Research Directions: Mine closure and transitions

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Tools to improve mine closure: 10 years of research in integration of environment in the mine life cycle

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Abstract

Mine closure can be approached by several points of view, from the technical, engineering, ecological, up to social and governance aspects. The definition of a good mine closure should cover most, if not all, of these aspects. This article provides a review of technical and engineering-oriented research work as a partial answer to the question 'what is good mine closure'. The article presents a ten-year research program realized in the framework of a Canada Research Chair in integration of environment in the mine life cycle. Research projects aimed at better planning mine closure and mine site reclamation from the early stages of a mining project life cycle are exposed as possible steps to strive for optimal mine waste management. At the exploration stage, geo-environmental characterization and modeling are proposed as tools to improve mine waste management planification. During mine operations, environmental desulfurization is suggested as a method to reduce environmental risks associated with sulfidic tailings and waste rock. Indeed, research has shown that acid mine drainage and metal leaching can be significantly limited via desulfurization. At the closure stage, desulfurized tailings can be used to replace at least part of natural materials used for reclamation cover systems. Research work done on other types of mine waste, such as waste rock and water treatment sludge, also show good potential for their reuse as closure material. All these tools can be integrated into the mine life cycle to better plan for closure, which ultimately will make mine closure more sustainable.

Introduction

The question 'what is good mine closure' proposed by Drs. Littleboy et al. (2024) triggered my interest and became the starting point of insights on the research work done through the scientific program of the Canada Research Chair in integration of environment in the mine life cycle, which ran from 2014 to 2024. The perspective taken to answer the question was that of a scientist in engineering and geoscience fields. This article is thus my own opinion on how to improve mine closure exposed through a collection of scientific research projects undertaken at the Research Institute on Mines and Environment in Canada. Other researchers worked, and still work, in similar fields, and served as inspiration for the research program. Due to the restricted scope of this article, many of these excellent scientists will be left out, but they are dutifully acknowledged in the publications that stemmed from the research projects, and which are cited herein. The complementary work performed by different research teams is essential to advance the scientific knowledge in a multidisciplinary fashion.

What is good mine closure?

Many answers are possible to this question, one promising perspective is expressed in this article. A good mine closure is one that is planned from the early stages of the mining process, and adapted as best available technologies evolve. However, not all mine sites benefitted from a thorough environmental assessment in the development stage, due to changing regulations from one period to another (for long-lasting mine operations and legacy sites) or from one region to another. In that sense, the research program developed for the Canada Research Chair aimed to investigate and propose recent approaches in mine waste management that can be implemented at different stages of the mine life cycle, depending on the development horizon of a given mine site.

Context of research

The mining industry has left an environmental damage legacy in Canada and worldwide after centuries of minerals and metals exploitation. This legacy can take the form of polluted water streams, contaminated soils and landscape modification, often caused by the storage of large quantities of mine waste (Moncur et al. 2014). Knowledge about contaminant generation, transport and fate increased significantly, identifying environmental issues related to mine waste, while metal production and consumption also progressed. Metal production is an important economic activity for Canada. Regulations are in place to minimize environmental impacts while still providing economic benefits to the Canadian population. Reclamation of mine sites, considered an integral part of responsible mining, is now required after operations to prevent future environmental damage from mine waste (MERN 2018). Indeed, since the Rio Earth Summit (1992) and the World Summit on Sustainable Development in Johannesburg (2002), sustainable development and ESG (environment, society and governance) principles have started to appear in mining companies' policies. Sustainable development implies the use of today's resources to fulfill our needs without compromising the future generation's ability to fulfill their own needs (WCDE 1987). For the mining industry, sustainable development may be defined as the enhancement of positive economic and social benefits while maintaining minimal adverse environmental and social impacts, from the beginning of the mine life cycle until well after closure (MMSD 2002). The principles of sustainable development adopted by the mining companies include environmental impact assessments that must be conducted at the project stage and for modification and expansion of current operations. One of the objectives of these environmental impact assessments is to predict environmental impacts caused by every aspect of the mining operations.

Mine closure and reclamation should be designed from the beginning of mining projects (McLellan and Corder 2013). Mine waste management during operations and reclamation are required to be defined to obtain the permits needed to start the construction of the mine. However, there is often minimal interaction between departments and disciplines involved in mine planning and environmental management, and an optimal design is often not achieved. The major portion of solid waste produced by a mining operation is waste rock and tailings; waste rock is the barren material removed to provide access to the orebody, and tailings are ground rock in which the valuable mineral and metals were removed. When these materials contain reactive (sulfide) minerals, their exposure to atmospheric air and rainwater triggers oxidation, releasing acidity and inorganic contaminants; this phenomenon is named acid mine drainage (AMD) (Nordstrom et al. 2015). Several management approaches were developed in order to prevent or to reduce environmental impacts caused by mine waste (Edraki et al. 2014). Characterization of mine waste is an important step of an environmental impact assessment.

Mine waste management, and subsequent site reclamation, is generally considered an 'end-of-pipe' process, meaning that management approaches are developed to be applied once tailings and waste rock are stored, at the end of the processing circuits. This management approach stems from a widespread tendency to separate the mining process into separate units, with minimal to some interaction between units. However, a better integration of the different disciplines (geology, mining, metallurgy, environment) would be beneficial for the mining operation. Recently, the concept of 'geometallurgy' has become more common to refer to the integration of metallurgical information into geological models of an orebody to enhance recovery at the processing plant and ultimately improve profitability of the operation (e.g., Lotter 2011; Philander and Rozendaal 2011). Geo-metallurgy is usually concerned by optimization of ore beneficiation processes based on geological data, but some researchers have started to investigate integrating environmental aspects into geo-metallurgy as well (Cracknell et al. 2018; Parbhakar-Fox et al. 2011). A more specific integration of disciplines into mine waste management was proposed through environmental desulfurization (Edraki et al. 2014; Leppinen et al. 1997; Mafra et al. 2022). Environmental desulfurization aims at reprocessing acid-generating tailings to reduce the footprint of the tailings storage facility and possibly reuse the desulfurized tailings as components in mine site reclamation methods (Benzaazoua et al. 2008; Demers et al. 2008).

The main objective of reclamation is to prevent sulfide oxidation and consequently prevent AMD, while secondary objectives involve dust suppression, revegetation and providing a future use for the site. Covers made of geological materials are generally used for reclamation. However, large mine sites require large volumes of reclamation material that may be unavailable, uneconomical, or unethical to obtain. Indeed, natural soils such as till, clay and sand from burrow pits are often sought for cover purposes; their cost being mainly related to transportation distance to the mine site. In addition, ethical issues related to disturbing a natural site to reclaim an industrial site may arise. Over the past century, many mines were not reclaimed and were abandoned once companies dissolved. The unfortunate legacy of old abandoned mine sites is an issue that must be dealt with as a society.

