

Unlocking value in mine waste and mine sites

No. 61
SRK Consulting's
International
Newsletter



A common theme in evaluating mine sites, even abandoned or closed sites, is the potential for sustainable development either through mining or in a post-mining phase.

The reality is that closing and abandoning mining areas is rarely due to complete consumption of a reliable resource but rather due to diminishing financial returns based on metal or mineral values, or social, political and environmental restrictions that lead to an uneconomic scenario for a resource unit. In assessing a mining area there are several potential sources of economic value, including:

- Previously unidentified resources in the mining area.
- Mining of known in-situ ore and stockpiled unprocessed ore.
- Recovery of value from previously processed waste and previously cited "mine waste".
- Recovery of value from undeveloped resource, such as processing mine water to recover metals and valuable salts.

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Unlocking value in mine waste and mine sites *(continued)*

- Recovery of new value from mining facilities, such as processing mine sludge to recover ferric oxyhydroxides as a source of iron, pigments and trace metals; developing energy resources from power generation using in-ground heat pumps, high geothermal gradients and/or storing excess CO₂.
- Developing mine water resource for agricultural, industrial or even potable water.

In the case of the first two potential sources, unconventional or innovative methods of exploration may be required to identify these resources; additionally, developing water as a resource either for

metal or salt recovery or as a source of useable water requires hydrogeochemical investigations. The successful development of these resources and value recovery often requires more efficient metallurgical circuits or new chemical and physical extraction procedures to recover value.

This paradigm shift in thinking has already taken place. High mining costs, increasingly stringent environmental regulations, and the need to reduce liabilities is encouraging the re-assessment of mine wastes as potential “new” resources. Water treatment and management technologies employed by SRK help to provide clean water for alternative use while creating by-products that could be marketable, or disposed of as a non-hazardous material, thereby reducing the cost and long-term liability of disposal. When these recycled or refined materials are found to have a market, a revenue stream is created which can offset ongoing treatment.

Furthermore, extracting resources from mine wastes and marketing these resources contributes to the long-term sustainability of the mining operation. This helps to offset closure issues and costs while allowing continued wealth generation. SRK has been involved in several such studies and continues to develop strategies to mitigate the impacts from mining operations while looking to provide more sustainable practices for mining operations and maximise shareholder value.

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Extremely acidic metal rich mine water, Richmond mine, California

Proactive not reactive geochemistry...



Contaminated mine workings

Russian mining companies are guided by compliance with the Russian Federation legislative requirements. Currently, these do not require specialized studies of aspects such as potential acid rock drainage and metal leaching (ARDML) and processing waste. Nevertheless, in recent years, Russian environmental legislation has considered implementing the principle of “best available technologies,” which, among other things, considers international industry practices. To date, however, most of the requirements are advisory in nature.

Traditionally, geochemical assessment of mines in Russia has largely gone unnoticed due to the lack of regulatory requirements. Waste rock material and processing waste are given hazard categories based on biotesting that does not account for ARDML. Based on this biotesting, mining and processing waste is most often classified as

“practically non-hazardous waste,” and the design solutions and environmental monitoring cannot fully assess these impacts and mitigate them.

For example, in 2019-2020, local concern emerged over drainage from the abandoned Levikhinsky (copper-pyrite ore) mine near the Levikha settlement (near Kirovgrad, Urals), impacting the Tagil River. Local pressure and media coverage have led to the regional government requesting assessment of technologies to control and treat the drainage with lime to neutralize the mine waters.

In addition to the key commercial metals copper, zinc, sulfur, gold, silver, selenium, germanium, and cadmium, the Levikhinsky ore also contains lead, tin, arsenic, antimony, tellurium, and indium. No closure or reclamation activities were carried out when production stopped in 2003, and in 2004 the mine was flooded. In 2010, the mine became state property.

Currently, the contaminated mine water, rain and snow melt water from the waste dumps are directed to the technical pond for neutralization. The ponds overflow into the Levikha River and then into the Tagil River. It is estimated that approximately 6,500t of lime are required annually to treat the contaminated water; however, it is currently not possible to completely remove the contaminants. For example, the concentrations of zinc and copper alone in the Tagil River after the confluence of the Levikha River exceeds the local water quality standards by up to 80 times.

A more proactive approach of assessing the potential problems before they occur and planning accordingly could have minimized both the costs and the resulting impacts.

Good stewardship in the global mining industry requires a comprehensive approach to evaluating closure studies during initial mine planning, not just for

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closed or abandoned mines, to ensure the full costs of mining from cradle to grave are covered in the economics of the life cycle of the mining operation. Closure and rehabilitation solutions should be planned based on local environmental and social conditions. Particular attention should be paid to predicting the ARDML potential from waste rock and processing waste, as well as modelling the possible composition of mine water and drainage water from waste rock dumps. With this information from the early stages of the project, it is possible to develop appropriate measures to minimize impacts and reduce overall costs and liabilities, making both good financial and technical sense.

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Claire has 25 years of experience in interpreting geochemical data, building conceptual models of processes that control in situ geochemical behaviour and applying geochemical modelling codes. Claire's experience includes sulfidic materials management: acid/alkaline rock drainage (ARD) assessment and prediction; water quality and pollutant mobility from waste rock dumps, tailings storage facilities, underground workings and pit walls; and assessing the effectiveness of potential mine closure strategies.



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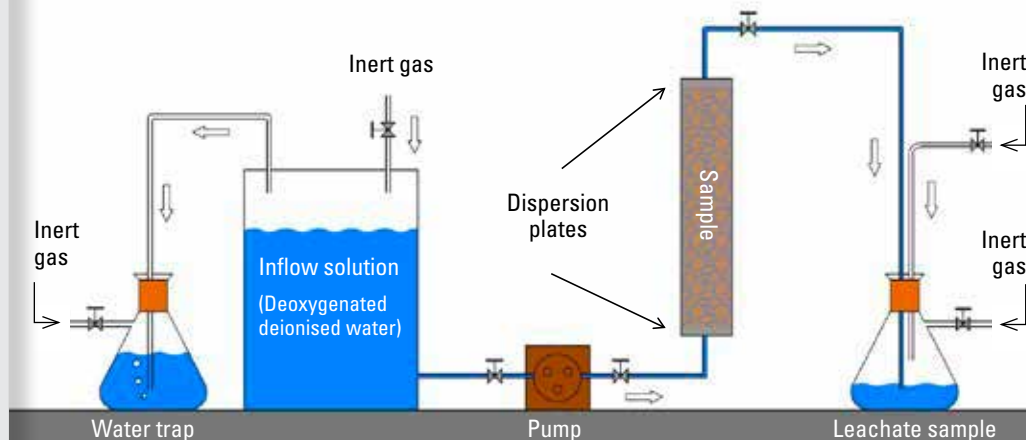
Alex has over 20 years of experience in environmental projects gained from working in the UK, South Africa and Australia. While his main area of expertise is geochemistry, he also has experience in water and waste management, mine closure planning, environmental impact and management and due diligence studies. Alex has experience in site investigation, characterisation and assessment (mine site/ mineral waste and contaminated land). He has provided consulting expertise to both the private and public sectors on projects concerning mining, industrial and waste management issues in order to achieve legal compliance, improve environmental performance or manage risk.



