Case study for Tailings Characterization, Reprocessing and Repurposing

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Teck Legacy Group

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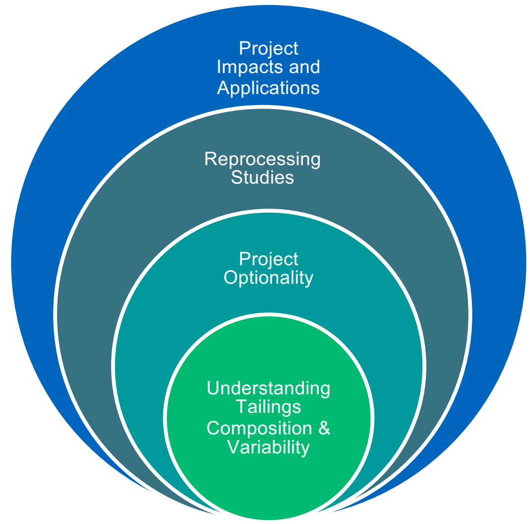
Opportunity: Knowing our Tailings

Unlocking value & de-risking for overall project stewardship

Strategic Vision: Seek to reduce quantities and/or improve quality of legacy mining materials on closed mine sites and allow of reconfiguration of legacy landforms and improve potential for transitioning land use.

Objective: To review opportunities to capitalize on residual value from legacy tailings at closed mines through repurposing and/or reprocessing.

How: Initiate a characterization and reprocessing program for prioritized legacy mines.



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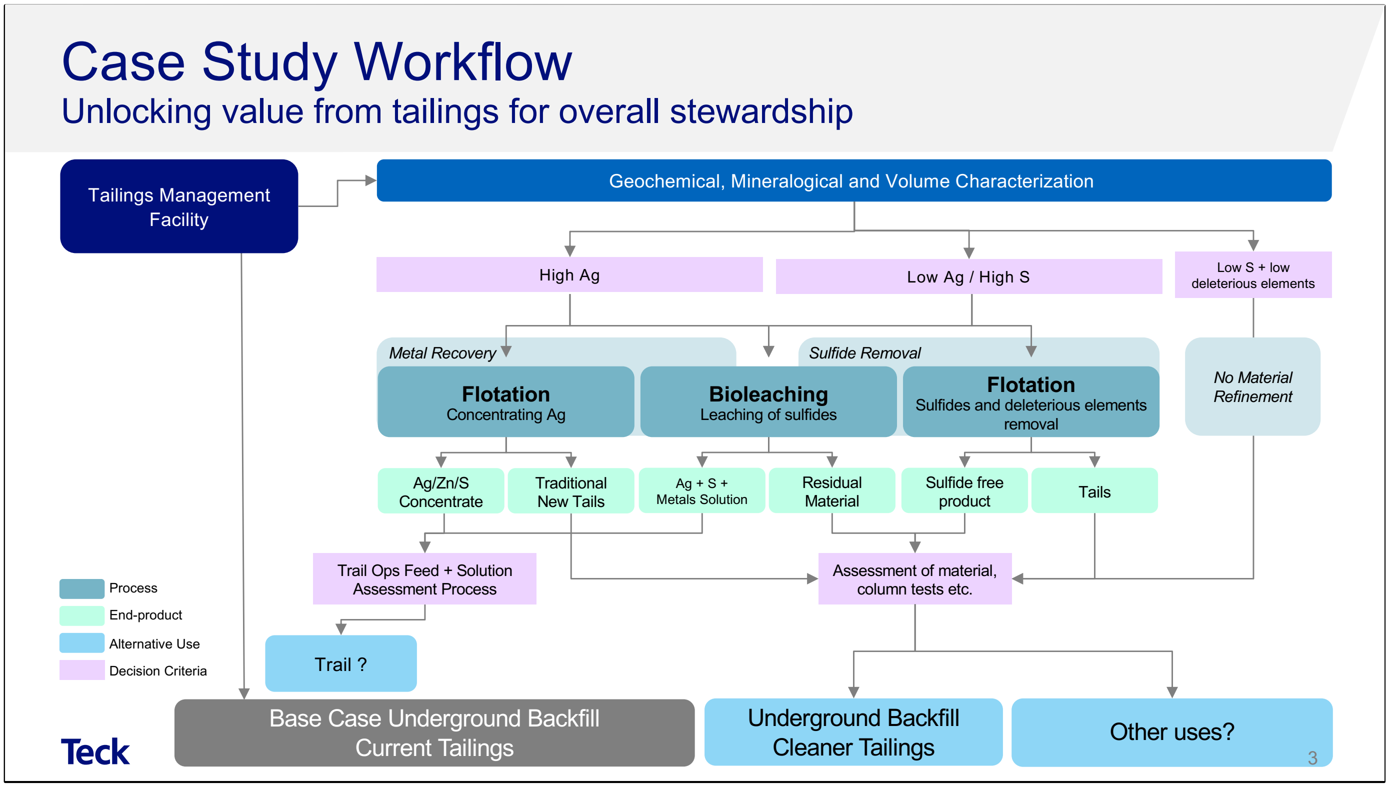
BETSY TALKING POINTS:

- Tailings can contain possible residual value and/or environmental risk.
- The legacy property strategy to reduce the long-term risk profile for closed mines and find all potential opportunities, such as repurposing residual mine waste to reduce the long-term reclamation liabilities and improve possibility for transitioning land use through this process – which could include a balance between risk (chemical and or physical) and possibly economics in tailings that are suspected to have (or known to have) higher grades of metal left.

