Mining and Mining Methods

Learning outcomes:

1. Contrast surface and underground mining.
2. Identify a mining company's goals with each of the following: exploration, extraction, concentration, reclamation, and remediation.
3. Describe how wastes are created during the different stages of product creation and use.
4. Discuss how waste products are/can be managed.
5. Summarize the effects of mining on land use and what can be done to minimize negative effects.
6. Identify how air, water, and land can potentially be polluted by mining and associated activities.
7. Give examples of how mining, beneficiation, etc. affects society and how mining processes/extent are influenced by societal factors (i.e., economics).

Introduction

Most of the mineral resources that we use in our daily lives aren't easily found and don't come out of the ground in a useable form. Finding these resources, obtaining (mining) them, and processing them into something useable takes many varied and often technologically advanced steps. For this unit, we'll focus on mining, particularly the mining of metal ores in the United States. An **ore** is a material that occurs naturally and that contains a mineral(s) that can be extracted for a profit.

The typical steps in recovering a mineral resource and converting it to a useable state include:

a) Locating it (Exploration)
b) Obtaining it (Extraction)
c) Concentrating it (Beneficiation/Smelting/Refining)
d) Cleaning up during/afterward (Remediation/Reclamation/Mine Closure)

Every step of the mineral extraction process is much more complex than described here.

Exploration

Estimates of the amounts of elements in the Earth's crust represent averages over the entire crust and seldom reflect the composition at a particular location. Rocks and minerals, and thus elements and compounds, are concentrated in certain locations due to rock-forming processes that occurred in the past and/or are occurring today.

During the *exploration* process, a mining company seeks an area where the desired mineral resource is concentrated and attempts to determine the size of the ore body and the mineral resource's **ore grade**. Higher ore grades (higher concentrations) make the mining project more viable (see Table 1). However, there are many other factors that can influence the decision to extract an ore from a specific area. These may include the shape and depth of the ore body; the available mining technology; the potential environmental impact; the need and availability of water; access to workers; proximity to transportation and consumers; state, federal, and other regulations; politics and/or political boundaries; social norms; and human health concerns.

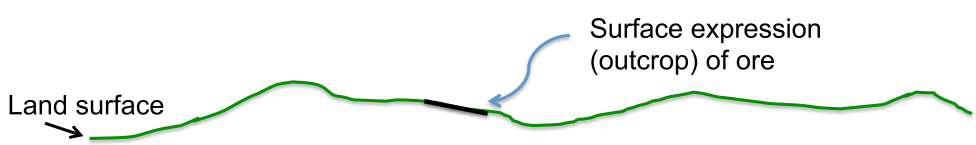
Metal	Average concentration in Earth's crust	Concentration in ore deposit
Aluminum	8%	35%
Gold	4 ppm (parts per million) = 0.0000004%	0.001%
Iron	5%	>20%
Titanium	0.57%	>32%

Table 1. Examples of metals (elements), their crustal abundances, and the concentrations needed to make mining viable as of 2001. From Pipken and Trent, 2001.

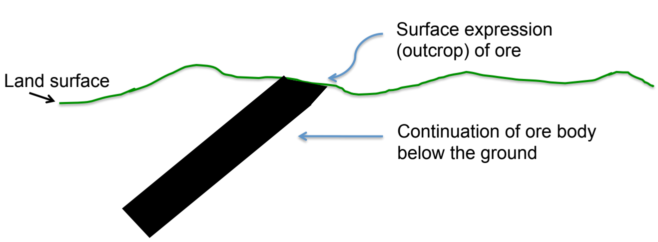
Mining is actually a very expensive process, so mining companies invest time and money to make sure they've picked a good location. In the exploration part of the process, there are usually multiple locations being explored and it may take a number of years to determine which sites are viable. Some sites deemed unfit for development may become more appealing in the future if technologies change and/or the price of the ore rises.

