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The challenges of mineral resources for society

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ABSTRACT

Trends in global mineral production and expanding uses of mineral resources foretell a bright future, though one with significant challenges, for exploration and development. Demand for mineral resources is likely to remain high and grow to meet increases in world population and standards of living. Significant challenges include meeting future demand with new discoveries and developing the resources in environmentally, socially, and economically sustainable ways. A historical perspective from the past 50 years on finding new mineral districts, discovering new types of ore deposits, and using new technologies in exploration suggests that the world will not run out of mineral resources. It is likely that substitution and recycling will play increasingly major roles in meeting global mineral demand. New technologies for ocean mining will help add to the resource base. Historical perspectives also suggest that mining scams will continue, and environmental, health, and safety concerns will be major factors in deciding where future mines will be located and how they will be operated.

TRENDS IN MINERAL PRODUCTION

With rising world population and ever-increasing average standards of living, demand for mineral and energy commodities is at an all-time high and can be expected to increase. Three commodities—iron (used primarily for steel in the construction of buildings, infrastructure, vehicles, and machinery), copper (used primarily to conduct electricity), and gold (used primarily as a substitute for money)—illustrate the point.

Iron-ore production has been climbing more or less steadily, as world population has increased, for over a century (Fig. 1). The rate of production has outpaced population growth, however. From 1911 to 2011, world population increased by a factor of 3.9, while production increased by a factor of 21. Per capita consumption, defined as global production divided by world population, has risen by a factor of 5.4 in that same 100 years.

Much of the recent rise in iron-ore production has been fueled by extraordinary economic growth in China. Not only is China now mining more iron ore than any other country (Fig. 2), it is importing much of the ore produced in Australia and Brazil, two other countries that have seen recent surges in iron-ore production. India has also seen iron-ore production increase dramatically in tandem with its economic growth. Historical iron-ore production by country (Fig. 2) also illustrates major world events. U.S. iron production declined significantly from 1930 until near the beginning of World War II. The U.S. then dominated global iron-ore production in the immediate post-war years but was overtaken by the Soviet Union (Russia in Fig. 2) in 1958. China's economic boom began in the mid-1980s and dramatically increased in ~2002, as shown by Chinese iron production.

If mineral resources were more or less evenly distributed geographically worldwide, China would be expected to produce roughly 19% of the world's mineral resources in line with its 19%

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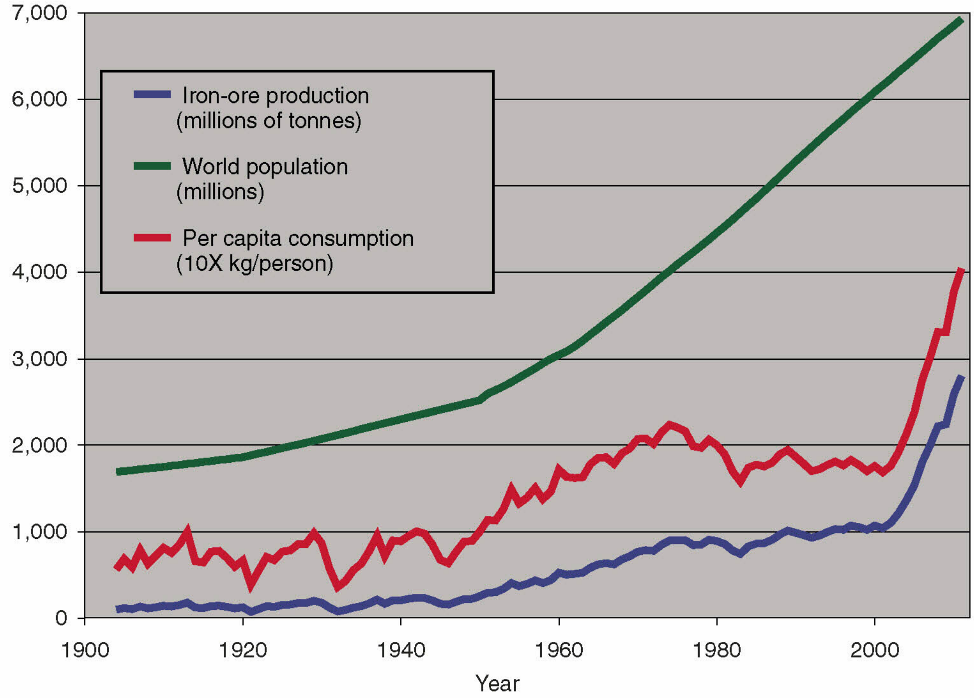


Figure 1. Annual global iron production, 1904–2011 (production data from U.S. Geological Survey and U.S. Bureau of Mines; population data from U.S. Central Intelligence Agency).

of world population. However, mineral resources are not distributed geographically evenly. For example, in recent years China has produced 97% of the rare earth elements (lanthanides) and holds ~50% of the world's reserves (U.S. Department of Interior, 2012). While China is a dominant producer of many commodities (Fig. 3), it is not necessarily because it is better endowed in mineral resources than other countries. China is producing its domestic resources rapidly, and it must import much of the chromium, cobalt, copper, nickel, and platinum-group elements that it needs for its growing economy. The uneven distribution of mineral resources places other countries at the forefront for these elements (Kazakhstan and South Africa for Cr; Democratic Republic of

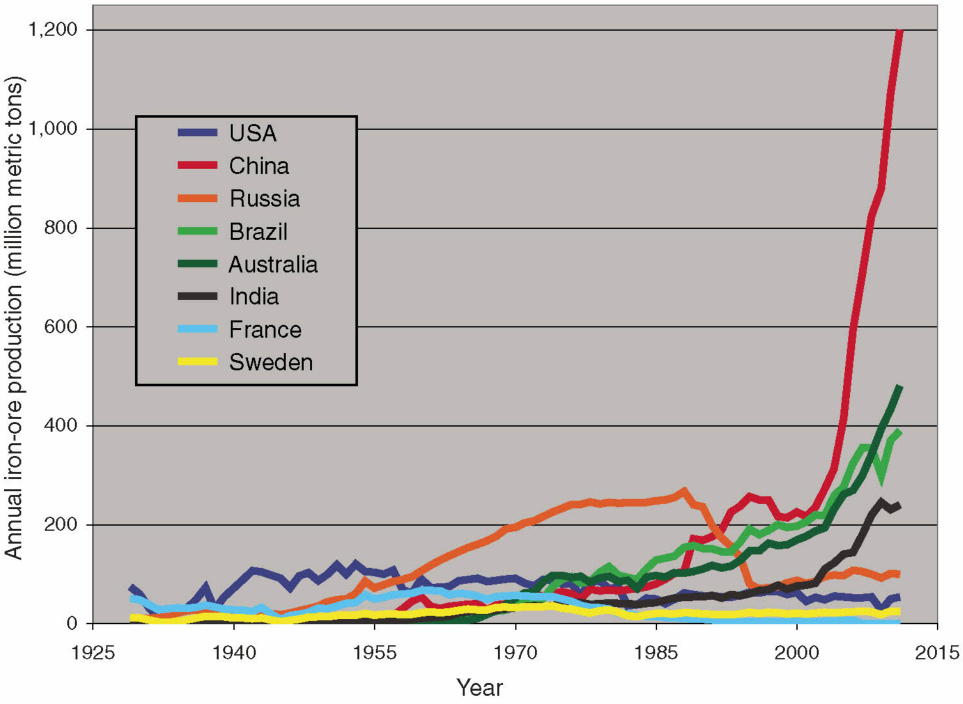


Figure 2. Annual iron production by major producing countries, 1929–2011 (data from U.S. Geological Survey and U.S. Bureau of Mines).

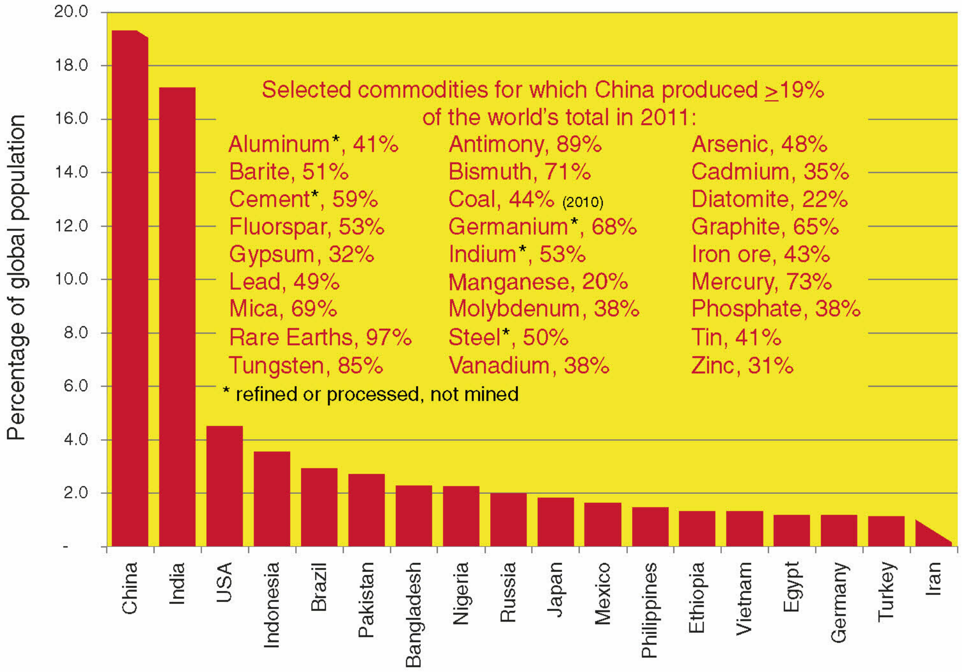


Figure 3. Most populous countries and China's percentage of global production for selected commodities (data from U.S. Geological Survey, U.S. Department of Energy, and U.S. Central Intelligence Agency).

