



# Mine remediation & restoration in the Yukon: The state of Research

Guillaume Nielsen, Industrial Research Chair in Northern Mine Remediation

North of 60 Window into the Canadian Arctic

January 28, 2025

## What's to be expected today?

- 1- Short Introduction – Active mining situation in the Yukon
- 2- Industrial Research Chair in Northern Mine Remediation
- 3- Science & Industrial research needs
- 4- Examples of research projects

30 min

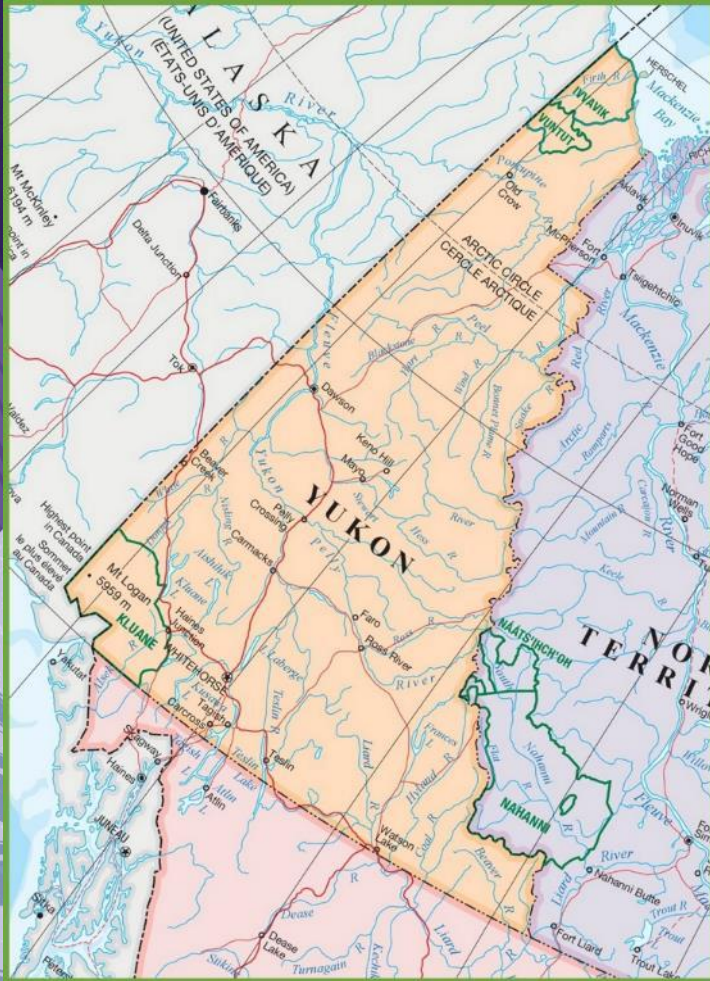
20 min



# 1- Introduction



# What's specific to the Yukon?



Smallest of Canada's three federal territories (482,443 km<sup>2</sup>)

36,000 people (25,000 in Whitehorse)

History linked to **the Klondike Gold Rush** between 1896 and 1899

- Yukon's historical major industry was mining (lead, zinc, silver, gold, and copper)
- Tourism



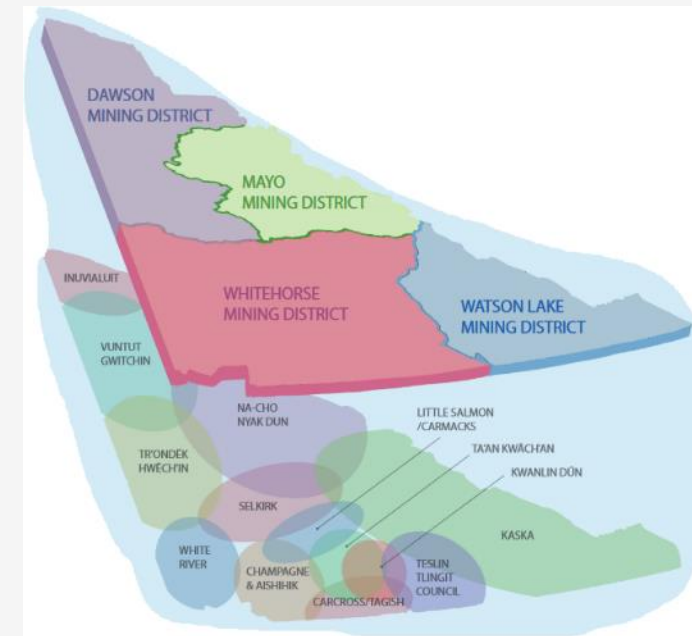
# Modern-day treaties with Yukon First Nations

Led to the development of the Umbrella Final Agreement and Self-Government Agreements. Individual Yukon First Nations have political powers.

## Regulatory framework

- YESAB. *Yukon Environmental and Socio-economic Assessment Board*. Independent board conducting environmental assessment
  - ✓ Public dialogue
  - ✓ Providing green lights to development projects (under certain conditions)
- Yukon Water Board. Independent board providing Water Licences (permit to use and discharge water)
  - ✓ Public consultation but very technical in nature. Typically limited to YG and FN interventions

## Reclamation & Closure Plan



# Climate

- Sub-arctic continental climate with temperatures reaching as high as 36.1 °C in the summer and as low as minus 60 °C in the winter
- All lot of light during the summer... to almost none during winter!
- Permafrost



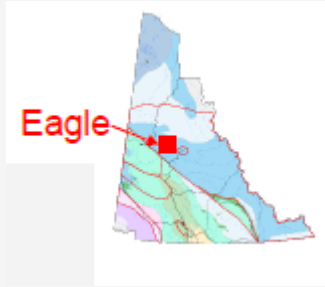
# What's specific to the Yukon?

Pristine environment

- Low density of people in the territory, abundant wildlife (salmon, caribou, moose)
- Few development projects and highly engaged yukoners (incl. YFNs)



# Yukon Mining update



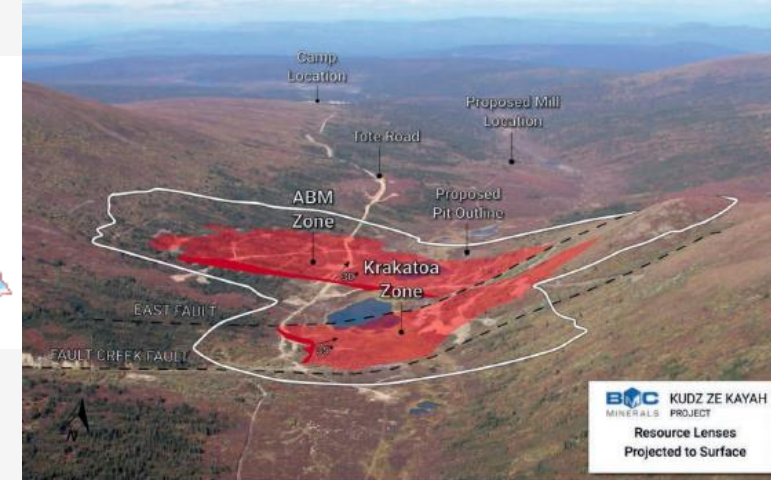
Victoria Gold - Eagle Gold mine



Minto Metals  
- Minto mine



BMC minerals  
- Kudz Ze Kayah

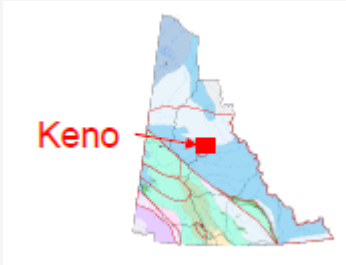


Newmont Corp.  
- Coffee mine

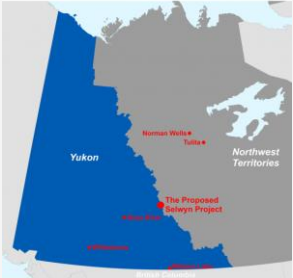
# Western Copper & Gold Corp. – Casino mine



# Hecla Mining Corp. Keno Hill mine



# Selwyn Chihong – The Selwyn project



### More info:

Yukon Exploration and Mining Overview 2021, Scott Casselman (Yukon Geological Survey)

# **2- NSERC Industrial Research Chair in Northern Mine Remediation**

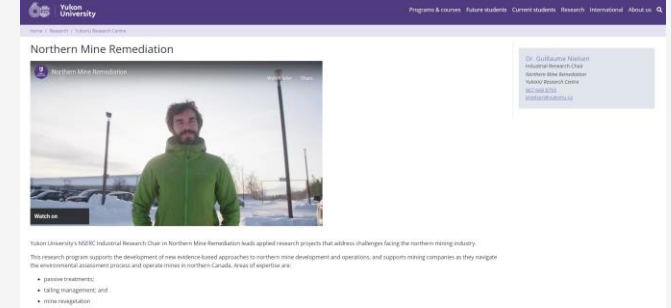




# How do I work with mining companies?

6 “Active” mines = Yukon Mining Research Consortium

YMRC meeting 4 times/year (environmental teams, mine managers and CEOs)



<https://www.yukonu.ca/research/research-centre/northern-mine-remediation>

IRC in NMR and YMRC highlighted **environmental challenges** the mining industry is facing, specific to the North → IRC in NMR must provide **answers** and **scientific evidences** to help facing these challenges.

