

Natural attenuation in the vadose zone: Nature's gift to mine closure

R Howell

SRK Consulting, Cardiff, UK

Queens University, Kingston, Ontario, Canada

Abstract

Natural geochemical attenuation in the vadose zone refers to the process by which chemical parameters are naturally degraded, transformed, or immobilized as they migrate through the unsaturated zone above the water table. The vadose zone that often underlies mine waste facilities is a chemically active environment that involves physical, biological, and chemical interactions. These processes can effectively reduce the concentrations and mobility of contaminants, leading to their eventual removal or degradation. Here are some key natural attenuation processes that can occur in the vadose zone:

Biodegradation: Microorganisms present in the soil can metabolize certain chemicals such as ammonia, cyanide or nitrates, breaking them down into simpler and less toxic compounds.

Sorption and adsorption are processes by which chemical parameters can be chemically or physically trapped or bound to soil particles through the mechanisms of sorption or adsorption. This can reduce their mobility and availability for further transport. These processes are a function of the pH and redox of the environment, minerals present in the soil and prevailing water chemistry.

Volatilization can also occur within the vadose zone and is an important control on the removal of parameters such as cyanide and ammonia.

In addition, other chemical reactions may occur involving oxidation-reduction reactions, hydrolysis, and photolysis that can lead to precipitation or incorporation of chemical parameters into non-soluble mineral forms. In addition, although not often spoken about dilution by lower concentration waters in the vadose zone, can reduce or mitigate groundwater impacts.

The effectiveness of natural attenuation in the vadose zone depends on several factors, including the nature of the chemicals, the redox and pH potential of the environment, soil properties, groundwater flow rates, and site-specific conditions, such as the availability of oxygen, nutrients, and suitable microbial populations. Such processes can occur in a wide variety of environments.

Natural attenuation is an important aspect in long-term management of chemical loading in the environment and whilst it has limitations, combined with other methods such processes are effective in mine closure and should be considered in the planning and assessment of long-term geochemistry in post closure facilities.

Keywords: *Natural Attenuation, Mine Closure, Geochemistry*

1 Introduction

The extent and rate at which chemicals are consumed through natural attenuation is dependent on several factors dominated by local climate and environmental conditions and as such are site specific. Dependent on the concentration and loading of chemicals to be attenuated, natural processes in the vadose zone may be sufficient to completely mitigate potential impacts to a receiving water (Botz and Mudder, 2000; Mudder et al., 2001; Howell et al 2017).

Natural attenuation refers to the inherent ability of soil ecosystems to mitigate and degrade contaminants without human intervention. This process, driven by a complex interplay of physical, chemical, and biological factors, plays a crucial role in the natural remediation of polluted soils. As concerns over environmental degradation and the need for sustainable solutions increase, understanding and harnessing the power of natural attenuation has become a vital area of research. This paper explores the concept of natural attenuation in soils, its mechanisms, and its significance in environmental management. The processes frequently invoked for acidity (Blowes and Ptacek, 1994; Kimball et al., 1994; Nordstrom and Alpers, 1999), cyanide (Smith and Mudder, 1991) and arsenic (Bowell, 1994; Berger et al 2000; Bowell and Craw, 2014). This can occur through several processes including volatilization, biological utilization, adsorption and even precipitation (Smith and Mudder, 1991; Raybuck, 1992; Mudder et al 2001; Akcil and Mudder, 2003).

2 Neutralization

Acid buffering and neutralization can be considered as potential mechanisms of passive attenuation (Blowes and Ptacek, 1994). A good example of this is within porphyry deposits with different zones of alteration surrounding the mineral deposit (Figure 1).

Porphyry Copper Deposits have a well-defined geological zonation reflecting the formation and alteration of the porphyry intrusion and subsequent mineralization events (Cox, 1986). The deposits have a strong hydrothermal alteration pattern and ore distribution that influences the environmental geochemistry of the deposit.

Understanding the controls is important to ensuring characterization adequately covers all aspects of the deposit and potential lithological and alteration types. As this overlap and vary the resulting combinations are grouped as material types. However, it is not just the primary element dispersion that is important but for many deposits, the zonation produced by oxidation as well (Figure 2).