- based on that, we initiated a characterization program at one of our priority properties and these are the results that were used for decision making on path forward (or something to that effect).

- Left is a diagram building on the studies:
  - Foundationally, we need to understand the variability of the tailings makeup on each site. Not all tailings are the same.
  - Tailings characterization within each site is foundational to understanding the opportunities and risks present
  - Each site/project whether active or legacy has it's own unique considerations, opportunities and risks
  - From that we can design reprocessing studies to either concentrate residual valuable metals and/or for removal of CI's and sulphide for cleaner tailings long term storage.
  - Ultimately these supporting studies give the foundational knowledge to for project impacts, applications and trade of studies.



BETSY TALKING POINTS:

(animated slide)

- This is our example workflow for a case study site with known elevated Ag and sulphide in the tailings.
- A possible base case is moving tailings for underground backfill. Given this material could be rehandled, we wanted to understanding what were possible options for the project
- First, and foundationally, we needed to understand the variability of the tailings
- Then, depending upon make up of High Ag / High Sulphides / Low we targeted reprocessing studies for conventional metal recovery and sulphide removal
- These processes result in new tails and new concentrates, that subsequently needed further evaluation for possible different downstream use, repurposing or cleaner backfill.

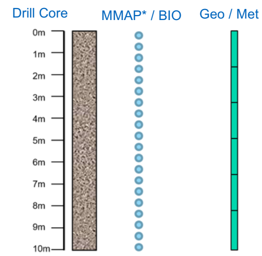
Case Study Sample Strategy

Leveraging existing data and multi-purpose sampling campaigns

Strategy

- Review available data and site history
- Assess gaps in collaboration
- Plan and execute multi-purpose sampling campaign

Types of Samples



Sampling from Drill Holes

Geological & Flotation Samples

MMAP Samples
(Mining Microbiome Analytics Platform)

BioLeaching Samples

Sonic Drill | *MMAP & Bio Samples | Geo & Met Samples

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*MMAP: Mining Microbiome Analytics Platform

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A Teck-led Digital Supercluster funded project that will

•identify the microbes that live in mining environments

•develop analytical tools that will enable understanding of what the microbes do and how they do it

- To execute the workflow, we need to be strategic about sampling strategy
- Reviewing available data and site history is critical
- Assess the gaps in knowledge and data in collaboration with the site team and others ensures best synergies
- Utilizing any new sampling campaigns for multiple down stream purposes.

- For this case study, there were a number of sonic holes drilled that were logged, sampled for characterization and floration, bio leaching and MMAP.
- I will talk through the characterization and initial flotation results.

James will talk more about the Bioleaching and MMAP results and context for the wider MMAP project.

Geochemical and Mineralogical Characterization

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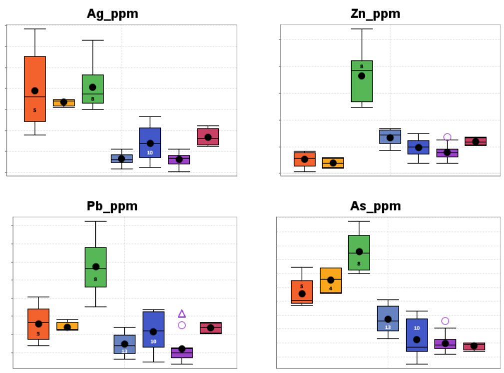
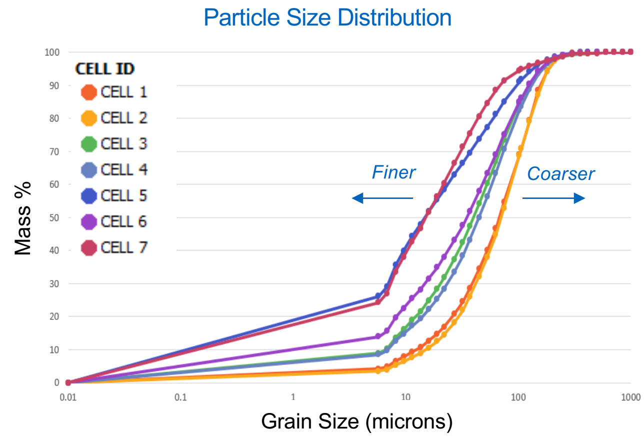
Understanding Tailings Composition
Geochemical and mineralogical characterization

Known Variables:
1) Mill Feed
2) Mill Conditions
3) Time – mining & post-mining weathering





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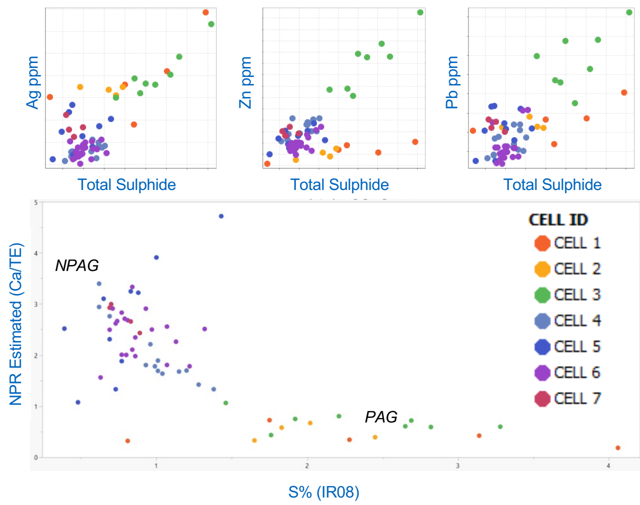
BETSY TALKING POINTS:

- Tailings are challenging to characterization. There are so many unknowns.
- However, We can't stress enough that tailings characterization is foundational. There are a number of things that determine the make up of tailings including: mill feed, mill conditions, time.
- For this case study, we found the individual cells within the TSF were similar within each cell, but varied throughout as shown in the box plots for Ag, Zn and Pb. And the PDS. It generally makes sense to with time as the earlier tailings were coarser than the later ones.
- These results therefore allow us to consider different processing possibilities for each cell

Understanding Tailings Composition

Geochemical and mineralogical characterization



Tailings Composition

- Cells 1, 2 are similar with elevated Ag and sulphides
- Cells 5 & 7 are similar with marginal Ag
- Cells 4 and 6 are similar with low Ag
- Cell 3 is a standout cell with elevated Ag, Zn, Pb and As in sulphide mineralogy

Tailings ABA & Screening

- Cell 1-4 have variable ABA classification ranging from PAG to NPAG
- Cell 5-7 were all classified as NPAG except two PAG and contain solid phase metal concentrations elevated above the BC CSR guidelines

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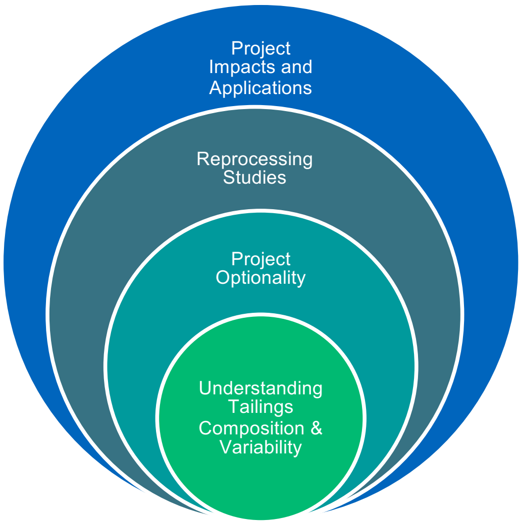
BETSY TALKING POINTS:

- More over while plotting these metals by total sulphide, it also demonstrates the similarities and differences in the variability of the TSF and various cells. Where:
  - Cells 1, 2 are similar with elevated Ag and sulphides
  - Cells 5 & 7 are similar with marginal Ag
  - Cells 4 and 6 are similar with low Ag
  - Cell 3 is a standout cell with elevated Ag, Zn, Pb and As in sulphide mineralogy
  - Cell 1-4 have variable ABA classification ranging from PAG to NPAG
  - Cell 5-7 were all classified as NPAG except two PAG and contain solid phase metal concentrations elevated above the BC CSR guidelines

- This now gives a foundation to consider options for the various cells where additional value to unlock and key cells to target for removal of CI's and sulphides for cleaner tailings for longterm storage.

Opportunity: Knowing our Tailings

Unlocking value & de-risking for overall project benefit



Case study tailings cells have variable composition for consideration for metal recovery and sulphide removal.

There are many possible options for conventional and novel reprocessing techniques unique to each cell.

Therefore, depending upon project's priorities, reprocessing studies were conducted for optionality.

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BETSY TALKING POINTS:

Transition Slides:

- Case study tailings cells have variable composition for consideration for metal recovery and sulphide removal.
- There are many possible options for conventional and novel reprocessing techniques unique to each cell.
- Therefore, depending upon project's priorities, reprocessing studies were conducted for optionality.

Reprocessing Studies

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Challenges and Limitations for Tailings Reprocessing

Conventional and novel reprocessing studies

Tailings reprocessing is rare and generally seems to be challenging:

- There isn’t a better technology to recover more metals than the first-time processing
- Often a new tailings facility needs to be built if there isn’t say an old pit or other place to put new tailings
- Disturbance of the tailings results in new environmental impact
- Could be a money losing exercise – although in some cases long term cost savings are likely if perpetual water treatment is needed.

How are we addressing these challenges?

- Testing conventional recovery with optimized flow sheet
- Testing additional methods (i.e. bioleaching)

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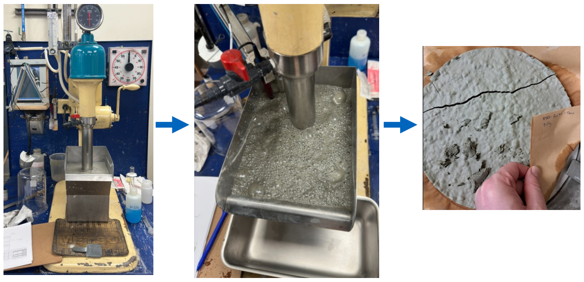
BETSY TALKING POINTS:

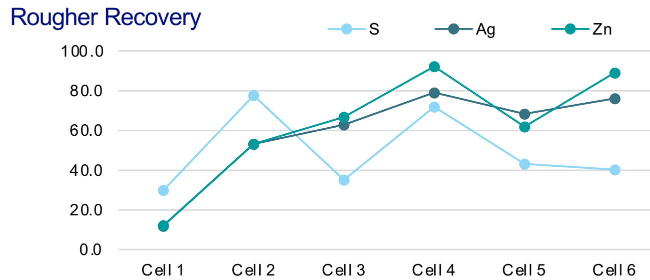
- What are the challenges/limitations? Tailings reprocessing is rare and generally seems to not be a winner in many cases for a few reasons:
    - There isn’t a better technology to recover more metals than the first time processing
    - Often a new tailings facility needs to be built if there isn’t say an old pit or other place to put new tailings
    - Disturbance of the tailings results in new environmental impact
    - It’s a money losing exercise – although in some cases long term cost savings are likely if perpetual water treatment is needed.

