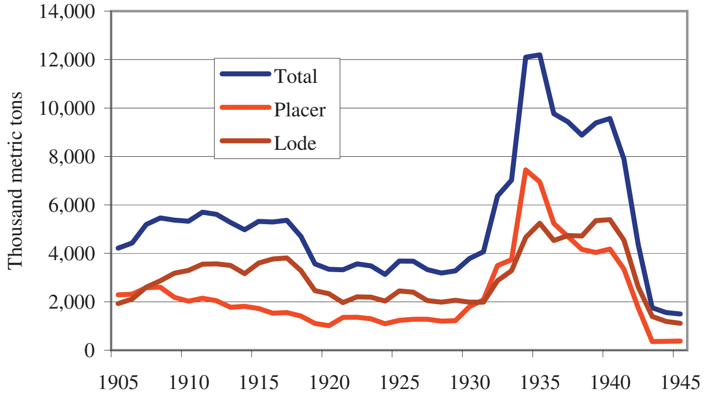

Figure 4. Numbers of U.S. gold mines, including byproduct producers, in production. Data from U.S. Geological Survey, 1879-1923; and U.S. Bureau of Mines, 1924-1931, 1932-1945.

At the beginning of the 20th century, roughly 4,000 gold mines, which included byproduct producers, were operating in the United States. The number of mines fluctuated above and below 4,000 until the years of the Great Depression when lack of employment opportunities and a sharp increase in the price of gold in 1934 impelled many people to establish small mines, often placer mines; the number peaked at more than 12,000 in 1934 and 1935 (fig. 4).

In 1942, most U.S. gold mines were shut down by Government order to free miners and equipment for the mining of minerals needed for the war effort. Because of increased costs, especially that of rehabilitation, only a few reopened after the war. Postwar production started at levels typical of the late 1920s (60-70 t/yr) and then drifted slowly downward to 30 t in 1979 and 1980, which matched the level in 1945 and were lower than any other annual level since the years before the California gold rush. Until the 1970s, the only large new mines developed after the war were the Carlin and the Cortez Mines in Nevada. Extensive exploration in the 1970s of disseminated-gold deposits along Nevada's Carlin Trend and the development and spread of heap leach technology in the same decade, however, positioned producers to take advantage of the rapidly rising gold prices of the late 1970s. The resulting spectacular twelvefold increase in domestic production in just 17 years made the United States the world's second largest producer after 1990 (fig. 5). Unlike earlier mining booms, this one has been characterized by the establishment of only a few large mines, rather than hundreds of small mines. In 2001, 53 domestic gold-producing

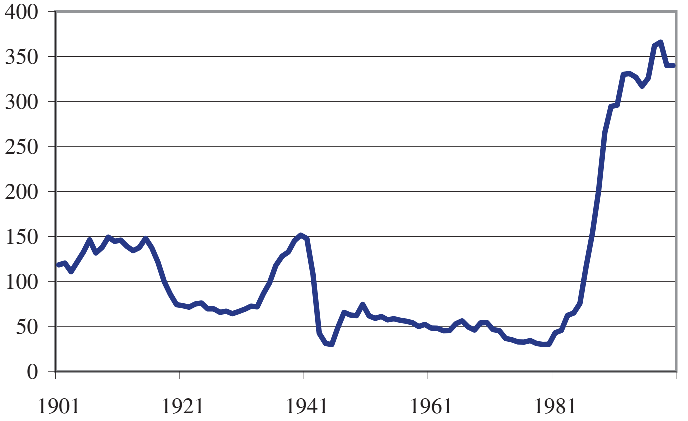

Figure 5. U.S. gold mine production. Data from U.S. Geological Survey, 1879-1923, 1996-1999; and U.S. Bureau of Mines, 1924-1931, 1932-1995.

lode mines, which included 8 base-metal mines, were operating along with several large placer mines and numerous small placer mines.

Description

Salient Facts

Gold, as well as silver and the six platinum-group metals, is known as a noble or precious metal. The first adjective refers to gold's extreme reluctance to combine chemically with nonmetallic elements, notably oxygen. The second adjective refers to a combination of rarity, durability, and beauty that until the 19th century made gold by far the most expensive of metals. Of 14 known isotopes, gold is found in terrestrial rocks as the single stable isotope, atomic number 79 and atomic weight 197, located in Group 1b of the periodic table of the elements along with copper and silver. The other 13 isotopes have half-lives that range from a few seconds to a few days. Gold crystallizes in a face-centered cubic lattice, melts at 1,064.18° C, and with a specific gravity of 19.3, is among the densest of metals. It is the most malleable of metals, is soft and highly ductile, has a bright pleasing color, is highly reflective to infrared radiation and to most of the visible spectrum, alloys readily with common metals, is readily joined by fusion bonding (soldering and brazing), and has high electrical and thermal conductivity. Chemically inert towards most naturally occurring substances, gold does not tarnish or corrode in use.

The name "gold," as well as the word "yellow," derives from the Sanskrit word for "to shine;" the chemical symbol for gold, Au, comes from the Latin "aurum," which means "glowing dawn."

Principal Forms, Alloys, and Compounds

Gold is usually traded in the marketplace as refined gold of 995 minimum fineness. In use, however, it is nearly always alloyed with one or more other metals that lend it abrasion resistance, hardness, and strength. Gold alloys used in jewelry and a few other uses are referred to as "karat golds" and designated by karat number; 22, 18, 14, 10, and 9 or 8 karat golds are commonly used jewelry alloys in the West. Yellow, rose, and green karat golds are essentially ternary alloys of gold, silver, and copper, often with additions of zinc and sometimes a little nickel or cadmium. For alloys of a given karatage in this system, color is primarily a function of the proportions of copper and silver contained. The white karat golds in common use are usually formulated in either of two alloy systems—either gold, copper, and nickel with additions of zinc or gold and palladium with lesser amounts of silver, platinum, nickel, and zinc. Alloys from the second system are also referred to as "noble metal white golds." The solders used to join the yellow, rose, and green karat golds are closely related in composition to the alloys being joined. They tend to be gold-silver-copper golds in which karatage is maintained while the copper-to-silver ratio is increased to depress the melting point, and one or more of zinc, nickel, cadmium, and tin is added to restore the desired color. In countries where jewelry is handmade from pieces soldered together, however, the karat level of the solders is typically three or four points lower than that of the alloy pieces being joined. Similarly, some white gold solders can be regarded as modifications of the alloys being joined, others have such high proportions of silver that they are in the gold-silver-copper system, and another distinct group is in the gold-nickel-copper system (Rapson and Groenewald, 1978, p. 30-94).

Alloys used in dentistry are manufactured to meet published industry standards for composition and a variety of other properties. Three forms of pure gold are available for use as fillings—gold foil, which is about 60 micrometers (µm) thick; gold powder, which has an average particle diameter of about 15 µm; and matted dendritic crystals. Dental gold casting alloys that cover a wide range of composition and color are manufactured for restorations. At least four types are available; all are based on the gold-silver-copper system and also contain palladium, platinum, and zinc. A separate class of casting alloys is made for bonding with porcelain dental materials. These alloys are based on the gold-palladium-platinum system but contain small amounts of several other metals—some act as grain-refining agents, some as age-hardening agents, and some as promoters of reaction bonding between the alloy and the porcelain. Wrought alloys for wires and plates are of at least two types, within each of which a range of color and composition is available. The components of these wrought alloys are gold, silver, copper, palladium, platinum, nickel, and zinc. Dental gold solders are essentially gold-silver-copper alloys. Individual solders are formulated to emphasize one or more properties, such as color; flow, which aids penetration into joints between metal parts; lack of flow, which is useful in building up metal; or high strength (Wise, 1964, p. 227-249; Rapson and Groenewald, 1978, p. 95-110).

Some of the high-temperature (850-1,400° C) brazing alloys used in the manufacture of aircraft turbine engines, dental appliances, electronics devices, and jewelry are gold-based alloys. Most of them are binary or ternary alloys of gold with copper, nickel, silver, or palladium. They are distinguished from the karat gold solders used in jewelry manufacture, which often have more complex compositions and are used in the 600 to 800° C range.

In addition to bullion, gold and its alloys are available in many standard metallic forms, such as bars, foil, granules, powder, rods, sheets, shot, and wire. The karat golds are often supplied as granules.

Although numerous gold compounds have been prepared and described, very few have practical use in industry or the arts. Most are unstable in solution because gold is very easily reduced and precipitated. Two chlorides, $AuCl$ and $AuCl_3$, as well as an acid, $HAuCl_4$, are used in the electrolytic refining of gold. “Liquid golds” are used extensively in the decoration of china and glassware and many other items. They are solutions of organogold compounds in organic solvents or emulsions of particulate gold in organic liquids. Liquid golds are formulated as inks or paints, applied by printing or painting, and then dried and fired, thus leaving coherent metallic gold films bonded to the substrate. Films deposited from the suspensions are generally much thicker than those derived from decomposition of organogold compounds.

Commercial Grades, Shapes, and Specifications

Most gold is marketed as refined gold “bullion” in purity that ranges from 995 to 999 fine. Gold of 995 to 998 fineness is produced by a chlorination process, and that of higher fineness, by an electrolytic process. The internationally traded standard bar of 12.44 kg (400 ounces) typically conforms to the specifications of the London Bullion Market Association for “good delivery bars.” It must have a purity of 995 fine minimum (typically ranging between 995 and 998 fine), carry a serial number, be of good appearance and regular shape, and bear the stamp of one of the four dozen or more refiners worldwide that are on the Association’s list of approved “melters.” Individual good delivery bars may range in weight from 350 to 430 ounces (10,886 to 13,374 g). This is the form of gold to which all widely quoted gold prices refer. The other principal bars traded on world markets are smaller, may be of higher purity, and range from 995 to 999.9 fine. The kilo bar is favored in Europe, the Middle East, and Southeast Asia; 5- and 10-tael bars are traded on Chinese markets; and 5- and (mostly) 10-tola bars are traded in India and to some extent in the Middle East. In addition to these bars, the baht and others of 10-, 50-, 100-, 250-, and 500-g weights are also available. Further, gold is available in polished wafers of 999.9 fineness in weights of 1, 2, and 5 ounces and 5, 10, 20, 50, and 100 g.

With regard to the karat golds, no universally accepted compositional standards have been adopted, but individual refiners and alloy makers make data available for their own products.

Dental golds conform to standards published by such industry organizations as the American Dental Association (ADM), the Fédération Dentaire Internationale, and the International Standards Organisation. Specification No. 5 of the ADM covers four types of dental gold casting alloys used for restorations and sets parameters for composition, elongation, fusion temperature, hardness, and tensile strength. Its Specification No. 7 covers wrought gold wires and sets parameters for composition, elongation, fusion temperature, tensile strength, and yield strength.

The gold used in electronics devices is electroplated onto components, bonded to a base metal to form a clad composite, or used as gold bonding wire. The electroplate and the clad plate are almost invariably alloyed with small amounts of hardener metals. Bonding wire ranges in purity from about 99.975 percent gold to 99.999 percent gold and is doped with minute amounts of beryllium to lend strength for drawing to extremely small diameters.

Most of the gold leaf used is general purpose leaf, which is about 0.1 µm in thickness, and 22 or 23 karat; the alloying metals are silver and copper. Pure gold leaf is susceptible to cold welding if accidentally folded or wrinkled, so the use of pure gold is usually restricted to foil, a thicker form, such as is used in dentistry. Leaf that is less than 22 karat can be made for use in selected environments. These latter kinds of leaf exhibit a wide range of colors, which are determined by the amounts and relative proportions of silver and copper in the alloy. Most beaten gold leaf is 0.07 to 0.1 µm thick and marketed in the United States as 3-3/8-inch squares that are interleaved with rouged tissue paper in books of 25 squares, 20 books to a pack. Electroplated leaf or leaf that is formed by sputtering or vacuum deposition onto a polymer film substrate can be made thinner than beaten leaf.

The term "liquid gold" is applied to suspensions of gold powder in organic vehicles and to solutions of organogold compounds in organic solvents. They are used as inks or paints, which are applied by any of several techniques to the articles to be decorated, dried, and then fired to volatilize the organics. This leaves very thin (on the order of 0.001µm) coherent gold films bonded to the substrate.

Many different baths (electrolytes) are available for the electroplating of gold, most of which are based on complexes of monovalent gold. The bath compositions are tailored to yield a gold plate that has the metallurgical properties and the surface finish desired and may contain, in addition to the principal plating salt, small additions of several compounds that act as brighteners, hardeners, scavengers, etc. The most commonly used plating salt is gold potassium cyanide, which is used in a wide range of processes. The other principal plating salt is sodium (or potassium) gold sulfite, which is often used for high-speed plating. Plating salts or solutions are available from several domestic firms, some of which recycle the spent solutions and credit recovered gold to the purchaser for use in a new batch.

Sources

Primary

Crustal Abundance

Although widely distributed through the Earth's crust and global waters, gold is a relatively scarce element. Its average crustal concentration is 0.004 g/t, or 4 parts per billion (ppb) (Lide, 1999, p. 14-14). It has been inferred from analogy with the composition of iron and stony iron meteorites that the Earth's core contains on average 150 to 300 times more gold than does the crust and that the crust is comparable in gold content to stony meteorites.

The average gold content of soils is about the same as the crustal abundance. The concentration in sedimentary rock tends to be above the crustal average, especially in sandstones. Among igneous rocks, the gold content in mafic rocks tends to be slightly higher than in felsic rocks. McHugh (1988) determined that the background concentration of gold in natural waters ranges from less than 0.001 to 0.005 ppb; natural waters from mineralized areas "probably" range from 0.010 to 2.8 ppb. The difficulty of measuring such minute quantities is formidable, but the accuracy achievable has increased as analytical methods have evolved. In two studies of gold in seawater, Koide and others (1988) and Falkner and Edmond (1990) found that some of the studies conducted earlier in this century had overstated the concentration of gold by between two and three orders of magnitude. The average gold concentration in Atlantic and Pacific seawaters was put by Falkner and Edmond at 0.00001 ppb and Koide and others (Pacific only) at 0.00003 ppb; this is good agreement if the level of accuracy of the methods is considered. Concentrations in Mediterranean deep waters, which are fed by rivers and collect wind-borne dust, ranged from 0.00002 to 0.00003 ppb, and gold in water around hydrothermal vents ranged from 0.002 ppb to more than 10 times that value (Falkner and Edmond, 1990). The concentration of gold in deposits that are economically mineable at today's gold price is typically between two and three orders of magnitude greater than the crustal average. The average recoverable gold content of U.S. gold ores mined in 1998 from all types of deposits and mines was about 1.5 g/t, or 1.5 ppm. The average mill head ore grade would have been somewhat higher—at least 1.8 g/t, or 450 times greater than the crustal average. The concentration in ore deposits ranges from about 0.2 g/t, which is perhaps the lowest content that can be economically extracted by cyanide leaching when combined with higher grades, to as much as 30 g/t in some of the richest South African mines and to several hundred grams per ton in some parts of those few deposits called bonanzas (Simons and Prinz, 1973, p. 268; Green, 1993, p. 82; Rota, 1997, p 7).

Geochemistry

The geochemical properties of gold are important determinants of the forms in which it is found in ore deposits and the formation of the deposits themselves. The electronic configuration of its atom has endowed gold with a very strong resistance to oxidation that makes it the most noble of metals. Another consequence of the electronic configuration is weak bonding, which is predominately covalent in character, with most anionic elements. "Gold salts are characterized by their easy decomposition, resulting in the release of metallic gold. Because of this fact, free ions can exist in aqueous solutions only in minute, often indeterminable amounts. On the other hand, gold complexes, such as gold cyanides, are exceptionally stable in aqueous solutions. As the entire industry of recovering gold from its deposits is based on stable complexes of the element, it would seem that the geochemical migration of gold in nature depends similarly on the formation of complex salts . . ." (Fersman, 1939, p. 105). Gold has been shown to have six oxidation states—+1, +2, +3, +4, +5, and +7. Of these, only the +1 (aurous) and +3 (auric) states are common; the others are rarely observed. Although the complex compounds of trivalent gold are markedly more stable than those of univalent gold, ore-forming fluids tend to have low oxidation potentials; therefore, +1 is the preponderant gold oxidation state in them, and gold is transported mainly in complexes of the type $[Au(HS)_2]$- and $[AuCl_2]$-, along with several other complexes of lesser quantitative importance (Seward, 1991).

Mineralogy

Gold occurs principally as flakes, scales, or crystals of native metal, in which it is typically alloyed with silver and other metals. More than 90 percent of native gold is alloyed with silver, copper, and iron, in the usual order of importance, and lesser fractions with more than two dozen other metals. Gold forms a complete range of solid solutions with silver, copper, nickel, platinum, and palladium. Electrum, which is an important naturally occurring alloy, contains from 18 percent to 36 percent by weight of silver. Gold forms relatively few minerals, however; Jones and Fleischer (1969, p. 2-3) identified 14 of them, and Boyle (1987, p. 12) cited 2 (table 4). In 8 of the 16 minerals in table 4, gold is combined with tellurium. Small amounts gold substitute for other metals in a few more minerals; these are sometime also listed as gold minerals. Aside from the native alloys, only aurostibite ($AuSb_2$), calaverite ($AuTe_2$), and sylvanite ($[Au, Ag]Te_2$) are important ores of gold; the other minerals are rare. Although gold is commonly associated in ores with the sulfide minerals of arsenic, copper, iron, silver, and other metals, it is occluded in them, usually as metal, and does not enter the crystal lattices except in the sulfotelluride nagyagite and perhaps the argentiferous gold sulfide uytenbogaardtite. Quartz and chalcedony are ubiquitous and intimately associated with gold in many different kinds of ores.

Table 4. Minerals formed by gold

[~, approximately; Ag, silver; Au, gold; Bi, bismuth; Cu, copper; Hg, mercury; Pb, lead; S, sulfur; Sb, antimony; Se, sellenium; Te, tellurium. Sources: Jones and Fleischer, 1969, p. 2-3; Boyle, 1987, p. 12]

Mineral	Composition	Common name	Chemical composition
Native gold	Gold alloyed with any of more than two dozen metals, most commonly with silver, copper, and iron	Sylvanite	$(Au, Ag)Te_2$; Au:Ag ~1:1
Aurian silver	Silver alloyed with 0-50% gold	Kostovite	$CuAuTe_4$
Gold-amalgam	Au_2Hg_3 (?)	Petzite	Ag_3AuTe_2
Maldonite	Au_2Bi	Hessite	Ag_2Te; up to 4.7% Au
Aurostibite	$AuSb_2$	Montbrayite	Au_2Te_3
Krennerite	$AuTe_2$ (orthorhombic)	Nagyagite	$Pb_5Au(Te,Sb)_4S_{5-8}$ (?)
Calaverite	$AuTe_2$ (monoclinic)	Aurobismuthinite	$(Bi,Au,Ag)_5S_6$ (?)
Fischesserite	Ag_3AuSe_2	Uytenbogaardtite	Ag_3AuS_2

The relative commercial importance of the gold associated with various types of domestic source ores is shown in table 5. In 1999, about 94 percent of mined gold was extracted from precious-metal ores and 6 percent from base-metal ores.

Table 5. U.S. gold byproduct/coproduct relations in 1999
[In metric tons. Do, ditto]

Source ores	Byproduct or coproduct	Quantity	Total byproduct/ coproduct output (percentage)
Gold ore	Silver	172.9	8.9
Do.	Copper	29.2	1.8
Do.	Zinc		(1)
Do.	Lead		(1)
Do.	Mercury		(1)
Do.	Iron	[2]2,853.0	(1)
Do.	Gold	324.1	93.3
Gold-silver ore	Silver		13.4
Do.	Copper		(1)
Do.	Zinc		(1)
Do.	Lead		(1)
Do.	Gold	3.9	1.1
Silver ore	do.	2.2	0.6
Copper ore	do.	12.4	3.6
Zinc ore	do.	4.7	1.3
Lead ore	do.		(1)

[1]Less that 0.05%. [2]From placer gold.

Gold Deposits

As is the case with other metals, only a minuscule part of the gold (about 0.0002 percent) in the Earth's crust has been sufficiently concentrated in mineral deposits to be economically recoverable (Craig and Rimstidt, 1998, p. 460). Mineral deposits are uncommon geological features, and the largest of them are rare, but these few large deposits have accounted for most of the gold discovered to date (Singer, 1995, p. 88; Long, DeYoung, and Ludington, 2000, p. 629; Sillitoe, 2000, p. 1). The largest 1 percent of world gold deposits, each of which contains 1,200 t or more of gold, which Singer (1995, p. 102) termed "supergiant deposits," had accounted for 57 percent of the gold discovered by the mid-1990s; some of the gold had been mined, and the rest remained in the deposits as a resource. The largest 10 percent of deposits, which Singer termed "giant" or "world-class" deposits, each contains 100 t of gold or more and accounts for 86 percent of the gold; this total includes the gold in supergiants. The largest 50 percent of deposits, each of which contains 6 t or more of gold, accounts for 99 percent of the gold found to date. The total content of gold in deposits is a function of the tonnage of mineralized rock and the grade. As these two factors tend to correlate positively, larger amounts of gold are found in the higher grade deposits; about three-fourths of the gold that has been discovered is contained in the richest 50 percent of deposits. Moreover, more than three-fourths of the gold found to date has been found in just eight countries—South Africa (42 percent), the United States (10 percent), Australia (5 percent), Canada (5 percent), Russia (4 percent), Uzbekistan (4 percent), Brazil (4 percent), and Indonesia (2 percent). More than two-thirds of the gold has been found in just four types of deposits—quartz-pebble conglomerate (42 percent), which is the source of virtually all South Africa's gold; placer (11 percent); porphyry copper (8 percent); and Homestake (archean lode/iron-formation-hosted) (7 percent) (Singer, 1995, p. 90). These habits of occurrence suggest that only the larger deposits influence gold supply significantly and that the quantity of gold contained in the below-median-sized deposits is small and relatively inconsequential. Because the largest deposits can be the most profitable to mine, they are the most likely to be developed partly because of economies of scale and partly because of the above-average grade of the ore contained in them.

Economic gold deposits have been found associated with nearly all varieties of common rocks. As the science of mineral deposits has evolved, the deposits themselves have been classified in various ways, some emphasizing genesis and others emphasizing characteristic combinations of chemical and mineralogical compositions, geochemical and geologic environments, host-rock associations, and morphology. In the past two decades, much work has gone into compiling mineral deposit models, each of which comprises "the systematically arranged information describing the essential attributes (properties) of a class of mineral deposits" (Cox and Singer, 1986, p. 2). Such models are works in progress, modified or supplemented by new models as knowledge and understanding of the deposits grows. Collections of models and further explication of them may be found in Cox and Singer (1986, p. 110-114; 123-124; 143-161; 175-177; 199-200; 239-251; 261-269) and Bliss (1992, p. 63); U.S. gold deposits are summarized in Ashley (1991).

A distinction is commonly made between lode deposits, which are primary bedrock deposits still in place, and placer deposits, which are secondary deposits of gold derived from lode deposits by the geologic processes of weathering and erosion followed by transportation and gravitational concentration by water or wind. Lode gold deposits come in a great variety of sizes and shapes. They form tabular cross-cutting vein deposits but also take the forms of breccia zones, irregular replacement bodies, pipes, stockworks, and other shapes.

Placer deposits exist because of the superior chemical stability, structural strength, and high specific gravity of the few minerals that are characteristically found in placers—native gold, native platinum, cassiterite, monazite, zircon, rutile, magnetite, and several others. Freed from their host rocks by weathering, these minerals are able to survive mechanical degradation and chemical decomposition as they are carried downslope to streams or beaches where the action of currents and waves winnows less dense minerals from them and leaves them concentrated and mixed with sand and gravel in places where the water action is relatively subdued. Lodes and placers differ completely in genesis, geochemical and geologic conditions of formation, and characteristic mineral associations.

More than 90 percent of gold being mined in the United States at the end of the 20th century came from precious-metal ores. Of the gold discovered in the United States through 1994, three-fourths had been found in six types of precious-metal deposits and one type of byproduct deposit (table 6). Of the U.S. gold resources that remain in the ground, more than 93 percent is in precious metal-deposits (table 7).

Table 6. Gold discovered through 1994 in the United States, by deposit type

[In metric tons. Data from Singer, 1995, p. 90. Data are rounded to three significant digits]

Deposit type	Quantity
Placer	3,330
Homestake (Archean lode/iron formation hosted)	1,280
Low-sulfide quartz gold veins	2,130
Comstock epithermal veins	1,330
Sediment hosted (Carlin)	3,080
Epithermal quartz alunite	1,400
Porphyry copper	2,100
Other types	4,990
Total	19,600

Table 7. Remaining U.S. resources of gold, by deposit type

[Source: Long, DeYoung, and Ludington, 2000, p. 640]

Deposit type	Quantity (percentage)
Sediment hosted gold (Carlin)	27
Placer gold	20
Epithermal vein[1]	18
Porphyry copper	7
Low-sulfide quartz gold vein	5
Skarn	4
Other	19
Total	100

[1] Includes the Comstock, Creede, hot-springs, quartz alunite, and Sado deposit models.

