

Hard Rock Mine Reclamation

From Prediction to Management
of Acid Mine Drainage

EDITED BY

Bruno Bussière and Marie Guittonny



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Introduction

Marie Guittonny and Bruno Bussière

CONTEXT

As the mining industry continues to grow, so too do its environmental impacts and the need for efficient reclamation methods.

The mining industry produces metals that are essential for global economic development. To do so, mining operations exploit ore deposits. For these ore bodies, both those exploited by open pits and underground mines, the proportion of the economic value compared to the whole excavated rock is very low, which implies that large quantities of solid wastes are produced annually, particularly waste rocks and mine tailings (Lottermoser 2007). Waste rocks are economically nonviable material excavated to reach ore-bearing rock. They are usually stored in waste rock piles at the surface. Tailings are ground rock particles resulting from ore processing. Tailings are usually pumped or transported into tailings storage facilities (Bussière 2007). Both waste types must be stored in a manner that assures their long-term physical and chemical stability. Many environmental challenges are associated with waste rock and tailings storage areas, the main one being the generation of acid mine drainage (AMD). AMD can occur if meteoric water and atmospheric oxygen come into contact with sulfide minerals that can be contained in both types of mine wastes. When the problem is poorly controlled, it can cause significant impacts on ecosystems located near mining operations (e.g., Wolkersdorfer and Bowell 2004; Moncur et al. 2005; Bussière 2009; Salvarredy-Aranguren et al. 2008).

Despite the potential negative impacts of mining operations, metal needs are continuously increasing in our society, and recycling does not provide enough raw materials to satisfy those needs. Moreover, with the development of large-scale mining equipment, the global trend is more toward the exploitation of large and low-grade ore deposits via open-pit mines that generate larger amounts of wastes. Thus, to fulfill the needs of both developed and developing countries, more and more metal mines will be opened, more and more mine wastes will be generated, and the potential to generate more and more AMD will also grow.

In addition to managing technical challenges, new mines will have to obtain the social acceptance of communities. Because the management of AMD problems associated with hard rock mines started only in the 1970s, a lot of old mine sites generate environmental contamination and degrade the quality of life in adjacent communities. Furthermore, the costs of reclamation for abandoned mine sites are transferred to taxpayers, which increases communities' circumspection of any proposals for new mine projects. To accept non-renewable resource extraction on their land, communities have increasingly elevated reclamation requirements. Consequently, stakeholders attach a growing importance to social and environmental responsibilities of mine companies when selecting the projects they fund. In particular, mine companies must demonstrate to financiers and communities at the design stage that negative environmental impacts such as AMD will be minimized during and after mining operation and that there will be efficient reclamation techniques at the post-closure stage.

Within this context, this book provides fundamental background about the main bio-chemical-geotechnical mechanisms underlying mine site reclamation and describes practical methods to reclaim hard rock mine wastes facilities and control their AMD contamination potential. The book focuses on mine site reclamation from an engineering point of view. The authors identify new reclamation issues and propose well-tested as well as innovative approaches to addressing them.

The research on AMD and hard rock mine site reclamation is 50 years old, and the accumulated knowledge is ripe to be gathered and integrated.

AMD is not a recent problem in the mining industry. Georgius Agricola (1556 [1912]), in his famous book *De re metallica*, mentions water contamination from ore extractions: “[W]hen the ores are washed, the water which has been used poisons the brooks and streams, and either destroys the fish or drives them away”.

In many countries that produce mineral products, the problem of AMD was (and still is) mainly linked to hard rock mines. Initially, this environmental problem was not considered as important in hard rock mines as it was in U.S. coal mines, which may explain the relatively small volume of research on the subject before the 1970s. In the early 1970s, a few publications in Canada rang the alarm by identifying serious environmental problems related to AMD (e.g., Hawley and Shikaze 1971; Rivett and Oko 1971; Hawley 1972). At the time, reclamation of tailings impoundments (as for coal mine land; e.g., Bramble and Ashley 1955) was done mainly by stabilizing the surface with vegetation combined to lime amendments (e.g., Leroy 1973; Ludeke 1973). However, research on acid-generating tailings impoundments conducted in Canada and elsewhere showed that revegetation success and the neutralization effects of the amendment were temporary and that AMD was only slightly reduced, and only for a short period of time (e.g., Moffet et al. 1977). Since then, most engineering research has been devoted to finding solutions to this problem with an emphasis on controlling AMD formation at the source. Nonetheless, the science of AMD control for the reclamation of hard rock mine sites is young, and the information available is disseminated in journal articles, conference papers and reports, lacking an integrative effort.

This book aims to gather the available information in one contemporary, interdisciplinary, and integrated document. It allows geoenvironmental engineers and professionals to get an overview of reclamation methods to control AMD and to update their knowledge to design efficient mine site reclamation methods.

CONTENT AND AUTHORS

A book on mine site reclamation that takes an interdisciplinary approach is highly needed by the scientific and mining community.

Since mine site reclamation is a young science, the training needs for professionals and graduate students working in this field are huge. **Thus, this book targets students in graduate programs focused on mines and the environment as well as professionals who are already working in departments related to mine site reclamation.** It is written for an audience who is already familiar with the subject of mine site reclamation.

The book focuses on the reclamation of waste storage facilities from hard rock mines operations. These facilities constitute the main source of AMD pollution during and after hard rock mine operations. Reclamation aims to return a mine site to a satisfactory state, which means that the site should not threaten human health or security, should not generate in the long term any contaminant that could significantly affect the surrounding environment, and should be aesthetically acceptable to communities. Moreover, long-term control of the contamination must be done without continuous maintenance, which excludes the collect and treat option to reclaim a mine site. The establishment of vegetation on the site is also favored to control erosion and restore the site’s natural appearance. Finally, when possible, reclamation that allows the site a second life after the mine closure is preferred.

The book is composed of 14 chapters, divided into four main themes (see Figure 0.1): fundamentals, reclamation approaches, tools to design and validate, and performance improvement.

Fundamentals: The book begins with an explanation of the biogeochemical processes underlying the problem of mine water contamination from AMD, followed by a chapter that reviews the fundamental concepts linked to water, gas, and heat movement in geological materials used in covers. These chapters prepare the reader for the following chapters, which describe six main reclamation techniques for hard rock mines.

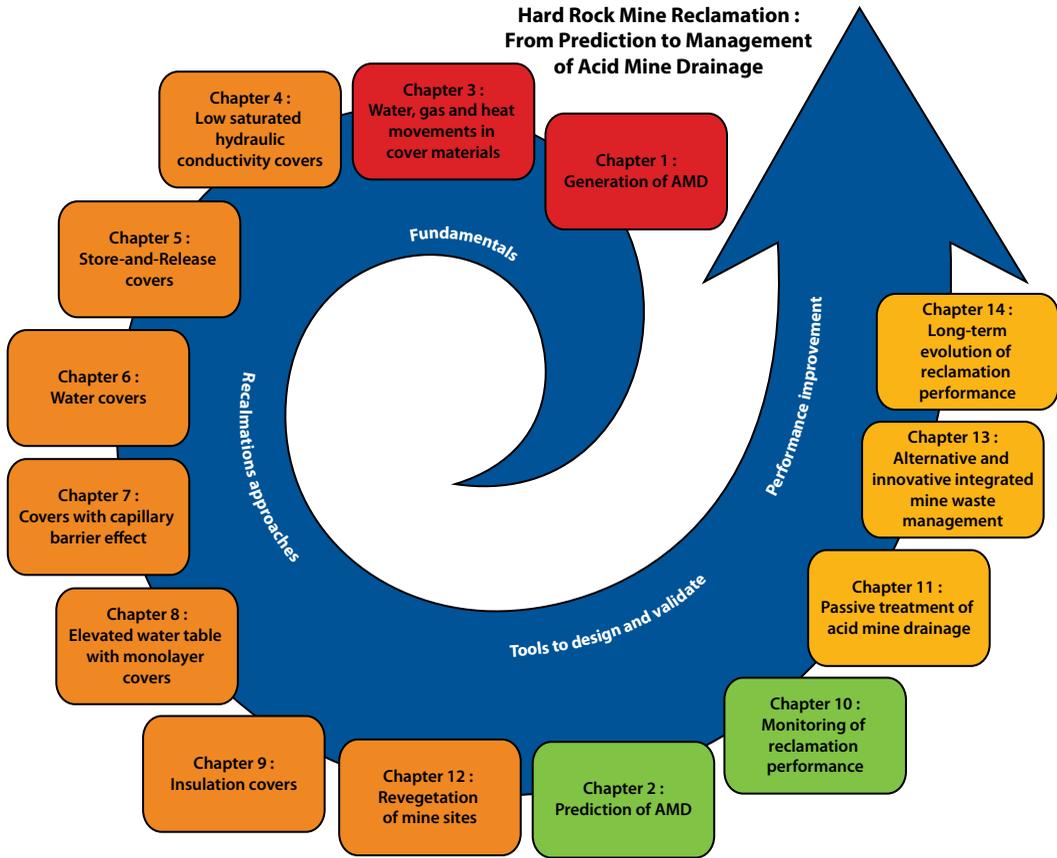


FIGURE 0.1 Content and structure of the book.

