Chapter 1

Introduction to Mine Wastes

1.1
Scope of the Book

This book focuses on “problematic” solid wastes and waste waters produced and disposed of at modern mine sites. They are problematic because they contain hazardous substances (e.g. heavy metals, metalloids, radioactivity, acids, process chemicals), and require monitoring, treatment, and secure disposal. However, not all mine wastes are problematic wastes and require monitoring or even treatment. Many mine wastes do not contain or release contaminants, are “inert” or “benign”, and pose no environmental threat. In fact, some waste rocks, soils or sediments can be used for landform reconstruction, others are valuable resources for road and dam construction, and a few are suitable substrates for vegetation covers and similar rehabilitation measures upon mine closure. Such materials cannot be referred to as wastes by definition as they represent valuable by-products of mining operations.

This books attempts to gather the scientific knowledge on problematic wastes accumulating at modern mine sites. Wastes are also produced at mineral processing plants and smelter sites and include effluents, sludges, leached ore residues, slags, furnace dusts, filter cakes, and smelting residues. Such wastes are not mine wastes by definition as they generally do not accumulate at mine sites. Thus, this book largely focuses on mining wastes. It limits the presentation of mineral processing and metallurgical wastes to those waste types accumulating at or near mine sites. Readers interested in the general areas of mineral processing and metallurgical wastes are advised to consult the relevant literature (e.g. Petruk 1998).

Mine wastes are commonly classified according to their physical and chemical properties and according to their source. Such a classification scheme is followed in this work. The book attempts to cover the major sources of mine wastes including the mining of metal, energy and industrial mineral resources. Wastes of the petroleum industry, in particular, wastes of the oil shale and oil sand industry, have been excluded as they are beyond the scope of this book. The book has been organized into seven chapters which document the different sources and properties of mine wastes. The contents of Chapters Two (Sulfidic Mine Wastes), Three (Mine Water), Four (Tailings), and Five (Cyanidation Wastes of Gold-Silver Ores) are inherent to most metal and/or coal mines. The contents of Chapter Six (Radioactive Wastes of Uranium Ores) are of importance to uranium mining operations, whereas Chapter Seven (Wastes of Phosphate and Potash Ores) discusses topics that are relevant to the fertilizer producing industry.

1. Chapter 1 sets the scene as introduction. It gives important definitions, describes the environmental impacts of mine wastes in human history, presents the nature and scope of waste production in the mining industry, and lists the general resources available to acquire knowledge on mine wastes.
2. Chapter 2 provides an insight into sulfidic mine wastes. Mining of many metal ores and coal exposes and uncovers sulfide minerals to oxidizing conditions. This chapter documents the oxidation and weathering processes of sulfides which cause and influence acid mine drainage. This is followed by discussions of the available tools to predict and to monitor the behaviour of acid generating wastes. The chapter also lists the various technologies available for the control and prevention of sulfide oxidation.
3. Chapter 3 covers the fundamentals of acid mine waters. It explains important processes occuring within such acid waters and documents predictive and monitoring techniques. A documentation of technologies applied for the treatment of acid mine drainage completes the chapter.
4. Chapter 4 addresses the wastes of mineral processing operations (i.e. tailings). The chapter presents the characteristics of tailings solids and liquids. It also gives details on the disposal options of tailings whereby most tailings are stored in engineered structures, so-called "tailings storage facilities" or "tailings dams".
5. Chapter 5 covers the characteristics of cyanide-bearing wastes which are produced during the extraction of gold and silver. The chemistry of cyanide is explained before the use of cyanide in the mineral industry is shown. A documentation of treatment options for cyanidation wastes concludes the chapter.
6. Chapter 6 summarizes radioactive wastes of uranium ores. It provides the mineralogical and geochemical characteristics of uranium ores and gives the principles of radioactivity. The chapter describes uranium mine wastes and the techniques available for their disposal and treatment. The potential hazards and environmental impacts of uranium mining have been discussed in some detail.
7. Chapter 7 describes wastes of the phosphate and potash mining and fertilizer producing industry. Phosphogypsum is the major waste product of fertilizer production. The characteristics, storage and disposal practices, and recycling options of this waste material are documented to some extent.

Sulfidic wastes and acid mine waters have been studied extensively from all scientific angles, and there is a vast literature on the subjects including books, reviews, technical papers, conference proceedings, and web sites. On the other hand, wastes of potash ores have received in comparison only limited attention. Such a disproportionate knowledge has influenced the presentation of this work and is reflected in the length of individual chapters.

Several chapters contain case studies and scientific issues which demonstrate particular aspects of chapter topics in greater detail. Some case studies highlight the successes in handling mine wastes, others point to future opportunities, whereas some document the environmental impacts associated with them. The reasoning behind this is that we have to learn not only from our successes but also from our mistakes in handling mine wastes. Most of all, we have to pursue alternative waste treatment, disposal, use and rehabilitation options.

1.2
Definitions

1.2.1
Mining Activities

Definitions are essential for clear communication especially when discussing technical issues. Therefore, important and relevant terms have been defined in the following sections. Operations of the mining industry include mining, mineral processing, and metallurgical extraction. "*Mining*" is the first operation in the commercial exploitation of a mineral or energy resource. It is defined as the extraction of material from the ground in order to recover one or more component parts of the mined material. "*Mineral processing*" or "*beneficiation*" aims to physically separate and concentrate the ore mineral(s), whereas "*metallurgical extraction*" aims to destroy the crystallographic bonds in the ore mineral in order to recover the sought after element or compound. At mine sites, mining is always associated with mineral processing of some form (e.g. crushing; grinding; gravity, magnetic or electrostatic separation; flotation). It is sometimes accompanied by the metallurgical extraction of commodities such as gold, copper, nickel, uranium or phosphate (e.g. heap leaching; vat leaching; in situ leaching).

All three principal activities of the mining industry – mining, mineral processing, and metallurgical extraction – produce wastes. "*Mine wastes*" are defined herein as solid, liquid or gaseous by-products of mining, mineral processing, and metallurgical extraction. They are unwanted, have no current economic value and accumulate at mine sites.

1.2.2
Metals, Ores and Industrial Minerals

Many mine wastes, especially those of the metal mining industry, contain metals and/or metalloids at elevated concentrations. There is some confusion in the literature over the use of the terms "*metals*", "*metalloids*", "*semi-metals*", "*heavy metals*" and "*base metals*". Metals are defined as those elements which have characteristic chemical and physical properties (e.g. elements with the ability to lose one or more electrons; ability to conduct heat and electricity; ductility; malleability). In contrast, metalloids or semi-metals are elements with metallic and non-metallic properties; that is, arsenic, antimony, bismuth, selenium, and tellurium (e.g. elements with the ability to gain one or more electrons; lower ability to conduct heat and electricity than metals). Heavy metals are those metals with a density greater than 6 g cm^{-3} (i.e. Fe, Cu, Pb, Zn, Sn, Ni, Co, Mo, W, Hg, Cd, In, Tl) (Thornton et al. 1995). The term "heavy metals" is used in this work reluctantly because there are alternative, scientifically rigorous definitions (Hodson 2004). Base metals are those metals used in industry by themselves rather than alloyed with other metals (i.e. Cu, Pb, Zn, Sn).

In most metal ores, the metals are found in chemical combination with other elements forming metal-bearing "*ore minerals*" such as oxides or sulfides. Ore minerals are defined as minerals from which elements can be extracted at a reasonable profit.

In contrast, "*industrial minerals*" are defined as any rock or mineral of economic value excluding metallic ores, mineral fuels, and gemstones. The mineral or rock itself or a compound derived from the mineral or rock has an industrial use. Ore and industrial minerals are commonly intergrown on a microscopic or even sub-microscopic scale with valueless minerals, so-called "*gangue minerals*". The aggregate of ore minerals or industrial minerals and gangue minerals is referred to as "*ore*". Thus, ore is a rock, soil or sediment that contains economically recoverable levels of metals or minerals. Mining results in the extraction of ore/industrial minerals and gangue minerals. Mineral processing enriches the ore/industrial mineral and rejects unwanted gangue minerals. Finally, metallurgical extraction destroys the crystallographic bonds of minerals and rejects unwanted elements.

1.2.3
Mine Wastes

Mining, mineral processing, and metallurgical extraction produce solid, liquid and gaseous wastes. Mine wastes can be further classified as solid mining, processing and metallurgical wastes and mine waters (Table 1.1):

- *Mining wastes.* Mining wastes either do not contain ore minerals, industrial minerals, metals, coal or mineral fuels, or the concentration of the minerals, metals, coal or mineral fuels is subeconomic. For example, the criterion for the separation of waste rock from metalliferous ore and for the classification of materials as economic or subeconomic is the so-called "cut-off grade". It is based on the concentration of the ore element in each unit of mined rock and on the cost of mining that unit. As a result, every mine has a different criterion for separating mining waste from ore. *Mining wastes* include *overburden* and *waste rocks* excavated and mined from surface and underground operations. *Waste rock* is essentially wall rock material removed to access and mine ore (Fig. 1.1). In coal mining, waste rocks are referred to as "*spoils*".

  Mining wastes are heterogeneous geological materials and may consist of sedimentary, metamorphic or igneous rocks, soils, and loose sediments. As a consequence, the particle sizes range from clay size particles to boulder size fragments. The physical and chemical characteristics of mining wastes vary according to their mineralogy and geochemistry, type of mining equipment, particle size of the mined material, and moisture content. The primary sources for these materials are rock, soil, and sediment from surface mining operations, especially open pits, and to a lesser degree rock removed from shafts, haulageways, and underground workings (Hassinger 1997).