In addition to the gold found in precious-metal deposits, gold is commonly found in or associated with base-metal ores and is recovered during smelting or refining of the base metals (table 5). The vast tonnages of base metals mined, especially from porphyry copper ores, make these deposits important sources of gold. In the 1990s, for example, the Bingham Canyon copper mine in Utah, which was the third largest individual producer of gold in the United States, yielded nearly 19 t/yr. Bingham Canyon, which is unusually rich in precious metals, accounted for about two-thirds of U.S. byproduct gold output during those years. Base-metal ores accounted for 30 percent to 40 percent of U.S. mined gold for more than three decades following World War II, but with the great increase in production from Carlin-type gold deposits, base-metal ores accounted for only 4 to 7 percent U.S. gold production during the 1990s (fig. 6). Of this, more than 85 percent came from copper deposits, and the remainder, from lead, zinc, and complex base-metal ores. Worldwide, byproduct gold accounts for probably 5 percent to 15 percent of total gold mined and is likely to remain an important source of gold in the foreseeable future.

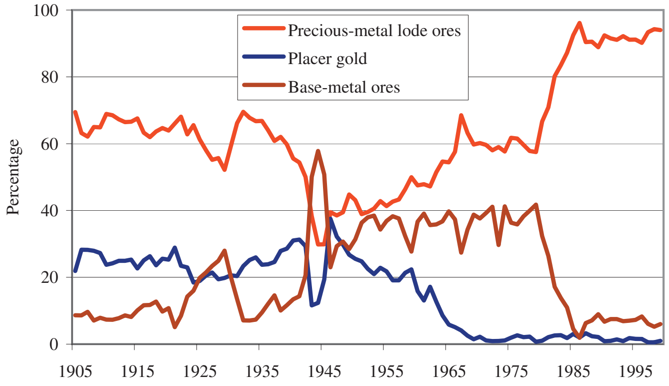

Figure 6. Gold mined in the United States, by type of ore. Data from U.S. Geological Survey, 1879-1923; and U.S. Bureau of Mines, 1924-1931, 1932-1995.

Reserves, Reserve Base, and Resources

Reserves and reserve base for several of the leading gold-producing countries are shown in table 8. These are regional estimates and necessarily imprecise because they are gathered from a variety of sources and include figures taken from diverse resource classification schemes that are only partially compatible. Nonetheless, they are useful in showing the geographic distribution of world gold. (Definitions of reserves, reserve base, and resources can be found in the Appendix.)

Table 8. Gold reserves and reserve base as of yearend 2001
[In metric tons. World totals are rounded to no more than three significant digits. Source: Amey, 2002a]

Country	Reserves	Reserve base
United States	5,600	6,000
Australia	5,000	6,000
Canada	1,500	3,500
China	1,000	4,300
Indonesia	1,800	2,800
Peru	200	650
Russia	3,000	3,500
South Africa	19,000	36,000
Others	13,000	16,000
World total	50,000	78,000

NA Not available.

Identified world resources of gold in the ground are estimated to total about 100,000 t, of which perhaps 15 percent to 20 percent is in base-metal deposits from which gold is extracted as a byproduct of base-metal mining. South Africa has about one-half of world resources, and the United States, about 12 percent. Incidentally, the gold dissolved in seawater is not an economic resource because it amounts to only 14,000 t of gold in 1.35×10^{21} liters of global seawater, or about $100 in gold per billion metric tons of seawater (Falkner and Edmond, 1990, p. 219). At 2001 rates of mine production, the world reserves listed in table 8 could be used up in about 18 years; the reserve base, in 35 years; and all identified resources, assuming they could be produced economically, in 39 years. Such a complete exhaustion of the presently identified resources will not, however, happen. Reserves tend to be replaced as they are mined, and exploration is likely to discover new deposits, some of which will be economically mineable. Regional resource estimates are built ultimately from measurements and ore analyses made by mining companies at individual deposits. In some mines, especially those operating at deep levels in vein or reef deposits, blocking out more ore than is needed for operations in the few years immediately ahead is not cost effective; they may operate for decades without ever having more than a few years' reserves blocked out at any one time. Identified world gold resources or those of individual countries may, of course, decrease or increase from time to time depending on the market demand and price for gold and the success or lack of success in locating replacement resources. Because mineral resources ultimately are finite, a time will come—probably far in the future—when gold resources are exhausted.

Secondary

Secondary gold, which is gold that is recovered from scrap, is a significant part of the total gold supply. Gold recovered from process scrap, termed "new scrap" or "manufacturing scrap," is commonly recovered and remelted in the manufacturing plants in which it is generated. This is especially true of the high-grade scrap from the manufacture of jewelry or dental appliances where the scrap from specific alloys can be segregated and remelted separately. In the instance of products like electronic circuitry, the new scrap, which is usually low grade because of its combination with nongold materials, may be accumulated and then shipped periodically to an off-site refinery for recovery of the gold. The scrap that is remelted by the manufacturer is termed "home scrap"; the scrap that is shipped to a secondary refiner is termed "purchased scrap" (irrespective of whether the refiner actually purchases it or instead refines it on toll for its owner). Purchased scrap may consist of new scrap and old, or postconsumer, scrap.

Data on home scrap are usually not available, and no serious effort is made to collect them. Data on purchased scrap are collected in some countries, such as the United States, and are useful in determining the total volume of scrap. They are of almost no help, however, in identifying the industries or products of origin, in quantifying the separate flows, or in providing a reliable breakdown between new and old scrap. The reason for this is that scrap is often purchased from a dealer as mixed scrap that was derived from unidentified products and manufacturers and in unknown proportions. The lots of scrap are sampled and assayed to the satisfaction of the refiner and the dealer, and the refining process is modified in accordance with the results of the assay. Neither the dealer nor the refiner has much incentive to keep accurate records about the origins of the scrap except to assure themselves of the absence of chemical or radiological hazards.

In its annual "Gold Survey," Gold Fields Minerals Services Ltd. provides an estimate of the quantity of gold recovered from old scrap, most of it derived from jewelry. It excludes process (new) scrap to the extent possible. Gold Fields' scrap estimates are used in this publication except in the U.S. statistics shown in table 17 and figure 26. In 6 of the 8 years from 1994 through 2001, the world estimate ranged between 605 and 642 t; the exceptions were 1998, when the Southeast Asian economic crisis and the resulting distress sales of jewelry boosted the total to 1,089 t, and 2001, when the total was 706 t. Except in 1998, old scrap has constituted between about 14 percent and 19 percent of the world's annual gold supply in the 1990s. U.S. Bureau of Mines data for the United States in the1975-to-1988 period, which was before the data became too unreliable to use, showed average recovery of 50 t/yr from old scrap and 48 t/yr from new scrap. During that same period, old scrap accounted for, on average, about 15 percent of total annual U.S. supply. The comparable average for total scrap was about 29 percent. U.S. Geological Survey figures for 1996 through 2001 show that total scrap has in recent years provided only about 11 percent to 17 percent of the total annual supply even as the quantities of secondary gold recovered from scrap have risen to as much as 163 t/yr (Amey, 2002b). This is attributable to the doubling of the domestic gold supply between 1990 and 1998 when mine production, bullion imports, and sales of foreign-owned gold to the market all increased rapidly. Gold recycling flows in 1998 are shown in figure 7.

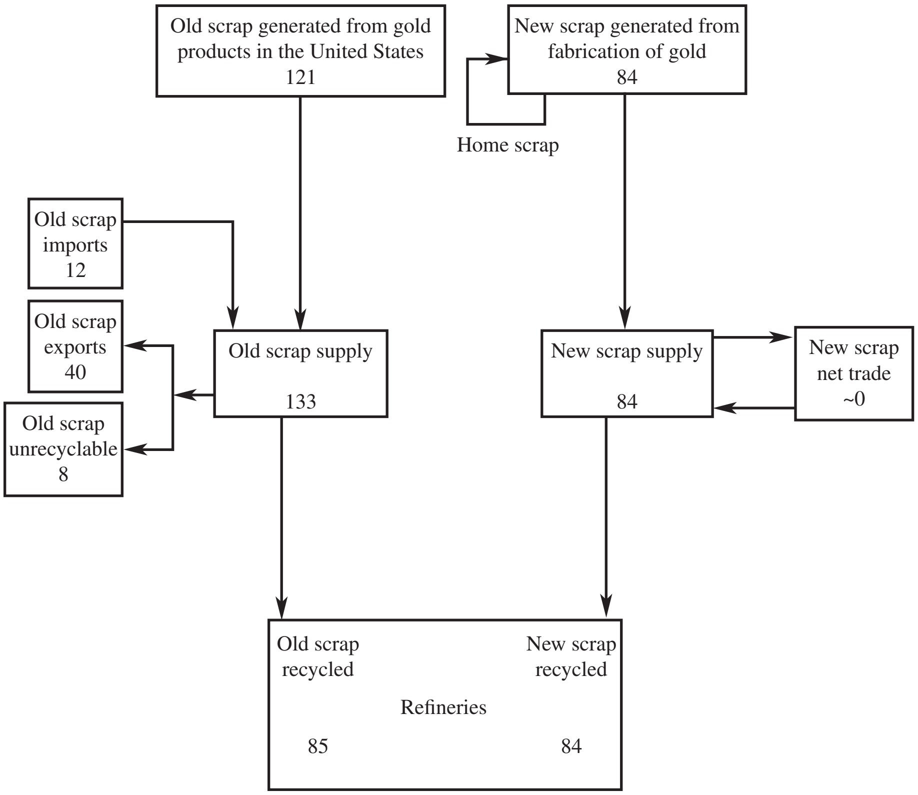

Figure 7. Recycling flow of gold in the United States in 1998. Quantities are in metric tons of contained gold. Modified from Amey, 2000b, fig. 1.

Other Sources

This section has focused on the sources of mined gold and of gold recovered from scrap. The large stocks of refined gold held by industry, banks, and investors, however, constitute an important part of actual and potential world gold supply. Along with gold-containing products, they are part of what is sometimes referred to as "above-ground reserves." They are discussed in the section "Supply, demand, and sustainability."

Production Technologies

Exploration

Typically, the multiyear project that leads to the discovery and exploitation of a new gold deposit begins with the selection of a target area or areas. This is followed by reconnaissance exploration in which satellite remote-sensing, airborne surveys, field reconnaissance, geologic mapping, and geophysical and geochemical surveys are used. In turn, this is followed by more-detailed mapping, geophysical and geochemical prospecting, selected drilling, trenching, and assaying. Further exploration consists of detailed drilling, assaying, and mineralogical analysis of the ore. At this point, most of the exploration has been completed, and the project will pass to the feasibility study stage, in which the commercial practicability of the venture will be assessed.

Gold deposits are sought with the half dozen or so geophysical methods commonly used to locate hardrock metalliferous deposits; in some circumstances, other methods may also be used. Commonly more than one method is used to resolve ambiguous search results and to delineate the ore body more closely. In using these methods, the geologist is looking for local anomalies (disturbances) in one or more physical properties of the crustal rocks; the anomalies are caused by the presence of an ore body (table 9).

Geochemical exploration methods seek anomalous concentrations of certain elements (pathfinders) that are typically associated with the metal sought. Pathfinder elements typically associated with gold in one or another type of ore deposits are antimony, arsenic, copper, mercury, selenium, sulfur, tellurium, and tungsten (Kearey and Brooks, 1991, p. 139).

Table 9. Geophysical exploration methods commonly used for locating gold lode deposits
[Do, ditto. Source: Kearey and Brooks, 1991, p. 2-3]

Class of method	Anomalous value detected
Electrical:	
Induced polarization	Electrical capacitance
Resistivity	Electrical conductivity
Self-potential	Do.
Magnetic	Magnetic susceptibility and remanence using the Earth's magnetic field
Electromagnetic	Electrical conductivity and inductance

Applications of exploration methods to selected kinds of gold deposits are discussed in Foster (1991).

Mine Development

In general, low-grade gold ores are mined from open pits by bulk mining, a method in which large quantities of ore are mined with no or a minimal attempt to segregate and process a high-grade fraction separately. The deposit is delineated and characterized by drilling a large part of it early in the development process, before mining begins, so that the mining company can be reasonably assured of the presence of enough accessible ore of satisfactory quality to sustain operations during the planned life of the mine. Later, drilling to characterize the ore in more detail accompanies mining. This sequence is in contrast to the development of the higher grade but more elusive ores typically mined by selective underground methods. For these more-elusive ores, exploratory drilling from the surface is used to block out a reserve of sufficient size to justify proceeding with mine development and mining. Once the underground workings are established, the narrow and often discontinuous veins are explored by drilling from working faces and test tunnels as mining progresses. Thus, the working reserve of an underground mine is typically of modest size and is more or less continually undergoing developmental exploration during the life of the mine. In this way, an underground mine can operate for decades without ever having established more than a few years' reserve at any point in its lifetime.

Mining

Gold mines are broadly categorized as either placer or lode. Placer mines are established to recover gold from alluvial sand and gravel in which particulate native gold has been segregated and concentrated by gravity acting in concert with hydrodynamic forces. They may be designed to extract gold from beach deposits, streambed deposits, or above-water deposits, such as are found in stranded terraces that stretch along valley walls. The term "lode mine" is applied to all nonplacer mines. "Lode" is an old miner's term, a corruption of "lead," as that term was used in vein gold mining. Veins typically change direction frequently, and the underground miner, who cannot afford to excavate any more barren rock than is absolutely necessary to free the ore, always strives to follow the "lead," or vein, as mining progresses.

The technology of gold mining has evolved over the centuries. Placer mining was once the most important method of mining gold but has been relegated in this century to a minor role except in a few places in the world, such as Alaska, Colombia, and Siberia. Most of the gold mined in the world in the 20th century has come from either deep narrow veins or thin-bedded layers called reefs. The deeper mines in these deposits have been difficult and dangerous places in which to work because at the great depth of the workings, temperature is very high, as is lithostatic pressure, which can cause dangerous rock bursts. They have been expensive to mine as well because of the cost to support the open deep workings against tremendous lithostatic pressure after removal of the ore, to refrigerate the incoming air to keep working conditions tolerable, and to transport ore and pump water over great vertical distances. With the development in the 1960s of methods of recovering gold economically from low-grade bulk-mineable ores and the ensuing discovery of numerous deposits of such ores, the importance of the underground mine, outside of South Africa and a few other countries, has waned.

Placer Mining

The old-time placer miner removed the gold-bearing gravel with a shovel and recovered the gold flakes by washing the gravel in a sluice box. A recreational gold hunter in 2000 is more likely to use a small portable floating suction dredge to bring the gravel to the surface. The miner's gold pan was and still is used in the search for concentrations of gold in the gravel ("pay streaks") rather than for the commercial-scale recovery of gold. In commercial placer mining today, the gold-bearing gravels are excavated by using, in various combinations, backhoes, bulldozers, clamshell excavators, dragline excavators, front-end loaders, bucketline dredges, suction-cutter dredges, and high-pressure water nozzles (called hydraulic giants or monitors). Bulldozers, front-end loaders, and monitors are restricted to above-water placers. Dredges can also be used on above-water placers, which is where gold dredges usually operate. A cavity large enough to hold the dredge is dug into the placer gravels, and the dredge is assembled in the cavity, which is then filled with water to float the dredge. As the dredge slowly digs its way forward, it separates gold from gravel in an onboard recovery plant and disposes of the barren gravel rearward. In this way, pond and dredge progress together through the placer deposit. Suction-cutter dredges are confined to use in fine sediments or loose relatively unconsolidated gravels; they are especially useful for the removal of overburden. Their hull-mounted suction pumps have a maximum lift of about 5 m, although offshore tin-mining dredges in Southeast Asia go much deeper with the aid of pumps mounted along the suction ladder. Bucketline dredges, however, successfully excavate consolidated gravels, and modern ones can dig as deep as 45 m. These huge machines are costly to transport, assemble, and maintain and, consequently, can be justified for use only in deposits of several tens of millions of cubic meters of gravel. Only one bucketline dredge was producing gold in the United States (in California) in 2000, but three were producing gold in Colombia (working together with three suction dredges), several more in operate in Russia, and perhaps a few others are operating elsewhere in the world (Mining Magazine, 2000b).

High-pressure jets of water can be used to disintegrate and fluidize thick beds of gravel and sand and wash the slurry toward a sump. They were used by the Romans in their Spanish gold-silver mines in hilly or mountainous terrain where plentiful water could be diverted to produce hydraulic pressures (heads) that at a minimum were equivalent to that exerted by a vertical 30-m column of water. Today, pumps are used to provide a hydraulic head of at least 60 m, and the water is directed at the gravel bank through large metal nozzles (Yannopoulos, 1991, p. 32-38).

In the United States and many other countries today, placer mines are closely regulated to prevent damage to downstream and shoreline environments. The use of mercury to help trap gold in sluices by amalgamation is no longer practiced in most places. Settling ponds must be established at the mine site to trap fine sediment, and the effluent from the ponds must meet local or national water-quality standards. In Alaska, where nearly all the commercial U.S. placer mines are located, about 100 companies and individuals submitted applications to the State for placer mining in 1999, but low prices may have discouraged some companies from operating. The State reported production of 2,184 kg from 58 placer mines, which accounted for nearly 14 percent of Alaska's gold production. The average per-mine output for this group of mines was just under 38 kg, which was worth $339,000 at the average 1999 price (Swainbank and others, 2000, p. 18-23).

Lode Mining

Lode mines are either surface mines, which are also known as open pit or open cast mines, or underground mines or a combination of the two. The rising importance of surface mines in the past three to four decades is attributable primarily to increases in the efficiency of computer-controlled open pit operations that involve very large scale equipment and the development of cyanide vat- and heap-leaching methods that have made it economical to process low-grade ores. Worldwide, most newly mined gold comes from roughly 375 to 425 lode mines. In the United States, where placer gold mining is of minor importance, more than 99 percent of domestic gold mine production in 2001 came from 53 operating lode mines, of which 45 produced gold as a principal product and 8 produced gold as a byproduct of base-metal mining. Byproduct production amounts to about 6 percent of total domestic gold production. Nearly all the large domestic gold mines are producing from low-grade deposits. To be profitable, they must mine and process ore on a large scale. Underground mining is restricted to higher-grade ores. The ore at Homestake, for example, graded 5.9 g/t in 1999, whereas the average mill-head grade of U.S. gold ores was about 1.8 g/t. Worldwide, surface mines are more numerous than underground mines and yield more than one-half of the gold produced. Surface mines, however, dominate gold output worldwide much less than in the United States because nearly one-fifth of world gold mine production comes from very large underground mines in South Africa, which is the largest producer, and additional production comes from underground mines in several other countries where they predominate, such as Brazil, Canada, Mexico, and the Philippines (table 10).

Table 10. Gold lode mines and production in 1999
[In percantages. NA, not available. World data from Mining Magazine, 2000a; U.S. data from U.S. Geological Survey unpublished data]

	Surface	Underground	Surface/ underground
World:			
Lode gold mines	50	35	15
Gold produced	50–55	45–50	NA
United States:			
Lode gold mines	80	15	5
Gold produced	56	6	37

Surface Mines

Development of a surface mine begins with the removal of the overburden layer, a process that can require many months. Soil is stored separately to be used in revegetation of the site when mining has ceased. Then the subsoil part of the overburden is removed to expose the ore body, and excavation of a terraced pit is begun. In the mining phase, the perimeter wall of the pit is terraced, and as mining progresses, the pit is enlarged by the outward retreat of the benches (terraces) and the serial establishment of new benches at increasing depth. The benches are drilled on a grid for blasting, and the grade and other characteristics of the ore are determined from drill cuttings. If necessary, the benches are blasted selectively and in such a sequence as to maintain a stable pit wall slope, to obtain a blend of ores that will maintain the mill feed at an optimum fixed grade. Except in the case of very porous ore, the broken ore usually is crushed before it is milled or placed on a leach pad. The ore is transported to a cone or jaw crusher by 70- to 200-t trucks; from the crusher it is sent to either the leach pad or a battery of rod or ball mills for further reduction in particle size if vat or tank leaching is intended.

Underground Mines

In underground gold mines, ore is removed by the same hardrock mining methods used for the ores of other metals. The method or combination of methods used in a given mine is determined largely by the grade, depth, geometry, mineralogy, and mechanical properties of the ore body and the surrounding rock. Before mining can begin, the ore body or a discrete part of it (an ore block) must be developed; that is, a connected system of horizontal and vertical tunnels (adits, drifts, raises, winzes, manways, ore chutes), spiral ramps, shafts (for ventilation, ore hoisting, personnel transportation, power and communications cables) must be established. Ore removal, or stoping, consists of the excavation of chambers by drilling, blasting, and removal of the fragmented ore to the surface for processing. After excavation of ore or the development structures, the open chambers must be supported by either leaving some ore pillars in place or using timbers, roof bolts, or other support devices to prevent the collapse of the workings. Ground water must be pumped out of the workings, and, if the mine is deep, refrigerated air must be pumped through the workings. Because underground mining imposes limits on the size of the mechanical equipment that can be used and on work time (stopes must be cleared for blasting and fume abatement), labor productivity (in metric tons of ore per worker per unit time) may range from several times lower than for surface mining to as much as 50 times lower. Compared with surface-mined ore, however, the ore mined underground is of considerably higher grade and is much less diluted with waste rock, thus making productivity in terms of contained gold comparable with the productivity of surface mining.

Ore Control

In all mines, whether surface or underground, sampling of the ore body through exploratory drilling is a continuous activity. Samples are analyzed for grade and mineralogical and chemical characteristics that may affect processing; the aim is to blend ores from different parts of the mine to feed the mill with ore of uniform grade, milling characteristics, and mineral composition.

Ore Processing

Gold is extracted from its ores by various combinations of cyanidation, flotation, gravity separation, and smelting. Gravity concentration is especially useful in the separation of placer gold from the accompanying alluvial gravel and sand. Froth flotation is confined to sulfide ores. Cyanidation is applied at one stage or another to the recovery of nearly all gold extracted from precious metal ores. When gold is associated with sulfides in refractory ores, it may be concentrated by froth flotation, and when it is in copper ores, it travels with the base metal through concentration and smelting. Typically, about 40 percent of the gold in copper ores is lost in flotation concentrating, although this percentage varies greatly from mine to mine. The gold is eventually recovered with little further loss from anode slimes that accumulate in the electrolytic refining cells of the copper refinery.

Individual gold ore bodies are sufficiently different from each other that the mill (the plant in which crushing, grinding, and concentration take place) is usually designed to work efficiently with the ore of a specific ore body. The ore's unique set of chemical, mineralogical, and physical properties determines the choice of grinding, concentration, and gold recovery methods and the configuration of the mill. The onsite facilities at gold mines also include one or more small tilt furnaces in which the crude gold precipitate and/or the electrodeposit obtained from the gold cyanide solution is smelted to crude bullion, often doré, which is a gold-silver bullion of variable composition.

Placer Gold

Placer gold is recovered from its encompassing sand and gravel by any of several gravity concentration devices. The efficiency of gravity separation methods increases directly with the difference in specific gravities of the minerals to be separated, and with their particle size. Gold particles that are less than 0.2 millimeter (mm) in diameter are not recovered very efficiently by many of the concentrators, and fine (flour) gold, which is less than 0.1 mm in diameter, is often not recovered at all by gravity devices.

The sluice in various configurations has been used for centuries. In effect, this long, tilted, flat-bottomed trough with transverse ridges (riffles) fixed to its bottom simulates the natural flowing-water environment in which the particulate gold was originally deposited as a sediment. Gold-bearing sand and gravel are fed through a screen into flowing water at the top of the sluice; the gold is deposited in the loose bed of sand that is allowed to form on the bottom of the sluice between riffles. Periodically, the flow of water is stopped and the gold collected (Taggart,

p. 11-95-11-104). To help trap the gold, mercury is sometimes added to the riffles where it forms an amalgam with the gold. In some countries, including the United States, strict environmental regulation of mercury has nearly abolished its use in placer mining. Modern commercial placer mining is more likely to use several other gravity concentration devices in various combinations. These include jigs, shaking tables, cone separators, spiral separators, and cross-belt separators.

Lode Gold

The gold in lode ores is extracted by chemical solution (cyanidation), for which several processing schemes are available, as shown in figures 8 and 9.