Reclamation approaches: Chapters 4 to 9 provide historical context for the development of a specific reclamation method, conceptual and technical descriptions of the method, and the factors that influence its design and performance. Special attention is paid to providing design approaches for each main reclamation method. Finally, the main advantages and limits of the different reclamation techniques are specified to promote comparative analysis, and research and development needs are identified. Thus, the reader will understand the remaining work to be done to reach an optimal application of the different reclamation methods.

The two first reclamation techniques presented aim to control water infiltration. Two types of impervious covers are described: low saturated hydraulic conductivity covers (LSHCC) (Chapter 4) and store-and-release (SR) covers (Chapter 5). Then, oxygen barrier techniques are described, including water covers (Chapter 6), covers with capillary barrier effects (CCBE) (Chapter 7), and elevated water table (EWT) with monolayer covers (Chapter 8). Chapter 9 discusses insulation covers, which control mine waste temperature in order to avoid contaminant generation; this type of cover, however, can only be used under Arctic climates. To finalize the reclamation after implementation of AMD control methods, Chapter 12 presents ecological knowledge and a general design approach related to the revegetation of mine sites, a mandatory step in most recent regulations on mine site reclamation.

Tools to design and validate: Designing a reclamation plan is a long process that starts with the environmental characterization of the mine wastes and the validation of preliminary scenarios in the laboratory. Chapter 2 presents the different tools available to characterize the AMD potential of

mine wastes and how we can simulate reclamation scenarios at the laboratory or field scale. Chapter 10 presents the different parameters that must be monitored after reclamation implementation and the equipment available to measure these parameters. The objective is not to describe in detail all technologies but to identify the different approaches and their advantages and limits.

Performance improvement: Since interstitial waters in mine wastes sometimes have had the time to be contaminated before a reclamation method is applied, water needs to be temporarily treated. In a reclamation context, passive treatment techniques of water are more appropriate due to the reduced maintenance needed for their functioning and because they do not rely on human presence to operate the systems; these techniques are the focus of Chapter 11. Most of the time, reclamation is not integrated at the development stage of a mine project even if the concept of design for closure could significantly help mining companies reduce their long-term liabilities and reclamation costs. In Chapter 13, the main waste management modes are presented with an emphasis on how each of them can affect the final reclamation, from both a technical and economical point of view. This chapter connects the different stages of mine life cycle (exploration, operations, and ore treatment) to reclamation. Subjects such as co-disposal of waste rocks and tailings, tailings desulfurization, waste segregation and reduction at the source, and progressive reclamation are discussed. Finally, the book dedicates an entire chapter to the long-term performance of reclamation methods by considering that reclaimed sites are integrated into a changing environment. In particular, exposure to organisms' colonization from the surrounding environment, as well as changes in the properties of materials, are tackled because they can reduce the long-term performance of reclamation methods and eventually lead to the contamination of the environment. Similarly, the need to conceive covers by using climate data that integrate climate changes and their prediction uncertainty is discussed. These considerations will improve our capacity to design reclamation methods that ensure an acceptable long-term performance.

Mine site reclamation involves different sciences, and professionals with different expertise must work together to optimize the reclamation process.

Environmental impacts of mine activities affect different land components, such as rocks, soils, water, air, and organisms. Thus, a complete reclamation plan requires the knowledge and integration of several disciplines, including hydrology, geology, chemistry, biology, pedology, geotechnics, engineering, and ecology, among others. This interdisciplinarity represents an important challenge because each discipline has its own vocabulary, studied objects, problem-solving approaches, and spatiotemporal frame. **To address this challenge, the book involved ten main authors who agreed to work collectively and interdisciplinarily.** The editors have paid particular attention to the structure of each chapter and to the terminology used to guarantee the consistency of the content.

Most authors and the two editors belong to the Research Institute on Mines and the Environment (RIME) UQAT-Polytechnique. RIME UQAT-Polytechnique was created in 2013, following over ten years of applied research collaboration, by the Université du Québec en Abitibi-Témiscamingue (UQAT) and Polytechnique Montréal. Focused on environment and mine waste management, RIME aims to develop environmental solutions for the entire mine lifecycle. During our years spent working together, the mining industry, regulations authorities, and the research team members have shared disciplinary skills to create a wholistic vision of reclamation projects and their associated challenges. Each reclamation project integrates contamination prediction, waste management, contamination mitigation and treatment, to end with storage facilities' revegetation. Over the 20 last years of collaboration, the RIME team has had to apply and combine developed techniques on sites managed by industrial and government partners; these real case studies, mainly Canadian, are used throughout the book to concretely illustrate its interdisciplinary approach.

FINAL REMARKS

The book prioritizes the chemical stability of mine wastes over their physical stability, even if both must be evaluated at the design stage of any reclamation plan. We consider physical stability of mine waste storage facilities a subject of its own and beyond the scope of the book. The subject has also been covered by others in relatively recent books (e.g., Blight, 2010).

The book presents six mine site reclamation methods, with complementary chapters (Chapters 11 to 14) essential to perform a complete and successful work. The editors consider these methods the most relevant in the context of hard rock mines. However, other methods have been suggested in the literature to reclaim AMD mine sites, such as organic covers (Ribeta et al. 1995), use of bactericide (Kleinmann 1998), passivation or coating of sulfide minerals (Zhang and Evangelou 1998), and amendment with neutralizing agents (Hakkou et al. 2009). However, they are not described in this book mainly because of one or more of these reasons: the low material availability, the incapacity to maintain AMD control with time, the relatively low efficiency to control AMD, and the costs associated with implementation.

The book focuses on the control of AMD generated by mine wastes from hard rock mines, especially on base and precious metal mines. More recently, some of these mines faced a new type of contamination called contaminated neutral drainage (sometimes referred to as metal leaching; Plante et al. 2014). This aspect is not directly treated in the book. The authors are also aware that the same and other challenges are related to mine site reclamation from other types of hard rock mine ores. For example, uranium mines can generate radioactive contamination. The editors decided not to focus on radioactive contaminants. However, if uranium mine wastes are AMD generating, the methods presented in the book could be applied (Peacey et al. 2002). Also, the development of electronics and energy storage technologies pushes for the exploitation of rare earth elements and lithium mines. The biogeochemistry and environmental effects of mine drainage from wastes coming from these new types of mines are still poorly documented and may need specific reclamation methods (Edahbi et al. 2019). The AMD reclamation methods described in the book may constitute a useful knowledge basis for the adaptation and development of specific reclamation methods for these strategic metals.

Despite its interdisciplinary approach, the book doesn't include the contribution of social sciences specialists to deal with social aspects of reclamation plans. Given the need to obtain a social license to operate for new mine projects (Moffat and Zhang 2014), however, we think that special attention should be given to integrate the social aspects by co-designing the reclamation plans with the communities impacted by mining activities. Communities should also be involved in the long-term monitoring, and efforts should be paid to maximizing the economic impacts of reclamation for communities.

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1 Generation of Acid Mine Drainage

Benoît Plante, Gary Schudel, and Mostafa Benzaazoua

The aim of this chapter is to provide an overview of basic geochemical knowledge regarding the generation of acid mine drainage (AMD). Chapter 2 then describes the most common procedures used to predict the onset of AMD in order to comprehend the objectives and mechanisms of the different reclamation methods discussed in the subsequent chapters (Chapters 4 to 9). This chapter focuses on the fundamentals of the acid-generating and acid-consuming geochemical reactions, the most significant factors that influence these reactions, and the associated current research and development need. To concentrate on the most common reactions and most significant factors affecting reaction rates, we have omitted some details on related subjects. Readers are directed to the most relevant studies should they want to supplement the information provided here.

