Geosyntec consultants

From Silicates to Solutions

Practical Insights from the Ekati Mine Effective Neutralization Potential Study

November 2024

Acknowledgements

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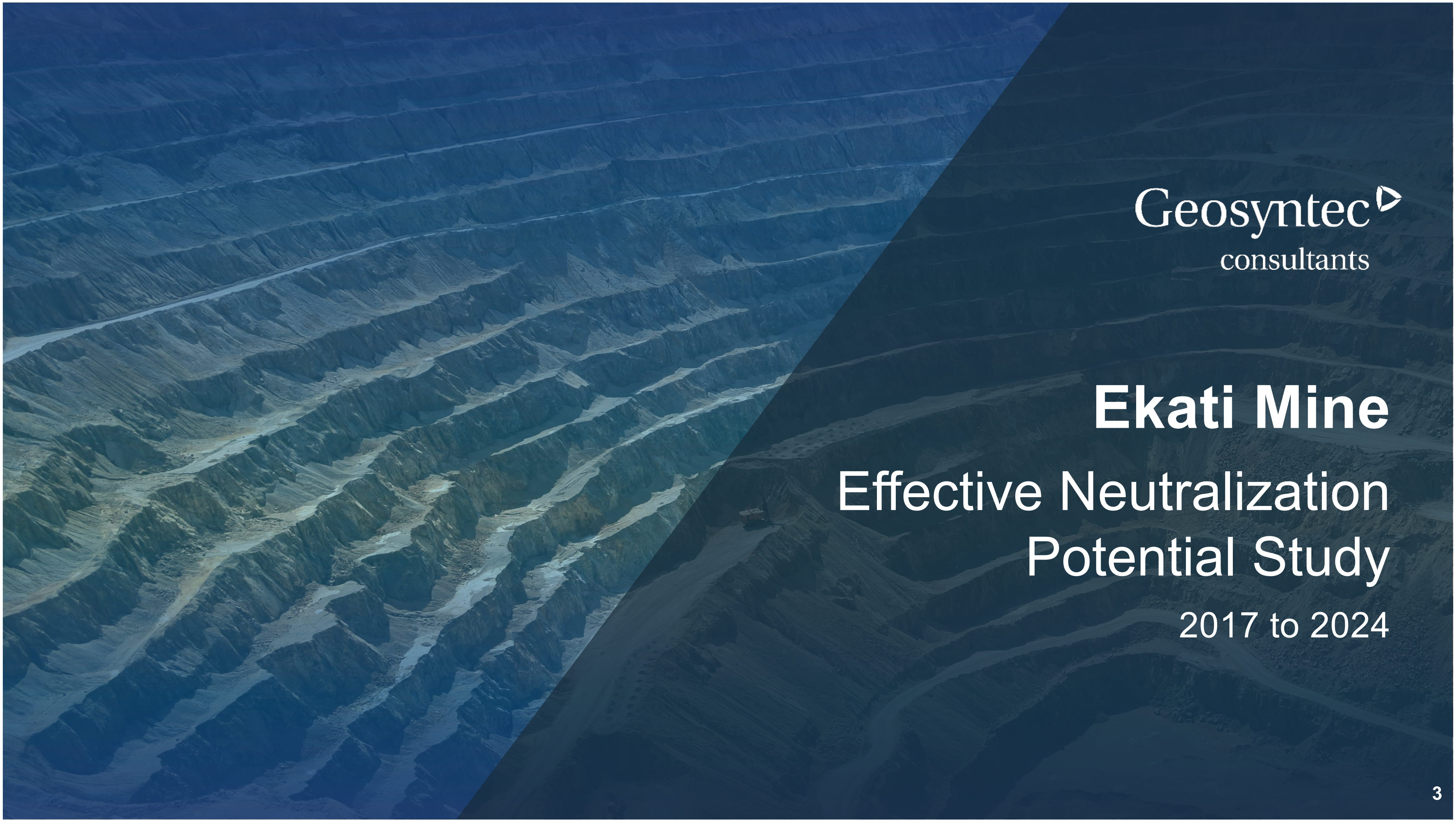

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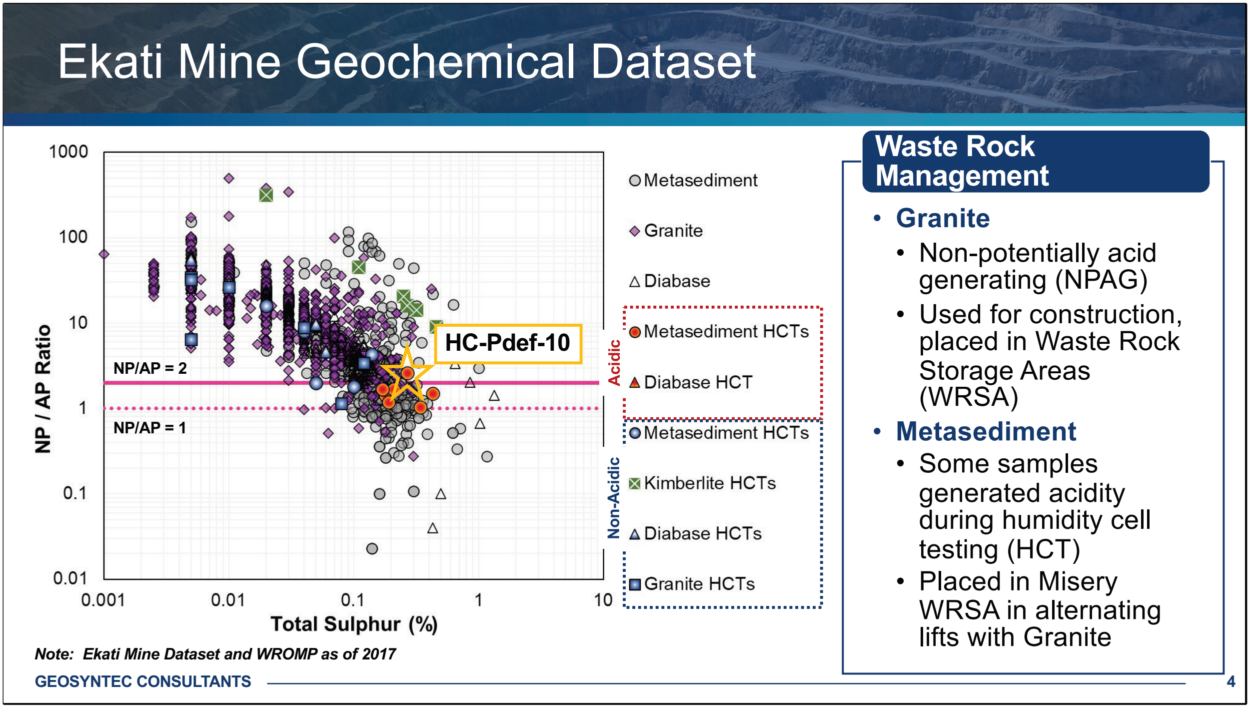
Ekati Mine