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Backfilled pits - optimising leach datasets for closure planning

System isolated from atmosphere using and inert gas used to ensure anoxic conditions are maintained over test duration



Samples undergoing saturated column leach test

In the Pilbara region of Western Australia, management of waste rock includes backfilling of mined out pits. Where the backfill is expected to become inundated following groundwater rebound, flow-through conditions are likely to develop. An understanding of the potential for solute release under these conditions is important when assessing the possible impacts backfilled pits could have on the post-closure groundwater quality.

SRK's geochemists have a range of leach tests available in their toolbox for use in assessing the leaching potential of mine wastes. These include conventional, nationally and internationally recognised tests, and niche tests tailored to address the specific needs of a project.

An example of a niche test is the saturated column test, designed to assess solute leaching under anoxic conditions that are representative of inundated backfill. SRK has applied this method to a range of sample types, including: Low sulfur, but metalliferous,

samples, and high sulfur, acid generating samples, which had previously been subjected to 'accelerated' weathering and oxidation in free draining columns.

The inflowing solution was actual groundwater collected from the project site, since interaction with solutes present in the groundwater is another key consideration in determining leaching potential from backfilled materials.

The test results demonstrated a number of geochemical trends that may be expected under saturated conditions, such as:

- Readily soluble salts containing major species such as sulfate were progressively flushed over multiple pore volume exchanges. Such salts were present in significant quantities in the high sulfur wastes that had been 'weathered' prior to inundation.
- Dissolution of sparingly soluble minerals released low concentrations of contaminants, such as arsenic,

boron, barium, cobalt, manganese, thallium and uranium on an ongoing basis.

- Some elements (e.g. arsenic, manganese) were shown to be very sensitive to dissolved oxygen levels in the inflow solution – interpreted as changes in source mineral solubility in response to redox or oxidation reduction conditions. Within inundated backfill, oxygen concentrations are expected to be low; assessing the applicable redox conditions will be an important factor in determining leaching behaviour for some elements.
- Sorption of some solutes (including antimony, molybdenum, selenium and zinc) from the inflowing groundwater was observed.

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Geochemical modelling to support closure

Geochemistry formed a critical aspect of closure planning for the Century open cut zinc mine. The mine is located in Queensland and the mining infrastructure includes three out-of-pit waste rock dumps, one in-pit dump and a tailings storage facility.

Closure objectives were developed for the infrastructure at site and the plan for the pit was that it would remain in place with a lake developing within it, post-closure. The water quality that may develop within the lake post-closure was identified as a potential risk to meeting downgradient water quality objectives (surface and groundwater).

To evaluate the risk, SRK developed a pit lake model that integrated the outputs from geochemical characterisation programmes, water balance studies and hydrogeological modelling. The model quantified solute production rates from pit walls and mineralised wastes located within the pit and accounted for potential influences from out-of-pit waste dumps.

Pit lake water quality was calculated over time, allowing the assessment of potential impacts to surface and groundwater, and third party receptors. Using the predictions from the model it was possible to compare potential environmental outcomes for different closure strategies and assumptions, and set priorities for forward works and make informed selection of optimal closure measures.

Modelling indicated that the pit water would be acidic and become more saline with time due to solute accumulation combined with evapo-concentration effects. The effects were greatest where the pit was modelled as a permanent sink, but were still significant for cases where modelling indicated release via groundwater through flow and overtopping. The modelling suggested that pit lake water may not be suitable for discharge.

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Lake forming in the open pit

Determination of the rate of release of nitrates from waste rock, tailings and kimberlite in field conditions: a case study

The release of nitrates (NO_3^-) and ammonia (NH_3) from explosives during mining are usually attributed to spillage or incomplete detonation and subsequent dissolution of ammonium nitrate (NH_4NO_3). Field Kinetic Cells (FKT) monitored over three years were used to determine the rate of release of the nitrates from pre-blast, freshly blasted (<10 days old) waste rock and kimberlite (KMB), and fresh tailings.

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Levi, Pr Sci Nat, is a Senior Geochemist and holds an MSc. degree in Environmental Analytical Chemistry and a PhD in Analytical Chemistry. He has over 10 years of experience specialising in source term characterisation, water monitoring, mine drainage, mobility assessment of heavy metals and analytical methods development. Levi has been involved in the application of new regulations to assess mine waste. He has worked on diverse projects in coal, base metals, and precious metals in Botswana, Democratic Republic of Congo, Lesotho, Guinea, Sierra Leone, South Tanzania, Turkey, and Zambia.

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The field conditions were -15°C and 10°C (extreme winter), 23°C maximum average temperatures, 750 mm mean annual rainfall, and frequent snowfall.

The study indicated that >75% of the nitrates are flushed by recharging water during the displacement of the first stored water volumes. Leaching occurred during summer. No leaching occurred in winter due to frozen conditions and lack of rainwater to mobilise nitrates. The leaching rates were established to be as follows in decreasing order in mg/kg/day:

Blasted KMB (0.0002–0.024) > Blasteds Waste Rock (BWR) (0.0001–0.019) > Tailings (0.0002–0.008) > Unblasted Waste Rock (UBWR) (0.0001–0.0024)

The study followed the recommended procedure for predicting nitrates export by Ferguson and Leask (1988). The FKT leaching rates were scaled to field rates using particle size (density) scaling factors. The results indicated that it will take 12–17, 2.6–3.5, and 2.2–2.9 years for nitrates to be leached from WRD1, WRD2, and TSF respectively. The apportionment of the nitrates' loads to the site components will affect the predicted times and can be refined based on the number and sizes of the waste facilities over time.

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Set up of field kinetic cells

Methodology for managing and using solid and liquid mining waste



Left: Surface water quality monitoring in mining area at 5000 msnm, Mina Arcata, Peru
Right: Measuring field parameters in acid drainage of old mining operations in the area of Hualgayoc, Peru

This article describes a methodology for managing solid and liquid waste generated in mining processes to reuse and recover by-products of mine effluents that have economic value. This is known as the circular economy of mining waste.

To evaluate the possibilities of using solid mining waste, it is necessary to characterise them geochemically to predict their behavior over time, and to identify their possible use in other activities of the mining process, or to identify their definitive storage in case of reactive residue. This reduces the volume of waste to be stored and chooses the most adequate coverage to ensure the physical, chemical and hydrological stability of the deposits where they will be permanently deposited.

In evaluating acid generation, we depend on static tests (ABA),

short-term leaching tests (NAG, SPLP, SFE) and kinetic tests, which assess indicators such as the net neutralisation potential, acid/base ratio, and sulfur content.

Comparative studies are usually added, correlating them with aspects such as the mineralogical and petrological composition of the residues, physicochemical characteristics of the excavated rock mass, storage conditions of these materials and residues, and the possibility that these materials will come into contact with water and air.

With this geochemical characterisation, inert or non-acid generating waste can be reused while wastes that generate acidity must be stored in watertight or waterproof tanks.

To control liquid mining waste such as effluents and contact waters, the effluent is treated before being

discharged to a receiving body if it complies with the LMP limits and current ECA standards.

Prior to treatment, we geochemically characterise mine effluents and evaluate the possibilities of recovering by-products with economic value during the treatment. This makes the process more efficient, since in addition to the protonic acidity, the mineral acidity is assessed, an aspect that usually is not considered in classic characterisation methods.

With this information, we proceed to sizing the acidic water treatment system based on the acidity content and by stages. This reduces the amount of lime used in the neutralisation process and allows the recovery of metals from the sludge of the process. This makes acidic water treatments more efficient, at lower cost with greater environmental control.

