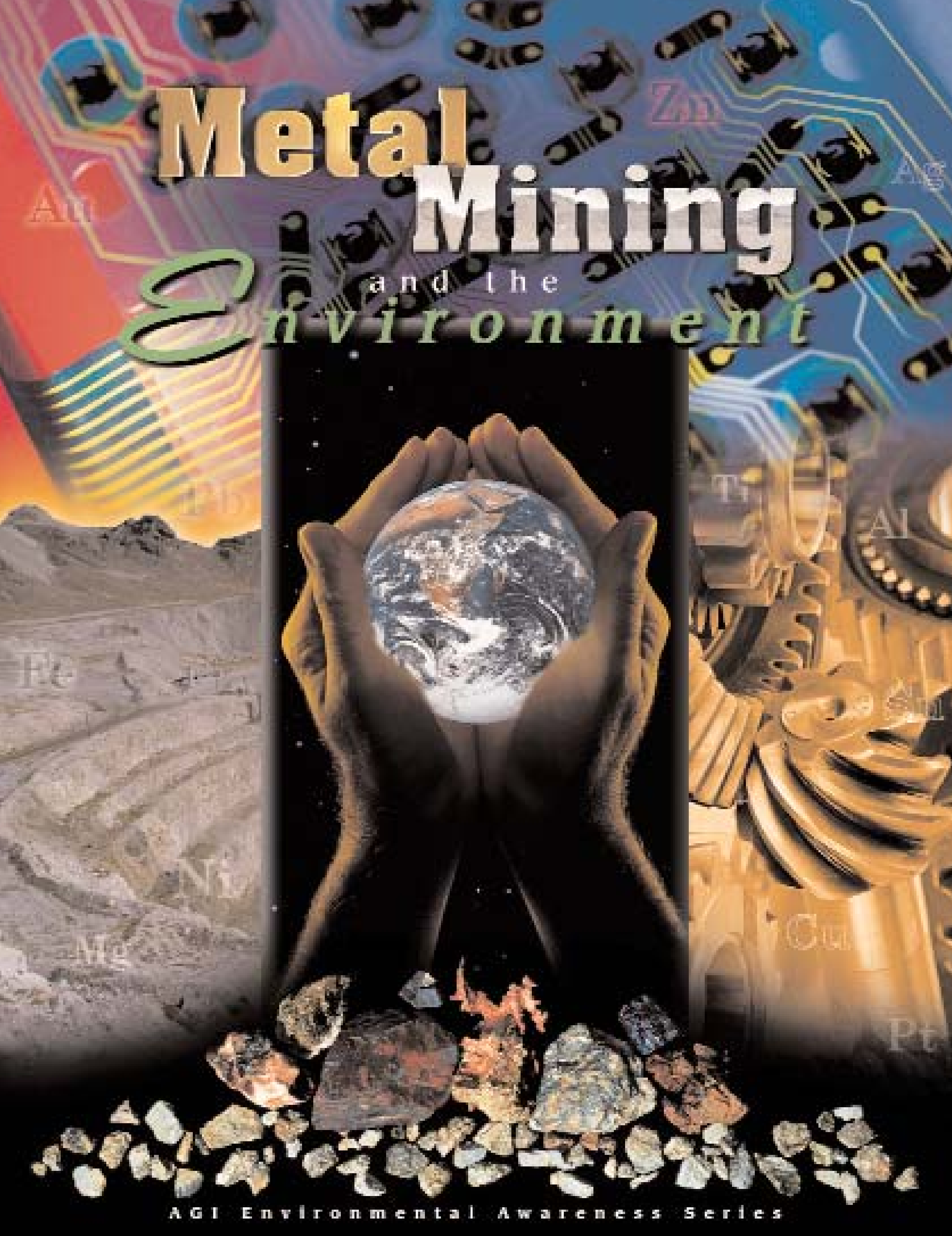
Metal Mining and the Environment



AGI Environmental Awareness Series

A better scientific understanding of the environmental impacts of mining, coupled with great advances in mining and environmental technologies, have enabled modern miners to better predict, plan for, and prevent or minimize potential adverse environmental impacts.

About the Authors

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AGI Environmental Awareness Series, 3

Metal Mining and the Environment

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Frederick D. Fox
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American Geological Institute
Alexandria, Virginia

In cooperation with

Society of
Economic Geologists

Society for Mining, Metallurgy,
and Exploration, Inc.

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

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The American Geological Institute (AGI) is a nonprofit federation of 34 geoscientific and professional organizations, including the Society of Economic Geologists and the Society for Mining, Metallurgy, and Exploration. The AGI member societies represent more than 130,000 geologists, geophysicists, and other Earth and environmental scientists. Since its founding in 1948, AGI has worked with its members to facilitate intersociety affairs and to serve as a focused voice for shared concerns in the geoscience profession; to provide leadership for improving Earth-science education; and to increase public awareness and understanding of the vital role the geosciences play in society's use of resources and its interaction with the environment.

Society of Economic Geologists
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The Society of Economic Geologists (SEG), established in 1920, advances the science of geology, especially the scientific investigation of mineral deposits and their applications to mineral resources appraisal, exploration, mining, and other mineral extractive endeavors; disseminates information about these topics; and encourages advancement of the profession and maintenance of high professional and ethical standards among its 3,400 members.

Society for Mining, Metallurgy, and Exploration, Inc.
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The Society for Mining, Metallurgy, and Exploration (SME), which traces its origins back to 1871, advances the worldwide mining and minerals community through information exchange and professional development. This international society of more than 15,000 members has five divisions: coal, environmental, industrial minerals, mineral and metallurgical processing, and mining and exploration.

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mine-drainage.usgs.gov/mine/ (USGS Mine Drainage Interest Group)

As the nation's largest water, Earth and biological science and civilian mapping agency, the U.S. Geological Survey (USGS) works in cooperation with more than 2000 organizations across the country to provide reliable, impartial scientific information to resource managers, planners, and other customers. This information is gathered in every state by USGS scientists to minimize the loss of life and property from natural disasters, to contribute to the conservation and the sound economic and physical development of the nation's natural resources, and to enhance the quality of life by monitoring water, biological, energy, and mineral resources.

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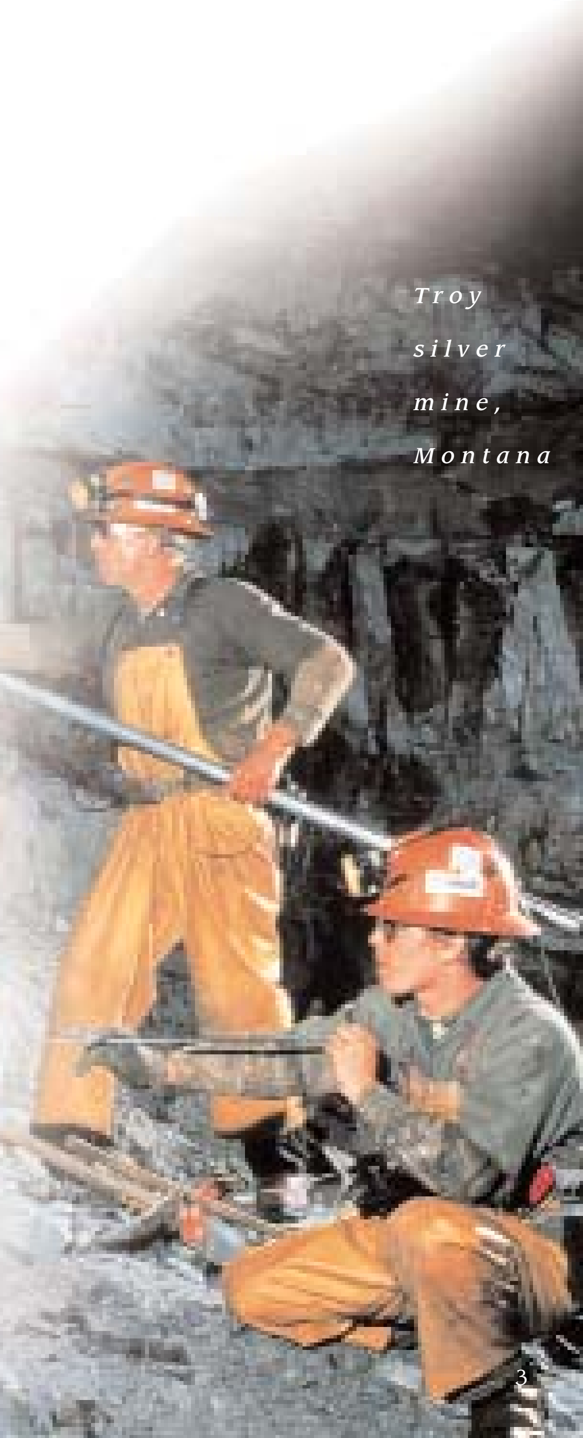


Troy silver mine, Montana

Foreword

Metal Mining and the Environment is part of the AGI Environmental Awareness Series. The American Geological Institute produces the series in cooperation with its member societies and others to provide a nontechnical framework for understanding environmental geoscience concerns. This book was prepared under the sponsorship of the AGI Environmental Geoscience Advisory Committee with support from the AGI Foundation. Since its appointment in 1993, the Committee has assisted AGI by identifying projects and activities that will help the Institute achieve the following goals:

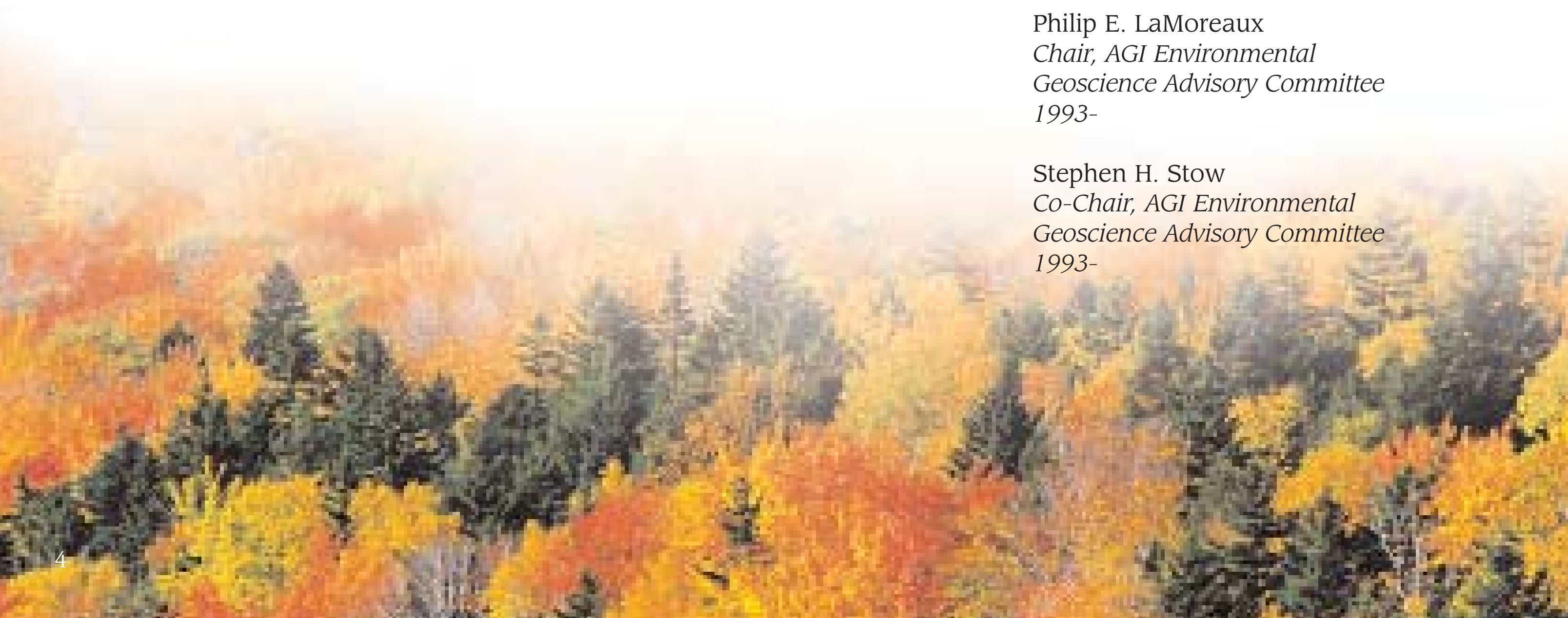
- Increase public awareness and understanding of environmental issues and the controls of Earth systems on the environment;
- Communicate societal needs for better management of Earth resources, protection from natural hazards, and assessment of risks associated with human impacts on the environment;
- Promote appropriate science in public policy through improved communication within and beyond the geoscience community related to environmental policy issues and proposed legislation;
- Increase dissemination of information related to environmental programs, research, and professional activities in the geoscience community.

The objective of the Environmental Awareness Series is to promote better understanding of the role of the geosciences in all aspects of environmental issues. Although metal production is of critical importance to the future of society, the very nature of mining and mineral processing activities raise many environmental questions. We hope that *Metal Mining and the Environment* will help you identify and consider those questions. Through improved science and technology, environmental concerns associated with metal mining can be better assessed and significantly reduced.

David A. Stephenson
AGI President, 1999

Philip E. LaMoreaux
Chair, AGI Environmental
Geoscience Advisory Committee
1993-

Stephen H. Stow
Co-Chair, AGI Environmental
Geoscience Advisory Committee
1993-



Preface

The process of extracting natural resources, such as metals, from the Earth commonly raises public concerns about potential environmental impacts. *Metal Mining and the Environment* provides basic information about the mining cycle, from exploration for economic mineral deposits to mine closure. The booklet discusses the environmental aspects of metal mining and illustrates the ways science and technology assist in preventing or reducing environmental impacts.

Society's requirement for metals establishes a strong link between our standard of living, the Earth, and science. Understanding the highly technical process of metal mining can help prepare citizens for the necessary discussions and decisions concerning society's increasing need for metals and the related environmental tradeoffs. Decisions about the development and use of Earth's metallic resources affect the economic, social, and environmental fabric of societies worldwide. Our challenge is to balance these important attributes. *Metal Mining and the Environment* helps answer the following questions:

- Why does society need metals?
- What are the principal sources of metals?
- How are metals recovered from the Earth?
- What are the major environmental concerns related to producing metals?
- How can these environmental concerns be managed and mitigated?
- What role can technology play in reducing environmental impacts?
- What is the future need and environmental outlook for metal mining?

The authors are grateful for the technical reviews provided by many colleagues in industry, academia, and federal agencies. Editorial assistance from Alma Paty and Julia Jackson has been invaluable, as the authors' tendency towards technical and scientific discussion necessitated modification of the original manuscript. Our special thanks go to the many individuals and companies who provided illustrations and other forms of support for the project.

Travis L. Hudson
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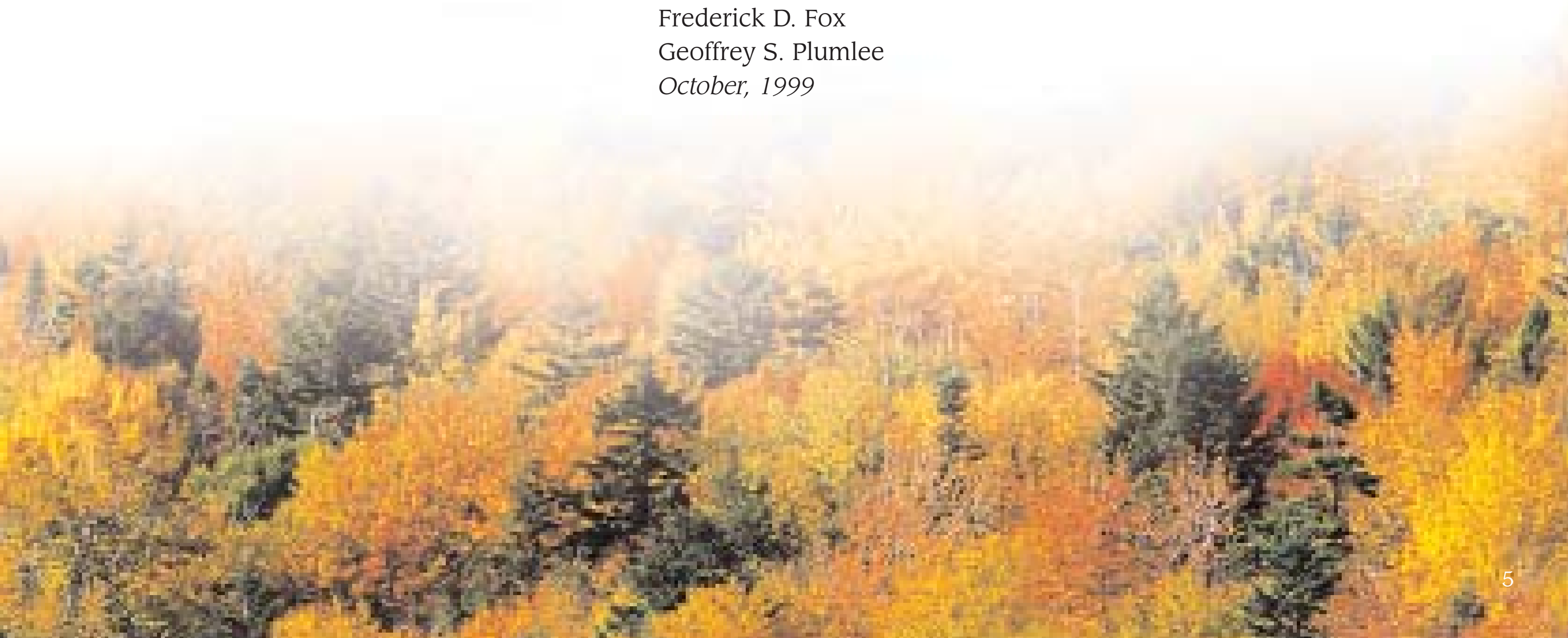
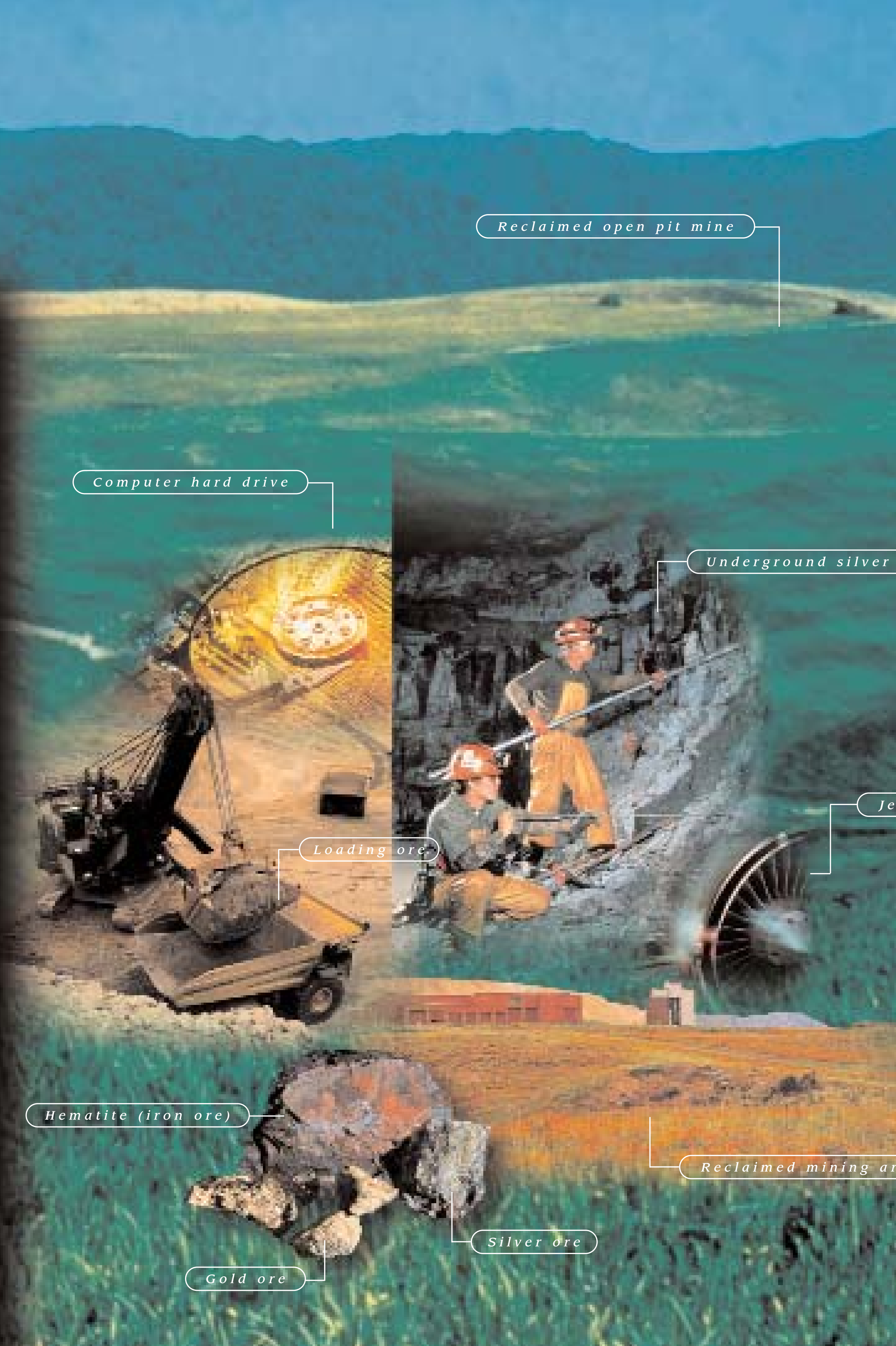
Geoffrey S. Plumlee
October, 1999