Congo for Co; Chile for Cu; Russia, Indonesia, Philippines, Canada, and Australia for Ni; South Africa and Russia for Pt and Pd).

Global annual copper production reached an all-time high of 16.1 million tonnes (metric tons) in 2011 (Fig. 4). To put this amount into perspective, it is about the same as the total production from the Bingham Canyon copper mine (Fig. 5)—17.2 million tonnes throughout its history from 1906 to 2011 (Rio Tinto, 2012a)—to date the world's largest copper mine. Similar to iron, global copper production increased 18-fold from 1911 to 2011 (Fig. 4). Per capita consumption increased by a factor of 4.6 during this period, another indication of improving average standard of living, as more people throughout the world have electricity, refrigerators, cars, and other conveniences that need copper.

Chile has been the leading copper-producing country since 1982 (Fig. 6). Its production feeds much of global demand, including imports to China. Although China's production has

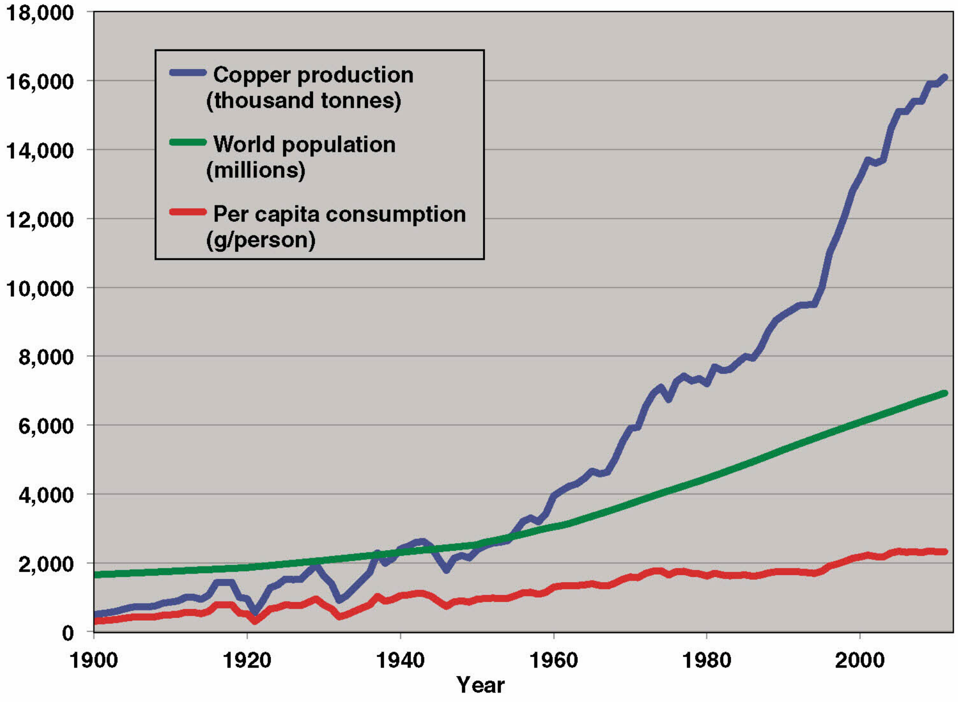


Figure 4. Annual global copper production, 1900–2011 (production data from U.S. Geological Survey and U.S. Bureau of Mines; population data from U.S. Central Intelligence Agency).

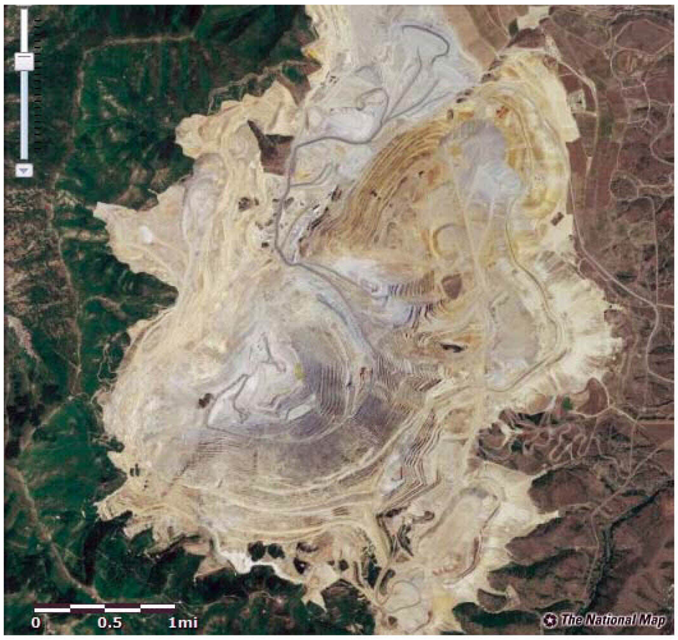


Figure 5. Aerial photograph of the footprint of the Bingham Canyon mine, Utah (source: U.S. Geological Survey, 2012). The mine is currently ~4.4 km wide and 1.2 km deep (Rio Tinto, 2009).

risen dramatically in recent years, it currently produces only 7% of the world's total. As a result, Chinese companies are aggressively making deals in other parts of the world to secure copper resources for the future.

Global gold production also reached an all-time high in 2011 (Fig. 7). Although gold has many industrial uses (e.g., in electrical wiring in computers and cell phones, as a heat reflector, and in dentistry), its major use is as a substitute for money, either as bullion or, in much of the world, jewelry. From 1910 to 2011, per capita production has oscillated somewhat (by a maximum factor of 2.4) with the global economy and world events; global production of gold has more or less followed the rise in world population.

The remarkable change in global gold production is the recent dominance of China as the world's leading producer (Fig. 8). For over 100 years, South Africa's Witwatersrand gold deposits dominated global production, but China captured the lead in 2007 and has steadily increased its production since then.

A clear challenge for the future is to meet global demand for mineral resources such as iron, copper, and gold. Exploration geologists, geochemists, and geophysicists (collectively, "geos") need to find, and engineers need to develop and mine, huge resources to meet current demand (e.g., the equivalent of one Bingham Canyon–size copper deposit each year). Clearly geos, with their knowledge of ore systems, tectonic environments, regional geology, and potential environmental consequences, will be the leaders in discovering new deposits.

EXPANDING USES OF MINERAL RESOUCES

Whereas nearly every naturally occurring element has several significant uses today, 80 years ago far fewer elements were widely used (Fig. 9). In 1932, during the Great Depression, mineral production and industrial activity in the United States had plummeted, relative to boom years after World War I. At that time, uranium and the rare earth elements had only minor uses, and the U.S. Bureau of Mines wasn't tracking the production or

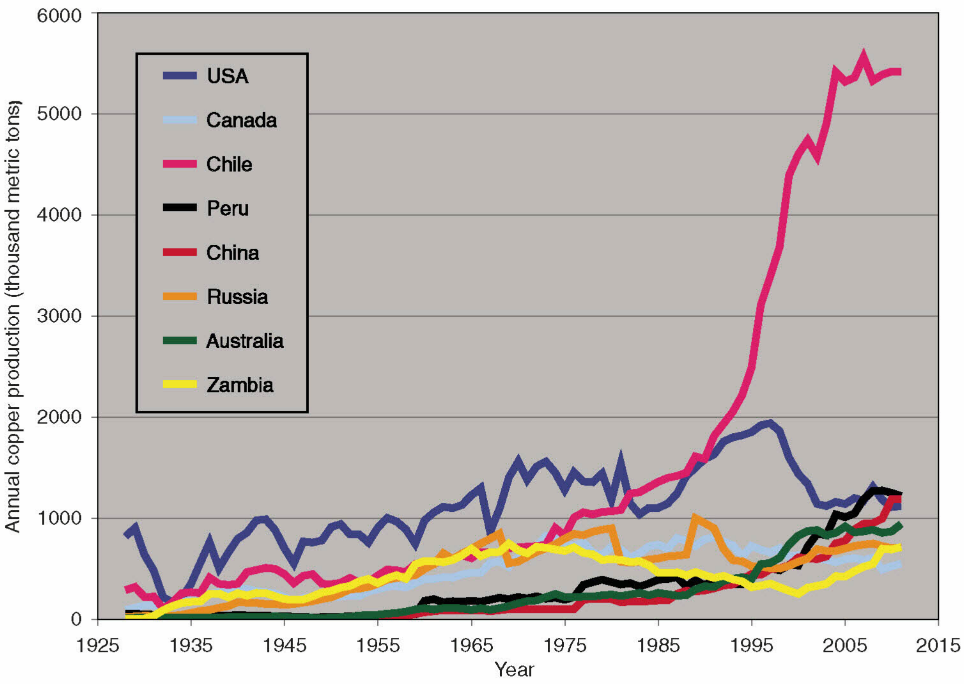


Figure 6. Annual copper production by major producing countries, 1928–2011 (data from U.S. Geological Survey and U.S. Bureau of Mines).