Effective Neutralization Potential Study

2017 to 2024



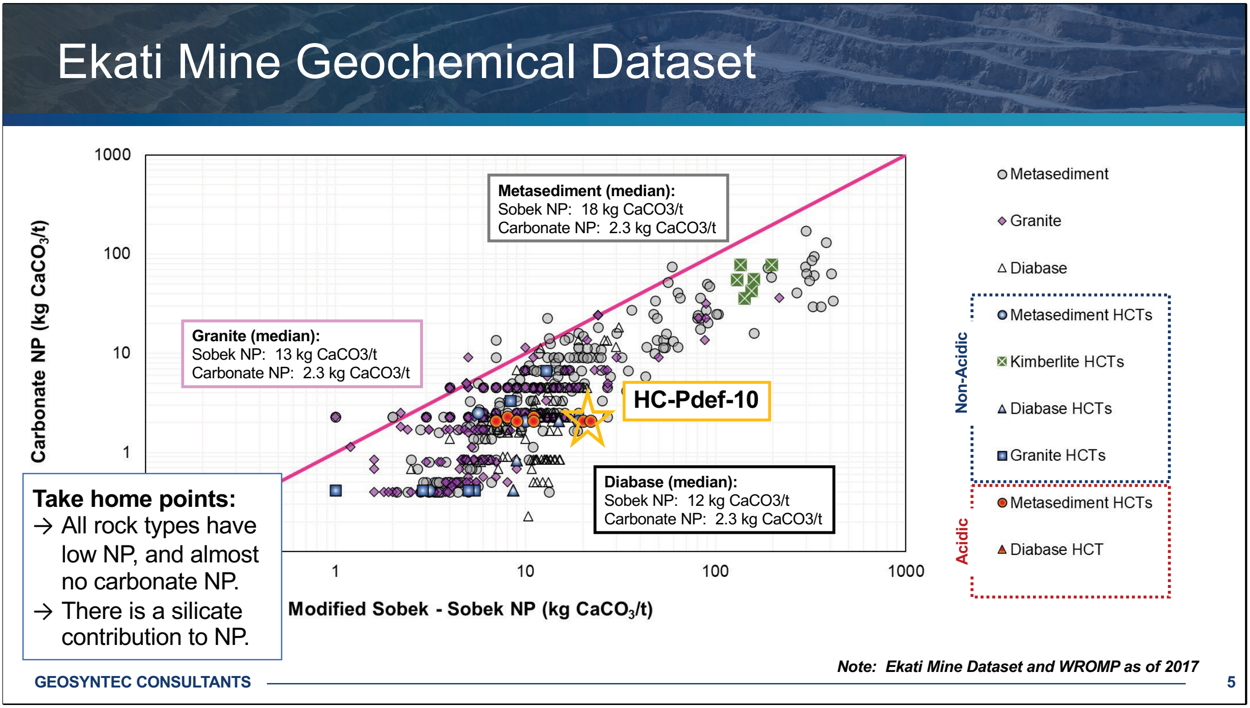
I'm going to start the presentation by telling the story of how we got here.

In the early 2010s, I worked with a team supporting Ekati with a water license application for a new mining area. As part of this work, we were asked to analyze the mine's geochemical dataset to identify an opportunity to propose a classification criterion for potentially acid-generating rock

- **Per the waste rock and ore storage management plan for the mine,**
    - Granite is classified as Non-Potentially Acid Generating (NPAG) and metasediment as Potentially Acid Generating (PAG).
    - This classification was based on the original geochemical characterization during the Environmental Assessment (EA) and ongoing kinetic testing.
    - Only metasediment samples generated acidity in kinetic tests, and only a small fraction of the metasediment samples at that.
- As mining progressed into areas with more metasediment, questions

arose about the uniformity of metasediment reactivity, and whether it was appropriate to classify all metasediment as PAG. These are real estate and planning questions – did another PAG rock storage facility have to be designed.

- Using this dataset,
  - A threshold of NP/AP ratio of 2 was proposed to classify PAG rock. ANIMATION
  - All acidic samples had NP/AP ratios below 2, except one.
  - Understanding why this sample differed became crucial because we received extensive regulatory inquiries questioning the suitability of the NP/AP threshold of 2 for classifying PAG rock because of this one sample. Those questions focused on the effectiveness of neutralization potential.