## Yukon Mining Research Consortium Vision

- (i) Water Treatment by Passive or Semi-Passive Technologies;
- (ii) Mine Waste Management;
- (iii) Mine Revegetation

Community engagement throughout the process – not researching community engagement specifically, but it is embedded in the rest of the program.

Guiding principles: neutrality; independent; transparent researcher. No IP. Scientific evidences available for public. Training of students and HQP.

# Applied Research Capacity



The YRC laboratory



- A ~1000 square foot dedicated research laboratory with analytical capacity
- Atomic absorption spectroscopy, which provides capacity to measure heavy metals at trace levels in water, soil, or other solid materials;
- A Smartchem analyzer to measure sulfate and other nutrients in water;
- Carbon and nitrogen analyzer for organic and inorganic carbon and nitrogen measurement in water and solid samples rest;
- A Mercury Analyzer (DMA-80 Direct Mercury Analyzer);
- Fridges and freezer to mimic cold conditions;
- A modified sea can and a 12 x 8ft shelter for cold weather testing and experimentation; and
- A greenhouse and environmental chambers for plant growth experiments

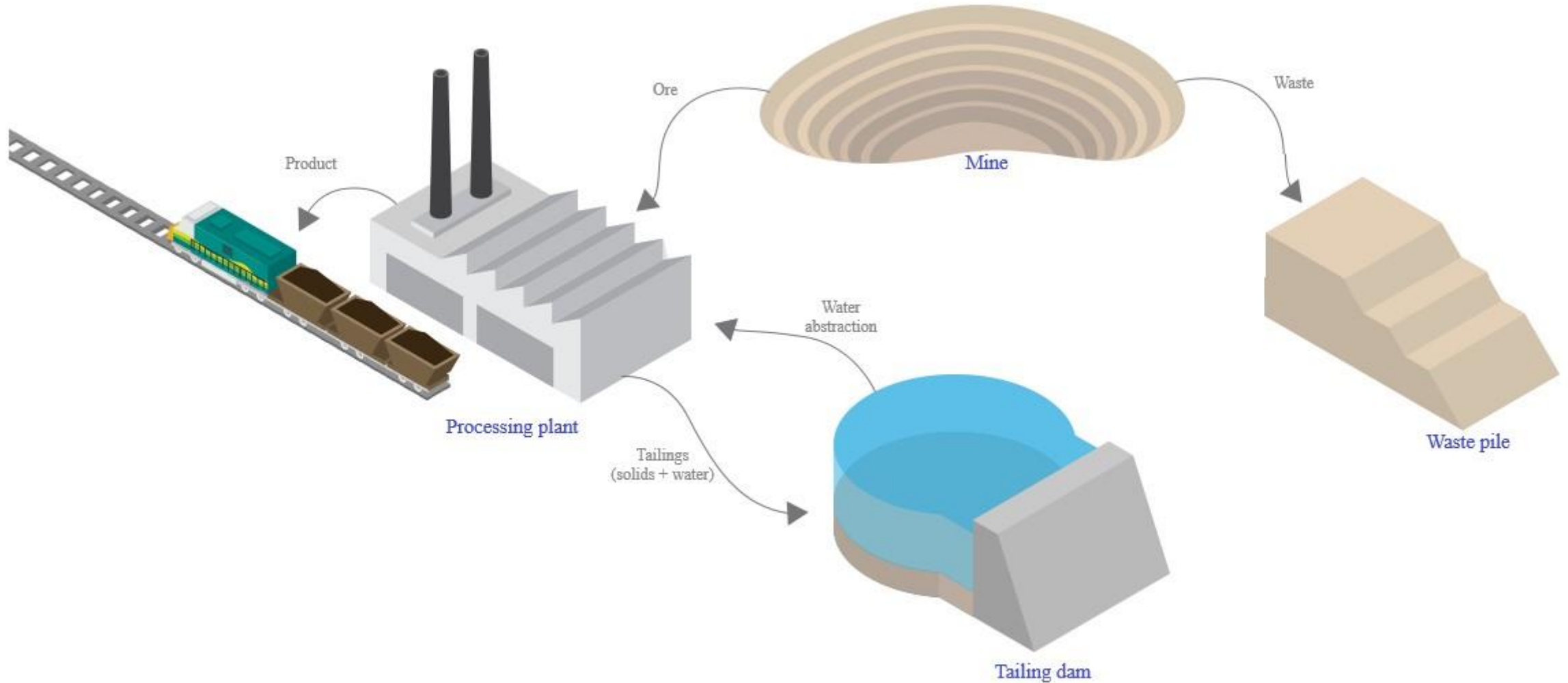
*But also...*

- CNIM, CCR
- YC faculty
- Mine environmental staff's expertise

# 3- Science & Industrial research needs



# Where does MIW come from and why passive treatments are needed?



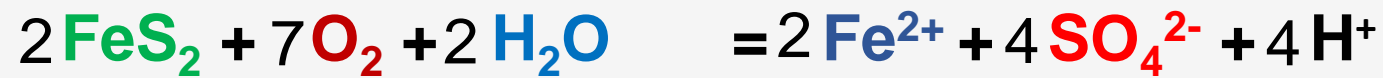
# Contaminated water or Acid mine drainage (AMD)

Sulfidic mineral + O<sub>2</sub> + H<sub>2</sub>O (without neutralizing reagent)

*Bacterial catalysis*

Acidity (H<sup>+</sup>), SO<sub>4</sub><sup>2-</sup>, Me<sup>z+</sup>

**Example: Pyrite**



**Notion of leaching**: process of a solute becoming detached or extracted from its carrier substance by way of a solvent.





# Other contaminants specific to mining industry

**Cyanides and derivatives** (example: Gold extraction)

**Nitrogen compounds** (example: blasting)

**Thiosels and sulfate**

**Phosphates** (example: Apatite = phosphate minerals used as a fertilizer – source of phosphorus)

**Radioactivity** (example: Uranium mines)

**Salinity and solid materials** (Salinity = dissolved salts...)

# Mine Water Treatment

Actives	Passives
Continuous chemical addition to mine drainage to neutralize acidity and / or precipitate metals in solution	[Pseudo-natural] Use of chemical, physical and biological processes occurring in nature to achieve the same effects.
Active mine	Closed or abandoned mines (historic legacy)

Definitions unclear/uncertain because all types of systems require some level of monitoring and maintenance

# Mine Water Treatment – Active Treatment

## ➤ Conventional treatment

Lime precipitation (Calcium Oxide (CaO)) or hydrated lime (Ca(OH)<sub>2</sub>)

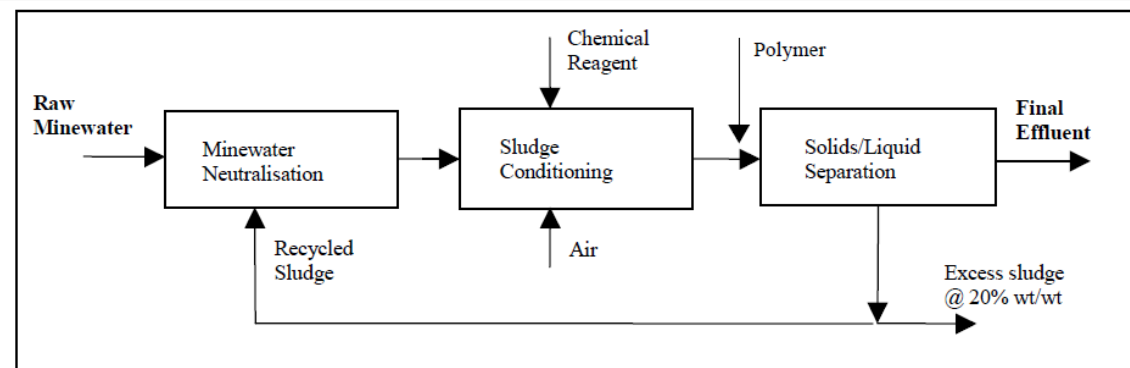
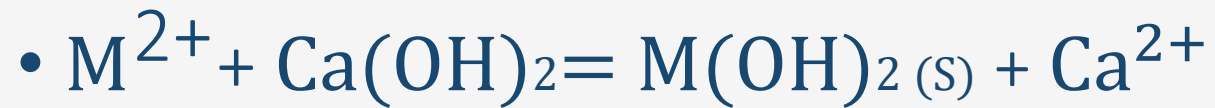