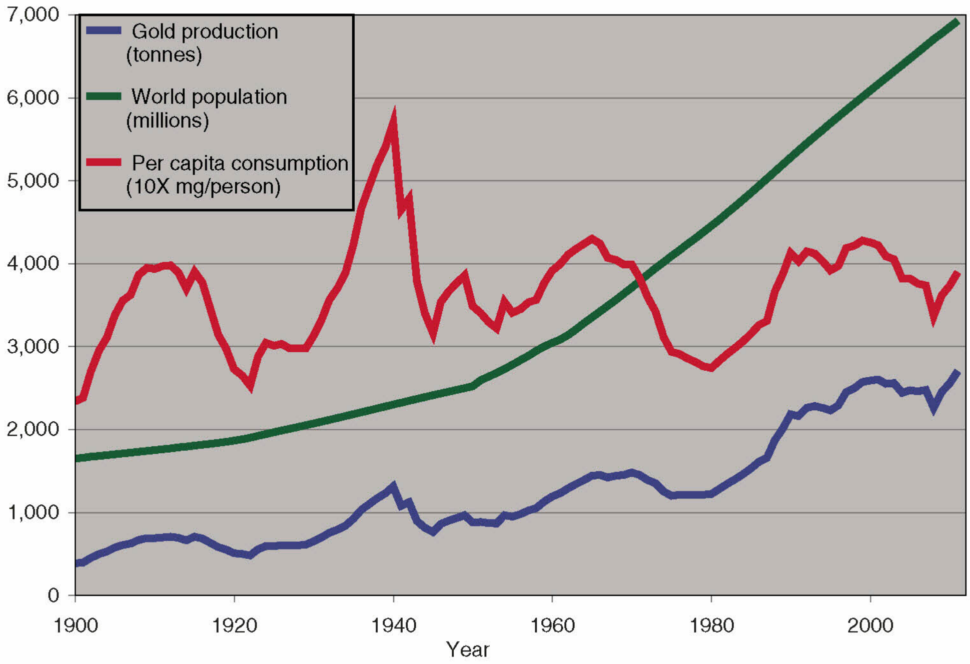


Figure 7. Annual global gold production, 1900–2011 (production data from U.S. Geological Survey and U.S. Bureau of Mines; population data from the U.S. Central Intelligence Agency).

use of lithium, gallium, germanium, rhenium, or several other elements. Activity increased by 1952, in the boom years after World War II and during the Korean War. New technologies, including various applications of rare earth elements, lithium, and gallium were creating demands for more elements. By 2012, essentially all naturally occurring elements were being used, although primary applications have changed over time.

As an example, in the late 1920s and early 1930s, mercury was used widely in drugs and the chemical industry, detonators and ammunition, thermometers, electronics, the production of felt (although mad hatter's disease from mercury poisoning was already recognized at that time) and, in limited amounts, in boilers for generation of electricity. By 1952, mercury uses included electronics, thermometers, pesticides, the industrial production of chlorine and caustic soda, drugs, and dental amalgam. Today, recognizing the dangers of breathing mercury, its use in the United States and Europe has declined considerably, with primary applications in lighting and the production of chlorine and

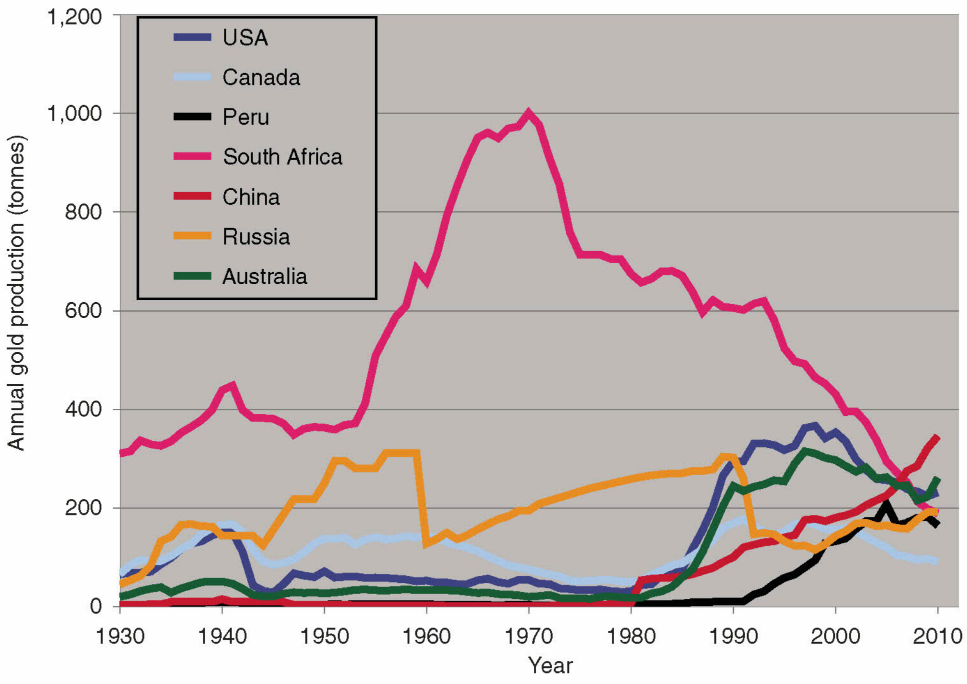
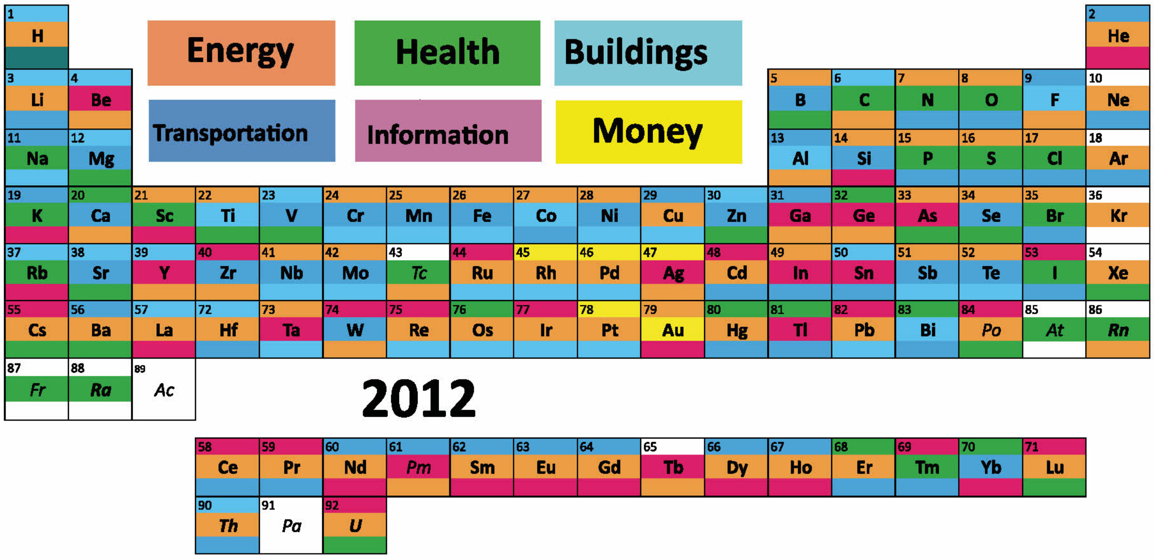
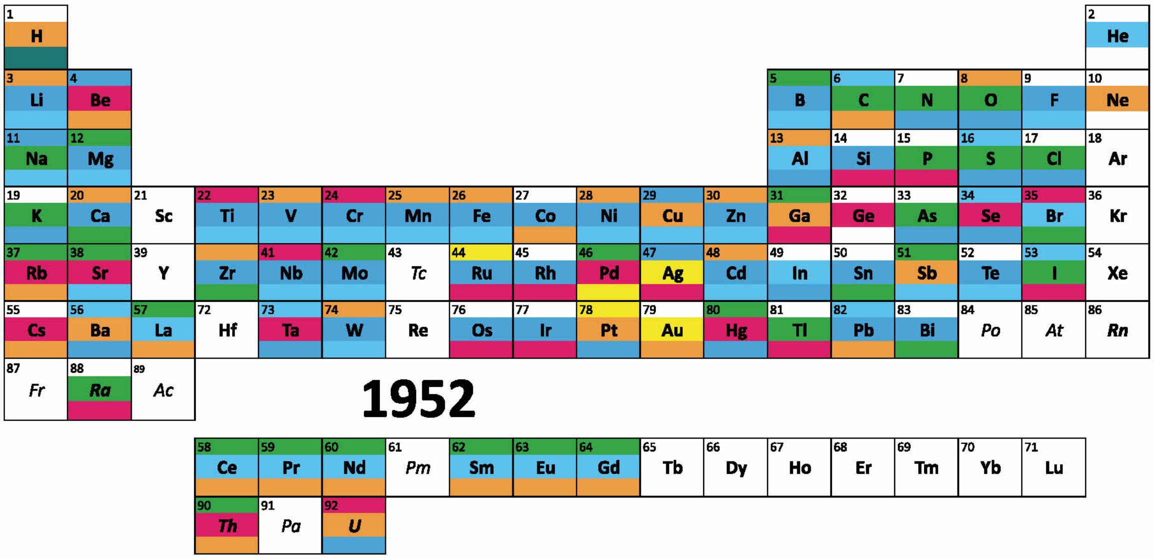


Figure 8. Annual gold production by major producing countries, 1930–2011 (data from U.S. Geological Survey and U.S. Bureau of Mines).