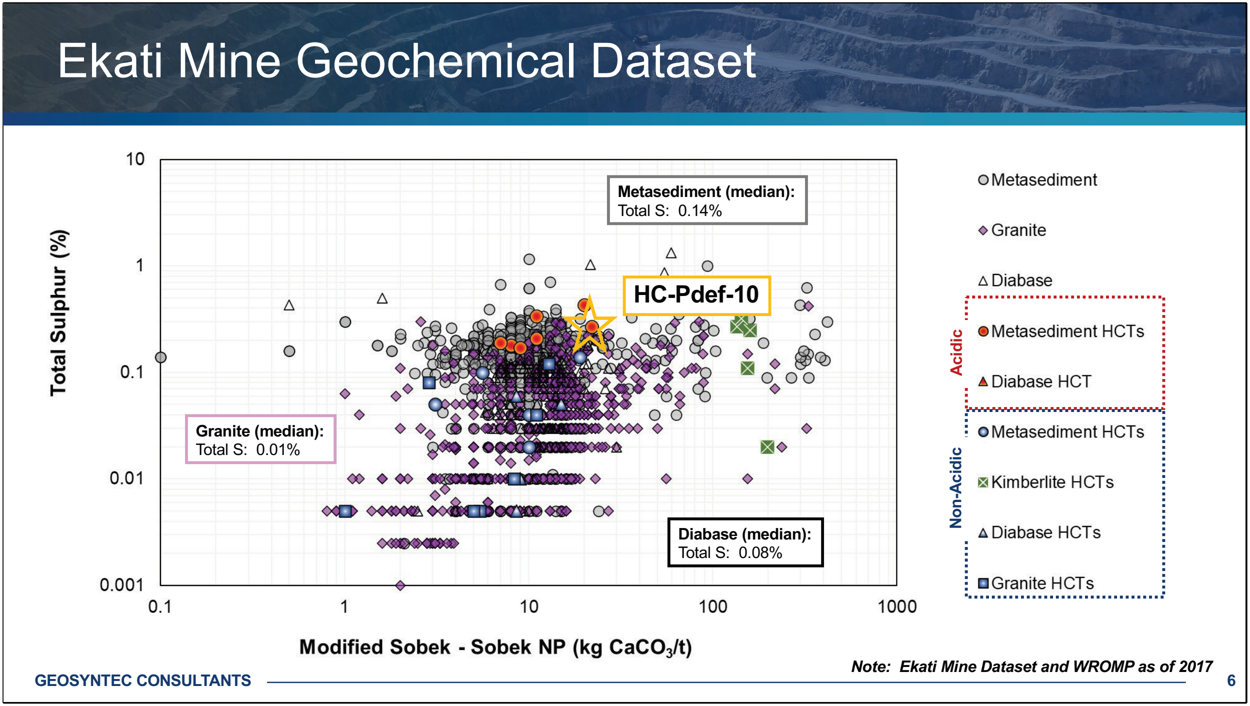
So, let's talk about neutralization potential in this dataset. Its our fearless era.

To lend some insight to the general characteristics of the waste rocks at the Ekati Mine, an important take home point is that all rock types at Ekati Mine have low neutralization potential, and almost no carbonate mineralization. While the metasediment NP is the highest of the 3 main rock types, it is not "high" by any means at 18 kg CACO3 equivalent/t

ANIMATION FOR THP

Just using the ABA data, and some limited mineralogical data that was available for this dataset, the derived conclusiosn were:

→ All rock types have low NP, there is a silicate contribution to NP.



However, the other important thing to note is that the sulphur content of these rock types is low – generally detection limit values in granite, and 0.14% in metasediment.

The interpretation of site specific acid generation potential required an understanding of why some of these low sulphur samples generated acidity ANIMATION FOR SAMPLE and some did not.

Effective Neutralization Potential Study Framework

Study Requirements

- Based on intervenor comments during Jay Water License process
  - Schedule 6, Condition 3 of Draft Water License amendment
  - Schedule 6, Condition 2 (WROMP)
- **2017 study design**
  - Geochemical testing program
  - Development of waste rock placement and monitoring system
  - Misery WRSA – geochemical and geotechnical monitoring program

Interim Closure and Reclamation Plan

- **2018 Misery Waste Rock Storage Area Investigation**
  - Sample collection from Misery WRSA
  - Study performed as a component of the Reclamation and Research Plan for the ICRP
  - Study results also intended to supplement Jay WRSA Co-Placement Study

Updated Study Design

- Study continued as part of the ICRP Reclamation Research Plan RP 6 and Schedule 6, Condition 3 of the Jay Project Water License
- **2020 updated study design**
  - Site-specific investigation of effective neutralization potential
  - Does the reactivity of NP and AP differ between the fine fraction of run-of-mine (ROM) blasted rock and samples crushed for standard HCT testing?
    - Can the differences be accounted for when managing waste rock?

Take Home Points

- This study was planned and executed over a long period of time (2017 to 2022).
- The design of the study was informed by extensive intervenor input.
  - → The study was initially developed to support to a Water License amendment specific to a proposed waste rock storage area design.
  - → It was ultimately updated to support questions specific to the interim closure and reclamation plan.

The questions raised by project reviewers led to the development of the effective neutralization potential study.

This study was conceived between 2017 and 2019 and conducted from 2019 to 2022.

Initially focused on designing a new waste rock storage facility, it was later repurposed to investigate the reactivity of waste rock in existing storage areas.

Effective Neutralization Potential Study

Key Questions

1. What are the most important factors and variables that influence ENP at the Ekati Mine?
   - Factors to consider include temperature, mineralogical composition, mineral reactivity and exposure, and particle size.
2. Do ENP and effective acid potential differ between the fine fraction of run-of-mine (ROM) blasted rock and rock that has undergone physical handling (e.g., crushing)?
   - If differences are identified, is it feasible to represent a means of accounting for such variations when managing waste rock?
3. Can the components of the ENP be quantified, and can this quantification be extrapolated to a wider dataset?

We are now a bit older. A bit wiser. Kanye West has jumped on the stage at the VMAs. We are in speak now and red territory.

Using the extensive regulatory feedback, we designed a study focused around the key questions on the screen. We wanted to provide lines of evidence that spoke to

The key factors influencing ENP at the Ekati Mine considering temperature, mineral composition, mineral reactivity, exposure, and particle size.
Whether ENP and effective acid potential differ between the fine fraction of run-of-mine (ROM) blasted rock and the samples that we prepare in the lab for kinetic testing
The quantification of components of effective NP

How to Define Effective Neutralization Potential?