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Correcting the imbalance between geochemistry regulation and innovation



Examples of acidic water

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Jeff has over 35 years of project experience in North America and internationally. He holds a degree in Geology from Dartmouth College, Hanover, New Hampshire. Jeff's expertise includes mine closure and remediation, mine environmental studies, mine permitting, and environmental geochemistry. In particular, he has specialised in closure cost estimating work including the development of the public domain Standardized Reclamation Cost Estimator (SRCE) model used by mining companies around the world to prepare closure cost estimates.

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There is a certain predictability to how the regulatory framework of a mining jurisdiction evolves. In the beginning, regulators embrace the best methods and technologies of the day, readily updating the standards whenever evidence of better practice becomes available. But as a jurisdiction matures, standards are hard-coded into legislation and rigidity sets in.

The prevailing standards may be based on good science, but it is old science; as a result, innovation is suppressed. Rigid numerical and procedural standards remove the space for the mining industry to develop new approaches to geochemistry work such as analysis of data collected from water-quality monitoring programs.

In a recent SRK project, we understood that applying the jurisdiction's rigid standards for a very small effluent

discharge into a receiving water with naturally elevated metals would force our client into an expensive and potentially unsustainable solution for site closure. We rethought the whole process, approaching it from the simple concept of 'do no harm'. This enabled us to evaluate the impact of various closure alternatives on the geochemical environments downstream of the mine. As a result we devised a method of sustainable closure that would cause no harm to the environment, even if it fails to meet the strict numerical standard at the discharge point. This approach now awaits regulatory approval.

Even when regulators are willing to accept new approaches, they usually put all the financial and other risk on the mine operator. For example, they might allow the operator to pursue a

new approach but still evaluate it using the standard approach. Most mining companies are unwilling to take on that level of risk, stifling innovation in how we look at geochemical systems on mine sites and how we apply the information collected from geochemistry studies to mine operations and closure.

We as an industry should always look for new ways to do things, but if strict rules or standards prevent us from applying these methods in real life, and if the risk is borne entirely by the operator, then we miss out on the opportunity to do our jobs better going forward.

Regulators can correct this situation by minimizing the prescriptive standards or methodologies written into law. Instead,

these standards should be written into policy and guidance documents, making them easier to change when new innovations and technologies become available.

If the standard is written into law, then a back door should always be left open for the mine operator to propose a different approach so long as they can demonstrate that it meets the overall objective of the law. When Nevada introduced its water pollution control legislation, the underlying principle was that operators 'will not degrade waters of the state'. Although specific methods were written into the law, operators were given the option of submitting alternative approaches to the Division of Environmental Protection. The problem is that as regulators become more

accustomed to specific methods, it makes it harder for mine operators to propose an alternative.

Mine operators and consultants can also help to improve the situation: we must be willing to propose alternative approaches, educate regulators and local communities, and put in the work required to prove that our approach is the right one.

In short, we must always continue to innovate and educate.

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Better mine waste management through drill core optimization

The amount of time, effort, risk, and cost to run an effective resource drilling campaign is not trivial. It is surprising, then, to find that after collecting and cataloging metres upon metres of drill core, very little analysis is completed. The addition of multi-elements can provide orders of magnitude benefits to geometallurgy and geoenvironmental disciplines, not to mention the benefits of using multi-element geochemistry to find even more resources.

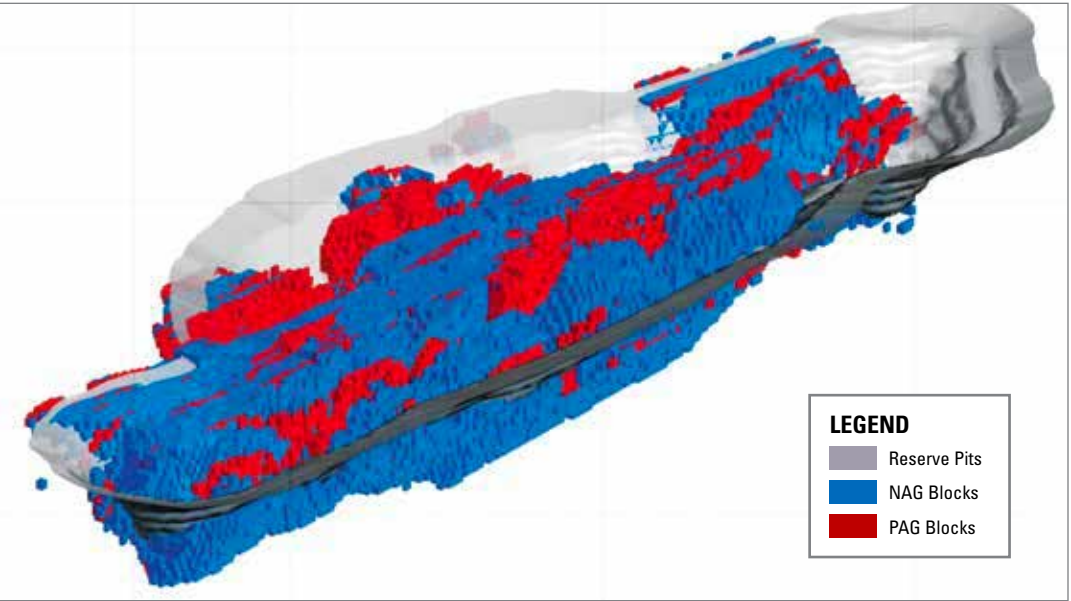
Predicting the geochemical reactivity of mine waste (e.g. waste rock, tailings, pit walls, borrow sources, etc.) is often only based on hundreds of samples, in stark contrast to the tens of thousands of samples used to develop the resource model. While the economics of a project are key, the lack of data for other disciplines results in creating significant long-term liabilities. This impacts mine waste management decisions mainly by creating overly conservative and onerous requirements for the mine site, high financial assurance requirements, and in many cases missing risks that manifest in post-closure.

One step forward for many resource development programs is the inclusion of multi-element analyses of the drill core at the same frequency as the commodity assay. The mine waste management benefits of doing this include:

- High resolution understanding of rock composition throughout the deposit in the ore as well as the tailings, waste rock, and pit walls
- Potential to block model mine waste (see image below and related article by L. Donkervoort and A. Bailey on page 18 of this issue) before it is mined, which is more effective for mine planning and managing waste than analysing blast hole cuttings during operations.
- Identification of non-reactive borrow materials within the waste rock zone around the ore deposit and potentially eliminating the need to quarry for borrow material in some projects
- Assessment of metal leaching could be completed at the scoping level stage of project development, which may require a water treatment plant or require a change to the mine plan to mitigate the leaching process

Cost is often the main barrier to not including multi-element scans. However, if drill core is already being submitted for commodity assay, sample analysis can be a fraction of the assay cost per sample. The cost should be considered insignificant when considering the costs of managing the risks and uncertainties.

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Declassifying potentially acid-generating mine waste rock



Carbonate in waste rock fines at CMM reacting strongly with dilute hydrochloric acid

When the historic Copper Mountain Mine in south-western British Columbia restarted mining in 2010, waste rock and low grade ore (LGO) had to be segregated based on their acid rock drainage (ARD) potential, using operational monitoring of blast hole cuttings. Subsequent testing of waste rock and LGO blast fines showed that rock initially classified as potentially acid-generating (PAG) was expected to behave as non-PAG in stockpiles.