The research work's main orientation was to integrate different aspects of the mine life cycle into environmental assessments to ultimately optimize mine waste management and closure and minimize negative environmental impacts. Indeed, a major conceptual gap identified in mine closure is the difficulty in transferring information and practices from one stage of mining to the next and from one department to another. The mine closure mindset is gradually changing to view closure as a mine life-long endeavor, therefore the research program intended to propose new tools to help practitioners reach good environmental performance from early exploration to post-closure. The originality and innovativeness of the research arises from this integration and on the 'proactive' approach, as opposed to the traditional 'reactive' strategy. A significant contribution of the CRC scientific program was to plan mine waste management from the beginning of the mine cycle, i.e., from geological core data, and to adapt processes during beneficiation to facilitate future tailings facilities reclamation.

Research objectives

The overall objective of the research program was to develop and provide tools to integrate environmental management of mine waste into the mine life cycle, from exploration, operation to post-closure. For simplicity, the mine life cycle was divided into three main phases: exploration, operation, closure, to develop the research projects. Since the aim of the program is to take down the division between phases, the work was performed with a specific emphasis on the other phases to establish or reinforce links between expertise fields. Figure 1 illustrates the specific objectives developed over the 10-year program. Two objectives were defined for the exploration phase: (1) development of a geo-environmental characterization protocol, and (2) geo-environmental planning from exploration data. These two objectives aimed to better use exploration data for mine waste management and reclamation. For the operation phase, the objectives revolved around the environmental desulfurization process as a method to optimize operations to facilitate mine waste management and site closure.

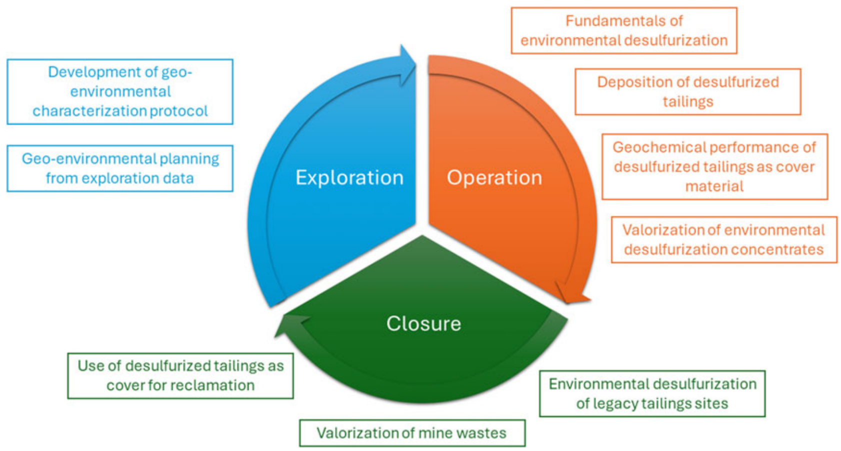

Figure 1. Illustration of the research program topics.

Four topics were investigated: (3) fundamentals of desulfurization; (4) deposition of desulfurized tailings in storage facilities; (5) geochemical performance of desulfurized tailings as cover material; (6) valorization of desulfurization concentrates. Finally, the closure phase covered three subjects related to operation and characterization: (7) use of desulfurized tailings as cover for reclamation; 8) valorization of mine waste; and (9) environmental desulfurization of legacy tailings sites.

The research work done to address these issues over the 2014–2024 period is described in the next sections.

Exploration

Mine exploration generates a large number of samples and data that could be useful for environmental management purposes. Geological description of core samples, chemical and mineralogical analyses are done to identify and delimitate the orebody. The available data could also be used to identify potential environmental issues, such as AMD and metal leaching, which in turn will affect the overall value of the mining project. The concept of geo-environmental models was proposed at the end of the 1990s (Plumlee and Nash 1995; Schmiermund et al. 2006; Seal and Foley 2002) at the orebody type scale. Depending on the rock types composing the orebody and encasing rock mass, environmental impacts could be anticipated. These models were precursor work but are not detailed enough to predict environmental issues for a specific mine site. Geometallurgy, i.e., the integration of mineralogy and mineral processing to optimize production and benefits, provides a framework to break barriers between disciplines involved in mining operations. It involves a multidisciplinary and detailed characterization of geological samples to optimize the mining sequence and the metallurgical process and to account for ore variability, with an emphasis on mineral and texture description (Lotter 2011). Lotter (2011) exposed that geometallurgy is rapidly developing mostly because of the advances in mineralogical characterization techniques (MLA, QEMSCAN, Core Mapper, etc.). These characterization techniques could also be used to identify minerals involved in acid mine drainage and metal leaching, so that the geochemical behavior of the samples can be predicted and linked to the environmental behavior of the future mine wastes, to ultimately manage separately the waste according to their contamination potential. Application of the geometallurgical framework to environmental prediction was proposed by a few researchers. Brough et al. (2013) introduced the concept of 'geo-waste units', where areas of the orebody are grouped by potential weathering behavior instead of typical lithologies. Parbhakar-Fox et al. (2011) proposed the GMT (geochemistry-mineralogy-texture) approach, in which samples are classified according to AMD potential at an early stage of characterization. Guseva et al. (2021) showed the value of using quantitative textural tools (QEMSCAN) for AMD potential assessment in conjunction with kinetic tests.

A geo-environmental protocol could give good indications on the AMD and metal leaching potential and provide a spatial representation of contamination potential. The next step was to integrate this representation into a mine planning model for efficient mine waste management throughout the mine life cycle. Typical modeling techniques in mine waste management are process-based approaches that study single aspects of mining and waste interactions (e.g., water balance, AMD). A dynamic simulation model, TMSim, proposed by Beier (2015), consists of a tailings technology evaluation tool to incorporate the mine production plan, tailings dewatering, tailings deposition, post-deposition dewatering and a tailings storage facility material balance. The simulation was developed based on oil sand mine sites and does not include geochemical aspects. However, the methodology could be extended to metal mines and acid/metal contamination issues, if coupled with a geo-environmental mine plan. Stochastic modeling has also been developed to optimize mining sequence operations, material handling and mineral processing for maximal net present value (NPV) and lower economical risks. Goodfellow and Dimitrakopoulos (2016) presented a framework for optimization of open-pit mining sequences and material destination (stockpile, mill, waste, etc.) with constraints imposed by geological and economic uncertainties. Navarra et al. (2018) also integrated geometallurgical models into stochastic formulations to evaluate the influence of alternative processing flowsheets for the different geometallurgical units. Mine waste management costs (e.g., water treatment, tailings storage facilities, reclamation) and environmental risk would be the next elements to integrate into the models to obtain a global picture of the mine site throughout its life cycle.