- How do we propose to address the challenges: The deck should at least highlight how new technologies (e.g. bioleaching) could address at least some of the deficiencies above.

Reprocessing Studies

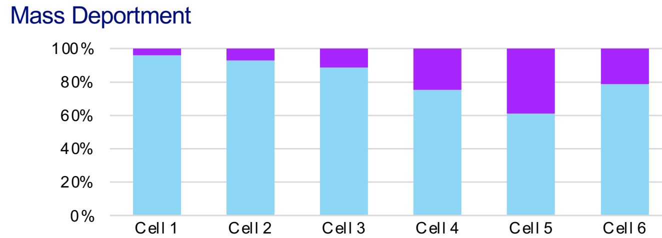
Conventional flotation rougher results





Rougher Flotation Performance

- First pass rougher variability tests show expected variable recovery and mass pull under same flotation conditions
- Optimization is ongoing for increased recoveries concentrate quality or increased “new tailings” cleanliness



	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
Concentrate	4%	7%	11%	25%	39%	21%
New Tailings	96%	93%	89%	75%	61%	79%

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Note: Cell 7 not processed.

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BETSY TALKING NOTES:

- Conventional flotation was carried out on a suite of sub samples from the TSF cells with variable sulphide mineralogy and metal content.
- Here are the first pass rougher recoveries showing variable recovery (which was expected)
- Optimization for these studies is ongoing.

Bioleaching

Mining and environmental remediation applications

- Used at commercial scale for leaching Cu, Au, Co, Ni, and Zn
- Interest in bioleaching research in the mining industry is growing!
- A potential method for reprocessing of waste rock and tailings

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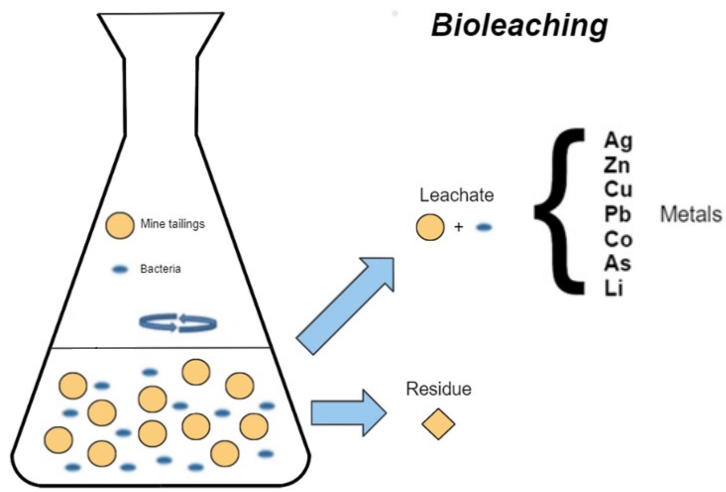
My goodness everyone, it is a pleasure to be here to speak with you about some of the work we have been conducting at our microbiology lab in Trail BC.

I am sure that most of you are aware that Bioleaching, is a process that uses microorganisms to extract valuable metals from ores and concentrates. As far back as 2000 years ago there are records from Spain, China, and India of the recovery of copper and zinc from solutions emanating from rocks. But It wasn't until the late 1940s that research established that bacteria were responsible for this leaching process. There are a number of benefits to bioleaching when compared to conventional processing methods which include reduced energy consumption, reduced chemical consumption and leading to lower operational costs. While bioleaching has remained a niche technology in the mining industry, the increasing imperative to achieve net zero science-based CO2 emissions targets by 2050 by most major mining companies may lead to expansion of this technology in the next decades as the technology produces less CO2. For example, a recent independent study found the production of Nickle Sulfate via bioleaching emitted only 32% CO2 emissions compared to conventional processing. Research in the field of bioleaching has moved beyond heap and tank bioleaching studies with a focus on programs including, in situ bioleaching of copper, gold, and uranium, metal recovery from electronic waste, and environmental remediation via the reduction or control of ARD. Furthermore there are growing concerns about the social acceptance of mining which has led to increased interest in researching this technology. As resources decline and or cost for their exploration rise, waste rock and tailings have become more attractive to consider as easily accessible resources. Waste Rock and tailings have already been removed from the ground and some cases have higher grades than ore currently being mined. Hence the interest by Teck to investigate whether tailings can be processed successfully via bioleaching.

Bioleaching

What is it and how does it work?

- Using microorganisms to extract valuable metals from ore.
- Typically used for extracting metals like Cu, Zn, Ni, and Au.
- Low energy requirements, chemical consumption, and operational costs.