SRK evaluated the influence of rock type and age of the rock on ARD potential in several blast rock size fractions ranging from -2 mm to +25 mm. Samples were analysed by size fraction for parameters used

to classify their ARD potential (sulphide sulphur and total inorganic carbon). Bulk rock classified as PAG was found to be predominantly non-PAG in the 2 mm fraction; an observation attributable to the occurrence of carbonate as fracture fillings rather than a matrix component. Differences due to rock type and rock age did not significantly change the outcome.

These findings, in conjunction with the observed lack of ARD at the Copper Mountain Mine, despite historical mining spanning more than a century, resulted in the recommendation to the owner and regulator that geochemical segregation was not needed. Segregation is no longer required resulting in substantial

reduction of costs for managing current and future waste rock and LGO. The ARD Management Plan for the mine was revised to include provisions for ongoing evaluation of the finding and re-imposing segregation based on alert and trigger levels.

This study demonstrated the value of a systematic rock ARD monitoring program implemented at start-up. The monitoring program was developed from a sound understanding of site-specific factors including deposit geology, climate, mining method, waste mineralogy and reactivity, and waste storage.

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Bronwen is an Environmental Geochemist with experience in characterising mine waste and modelling contact water chemistry from metalliferous sedimentary, copper porphyry, coal, and oil sand deposits in Australia and North America. She has a PhD in Environmental Geochemistry and has spent four years characterising the mineralogy and long-term metal leaching and acid rock drainage potential of tailings at the Mount Isa Mine in North-West Queensland, Australia, as part of her PhD research. Bronwen's experience includes geochemical characterisation of mine wastes, geochemical modelling, water quality prediction, and developing mine waste and water quality management plans.

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Mine waste geochemistry issues in China

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ML/ARD seepage from a pyrite mine tailings storage facility in Southern China

Due to the lack of ML/ARD regulations and guidelines in China's mining industry, mine waste geochemistry studies are limited to the academic society funded by the government bodies. SRK China has recently completed a comprehensive literature review of these studies.

In general, Southern China due to higher rainfalls and warmer temperatures, has experienced more noticeable events of metal mining impacts. As a result, more research grants are biased towards that region.

Sulfur-bearing minerals are quite common among the identified mineral deposits in China, and the mining industry is criticized for the adverse effects of pollution. According to the data disclosed in journal articles, the pH values from some leachate were reported between 3 and 5, with As, Cd, Pb, and Zn concentrations far above the Chinese wastewater discharge criteria. Even worse, most farmlands nearby

are irrigated with the polluted water, apparently causing soil contamination and producing toxic agricultural crops.

Some researchers have argued that soil contamination observed is natural, reflecting background anomalous levels of metals associated with mineralised rocks. However, evidence collected to date indicates that the high levels of Hg, As, and Cd observed in southwest China is due to anthropogenic dispersion of metals due to poor mine waste management practices. SRK suggests that environmental regulations should be followed regardless: all relevant wastewater discharge criteria must be met before being discharged. It's possible that mining activity could increase the naturally occurring contamination by two or three orders of magnitude, if no environmental protection measures are taken. Many of the studies published do not report sample methodology and/or collect a low density of samples. Therefore, the representativeness of samples is

problematic, and the results could not be a direct indicator of pollution under natural site conditions. According to SRK, a standard sampling program conducted by the academic society is critical, and the mining industry must continue it in the future.

Researchers conduct both static and kinetic tests, but all are generally at a bench scale test. The duration of a kinetic test is too short in general (usually two weeks maximum) to mimic the natural weathering and oxidation conditions, since pollution ML/ARD may not necessarily occur at that early stage. For example, a wastewater treatment facility operation could fail if the wastewater parameters are incorrectly estimated and applied. These results could mislead the mine waste management.

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Integrating geochemical solutions into mine closure

SRK South Africa was recently appointed to assist one of the older gold mines in the Witwatersrand Basin develop a closure strategy, particularly focussed on post closure water management of the water expected to rewater the underground workings. As the operation is in a region of dolomite with the aquifers associated with the host rock being a potentially valuable resource in a water-scarce country, SRK was required to develop a closure solution that would limit potential post-closure impacts on this resource.

We were able to demonstrate that although the orebody and surrounding rock had the potential to generate acid rock drainage and metal leaching, the relatively rapid rewatering of the workings would limit acid production and associated metal and salt formation. As the workings rewatered and the water table intersected the dolomite geology, the inherent neutralising potential of the geology and the rapid water movement through the aquifer would limit potential geochemical impacts to a very narrow radius around the shaft collars.

We were able to geochemically demonstrate that because the impact was limited and rapidly dissipated in

the surrounding aquifer, no specific post-closure measures were required to maintain a water level below the dolomite aquifer. Our ability to demonstrate that no postclosure water management was required translates into a potential cost saving of hundred of millions of rands to the company as there is no longer a closure requirement to abstract and treat water.

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James is a Principal Scientist with 22 years' experience. Trained as a geochemist, he developed broad experience in general environmental management working on a colliery in South Africa and on various consulting projects. Over the last 15 years, James specialised in preparing closure liability assessments and closure plans in many jurisdictions for numerous minerals, where he is able to integrate his geochemical training into identifying water management solutions.



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Current discharge and treatment of underground water can now cease

Using portable XRF to identify PAG rock

Acid-base accounting (ABA) is a widely accepted method of classifying acid rock drainage (ARD) potential of geological materials. For remote projects that require classification and identification of potentially ARD generating (PAG) rock but lack onsite analytical capabilities, portable X-ray fluorescence (pXRF) is a field monitoring tool that is an option. Example applications include classifying PAG rock that needs special mitigation/management after excavation, or classifying and segregating PAG waste rock from rock that is non-PAG and/or has a low risk of metal leaching (ML) for use as construction material.

Portable XRF is not an off-the-shelf product and its selection as a field tool for ML/ARD classifications must first be demonstrated. SRK has designed and implemented ML/ARD monitoring programs at proposed, operating and closed mines using pXRF at the operational scale. The first step in determining if pXRF is a suitable field tool

is a review of geochemistry, geology and mineralogy. This desktop review will reveal if pXRF is potentially a viable field tool and identify proxies for characterization of ARD and/or ML potential. The next step is to establish threshold limits for material classification and design a pXRF program that will demonstrate proof of concept. The latter includes establishing sample collection methods that will be representative of the rock and sample preparation methods that will provide the fastest turnaround time. The program also needs to include a pair-wise sample analysis program using pXRF and laboratory methods to develop a site-specific pXRF calibration for parameters of interest and design an analytical program that includes a QA/QC program to ensure data integrity.

After the design of the pXRF program, the final step is to adapt the pXRF program to the operational requirements of the project. This includes designing a program that meets the overall geochemical objectives yet can be practically executed by the Contractor at the operational scale. Implementing a pXRF monitoring program can be an expensive undertaking; however, under the right circumstances, it can lead to overall savings for a project.

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Lisa Barazzuol is a geochemist and Principal Consultant in the Vancouver office specializing in the geochemical characterization and management of mine waste. Her technical practice has included a variety of different geological deposit types for proposed, operating and closed mines. Lisa has acted as technical reviewer on behalf of regulatory bodies and also engaged with project stakeholders on behalf of industry clients.