Leaching Ores

If the ore is low grade, then it may not support the cost of multistep processing and, therefore, may be dump, heap, or vat leached. In dump or heap leaching, a pad, or base, that is impervious to the leach solution is prepared and contoured so that the gold-bearing cyanide solution drains towards one corner and then into a nearby holding pond called the pregnant solution pond (fig. 10). If it is sufficiently permeable and relatively free of clay minerals, then the run-of-mine ore, which has not been crushed or prepared in any way, is stacked on the pad to a predetermined height, and the top of the heap is leveled off. A weak solution of sodium or potassium cyanide is then sprinkled, trickled, or ponded on the top of the heap; it percolates slowly through the ore mass, collects on the pad, and drains to the pregnant solution pond. The same process, when used on very low grade ore or even gold-bearing overburden, is called dump leaching (U.S. Bureau of Mines, 1994, p. 6-10). Most ore, however, is less permeable and must be crushed before being heaped. If excessive fines or clay minerals are present after crushing, then they

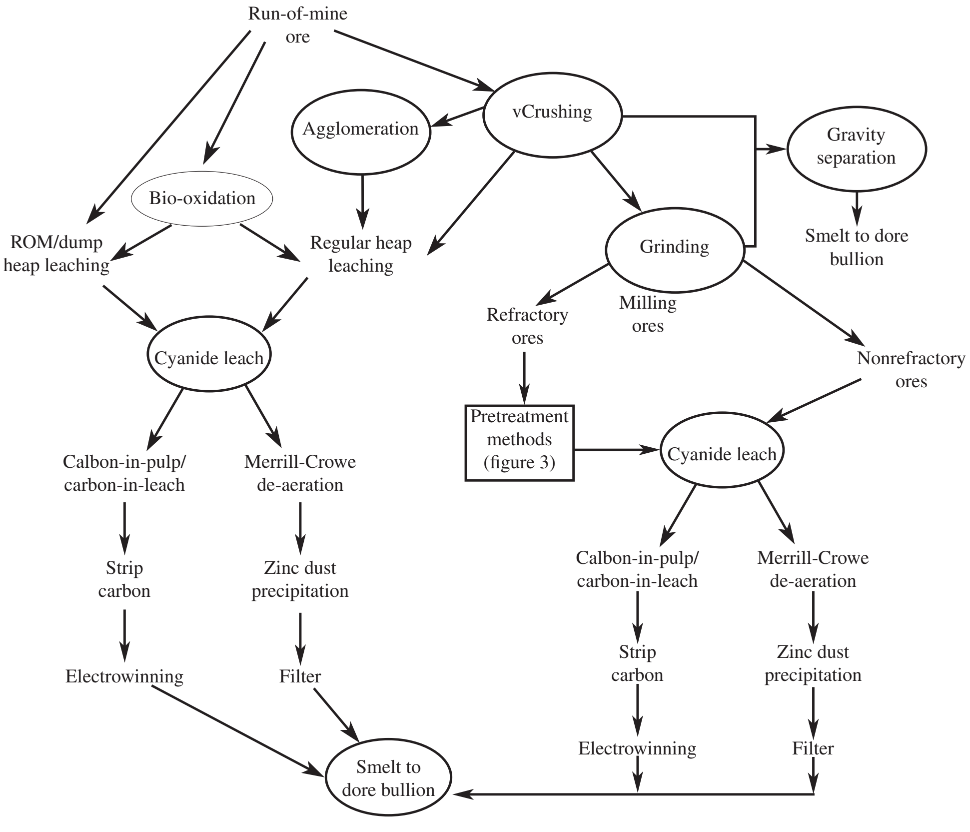

Figure 8. Processing technologies for gold ore. Source: U.S. Bureau of Mines, 1994, fig. 2.

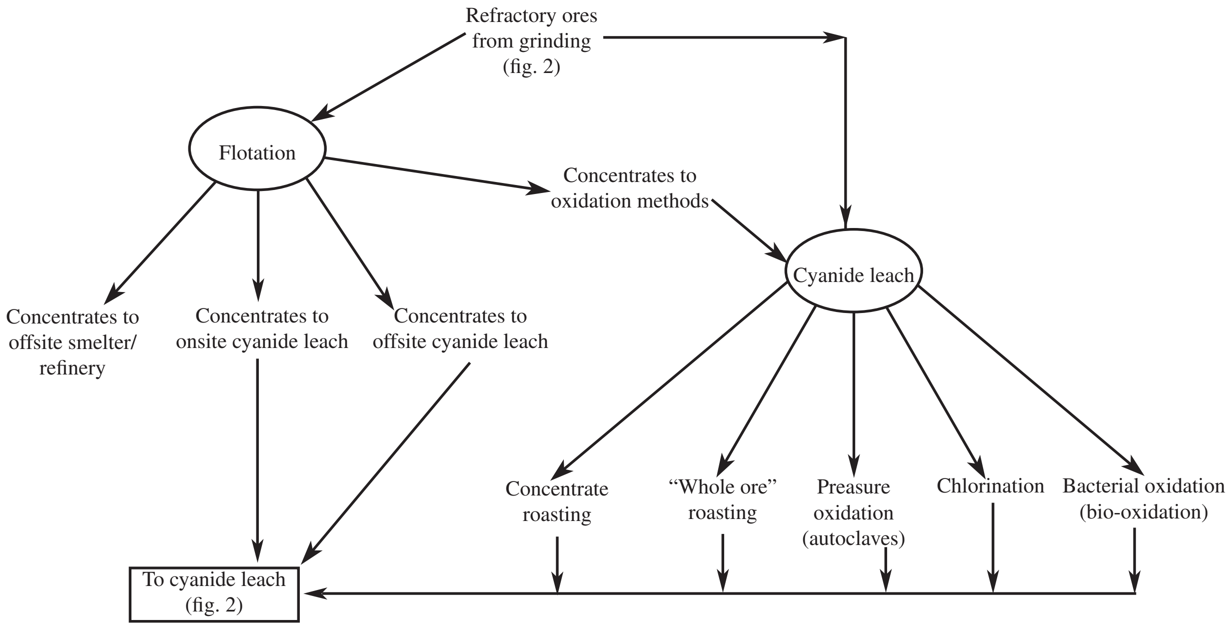

Figure 9. Pretreatment processes for sulfide ores. Source: U.S. Bureau of Mines, 1994, fig. 3.

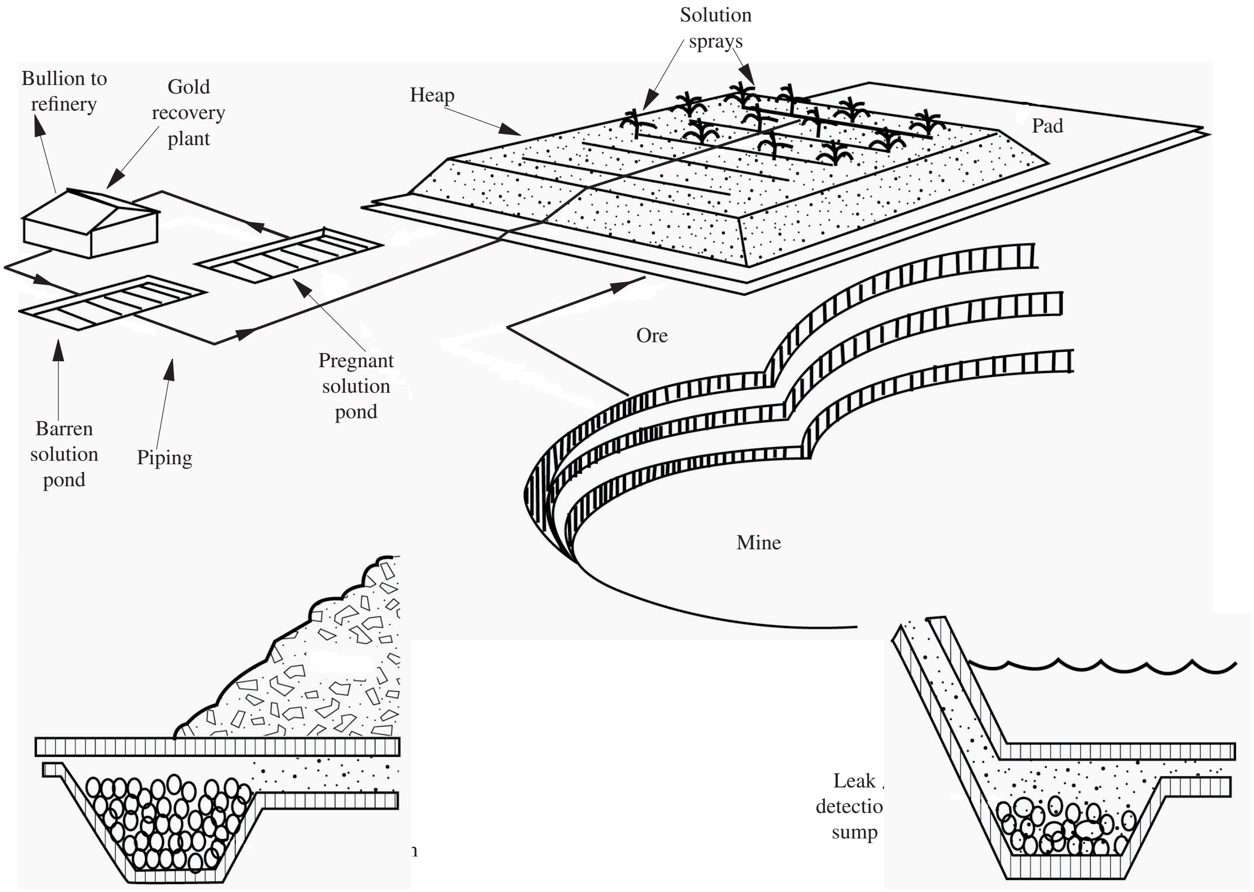

Figure 10. Process components of heap leaching. Liners are high-density polyethylene or polyvinyl chloride, 1 to 2.5 millimeters thick (60 to 100 mils). Source: Lucas, 1991, fig.1-2.

may block the uniform flow of solvent, which channels and leaves the interiors of large blocks of ore untouched by the solvent. To prevent this, the ore is tumbled with lime or portland cement and a small amount of water to agglomerate the fines; it is then cured for up to 2 days. Whether the ore is agglomerated or not, lime is added during crushing and stacking; its function is to keep the solution alkaline, which reduces the consumption of cyanide and safeguards the miners by preventing the formation of toxic gas from cyanide decomposition.

The duration of the leaching process depends on the characteristics of the ore and the economics of the operation but is usually measured in weeks or months. If the leach pad is not designed to be reusable, then the ore is left in place, and stripping of the gold can continue as long as the operation is economical. The ore heaps typically range in size from less than 50,000 to more than 300,000 t (Yannopoulos, 1991, p. 131); in 2001, the largest heap, which contains 1 billion metric tons of run-of-mine ore, was at the Yanacocha Mine in Peru.

For an ore to be suitable for heap leaching, the contained gold must be in very small or flaky particles; because the amount of solvent that reaches each particle is small, large particles may not dissolve completely. The host rock must be sufficiently permeable to allow the solution to reach the gold. The ore must also be relatively free of cyanide-consuming minerals, such as copper and iron minerals; carbonaceous matter, which precipitates gold from solution; acid-formers, which consume both cyanide and lime; and clay minerals or fines if the grade is low.

Low-grade ores in which the gold is associated with sulfide minerals must be oxidized before cyanide leaching. For ores intended for heap-leaching, one method is bio-oxidation. Sulfur-metabolizing bacteria are introduced into the heap and allowed to proliferate, thus oxidizing sulfides and freeing the gold. The heap is then neutralized with an aqueous solution of lime before cyanidation is begun (Yannopoulos, 1991, p. 105-107).

An alternative to heap leaching is vat leaching, in which 1,000 t or more of finely crushed ore is agglomerated with lime that has been wetted with cyanide solution, loaded into large vats and cured for several hours, and then flooded with cyanide solution. Several tanks are connected in a circuit with cyanide solution flowing from one to another in the direction of the vat holding the freshest ore. The solution percolates through the ore in each tank for a few days compared with a few months for heap leaching. For a given low-grade ore, vat leaching may or may not extract more gold than heap leaching but has advantages in localities that have freezing temperatures or high or low rainfall or are at high altitude.

Milling Ores

Although heap leaching or vat leaching are relatively low-cost processes and have contributed greatly to the rapid increase in U.S. and world gold production in the past two decades, they extract somewhat less of the contained gold than the cyanide-extraction methods used for higher grade ore. If the grade of the ore can support the cost, then better recovery of the gold—as high as 97 percent—can be obtained by milling the ore and then cyaniding it in mixing tanks. These "milling ores" are classified as "amenable ore" when cyanidation alone extracts at least 88 percent of the contained gold or "refractory ore" when cyanidation extracts less than 88 percent (Yannopoulos, 1991, p. 55). In either case, the milling (grinding) takes place in cylindrical tumbling mills. Grinding may be wet or dry but is almost always, especially at the end stage, in closed circuit, in which ore of the required size (the overflow) is separated from oversize in a classifier and removed from the circuit; the oversize particles (the underflow) are returned to the ball mill (fig. 11). After crushing and grinding, gravity separation is commonly used to remove the larger particles of gold from the pulp that is to be cyanided. Amalgamation with mercury may also be used, although this is not common in the United States.

When amenable (nonrefractory) ores are being ground, cyanide solution is often introduced into the ball mill, and one-third to two-thirds of the gold goes into solution during the grinding process. The ground-ore slurry is sent from the ball mill through a hydrocyclone classifier. The fraction of ore that is satisfactorily ground (the overflow) flows from the classifier to a thickener. From there, the adjusted slurry goes to a series of mixing tanks where it is agitated continuously in cyanide solution for 2 to 4 days. The pregnant solution with entrained solids is pumped from the last mixing tank to the first of a series of thickeners in which the solids are gradually separated from the liquid. The overflow from this thickener goes to a thickener that is dedicated to clarification of the gold cyanide solution. The underflow, which contains most of the solids, progresses through several thickeners connected in series and is washed by a counter-current flow of (initially barren) cyanide solution. The overflow (gold cyanide solution) from the line of thickeners is added to the clarifier, while the solids slurry, which has been washed free of gold-containing solution, is pumped to a tailings disposal area (Yannopoulos, 1991, p. 55-77).

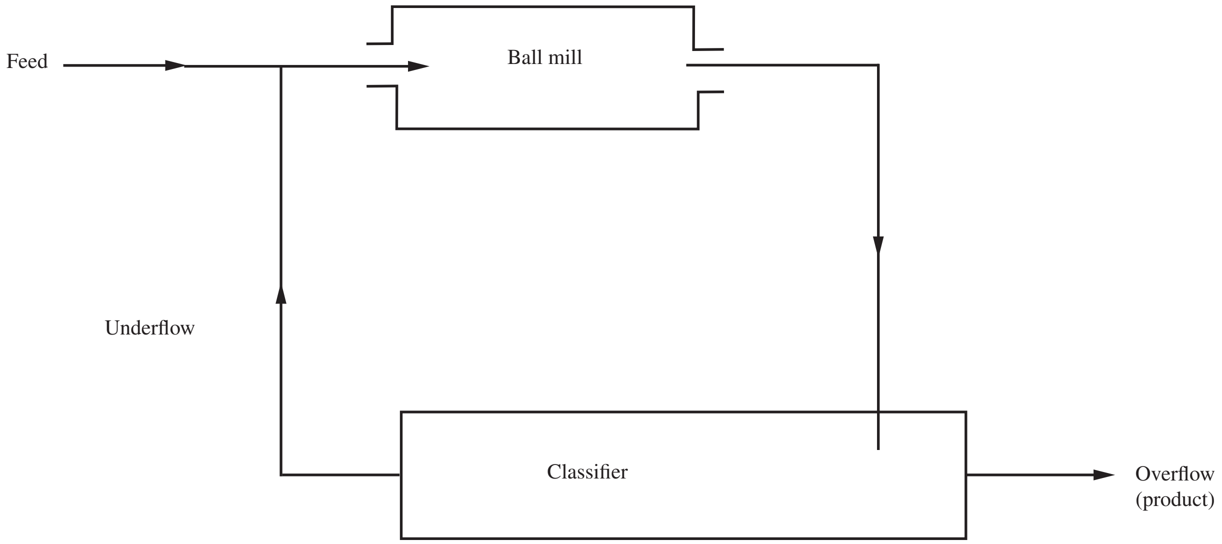

Figure 11. Simple closed-grinding circuit.

The refractory ores, however, must undergo pretreatment before cyanidation to achieve satisfactory gold recovery at acceptable levels of reagent consumption. If the ore is refractory because of the presence of abundant sulfide minerals, then it may be put through a froth flotation circuit to concentrate the auriferous sulfides. The concentrate is then smelted, cyanided, or oxidized before cyanidation, by one of several methods that remove harmful constituents, make them more soluble, or free the gold so that it can be dissolved by the cyanide solution (fig. 9). Alternatively, flotation is skipped, and the whole ore is oxidized. The predominant oxidation methods used in the United States for treating refractory ores are whole ore roasting and pressure oxidation, although bio-oxidation is also used (U.S. Bureau of Mines, 1994, p. 6-10).

Recovery From Solution

Gold is recovered from pregnant cyanide solution either by precipitating it with zinc dust (the Merrill-Crowe process) or by adsorbing the gold complexes onto activated carbon, stripping a condensed pregnant solution from the carbon, and recovering gold from that solution by either electrolysis (electrowinning) or zinc precipitation (Zadra, 1950, p. 29B32; Zadra and others, 1952, p. 7B10). For solutions extracted from milling ores, the gold complexes are adsorbed onto coarsely granular activated carbon in one of the following operational adsorption modes: in the cyanidation mixing tank concurrent with dissolution of the gold (the carbon-in-leach process), from the pulp after it leaves the cyanidation tank (the carbon-in-pulp process), or from the pregnant solution in columns packed with activated carbon (the carbon-in-columns process). The activated carbon processes have the advantages of reducing or eliminating pretreatment of the pregnant solution, removing some of the usual contaminants, and reducing the volume of solution from which gold is to be recovered (Yannopoulos, 1991, p. 193B230). Other gold recovery methods, such as solvent extraction, and the use of ion-exchange resins and chelating agents have been proposed but have seen little or no commercial application.

The gold precipitate from the Merrill-Crowe process or the loaded steel wool cathodes from electrowinning cells are smelted with borax ($Na_2B_4O_7$), niter ($NaNO_3$), and silica (SiO_2) until the melt separates into slag and metal. At this point, the slag is skimmed off, which leaves gold-silver doré. This is a batch process that is usually carried out at the mine in small induction furnaces or gas-fired tilting furnaces. At the refinery, gold is recovered from doré by chlorination in the molten state (the Miller process) and/or by electrorefining (the Wohlwill process). Typically, a two-part process is used with chlorination as the first step, which yields gold of 99.5 percent to 99.8 percent purity, and electrorefining as the second step, which yields gold of more than or equal to 99.9 percent purity.

Other Solvents

Solvents other than cyanide have been used to a limited extent for leaching gold from refractory ores. An acid solution of thiourea [$CS(NH_2)_2$] produces very high yields of gold and has some advantages over cyanide because it leaches faster; is more selective and, therefore, less susceptible to reaction with base metals in the ore; produces satisfactory gold recovery from carbon-containing ores; and results in high gold recovery from chalcopyrite and pyrite concentrates. For many ores, however, reagent cost is high, which makes the process uneconomical. Gold can also be leached with an alkaline solution of sodium thiosulfate that contains oxidizing agents, but as far as is known, thiosulfate leaching has not been used commercially. Bromine, chlorine, and iodine can extract gold from low-sulfur ores in the presence of an oxidizer, but reagent cost is an obstacle to their use (Yannopoulos, 1991, p. 171-183).

Recycling

The scale of commercial gold recycling efforts ranges very widely—from individuals working in a corner of a room to large industrial refineries. Recycling on a small scale is the norm in developing countries, but in industrial countries, it is an economically viable activity only if fairly high-grade scrap is treated, such as that available from jewelry fabrication and from old jewelry. Low-grade scrap, such as that generated in large volumes by the electronics industry, is treated by large refiners, some of which are base metal refiners.

The methods of recycling are adapted to suit the scale of operation and the type of scrap materials processed. The individual is likely to use laboratory-scale methods, and the large commercial refiner will use those methods in the control laboratory and industrial-scale methods in the refinery itself. In either case, recycling is a batch process, each batch being kept separate from other batches as it is first assayed and then processed through several steps. Efficiency requires that the refiner establish a minimum batch size and a minimum refining charge per batch. The first step is to determine the composition of the scrap, to establish the value of the recoverable gold, and to adapt the recovery process (or to choose among alternative processes) to recover as much gold as possible as cheaply as possible. In the case of manufacturing scrap, the generating industry will try to keep its scrap segregated by type as it accumulates or to sort it into types before shipment to the refiner. This effort is generally rewarded with lower refining costs, because the refiner, who deals with scrap having a limited number of components and a limited range of composition, may be able to use a simplified processing scheme (Simmons, 1981).

Old, or postconsumer, scrap is often received by the refiner as a complex mixture of pieces of unknown origin and widely differing character; this scrap may require the full array of identifying and refining methods (Simmons, 1981). The small refiner will evaluate individual pieces of scrap on the basis of appearance, heft, and the use of simple diagnostic tools, such as a set of touch needles, a touchstone, and a few acids and other wet chemical reagents. The commercial refiner will use modern instrumental methods of analysis. Even then, either the scrap owner or the refiner may require that a fire assay be made. The actual refining may be as simple as chemical leaching but is more likely to involve pulverizing and burning to get rid of organics followed by sieving, magnetic separation, gravity separation, and other methods for removing nonprecious metal materials, wet chemical methods for separating and purifying individual metals, and electrochemical cells for stripping gold plate from substrates. Alternatively, especially in the case of low-grade scrap and waste, the scrap articles may be disassembled or pulverized, burned, and then smelted with copper to form a copper-base bullion that is then refined by standard copper refinery electrolysis. The gold and other precious metals collect on the floor of the electrolytic cell as slimes from which they are recovered and separated by wet chemical procedures (Williams and Drake, 1982, p. 3).

Whatever process is used, the intermediate product is a crude bullion that probably contains silver and perhaps other precious metals. The gold in this bullion will be separated from the other metals and further refined to commercial grade by Miller chlorination or Wohlwill electrolysis or both. Refined gold derived from scrap and refined gold derived from ore are not distinguished from each other in use or in the market and, in fact, are often commingled in the same bullion bar.

Uses

Gold is used in three principal ways—as a manufactured product in industry and the arts, as an investment good, and as a monetary metal. The first two are discussed in this section; monetary uses were discussed in the section "Historical background." Of the gold supplied to the international market yearly, about 88 percent is destined for fabrication, and 12 percent for investment and bullion stocks. Gold is used in two basic forms—unwrought (bullion and other refinery shapes) and wrought (manufactured into products). The discussion of the use of gold in industry and the arts deals with the wrought, or fabricated, forms as end products. The discussion in the sections on monetary use (in the section "Historical background") and investment (in subsection "Use as an Investment Good") deal, for the most part, with unwrought forms, but some fabricated products can also function as investments (certain kinds of jewelry and art) and some have monetary use (official coins).

Properties That Determine Use

Cost, chemical inertness, workability, and appearance are the most important determinants of how and where gold is used in its most important role as an industrial and decorative metal. Among items of adornment or decoration, cost restricts its use to those expensive items for which its attractive color, freedom from corrosion, and luster recommend it. Among industrial products, cost restricts gold to those uses for which reliable functioning is of paramount or even crucial importance. Chemical inertness is important where metal parts, such as dental bridges or critical electronic circuitry, must endure in a pristine, uncorroded condition for long periods. The ready workability of gold allows it to be used economically as, for example, cladding on base metals in jewelry, inlays in base-metal electrical contacts, extremely thin decorative/protective coverings in architecture, and a coating on reflective shrouds for spacecraft. Nearly all gold contained in end products is present as metal, usually hardened and strengthened by alloying with such metals as copper or silver. Gold compounds are important primarily as intermediates, such as the organometallic compounds used in applying gold decoration to porcelain or the gold cyanides and chlorides in gold plating solutions.

Gold's unique combination of physical and economic characteristics make it a natural choice for a monetary medium. Its great resistance to corrosion make it essentially imperishable and, together with its unmistakable color and workability, suitable for coinage. In addition, it possesses two interrelated attributes of great importance for a monetary medium—it is valuable and scarce (but not too scarce). As a consequence of its very high unit value, small quantities, often easily carried on the person, are sufficient for relatively large purchases. As a consequence of its scarcity, the minting authority can establish exclusive rights to its possession, thus controlling the amount of coinage in circulation. This provides the minters and the users of coinage some assurance that the amount of gold available for coins can not easily be increased, and, thus, the stability of a gold currency can be maintained. Although gold coinage is no longer an important working currency in most of the world, gold's relative scarcity in nature still suits it for use as a monetary reserve, a backing for at least part of the paper money in circulation. For most of the same reasons, gold, among all investment goods, has long been considered to be the ultimate store of value.