  Once the metalliferous ore, coal, industrial minerals or mineral fuels are mined, they are processed to extract the valuable commodity. In contrast, mining wastes are placed in large heaps on the mining lease. Nearly all mining operations generate mining wastes, often in very large amounts.
- *Processing wastes.* Ore is usually treated in a physical process called beneficiation or mineral processing prior to any metallurgical extraction (Fig. 1.2). Mineral processing techniques may include: simple washing of the ore; gravity, magnetic, electrical or optical sorting; and the addition of process chemicals to crushed and sized ore in

Table 1.1. Simplified mining activities whereby a resource is mined, processed and metallurgically treated. Each step of the operation produces solid, gaseous and liquid wastes

Acitivity generating the mine waste	Mine wastes
Open pit mining, underground mining	Mining wastes (e.g. waste rocks, overburden, spoils, mining water, atmospheric emissions)
Mineral processing, coal washing, mineral fuel processing	Processing wastes (e.g. tailings, sludges, mill water, atmospheric emissions)
Pyrometallurgy, hydrometallurgy, electrometallurgy	Metallurgical wastes (e.g. slags, roasted ores, flue dusts, ashes, leached ores, process water, atmospheric emissions)

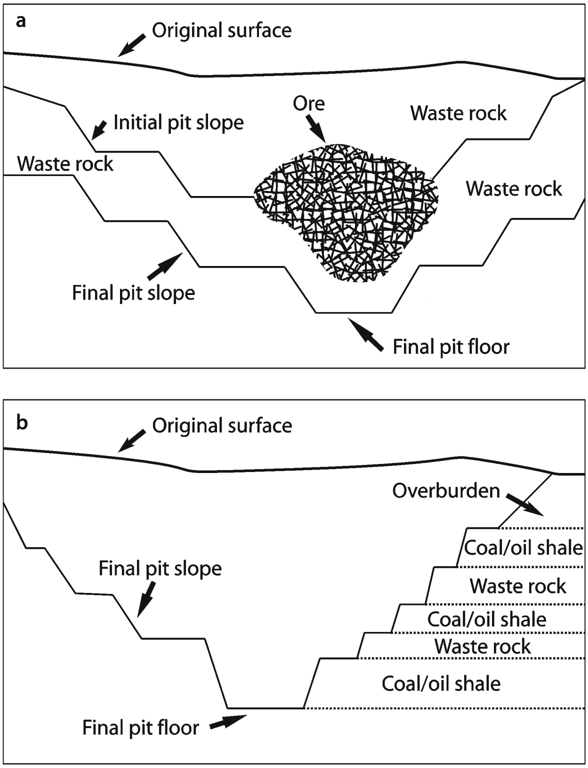

Fig. 1.1. Schematic cross-sections of open pit mines: **a** metal mines; **b** coal and oil shale mines. Waste rocks have to be mined in order to obtain ore, coal or oil shale

order to aid the separation of the sought after minerals from gangue during flotation. These treatment methods result in the production of "*processing wastes*". Processing wastes are defined herein as the portions of the crushed, milled, ground, washed or treated resource deemed too poor to be treated further. The definition thereby includes tailings, sludges and waste water from mineral processing, coal washing, and mineral fuel processing. "*Tailings*" are defined as the processing waste

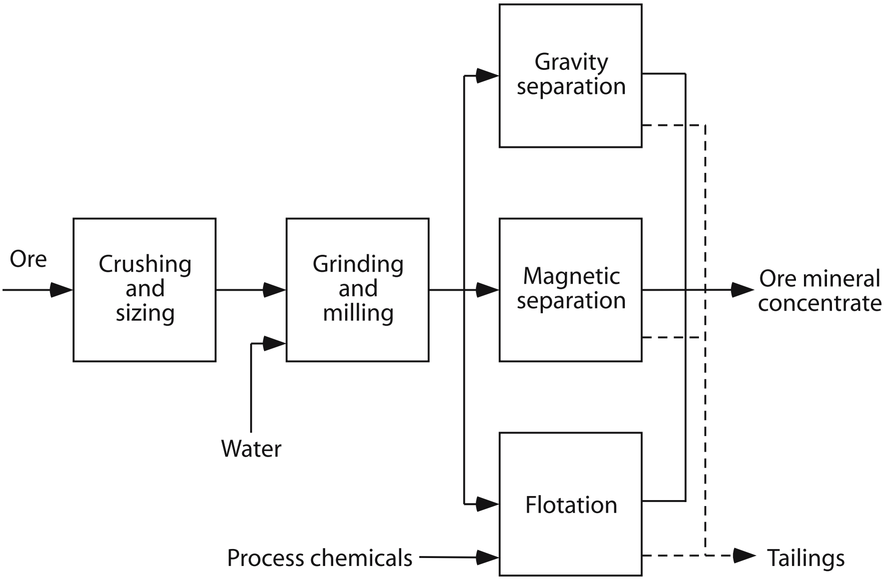

Fig. 1.2. Simplified flow-chart of a mineral processing operation, in which ore is processed to yield an ore mineral concentrate and tailings (after Ripley et al. 1996)

from a mill, washery or concentrator that removed the economic metals, minerals, mineral fuels or coal from the mined resource.

The physical and chemical characteristics of processing wastes vary according to the mineralogy and geochemistry of the treated resource, type of processing technology, particle size of the crushed material, and the type of process chemicals. The particle size for processing wastes can range in size from colloidal size to fairly coarse, gravel size particles. Processing wastes can be used for backfilling mine workings or for reclamation and rehabilitation of mined areas, but an alternative method of disposal must be found for most of them. Usually, this disposal simply involves dumping the wastes at the surface next to the mine workings. Most processing wastes accumulate in solution or as a sediment slurry. These tailings are generally deposited in a tailings dam or pond which has been constructed using mining or processing wastes or other earth materials available on or near the mine site.

- *Metallurgical wastes.* Processing of metal and industrial ores produces an intermediate product, a mineral concentrate, which is the input to extractive metallurgy. Extractive metallurgy is largely based on hydrometallurgy (e.g. Au, U, Al, Cu, Zn, Ni, P) and pyrometallurgy (e.g. Cu, Zn, Ni, Pb, Sn, Fe), and to a lesser degree on electrometallurgy (e.g. Al, Zn) (Ripley et al. 1996; Warhurst 2000). Hydrometallurgy involves the use of solvents to dissolve the element of interest. For example, at gold mines leaching of the ore with a cyanide solution is a common hydrometallurgical process to extract the gold. The process chemical dissolves the gold particles and a dilute, gold-laden solution is produced which is then processed further to recover

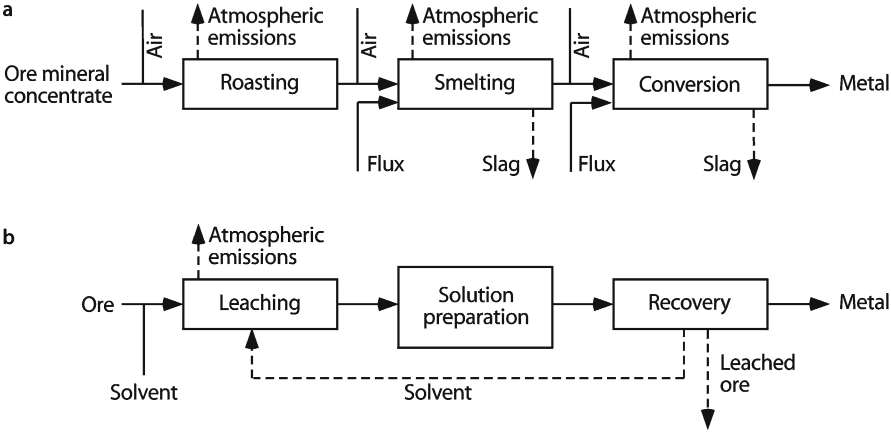

Fig. 1.3. Simplified flow-charts of **a** pyrometallurgical and **b** hydrometallurgical operations, in which ore is treated to yield metals and wastes

the metal. In contrast, pyrometallurgy is based on the breakdown of the crystalline structure of the ore mineral by heat whereas electrometallurgy uses electricity. These metallurgical processes destroy the chemical combination of elements and result in the production of various waste products including atmospheric emissions, flue dust, slag, roasting products, waste water, and leached ore (Fig. 1.3).

"*Metallurgical wastes*" are defined as the residues of the leached or smelted resource deemed too poor to be treated further. At many gold, uranium or phosphate mines hydrometallurgical extraction is performed, and hydrometallurgical wastes accumulate on site. In contrast, electro- and pyrometallurgical processes and their wastes are generally not found at modern mine sites, unless there is cheap fuel or readily available energy for these extractive processes. At many historical metal mines, the ore or ore mineral concentrate was smelted or roasted in order to remove sulfur and to produce a purer marketable product. Consequently, roasted ore, slag, ash, and flue dust are frequently found at historical metal mine sites.

- *Mine waters.* Mining, mineral processing and metallurgical extraction not only involve the removal and processing of rock and the production and disposal of solid wastes, but also the production, use and disposal of mine water. "*Mine water*" originates as ground or meteoric water which undergoes compositional modifications due to mineral-water reactions at mine sites. The term "mine water" is collective and includes any water at a mine site including surface water and subsurface ground water (Morin and Hutt 1997) (Table 1.2).

Water is needed at a mine site for dust suppression, mineral processing, coal washing, and hydrometallurgical extraction. The term "*mining water*" is used here in a general sense to refer to waters which run off or flow through a portion of a mine site and had contact with any of the mine workings (Table 1.2). "*Mill water*" is water that is used to crush and size the ore. "*Process water*" is water that is used to process the ore using hydrometallurgical extraction techniques. The water commonly contains process chemicals. At some stage of the mining operation, water is unwanted and has no value to the operation. Such mine water is generated and disposed of at various stages during mining, mineral processing or metallurgical extraction. Water of poor quality requires remediation as its uncontrolled discharge, flow, drainage or seepage from the mine site may be associated with the release of heat, suspended solids, bases, acids, and dissolved solids including process chemicals, metals, metalloids, radioactive substances or salts. Such a release could result in a pronounced negative impact on the environment surrounding the mine site.