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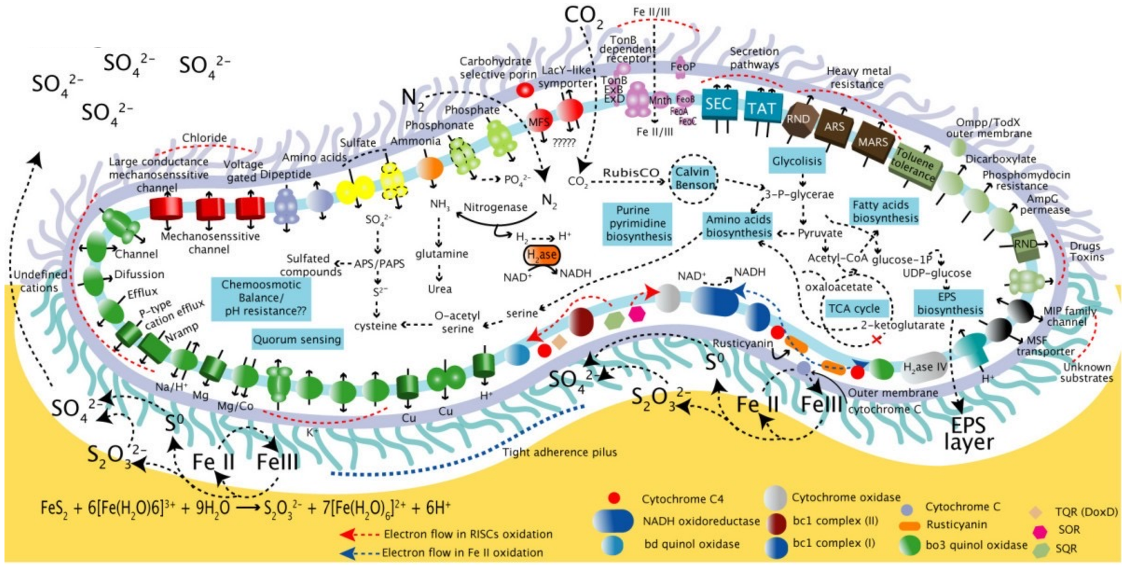
Bioleaching is typically used for the extraction of metals like copper, zinc, nickel, gold, as well as other minerals. The process is fairly straight forward, and the steps include taking a crushed material with a high surface area and introducing microbes to an ore heap or tank. The microbes, mainly acidophilic bacteria, oxidize the metals sulfides in the ore, producing metals ions and sulfuric acid as a byproducts. The metal ions are solubilized in the acid solution making them easier to extract. The metal-rich solution, is collected and further processed to separate the metal from the solution. This may involve methods such as precipitation, solvent extraction, or electrowinning. There are even some exciting new methods of metal recovery from solutions via the absorbance of metals biological material such as fungal tissue which acts almost like a sponge to the metals in the solution.

The biological mechanism of bioleaching

An example via *Acidithiobacillus ferrooxidans*



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https://bmcgenomics.biomedcentral.com/articles/10.1186/1471-2164-9-597/figures/7

I am a microbiologist so before we get further into my talk, I would briefly like to speak to the microbes responsible for bioleaching and mechanisms of bioleaching. There are many bacteria and archaea which are able to leach metals, but the one that is the most well studied and you may have heard of before is called *Acidithiobacillus ferrooxidans.* This bacterium is commonly found in environments where ARD is prevalent. The point of this slide here is just to provide some context for how complex this single species of bacteria is, and we are just getting started on understanding its compatibilities with the advances in technology over the past decade. Finally, for scale this bacterium is approximately one micron in length.

Bioleaching of tailings

A bench top scale study

1. Can bioleaching recover metals from tailings?
2. How does bioleaching compare to conventional methods?
3. Could bioleaching be used a polishing step?

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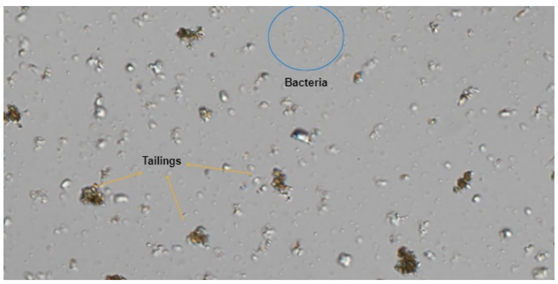
- Now that I have provided a bit of background. We set out to conduct a bench top scale experiment in our lab to investigate whether bioleaching could be a technology utilized to process tailings Teck has at their legacy sites. We specifically were interested in answering the following questions.

  1: Simply, can bioleaching recover metals from the tailings
  2: How does bioleaching compare in effectiveness to conventional techniques for recovering metals such as flotation.
  3: Can bioleaching be used as polishing step to flotation residues.

Bioleaching of tailings

A bench top scale study

Species of bacteria	Abundance
Acidithiobacillus ferrooxidans	84%
Acidibrevibacterium fodinaquatile	6.5%
Ferrimicrobium acidiphilum	3.3%
Acidiphilium iwatense	2.8%
Leptospirillum ferriphilum	1.5%
Other	1.9%