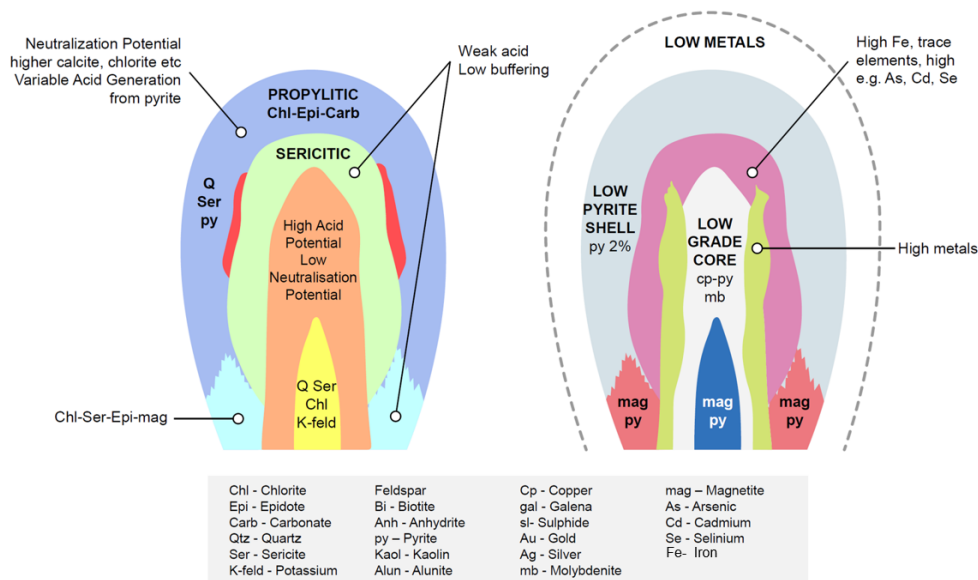


Figure 1: Geoenvironmental model of an idealized porphyry copper deposit (based on Beane and Titley, 1981)

The different mineralogy in the different zones, leads to different potentials for neutralization and metal attenuation which is generally higher with more ferric hydroxide for metal control and neutralization by

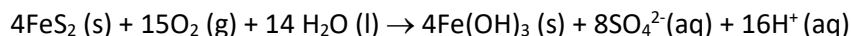
carbonates and chlorite in the propylitic zone. The presence of secondary minerals as a function of oxidation and precipitation can be clearly mapped (Figure 2).



Figure 2: Oxidation zoning in porphyry copper (Santa Rita pit, New Mexico)

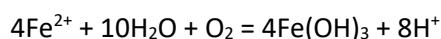
Thus, it is critical to define the different material types that constitute the deposit as they will have different of neutralization and attenuation in terms of acid neutralization and metal release (Figures 3). In the evaluation of acid generation-neutralization potential, the aim is to balance processes that generate low pH environments with those that can buffer (Price, 1999). In doing so it is important the testwork reflects actual mineralogical reactions that influence environmental conditions and not generate artefacts related to interaction with reagents not representative in nature.

The process we wish to measure in acid generation is the oxidation of pyrite and liberation of protons. The general equation for pyrite oxidation is summarized below,



The net effect of sulfide oxidation is the potential to increase the loading of metals, sulfate and acidity in the receiving environment.

Although this is unlikely to cause an impact at low levels, at high concentrations there is the potential for significant impact to water and the surrounding environment. Oxidation of ferrous iron and hydrolysis of ferric iron at $\text{pH} > 2$ provide the additional source of acidity through the reactions:



For each mole of pyrite oxidized, only a portion of the available hydrogen is released. The rest is stored as partly oxidized metal-sulfate minerals. These minerals are highly soluble so can represent an instantaneous source of acidic, metal sulfate-rich water upon dissolution and hydrolysis, for example the dissolution of melanterite:



The ability of these minerals to react with water will depend on solubility. In arid environments these minerals can represent an important source of acidity and metal release in partially oxidized material (Nordstrom and Alpers, 1999) Hence these minerals are important as both sinks and sources of acidity, sulfate and possibly metal ions on precipitation and rapid release on exposure to moisture.

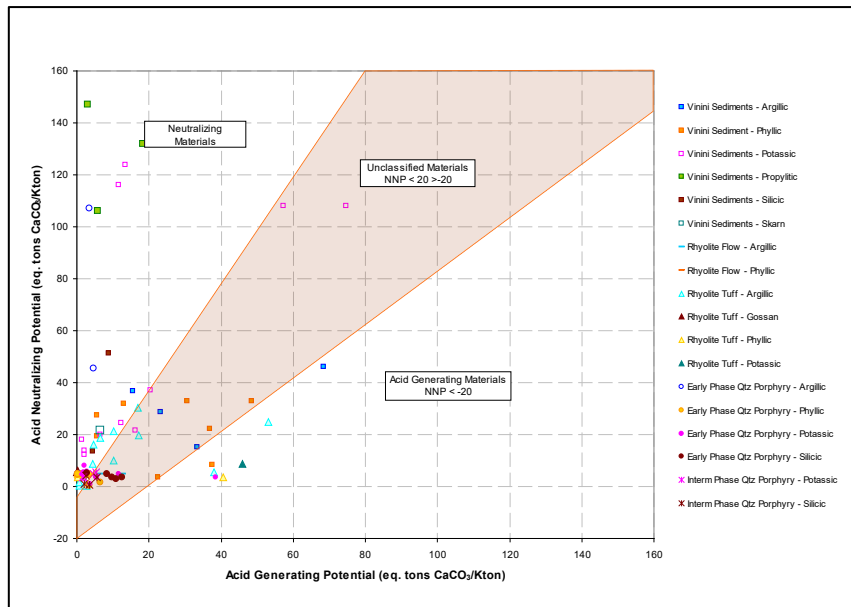


Figure 3: Variation in net neutralization potential and net acid generation potential with alteration, lithology, and oxidation for a porphyry copper project

To counter excess free protons in nature, some minerals buffer or consume (neutralize) the generated acid. Acid-neutralization reactions result from mineral buffering of H⁺ in drainage. This buffering is frequently accompanied by the precipitation of secondary minerals (Kwong and Ferguson, 1997; Lawrence and Wang, 1997; Nesbitt and Jambor, 2008).