"*Acid mine drainage*" (AMD) refers to a particular process whereby low pH mine water is formed from the oxidation of sulfide minerals. A number of other terms are also used to describe this process such as "*acid drainage*" or "*acid rock drainage*" (ARD). These latter two terms highlight the fact that there are naturally outcropping sulfide orebodies and sulfidic rocks, which actively weather, oxidize, and cause acidic springs and streams (Furniss et al. 1999; Posey et al. 2000; Munk et al. 2002). In fact, the acid streams draining such ores and rocks can contain high levels of metals and metalloids that exceed water quality standards and result in toxic effects to aquatic life. The use of these terms tries to highlight the fact that AMD occurs naturally and unrelated to mining activities. However, such natural situations are rare compared to those where mining has been directly responsible for the acidification of waters. Therefore, in this work the term AMD is preferred. AMD

Table 1.2. Mine water terminology

Term	Definition
Type of mine water	
Mine water	Any surface water or ground water present at a mine site
Mining water	Water that had contact with any of the mine workings
Mill water	Water that is used to crush and size the ore
Process water	Water that is used to process the ore using hydrometallurgical extraction techniques; it commonly contains process chemicals
Leachate	Mine water that has percolated through or out of solid mine wastes
Effluent	Mining, mill or process water that is discharged into surface waters
Mine drainage water	Surface or ground water that actually or potentially flows from the mine site into surrounding areas
Acid mine drainage (AMD) water	Low pH surface or ground water that formed from the oxidation of sulfide minerals and that actually or potentially flows from the mine site into surrounding areas
Type of process	
Mine seepage	Slow flow of ground water to the surface at pit faces, underground workings, waste dumps, tailings dams, and heap leach piles
Mine drainage	Process of water discharge at a mine
Acid mine drainage (AMD)	Process whereby low pH mine water is formed from the oxidation of sulfide minerals

is still an unfortunate term since AMD impacts more frequently on ground water quality than on the surface drainage from a mine (Bennett and Ritchie 1993). Such impacted ground water has also been named "*acid ground water*" (AG). Finally, the waters generated by the oxidation of sulfide minerals are also referred to by some authors as *"acid sulfate waters"* (ASW).

1.3
Mine Waste Production

The modern mining industry is of considerable importance to the world economy as it provides a great diversity of mineral products for industrial and household consumers (Table 1.3). The consequence of the large size of the mining and mineral processing industry is not only the large volume of materials processed but also the large volume of wastes produced.

Table 1.3. World production of selected non-fuel mineral commodities in 1999 (USGS Mineral Resources Program 2001)

Metals	Production		Industrial minerals	Production	
Antimony	0.122	Mt	Asbestos	1.93	Mt
Arsenic trioxide	38 800	t	Barite	5.66	Mt
Bauxite	127	Mt	Boron minerals	6.37	Mt
Beryl	6 210	t	Cement	1 610	Mt
Chromite	14	Mt	Bentonite	9.82	Mt
Cobalt	29 900	t	Fuller's earth	3.52	Mt
Copper	12.6	Mt	Kaolin	41.6	Mt
Gold	2 540	t	Feldspar	8.98	Mt
Iron ore	990	Mt	Fluorite	4.51	Mt
Lead	3.02	Mt	Graphite	0.685	Mt
Manganese ore	20.4	Mt	Gypsum	106	Mt
Mercury	1 800	t	Lime	141	Mt
Molybdenum	0.123	Mt	Magnesite	10.7	Mt
Nickel	1.12	Mt	Mica	0.304	Mt
Niobium-tantalum concentr.	57 100	t	Peat	27.2	Mt
Platinum-group elements	379	t	Perlite	1.85	Mt
Silver	17 700	t	Phosphate rock	141	Mt
Tin	0.198	Mt	Potash	25.7	Mt
Titanium concentrates	4.17	Mt	Salt	209	Mt
Tungsten	31 000	t	Sand and gravel	107	Mt
Vanadium	42 200	t	Sulfur	57.1	Mt
Zinc	8.04	Mt	Vermiculite	0.534	Mt

The exploitation of mineral resources results in the production of large volumes of waste rocks as they have to be removed to access the resource. Once the resource has been extracted from the Earth, it is processed for its valuable components. These valuable components vary in mass from 100% to a few parts per million of the original resource. For instance, extraction and production of clay, sand and gravel generally do not produce any waste. Operators extract and process the entire mined material. Also, crushing, washing and sizing of rock aggregates generate only minor amounts of unwanted fine-grained slimes and dust particles. These slimes and dust particles can be put to good use as mineral fertilizer. In contrast, exploitation of a metalliferous mineral resource aims to extract only a few percent concentrations of copper, lead or zinc or even parts per million values of gold. Only a very small valuable component is extracted from metalliferous ores during processing and metallurgical extraction. The great majority of the total mined material is gangue which is generally rejected as processing and metallurgical waste. Therefore, mining, mineral processing, and metallurgical extraction result in the production of a high volume of unwanted material.

In general, coal mining and processing generate the largest quantity of waste followed by non-ferrous and ferrous ores and industrial minerals. Waste production varies greatly from nation to nation. For example, more than 4 700 Mt of mining waste and 1 200 Mt of tailings are stored all over the European Union, most of the mine waste in Finland, Germany, Greece, Ireland, Portugal, Spain, Sweden, and the United Kingdom (BRGM 2000). The production of mine wastes is particularly significant in nations with a major mining industry. In Australia, the mining industry produces 1 750 Mt of mine wastes per year. It is by far the largest producer of solid, liquid and gaseous waste and exceeds municipal waste production by at least 450 Mt. Of the 2 100 Mt of solid waste generated annually in Australia, 80% is produced by the mining sector (Connor et al. 1995; cited by Boger 1998). In South Africa, over 1 100 mines contribute to 72.3% of the country's total solid waste stream, with approximately 25 000 ha of land utilized as dumping areas in the form of tailings storage facilities (Maboeta and Rensburg 2003).

The global quantity of non-fuel mineral commodities removed from the Earth's crust each year by mining is now of the order of 3 700 Mt (Table 1.3). While the consumption of mineral commodities is well documented, there is no data available on the global production of mine wastes. Therefore, an estimation of the annual quantity of mine waste produced globally has to be based on several assumptions. In 1999, approximately 40 Mt of metals (As, Be, Co, Cr, Cu, Hg, Nb, Ni, Pb, Sb, Sn, Ta, V, W, Zn) were produced worldwide (Table 1.3). Assuming that the average ore grade of the metal deposits was 0.5%, mining, processing and extraction of the ores generated 8 000 Mt of solid wastes. Similarly, the production of 2 540 t of gold generated about 1 250 Mt of solid wastes, assuming an average gold ore grade of 2 ppm. In addition, every year approximately 4 500 Mt of coal, 990 Mt of iron ore, 127 Mt of bauxite, and 2 500 Mt of industrial minerals are consumed globally. For every tonne of these ores consumed, there will be at least the same amount of solid waste generated (i.e. waste rocks, tailings). Such calculations indicate that approximately 15 000 to 20 000 Mt of solid mine wastes are being produced annually around the world.

These calculations and statistics represent approximations and can only serve as an indication of the magnitude of waste production. Furthermore, every mine site has its own unique waste because there are compositional differences in the mined ore, and there is a great diversity of applied mining and mineral processing methods. Wastes generated at different mines vary considerably in their properties. While certain scientific principles apply to particular commodities, every mine requires its very own waste characterization, prediction, monitoring, control, and treatment.

Mine wastes represent the greatest proportion of waste produced by industrial activity. In fact, the quantity of solid mine waste and the quantity of Earth's materials moved by fundamental global geological processes are of the same order of magnitude – approximately several thousand million tonnes per year (Fyfe 1981; Förstner 1999). Fundamental global geological processes such as oceanic crust formation, soil erosion, sediment discharge to the oceans, and mountain building naturally move Earth's materials around the Earth's crust and shape our planet. In contrast, mankind extracts material from the Earth during mining and discards most of the extracted crust as waste. As a result, the Earth is getting increasingly shaped by mine wastes rather than by natural geological processes. In addition, metal ores of increasingly lower grades are being exploited, and more wastes are being produced as a result of it. The production of mine wastes may even double within a period of 20 to 30 years (Förstner 1999). Today and in the future, commercial exploitation of a mineral resource is about waste production and waste disposal as well as resource production and provision.

1.4
Mine Wastes: Unwanted By-Products or Valuable Resources?

The term "mine waste" implies that the material has no current economic value and is an unwanted by-product of mining. However, some mine wastes can be useful and this has been recognized since the beginning of mining and smelting. For example, the use of slag in road construction can be traced back to the very early days when the Romans used iron slag as a pavement material for their roads. Also, while wastes of the mineral industry are generally useless at the time of production, they can still be rich in resource ingredients. Unfavourable economics, inefficient processing, technological limitations or mineralogical factors may not have allowed the complete extraction of resource ingredients at the time of mining. In the past, inefficient mineral processing techniques and poor metal recoveries produced wastes with relatively high metal concentrations (Scientific Issue 1.1; Fig. 1.4). In some cases, old tailings and waste rock piles that were considered worthless years ago are now "re-mined", feeding modern mining operations. This approach is widely used in the mining industry.

Hence, changing circumstances may turn a particular waste into a valuable commodity, either because the economic extraction of resource ingredients may now be possible using improved technology, or a market has been found for the previously unwanted material. What may be waste to some miners, can be a very important, useful resource to other mining operations, either now or in the future. Yesterday's waste can become today's resource.

Recycling today's waste is similarly possible. Manganese tailings may be used in agro-forestry, building and construction materials, coatings, resin cast products, glass, ceramics, and glazes (Verlaan and Wiltshire 2000). Tailings can also be suitable fertilizers for golf courses; phosphogypsum can be used in the agricultural and the building industry; clay-rich wastes can improve sandy soils or are the raw material for brick

Scientific Issue 1.1. Historical Base Metal Smelting Slags

The Principles of Smelting

Metals are extracted from metal ores by heating the ore minerals to their melting points. Flux (e.g. limestone, ironstone, ferrous silicate, silica) may be added to the charge of ore and fuel to lower the melting temperature and to decrease the viscosity of the slag. The fuel for the smelting may include coke, coal, firewood, and/or charcoal. Oxygen for the reactions is provided by a blast of compressed air, and temperatures within the interior of the furnace reach over 1000 °C. During the smelting process, the materials in the furnace react and a layered melt is produced. A lighter silicate melt accumulates above a heavier molten metal liquid, present at the bottom of the furnace. The silicate melt (i.e. slag) forms by the combination of the elements and compounds within the ores and fluxes. Once melting of the ore is achieved, the slag is drained off. The slag is dumped, commonly while still liquid, and solidifies and cools into a cohesive mass. Thus, historical smelting slag dumps are largely in the same form as they existed when smelting stopped.

Pyrometallurgy has its origin around 7000 to 6000 B.C. when early humans started to smelt sulfide and oxide ores. The earliest physical evidence for smelting is some slaggy material found in Turkey (Lambert 1997). The rise of early civilizations in Southwest Asia and the Mediterranean region came with the widespread use of and demand for metal tools and products. This in turn led to a steady increase of metal smelting, particularly of lead, which reached peak production during Roman times.