Faint traces of the benches show along the walls of this reclaimed open pit mine. Surface and underground metal-mining operations today plan for and deal with environmental impacts before, during, and after mining.



Chapter 1

It Helps to Know...

It is difficult to imagine life without iron, aluminum, copper, zinc, lead, gold, or silver. These and other metallic resources mined from the Earth are vital building blocks of our civilization — and society's need for them is increasing. Metal mining in the United States has evolved from small, simple operations to large, complex production and processing systems. Some historic mining activities that occurred when environmental consequences were poorly understood have left an unfortunate environmental legacy. Today, mining companies must plan for and deal with environmental impacts before, during, and after mining.

Mineral deposits containing metals are mined from the surface in open pit mines, or from underground. Later chapters describe the mining process, which separates metals from the rocks and minerals in which they occur, as well as potential environmental impacts and solutions. Included in this chapter is basic information about metal mining: what the environmental concerns are, how science and technology can help, why metals are important, and the steps in the mining cycle.

What the Environmental Concerns Are

Operations and waste products associated with metal extraction and processing are the principal causes of environmental concerns about metal mining, which may

- Physically disturb landscapes as a result of mine workings, waste rock and tailings disposal areas, and facility development.
- Increase the acidity of soils; such soils can be toxic to vegetation and a source of metals released to the environment.
- Degrade surface and groundwater quality as a result of the oxidation and dissolution of metal-bearing minerals.
- Increase air-borne dust and other emissions, such as sulfur dioxide and nitrogen oxides from smelters, that could contaminate the atmosphere and surrounding areas.

Modern mining operations actively strive to mitigate these potential environmental consequences of extracting metals. The key to effective mitigation lies in implementing scientific and technological advances that prevent or control undesired environmental impacts.

How Science and Technology Can Help

As scientific and technological advances increase the understanding of the physical and chemical processes that cause undesired environmental consequences, metal mines and related beneficiation or smelting facilities apply this understanding to prevent and resolve environmental problems. Ongoing mining operations and mine closure activities employ several different mitigation approaches including

- Reclamation of disturbed lands,
- Treatments and stabilization of metal-bearing soils,
- Prevention and treatment of contaminated water,
- Controls on the amount and character of emissions to the atmosphere,
- Minimizing waste and recycling raw materials and byproducts.

Better, more cost-effective approaches are needed for dealing with the environmental impacts of mining, beneficiation, and smelting, especially measures that prevent undesired environmental impacts. Scientific and technological research, focused on understanding the underlying processes important to these problems, can provide the foundation for new, cost-effective solutions. The challenge for future metal production is to develop environmentally sound mining and processing techniques that can also contribute to more widespread mitigation of historical environmental problems.

Why Metals Are Important

Metals are a class of chemical elements with very useful properties, such as strength, malleability, and conductivity of heat and electricity. Most metals can be pressed into shapes or drawn into thin wire without breaking, and they can be melted or fused. Some metals have magnetic properties, while others are very good conductors of

Metals Empower Us

Aluminum
Chromium
Cobalt
Columbium
Copper
Gold
Iron
Lead
Manganese
Mercury
Molybdenum
Nickel
Platinum
Silver
Tantalum
Tin
Titanium
Tungsten
Zinc
Zirconium

electricity. For example, gold is used in electronic equipment because it is an exceptional conductor of electricity and heat and it does not tarnish or corrode.

Metals and other minerals are essential components in such everyday necessities as our homes, cars, appliances, and tools. Indeed, we find ourselves becoming increasingly dependent on a vast array of new technologies — computer information systems and global communications networks — all of which need metals. Metals are also integral to the basic infrastructure of our society: transportation systems (highways, bridges, railroads, airports, and vehicles), electrical utilities for consumer power, and food production and distribution.

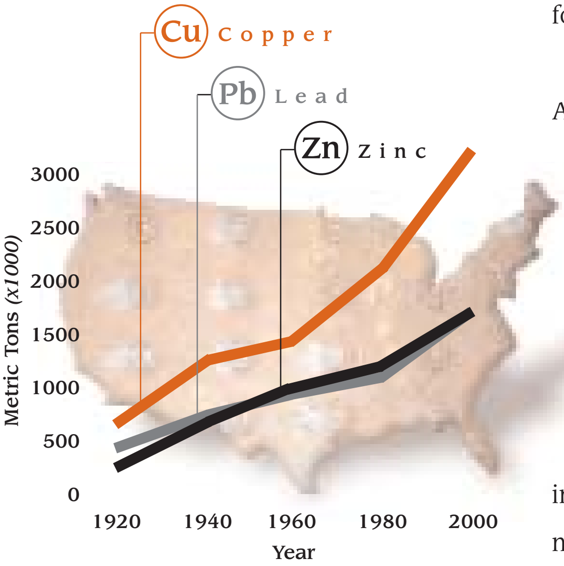


Fig.1. U.S. consumption of copper, lead, and zinc.

As the American population increases and our standard of living advances, so does our need for metals. We now use three times as much copper and four times as much lead and zinc as we did 75 years ago (Fig. 1).

The increasing need for metals in the United States is a need shared throughout the world. The desire to raise global living standards, coupled with a growing world population, will increase worldwide demand for metals in the future. This demand means that metal mining — the industry responsible for extracting metals from the Earth for use in our daily lives — will continue to be vital and necessary.

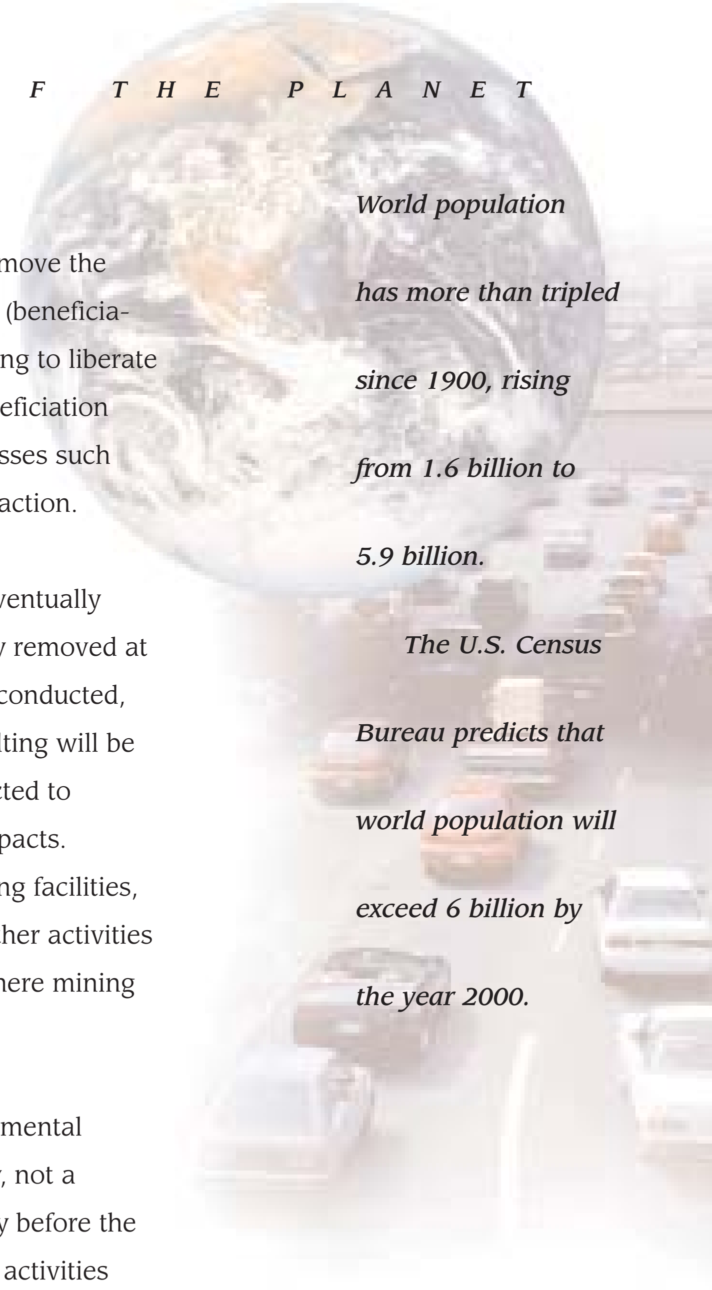
The Metal Mining Cycle

The geologic evolution of the Earth controls the quantity and the very uneven distribution of metal resources in the Earth's crust. Discovering metal-rich deposits commonly requires extensive searching, and exploration is the the first step in the mining cycle. Once exploration geologists find an area with metals, they determine whether it is of sufficient size and richness to be mined profitably. If the deposit is rich enough, activities to extract the metals from the Earth begin.

Extraction, the next part of the cycle, involves mining to remove the metal-bearing minerals from the Earth, mineral processing (beneficiation) to concentrate the metal bearing minerals, and smelting to liberate metals from the minerals that contain them. Although beneficiation and smelting are the most common processes, other processes such as chemical leaching are used for some types of metal extraction.

Mine closure is the final step in the mining cycle. Mining eventually depletes the metal-rich material that could be economically removed at a specific mine. When mining can no longer be profitably conducted, the mine and related facilities used in beneficiation or smelting will be closed. Closure involves many activities specifically conducted to prevent or mitigate undesired environmental and social impacts. These activities involve reclaiming disturbed areas, removing facilities, mitigating safety hazards, cross-training employees, and other activities that lead to environmentally benign and safe conditions where mining once took place.

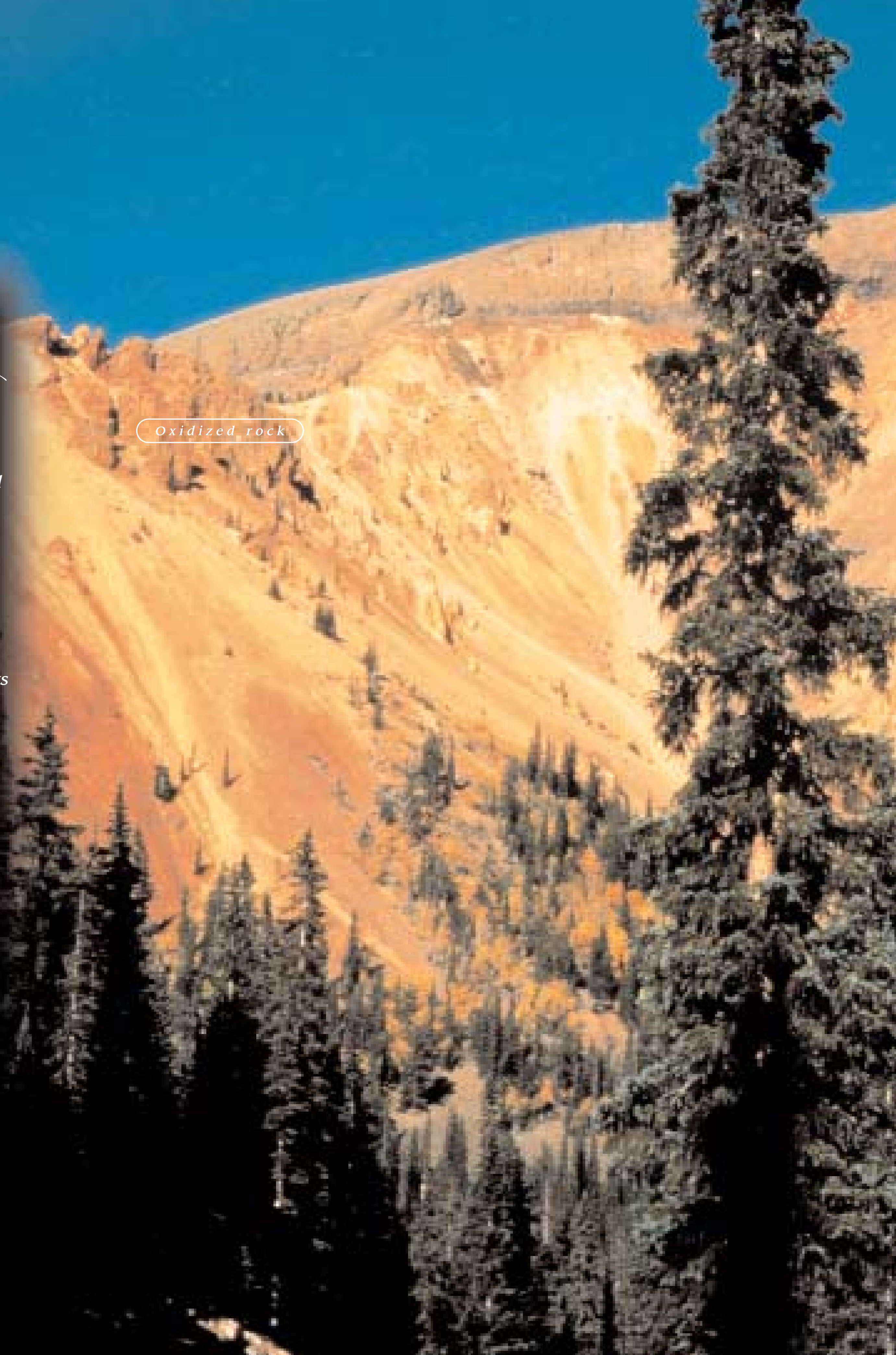
Mining in the early days took place at a time when environmental impacts were not as well understood and most importantly, not a matter of significant concern. During these times, primarily before the 1970s, the mining cycle did not necessarily include closure activities specifically designed to mitigate environmental or social impacts. As a result, historical mine sites may still have unreclaimed areas, remnants of facilities, and untreated water. This inherited legacy of environmental damage from mining is not indicative of the mining cycle today. Now, mine closure and a number of activities to mitigate the social and environmental impacts of mining are an integral part of all metal mine planning and mineral development from the discovery phase through to closure.



World population has more than tripled since 1900, rising from 1.6 billion to 5.9 billion.

The U.S. Census Bureau predicts that world population will exceed 6 billion by the year 2000.

Natural weathering and erosion of these unmined mineral deposits in Colorado release acidic waters and metal-bearing sediments into local streams.



Chapter 2

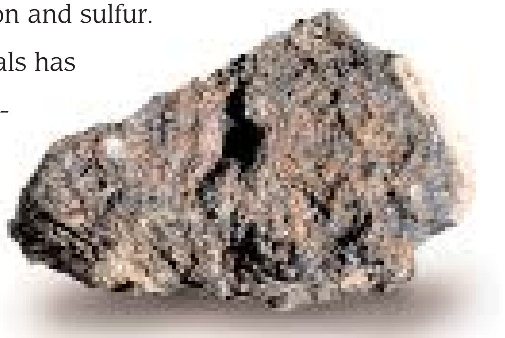
Exploring for Metals

The recovery of metals from the Earth starts with exploration. Mining companies expend tremendous amounts of time, effort, and money in the search for metallic resources. Metallic orebodies are rare; to find new ones, exploration geologists must understand how metals naturally occur, the special geologic processes that control orebody development, and how orebodies are physically and chemically expressed in the Earth.

The Geologic Foundation

Metals come from rocks and minerals in the Earth's crust. Minerals are naturally-formed chemical elements or combinations of elements that have specific chemical compositions and physical properties. Metallic and nonmetallic minerals occur in ordinary rocks throughout the Earth's crust, but only a few minerals contain high enough concentrations of metals to be mined profitably.

Certain metals, such as copper, lead, and zinc have a strong natural affinity for the element sulfur, and they combine with it to form minerals called sulfides. Probably the most familiar sulfide mineral is fool's gold (pyrite), which is composed of iron and sulfur. The mining and processing of sulfide minerals has historically been the source of most environmental concerns with metals extraction.



Ore rich in sulfide minerals

Mineral Deposits

Identifying deposits where geologic processes have concentrated sulfide minerals is a continuing challenge for exploration geologists. They search for mineral deposits that contain rich enough concentrations of metal-bearing minerals to economically justify mining. Metallic mineral deposits can be dispersed through entire mountains and can cause environmental impacts naturally — whether or not they are mined. For example, the mineralized deposits on the facing page are a natural source of acidic and metal-bearing water that enters the watershed.