These reactions can reduce acid generation by forming an inhibitory surface coating on the reactive sulfides. Under acidic conditions, carbonate minerals (e.g., calcite, dolomite and magnesite) readily dissolve and provide bicarbonate alkalinity, which results in neutralization of acid and precipitation of metal hydroxides.

The order of carbonate neutralizing capacity is calcite>dolomite>ankerite>siderite. In the case of siderite and to a lesser extent ankerite the reason for the limited neutralizing capacity is that ferrous iron in these minerals are an additional source of acidity due to the strong hydrolysis of ferrous iron in solution. This order of reactivity is partly controlled by equilibrium mass-action constraints and partly by kinetic limitations (Morse, 1983). Carbonate minerals (especially calcite) have often erroneously been thought of as the only geologic source of Neutralization Potential (NP). However, carbonates dominate only limestone, dolomite and marble rock types while the majority of geologic materials are composed of silicates and hydroxide-oxide minerals.

Silicate weathering as a proton sink has been demonstrated in previous studies (Sverdrup, 1990; Bhatti et al, 1994, Kwong and Ferguson, 1997). To assess the buffering capacity of mine wastes, silicate and hydroxide minerals therefore must also be considered. From soil acidification studies, Sverdrup (1990) divided the most common minerals into six groups according to pH dependency of their dissolution rate (Table 1).

Table 1: Mineral groups according to neutralization potential (Sverdrup, 1990)

Group Name	Typical minerals	Buffering pH range ¹ (s.u.)	Approx. NP ² range	Relative reactivity ³
1.Dissolving	Calcite, aragonite, dolomite, magnesite, aragonite, portlandite and brucite	6 - 11.2	7.8-14.8	1.0
2.Fast weathering	Anorthite, nepheline, olivine, garnet, jadeite, leucite, spodumene, kutnahorite diopside, siderite and wollastonite	5.5 - 11	2.8-0.6.2	0.6
3.Intermediate weathering	Epidote, zoiste, enstatite, hyperthene, augite, hedenbergite, hornblende, glaucophane, tremolite, actinolite, anthophyllite, serpentine, chrysotile, talc, chlorite, biotite.	4.8 - 7.3	1.7-5.8	0.4
4.Slow weathering	Albite, oligoclase, labradorite, vermiculite, montmorillonite, manganite, goethite, gibbsite and kaolinite.	2.4 - 5.1	0.5-2.9	0.02
5.Very slow weathering	K-feldspar, ferrihydrite and muscovite	2.2 - 4.1	0.2-0.6	0.01
6.Inert	Quartz, hematite, rutile and zircon	3.3 - 3.5	<0.01	0.004

¹buffering pH range evaluated by crushing 5g of pure mineral and mixing with 5mL of distilled water and left to react for 30 minutes. The pH of the distilled water was 3.4 s.u.

² NP range assessed as equivalent buffering potential of 10 g of pure mineral to calcite and titrated with hydrochloric acid. So for example, 10g of portlandite (Ca(OH)₂) was found to have the equivalent capacity to neutralise HCl acid as 14.8g of calcite. Whereas 10g of hornblende was required to buffer HCl acid to a similar pH to only 3.1g of calcite.

³Calculated from Sverdrup's equation (1990), see below and based on 100% mono-mineral sample

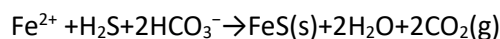
From the relative weathering rates of the mineral groups shown (Table 1), minerals in the poor to negligible neutralizing categories are unlikely to react, due to their sluggish reaction rates. Even for minerals in the intermediate and fast mineral weathering groups, they will not be practical neutralizing materials unless they occur more than ~10% (Sverdrup, 1990).

3 Volatilization

The most common approach of volatilization by interaction with atmospheric gases and loss of cyanide as hydrogen cyanide or through degradation to ammonia and carbon dioxide.

4 Biological controls

Biological oxidation is also an important mechanism for passive attenuation of sulfate, cyanide and other nutrient rich species, such as ammonia (Jones et al., 1995; Johnson and Hallberg, 2003; Walling et al., 2003). Carbon and nitrogen are important nutrients for many plant and microbial species (bacteria, fungi and algae). These can degrade reactive cyanide can detoxify cyanide quickly to environmentally acceptable levels and into less harmful by-products. In addition, such controls may also reduce metal concentrations in solution through reduction of sulfate to sulfide and formation of insoluble sulfide minerals. Some divalent metals (e.g. Fe, Zn, Pb) can be removed by precipitation as sulfide minerals following microbial sulfate reduction. Using Fe as an example, a simple, complete reaction can be written as:



FeS as mackinawite, or alternatively, greigite (Fe_3S_4) may form (Skousen et al 2017). Both are generally precursors to pyrite. Thus, precipitating metals as a sulfide is typically repeating the cycle that placed the metals in the deposit originally, reversing the oxidation reaction that liberated them (Rose, 2010)

Biological passive treatment technologies generally rely on bacterial activity, and may use organic matter to stimulate microbial sulfate reduction and to adsorb contaminants (Skousen et al 2017). Oxidation in situ of free cyanide can result in the formation of cyanate, OCN^- , or in the presence of sulfosalts which are considerably less toxic than cyanide. This can occur through interaction with oxygen in the air. Other reactions can also occur as part of natural attenuation such as interaction with UV radiation and photolytic degradation that oxidizes reduced ions such as Fe^{2+} to ferric, Fe^{3+} (Ackil and Mudder, 2003).