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Monitoring water quality of pit lakes and tailings ponds through Google Earth Engine

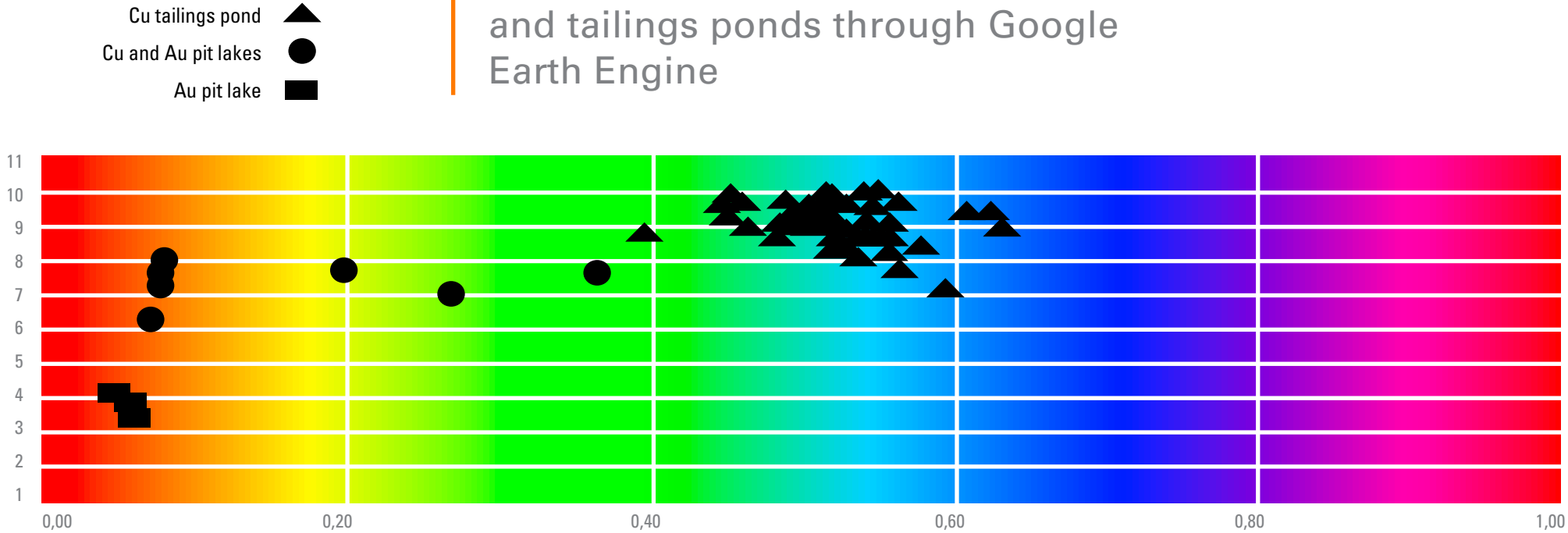


Figure 1: Relation between pH and hue values of surficial water bodies affected by mine drainage

The use of satellite images allows the visualization of the Earth's surface, including estimation of physical and chemical parameters of surficial water bodies. As reported in some crater lakes, the colour of different water bodies can be related with the physico-chemical characteristic of the water (Ohsawa et al., 2009; Murphy et al., 2017): (i) the blue component results from Rayleigh scattering of sunlight by very fine aqueous colloidal sulphur particles, (ii) the green component is attributable to absorption of sunlight by dissolved ferrous ions, and (iii) the red and yellow colors result from the presence of Fe-hydroxides colloids.

We applied this methodology to water bodies affected by mine drainage, specifically to Au and Cu pit lakes and Cu tailing ponds having distinctive pH values (between 3.5 to 9.5; Figure 1). We accessed different Landsat (4, 5, 7 and 8) images over the study period (Jan 1st, 1995 to Jan 1st, 2019) using Google Earth

Engine. After filtering the cloud-covered images, the blue, green and red bands were transformed to the Hue, Saturation and Value (i.e. HSV) colour model, and the temporal variations of the HSV parameters were compared with some physico-chemical characteristics of the water bodies.

For the study case, it was possible to establish that water bodies with higher electric conductivities reflect more light (higher V values) but their saturation component (S values) are lower. Similarly, S values show a decrease with the occurrence of external factors such rainfall, possible associated with clouds and water vapor. The pH exhibits a relation with the H values, which is related to the chemical composition of water, specifically to changes in Fe(II), Fe(III) and SO₄ concentrations. Pit lakes with pH values < 5, display red to orange colors (H values ranging between 0.05 to 0.1), possible associated with the saturation of Fe-hydroxides as calculated by PhreeQC. At pH values > 8.5, tailings ponds display blue to turquoise colors

which is associated to both sulphate and dissolved ferrous ions, as well as others divalent metal (such as Cu) that are soluble at these alkaline conditions. At pH values between 5 and 8.5, pit lakes and tailing ponds exhibit orange to green colors (H values ranging from 0.2 to 0.5), which seems to be associated to a decreasing Fe(III)/[Fe(II) + Fe(III)] ratio as pH values increase.

These preliminary results indicate that:

- HSV parameters of different water bodies affected by mine drainage can be obtained using Landsat imagery, particularly on surficial water bodies with sizes greater than the pixel of the satellite images used.
- Temporal variations of HSV parameters can be associated with the physico-chemical characteristics of these water bodies (e.g. pH, chemical composition), and therefore, can be used for monitoring purposes.

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OSCAR BENAVENTE

Oscar Benavente is a Geochemist with 10 years' experience in fields related to: (i) geochemical monitoring in environmental systems affected by mine drainage, (ii) numerical modeling of water-gas-rock interaction processes for support of both treatment analyses and fate and transport analyses, (iii) permitting and closure evaluation of pit lakes, heap leach piles, waste-rock dumps and tailings, (iv) geological and geochemical prospecting of geothermal and mineral resources, (v) geochemical monitoring of volcanic systems, and (vi) measurements of CO₂, H₂S, CH₄ and Hg fluxes from soils in volcanic, hydrothermal, and sedimentary areas.

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Multidisciplinary approach for the geochemical design of waste rock dumps at Cerro Moro, Santa Cruz

CAMILO DE LOS HOYOS

Camilo is a Principal Consultant at SRK Argentina. He specialises in environmental geochemistry, lithium-potassium brine, LCT pegmatites, hydrogeology, applied mineralogy and petrology. His experience includes acid rock drainage and metal leaching assessment, mine waste assessment, hydrochemical studies, water resource exploration, assessment of exploration potential for pegmatites, design and execution of lithium-potassium brine exploration programs, and technical audits.



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CLAUDINA GONZALEZ

Claudina is a consultant in SRK's Salta office. She has worked in assessing exploration potential for pegmatites and is involved in projects in the Puna region, evaluating exploration data used in the estimation of lithium resources in brine. Claudina has experience in hydrochemical characterization of water near mining areas and geochemical characterization of mining waste.



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Sampling point representing future mine waste material

Cerro Moro is an epithermal low-sulphidation, gold-silver deposit comprising at least 9 NW-SE trending high-grade quartz-adularia veins 1–5 m in width and 0.5–2 km in length. Proven and probable reserves were estimated at 529,000 oz gold and 30.5M oz silver in December 2019.