Energy
Health
Buildings
Transportation
Information
Money
2012


1952

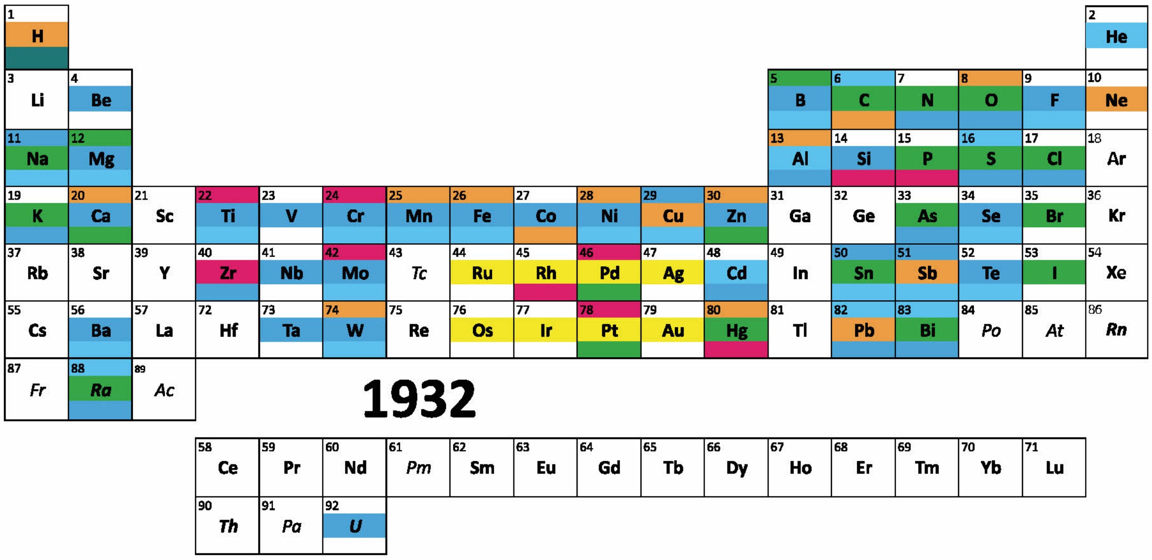

1932

Figure 9. Expanding major uses of the naturally occurring elements from 1932 to 1952 to 2012. There are more than three major uses for many elements today. Sources: U.S. Department of Commerce (1933), U.S. Department of Interior (1955, 2012). Six general categories of uses are listed, with information primarily from annual reports of the U.S. Geological Survey and U.S. Bureau of Mines. "Energy" includes the elements used in the production, transmission, and storage of energy, as well as lighting. "Health" includes elements necessary for life (in food and pharmaceuticals) and for the growing of crops (fertilizers and pesticides). "Buildings" include materials needed for structures and their general contents and the tools needed to construct them. "Transportation" includes elements needed for vehicles and infrastructure, including moving water and wastewater. "Information" includes communication systems, electronics, and optics. "Money" includes elements that are held as backing for currencies or as a substitute for money and used in jewelry and the arts.

caustic soda. Its use by artisanal gold miners in many underdeveloped countries continues.

As uses and demand for various mineral commodities have changed, so too have prices. Other factors affecting prices include availability (measured crudely by crustal abundance), geological rarity, costs of processing, and byproduct potential. In a broad sense, as one would expect, there is a negative correlation between price of commodities and crustal abundance (Fig. 10). More abundant elements are generally less expensive. Diamond and coal (two forms of carbon) stand out as anomalies on this chart. Diamond is geologically rare, and coal is abundant; thus their prices vary by over six orders of magnitude. Aluminum and iron prices illustrate variations in processing costs. As ores, both have prices that fall within predictable ranges, but as refined metal, aluminum is considerably more expensive, due to the form of energy needed to reduce the oxides to metals. Expensive electricity is used to break aluminum-oxygen bonds in bauxite ore, whereas inexpensive coal is used to reduce iron from magnetite and hematite ores. In comparison with crustal abundances, several commodities have relatively low prices because they are byproducts of the production of major metals (cadmium as a byproduct of zinc; tellurium and selenium as a byproduct of copper; rhenium as a byproduct of molybdenum production from porphyry copper deposits that are rich in molybdenum). Demand limits the prices of some commodities that have environmental toxicity concerns, including cadmium, arsenic, and lead.

PEAK OIL, PEAK FLINT, AND THE SUPPLY OF MINERAL RESOURCES

Hubbert (1956) more or less accurately predicted peak production of conventional oil for the conterminous United States and the world, and he predicted a likely peak for coal in the distant future. His analysis logically applies for these fossil fuels, because the recovery is limited to conventional technologies and because there is no reasonable chance of recycling them. Once they are burned to create energy through the oxidation of carbon to carbon dioxide, recycling would require even more energy (to convert the CO_2 back to C) than was initially produced. Hubbert's analysis does not apply to most mineral resources for two fundamental reasons: (1) the amount of ultimately recoverable resource depends primarily on the economics of supply and

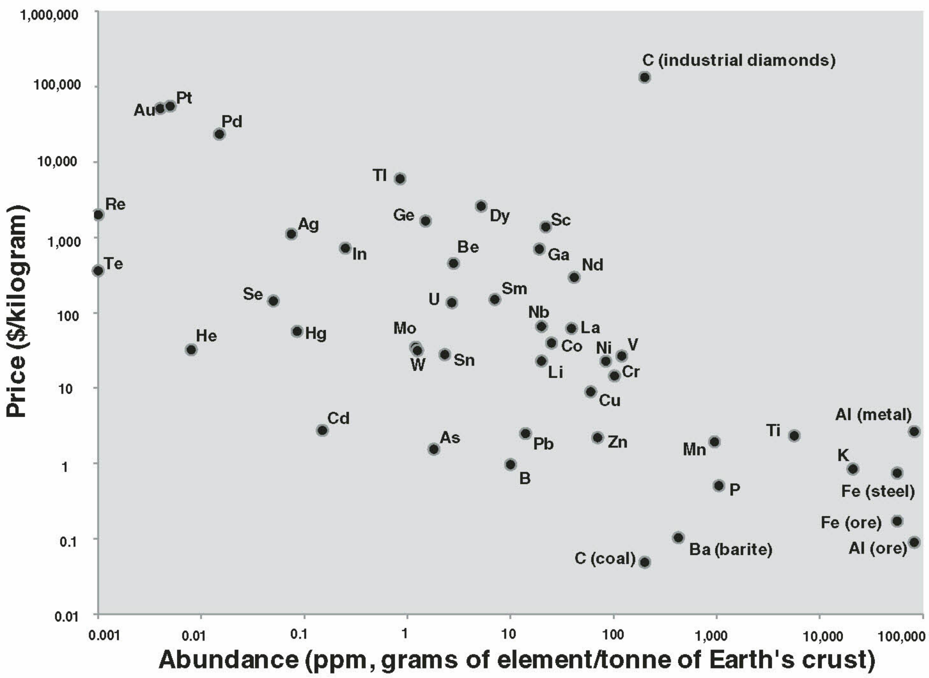


Figure 10. Price versus crustal abundance of selected commodities. Data are mostly from U.S. Department of Interior–U.S. Geological Survey (2012) for 2011 prices and from Lide (2005) for abundances.

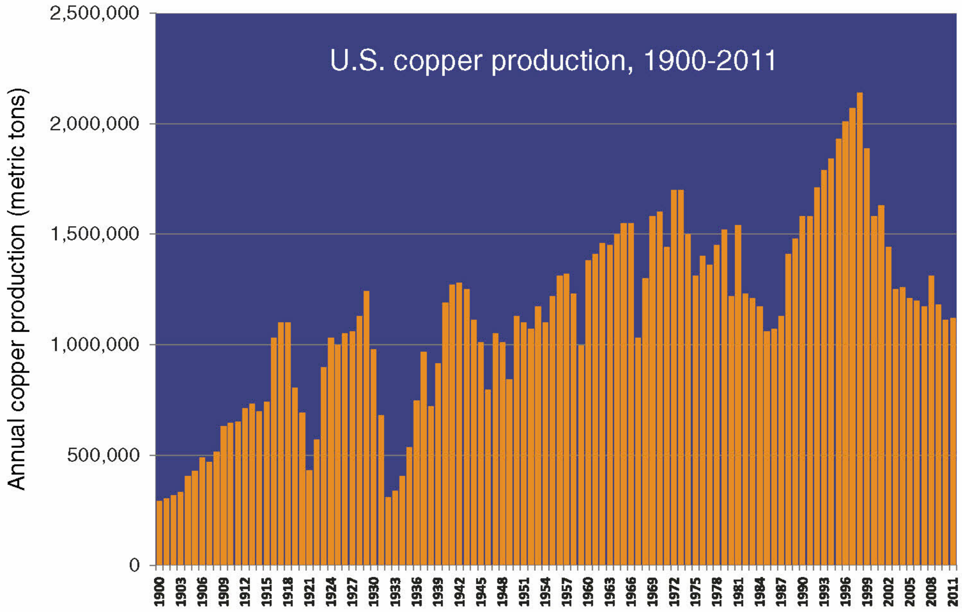


Figure 11. Copper production in the United States from 1900 through 2011 (data from the U.S. Geological Survey and U.S. Bureau of Mines).

demand, including grade of ore, new technology, and price of the commodity, such that low-grade ores are nearly always available, if prices are high enough, and (2) recycling can be economically viable for many mineral resources.