1.1 HISTORICAL PERSPECTIVE AND OVERVIEW OF THE PROBLEM

Contamination of the environment surrounding mining activities has been long recognized. In his well-known 1556 book, *De re metallica*, German mineralogist and metallurgist Georgius Agricola described what is perhaps one of the first accounts of environmental preoccupation related to mining operations. Agricola (1556/1912) states that the people recognized that mining and smelting activities not only contaminated streams' receiving process waters but also had a significant impact on nearby forests and lands, which, in turn, affected the associated fauna and flora:

But besides this, the strongest argument of the detractors is that the fields are devastated by mining operations, for which reason formerly Italians were warned by law that no one should dig the earth for metals and so injure their very fertile fields, their vineyards, and their olive groves. Also they argue that the woods and groves are cut down, for there is need of an endless amount of wood for timbers, machines, and the smelting of metals. And when the woods and groves are felled, then are exterminated the beasts and birds, very many of which furnish a pleasant and agreeable food for man. 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.

Despite Agricola's assessment that mine waters seemed to be poisonous to receiving streams, the first formal research on AMD began in the 1920s with studies of coal mine wastes from the Appalachian region of the United States (for an overview of early research on AMD, see Paine 1987). Fundamental studies on AMD, particularly pyrite oxidation, have also been performed from the 1920s onward (Colmer and Hinkle 1947), and the involvement of microorganisms in AMD generation, especially in ferrous to ferric iron oxidation, was assessed beginning in the late 1940s (Colmer and Hinkle 1947; Temple and Colmer 1951; Singer and Stumm 1970). The first AMD

prediction studies, which still focused on US coal mine wastes and were mainly qualitative, occurred in the 1940s and 1950s (Braley 1949, 1960). The first quantitative AMD prediction studies started in the 1970s at West Virginia University (1971). These studies lead to the famous United States Environmental Protection Agency report by Sobek et al. (1978), which described the procedures for determining the neutralization and acid generation potentials of mine wastes that would later become the basis for modern acid–base accounting tests (see Chapter 2). The first modern research on the reclamation of AMD-generating mine waste disposal areas was initiated in the 1980s. The International Conference on Acid Rock Drainage series was also established in the late 1980s and early 1990s. The conference, which is still held every three years, is attended by specialists from all fields related to AMD mine site reclamation.

The wide variety of geological settings in which AMD may arise leads to a similarly wide array of AMD compositions. The generally low-sulfide sulfur contents of coal mine wastes, which are also often poor in neutralizing minerals, leads to AMD containing relatively low concentrations of metals and sulfate. On the other hand, hard rock mines of base and precious metals operate in a wide array of mineralogical contexts, from low-sulfur/low-neutralizing minerals to high-sulfur/high-neutralizing mineral. This can lead to drainage waters with metal and sulfate concentrations ranging from several parts per million to hundreds or thousands of grams per liter. Table 1.1 compares typical AMD water quality data from base and precious metal mines.

Although there are no official, widely recognized definitions for the different types of mine drainages, the classification system suggested by Nordstrom et al. (2015), which is based on the *Global Acid Rock Drainage Guide* (INAP 2009), is used in this book (Figure 1.1). Under this system, AMD refers to any mine water sample with pH values below 6, where sulfate is the dominant ion. Neutral mine drainage, which is also called contaminated neutral drainage (CND) or more simply metal leaching, typically ranges in pH from 6.0 to 9.0. Metal leaching at near-neutral conditions can occur in a variety of geologic environments where the acid generated from sulfide oxidation is neutralized by sufficient acid buffering within the source materials but still allows for some metals, such as Ni and Zn, to leach into the drainage waters at problematic concentrations. CND can also develop in the lag time before the onset of AMD, which is essentially the period in which the neutralizing minerals present in a material are still able to buffer the pH of the drainage waters to near-neutral values. Finally, alkaline mine drainage is defined as having a pH ranging from 9.0 to 12.0. At present, there are very few examples of alkaline mine drainage in the literature, and the conditions and processes leading to its formation are not yet well understood.

TABLE 1.1
Examples of Acid Mine Drainage Occurrences from Metal Mines

	Lowest pH	SO ₄ (mg/L)	Fe (mg/L)	Cu (mg/L)	Zn (mg/L)
Richmond mine, Iron Mountain, California, USA¹	–3.6	Up to 760,000	Up to 141,000	Up to 4,760	Up to 23,500
Sherridon, Manitoba, Canada²	0.67	280,000	129,000	1,600	55,000
Manitou mine, Quebec, Canada³	2	2,500	10,000	235	350
Genna Luas, Sardinia, Italy⁴	0.6	203,000	77,000	220	10,800

Source: Data taken from

¹ Nordstrom et al. (2000);

² Moncur et al. (2003, 2005);

³ Ethier (2018);

⁴ Frau (2000).

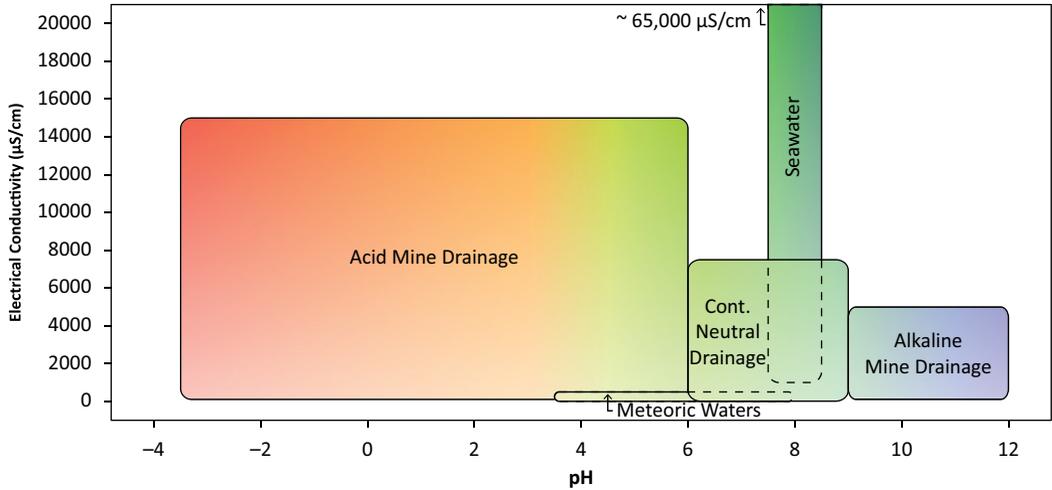


FIGURE 1.1 pH vs. electrical conductivity plot characterizing the different types of mine drainage waters, as well as meteoric waters and seawater. The pH values for AMD, CND, and alkaline mine drainage were based on Nordstrom et al. (2015) and INAP (2009). Data were gathered from various sources: AMD (Ball and Nordstrom 1989; Nieto et al. 2007; Søndergaard et al. 2008; Pope et al. 2010; Cruz et al. 2013), CND (Ball and Nordstrom 1989; Church et al. 2007; Conesa et al. 2006; Heikkinen et al. 2009), alkaline mine drainage (Nordstrom et al. 1989; Azzie 2002; Dahrazma and Kharghani 2012), meteoric waters (Zunckel et al. 2003; Topçu et al. 2002; Santos et al. 2011; Zhang et al. 2012), and seawater (Chester and Jickells 2012; Tyler et al. 2017).

1.2 MINERALOGICAL ASPECTS OF AMD GENERATION

The generation of acidic drainage waters relies on a combination of acid generation from sulfide oxidation and insufficient neutralization provided by other minerals. The resulting water quality of the mine drainage waters is influenced by a combination of geochemical phenomena, as represented in Figure 1.2. This section describes the geochemical reactions of the main minerals involved in AMD, as well as secondary mineral precipitation and sorption. This chapter covers only the basics

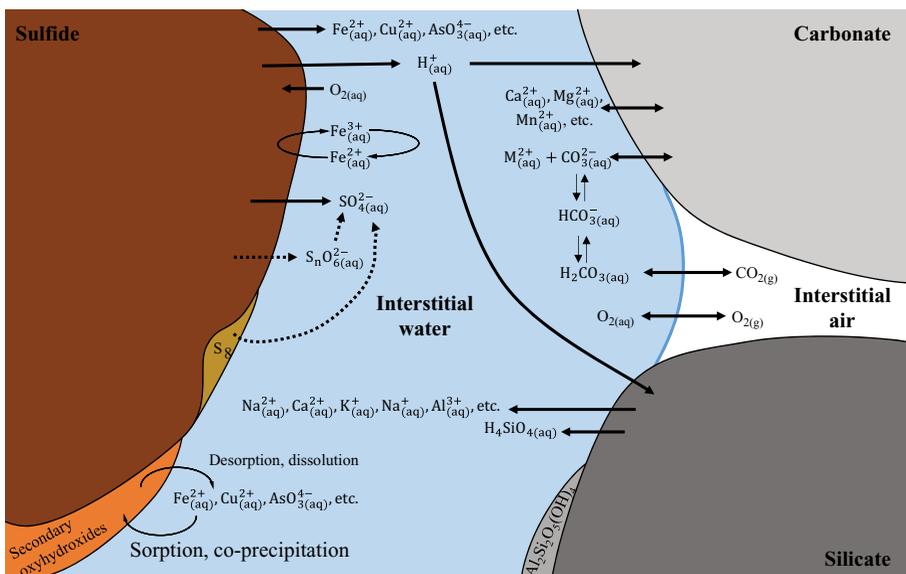


FIGURE 1.2 Schematics of the geochemistry of acid mine drainage waters.

of geochemical reactions behind AMD; the interested reader can find more exhaustive coverage in studies by Nordstrom et al. (2015), Lindsay et al. (2015), and Blowes et al. (2014).