5 Chemical adsorption and precipitation

Chemical adsorption and absorption of trace elements to mineral surfaces can occur through several mechanisms, including surface complexation, ion exchange, and precipitation (Chapman et al. 1983; Dzombak and Morel, 1991; Stumm and Morgan, 1996). The adsorption of trace elements to mineral surfaces has significant environmental implications (Bowell et al 2020). It influences the mobility, bioavailability, and fate of trace elements in natural systems. For example, the adsorption of transition metals to mineral surfaces can decrease their mobility, preventing them from leaching into groundwater or being transported in surface waters. This can help mitigate the environmental impact of contaminated sites and reduce the potential for human exposure. Adsorption onto mineral surfaces can also affect nutrient cycling in soils and sediments. Trace elements such as phosphorus or micronutrients can be adsorbed onto mineral surfaces, making them less available for uptake by plants or microorganisms. This can impact the productivity and nutrient balance of ecosystems.

Furthermore, understanding the adsorption behavior of trace elements can aid in the development of remediation strategies for contaminated sites. Often this requires site specific data to be calculated to determine efficiency and pathway of attenuation (Bowell, 1994; Bowell et al 2017, 2020). By characterizing the adsorption capacity and mechanisms of minerals, scientists and engineers can design efficient methods to remove or immobilize trace elements in soils, sediments, or water.

In tropical soils, adsorption of arsenic species for example by different iron oxyhydroxides can be very different and the soil mineralogy as well as arsenic speciation will determine the quantum of arsenic that can be attenuated (Figure 4).

Chemical adsorption is a fundamental process that occurs at the interface between a solid material and a fluid phase. In the context of trace elements, chemical adsorption refers to the attachment of these elements

to mineral surfaces. Trace elements are present in minute quantities in natural systems, but their interactions with minerals can have significant implications for nutrient cycling, pollutant transport, and the behavior of contaminants in the environment.

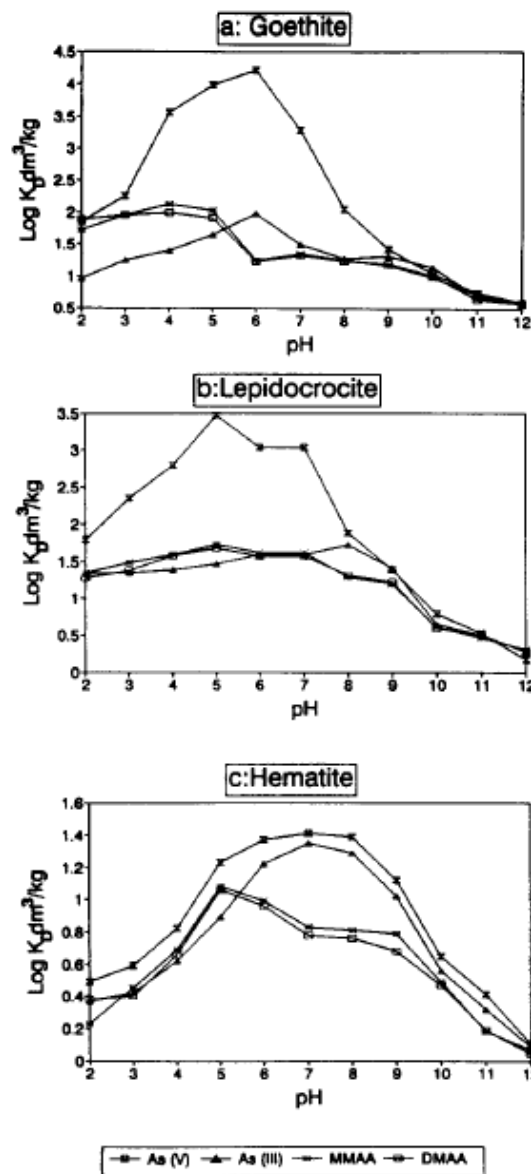


Figure 4: Adsorption of arsenic species as a function of pH. Plot of log distribution coefficient (K_d , $\text{dm}^3\text{kg}^{-1}$). $[\text{As}] = 10^{-6}\text{M}$. (a) Goethite; (b) lepidocrocite; (c) hematite (from Bowell, 1994)

Surface complexation involves the formation of specific chemical bonds between trace elements and functional groups on mineral surfaces (Stumm and Morgan, 1996). These functional groups may include hydroxyl (-OH), carboxyl (-COOH), or amino (-NH₂) groups, which are present on the surface of many minerals. The strength and stability of these bonds depend on factors such as the mineral composition, pH, and the nature of the trace element.