Development of a geo-environmental characterization protocol

Vermette (2018) proposed a protocol to define geo-environmental domains from exploration data, which were then subdivided into

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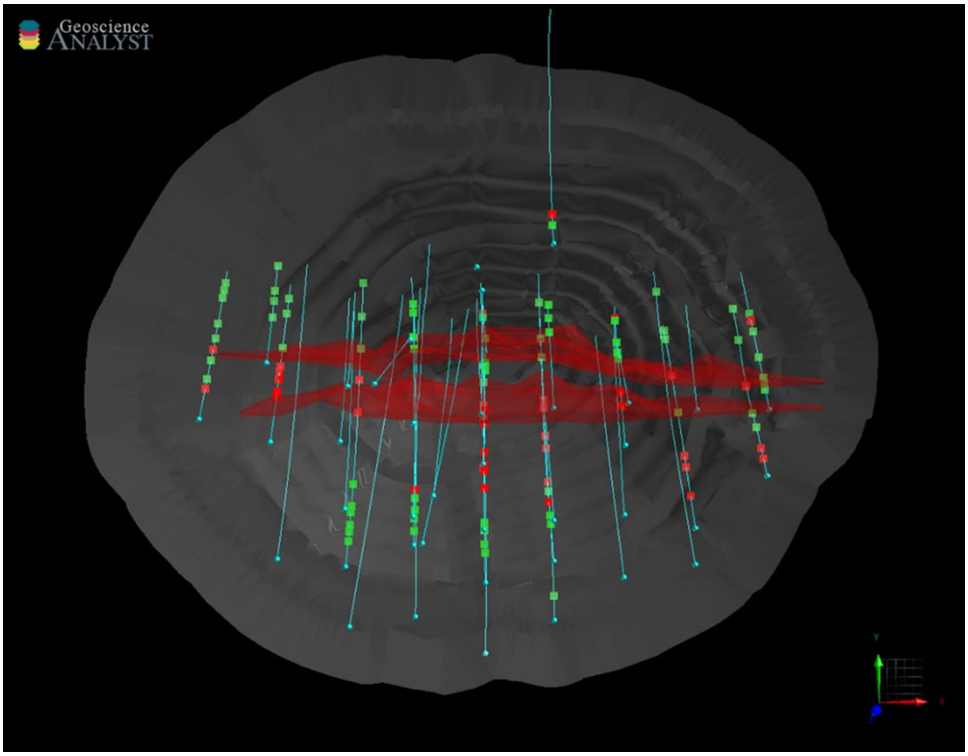

Figure 2. Representation of waste rock characterization in the future open pit Akasaba mine; red zone is the intermediate domain, green zone is the mafic domain, yellow zone is the dacitic domain. Dots represent samples with ratios of neutralization potential RNP > 3 (green) and RNP < 1 (red). (Vermette, 2018).

geo-environmental units at the pre-feasibility and feasibility stages of the mine development, based on the Akasaba Ouest mine project (Vermette 2018). The proposed protocol begins at the start of the mine cycle where core log data are interpreted with an emphasis on environmental issues. It was found that core logs contained significant amount of information that can be used to estimate environmental behavior of future waste rock. The protocol provides further tests to be done at the preliminary economic assessment, pre-feasibility and feasibility steps of the mine. For the Akasaba Ouest project, the waste rocks were divided into seven geo-environmental units and three geo-environmental domains, which were included into a GOCAD model of the mine (Vermette 2018), as shown in Figure 2. Areas of potential AMD, copper and manganese leaching were identified, and waste management was proposed to segregate the domains and units with contamination potential.

The work on geo-environmental characterization and modeling highlighted the need for good and representative data for numerical modeling and ultimately for environmental planning decisions. In the recent years much development of analytical tools was initiated mostly for geological investigations (Lemière and Uvarova 2019) and also for environmental assessment purposes. Indeed, Cracknell et al. (2018) used images from Corescan to obtain automated acid rock drainage index data. Since sample availability and budget are limited in the exploration and early development stages of a mine project, a project was initiated to investigate the application of existing non-destructive core analysis methods for a preliminary environmental assessment. Duvernois tested hyperspectral analysis, portable x-ray fluorescence and carbonate staining as tools to help identify acid generating minerals and neutralizing minerals to perform a preliminary environmental assessment. These tools were first validated on samples from a well-developed mine (Laronde zone 5), where the non-destructive analysis results were compared to existing geochemical data obtained using laboratory methods, such as ICP and x-ray diffraction (Duvernois et al. 2024). Then, the proposed tools were used to provide a preliminary assessment of acid generation and metal leaching potential for lithologies of a mine site under development (O'Brien). Afterwards, typical kinetic tests in columns were performed to verify the preliminary assessment. Results indicated that while the non-destructive tools were not entirely on target in terms of AMD generation, they can provide early results and help decide on which lithologies or geoenvironmental domains to focus the upcoming environmental assessment (Duvernois et al. 2024).

A challenge that was identified in using core scanning tools is the large number of data and the need for rapid interpretation. A project was recently initiated in partnership with a mining company to merge artificial intelligence with automated core scanning to predict geoenvironmental parameters of geological deposits.

Geo-environmental planning from exploration data

Several modeling approaches were investigated and adapted to environmental planning from geological data. Toubri first analyzed the geological database of a gold deposit of an operating mine in Quebec, Roberto deposit (Eleonore mine, Newmont). An environmental challenge at this mine site was the presence of arsenic in the tailings and waste rock, therefore the project involved trying to locate the sources of potentially arsenic-enriched waste rock directly in the orebody, to then propose an extraction sequence to minimize mixing of arsenic-rich and low-arsenic waste rock. Investigation of the geology database revealed that restricted

