MINERALS AND MINE DRAINAGE

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This chapter reviews the literature pertaining to environmental processes that affect mineral dissolution reactions and the generation of acid mine drainage, the fate and transport of metal contaminants within the environment, the toxic influences of metals and mine drainage on aquatic species, characterization of abandoned mines and their potential for contamination, and technologies for remediation of mining-impacted systems or removing metals from wastewater streams.

SITE CHARACTERIZATION AND ASSESSMENT

An important initial step during remediation plan development for mining-impacted areas is the assessment of a site's geologic composition and characterization of the future contamination potential. Airborne electromagnetic and magnetic surveys were used to provide an indication of metallic sulfide distribution in Copper Cliff (northern Ontario, Canada) (Shang et al., 2001). This technique was capable of providing information on mine tailing extent and showed promise for reducing ambiguity about interpreting mine tailing distribution and alterations in composition over time. Rare earth element (REE) fingerprinting was utilized to identify sources of acidic drainage and to better understand water-rock interactions in the Durham basin (England) (Worall and Pearson, 2001). Czaja (2001) prepared an account of the influence of mining and hydrological transformations in Upper Silesia (Poland) from the fifteenth to nineteenth centuries and described changes in environmental pollution relating to mining activity.

The potential for long-term pollution from an open cast lignite mine in Germany (the Janschwalde dump) was evaluated using a three-dimensional geochemical model to calculate the pyrite oxidation in different parts of the mine (Rolland et al., 2001). Another predictive modeling study was performed at the Janschwalde dump and coupled transport phenomena and a geochemical equilibrium model to simulate redox reactions, mineral dissolution and precipitation, and cation exchange in the groundwater zone (Hoth et al., 2001). A hydrochemical model was developed and applied at three waste mine rock sites to assess the potential threat of mining-related pollution (Banwart and Malmstrom, 2001). The authors attempted to estimate the amount of neutralization capacity present as calcite or magnesium silicate; however, due to the estimated length of time required to model acid generation (on the order of centuries), the model predictions developed had a high degree of uncertainty associated with them. A reactive transport model was used to evaluate geochemical reactions in porewater following closure of a former uranium mine (Konigstein mine in Sasony, Germany) (Bain et al., 2001). Dumpleton et al. (2001) conducted a risk evaluation for groundwater contamination below a concealed section of the South Nottinghamshire Coalfield (England) using 3-D visualization and predictive modeling. The authors identified the potential for groundwater contamination from the site for about 20 years after the end of dewatering operations. An investigation on the impact of regional groundwater flow on water quality in a post-mining lake indicated that there was a high probability that the lake (Lake Senftenberg, Germany) would be subject to acidification reactions by as early as 2010 (Werner et al., 2001). Razowska (2001) reports changes in groundwater chemistry resulting from the flooding of abandoned iron mines (in southern Poland) and developed a model to identify the impact of hydrological and hydrochemical processes on groundwater contamination. The author concluded that without remedial action, the residual pollution of groundwater in the flooded mines may persist for several centuries.

Tiwary (2001) provided a review of the environmental impact of coal mining on water quality and described water quality characteristics of coal mining-impacted systems and management strategies to minimize further pollution. Aston (2001) prepared a review of water pollution at abandoned mines sites, factors affecting acid mine drainage formation, and techniques that are applicable for reclaiming mined land. The impact of mining on water quality was studied at two sites in Korea and the influence of mineralogy and subsequent dilution were studied (Kang et al., 2001; Yu and Heo, 2001; and Kim and Chon, 2001). Factors affecting the reactivity and acidification potential of pyrite were studied with respect to sulfide impurities (Cruz et al., 2001) and sediment-specific properties such as cation exchange capacity and silica weathering potential (Ludwig and Balkenhol, 2001). A site assessment comparing pre- and post-reclamation conditions at a coal mine in Indiana (Green Valley, USA) indicated that ferrous iron sulfate aqueous species were in equilibrium with solid iron compounds, thereby presenting a continuing challenge to water quality (Brake et al., 2001a). Stuben et al. (2001) conducted a monitoring program for heavy metals and arsenic and characterized the mineralogical and chemical nature of the waste mining material. The study identified particulate emissions from the boundary of the tailing piles as a continuous source of pollution.