ENP = Measured NP – (nnNP + UNP + IRNP) + LSNP

nnNP = non-net NP
UNP = unavailable NP
IRNP = insufficiently reactive NP
LSNP = Long-term slowly reacting NP

Best practice – interpretation of bulk NP (modified Sobek) with site-specific knowledge of:

1) Mineralogy
2) Mineral exposure
3) Neutralizing mineral reactivity
4) Rates of acid generation

*"The effective NP can be measured empirically from the acid neutralization potential that is consumed prior to the onset of acid drainage (pH <6). For example, **effective NP prior to the onset of acid pH drainage in a humidity cell or column can be calculated from the cumulative calcium plus magnesium or sulphate released in drainage and precipitated in secondary minerals.**"* - (MEND 2009)

MEND 2009. Section 13.1.5. Page 13-7 (or page 396 of the pdf)

Before we get too far into the hows and whys of the study design, we have to take a quick pit stop on the way to welcome everyone to ENP (we've been waiting for you)

Bulk or carbonate measured NP measurements, at face value, can have some limitations because the numbers alone don't address inherent factors that can influence actual weathering rates

Limitations of NP Methods can be addressed by combining lab measurements with site-specific knowledge, considering:
Mineral reactivity
Exposure
Particle size

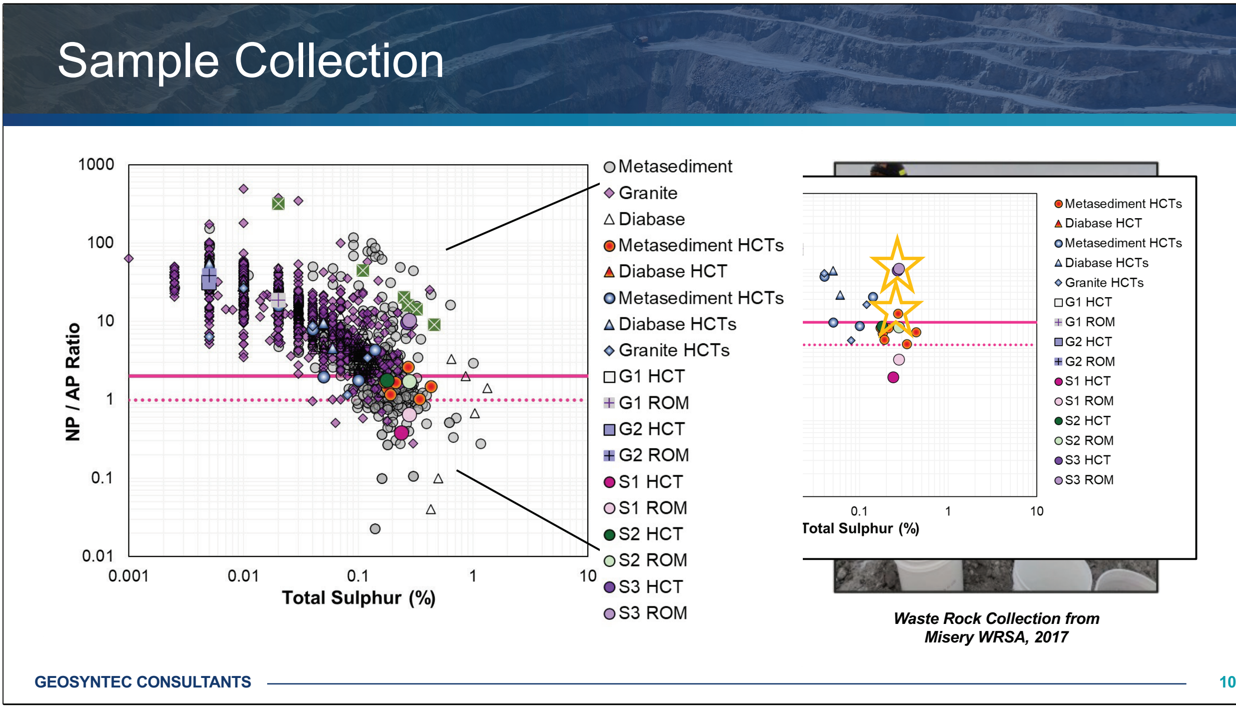
And as young Kristin learned, there is no one definition of effective neutralization potential, nor does a readily applied off the shelf method exist. Younger Kristin would have liked this. There is guidance, but not a method.

ANIMATION

The best Practice for ENP Assessment is to Consider acid generation rates alongside site-specific mineralogy, reactivity, exposure, and particle size.

We took the approach of developing a study that we could use to understand the various mineralogical components of ENP, including
Non-net neutralizing minerals (e.g., siderite)
Physically occluded minerals (cannot neutralize acidity)
Insufficiently reactive minerals under field weathering
Kinetically limited minerals that can neutralize acidity

We supplemented the mineralogical study with extensive kinetic testing to confirm rates



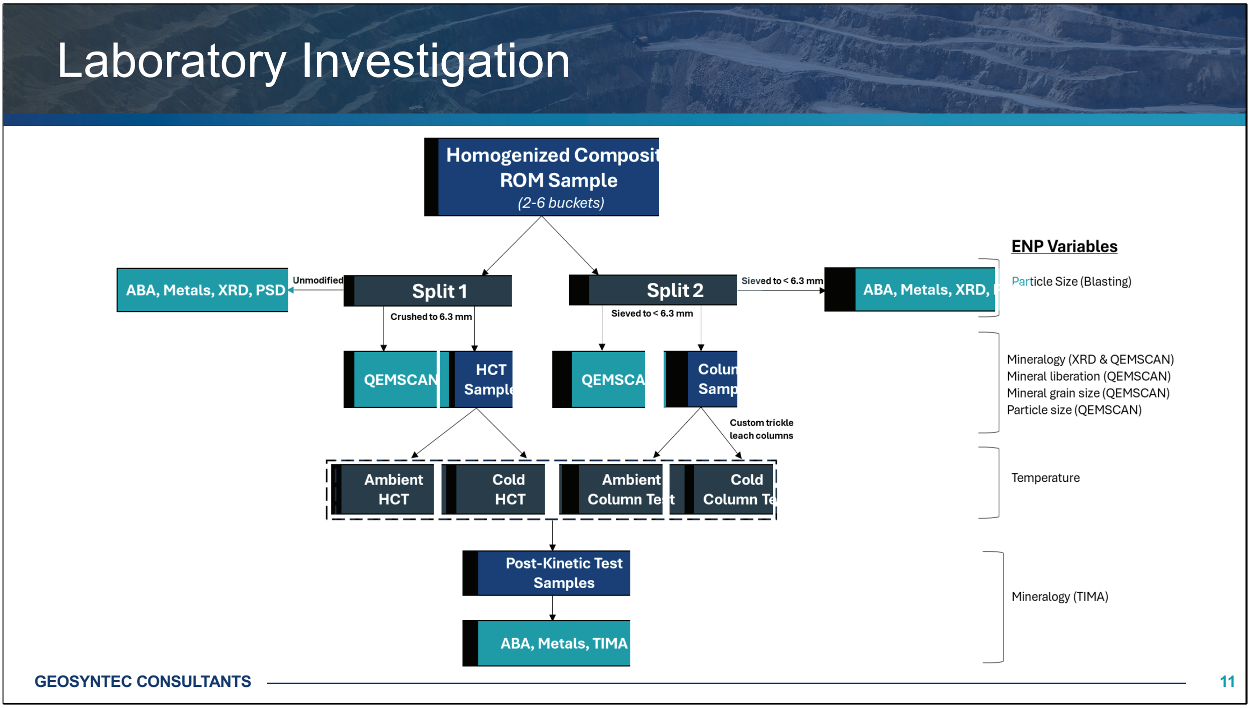
In order to be able to address the reviewer comments in a comprehensive manner, we used ROM rock from the Misery Waste Rock Storage Area rather than drill core. This allowed us to focus on those factors that might be influenced by blasting or handling, like mineral exposure.