Figure 4. High-density sludge plant

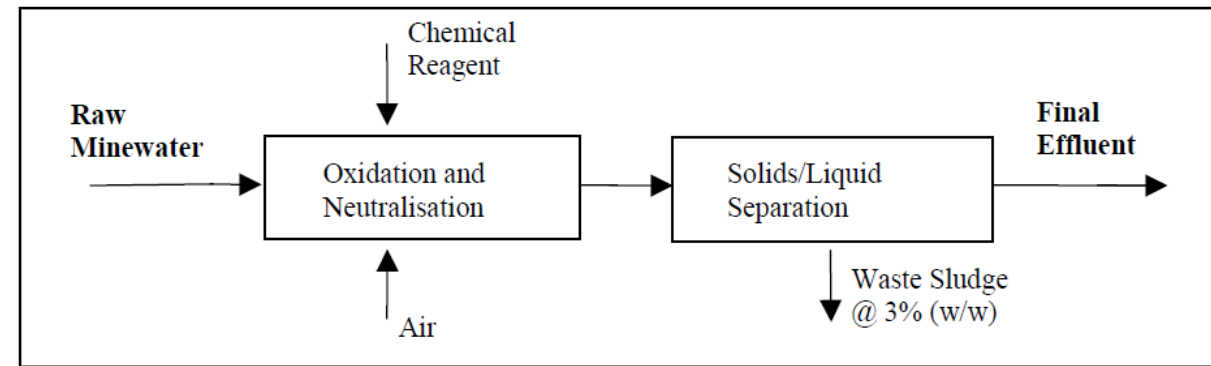


Figure 1. Conventional precipitation plant

[Coulton et al., 2003]

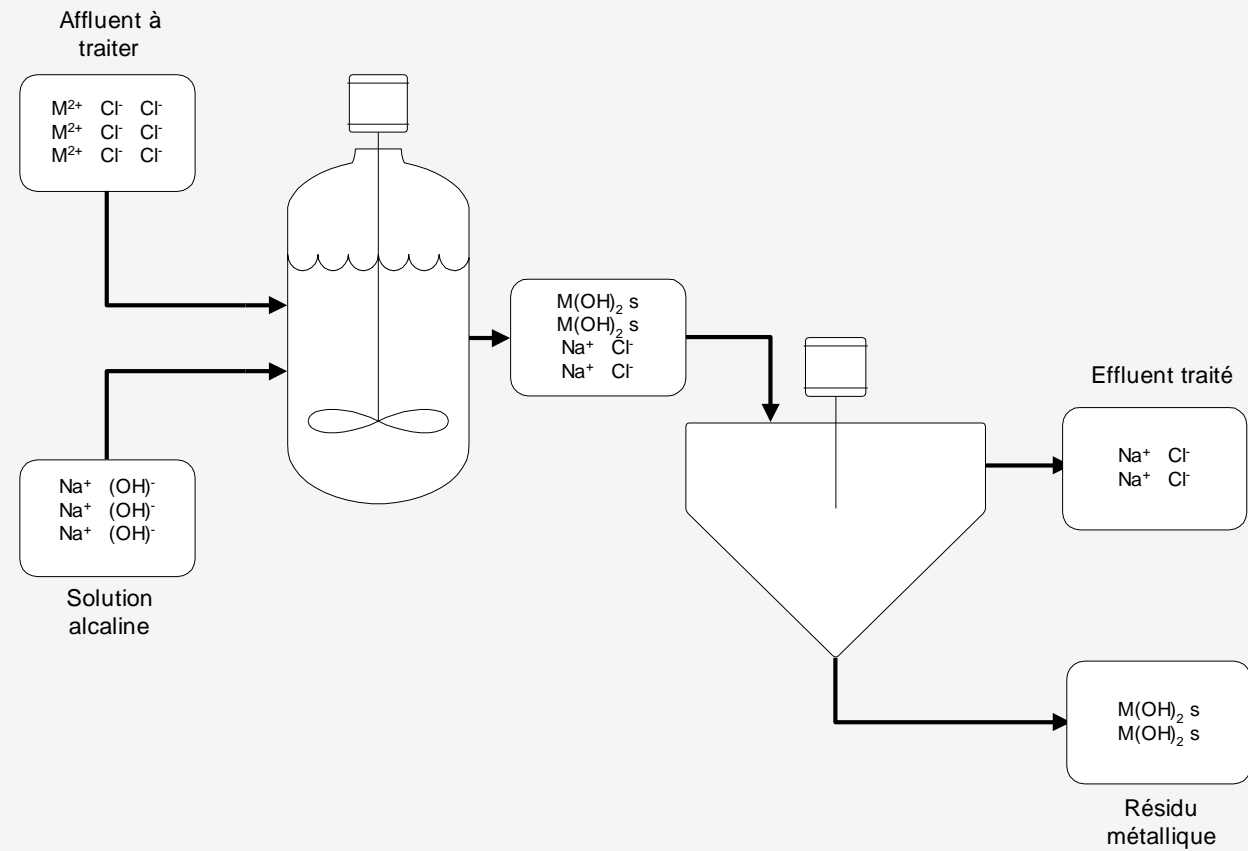
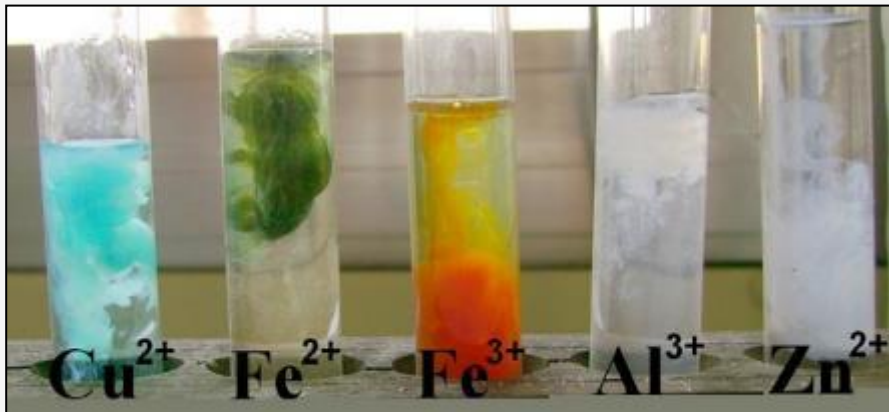
- **Metallic precipitates**

- Hydroxides ( $\text{HO}^-$ )

- Sulfides ( $\text{S}^{2-}$ )

- Carbonate ( $\text{HCO}_3^-$ )

- phosphates



# Mine Water Treatment – Active Treatment

## ➤ Conventional treatment

Lime precipitation

Efficient, but...

- 1) Mine the lime
- 2) Truck it
- 3) Transform & Store it (hazards)
- 4) Mix it with water, complete treatment
- 5) Manage metallic waste (sludge)



# Mine Water Treatment – Active Treatment

## ➤ Conventional treatment

Lime precipitation

Efficient, but...

- 1) Mine the lime
- 2) Truck it
- 3) Store it (hazards)
- 4) Mix it with water, complete treatment
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# Mine Water Treatment – Active Treatment

## A problem?





Dam at Brazil Vale's Corrego do Feijão mine that collapsed in January 2019, killing about 270 people.  
Image: BBC



The Imperial Metals Mount Polley gold and copper mine tailings dam disaster in British Columbia, Canada, dumped 24 million cubic meters (more than 31 million cubic yards) in 2014 of mine waste and sludge into neighboring Lake Polley and polluting the Hazelton Creek watershed.