Ion exchange is another mechanism by which trace elements are sorbed onto mineral surfaces. In this process, the trace elements replace other ions that are already present in the mineral lattice. This exchange occurs due to differences in the ionic charges and sizes of the ions involved. For example, in clay minerals,

cations such as sodium (Na^+), potassium (K^+), or calcium (Ca^{2+}) can be exchanged with trace elements such as transition metals.

Several factors influence the adsorption of trace elements to mineral surfaces. These include the mineralogy and surface properties of the minerals, pH, temperature, ionic strength, and the concentration of the trace elements in the fluid phase. The mineral composition determines the availability and reactivity of surface functional groups for adsorption. For example, minerals rich in iron and aluminum oxides tend to have a higher affinity for trace elements due to the presence of hydroxyl groups on their surfaces. The critical parameters that influence the speciation of trace elements and the surface charge of minerals are pH and Eh or reduction-oxidation potential As shown for arsenic schematically in Figure 5.

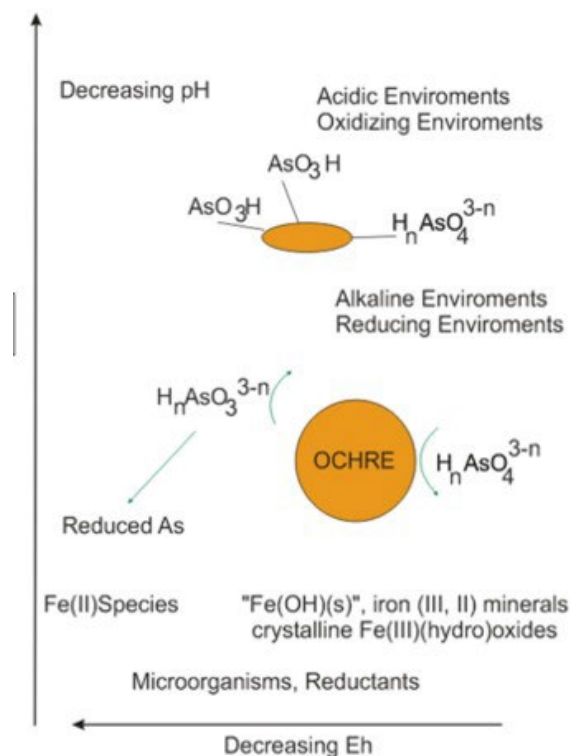


Figure 5: Schematic representation of arsenic attenuation as a function of Eh and pH

Changes in pH can alter the surface charge of minerals, thereby influencing the electrostatic interactions between the mineral surface and the trace elements (Howell, 1994). Additionally, variations in pH can affect the solubility and speciation of trace elements, which in turn influence their adsorption behavior. The concentration of trace elements in the fluid phase can also influence their adsorption onto mineral surfaces. At low concentrations, trace elements may compete for available adsorption sites on mineral surfaces, leading to greater adsorption efficiency. However, at higher concentrations, the adsorption sites may become saturated, resulting in reduced adsorption capacity.

Precipitation, or co-precipitation, occurs when trace elements are incorporated into the crystalline structure of minerals during their formation. This process can happen through the co-precipitation of trace elements with primary minerals or the precipitation of secondary minerals in the presence of trace elements. The solubility and speciation of the trace elements in the fluid phase play a crucial role in determining their propensity for precipitation onto mineral surfaces.

Mineral precipitation in the vadose zone is influenced by several factors, including the chemical composition of the infiltrating water, temperature, pressure, pH, and the presence of dissolved ions. Where there is potential for competing ions then a complex array of secondary minerals may form, for example at the Tsumeb Mine in Namibia (Bowell, 2014). Here in a polymetallic base metal deposit, changes in groundwater chemistry leads to zonation of the oxide zone (Figure 6).