As an example of the first reason, whereas conventional extraction of copper (through the smelting of chalcopyrite [$CuFeS_2$] and other copper sulfides) in the western United States declined in the late 1970s and 1980s, copper production was revitalized with the introduction of the solvent extraction and electrowinning (SXEW) technology for treating low-grade ores and producing a nearly pure copper product that can be directly made into wires. U.S. copper production has seen many peaks (Fig. 11). Further technological developments, similar to SXEW, could produce more peaks in U.S. copper production in the future.

Similarly, the current boom in gold production (Fig. 12), which far surpasses the earlier production peaks, including the 1849–1859 boom during peak production from the Mother Lode in California, has been driven by a combination of rising price and the introduction of new technologies such as heap-leaching and agglomeration, which helped make processing of low-grade, disseminated gold ores profitable.

Uranium, the fuel for conventional nuclear fission reactors, illustrates well that supplies may be nearly unlimited, if the price rises significantly. Like fossil fuels, ^{235}U cannot be practically recycled after it has undergone fission. Nonetheless, a nearly unlimited supply exists in seawater (~3.2 mg of U/L of seawater). Technologies are being developed that could reduce the collection costs of uranium from seawater using organic absorbents to a cost close to the current price of uranium (Tamada, 2009). Adding costs for deploying the technology onboard ships anchored in the Japanese current would not likely raise overall cost of uranium recovery more than a factor of ten. If we begin to run out of conventional resources of uranium from in situ leaching operations and open-pit and underground mines, the uranium resource in seawater could supply worldwide demand for thousands of years.

As examples of the second reason why Hubbert's peak oil doesn't apply generally to mineral resources, many mineral commodities are currently recycled in large quantities. (See the "Recycling" box.) Steel scrap, copper wires, aluminum cans, and lead batteries

Recycling

Considerably more can be done to increase the amount of recycling to meet increasing demand for mineral resources. Graedel et al. (2011) documented that the mass percentage of elements in discarded products that is recycled varies widely, with only 18 of 60 metals and metalloids (Al, Ti, Cr, Mn, Fe, Co, Ni, Cu, Zn, Nb, Rh, Pd, Ag, Sn, Re, Pt, Au, and Pb) recycled at a rate higher than 50%, and 34 of the 60 (Li, Be, B, Sc, V, Ga, Ge, As, Se, Sr, Y, Zr, In, Te, Ba, Hf, Ta, Os, Tl, Bi, and the rare earth elements) recycled at a rate less than 1%. Because the economics of supply and demand generally determine which elements are recycled, it is logical that elements available from aluminum cans, steel scrap, copper wires, and lead batteries are readily recycled, as are elements with high values, such as gold and platinum. Modern electronic equipment, however, with complex designs using many elements of the periodic table, are not recycled at significant rates today. Reck and Graedel (2012) noted that to increase rates of recycling more emphasis needs to be placed on increasing collection rates of various products, better product design with recycling in mind, and improvements in recycling technologies.

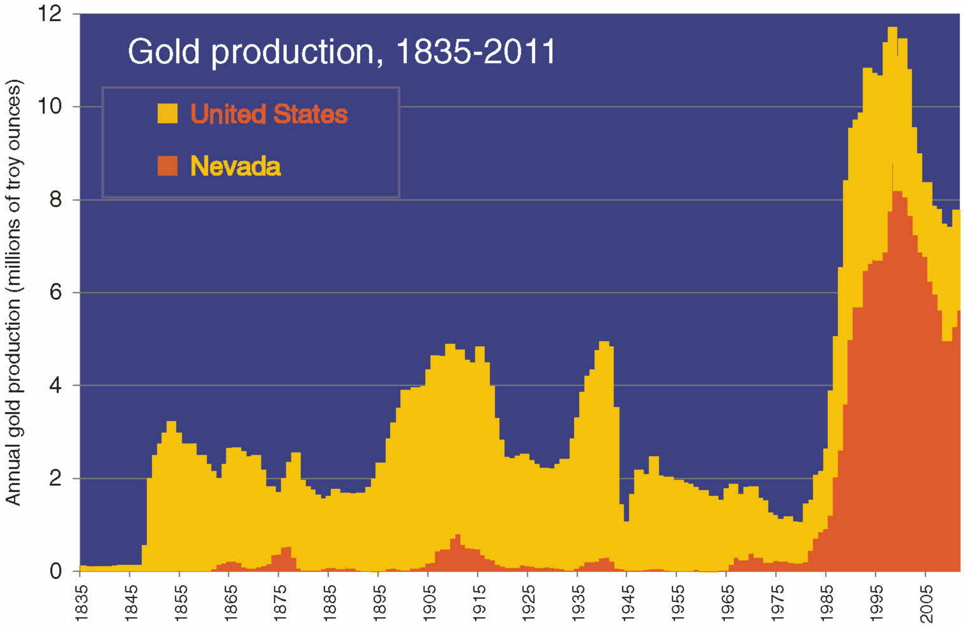


Figure 12. Gold production in the United States and in Nevada, 1835–2011 (modified from Price et al., 2011; data from Dobra, 2002, U.S. Geological Survey, and U.S. Bureau of Mines).

are routinely recycled to meet significant portions of demand. Because the rise in world population and average standard of living means that recycling to meet all demand for most mineral-resources cannot be achieved until both population and per capita demand stabilize, mining new mineral resources will continue to be needed.

We are not running out of mineral resources. Peak-flint production (Fig. 13) illustrates that some mineral commodities do experience what appear to be permanent production peaks, but in this case, the cause was not running out of resources but changes in technology, which allowed for substitution by other commodities. There are plenty of known resources of chert (flint), obsidian, and other excellent rocks for making stone tools, but there is little demand for these in modern society.

DISCOVERIES AND DEVELOPMENTS IN NEW AREAS

The continued demand for newly mined mineral resources has spurred exploration into new areas, looking for more examples of the types of ores that have been mined in the past. Exploration geos use various characteristics of similar ore deposits (host rocks, mineralogy, geochemistry, structural style, tectonic setting, etc.) to develop conceptual models of ore-deposit types. Armed with these models, in recent years they have made significant discoveries of diamonds, copper, gold, and other commodities. New areas, including the oceans, are being actively investigated as future sources of mineral resources.

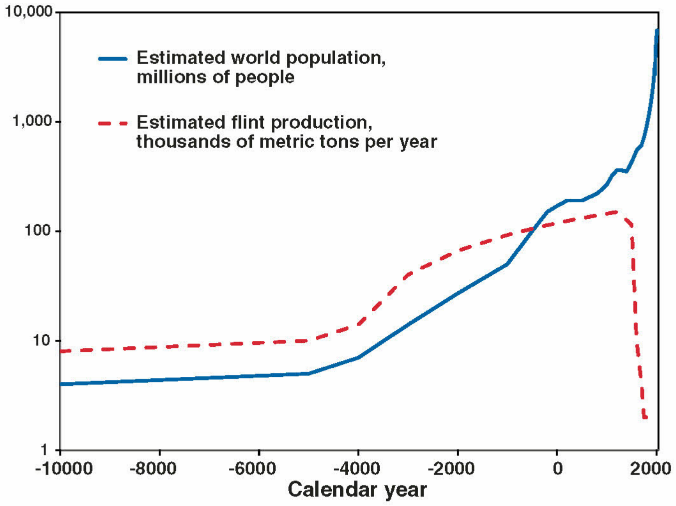


Figure 13. Estimated world population and production of flint over time, illustrating peak-flint production. Population estimates are from McEvedy and Jones (1978) through 1925 and from the U.S. Census Bureau from 1950 through 2010. To construct the chart of peak-flint production, the amount of flint collected (mined or quarried) each year was estimated to be two kilograms per person who relied on stone tools. Other assumptions were: (1) before the Bronze Age, beginning between 4000 and 3000 BCE, everyone used stone tools (including flint, where it was available); (2) as population rose rapidly in areas where bronze and later iron (beginning ~2000 BCE and widespread by 1000 BCE) were extracted from ores and used for tools, those people essentially abandoned the use of stone tools; (3) stone tools continued to be used in the Americas, Australia, and parts of Oceania, where iron tools and steel making did not catch on until the immigration of Europeans into these areas, largely after 1500; (4) pre-Columbus population in the Americas is assumed to dominate the world's use of stone tools after the beginning of the Iron Age, to have peaked at ~75 million around 1200, and to have been ~57 million in 1492. These latter numbers are within a factor of three of most estimates of population in the Western Hemisphere as summarized by Thornton (1990).

Using geochemical tools and indicator minerals in stream and glacial sediments to explore for diamonds, geologists Charles Fipke and Stewart Blusson discovered a diamond-bearing kimberlite in the Northwest Territories of Canada in 1991 (Fig. 14). BHP Billiton's Ekati diamond mine began production in 1998. The discovery sparked a modern era exploration rush, and Canada is now one of the world's major diamond producers (Net Resources International, 2011).

Politically opening new areas for modern exploration has led to some major discoveries. Magma Copper Corp. began exploration in Mongolia in 1996. In 1997, BHP Billiton, which had acquired Magma Copper, obtained favorable results from diamond core drilling at Oyu Tolgoi but did not follow through with exploration. Ivanhoe Mines began exploration in 2000 and discovered what is shaping up to be one of the largest porphyry copper-gold districts in the world. Production was scheduled to begin in 2012 (Ivanhoe Mines, 2012).