The occurrence of arsenic, copper, and zinc at a coal mine (Wangaloa, New Zealand) was studied and mobilization of these metals over several seasons was attributed to low pH mineral leaching (Black and Craw, 2001). An analysis of redox and pH conditions in the sediments of an acidic mining lake (in the Lusatian region of Germany) identified the importance of different iron compounds in the physico-chemical stability at different values of pH (Batchman et al., 2001). The influence of subzero temperatures on mineral oxidation was studied using a field-scale experimental program and the lower temperatures were found to result in a substantially lower mineral oxidation rate compared to temperatures greater than 30^oC (Meldrum et al., 2001). A one-dimensional soil water and heat model was calibrated and tested at an arctic site. Model results were in good agreement with experimental data indicating that subzero temperature conditions did exist in covered mine tailings (Kyhn and Elberling, 2001). Furthermore, the generation of acidity was quantified under subzero conditions by monitoring oxidation products and oxygen consumption in situ (Elberling, 2001). Bell et al. (2001) reported on the environmental impacts associated with an abandoned mine in the Witbank Coalfield (South Africa) and identified the deterioration of aquatic flora and fauna in a nearby stream. Craw (2001) studied the environmental impacts of mineral deposits in New Zealand and developed a relationship between metal release pathways and factors such as tectonic setting, mineralogy, and climate.

PROTECTION, PREVENTION, AND RESTORATION

Geological mapping and overburden data were used and analyzed by a modeling program to identify areas of coal reserves that could be remined for the purpose of improving water quality (Smith and Skema, 2001). A flue gas desulfurization byproduct was used as a material for a mine seal due to its low hydraulic conductivity and high alkalinity (Rudisell et al., 2001). Results of the study indicate that the seal has retained water within the mine complex, resulting in decreased contaminant loads to receiving waters. The effectiveness of bentonite as a barrier for containing acidic drainage was assessed and results indicated that permeation of the bentonite by acid mine drainage resulted in an increase in the hydraulic conductivity by more than an order of magnitude (Kashir and Yanful, 2001). An investigation on the long term water quality trends at a sealed, partially flooded underground mine was conducted and the authors reported an increase in mine water pH from 2.7 to 5.3, a decrease in conductivity from 2700 to 600 S/cm, and a dissolved oxygen level less than 2% saturation (Stoertz et al., 2001). Pyrite-containing mine waste was treated with phosphate or silica solutions to minimize and control pyrite oxidation by creating an impermeable coating that prevented pyrite oxidation (Evangelou, 2001). Field test plots of waste mine material amended with alkaline paper mill waste exhibited lower acidity and metal concentrations in leachate samples than control cells without the treatment, indicating that adding alkaline paper mill waste either mixed with mine material or as a cover could be an effective technique for minimizing mineral oxidation reactions (Chtaini et al., 2001). To improve the groundwater quality in tailing piles and dumps, the addition of crushed limestone or a mixture of limestone and fly ash was evaluated (Wisotzky and Obermann, 2001). Land contaminated with lead and zinc processing wastes was reclaimed using phytostabilization, which was deemed to be the most suitable management approach for the area (Leteinturier et al., 2001). Frazer (2001) provided a review of the extent of acid mine drainage in the United States and throughout the world and described techniques prevent acid drainage from occurring and treat acidic drainage before it enters a receiving stream.

TOXICITY ASSESSMENT

An integrative assessment of the toxic influence of mine drainage on aquatic organisms was studied using ten parameters that were directly related to acid mine drainage and an ecotoxicological rating (ETR) was developed to identify and diagnose at-risk sites (Cherry et al., 2001). Twelve of 15 sampling stations affected by acidic drainage were categorized as "severely stressed" and therefore deserving of a high priority placement for restoration. Another study reported that aluminum contamination at near neutral pH resulted in acute toxicity response for *Ceriodaphnia dubia* and that the presence of iron could lower the toxic influence of other metals such as aluminum, copper, and zinc (Soucek et al., 2001). A field experiment demonstrated the adverse effect of acid mine drainage inflow on phytoplankton mortality (a decrease in numbers by a factor of 2-5) in a natural reservoir (Bortnikova et al., 2001). Twenty-eight streams were sampled seasonally in the Hocking River drainage basin (Ohio, USA) to identify the influence of acid mine drainage on macroalgal communities (Verb and Vis, 2001). The authors reported that they were unable to utilize the macroalgal community to detect differences among reclaimed sites and clean streams; however, two taxa (*Klebsormidium rivulare* and *Microspora tumidula*) did appear to be useful assessors of acid mine drainage impact. The influence of pollution from a disused coal mine on two Coleoptera families (*Hydraenidae* and *Elmidae*) was assessed at the assemblage level by studying basic community parameters (Garcia-Criado and Fernandez-Alaez, 2001); however, the authors report that these families are not specific indicators for coal mining-associated drainage since their response to other types of pollution was similar.

