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Commentary

COMMENTARY – Environmental Microbiology

A case in support of implementing innovative bio-processes in the metal mining industry

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One sentence summary: Toxic acid and metal-containing waters can be remediated by sulfidogenic microorganisms. If the process is pH-controlled, different metals can be separated and reused for industrial applications.

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ABSTRACT

The metal mining industry faces many large challenges in future years, among which is the increasing need to process low-grade ores as accessible higher grade ores become depleted. This is against a backdrop of increasing global demands for base and precious metals, and rare earth elements. Typically about 99% of solid material hauled to, and ground at, the land surface currently ends up as waste (rock dumps and mineral tailings). Exposure of these to air and water frequently leads to the formation of acidic, metal-contaminated run-off waters, referred to as acid mine drainage, which constitutes a severe threat to the environment. Formation of acid drainage is a natural phenomenon involving various species of lithotrophic (literally 'rock-eating') bacteria and archaea, which oxidize reduced forms of iron and/or sulfur. However, other microorganisms that reduce inorganic sulfur compounds can essentially reverse this process. These microorganisms can be applied on industrial scale to precipitate metals from industrial mineral leachates and acid mine drainage streams, resulting in a net improvement in metal recovery, while minimizing the amounts of leachable metals to the tailings storage dams. Here, we advocate that more extensive exploitation of microorganisms in metal mining operations could be an important way to green up the industry, reducing environmental risks and improving the efficiency and the economy of metal recovery.

Keywords: mining industry; acidophiles; sulfate-reducing bacteria; selective metal precipitation

Metal mining is of crucial importance for the global economy, as its products are used in many industries and numerous and diverse applications. However, the supply of many minerals and metals is hardly keeping pace with their rapid increase in consumption, while accessible metal ore reserves are depleting. As an example, calculations on the production of copper have suggested that it will peak by 2040 and then decline (Kerr 2014). Improving extraction technologies are predicted to

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Figure 1. View of the Tinto River, an acid rock drainage environment. The rust-brown color is due to dissolved ferric iron. The water column has a pH of around 2.3 and contains elevated concentrations of several other transition metals, including copper and zinc.

delay this peak just by a further two decades. The increasing demand of metals and the convenience of continuing to operate existing mines have resulted in lower grade and polymetallic ores being exploited, and consequently there has been a substantial increase of waste rock material in recent decades (Mudd 2007). The overall estimated production of solid metal waste around the world is up to 20 000–25 000 Mt annually (Lottermoser 2010). For instance, gold mining typically generates more than 20 ton of waste to make a single 10 gram gold ring (Von Weizsäcker 1998).

Where mine wastes are exposed to both water and oxygen, acidic, metal-rich liquors can be generated via the chemical oxidation of sulfide minerals, which is catalyzed by acidophilic iron- and sulfur-oxidizing bacteria and archaea. As a result, insoluble metal sulfides are converted into soluble metal sulfates with co-production of sulfuric acid, which results in strong acidification of the water body. The low pH promotes the activities of these acidophilic prokaryotes and also increases the solubility of most (cationic) metals that occur as sulfide minerals. The resulting waters are referred to as acid rock drainage if generated by natural ore exposure, or acid mine drainage (AMD) if this is enhanced by mining activities (Fig. 1). These water bodies can threaten water resources (streams, rivers and lakes) in the immediate and wider vicinities, impacting the economy and having a detrimental environmental impact on the affected areas (Gray 1997).

The fine fraction of the mineral waste is held in tailing lagoons surrounded by dams. With 500 000 abandoned mines located in the USA alone (http://www.blm.gov/wo/st/en/prog/more/Abandoned_Mine_Lands/abandoned_mine_site.html), the potential harm caused by breaching of these dams is a serious problem. Just in the past century, more than 100 tailings dam failures have been reported (http://www.tailings.info/knowledge/accidents.htm), including the recent disasters in Minas Gerais in Brazil in November (2015), Gold King Mine in Colorado in August (2015), Zijinshan Gold and Copper Mine in China (2010), Baia Mare Gold Mine in Romania (2000) and Los Frailes mine in Spain (1998). In many cases, environmental problems associated with metal mines are legacies from historic activities, such as the Gold King Mine, which was abandoned almost a century ago (in 1919).