Photo courtesy of the Multinationals Observatory



*An aerial photo of the landslide off the heap leach facility at the Eagle Gold Mine taken on July 3. (Government of Yukon/Supplied)*

On June 23, 2024, a heap leach failure caused a landslide releasing Cyanide, Mercury, and Arsenic into the environment (FN of NND territory)

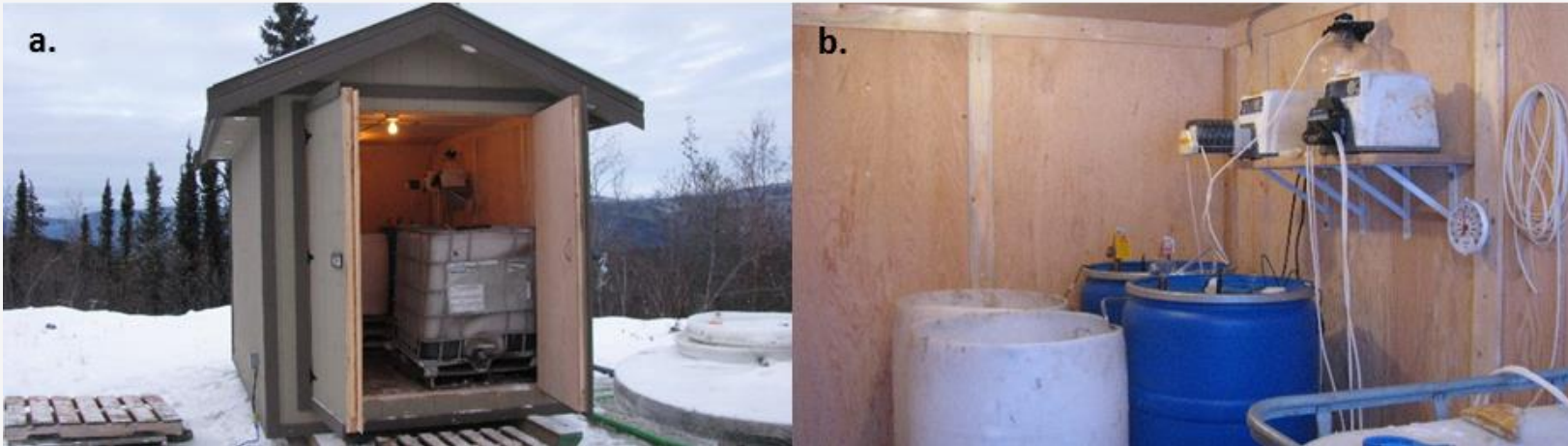
# Mine Water Treatment – Passive Treatment

*“Passive treatment systems (PTS) are based on chemical and biological reactions that naturally occur in the environment and offer a potential sustainable option that is adequate for long-term mine drainage treatment during and after mine closure”*

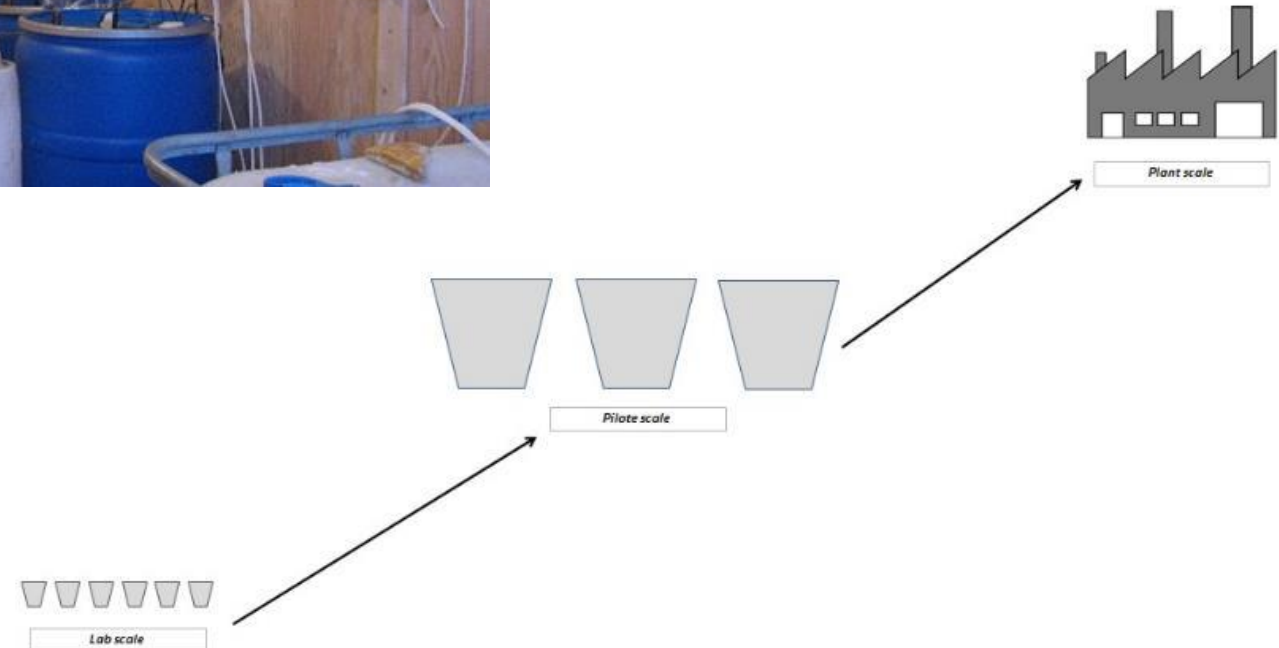
**BUT**

PTS face challenges in cold climates that include hydraulic failure due to freezing in winter, reduced microbial activity, and increased water flows during spring melt

# The industry needs... Passive treatments → answers and evidence Pilot scale studies



YRC shed(a.) and pilot bioreactors (b.)



# 3- Research project examples



# Mine water treatment



# Introduction to bioreactors

Following on a SRPB laboratory scale experiment & report (2012) and pilot scale BRs implemented in 2014 at Keno Hill mine:



- Native Microbial community can successfully remove Zinc, Cadmium & Selenium from Mine Impacted Water (MIW) if supported by appropriate carbon source.
- Genomic characterization showed that Microbial community (SRB)'s efficiency is temperature dependent BUT community survives over winter.



Semi-passive *in-situ* pilot scale bioreactor successfully removed sulfate and metals from mine impacted water under subarctic climatic conditions

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**ARTICLE INFO**

**ABSTRACT**

**Article history:** Received 20 November 2017; Received in revised form 21 March 2018; Accepted 15 April 2018; Available online 23 April 2018

**Keywords:** Semi-passive treatment; Bioremediation; Sulfate; Zinc; Cadmium; Sulfate-reducing bacteria

Mine drainage contaminated with metals is a major environmental threat since it is a source of water pollution with devastating effects on aquatic ecosystems. Conventional active treatment technologies are prohibitively expensive and so there is increasing demand to develop reliable, cost-effective and sustainable passive or semi-passive treatment. These are promising alternatives since they leverage the metabolism of microorganisms native to the disturbed site or, *in situ* or close to the site conditions. Since this is a biological approach, it is not clear if semi-passive treatment would be effective in remote locations with extremely cold weather such as at mines in the subarctic. In this study we tested the hypothesis that sulfate-reducing bacteria, which are microorganisms that promote metal precipitation, exist in subarctic mine environments and their activity can be stimulated by adding a readily available carbon source. An experiment was setup at a closed mine in the Yukon Territory, Canada, where leaching of Zn and Cd occurs. To test if semi-passive treatment could precipitate these metals and prevent further leaching from waste rock, molasses as a carbon source was added to anaerobic bioreactors mimicking the belowground *in-situ* conditions. Microbial community analysis confirmed that sulfate-reducing bacteria became enriched in the bioreactors upon addition of molasses. The population composition remained fairly stable over the 16 month operating period despite temperature shifts from 17 to 5 °C. Sulfate reduction functionality was confirmed by quantification of the gene for dissimilatory sulfate reductase. Metals were removed from underground mine drainage fed into the bioreactors with Zn removal efficiency varying between 20.5% in winter and 93.3% in summer, and Cd removal efficiency between 38% in winter and 90.5% in summer. This study demonstrated that stimulation of native SRB in MIW was possible and that *in-situ* semi-passive treatment can be effective in removing metals despite the cold climate.