Although not all ore bodies outcrop at the surface, some will. It is very important to determine not only the surface location (outcrop) of an ore, but also to figure out the size, depth, and orientation (trend) of the deposit. By just looking at the surface outcrop, it is impossible to tell the size and shape of the underground ore body. See Figure 1 below.

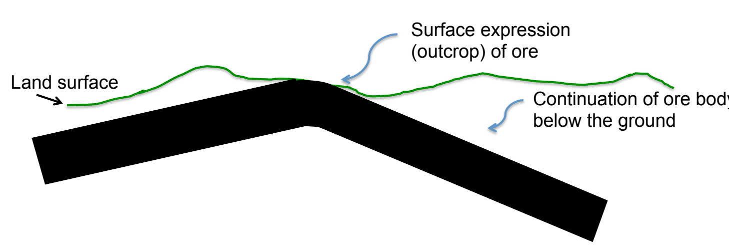
Figure 1. How a deposit might extend below the Earth's surface when looking at a surface exposure. Sketches by Leah Joseph.



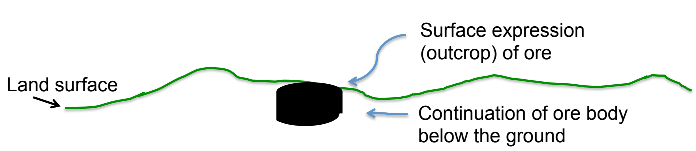
The deposit could go this way:



Or perhaps this way:



Or even this way:



During the exploration process, geoscientists will use several methods to find suitable locations and determine the depth and shape of the ore body. These include:

- Creating and reviewing *geological maps*. Geologic maps show the locations of different types of bedrock (bedrock is the rock that is closest to the surface), give exploration geologists hints as to what geologic processes acted in a given area and suggest how rocks are distributed at depth. Maps help geologists compare an area with other sites that have yielded highly concentrated ores in the past.
- Visiting a potential mine site and completing *field studies*, which might entail additional geological mapping, surface rock sampling, and/or chemical analyses of rock, soil, and water samples.
- Performing “noninvasive” studies to obtain underground information. These studies are similar to someone using a metal detector to find discarded coins on a beach. The larger-scale *geophysical studies* used by mining companies may include seismic, gravity, magnetic, or other surveys.
- *Drilling* down through the surface to obtain samples at depth. Hollow drills are used that bring cores (long cylinders of rock) to the surface.

Once an appropriate site is located, the mining company obtains any necessary permits, leases, etc. Then the extraction process can begin.

Extraction

In general, mining techniques are divided into two primary types: *surface mining* (including pit, strip, and **mountain top removal**) and *underground mining* (shaft). A single mine may employ both methods. Prior to 1900, underground mining was the most common method in the United States. Surface mining is now more common, thanks to the development of equipment that can easily move large amounts of rock at the earth surface. The large amount of rock broken up during mining that does not contain enough of the mineral resource to process the rock further is called **waste rock**.

Surface mining

The largest mines are usually surface mines. Heavy machinery and blasting procedures are used to remove large amounts of surface rock, which significantly disturbs the land (see Figure 2). A typical surface mine can produce up to 150,000 tons of ore every day. Sometimes whole mountains (or tops of mountains) are removed via surface mining processes.

Figure 2. Morenci Copper Mine, AZ. Credit: Michael Collier.

Underground mining

Underground mining includes the use of tunnels or vertical shafts to obtain ore from below Earth’s surface (see Figures 3 and 4). These shafts can penetrate down into the ground or sideways into a mountain side. Underground mines tend to be smaller operations than surface mines, generating a few 100,000 to a million tons of ore over the lifetime of the mine. Generally, less land is disturbed in underground mining as compared to surface mining.