1.2.1 SULFIDE OXIDATION: THE MAIN SOURCE OF ACID GENERATION

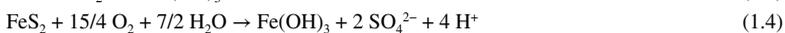
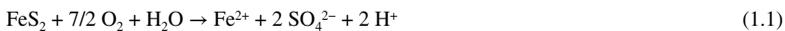
The main source of acid in mine wastes is the oxidation of sulfide minerals. The amount of acid (H^+) generated by sulfide oxidation varies depending on the mechanisms involved (Table 1.2) and is controlled by the kinetics of the reactions. Pyrite oxidation by dissolved oxygen generates acid and ferrous iron (Fe^{2+} ; Equation 1.1), which may undergo oxidation (Equation 1.2) and hydrolysis under certain conditions to generate oxyhydroxides such as ferrihydrite (Equation 1.3). Adding equations 1.1 to 1.3 gives the overall oxidation reaction of pyrite by dissolved oxygen (Equation 1.4), where 4 moles of H^+ are generated for each mole of pyrite oxidized. Pyrite can also be oxidized by Fe^{3+} (Equation 1.5) instead of oxygen if the geochemical conditions are favorable to Fe^{3+} solubility (i.e., unfavorable to its hydrolysis), which is typically in low pH waters (approximately 3.5–4.5) and oxidized environments (typically Eh >300 mV). Pyrite oxidation by Fe^{3+} generates Fe^{2+} and 16 moles of H^+ per mole of pyrite. Therefore, the acid generated by pyrite oxidation in acidic conditions is four times greater than that generated at higher pH values that promote iron oxyhydroxide precipitation (approximately at pH values >4.5, depending on the redox conditions and dissolved Fe concentrations). In addition, the 15 moles of ferrous iron produced can, in turn, undergo oxidation following Equation 1.2 (favored by the involvement of iron-oxidizing bacteria) and oxidize other pyrite molecules, therefore acting as a catalyst for pyrite oxidation.

Pyrrhotite can be oxidized by O_2 (Equations 1.6 and 1.7) or Fe^{3+} (Equation 1.8), just like pyrite. As can be deduced from Equation 1.6, the iron deficiency in the pyrrhotite crystal lattice (i.e., the value of “x”) makes the stoichiometry of its reaction slightly different depending on the extent of the deficiency, producing between $\frac{1}{4}$ mole of H^+ ($x=0.125$, $Fe_{0.875}S$ or Fe_7S_8) to none ($x=0$, FeS). However, the Fe^{2+} released upon pyrrhotite oxidation can also undergo oxidation and hydrolysis (Equation 1.2 and 1.3) and contribute to the generation of further acid; combining these reactions

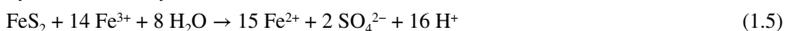
TABLE 1.2
Pyrite and Pyrrhotite Oxidation Reactions

Pyrite Oxidation

Pyrite oxidation by oxygen

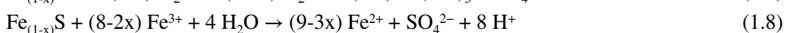
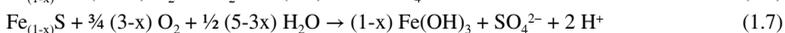


Pyrite oxidation by Fe^{3+}

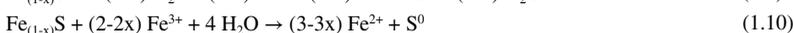
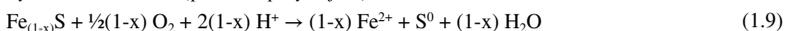


Pyrrhotite

Pyrrhotite oxidation (complete)



Pyrrhotite oxidation (partial—polysulfide)



Pyrrhotite dissolution (non-oxidative)



gives the overall oxidation reaction of pyrrhotite by dissolved oxygen (Equation 1.7), in which 2 moles of H^+ are generated per mole of pyrrhotite, regardless of its iron stoichiometry. Like pyrite, pyrrhotite generates four times more acid when Fe^{3+} acts as the oxidant (Equation 1.8).

In some circumstances, sulfur oxidation may not proceed to the sulfate state and may generate more reduced states such as elemental sulfur or polysulfides with O_2 (Equation 1.9) or Fe^{3+} (Equation 1.10) as the oxidant. The non-oxidative dissolution of pyrrhotite (Equation 1.11) occurs in acidic conditions and is characterized by the release of Fe^{2+} in solution, followed by sulfur release in the form of HS^- (Thomas et al. 1998, 2001; Janzen et al. 2000). More details on the oxidation of pyrrhotite can be found in studies by Belzile et al. (2004) and Blowes et al. (2014), and references therein. The oxidation of other metal sulfides, such as arsenopyrite ($FeAsS$), chalcopyrite ($CuFeS_2$), and sphalerite (ZnS), is also described by numerous authors (Rimstidt et al. 1994; Janzen et al. 2000; Chopard et al. 2017; see Blowes et al. 2014 for a compilation of other relevant references) but will not be covered explicitly here. Nonetheless, the readers should be aware that other metal sulfides can also be oxidized by O_2 and Fe^{3+} and keep in mind that some sulfides generate less acid than pyrite and pyrrhotite or no acid at all (such as sphalerite and galena), while others may generate more acid, such as for arsenopyrite (e.g., Rimstidt et al. 1994) and gersdorffite (e.g., Chopard et al. 2017).

The mechanistic details of sulfide oxidation are still the subject of intense debate among scientists after decades of studies (e.g., Lawson 1982; Schippers and Sand 1999; Belzile et al. 2004; see Blowes et al. 2014 for additional key references). However, the crucial aspect to remember from the stoichiometry of sulfide oxidation is that both the amount of acid and the rate at which it is generated increase when conditions become acidic and oxidizing enough, which explains why AMD is a chain reaction that is difficult to stop once it has started.

It is well known that microbial processes significantly influence the cycling of Fe and S in AMD-generating mine tailings. It is now generally accepted that microbes participate mainly through an indirect mechanism in which they facilitate and significantly accelerate the oxidation of Fe^{2+} to Fe^{3+} (Singer and Stumm 1970; Rohwerder et al. 2003). Therefore, given that the rate of abiotic Fe^{2+} oxidation is up to five orders of magnitude lower than that of biotic Fe^{2+} oxidation below pH 3 (Nordstrom 2003; Nordstrom and Southam 1997), iron-oxidizing acidophiles ultimately control the rate of sulfide oxidation under acidic conditions (Rohwerder et al. 2003; Lindsay et al. 2015).

The contact between two sulfide minerals in a conductive media (such as AMD) leads to a voltaic cell promoting galvanic interactions, where one mineral is preferentially oxidized and transfers electrons to the other, which is therefore protected from oxidation (e.g., Holmes and Crundwell 1995; Kwong et al. 2003; Cruz et al. 2005; Chopard et al. 2017; Qian et al. 2018). Therefore, galvanic interactions do not require oxygen or Fe^{3+} and can proceed despite the use of oxygen barriers in reclamation techniques (see Chapters 6, 7, and 8).

Pyrite oxidation rates have been studied extensively, and many of these rates were compiled by Holmes and Crundwell (2000) and reported in the study by Blowes et al. (2014), where the rates are expressed as a function of dissolved O_2 , pH, as well as concentrations of Fe^{2+} and Fe^{3+} . The pyrrhotite oxidation rate has not been studied as extensively as for pyrite, but studies by Nicholson and Scharer (1994) and Janzen et al. (2000) provide both oxidative and non-oxidative rate data for several pyrrhotite samples that highlight that pyrrhotite oxidation occurs at rates between 20 and 100 times faster than pyrite (Blowes et al. 2014). However, most of these rate data were obtained in closed systems under controlled environments and are difficult to upgrade to field conditions. Chopard et al. (2017) compared the oxidation rates of sulfides in laboratory kinetic tests, which showed that pyrrhotite oxidizes approximately eight times faster than pyrite. Thus, although pyrrhotite oxidation generates half as much acid as pyrite (see Equations 1.4 and 1.5 for pyrite and Equations 1.7 and 1.8 for pyrrhotite), it does so significantly faster than pyrite. Therefore, the presence of significant pyrrhotite in mine wastes requires fast, effective neutralizers in order to buffer this acid and prevent or delay AMD generation.