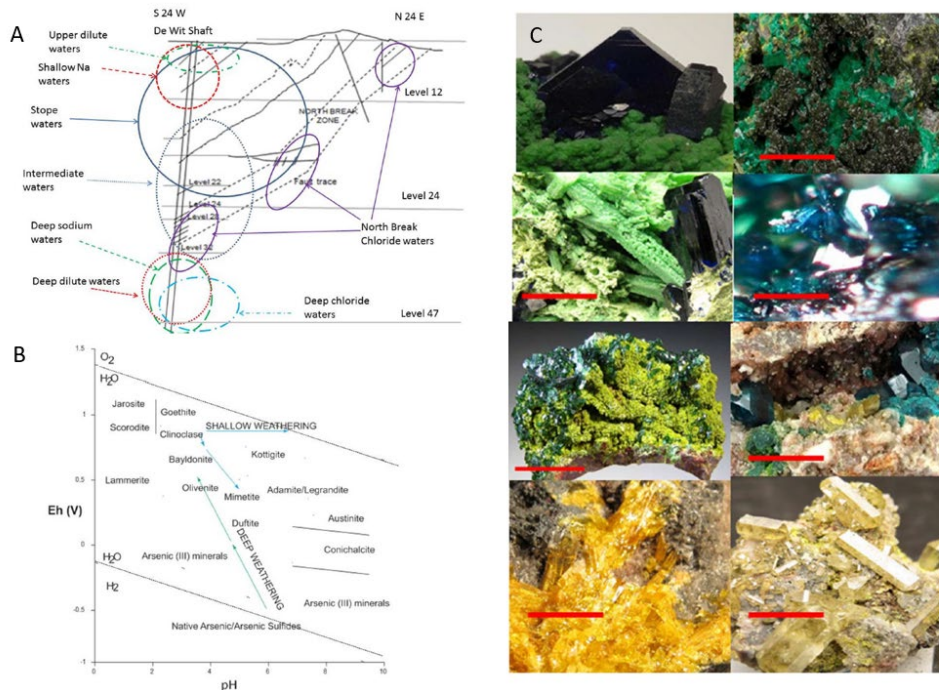


Figure 6: Characteristics of the Tsumeb oxidation zones

- A. Hydrogeochemical zonation of water chemistry types
- B. Schematic of the mineral stability relative to Eh-pH conditions
- C. Examples of different arsenate minerals formed in response to the different conditions within the deposit.
 - a Bayldonite and Arsentsumebite on Azurite, Level 8 "Easter Pocket". First oxidation zone. Scale bar is 1 cm
 - b Olivenite on cuprian adamite, Level 10 stope 15W, First oxidation zone. Scale bar is 2.5 cm
 - c Balydonite pseudomorphs of Mimetite. First oxidation zone. Scale bar is 1.5 cm.
 - d Keyite Second oxidation zone, Level 28, stope 10E. Scale bar is 0.3 mm
 - e. Olivenite with Gartrellite, Second oxidation zone. Scale bar is 1 cm.
 - f. Conchalcite, Molbdoformnacite with Dioptase, Second oxidation zone. Level 30 Stope 10W. Scale bar is 1 cm.
 - g. Legrandite on matrix. Third oxidation zone. Scale bar is 1 mm
 - h. Mimetite, "Gem pocket", Second oxidation zone, Level 34. Scale bar is 1 cm

However, in some deposits it is not just as oxide zone minerals that attenuation can occur but also as sulfide minerals, replacing the oxide zone assemblage. For example, in the case of Galena replacing pyromorphite (Breithaupt, 1863) identified in mineral deposits in Germany and the UK (Figure 7).



Figure 7: Galena pseudomorph of pyromorphite from Wheal Hope, Perranzabuloe, Cornwall

When water percolates through the vadose zone, it interacts with the surrounding rock and soil, leading to the dissolution of minerals. Subsequently, as the water moves upward or sideways, changes in chemical conditions can trigger mineral precipitation.

Mineral precipitation occurs when the concentration of dissolved ions in the water exceeds their solubility limit. Saturation occurs when the dissolved ions are in equilibrium with the mineral phase, while supersaturation arises when the ion concentration surpasses the equilibrium level. Supersaturation can be caused by evaporation, cooling, or changes in pH.

Nucleation is the initial step in mineral precipitation, where dissolved ions cluster together to form small solid particles, called nuclei. Nuclei act as the foundation for further crystal growth. The rate of nucleation is influenced by factors such as temperature, ion concentration, and the presence of nucleation sites. After nucleation, the nuclei grow through the addition of more ions from the surrounding solution. The growth rate depends on factors like temperature, ion concentration, pH, and the availability of space for crystal expansion. The resulting crystals can range in size from microscopic to macroscopic, and their morphology is determined by environmental conditions.

Not just metal(loid)s that can be precipitated but also the relicts of added process reagents. For example, cyanide can be attenuated in some abandoned heap leaches to form Kafehydrocyanite ($K_4[Fe(CN)_6] \cdot H_2O$) such as in the Medvezhii Log Au deposit, Ol'khovskoye ore field, Tuva, Russia (Povarennykh Rusakova 1973). Other cyanide bearing minerals have been found in abandoned heap leach piles in Canada (Sidenko et al 2009).

A challenge with relying on natural attenuation is the use of water to dilute the a source, particularly with a heap leach. This approach might be reasonable for a simple oxide gold ore with no labile oxyanions or sulfides present to remove nitrate or residual cyanide. But, with more complex chemistry rinsing may generate chemical mobility in other components and cause more long term issues than cyanide for example, in the Gold Acres heap rinsing led to mobilization of arsenic from the spent ore (Howell et al 2009). In addition, considerable volumes of water can be impacted requiring further treatment by such approach and still have little gain.

Natural attenuation of metal(loid)s is frequently observed in the surrounding catchment to the facilities(Markwiese et al. 2014; Druzbecka and Craw, 2015; Dordievski et al 2018). At the Bor mine in Serbia,

the Bor, Krivelj, and Bela Rivers receive metal-rich acidic wastewater from metallurgical facilities and acid rock drainage from mine wastes (Figure 8). The results showed that metallurgical facilities had the largest impact on Bor River by discharging about 400 t of Cu per year through highly acidic wastewater (pH = 2.6). The highest measured concentrations of Cu in river water and sediments were 40 mg L⁻¹ and 1.6%, respectively.