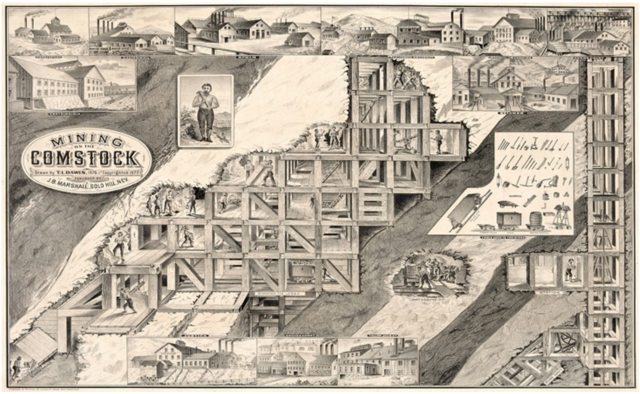


Figure 3. This old lithograph of the mining of the Comstock silver deposit in the western Utah Territory (now Nevada) from 1877 gives a sense of the complex tunneling within underground mines. Credit (drawing): T. L. Dawes.

Figure 4. Image from an underground mine. Credit: Travis Hudson.

Potential problem 1: Waste rock

Waste rock can include the non-ore containing rock on top of the ore body (overburden) and rock that contains ore that is not concentrated enough to mine. In surface mining, approximately 2–3 tons of waste rock is removed for each ton of ore. Underground mining generally creates less waste rock than surface mining; the waste rock is either moved to the surface or used to fill in areas of the mine no longer in use. Piles of waste rock are usually deposited close to the mine. These piles can cover hundreds to thousands of acres and be over 100 feet high (see Figure 5).

Figure 5. Waste rock filling in valley between mountains at Golden Sunlight Mine, MT. Credit: Stuart Jennings.

Mining increases both rates of *weathering* and *erosion*. Because digging and blasting break rock into smaller pieces (*mechanical weathering*), waste rock has more surface area exposed to *chemical weathering* (see Figure 6). For some mining wastes, this is only a small problem. However, some waste rock creates hazardous conditions when chemical weathering mobilizes metals or other undesirable chemicals. These undesirable chemicals may make stream or groundwater more highly acidic. The acidic (low pH) water may be harmful to local organisms, and many of the mobilized metals are toxic to humans, plants, and animals.

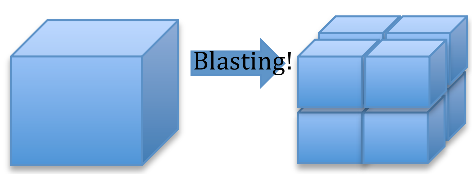


Figure 6. Blasting and digging mechanically weathers rock, creating more surface area to be chemically weathered.

In the United States, current mining operations carefully plan the placement and layering of waste rock, and monitor water flow through waste piles in order to minimize waste rock problems. However, this may not be the case in countries lacking government regulations and was not the case here in the past. Several old waste piles in the United States are hazardous, although some have been remediated.

Concentration

The extracted ore is usually a combination of the desired mineral resource and undesired rocks and minerals. During different concentration processes, the mineral resource is separated from the other rocks and minerals and purified.

Beneficiation

When taken from the mine, most ore looks like a bunch of rock chunks, with the desired mineral often visible only at the microscopic level. Therefore the desired mineral needs to be further concentrated in a process called **beneficiation**. The exact process varies depending on the mineral resource and available technology, but it usually requires a series of steps. Some examples of beneficiation processes are described below.

Milling

After the ore is transported from the mine site, it is crushed into smaller chunks and then may be milled. In **milling**, the crushed ore is placed into a rotating drum with steel rods or balls in order to break the ore down into individual mineral grains (something like a clothes dryer, but much louder! see Figure 7). The ore becomes a fine-grained powder. Afterward, water is added and the resultant rock **slurry** moves on to the next step in the process (flotation or leaching).