The next section describes acid neutralization processes in mine wastes.

1.2.2 ACID NEUTRALIZATION

While acid generation in mine wastes results primarily from the oxidation of iron-sulfide minerals, acid neutralization occurs through reactions between H^+ and a wide variety of rock-forming minerals, essentially carbonates, soluble silicates, and oxyhydroxides (Table 1.3; Blowes et al. 2014; Dubrovsky et al. 1985). Principally, acid neutralization involves the dissolution of carbonates, silicates, and oxyhydroxides, but acid may also be neutralized through exchanges with cations on the surface of clay minerals (Lottermoser 2010). The most effective acid-neutralizing minerals are carbonates (e.g., Sherlock et al. 1995; Blowes et al. 2014) because of their relatively high dissolution rate in comparison to silicates. Calcite (Equations 1.12 and 1.13) and dolomite (Equations 1.14 and 1.15), two carbonate minerals, consume different amounts of acid depending on the pH to which they are submitted.

Siderite is also able to consume acid (Equation 1.16). However, because of Fe^{2+} oxidation (Equation 1.2) and subsequent Fe^{3+} hydrolysis (Equation 1.3), which release as many hydrogen ions as consumed by siderite dissolution (Equation 1.16), the whole process is not globally acid neutralizing (Equation 1.17). In addition to Fe, metals that have the potential to undergo hydrolysis within acidic to near-neutral pH values, such as Al and Mn, will proportionally decrease the neutralization potential of their host mineral. The hydrolysable metal content of neutralizing minerals needs to be taken into account if their host minerals constitute a significant proportion of the overall neutralization potential of a given material (e.g., Paktunc 1999b; Plante et al. 2012; Bouzahzah et al. 2014; Elghali et al. 2019b).

Various silicate minerals, such as chlorite, biotite, olivine, pyroxene, and plagioclase feldspars (e.g., anorthite; Equation 1.18), are also able to neutralize acid. Numerous studies assess the contribution of silicate minerals to acid neutralization (e.g., Sherlock et al. 1995; Johnson et al. 2000; Jurjovec et al. 2002; Moncur et al. 2005; Jambor et al. 2002, 2007). Many silicates possess similarly elevated neutralization capacities relative to calcite and, as a group, silicates theoretically represent the greatest source of acid neutralization in most wastes. For example, considering only stoichiometry, the dissolution of 1 mole calcite is required to neutralize 1 mole of sulfuric acid (Equations 1.12 and 1.13), whereas only 0.5 mole of anorthite (Equation 1.18) is required to neutralize the same amount of acid.

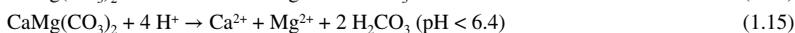
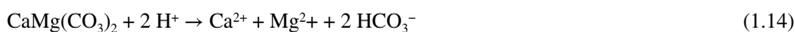
However, as stated earlier, the ability of silicate minerals to buffer mine waters is significantly limited by their slow dissolution kinetics relative to sulfide oxidation rates (e.g., Jamieson et al. 2015; Blowes et al. 2014). In determining which minerals will realistically contribute to buffering the pH of acid drainages on relevant timescales, both the stoichiometry of neutralization reactions

TABLE 1.3
Reactions of Acid-neutralizing Minerals

Calcite



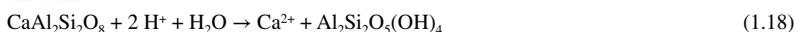
Dolomite



Siderite



Anorthite



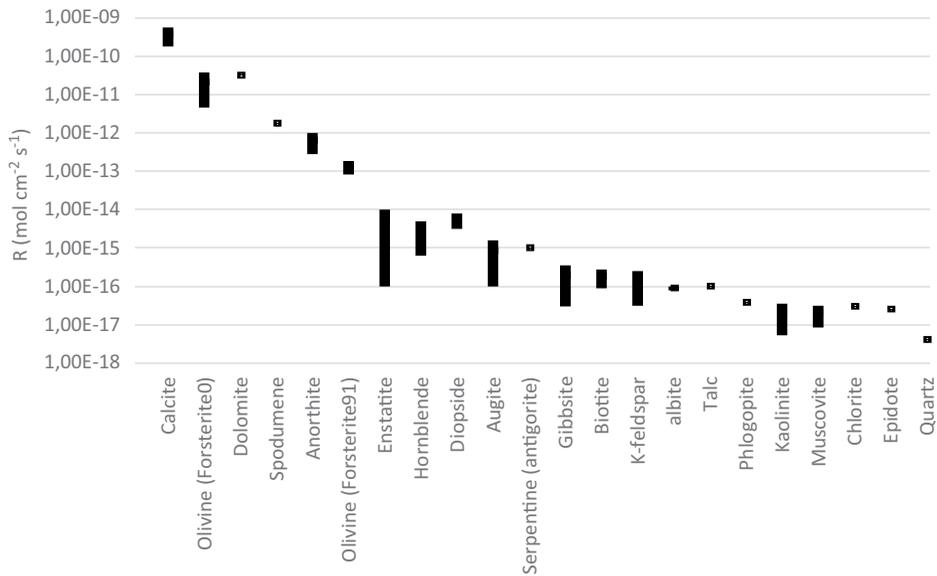


FIGURE 1.3 Dissolution rates at pH 5 (Adapted from Paktunc 1999a).

and their rates under given environmental conditions must be considered (Jamieson et al. 2015). Dissolution rates were compiled by Paktunc (1999a and references therein) and are shown in Figure 1.3. While calcite dissolution proceeds quite rapidly, rates of silicate dissolution are several orders of magnitude slower than typical rates for calcite (McKibben and Barnes 1986; Wollast 1990; Paktunc 1999a).

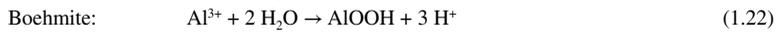
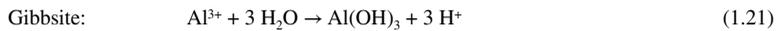
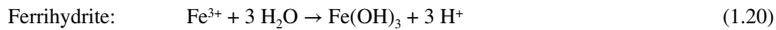
1.2.3 SECONDARY MINERALS

Secondary minerals are formed by combining reaction products of primary minerals in mining wastes upon their metallurgical treatment and/or exposure to atmospheric conditions in waste rock piles and tailings storage facilities. In potentially AMD-generating materials, the geochemical reactions are often driven by sulfide oxidation and the subsequent response of acid-neutralizing minerals. Therefore, many anionic and cationic products are leached in mine drainage waters. They may form a wide range of secondary minerals in situ, as their constituting ions are made available by reaction of their parent primary minerals (Table 1.4). The most significant secondary minerals encountered in mine drainage waters are sulfates, oxides/hydroxides (often named oxyhydroxides), and carbonates (e.g., Alpers et al. 1994; Blowes et al. 2014). Their crystallization may have a significant effect on the composition of the drainage waters and eventually on the hydrogeological properties of the materials themselves. Indeed, since secondary precipitates may partially fill the voids between the grains, a phenomenon that leads to the formation of a hardpan typical of highly weathered AMD-generating tailings (e.g., Blowes et al. 1991; McGregor and Blowes 2002; Moncur et al. 2005, 2009; Graupner et al. 2007; DeSisto et al. 2011; Elghali et al. 2018), their type and occurrence need to be assessed in mine water studies.