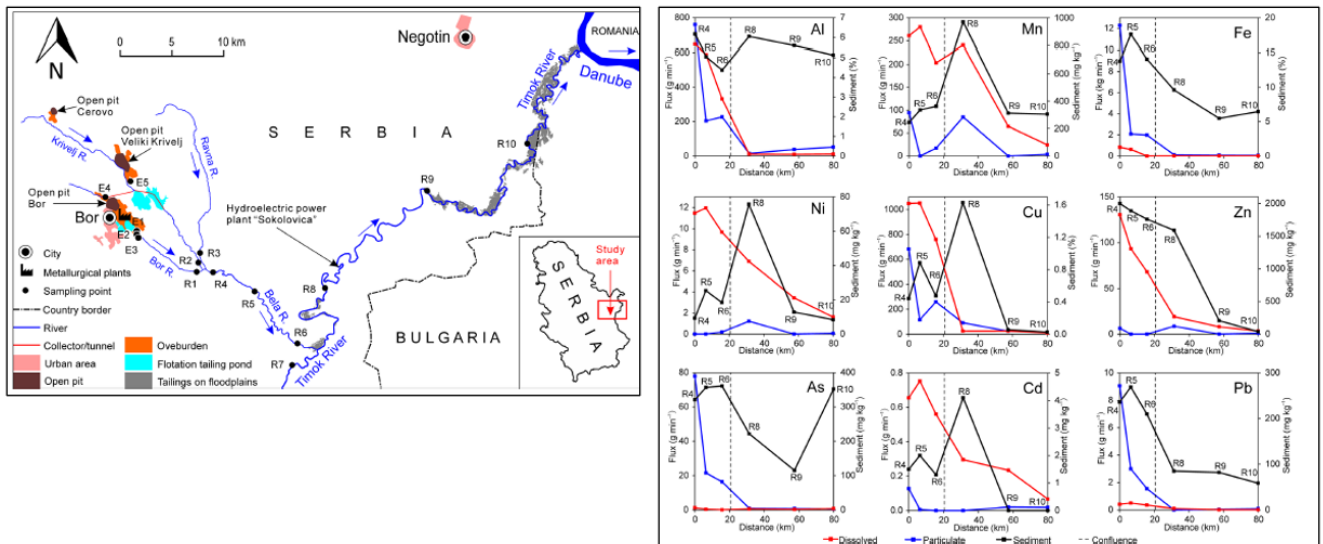


Figure 8: Fluxes of dissolved and particulate forms and sediment concentrations of metals and arsenic at sampling points along Bela River (R4–R6) and Timok River (R8–R10) as well as the sampling map (Dordievski et al 2018).

Calcite dissolution and a high alkalinity in the receiving water buffers pH and subsequent chemical precipitation of metal(loid)s (Figure 7). Decreases in the concentrations of Al, Fe, Cu, As, and Pb in river water were observed. By contrast, the metals Mn, Ni, Zn, and Cd appear to be largely controlled by dilution. Chemically precipitated materials and flotation tailings containing Fe-rich minerals (fayalite, magnetite, and pyrite) were transported toward Danube River during the periods of high discharge (Dordievski et al 2018). Natural attenuation occurs not only in soils but also in mine waste (Moncur et al., 2005; Flores & Sola, 2010). Mimicking the same processes as in nature, development of an iron oxyhydroxide hard pan layer generates a chemical sponge on which adsorption and co-precipitation of metal(loid)s can occur. For example, at the high sulfide Camp tailings, Sherridon, Manitoba (Moncur et al 2005). Here concentration of metals are highest in the near surface and decrease rapidly with depth (Figure 9). Reduction in aluminosilicate minerals and presence of sulfides indicate that although attenuation is occurring, release of acidity and metals will continue despite over 70 years of weathering.

6 Application in closure

The processes of natural attenuation that can be enhanced or engineered bring significant benefits to mine closure (Bannister et al 2018). Attenuation techniques limit the dispersion of contaminants from mine waste, safeguarding surrounding ecosystems. By controlling the release of transition metals, acidity, and other substances, the risk of water pollution, soil degradation, and ecological damage can be significantly reduced. Mining activities have the potential to expose nearby communities to hazardous substances. Engineered attenuation can prevent the migration of contaminants into water sources and minimize human exposure to toxic elements, thus protecting public health and ensuring the well-being of local populations.