In 2016, SRK started a conceptual-level geochemical characterisation

and design of waste rock dumps to prevent future acid rock drainage and metal release. Based on the 2016 mine plan, approximately 20 Mt of waste rock will be extracted from the open pits and 580,000 t remobilised in the underground mines. The 2016 mine plan specified that waste material would be deposited in 11 rock dumps ranging from around 300,000 t to 5.5 Mt. Characterisation and design was carried

out by an interdisciplinary team from the SRK's Argentina and UK offices. The work program included:

- Representative sampling: (1) definition of geo-waste units based on alteration mineralogy; (2) spatial pre-sampling through 3D visualisation of the geo-waste units on Leapfrog™; (3) on-site sampling from drill cores and waste rock.
- Static geochemistry and mineralogy: acid drainage potential, short-term leaching, sequential extraction, optical mineralogy.
- Kinetic geochemistry: up to 32-week humidity cell tests, scaled to site conditions.
- Based on results from geochemical characterisation: (1) estimation of a conservative on-site theoretical net

potential ratio from Stotal, Ca and Mg analyses from the Cerro Moro's database; (2) improved definition of waste material and incorporation into the mine plan via a mining engineering software.

- Conceptual rock dump design: (1) distribution of acid- and non-acid-forming material in the dumps; (2) water management of contact and non-contact water at the dumps.

Total sulphur contents are generally low (<2.5%) but highly variable between vein sectors. Sulphide is the dominant sulphur species. Acid drainage and metal leaching potential at Cerro Moro were considered to be low. However, high proportions of acid-forming material were found in two veins: 70% in Escondida Far West and 100% in Zoe. The proportion in other veins range from 10% to 40%. Considering the semi-arid climate and the low acid-forming potential, onset for acid drainage production is considered to be delayed, but may occur several years after project closure. Further geochemical characterisation and modelling for leachate chemistry predictions were recommended to update rock dump designs to a pre-feasibility level.

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LAURA DONKERVORT

Laura, MSc, is a senior consultant in geochemistry with ten years' experience. Laura has specialized in the area of acid rock drainage and metal leaching with particular focus on coal deposits. Laura's areas of expertise include sampling design, water quality predictions and the development of waste rock management plans. During her time at SRK, she has contributed to the permitting of a variety of deposit types within Canada and Nevada's regulatory environments.

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ALEXANDRA BAILEY

Alexandra, MSc, is a consultant in geochemistry with degrees in environmental geochemistry and geology. She has a background in dust geochemistry, mineralogy, and soil science, and has ample experience with geochemical analysis and field study design. Alexandra has been involved in a variety of geochemical characterization programs at SRK and has developed experience with field studies, water quality predictions, and geochemical modeling.

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Use of geological block modeling in the prediction and management of mine waste

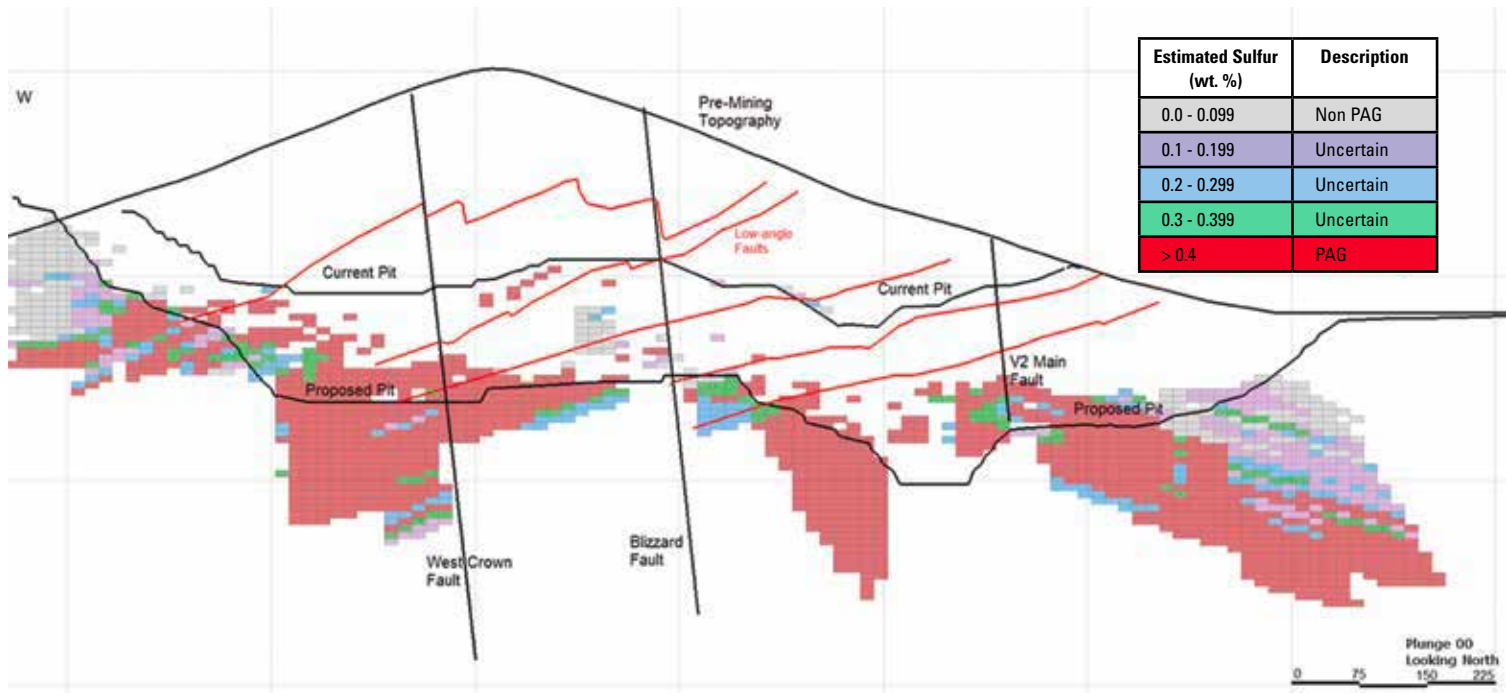


Figure 1: Cross Section of In Situ Waste Blocks in the Sulphur Block Model. Red blocks indicate Potentially Acid Generating (PAG) Material.

A key consideration with the use of routinely collected geochemical data is the appropriate extrapolation of discreetly selected samples over an entire mineral deposit. At the Rochester mine in west-central Nevada, SRK used the existing deposit-wide total sulphur database to predict acid-generating waste at the mine scale.

The Rochester mine is a low sulfidation epithermal gold-silver deposit hosted in silica-rich volcanic rocks. In this deposit type, neutralizing minerals are rare and acid generation is almost entirely a function of the sulphide content of the rocks. Total sulphur data are routinely collected on site to differentiate areas of potentially acid-generating waste rock

as part of the waste rock management plan. To supplement the spatial distribution of this dataset, logged sulfide data were used as a proxy for total sulphur in the absence of analytical data. These data were transformed into total sulphur values which were included in the geological model. This dataset was combined with modeled structure, lithology and grade to produce a sulphur block model, utilizing similar approaches to those used in resource estimation models (Figure 1).

The development of a sulphur block model using mineral resource estimation methodology enabled detailed scheduling of potentially acid-generating waste rock at the mine scale. This study

demonstrates that utilizing available, applicable data as a site-specific analogue is beneficial for the prediction of environmental impacts across a deposit. This work has been accepted for publication in Economic Geology under the title "Sulfide Variation in the Coeur Rochester Silver Deposit: Use of Geological Block Modeling in the Prediction and Management of Mine Waste."