Stevens et al. (2001) studied the metal content of algal mats taken from acid mine drainage waters in southeastern Ohio (USA) and reported that metal assays of algal mats may be a good indicator for iron concentration in water but not for aluminum, zinc, or manganese. High concentrations of sulfate were found to have an adverse effect on growth of a benthic photosynthetic protozoan (*Euglena mutabilis*) in acid mine drainage contaminated stream originating from an abandoned coal mine (Brake et al., 2001b). However, the researchers observed that *E. mutabilis* had a high tolerance for elevated total dissolved solids (TDS) and acid conditions (as low as pH 1.7) and may be capable of naturally mitigating poor water quality by sequestering iron (Brake et al., 2001c). To quantify the effects of acidic drainage on macroinvertebrate assemblages in

Rocky Mountain streams, Griffith et al. (2001) used redundancy analysis (RDA) and canonical correspondence analysis (CCA) to assess relationships among the chemical and physical characteristics of drainage water and macroinvertebrate community size. The influence of acidic mine drainage on leaf litter in receiving streams was shown in laboratory studies to decrease the rate of littoral breakdown, which was attributed to the absence of shredders (Siefert and Mutz, 2001). Niyogi et al. (2001) conducted a similar study of litter breakdown in a mountain stream and estimated the litter breakdown rates from changes in mass of willow leaves in litterbags. The investigators found that the biomass of shredding invertebrates was negatively related to the concentration dissolved zinc and deposition of metal oxides and that microbial respiration was positively related to the concentrations of nutrients. The toxic effect of heavy metals to acetate-utilizing cultures of sulfate-reducing bacteria was studied in an effort to identify the optimal operating conditions for sulfate-reducing treatment systems (Utgikar et al., 2001). The authors report that dissolved metal concentrations were effective as indicators of the effect of heavy metals.

To identify the effect of acidic drainage on fish and insects, Saiki et al. (2001) tested copper, cadmium, and zinc concentrations in juvenile Chinook salmon and selected aquatic insects in the upper Sacramento River (California, USA). The results of the study demonstrated that the dry-weight concentrations of copper, cadmium, and zinc were generally greater in salmon and insects obtained from the study site than from reference sites. The toxicity of acid mine drainage entering a stream was identified by placing bluegill (*Lepomis macrochirus*) at the confluence of a neutral stream and a stream contaminated with acid mine drainage (Henry et al., 2001). The study concluded that aluminum precipitation on the gills of the bluegill was more rapid than iron accumulation and that mixing zones could be more toxic to fish than equilibrated zones. Duis (2001) studied the toxic effect of acid mine drainage on the early life stages of tench (*Tinca tinca*) and reported that at pH less than 5.5, tench embryos were not able to survive.

The influence of limestone treatment was studied with respect to physiology and behavior of stonefly nymphs and no significant difference was observed between nymphs exposed to treated effluents and those exposed to non-polluted controls (Cole et al., 2001a). Limestone neutralization of acid mine drainage was also found to significantly decrease metal toxicity in brook charr compared to untreated drainage water despite the presence of moderate manganese concentrations (3-4 mg/L) in the limestone-treated water (Cole et al., 2001b). Another study tested blood physiological variables as well as behavior in fish exposed to limestone-neutralized acid mine drainage (Ross et al., 2001). The authors report that while elevated levels of carbon dioxide or bicarbonate can lead to some behavior abnormalities in fish, the overall risk associated with limestone neutralization are minimal. Grout and Levings (2001) studied the effects of acid mine drainage from an abandoned copper mine on the growth of transplanted blue mussels (*Mytilus edulis*) and observed that the mine effluent had a deleterious impact on mussel survival. A study of metal toxicity in plants (*Mimulus guttatus*) indicated that the acquisition of multiple metal tolerance in this species was due to independent genetic mechanisms for specific metals and was not associated with tolerance to nickel (Tilstone and Macnair, 2001).