Use in Industry and the Arts

Although gold is used in the same products the world over, the relative importance of those products differs from region to region. The difference is especially marked between the industrial countries and the developing countries (fig. 12). In the industrial countries, gold is predominately a jewelry metal, but in the developing countries, it is almost entirely a jewelry metal. More than three-fourths of the gold used in electronics is consumed in the industrialized countries, and the remainder, in developing countries. In the industrial countries about 6 percent of the gold consumed goes into official coins; in the developing countries, the figure is about 0.6 percent. In industrial countries, about 4.5 percent of the gold consumed yearly goes into dental alloys; in developing countries, about 0.3 percent. Medals, medallions, imitation coins, and commemorative objects of various kinds account for much less than 1 percent of the gold used in industrial countries but about 1.5 percent in developing countries. The remaining

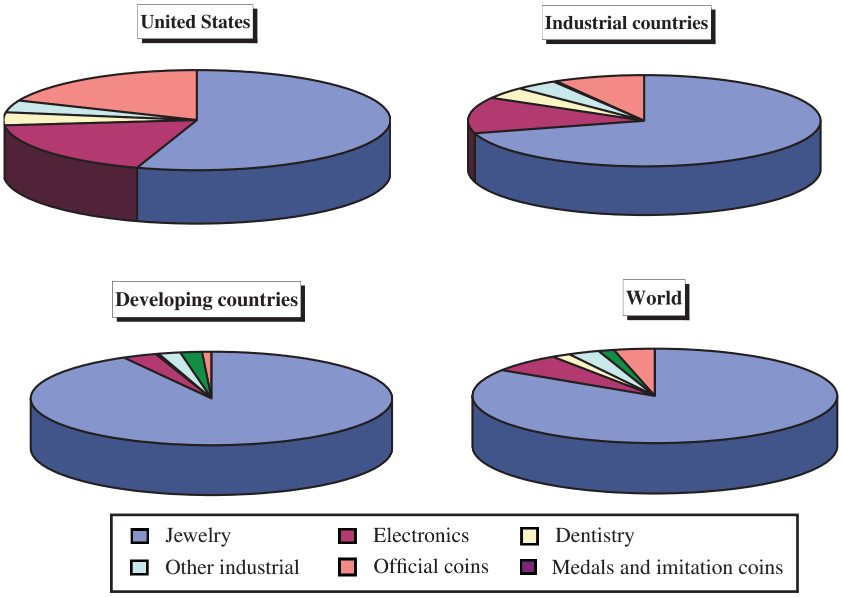

Figure 12. Gold consumption patterns in 1999. Data from U.S. Geological Survey, 1999; Gold Fields Mineral Services Ltd., 2000.

4 percent to 5 percent of the gold consumed in industrial countries goes into a variety of other uses; the comparable figure for the developing countries is about 2 percent. Of course, other region-to-region and country-to-country differences affect the consumption pattern; these will be discussed below.

The amount of gold used in industry and the arts worldwide has nearly quadrupled since 1980 because of the very strong growth of demand in developing countries. These countries first exceeded fabrication in the industrial countries in 1988 and by the late 1990s were using two-thirds more gold than the latter (fig. 13). U.S. fabrication during the same period nearly doubled to 323 t in 1999 from 170 t in 1980, before falling off in 2000 and 2001 (fig. 14).

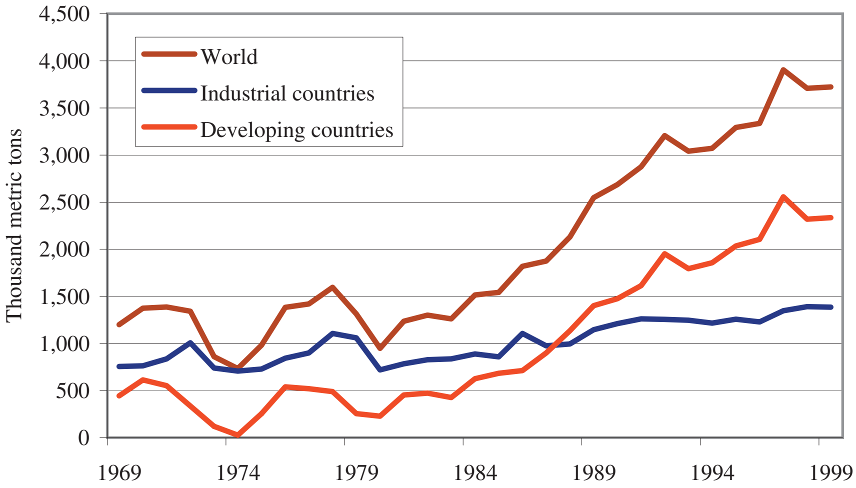

Figure 13. World gold fabrication. Data from Gold Fields Mineral Services Ltd., 1981, 1990, 1993, 1998-2000.

Jewelry

Far more gold is used in jewelry than in any other end use. Worldwide, jewelry manufacturing accounts for about 85 percent of the gold that is fabricated each year. Gold has several qualities that recommend its use in

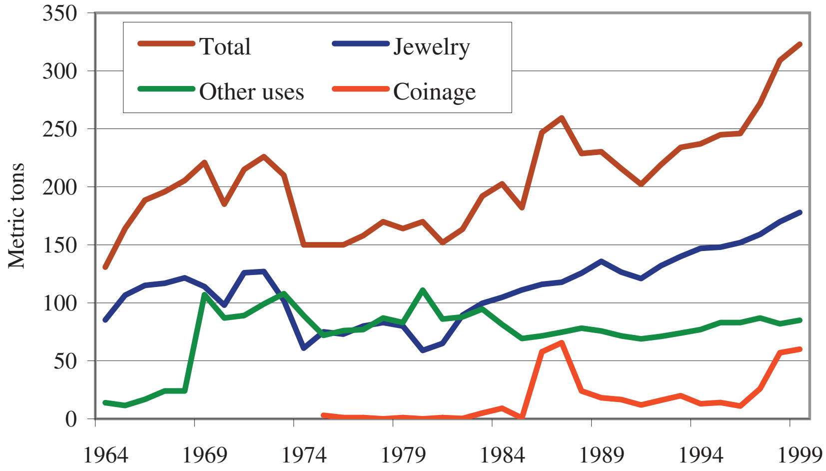

Figure 14. U.S. gold fabrication. Data for 1964-1968 from U.S. Bureau of Mines and for 1969-1999 from Gold Fields Mineral Services Ltd.

jewelry and decorative items—corrosion resistance of a very high order, an attractive color and luster, excellent workability, and tradition. In addition, it is nonallergenic and is available in a variety of alloys of widely differing color, luster, strength, and durability. Finally, it is the precious metal par excellence, scarce in natural occurrence and long considered unequaled as a store of value. This last attribute is especially important in some parts of Asia and the Middle East where jewelry functions not only as adornment but as a kind of portable wealth, convertible to money when that is needed.

The term "jewelry," as used in this section and as is customary in assembling gold use statistics, refers to what is called "karat jewelry" to distinguish it from inexpensive nonkarat, or "costume," jewelry. Typically, gold is applied to costume jewelry as thin plating or even thinner "washes" or "flashings." Although the market for costume jewelry is very large, the total quantity of gold used is small; in this report, it is discussed in the section on "Decorative Arts." The karat jewelry market itself is sometimes divided conceptually into adornment jewelry, the demand for which comes mainly from the industrial countries, and investment jewelry, the demand for which comes mainly from the developing countries. Adornment jewelry tends to consist of intricate, finely worked pieces fashioned from 18-, 14-, and 10-karat alloys. Although most pieces are made for the mass market, they carry a markup of 200 percent to 400 percent above the value of the gold content. Typically, they have long lifetimes and remain in their owners' hands for many years. Investment jewelry pieces are more likely to be individually crafted and tend to be more massive, although not invariably. They are fashioned from high-karat (21 to 23) alloys or—for the large Chinese and Southeast Asian markets—990 fine gold for chuk kam ("pure gold") jewelry. Investment pieces tend to have short lifetimes because as refabrication costs in the countries in which they are popular are moderate (the pieces usually are priced no more than 10 percent to 20 percent above the value of the gold content), the owners often exchange old pieces for new ones when they tire of them or sell them back to the goldsmith when the gold price is high or rising (Green, 1991, p. 80).

The methods of making gold jewelry, such as casting, drawing, electroplating, machining, soldering, spinning, and stamping, have engendered the development of a variety of gold alloys of differing physical and metallurgical properties. Of the yellow gold alloys used in jewelry, the high-karat (23, 22, 21, and 20) golds possess the richest color and luster and are the most resistant to tarnish and corrosion. They are, however, low in strength, hardness, and abrasion resistance and consequently are used primarily in rather massive types of jewelry that sometimes comprise components soldered together with alloys of somewhat lower karatage. At the other end of the karatage spectrum, the 10-, 9-, and 8-karat golds lack some of the rich color and luster of gold and are in some instances more susceptible to tarnish from chemicals present in perspiration. They are nonetheless used extensively in the more economically priced items of gold jewelry and in such items as finger rings, where wear resistance is important. The intermediate yellow karat [18 and 14 (16 is seldom used)] golds are much used in jewelry of all types because of their pleasing appearance, excellent mechanical properties, and good corrosion resistance. The 990 fine gold used in chuk kam jewelry is very soft; a 1 percent titanium alloy, still 990 fine, has better abrasion resistance and is gaining popularity.

Originally, white golds were introduced into jewelry as substitutes for platinum. The white golds now commonly used in jewelry are either nickel or palladium (noble metal) alloys. The nickel white golds are less expensive than the noble-metal white golds but are difficult to produce with both good color and good workability present in the same alloy. Jewelry manufacturers commonly choose the nickel white gold alloys that have good working characteristics and then achieve satisfactory color by electroplating a thin layer of rhodium onto the finished jewelry pieces. To prevent localized corrosion in low-karat pieces of this type, the nickel content of the alloy is kept low, partly replaced by silver. Rhodium-plated gold is not suitable for jewelry pieces that are subject to abrasive wear, such as finger rings. Nickel white golds also have limitations with respect to metallurgical processing because they are difficult to anneal to a ductile state, unsuitable for vacuum casting, and susceptible to weakening attack by sulfur and silicon. Palladium white golds are suitable for casting and have the advantages of good working characteristics, good corrosion resistance, and color that remains stable upon heating (Rapson and Groenewald, 1978, p. 41).

Although gold alloys of other colors have been formulated, such as the violet alloy formed by gold and aluminum or the blue alloys formed by gold and iron, they have severe limitations and have found little use in jewelry. What has been done since ancient times to achieve colors, such as violet or blue or green, or to enhance the richness of the gold color of an alloy in which the gold is considerably diluted is to treat the surface of a finished piece with one or more chemical compounds. In depletion gilding, which is perhaps the oldest of color enhancement processes, the chemicals, whether oxalic acid from the wood sorrel used by the pre-Columbian Incas or the mineral acids used in more recent times, preferentially leach base metals from the surface of the alloy and leave it enriched in gold, thus achieving the rich color of pure gold. Chemicals and conditions can be adjusted to make the base metals leach differentially, which leads to changes in surface color. Today, surface coloration is done by codeposition during electroplating of such alloy metals as cadmium, cobalt, copper, silver, tin, and zinc (Rapson and Groenewald, 1978, p. 65). The high-karat gold jewelry favored in the developing countries is well over 90 percent yellow in color, but even in the industrialized countries, yellow gold is the overwhelming favorite. In some European countries, however, white gold accounts for as much as one-fifth or even one-fourth of the market.

Likewise, the karatage of alloys favored for gold jewelry customarily differs from country to country and region to region. As noted above, karatage in the developing countries is typically high. Among the industrial countries however, differences in preference are marked. In these countries, the bulk of gold jewelry purchased is either 18 or 14 karat. Little is higher than 18 karat, and the demand for alloys below 14 karat is modest, with some exceptions—8-karat alloys account for nearly one-half of the market in Germany, 9-karat alloys for about three-fourths of British purchases, and 10-karat alloys for about one-eighth of U.S. purchases and more than one-half of Canadian purchases. The variation in karatage from year to year depends on changes in fashion and in gold price. In the United States, for example, in the late 1980s, about 65 percent of the gold alloys used in jewelry was 14 karat, 25 percent was 10 karat, and the balance (less than 10 percent) was 18 karat (Michalopoulos, 1991, p. 7). By 1997, the distribution of alloys had changed—69 percent was 14 karat; 13 percent, 10 karat; 10 percent, 18 karat; 4 percent, 24 karat; 2 percent, 22 karat; and 1 percent each, 8 and 9 karat (World Gold Council, New York, unpublished data, April 6, 2000).

The less expensive karat gold jewelry is made not only by using lower karat alloys, but by forming composites with cheaper components, such as semiprecious stones, silver, or base metals. Some articles are made by the chemical plating or electroplating of gold alloy onto a substrate, usually a base or ferrous metal. Others are made from a “rolled gold” or “filled gold” composite of layers of karat gold and base metal bonded together. The terms “rolled gold” and “gold filled” are used interchangeably in most countries. The terms “plate” or “overlay” are sometimes added, as in “gold-filled plate” (or overlay) and “rolled gold plate” (or overlay). Gold-filled plate is made by bonding, such as by brazing or hot rolling, a bar of karat gold to a bar of base metal and then rolling to the desired thickness. The base-metal bar may be plated with nickel to inhibit diffusion across the gold/base metal join during brazing and annealing. Gold-filled wire or tubing is made by inserting a base metal rod or tube into a tube of karat gold and then drawing the combination to the desired dimensions. Rolling and drawing are done in stages with stress-relieving anneals carried out between stages (Rapson and Groenewald, 1978, p. 273-276). Electroplating has been developed to the point where it is now capable of producing thick, nonporous coatings of the common karat golds economically and even supplanting, to some degree, the mechanically bonded composites.

Gold jewelry is manufactured in more than 80 countries and on all the populated continents (fig. 15). Of the principal fabricating countries, India, Indonesia, Italy, and Turkey are net exporters of gold jewelry; the other countries are net importers (fig. 16). Italy, which is the world's second largest fabricator of gold jewelry (primarily gold chain), exports more than three-fourths of its manufactures. The United States imports one-half of its karat gold jewelry. These statistics have shifted dramatically during the past two decades because jewelry fabrication in the developing countries has grown more than twice as fast as in the industrial countries and now accounts for more than two-thirds of world fabrication. In the past two decades, total world fabrication of gold into jewelry has grown to more than 3,100 t in 1999 from about 500 t in 1980 (fig. 17).

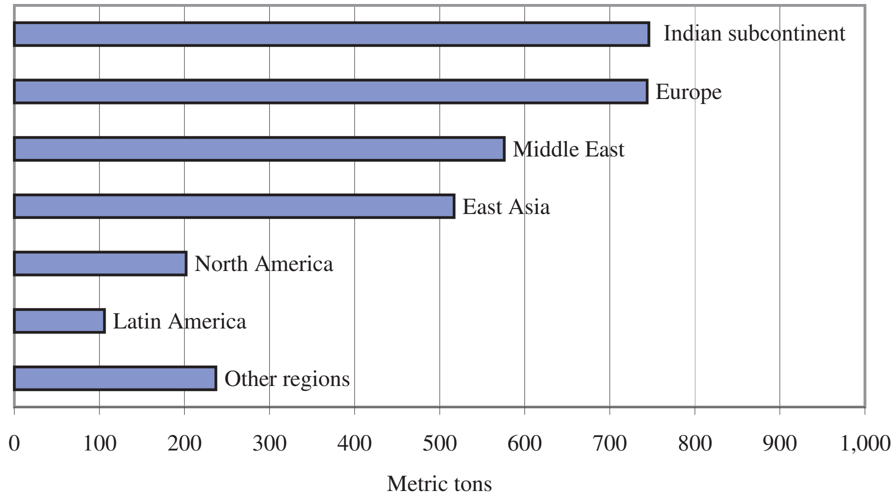

Figure 15. Regional gold fabrication. "Other regions" includes China and the Commonwealth of Independent States. Data from Gold Fields Mineral Services Ltd., 2000.

In jewelry, gold competes with silver, base metals, precious and semiprecious stones, glass, plastics, and other materials. The extent to which these other materials are substituted for gold is determined by culture, fashion and jewelry design trends, and the price of gold. Being rare and very expensive, gold was confined to the very wealthy until the 19th century when new discoveries in Australia, Russia, and the United States (California) increased the supply of gold dramatically. Even so, ". . .until the end of the Second World War, jewellery of even the best design was by no means primarily gold. Glass, brass, and even punched iron were used . . ." (Weston, 1983, p. 80). The relatively low gold prices of the 1990s undoubtedly encouraged the growth of gold use in jewelry, but

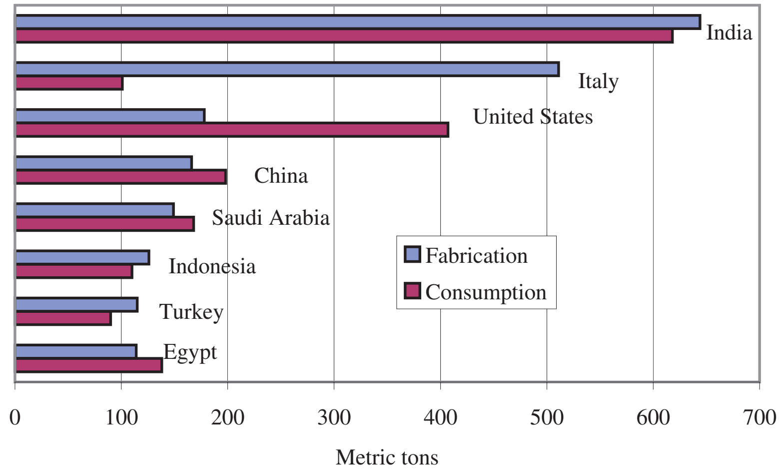

Figure 16. Gold fabricated into and consumed as karat jewelry by principal fabricating countries in 1999; these totals represent 54 percent of the gold fabricated into jewelry worldwide. Data from Gold Fields Mineral Services Ltd., 2000.

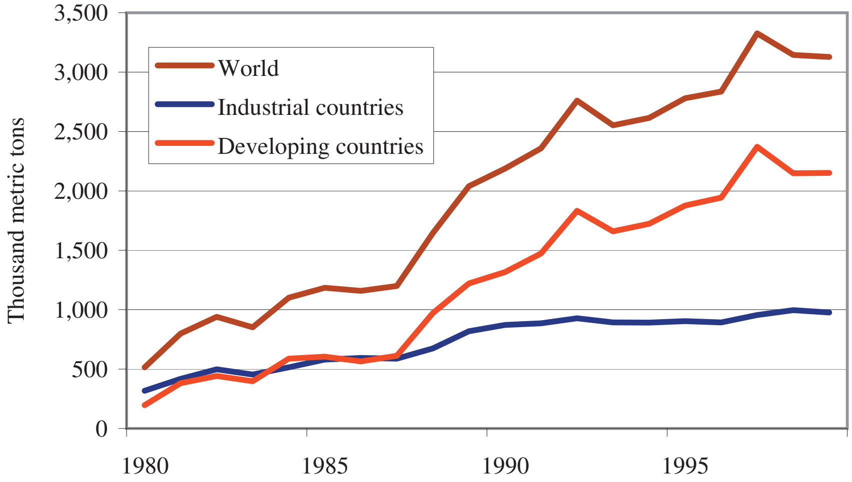

Figure 17. Gold used in the fabrication of karat jewelry. Data from Gold Fields Mineral Services Ltd., 1981, 1990, 1993, 1998-2000.

should the price rise again, substitution can be expected, and as the substitutes have all been used in years past and the technology for substitution is well known, very abrupt swings in gold consumption for jewelry are possible.

The standards of quality for gold jewelry items range widely from country to country, from almost nonexistent to fairly detailed. Hallmarking of gold jewelry, which is a visual certification of its quality, is compulsory in the United Kingdom, where it was introduced in the 14th century, and is used in some form in another two to three dozen countries, although it is not compulsory in all (Weston, 1983, p. 80). The countries of the European Union are considering the introduction of a common system of hallmarking. In the United States, the National Gold and Silver Stamping Act of 1906, as amended in 1976, sets the standard for fineness of gold in jewelry and other gold-containing articles, such as flatware, spectacles, watch cases, and so forth. The standard requires that the fineness of parts denoted by a karat-quality mark, which does not include solders or brazes, be no more than 3 points below the nominal fineness. For example, the nominal fineness of 14 karat gold is ${}^{14}/_{24}$ x 1,000 = 583; the actual fineness of an article marketed as 14 karat must then be no lower than 580 fine. The fineness of whole articles, which does include solders and brazes, must be no more than 7 points below from the nominal fineness; an exception is made for watch cases and flatware, for which the whole-article tolerance is 3 points. The law does not require that jewelry be marked with the karat number, although most of it is so marked. If a karat number is shown, then the U.S. registered trademark of the manufacturer or vendor responsible for the quality of the article must be placed next to the karat mark. Marketing and advertising standards are published in a set of trade practice guides for the jewelry industry; these standards were developed jointly by the industry and the Federal Government and promulgated by the Federal Trade Commission. They include, but are not limited to, the following guides (paraphrased):

- An article described as gold, without qualification, must be composed throughout of 24-karat (pure) gold.
- An article whose description includes the word “gold,” even when the term is qualified, must be composed throughout (exclusive of solders or brazes) of gold of at least 10-karat purity. For example, a 9-karat ring could not be marketed in the United States as a “gold” ring.
- An article composed of gold of at least 10-karat purity and not hollow may be labeled solid gold.

A jewelry piece made of a mechanically bonded composite may be labeled gold-filled if the gold alloy is of at least 10-karat purity and constitutes at least one-twentieth of the weight of metal in the piece. If the gold alloy constitutes less than one-twentieth, then the piece cannot be called gold-filled; rather, it is labeled gold overlay or rolled gold plate and further marked to show the actual gold content of the metal article. For example, an article marked ${}^{1}/_{30}$ 14-karat gold overlay contains $({}^{1}/_{30} \times {}^{14}/_{24}) \times 100 = 1.94$ percent gold.

Items coated with electroplate of at least 10-karat fineness to a thickness equivalent to at least 0.175 µm (seven one-millionths of an inch) of fine gold may be labeled gold electroplate. Items coated with thinner plate may be labeled gold washed or gold flashed. If the coating is at least 2.5 μm (one hundred one-millionths of an inch) thick, then the item may be labeled heavy gold electroplate.

It should be noted that the marking conventions do not tell the purchaser of gold jewelry anything about the metals alloyed with the gold—they convey information only about the proportion of gold in the alloy. Although karat golds have no compositional standards, some manufacturers supply data on the composition of the alloys they produce (Wise, 1964, p. 261; Federal Trade Commission, 1989; 2000).

Electronic/Electrical Uses

Of the purely industrial uses of gold, the most important quantitatively is in electronics circuitry. Modern solid-state electronic devices use very low voltages and currents. In such low-energy electronic circuitry, electrical continuity is easily interrupted by the development of oxide films or other tarnish films on critical circuit components. In more-energetic circuits, such as those used in conventional industrial or household electrical devices, surface oxide films or tarnish films are inherently less disruptive and, on connector points or spring contacts, are broken up repeatedly by a mechanical wiping action and/or arcing. Solid-state electronic circuitry, however, requires that connectors, switch and relay contacts, soldered joints, and connecting wires and strips remain completely free of tarnish films and chemically and metallurgically stable over the life of the device. Gold is invaluable in these circuits because its freedom from high resistance surface tarnish and corrosion films, its excellent electrical conductivity (rated at 73 percent of copper's conductivity), and its low modulus of elasticity and low yield point help retain a low, constant contact resistance during long periods of time in hostile environments. In addition, gold does not form resistive films by polymerizing compounds adsorbed from organic vapors in the ambient atmosphere as do platinum-group metal low-energy contacts in some circumstances nor does it form small conductive metal whiskers, which can short-circuit open contacts. It also possesses excellent thermal conductivity, which contributes to the stability of circuit components by dissipating heat rapidly. In electronic devices that must perform critical functions without fail, gold is used extensively; in terms of quantity, most of it is used in connectors and contact points. Gold is normally restricted to those critical parts of the circuitry where it is indispensable, but its excellent ductility and good plating and brazing characteristics allow economy of use. Economy of use has been enhanced during the past three decades through such means as the use of thinner plated coatings, which were made possible by the development of dense plate with better metallurgical characteristics, selective area plating, and making contact points from gold inlay and other types of bimetallic (or trimetallic) strip.