**1. Introduction**

On both operating and abandoned mines, waste material containing sulfide minerals can, under certain environmental conditions, oxidize resulting in increased sulfate concentrations and mobilization metals in mine drainage (Baker and Barfield, 2003). Furthermore, natural sources of water seepage, such as infiltration of snowmelt and rain into waste rock piles or tailings might result in metal leaching and subsequent contamination of downstream aquatic environments (Wiliam and Cohen, 2003). Mine impacted waters (MIW) can be acidic (acid mine drainage (AMD)), or have a circum-neutral pH (values ranging between 6 and 9) referred to as neutral mine drainage (NMD) (Nordstrom et al., 2015). NMD occurs where the waste material contains

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# Passive treatment : Sulfate-reducing passive bioreactor (SRPB)

Consumes  $\text{SO}_4^{2-}$

Produces  $\text{S}^{2-}$  ;  $\text{H}_2\text{S}$

Precipitates as metal sulfide

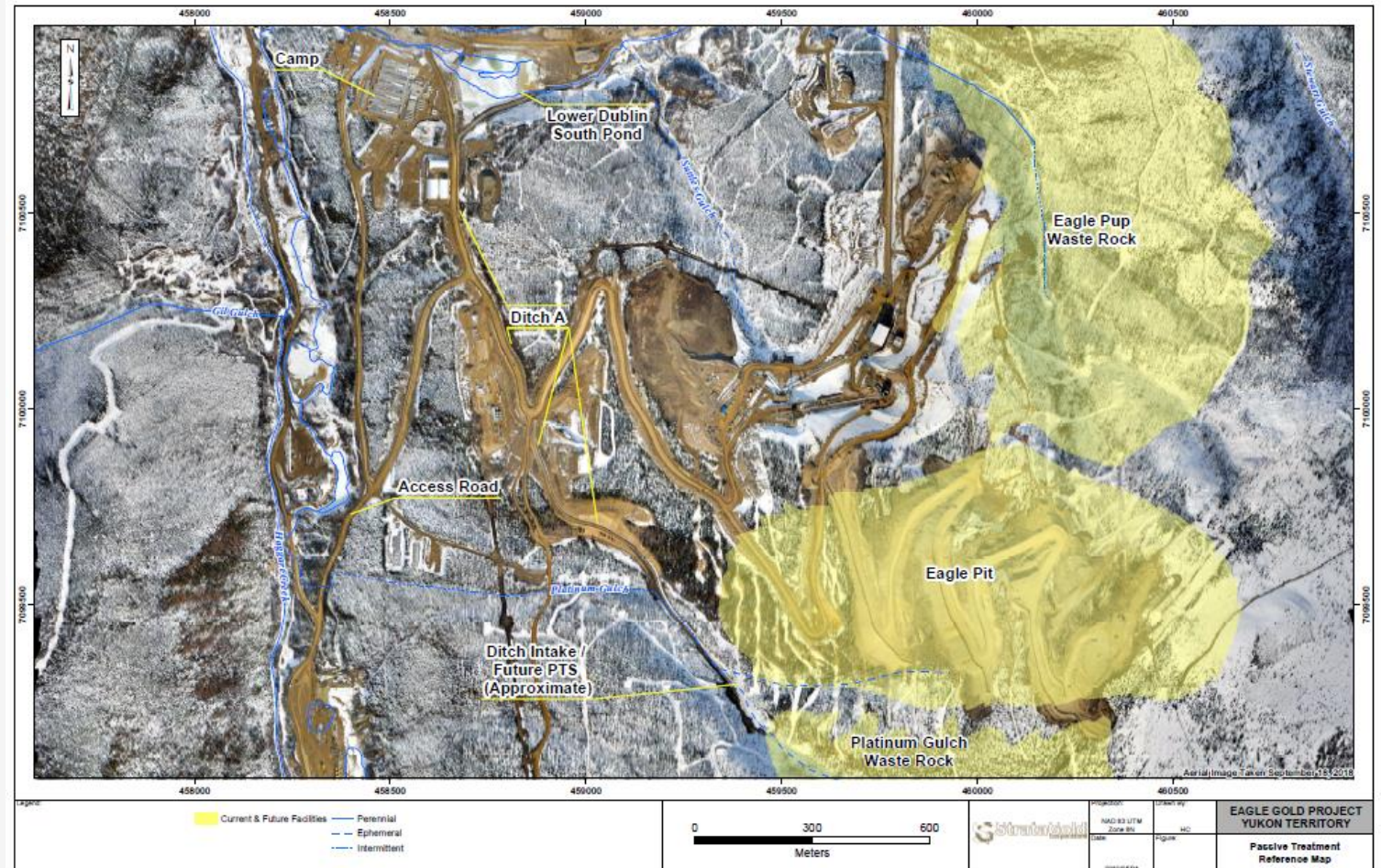
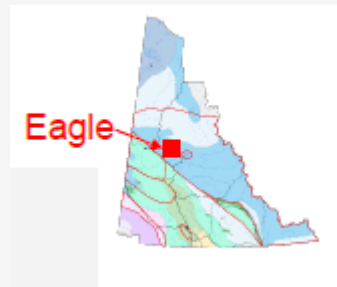


The industry had a follow up question:

**What happens to the BRs and microbial community if it freezes for many months?  
Can microbial population handle Yukon Freeze-Thaw cycles? Can it treat Sb, Se and As?**



At Eagle Gold mine  
Ditch A, collecting  
drainage from  
Platinum Gluch Waste  
Rock pile freezes  
completely in winter  
time...

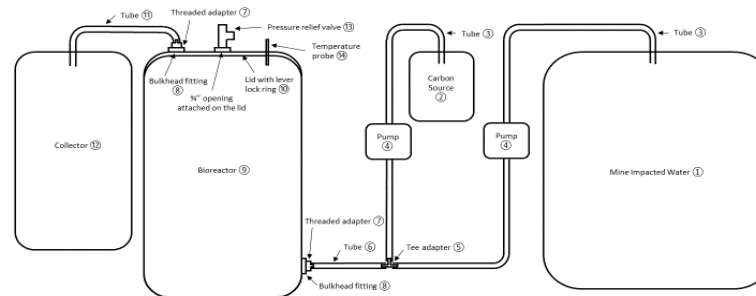


**What happens to the  
BRs?**

# Eagle Gold Bioreactors (Victoria Gold)



- Microbial communities in Freeze/Thaw cycles
- Subsequent removal of Contaminant of Concern (As, Sb and Se)



Number	Name	Number	Name	Number	Name
①	1000 L Drum	⑥	7" Tube	⑪	7" tube
②	7 L Drum	⑦	1/2" - 7" Threaded Adapter	⑫	7 L Drum
③	7" Tube	⑧	2" - 1/2" Nylon Bulkhead Fitting	⑬	30 psi Pressure Relief Valve
④	Peristaltic Pump	⑨	55 Gallon Open Head Polyethylene Drum	⑭	Oakton PCD 650 Probe
⑤	7" Tee Adapter	⑩	Polyethylene Lid with Steel Lever Lock Ring		

# Bioreactors Composition

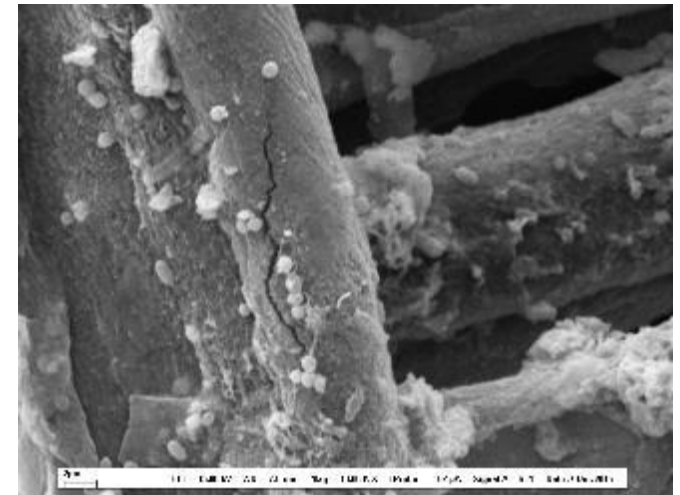
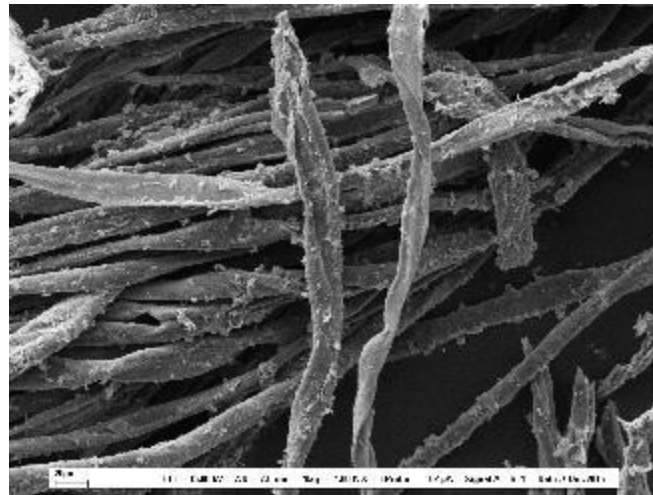


# Sulfate reducing bacteria

- Use sulfates as final electron acceptors for respiration
- Ubiquitous

## *Optimal conditions*

- pH = 7
- Anaerobic
- Carbon source
- T° = 25°C (mesophilic)



Bioreactors from Keno

# FOOD IS THE KEY!

Carbon = molasses, ethanol, methanol, ethylene glycol, sodium acetate etc...

In the North?