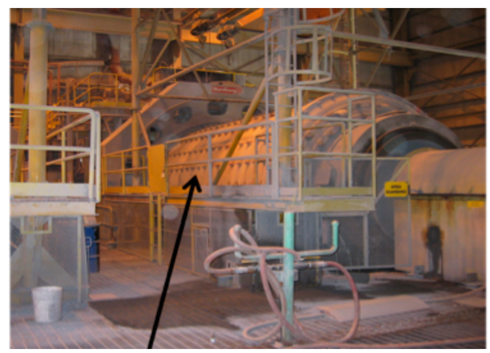


Figure 7. Rotating drum filled with crushed ore and steel balls. Note the 5 gallon bucket in the front left for scale. Golden Sunlight Mine, MT.

Flotation

Flotation is one way to separate the grains of the desired mineral from the grains of other minerals. During flotation, the rock slurry is mixed with a specifically selected reagent that adds bubbles. Due to the particular chemistry, the desired minerals will attach themselves to the bubbles and then float to the top (for example, pine oil is a reagent that can be used in copper flotation; copper will attach to bubbles of pine oil, but other minerals will not). The froth of bubbles and attached minerals is skimmed off the top. The extra water and/or reagent is filtered off, and the mineral may go on to be further concentrated, possibly with other processes including using activated carbon, **electroplating**, and/or leaching with other reagents such as sodium cyanide (discussed further below; see Figure 8).

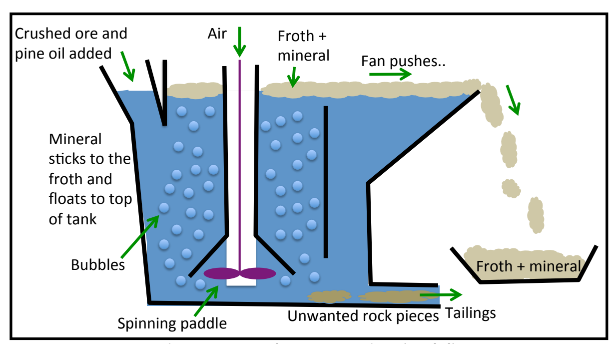


Figure 8. Schematic of one method of flotation.

The slurry remaining at the bottom of the flotation tank is considered a waste product called tailings.

Potential problem 2: Tailings
Tailings, the waste product from the flotation process, are usually pumped downhill into impoundments called tailings ponds. Tailings ponds can be thousands of acres in extent with thicknesses of a few hundred feet (see Figure 9).

If one of the walls/dams of the impoundment breaks, then a lot of contamination can be released very quickly. Additionally, if a tailing pond dries out, the metals may be transported as dust on the wind and thus have the potential to be inhaled by nearby residents. A leaky tailings pile is especially problematic because sulfide minerals, often found in association with metal ores, may occur in high concentrations within the tailings. When exposed to oxygen, sulfide minerals can form sulfuric acid and lead to the development of acidic soils and waters (see Figure 10). This may influence water quality in the area by making the it highly acidic or by an increase in dissolved (and undesirable) metals that results from this acidity (sulfide minerals can be the ones to cause problems in waste rock as well).

Today, plastic liners can be put down to prevent drainage of these contaminated waters into the groundwater system, and the water from tailings ponds can be treated to neutralize the acids. Once filled, tailings ponds are covered (capped) with an impermeable liner, or soil and water flow is managed, treating any water leaving the ponds. However, as with the waste rock, there is a legacy of issues surrounding older and unlined/untreated tailings piles.

Figure 9. Satellite image of the Berkeley Pit (MT) and mining area with tailings and tailings pond (2006). Credit: NASA.

Figure 10. Acidic mine tailings on the floodplain of Silverbow Creek in MT before remediation, ca. 1998. Credit: Stuart Jennings.

Leaching
Leaching is the use of chemicals (such as sulfuric acid or sodium cyanide) to dissolve only the desired metals. The liquid containing the desired metal is removed from the remaining solids and the desired metals are precipitated out of the solution.

Leaching can take place in a vat after milling or instead of milling (either before or after being crushed) or even within the ground itself as a form of 'in-situ" extraction.