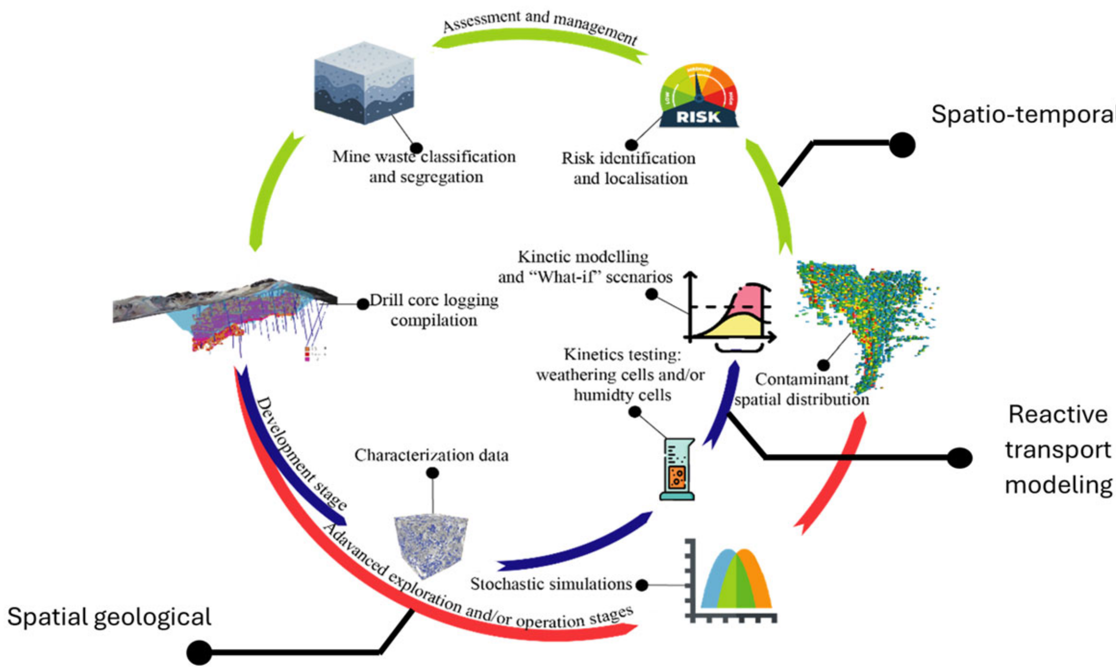

Figure 3. Geo-environmental modelling process, from static to dynamic mine waste management. Modified from Toubri et al. (2021c).

arsenic grades were available, which were insufficient to obtain a good view of the arsenic distribution in the orebody. Toubri developed a stochastic approach to correlate the limited arsenic grade available to the geological logging of arsenopyrite, which enabled to fill the missing arsenic grades and populate a 3D block model of arsenic distribution (Toubri et al. 2021a). The superposition of the arsenic block model with the mine plan becomes an interesting tool to plan waste rock management to minimize environmental risk associated with arsenic-bearing minerals.

However, the spatial distribution of an element cannot provide the entire story about potential environmental risk. Kinetic leaching assessments are usually required to evaluate environmental risks. Kinetic tests can be difficult to perform adequately at the early stage of a mine project when sample availability is restricted, or unrepresentative. Toubri calibrated a numerical model of weathering cell experiments of geoenvironmental domains identified by Vermette for the Akasaba Ouest site. Once calibrated and validated, the model was used for parametric analyses (variables tested: mineral assemblages and residence time) to determine the most significant parameters affecting metal leaching (Toubri et al. 2021c). Knowing which mineral combinations and water flow patterns enhance metal leaching enable to plan the waste management to reduce environmental risks.

The final step in the numerical modeling aspect of geoenvironmental planning was to combine spatial and kinetic models to promote proactive mine waste management, as proposed in Figure 3. Toubri integrated the approaches proposed in the first two steps (stochastic + kinetic modeling) in a fictious case study based on Akasaba Ouest and Roberto. For each block in the geological model, called a voxel, he assigned a mineralogical composition and proceeded in kinetic modeling to simulate the deposition of the given block in a surface waste rock pile exposed to atmospheric conditions (Toubri et al. 2022). The visualization of the effluent pH associated with each block was then proposed and becomes a useful tool to plan waste extraction and management.

Finally, Alvarez Zuniga worked on a methodology to predict the tailings management and reclamation costs depending on their geochemical parameters. Using different orebodies from the Raglan mine as the case study, he adapted the life cycle cost methodology proposed by Carneiro and Fourie (2020) to introduce environmental impacts as a long-term monitoring factor in the life cycle cost equation. Tailings were divided into two categories: potentially acid generating (PAG) and non-potentially acid generating (NPAG). The net costs for four different configurations of tailings management were evaluated (i: PAG tailings + multilayer cover; ii: NPAG tailings + vegetation cover; iii: 10% PAG tailings + multilayer cover and 90% NPAG tailings + vegetation cover; iv: 10% PAG tailings + multilayer cover and 90% NPAG tailings + dry stack), resulting in a range of minimum and maximum values. Results indicated that the separation of acid-generating material from tailings have showed economic advantages. However, the significant spread between minimum and maximum values represented a major limitation of the applied methodology. The distribution of net costs per scenario and alternative was also analyzed, revealing that the share of environmental monitoring costs did not exceed 1% of the total waste management cost. Furthermore, it was observed that the proportion of reclamation costs within the total waste management costs increased as the tailings were less densified (Zuniga Alvarez 2023).

Operation

In the late 1990's and early 2000's, several researchers investigated the use of flotation to produce non-AMD generating tailings from end of process sulfidic tailings (Benzaazoua et al. 2000; Leppinen et al. 1997; Yalcin et al. 2004). The environmental desulfurization process, generally performed by froth flotation, allows recovering most sulfide minerals in the tailings to significantly reduce its reactivity, thus making it chemically suitable as cover material

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(Benzaazoua et al. 2000; Benzaazoua et al. 2008). While previous work demonstrated that desulfurized tailings can be effectively used as cover material to prevent acid mine drainage (Benzaazoua et al. 2008; Demers et al. 2008, 2009a; 2009b), there are still some issues to be resolved related to the desulfurization process and to the production of tailings with the appropriate properties to be used as cover material.

Companies now seriously consider desulfurization for reclamation as part of responsible mine development. However, desulfurization is still not often utilized in operating mine sites for production of cover material, in part because not many successful full-scale examples are available. Full-scale implementation of desulfurized tailings as monolayer covers was performed on a few sites in Canada, e.g., Detour (Dobchuk et al. 2013), Strathcona (Martin and Fyfe 2007) and Manitou (Éthier et al. 2013, 2014). Challenges were identified on full-scale covers, mainly related to variability of desulfurized tailings sulfur content and particle size distribution (PSD) (Dobchuk et al. 2013). The effect of chemical and PSD variability on full-scale cover performance was not thoroughly evaluated. Furthermore, desulfurized tailings may evolve over their service life as cover material. Geochemical evolution may occur because of residual sulfide consumption within the cover. Other elements may be released over time from the cover and affect effluent quality (e.g., Zn, As). Numerical modeling by Demers, Ethier, Pabst (Demers et al. 2009a; Ethier et al. 2018; Pabst et al. 2018) provided preliminary evaluation of cover performance using estimated average cover properties that did not change with time. Recent research work (Lindsay et al. 2015) highlighted the possible geochemical evolution of tailings when subjected to anoxic conditions. The new reducing conditions in the sulfidic tailings, while preventing sulfides oxidation, may trigger other reactions leading to the release of metals (Lindsay et al. 2015).