Brewery residue, Peat, Biochar, Straw, wood chips, invasive species compost



# The Chemistry. Sulfate

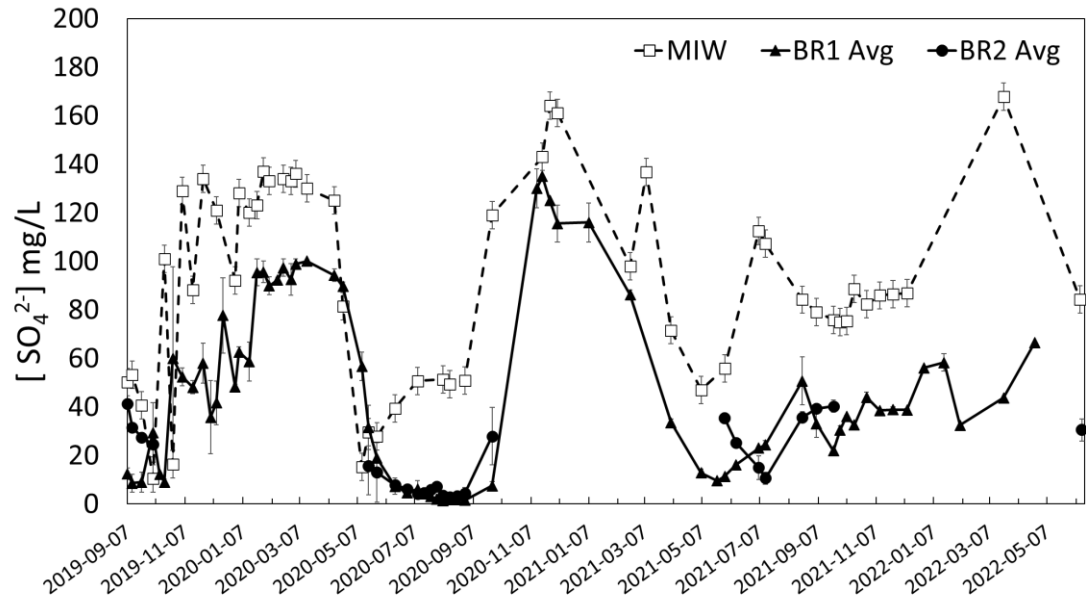


Figure 5: Sulfate concentration in mg/L in mine-contact water (MCW, empty square and dashed line), average BR1 (BR1 Avg, black triangle and full line) and average BR2 (BR2 Avg, black circle and full line) function of time.

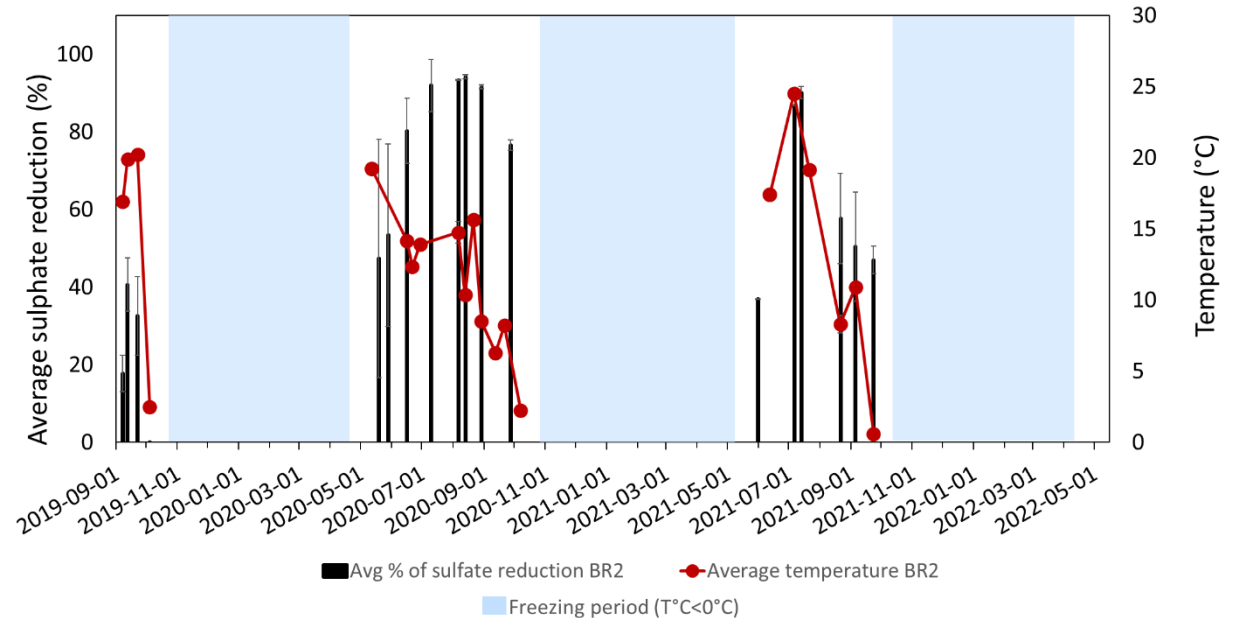
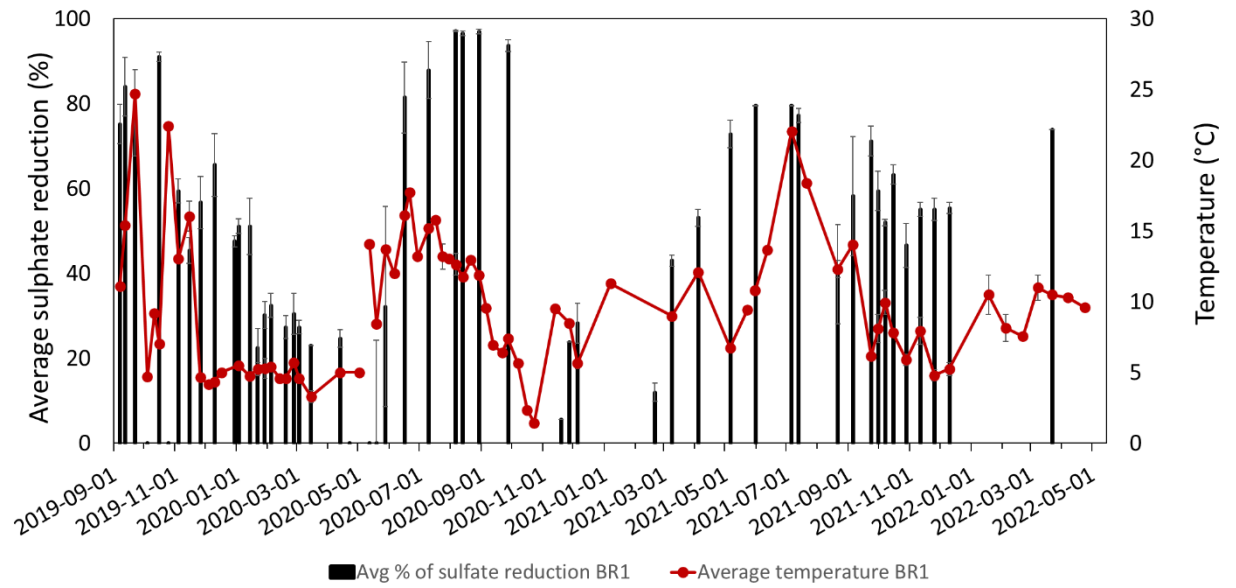


Figure 6: Percentage of Sulfate removal from BR1 average (top) and BR2 average (bottom) function of time.