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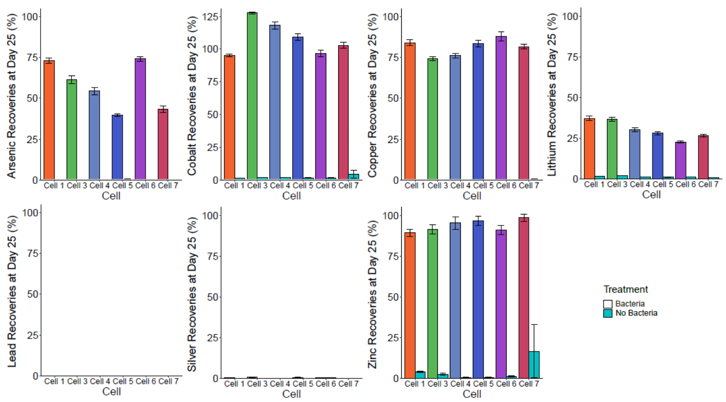
Throughout our experiments we used a mixture of bacteria to perform the bioleaching. You will see on the table on the top left that this mixture was primarily made up of Acidithiobacillus ferroxidans but there are a number of other species within the mixture. The photo on the bottom left shows you what the mixture looks like at a microscopic level. The larger pieces are the tailings, and the very small grey dots are the bacterial cells, approximately 1 micrometer in length. Finally, the photo on the right shows some of the flasks used in our experiments. Flasks with green tape have bacteria present while flasks with red tape do not. As you can see there is quite a difference in the amount of oxidation occurring with the bacteria present in flasks with green tape compared to those without.

Bioleaching of tailings

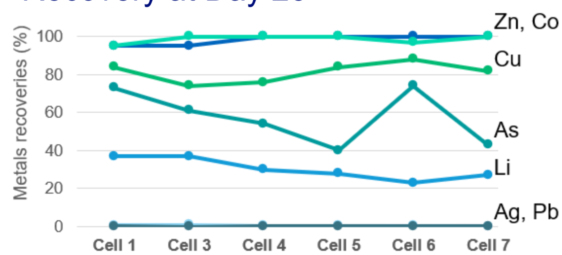
Initial Test Work Results

Live vs Sterile Metal Recovery



- Initial experiment revealed variable recovery of metals
- Absence of dissolved Ag and Pb
- Co, Zn, Cu high
- As, Li moderate