Mining from the sea and seafloor will likely be more common, as commodity prices rise or new technologies lower costs for mining and mineral processing in the future. Halite (NaCl) has been economically recovered from seawater for centuries; sand and gravel have been dredged from offshore areas of the North Atlantic Ocean for decades; and offshore placer deposits of tin, platinum, gold, and diamonds have been locally significant, but large-scale commercial production of massive sulfide deposits of copper, gold, and zinc from ocean ridges and subaqueous silicic calderas; manganese from seafloor nodules and crusts (Bodenlos and Thayer, 1973); and uranium from seawater (Finch et al., 1973) will, in the author's opinion, be many years in the future. Investigations in the 1970s and 1980s of the technological and economic feasibility of recovering manganese and associated cobalt, copper, and nickel from seafloor nodules failed to lead to commercial operations (Glasby, 2000).

Figure 14. Cut Ekati diamond, mounted into a piece of ~7-cm diameter kimberlite core, from an award made to Nora Dummett, in memory of Hugo Dummett, past president of the Society of Economic Geologists and leader of the BHP Billiton exploration team whose discoveries helped create the Canadian diamond industry.

Serious attempts are being made in exploration and development of seafloor massive sulfide, manganese nodule, and phosphate nodule deposits (Scott, 2012). For example, in 2012 the government of Papua New Guinea granted Nautilus Minerals a 20-year license to mine copper and gold from hydrothermal vents 1.6 km below sea level in the Bismarck Sea (Milman, 2012). Fearing ecological harm, particularly as the technology used for mining seafloor vents improves and more areas are exploited, some environmentalists and local fishermen have objected to this license. The International Seabed Authority (2012), which handles permitting in international waters according to the 1982 United Nations Convention on the Law of the Sea, has issued permits to countries and companies for massive sulfide exploration in the Atlantic and Indian Oceans and for manganese nodule exploration in the Pacific Ocean.

Japan has maintained a program to investigate mining of manganese nodules, cobalt-rich manganese crusts near seamounts, and massive sulfide deposits on the seafloor (Yamazaki, 2007). Japan has also attempted to recover uranium from seawater using polymer absorption fibers (Seko et al., 2003). Improvements in the technology by researchers from Oak Ridge National Laboratory and Pacific Northwest National Laboratory were recently announced (Ferguson, 2012), but the costs are still several times higher than the price of uranium that is available from in situ, open-pit, or underground mining.

DISCOVERIES IN OLD AREAS WITH NEW IDEAS

There are many examples of discoveries of ore deposits in known mining districts and regions. Hence, the industry adopted the adage "you should hunt elephants in elephant country." Often these discoveries require new ideas. A novel example is the Goldcorp Challenge. The following story is summarized from the account by Tischler (2002). In 2000, Rob McEwen, chairman and CEO of Goldcorp Inc., offered $575,000 in prize money for ideas to find another six million troy ounces of gold at its Red Lake mine in Ontario. Historically, more than 18 million ounces had been produced in the district, but only three million from the Red Lake mine itself. McEwen posted the company's 3D geological and geochemical data online and excited many in the exploration community, with more than 1000 individuals downloading the data. Fractal Graphics from West Perth, Australia, the winning organization, developed a new 3D model of the deposit and recommended drill holes that, when drilled, resulted in the discovery of new, high-grade reserves. By 2007, Goldcorp had discovered another eight million ounces of gold at the Red Lake property (Tapscott and Williams, 2007).

NEW ORE-DEPOSIT TYPES

Although models of ore-deposit types are generally used to guide exploration, several new types of ore deposits have been recognized in recent years, generally from the discovery of a type example that doesn't fit previous models (Table 1). Additional discoveries of deposits of these new types have added significantly to global resources of gold, nickel, uranium, and rare earth elements, among others. One of the major geological discoveries in recent years was the Carlin deposit in Nevada in 1961 (Coope, 1991). Combining new information on the structural history of the area, developed largely from geologic mapping by Ralph Roberts of the U.S. Geological Survey, with geochemical exploration, Newmont Mining Corporation discovered the deposit that stimulated further development of what became known as a new class of ore deposits, Carlin-type deposits. Although most investigators today believe these are a variation on the theme of epithermal ores associated with igneous intrusions and volcanism (Cline et al., 2005; Muntean et al., 2011), they were a new class of deposits, with submicroscopic particles of gold (and gold in solid solution in arsenic-rich pyrite) in Paleozoic silty limestones and siltstones (Fig. 15). Continued exploration for Carlin-type deposits in Nevada and elsewhere led to the current boom in gold production in the United States (Fig. 12). Production from the Carlin deposit began in 1965, but the current boom did not begin until a few years later, after the U.S. government decided to no longer fix the price of gold in dollars. The subsequent rise in price in the mid-1970s stimulated exploration and development that resulted in the current boom (Fig. 12). New discoveries of Carlin-type deposits continue to be made, including the multimillion-ounce Red Hill and Goldrush deposits in Nevada (Barrick Gold Corporation, 2011).

A major geophysical (gravity and magnetic) discovery, below 300 m of cover and based in part on understanding of the geological framework, was the Olympic Dam deposit in South Australia, discovered by Western Mining Corporation in 1975. This large ore deposit, variously described as sediment-hosted, stratabound, or magmatic-hydrothermal (Roberts and Hudson, 1983; Reeve et al., 1990; Oreskes and Einaudi, 1990; McPhie et al., 2011), has become the type locality for a new class of deposits, iron-oxide-copper-gold (Hitzman et al., 1992; Williams et al., 2005). Olympic Dam, which began production in 1988, is also a major producer of uranium. Spurred by rising demand for fuel for nuclear power plants, several new types of uranium deposits were discovered and developed in the 1960s and 1970s. Economically recoverable ore in uranium-rich granite (alaskite or leucogranite) was defined by Rio Tinto Corporation's exploration in the 1960s at Rössing, Namibia (Schreiber, 2005; Ministry of Mines and Energy, 2010). Mining at Rössing, now one of the world's largest uranium deposits, began in 1974 and reached full production in 1979. In Saskatchewan, Canada, Cameco Corporation's Rabbit Lake deposit, representing the new, high-grade unconformity-type of uranium deposits, was discovered in 1968 and began production in 1975 (World Nuclear Association, 2012a). Roll-front

TABLE 1. EXAMPLES OF SOME NEW TYPES OF ORE DEPOSITS RECOGNIZED AND BROUGHT INTO PRODUCTION IN THE LAST 55 YEARS

Deposit type	Type locality (year discovered) and new features	References
Carlin Au	Carlin, Nevada (1961) Disseminated in sedimentary rocks	Cline et al. (2005), Muntean et al. (2011)
Iron oxide Cu-Au	Olympic Dam, S. Australia (1975) Iron-oxide-rich ores associated with granitic rocks	Roberts and Hudson (1983), Reeve et al. (1990) Oreskes and Einaudi (1990), Hitzman et al. (1992), Williams et al. (2005), McPhie et al. (2011)
Intrusion-related Au	Fort Knox, Alaska (1980s) Au in granitic rocks, without Cu	Sillitoe (1991), Lang et al. (2000), Hart (2005)
Disseminated Ni	Mt. Keith, W. Australia (1969) Ni not in massive sulfide pods	Butt and Brand (2003), Grguric (2003), Barnes et al. (2012)
Granite-hosted U	Rössing, Namibia (1960s) U-rich granite	Schreiber (2005), Ministry of Mines and Energy (2010)
Unconformity U	Rabbit Lake, Saskatchewan (1968) High-grade U near unconformities	Kyser and Cuney (2008), World Nuclear Association (2012a)
Roll-front U	Wyoming, Kazakhstan (1960s) Redox boundaries in sandstones	Granger and Warren (1969), World Nuclear Association (2012b, 2012c)
Laterite REE	South China (1980s) Low-grade REEs with kaolinite	Chin (1980, 1981), Chengyu et al. (1990), Hedrick (1990)

uranium deposits hosted in sandstones were first exploited as open-pit mines in Wyoming in the 1960s. In situ leaching (solution mining) technology, developed in the early 1960s and brought into commercial production in Wyoming in 1974, allowed mining of low-grade examples of this type of deposit (World Nuclear Association, 2012b). Similar deposits now make Kazakhstan the world's leading uranium producer, with ~35% of global production in 2011 (World Nuclear Association, 2012c).

The Mount Keith deposit in Western Australia, one of the world's largest nickel deposits, operated by BHP Billiton, is an example of what may be considered a new type of nickel deposit. Rather than occurring in massive sulfide pods at the base of a mafic intrusion or ultramafic flow, like most other nickel deposits throughout the world, the Mount Keith nickel sulfides are disseminated throughout a serpentinized dunite within a peridotite-dunite komatiite body (Butt and Brand, 2003; Grguric, 2003; Barnes et al., 2012). The main deposit (called MKD5) was discovered in 1969 and brought into production in 1993 (Fig. 16).

High demand for rare earth elements led to recognition in the early 1980s that heavy rare earth elements could be extracted from a new type of deposit—rare earth–enriched weathered granites in South China (Chin, 1980, 1981; Chengyu et al., 1990; Hedrick, 1990). The so-called ion-adsorption or laterite type deposits were known to be significant resources but apparently not yet in production in 1981 (Chin, 1980, 1981), although they were in production by 1982 (Chin, 1982). Mariano (2010) questioned whether such deposits could be mined with the environmental controls that are practiced in western countries, because the acid leaching of the ores has been done in unlined heaps, and surface and ground waters have been locally contaminated.