Connectors come in a very wide array of configurations and sizes. Most are designed and manufactured by companies for which they are the principal or sole products. Perhaps the most familiar and ubiquitous are those used in personal computers and many other electronic devices—the edge connectors that are used to mount microprocessor and memory chips to a motherboard or printed circuit board and the plug-and-socket connectors that are used for cable ends. Most of the gold used in connectors is electroplated and in thicknesses that range from 0.5 to 2 μm. To harden the gold, thus increasing its wear resistance and eliminating any tendency to friction weld, it is alloyed with minute amounts (less than 1 percent) of such metals as cobalt or nickel. The substrate metals, which may serve as spring elements, are usually a 98.1 percent copper-1.9 percent beryllium alloy, an 88.2 percent copper-9.5 percent nickel-2.3 percent tin alloy, or a 94.8 percent copper-5.0 percent tin-0.19 percent phosphorus alloy (phosphor bronze). To minimize or eliminate the diffusion of copper through the gold layer, which can result in the formation of surface oxide films, an underplate of nickel is commonly used. For connectors that are faced with thin and somewhat porous gold plate, corrosion of the substrate at pore sites, which would allow oxide films to form and migrate to the gold surface, must be avoided. In these instances, an underplate of a corrosion-resistant alloy, such as 65 percent tin-35 percent nickel, may be used (Antler, 1994, p. 53). For gold layers that are greater than 1μm thick, making the contacts from clad metal, in which the gold alloy is bonded to the substrate metal by high-pressure rolling, can be more economical. If the gold, usually with a diffusion barrier underlay, is inserted into a groove in the substrate rather than covering the whole substrate, then the bonded assembly is referred to as an "inlay." The electrical and metallurgical properties that are important in the design of gold-faced connectors are also important in the design of switch and relay contacts. Use in contacts, however, entails much greater frequency of cycling, different closure pressures, and the possibility of building some mechanical wiping action into the design, which can disrupt surface films and in some instances lessen the need for noble metal facing.

The next largest application of gold in electronics is the use in gold bonding wire, which is used widely for connecting semiconductor chips to chip carriers or leadframes. Bonding wire is made from high-purity (99.975 percent-99.999 percent) gold and is commonly 20 to 30 µm in diameter, although it has been made in a somewhat wider range of sizes from about 13 to 37 µm (Rapson and Groenewald, 1978, p. 292; Gold Fields Mineral Services Ltd., 1995, p. 53). The difficulty of drawing a metal of such low tensile strength to such a small diameter has led to doping the gold with minute amounts of beryllium, which serves as a grain-refining agent and effectively strengthens the wire. To obtain a uniform, flaw-free wire suitable for high-speed thermocompression bonding, manufacturers often process the gold wire-rod in a vacuum to avoid entrapment of gases and then draw it into wire through diamond dies in a clean-room environment. Aluminum alloy bonding wire is used in some high-performance microprocessor "chips" that are hermetically sealed in ceramic or metal capsules. Most microprocessors and other "chips" of this sort, however, are embedded in organic polymers; the polymers are slightly permeable to moisture, which would eventually degrade aluminum wire. For these devices, which constitute the bulk of the market, gold bonding wire is used.

Gold is also introduced into electronic devices in thick- and thin-film conductive coatings. Thick-film conductors were developed for the interconnection of electronic components on printed circuit boards or other substrates; later, thick-film resistors, capacitors, and certain kinds of sensors were developed. These circuit elements are formed from a thick paste, or "ink," that consists of powdered gold and either powdered glass or an organic bonding agent in a liquid organic vehicle. The inks are printed onto the substrate, dried, and then fired to volatilize the organic vehicle, to sinter the gold or gold alloy, and to bond the circuit element to the substrate. During firing, the glass-containing mixtures are bonded to the ceramic substrate by the sintered glass, and the sintered gold tends to accumulate at the surface of the conductor. In pastes that do not contain glass, small amounts of base-metal oxides are added to the gold or gold alloy to achieve reaction bonding to the substrate upon firing. In contrast, thin-film conductive or protective coatings are formed in vacuum either from evaporation of gold at high temperature or by sputtering, which is the transfer of atoms from a gold or gold alloy cathode by bombarding it with positive ions of an inert gas. In many instances, sputtering has become the preferred method, especially for gold alloys, which must be deposited on the substrate without change of composition. Thin films are used in electronics devices mainly as conductive circuit elements whether used as patterns of conductors or as radiation shields, although specialized sensors, such as strain gauges, have incorporated thin films in the sensing element.

Finally, gold and its alloys have long been used in many electronic/electrical instruments, such as slide-wire potentiometers, thermocouples, low-temperature thermometer devices, sensitive resistance thermometers, strain gauges, and other applications for which long-term reproducibility of response is essential. Instrumentation constitutes a small but steady market for gold.

The manufacture of electronic/electrical devices is dominated by the industrial countries (fig. 18). More than two-thirds of the gold used in such devices is consumed by manufacturers in only 3 countries, and 94 percent of it is consumed in the top 10 countries (fig. 19). Japan, with 36 percent of the world total, and the United States, with 22 percent, are by far the largest fabricators. Japan is estimated to make more than two-thirds of the gold bonding

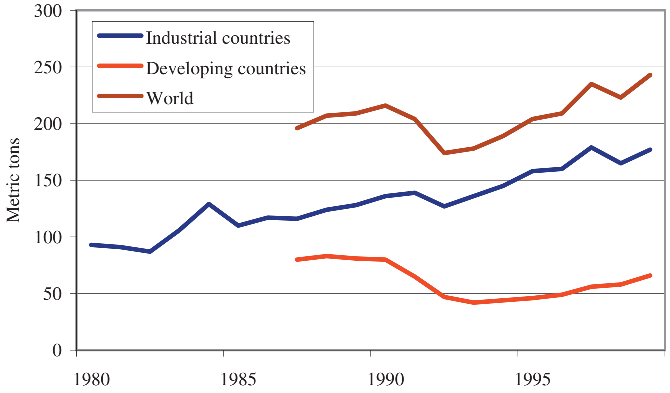

Figure 18. Gold used in electronics. Data from Gold Fields Mineral Services Ltd., 1981, 1990, 1993, 1998-2000.

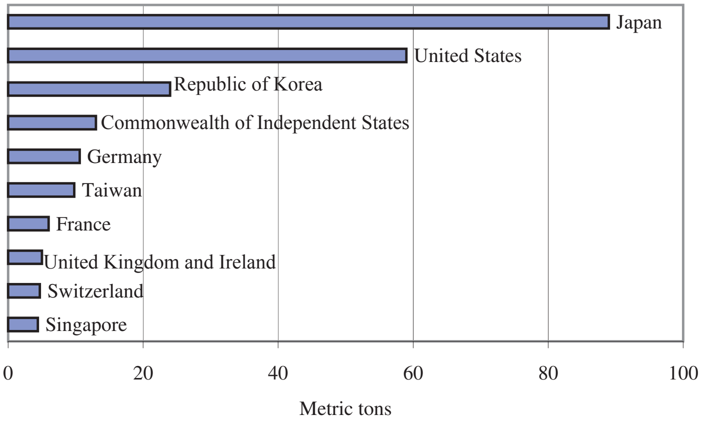

Figure 19. Gold used in electronics by principal fabricating countries in 1999 these totals represent 93 percent of the world total. Data from Gold Fields Mineral Services Ltd., 2000.

wire used in the world, much of it for export to Southeast Asia. The United States, by contrast, imports much of its bonding wire; it is, however, an important producer of connectors, computer chips, electronics of all kinds, and gold-plating salts.

When the price of gold was increasing rapidly in the 1970s, electronics manufacturers sought ways to economize on its use. They developed thinner but denser electroplate and selected-area electroplating. They made greater use of gold inlays and gold cladding and found ways to draw and use thinner bonding wire. Where feasible, other metals were substituted for gold—silver that was treated to make it tarnish-resistant, palladium, and combinations of palladium and gold and palladium and nickel were among the prominent substitutes. In succeeding years, the electronics industries made enormous strides in reducing the size of circuit components even as the number of circuits manufactured each year rose very steeply. The result of these countervailing trends is that the use of gold in electronic/electrical devices has grown at a modest 3 percent per year in the industrial countries during the past two decades.

Dental and Medical Uses

Gold is used in dentistry for some of the same reasons it is used in jewelry—it is nonallergenic, chemically inert, and comparatively easy to fabricate. It has been used in pure form as a cavity filling and in alloyed form with strengthening metals in crowns, inlays, bridgework, and orthodontic appliances. Gold-based dental alloys, in which gold is alloyed with various noble and base metals, combine ease of casting and working, long-term proof against corrosion by oral fluids, and good hardness and strength.

Pure gold has been used for centuries as a filling for cavities in dental positions not subjected to high stress. After brief heating in a flame to remove surface contaminants, gold foil (about 60 µm thick), gold powder (average particle diameter, 15 µm) wrapped in gold foil, matted dendritic crystals of gold, or some combination of these forms is packed and malleted into a cavity. The finished filling is a cold-welded mass that has about three-fourths of the density of pure gold. A foil of platinum sandwiched between layers of gold yields stronger fillings but is more difficult to emplace. Pure gold fillings are very stable and leak free but have the disadvantage of high thermal conductivity and require considerable skill and time to place them in the cavity. Today, pure gold has been almost completely supplanted by other filling materials.

One class of casting alloys, which is based on the gold-silver-copper alloy system, is used for dental restorations and typically contains between 60 percent and 80 percent gold with enough palladium, platinum, or silver to bring the noble-metal content to at least 75 percent with the balance being copper and zinc. Another class of casting alloys, which is based on the gold-palladium-platinum alloy system and typically contains small amounts of several other metals, is designed for bonding with porcelain dental materials. Individual alloys in this latter class are formulated to match the thermal expansion of specific porcelain materials during firing and cooling; this precaution is necessary to avoid overstressing the alloy-porcelain joint and the individual components. Also, these alloys are formulated to avoid discoloring the porcelain during firing and to form strong reaction-bonded joints.

Wrought alloys, in the form of wire and plates, are used in orthodontic applications. These are of at least two types, which differ mainly in strength and the range of colors available. Alloys of both types contain gold, silver, copper, palladium, platinum, nickel, and zinc.

Dental gold solders are essentially gold-silver-copper alloys. Individual solders are formulated to emphasize one or more properties, such as color, high strength, flow (aids penetration into joints between metal parts), or lack of flow (useful in building up metal) (Wise, 1968, p. 227-249; Rapson and Groenewald, 1978, p. 95-110).

Ninety-seven percent of the gold consumed for dental alloys is accounted for by only eight countries; Japan, Germany, and the United States, in order of consumption, account for about 74 percent of the world total (fig. 20).

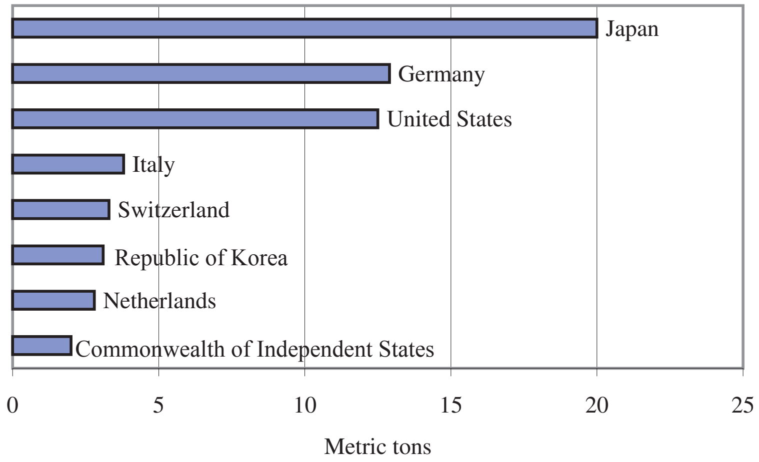

Figure 20. Gold used in dentistry by principal fabricating countries in 1999; these totals represent 93 percent of the world total. Data from Gold Fields Mineral Services Ltd., 2000.

For individual countries, the quantities used in making alloys are not always close to the quantities actually used in dentistry in the countries. Switzerland, for example, is estimated to export three-fourths of the gold-based dental alloys it manufactures. The quantity actually used in dentistry in each country is strongly influenced by the price of gold and its relation to maximum amounts paid by health insurance plans. The strong run-up in the gold price in the late 1970s dampened the demand for gold dental alloys for years. In the United States, gold use in dentistry in the past two decades has been only about one-half of the amounts used in the 1960s and 1970s. After 1987, however, use began to trend upward slowly at about 1.7 percent per year. The trend since 1987 in the developing countries has been downward, whereas it has risen at a little more than 3 percent per year in the industrial countries (fig. 21). A factor that may have impelled the increase in the use of gold in dentistry in the past two decades is the public's perception, especially in some of the European countries, that substitute alloys may be somewhat toxic. Thus, the noble metals—palladium, platinum, and silver—are firmly established components of dental alloys and are the principal substitutes for gold in dental alloys. In Japan, for example, the most used dental alloy, Kinpara 12, contains 55 percent silver, 20 percent palladium, 12 percent gold, and 13 percent other metals (Gold Fields Mineral Services Ltd., 1990, p. 47-48; 1996, p. 54-55).

In medicine, graduated injections of a weak solution of gold salts, usually sodium aurothiomalate or aurothioglucose, are used to treat rheumatoid arthritis. "Grains" of irradiated gold, specifically Au^{198}, which has a half-life of 2.7 days, are implanted in tissue to serve as sources of gamma radiation in the treatment of some cancers. The same isotope is also used in colloidal suspension as a beta emitter for therapeutic and diagnostic purposes for various medical conditions. Other than in India, where it has been estimated that about 2 t/yr of gold are used in Ayurvedic medicines, the amount of gold used in medicine is minuscule in comparison with the amounts consumed in other applications.

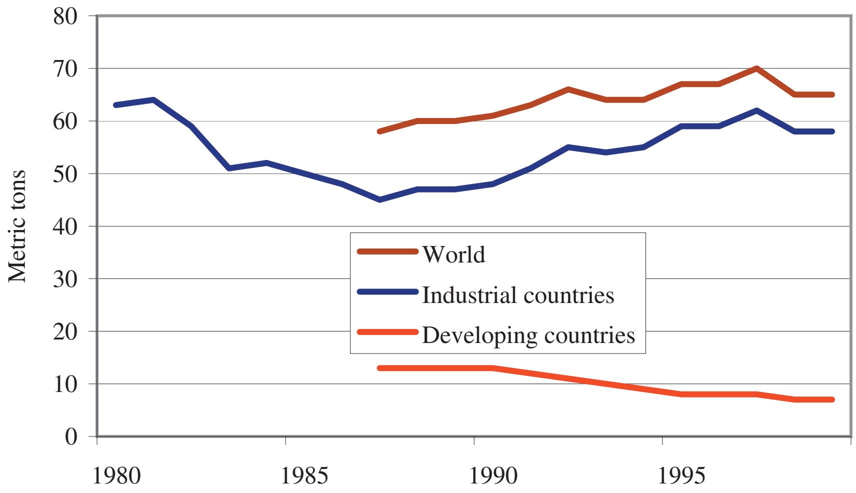

Figure 21. Gold used in dentistry. Data from Data from Gold Fields Mineral Services Ltd., 1981, 1990, 1993, 1998-2000.

Other Industrial Uses

Gold is used in smaller amounts in a variety of other ways. Some of the high-temperature (850°-1,400° C) brazing alloys used in the manufacture of aircraft turbine engines, jewelry, dental appliances, and electronics devices are gold-base alloys. In addition to offering suitable bonding and metallurgical properties, these alloys provide long-term protection against degradation of metal-to-metal joins in hostile environments. Most of them are binary or ternary alloys of gold with copper, nickel, palladium, or silver; they are distinct from the karat gold solders used in jewelry manufacture, which often have more-complex compositions and are used in the range of from 600° to 800° C.

Spinnerets, which are the perforated nozzles through which cellulose acetate (rayon) fibers are extruded, are machined from 50 percent Au-50 percent Pt alloy and then precipitation hardened. They resist corrosion and are hard enough to withstand the abrasion of any filler pigment, such as titanium dioxide, that may be incorporated in the acetate. Gold and its alloys are used in pressure rupture discs and in corrosion-resistant alloys used in chemical process equipment. The electrodes in certain spark plugs designed for use in difficult ambient conditions, such as in snowmobile engines, are tipped with a gold-palladium alloy.

Gold plays a prominent role in space exploration. The electronics of the space vehicles the kinds of devices that must be absolutely dependable, and hence incorporate gold in crucial circuitry, but mechanical parts also must function dependably and require the unique properties of gold. For example, conventional organic lubricants are not suitable for the lubrication of moving parts in space because they are too volatile in the near-vacuum and are degraded by the intense radiation encountered. Leaving the metal parts unlubricated could lead to cold welding as friction from movement disrupts surface oxide films, which are then unable to reestablish themselves in the absence of an atmosphere. In these situations, gold, which has a very low shear strength, has been used as a solid film lubricant for moving parts in space vehicles. In addition, large parts of space vehicles, such as the lunar lander, have been fitted with covers of gold-coated polyester film to reflect infrared radiation, thus helping to stabilize the temperature of the vehicle (Weston, 1983, p. 88-89).

Gold is used on architectural glass as an optical coating or dispersed within the glass itself. In either case, it reduces building heating and cooling costs by reflecting building heat inward and solar heat outward. The reflection of long-wave radiation from a single gold vacuum-deposited film is so efficient that it transmits only about one-fourth of the incident energy in solar radiation. The transmission of visible light, however, is in the range of 20 percent to 40 percent of the incident light, which is unacceptably low in many applications. If the film is made thin enough to raise the transmission of visible light above 40 percent, then the reflection of infrared radiation declines. If the film is made thick to obtain strong reflection of infrared radiation, then the transmitted light becomes greenish. To provide good transmission of visible light of a neutral color while retaining good infrared reflectivity, a gold film is used in combination with one or more dielectric films to shift the phase of reflected visible light 180°, which, in effect, increases transmittance (Rapson and Groenewald, 1978, p. 150-166).

Gold in various forms has been considered for use in solar energy absorbers and in fuel cells, but as yet no markets have developed for these applications. It has also been investigated in gold-copper-zinc shape memory alloys. Gold has been shown to catalyze a number of chemical reactions, but as the catalytic effect is generally weak, gold catalysts have found little or no practical use (Rapson and Groenewald, 1978, p. 310). Finally, small amounts of gold in the form of thiocyanate or thiosulfate complexes are used to sensitize silver halide photographic emulsions.

Decorative Arts

Gold is widely used in the decorative arts. Because it is used economically in most of these applications, the whole category accounts for no more than about 2 percent of fabricated gold worldwide. Gold is used to color inexpensive (costume) jewelry, wristwatches, and similar items, which, together, constitute the single largest component of use in the decorative arts category. It is present in these items as thin electroplate or even thinner electroplated “washes.” Outside of the costume jewelry class, heavier electroplated deposits form attractive, durable coatings on cutlery, eyeglasses, bathroom fixtures, pens, watches, and other premium-quality items. In India, as much as 10 t/yr of gold goes into jari, which is the decorative gold-plated silver-wound silk thread woven into expensive saris, such as those worn at weddings.

Because of its extraordinary malleability, which is much greater than that of any other metal, gold can be beaten into sheets only a few millionths of an inch thick. In this form, called gold leaf, it is used for the decoration of various articles of disparate size—from picture frames and the gilded edges of books to the interiors and exteriors of buildings, usually large public buildings. In architectural gilding, it is used as a durable and corrosion-resistant exterior covering of domes, cupolas, cornices, and other decorative features; in interiors, it is used in the patterns on expensive interior wall coverings and for decorating diverse furniture and architectural components. The cost per unit area of covering a domed roof with gold leaf is high—not because of the cost of the refined gold used, which, at $300 per ounce, is roughly $2.00 per square foot, but because the costly artisanship and time needed, first to manufacture the leaf and then to cement fragile 3 $^3/_8$-inch squares of leaf, four one-millionths of an inch (0.1μm) thick onto imperfect surfaces raises the cost by perhaps two orders of magnitude.

Some very thin “leaf” is now produced by electrolytic plating, sputtering, or vacuum volatilization. The gold is usually deposited on a polymeric substrate, such as mylar (PET), and lightly coated with an adhesive. When applied to a work piece, it adheres preferentially to the work and separates from the substrate. These processes have the advantage of being relatively faster than beating and of producing thinner sheets with larger dimensions.

“Liquid gold” is applied as decoration on porcelain and glass dinnerware and then fired to leave a coating of gold metal. A form of colloidal gold called Purple of Cassius is used in certain red porcelain enamels that range in color from pink to dark red and in the production of ruby glass. The rich red color of ruby glass is imparted by gold crystallites developed from a Purple of Cassius suspension in the glass when it is annealed.

Medals, Medallions, and Imitation Coins

Very little gold, only about 2 t, is used for medals, medallions, and imitation coins in the industrial countries, whereas much more, about 40 to 45 t, is used in the developing countries. India and Turkey account for more than 80 percent of the gold use. Imitation coins, which are reproductions of official bullion coins of various nations, are popular in the Middle East and the Indian subcontinent where they were once used to circumvent restrictions on the private ownership of gold but are now used largely as ornaments on bracelets or chains. The amount of gold used for these items is only about 1 percent of world fabricated gold, partly because, at least in the industrial countries, many of these items are gold plated, not solid gold. In the 1990s, consumption in the industrial countries was drifting downward from more than 8 t of gold in 1990 to about 2 t in 1998, whereas the trend in the developing countries was upward from 13 t in 1990 to about 44 t in 1998 (Gold Fields Mineral Services, 1999, p. 97).

Use as an Investment Good

Given its imperishability, scarcity, and identification with money, gold came to be regarded early in history as the ultimate store of value, a reservoir of wealth to be drawn upon in unsettled times (Jastram, 1977, p. 1). It was long considered to be essentially a monetary metal, and much of the bullion produced each year went into the vaults of national treasuries or central banks. With the late 1950s, however, the flow of gold to fabricators of jewelry and other goods and to private investors (in countries where private ownership was allowed) began to exceed monetary acquisitions, and after 1968, when the major industrial nations agreed to abstain from further governmental acquisitions of gold, the metal became essentially a free market commodity whose price changed daily in response to changes in supply and demand.

As described in the section "Historical background," gold has been used as circulating money for hundreds and, in some cases, thousands of years in virtually every country. Today, however, the "official" gold coins being issued are not intended for circulation as currency, but as investments and collectors' items. These fall into one of at least three varieties—updates or restrikes of established coins, such as the "new" British sovereign; commemorative coins struck in honor of some person, organization, or event; and so-called bullion coins, which are legal tender coins stamped with the weight of contained gold and sometimes with a declared face value. All these are priced in the market primarily according to the value of their gold content, which sometimes differs greatly from the denominated value.

Competitive Materials and Processes

In general, the other precious metals (mainly palladium, platinum, and silver) and the electrical metals (aluminum and copper) are the only quantitatively important substitutes for gold alone or gold in alloys. In electronic/electrical devices, solid gold contacts have been largely replaced during the past quarter century with gold-faced base metals to economize on the use of gold while still retaining its benefits. In addition, precious stones, certain base metals, and organic polymers compete with the precious metals for prominence in individual jewelry pieces, and porcelain and acrylic restoration materials compete with gold alloys in dentistry.

Industry

Structure

In the developed countries, there tends to be relatively little vertical integration in the gold producing industry. Gold mines produce doré, which is then shipped elsewhere for refining to commercial-grade gold. Refineries are more likely to be located near the markets for fabricated products than in the mining regions. There tends to be more connection between refining and fabricating; both functions sometimes are carried out within the same company. By and large, however, mines, refineries, and fabricating facilities tend to be physically and organizationally separate. In the United States, cross-ownership among mines, refineries, and manufacturing establishments appears to be minimal. Typically, organizational connection between miners and refiners in the developing countries and those still converting from the Communist system of government is greater. This is true of some developed countries as well. For example, in South Africa, nearly all the gold is mined by members of a central cooperative organization, the Chamber of Mines of South Africa, and perhaps 60 percent or more of South African gold is refined at the Rand Refinery, which is controlled by the Chamber of Mines.

In some countries, a division between the "formal" and "informal" sectors of the mining industry is recognized. The formal sector consists of the largest mining companies, which are either state owned or have licensing and royalty agreements with the Government that cover their operations. The informal sector consists of individuals and small groups who find and start mining gold without formal agreements with the Government, although usually with tacit approval. Whether such activities are considered to be legal or illegal and are encouraged or discouraged depends on the motives of the Government at a given time. For example, in Brazil, where a gold rush began in earnest about 1980, informal production by independent miners (garimpeiros) accounted for as much as 88 percent of the country's production in some years of the 1980s, and for the decade as a whole, they produced nearly three-fourths of the nation's gold. They were encouraged by the Government and were paid a premium over world gold prices. The incentives were then scaled back in the late 1980s and into the 1990s, and some controls were imposed in recognition of such problems as conflict with the aboriginal populations in the interior, hazardous working conditions, and the dumping of more than 200 t/yr of mercury into the Amazon River. As a result of these disincentives as well as shrinking ore reserves, declining ore grades and declining gold prices, garimpeiro production in the late 1990s accounted for only about 30 percent of Brazilian gold production (U.S. Bureau of Mines, 1932-95; Roskill Information Services, 1991, p. 208; U.S. Geological Survey, 1996-99). In China, the formal sector of state-owned mines dominates, but in the mid-1990s, as many as 40,000 "informal" miners were collectively producing significant quantities of gold, perhaps 15 to 25 t/yr. Informal mining is active in several developing countries but is usually a minor source of gold.