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Characterization of waste associated with rare earth element (REE) and rare metal projects

SRK has been involved with characterizing the wastes and ore associated with REE and Niobium (Nb) projects for ML/ARD potential for projects in the USA and Canada. These deposits are often relatively low in sulphides, and therefore may have a different set of concerns to those of acidic drainage and leaching of metals with high mobility at low pH, which may be of concern for sulphidic base metal projects.

Alkaline igneous rocks including carbonatites and pegmatites are typically the host rocks to REE/Nb deposits. The REEs and Nb are currently not regulated in Canada or the USA in mine effluent; however, the body of literature on toxicity of some of these elements is increasing and regulation may come. REE- and Nb-bearing minerals typically contain thorium and uranium, which may be present in a wide array of minerals including oxides, phosphates, carbonates and silicates. Parameters that are regulated that are likely to be enriched in these deposits include fluorine, uranium, and several radionuclides which occur naturally and may be enriched further by mineral processing. In addition, leaching under neutral to alkaline pH conditions may enhance the mobility of elements such as arsenic, antimony, selenium, and molybdenum which may be present at low levels in waste rock and ore if trace sulphide minerals are present.

Leaching of uranium from ore minerals may be problematic, particularly due to enhanced mobility of uranium in the presence of carbonate. Low levels of uranium-238, thorium-232, and their radioactive decay products may be present in waste rock, with higher activities in ore and processing wastes. Management of solid-phase wastes for radiation protection may be necessary, and at alkaline pH, uranium and radium radionuclides may be mobile in the aqueous environment.

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KIRSTY KETCHUM

Kirsty, Ph.D., P.Geol., is a Principal Consultant in Geochemistry with 12 years' experience in environmental geochemistry in the consulting industry, and 13 years' research experience in lithogeochemical, mineralogical, and isotopic studies of Archean rocks. Kirsty has a Ph.D. in the geochemistry and tectonic setting of early Precambrian greenstone belts in northern Ontario. Kirsty now specializes in characterization of metal leaching and alkaline/acid rock drainage (ML/ARD) potential, with focuses including geochemical controls on selenium release/attenuation, evaluating the silicate neutralization potential of low sulphur waste rock, and characterizing rare earth element (REE)/rare metal projects, including radionuclide aspects of mine wastes.

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Euclalyte (REE-bearing silicate mineral) from Norra Kärr pegmatite, Sweden (4 cm long). Photo credit Rob Bowell

Assessment of chemical stability of sub-sea deposition of tailings

Chilean mining legislation requires physical and chemical stability of mining sites. Deposition of tailings at sub-sea environments has not been specifically included in chemical stability guidelines. Only “Sub-Sea Tailings Deposition Evaluation Guideline – prSN/TR-9432”, published by KREC-Norsk Berdindustri, could be considered an antecedent. This guideline includes specific analytical standards and criteria for impact analysis, potential approaches for the characterization of the sub-sea environment and methods for characterization of materials in tailings facilities.

Sub-sea deposition of tailings is not a common practice in Chile. The practice was developed by Chilean iron mining in different coastal contexts for about 40 years, but was abandoned without knowing the extent of its impact.

MARCELA CUROTTO

Marcela is a Civil Chemical Engineer with 23 years of experience in environmental issues for the large-scale mining industry in Chile and abroad. She has served as project manager and specialist engineer in closure plans, estimating closure costs, conducting environmental audits, due diligence, environmental and geochemical studies. Marcela has carried out consulting projects, proposing environmental solutions as well as identifying geochemistry characteristics of dump materials, tailings, water quality and waste management for closure cost estimation for the large-scale mining industry of copper, iron and gold in Chile.

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SRK Consulting (Chile) and the Chilean iron mining industry are developing methodologies to assess solute release rates from tailings deposited at sub-sea environments. Environmental conditions of sub-sea deposition do not correspond to those of continental facilities. Sub-sea environmental parameters affect the thermodynamics reactivity of mineral phases that generate mining drainages and metal and metalloid leaching capabilities. Some of these variables are pressure, temperature, luminosity and irradiance, microbial activity, concentrations and mechanisms of supply of oxidizers, catalysts and nutrients, and chemical composition of seawater.

To determine reaction mechanisms and the release rates of solutes from tailings, Kinetics Tests are usually applied under standardized lab conditions (CANMET, 2009; INAP, 2012). However, the effects of the variability of these mechanisms under sub-sea conditions could not be scaled from the results of these tests. Consequently, a modified Kinetics Test methodology was designed considering: (1) a constant P-T corresponding to the environmental pressure and temperature of the sub-sea site, (2) a rate of renewal of inflow solutions that assimilates constant concentrations of seawater, (3) inoculation of microorganisms and nutrients, and (4) isolation from site luminosity conditions. These conditions were implemented in a stainless steel “Zero Headspace Extractor”. Preliminary tests were performed using distilled water to assess the capability to leach solutes from the kinetics cell, and to modify the chemistry of the resulting solutions. Some tests were implemented considering different renewal times of seawater.

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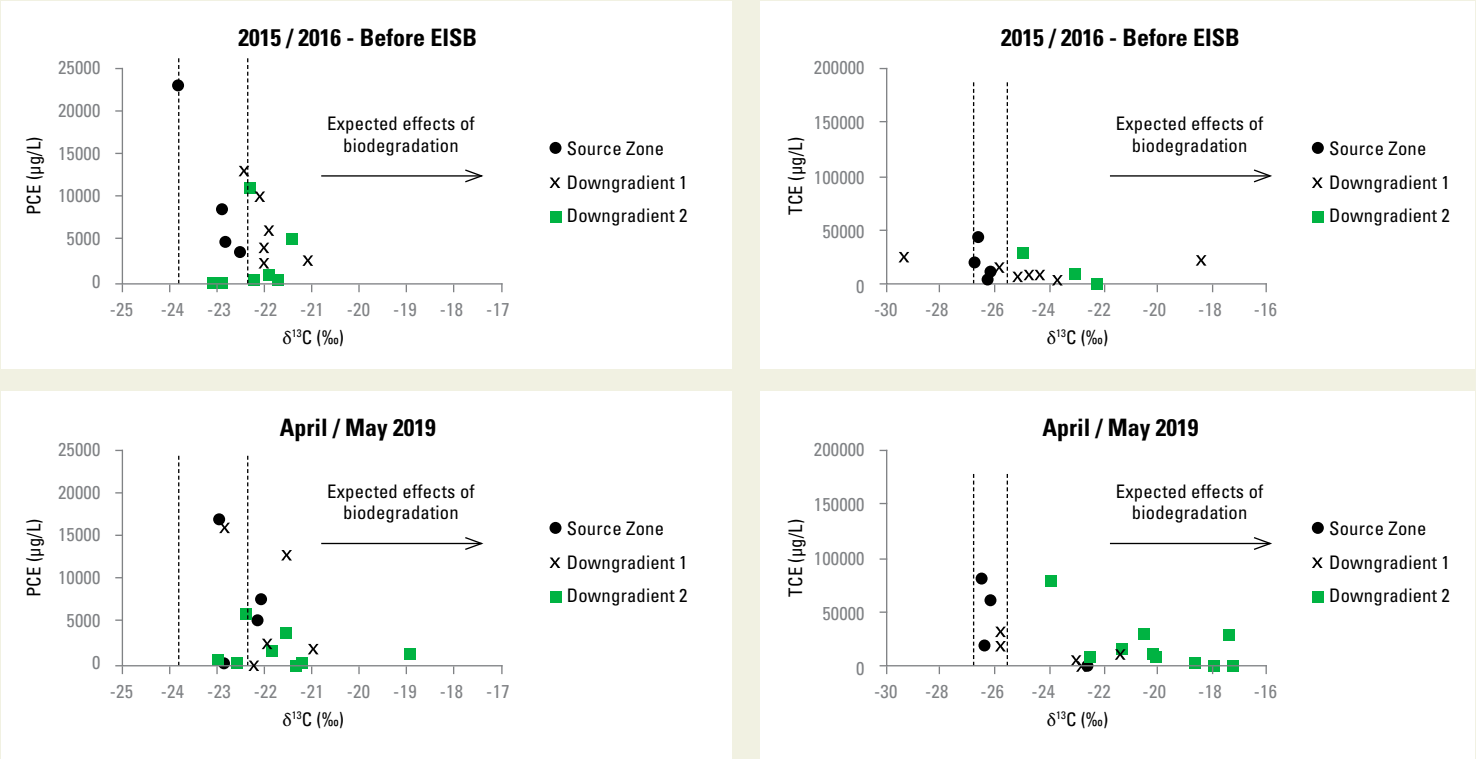
Figure 1 (right): $\delta^{13}\text{C}$ vs PCE and TCE concentrations (before and after biobarrier installation) indicating bacterially mediated degradation