NEW TOOLS FOR EXPLORATION

During the past few decades a number of new and improved tools have been applied in mineral exploration. Although the new tools were not necessarily developed for the purpose of mineral exploration, they have been rapidly adopted. Geos now integrate data sets with the aid of major advances in computing, remote-sensing technology, and analytical speed and capabilities.

Remote sensing has blossomed in recent years. In mineral exploration, commercially available satellite aerial photography is providing detailed imagery across the planet, and visible-to-infrared spectrometers are used in reconnaissance-scale lithologic and alteration mapping. Hyperspectral scanners aboard airplanes are capable of identifying many mineral species and groups, particularly useful in lithologic and alteration mapping. Airborne light detection and ranging (LIDAR) is the basis for detailed topographic maps, easily converted into 3D digital elevation models, and is providing spectacular images of active faults and

Figure 15. Folded Paleozoic sedimentary rocks in Newmont's Gold Quarry mine on the Carlin trend in Nevada.

landslides. Satellite interferometric synthetic aperture radar (InSAR) is used in subsidence detection, while ground-based InSAR is used for slope-stability monitoring and rock-volume calculations in open-pit mines and in underground 3D mapping. Airborne gamma-ray spectrometer surveys, applied widely in the 1960s and 1970s in uranium exploration, are used in exploration for other ores with anomalous concentrations of uranium, thorium, and potassium, including deposits of rare earth elements and magmatic-hydrothermal deposits with potassic alteration zones. Civilian use of drones (unmanned aerial vehicles) in remote sensing is expanding.

The commercial availability of the global positioning system (GPS) has enhanced the locational accuracy of airborne geophysical surveys and mapping on the ground. Airborne gravity surveys are only possible with GPS. The integration of various sets of geophysical, geological, and geochemical data into geographic information systems (GIS) has allowed geos to rapidly evaluate exploration data and locate future drilling sites. Other geographic data, including topographic maps and digital elevation models, land-ownership maps, ecosystem maps, and maps of archaeologically or culturally sensitive areas are merged in GIS to aid in permitting and mine design.

Many advances in exploration technology are aided by improved computer-processing speed and data-storage capacity. Visualization and 3D modeling software is allowing geos, engineers, and others to view exploration data and geological models from any perspective and to rapidly design mines. Faster and smaller computers have also revolutionized analytical instrumentation.

Analytical capabilities have expanded to allow detection of all the economically important naturally occurring elements at background levels in all types of rocks. Inductively coupled plasma–mass spectrometry (ICP-MS) has become a standard for multi-element analytical work in mineral exploration, while other chemical analytical techniques, including instrumental neutron activation analysis (INAA), inductively coupled plasma–atomic emission spectroscopy (ICP-AES), X-ray fluorescence (XRF), atomic absorption (AA), ion chromatography (IC), and fire assay (FA), continue to be valuable for specific applications. Laser ablation ICP-MS is a promising tool for specialized analyses of small samples (with lower detection limits than electron microprobes for many trace elements of economic interest) and for whole-rock powders (Wilson et al., 2002).

Field-portable infrared spectrometers are used in the identification of some minerals at drill sites and in alteration and lithologic mapping. Portable XRF spectrometers for major and some trace elemental analyses and, more recently, portable X-ray diffractometers for mineral identifications, are putting sophisticated, accurate analytical tools in the hands of the field geos.

Figure 16. Large open-pit nickel operation at the Mount Keith mine, Western Australia.

Techniques developed specifically for the petroleum and natural gas industries are seeing applications in the mining sector. For example, Milkereit et al. (2000) documented the use of 3D seismic exploration for massive nickel-copper sulfide deposits at Sudbury, Canada. As costs for techniques such as directional drilling (including horizontal drilling) are lowered with improved technology and new markets, we will likely see major advances in the tools available to the exploration geos.

ENVIRONMENTAL, HEALTH, AND SAFETY CONCERNS

Mining, by its very nature, disturbs the ground and involves major industrial processing, which, if unregulated or uncontrolled, can have devastating worker-safety and health impacts and negative offsite consequences. In the developed countries, having learned from such disasters as underground coal-mine fires, cave-ins, acid-mine drainage in streams, and cyanide spills, government regulations have been put into place to protect worker safety and health and the health of the environment. Governments and industry have funded research to reduce fatalities, injuries, and environmental damage while improving efficiency and lowering costs. As new technologies are developed, continued diligence and continued research are needed.

Despite the best efforts of companies and governments to eliminate fatalities, reduce injuries, and minimize environmental impacts, there have been some significant problems in the global mining community. Deaths associated with coal mining in China have been particularly troublesome, in part due to poor ventilation and lack of fire-control systems in many of the country's mines. The Chinese government is trying to reduce fatalities by shutting down unsafe mines, but the demand for coal is immense. China produced 44% of the world's coal in 2010.

In 1984, Summitville Consolidated Mining Company, Inc., a Canadian junior mining company, started gold mining at Summitville, Colorado. According to Plumlee and Edelmann (1995), acid-mine drainage developed shortly after mining began, and cyanide-bearing process water escaped its engineered containment. The company declared bankruptcy in 1992, and the U.S. Environmental Protection Agency used its Superfund authority to control the situation. The State of Colorado subsequently tightened its mining-environmental regulations as well.

In 2000, a dam failure caused cyanide-containing water to spill from a gold-mining operation near Baia Mare, Romania, killing fish in Romania, Hungary, and Yugoslavia and contaminating drinking water downstream along the Danube River (BBC News, 2001). The operator was a joint venture company formed by an Australian junior mining company and the Romanian government. Poor design or construction likely contributed to the dam failure.

Although there have been modern instances of environmental and safety mistakes by the mining industry, the industry and governments continue to make efforts to minimize damage, injuries, and loss of life. Most environmental problems associated with mining can be addressed successfully if the deposit is economically robust enough to allow for proper mitigation. Governments provide the regulations for worker safety and environmental protection, and major companies are committed to safety and environmental protection. For example, Rio Tinto (2012b) states that their "safety vision is that together we will create an injury and illness-free workplace where everyone goes home safe and healthy each day of their working life." Freeport-McMoRan Copper and Gold Inc. (2012) has a corporate environmental policy that "is based on our objective to be compliant with law and regulations and to minimize environmental impacts using risk management strategies based on valid data and sound science. It requires that we and our subsidiaries review and take account of the environmental effects of each activity, whether exploration, mining or processing; and that we plan and conduct the design, development, operation and closure of each facility in a manner that optimizes the economic use of resources while reducing adverse environmental effects." Major international mining companies that operate in developing countries apply standards that are similar to those in regulations that are enforced in the developed counties. Not only do investors demand it, in part because of potential liabilities, but it is the right thing to do.

SOCIAL AND CULTURAL CONCERNS

Sustainability, defined by the World Commission on Environment and Development (1987) as "meeting the needs of today without compromising the ability of future generations to meet their needs," and sustainable development are generally discussed in the context of sustaining three features of an area: the environment, the economy, and the social or cultural structure. Industry and governmental groups have developed principles of sustainable development that are specific to mining (Table 2). Considerable progress has been made worldwide in sustainable development, although conflicts between industry and opposition groups do arise. For the most part, governments, industry groups, individual companies, and non-governmental organizations representing local populations have been able to agree on the environmental and economic aspects of a sustainable development, but some of the social and cultural concerns have been more difficult to address.

Newmont Mining Corporation (2012) states "our commitment to sustainability is fundamental to who we are and how we do business." As a major gold company, Newmont has faced social challenges at some of its properties. Community relations for the company suffered in 2000, when a truck contracted to transport mercury spilled mercury in a town along the route from the Yanacocha mine in the Andes Mountains of Peru to the port. In 2004, responding to local opposition concerned about possible water contamination for the town of Cajamarca, Newmont decided not to develop a satellite deposit to Yanacocha. In 2011, Dave Baker, Newmont's senior vice president and chief sustainability officer, emphasized that Newmont's approach to

TABLE 2. EXAMPLES OF MINING-SPECIFIC STATEMENTS REGARDING SUSTAINABILITY

The World Bank (2012), a significant lender for projects in developing countries, states that its “objective [for mineral-resource projects] is to facilitate the extractive industries’ contribution to poverty alleviation and economic growth through the promotion of good governance and sustainable development.”

The International Council on Mining and Metals (2012), a group of 22 mining and metals companies, in 2003 adopted a sustainable development framework, which includes ethical business practices; integrating sustainable development into corporate decision making; upholding human rights and respecting cultures; conservation of biodiversity; contributions to the social, economic, and institutional development of communities; public reporting; and independent assurances.

The Prospectors and Developers Association of Canada (2007), which represents many of the Canadian junior companies that are exploring for mineral resources throughout the world, developed standards for the exploration side of the mineral industry. To operate, companies recognize that they need a social license (from the people, including local indigenous tribes, and the levels of government that represent them).

The National Mining Association (2012) members “are committed to integrating social, environmental, and economic principles in our mining operations from exploration through development, operation, reclamation, closure and post closure activities, and in operations associated with preparing our products for further use.… From a social perspective this involves:

- Being committed to the safety, health, development and well-being of our employees;
- Respecting human rights;
- Treating our employees with respect, promoting diversity, and providing competitive compensation programs consistent with performance and industry practice;
- Being a progressive and constructive partner to advance the economic, educational, and social infrastructures of the communities in which we operate;
- Respecting the cultures, customs and values of people wherever we operate, being responsive to - and respecting - community needs and priorities and encouraging and participating in an open and on-going dialogue with constituencies; and,
- Adhering to the highest ethical business practices in all our operations and interacting with communities in a responsible manner.”