Slags of Lavrion, Greece

The Roman and Greek Empires had mining and smelting operations throughout the Mediterranean region, and ancient smelting slags are common features of these historic sites. The mines and smelters of Lavrion (Greece) are examples of such an historic site. The Lavrion ores have been a source of lead, silver and copper since 3000 B.C., with much of the mining performed by 10000 to 20000 slaves between 600 and 400 B.C. (Jaxel and Gelaude 1986; Wendel 1999). The mining activities not only resulted in over 2000 shafts and over 300 km of underground workings but also in the production of several million tonnes of slag. The slag was dumped next to the mine sites. As the ancient pyrometallurgical processes and metal recovery technologies were relatively inefficient compared to today's standards, the slag dumps are rich in metals and metalloids. Today, the Lavrion smelter slags are famous among mineral collectors for their rare and exotic secondary minerals which have formed during several thousand years of slag weathering.

Potential Recycling

Since the beginning of the industrial age, slag has been considered harmless. It is therefore widely used for sand blasting and to construct roadways and railway beds. However, historical base metal smelting slags are not suitable for such applications as they can contain high levels of potentially toxic elements. Natural weathering can release them into the environment causing contamination of soils, sediments and waters.

The metal concentrations of many historical base metal smelting slags are similar to or even higher than those of geological ore deposits currently being mined for metals. Consequently, the recovery of resource constituents from the slags has been considered. Much of the metals and metalloids are hosted by glass and microcrystalline silicates. This leaves hydrometallurgical processing using acids as the only treatment option.

manufacturing; mine waters can be converted into drinking water (Schwartz and Ploethner 2000; Smit 2000; Varnell et al. 2004); mine water can be used for heating or cooling purposes (Banks et al. 2004; Watzlaf and Ackman 2006); mine drainage sludges can be a resource for pigment (Kirby et al. 1999); and pyritic waste rock can be an excellent soil amendment to neutralize infertile alkaline agricultural soils (Castelo-Branco et al. 1999). If such innovative alternatives to current waste disposal practices are pursued and if wastes are used as raw materials, then waste disposal problems are

Fig. 1.4. Derelict copper-lead-gold-silver smelting works at Chillagoe, Australia. Smelting operations were conducted from 1901 to 1943 and produced 1 Mt of slag. The slag contains wt.% levels of zinc that is principally hosted by glass, olivine and hedenbergite

eliminated. Total resource utilization, where all of the material extracted is put to good use, is a challenging concept for researchers and miners.

1.5
Mining and Environmental Impacts

Major impacts of mining on land can occur before, during and after operation and may include: vegetation clearance; construction of access roads, infrastructure, survey lines, drill sites, and exploration tracks; creation of large voids, piles of wastes, and tailings dams; surface subsidence; excessive use of water; destruction or disturbance of natural habitats or sites of cultural significance; emission of heat, radioactivity, and noise; and the accidental or deliberate release of solid, liquid or gaseous contaminants into the surrounding ecosystems.

An understanding of the long-term release of contaminants requires a solid knowledge of the factors that control such discharge. The major factor that influences contaminant release is the geology of the mined resource (Scientific Issue 1.2). Climate and topography as well as the applied mining and mineral processing activities also play their role in the type and magnitude of contaminant release from a specific mine site or waste repository. The long-term off-site release of contaminants is particularly possible from mining, processing or metallurgical wastes or waste repositories. As a result, the operations of the mining industry have been criticized by the conservation lobby for some time (Scientific Issue 1.3).

Scientific Issue 1.2. Geology and Its Influence on the Environmental Impacts of Mineral Deposits

The Environmental Geology of Mineral Deposits

Mineral deposits are concentrations of metallic or other mineral commodities in the Earth's crust and result from various geological processes (Plumlee 1999). During these processes, the deposits acquire specific geological characteristics, including the amount and type of metals enriched in the deposits, the kind of minerals formed and their grain size, and the type of rocks associated with the deposit. Such fundamental geological aspects of mineral deposits exert important and predictable impacts on the environment (Plumlee 1999; Seal and Hammarstrom 2003). The geology of a deposit may influence, for example, the chemistry of local ground and surface waters and the properties of soils. Also, local soils, sediments and waters can be naturally burdened with trace elements. This is especially the case where weathering and erosion have exposed metallic mineral deposits and have led to the mobilization of trace elements into the environment. At such sites, soils, sediments and waters are naturally enriched in metals and metalloids.

The natural occurrence of elements varies between different ore deposit and rock types. Certain ores and rocks can provide exceptionally high metal and metalloid concentrations to soils, sediments and waters. Different rocks and ores supply different elements. For example, ultramafic igneous rocks and serpentinites and their associated ores can provide high iron, magnesium, chromium and nickel concentrations to overlying soils. Such bedrocks form nutrient-poor, metal-rich soils, and the vegetation has to adapt to such substrates. The flora is so distinct that it is referred to as "serpentine flora". Also, marine and lacustrine sediments including coals may possess high boron and selenium concentrations. Boron enrichment in topsoils overlying such bedrocks can be a widespread constraint to cereal and legume crop and pasture production. By contrast, the selenium abundance in soils and plants may induce acute toxicity in grazing animals.

Thus, rocks and ores with particular element enrichments cause environmental signatures in receiving streams, soils and sediments, and these enrichments may even bring about adverse effects on local and regional ecosystems. The environmental signatures and impacts of mineral deposits may occur naturally. Alternatively, they can be exacerbated or even caused by improper mining and mine waste disposal practices.

The Environmental Geology of Gold Deposits, New Zealand

New Zealand has a number of mineral deposits, including mesothermal and epithermal gold deposits. These deposits possess noticeably different geological characteristics which in turn lead to different impacts on the environment (Craw 2001).

Mesothermal gold deposits are vein-type gold deposits that formed by intermediate-temperature (200–300 °C) hydrothermal solutions in continental collision zones. On the South Island of New Zealand, the mineral deposits are located in cool semiarid or alpine settings and have calcite-bearing host rocks. The abundance of acid-buffering calcite and the lack of water interacting with sulfides control the environmental impacts of these deposits. The calcite buffers any acid generated from the oxidation of sulfides and, the lack of available meteoric water restricts acid generation. As a result, the oxidation of mesothermal gold ores does not result in significant acidification of streams. Yet, these deposit types contain elevated arsenic contents, and this metalloid is mobilized from the deposits at neutral to alkaline pH values (Craw and Pacheco 2002).

Epithermal gold deposits are found on the North Island of New Zealand and represent shallow gold deposits formed by low-temperature (50–200 °C) hydrothermal solutions. These mineral deposit types are characterized by a lack of carbonate and an abundance of pyrite. The deposits occur in a temperate to subtropical climate and hence, unconstrained sulfide oxidation favoured by higher temperatures and abundant meteoric water causes the development of low pH waters from mineralized materials. Consequently, oxidation of these deposits leads to the acidification of streams, and copper, cadmium, lead and zinc are mobilized into the environment (Craw 2001).

Thus, the geology of mineral deposits as well as climate and topography together with mining and mineral processing practices control the release of contaminants from mine sites and mine wastes (Plumlee 1999; Craw 2001). A solid understanding of the environmental geology of mineral deposits is vital to any mining operation, environmental impact assessment or rehabilitation plan. Such knowledge allows the development of effective prediction, prevention and remediation tools necessary for the successful environmental management of these sites.

Scientific Issue 1.3. The Debate on Mining and Its Environmental Impacts

In recent decades the conservation lobby has criticized the operations and actions of the mining industry. Some of the issues raised by conservation groups also relate to the production and environmental impacts of mine wastes. These issues and the likely responses of both parties are presented below.

Issue 1 – Land Disturbance

Critics of the Mining Industry
The mining industry "rapes virgin territory" and leaves permanent scars and massive "footprints" in landscapes. For example, there are more than 32 000 abandoned or inactive underground mines in the western United States alone, and the total area of land having been mined in India is equivalent to one-third of that under agricultural production (Hossner and Hons 1992). The area of land disturbed by mining globally is estimated to increase by approximately 1 million hectares per year (Hossner and Hons 1992).

The Mining Industry
Mining of an area should be regarded as a stage in the sequential use of land. Once mining ceases, the mined and rehabilitated land should be used for industrial, agricultural or recreational activities. Also, mines are local phenomena and account for only a small part of a land area of a country. For example, the mining industry accounts for less than 1% of the total area of South Africa or the United States. In Australia, mining activities occupy only about 0.06% of the land mass. This is less than one big city and less than land used by the defense forces (0.24%), and it is a tiny fraction compared to the vast tracts used for and degraded by agriculture (6%).

Issue 2 – Waste Production

Critics of the Mining Industry
Waste production by the mining industry is enormous. For example, the extent of derelict land covered by waste is estimated to be 100 000 ha in the United Kingdom, 200 000 ha in Malaysia and several million hectares in the United States (Hossner and Hons 1992). The global area covered with mine waste is probably in the order of 100 million hectares containing several hundred thousand million tonnes of mine wastes. Every year another 15 000 to 20 000 Mt of solid mine waste are added to the piles.

The Mining Industry
Mine waste production and waste repositories are a necessary and inevitable adjunct to a mine as are garbage bins and sewage pipes to a dwelling. The modern mining industry plays a leading role in waste management. For example, it is one of the few industries recycling some of its own waste (e.g. the use of slag in cement, the extraction of metals from historical mine wastes) and that of others (e.g. lead batteries, scrap iron). Much of the modern mining industry applies current knowledge and state-of-the-art technology to limit waste production, to recyle wastes, and to reduce the risks of contamination arising from mine wastes.

Issue 3 – Recycling Rather Than Mining

Critics of the Mining Industry
Mining is an unnecessary industrial activity. Recycling is the answer to the ever increasing demand for natural resources.

The Mining Industry
Today's standard of living relies on the supply of natural resources. There will always be a need for mining in addition to recycling and substitution. Moreover, certain mined rocks and minerals are essential and important "environmental minerals" as they are needed to alleviate environmental problems. For example, clays are used as liners and sealants for industrial waste sites, and calcium carbonate minerals in the form of limestone are applied for the remediation of acid waters and acid sulfate soils.