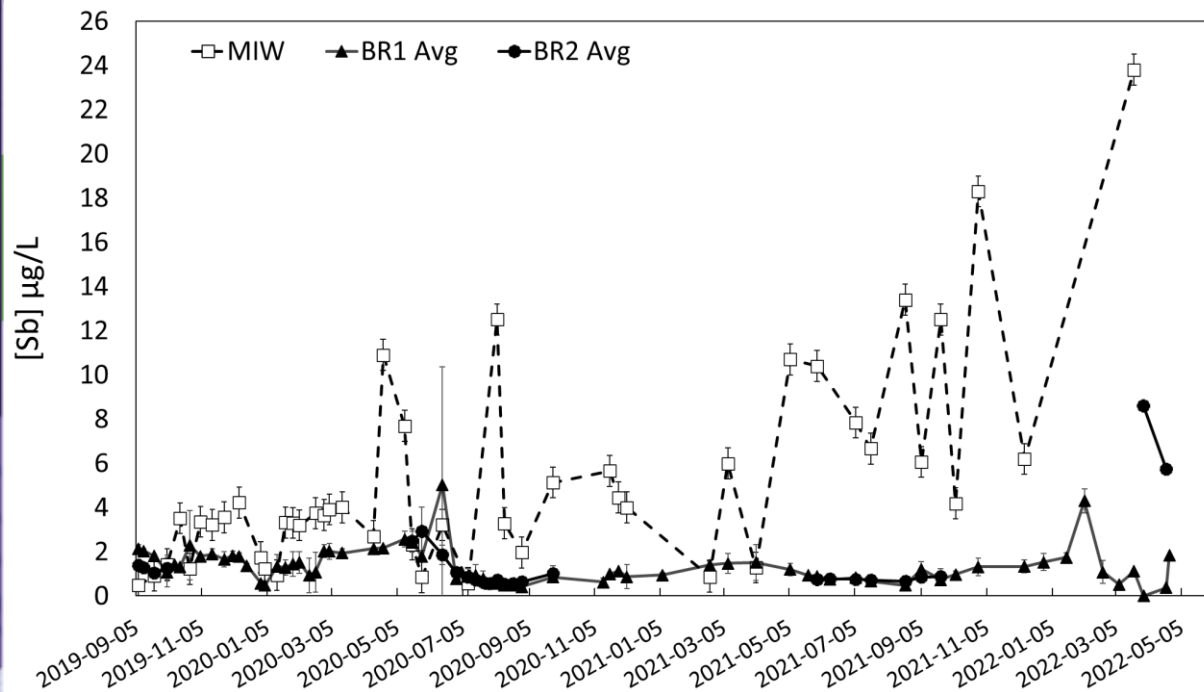


Figure 8: Antimony concentration in  $\mu\text{g/L}$  in mine impacted water (MIW, empty square and dashed line), average BR1 (BR1 Avg, black triangle and full line) and average BR2 (BR2 Avg, black circle and full line) function of time.

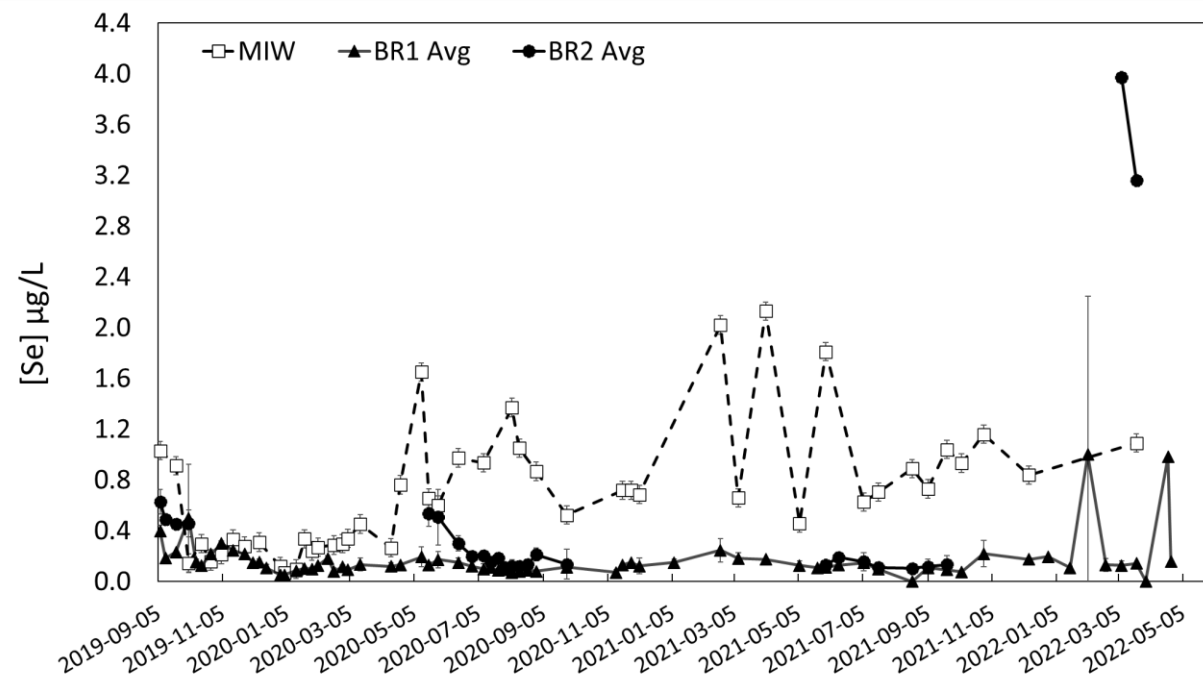
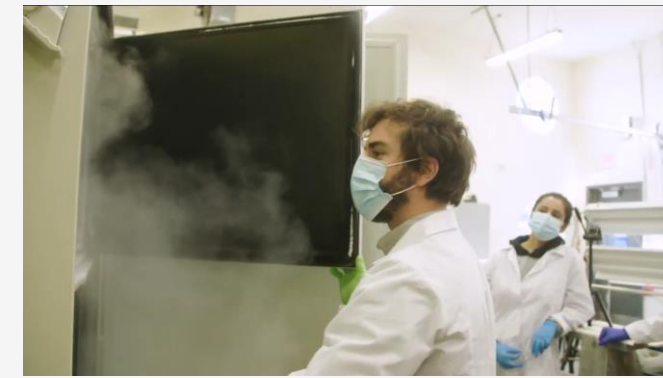


Figure 10: Antimony concentration in  $\mu\text{g/L}$  in mine impacted water (MIW, empty square and dashed line), average BR1 (BR1 Avg, black triangle and full line) and average BR2 (BR2 Avg, black circle and full line) function of time.

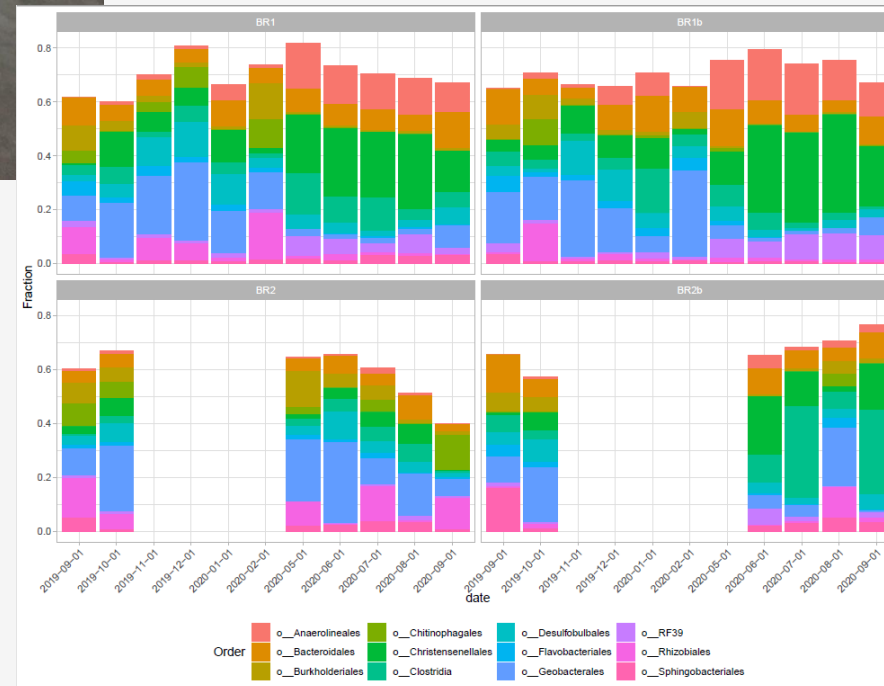
# Eagle Gold Bioreactors (Victoria Gold)



- Stored in  $-86^{\circ}\text{C}$
- DNA Extraction and sequencing done in summer 2021
- Genomic characterization soon



Faculty of Applied Science  
Chemical and Biological Engineering



## Conclusion:

The freeze-thaw cycle affects the relative abundance of the microbial population, but the removal capacity of the BRs is not substantially impacted by the freezing event.

- Se removal between  $94.6 \pm 0.2\%$  and  $13.3 \pm 7.1\%$ .
- Sb removal between  $96.4 \pm 3.6\%$  and 10%.

August 2023

Pilot scale Bioreactors at Eagle Gold Mine site:  
Studying bacterial populations' adaption to  
seasonal freeze and thaw cycles and their  
capacity to remove Sb, Se and As.



## Metal(loid)s Removal Response to the Seasonal Freeze–Thaw Cycle in Semi-passive Pilot Scale Bioreactors

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### Abstract

There is an increasing demand for cost-effective semi-passive water treatment that can withstand challenging climatic conditions and effectively and sustainably manage mine-impacted water in (sub)arctic regions. This study investigated the ability of four pilot-scale bioreactors inoculated with locally sourced bacteria and affected by a freeze–thaw cycle to remove selenium and antimony. The bioreactors were operated at a Canadian (sub)arctic mine for a year. Two duplicate bioreactors were installed in a heated shed that was maintained at 5 °C over the winter, while two other duplicates were installed outdoors and left to freeze. The removal rate of selenium and antimony was monitored weekly, while a genomic characterization of the microbial populations in the bioreactors was performed monthly. The overall percentage of selenium and antimony removal was similar in the outside (10–93% Se, 20–96% Sb) and inside (35–94% Se, 10–95% Sb) bioreactors, apart from the spring thawing period when removal in the outdoor bioreactors was slightly lower for Se. The dominant taxonomic groups of microbial populations in all bioreactors were Bacteroidota, Firmicutes, Desulfobacterota and Proteobacteria. The microbial population composition was consistent and re-established quickly after spring thaw in the outside bioreactors. This demonstrated that the removal capacity of bioreactors inoculated with locally sourced bacteria was mostly unaffected by a freeze–thaw cycle, highlighting the strength of using local resources to design bioreactors in extreme climatic conditions.