Fig. 2. *Galena (lead sulfide) is the principal ore mineral of lead. Crystals of this bright metallic gray mineral characteristically show right-angle surfaces. Mining operations where lead is the primary metal typically require ores that contain a minimum of 8 percent lead.*

Special geologic processes lead to the development of mineral deposits having high concentrations of metal-bearing minerals. These types of mineral deposits are rare, and they occur in very diverse locations. Large mineral deposits are being mined today from various environmental and geographic settings, such as high mountainous rain forests located in Indonesia, arid deserts in Arizona, and the treeless Arctic tundra of Alaska.

The settings where mineral deposits occur can play a significant role in determining the nature and the extent of environmental concerns at specific mine locations. The potential environmental impacts of mining the same type of mineral deposit can be very different in different locations and settings. For example, mining in arid parts of Arizona has different potential impacts on surface water and groundwater quality than if the same mining had occurred in areas of temperate climates, such as the Rocky Mountains or the midwest. Although many metallic mineral deposits have been identified through exploration, only a few deposits are large enough and have a metal content great enough to support commercial operations. The economically important part of a mineral deposit is known as the “ore” or “orebody” (Fig. 2).

Once an orebody is identified within a mineral deposit, geologists determine its form. The form of the orebody is important for two reasons: the shape of an orebody helps determine the best way to mine it, and the orebody form influences the potential environmental impacts associated with mining. Although every mineral deposit has distinctive features, they generally exist in two common forms. In one form, the orebody can have dimensions (length, width, and depth) measured in miles (kilometers) and can include a large volume of rock at or near the surface. These ore deposits are most efficiently mined from surface excavations called open pits.

The other general orebody form is one characterized by tabular shapes in which either the vertical or horizontal dimension is much greater than the other — at the most one or two miles (1 to 3 km) in depth or length. These types of deposits can extend to considerable depth and are most commonly mined by underground mining techniques. Large massive orebodies occurring at depths greater than about 1000 feet (350 meters) also must be extracted by expensive underground mining techniques.

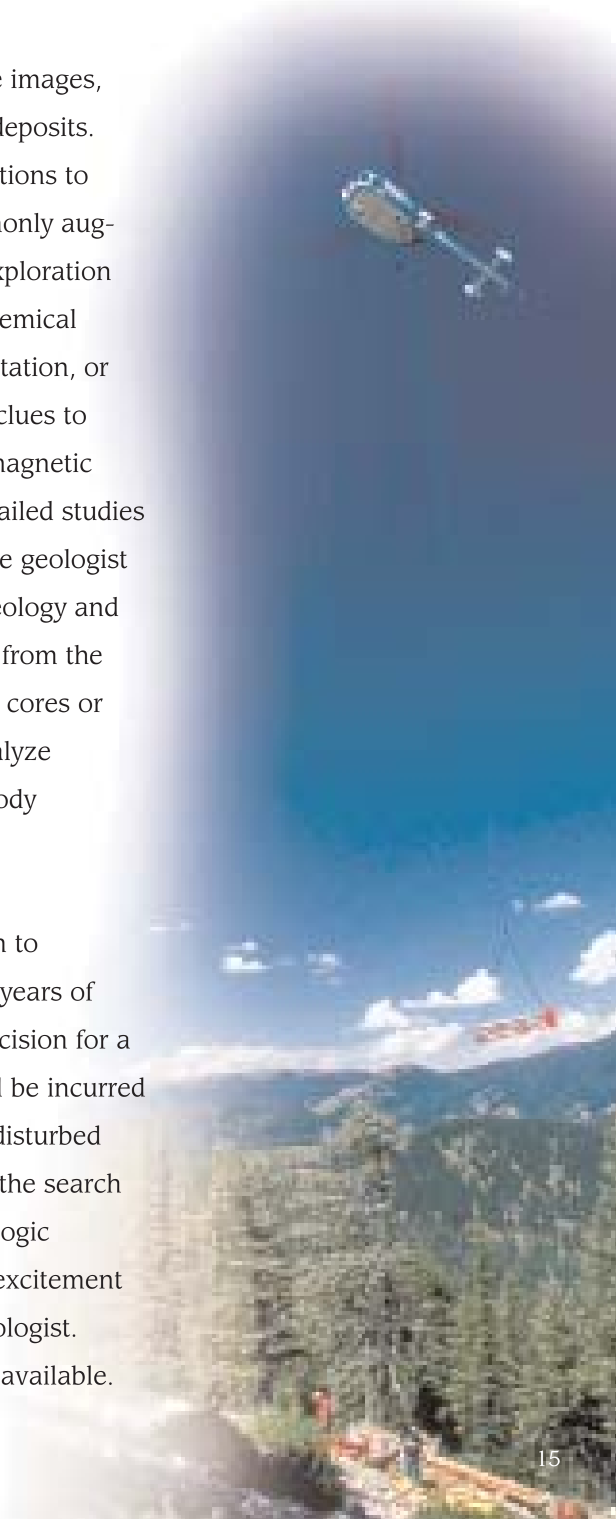
The Exploration Process

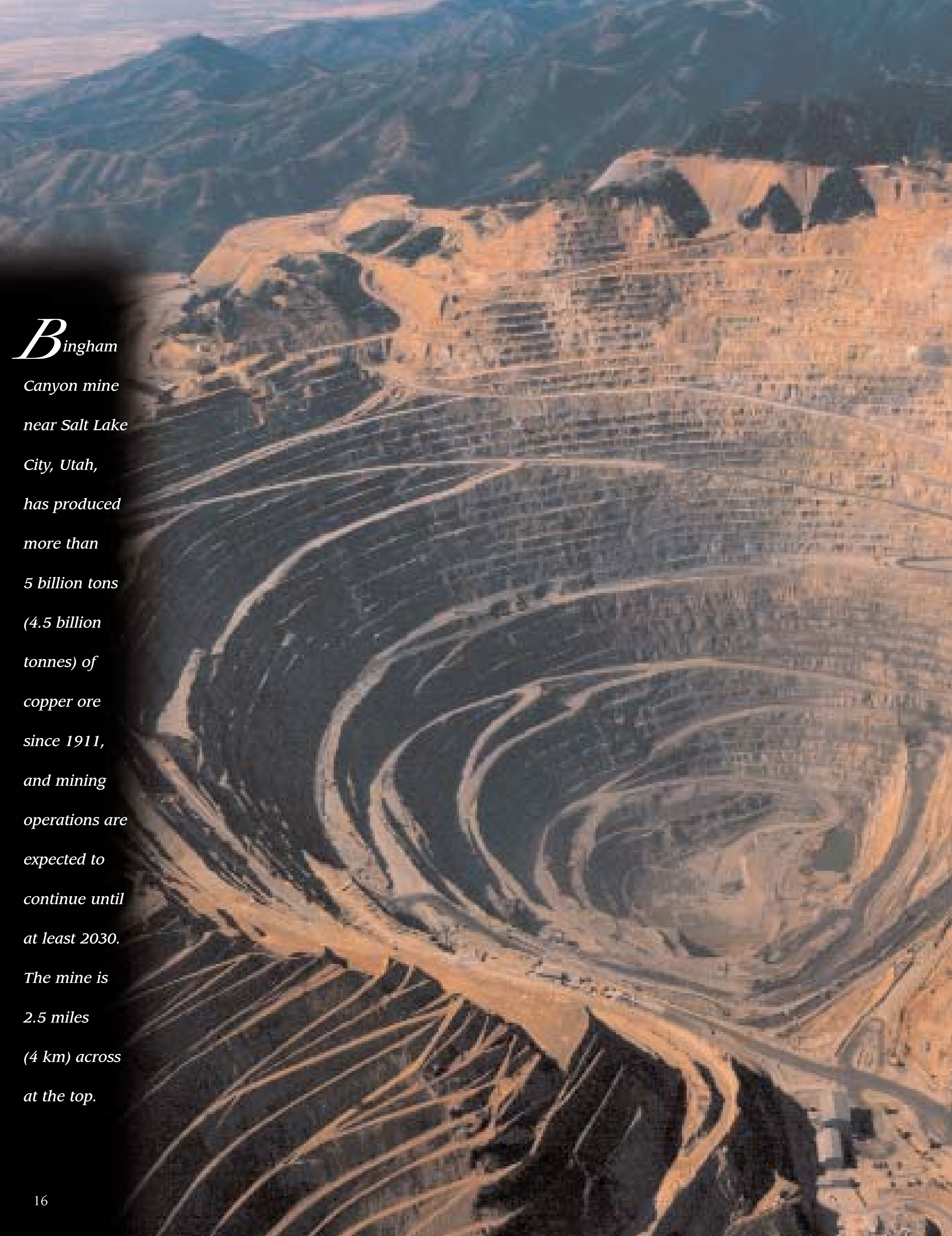
Mineral exploration is a challenging enterprise that takes geologists to remote regions throughout the world and requires a variety of scientific and technical skills. Exploration geologists need exceptional perseverance, for they may examine dozens and dozens of mineral deposits without finding one ore body that is rich enough to support mining. On a worldwide scale, however, geologists find a few new orebodies each year.

The exploration process begins with a geologist examining satellite images, geologic maps, and reports to identify areas favorable for mineral deposits. Once these areas are defined, the geologist conducts field examinations to create more detailed maps and rock descriptions. Geologists commonly augment their field examinations with geochemical and geophysical exploration techniques that help them identify specific mineral deposits. Geochemical techniques are used to analyze samples of rocks, soils, water, vegetation, or stream sediments which may contain elements that are important clues to possible nearby metal deposits. Geophysical techniques, such as magnetic surveys, can help characterize rocks beneath the surface. Very detailed studies are done to determine if a mineral deposit contains an orebody. The geologist carries out these studies by making detailed maps of the surface geology and combining these with detailed characterizations of rocks extracted from the mineral deposit. Drilling into a mineral deposit commonly recovers cores or chips of the subsurface rocks that geologists then examine and analyze chemically. Verifying the subsurface character and form of an orebody requires extensive drilling.

In general, the exploration process — from initial office compilation to extensive drilling — is expensive and time-consuming. It may take years of work and millions of dollars of expense to reach a development decision for a specific mineral deposit. In most cases, this work and expense will be incurred only to determine that an orebody is not present. In that case, the disturbed sites will be reclaimed and the exploration process starts over and the search for another favorable area begins. Perseverance and insightful geologic analysis are the keys to success — eventually they can lead to the excitement of an orebody discovery, the ultimate reward for an exploration geologist. Discovery of an orebody is the first step toward making the metals available.

Mineral exploration





Bingham Canyon mine near Salt Lake City, Utah, has produced more than 5 billion tons (4.5 billion tonnes) of copper ore since 1911, and mining operations are expected to continue until at least 2030. The mine is 2.5 miles (4 km) across at the top.

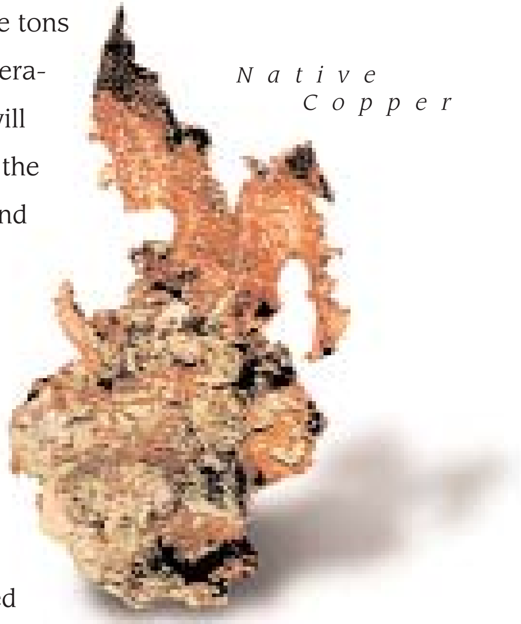
Chapter 3

Mining Metals

The mining process, from the surface in open pit mines or from underground, separates the ores from the surrounding rocks. Although both surface and underground mining disturb the landscape, the scale of these disturbances differs markedly.

Surface Mining

Open pit mining commonly disturbs more land surface and earth material than underground mining. The leading mines in the world are open pit mines. The open pit mining process includes blasting the ore loose, hauling it to a crusher, and breaking it into pieces small enough for milling (Fig. 3). Technology has evolved to handle tremendous volumes of material in this highly mechanized process of open pit mining. Mines like the one shown on these pages produce up to 150,000 tons (136,000 tonnes) of ore daily. Typically, for every ton of metal ore produced, as much as two or three tons of waste rock are also produced. As mining operations expose the orebody, the mine geologist will continue to map and describe it to ensure that the most cost-effective mining plan is developed and implemented.



Native Copper

Waste rock, the name for rocks and minerals that enclose the ore and need to be removed in order to recover it, contains too few valuable minerals to process. Although the metal content of waste rock is too low to be recovered profitably, the environmental issues related to its characteristics and handling are very important. Large volumes of waste rock are created during the open pit mining process. For example, the waste rock disposal areas that develop at a surface mine like the Bingham Canyon mine sometimes cover hundreds or even thousands of acres (tens of km^2) and may be several hundred

Open Pit Mining Process

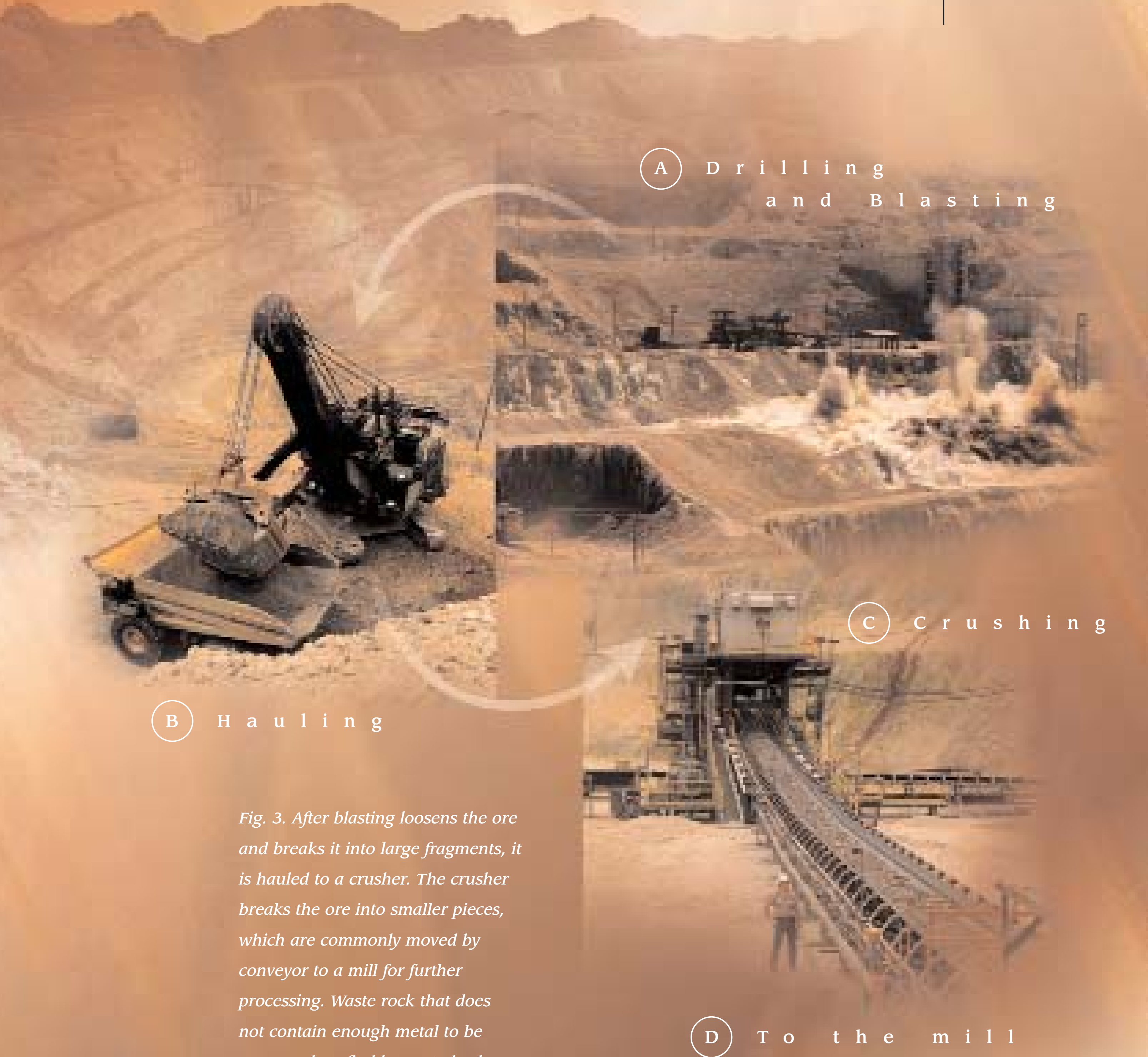


Fig. 3. After blasting loosens the ore and breaks it into large fragments, it is hauled to a crusher. The crusher breaks the ore into smaller pieces, which are commonly moved by conveyor to a mill for further processing. Waste rock that does not contain enough metal to be processed profitably must also be removed; trucks haul waste rock out of the pit to nearby disposal areas.

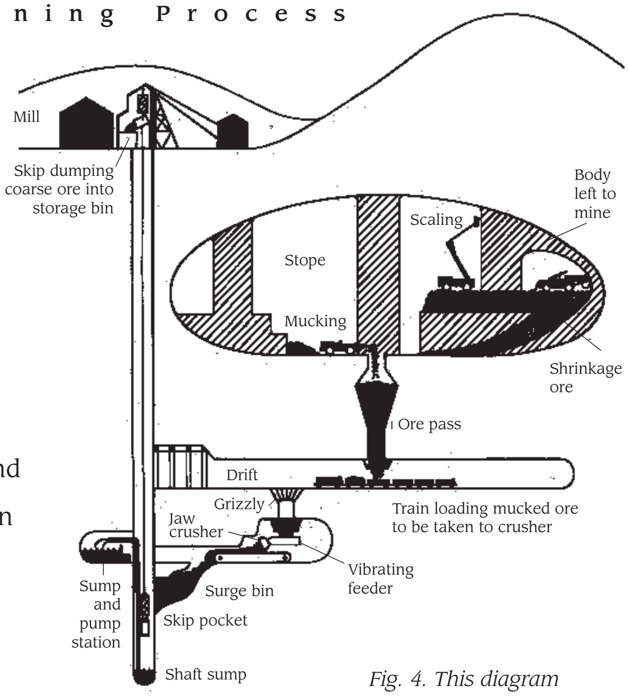


Fig. 4. This diagram of a zinc mine in Tennessee shows the basic components of an underground mine.

feet (one to two hundred meters) high. Waste rock disposal areas are commonly one of the most visible aspects of a surface mine.

Underground Mining

Figure 4 illustrates the underground mining process. Underground mines may use vertical shafts as shown, or mine openings driven into mountainsides, known as “adits.” Although the primary challenge for underground and open pit mining is the same — to remove ore economically from the enclosing rocks — underground mining differs in two important ways.