ENVIRONMENTAL FATE AND TRANSPORT

Microscale measurements of oxygen in laboratory studies were compared to in situ profiles in an effort to identify the effectiveness of maintaining subaqueous conditions in waste mine pits for controlling pyrite oxidation (Elberling and Damgaard, 2001). McGuire et al. (2001) used near-infrared Raman imaging microscopy to map elemental sulfur on pyrite and arsenopyrite and found that elemental sulfur was present in isolated patches on the mineral surface with diameters of approximately 10 micrometers. The fate, transport, and speciation of metals leaching from an abandoned gold and silver mine were identified using geochemical modeling techniques and anodic stripping voltammetric analysis (Yun et al., 2001). A coupled multi-component reactive mass transport model was developed and applied to predict the natural attenuation of a metal-laden groundwater plume originating from a uranium mill tailings site in the western US (Zhu and Burden, 2001). The results of model simulations under field conditions indicated that mineralogical compositions are an essential component of models to ensure that an accurate prediction of contaminant fate and transport is obtained. Lefebvre et al. (2001a and 2001b) developed a multiphase conceptual model and applied a numerical simulation to represent the interaction of the multiple reactions within a waste mine rock environment and utilized simulation results to predict the effectiveness of control measures (application of a membrane barrier and layering of tailings). Metal release from a copper mine in Italy (the Vigonzano mine) was investigated by analyzing waste mine materials, surrounding surface soils, sediment samples, and stream water (Dinelli and Tateo, 2001). The researchers report that the alkaline character of ultramafic rock in the area limited the transport of metal contamination from the mine. A multi-component reactive transport model (REACTRAN2D) was used to simulate the transport of reactive species in saturated and unsaturated groundwater systems affected by acid mine drainage (Gao et al., 2001). The influence of physical and chemical heterogeneity associated with pyritic overburden on solute leaching and the subsequent transport in a tailings pile were tested and modeled for mineral systems with different relative sulfide content (Gerke et al., 2001).

Suspended particles associated with iron were found to significantly influence the geochemical reactions in mountain streams and represented a potential source or sink for phosphorus (Sullivan and Drever, 2001a). The influence of mine drainage on the spatial and temporal (on both daily and seasonal scales) geochemistry of a high-elevation mountain stream was studied and order of magnitude changes in geochemical species were observed due to variations in stream dilution and precipitation of solids (Sullivan and Drever, 2001b). Brooks et al. (2001) identified annual patterns for zinc concentrations in mine drainage-impacted streams affected by snowmelt and reported that a portion of the zinc flushed during snowmelt events was retarded (compared to sulfate). The authors attributed this to interaction with cation exchange sites in soil and sediment. The influence of pH on precipitation and dissolution of iron hydroxides, photoreduction of dissolved iron and hydrous iron oxides, and oxidation of ferrous iron was studied in an acid mine drainage-impacted mountain stream and diel changes in iron species were characterized with a reactive solute transport model (McKnight et al., 2001). In an effort to develop a predictive relationship between geochemical parameters in mining polluted rivers, Gundersen and Steinnes (2001) sampled eight rivers in Norway for metal concentration (copper, zinc, cadmium, and aluminum), alkalinity, pH, and river discharge. Results of the study indicated that the dissolved fractions of zinc, cadmium, and aluminum showed a negative correlation with river discharge (i.e., they were low at high magnitudes of discharge) whereas copper speciation was more directly influenced by the river pH. Cobalt and copper geochemistry in the Kafue River (Zambia) was studied over a one year period (Pettersson and Ingri, 2001). The authors report that the highest dissolved concentrations of copper and iron were measured during periods of high water discharge from the abandoned mine site, suggesting that washout of leached weathering products from spoil heaps was a dominant factor in metal release.