Sample collection was completed in 2017, and sample collection was… somewhat limited by site conditions.

ANIMATION

Ultimately, we collected several large samples that were analyzed and then composited to represent the range of characteristics in the geochemical dataset – let's blow this up so we can see how those samples compare.

> **2 granite composite samples** that could represent the range of silicate mineral compositions
>
> **3 metasediment composite samples** that represent the range of acid generation potential in the existing Ekati Mine HCT dataset



And last bit of background information… this is the road map for the lab investigation.

Five samples: 2 granite, 3 metasediment.
EACH sample was split into two sub samples that were manipulated for particle size: one split crushed (HCT protocol), one sieved to a top size, so it could fit into the column.

For EACH split
- We set up column and HCT tests to study test scale and sample preparation.
- Variations in flow rate and temperature were also tested.

And we performed
- Comprehensive characterization before and after kinetic testing.
- Analysis of primary composition and its variation due to sample preparation.

This is a big study. In combination, it's effectively the lover-folkloreevermore triumvirate. If we presented the entire study, we would be here for 3.5 hours. I am not Taylor Swift, and I was not given the time nor the stamina for that. So instead, I'm going to present the most important things I think we learned as a study team, in the hopes that it informs future studies about ENP.

Extensive mineralogical testing was performed on samples pre- and post-kinetic testing.

- Reitveld XRD for comparison to historic dataset
- QEMSCAN prior to kinetic testing, TIMA post-kinetic testing
  - *Note: method change owing to time elapse*

Mineralogical methods were selected to evaluate bulk composition AND texture.

- Mineralogical content in relation to ENP
- Mineral form, associations and liberation
- Identify mineral reaction products (if any)

1. Three out of four insights emphasize the value of mineralogical data.
2. Feel free to grab a coffee for the next 20 slides!

Let's begin. Insight #1. Mineralogical data is the kinetic testing roadmap. Yes, I know this is pretty basic, but I can't underscore the relevance for this study, which was basically about providing receipts.

For this study, we were fortunate to be provided a budget to perform extensive mineralogical analysis to interpret kinetic testing results and field behaviors.
We used semi-quantitative methods for referencing earlier geochemical test results.

1. We employed automated SEM-based methods (QEMSCAN and TIMA) to observe mineral form and liberation.
2. Lastly, we confirmed the conceptual model by checking samples for reaction products.

Mineralogy

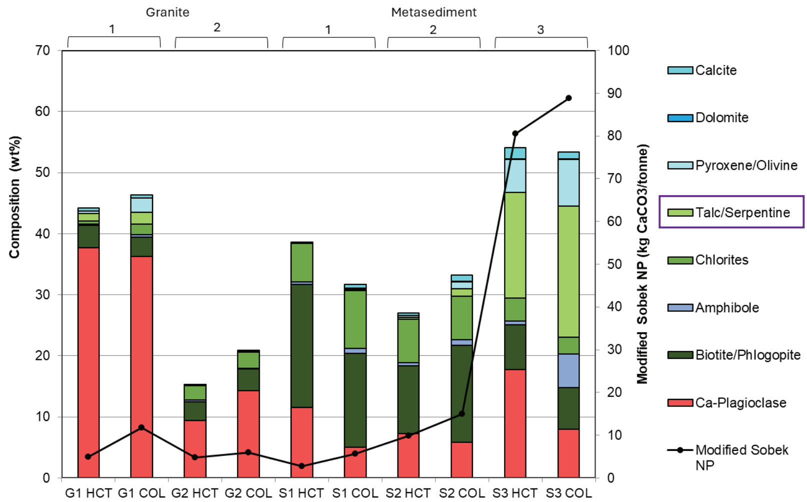
Bulk Mineral Composition

Granite

- Quartz, plagioclase and feldspar
- Negligible pyrite and calcite

Metasediment

- Quartz, plagioclase and very fine grained “mafic” minerals – biotite, chlorite, pyroxene / olivine, chlorite, talc / serpentine / lizardite / smectite
- Pyrite with trace pyrrhotite
- Calcite, with trace dolomite