Potential problem 3: Leach piles
Heap leaching is one form of leaching where the leaching solution percolates down through a large pile of ore (see Figure 11). Piles can be extensive, cover tens to hundreds of acres, and be a few hundred feet in height. After the metals are leached out, usually after successive treatments with recycled solution, the remaining rock piles have many of the same environmental concerns as tailings ponds. To limit problems, the leach piles can be rinsed once leaching is completed and built upon specially designed pads.

Figure 11. An example of heap leaching using sodium cyanide at the Zortman Landusky mine, ca. 1996. Credit: Stuart Jennings.

Smelting
The process of **smelting** separates the metal from the mineral by heating the mineral in the presence of a material known as a flux (see Figure 12). The desired mineral settles to the bottom of the melt and can be separated out. The (unwanted) material at the top of the melt can harden into slag. The smelter is often in a different location than the mine. After this the desired mineral goes on to a **refinery**, to be concentrated further.

Figure 12. Smelting gold. Credit: A.J. Mandolesi.

Potential problem 4: Smelter emissions
Emissions from this process can be a source of pollution, including sulfur dioxide and other gases, heavy metals, and particulates. Increasing regulation and improved technologies since the 1970s in the United States have resulted in a reduction in dangerous emissions.

Cleaning up Afterward

Preparing for Mine Closure
Once the ore material runs out, or becomes technologically or economically inaccessible, the mine will close. In places where water was continually pumped out to keep mining operations dry, the closed mine will fill with water.

The United States has many mines that were closed prior to the 1970s (when environmental regulations were passed) that have many environmental problems, such as **acid mine drainage**. Mines operating in the United States today must meet higher standards; they must provide some amount of environmental and human health protection while they are in operation and enact a plan to limit environmental and human health problems well after the mine closes. For example, while the mining is still happening, the company will plan how they will grade slopes to decrease erosion and make slopes more stable once they close the mine.

Reclamation

Reclamation, the restoration of land to either natural conditions or another useful purpose, often involves the process of stabilizing soils and slopes in an area through grading (creating a different, more gentle slope) and planting trees and plants (see Figure 13). Usually the addition of new soil, or treatment of the existing soil, is necessary prior to revegetation. This step can be started before the mine fully closes; reclamation can occur as sections close (either parts of the surface mine or the waste rock piles). This can also help improve the aesthetics of the mine area while it is still open.

Figure 13. Revegetation of waste rock area at the Zortman-Landusky Mine, ca/ 1996. Credit: Stuart Jennings.

Remediation

Remediation is the process of fixing, removing, or counteracting an environmental problem. In mining, the water leaving the mine area (waste rock, tailings ponds, leach piles, or from the mine itself) often must be treated (remediated) before being released back into the natural system (see Figure 14). Like reclamation, treatment of acidic or otherwise contaminated water does not need to wait until the mine closes but should be part of the mining plan and be done as mining happens.

Figure 14. One method of treating acidic mine water is to add alkaline material, causing iron and other metal to precipitate out of the water. Credit: Stuart Jennings.

Environmental and Societal Concerns

The mining industry provides raw materials for the products on which we rely, provides jobs (directly and indirectly tied to the mine), pushes technology forward, and plays a key role in local and global economic systems. In spite of these benefits, mining poses several environmental consequences.

Since the late 1960s, a series of U.S. federal regulations were enacted in the interest of protecting human health and the environment. A number of these acts directly or indirectly regulate the mining industry (see Table 2). Some states also enforce more stringent rules on top of these federal regulations. Because these acts only apply to mining operations underway after the year the act passed, a number of the older mine areas created prior to these regulations contain hazardous waste. The EPA's **Superfund** program has remediated some of these sites.

Federal Act	**Year Passed**
National Environmental Policy Act (NEPA)	1969
Clear Air Act (CAA)	1970
Resource Conservation and Recovery Act (RCRA)	1976
Clean Water Act (CWA)	1977
Toxic Substances Control Act (TSCA)	1977
Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)	1980
Clean Water Drinking Act and others	

Table 2. Environmental regulations that affect mining operations. Info from Hudson, T. L., et al. (1999).