A study of the hydrogeochemistry of mine, surface, and groundwater from a mining-impacted creek (Korea) indicated that although the mine drainage contained metals at concentrations tens to hundreds of times greater than the unpolluted surface or groundwater, the majority of toxic metal pollutants were removed during precipitation of aluminum and iron oxyhydroxides (Lee et al., 2001). In an effort to quantify subsurface mine drainage inflow to Little Cottonwood Creek (Utah, USA), Kimball et al. (2001) conducted a tracer injection and synoptic sampling study. Results of the investigation indicated that inflow of acid mine drainage resulted in the formation of colloidal mineral solids which adsorbed and accumulated on the streambed. To quantify the effects of bacterially-induced mineralization of schwertmannite and jarosite in sulfuric acid spring water, Kawano and Tomita (2001) conducted laboratory incubation experiments to determine iron oxidation rates in the presence and absence of bacteria. The study concluded that the iron oxidation rates for Fe^{2+} were 5.3×10^3 to 7.2×10^3 times greater in microbe-containing systems than abiotic systems, suggesting that formation of the iron minerals is promoted by bacterially-mediated iron oxidation.

In an effort to model metal adsorption in sulfate-rich waters and better understand the influence of adsorption reactions on metal speciation in acid mine drainage, Swedlund and Webster (2001) conducted laboratory experiments to calculate intrinsic adsorption constants for copper and zinc sorption to ferrihydrite and schwertmannite. The authors report that metal adsorption could be accurately modeled for both copper and zinc in the presence of ferrihydrite and schwertmannite. The influence of dissolved ferrous iron (Fe^{2+}) in acid mine drainage on the reductive dissolution of MnO_2 was investigated using a flow through reaction cell and synchrotron X-ray absorption spectroscopy (Villinski et al., 2001). The authors observed a decrease in the rate of manganese oxidation during the course of experiments and attributed this to the formation of an intermediate, solid-phase complex on the mineral surface. Microcosm experiments were performed with sediment samples obtained from a coal mining-impacted lake to study the microbially-mediated release of sulfur under anoxic conditions (Kusel et al., 2001). Results suggested that acid-tolerant sulfate-reducing bacteria played an important role in the anoxic cycling of sulfur and that pH was an important controlling factor.

REMOVAL TECHNOLOGIES

A zeolitic material synthesized from coal fly ash was evaluated for heavy metal removal from acid mine drainage waters (Moreno et al., 2001). The treated effluent contained 0.1 mg/L or less for zinc, copper, manganese, lead, and cadmium with removal of iron possible down to 0.8 mg/L. Both precipitation and cation exchange were identified as the dominant removal mechanisms. Canty and Everett (2001) conducted a physical and chemical evaluation of coal combustion byproducts (CCBs) for treatment of metal-laden, acidic drainage water. The authors report that CCBs with a high alkaline content, nonsetting characteristics, and a low content of exchangeable toxic constituents may be effective for treating acid mine drainage streams. Morgan et al. (2001) studied a one step ferrite process for treating iron and heavy metals in acid drainage. Removal efficiencies up to 99.9% for iron were reported with production of a solid product with good settling characteristics (sludge volume index, SVI, of 8 mL/g). An investigation of copper adsorption on olivine concluded that the mineral has a high acid buffer capacity and is an effective adsorbent for copper present in acidic drainage (Kleiv et al., 2001). Underground mine water was found to have a deleterious effect on the performance of a floatation process operating at a copper mine; however, by adjusting the location of quicklime addition to the process, minimization of the negative effects was achieved (Ng’andu, 2001).

A study of the factors affecting alkalinity generation by successive alkalinity-producing systems (e.g., limestone drains) found that the residence time within the treatment system and the influent concentration of iron acidity both exhibited a strong positive correlation with alkalinity generation (Jage et al., 2001). Mohan and Chander (2001) utilized activated carbon adsorption to recover metals present in acid mine drainage and reported that the Langmuir isotherm model fit the data better in single component systems but the Freundlich isotherm was a better model in multi-component systems. Bunce et al. (2001) studied the electrochemical treatment of acidic ferrous sulfate and copper sulfate solutions and observed near-quantitative removal of iron when air was sparged into the catholyte effluent, which led to iron precipitation outside the electrochemical cell. Electrochemical peroxidation of metal-rich streams was studied and the effects of pH, hydrogen peroxide (H_2O_2), and electric current process times on metal removal efficiency were identified (Arienzo et al., 2001). The authors reported optimal operating conditions at pH 6.0, a H_2O_2 concentration of 100 mg/L, and a process time of 3 minutes.