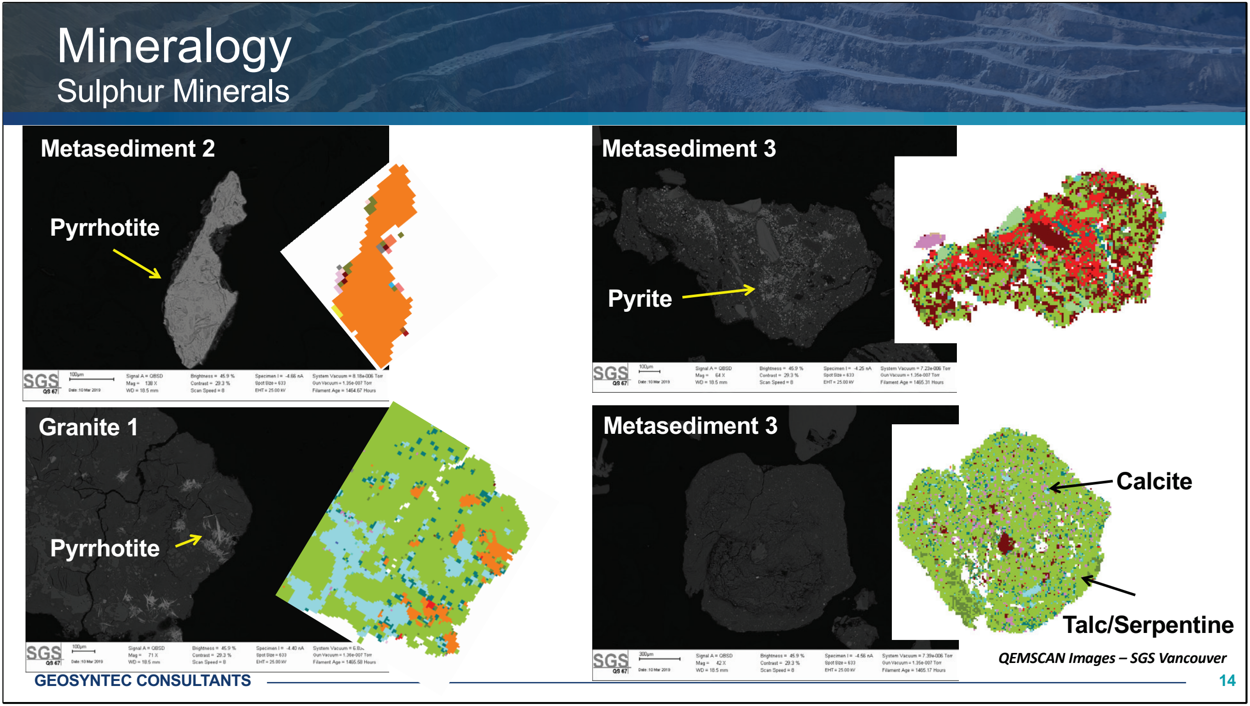


This is a snippet of some of the mineralogical data. In this case, I’m only presenting the subset of data related to silicate and carbonate minerals.

Bulk mineralogy in granite dominated by quartz, plagioclase and feldspar with negligible calcite and pyrite

Metasediment was more varied – this is the Burwash metasedimentary unit, which is ubiquitous at several sites in the Slave province in NWT
Contains Quartz, plagioclase and very fine grained "mafic" minerals like biotite, chlorite, pyroxene / olivine, chlorite, talc / serpentine / lizardite / smectite – main sulphides were pyrite with trace po

If you HAVEN’T left the room for a cup of coffee (come back, be here), I want to draw your attention to sample S3, which is our sample with an anomalous NP. This sample has a high content of talc and serpentine.



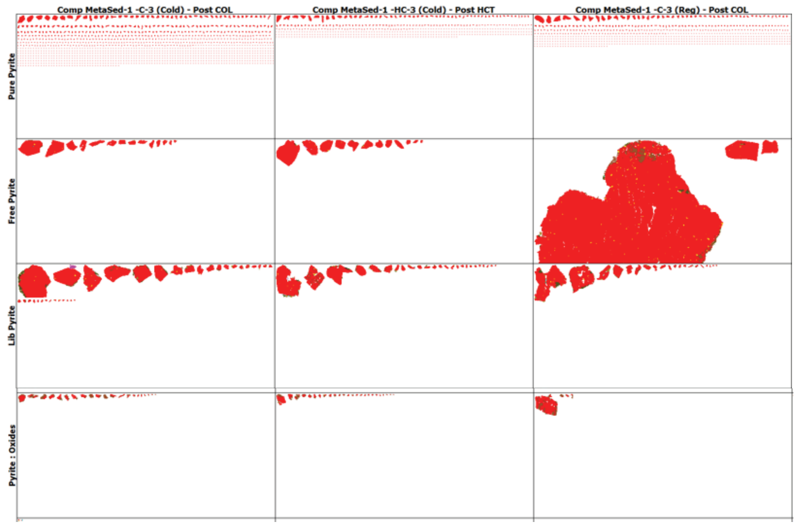
Some examples of sulphide occurrence in granite and metasediment samples, pre-kinetic testing

Particularly the photo micrograph on the lower left that demonstrate how measured NP might not necessarily translate to site specific ENP

- The high talc/serpentine content in S3 is evident in this figure.