Scientific Issue 1.3. ***Continued***

Issue 4 – Pollution

Critics of the Mining Industry
The mining industry is intrinsically "dirty and polluting".

The Mining Industry
The great majority of mine site pollution problems are legacies from the past. Environmental disasters caused by mining are found in developing nations and former or current communist states where economic growth and mining have been or still are enforced at the expense of the environment. In industrialized countries, the mining industry is one of the most environmentally regulated industries.

Issue 5 – Heavy Metal Release

Critics of the Mining Industry
The mining industry releases toxic heavy metals to the environment that negatively affect people's health and impact on ecosystems.

The Mining Industry
Heavy metals have become the "geochemical bogey men" (Hodson 2004). They are synonymous with pollution and toxicity, responsible for all manner of evils in the environmental world. This is nothing but a myth today. Metals are not only vital for our well-being, perform essential functions in our own bodies and are ubiquitous in our environment, but natural concentrations of metals can exceed their man-made levels (Fig. 1.5). Such natural metal contamination can create some problems, especially in communities attuned to the view that natural must be healthy.

Issue 6 – Environmental Damage

Critics of the Mining Industry
The mining industry is the major "environmental vandal" on our planet.

The Mining Industry
Mining's contribution to environmental damage pales by comparison to other human activities. Critics of the mining industry commonly ignore those human activities which cause damage on a continental scale. For example, cities and towns cover significant parts of continents and urban dwellers, including the conservation lobbyists, continue to impact on the environment. They themselves cause the consumption of natural resources, suburban sprawl and associated air, soil and water pollution, climate change, habitat destruction, species extinction, concreting of land, and production of household wastes. Such urban activities not only damage the environment but alter and seal natural landscapes for good whereas mine sites are rehabilitated for other land uses once mining ceases. Is it more acceptable to concrete nature, to flush sewage into rivers and oceans, to dump vast amounts of domestic waste, to create smog, or to cause global and micro climate change? Also, farming and pastoral activities have significantly degraded land masses and have impacted on soils and the aquatic environment. Poor agricultural practices cause salinization, acidification and erosion of soils as well as pesticide and nutrient transfer (N, P) into inland and coastal waters. Such activities even impact on World Heritage Areas and have received surprisingly little attention by the conservation lobby.

1.5.1
Contamination and Pollution

Much of the environmental impacts of mining are associated with the release of harmful elements from mine wastes. Mine wastes pose a problem not just because of their

Fig. 1.5. Noble Island, Australia. Much of the island is naturally enriched in metals and metalloids (i.e. tungsten-tin-arsenic-copper ores). Weathering and erosion lead to the physical and chemical transport of metals and metalloids into the surrounding Great Barrier Reef

sheer volume and aerial extent, but because some of them may impact on local ecosystems. As a result, in many cases mine wastes must be isolated or treated to reduce oxidation, toxicity, erosion or unsightliness and to allow the waste repositories to be used for other purposes after mining ceases. If uncontrolled disposal of mine wastes occurs, it can be associated with increased turbidity in receiving waters or with the release of significant quantities of potentially harmful elements, acidity or radioactivity. These contaminants may spread to the pedosphere, biosphere, atmosphere, and hydrosphere and cause environmental effects. For example, anthropogenic inputs of metals and metalloids to atmospheric, terrestrial and aquatic ecosystems as a result of mining have been estimated to be at several million kilograms per year (Nriagu and Pacyna 1988; Smith and Huyck 1999).

However, it is important to understand that releases of elements or compounds from mine wastes do not necessarily result in damage to the environment. Even if strongly elevated metal and metalloid concentrations are present in mine wastes, the elements may not be readily bioavailable (i.e. available for uptake into the organism) (Williams et al. 1999). Furthermore, even if the elements are bioavailable, they are not necessarily taken up by plants and animals. In cases where the elements are taken up, they do not necessarily lead to toxicity. Many metals are essential for cellular functions and are required by organisms at low concentrations (Smith and Huyck 1999). It is only when these bioavailable concentrations are excessively high that they have a negative impact on the health of the organism and toxicity might be seen. Processes that cause toxicity, disrupt ecological processes, inflict damage to infrastructure, or pose a hazard to human health are referred to as pollution (Thornton et al. 1995). In contrast, contamination refers to processes which do not cause harmful effects (Thornton et al. 1995).

Environmental contamination and pollution as a result of improper mining, smelting and waste disposal practices have occurred and still occur around the world. Problems encountered are as diverse as the emissions from smelters, or the environmental clean-up of collapsed mining ventures which have to be paid for by the taxpayer. This is unacceptable to those of us who believe that technologies can be used to prevent pollution and regulations should be enforced to ensure that the environmental performance of companies is adequate. Regardless of this debate, the challenges for the modern mining industry will remain the same:

- To continue to improve its environmental operations
- To operate in a sustainable manner
- To prove its critics wrong

1.5.2
Historic Mining

Mining has been with us for thousands of years. Even the earliest mining operations during the Copper, Bronze and Iron Ages resulted in the production of gaseous, liquid and solid wastes. In historic times, mine wastes were released into the environment with some of them causing contamination or even pollution on a local or regional scale. Environmental contamination as a result of mining is not new to the industrialized world.

Air contamination as a result of smelting has been detected as far back as 5 000 years ago. Stratigraphic and physicochemical investigations of numerous European peat bogs have confirmed that smelting of sulfide minerals led to metal contamination of the environment (Shotyk et al. 1996; Ernst 1998). For example, the smelting of lead-rich silver ore in Spain by the Romans 2 000 years ago quadrupled the levels of lead in the atmosphere as far away as Greenland (Rosman et al. 1997). Generally, the smelting of sulfide ore in open air furnaces by the Greeks and Romans resulted in a vast area of the Northern Hemisphere being showered with metal-rich dust (Hong et al. 1996; Shotyk et al. 1996; Rosman et al. 1997). Human contamination of the atmosphere with arsenic, antimony, copper, mercury, lead and zinc, at least in the Northern Hemisphere, began well before the Industrial Revolution.

Water and sediment contamination and pollution are similarly not a by-product of industrialization. For example, soil erosion began with clearing of land and primitive agricultural practices 5 000 years ago (Lottermoser et al. 1997a), and metal mining in the northern Harz province of Germany resulted in metal pollution of regional stream sediments as far back as 3 500 years ago (Monna et al. 2000). Similarly, exploitation of the Rio Tinto ores in Spain has caused massive metal contamination of stream and estuary sediments since the Copper Age 5 000 years ago (Leblanc et al. 2000; Davis et al. 2000).

Acid mine drainage resulting from the oxidation of sulfides in mine wastes is a major environmental issue facing the mining industry today. This pollution process has a long history dating back thousands of years when the Rio Tinto mining district of Spain experienced periods of intense mining and the associated production of pyrite-rich wastes and AMD waters. AMD production must have been occurring at least since the first exploitation of the Rio Tinto ores 5 000 years ago, which highlights the long-term nature of AMD.

The knowledge that mining and smelting may lead to environmental impacts is not new to modern science either. The Greek philosopher Theophrastus (ca. 325 B.C.) recognized the oxidation of pyrite, the formation of metal salts and the production of acid. During the Middle Ages, AMD in central Europe was documented by Agricola who wrote the first systematic book on mining and metallurgy. In this 16th century classic, Agricola (1556) also recognized the environmental effects of ubiquitous mining in central Europe and described mining pollution:

> "The fields are devastated by mining operations … Further, when the ores are washed, the water which has been used poisons the brooks and streams, and either destroys the fish or drives them away. Therefore the inhabitants of these regions, on account of the devastation of their fields, woods, groves, brooks and rivers, find great difficulty in procuring the necessaries of life, and by reason of the destruction of the timber they are forced to greater expense in erecting buildings. Thus it is said, it is clear to all that there is greater detriment from mining than the value of the metals which the mining produces." (Reprinted from Agricola 1556, De re metallica, p. 8. Translated by Hoover HC, Hoover LH, 1950, Dover Publications, New York, with permission of the publisher)

As the scale of mining increased during the Middle Ages, so did the degree of contamination and pollution (Ernst 1998). Coupled with this increase in scale came changes in smelting and processing techniques, including the use of chemicals and the transport of ores and concentrates over greater distances. However, it was not until the Industrial Revolution, with the event of major technological changes including the introduction of blast furnaces, that base metal smelter operations throughout the world became one of the primary sources of metal contamination (Ernst 1998). When this large-scale smelting technique was developed, contamination became even larger in scale. The smelting process released massive amounts of sulfur dioxide and metals into the atmosphere (Fig. 1.6). These activities resulted in ever-increasing environmental impacts which largely went unchecked until the second half of the 19th century (Case Study 1.1). Until then environmental impacts of mining and mineral processing were poorly understood, not regulated, or viewed as secondary in importance to resource extraction and profit maximization. The advent of environmental laws and regulations in the 20th century made the mining industry more accountable and enforced environmental protection (Fig. 1.7).

The concern for the health of miners has evolved in parallel with mining development, particularly in respect to the exposure of humans to mercury and arsenic. Mercury deposits in the Mediterranean were first worked by the Phoenicians, Carthaginians, Etruscans and Romans, who used the ore as a red pigment for paint and cosmetics. To protect local workers and the environment, the Italian mines were closed by the Romans (Ferrara 1999). The mercury was then mined by slaves in occupied Spain.