Another aspect that deserves investigation is the possibility of using environmental desulfurization to reprocess old tailing ponds to recover gold or other valuable metals that were not recovered in the past (Li et al. 2024), while at the same time to facilitate site reclamation by producing neutral and decontaminated tailings that reduce the environmental liability of the site.

Fundamentals of environmental desulfurization

The desulfurization process for tailings with pyrite as the main sulfide mineral is now fairly well understood. The first project in this theme involved an evaluation of the effects of the orebody compositional variability on the performance of environmental desulfurization to produce non-acid-generating tailings. Working from ore samples from 18 zones within a gold ore deposit, it was found that sulfur content by itself was not a sufficient indicator for the success of desulfurization. Some zones had variable sulfate contents, as well as various levels of neutralizing minerals. The research proposed to consider not only sulfur (or sulfide) content in an ore to determine suitability for environmental desulfurization, but also neutralization potential (NP) as an important indicator (Demers et al. 2023, 2024).

In parallel, research projects investigated the environmental desulfurization of tailings containing other types of sulfide minerals (other than pyrite). Tailings from Raglan mine, being composed mainly of pyrrhotite, were investigated by Ait-Khouia. Fundamentals of covellite flotation were examined by Botero. Experiments were also performed to use environmental desulfurization to prevent contaminated neutral drainage, especially involving sulfosalts gersdorffite, skutterudite and nickeline. In all cases, experiments were done first on pure minerals to study the interactions between mineral surfaces and collectors. It was found that the collector adsorption species varies with the sulfide mineral and influences the dosage and flotation performance (Ait-khouia et al. 2023b; Botero et al. 2022a; El-bouazzaoui et al. 2022). Then, real mine tailings were desulfurized according to the parameters determined in the fundamental studies. Optimal parameters were identified for Amaruq and Raglan tailings (Ait-khouia et al. 2022; El-bouazzaoui et al. 2022) and a porphyry copper mine tailings (Botero et al. 2021), as presented in Table 1. These results suggest that environmental desulfurization can be successfully applied to tailings containing different types of sulfide minerals for the prevention of acid mine drainage and metal leaching.

Environmental desulfurization has been considered and applied mostly on tailings from base metal and coal mines (Kotsiopoulos and Harrison 2018; Mafra et al. 2022). Another aspect of the research investigated its potential application to waste rock management. Since waste rocks have a wide particle size distribution, from coarse blocks to very fine particles, the desulfurization strategy has to be adapted. Using the concept of diameter of physical locking of sulfides (DPLS) (Elghali et al. 2018), waste rock samples from Amaruq and Centinela mines were classified by size fractions to determine the DPLS and the size fractions that require desulfurization, which were <2.5 mm for Amaruq and <2.4 mm for Centinela (between F4 and F5). Degrees of liberation per size fraction for pyrite and carbonates are presented in Figure 4. Then, depending on the size of particles to desulfurize, processes were selected and tested to reach desulfurized waste rock. Ait-Khouia tested screening, dense medium separation, gravity concentration, flotation and combinations of these processes to successfully desulfurize waste rock (Ait-khouia 2022; Ait-khouia et al. 2023a). Botero used flotation in a Hydrofloat unit (fluidized-bed flotation) to desulfurize particles >212 µm and Denver cell for particles <212 µm (Botero et al. 2022b). These options offer new applicability for environmental desulfurization of mine waste, including waste rock.

A further objective involved flotation tests in a laboratory flotation column to investigate the influence of hydrodynamic parameters on tailings particle size distribution. Results showed that residence time had no visible impact on particle size distribution of the desulfurized tailings, but an increase in slurry density made the desulfurized tailings coarser than the feed. Using empirical relationships, saturated hydraulic conductivity in the range of 10^{-5} cm/s were obtained, as well as an air-entry value (AEV) of 200 and 300 cm (Guimond-Rousson et al. 2018). Air flowrate was shown to influence mainly sulfur recovery but had no effect on tailings particle size distribution.

Deposition of desulfurized tailings

Deposition of desulfurized tailings as a cover layer in a tailings storage facility is generally done by hydraulic transportation and disposal at the end of a pipe, or multiple pipes (spigots). Hydraulic slurry deposition can cause rapid settling of coarse particles and a further travel distance before settling for fine particles. This settling induced variations in saturated hydraulic conductivity (k_{sat}) of one order of magnitude from near the deposition point to the farther edge of the pond (Demers et al. 2017a). Considering that hydrogeological properties are associated with particle size distribution, size segregation following tailings disposal may affect the performance of the desulfurized tailings cover to maintain a high degree of saturation. Projects were initiated to evaluate the

Table 1. Optimal desulfurization conditions obtained in three studies

Tailings (reference)	pH	Slurry density	Collector type and dosage	Activator type and dosage	Frother type and dosage	% S in desulfurized tails
WTT (Ait-Khouia et al. 2022)	11.5	29%	PAX : 158 g/t	CuSO4 : 300 g/t	MIBC : 55 g/t	0.11
Porphyry Cu (Botero et al. 2021)	8	36%	IPETC : 5 g/t	None	Matfroth 202 : 20 g/t	N.A.
Amaruq (El-bouazzaoui et al. 2022)	11	30%	Aero 4077 : 350 g/t	CuSO4 : 250 g/t	MIBC	< 0.5

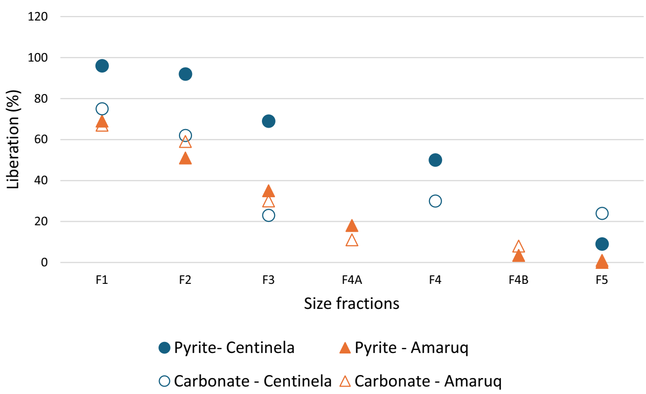

Figure 4. Degree of liberation of pyrite and carbonates by size fraction for waste rock from Centinela and Amaruq mines.