Mineralogy – Post-Kinetic Testing

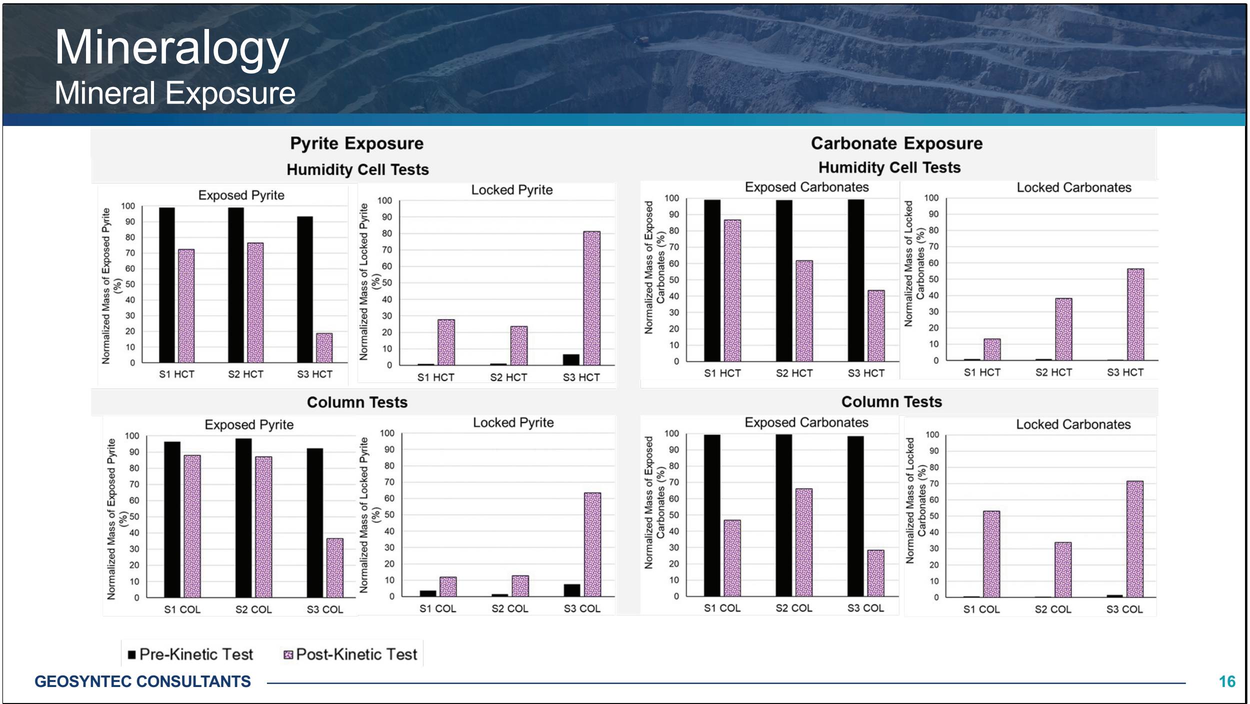
Sulphur Minerals



TIMA Results – SGS Vancouver

Example of information we received for post kinetic test samples, if you get very very close to the screen, you can see the brown reaction products on sulphide minerals, which are the color coding scheme for iron oxides

We received these visual images, but also quantification of mineral association and liberation that allowed for confirmation of the conceptual geochemical model



And a last piece of some of the important mineralogical information we received, with a focus on pyrite and carbonate exposure in pre- and post- kinetic testing samples

- **Granite vs. Metasediment** – general observations that are not captured in these plots
  - In granites, sulphide minerals were finer and more locked than carbonates.
  - In metasediments, sulphide minerals were coarser.

This plot shows that

- **Before kinetic testing**
  - >92% of sulphides and >98% of carbonates were exposed and reactive.

- **Post-Kinetic Testing**:
  - Decrease in exposed grains; increase in locked pyrite and carbonate.
  - Indicates low reactivity of encapsulated minerals.

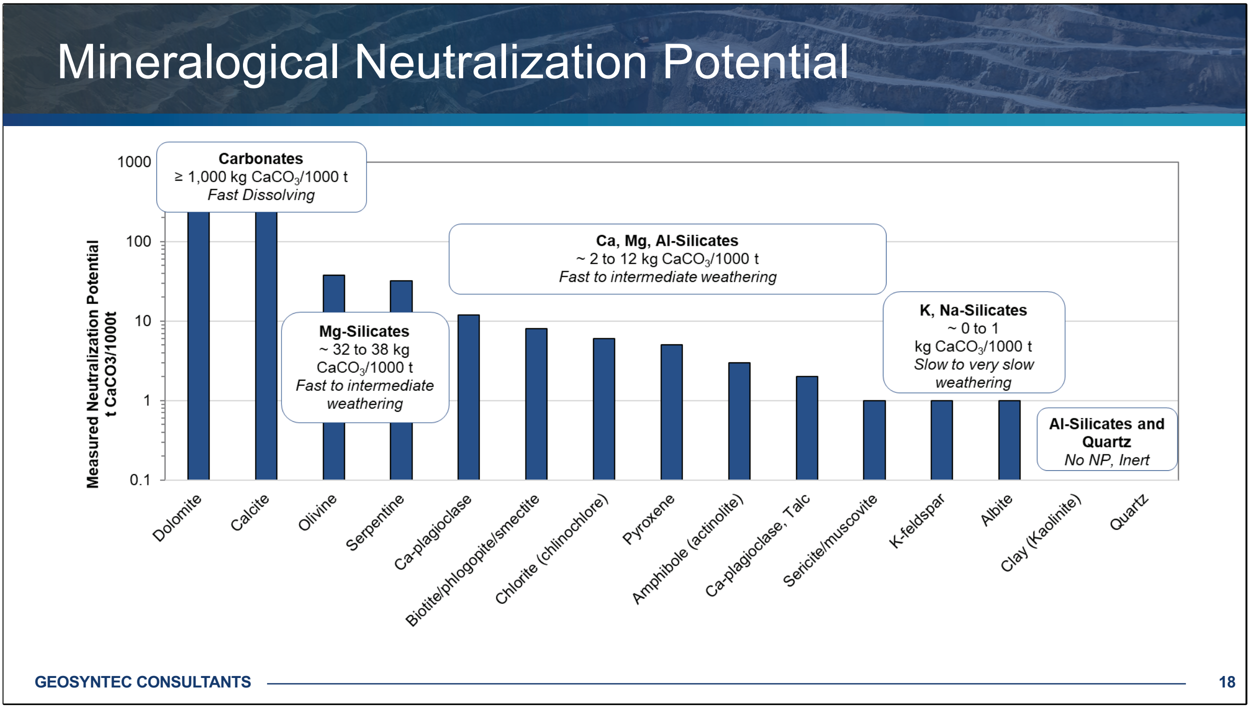
Insight #2: Mineralogical data should be used to confirm NP.

Mineralogical data is your best resource for understanding effective acid generation potential and effective neutralization potential.

- Mineralogy results can be used to qualify kinetic test results and field behaviors
  - Exposure / liberation, particle size and bulk composition play a role
- Mineralogy should be used to QA/QC laboratory NP measurements
  - Bulk mineral composition can help identify key contributors to ENP

Our second insight was that you should use the mineralogical data to perform some basic calculations to QA/QC laboratory measurements. I would consider this a best practice for confirming sulphur speciation as related to AP estimation, and it’s also not uncommon to perform this check using carbonate mineral percentages to confirm TIC.

I’m going to walk through how we used our more comprehensive mineralogical data to calculate NP using a few different methods.



ENP enthusiasts might recall that I showed this plot during my talk last year.

There are a few different ways to quantify mineralogical NP. John Jambor performed research in the early 2000s to quantify NP values on a mineral by mineral basis. There are also publications that equate mineralogical NP to reactivity groupings. I have references for these methods on the next slide.

1. Mineralogical NP defines Inherent neutralization capacity whereas
2. Reactive mineralogical NP Considers mineral weathering rates using relative reactivity scaling.