While regulations in the United States have become much more stringent since the 1970s, there are still environmental and health issues related to mining, including:

- The use of water, especially in arid environments where water is scarce.
- The impact on forests and ecosystems, including habitat destruction or alteration.
- Contamination of water through acid mine drainage, accidental spills, etc.
- Worker health and safety, although this has been improved through labor laws.
- Unsafe practices when mines do not meet the federal or state regulations.
- The use of public lands, such as in National Forests, for mineral extraction.
- Ground subsidence above underground mines.

Other Countries

While some countries also have well-developed regulations similar to those in the United States, others do not, and some may not enforce the regulations that they do have in place.

Artisanal and small-scale mining (ASM) is mining that is enacted by individuals, small groups, or communities, often with limited technology and/or mechanization. It is common in some, often developing, countries. An estimated 13 million people work in the ASM industry globally, while another 80–100 million people are affected by the industry. ASM is a significant provider of mineral resources, making up about 15–20% of the global nonfuel mineral production.

ASM can offer rural and impoverished communities an improved local economy. However, ASM tends to lack mechanization, meaning that people carry out physically demanding labor. Workers tend to have low incomes and no established employer to provide safety and/or health protection. These small-scale mines are often not regulated, and thus often employ children in harsh conditions, and damage the environment.

Other helpful/interesting information:

Exploration:

Seismic Survey Animation at http://www.oerb.com/ Default.aspx?tabid=274 to see how seismics work.

Latimer, Cole. 2012. "Working Like A DOG" *Australian Mining.* http://www.miningaustralia.com.au/features/working-like-a-dog.

Nadoll, Patrick. 2014. "Mineral 'Fingerprints' to Aid More Cost-Effective Exploration." *Australian Mining.* http://www.miningaustralia.com.au/features/mineral-fingerprints-to-aid-more-cost-effective-ex.

Extraction:

"The World's Largest Recorded Mining Blast" video: http://www.miningaustralia.com.au/news/the-world-s-largest-recorded-mining-blast-video- (~5 min.) video on blasting. This video is also embedded within the PowerPoint.

Concentration:

http://www.abc.net.au/catalyst/stories/2533477.htm (~5 min) video on one method of flotation.

Sources

Flotation: http://www.st-augustines.worcs.sch.uk/intranet/departments/sci2007a/Chemistry/NEWchemstart/metals%20stuff/copper%20stuff/copper%20extr/froth%20float%20diag.gif.

Global Acid Rock Drainage Guide. INAP: The International Network for Acid Prevention. http://www.gardguide.com/index.php/Main_Page.

Hentschel, T., Hruschka, F., and Priester, M. 2002. "Global Report on Artisanal & Small-Scale Mining." *Minerals, Mining and Sustainable Development,* No. 70. 67 pages. http://pubs.iied.org/pdfs/G00723.pdf.

Hudson, T. L., Fox, F. D., and Plumlee, G. S. 1999. *Metal Mining and the Environment.* American Geological Institute. 68 pages. http://www.agiweb.org/environment/publications/metalsfull.pdf

Lide, D. R. 2000. *CRC Handbook of Chemistry and Physics.* CRC Press.

Pipken, B. W., and Trent, D. D. (2001) *Geology and the Environment.* Brooks/Cole. 541 pages.

Tour of Golden Sunlight Mine. 2012.

Salamon, M. 2010. "Miners Face Health Risks, Even on Good Days." *Live Science.* http://www.livescience.com/11173-miners-face-health-risks-good-days.html.

Superfund: Basic Information. http://www.epa.gov/superfund/about.htm.

Additional Image Information

Figure 1: Sketched by Leah Joseph.

Figure 2: Credit: Michael Collier. "At Morenci near Clifton, Arizona the countryside is denuded of trees and a large open-cut mine reveals multicolored layers of copper bearing rock." Image courtesy of the Earth Science World Image Bank, http://www.earthscienceworld.org/images. Reproduction under certain conditions is allowed for noncommercial use, http://www.earthscienceworld.org/images/imageuse.html.