First, the size of the operation is much smaller than in open pit mining, and the mining activities are not as visible at the surface. Figure 5 shows examples of relatively large underground openings and related mining equipment. Over the life of an underground mine, the volume of ore produced is most commonly only a few hundred thousand to a few million tons. This compares to production at larger open pit mines where one million tons of ore may be produced in just one week of operations.

Fig. 5. Large equipment used in underground mining includes scalers that remove loose materials left on the walls and roof after blasting.

The second big difference is the volume and disposal of waste rock. It is common in underground mining for the volume of waste rock to be equal to or less than the volume of the ore produced. In optimum situations, very little waste rock is generated and the waste rock can be used to fill underground areas where access is no longer needed. Where waste rock must be hauled to the surface, the resulting disposal areas, although much smaller in size and volume than those at open pit mines, may still be highly visible. As underground mining was the most common mining method before 1900, waste rock disposal areas at the portals of mine workings are common in historical mining districts.

Potential Environmental Impacts of Mining

The most common environmental concerns associated with metal mining operations are

- **physical disturbances to the landscape,**
- **waste rock disposal,**
- **development of metal-bearing and acidic soils and waters,**
- **public safety.**

Physical Disturbances

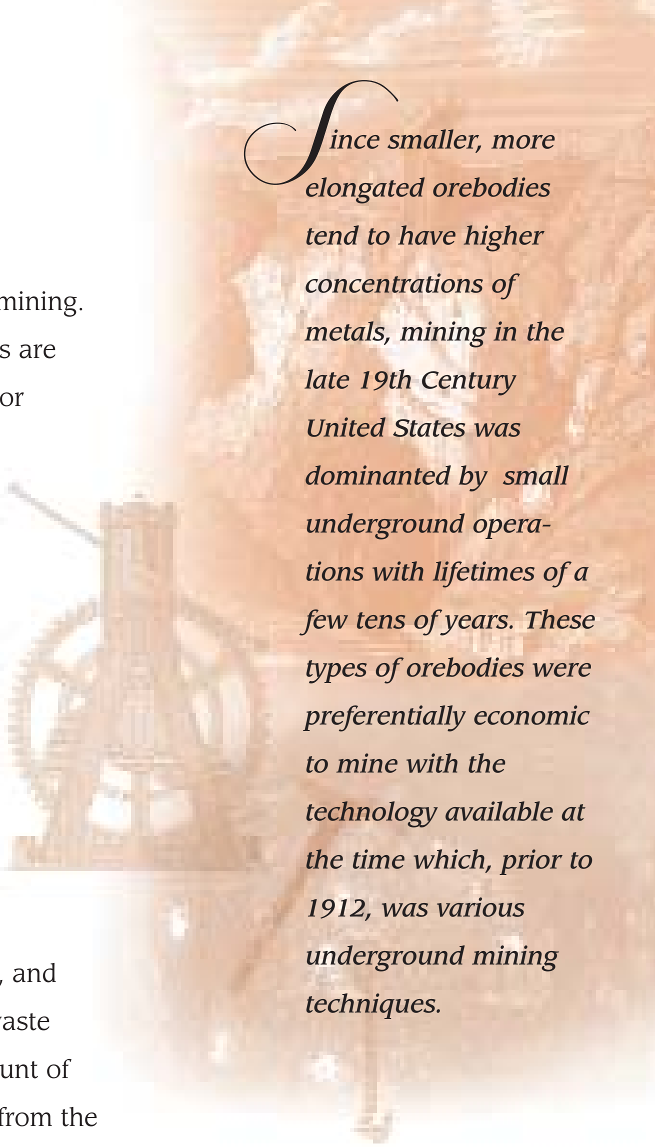
The largest physical disturbances at a mine site are the actual mine workings, such as open pits and the associated waste rock disposal areas (Fig. 6). Mining facilities such as offices, shops, and mills, which occupy a small part of the disturbed area, are usually salvaged or demolished when the mine is closed. The open pits and waste rock

Fig. 6. The light-colored bare piles of waste rock near these houses in Butte, Montana, remain from the early underground mines. Open pit operations followed, and some waste rock and mill tailings from that stage show in the distance.

disposal areas are the principal visual and aesthetic impacts of mining. These impacts remain on the landscape until the disturbed areas are stabilized and reclaimed for other uses, such as wildlife habitat or recreation areas, after mining has ceased.

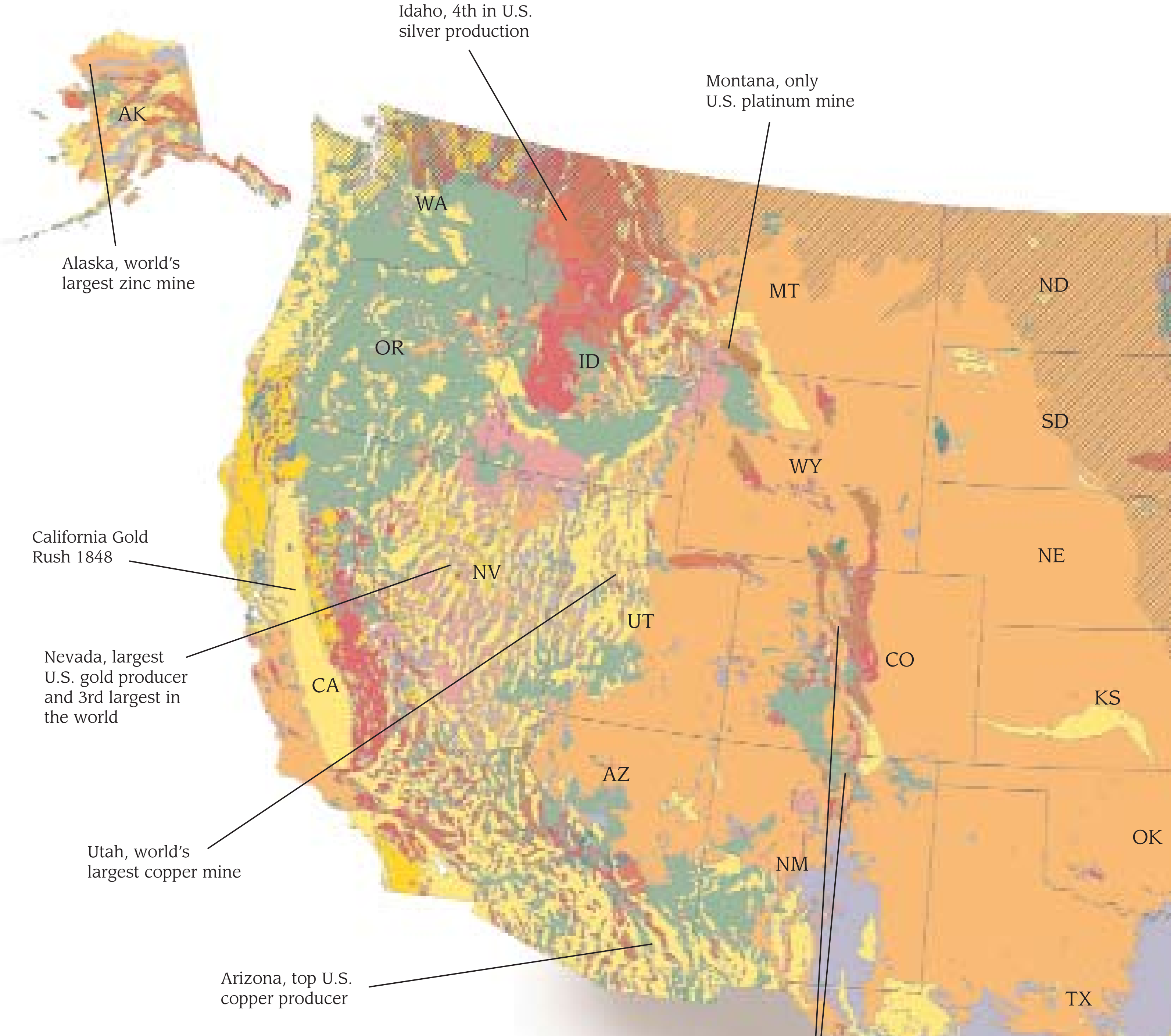
Underground mining generally results in relatively small waste rock disposal areas ranging from a few acres in size to tens of acres (0.1 km^2). These areas are typically located near the openings of the underground workings. Some waste rock areas, if not properly managed, can be sources of significant environmental impacts, such as stream sedimentation if erosion occurs, or the development of acidic water containing metals.

Open pit mining disturbs larger areas than underground mining, and thus has larger visual and physical impacts. As the amount of waste rock in open pit mines is commonly two to three times the amount of ore produced, tremendous volumes of waste rock are removed from the pits and deposited in areas nearby. During active mining operations, this type of waste rock area (Fig. 7) and the associated open pit, are very visible physical impacts. Although the physical disturbance associated with metal mining can be locally significant, the total land area used for metal mining is very small compared to other major types of land use (Fig. 8).



Since smaller, more elongated orebodies tend to have higher concentrations of metals, mining in the late 19th Century United States was dominanted by small underground operations with lifetimes of a few tens of years. These types of orebodies were preferentially economic to mine with the technology available at the time which, prior to 1912, was various underground mining techniques.

Fig. 7. The reclaimed waste rock area in the foreground offers a preview of how Kennecott Utah Copper will ultimately reclaim the active waste rock pile in the background.



Idaho, 4th in U.S. silver production

Montana, only U.S. platinum mine

Alaska, world's largest zinc mine

California Gold Rush 1848

Nevada, largest U.S. gold producer and 3rd largest in the world

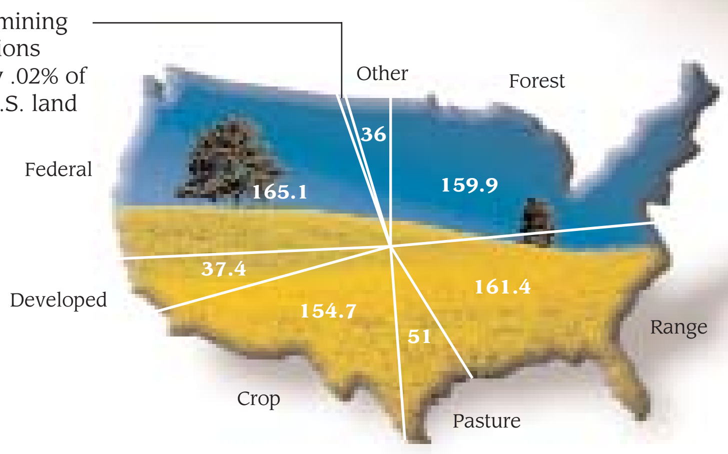
Utah, world's largest copper mine

Arizona, top U.S. copper producer

Colorado & New Mexico produce molybdemun

Missouri, leading U.S. lead producer

Metal mining operations occupy .02% of total U.S. land



U.S. land use in millions of hectares
(1 hectare = 2.47 acres)

Key Mining Areas

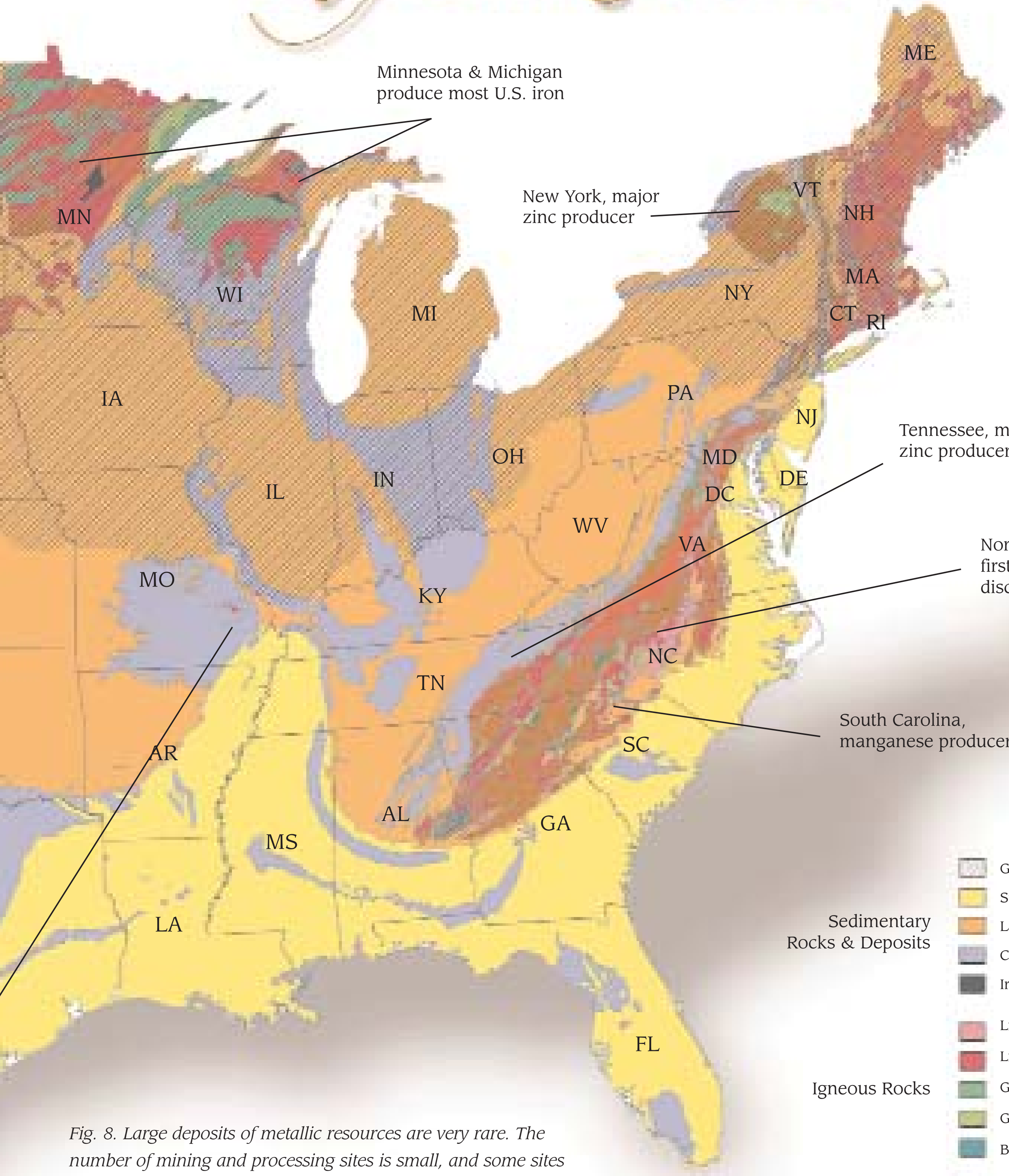


Fig. 8. Large deposits of metallic resources are very rare. The number of mining and processing sites is small, and some sites produce several metals. Metal mining operations in the United States occupy less than one-quarter of one percent of the total land area. This generalized map points out 16 states containing important metal resources. The map also shows the general distribution of the dominant types of rocks and deposits of sediments.

Waste Rock Disposal

Waste rock disposal areas are usually located as close to the mine as possible to minimize haulage costs. Although the waste rock may contain metals, such as lead, zinc, copper, or silver, the rock is still considered a waste, because the cost to process it would exceed the value of the metals it contains. If not properly managed, erosion of mineralized waste rock into surface drainages may lead to concentrations of metals in stream sediments. This situation can be potentially harmful, particularly if the metals are in a chemical form that allows them to be easily released from the sediments into stream waters. When this occurs, the metals are considered to be "mobilized" and "bioavailable" in the environment. In some cases, bioavailable metals are absorbed by plants and animals, causing detrimental effects. Although current U.S. mining and reclamation practices guided by environmental regulations minimize or prevent waste rock erosion into streams, disposal of waste rock in places where it could erode into surface drainages has occurred historically. These conditions still exist at some old or abandoned mines (Fig. 9).

Fig. 9. At this waste rock disposal area of a small underground mine in Colorado, the river in the foreground flows against the waste rock pile. Erosion of the waste rock formerly released metal-bearing materials into the stream until remediation of the site in 1996 prevented further erosion.

Acidic and Metal-Bearing Soils and Waters

Although the character of waste rock varies with the type of ore, many waste rocks contain sulfide minerals associated with metals, such as lead, zinc, copper, silver, or cadmium. An important sulfide mineral common in waste rock is pyrite, iron sulfide (FeS_2). When pyrite is exposed to air and water, it undergoes a chemical reaction called "oxidation." Oxidation of pyrite results in the formation of iron oxides that typically impart an orange or red "rust" color to waste rock (Fig. 10). The oxidation process, which is enhanced by bacterial action, also produces acidic conditions that can inhibit plant growth at the surface of a waste pile. Bare, non-vegetated, orange-colored surface materials make some waste rock areas highly visible, and they are the most obvious result of these acidic conditions.

Fig. 10. The bright flecks in the largest piece of waste rock from the site in Fig. 9 are unoxidized crystals of pyrite (fool's gold). Oxidation of this sulfide mineral produces iron oxides and characteristic rusty staining of rocks, soils, and water.

If water infiltrates into pyrite-laden waste rock, the resulting oxidation can acidify the water, enabling it to dissolve metals such as copper, zinc, and silver. This production of acidic water, is commonly referred to as "acid rock drainage." If acid rock drainage is not prevented from occurring, and if it is left uncontrolled, the resulting acidic and metal-bearing water may drain into and contaminate streams or migrate into the local groundwater. The acidity of contaminated groundwater may become neutralized as it moves through soils and rocks (Fig. 11). However, significant levels of dissolved constituents can remain, inhibiting its use for drinking water or irrigation.

Where acid rock drainage occurs, the dissolution and subsequent mobilization of metals into surface and groundwater is probably the most significant environmental impact associated with metallic sulfide mineral mining. Acidic and metal-bearing groundwater occurs in abandoned underground mine workings and deeper surface excavations that encounter the groundwater of a mineralized area. Because they are usually located at or below the water table, underground mines act as a type of well which keeps filling with water. Removal and treatment of this accumulated water in underground mines must be continuous in order to conduct operations. However, after mining ceases, the mine workings will fill up with water and some of the water may discharge to the surface through mine openings. Because these waters migrate through underground mine workings before discharging, they interact with the minerals and rocks exposed in the mine. If sulfide minerals are present in these rocks, especially pyrite, the sulfides can oxidize and cause acid rock drainage (Fig. 12).

Fig. 11. Despite the ominous color, the acidity of these red iron-rich waters is so close to neutral that they support life and natural wetlands. The wetlands are visible in Fig. 9 as green areas along the back of the waste rock pile. The rusty water flows from a collapsed adit that was once an open mine portal like the one in Fig. 12 below.

Fig. 12. Unlike the neutral water in Fig. 11, the green water flowing from this adit portal of a small underground mine in southern Colorado is so highly acidic that it carries high levels of dissolved metals, such as copper, iron, aluminum, zinc, and arsenic.