Recovery at Day 25



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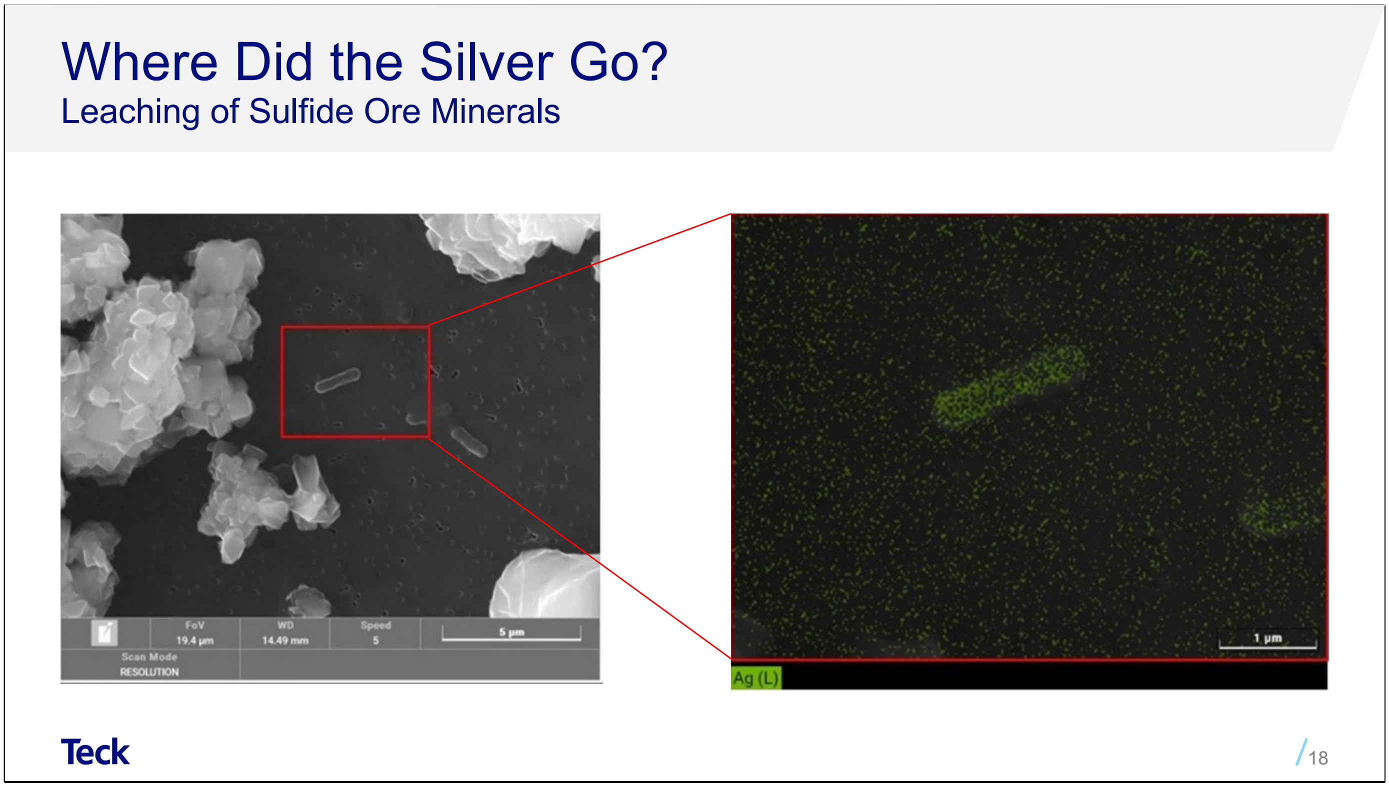
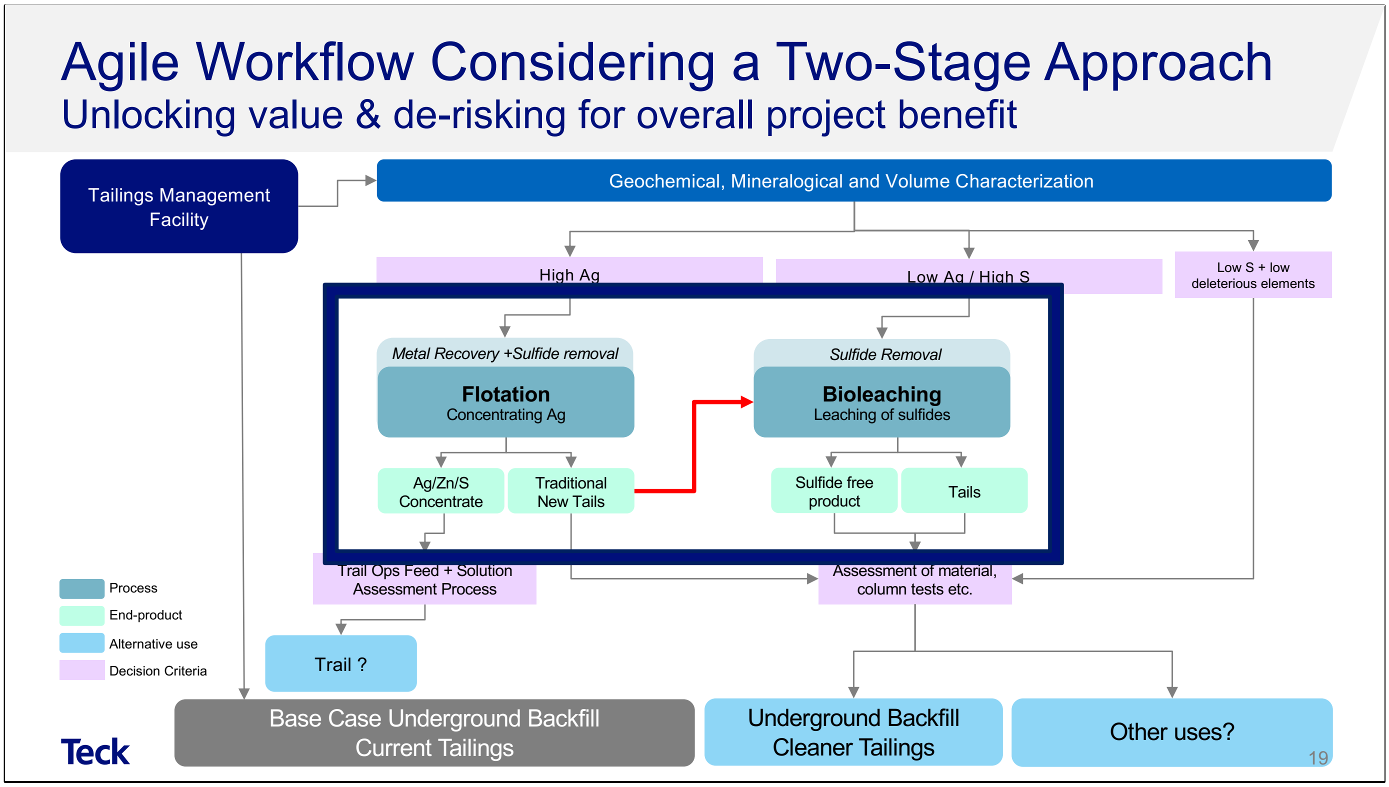
- Let’s get into some results. As I previously mentioned throughout the experiment, we had tailings that were placed in a flask with either bacteria present or absent. These bar graphs here represent the recovery of each metal. Starting with Arsenic, Cobalt, Copper, and so on. Each color is a different cell. What these bar graphs show is the recovery of each metal with and without the bacteria present. There just isn’t a gap between each bar but in fact, and this is shown the best with Zinc on the bottom right of these graphs is there are light blue bars beside each representing the recovery of each metal without the bacteria present. This is a great example of how the bacteria were responsible for the leaching of the metals into the solution.

- Next the graph on the right better shows the recovery of metals at day 25 of the experiment. We let the experiment run for 25 days to give the bacteria as much time as possible to leach the metals from the sulfides. However, our results from this experiment indicate this amount of time could be shortened considerably to approximately 10 days and potentially even less time with further optomizaiton. The percent of metals recovered is provided on the y axis and on the x axis we have the cells listed. Graph on right: Cobalt, copper, and Zinc had recoveries 70-100%, arsenic recovery was in the range of 40 to 70 percent., Additionally, lithium recovery ranged from 20 to 40 percent. We also note, lead and Silver were not recovered during this experiment. The explanation for the lack of lead in solution is because lead sulfate is insoluble at pH 2, which is the pH this experiment was conducted at. Interestingly, when we calculated the mass balance for silver in the leachate solution and the solids that remained, we found that the numbers didn’t add up. We set out to try and determine why this was. Luckily at Teck we have access to some fun toys and one of these just so happens to be a Scanning electron microscope.