Mercury has also been used for nearly 3 000 years to concentrate and extract gold and silver from geological ores (Lacerda and Salomons 1997). The use of mercury in gold mining is associated with significant releases of mercury into the environment and with an uptake of mercury by humans during the mining and roasting processes (Lacerda and Salomons 1997). Around 2 100 years ago, Roman authorities were import-

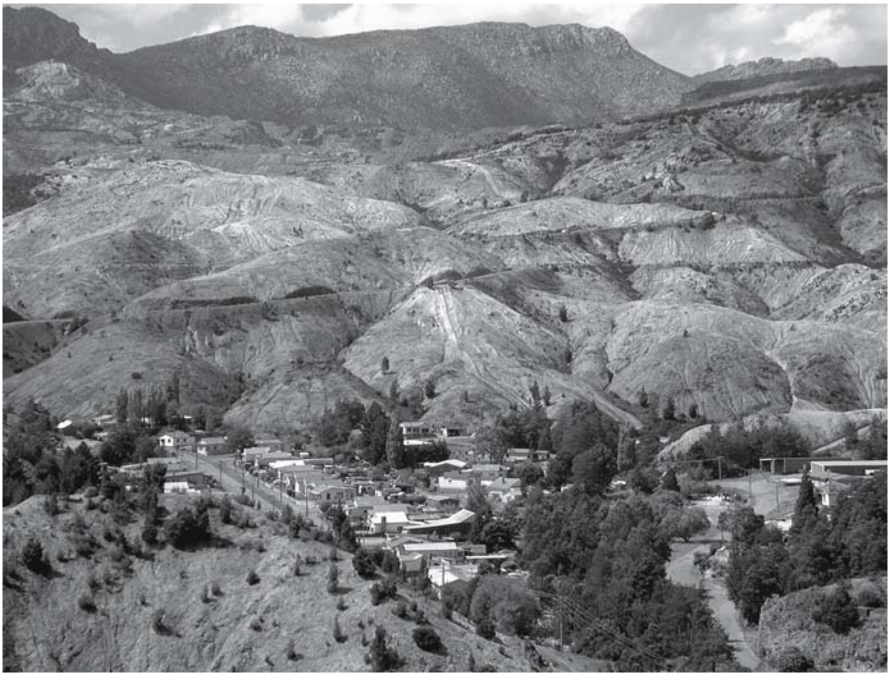

Fig. 1.6. Denuded, bare hills at Queenstown, Australia. During the late 19th and early 20th centuries, smelting operations were conducted at the Mt. Lyell copper-gold mine. The smelting operations combined with timber cutting, frequent bushfires and high annual rainfall resulted in extensive loss of vegetation and considerable soil erosion on the surrounding hills

ing mercury from Spain to be used in gold mining in Italy. Curiously, after less than 100 years, the use of mercury in gold mining was forbidden in mainland Italy and continued in the occupied territories. It is quite possible that this prohibition was already a response to environmental health problems caused by the mercury process (Lacerda and Salomons 1997).

The above mentioned practice to enforce mining operations in occupied territories with no environmental management and no regard for the health of local miners has continued into modern times. For example, the former Soviet Union conducted mining in occupied East Germany from 1946 to 1990. Environmental management of mining and proper waste disposal did not occur, local uranium miners were exposed to deadly radiation levels, and poor regard for the environment left an environmental disaster on a massive scale (Case Study 6.1).

1.5.3
Present-Day Unregulated Mining

Today, mines wastes are produced around the world in nearly all countries. In many developing countries, the exploitation of mineral resources is of considerable importance for economic growth, employment and infrastructure development. In these

Fig. 1.7. Abandoned tin dredge in the dry stream bed of Nettle Creek, Innot Hot Springs, Australia. The bucket dredge was used in the 20th century to extract alluvial cassiterite. During mining, the dredge caused a massive increase in suspended sediment loads and the deterioration of stream water quality. Consequently, the Mining Act Amendment Act 1948 was introduced which is one of the first pieces of Australian legislation specifically concerned with environmental protection. The act required operators to construct settling ponds for turbid mine waters

developing nations and in former communist states the environmental management of municipal, industrial and mine wastes is often unregulated, lax, not enforced or overruled for economic reasons. Strict environmental management of wastes and regulation of mining still remains a luxury of wealthy industrialized nations.

Many of the world's poorest countries and communities are effected by artisan mining and the associated uncontrolled release of mine wastes. Operations are referred to as artisan when the applied mining techniques are primitive and do not employ modern technology. Such small-scale mining has been estimated to account for 15 to 20% of the world's non-fuel mineral production (Kafwembe and Veasey 2001). Artisan mining is highly labour intensive and employs 11.5 to 13 million people worldwide, and up to 100 million people are estimated to depend on small-scale mining for their livelihood (Kafwembe and Veasey 2001). The largely unregulated mining practices and associated uncontrolled release of mine wastes cause environmental harm. One example is the use of mercury in gold mining.

Gold mining and extraction have been with us for over 3 000 years. In the past much of the gold has been exploited either by physically concentrating the gold particles and/or by applying mercury. From the late 19th century onwards, mercury was no longer used since cyanide leaching was invented which allowed large-scale gold mining operations. In the 1970s, the mercury process was reintroduced in developing countries like Brazil, Bolivia, Venezuela, Peru, Ecuador, Colombia, French Guyana, Indone-

Case Study 1.1. Historic Mining in Australia and Its Environmental Impacts

Introduction

Australia has been a major mining nation for more than 150 years. While coal was the first commodity discovered in the late 18th century, the copper finds in South Australia in the early 1840s developed mining in a significant way. This was closely followed by major gold rushes in New South Wales and Victoria in the early 1850s. The development of these resources was associated with the uncontrolled release of gaseous, liquid and solid mine wastes into the environment (Blainey 1991):

"*The old gold mining industry usually paid little attention to the environment. Victorians in the 1880s could tell when a new digging had opened up forty miles upstream: the river water downstream quickly changed colour with the clays and gravels that had been overturned upstream … Stawell, which, in the late 1870s, was the deepest goldfield in Australia, announced its presence to the approaching travellers by the taste of sulfur from the kilns where the gold bearing pyrite was roasted. People did not see Stawell as they approached: they tasted it.*" (Reprinted from Blainey G (1991) Eye on Australia, p. 186, Schwartz & Wilkinson, with permission of the author).

Environmental Impacts of Historic Mines

In Australia, there are notable examples of large-scale environmental degradation caused by mining and associated smelting operations carried out during the mid to late 19th and early 20th centuries when there were few or no legislative constraints placed on operators. These operations ranged from river dredging tin operations in Queensland to hard rock copper mines in Tasmania. Some of these mining activities still impact on the environment today, even years after the mines closed.

- *Gold mining.* During the 19th century, placer gold was mined and extracted using mercury. It is estimated that several thousand tonnes of mercury were used on Australian goldfields, most of which was lost into the environment during gold recovery. The widespread use of mercury has left a legacy of mercury contamination in the former goldfields, particularly in streams (Bycroft et al. 1982). Today, some of the mercury is entering the foodchain of local streams. In addition, large areas of mined forest and bush land are still without topsoil and display sparse vegetation and stunted regrowth.
- *Base metal mining.* Abandoned copper, lead, zinc and tin mine sites of the late 19th and early 20th centuries are characterized by severely modified (or lack of) vegetation, waste rock heaps, ore stockpiles, tailings dumps, slag and flue residue deposits, disused mining and processing equipment, ruins, and commonly, acid mine drainage. The latter is a consequence of mining activities involving sulfide minerals, especially pyrite. The oxidation of pyrite causes formation of sulfuric acid and the dissolution of many metals (Chapman et al. 1983; Jacobson and Sparksman 1988; Koehnken 1997; Lottermoser et al. 1997b, 1999; Ashley and Lottermoser 1999a,b).
- *Alluvial tin mining.* Alluvial cassiterite was extracted from shallow surface deposits in eastern Australia from the 1870s to the early 1980s. In Tasmania, pyritic overburden sediment had to be removed and this material was dumped next to the mine sites. The pyritic waste heaps generate acid, metal-rich waters which contaminate ground and surface waters and impact on local ecosystems (Jong et al. 2000).
- *Asbestos mining and processing.* Asbestos was mined in Australia from the early 1900s until the 1980s. Asbestos pollution problems are related to dry processing methods and the absence of proper waste management in the pre-1980s. Asbestos fibres in run-off waters and leaching of metals from the waste materials possibly impact on local water quality (Toyer 1981). In addition, uncovered tailings, waste rock dumps and ore stockpiles can be sources of airborne asbestos.

sia, Ghana, and the Philippines. Here, individual artisanal miners use mercury because its application is cheap, reliable and simple (Salomons 1995; Lacerda and Salomons

Case Study 1.1. ***Continued***

- *Smelting*. Many historic base metal smelters were constructed in the immediate vicinity of the mines (Ashley and Lottermoser 1999b; Lottermoser 2002). The smelter operations produced metallurgical waste, smelting slags and flue residues, which were dumped close to the smelting works. The large scale smelting techniques caused impacts on human and animal health as well as lead poisoning during smelting operations. The metal particles and sulfur oxides were released during the smelting processes, settled in the surrounding environment, and contaminated and acidified local soils. Today, these polluted areas are clearly visible as they are devoid of vegetation or support only a depauperate flora. Metal poisoning may occur in farm animals eating the contaminated pasture and soil.
- *Riverine discharge of wastes.* Many historic mining operations discharged their mine and process wastes into nearby water courses. These waste management practices of the past continue to cause water and sediment contamination today. The discharge of some mines has led to metal and metalloid contamination of stream, estuary and coastal sediments and can be traced over a distance of hundreds of kilometers.

Early Rehabilitation at Historic Mines

While there are numerous examples of environmental degradation caused by historic mining and smelting activities, there are also early examples of mine site rehabilitation works. For example, Broken Hill is not only famous for its ore and mining history but also for its successful revegetation scheme in the 1930s. The Broken Hill area was cleared of vegetation when base metal mining, settlement and over-grazing began in the late 19th century. Within a few years the area surrounding Broken Hill was bare, entirely denuded of its natural, yet sparse vegetation cover. As a result, the town was plagued by dust storms causing damage to mining equipment and private property. In 1936, a mining company, Zinc Corporation Ltd, initiated a massive revegetation program of the disturbed areas. Belts of European and native vegetation – irrigated with waste water from showers and septic tanks – were established surrounding the city. The revegetation of waste and tailings dumps was similarly pursued to provide surface cover and to reduce wind erosion. This pioneering work not only reduced the frequency and intensity of dust storms and provided local ecosystems for animals and plants, but it also demonstrated that vegetation can be reestablished on mined and degraded lands.

Conclusions

In Australia, historic mining of the late 19th and early 20th centuries occurred while there were no environmental acts, laws and regulations for operators. This has left a legacy of contaminated sites dispersed throughout the continent. Some of these sites have undergone costly environmental clean-up operations, others still await remediation, while a few perhaps should be monitored in perpetuity rather than rehabilitated at extraordinary costs to the taxpayer. While historic mining has produced contaminated sites, soils, sediments and waters and associated impacts on ecosystems today, environmental degradation as a result of mining has also been recognized and addressed by some early miners. These historic rehabilitation efforts largely focused on the revegetation of mined and disturbed land.