Preventing and treating acid rock drainage is a key environmental challenge.

Crystals of unoxidized pyrite (fool's gold)

Fig. 13. This former open pit mine in Montana is filling with acidic and metal-bearing water, as a result of acid rock drainage. Oxidation of sulfide minerals — especially pyrite — can result in acid rock drainage.

If left unmanaged, significant volumes of acid rock drainage can form at large mine workings (Fig. 13), which can degrade the quality of surface waters into which it flows. Preventing and treating acid rock drainage from mine workings is a key environmental challenge.

Public Safety

Old mining sites are inherently interesting to people, but potentially dangerous as well. They may have surface pits, exposed or hidden entrances to underground workings, or old intriguing buildings. Another safety consideration at some mine sites is ground sinking or "subsidence." The ground may sink gradually where underground workings have come close to the surface. Because an unexpected collapse can occur without warning, such areas usually are identified and should be avoided. When modern mines are closed, mine owners mitigate such hazards by closing off mine workings, regrading and decreasing the steep slopes of surface excavations, and salvaging or demolishing buildings and facilities.

In some states where old mining areas are common, such as Colorado and Nevada, current mine owners, government agencies, or other interested parties may undertake reclamation and safety mitigation projects that address hazards at these sites. At a minimum, these programs identify hazards, install warning and no trespass signs, and fence off dangerous areas (Fig. 14). The closing of entrances to old underground workings may also be done as a part of these efforts. Some abandoned mine workings have become important habitats for bat colonies. Closure of mine openings can be designed to allow the bats continued access and protection. This practice is especially valuable for endangered bat species. Because many old mine sites may not be safe, the casual visitor to such sites is cautioned to exercise care and avoid entering them.

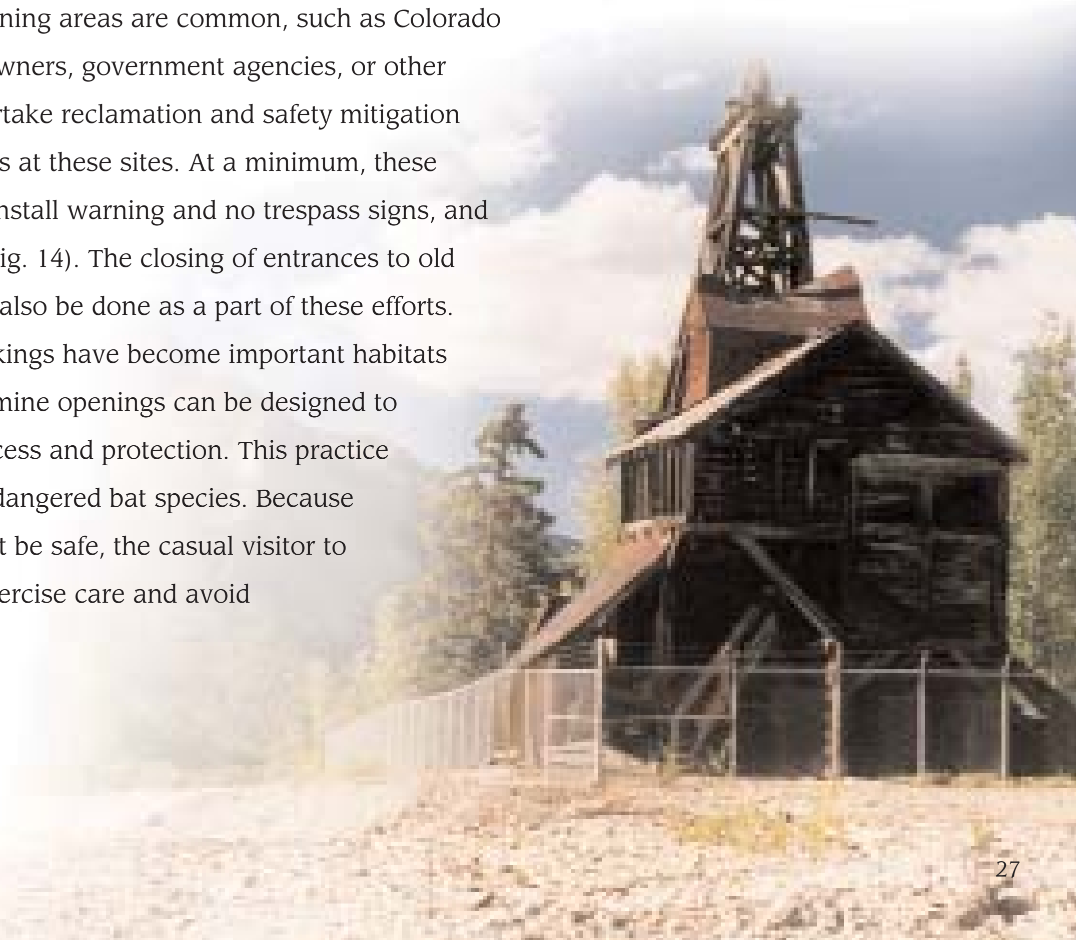
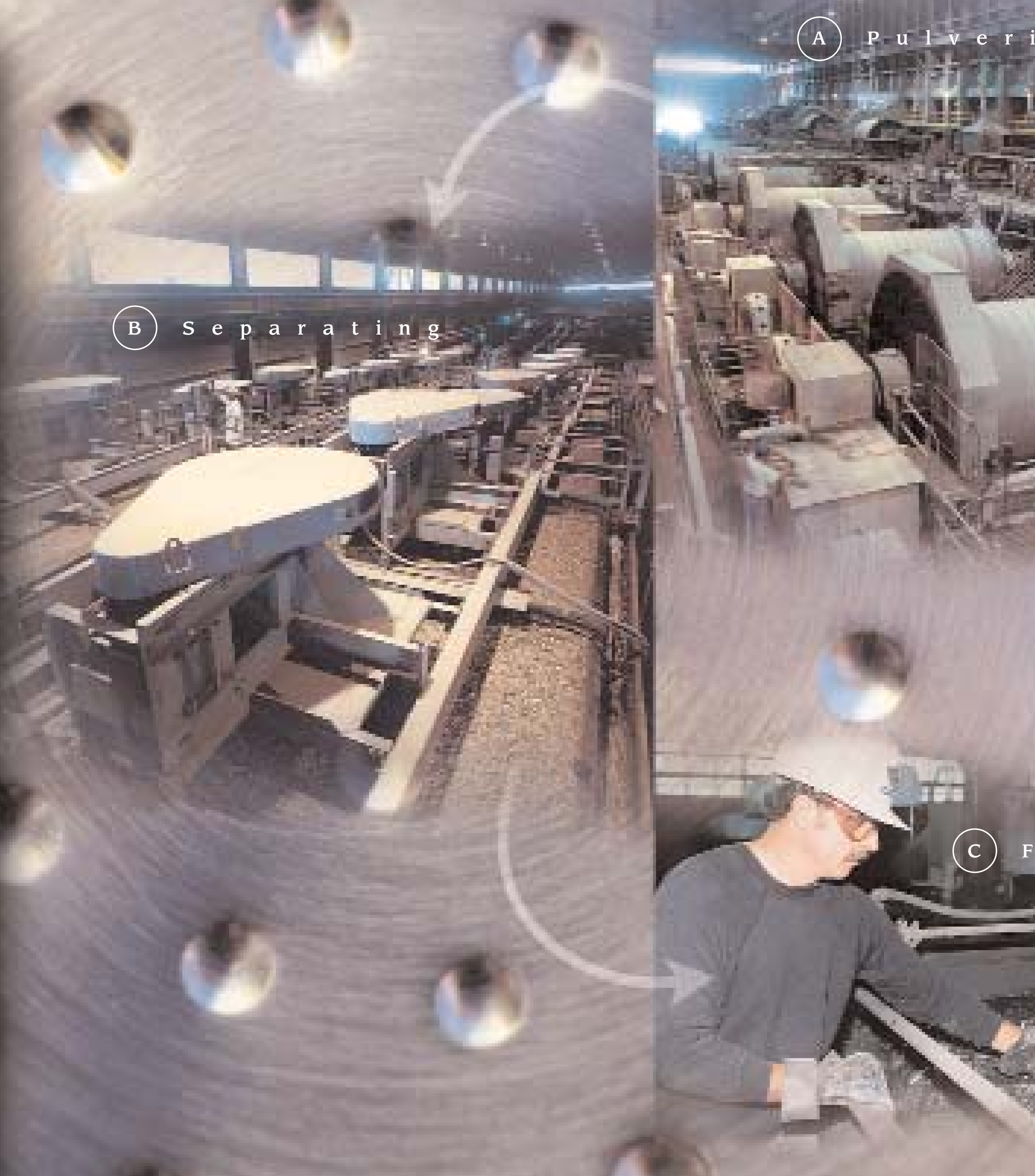


Fig. 14. To help ensure public safety, the former owner of this small underground mine in southwestern Colorado installed a fence around it. The wooden head-frame covers the mine shaft.

Milling and Flotation

After grinding the ore in rotating mills, the tiny grains of ore go into a watery slurry that is pumped to flotation cells. There most of the metallic grains stick to the surface of the bubbles and float off the top of the cells. Filtering the bubbly mixture concentrates the metals. This process has been in common use for copper, lead, and zinc ores for more than 80 years.



Chapter 4

Concentrating Metals

Because ore is a mixture of minerals, it is necessary to separate the minerals that contain metals from the others. Beneficiation is the step in the mining process that crushes the ore, separates, and concentrates the valuable minerals. Beneficiation includes milling or leaching, flotation, and the creation of a waste product called tailings.

Milling and Leaching

Large rotating mills use metal balls or rods to grind the ore into tiny particles to the consistency of silt, sand, and clay. The actual particle size can vary, but the objective is to break the ore into individual mineral grains. The crushed and ground ore leaves the mill as a water-rich slurry, which may be processed in a variety of ways to concentrate the valuable metallic minerals.

A concentration process commonly used for sulfide ores of copper, lead, and zinc is "flotation". In this process, the water-rich slurry from the mill is passed through large vats containing special bubble-making chemicals or "reagents". The vats are agitated and the metal-bearing minerals selectively attach themselves to the reagent bubbles and float off the surface of the vats — hence, the name flotation. Water is filtered from the bubble-rich liquid, and the resulting material is an ore concentrate that is rich in metal-bearing minerals.

Flotation leaves behind minerals, such as quartz and pyrite, that do not contain valuable metals. The nonvaluable minerals remain as part of the water-rich slurry in the agitated vats until almost all of the valuable metal-bearing minerals have been floated off. After it has been stripped of valuable metals, the slurry is a waste product called tailings. The tailings are pumped into large ponds, called "impoundments", for disposal (Fig. 15).

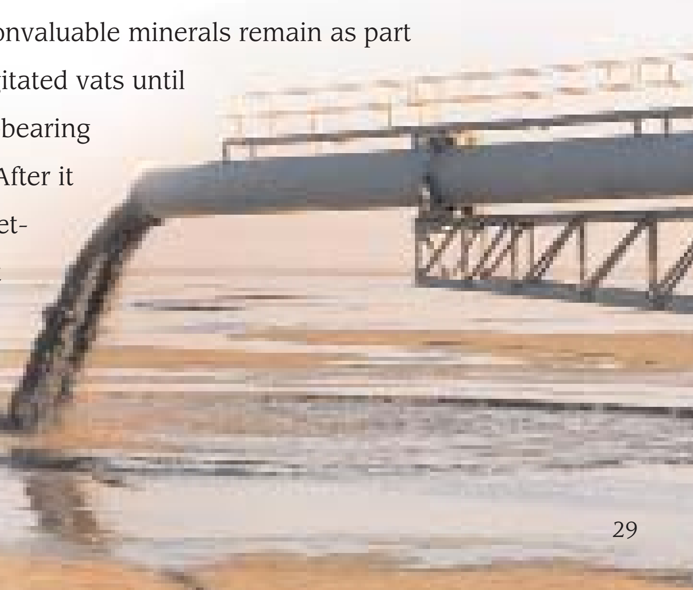


Fig. 15. The watery slurry of tailings, the nonvaluable minerals left from the milling and flotation process, is pumped into impoundments for disposal.

Tailings are the primary waste material and a potential source of environmental impacts from the milling process. In some cases, tailings have high concentrations of pyrite (up to tens of percent by volume). Some of the most significant environmental issues associated with beneficiation stem from the disposal of sulfide-rich tailings.

Instead of milling, some metals — mostly from certain kinds of copper and gold ores — are concentrated through the process of leaching. After the ore has been placed in large piles or heaps on specially designed pads (Fig. 16), water containing solutions of sulfuric acid or dilute sodium cyanide is dispersed throughout the ore leach pile. The solutions percolating down through the pile of ore dissolve the desired metals before being collected from the base of the pile. Well-designed leach pads have synthetic or natural clay liners that prevent leakage of the chemical- and metal-laden fluids into the ground.

Fig. 16. Heap leaching is an alternative way to recover certain metals. Heap leach operations, such as this one in Nevada, process gold ore by dissolving the metal with solutions that percolate through the ore heap. The dissolved gold is harvested from the solutions that collect at the bottom of the pile. The solutions are returned to the top to start the leaching process again. Large waste piles that may still contain some metals and residual chemicals are the chief environmental concerns about this process.

The dissolved metals are precipitated in various ways from the collected waters, which are then returned to the top of the pile to start the leaching process over again. Although leaching avoids milling and the generation of tailings, it leaves behind large heaps of metal-depleted materials that may contain residual chemicals from the leach waters that have passed through them. Rinsing spent leach piles is done to ensure that the chemicals have been removed. Spent leach piles are nevertheless a source of environmental concern, and they must be properly reclaimed and closed.

Potential Environmental Impacts of Beneficiation

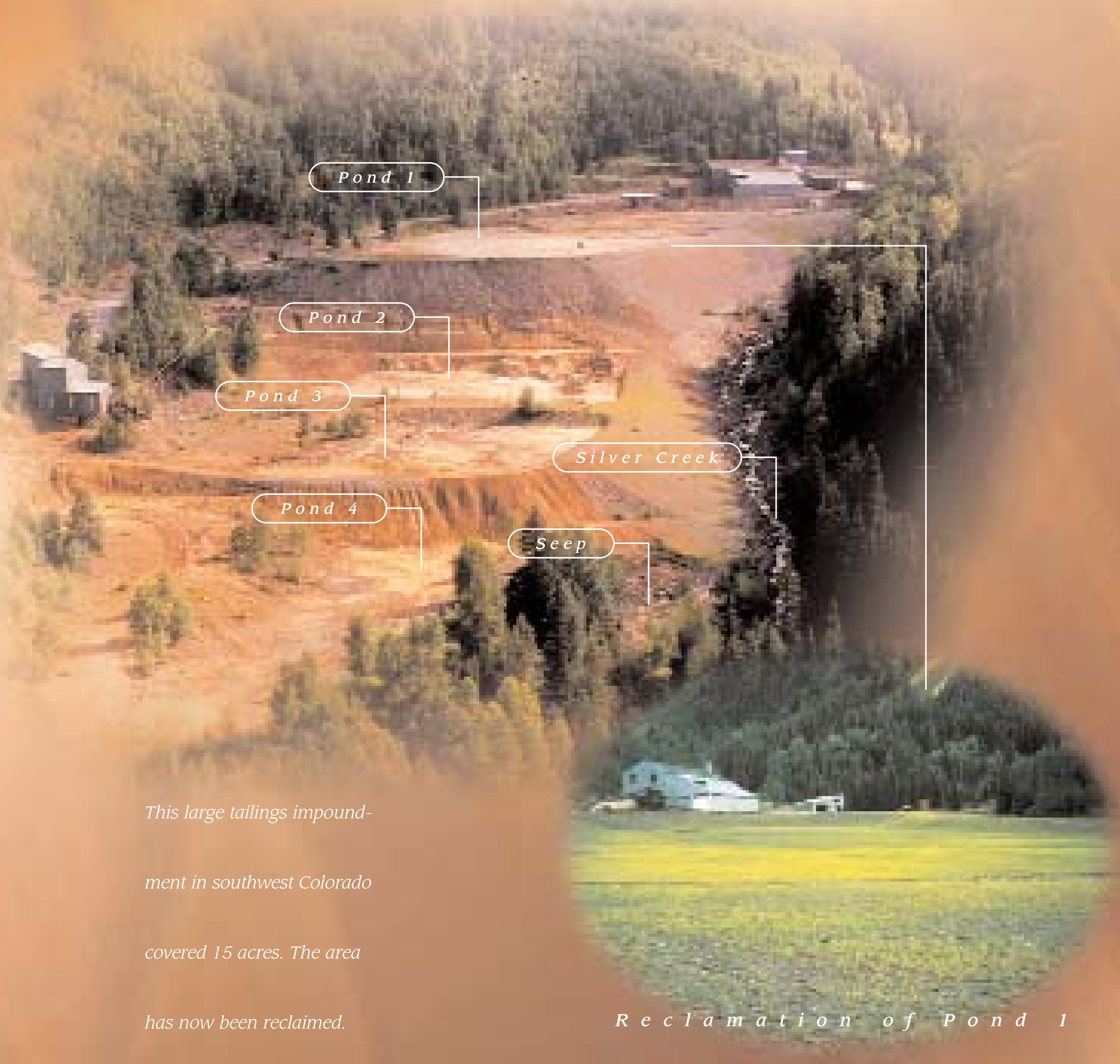
The potential environmental impacts of tailings impoundments and leach piles include several aspects similar to those of waste rock disposal areas. However, in some ways the wastes from beneficiation processes present greater challenges than those from waste rock. The potential impacts include

- **physical disturbances to the landscape,**
- **development of acidic soils and waters,**
- **erosion of tailings by wind and water,**
- **leach piles containing residual chemicals.**

Physical Disturbances

Tailings impoundments and leach piles vary in size, but both can be very large. To save energy, tailings impoundments are commonly created somewhere down slope from the mill so that gravity will help move the tailings slurry to the impoundment. Tailings impoundments may be located miles (kilometers) away from the mill where they are produced. The impoundments associated with some of the largest mills, such as at open pit copper mines, can cover thousands of acres (tens of km^2) and be several hundred feet (about 100 m) thick. Some tailings impoundments present reclamation challenges even more significant than those presented by waste rock.

Reclaiming a Tailings Impoundment



Reclamation of Pond 1

This large tailings impoundment in southwest Colorado covered 15 acres. The area has now been reclaimed. The inset shows the upper pond after reclamation.

Heap leach piles can cover tens to hundreds of acres (0.1 to 1 km^2) and be a few hundred feet (about 100 m) high. They resemble waste rock piles in location and size, but they have a more precisely, engineered form to facilitate the leaching process.