**Keywords** Sulfate reduction · Mine-contact water · (sub)arctic · Genomics · Bioremediation

### Introduction

The (sub)arctic regions are rich in strategic mineral resources and are becoming more accessible thanks to infrastructure development and expanding interest from the mining sector (Haley et al. 2011; Tiainen et al. 2015). However, when not adequately managed, mining activities present environmental concerns (Sengupta 2021). One major challenge is controlling the release of mine-impacted water (MIW) into the environment. Unmanaged MIW containing metal(loid)s and other inorganic constituents at concentrations exceeding the regulated limits can have deleterious effects on downstream

aquatic environments (Leppänen et al. 2017; Wright et al. 2015). Thus, the development of sustainable, efficient, and cost-effective water treatment technologies is required for mineral exploitation to expand in (sub)arctic areas.

Different water treatment technologies are available. Active chemical water treatment technologies are still preferred for operating mines (Qin et al. 2019). These systems rely heavily on infrastructure, labor, and chemical reagent utilization, usually producing large amounts of sludge or liquid waste, which limits their sustainability over the long term (Ness et al. 2014). Passive and semi-passive water treatment systems are considered viable alternatives in closure scenarios because they are more economical and environmentally friendly (Martin et al. 2009). For example, in Canada, many active mines proposed passive or semi-passive treatment technologies for their future closure plans (Eagle Gold mine's closure plan (Victoria Gold Corp. 2022); Casino mine's closure plan (Brodie Consulting Ltd. and Casino Mining Corporation, 2013)). However, local regulation entities such as the Yukon Environmental and

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# Semi-passive treatment of nitrogen compounds in mine impacted water in cold climates

Taylor Belansky, Master's Student, INRS

Dr. Guillaume Nielsen, NSERC IRC in Northern Mine Remediation

Prof. Jean-François Blais, Professor of Earth Sciences, INRS



# Objectives

Specific → Develop a **semi-passive** nitrogen treatment system that functions in **cold temperatures** using **native bacteria** from Minto mine

Broad → To assess the merits and design parameters of semi-passive biological treatment systems in the North using locally available carbon sources

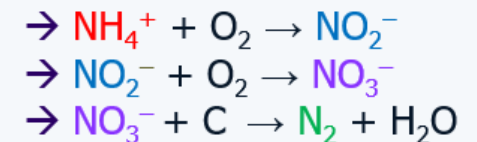


**Nitrification** – requires oxygen

**Ammonium** → **Nitrite** → **Nitrate**

**Denitrification** – requires anoxic condition

**Nitrate** → **Nitrogen Gas**



# Winning carbon source – White Sweetclover



Invasive sweetclover a 'safety hazard' for Yukon roads | CBC News



- Mines are mandated to manage the invasive species on their sites

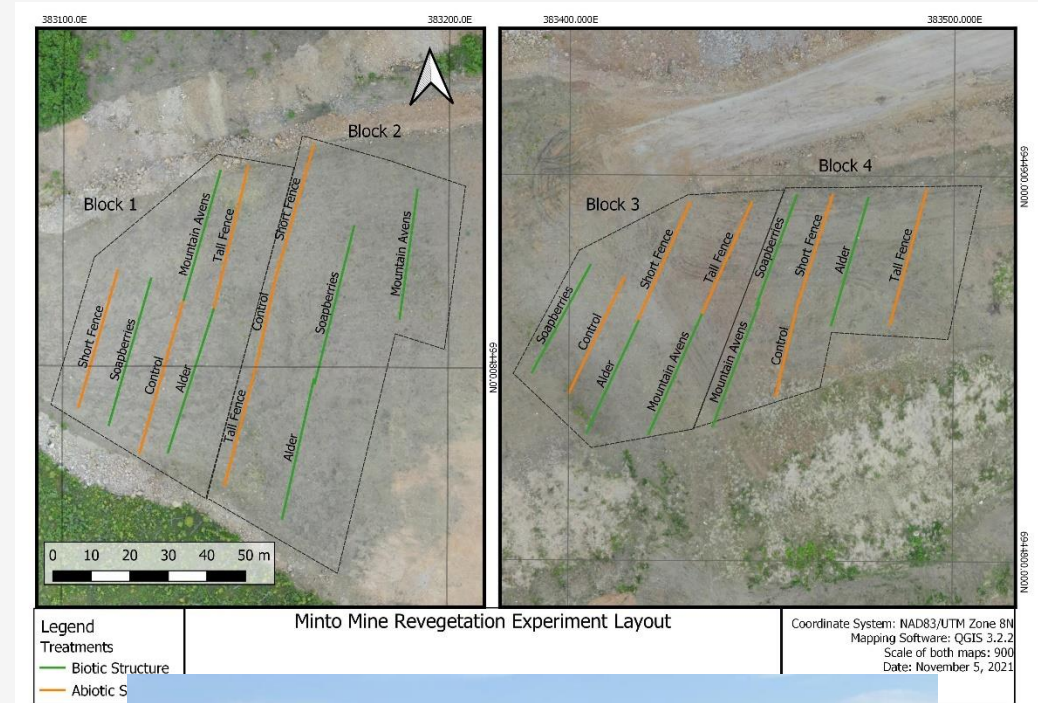


- White sweet clover is readily available on site and easy harvest
- Works well as a C source for bacteria

# Mine Revegetation



# Mine Revegetation (Master's degree project)



## **Problem:**

- 1- Lack of knowledge on how to do revegetation in the North
- 2- Lack of Commercially available seed bank
- 3- Need for new revegetation technologies/techniques in Sub-Arctic Climate
- 4- Definition of Success?



# NMR course for communities



# Northern Mine Remediation Workshop for communities



## Mining Workshops

Hosted by NSERC Industrial Research Chair in Northern Mine Remediation, Dr. Guillaume Nielsen

**DOES YOUR COMMUNITY HAVE INTEREST IN THE FOLLOWING?**

- Understanding the mining industry and mine contamination in the Yukon
- Treatment for mine contamination
- Active treatments vs. passives treatments
- Mine revegetation
- Involving First Nation students in environmental projects

If so, we will work with you to set up a Mining Workshop in your community!

**YUKON RESEARCH CENTRE**  
Yukon College



# Northern Mine remediation course

**Module 1**, Title: Laboratory scale sulfate reducing bioreactor implementation ; Speaker: Guillaume Nielsen

**Module 2**, Title: Environmental monitoring program at Yukon University , Speakers: Guillaume Nielsen; David Petkovich (YukonU Instructor), Helaina Mose (NND citizen, Environmental technician at Victoria Gold)

**Module 3**, Title: Environmental monitoring at Minto Mine - how we ensure that downstream water sources are not impacted, Speakers: Chris Wall/Ian Smith (Minto Environmental Officer); Journey Paulus (Sr. Coordinator); Dylan MacGregor or Laura Volden (SRK via Skype or in person); Guillaume Nielsen

**Module 4**, Title: Mine Revegetation in the North: Meeting Yukon community expectations of reclamation success. Speakers: Krystal Isbister (UofA & YukonU Ph.D candidate); Guillaume Nielsen

**Module 5**, Title: Why involving First Nation communities in research projects important? Speakers: David Silas (First Nations Engagement Advisor at Yukon University); Kevin McGinty or Dawna Hope (SFN); Guillaume Nielsen

**Module 6**, Title: YukonU Research lab visit. Speakers: Guillaume Nielsen, Ben McGrath (lab tech, YukonU)

**Module 8**, Title: Minto's constructed wetland treatment system (CWTS) presentation. Speakers: Chris Wall/Ian Smith (Minto Environmental Officer); Journey Paulus (Sr. Coordinator); an expert on constructed wetland treatment systems from Ensero Solutions Inc. (via Skype)

**Module 9**, Title: Bioreactors conclusion. Speakers: Guillaume Nielsen



**Science for Citizens 11, 4 credit course.**

# Conclusion

- More Research is needed to lead to better environmental practices in mining
- New ways of conducting research with First Nation world view and Western Science - *RESEARCH with Remediation component and or restoration IS A TOOL THAT MAY BE USED TO Reconciliation*

Questions?