Mines

Mines producing 20 t or more accounted for 26 percent of world production in 2001 (table 11). The 15 largest producing companies accounted for 51 percent of world production in 2001 (table 12).

Table 11. World's largest gold mines in 2001

[In metric tons. Data from company annual reports and U.S. Geological Survey unpublished data]

Mine	Country	Owners	Production
Grasberg	Indonesia	Freeport McMoran Copper & Gold Co.; Rio Tinto Ltd.	108
Nevada Operations	United States	Newmont Gold Co.	84
Yanacocha	Peru	Cia. de Minas Buenaventura S.A.; Newmont Gold Co.; International Finance Corp.	60
Betze-Post/Goldstrike	United States	Barrick Gold Corp.	46
Driefontein Consolidated	South Africa	Gold Fields Ltd.	42
Kloof	do.	Gold Fields Ltd.	38
Cortez	do.	Placer Dome Inc.; Rio Tinto Ltd.	37
Great Noligwa	do.	AngloGold Ltd.	31
Durban Deep	do.	Durban Roodeport Deep Ltd.	30
Pierina	Peru	Barrick Gold Corp.	28
Porgera	Papua New Guinea	Placer Dome Inc./Orogen Minerals Ltd.; Gold Fields Ltd.	24
Round Mountain	United States	Echo Bay Mines Ltd.; Homestake Mining Co.	23
Randfontein	South Africa	Harmony Gold Mining Co.	23
Meikle/Goldstrike	United States	Barrick Gold Corp.	22
Kalgoorlie/Super Pit	Australia	Homestake Mining Co.; Normandy Mining Ltd.	22
Bajo de la Alumbrera	Argentina	MIM Holdings Ltd.; Rio Algom Ltd.; North Ltd.	22
Free State	South Africa	Harmony Gold Mining Co.	21

Of the gold produced in the United States in 2001, 92 percent was the principal product at 45 lode mines and about 8 percent was a byproduct at 8 base metal lode mines, chiefly copper mines. The 8 largest mines accounted for 77 percent of domestic gold production (table 13); the 25 largest mines accounted for more than 95 percent. Gold mines employ 9,000 mine and mill workers, who produced gold worth $2.9 billion, as valued at the refined metal stage, in 2001.

Refineries

Gold is normally smelted at the mine into doré, which is a crude gold-silver bullion. The doré is shipped to a commercial precious-metals refinery for separation and purification of the gold and silver. Byproduct gold follows the host base metal through smelting and refining. The gold-bearing material produced at the base-metal refinery (sludge deposited in the electrolysis tanks) may be converted to commercial grade bullion at that refinery or, more often,

Table 12. World's largest gold mining companies in 2001

[In metric tons. Do, ditto. Data from Gold Fields Mineral Services Ltd., 2002, p. 31]

Company	Country	Production
AngloGold Ltd.	South Africa	217
Barrick Gold Corp.	Canada	190
Newmont Gold Co.	United States	168
Gold Fields Ltd.	South Africa	117
Rio Tinto Ltd.	United Kindom	111
Placer Dome Inc.	Canada	86
Freeport McMoRan Copper and Gold Co.	United States	82
Normandy Mining Ltd.	Australia	76
Harmony Gold Mining Co.	South Africa	71
Ashanti Goldfields Ltd.	Ghana	49
Cia. De Minas Buenaventura	Peru	32
Durban Roodeport Deep Ltd.	South Africa	32
Kinross Gold Corp.	Canada	29
WMC Ltd.	Australia	26
Newcrest Mining Ltd.	do.	22

Table 13. Leading gold-producing mines in the United States in 2001

[In metric tons. Data from company annual reports and U.S. Securities and Exchange Commission 10-K and 6-K reports]

Mine	State	Operator	Production
Nevada Operations	Nevada	Newmont Gold Co.	84
Betze-Post/Goldstrike	do.	Barrick Gold Corp.	48
Cortez	do.	Placer Dome (U.S.) Inc.	37
Round Mountain	do.	Smokey Valley Common Operation	23
Meikle/Goldstrike	do.	Barrick Gold Corp.	22
Bingham Canyon	Utah	Kennecott-Utah Copper Corp.	18
Fort Knox	Alaska	Fairbanks Gold Mining Inc.	13
Jerritt Canyon	Nevada	Independence Mining Co.	12

shipped to a precious-metals refinery for processing. As mentioned in the section "Production Technologies," the scale of gold refineries covers a very wide range—from individuals working in one room to full-scale industrial refineries. Even the full-scale industrial refineries, however, are much smaller plants than base-metal refineries. An exception must be made, of course, for the Rand Refinery, which processes most of the output of South Africa's gold mines.

In the United States, more than two dozen refiners produce commercial-grade refined gold; the three largest of these account for more than 90 percent of domestic refined production, which totaled about 274 t in 2001. The ten largest domestic refiners are listed in table 14. Aside from Johnson Matthey plc.'s refinery in Utah, and the copper company refineries, one in Utah (Kennecott-Utah Copper Corp.) and two in Texas (ASARCO Incorporated and Phelps Dodge Refining Corp.), most precious metals refineries are located in the Northeastern States close to the concentrations of jewelry and silverware companies.

Table 14. Leading refiners of gold in the United States in 2001

[In descending order of size. Production figures are withheld to avoid disclosing company confidential information]

Refiner	Location
Johnson Matthey plc.	Salt Lake City, UT
Metalor USA Refining Group	North Attleboro, MA
Kennecott-Utah Copper Corp.	Magna, UT
Ohio Precious Metals Inc.	Jackson, OH
ASARCO Incorporated	Amarillo, TX
Phelps Dodge Refining Corp.	El Paso, TX
Glines & Rhodes Inc.	Attleboro, MA
JC Nordt Company Inc.	Roanoke, VA
Hoover and Strong	Richmond, VA
OMG	South Plainfield, NJ

Fabricators

Jewelry

The majority of jewelry industry manufacturing establishments worldwide consists of small shops and individual artisans. This characteristic is particularly striking in developing countries where an artisan or small group of artisans may work for one or two retail shops. In the early 1990s, Gold Fields Mineral Services Ltd., (1990, 1991, 1993) estimated that perhaps 2 million goldsmiths were working in India, 6,000 fabricators in Turkey, 4,000 small jewelry workshops in Taiwan, and 400,000 people employed in the jewelry industry in China. In most countries, whether developing or industrialized, the bulk of jewelry production is concentrated in just a few centers usually in or around large towns or cities.

In the United States, jewelry manufacturers number about 2,300 and employ nearly 35,000 people (fig. 22); manufacturers of costume jewelry are not included in these totals. The 58 largest companies (those with 250 or more employees) account for one-half of domestic shipments valued in dollars. Jewelry is manufactured in at least 18 States and is concentrated in the Northeastern United States and California (table 15).

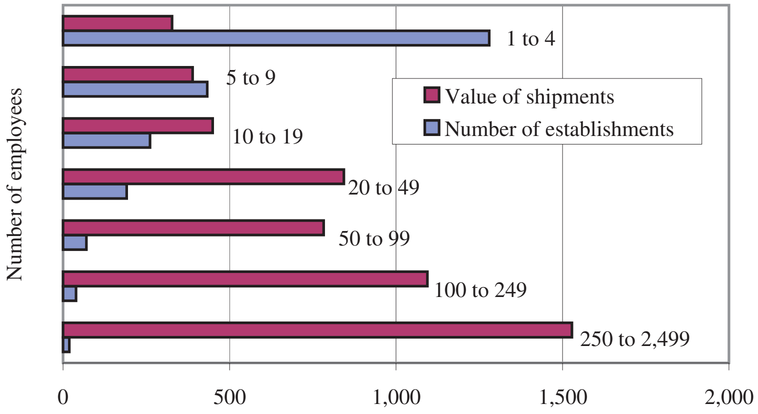

Figure 22. U.S. jewelry manufacturers; establishments totaled 2,300 and employed 34,700 people. Data from U.S. Census Bureau, 1999, p. 9.

Table 15. Geographical distribution of U.S. jewelry manufacturing in 1997
[In percentages. Data from the U.S. Census Bureau, 1999]

State	Manufacturing establishments	Value of shipments
New York	27	37
California	17	11
Connecticut, Massachusetts, and Rhode Island	11	14
Florida	6	2
New Mexico	5	2
Texas	5	5
Other	29	29

For the most part, domestic manufacturers have somewhat specialized product lines and rely on wholesalers for distribution of their products. Although a few of the larger companies cover all aspects of jewelry manufacture from the making of alloys to the design and fabrication of jewelry pieces to the retailing of jewelry, most companies are not at all vertically integrated. Of the $5.4 billion for all kinds of jewelry except costume jewelry in 1997, shipments of domestically manufactured precious metal jewelry totaled $4.6 billion (U.S. Census Bureau, 1999§).

Other Manufacturers

Although the number of manufacturers of dental alloys worldwide is not readily available, it seems likely, by analogy with the United States, to be only a few dozen. As mentioned in the section “Uses,” more than 90 percent of the gold used in making dental alloys is consumed in, in order of consumption, Japan, Germany, the United States, Italy, Switzerland, the Republic of Korea, the Netherlands, and the former Soviet Union. In the United States, only a handful of companies supply dental alloys to the more than 7,500 dental laboratories in the country. These companies are also apt to be refiners of gold. The principal domestic makers of dental alloys are listed in table 16.

Table 16. U.S. major dental alloy manufacturers

Company	Location
Dentsply International Inc.	York, PA
J. F. Jelenko & Co.	Armonk, NY
Glines & Rhodes, Inc.	Attleboro, MA
W. E. Mowrey Co.	St. Paul, MN

The number of companies that use gold in electronic/electrical circuitry and devices is large, but not readily determined. They are companies that make, among other products, electrical connectors, computer chips, instrumentation, and communications equipment,. Most of them are in five countries that account for about 80 percent of the gold used for these purposes; these countries are, in order of consumption, Japan, the United States, the Republic of Korea, Russia and the other members of the Commonwealth of Independent States (CIS), and Germany.

Traders

Metal Traders of the World lists 86 gold bullion traders worldwide (Moreno, 1997, p. 504-507). The actual number of distinct companies is a little smaller because some of the larger traders have subsidiaries in more than one country. Most of them also deal in refined gold in forms other than bullion, and a substantial number deal in other metals in addition to the precious metals. Of the active traders, 28, which includes 17 of the bullion traders, deal in semimanufactured forms of gold, such as sheet, tubing, and wire. Because the international trade in gold is so extensive, most gold traders can be assumed to be importers/exporters as well.

Gold and the Environment

Production

The production of primary gold affects the physical environment principally at two of the production stages—mining and ore processing. The smelting/refining stage poses no appreciable threat to the environment, providing standard procedures are followed and safeguards observed, because of the very small volumes of material treated. With respect to mining and ore processing, both of which take place at the mine site, the extremely low content of gold in all its ores means that extremely large volumes of ore must be excavated and processed for each unit of gold recovered.

In the case of mining, environmental disturbance is much greater in a country, such as the United States, where most of the gold is obtained from surface mines than in a country, such as South Africa, where gold is obtained from underground mines. For every metric ton of gold mined in the United States in 1998, 2.6 Mt of ore and waste was excavated. Among all metals mined in the United States in that year, gold, at 966 Mt, ran a close second to copper in the amount of ore and waste handled. In South Africa, by contrast, less than 200,000 t of ore was milled to recover each ton of gold in 1998. Roughly one-half of the world’s primary gold is now produced from surface mines. Opponents of gold mining who believe that mankind does not need any more gold than is already at hand to sustain civilization object on aesthetic grounds to the vast open pits left after the gold ore has been excavated. They object to other aspects of gold mining as well—acid mine drainage that results from oxidation of the excavated sulfide minerals that are left in huge piles of waste rock after mining and to the air and noise pollution engendered by the mining process itself. Proponents of gold mining hold that modern reclamation practices can return the land to a state that, although different than before mining, is not necessarily inferior aesthetically or inferior with respect to suitability for other subsequent land uses. They also point to the undoubted economic benefits that mining contributes to the surrounding region. The environmental concerns about ore processing center around the universal use of cyanide, which is a lethal poison, to extract gold from its ores. Although the cyanide radical tends to decompose rather quickly, some metal cyanides can persist long enough in ground water to cause concern. Thus, the seepage of cyanides into aquifers can pose a danger to communities near the mine site. In accordance with environmental regulations, current good practice now provides for constant monitoring of ground water from wells deployed around the mine site. In the past, migrant waterfowl have been attracted to spent leach solution ponds, especially in arid regions, and then sickened or killed by the ingestion of cyanide. This problem is now minimized by the widespread use of netting stretched above the ponds. The safety of the earthen dams used to contain the spent solution ponds and whether the ponding systems have the capacity to cope with regional flooding in the wake of abnormally heavy rainfall are also of concern.

Twenty-first-century technology can cope quite well with gold mining's nonaesthetic threats to the environment. Good engineering practices in designing and building solution ponds and containment dams, the installation of equipment for the rapid oxidation of cyanide in emergencies, the monitoring of ground-water quality, the use of netting over spent solution ponds, and the reclamation of mine sites all are routinely used in the U.S. gold mining industry to protect the public and the environment.

Fabrication and Use

In general, gold as a constituent in end products is not a danger to the bioenvironment. By virtue of its chemical and biological inertness, it is among the most environmentally benign of materials. Most of the fabrication processes are likewise harmless to the environment. The potential exceptions are the cyanide electroplating processes, which are widely used in the fabrication of jewelry, electronic/electrical components, architectural glass, and other gold-containing products. The transportation and handling of electroplating salts or fluids, the work environment in electroplating facilities, and the control and treatment of effluents from electroplating lines in the United States are subject to regulations and standards promulgated by the U.S. Occupational and Health Administration and the U.S. Environmental Protection Agency. On the one hand, gold in discarded products that are landfilled poses no threat to the environment. On the other hand, when gold-containing products are disposed of without recycling the constituent materials, the gold is lost to use and is then replaced by newly mined gold with the environmental consequences engendered by mining, ore processing, and smelting.

Market

Physical Gold Market

This section is confined to the market for gold bullion and does not cover the semifabricated shapes, such as alloys, foil, granules, sheet, strip, and wire, that are sold to fabricators. Bullion is usually traded in the international marketplace as refined gold of 995 minimum fineness in 400-ounce bars (nominal weight) typically conforming to the specifications of the London Bullion Market Association for "good delivery bars." This is the form of gold to which all widely quoted gold prices refer. As mentioned in the section "Description," the other principal bars traded on world markets are smaller and may be of higher purity, and range from 995 to 999.9 fine. The kilo bar is favored in Europe, the Middle East; and Southeast Asia; 5 and 10 tael bars are traded on Chinese markets; and 5 and (mostly) 10 tola bars are traded in India and to some extent in the Middle East. Smaller bars and wafers in gram-denominated weights are also available (Weston, 1983, p. 45).

The gold bullion market is international. The cost of transportation is no impediment, being very small in relation to the value of the gold. The demand is global; gold is being traded somewhere in the world at virtually every hour of the day. Gold is shipped to buyers by banks, bullion dealers, mining companies, and refiners. London is perhaps the most influential center for price setting, or "fixing" as it is known, where the same 5 bullion dealers from among the more than 60 members of the London Bullion Market Association meet twice daily to match orders and purchases. The price at which orders and purchases match at each fixing is immediately made available by news services and over the Internet and is used as a reference point worldwide. The other principal gold trading centers are Frankfurt, Hong Kong, New York, Singapore, Tokyo, and Zurich. The principal bullion dealers often have offices in several of the principal trading centers spread around the world (Green, 1991, p. 51, 85).

Much of the gold that is sold on these principal markets is not actually shipped to the buyers; if it has been purchased as an investment, then it may be left in the seller's bank vault after the transfer of ownership has been documented. Some of the stored gold is eventually shipped, but other bars may remain in the vaults indefinitely, sometimes going through several changes in ownership.

Unlike large-volume, low-cost mineral commodities for which the cost of transportation is a substantial part of the commodity cost, gold is not constrained by economics to flow directly from producing countries to terminal markets in specific consuming countries. For the most part, gold still flows from the producing countries, which are scattered around the world, through the major markets already mentioned and through regional centers of trade, such as Dubai, Hong Kong, Turkey, and others, from which it is distributed to the dozens of consuming countries. The direction, number, and size of international trade flows are determined not only by fabrication demand, but also by investment demand; changes in the latter are frequent and can alter the trade pattern abruptly.

Futures Market

Futures trading in agricultural products has been flourishing in the North American Midwest since the mid-19th century. Building on its experience in futures trading, the Winnipeg Commodity Exchange turned to a nonagricultural product in 1972 by offering the world's first gold futures contract. After the right to own gold was restored to U.S. citizens at the end of 1974, the U.S. gold market, and especially the futures trading sector, grew very rapidly. Only 5 years later, 2,640 t (85 million ounces) of gold was being traded monthly on U.S. futures markets, and commercial stocks of bullion, which included futures exchange stocks, totaled more than 93 t (3 million ounces). By 1982, which was the peak year for domestic-futures trading, 3,580 t (115 million ounces) was being traded monthly. In the 1990s, trading volume ranged from 1,560 to 2,520 t (50 million to 81 million ounces) per month. The annual volumes through 1999 are plotted in figure 23. Four of the five U.S. commodity exchanges dealing in gold in 1975 had dropped out by 1989 as trading gradually moved to the New York market, thus making Commodity Exchange Inc. (COMEX) the largest gold futures market in the United States and in the world, a position it still holds. As deregulation of gold spread around the world in the 1970s and 1980s, other futures markets were established, but not all flourished. The Tokyo Commodity Exchange (TOCOM), which first offered a gold contract in 1982, has been by far the most successful gold futures market after COMEX. In 1999, COMEX and TOCOM traded 29,780 t (957.6 million ounces) and 16,010 t (514.8 million ounces) of gold, respectively. Only about 1 percent of the vast quantities of gold sold in futures markets is actually delivered as physical metal.

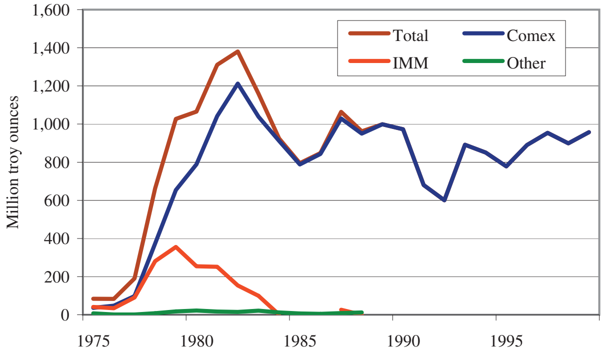

Figure 23. Annual volume of U.S. gold futures trading. Data from U.S. Bureau of Mines, 1932-1995; and U.S. Geological Survey, 1996-2000.

Options Market

Another important component of the gold market is options trading. A gold option is a contract that gives the buyer the right, but not the obligation, to buy or sell a specified quantity of gold at a specified price by a specified date. The cost of the option, or premium, is the option writer's compensation for the risks associated with selling the option. The buyer risks losing the premium, but that is the extent of his liability. Options transactions are highly leveraged; the premium typically ranges from 4 percent to 6 percent of the price of gold, although it can be much higher. Over-the-counter (OTC) options on gold were first introduced in the late 1970s by banks and bullion dealers. Exchange gold options, which are actually options on futures contracts, were first offered by COMEX in late 1982. Their volume grew rapidly from about 1,210 t (39 million ounces) in the first full year of trading to more than 6,470 t (208 million ounces) in 1987, a level still typical in the mid- to late-1990s. Because OTC options are private contracts, their total volume is unknown but is probably at least as large as the total volume of Exchange options sold by COMEX and several other commodity exchanges, and possibly several times larger. OTC options are favored by corporate buyers, such as mining companies, because, unlike Exchange options, they can be custom-tailored to fit the needs of individual buyers and sellers. Options and futures are often used in combination in hedging strategies (Green, 1991, p. 101-103; 1993, p. 62-65).

Supply, Demand, and Sustainability

Current Supply and Demand

Primary gold (that is, newly mined gold) was mined in 94 countries in 2001. Most of the 2,570-t total, however, came from the principal gold mining countries shown in figure 24. World annual production in the 1990s was in excess of 2,000 t/yr (fig. 2).

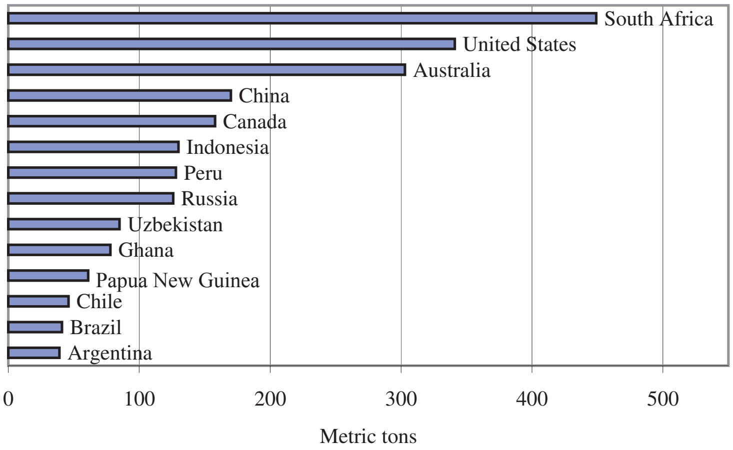

Figure 24. Principal gold mining countries in 1999; these represent 86 percent of world production. Data from U.S. Geological Survey, 1996-2002.

Secondary gold (that is, gold reclaimed from scrap) is an important component of total supply. New scrap, which is also called manufacturers' scrap or process scrap, is usually not counted as part of supply because it is not a net addition to supply. Gold from discarded products, which is termed "old scrap," however, is a net addition to supply. Worldwide, more than 600 t/yr of gold is recovered from old scrap in a typical year; this is equivalent to about 16 percent of the gold consumed in fabrication. For instance, in 1997, regional recovery of old scrap as a percentage of gold consumed in fabrication ranged from 49 percent in Africa to 23 percent in East Asia, 22 percent in the Middle East, 20 percent in the United States, 18 percent in Latin America, and 7 percent in Europe. In the United States in recent years it has been as high as 34 percent. The quantity of old scrap processed can vary widely from year to year depending on economic stability, the price of gold, and even fashion trends in jewelry.

World gold supply and demand figures for 1999 (fig. 25) include world mine supply, secondary metal, deliveries from official bullion stocks, fabrication, and additions to private bullion and coin stocks published by Gold Fields Mineral Services Ltd. (2000). The figures for 1999 are fairly typical of the 1990s, the supply of secondary metal having contracted to normal levels again after having been inflated by the liquidation of much high-karat jewelry in Southeast Asia as a result of the economic crisis that started there in 1997.

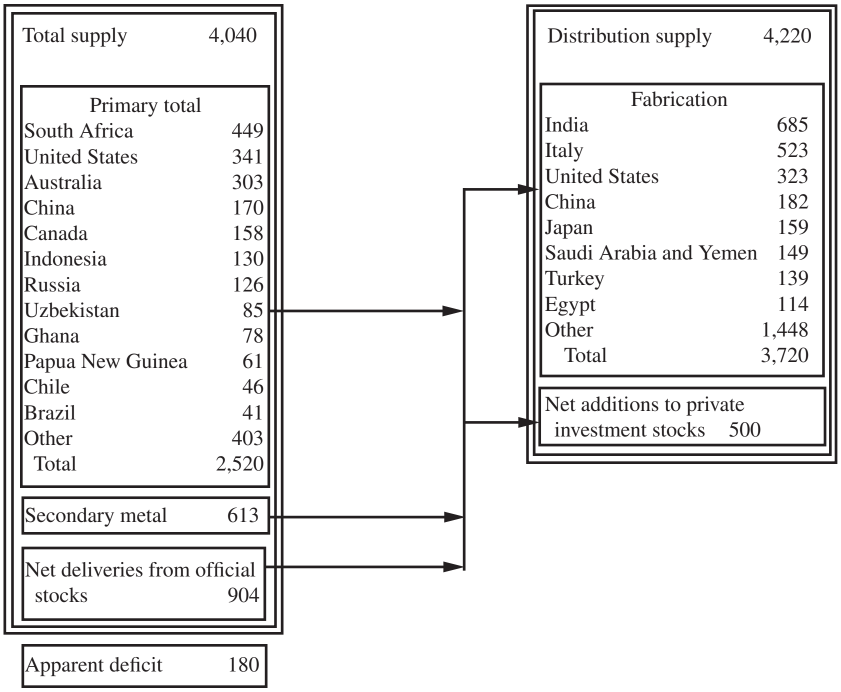

Figure 25. World gold supply and demand in 1999, in metric tons. Data are rounded to no more than three significant digits; because of independent rounding, components may not add to totals shown. Secondary metal is considered to be recovered from postconsumer (old) scrap; process (new) scrap is excluded by GFMS Limited as far as possible. Net deliveries are 420 tons sold and 484 tons leased. Data for primary metal supply from U.S. Geological Survey; other data from Gold Fields Mineral Services Ltd., 2002.