Acidic Soils and Waters

Tailings produced from the milling of sulfide ores — primarily copper, lead, and zinc ores — may have concentrations of pyrite that are greater than those common in waste rock. Also, because tailings are composed of small mineral particles the size of fine sand and smaller, they can react with air and water more readily than waste rocks. Therefore, the potential to develop acidic conditions in pyrite-rich tailings is very high. The resulting acidic soil conditions give some tailings impoundments orange and buff-colored, nonvegetated surfaces, similar to some sulfide-bearing waste rocks. Tailings are saturated with water upon disposal. If it is not prevented or controlled, acidic waters, commonly a form of acid rock drainage, can seep from their base (Fig. 17).

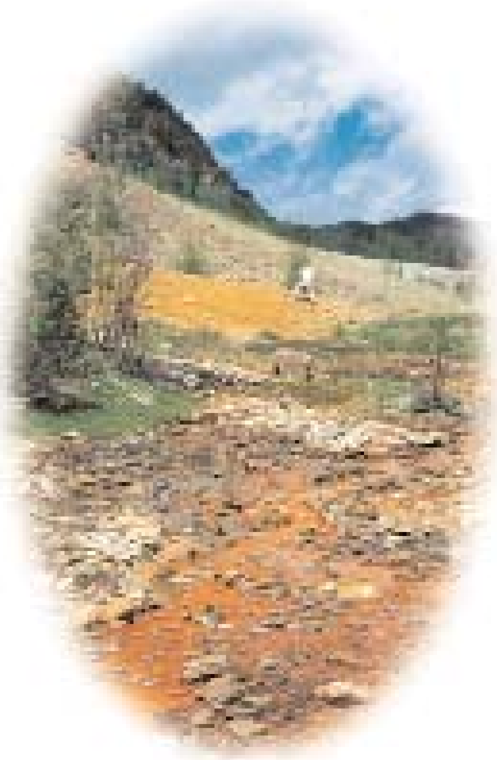


Fig. 17. Metal-bearing waters seep from the base of a mill tailing impoundment along Silver Creek in the Rico mining district of southwest Colorado.

Some parts of tailings impoundments contain high proportions of very fine-grained material. This clay-size material, called "slimes," is relatively impermeable, and surface waters can form ponds on it (Fig. 18). The ponding of water on a tailings surface keeps the tailings saturated with water and enables seepage to continue indefinitely.

Fig. 18. Low permeability of the tailings caused surface water to collect as a large pond on top of this tailings impoundment in Colorado. This situation may lead to seeps (such as the one shown in Fig. 17) in impoundments that lack an impermeable barrier which prevents drainage.

Fig. 19. The grinding of ore in a mill produces fine tailings particles that may blow away, as the dust cloud over this impoundment in Nevada illustrates.

This situation presents a formidable challenge for closure. However, the saturated condition of a tailings impoundment also prevents the fine particles of tailings from becoming wind borne and creating fugitive dust.

Seepage from tailings can be prevented or minimized by placing an impermeable barrier, such as clay, at the bottom of the impoundment before tailings disposal. Many pre-1970s tailings impoundments did not have such barriers. The infiltration of surface water into tailings can be prevented by using reclamation methods that facilitate runoff rather than ponding of surface waters. If not prevented or controlled, the acidic and metal-bearing waters from tailings can impact stream habitats and groundwater. Fortunately, the reagents used in the beneficiation process can neutralize the acidity of the tailings, making acid and metal-bearing waters less of an environmental issue.

Fig. 20. As this small stream in Colorado erodes the mill tailings pile, it releases oxidized metal-bearing minerals into sediments downstream. The steep gray bank of unoxidized sulfide minerals shows characteristic layering that develops as tailings are deposited.

Erosion and Sedimentation

If tailings ponds are not satisfactorily stabilized, erosion by both wind and water can take place. Because tailings contain high volumes of fine-grained material, wind can easily pick up and transport dust from the surface of a tailings impoundment (Fig. 19). Tailings dust may create health concerns if people or wildlife breathe it. Its migration into homes can increase human exposure to any harmful constituents that may be present.

If tailings are eroded by surface water runoff and enter streams (Fig. 20), metallic minerals can be dispersed into stream, lake, and even ocean sediments. In some cases, instability of a tailings impoundment has led to catastrophic releases of metals into stream sediments. Historically, some tailings were disposed of directly from the mill into streams or other water bodies, rather than being stored in stabilized impoundments. Although this practice is no longer conducted in the United States, some streams and lakes still contain concentrations of widely dispersed metals in their sediments stemming from this old practice.

Native Copper

Metals in sediments can be a problem if they are in a chemical form or setting that allows them to be dissolved in water, or readily ingested and absorbed by plants and animals. In these situations, concentrations of bioavailable metals can be high enough to be toxic to organisms. Some metals can be dissolved and made bioavailable if the tailings oxidize and release acid in metal-bearing water. If metal-bearing sediments remain unoxidized and physically remote from interaction with wildlife, they will not create significant environmental impacts.

Leaching Solutions

If appropriate prevention and control measures are not taken, the leaching processes, which use sulfuric acid to dissolve copper and dilute water/cyanide solutions to dissolve gold, may be a potential source of contamination harmful to plants, animals, and in some situations, even people. Cyanide naturally degrades rapidly in the presence of sunlight, atmospheric oxygen, and rainfall. Potential toxicity problems with this chemical are most likely to occur if concentrated cyanide solutions are accidentally spilled or released during leaching operations. A combination of impermeable liners on the bottom of leach pads, leak-detection monitors, and solution-collecting facilities is commonly used to minimize leakage of leaching solutions. Because some leaching chemicals may be left behind in the residual materials on the leach pad after the metals have been removed, a combination of rinsing, physical isolation, and detoxification of heap leach pads is common practice before the leach piles are reclaimed.

Gold

Although modern smelters collect and control the metal fumes and emissions from all stages of the smelting process, historical processes (as shown here) involved open transfers of molten metal from large furnaces, and they did not capture all of the fumes emitted from the molten metal.

Chapter 5

Removing Impurities

Mining concentrates ore, and beneficiation concentrates valuable minerals. The processing step called “metallurgy” further concentrates the metals by separating them from their parent minerals. The most common technique for doing this has involved heating the minerals to a melting point. This type of pyrometallurgy is also the most significant with respect to environmental issues.

Smelting

The heating process in pyrometallurgy is generally called smelting. Historically, smelting facilities, called “smelters,” have been large industrial developments located near mines or in other areas that can provide the necessary transportation facilities, water, and energy supplies.

In the smelting process, the ore concentrate is mixed with other materials known as “fluxes” and then heated in furnaces until it melts. As the molten metals or the metal-bearing minerals separate from the other materials, they accumulate in the bottom of the furnaces and are removed. The other constituents, primarily iron and silica, float to the top of the furnaces. After they are removed, they cool to a solid glassy substance called “slag” (Fig. 21). In some cases, the large piles of dark-colored slag that remain near smelters make it the most visible solid waste product produced by the process.

Fig. 21. The principal solid waste product of the smelting process is slag, an iron and silica-rich glassy material that typically has a dark color and wavy, irregular surface.

Fig. 22. Advances in smelting technology have drastically reduced the emissions from modern smelters.

Fig. 23. Historically, smoke stacks of smelters, such as this lead smelter in Tacoma, Washington, in the early 1900s, have been major polluters and one of the most lasting images of the industrial developments associated with mining.

In addition to slag, the other significant by-products from smelting are gases, which contain suspended particles. The gases are collected as they rise off the top of the smelter furnaces, and they are treated to remove certain constituents. Sulfur dioxide gas is typically captured and converted to sulfuric acid, which is sold as a by-product of the smelting process. Treated gases enter the atmosphere through vents and stacks (Fig. 22). Historically, uncaptured sulfur dioxide was the constituent of greatest concern in smelter emissions, but other constituents, such as lead and arsenic, were locally important (Fig. 23).

Potential Environmental Impacts

The environmental concerns related to the smelting process are primarily smelter stack emissions and, in some cases, disposal of slag material and flue dust.

Smelter Stack Emissions

At some sites, gas and particulate emissions that were released to the atmosphere from historical smelting operations have been a source of human health concerns and environmental impacts. Recognizing the importance of minimizing and mitigating this impact, modern smelters use processes that drastically reduce particulate and sulfur dioxide emissions (Fig. 24).

In the past, sulfur dioxide has been the most common emission of concern, because it reacts with atmospheric water vapor to form sulfuric acid or "acid rain." The acidic conditions that develop in the soils where these emissions precipitate can harm existing vegetation and prevent new vegetation from growing. Barren areas near smelting operations have been an enduring environmental impact of historical smelting. Some impacted areas that have existed for decades are now beginning to recover.

In some cases, the emissions from older metal smelters may have affected human health. For example, elevated levels of lead in blood have been measured in residents of some communities located near lead-zinc smelters during their operation. Today, smelting operations, combined with environmental controls, are implemented to prevent potential environmental and health issues related to emissions.

Slag Disposal

The principal solid waste from the smelting process, slag, is an iron and silica-rich glassy material that may contain elevated concentrations of metals, such as lead and arsenic. The actual composition and form of slag will vary depending on the type of ore and smelting technology used. Most slags, because they are composed primarily of oxidized, glassy material, are not as significant a potential source of metals released into the environment as mine wastes and mill tailings. However, some slags may contain remnant minerals that can be a potential source of metal release to the environment.

The main problems with slag are the physical disturbances and aesthetic impacts associated with large slag piles that cannot support vegetation (Fig. 21). Slag piles can cover tens to hundreds of acres (0.1 to 1 km^2) and be over 100 hundred feet (30 m) high. Reclaiming these piles so that slag disposal areas can be used for other purposes is commonly done today.

Modern smelters use processes that drastically reduce particulate and sulfur dioxide emissions.

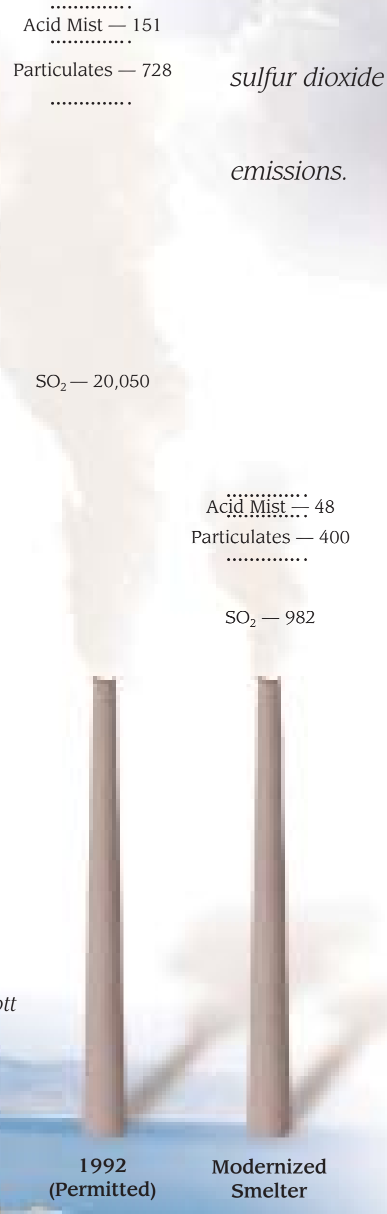
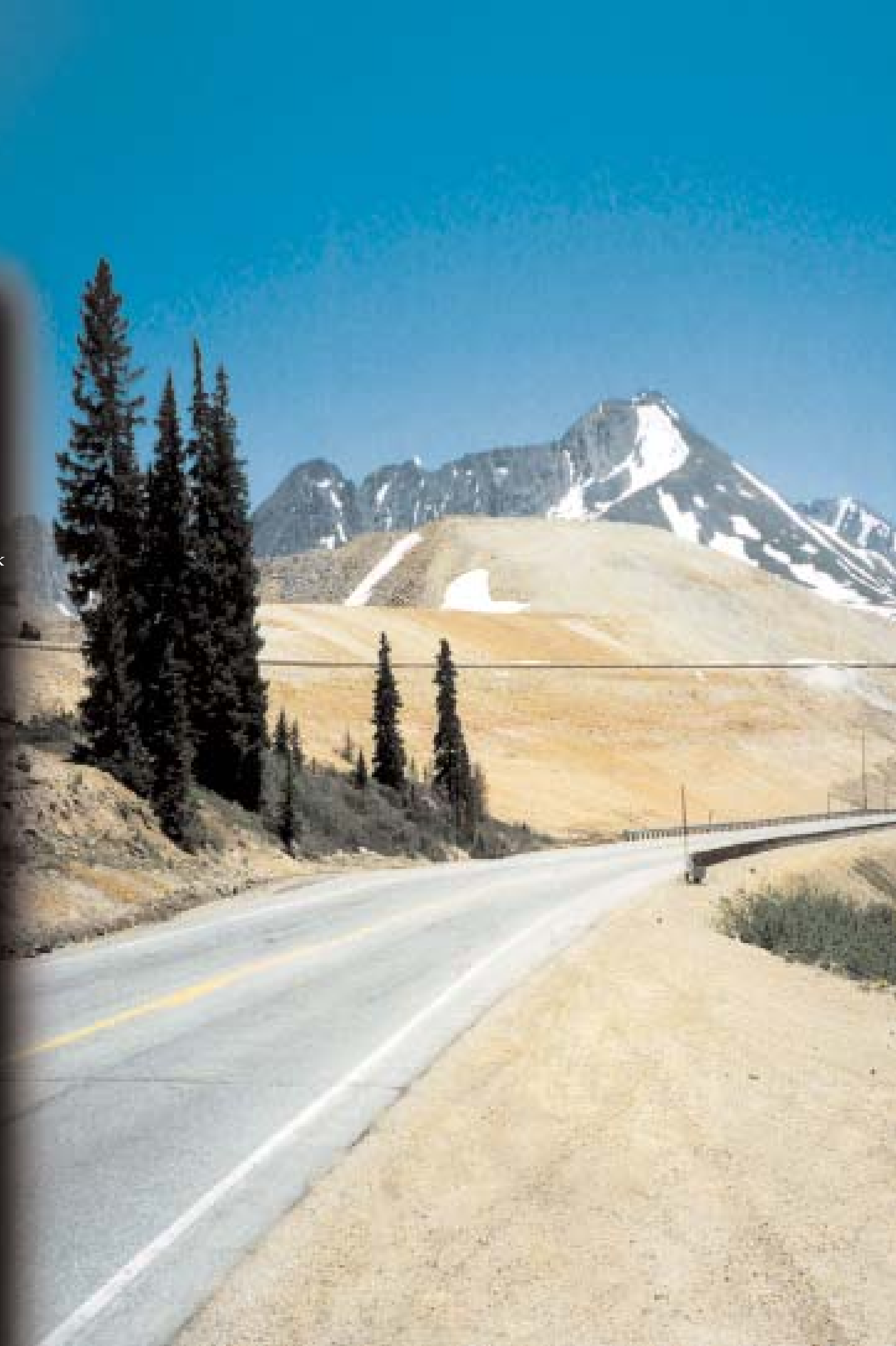


Fig. 24. Comparison of smelter gas discharges in metric tonnes by the Kennecott smelter at Salt Lake City, Utah



Grading has stabilized the slopes in this waste-rock disposal area associated with an open pit mine in Colorado. The dark pipeline carries mill tailings to an impoundment in a nearby valley.

Chapter 6

Protecting the Environment

The major potential environmental impacts associated with metal production — mining plus associated mineral processing operations are related to

- Erosion-prone landscapes,
- Soil and water quality, and
- Air quality.

These potential impacts are recognized and addressed in current mining operations as well as in some former mining operations by

- Reclaiming areas of physical disturbance to prevent erosion,
- Stabilizing soils containing metals or chemicals to prevent unwanted metal releases into the environment,
- Preventing and/or treating water contamination,
- Controlling air emissions.

At many sites, the key reclamation, soil treatment, and water quality concerns owe their origin to the same process — the oxidation of sulfide minerals, especially the iron sulfide, pyrite. Oxidation of sulfide minerals can produce acidic conditions that release metals in both waste materials and water (Fig. 25).

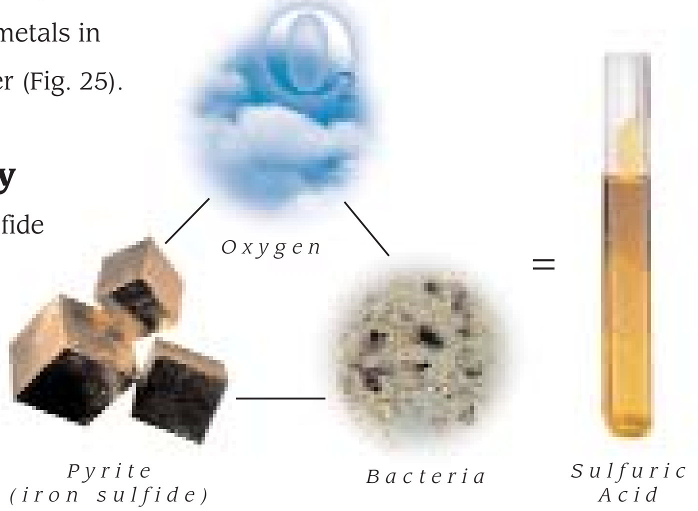


Fig. 25. Pyrite, oxygen, and bacteria are the main ingredients that combine in nature to make the sulfuric acid that acidifies soil and water. Oxygen changes the character of the iron and sulfur by oxidation, and bacteria speed the process. Removing any of the three components can significantly slow or stop the process.

Prevention is the Key

Preventing the oxidation of sulfide minerals is a critical step toward mitigating the environmental impacts of metal mining and processing. If oxidation is allowed to take place, acidic conditions develop in soils and waters changing the residual metal into more bioavailable forms.

Developing more efficient and cost-effective approaches for handling mining-related environmental impacts is desirable, particularly if the approaches promote the widespread cleanup of old mining sites. Innovative methods for preventing and mitigating mining impacts will also help ensure cost-effective development of future mines and the continued supply of metals. Environmentally sound mining and metal production practices will meet the key challeges of

- reclamation,
- soil treatment,
- water treatment,
- prevention of acid rock drainage,
- control of gas emissions, and
- recycling.