HANDLING THE ACID DRAINAGE

Practices used for long-term storage of mine wastes in order to minimize the generation of AMD, such as securing waste rocks under dry covers and mine tailings in anoxic lagoons, have improved in recent years. To mitigate the impact on the wider environment of the (inevitable) generated AMD, several treatment technologies are being applied. Abiotic remediation methods have been widely used, mostly based on the addition of neutralizing chemicals such as CaO or $CaCO_3$. When these chemicals dissolve in water, the pH increases, and the metals precipitate as hydroxides or carbonates. The calcium removes some of the sulfate present in AMD as gypsum ($CaSO_4 \cdot 2H_2O$). Strict legislations for discharge of sulfate (<250 mg/l)—a useful index measure of sulfide mineral oxidation—have been adopted by more than 90 countries (WHO, http://www.who.int/water_sanitation_health/dwq/chemicals/sulfate.pdf?ua=1). Residual sulfate concentrations after chemical treatment are often well above discharge consent levels (Johnson 2005). In addition, the generated, metal-rich bulky sludge is a hazardous waste, which requires storage in specially designated landfill sites, where changes in environmental conditions (most notably redox potentials) can result in remobilization of transition metals and metalloids such as arsenic, and the continuing threat of environmental pollution.

While microorganisms involved in the oxidative reactions in the biological sulfur- and iron-cycles that occur in mine waters are responsible for the formation of acid mine waters, others offer a solution to the problem (Fig. 2). Sulfate-reducing bacteria (SRB) can essentially reverse this process, regenerating metal sulfide minerals. When an appropriate electron donor is available and oxygen is avoided, sulfate reduction results in the formation of hydrogen sulfide, which reacts with many of the transition metals often found in AMD (such as copper, cobalt, zinc and nickel) to form insoluble metal sulfides. Interestingly, SRB often possess the additional ability to directly reduce metals such as uranium, chromium or tellurate to insoluble forms (Barton *et al.* 2015), though these (and other) metals can also be reduced indirectly via the hydrogen sulfide produced by SRB. Thus, SRB possess the potential to treat metal 'cocktails' by using different biochemical pathways.

FROM WASTE TO RESOURCE

One immediate challenge for the mining industry is to enhance the efficiency of metals extraction from primary ores, which will reduce the amount of mineral waste and therefore the AMD problem. Another challenge is to enhance the metal recovery at the production sites, trying to separate (by the aforementioned metal sulfide precipitation) metals present in the waste stream. Lowering the metal concentrations in the streams will reduce the toxicity of AMD. The value of the additional obtained metals can be an economic driver, reducing the net cost of a process while recovering metals.

A prime example of using sulfidogenic microorganisms to remediate metal waste at an industrial scale is the copper recovery plant at the gold mine Pueblo Viejo located in the Dominican Republic. During the gold extraction process, acid is used in high pressure to release the gold particles. The ore is oxidized and a water stream is released containing sulfuric acid and various metals present in the ore. In typical plants, after separating the gold, this metal-contaminated water is neutralized with lime and the gypsum-rich sludge formed is sent to the tailing facilities. However, a copper recovery plant based on sulfide