U.S. gold supply and demand for 1999 are shown in figure 26. U.S. supply and demand for a 36-year period are listed in table 17. Salient observations include the following:

- Refined production from domestic ores increased tenfold during the period, and total refined production, which was constrained by slower rising scrap availability, increased sevenfold. These are reflections of the twelvefold increase in domestic gold mine production during the 18-year period beginning in 1980.
- Refinery production from old scrap was significant during the entire period. It climbed from 45 percent of total refined production in 1965 to 74 percent in 1980, but domestic mine production began its steep climb in the mid-1980s, and by the 1990s, secondary production from old scrap in most years accounted for only about 16 to 25 percent of total refinery production.
- From importing little or no commercial bullion in the 1960s, when the ban on private ownership of unfabricated gold was still in effect, to being a net importer in some years of the 1970s and 1980s, the United States became a large net exporter of bullion and doré in the 1990s.
- In most years, net sales of gold have been made to the U.S. market from the stocks of earmarked (foreign official) gold held at the Federal Reserve Bank of New York.
- The quantity of gold used in fabrication of gold products, which grew much more slowly than did the supply of gold, increased by only about 50 percent during the period. Whatever growth took place can be attributed to growth in jewelry fabrication; total consumption for other uses either fell or was stagnant over the period (fig. 14). The consumption pattern remained relatively stable as jewelry increased its fraction of the total by a few percentage points in the 1980s and 1990s to 68 percent of the total in 1999.

Table 17. U.S. supply and demand for unfabricated gold

[In kilograms of contained gold. NA Not available. --- zero. Data include estimates. All data are rounded to three significant digits; because of independent rounding, they may not add to totals shown. Note change at 1995 from 10- to 1-year intervals]

	1965	1975	1985	1995	1996	1997	1998	1999	2000	2001
Components of U.S. supply:										
Refined production:										
Domestic ores	25,500	34,000	45,000	238,000	247,000	257,000	261,000	241,000	164,500	165,600
Imported dore and ore	8,580	7,780	19,600	12,000	13,000	13,000	16,000	24,400	32,500	25,400
Secondary (from old scrap)[1]	18,700	34,900	49,800	75,000	63,000	50,000	82,000	72,000	41,000	41,000
Total refined	52,800	76,700	114,000	325,000	323,000	320,000	359,000	337,000	238,000	232,000
Imports of refined bullion[2]	NA	73,100	198,000	111,000	143,000	194,000	257,000	196,000	184,000	161,000
Net deliveries from foreign accounts[3]	---	17,900	15,100	244,000	373,000	143,000	310,000	380,000	356,000	259,000
Deliveries, U.S. Government sales	146,000	39,000	---	---	---	---	---	---	---	---
Net deliveries from commercial stocks[4]	---	34,500	12,700	13,800	13,000	23,200	---	---	---	54,700
Total U.S. supply	199,000	241,000	340,000	694,000	852,000	680,000	926,000	914,000	778,000	707,000
Distribution of U.S. supply:										
Net additions to commercial stocks[4]	10,200	---	---	---	---	---	3,000	10,800	9,600	---
Exports:										
Refined bullion[2]	---	71,400	89,800	277,000	406,000	391,000	430,000	435,000	440,000	395,000
Dore	5	[5]	2,980	69,700	59,000	74,300	91,600	87,500	103,000	91,800
Scrap	1,560	12,300	30,500	65,800	72,800	54,000	43,000	34,800	64,100	40,100
Consumption, industry and arts[6, 7]	164,000	124,000	180,000	231,000	235,000	246,000	252,000	263,000	275,000	232,000
Total distribution of supply	176,000	208,000	303,000	644,000	773,000	765,000	820,000	831,000	892,000	759,000
Apparent surplus	22,800	33,000	37,000	50,000	79,000	-85,000	106,000	83,000	-114,000	-52,000
U.S. consumption pattern:[6, 7]										
Jewelry and arts	107,000	64,700	111,000	148,000	152,000	159,000	170,000	178,000	182,000	158,000
Dental supplies	11,000	18,500	12,000	11,000	12,000	12,000	13,000	12,500	14,000	13,600
Electronic/electrical uses	8	[8]	37,000	53,000	51,000	57,000	52,000	59,000	64,000	41,500
Other uses	46,000	40,900	21,000	19,000	20,000	18,000	17,000	13,100	14,900	18,600
Total consumption	164,000	124,000	180,000	231,000	235,000	246,000	252,000	263,000	275,000	232,000
U.S. consumption of primary gold[9]	145,000	89,000	130,000	156,000	172,000	196,000	170,000	191,000	234,000	191,000

[1] Includes imported scrap.

[2] Excludes monetary gold.

[3] Net bullion flow between domestic market and stocks held for foreign and international official accounts at New York Federal Reserve Bank.

[4] Stocks include fabricated gold through 1974; beginning January 1, 1975, consist of unfabricated gold only, and, except in 1975, include futures exchange stocks.

[5] Included with scrap.

[6] Arts and industry only; official coins are excluded.

[7] Source: 1965-1975, U.S. Bureau of Mines; 1980-2001, Consolidated Gold Fields/Gold Fields Mineral Services Ltd.

[8] Included in "Other uses."

[9] Defined as total consumption less consumption of gold recovered from old scrap.

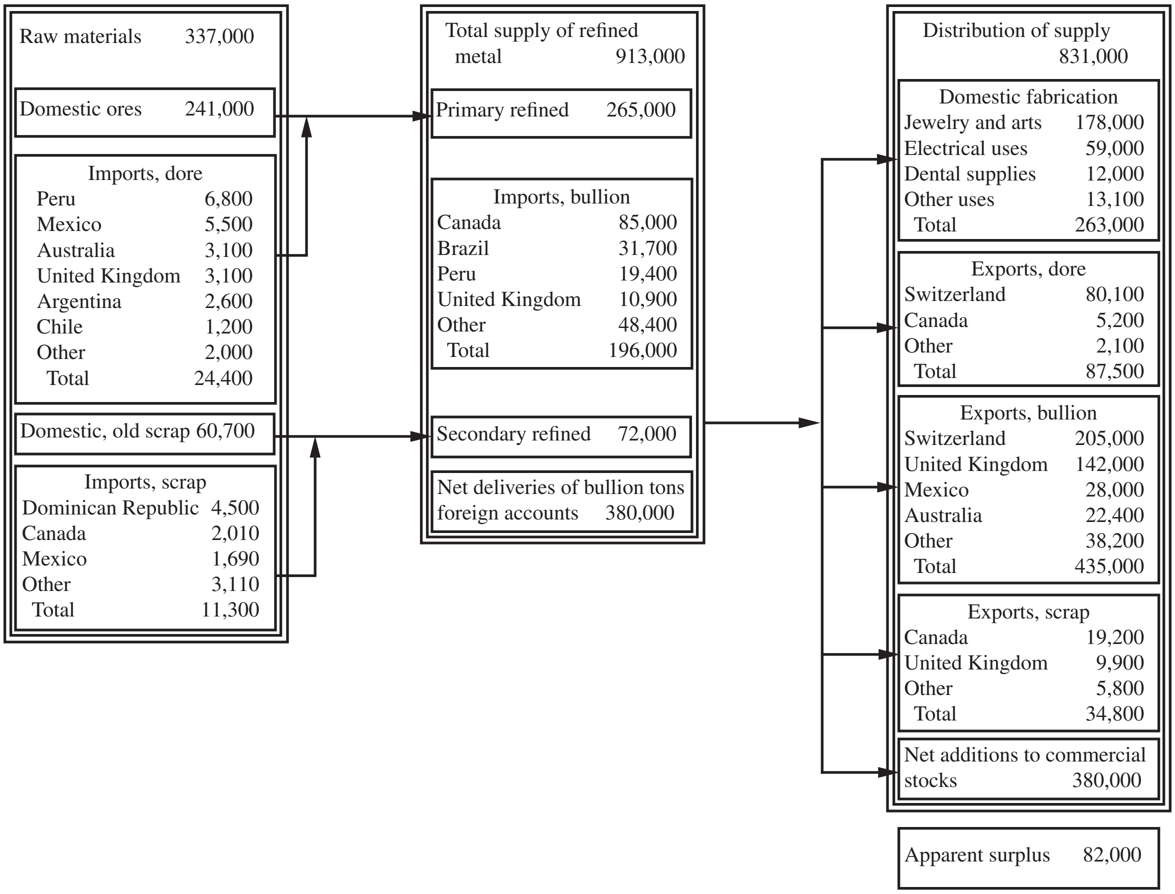

Figure 26. Gold supply and demand in the United States in 1999, in kilograms. Excludes foreign trade in manufactured products. Data are rounded to no more than three significant digits; because of independent rounding, components may not add to totals shown. Totals for imports and exports each include about 100 kilograms (kg) in ores and concentrates. Imports of scrap are considered to be old scrap. Commercial stocks totaled 41,800 kg on January 1, 1999, and 52,600 kg on December 31, 1999. Data for fabrication from Gold Fields Mineral Services Ltd., 2002; other data from U.S. Geological Survey.

- For every year represented in the table, a numerical difference between supply and demand is shown. Part of each difference may be caused by imperfect statistics, but most of the difference probably can be attributed to flows in and out of investors' bullion stocks, for which data are not available.

Potential Supply

Unlike the large-volume metals, nearly all the gold that has been mined in the last five millennia is still above ground, is more or less locatable, and, in large measure, is either still in use or potentially available for use. This trillion dollar "stockpile" is the natural consequence of gold's unique set of properties—its chemical inertness, which limits its combination with other chemical elements; its mechanical toughness, by which it resists dispersion by abrasion or comminution; and its scarcity and associated high price, which ensure that it is conserved in use and is economically worthwhile to recycle, even in minute quantities and low concentrations. It is proposed in this report that of the roughly 140,000 t of gold mined through history to yearend 1999, perhaps 5 percent, or 7,000 t, is a plausible estimate of the amount that has been reburied in landfills and graves or otherwise so dispersed that it is no longer a resource (estimates in the literature range from 1 percent to 15 percent). Of the remainder, an estimated 74,000 t is embedded in fabricated products currently in use. Of this quantity, about 15 percent, or a little more than 11,000 t, is in use in a variety of nonjewelry uses. This gold cannot reasonably be called a stock because it could not, to any considerable extent, be collected and recycled in the event of an acute shortage of gold partly because the products in which it is embedded, such as electronic devices and instruments, are needed in use and partly because they would not quickly yield large volumes of gold. The other 85 percent, which amounts to nearly 63,000 t, is embedded in jewelry and coins, discretionary products of which a large part could be expected to come onto the market in response to the high gold prices engendered by dwindling supplies of gold. It is, therefore, counted as a stock, even though it would not all be offered to the market. The same can be said of the bullion owned by investors and hoarders and of the "official" or "monetary" bullion owned by national governments, few of which still view gold as indispensable to monetary management (fig. 27; table 18).

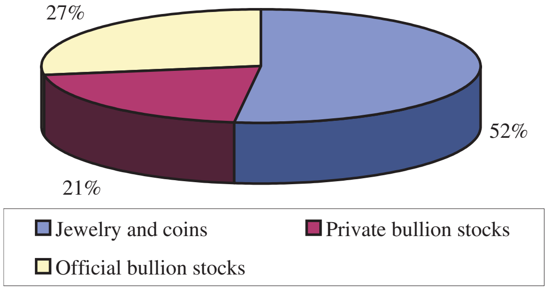

Figure 27. Available above-ground gold worldwide in 1999, which totaled about 122,000 metric tons. Data on official bullion stocks from International Monetary Fund, 2000; data on private investment stocks from Gold Fields Mineral Services Ltd., 2000.

Table 18. Estimate of aboveground stocks of world gold, yearend 1999
[In metric tons]

	Stocks
Total gold mined through 1999[1]	140,000
Irretrievable losses (conjectural)[1]	-7,000
Unavailable (nonjewelry, nonmonetary uses)[1]	-11,000
Total available aboveground stocks	122,000
Composition of available aboveground stocks:	
Official reserves:[2]	
Countries	29,253
International Monetary Fund	3,217
European Central Bank	747
Bank for International Settlement	204
Total	33,400
Private investment[3]	25,200
Jewelry and coins (by difference)	63,000
Total available aboveground stocks	122,000

[1] Data estimated by the U.S. Geological Survey.

[2] International Monetary Fund, 2000.

[3] Gold Fields Mineral Services Ltd., 2000.

Of the total monetary bullion, 84 percent is owned by industrial countries, and 16 percent by developing countries; the United States owns about 26 percent of the world total. The geographical disposition of jewelry and privately owned bullion and coins is not readily quantifiable, but the bulk of the gold is likely to be in Europe, India, the Middle East, North America, and Southeast Asia.

Identified underground resources of gold are conservatively estimated to total about 100,000 t (Amey, 2001). Of this, at yearend 2000, 77,000 t is in the reserve base, and 48,000 t is reserves; the reserve base is equivalent to about 32 years of mining at the 2000 rate. The United States has 5,600 t in reserves and 6,000 t in the reserve base, the latter being equivalent to nearly 18 years of mining at the current domestic rate. The adequacy of reserves and reserve base with respect to projected consumption of mined gold through 2020 is listed in table 19. The total potential world gold supply consists of roughly 122,000 t above ground and available and 100,000 t below ground.

Table 19. U.S. and world gold reserves, reserve base, and demand
[In metric tons. Amey, E.B., 2001, Gold: U.S. Geological Survey Mineral Commodity Summaries 2001, p. 70–71]

	United States	World
Reserve base, yearend 2000	6,000	77,000
Reserves, yearend 2000	5,600	48,000
Projected cumulative mined gold demand, 2001–2010	1,060	30,600
Projected cumulative mined gold demand, 2001–2020	2,280	67,500

Strategic Considerations

Gold is an essential metal that cannot be easily replaced in some uses related to national defense. Its use in electronic devices and as a solid lubricant in moveable joints on spacecraft are examples of defense-related uses. The amounts required, however, are very small compared with those stockpiled. The United States, for example, requires 50 to 55 t/yr of gold for electronic/electrical uses of all kinds. The U.S. Treasury has a stock of 8,140 t, which is enough to supply that requirement, at the current rate of use, for more than 150 years. In addition, some private bullion stocks and "stocks" of jewelry could come onto the market in the event of a national emergency.

Sustainability of Production and Use

Sustainable development of natural resources (that is, satisfying today's needs without injuring the ability of future generations to meet their needs) is an important concept in today's world. Flows of material goods have become so large and the environmental degradation wrought by the extraction of raw materials and the fabrication of finished goods have become so troublesome that many question mankind's ability to sustain these flows as they continue to grow rapidly. Since 1980, U.S. gold consumption in noncoinage uses has increased by more than one-half, and comparable world consumption has more than quadrupled.

If undue degradation of the environment can be avoided, then gold mining will continue, as it has for the past 6,000 years, so long as underground resources remain adequate. Absolute depletion of underground gold resources will not be reached because the price of extracting metal from the remnant low-grade resources will become too high, which will dampen and then extinguish demand. Gold mining's future may be shortened if consumption grows rapidly enough to exhaust resources or if social and monetary environmental costs become prohibitive. Its future may be lengthened if technological advances result in the discovery of new resources or greater efficiency in the extraction of resources that are presently classed as uneconomic. It may also be prolonged by the development and use of substitutes for gold, or, because so much of the discussion of demand centers around jewelry, the development of customer acceptance of substitutes.

How fast gold mine production can grow in the future without causing serious environmental problems is limited. If an effort were made to satisfy a rapidly rising world demand for gold at all costs, then the environmental component of those costs would be high and possibly unacceptable in countries where most of the gold is produced from surface mines. Legislation and regulations that relate to environmental damage and the potential danger from cyanide treatment of ore may effectively limit mine production in some countries. The curtailment already in effect in the United States is the result of legal actions, voter initiatives, or Executive orders that have impeded the development of new gold mines in recent years (American Metal Market, 1997, 2001; Platt's Metals Week, 1998).

The secondary (recycled gold) component of supply is much less likely to become a problem. Gold is the ultimate survivor among metals—it can be recycled innumerable times with no loss in quality and with relatively little physical loss. Because the adverse environmental effects of fabricating and recycling appear to be controllable and the costs acceptable, sustaining the flow of secondary gold appears to be quite feasible.

World consumption of gold in all fabricated products, led by consumption in jewelry, grew at nearly 8 percent per year between 1980 and 1999. Growth slowed thereafter and has averaged about 2.8 percent per year since 1992. If growth were to continue at 2.8 percent per year from 2000 through 2020, about 104,000 t of gold would be required for fabrication. Assuming that newly mined gold were to constitute about 65 percent of the annual world supply, as it has through the 1990s, more than 67,000 t would be required plus 37,000 t from scrap and other above-ground stocks. To produce 67,000 t would require that world mine production grow at about 2.8 percent per year for two decades. This seems feasible, considering that although world gold mine production grew, on average, only 1 percent per year in the 1990s and 1.9 percent per year in the 20th century as a whole, it has, at times, grown faster, as in the first decade of the century, again in the 1930s and 1950s, and most recently, in the 1980s, when it grew by nearly 6 percent per year.

Rapid growth in gold consumption would be easier to sustain in the United States not only because of very large bullion stocks, but because mine production is large and still has good growth potential. Domestic consumption of gold for fabricated products seems unlikely to test the limits of sustainability anytime soon. It has been growing quite slowly for several decades and is projected to grow only a little faster in the years ahead. The quantities of primary gold required can be supplied easily by domestic mine production.

Economic Factors

This section will focus on the economics of gold production, especially in the United States. The economics of gold consumption has been mentioned in earlier sections that cover the uses of gold. Although a detailed discussion is beyond the scope of this report, a few salient points are recapitulated here. Worldwide gold consumption for jewelry, which accounts for 85 percent of the gold fabricated each year, is highly price-sensitive and liable to sharp changes in demand in response to changes in the price of gold. Gold use in dentistry also responds to price changes but to a lesser degree and is partly influenced by dental insurance payment limitations. Gold use in many other product classes is relatively price inelastic in the short term and only moderately price elastic in the medium to long term. This is so because gold is nearly indispensable in some uses and is usually an item of small cost in relation to the total cost of the end-use product. In products where the use of gold is desirable, but not critical, the loss of performance or durability upon substitution of another metal for gold plus the cost of reengineering the product often outweighs the savings gained by reducing or eliminating the use of gold.

Exploration

Replacement of its ore bodies is critical to the long-term survival of a mining company. It may choose to purchase mineral properties discovered by someone else or do its own exploration or both. Many of the world's mining companies that are large enough to have an exploration division, as well as many of the mineral exploration service companies that work on a contract basis, are based in developed countries that have a well-established mining industry—such as Australia, Canada, France, South Africa, the United Kingdom, and the United States. Worldwide, the annual budget for gold exploration is influenced heavily by the price for gold and more particularly by the forecast for price in the years ahead when mine investment costs are to be recovered along with suitable profits. The exploration arena shifts geographically as promising new gold terranes are outlined; new, lower cost ways of processing ores are developed; the level of political stability in host countries changes; and those countries modify their laws on investment, mineral ownership, and taxation in ways that encourage or restrict exploration of their resources. Mining companies shift their exploration efforts to countries that have favorable resource prospects and a favorable business climate and divert exploration funds away from countries where those factors have become less favorable or decidedly unfavorable. In the 1990s, exploration budgets targeted for the industrialized countries trended downward, and those for the developing countries trended upward; the trend lines intersected in 1994, after which the funds budgeted for developing countries became the larger segment and reached about 63 percent of the world budget in 1997 (fig. 28; Wilburn, 1998, p. 56; 1999, p. 46). In the case of gold, the resurgence of exploration in developing countries has been fueled not only by political and economic considerations, but also by the redirection of exploration in the past quarter-century to low-grade bulk-mineable gold ores amenable to treatment by cyanide heap leaching or vat leaching. Such deposits are now being sought in developing countries, after having been bypassed in earlier years because they were then uneconomic to mine and process.

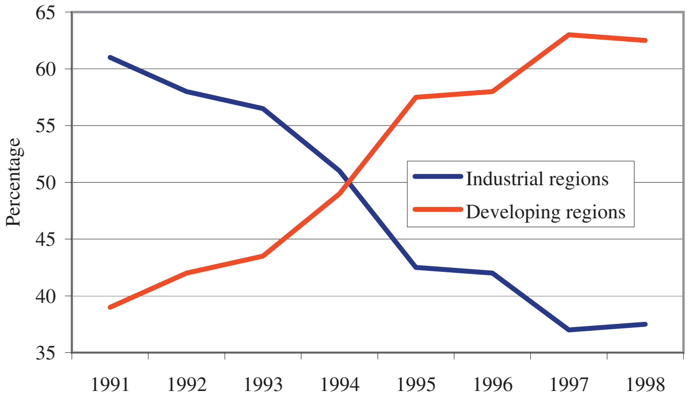

Figure 28. World exploration budgets for nonfuel, nonferrous materials. Data from Wilburn, 1998, p. 56; 1999, p. 46.

For many years, more money has been spent in the search for new gold deposits than has been spent for all of the other nonfuel mineral commodities combined. Data published by Metal Economics Group that covered an estimated 79 percent of world exploration budgets indicate that gold accounted for about 65 percent of exploration expenditures in 1997. Extrapolated to 100 percent coverage, this suggests that gold accounted for something like $3 billion, possibly as high as $3.3 billion, of an estimated $5.1 billion budgeted worldwide for exploration for all nonfuel minerals (excluding iron ore) (Wilburn, 1998, p. 57). By 1998, falling commodity prices had brought the total exploration budget down to $3.5 billion, of which gold accounted for perhaps $1.8 billion or $1.9 billion (Wilburn, 1999, p. 45). From 1990 through 1997, budgets for exploration in the United States, which were dominated by gold exploration, remained fairly stable on a dollar basis but shrank by more than one-half as a share of the world budget. This is at least partly attributable to the perception by domestic mining companies that U.S. environmental regulations and the environmental permitting process are costly and time-consuming hindrances. In 1998, the domestic exploration budget was estimated to be $243 million; the share allotted to gold was not specified (Wilburn, 1999).

Mining

Importance, Size, and Profitability

As with other basic industries, the economic mark of the gold mining industry extends considerably beyond the miners who are employed and the immediate localities of the mines and processing plants. The industry creates jobs, earnings, and economic output directly and additional jobs, earnings, and economic output indirectly in industries and businesses from which the gold industry and its employees purchase goods and services. For example, although about 26,000 people were directly employed in the U.S. gold mining industry in 1997, additional indirectly created jobs in other sectors led to a total in excess of 80,000 people in producing States plus several thousand more across the Nation (Dobra, 1999, p. 8). The Gold Institute estimates the U.S. direct and indirect total to be nearly 100,000 (Gold Institute, 2000§). The industry pays higher wages than are typical of most other industries and tends to buy services from high-wage sectors of the economy, such as the engineering and financial sectors. In 1995, for example, average annual earnings per job in metal mining in Nevada, where metal mining is completely dominated by gold mining, was $47,540, or nearly twice the average salary in the State (Dobra, 1997, p. 6). As would be expected, the economic importance of gold mining relative to other economic sectors varies widely from place to place and is very important to local mining communities but less important on a regional or national scale. There are, however, a few exceptions. South Africa is probably the best example of a country in which gold mining retains considerable national importance; in 1997, mining accounted for about 3 percent of the gross domestic product (perhaps twice that percentage if indirect multiplier effects are included), employed 343,000 people (or 6.5 percent of "all people employed in the non-agricultural sectors of the economy") , and brought in nearly one-half of the revenue from mineral export sales (Chamber of Mines of South Africa, 2000). On a smaller geographic scale, gold mining also is very important in Nevada where, in 1997, direct and indirect employment in gold and silver mining amounted to nearly 52,000 jobs, and economic output was nearly $4.9 billion; in 1996, its economic output amounted to about 9 percent of the gross State product (Dobra, 1999, p. 8-9). The mining industry itself is of modest size. One measure of size—market capitalization—helps provide a perspective. In mid-1999, the four largest general mining companies in the world, all of which were public companies, had market capitalizations that ranged from $18 billion to $23 billion. By contrast, four of the largest U.S. companies (two computer-related, one general manufacturer, and one petroleum refiner) had market capitalizations that ranged from $200 billion to $400 billion (David Williamson Associates, Ltd., 1999).

The revenue generated by gold mining might seem impressive, but profits should also be considered. Although certain individual mines may be very profitable, the gold mining industry as a whole ranks rather low in return on investment. For example, in 1995, which was a fairly representative year, gold mining in the United States returned about 5.5 percent on equity, better than the 3.8 percent for all mining, but poor in comparison with nondurable goods manufacturing (16.8 percent) and with all U.S. manufacturing (16.5 percent) (Dobra, 1997, p. 12). In reference to gold mining specifically, Dobra (1999, p. 27) commented that ". . . earnings in the industry will always tend to lag behind market averages. Investor bias, resulting from the fact that those willing to invest in gold mining tend to believe that the price of gold will rise, leads to financing of marginal projects that lower returns. If prices do rise, financial performance will initially be outstanding, but financing of marginal projects will ultimately bring these returns down."