1997). However, the unregulated mining practices have caused mercury contamination of rivers such as the Amazon on a massive scale (Case Study 1.2).

1.5.4
Regulation of Modern Mining

The present-day worldwide utilization of mercury by individual miners is a good example of how unregulated mining by non-professionals causes harm to humans and the environment. In contrast, many modern mines particularly in industrialized nations are designed to have minimum environmental impacts outside an area set aside for the mine operation and waste disposal. However, waste discharges into the environment have been allowed to occur and still occur under communist regimes (Fig. 1.8), in developing countries (Fig. 1.9), and also in industrialized nations (Fig. 1.10), and thus even in countries where the mining industry is regulated.

In many countries, mining companies are required to conduct environmental impact assessments prior to the development of proposed mining and mineral processing operations. In preparing such an assessment, operators identify the actions they intend to implement to limit environmental impacts. Acceptance of the proposed actions are subject to the approval of governmental regulatory agencies. These agencies monitor the activities when the facilities are in operation. Nowadays, the environmental aspects of mining are paramount in determining the viability of a modern mining operation, certainly in developed countries (Maxwell and Govindarajalu 1999). Mining companies have to operate under environmental laws and regulations and are required to place multi million dollar bonds to cover all the costs of rehabilitation according to the designated future land use.

Environmental impact assessments and environmental protection are essential parts of a modern mining operation. These aspects become increasingly important

Fig. 1.8. Abandoned slag and waste heaps of copper ores, Eisleben, Germany. Mining in the area occurred for over 800 years, resulting in over 2 000 individual waste heaps, 1 000 km of underground workings and 56 million cubic metere of mine voids. Under the East German communist regime, the extraction of metals from very low grade, uneconomic copper ores was pursued, and large volumes of fly ashes, tailings, and smelting slags were generated. The unconstrained release of wastes into the local environment, especially of atmospheric emissions from smelting works, has caused widespread contamination of streams and lakes with metals and metalloids

Case Study 1.2. Mercury Pollution and Gold Mining in the Brazilian Amazon

Agglutination and Amalgamation

For over 2000 years, mercury has been used to recover gold from alluvial gold ores. Mercury has a strong chemical affiliation with gold, and this chemical relationship is used in the so-called "agglutination" and "amalgamation" processes. The agglutination process is based on the presence of mercury in wooden boxes, so-called "riffles". Gold-bearing sediment is dredged from river beds or taken from river banks. This sediment is channelled down the riffle which has an inclined, cloth- or carpet-lined bottom. The cloth or carpet is impregnated with elemental mercury to make the fine gold particles clump together in the cloth. The sediment-mercury mixture from the riffles is then collected in barrels and treated with mercury. The barrels are stirred, often by hand, to achieve maximum gold amalgamation. In the amalgamation technique mercury dissolves the solid gold in a physical solution called an amalgam. The gold is then recovered by heating the amalgam solution which causes the mercury to evaporate.

Mercury Release to the Amazon Environment

The widespread application of these ancient extraction techniques has resulted in mercury contamination of many streams around the world. Such contamination has been caused by historic gold mining operations in the United States (Leigh 1997; Miller et al. 1998; Mastrine et al. 1999; Ambers and Hygelund 2001; Domagalski 1998, 2001; Thomas et al. 2002; Gray et al. 2002a), Russia (Laperdina 2002), South America (Ogura et al. 2003; Higueras et al. 2004), Asia (Williams et al. 1999), Europe (Covelli et al. 2001), and Australia (Bycroft et al. 1982). Today, artisanal miners use the agglutination and amalgamation techniques to mine and extract alluvial gold ores (James 1994; Kambey et al. 2001; Lacerda 2003; Limbong et al. 2003; Getaneh and Alemayehu 2006).

Since the early 1980s, the Amazon has become the stage of a major gold rush. Several hundred thousand men have been digging for gold in the Brazilian Amazon rainforest. Thousands of tonnes of alluvial gold have been mined from river banks and beds of the Amazon, often dug out by hand without the help of machinery (Cleary and Thornton 1994; Lacerda and Salomons 1997; Lacerda 2003). At all mine sites, mercury has been used to extract gold from the sediment using the agglutination and amalgamation processes.

The use of mercury in gold mining is associated with large losses of mercury waste to the environment. The agglutination process is prone to mercury loss, and much of the mercury used in the agglutination process ends up in the rivers. The elemental mercury after reaching the rivers is transformed partly to the highly toxic methyl-mercury form. A major proportion of the mercury is also lost to the atmosphere through burning of the gold-mercury amalgam or through degassing of metallic mercury from tailings, soils, sediments, and rivers (Pfeiffer et al. 1993; Lacerda and Marins 1997). Nearly 3000 t of mercury have been released into the Amazon environment in the last 15 years. The annual emission of mercury to the atmosphere in the Brazilian Amazon has been estimated to be greater than the total annual emission of mercury from industry in the United Kingdom.

Uncontrolled gold mining in the Amazon not only results in mercury contamination of air, soils, sediments, rivers, fish and plants but also in the destruction of rainforests, increased erosion of riverbanks, and the exposure of miners, gold dealers, fishermen and residents to toxic mercury concentrations. The miners show symptoms of mercury poisoning also known as Mad Hatter's or Minamatta Disease. They burn off the gold-mercury amalgam in an open pan or closed retort to distill the mercury and to concentrate the gold. Roasting of the amalgam commonly takes place in a hut and on the same fire used to cook food. Miners – eager to see how much gold will remain once the mercury is burned off – will stand directly over the amalgam as it is burned. The gold miners end up inhaling the mercury vapor and as a result, many have been poisoned.

as waste production in the mining industry is significant in volume and diverse in composition when compared to other industries. However, the demands on the mining industry are the same as they are for all industries producing waste:

- To reduce and to recycle waste;
- To ensure that there are no or minimal impacts from wastes on the environment and humans;
- To understand the composition, properties, behaviour and impacts of wastes.

1.6
Rehabilitation of Mine Wastes and Mine Sites

Mining creates wastes and disturbs proportions of land and areas of existing vegetation and fauna. Mining activities may also cause distinct changes in topography, hydrology and stability of a landscape. Once mining ceases, the mined land and its waste repositories need to be rehabilitated. Rehabilitation of mine sites is an integral part of mine planning, development and final closure. This process does not start with mine closure. In industrialized nations, the operator of a mine is required to undertake monitoring as well as progressive rehabilitation of areas of the mine site wherever possible. The latter generally involves revegetation and contouring but operational constraints allow in most cases little ongoing rehabilitation work.

There are several issues which must be addressed in the successful rehabilitation of a mine site. Some rehabilitation issues are common to almost all mines regardless of the type of resource extracted or whether they have used open pit or underground mining methods. These general aspects of mine site rehabilitation include:

Fig. 1.9. The Ertsberg open pit, Irian Jaya, Indonesia. The Grasberg-Ertsberg mine – located at about 4 000 m among the jagged alpine peaks of the Jayawijaya mountain range – is one of the world's largest mining operations. Approximately 0.24 Mt of copper ore are mined every day, and 0.2 Mt of tailings are dumped into the Ajkwa River system every day, causing increased sedimentation on the coastal floodplains

- *Removal of mine facilities.* All mine facilities such as crushers and processing plants need to be dismantled and removed.
- *Sealing and securing of mine workings.* Underground workings such as shafts and adits are sealed at the surface, and open pits may need to be fenced.
- *Ensuring long-term stability of waste repositories.* Waste rocks and tailings must be contained within repositories which have to remain stable in the long-term and prevent migration of contaminants into the environment. The safe long-term isolation of problematic mine wastes represents one of the most challenging tasks facing the mining industry.
- *Modeling future water quality and quantity in pit lakes.* Many surface mining operations create voids which may fill with water once mining ceases. Such open pits need to be modelled for future water quality and quantity.
- *Modeling future water quality in underground workings and aquifers.* Similar to open pits, the closure of an underground mine leads to mine flooding. Deep saline ground waters may rise to shallow levels or contaminants may be leached from the workings into shallow aquifers. Therefore, an assessment of the potential contamination of shallow ground waters is needed.
- *Construction of suitable landforms.* Artifical land forms which will remain after mine closure such as waste rock dumps must be shaped to reduce wind and water erosion. Also, the topography of the mine site and waste repositories needs to be sculptured to create adequate drainage and to resemble the surrounding landform.

Fig. 1.10. The copper and lead smelter stacks at Mt. Isa, Australia. Until recently, the sulfurous plume was dispersed over the town and across 100 000 km^2 northwest of Mt. Isa. Over the years, the emissions resulted in the acidification of local soils and killed or reduced vegetation in the vicinity of the smelters. The recent installation of a sulfuric acid plant has reduced sulfur emissions

- *Development of a suitable plant growth medium.* A suitable plant growth medium needs to be developed for the covering of waste repositories and for the revegetation of mined/disturbed areas. This can be achieved through the selective handling of soil and waste. Many mine wastes are structureless, prone to crusting, and low in organic matter and essential plant nutrients (P, N, K), have low water-holding capacity, and contain contaminants such as salts, metals, metalloids, acid, and radionuclides. If the waste is left uncovered, few mine wastes can become colonized by plants.
- *Establishment of a vegetation cover.* Suitable vegetation and soil amendments must be chosen for the local conditions. Planting stock needs to be propagated in a nursery on the mine site, and local species have to be chosen for the vegetation cover.
- *Addressing generic mine waste issues.* Every mine produces its very own unique waste, and this waste requires its very own characterization, prediction, monitoring, treatment, and secure disposal. For example, sulfidic waste rock dumps require covers to prevent sulfide oxidation, and acid mine waters or cyanide-bearing waters need treatment. Hence, mine waste issues are generic to individual mine sites depending on the waste characteristics, the local mining methods, and the hydrology, geology, meteorology and topography of the area. These generic waste issues are presented in the following chapters.

The construction of post-mining landforms including the shaping of waste repositories, the development of suitable plant growth media, and the establishment of vegetation on waste repositories are all integral parts of mine waste disposal. These topics also represent the final aspects of mine waste management. Such detailed soil science and botanical aspects of mine wastes and mine sites are beyond the scope of this book. In addition, these aspects have already been addressed to some degree by the specialized soil science, plant nutrition and botany literature, and interested readers are directed to these works (e.g. Loch and Jasper 2000).