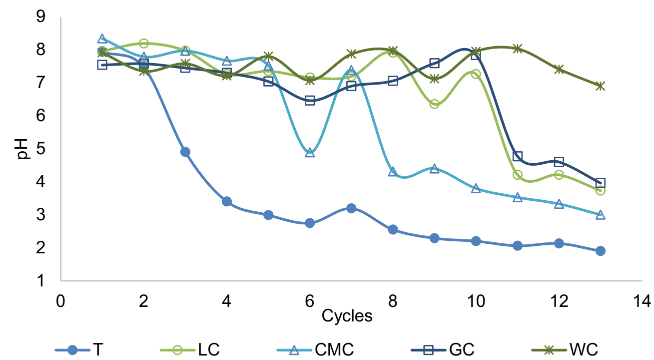

Figure 5. pH of column test effluents where desulfurized tailings were placed as cover over sulfidic tailings. T: uncovered tailings 12% S, LC: desulfurized tailings 0.26% S, CMC: desulfurized tailings 0.14% S, GC: desulfurized tailings 0.12% S, WC: desulfurized tailings 0.15% S (modified from Demers et al. 2020).

impact of segregation on the spatial heterogeneity of hydrogeotechnical and hydrogeological properties of tailings. Using core samples extracted from a tailings pond in Abitibi, characterization was performed in layers selected from visual observations. In general, the tailings were fine-grained (P_{80} was greater than 72%), except the tailings located deeper (100–125 cm) that were mostly coarse-grained with $29\% \leq P_{80} \leq 56\%$. Particles tended to be finer and specific gravity lower along the beach. Furthermore, the percentage of sulfide minerals, particularly pyrite, decreased along the beach from the discharge point to the pond (Temgoua 2021). Oxygen consumption tests revealed that the K_r values decreased along the beach from the discharge point to the pond (Driouky 2020).

Geochemical performance of desulfurized tailings as cover material

The geochemical performance of covers made of desulfurized tailings was investigated, to make sure that desulfurized tailings remained non-acid generating when used in covers exposed to the atmosphere and climatic conditions. Four desulfurized tailings from gold mines in Abitibi with sulfur content between 0.11% S and 0.26% S were tested in laboratory columns as covers to prevent acid mine drainage. Although the four desulfurized tailings yielded neutral effluents with very low metal concentrations when tested individually, when used as a cover in non-optimal hydrogeological conditions (i.e., degree of saturation allowed some oxygen flux), some materials were unable to maintain neutral conditions (see Figure 5). Results indicated that the type of neutralizing and residual sulfide minerals have an effect of cover geochemical performance (Demers et al. 2020).

The geochemical evolution of desulfurized tailings is strongly related to the conditions in which they are placed. Projects investigated the impact of reducing conditions, such as in a water saturated cover, or under a cover, as well as the role of microorganisms naturally present on the mine sites (Pakostova et al. 2022; Pinto et al. 2014). Results from samples collected on an inactive and uncovered mine site showed that metals and metalloids associated with various secondary phases, particularly Fe(III) oxyhydroxide phases, can be remobilized via biotic and abiotic reductive dissolution reactions if these conditions were to occur (Agau 2023). More specific experimental work is ongoing where desulfurized tailings are placed in oxic and anoxic conditions for kinetic tests, either as individual materials (weathering cells), or as cover layer over oxidized tailings.

Valorization of desulfurization concentrates

Gold recovery from desulfurization concentrates was investigated from three desulfurization concentrates, using cyanidation and gravity recovery processes. The three concentrates behaved very differently, highlighting the need to have a detailed characterization of the gold and associated particles. Concentrate A had 1.85 g/t Au, concentrate B had 1.75 g/t Au, and concentrate C had 0.72 g/t Au. Recoveries obtained by cyanidation and gravity processes (Knelson concentrator and Mozley table) are presented in Figure 6. There was no relationship between initial gold content and recovery. Indeed, gravity separation was limited by the fine particle size, while cyanidation was limited by gold liberation. Proposed flowsheets can include the recirculation of the desulfurization concentrate into the existing cyanidation circuit, where applicable, or can include a dedicated gravity concentration circuit (Allard et al. 2022).

Closure

Mine tailings can cover significant surface area in tailings storage facilities, which ultimately need to be reclaimed. The reclamation

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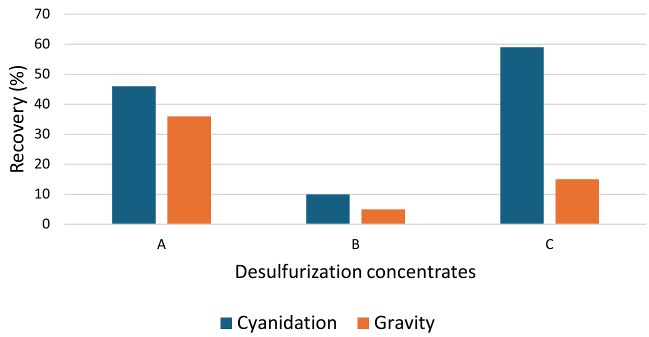

Figure 6. Gold recovery by cyanidation and gravity processes performed on three desulfurization concentrates.

of tailings ponds with a dry cover (single-layer cover or cover with capillary barrier effects, CCBE) requires the use of granular material, such as silt, from borrow pits. To reduce the amount of material excavated from a borrow pit, it may be possible to use the tailings themselves as cover material, if the tailings are not acidic and/or metal-generating (Bussiere et al. 2004).

Previous laboratory tests (Demers et al. 2008, 2009b) evaluated the effect of desulfurized tailings cover thickness, sulfide content and water table level on the oxygen flux migrating through a monolayer cover and a multilayer cover (CCBE). Mbonimpa et al. (2003) proposed analytical solutions to Fick's Laws to describe oxygen movement through desulfurized tailings covers. Numerical simulations were performed (Demers et al. 2009a; Ethier et al. 2018; Pabst et al. 2017; Romano et al. 2003) to replicate and predict cover performance, based mainly on laboratory data. These laboratory and numerical works validated the possible use of desulfurized tailings as cover material, as long as the cover itself does not generate AMD. Furthermore, the presence of residual sulfur in the desulfurized tailings cover can be beneficial, at least for the short term, to reduce further oxygen transport by consumption within the cover through residual sulfide oxidation (Bussiere et al. 2004; Demers et al. 2009b; Dobchuk et al. 2013). The demonstration of the use of desulfurized tailings for cover applications was performed in experimental field test cells exposed to atmospheric conditions. Work by Rey and Kabambi (Kalonji-Kabambi et al. 2016, 2018; Rey et al. 2016, 2017) on mine sites in Abitibi, Canada, provided data to further validate the reclamation design and evaluate the influence of seasonal climatic conditions on two types of oxygen barriers (monolayer cover with elevated water table and CCBE).