Figure 3: Comstock Deposit: Image of Lithograph from U.S. Library of Congress: Credit for drawing: T. L. Dawes (1877). Downloaded http://upload.wikimedia.org/wikipedia/commons/thumb/1/1c/Mining_on_the_Comstock.jpg/1280px-Mining_on_the_Comstock.jpg as a public domain file as it was published in 1877 (http://commons.wikimedia.org/wiki/File:Mining_on_the_Comstock.jpg).

Figure 4: Credit: Travis Hudson, American Geological Institute. "Large equipment used in underground mining operations." Image courtesy of the Earth Science World Image Bank, http://www.earthscienceworld.org/images. Reproduction under certain conditions is allowed for noncommercial use, http://www.earthscienceworld.org/images/imageuse.html.

Figure 5: Credit: Stuart Jennings, Montana State University. "Waste rock valley fill at the Golden Sunlight Mine." Image courtesy of the Earth Science World Image Bank, http://www.earthscienceworld.org/images.

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Figure 6: Sketched by Leah Joseph.

Figure 7: Taken by Leah Joseph.

Figure 8: Modified by Leah Joseph from drawing found at: http://www.st-augustines.worcs.sch.uk/intranet/departments/sci2007a/Chemistry/NEWchemstart/metals stuff/copper stuff/copper extr/froth float diag.gif.

Figure 9: Credit: NASA (2006) downloaded from: http://www.nasa.gov/multimedia/imagegallery/image_feature_697.html and is freely available for reuse under these terms: http://www.nasa.gov/audience/formedia/features/MP_Photo_Guidelines.html#.U6MgBxbntvU.

Figure 10: Credit: Stuart Jennings, Montana State University (1998) "Acidic mine tailings cover the floodplain of Silverbow Creek, near Butte, Montana, prior to remediation work (image 1998)." Image courtesy of the Earth Science World Image Bank, http://www.earthscienceworld.org/images. Reproduction under certain conditions is allowed for noncommercial use, http://www.earthscienceworld.org/images/imageuse.html.

Figure 11: Credit: Stuart Jennings, Montana State University (1996). "Sodium cyanide heap leaching and metal recovery operations at the Zortman-Landusky Mine." Image courtesy of the Earth Science World Image Bank, http://www.earthscienceworld.org/images. Reproduction under certain conditions is allowed for noncommercial use, http://www.earthscienceworld.org/images/imageuse.html.

Figure 12: Credit: A. J. Mandolesi, American Geological Institute. "Refining gold." Image courtesy of the Earth Science World Image Bank, http://www.earthscienceworld.org/images. Reproduction under certain conditions is allowed for noncommercial use, http://www.earthscienceworld.org/images/imageuse.html.

Figure 13: Credit: Stuart Jennings, Montana State University (1996) "Waste rock revegetation at Zortman-Landusky Mine, circa July 1996." Image courtesy of the Earth Science World Image Bank, http://www.earthscienceworld.org/images. Reproduction under certain conditions is allowed for noncommercial use, http://www.earthscienceworld.org/images/imageuse.html.

Figure 14: Credit: Stuart Jennings, Montana State University. "Mike Horse Mine pretreatment pond with alkaline addition, precipitation of iron and other metals." Image courtesy of the Earth Science World Image Bank, http://www.earthscienceworld.org/images. Reproduction under certain conditions is allowed for noncommercial use, http://www.earthscienceworld.org/images/imageuse.html.

Acknowledgments

Thank you to the Golden Sunlight Mine (near Whitehall, MT). who in 2012 not only led us around on a tour but also allowed us to take pictures.

Thank you also to SERC and the Environmental Geology workshop in 2012 and in particular David Mogk for coordinating our tour of, and other related visits to and information about, Golden Sunlight Mine and also the Berkeley Pit in Butte, MT.