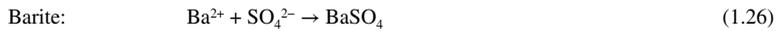
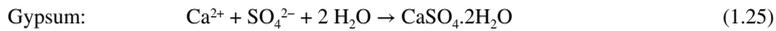
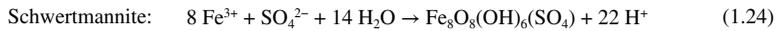
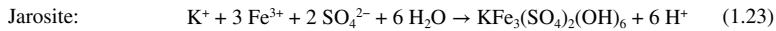
The iron released from sulfide oxidation leads to the formation of a variety of iron oxyhydroxides, the most thermodynamically stable and most widely encountered being goethite (α -FeOOH; Equation 1.19), which is responsible for the ochre color typical of highly oxidized AMD-generating mine wastes (Blowes et al. 2014). Ferrihydrite (Equation 1.20), often reported as amorphous $\text{Fe}(\text{OH})_3$, is a poorly crystalline secondary mineral that is also widely reported in oxidized AMD-generating mine wastes (Jambor and Dutrizac 1998; Blowes et al. 2014). Aluminum oxyhydroxides such as gibbsite (Equation 1.21) and boehmite (Equation 1.22) are also

TABLE 1.4
Examples of Secondary Mineral Formation

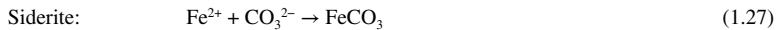
Oxides and Hydroxides



Sulfates



Carbonates



often encountered in AMD-generating mine sites where the dissolution of aluminosilicate minerals is significant (e.g., Blowes et al. 2014; Lindsay et al. 2015; and references therein). Iron and aluminum oxyhydroxides are also known to sorb and co-precipitate a wide variety of metals, and it has often been demonstrated that they exert a significant control on the concentrations of metals in mine drainage in tailings (e.g., Al et al. 2000; Heikkinen and Räsänen, 2008, 2009; Hakkou et al. 2008; Blowes et al. 2014; Lindsay et al. 2015) as well as in waste rocks (Stockwell et al. 2006; Blackmore et al. 2018).

Most sulfate minerals are hydrated and quite soluble. They will only be encountered in dry periods as efflorescent salts and will disappear upon re-wetting of the material (e.g., Nordstrom and Alpers 1999; Nordstrom 2011; Blowes et al. 2014). Typical examples of soluble hydrated sulfates comprise iron sulfate $\text{FeSO}_4 \cdot n\text{H}_2\text{O}$ ($1 < n < 7$) and magnesium sulfates such as epsomite $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$. Although jarosites are often composed of its K end-member ($\text{KFe}_3(\text{SO}_4)_2(\text{OH})_6$; Equation 1.23), they will incorporate other cations as they are formed. More rarely, other end-member jarosites can also be encountered depending on the geochemical environment in which they are formed. Schwertmannite (Equation 1.24) may also be encountered in acid-generating tailings (Blowes et al. 2014) but is metastable and will transform to goethite (Schwertmann and Carlson 2005). However, some sulfate minerals are partly soluble, such as gypsum $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ (Equation 1.25), or highly insoluble, such as barite BaSO_4 (Equation 1.26), and may exert a significant control over the aqueous concentrations of their constituents. Gypsum is by far the most common secondary sulfate encountered in acid-generating mine wastes (Blowes et al. 2014) because of the prevalence of sulfate (from sulfide oxidation) and calcium (from carbonate and silicate dissolution) ions in mine waters.

Secondary carbonates can form in waters having high alkalinity values. Secondary siderite (Equation 1.27) has been reported in the Kidd Creek tailings as coatings on ankerite-dolomite grains in association with iron oxyhydroxides (Al et al. 2000), as well as at Elliott Lake (Paktunc and Davé 2002), where secondary calcite was also detected. However, these secondary carbonates will be temporary in AMD-generating tailings since they will dissolve as the pH is lowered by continued acid generation.

Microorganisms are also known to have an effect on the stability of secondary iron oxyhydroxides by facilitating the reductive dissolution of iron (such as the acidophilic bacteria *Acidiphilium* spp. and *Ferrimicrobium acidiphilum*, and the mixotrophic acidophiles *Sulfobacillus* spp. and *Am. ferrooxidans*; Blowes et al. 2014; Bridge and Johnson 1998, 2000; Johnson et al. 2009) or sulfur (such as the autotrophic acidophiles *Acidithiobacillus* spp.; Blowes et al. 2014; Hallberg 2010;

Ohmura et al. 2002). Many specific examples of the microbiological influence on secondary mineral stability can be found in studies by Blowes et al. (2014), Lindsay et al. (2015), Nordstrom et al. (2015), and references therein.

1.3 FACTORS INFLUENCING THE DEVELOPMENT OF AMD CONDITIONS

Numerous factors influence the development of AMD conditions by affecting the kinetics of the reactions involved. Some of these factors are intrinsic to the materials themselves, such as their mineralogical composition (e.g., modal composition, grain size distribution, specific surface area, and degree of liberation) and its evolution over time (e.g., depletion of certain minerals, buildup of a passivating layer of secondary minerals over sulfides and neutralizers), as well as their hydrogeological properties (e.g., hydraulic conductivity, water retention curve, and permeability function). In addition, extrinsic factors can also have a significant influence on the rates of reactions, such as climatic conditions (temperature, atmospheric humidity, etc.) and geochemical environments (pH, microbiological activity, degree of saturation, redox conditions, oxygen availability, etc.), which are closely linked to the management and reclamation techniques used. Consequently, the factors influencing the development of AMD conditions are discussed parallel to the hydrogeological and geochemical environments typically encountered in tailings storage facilities (TSFs) and waste rock piles. The reader is directed to Chapter 3 for a comprehensive description of fluid flow control (gas and water), which is responsible for these conditions.

1.3.1 MINERALOGICAL AND HYDROGEOLOGICAL PROPERTIES

The mineralogical composition of the materials, as well as their physical and hydrogeological properties, influence their reactivity. Obviously, the grain size distribution and degree of liberation of the reactive minerals within the materials, concomitant to their specific surface area and textures, have a significant impact on sulfide oxidation; finer grain sizes will present greater surface areas available to oxidation (e.g., Nicholson and Scharer 1994; Parbhakar-Fox et al. 2013; Kalyoncu Erguler et al. 2014; Erguler and Kalyoncu Erguler 2015; Elghali et al. 2018, 2019a, 2019b, 2019c). More particularly, the degree of liberation of minerals plays a key role in reactivity, as surface processes such as sulfide oxidation or acid neutralization will only be possible on exposed surfaces (e.g., Elghali et al. 2018, 2019c). Thus, efforts to predict the onset of acidic drainages from mine wastes (Chapter 2) may need to consider the differential segregation and degree of liberation of sulfides and neutralizing minerals within different grain sizes (Elghali et al. 2018, 2019a) in order to avoid inaccurate predictions, particularly for waste rocks.

Similarly, if the mine waste management scenario involves conditions favorable to a differential distribution of grain sizes (such as end- or push-dumping for waste rock piles and spigoting for TSF), the creation of local heterogeneities in material properties will induce a heterogeneous geochemical behavior (e.g., Bussière 2007). Furthermore, the differentiation of grain sizes will also have an effect on the hydrogeological properties of the materials governing gas and water movement through them (see Chapter 3 for a description of hydrogeological properties and their relationship with fluid movement).

The next section of this chapter discusses the influence of typical storage conditions of mine tailings and waste rocks on the development of acidic drainage. Chapters 4 to 9 detail on how to successfully design and implement reclamation scenarios using the materials' properties to control fluid movement and sulfide oxidation in tailings ponds and waste rock piles.

1.3.2 TAILINGS

The storage conditions of acid-generating mine wastes will have a significant effect on their geochemical behavior. Conventional TSFs are constructed by pumping a slurry that typically contains between

25% and 45% of solids retained within an impoundment (e.g., Bussière 2007). The tailings are often discharged from the crest of the surrounding dikes, and the natural segregation of the particles create beaches made of coarser and denser particles close to the discharge points, whereas the finer and lighter particles are transported further down the middle of the impoundment (e.g., Blight 2003).

The grain size distribution of hard rock mine tailings typically shows a D_{10} from 1 to 4 μm and a D_{60} ranging from 10 to 50 μm , whereas their proportion passing 80 μm vary between 70% and 97% (e.g., Bussière 2007). Upon consolidation, these tailings show typical porosity values between 0.33 and 0.5 (Bussière 2007). In conventional TSFs and under temperate climates, capillary forces between the grains can keep the water table close to the surface of the tailings at a variable degree of saturation, depending on the storage conditions. However, the water table can be much deeper in certain circumstances, for example, under arid climates or at the surface of high TSFs (approximately higher than 30 m). For more details, see the water covers, CCBEs, and EWTs in Chapters 6, 7, and 8, respectively.

Figure 1.4 illustrates the hydrogeological and geochemical environments in a typical profile of acid-generating tailings within a conventional TSF located under typical Canadian conditions (i.e., a wet climate). The degree of saturation is typically lowest at the surface and increases deeper within the vadose zone (unsaturated) to complete saturation below the capillary fringe, where the water table cycles up and down. Since oxygen can only migrate from the surface of the tailings downward (within the vadose zone), sulfide oxidation and acid generation mainly proceed from the top down. As the weathering progresses, the sulfides toward the surface are depleted and/or passivated with a rim of secondary oxyhydroxides, which allows the oxygen to migrate further beneath the surface and oxidize the sulfides deeper within the impoundment (gaseous O_2 profiles in Figure 1.4).