The U.S. Forest Service (2003) and Bureau of Land Management jointly adopted sustainability principles from the World Summit on Sustainable Development in Johannesburg, South Africa, in 2002, noting that “these basic concepts of balancing environmental, social, and economic aspects, environmental stewardship, and stakeholder participation are ones we have embraced in our agencies.”

sustainability “is based upon a focus in striving to achieve industry leading environmental performance and by creating shared value with the communities that host our operations.” In terms of environmental protection, this involves International Standards Organization environmental management (ISO 14001) certification for all Newmont mining operations and independent certification by the International Cyanide Management Institute. In terms of shared value, this involves “building or strengthening the local economy; enhancing the asset base of a community, such as through infrastructure; increasing the resilience of a community, or a vulnerable group within the community; and ensuring that processes and outcomes are socially and environmentally sustainable and have an intergenerational focus.” In 2012, the U.S. Department of Interior/Bureau of Land Management presented Newmont with the “Hard Rock Mineral Community Outreach and Economic Security Award” in recognition of the company’s and its employees’ efforts to contribute to local charities, schools, and universities near its operations in Nevada and for the company’s efforts to sustain the local economy after mines eventually close.

In 2007, the Afghanistan government awarded a $3.5 billion contract to China Metallurgical Group Corporation for the development of a large copper mine at Mes Aynak in the Logar province 40 km south of Kabul, but concerns over preservation of archaeological relicts changed development plans (Lawler, 2012). Ironically, Mes Aynak is a historically important site of ancient copper mining and smelting, perhaps at least 4000 years old. Initial plans had called for destroying 1500-year-old Buddhist monasteries and associated copper-processing facilities at the site, but faced with international pressure from archaeologists, the Afghan Ministry of Mines undertook a three-year project, funded by an $8 million grant from the World Bank, to collect and preserve artifacts. Because the archaeological excavations were delayed by security and bureaucratic issues, and because mining will not begin for at least another year, archaeologists have requested more time for their excavations.

The public occasionally sees aspects of modern mining that are not reflective of the large corporations that work within the legal framework established by governments. Unfortunately, mining scams (see “Scams” box) continue to be perpetrated on unwary investors, although stock-exchange regulations have been strengthened as a result of one of the more egregious examples. In addition, small-scale subsistence mining

Scams

Mining scams had been prevalent well before the Geological Society of America's first year (1888) and, unfortunately, continue today. Mark Twain (1872) described a classic scheme involving an unscrupulous assayer (Fig. 17).

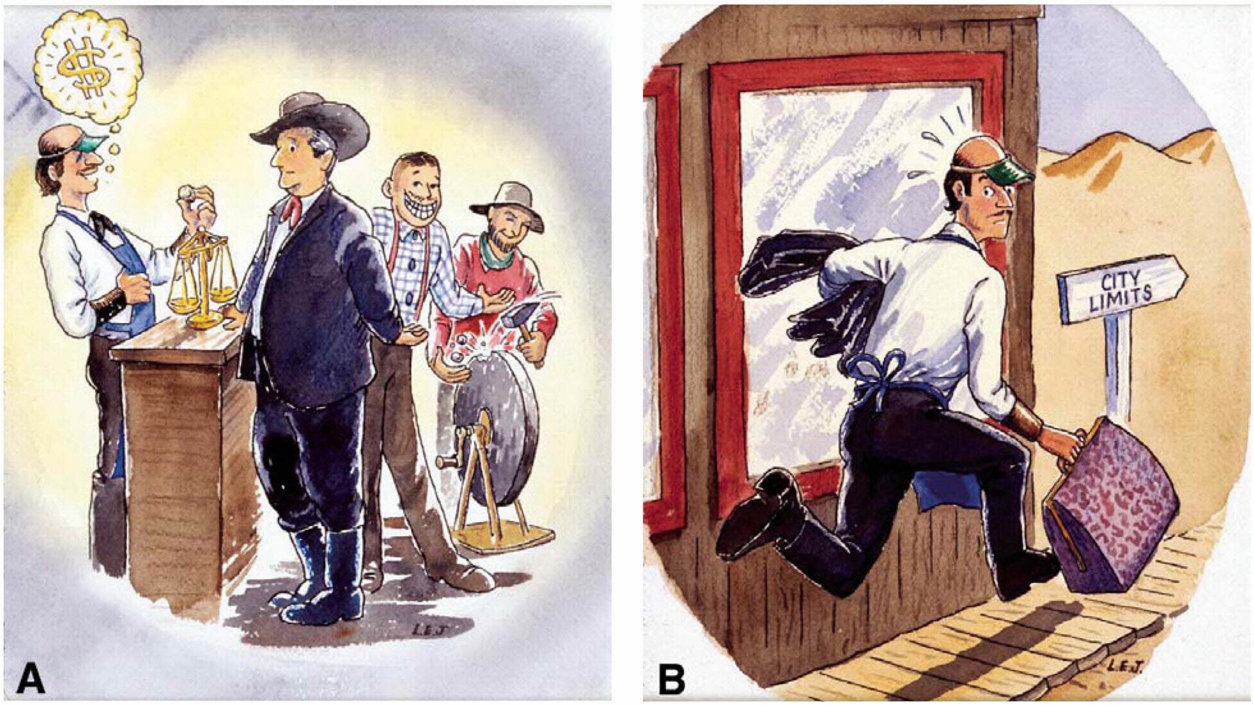


Figure 17. Illustrating Mark Twain's assaying scam (L. Jacox, Nevada Bureau of Mines and Geology). (A) "Assaying was a good business, and so some men engaged in it, occasionally, who were not strictly scientific and capable. One assayer got such rich results out of all specimens brought to him that in time he acquired almost a monopoly of the business. But like all men who achieve success, he became an object of envy and suspicion. The other assayers entered into a conspiracy against him, and let some prominent citizens into the secret in order to show that they meant fairly. Then they broke a little fragment off a carpenter's grindstone and got a stranger to take it to the popular scientist and get it assayed. In the course of an hour the result came—whereby it appeared that a ton of that rock would yield $1,284.40 in silver and $366.36 in gold!" (B) "Due publication of the whole matter was made in the paper, and the popular assayer left town 'between two days.'"

The most notorious recent scam was the Bre-X hoax of the mid-1990s (Louis, 2007). A Calgary-based junior mining company, Bre-X Gold Minerals Ltd., supposedly discovered a major gold deposit at Busang, Indonesia. The company reported a discovery of over 30 million ounces of gold in 1995 and increased its resource estimate to 70 million ounces in 1997. The scam fell apart later that year, when Freeport-McMoRan Copper and Gold evaluated the deposit and found nothing of value. It was then discovered that samples sent to the assayers had been salted. With worthless stock, investors lost about $2 billion. The Bre-X hoax led to the development of Canadian National Instrument 43-101, Standards of Disclosure for Mineral Projects.

Unfortunately for the unwary investors and the image of the legitimate industry, mining scams continue today, much as in the days of the Comstock. Lechler et al. (2008) described some of the recurring scams, including unscrupulous assayers, ores that can only be assayed with proprietary or unconventional techniques, and ore-grade gold in geologically unreasonable settings, such as unaltered playa sediments and unaltered basaltic cinder cones. Competent geos can easily detect most scams, but the challenge for society is to connect investors with competent individuals.

Artisanal Mining

The lure of gold and diamonds has kept artisanal mining alive for centuries. Although contributing a small amount to global production, sometimes the consequences of this activity are unacceptable in modern society. Safety, which is a priority for nearly all major mining companies housed in the developed countries, is commonly lacking (Fig. 18). Environmental protection and worker health are often ignored as well. In much of the underdeveloped world, panning and other methods of separation of minerals by density are used to concentrate coarse grains of gold (Fig. 19), but mercury is still used to extract fine particles of gold and silver in an amalgam. As we learned from mining in the 1800s in the now-developed world, two problems occur with amalgamation—loss to the environment, which leads to unsafe levels of mercury in fish and animals up the food chain, and toxicity to workers, who breathe mercury fumes during the process of removing gold and silver from the amalgam. Having learned from mistakes of the past, modern regulations prohibit amalgamation at major mining operations, but the practice continues among artisanal miners.

Figure 18. Four artisanal miners (galamsey) work unsafely, without personal protective equipment or ground support, near Kyereboso in Ghana in 2008.

Figure 19. Gold is panned by the artisanal miners in an inner tube, near Kyereboso in Ghana in 2008. Field of view is approximately 30 cm.

(see "Artisanal Mining" box) often causes local environmental, health, and safety problems.

SUMMARY

The future is bright for exploration and development of mineral resources, and for jobs for geos in the mineral arenas of industry, government, and academia. Geos will be called upon to address the challenges of finding and developing new resources in environmentally, socially, and economically sustainable ways. Demand is likely to remain high and grow, as world population and standards of living grow. The world will not run out of mineral resources, although substitution of different resources for the same function and recycling likely will play increasingly major roles in meeting global demand. Assuming that high commodity prices will spur research and exploration, new types of ores will be found. Deposits will be found in places where they were not known to occur before as well as in established mining districts. New technologies, often developed with the stimulus of higher prices, will aid exploration for ores buried beneath cover. Environmental, health and safety, and social concerns will be major factors in deciding where future mines are located and how they are operated.

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