Reclamation

Reclamation entails the re-establishing of viable soils and vegetation at a mine site. Figure 26 illustrates a simple design for the reclamation of mine waste rock and tailings. Although regulatory agencies may require more complex reclamation designs, this simple approach can be very effective. It depends on adding lime or other materials that will neutralize acidity plus a cover of top soil or suitable growth medium to promote vegetation growth. Modifying slopes and other surfaces and planting vegetation as part of the process stabilizes the soil material and prevents erosion and surface water infiltration. Even this simple approach is likely to cost a few thousand dollars per acre to implement. Where soils

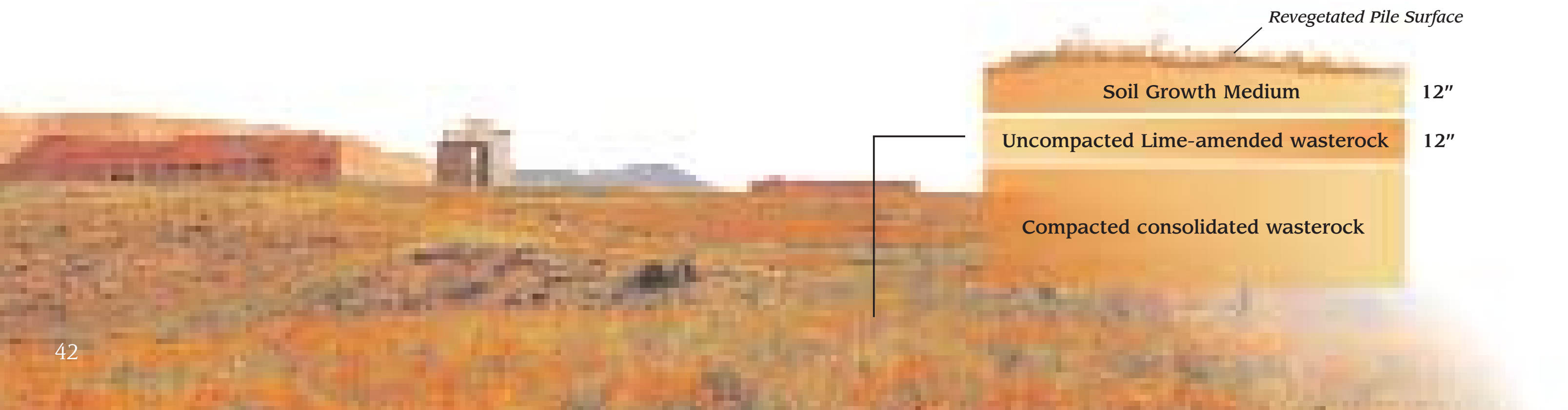


Fig. 26. Reclaiming this site in Utah entailed covering the base of compacted waste rock with a mix of loose waste rock and lime, topping that with 12 inches of soil and then planting vegetation. This reclamation design is effective for many settings. Reclamation planning includes consideration of variables, such as climate and precipitation.

have a sustained high acidity, the costs of using this approach can increase, sometimes to tens of thousands of dollars per acre.

The challenge to find cost-effective reclamation approaches continues. Promising reclamation options in the future may include using sludge, "biosolids," from municipal waste water treatment processes as an organic soil amendment and growing plant species that are more tolerant of acidic conditions (Fig. 27).

Fig. 27. Seeds of sage, rubber rabbit brush, and other acid-tolerant plants growing in waste rock disposal areas were collected and planted as part of this reclamation effort in Bingham Canyon, Utah.

Soil Treatment

High levels of metals in soils, not just acidity, can be harmful to plants, animals, and, in some cases, people. A common approach used in dealing with contaminated soil is to move it to specially designed repositories (Fig. 28). This approach can be very expensive and controversial, but it is sometimes required. With this approach, the volume and toxicity of the soil is not reduced, the soil is just relocated. Effective soil treatment approaches in the future depend upon better understanding of the risks associated with metals in mine wastes. These "natural" metals in minerals may not be as readily available in the biosphere, and therefore, they may not be as toxic as the metals in processed forms, such as lead in gasoline.

Fig. 28. In residential areas of mining communities, regulatory agencies commonly monitor metal concentrations in soils and mandate soil replacement. Although lead concentrations were elevated in these soils near Salt Lake City, lead concentrations in the blood of local residents were below the national average at the time of the soil removal shown.

Fig. 29. At this site in Montana, flooding of the tailings area shown above has stopped oxidation of tailings material and created a wetlands habitat where fish, birds, and other wildlife and vegetation flourish.

Future approaches may include

- Using chemical methods to stabilize metals in soils, making them less mobile and biologically available.
- Using bacteriacides that stop the bacterial growth that promotes the oxidation of pyrite and the accompanying formation of sulfuric acid.
- Using bioliners, such as low permeability and compacted manure, as barriers at the base of waste piles.
- Permanently flooding waste materials containing pyrite to cut off the source of oxygen, stop the development of acidic conditions, and prevent mobilization of metals (Fig. 29).

Water Treatment

The most common treatment for acidic and metal-bearing waters is the addition of a neutralizing material, such as lime, to reduce the acidity. This "active" treatment process, which causes the dissolved metals to precipitate from the water, usually requires the construction of a treatment facility (Fig. 30). The ongoing maintenance that such a plant requires makes this treatment technique very expensive.

Fig. 30. Active water treatment plants, such as this one on Silver Bow Creek in Montana, commonly add lime and other chemicals to acidic waters to neutralize them and help remove metals.

Aside from the expense, some active treatment plants generate large amounts of sludge. Disposal of the sludge is a major problem. Because of the cost and the physical challenges of dealing with sludge, alternatives to active treatment facilities are needed. Some possible alternatives include

- Using "passive" wetland systems to treat metal-bearing water. This approach has been successfully used where the volumes and acidity of the water are not too great. Passive wetland systems have the added advantage of creating desirable wildlife habitat (Fig. 31).
- Using in-situ treatment zones where reactive materials or electric currents are placed in the subsurface so that water passing through them would be treated.
- Combining treatment with the recovery of useful materials from contaminated water.

Acid Rock Drainage

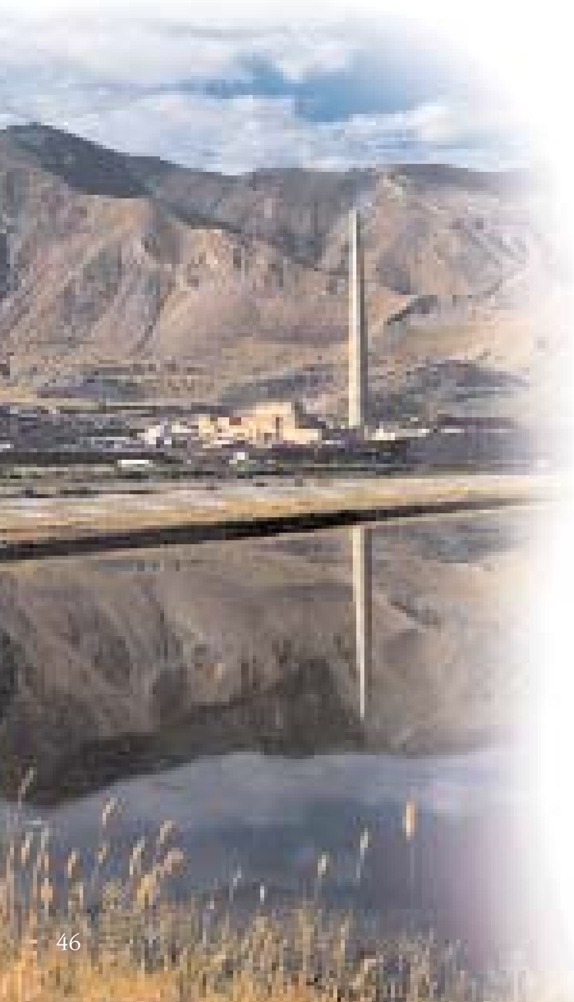
Although the discharge of acidic drainage presents several challenges to protecting water quality, the significance and widespread occurrence of acid rock drainage warrant special efforts to prevent or minimize its occurrence. Prevention must be addressed during exploration activities, before the beginning of newly-planned mining operations. In some

Fig. 31. Constructed wetland systems, such as this one, have potential for treating certain metal-bearing waters and stabilizing tailings in place. The wetlands create anaerobic conditions and prevent continued oxidation of sulfide minerals in the tailings.

cases, it may even be possible to prevent or reduce acid rock drainage in old or abandoned mining areas. Current and potential treatment approaches for acid rock drainage are similar to those already described. Possible measures to prevent or significantly reduce acid rock drainage include

- Flooding of old underground mine workings to cut off the oxygen supply necessary to the sustained generation of acidic waters.
- Sealing exposed surfaces in underground workings with a coating of material that is non-reactive or impermeable to inhibit the oxidation process.
- Backfilling mine workings with reactive materials that can neutralize and treat waters that pass through them.
- Adding chemicals to the water in flooded surface and underground mine workings that can inhibit acid-generating chemical reactions and precipitate coatings that will seal off groundwater migration routes.
- Isolating contaminated waters at depth by stratification, allowing viable habitat to develop near the surface in the water that fills large open pits.

Copper Smelter



Smelter Emissions

Smelter emissions, especially sulfur dioxide and particulate materials, have historically presented significant environmental problems. Modern smelting technology has met this challenge by drastically reducing the amount of emissions. An example is the modernized smelter built by Kennecott Utah Copper that processes ore concentrates from the Bingham Canyon Mine near Salt Lake City. Using technology developed by the Finnish company Outokumpu, this smelter has reduced sulfur dioxide emissions to 95 percent of previous permitted levels (p. 39). This smelter, which came online in 1995, is the cleanest in the world. It captures 99.9 percent of the emitted sulfur.

Recycling

Recycling can be an alternative source of metals that reduces the need for new metal mines. However, recycling facilities themselves are industrial developments having their own set of environmental impacts. Even so, recycling is a significant source of metals (Fig. 32).

According to the U. S. Bureau of Mines, which completed a data synthesis on U. S. metal recycling in 1990, the value of recycled metals totaled $37 billion, or only $2 billion less than the value of newly mined metal in that year. The five metals listed in Figure 32 accounted for 99% of the quantity and 92% of the value of recycled metals in 1990. Precious metals — gold, silver, and platinum-group elements — and chromium accounted for 6% more of the value and the remainder came from recycling of at least 14 other metals.

Recycled metals meet varying fractions of U.S. metal consumption. This variance occurs primarily because the end uses of some metals inhibit their effective recovery and because recycling systems and technologies are less efficient for some metals. Although recycling is important, there is an upper limit to the amount of metal that recycling can provide. For example, recycled lead, which is predominately used in batteries and for which secondary recovery systems are well-developed, could satisfy 78% of U. S. demand by 2000, but recycled zinc will probably not increase above 35 to 40% of consumption.

Although recycling is a significant source of metals, mining and production will still be necessary to meet society's growing demand.

Even though extensive and efficient recycling is an important commitment, metal mining and production will still be necessary to meet society's demand for metals.

	Amount of Recycled Metal (metric tons)	Percent of U.S. Supply
Iron & Steel	58,000,000	59 % *
Aluminum	3,500,000	39 %
Copper	1,500,000	37 %
Lead	1,145,000	66 %
Zinc	425,000	22 %

**Percent of U.S. production.*

Fig. 32. Preliminary metal recycling figures for 1998.

Permits and Regulations

An extensive regulatory system has been developed to govern current mining operations, as well as to guide the cleanup of historical ones. This framework is primarily based on Federal laws dating back to the late 1960s. These laws outline the responsibilities of several Federal agencies, such as the Environmental Protection Agency (EPA), in regulating mining operations. In many cases, these regulatory responsibilities have been delegated to the states, which have in turn developed their own sets of environmental laws, regulations, and standards. Regulatory standards established at state levels are commonly equal to or more stringent than Federal standards. Some important acts authorizing and guiding environmental regulation of mining in the United States are outlined below. Several of these acts have been amended through the years. Some acts require Congressional reauthorization every five years.

National Environmental Policy Act (NEPA)

The NEPA, passed in 1969, established the basic environmental policies for the nation. NEPA defines processes for evaluating and communicating the environmental consequences of Federal decisions and actions, such as the permitting of new mine development on Federal lands. The processes established by NEPA are used by concerned parties to ensure that environmental considerations are included in Federal decisions. NEPA applies to mining operations that require Federal approvals.

Clean Air Act (CAA)

The CAA, passed in 1970, authorizes regulations to address airborne pollution that may be potentially hazardous to human health or natural resources. Efforts to combat urban air pollution, such as emission controls on cars, are well-known examples of regulations developed under CAA. Examples of mining-related situations that are covered by CAA-based regulations include dust emissions that accompany operations or tailings disposal in impoundments, exhaust emissions from heavy equipment, and emissions from processing facilities, such as smelters.

Resource Conservation and Recovery Act (RCRA)

The RCRA, passed in 1976, focuses on preventing the release of hazardous wastes into the environment by providing for their management from generation to disposal. Most mining, milling, and smelting solid wastes, like those discussed in this booklet, are "high-volume, low-hazard" materials that have been exempt from regulation under RCRA. Regulation of high-volume, low-hazard mining wastes is now the primary responsibility of the states.

> *"Regulatory standards established at state levels are commonly equal to or more stringent than Federal standards."*

Clean Water Act (CWA)

The CWA, passed in 1977, authorizes regulations that cover discharges of toxic and nontoxic pollutants into the surface waters of the nation. The CWA's goal is to make all surface waters safe and eventually to stop all harmful discharges. One of the principal tools established by CWA is a permitting system for surface water discharges, known as the National Pollutant Discharge Elimination System. CWA-based regulations cover such mining-related situations as the disposal of mining-related waters, the pumping or draining of mine water to the surface, storm water runoff in mining operation areas, and control of seeps from mine tailings impoundments.

Toxic Substances Control Act (TSCA)

The TSCA, passed in 1977, focuses on controlling the development and application of new and existing chemical substances. Chemicals and hazardous materials used in the processing of ore or ore concentrates, such as sodium cyanide solutions used in the leaching of gold ores, are regulated under TSCA.

Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)

The CERCLA, passed in 1980, enables the government to clean up any site where there is an unremedied release of a hazardous substance. Hazardous substances are broadly defined under CERCLA and have included mining, milling, and smelter wastes that are currently excluded from regulation under RCRA. Regulators have the authority to use special funds, undertake emergency responses, and hold all historical owners or contributors — principal responsible parties — liable for cleanup costs. The definitions of liability are very broad and controversial under CERCLA and provide regulators tremendous enforcement powers. Because of its funding aspects, this act is commonly referred to as "Superfund".

Other acts, such as the Safe Drinking Water Act, can be relevant to specific mining operations. Government-approved permits are required for all new and ongoing mining operations, including exploration activities. This permitting process ensures that environmental standards are maintained from the beginning to the end of mining and metal production operations. New mine developments are now required to have operation and closure plans that define how a specific site will be reclaimed upon cessation of mining. This attention to the full life-cycle of a mining site prevents negative environmental impacts.

If this much ore is mined and processed to produce one nickel and copper coin, imagine the mineral resources needed to build a skyscraper.

Chapter 7

Providing for the Future

Mining provides us with essential resources. Historically, mining has evolved from small and simple operations to large and complex mining and processing systems that employ the latest in engineering technology. The environmental impacts of mining have also evolved through time. A better scientific understanding of the environmental impacts of mining, coupled with great advances in mining and environmental technologies, have enabled modern miners to better predict, plan for, and prevent or minimize potential adverse environmental impacts. Mining operations near Sudbury, Ontario, Canada, which has produced metals since 1886 and maintains a renowned environmental restoration program, illustrate these changes (p. 52).

The environmental consequences from some early mining operations have left a historical legacy of negative environmental impacts that still affect our perception of mining. Modern mining operations, with their emphasis on the economies of scale that come with open pit mining and large volume mineral processing techniques, have also influenced public perception. The large volumes of waste rock and mill tailings, impressive mine workings, and the large industrial complexes

Sudbury

The Sudbury region of Ontario is rich in metallic ores. Underground mining operations at the 15 active mines of Inco Ltd. and Falconbridge Ltd. in Sudbury currently produce 51,000 tons of ore per day, and five other mines within 500 km of Sudbury produce another 50,000 tons per day. By-products of nickel-copper production include cobalt, platinum group metals, gold, silver, selenium, tellurium, sulfuric acid, liquid sulfur dioxide, and slag for road construction.

In the mid-1800s, during the building of the Canadian Pacific Railroad, a blacksmith working on the CPR discovered the first nickel-copper orebody known in the Sudbury area. The discovery fueled the growth and development of Sudbury, and the Canadian Copper Company mines started production in 1886. Although the ore was rich in nickel, that metal was considered of little value. Demand for nickel was less than 1,000 tons per year worldwide in 1887, and it only became a marketable commodity early in the 20th century.

As mining, stripping, sintering, and smelting operations increased with world demand for metals, Sudbury's landscape began to look like a barren moonscape. The mining and processing of sulfide minerals released sulfur that contaminated and acidified soils. In the past 25 years, however, residents have restored and transformed the landscape. Today, Sudbury boasts the largest, most successful environmental restoration program in the world.

When restoration efforts began in 1969, germinating seeds died on contact with contaminated soils, and thousands of tree seedlings planted in the first two years died within a year of planting. Residents decided to try a different approach. They applied lime to the soils to neutralize the acidity and planted grasses and clovers instead of trees. By 1974, a 3-hectare (7.4 acre) patch had a sparse grass cover. Nature took over then, and wildflowers, shrubs, and birches and poplars began to grow.

While citizens and students worked to restore the environment, the mining companies worked to reduce pollution and control wastewater quality. In 1972, Inco completed construction of a giant smokestack that reduced sulfur dioxide emissions. Inco completed a sulfur abatement program in 1994 that further reduced emissions to 10 percent, and planted the millionth tree seedling of its own land reclamation program. Falconbridge has planted 600,000 trees on its properties in the Sudbury area since 1955. The company opened a new smelter and acid plant in 1978 that reduced sulfur emissions. The smelter was renovated in 1994 to reduce emissions further. Falconbridge recycles nearly half of the water it uses and treats wastewater to control acidity, heavy-metal content, and suspended solids. The treated water flows into a 299-hectare (494-acre) peat bog that in 15 years was rejuvenated from an acidic wasteland to a productive wetland and transformed from a hostile environment into a wildlife sanctuary.

More than 3,000 hectares (7,410 acres) of land have been restored. An additional 2 million trees were planted through a joint program run by the Regional Municipality of Sudbury and financed by job-creation funding from the government and industry. In recognition of its environmental transformation, Sudbury received the United Nations Local Government Honors Award at the 1992 Earth Summit in Rio de Janeiro.