As the oxidation front migrates inward, a neutralization sequence develops within the tailings. Indeed, the different rates of acid neutralization shown in Figure 1.3 engender a series of sequential neutralization reactions upon weathering, which result in the progressive depletion of specific neutralizing phases, as observed in numerous tailings impoundments (Dubrovsky et al. 1985; Johnson et al. 2000; Blowes and Jambor 1990; Blowes et al. 1991; Lindsay et al. 2015). Blowes et al. (2003) outlined a sequence involving the following reactions with decreasing pH plateaus, as illustrated in Figure 1.4:

- pH 6.5–7.5: buffering by calcite and dolomite dissolution, precipitation of siderite, gibbsite $\text{Al}(\text{OH})_3$, and ferrihydrite $\text{Fe}(\text{OH})_3$;
- pH 4.8–6.3: buffering by siderite, precipitation of $\text{Al}(\text{OH})_3$ and $\text{Fe}(\text{OH})_3$;

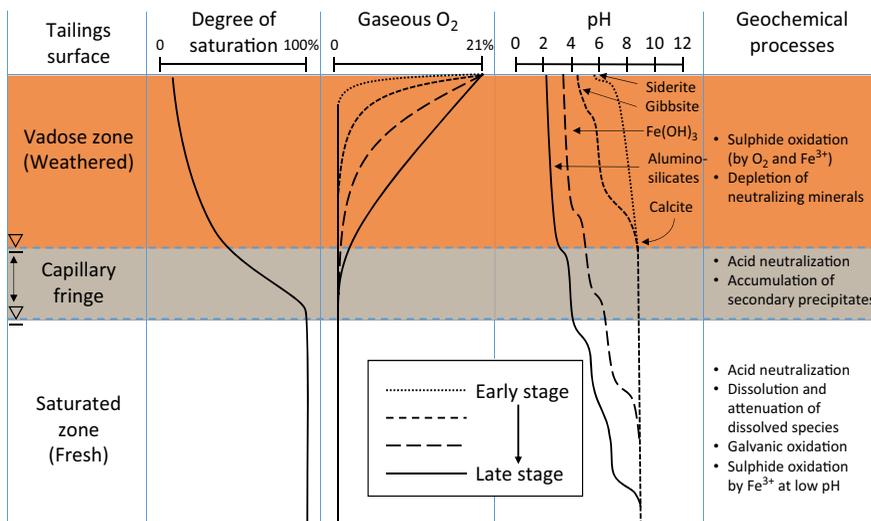


FIGURE 1.4 Hydrogeological and geochemical processes within AMD-generating tailings ponds.

- pH 4.0–4.3: buffering by $\text{Al}(\text{OH})_3$;
- pH 2.5 < 3.5: buffering by $\text{Fe}(\text{OH})_3$;
- pH < 3.0: buffering by aluminosilicates.

The soluble reaction products (from sulfide oxidation and acid neutralization) are transported by the infiltrating water toward the capillary fringe, where the water table height oscillates up and down, making this specific area particularly prone to secondary precipitations. As a result, secondary precipitates tend to accumulate near this capillary fringe and may cement the grains together into a hardpan (see Section 1.2.3), which significantly affects fluid movement through the tailings and, potentially, the effectiveness of reclamation methods based on fluid flow control (Gilbert et al. 2003; Ethier et al. 2018; Pabst et al. 2017, 2018; Ethier 2018; Elghali et al. 2019b).

Oxygen migrates significantly slower below the capillary fringe, where the tailings are saturated (see Chapter 3). Therefore, it is often hypothesized that the saturated zone mostly involves acid neutralization, dissolution of neutralization products, and attenuation of metals leached from the vadose zone. However, galvanic mechanisms are possible within the saturated zone, if two different sulfide particles are in contact within acidic and conductive waters, even if these conditions are limited to a microenvironment surrounding the grains involved. The iron pathway of sulfide oxidation is also possible where iron-rich waters are in contact with available sulfide surfaces, with the contribution from microorganisms.

The secondary minerals formed upon tailings and waste rock weathering can accumulate in acid-generating materials. Changes in microenvironment conditions will affect the stability of these minerals. For example, when submitted to wet–dry cycles, they will release part of their constituents (e.g., Fe, H^+ , SO_4^{2-} , and K^+), as well as the adsorbed and co-precipitated metals associated with them, back into drainage waters (e.g., Johnson et al. 2000; Moncur et al. 2005; Lindsay et al. 2015; Blackmore et al. 2018; Elghali et al. 2018). In addition to the acid released by the dissolution of acidic salts, the released Fe will undergo a second round of hydrolysis (Equation 1.3) to generate tertiary minerals, generating acid in the process (e.g., Moncur et al. 2005, 2009; Blowes et al. 2014). For this reason, highly oxidized mine wastes (such as in abandoned tailings facilities) will continue to generate acidic leachates even after complete depletion of the available sulfides (e.g., Elghali et al. 2019b).

This Fe release will also be increased when highly oxidized wastes are placed in more reduced conditions—for example, if an oxygen barrier–type cover is installed over tailings (e.g., see Chapters 6, 7, and 8). As a result, covering weathered AMD-generating tailings in a manner that prevents oxygen ingress will not instantly improve the water quality. Instead, a gradual improvement is to be expected, as a new equilibrium is established within the more reduced, induced conditions (e.g., Bussière et al. 2009; Ethier 2018; Ethier et al. 2018; Pabst et al. 2017, 2018). An increase in acid generation and metals release can even be anticipated within the first months or years after reclamation, which will gradually decrease upon depletion of the accumulated secondary iron oxyhydroxides (e.g., Ribeta et al. 1995; Ethier et al. 2018). In the meantime, it can be appropriate to install a passive treatment system in order to meet the water quality criteria (see Chapter 11 for a review of passive treatment methods).

1.3.3 WASTE ROCKS

Waste rock piles contain the non-economical rocks that were blasted to reach the ore. They consist of a wide range of particle sizes from fine, micron-scale grains to boulders of several meters, stockpiled either in a single bench or successive benches. The waste rock pile construction method influences geotechnical and hydrogeological properties by creating heterogeneities within the piles in terms of porosity and particle segregation (e.g., Smith et al. 2013; Dawood and Aubertin 2014; Amos et al. 2015; Lahmira et al. 2016, 2017). Typically, the surfaces where machinery circulates

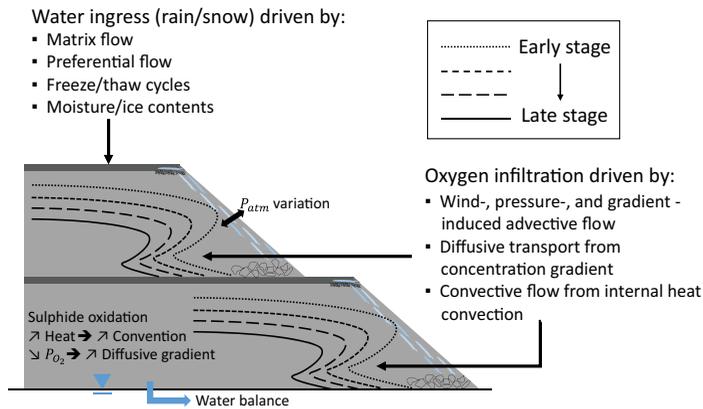


FIGURE 1.5 Hydrogeological and geochemical processes within AMD-generating waste rock piles; darker areas are made of denser, smaller particles (Modified from Amos et al. 2015; Lefebvre et al. 2001; Ritchie 1994).

will be composed of denser, smaller particles, while the extremities of the pile or benches show a segregation of particles, as the biggest boulders roll down the slope, while the smaller particles tend to remain upslope.

When waste rock piles are constructed in successive benches, each bench will show these heterogeneous properties, and the piles will show a succession of those heterogeneities. Figure 1.5 illustrates a conceptual model of a waste rock pile made of two successive benches (for more details, see also Chapter 13 on integrated mine waste management methods). As a result, fluid circulation within waste rock piles, and consequently the geochemical behavior of the materials within, will be driven by a complex arrangement of heterogeneous hydrogeological and geotechnical properties (e.g., Dawood and Aubertin 2014; Lahmira et al. 2016, 2017), as illustrated in Figure 1.5.