Another aspect that deserves investigation is the possibility of using environmental desulfurization to reprocess old tailing ponds to recover gold or other valuable metals that were not recovered in the past, while at the same time to facilitate site reclamation by producing neutral and decontaminated tailings that reduce the environmental liability of the site. According to the Ministry of Natural Resources and Forests (MRNF), there are 459 legacy sites (exploration, mine, quarry) registered on the environmental passive registry, including 255 mine sites (MERN 2018). Some of these sites contain AMD generating and metal leaching tailings, which must eventually be reclaimed to reduce their environmental impact. Reclamation of legacy sites can be difficult because of tailings properties, not being designed for closure, contaminated pore water, material supply, accessibility and costs (Bussière et al. 2005). Oxidation products from sulfide exposure to atmospheric conditions can be deposited on the particle surfaces in unsaturated conditions. When pyrite is present, the weathering products found on its surface depend on the pH: goethite in neutral conditions, ferric hydroxysulfates in acidic conditions (Nordstrom et al. 2015). When pyrrhotite oxidize, ferric oxyhydroxides precipitate on the surfaces. Dissolution of metal species also contributes to low-quality effluents. For legacy sites, desulfurization could be considered as a method to produce cover-quality materials and/or to reduce AMD generation and metal leaching from the tailings.

The re-use of mining materials, and particularly mine waste, as part of the materials required for reclamation scenarios construction, is considered to fit perfectly with the objective of integration of environment in the mine life cycle. Waste produced during operations can become raw materials for closure reclamation (Nason et al. 2014). Three types of materials were tested: desulfurized tailings, waste rock and AMD treatment sludge.

Use of desulfurized tailings as cover for reclamation

Rey tested desulfurized tailings as monolayer cover over reactive tailings at the intermediate field scale, using experimental test plots installed on site at the Westwood-Doyon mine (Figure 7). His work, which also involved laboratory tests, showed that water table level is the main parameter that affects oxygen transport toward the reactive tailings. Two types of low-sulfide covers were tested: a fine-grained material and a coarser-grained material. Both were effective in preventing AMD from the reactive tailings although their function is different. The fine-grained material acts as an oxygen barrier by maintaining a high degree of saturation while the coarse-grained material prevents desaturation of the reactive tailings by limiting evaporation (Demers et al. 2015c; Rey et al. 2016, 2017). However, the mine life cycle does not end once reclamation is complete. The post-reclamation period can stretch to decades and centuries. Nowadays, long term prediction of reclamation scenarios performance cannot be separated from climate change effects. The numerical modeling of desulfurized tailings cover performance evolution with climate change involved the use of projected local climate data to estimate the future climate (Alam et al. 2020). The modeling showed that warmer and drier periods in the future may lead to decreased performance of the cover punctually (Lieber et al. 2022). The climate change risk evaluation approached elaborated is now used in MRNF's reclamation plan, where it is used as a guide for mining companies to integrate climate change in their reclamation plans (Bresson et al. 2022). Furthermore, a drought index specific for design of reclamation purposes was developed (Bresson et al. 2018a, 2018b; Hotton et al. 2018, 2019).

Valorization of other mine wastes

Desulfurized tailings and low-sulfide waste rock were tested as components of a cover with capillary barrier effects, both in the laboratory and field. Hydrogeotechnical monitoring of the laboratory columns and the intermediate field scale cells revealed that the contrast between the waste rock and desulfurized tailings is adequate to create a capillary barrier, to maintain the desulfurized tailings at a high degree of saturation and to reduce significantly the oxygen flux towards the reactive tailings (Kalonji-Kabambi et al. 2020a; 2020b). However, the oxygen flux reduction was not sufficient to prevent acid mine drainage, due to the highly reactive nature of the tested tailings (Kalonji-Kabambi et al. 2020c). The combination of desulfurized tailings and waste rock was also evaluated on an inclined surface to prevent AMD from dikes formerly built with acid generating materials and was found

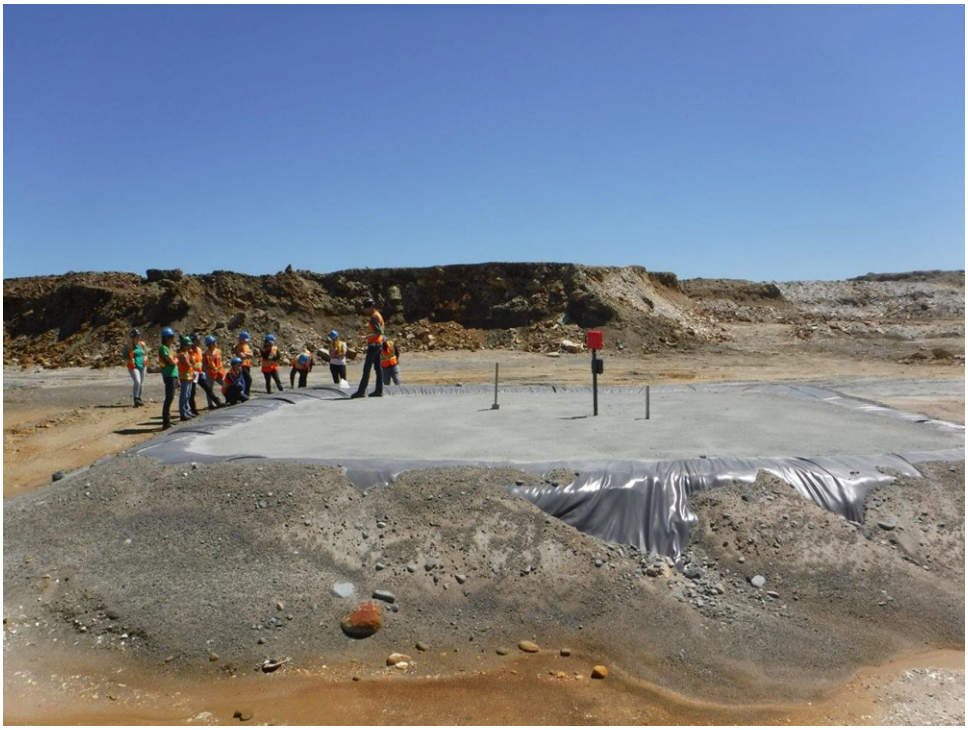

Figure 7. Field experimental cell representing a monolayer cover made with low-sulfide tailings with elevated water table.

successful in deviating rain from infiltration into the dyke (Kalonji-Kabambi et al. 2021).

Another project investigated the use of reactive waste rock as cover material, more specifically for a monolayer cover with elevated water table. Removal of fine particles was tested both as a method to reduce the contamination potential of the waste rock and to favor a capillary break between tailings and waste rock layer to prevent evaporation of the tailings pore water. Waste rock from three mine sites were separated into size fractions and tested in leaching columns to obtain the evolution of leachate quality. For two out of the three waste rocks, a significant decrease in sulfate release rate was observed when the particle size is above 1 mm, as shown in Table 2. The third waste rock is already oxidized and was found to be unsuitable for re-use as cover material, especially when exposed to the atmosphere (Sylvain et al. 2023; 2024).