A constructed wetland was tested for its efficiency in treating acid mine drainage entering Slippery Rock Creek (Pennsylvania, USA) (Brenner, 2001). It was estimated that since the initial wetland construction in 1995, 39% of the acidity in the mine drainage was removed and approximately 192 kg of alkalinity was added. Sikora et al. (2001) developed design criteria for removing manganese using subsurface wetlands. The authors reported that manganese removal was higher in limestone than gravel and was likely influenced by the higher pH in the limestone system (6.9) compared to the gravel system (5.5). Oxygen levels between 3 to 5 mg/L were required for favorable manganese removal. Lead and zinc removal (90% and 72%, respectively) from neutralized mine effluent was reported in a laboratory-scale constructed wetland system (Song et al., 2001). Whole effluent toxicity tests using undiluted wetland effluent with fathead minnows and *Daphnia magnia* resulted in 100% survival of both types of organisms. A seasonal study was conducted to measure the retention and transformation of both dissolved and particulate iron and manganese in a constructed wetland (Goulet and Pick, 2001a). Results indicated that the wetland mediated transformation of dissolved iron and manganese to particulate species from spring to fall; however, during the winter, dissolved iron and manganese were released. Diel changes in iron concentration in a subsurface wetland were measured, with the lowest iron concentrations measured during the day and higher concentrations at night (Goulet and Pick, 2001b). As a result of these variable conditions, the authors suggest that wetland performance can be overestimated when based solely on samples collected during the day. The presence of cattails (*Typha latifolia*) was found to have no significant effect on the accumulation and partitioning of metals in the surficial sediments of a subsurface flow constructed wetland (Goulet and Pick, 2001c). Metal retention in a constructed wetland was evaluated by measuring metal content of a common pond snail (*Helisoma trivolvis*) (Goulet et al., 2001a). The authors report that in general, metal concentrations in snails at the downstream end of the wetland were higher than those near the inlet and suggested that the higher concentration of metal particulates at downstream locations facilitated metal uptake from the metal precipitates. A comparison of heavy metal accumulation in a natural and constructed wetland receiving acid mine drainage indicated that loading rates and removal efficiencies for most metals were generally higher in constructed wetlands than natural systems (Mays and Edwards, 2001). Goulet et al. (2001b) studied the applicability of the first order removal model for metal retention in a constructed wetland and reported that the model was inadequate to predict metal retention on a seasonal basis. The authors proposed that models incorporate both a temperature and hydrological variable to account for seasonal changes.

BIOLOGICAL CHARACTERIZATION AND TREATMENT

A full-scale rotating biological contactor was used with *Thiobacillus ferrooxidans* (an iron-oxidizing microorganism) to oxidize ferrous iron in mine drainage water (Nikolov et al., 2001). While the efficiency of the system was reported to decrease with increasing volumetric loading rates, the authors commented on the promise of the technology. Sand-immobilized *T. ferrooxidans* cells were studied in repeated batch and continuous flow packed bed bioreactors for treating acid mine drainage (Wood et al., 2001). At a dilution rate of 0.64 hr^{-1}, between 95-99% of the influent ferrous iron was oxidized, equivalent to an iron oxidation rate of 0.31-0.33 g/L-hr. Another study evaluated the use of microorganisms for ferrous iron oxidation as a pre-treatment strategy for metal recovery from mine drainage (Sandstrom and Mattsson, 2001). The pilot plant achieved a steady state rate of 750 mg/L-hr with an initial ferrous iron concentration of 3.5 g/L, a pH of 1.8, a flow rate of 330 L/hr, and a temperature of 35^{o}C. Mazuelos et al. (2001) studied the influence of pH, temperature, particle size, support material, and air distribution on ferric iron production in a packed bed bioreactor inoculated with *T. ferrooxidans* and *Leptospirillum ferrooxidans*. The study reported maximum iron oxidation rates of 11.1 g/L-hr and emphasized the importance of the type of air diffuser since poor oxygen transfer can limit the iron-oxidizing activity of the system.