Water circulation in waste rock piles will be driven by matrix flow in areas with smaller particles and smaller pores exerting capillary forces, and by preferential flow paths where larger boulders offer bigger, more connected voids in which capillary forces are negligible (see Chapter 3 for details). Oxygen movement through the piles will be much easier than within tailings, as the bigger voids enable air to infiltrate all sides that are open to the atmosphere and move toward the core of the dump. In addition, wind- and gradient-driven advective flows will drive air inside the pile, as will conductive flows from the heat generated by sulfide oxidation and diffusive transport caused by the concentration gradient resulting from oxygen consumption inside the reactive zone of the pile (e.g., Amos et al. 2015; Lorca et al. 2016; Vriens et al. 2018). Consequently, waste rock piles will tend to be weathered from the exterior toward the interior of the benches, and as weathering progresses, oxygen is allowed to migrate further inside the pile, as illustrated in Figure 1.5, where the advancement of the weathering front is outlined (Ritchie 1994; Lefebvre et al. 2001; Amos et al. 2015). Finally, the results obtained by Blackmore et al. (2018) show that water quality in acid-generating waste rock piles is controlled by a combination of (hydro-)geochemical and microbiological mechanisms.

1.3.4 OPEN PITS

Open pits and underground galleries walls are also weathered upon exposure to atmospheric conditions until they are flooded and/or refilled. The soluble weathering products from the walls are transported down to the bottom of the pit and/or galleries (and eventually to the groundwater), where secondary precipitates are likely to accumulate (e.g., Blowes et al. 2014; Castendyk et al.

2015a, 2015b; Gammons and Duaiame 2006). When the pits or galleries are flooded, the secondary precipitates formed upon weathering may be solubilized under the more reduced conditions induced by flooding, which releases their constituents back into the flood water or the groundwater (e.g., Blowes et al. 2014) along with the sorbed and co-precipitated species associated with them. An extensive review of pit lake water quality can be found in the study by Castendyk et al. (2015a). Therefore, the presence of secondary precipitates in open pits and underground workings need to be assessed when planning the water management upon refilling. However, the sulfide minerals that remain over the surface of the flooded pit will continue to oxidize after flooding. In addition, if the pit lake is acidic enough and contains dissolved Fe^{3+} , the iron pathway of sulfide oxidation can continue even if O_2 is low within the pit lake (e.g., Pellicori et al. 2005; Gammons and Duaiame 2006). More details about pit backfilling are presented in Chapter 13.

1.3.5 TEMPERATURE

The temperature to which the mine wastes are exposed has a significant effect on their reactivity. Since sulfide oxidation is an exothermic reaction, the rate of oxidation increases with temperature, which increases heat production, feeding a chain reaction that can lead to high temperatures, especially within waste rock piles (e.g., Amos et al. 2015). In turn, this chain reaction induces pressure, oxygen concentration, and temperature gradients that promote gas convection through waste rocks, further promoting AMD. Indeed, temperatures over 65°C were recorded within the Doyon waste rock pile (Lefebvre et al. 2001).

Inversely, the decrease in the sulfide oxidation rate with decreasing temperature is often reported to follow an Arrhenius behavior (Equations 1.28 and 1.29; e.g., Coulombe et al. 2012; Elberling 2001, 2005; Meldrum et al. 2001).

$$k = A e^{\frac{-E_a}{RT}} \quad (1.28)$$

$$\ln \frac{k_2}{k_1} = -\frac{E_a}{R} \left(\frac{1}{T_2} - \frac{1}{T_1} \right) \quad (1.29)$$

where k_1 and k_2 are the reaction rates at temperatures T_1 and T_2 , respectively; E_a is the activation energy; A is a pre-exponential factor, and R is gas constant. The different iron oxidizers and sulfur oxidizers identified in the previous section are mesophiles that are optimally active within temperatures that mostly range between 20°C and 45°C (Blowes et al. 2014; Lindsay et al. 2015). Thus, lowering the temperature will decrease the rate of microbial processes involved in sulfide oxidation (e.g., Elberling 2001, 2005). In addition, since the different mechanisms of sulfide oxidation require aqueous media, freezing the wastes will significantly decrease the amount of liquid water and, consequently, the extent of oxidation that might occur. Therefore, the mine waste management and reclamation scenarios for many mines operating in cold environments are aimed at keeping their wastes frozen (see Chapter 9). However, the sulfides may oxidize below the freezing point, as demonstrated using oxygen consumption tests in mine tailings at temperatures between 0°C and -4°C (Elberling 2001; Meldrum et al. 2001; Coulombe et al. 2012) and as low as -11°C (Elberling 2005). Hence, for each site located in cold environments, it is crucial to determine the temperature at which the mine waste can be considered non-acid-generating (T_{target} ; see Chapter 9 for more details).

Since acid generation accelerates when the pH reaches acidic values (as described in Section 1.2.1), sulfide oxidation needs to be slowed down as early as possible upon surface deposition or at least during the lag time before AMD is clearly established. When tailings are stored in such a way that the oxygen ingress is significantly slowed down, then acid generation will be equally decreased. The same reasoning applies to freezing acid-generating tailings in order to diminish sulfide oxidation through liquid water availability and temperature control.

1.4 RESEARCH NEEDS

Despite the extensive research performed since the 1970s on the geochemistry of AMD generation, many knowledge gaps remain and require additional research. This section describes current research needs.

- *The influence of management and reclamation methods on AMD generation and water quality*
The impacts of novel mine waste management and reclamation methods (e.g., desulfurization, progressive reclamation, segregation, co-disposal, backfilling, densified tailings, etc.) on the generation of AMD need to be investigated. More specifically, the impact of gas and water flow through the mine waste disposal areas on the geochemical response of the materials need to be understood in order to determine their short- and long-term effects on drainage water quality.
- *Geochemical behavior of weathered AMD-generating mine wastes after reclamation*
More research efforts need to be invested toward understanding the time needed for reclaimed sites containing weathered mine wastes to stop generating AMD, including through the use of numerical reaction transport tools. Further research on the long-term effectiveness of reclamation methods based on freezing the mine wastes should also be conducted, particularly to understand the geomicrobial mechanisms that occur below the freezing point.
- *Geometallurgical tools and geoenvironmental modeling*
There is an increasing interest in the use of automated mineralogical tools to identify potential contaminants and their source terms (e.g., Parbhakar-Fox et al. 2013; Benzaazoua et al. 2017; Elghali et al. 2018). However, automated mineralogical analyses are used on a case-to-case basis, and results interpretation relies on the sole expertise of the geochemists analyzing the data. Therefore, more research is needed to develop and test systematic approaches that would enable the identification of potential contaminants as early as possible in the mining cycle (e.g., during exploration and feasibility studies) while taking into account the factors that influence their potential release in mine waters (e.g., their texture, degree of liberation, and mineralogical associations).
- *Microbial processes involved in the geochemistry of mine wastes*
Recent advances in culture-independent techniques, which are based on the analysis of DNA or RNA extracted directly from environmental samples without the need for prior cultivation, have exponentially increased knowledge on microbial communities in mine wastes. These techniques have revealed that the microbiomes of mine wastes and acidic drainages are comprised of complex consortiums of bacteria, archaea, and Eukaryotes (e.g., Auld et al. 2013; Baker and Banfield 2003; Hallberg 2010; Hua et al. 2015; Johnson 2007; and references therein). Hence, the development and democratization of these genomic techniques will help fulfill research needs in microbiological involvement in the development of contaminated mine waters. Among other aspects, there needs to be additional research into the influence of pH, salinity, dissolved oxygen, and organic carbon availability on the microbiological involvement in S and Fe cycling in mine wastes, as well as on identifying the microbial involvement in sub-zero sulfide oxidation.
- *Water quality prediction using numerical reactive transport modeling tools*
Numerical reactive transport modeling tools, such as MIN3P (Mayer et al. 2002), have been demonstrated to adequately reproduce the geochemical and hydrogeological processes in a wide variety of settings, from mine tailings reclamation scenarios (e.g., Molson et al. 2008; Pabst et al. 2017) to water treatment using reactive barriers (e.g., Mayer et al. 2001; Weber et al. 2013), including isotopic fractionation during groundwater treatment processes (e.g., Gibson et al. 2011; Jamieson-Hanes et al. 2017). More recently, numerical reactive transport modeling tools have been used to successfully predict the water quality of intermediate-scale field lysimeters containing over 9000 kg of waste rocks using a conceptual model based on

laboratory-derived rates of reaction (Wilson et al. 2018a, 2018b). However, more research is needed to better define the proxies necessary to scale the laboratory results up to intermediate and full scales.

- *CND or metal leaching from mine wastes*

As environmental regulations related to mining become more restrictive, and as the mining industry seeks to continually decrease its environmental impacts, increasing research and development efforts are driven toward understanding CND development and its prevention, control, and treatment. Although CND is not discussed in this chapter, the mechanisms leading to its development are the same as for AMD, and many of the research needs identified for AMD are also applicable to CND.

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