Rehabilitation of mined land does not imply that the mine site and its waste repositories are to be converted to a pristine wilderness, which may or may not have existed prior to mining. Mine site rehabilitation returns mined land to future land use. The future land use of a waste repository and the entire mine site is highly site specific. In sparsely populated areas, mine waste repositories and mine sites may be rehabilitated to a standard which may allow only limited grazing. In densely populated areas, rehabilitated mine waste dumps have become centres of social amenity such as parklands, football fields, golf courses, and even artificial ski slopes. Open pits may be used as: water storage facilities; wetland/wildlife habitats; aquaculture ponds for fish and crustaceans; recreational lakes; heritage sites; engineered solar ponds to capture heat for electricity generation, heating, or desalinisation and distillation of water; or as repositories for mining, industrial or domestic waste. Underground mines are used as storage facilities, archives, and concert halls, and in Europe some radon emitting mines become part of health spas.

Whatever the future land use of a former mine site or a waste repository may be, mining has to be regarded as a stage in the sequential use of land. Therefore, rehabilitation of a mine should aim to return mined land in such a manner that it is consistent with intended future land use. The goals for mine site rehabilitation are based on the anticipated post-mining use of the area, and this process includes the rehabilitation of mine waste repositories. However, some historic mines, particularly those with AMD, can only be monitored and managed in order to restrict contamination to the mined area. In these cases, collection and treatment of AMD waters represents the only viable and cheapest option. Finally, mine site rehabilitation efforts should not be evaluated and awarded too quickly. In many cases the success of mine site rehabilitation can only be judged well after mining has ceased.

1.7
Sources of Information

There are considerable and excellent resources available for the study of mine wastes and other related topics such as surface reclamation of wastes (i.e. revegetation, landform design), environmental impacts of mine wastes, and mine site rehabilitation. Several organizations are instrumental in supplying a number of publications including journals, reports, conference proceedings, workshop abstracts, databases, and textbooks. These publications and other important resources including web sites are listed in Tables 1.4 and 1.5.

1.8
Summary

All human activities produce wastes and mining is no exception. Mine wastes are liquid, solid and gaseous by-products of mining, mineral processing, and metallurgical extraction. They are unwanted and have no current economic value. While some mine wastes are benign and pose no environmental threat, and others can be used for the rehabilitation of mine sites, many mine wastes are problematic wastes as they contain contaminants which may impact on ecosystems.

Mineral resources contain valuable components which vary in mass from 100% to a few parts per million of the original geological resource. For example, in the metal mining industry only a small valuable component is extracted from the originally mined ore during processing and metallurgical extraction. The great majority of the total mined material is gangue which is rejected as mining, processing and metallurgical waste.

Mine wastes present the highest proportion of solid waste produced by industrial activity, with approximately 15 000 to 20 000 Mt being produced annually. The mining industry is the most significant industrial producer of solid, liquid and gaseous wastes. Every mine thereby produces its own unique waste because there are compositional differences in the mined ore and there is a great diversity of applied mining and mineral processing methods.

Changing circumstances may turn a particular waste into a valuable commodity, either because the economic extraction of resource ingredients may now be possible using improved technology, or a market has been found for the previously unwanted material. Yesterday's waste can become today's resource. What may be mine waste to some, can be a very important, useful resource to others, either now or in the future.

Table 1.4. Resource materials covering aspects of mine wastes

Textbooks and reports
Alpers CN, Blowes DW (1994) Environmental geochemistry of sulfide oxidation. American Chemical Society, Washington (Symposium Series 550)
Azcue JM (1998) Environmental impacts of mining activities: Emphasis on mitigation and remedial measures. Springer, Berlin Heidelberg New York
Brown M, Barley B, Wood H (2002) Minewater treatment: Technology, application and policy. International Water Association Publishing
Environment Australia (1995–2002) Best practice in environmental management in mining booklets. Environment Australia, Canberra
Evangelou VP (1995) Pyrite oxidation and its control. CRC Press, Boca Raton
Filipek FH, Plumlee GS (1999) The environmental geochemistry of mineral deposits. Part B: Case studies and research topics. Society of Economic Geologists, Littleton (Reviews in economic geology, vol 6b)
Geller W, Klapper H, Salomons W (1998) Acidic mining lakes: Acid mine drainage, limnology and reclamation. Springer, Berlin Heidelberg New York
Hutchison I, Ellison R (1992) Mine waste management. Lewis Publishers, Boca Raton
Jambor JL, Blowes DW (1994) The environmental geochemistry of sulfide mine-wastes. Mineralogical Association of Canada, Nepean (Short course handbook, vol 22)
Jambor JL, Blowes DW, Ritchie AIM (2003) Environmental aspects of mine wastes. Mineralogical Association of Canada, Nepean (Short course handbook, vol 31)
Lacerda de LD, Salomons W (1997) Mercury from gold and silver mining: a chemical time bomb? Springer, Berlin Heidelberg New York
Marcus JJ (1997) Mining environmental handbook: Effects of mining on the environment and American environmental controls on mining. Imperial College Press, London
Morin KA, Hutt NM (1997) Environmental geochemistry of minesite drainage. MDAG Publishing, Vancouver
Mudder T, Botz M, Smith ACS (2001) Chemistry and treatment of cyanidation wastes. The Mining Journal Ltd., London
Mulligan DR (1996) Environmental management in the Australian minerals and energy industries: Principles and practices. University of New South Wales Press, Sydney
Plumlee GS, Logsdon MS (1999) The environmental geochemistry of mineral deposits. Part A: Processes, techniques and health issues. Society of Economic Geologists, Littleton (Reviews in economic geology, vol 6a)
Ripley EA, Redmann RE, Crowder AA (1996) Environmental effects of mining. St Lucie Press, Delray Beach
Ritcey GM (1989) Tailings management problems and solutions in the mining industry. Elsevier, Amsterdam
Salomons W, Förstner U (1988) Chemistry and biology of solid waste, dredged materials and mine tailings. Springer, Berlin Heidelberg New York
Sengupta M (1993) Environmental impacts of mining: monitoring, restoration and control. Lewis Publishers, Boca Raton
Skousen JG, Ziemkiewicz PF (compilers) (1996) Acid mine drainage control and prevention, 2nd edn. West Virginia University, National Mine Land Rehabilitation Center, Morgantown
Skousen J, Rose A, Geidel G, Foreman J, Evans R, Hellier W (1998) A handbook of technologies for avoidance and remediation of acid mine drainage. Acid Drainage Technology Initiative (ADTI), West Virginia University, National Mine Land Rehabilitation Center, Morgantown

Table 1.4. *Continued*

Textbooks and reports
Warhurst A, Noronha L (1999) Environmental policy in mining. Lewis Publishers, Boca Raton
Younger PL, Robins NS (2002) Mine water hydrogeology and geochemistry. Geological Society, London
Younger PL, Banwart SA, Hedin RS (2002) Mine water: hydrology, pollution, remediation. Kluwer Academic Publishers, Dordrecht
Journals
American Mineralogist
Applied Geochemistry
Ecological Engineering
Engineering and Environmental Geoscience
Environmental Geochemistry and Health
Environmental Geology
Environmental Science and Technology
Geochemistry: Exploration, Environment, Analysis
Geochimica et Cosmochimica Acta
International Journal of Surface Mining, Reclamation and Environment
Journal of Contaminant Hydrology
Journal of Environmental Quality
Journal of Geochemical Exploration
Mine Water and the Environment
Mineralogical Magazine
Mining Environmental Management
Science of the Total Environment
Water, Air, and Soil Pollution

Mine wastes have been with us since the beginning of mining. Thus, anthropogenic contamination of air, water, sediments and soils by mine wastes is as old as people's abilities to mine, smelt and process ores. The impact of mine wastes on the environment has been recognized for more than 2 000 years, well before 20th century organizations took on the issue. Also, the detrimental effects of mine wastes on the health of workers have been of concern to authorities and miners for over 2 000 years.

In many industrialized countries, the majority of mining environmental problems are legacies from the past. Today, improper disposal practices of wastes continue to occur in developing nations and communist states where unregulated mining and uncontrolled release of mine wastes cause environmental harm.

Rehabilitation of mine sites is an integral part of modern mine planning, development and mine closure. Several issues have to be addressed in the successful rehabilitation of a mine site including: removal of all mine facilities; sealing and securing of mine workings; ensuring long-term stability of waste repositories; modeling of future

Table 1.5. Web sites covering general aspects of mine wastes

Organization	Web address and description
United Nations Environmental Programme (UNEP) Mineral Resources Forum	*http://www.mineralresourcesforum.org* Information, publications and case studies on mining and the environment
International Council on Mining and Metals (ICMM)	*http://www.icmm.com* Publications, factsheets, newsletters
US Office of Surface Mining	*http://www.osmre.gov* Protection of the environment during coal mining and reclamation of mined lands
US Bureau of Land Management – Abandoned Mine Lands	*http://www.blm.gov/aml/* Abandoned mine reclamation
US Geological Survey (USGS) Abandoned Mine Lands	*http://amli.usgs.gov/amli* Data, reports, and pictures on abandoned mines
US Environmental Protection Agency (EPA)	*http://www.epa.gov/superfund/programs/aml/tech/index.htm* *http://www.epa.gov/ORD/NRMRL/std/mtb/mwt/* *http://www.epa.gov/osw* Information on abandoned mine lands and information on mining and mineral processing wastes
American Society for Surface Mining and Reclamation (ASSMR)	*http://ces.ca.uky.edu/assmr* Annual conference proceedings on various aspects of minesite rehabilitation
Department of Industry, Tourism and Resources, Australia	*http://www.deh.gov.au/settlements/industry/minerals/index.html* Training kits and electronic booklets on best practice environmental management in mining
Mining Environment Database, Laurentian University, Canada	*http://www.laurentian.ca/library/medb/medlib_e.php* Database on acid mine drainage, abandoned mines, and reclamation
Mining Information Service EnviroMine	*http://technology/infomine.com/enviromine* Information network on mining and the environment

water quality and quantity in pit lakes; modeling future water quality in underground workings and aquifers; construction of suitable landforms; development of a suitable plant growth medium; establishment of a vegetation cover; and addressing generic mine waste issues. Every mine produces its very own unique waste, and this waste requires its very own characterization, prediction, monitoring, treatment, and secure disposal.