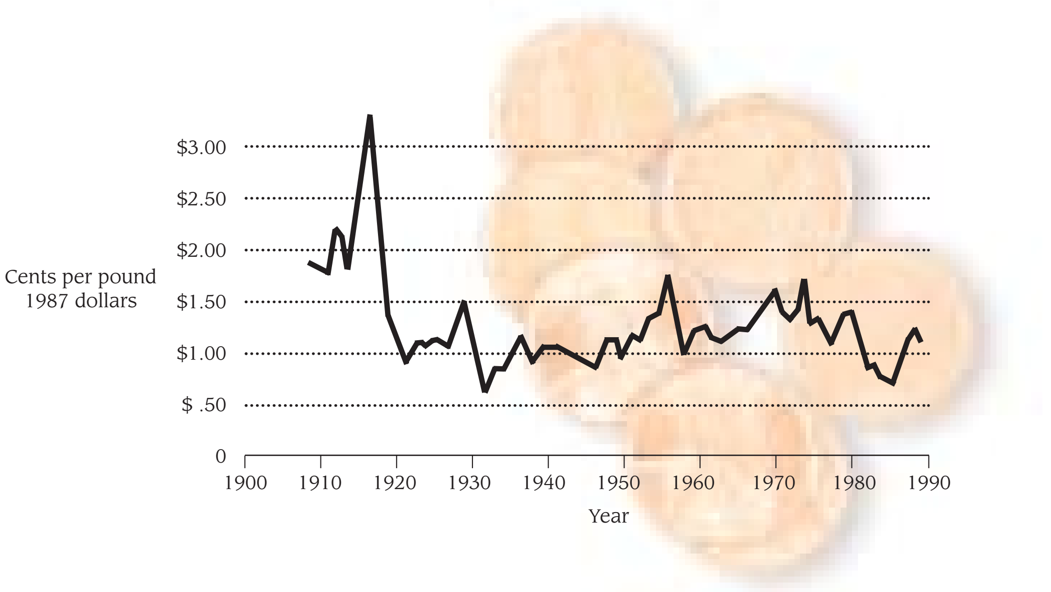
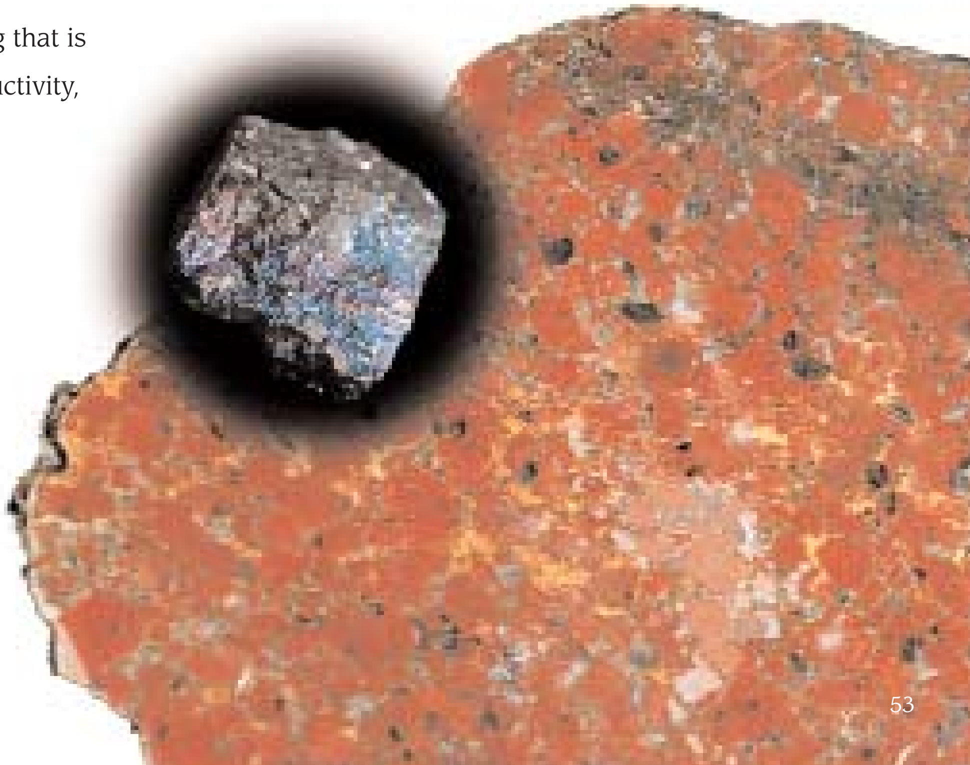


Fig. 33. Prices of copper and other metals fluctuate in response to global supply and demand. In dollars adjusted for inflation, copper prices have ranged from $.60 to $1.70 per pound since 1920 and the implementation of open-pit mining technology.

that characterize today's efficient smelter operations are visual impacts that influence public opinion about mining. Conversely, the evolution of mining and mineral processing technology has played an important role in supplying our national resource needs at stable or actually declining costs to consumers. For example, the demand for copper in the United States has increased historically (Fig. 1, p. 10), while at the same time the real price for this key metal is far less than it was in 1915 (Fig. 33). The technological advances that enable metal production to meet demands at reasonable prices are an important foundation for maintaining the standard of living around the world. Mining is one of the most regulated industries in the United States.

In order to stay in business, companies have found it necessary and desirable to invest huge amounts of time and money into research and training that is designed to increase efficiency, productivity, and safety. The mining workforce is among the most highly trained and



Two types of copper ore. The mineral bornite (peacock ore) is rich in copper. The polished slab from the "Copper Country" of northern Michigan is a conglomerate, a rock composed of rounded pebbles. In this ore, the "cement" binding the conglomerate together contains native copper.

most highly paid in American industry, and mining operations are among the safest places to work.

Mining and related mineral processing will continue to supply the metals society needs to sustain and advance its standard of living.

The demands for both minerals and metals, and for environmental protection, are expected to increase in the decades ahead. World population growth and rising standards of living in developing countries will require more minerals and metals. At the same time, our improved understanding of the harm that environmental degradation can cause to wildlife and human health, is leading to higher and higher standards of environmental protection. This situation challenges each of us to understand the need for balance in our approaches that will best achieve both meeting society's needs for metals and for a healthy environment.

Balanced approaches for mineral supply and environmental protection are complex and demanding. There are no simple choices. For example, mining during the 1800's created many "mining camps" in the western United States that are popular historic sites and tourist attractions. Were they to be completely reclaimed, an important part of our national history would be lost. At the same time, any active damage they may be causing to the environment, such as acid drainage into streams, must be addressed. Reasoned approaches by knowledgeable geologists, biologists, environmental engineers, historians, and concerned citizens are ways to achieve balanced solutions.

Prevention of environmental damage will be served by the coordinated oversight of mine planning and permitting that involves the mining industry and regulatory agencies. The performance of mining companies will benefit from incentives for successful environmental protection and penalties for environmental damage. Changes in technology and our understanding of natural environments will present opportunities for better protection and reclamation methods. These opportunities must be implemented when it is clear that they are sound.

Mining and related mineral processing will continue to supply the metals society needs to sustain and advance its standard of living. Geologists will be successful in their search for new orebodies, metal extraction from the

Earth will become more efficient, and the environmental consequences of these activities will be managed in continually improved ways. Today, society's expectations and the future of the mining industry require that the long-term environmental impacts of mining be adequately addressed.

Important research directions hold promise for addressing the many environmental challenges facing metal extraction from the Earth. These research areas need support and encouragement, as research can provide a foundation for resolving conflicts between mining and environmental priorities. The challenge to us as individuals and as a society is to develop an appropriate balance and policies for sustaining both Earth's metallic and environmental resources. This can be done. Acceptance of this challenge — by the mining industry, national leaders, environmental activists, research scientists, and all concerned citizens — is the first step and the necessary common ground for success in providing for the future.

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Credits

Cover — Hands with earth (Digital Vision Stock Photography), Clockwise from top: Computer disc metal etchings (Adobe Image Library), Industrial metal gears (Digital Vision Stock Photography), Metallic mineral samples (G. James, R. Busch, ASARCO Inc.), Open pit gold mine, Nevada (M. Miller, Univ. of Oregon)

Inside covers — After reclamation, Sunnyside Mine, Colorado (Gold Institute/Echo Bay Mines/S. Warren)

Page 3 — Troy silver mine, Montana, (ASARCO Inc.)

Pages 4-5 — Autumn landscape (Digital Stock Library)

Page 6 — Background: Reclaimed open pit mine (Gold Institute), Clockwise from top right: Silver miners in Troy Mine (ASARCO Inc.), Jet engine (Digital Stock Library), Reclaimed mine in Utah (Kennecott Utah Copper Company), Ore samples (G. James), Loading ore in open pit mine (Kennecott Utah Copper Company), Computer hard drive (Adobe Image Library)

Page 9 — Photo montage, clockwise from upper left: Movie reel (Photodisc), Suspension bridge with evening cityscape (Digital Vision Stock Photography), Industrial cog/gear (Photodisc), Tennis raquet and balls (Photodisc), Electrical plug and outlet (Adobe Image Library), Computer chip/ transistors (Adobe Image library), Safety pin (photodisc), Telephone (Adobe Image Library)

Page 10 — Figure 1, U.S. consumption of copper, lead and zinc (De Atley Design, Data from U.S. Geological Survey)

Page 11— Earth (Digital Stock Library), Cars (Corel Stock Photography)

Page 12-13 — Lookout Mountain, Colorado (G. Plumlee, USGS)

Page 13 — Sulfide ore (G. James)

Page 14 — Figure 2, Galena sample (ASARCO Inc.)

Page 15 — Helicopter exploration (Gold Institute/Echo Bay Mines/D. Wiener)

Page 16 — Bingham Copper Mine, Salt Lake City, Utah (Kennecott Utah Copper Company)

Page 17 — Native copper (G. James)

Page 18 — Figure 3, Background: Open pit gold mine, Nevada, (M. Miller, Univ. of Oregon), open pit mining photos (Kennecott Utah Copper Company)

Page 19 — Figure 4, Underground mining diagram (ASARCO Inc.), Figure 5, Underground scaler (Kennecott Utah Copper Company)

Page 20 — Figure 6, Butte, Montana (Atlantic Richfield Company)

Page 21— Historic mining (Dover Pictorial Archive), Figure 7, Waste rock reclamation (Kennecott Utah Copper Company)

Page 22-23 — Figure 8, U.S. Land Use (De Atley Design, Data from USDA Soil Conservation Service, 1994), Key Mining Area Map (De Atley Design, Adapted from Geological Investigation Series Map I-2654, U.S. Geological Survey, 1998)

Page 24 — Figure 9, Colorado waste site (ESA Consultants Inc.), Figure 10, Pyrite laced waste rock (T. Hudson, Applied Geology)

Page 25 — Figure 11, Neutral mine water (T. Hudson, Applied Geology), Figure 12, Acidic mine water (G. Plumlee, USGS)

Page 26 — Figure 13, Berkeley Pit (Atlantic Richfield Company), pyrite crystals (R. Busch, West Chester Univ.)

Page 27 — Figure 14, Safety fencing around headframe (E. Schneider, ESA Consultants Inc.)

Page 28 — Milling and flotation montage (ASARCO Inc.)

Page 29 — Figure 15, Slurry of tailings (Kennecott Utah Copper Company)

Page 30 — Figure 16, Heap leaching operations (Nevada Bureau of Mines and Geology)

Page 31 — Discolored water and rocks (T. Hudson, Applied Geology)

Page 32 — Tailings impoundment and its reclamation, (ESA Consultants Inc.)

Page 33 — Figure 17, Tailings impoundment seepage (T. Hudson, Applied Geology), Figure 18, Ponding on tailings impoundment (T. Hudson, Applied Geology)

Page 34 — Figure 19, Tailings dust cloud (Kennecott Nevada Copper Company), Figure 20, Tailings erosion (G. Plumlee, USGS)

Page 35 — Native copper (G. James), Native gold (R. Busch, West Chester Univ.)

Page 36 — Copper smelter (Kennecott Utah Copper Corporation)

Page 37 — Figure 21, Slag and slag pile (T. Hudson, Applied Geology)

Page 38 — Figure 22, Hayden Smelter, Arizona (ASARCO Inc.), Figure 23, Tacoma Smelter, Washington (Atlantic Richfield Company)

Page 39 — Kennecott Smelter, Salt Lake City, Utah (Kennecott Utah Copper Company), Figure 24, Comparison of smelter gas discharges (De Atley Design)

Page 40 — Stabilized waste rock pile (T. Hudson, Applied Geology)

Page 41 — Figure 25, Sulfide mineral oxidation cycle (De Atley Design; Photos, USGS)

Page 42 — Figure 26, Reclaimed mining area in Utah with reclamation cover design (Kennecott Utah Copper Company/De Atley Design)

Page 43 — Figure 27, Acid-tolerant plants (Kennecott Utah Copper Company), Figure 28, Contaminated soil removal, (Atlantic Richfield Company)

Page 44 — Figure 29, Flooding of waste materials area, before and after (Kennecott Utah Copper Company), Figure 30, Water treatment facility (Atlantic Richfield Company)

Page 45 — Figure 31, Creation of a passive wetland system, before and after (ASARCO Inc.)

Page 46 — Smelter at Garfield, Utah (Kennecott Utah Copper Company)

Page 47 — Figure 32, Metal Recycling (De Atley Design, Data from U.S. Bureau of Mines)

Pages 48-49 — Metallic background (John Foxx Image Collection)

Page 50 — Metal machinery background (John Foxx Image Collection), ore requirements for nickel (U.S.Bureu of Mines/USGS)

Page 51 — Modern skyscapers (Digital Vision Stock Photography)

Page 52 — Metals background (John Foxx Image Collection)

Page 53 — Figure 33, Copper prices chart (De Atley Design/ R. Busch, West Chester Univ., Data from U.S. Geological Survey), Figure 34, Bornite (peacock ore) and copper ore (G. James)

Page 55 — Reclamation of Sunnyside Mine, Colorado, before and after (Gold Institute/ Echo Bay Mines/S. Warren)

Page 56 — Photo montage, clockwise from left: Open pit gold mine, Nevada (M. Miller, Univ. of Oregon), Jet airplane (Digital Stock Library), Satellite (Digital Stock Library), Smelter, Computer cables (Adobe Image Library), Brooklyn Bridge and Manhattan (Digital Vision Stock Photography), Automoblile manufacturing (Digital Vision Stock Photography), Computer hard drive (Adobe Image Library)

Page 64 — Photo montage (De Atley Design)

Glossary

acid rock drainage (ARD) Water which contains free sulfuric acid (and commonly dissolved metals) mainly due to the weathering (oxidation) of pyrite (iron sulfide).

adit A horizontal or nearly horizontal passage driven from the surface for the working or dewatering of a mine. If the passage is driven through the hill or mountain to the surface on another side it is called a tunnel.

alloy A substance having metallic properties, and composed of two or more chemical elements, of which at least one is a metal.

beneficiation The processing of ores for the purpose of regulating the size of a desired product, removing unwanted constituents, and improving the quality, quantity, or concentration of a desired product.

bioavailability The degree to which a metal or other substance is free for movement into or onto an organism.

concentrate The metal-rich product of the beneficiation process that is fed to the smelter.

drift An underground opening in a mine that connects one area of workings to another.

element A substance all of whose atoms have the same atomic number.

flux In metallurgy, a substance that promotes the fusing of minerals or metals or prevents the formation of oxides.

gangue The valueless minerals in an ore; that part of an ore that is not economically desirable but cannot be avoided in mining. It is separated from the ore during beneficiation.

metal Any class of chemical elements, such as iron, gold, and aluminum, that have characteristic luster, are good conductors of heat and electricity and are opaque, fusible, and generally malleable and ductile.

metallurgy The science and technology of extracting and refining metals.

milling The crushing and grinding of ore as part of the beneficiation process.

mineral A naturally formed chemical element or compound having a specific chemical composition and, most commonly, a characteristic crystal form.

mineral deposit A mass of naturally occurring mineral material; that might, under favorable circumstances, be considered to have economic potential.

mining The process of extracting useful minerals from the Earth's crust.

open pit mining The mining of ores by surface mining methods.

ore The naturally occuring material from which a mineral or minerals of economic value can be extracted profitably. The term is generally but not always used to refer to Earth materials containing metals, and is often modified by the names of the valuable constituent; e.g., iron ore.

ore mineral The part of an ore, usually metallic, which is economically desirable, as contrasted with the waste or "gangue."

orebody The economically important part of a mineral deposit.

oxidation A chemical process involving reaction(s) that produce an increase in the oxidation state of elements such as iron or sulfur.

pyrite A common, pale bronze or brass-yellow iron sulfide (FeS_2) mineral. The most widespread and abundant of the sulfide minerals, pyrite, when oxidized, can lead to generation of acidic waters.

pyrometallurgy Metallurgy involved in extracting and refining metals where heat is used, as in roasting and smelting. It is one of the most important and oldest of the metallurgical processes.

reclamation The process of reestablishing stable soils and vegetation in disturbed areas.

reduction A chemical process involving reactions that produce a decrease in the oxidation state of elements such as iron or sulfur.

remediation The process of correcting, counteracting, or removing an environmental problem.

rock Any naturally formed material composed of mineral(s); any hard consolidated material derived from the Earth.

shaft A vertical or inclined opening from the surface that provides access to underground mine workings.

sintering A heat treatment for collecting small particles to form larger particles, cakes, or masses. In the case of ores and concentrates, sintering is accomplished by fusion of certain constituents.

slag A glassy waste of the smelting of ores. A mixture of impurities that separate from reduced metal during smelting, rise to the top of the furnace, and upon removal and cooling, commonly become partly glassy in character.

sludge A soft slush or slimy mass produced by the precipitation of amorphous hydroxides during water treatment.

slurry A watery mixture of a fine insoluble material such as milled rocks and minerals.

smelting The chemical reduction of metal-bearing material such as ore, most commonly by a process involving fusion, so that lighter and more fusible impurities can be readily removed. The process commonly involves addition of reagents (fluxes) that facilitate chemical reactions and the separation of metals from impurities.

stope An underground opening in a mine from which ore is recovered.

sulfate The oxidized form of sulfur that is common in waters and minerals in the mined environment.

sulfide A mineral compound characterized by the linkage of the element sulfur with a metal; e.g., galena, PbS, or pyrite, FeS_2.

sulfur The native nonmetallic element S. Some forms of sulfur readily react with metals to form sulfide minerals.

tailings The waste materials regarded as too poor in quality to be further processed that result from the beneficiation of ore.

tailings impoundment An area for tailings disposal that is closed at its lower end by a constraining wall or dam.

tonne A metric ton; 1,000 kilograms.

toxicity The poisonous character of a substance.

waste rock The rock that must be broken and disposed of during mining in order to gain access to, or increase the quality of, ore.

workings The entire system of openings (underground as well as at the surface) in a mine.

Index

AGI Foundation

The AGI Foundation was established more than a decade ago to assist the Institute in seeking funding and partnerships with foundations, corporations, other organizations, and individuals that share our commitment to create innovative Earth-science programs of benefit to all citizens. AGI's programs — focusing on education, worldwide information systems, government affairs, environmental awareness and other issues — offer new opportunities for geoscientists, enhance research capabilities of professional Earth scientists, and develop innovative education tools to expand the Earth-science knowledge base of all Americans, not just those who will choose geoscience as a career.

AGI's "popular" Environmental Awareness publications provide a balanced review and discussion of key environmental geoscience concerns. The colorful booklets and posters present accurate environmental geoscience information in an easy-to-digest format. AGI produces the Series with Foundation support — and in cooperation with its member societies and others — to raise public understanding of society's complex interaction with the Earth. In addition to soils, metal mining, and petroleum, the Series will cover environmental geoscience concerns related to water, minerals, global change, caves, mapping, and other important topics.

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Society's requirement for metals establishes a strong link between our standard of living, the Earth, and science. Decisions about the development and use of Earth's metallic resources affect the economic, social, and environmental fabric of societies worldwide. Our challenge is to balance these important attributes. *Metal Mining and the Environment* helps answer the following questions:

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