A mixed culture of sulfate reducing bacteria (SRB) that was isolated from the bottom of a pyritic tailing pond was evaluated for its capacity to bioremediate acid mine drainage (Garcia et al., 2001). Copper and iron were successfully removed and the microbial culture was able to remove up to 9,000 ppm of sulfate at pH > 4. Harris and Ragusa (2001) used decompostable plant material and soil (non-lime) in a continuous flow bioreactor to pre-treat acid mine drainage prior to use in sulfate-reducing conditions. The authors reported increases in pH and decreases in the concentration of soluble iron, aluminum, and sulfate. Kolmert and Johnson (2001) used SRBs immobilized on porous glass beads to remediate acidic mine water and evaluated the process efficiency using different carbon and energy sources. Typical conversion rates of 0.25-0.30 g/L-day were achieved with the bioreactors operating at a pH = 4. A laboratory pilot-scale SRB bioreactor fed with a H_2/CO_2 mixture was used to treat acid mine drainage in an effort to recover dissolved metals (Foucher et al., 2001). The system was capable of selectively recovering copper and zinc at pH = 2.5 and 3.5, respectively. Ristow and Hansford (2001) modeled a falling sludge bed reactor fed with primary settled sewage for sulfate reduction of acid mine drainage streams. The authors identified hydrolysis of particulate organic matter as the rate-limiting step in the process and commented on the importance of monitoring sulfide inhibition during treatment. The microbial ecology of iron-rich wetland sediments receiving acid mine drainage was assessed using gel probes that were inserted into sediment (Edenborn and Brickett, 2001). Results from field testing of the gel probes resulted in significantly different depth profiles from the SBR activity measured in situ. The authors reported that selective use of the substrate material might account for the observed differences. Conductivity measurements were correlated to SRB activity in fed-batch column reactors treating acid mine drainage, with increases in conductivity observed during treatment (Lyew and Sheppard, 2001). Benner et al. (2001) developed a model to identify and predict preferential flow in reactive barriers used to treat metal-containing, acidic drainage water. Model simulations indicated that the impact of heterogeneities in the hydraulic conductivity (K) were a function of their location and distribution within the barrier and more localized high K zones resulted in greater preferential flow.

Hallberg and Johnson (2001) compiled a review describing the biodiversity of acidophilic prokaryotes in acidic environments. The authors examined the characteristics of the different acidophiles identified to date and discussed novel microbial cultures and their potential impact on acid generation reactions. In an effort to study the microbial ecology of acid mine drainage environments and identify active microbial species, Bond and Banfield (2001) developed and used oligonucleotide probes and fluorescent in situ hybridization (FISH) techniques. In another study, bacteria in acid mine drainage were monitored by reverse sample genome probing and strains showing homology with *T. ferrooxidans* and *Thiobacillus acidophilus* were found to be a major component of the microbial community (Leveille et al., 2001). This enabled the authors to study the abundance and distribution of organisms, including novel and uncultivated taxa, and better understand the specific influence of each group on the catalysis of acid-producing reactions. The structure and diversity of microbial mats in an acidic (pH 3.1) thermal (ca. 60^{o}C) spring in Yellowstone National Park (Wyoming, USA) was investigated (Jackson et al., 2001). Based on the experimental results, the authors report that uncultured members of the Archaea microbial domain may contribute to arsenite oxidation in the acidic hot springs. Provencio and Polyak (2001) report the finding of iron oxide-rich filaments in a Lechuguilla Cave (New Mexico, USA) and suggest that the samples represent fossilized, acidophilic iron-oxidizing bacteria. The influence of acidophilic, iron-oxidizing microorganisms on iron-silicate dissolution and subsequent solution neutralization was studied using model chemolithotrophic bacteria and an iron-containing silica mineral, fayalite (Santelli et al., 2001). Results of the study indicated that microorganisms can significantly reduce the rate at which silicate hydrolysis reactions neutralize acidic solutions. The mechanism associated with this phenomenon was reported to be related to the interaction of the ferric iron byproduct of microbial metabolism with the mineral surface.

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