SRK designed and implemented an Enhanced In-Situ Bioremediation strategy to mitigate the impacts of a historical chlorinated hydrocarbons (CHC) contamination to both soil and groundwater and a site in South Africa. The EISB utilises a biobarrier generated through the addition of electron donor (emulsified vegetable oil (EVO)) into the aquifer. The site has a complex hydrogeological setting comprising both primary and fractured rock aquifers.

The performance evaluation of the EISB system based on the interpretation of concentration data alone is ill-advised as contaminant concentrations may be influenced by various non-degradation processes (including dilution, sorption, volatilisation). Despite of the complexity of the site, the application of Compound Specific Isotope Analysis (CSIA) along with groundwater concentration data and historical information was important in providing a direct and unequivocal line of evidence that degradation has been stimulated by the microbial consortia established in the biobarrier.

CSIA is the measurement of the relative abundance of the two stable isotopes of carbon (^{13}C and ^{12}C) for a specific contaminant of concern (e.g. TCE or PCE). The CSIA evaluation is sensitive enough to detect isotopic differences in the sources of contamination, as well as shifts in isotopic signatures caused by abiotic or biotic degradation where bacteria preferential utilise the contaminant molecules containing the lighter C isotopes. The isotopic fractionation (shifts in isotopic composition)

The use of compound specific isotope analysis during the performance evaluation of in situ bioremediation of DNAPL site, South Africa



Top left: PCE $\delta^{13}\text{C}$ distribution prior to full scale remediation
Bottom left: PCE $\delta^{13}\text{C}$ distribution during the 2019 Performance Monitoring Programme (following EVO injections)
Top right: TCE $\delta^{13}\text{C}$ distribution prior to full scale remediation
Bottom right: TCE $\delta^{13}\text{C}$ distribution during the 2019 Performance Monitoring Programme (following EVO injections)

results in an enrichment in the heavy isotope in the remaining undegraded parent compound, with a corresponding enrichment of the lighter isotope in the intermediary or daughter products.

The monitoring of the geochemical environment, and concentration monitoring data following the completion of a 5-year EVO injection programme in 2020 showed some evidence of CHC attenuation in the monitoring wells downgradient of the biobarrier. However, the constant dissolution and recharge of contaminants from the source area made it difficult to determine if the attenuation was biotically mediated. The

CSIA and the groundwater monitoring data for from monitoring wells downgradient of the biobarrier show a strong correlation between enriched $\delta^{13}\text{C}$ signatures and lower PCE and TCE concentration, with an estimated extent of biodegradation >90% at some locations. This evaluation was critical in proving that the enhancement of the naturally occurring microbial biomass was successfully stimulated by the EVO to result in the observed order of magnitude decrease mass flux downgradient of the biobarrier.

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Richard has 18 years of experience in land contamination. He specializes in the management, assessment, and remediation of contaminated land, industrial waste and mine residue characterization, the design and implementation of groundwater monitoring programmes, and environmental due diligence investigations. His areas of expertise also include environmental site assessments; conceptual site model development; vapour intrusion sampling and assessment, surface and groundwater quality monitoring and assessment; and environmental sampling.

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The search for truly permanent solutions to mine waste management

At Conuma's Perry Creek Mine located in northeastern British Columbia, SRK has supported the long term implementation of waste rock blending to manage potential acid generating waste rock.

STEPHEN DAY

Stephen is an experienced specialist in the development of waste management plans to address acid rock drainage and leaching of mine wastes in general.



Stephen has particular expertise in the development of prediction methods for mine planning and modeling of leachate chemistry.

His project experience includes development of innovative approaches to the management of potentially acid generating wastes at new mines, assessment of existing waste disposal facilities at operating and abandoned mines to determine options for reduction or elimination of contaminated drainage, and environmental audits of mines.

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In 1974, when Oskar Steffen, Andy Robertson, and Hendrik Kirsten established SRK in Johannesburg, South Africa, mine water quality management acid mine drainage (AMD) was emerging as a major concern for sustainably managing mine sites. A few years after SRK established its office in Vancouver, British Columbia in 1979, SRK became very involved in helping the provincial government develop technical guidance for prediction, prevention, control and treatment of AMD, or acid rock drainage (ARD) as it was coined by Andy Robertson to reflect that acidic drainage can develop under conditions when sulphidic mine waste is exposed. A major push at the time was to prevent ARD at new mines by incorporating the

technical solution of water covers into mine design, often by the construction of earthen impoundments. This resulted in nearly stopping oxidation of sulphide minerals due to the low concentration of oxygen in water compared to air but also led to the need for permanent management of structures to ensure the water cover remained intact forever.

However, since the mid-2010s, the mining industry has experienced several high-profile failures of dams which has highlighted the risk of using impoundments to permanently manage saturated mine wastes. This has resulted in the commitment of the industry to phase out permanent water covers and renewed focus on mine waste

management to prevent ARD and related metal leaching (ML) without relying on saturation to limit oxygen availability. The preferred technology of dry covers has become very well developed to the point now where covers can achieve very low oxygen concentrations in wastes. Nonetheless, the question needs to be asked whether this approach achieves permanent prevention of the need for active management of water quality rightfully demanded by the long term users of the lands impacted by mines. In many cases, there is confidence covers will be intact for decades to centuries but these time frames do not consider use of the lands and geological processes in landscapes which span thousands to millions of years.

The real solution to mine waste management to limit the potential for long term water quality effects is to adopt technologies that result in the perpetual slow release of potential contaminants of concern (PCOCs) or result in substantial depletion of the PCOC in parallel with slow failure of the technology. It is possible that covers can achieve this objective but there are greater opportunities with co-disposal technologies, optimization of mine workings to allow saturated disposal, and appropriate use of natural water bodies without dams.

As an example, SRK has been working with several clients for over a decade to implement blending of acid generating

and acid consuming waste rock such that the resulting mixture not only is non-acid generating on balance but also limits accelerated weathering associated with the acid generating components such that PCOC leaching occurs slowly. Properly implemented, this technology can achieve the goal of slow steady leaching without long term active management.

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