Treatment sludge produced by the lime neutralization process applied to acidic effluents was investigated as reclamation material. AMD treatment sludge being very fine and at low solid density, it was mixed with either waste rock, tailings or soil, as part of a cover system to prevent AMD from reactive tailings (Demers et al. 2015a, 2015b; Demers et al. 2017b; Mbonimpa et al. 2016). Results confirmed that AMD treatment sludge mixed with soil makes a good water retention material, with hydrogeotechnical properties required for a monolayer or part of a multilayer cover scenario. The tendency of sludge to facilitate vegetation growth began to be investigated in this project through bioaccumulation studies, which showed no bioaccumulation in roots, stems and leaves (Smirnova et al. 2013).

Environmental desulfurization of inactive and legacy tailings sites

Legacy sites can become a valuable resource in a context of increased demand for minerals and metals and shrinkage of reserves. Reprocessing could also be an opportunity to apply an appropriate closure plan on those sites. Environmental desulfurization could produce required low-sulfide fine material for cover construction. However, desulfurization by flotation is complicated by weathering products present on the sulfide particle surfaces due to prolonged exposure. Oxidation products have low affinity with flotation collectors because they inhibit collector adsorption at particles surfaces (Clarke et al. 1995). Skandrani investigated three pre-treatments to enhance sulfide recovery by flotation and recover gold in the sulfide concentrate. Her experiments tested agitation, attrition and regrinding on aged arsenic-leaching tailings, in which arsenopyrite and pyrite were the main sulfide minerals, and almost 50% of sulfur came from sulfates (or weathering products). Regrinding was the most efficient pre-treatment in both residual %S in tailings and gold recovery to the concentrate (68% Au recovery at a grade of 20 g/t) (Skandrani et al. 2019). Agitation was also relatively efficient but required longer flotation time because of slower kinetics. The objective being to produce non-AMD and metal leaching desulfurized tailings, small scale kinetic tests were performed and revealed that while regrinding enhanced sulfide and gold recovery, it liberated arsenic-bearing particles and generated a As-enriched effluent (Figure 8). In this case, the two objectives of gold recovery and production of inert tailings for reclamation were not compatible.

Discussion

The collection of research projects presented in this article aimed to show different pieces of a puzzle that can be part of a good mine closure. As stated above, good mine closure should be planned from the start of the mining project and be adapted as technology and scientific knowledge evolve, with the ultimate goal of leaving a positive legacy after the mining operations, for the communities and environment.

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Table 2. Cumulative sulfate release rates per size fraction for three waste rocks (adapted from Sylvain et al. 2023)

Size fraction	Sulfate release rate (mg/kg/d)		
	Waste rock #1	Waste rock #2	Waste rock #3
0–1 mm	7.5	42.9	43.3
1–2.36 mm	1.1	1.1	16.9
2.36–3.35 mm	0.4	0.9	17.9
3.35–4.75 mm	0.4	0.8	21.1

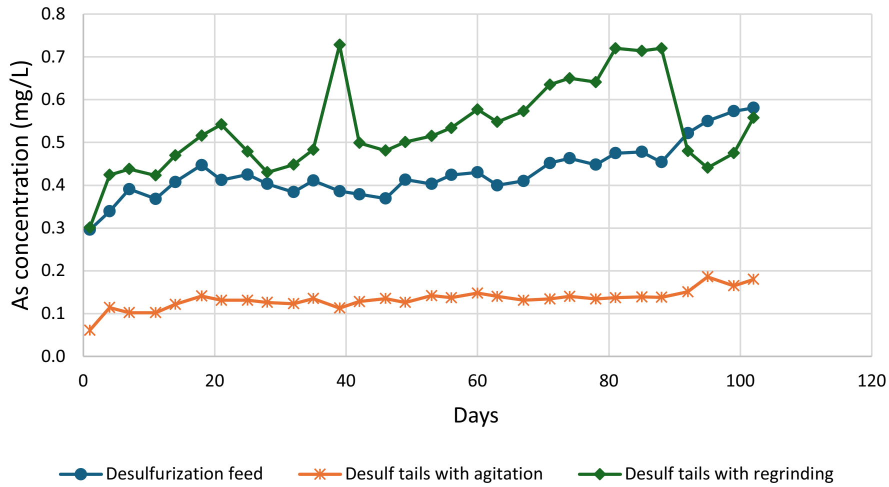

Figure 8. Arsenic concentration evolution in leachate from weathering cells kinetic test performed on feed tailings to environmental desulfurization and desulfurized tailings produced with previous treatments: agitation or regrinding. Modified from Skandrani (2019).

The proposed tools and methods described in this article cannot be applied systematically to all mining projects and operations. For instance, environmental desulfurization was found to be applicable to several types of sulfidic and sulfosalts minerals (see Section 2.1), however, when neutralizing minerals are absent or in very low amount, environmental desulfurization as it is done nowadays is likely to be unsuccessful (see Sections 2.1 and 2.3). The intent with the Canada Research Chair scientific program was to add more tools to the mine planner and closure managers' toolbox to make the best-informed decisions on their site closure.

Conclusions and impact statement

The question proposed by Drs. Littleboy, Marais and Baumgartl provided an opportunity to reflect on mine closure. In this article, the engineering and geoscience perspectives were taken to present recent research work to improve mine closure. The research work was performed through the Canada Research Chair program. The underlying principle of all the work presented here is that good mine closure is one that is planned from the beginning of the mine life cycle. Results from research projects focused on the three main phases of the mine life cycle were presented.

In the exploration stage, characterization of the orebody should also focus on waste rock and tailings geochemistry. These materials are often overlooked due to their lack of value, but a better knowledge of the upcoming waste material helps to optimize their management during operations and the closure plan.

During operations, environmental desulfurization was proposed as a method to prevent the disposal of acid generating tailings and waste rock, which will reduce the environmental liabilities and facilitate closure. Desulfurized tailings can also be reused as construction material for reclamation cover systems, reducing the requirements of natural soils.

Finally, at closure, the research projects proposed to valorize existing mine waste, such as desulfurized tailings, waste rock and water treatment sludge. Legacy sites deserve a special attention due to the oxidized nature of the tailings.

The combination of several approaches at the different steps of the mine life cycle should enable to improve the technical closure performance for a given mine site. An important perspective that was obtained from the research program is that mine closure and environmental performance is a multidisciplinary engagement, requiring several disciplines such as engineering, geology, mineral processing, geotechnique, chemistry, to reach and sustain the best applicable practices throughout the mine life cycle. It is also important to keep in mind that closure performance needs to include social and community engagement, strong policies and regulation, and environmental protection, among other aspects. This article is thus only one part in the global answer to the question: 'what is good mine closure'.

Data availability statement. Data availability is not applicable to this article as no new data were created or analyzed in this study.

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