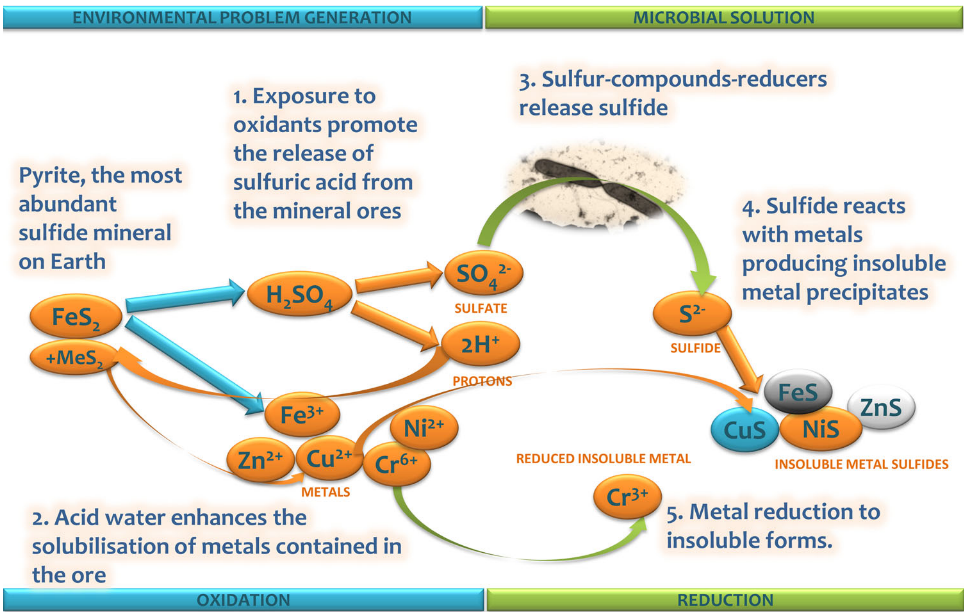

Figure 2. Microbial sulfur cycle related with acid drainage generation and remediation.

precipitation was installed in 2014 at this gold mine. The required amount of H_2S is produced in a high rate bioreactor (Paques B.V., the Netherlands) in which elemental sulfur is reduced by bacteria. The bioreactor produces a 10% H_2S-containing gas stream (up to 20 ton H_2S per day) which is used for the recovery of up to 12 000 ton per year copper. The copper concentrate produced has up to 60% copper content and is shipped to a copper smelter in Europe. So this plant minimizes the amount of copper sent to the tailing dam and creates additional revenue from it.

Currently, an increasing number of mining companies are evaluating biological sulfate- and sulfur-reduction technologies, either in their processes or in wastewater treatment applications. The application of these microorganisms offers the potential for enhanced metal recovery and a sustainable strategy for handling water and solid wastes. However, there are still barriers to overcome before these biotechnologies receive more widespread implementation (each mine and metallurgic company is a different case).

One opportunity for improvement is to use sulfidogenic microorganisms that have greater tolerance to low pH and metals (aluminium, or a variety of transition metals) that occur in AMD. Although acidophilic SRB have been known for more than a decade, relatively few species, mostly belonging to the genus *Desulfosporosinus*, have been fully characterized (Alazard *et al.* 2010; Sánchez-Andrea *et al.* 2015). Acidophilic SRB are attractive because acidic mine waters do not need to be neutralized prior to treatment. At $pH < 6$, sulfidogenesis is a proton-consuming reaction, thereby causing water pH to increase. In addition, as metal sulfide precipitation is pH dependent, controlling pH allows the selective recovery of target transition metals. For instance, copper and zinc present in mine waters can be selectively precipitated, as metal sulfides by varying the pH of the reactors (Hedrich and Johnson 2014).

ECONOMICAL ENVIRONMENTAL FACTORS

In some case studies, the costs of mine water remediation have been evaluated. One estimate of the total worldwide liability for remediating AMD was $100 billion US (Tremblay 2001). While these costs are high, they are still low in comparison with the costs of cleaning spills after dam failures, and the incalculable costs of environmental impact. In the case of the Aznalcollar-Los Frailes disaster in 1998, the clean-up operation took three years, at an estimated cost of $267 million US. The spill affected a natural protected area, the Doñana National Park, a UNESCO Reserve of the Biosphere and the largest bird reserve in Europe. For the recent incident in Colorado (2015), 'it will take many years and many millions of dollars simply to manage and not even remove the toxic wastewater' (Brown, Biesecker and Solomon Banda 2015). Brazilian mining company Samarco Brazilian state has to pay the equivalent of five billion dollars to compensate the damage that has caused the dam burst of last November.

Microbiological and technological knowledge to control and exploit the biological sulfur cycle could help the mining industry to maximize the extraction and the recovery of resources from metal ores. Additionally, further research can foster new (bio)technologies that will broaden the application window. By doing so, new mining sites should be planned that incorporate innovative practices for metal recovery and which minimize the production of toxic wastes. In the future, a more sustainable mining industry would create value from all its resources – a win–win situation that should not be missed. We encourage the governments to find ways to stimulate the transition towards a green metal mining industry through research and economic incentives.

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