- Here on the left we have a slide showing a bacterial cell next to iron sulfate crystals. The image on the right shows a zoomed into image of the cell but we have added a filter that shows silver in green. As you can see the bacterial cell is strongly associated with nanoparticles of silver. What we think has happened is when we were filtering our samples for total and dissolved metals in the leachate some of the bacterial cells were removed during the filtering step, leading to an unbalanced mass balance.

So, to answer our first question, can we use bacteria to recover metals from tailings. Yes, we can, but it depends on the target metal.

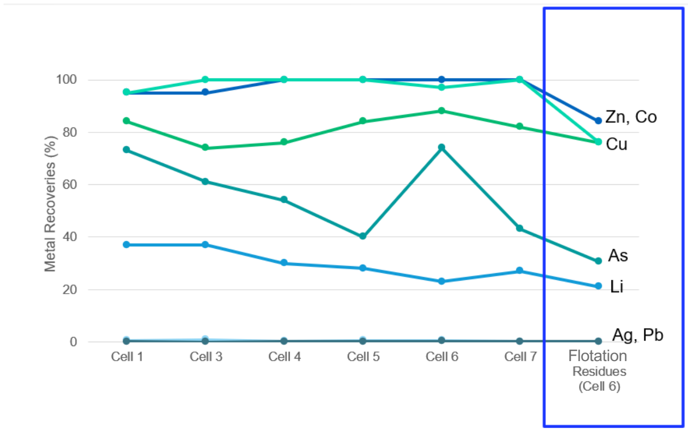


So we found that we could remove a good amount of the metals from the tailings with bioleaching, but floatation was able to recover, lead and silver with some variation in recoveries. But we still wanted to determine how do these methods compare to one another in regard to metal recovery and can we take these two methods and use them in series, making bioleaching almost a polishing step. Silver and lead would be recovered with conventional flotation while the remaining sulfides would be leached out with bioleaching.

Agile Workflow Considering a Two-Stage Approach

Bioleaching is effective in sulphide removal for cleaner tailings!

Recovery of metals at day 25



- Similar results to the first experiment
- Absence of dissolved Ag and Pb
- Co, Zn, Cu high; As, Li moderate

Method	Total Sulfides Removed (%)
Flotation of tailings	54
Bioleach of tailings	73
Bioleach of flotation residues	87

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The first step was to determine if metals could be recovered from flotation residues via bioleaching. This graph again shows the recoveries of each metal from all the cells if we just were to bioleach them. The results highlighted in the blue rectangle shows if I were to take the residues from flotation and bioleach them. You can see we get similar recoveries of the metals compared to bioleaching. So yes, we can leach remaining metals in flotation residues with bacteria. Now I did say I would compare our bioleaching results to flotation. I also want to point out that these are preliminary results and optimization of both methods is still ongoing. Overall, preliminary results of floating the tailings found that 54% of the total sulfides were removed while bioleaching removed 73%. However, when bioleaching is used on flotation residues, we found 87% of all the sulfides were removed from the material.

Bioleaching of tailings

A bench top scale study

1. Can bioleaching recover metals from tailings? — Yes, a majority of metals can be recovered via bioleaching.
2. How does bioleaching compare to conventional methods? — Overall bioleaching removed a greater amount of sulfides from the tailings than flotation.
3. Could bioleaching be used a polishing step? — Yes, flotation followed by bioleaching recovered more metals and removed more sulfides than either method alone.

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1: Can bioleaching recover metals from the tailings?
Yes, a majority of metals can be recovered via bioleaching.

2: How does bioleaching compare in effectiveness to conventional techniques for recovering metals such as flotation. Overall bioleaching removed a greater amount of sulfides from the tailings than flotation.

3: Can bioleaching be used as polishing step to flotation residues. Yes, flotation followed by bioleaching recovered more metals and removed more sulfides than either method by itself.

And with that I would like to thank you for being a great audience and I will pass it back to Betsy for the last few slides.

Reprocessing Methods for Site Optionality

Case Study Learnings for Cell and Site Optimization

Flotation and bioleaching:

- Promising recoveries for metals
- Sulfides are reduced

Key learnings from case study:

- Anticipated site specific and cell specific optimization required
- Insights into a road map and methods

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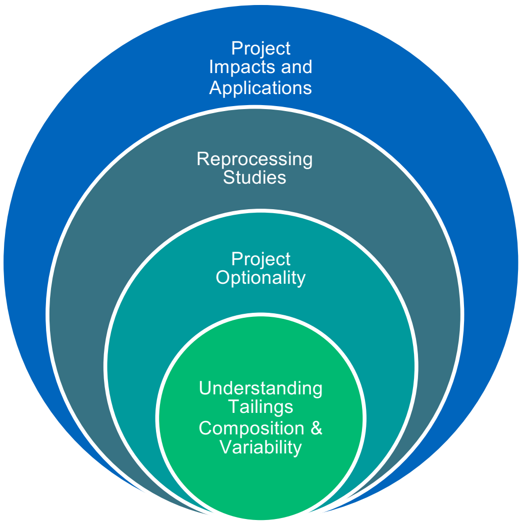
JAMES TALKING NOTES:

Optionality /

Opportunity: Knowing our Tailings

Unlocking value & de-risking for overall project stewardship



This case study provides a road map for evaluation, characterization and reprocessing options for smart and sustainable decision making.

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JAMES TALKING NOTES:

This case study provides a road map for evaluation, characterization and reprocessing options for smart and sustainable decision making.