Operating Environment

In most of the world, landowners own only the surface rights of their properties, while ownership of mineral deposits on the properties is reserved to the national government. A notable exception is the United States, where, until early in the 20th century, title to all Federal land was conveyed to the States and private individuals as land grants or under several disposal statutes, in "fee simple"; that is, both surface and subsurface rights were transferred to the buyer (Maley, 1977, p. 55). When a mineral deposit on one of these privately owned properties is exploited, the mine operator pays the land owner a royalty based on the value of minerals produced, just as a miner pays a royalty to the national government in most other countries. When minerals are extracted from metal deposits located on U.S. Federal land, however, no royalty is collected by the Government. The mining of metals on Federal land is governed by the Mining Law of 1872, which does not require payment of royalties.

This is an issue of particular importance because 54 percent of the land in the Western States, which is the location of most of the country's metal mining, is Federal land, of which nearly one-third is still open to location of mining claims (table 20). In Nevada, which is the State with the largest gold production, 83 percent of the land is owned by the Federal Government.

Table 20. Federally owned lands in the United States versus non-Federal lands
[XX, not applicable. Source: U.S. General Services Administration, 2000, Public land statistics 1999—Part 1—Tables 1–3: Web site at http://www.blm.gov:80natacq/pls98 (Accessed June 20, 2000.)]

	Total State area (acres)	Federally owned land (percentage)	
		State lands	U.S. total
Western States:			
Alaska	365,481,600	67.9	10.9
Arizona	72,688,000	45.6	1.5
California	100,206,721	44.9	2.0
Colorado	66,495,760	36.4	1.1
Idaho	52,933,120	62.5	1.5
Montana	93,271,040	28.0	1.2
Nevada	70,264,320	83.1	2.6
New Mexico	77,766,399	34.2	1.2
Oregon	61,598,720	52.6	1.4
Utah	52,696,960	64.5	1.5
Washington	42,693,760	28.5	0.5
Wyoming	62,343,040	49.9	1.4
Total	1,118,439,440	54.1	26.6
Other	1,152,903,920	4.4	2.2
Grand total U.S. land	2,271,343,360	XX	28.8

Under the current mining law, any U.S. citizen or anyone who has declared an intention to become a citizen and corporations organized under the laws of any State can file an unlimited number of mineral claims for "locatable minerals," a category that includes most metals. After staking and recording a claim to a valid mineral discovery, the possessor may proceed to develop and mine the claim contingent on the payment of a $100 annual claim maintenance fee. Although the fee title to a registered (but unpatented) mining claim remains with the Federal Government, the locator "acquires an exclusive possessory interest in the claim, a form of property which can be sold, transferred, mortgaged, or inherited, without infringing the paramount title of the United States" (Maley, 1977, p. 145). The 1872 law also allows established mining companies to obtain patents on their claims, which gives them title to the property, including minerals thereon, and makes their claims no longer challengeable. About 90 percent of U.S. gold is mined on patented land (Dobra, 1999, p. 22). Debate on the merits of reforming the Mining Law of 1872 has continued on and off in the U.S. Congress for several years, and since 1994, the Government has maintained a moratorium on new patent applications. In the United States, the gold royalties that are paid to landowners usually range from 1 percent to 5 percent of the unit sale price of refined metal derived from the mine less certain processing costs. These may be "net smelter royalties"—a term that dates from earlier times when mines commonly shipped gold ore to smelters rather than smelt ore to doré and ship doré to refiners, as is done today—or "net proceeds royalties," which are similar except that mining costs, in addition to smelter/refiner costs, are deducted from the unit sale price before imposition of the royalty. U.S. gold mines are moving towards the negotiation of royalties based on profitability either tying the percentage to the price of gold or using a flat percentage coupled with deduction of certain production costs. Despite the location of many gold deposits on or surrounded by federally owned land, the payment of royalties is the rule rather than the exception. This suggests that many claims are either leased or purchased and that the lessors/sellers have reserved a royalty interest in the properties. In 1997, royalties were paid on 80 percent of U.S. gold mine production and averaged $13.76 per ounce, or 4.2 percent of the $332 average price for gold (Dobra, 1999, p. 20-24).

Governments in many countries have traditionally provided direct subsidies or tax concessions to their mining industries. These benefits provoke endless recrimination in trade discussions. In the United States, the depletion allowance, which is a percentage of the income from mine production and is considered to be a return of capital not subject to income tax, attracts opposition by those who consider it a kind of corporate welfare. It is intended to be similar to depreciation, except that it is based on the need of a mining company to replace its reserves, which are depletable assets, whereas depreciation allows for the replacement of worn out plant and equipment. The depletion allowance for domestic and foreign production of gold is 15 percent (Amey, 2001).

Production Costs

Mineral production costs have been classified in several ways. A distinction is usually made between operating and capital costs and sometimes between direct and indirect costs. Among those principal categories, many ways have been used to group and name subsidiary costs. Direct costs, which are those involved directly in extracting and processing the ore may be categorized according to the stages of production, such as development, stoping, haulage, pumping, ventilation, crushing, milling, and so forth. Alternatively, they may be categorized according to the factors of production, such as explosives, labor, power, supplies, and so forth. Indirect costs include a long list of ancillary costs, such as supervision, engineering, assaying, repair, shaft sinking, exploratory drilling, and insurance, some of which are considered to be direct costs in some cost schemes. Because the cost structure varies greatly from one mine to the next, investors and stock analysts have had difficulty in evaluating mines and prospects relative to each other or to industry norms. To aid in comparison of gold operations and properties, North American gold producers adopted the following uniform "disclosure-based" way of reporting costs in 1996:

- Cash costs equal extraction costs plus processing costs plus on-site administrative costs;
- Total cash costs plus cash costs plus State/local production taxes plus royalties; and
- Total costs (or total production costs) equal total cash costs plus noncash costs (such as off-site depreciation, depletion of ore reserves, corporate overhead, exploration/development costs, reclamation costs, and Federal income tax).

In this scheme, cash costs and total cash costs are associated with specific gold properties and, thus, are useful in comparing different properties (Gold Institute, 1999). The relative importance of classes of operating cost on an industrywide basis and the ranges of cash costs for individual mines or projects are presented in tables 21 and 22.

Capital costs per unit of production range widely, as may be seen from the examples in table 23. Although the costs in table 23 are amortized over the mine life, which typically is 10 to 15 years, they add significantly to the costs of producing each ounce of gold, and the higher costs among those in the table may make it difficult to make a profit at the low prices prevailing in 1999-2000.

The overall unit cost of production is, of course, strongly influenced by the amount of gold contained in the ore and the efficiency of recovery of that gold. As heap-leach, carbon-absorption technology spread rapidly

Table 21. Cash and long-run average total costs at U.S. gold mines
[In dollars per troy ounce. Data from Dobra, 1999, p. 11]

	1994	1995	1996	1997
Extraction	107	144	136	102
Processing	84	75	66	72
Administration	18	12	11	25
Cash costs	209	231	213	200
Taxes and royalties	22	25	21	19
Total cash costs	231	256	234	219
Noncash costs	86	51	47	75
Total costs	317	307	281	294

Table 22. Actual and projected cash operating costs for selected gold mines and projects
[In dollars per troy ounce. Data from Metals Economics Group, 1998, 1999a-c, 2000]

	Year of evaluation	Average gold price	Range of cash costs	Average (weighted) cash cost
United States, producers (39)	1998	295	57–445	180
Canadia, producers (37)	do.	295	145–345	195
Commonwealth of Independent States, late-stage gold projects (9)	do.	295	113–200	154
Australia, late-stage gold projects (13)	1999	280	153–218	189
Africa, late-stage gold projects (13)	do.	280	133–250	178
Latin America, late-stage gold projects (13)	do.	280	98–231	138

Table 23. Projected capital costs of selected gold projects under development
[Ag, silver; Au, gold; Cu, copper; g/t, grams per metric ton; koz/yr, thousand troy ounces per year; $/oz, dollars per troy ounce; S, surface mine; UG, underground mine. Data from Metals Economics Group, 1999a-c, 2000]

Mine	Location	Type	Products	Gold grade (g/t)	Production capacity (koz/yr)	Year of evaluation	Capital cost of annual produciton capacity ($/oz)
McDonald	United States (Montana)	S	Au, Ag	0.69	567	1999	423
Kensington	United States (Alaska)	UG	Au	4.23	200	do.	985
Crown Jewel	United States (Washington)	S	do.	6.24	185	do.	730
Olympias	Greece	UG	Au, Ag	8.33	295	2000	837
Sappes	do.	UG/S	Au, Cu	13.83	135	do.	274
Nalunaq	Greenland	UG	Au	32.00	145	do.	137
Zod	Armenia	S	do.	7.42	50	do.	200

in the 1980s, the average ore head grade in the United States trended downward to 1.5 g/t in 1991 from 3.6 g/t in 1981 (Slater and Ward, 1994). The average grade of U.S. ores is currently (1999) about 1.85 g/t. A study of 33 U.S. operating lode gold mines found that 20 percent to 85 percent of contained gold was being recovered from heap-leached ores and 72 percent to 96 percent from milled ores. The production-weighted averages were 67 percent for heap leached ores and 88 percent for milled ores. Recovery from base metal ores was said to range from 60 percent to 70 percent (U.S. Bureau of Mines, 1994, p. 16-22).

Another important factor in the cost of production is labor productivity. Modern gold mining and ore-processing methods are used everywhere gold is mined in large quantities, but labor productivity ranges widely according to the degree of mechanization at mines and, to a lesser extent, at processing plants, as well as to the difficulty of mining the several kinds of deposits and processing various kinds of ore. In South Africa, which is the most important producer from very hard ores in very deep mines, gold mining is still labor intensive. In 1997, each underground worker in South African mines produced, on average, about 2.4 kg of gold. In the United States, where production was mostly from surface mines and shallower underground mines, the comparable figure for mine/mill workers was about 22.1 kg. The productivity of U.S. mine/mill workers rose along with mine production in the 1980s and 1990s to about 23 kilograms per worker in the mid-1990s from 5.5 kilograms per worker in 1980. From 1996 to 1999, it rose abruptly to 33 kilograms per worker as mine/mill employment was cut sharply to 10,300 workers in 1999 from 16,900 workers in 1996. Whether such high productivity can be sustained in the longer term remains to be seen.

Mining costs are sometimes stated in terms of cost per ton of ore mined. The cost per ton of ore for underground mines is normally higher than that for surface mines; the grade of ore mined underground, however, is typically higher than that taken from surface mines. The result is that the cost per unit of gold output is comparable for the two types of mining.

Adjustment to Price Changes

After the all-time high annual average price of $612.56 per troy ounce in 1980, the annual average price for gold ranged from $318 to $478 through the rest of the 1980s. From 1990 through most of 1996, it ranged from $345 to $385. A downward trend in the monthly average price began in the last few months of 1996, and by yearend 1997, it had dropped below $300 where, except for 2 months, it remained through 2000. When adjusted for inflation, current prices are the lowest they have been since the early 1970s (fig. 29; Amey, 1999).

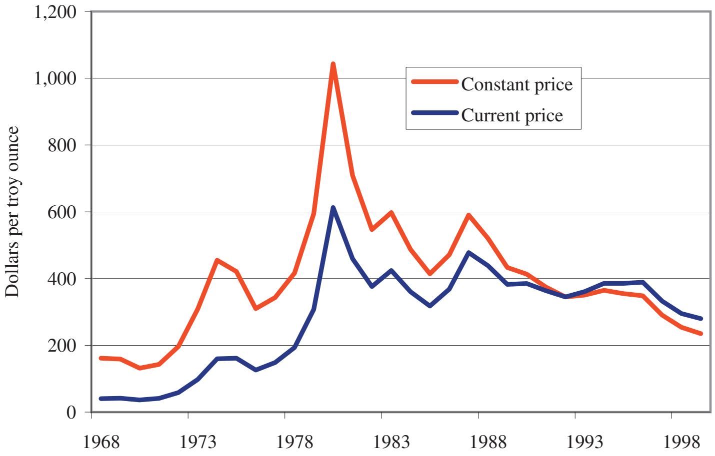

Figure 29. Annual average price of gold, as quoted by Englehard Corporation.

The mining industry adjusts to protracted periods of low product prices in several ways. One is to consolidate operations and companies to achieve economies of scale. This tactic changed the structure of the South African gold mining industry extensively in the 1990s as new legislation allowed the formation of more efficient working units through mergers and transfers of properties (Coakley and Dolley, 1999, p. KK2-KK3). It has also been important in North America and elsewhere in the past few years.

Mining companies also adjust to lengthy periods of low prices by closing marginal operations. Most of the mines that remain in operation, whether they have restructured or not, survive by yet another tactic—they raise the ore cutoff grade, which is the lowest grade that can be mined and still allow the operator to cover expenses and make an acceptable profit. The mining plan that is developed before a mine is opened prescribes a rate of mining and a cutoff grade that will allow return of capital plus a reasonable profit while maximizing the amount of ore that can ultimately be removed from the deposit. Because most ore bodies are heterogeneous to some degree, ores from different parts of the deposit can be blended to achieve a grade representative of the ore body as a whole if the mining method in use permits it. When the cutoff grade is raised above the planned grade, which is called high-grading, some of the regions of low-grade ore are bypassed. Many of these regions will never be mined, even if product prices rise, because if it was uneconomical to mine them when high-grade ore was available to blend with them, then it will usually be even more uneconomical to mine them later by themselves. This is especially so if much time elapses, thus allowing high -grade ores to be depleted, pits and underground workings to flood, and mine structures and machinery to deteriorate. High-grading may allow the mine to remain in operation but at the price of forfeiture of part of the mineralized material in the deposit. When widely practiced, high-grading often has the paradoxical result that national mine production rises for a year or two after a period of low price establishes itself and falls when prices rise again.

Although high-grading is wasteful of natural resources, it helps avoid the detrimental business and social consequences of a widespread industry shutdown and is not usually a long-term solution. In a long-term low-price regime as prevailed in the United States in the 1940s, 1950s, and 1960s, when domestic miners had to sell gold at the fixed monetary price, most mines were eventually shut down. Some companies left the business and others tried to retain ownership of mineral deposits they believed would once again become valuable properties.

Other Survival Techniques

In the late 1980s when the price of gold was above or just below $400 per ounce but on a downward trend, gold loans offered by bullion banks were popular with producers. A producer would borrow a quantity of bullion at an interest rate lower than charged for other forms of capital, sell it at the current gold price, use the proceeds to fund mining projects, and then repay in gold at a future date. When the payoff dates were in the 1990s, by which time the gold price had declined by $40 to $60, the producer reaped the added benefit of the price differential. In the early 1990s, most participants in the market believed in the probability of higher gold prices in the future, and gold loans quickly became unattractive and soon lost favor to hedging. Hedging, whether in futures or in options, became widely used in the gold mining industry in the 1990s. By selling futures or option contracts for delivery of gold at a future date, producers were able to reduce downside price risks, and in some instances, when the price fell more than anticipated, actually make a profit from the hedging. The strategy is not without risk, as shown by the difficulty several producers had in meeting their contractual obligations with brokers and avoiding financial ruin when the gold price surged upward in September 1999 when 14 European central banks announced that they would limit the sale of gold stocks to 400 t/yr during the ensuing 5 years . Also, by hedging several years' production, producers forego the possible profit to be made should the gold price rise; for this reason, several producers in the United States and some other countries have been reluctant to hedge. Hedging has been used most by Australian and North American producers. In the late 1990s, a movement away from straight futures hedging and toward options hedging became strong (Green, 1993, p. 62-66; Gold Fields Mineral Services Ltd., 2000, p. 50).

Recycling

To a refiner, whether the gold scrap being recycled is classified as new (manufacturing) or old (postconsumer) makes little difference. If the scrap is received from a collector, then it may be old or new or a mixture of both. What does matter is the tenor (gold content) of the scrap and whether it is clean or dirty, complex or simple because those attributes will determine the process to be used and the costs of recovering the gold. Those who keep statistics on the gold industry are interested in the breakdown between old and new scrap because the quantities in the two categories respond to economic forces differently. The statistics collected from refiners, however, for reasons mentioned above, are not very reliable. Michalopoulos (1983) analyzed U.S. secondary gold statistics for the relatively short period from 1975 to 1983 for which separate figures for old scrap and new scrap had been available for the United States. The following points are drawn from his study:

For 1983, jewelry and electronics together accounted for about 90 percent of the gold recovered from scrap, and each contributed about the same quantities. Whereas jewelry scrap consisted of about one-third old scrap and two-thirds new scrap, the proportions were exactly reversed in electronic scrap. In forecasting trends in secondary production, these proportions have important implications.

Gold recovery from old scrap is directly related to the price of gold and to the availability of gold-containing scrap. When the price of gold is high, old gold comes onto the market in larger quantities sometimes, as in the time of record high gold prices in 1980, thus outstripping the capacity of the refining industry.

Gold recovery from new scrap is directly related to the general state of the economy. Gold price is not as important and may even be inversely related to the production of new scrap.

For old scrap, the costs of collection are greater than the costs of recovering gold from the scrap.

Outlook

The use pattern for fabricated gold is unlikely to change much in the next 10 to 20 years. Jewelry will remain the largest use by far. Most new developments will be in dentistry, electronics, or other industrial uses and are not likely to introduce large tonnage changes. Substitution of other metals for gold will be minimal despite the ongoing pressure to use cheaper materials. Projected consumption between 2000 and 2021 and the tonnages of newly mined gold required are listed in table 24. Known gold resources in the current (2002) reserve base are adequate to cover the projected need for newly mined gold. The supply of secondary gold, as well as primary gold from other sources (table 17) will provide the remainder of the gold needed.

Table 24. Projected consumption of gold for fabrication, by end use

[NA, not applicable; ---, zero. Except in consumption trend line column, data are limited to three significant digits. Because of independent rounding, data may not add to totals shown]

	Consumption in 1999 (metric tons)		Projected consumption (metric tons)		Annual growth rate for 1999-2020 (percentage)
	Actual	Trendline	2010	2020	
United States:					
Karat jewelry	178	170	233	310	3
Electronic/electrical	59	54	69	87	2
Dentistry	13	12	13	13	---
Other arts/industry uses	13	17	12	8	-4
Total, noncoinage uses	263	252	327	418	2
Official coins[1]	60	NA	30	30	NA
Total, all fabrication uses	323	NA	357	448	NA
Cumulative newly mined gold[2]	NA	NA	1,060	2,280	NA
World:					
Karat jewelry	3,130	3,060	4,010	5,130	3
Electronic/electrical	243	242	410	661	5
Dentistry	65	67	69	71	---
Other arts/industry uses	151	161	253	382	4
Total, noncoinage uses	3,590	3,530	4,740	6,250	3
Official coins[1]	135	NA	100	100	NA
Total, all fabrication uses	3,720	NA	4,840	6,350	NA
Cumulative newly mined gold[2]	NA	NA	30,600	67,500	NA

[1] This use was considered unpredictable. For the United States, 30 t, which is a rounded version of the 1984 to 1999 average, was chosen, and the growth rate was put arbitrarily at zero. For the world, 100 t was chosen as a representative figure to carry forward at zero growth.

[2] Newly mined gold is assumed to account for about 30 percent of the U.S. market supply and 65 percent of the world market supply as in the 1990s.

Mining is expected to be able to grow fast enough to provide the needed new gold; U.S. mine production already is ample, but world mine output will have to grow faster than it has in the past decade. Environmental constraints may not be so severe as to preclude the faster growth. Recycling, which has always been important in the gold fabrication industry and is highly efficient, will maintain its share of supply, but will not enlarge it appreciably.

The processes for extracting gold from its ores will probably see the development of alternatives to cyanide leaching (probably thiourea or sodium thiosulfate systems) and advances in the bio-oxidation of sulfide ores.

Although the demonetization of gold in the industrial countries likely will continue to completion in the next few decades, the most important European central banks have declared their intention to work together in limiting sales from official bullion reserves during the next few years (Gold Fields Mineral Services Ltd., 2000, p. 56). They may be expected to continue that policy indefinitely because it is not in their interest, as sellers, to depress the price of gold.

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Glossary

Alloy A very old term for the admixture of a precious metal with a metal of lesser value. Now the term applies more generally to any [atomic] combination of metals (Brady and Clauser, 1977, p. 27).

Bullion coins Legal tender coins minted by national governments of declared gold content but without a declared face value, such as the Britannia (United Kingdom), Eagle (United States), Ecu (France), Krugerrand (South Africa), Maple Leaf (Canada), and Philharmoniker (Austria). Sold at a premium over the value of the contained gold, and intended as a convenient form of gold for small-scale investment.

Chasing The art of ornamenting metal surfaces by indenting them with hammer and tools or cutting with a graver. Also used to refer to the pattern so produced or the entire work so chased.

Depletion allowance In the United States, a proportion of income derived from mining or oil production that is considered to be a return of capital not subject to income tax (U.S. Bureau of Mines, 1996).

Doré A crude gold-silver bullion usually produced at the mine site and sent to a refinery where silver and gold are parted and the gold refined to commercial-grade gold bullion.

Fine gold Used by itself, without numerical qualification, this term refers to unalloyed, or “pure” gold as distinguished from coin gold or other gold alloys.

Fineness The purity of gold expressed in parts per thousand. For example, gold that contains 90 percent gold and 10 percent alloy metal is referred to as “900 fine.” More information can be found in the description for “Karat.”

Gangue or gangue minerals That part of an ore that is not economically desirable but cannot be avoided in mining. It is separated from the ore minerals during concentration. These are the valueless minerals in an ore (U.S. Bureau of Mines, 1996).

Hallmark “A mark, or number of marks, made on gold, silver, or platinum jewellery or plate to confirm that its quality is up to the correct legal standard” (Green, 1991, p. 66). Now used in many countries, hallmark originally referred to the mark of the Goldsmiths’ Hall in London.

Karat Like fineness, karat refers to purity, but is expressed in twenty-fourths. For example, 24-karat gold is 1000 fine, or pure gold, and 12-karat gold refers to an alloy of gold and one or more other metals that is 12/24 (50 percent or 500 fine) gold.

Liquid gold A term applied to suspensions of gold powder in organic vehicles, such as essential oils, and to solutions of organogold compounds in organic solvents. The liquid golds are used as inks or paints, which are applied by any of several techniques to the articles to be decorated with thin films of gold.

Medal “A small disc or piece of metal struck by a government, institution, company, or private individual to commemorate a specific event or person. A medal usually has no monetary function or value, but is struck on both sides as is a coin” (Weston, 1983, p. 58).

Medallion “A medallion is a medal of two inches or more in diameter and may only be struck on one side” (Weston, 1983, p. 58).

Mineral deposit “A mineral occurrence [concentration] of sufficient size and grade that it might, under the most favorable of circumstances, be considered to have economic potential” (Cox and Singer, 1986, p. 1). More information can be found in the description for “Ore deposit.”

Ore deposit “A mineral deposit that has been tested and is known to be of sufficient, grade, and accessibility to be producible [at] a profit” (Cox and Singer, 1986, p. 1). More information can be found in the description for “Mineral deposit.”

Paper gold Gold contracts, such as futures contracts or options, which may, but do not usually, involve the actual transfer of physical gold (Green, 1991, p. 105).

Purple of Cassius “Red colloidal tin oxide with adsorbed gold, formed on adding alkali to a mixture of solutions of stannous, stannic, and gold chlorides; used in the manufacture of ruby glass and red enamels” (Grant, 1969, p. 555).

Repoussé Thin metal sheet on which patterns in relief have been created by hammering on the reverse side or pressing on the reverse side into a mold. The art of creating repoussé is called repoussage.

Specie Money in the form of coin, which can be gold, silver, or any other coinage metal.

Troy ounce A traditional unit of weight used for the precious metals. One troy ounce is equivalent to 1.097 ounces avoirdupois or 31.10 grams. Troy weight is still used widely, especially in English-speaking countries, for prices and for expressing the grades of gold deposits in troy ounces per short ton of ore.

Appendix

Definitions of Reserves, Reserve Base, and Resources

The term “resources,” as applied to metals, refers to those concentrations of metal-bearing minerals in the Earth’s crust that are currently or potentially amenable to the economic extraction of one or more metals from them. “Reserves” and “reserve base” are subcategories of resources. “Reserves” refers to the in-place metal content of ores that can be mined and processed at a profit given the metal prices, available technology, and economic conditions that prevail at the time the reserves estimate is made. “Reserve base” is a more-inclusive term that encompasses not only reserves proper, but marginally economic reserves and a discretionary part of subeconomic resources—“those parts of the resources that have a reasonable potential for becoming economically available within planning horizons beyond those that assume proven technology and current economics” (U.S. Bureau of Mines and U.S. Geological Survey, 1980).