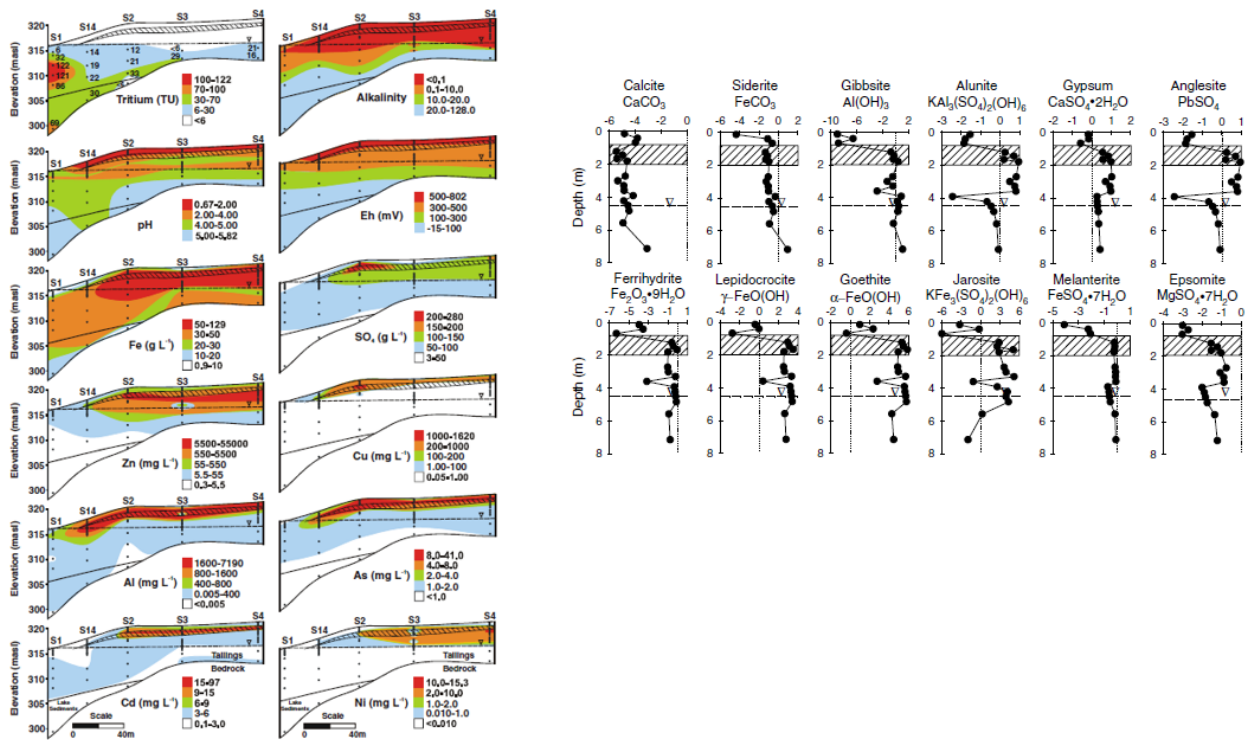


Figure 9: Water chemistry across the Camp tailings. Black dots represent piezometer sampling locations. Dashed line with inverted triangle represents the water table. The cross-hatched area indicates the extent of the hardpan. Alkalinity is expressed as mg/L CaCO₃. SI calculated using MINTQA2, plotted versus depth at piezometer nest S3. Dashed line with inverted triangle represents the water table. The cross-hatched area indicates the extent of hardpan (Moncur et al 2005).

Traditional mine waste management methods often involve containment structures that require perpetual maintenance and/or active water treatment. Engineered attenuation offers a more sustainable approach by transforming the waste into a more stable form that poses less risk to the environment over the long term. This can reduce the need for ongoing management and provide a more sustainable solution for future generations. With stricter environmental regulations and increased public scrutiny of mining projects, mining companies face mounting pressure to manage their waste more responsibly. Adopting engineered attenuation techniques not only helps meet regulatory requirements but also demonstrates a commitment to sustainable practices, enhancing a company's reputation and social license to operate.

Utilizing methods based on natural attenuation processes have emerged as promising approaches to expedite the natural remediation of contaminants in the vadose zone. By leveraging the inherent capabilities of this critical zone, these strategies enhance microbial activity, promote chemical reactions, and optimize environmental conditions. The implementation of enhanced attenuation not only offers cost-effective and sustainable solutions but also contributes to the long-term effectiveness of environmental remediation efforts. Further research, technological advancements, and case studies are needed to refine and optimize these techniques, ensuring their wider adoption and successful application in diverse contaminated sites.

7 Summary

This review presents a summary of natural attenuation methods that occur with the weathering and erosion of mine wastes and interaction of leachates in the vadose zone. These methods lead to the reduction in concentration of metal(loid)s, salts and reagents from mine waste into the surrounding environment. Enhancement or engineering based on these natural mechanisms presents an opportunity to manage and mitigate long term impacts predicted on mine closure.

They expedite the natural remediation the vadose zone. By leveraging the inherent capabilities of this critical zone, these strategies enhance microbial activity, promote chemical reactions, and optimize environmental conditions. The implementation of enhanced or engineered attenuation not only offers cost-effective and sustainable solutions but also

While attenuation-based methods holds significant promise, it is not without challenges. Factors such as the diversity of mine waste composition, site-specific conditions, and the long-term performance of engineered systems must be carefully considered. Research and development efforts are necessary to optimize attenuation techniques, improve cost-effectiveness, and ensure long-term monitoring and maintenance of engineered systems.

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