IN GENERAL

1. **Carbonate Minerals**:
   1. Highly reactive; largest contributors to bulk NP (≥ 1000 kg CaCO3/t).
2. **Silicate Minerals**:

1. Magnesium-rich (e.g., olivine, serpentine): Intermediate reactivity (NP ~ 32–38 kg CaCO3/t).
2. Calcium-aluminum-magnesium (e.g., biotite, amphibole): Lower NP (2–12 kg CaCO3/t) due to slower weathering.
3. Potassium/sodium-rich (e.g., quartz, K-feldspar): Inert; do not contribute to bulk NP.

Mineralogical Neutralization Potential

Modified Sobek / Sobek NP
- Laboratory measured

Carbonate NP
- Calculated using inorganic carbon measurement

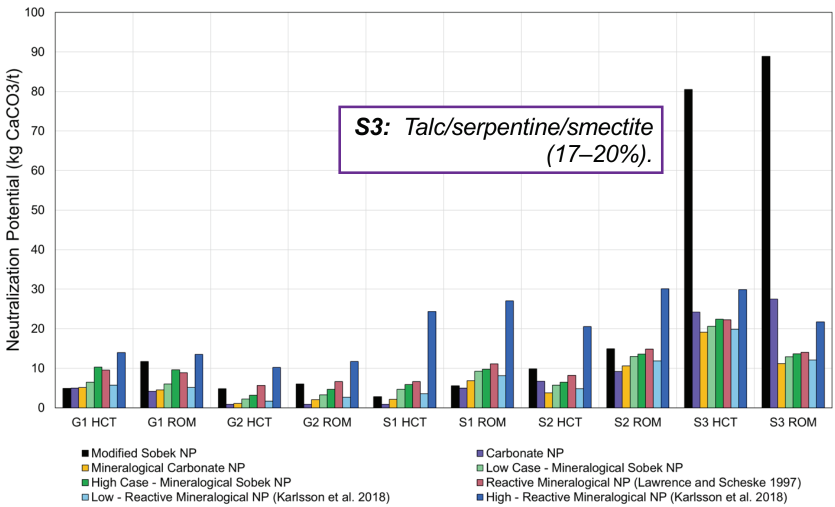
Mineralogical Carbonate NP (MEND 2009)
- Calculated using mineral weight percentages for neutralizing carbonate minerals (calcite and dolomite)

Mineralogical Sobek NP (Jambor et al. 2006; 2007)
- Calculated using mineral weight percentages and the relative mineral NP of silicate minerals

Reactive Mineralogical NP (Karlsson et al. 2018; Lawrence and Scheske 1997)
- Calculated using mineral weight percentages and a factor related to mineral reactivity to estimate reactive mineralogical bulk NP

I don't expect anyone here to read this slide, for the ENP enthusiasts, a summary and the references are provided for your future use.

Estimation of Mineralogical Neutralization Potential



- **Main minerals contributing to NP:** Ca-plagioclase, albite, K-feldspar, muscovite, biotite/phlogopite, and chlorite
- Modified Sobek NP comparable to calculated mineralogical NP, ***except in S3 samples***

Using our extensive mineralogical dataset, we calculated NP several ways for comparison to our sobek NP measurements.

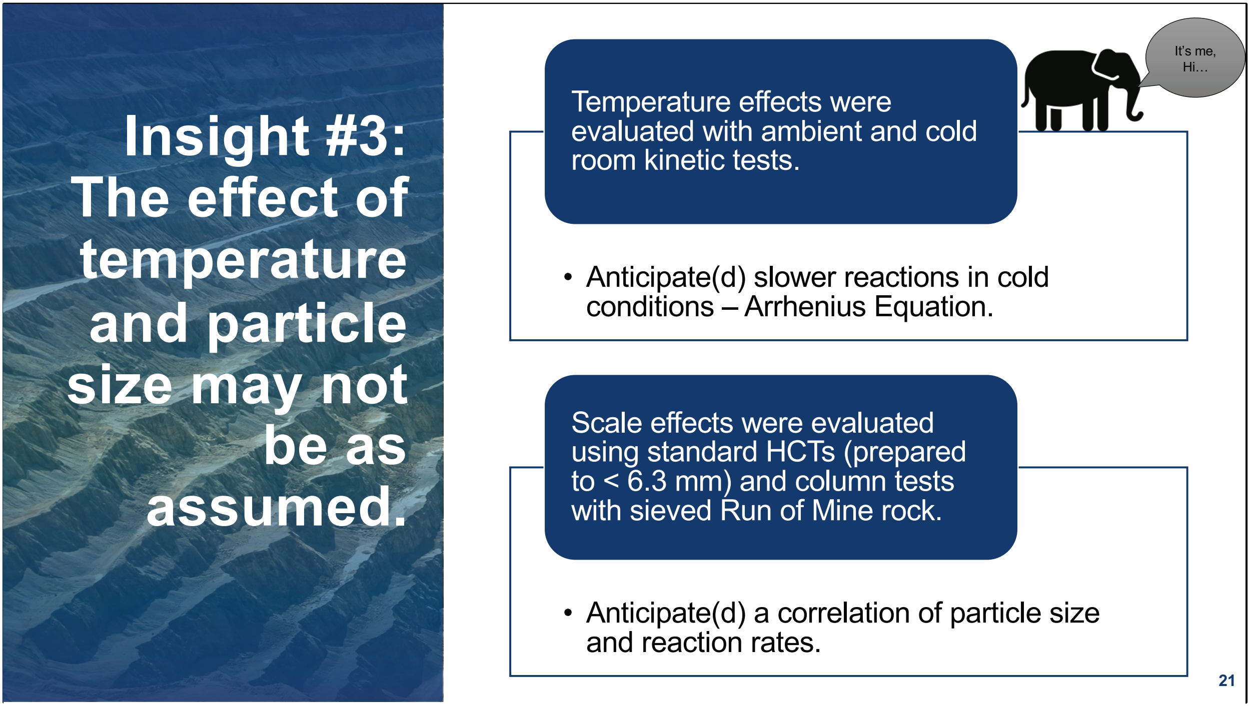
What we know is that the main minerals likely contributing to NP include

1. Ca-plagioclase, Albite, K-feldspar, muscovite, biotite/phlogopite, and chlorite.
2. Unique proportions in granite vs. metasediment.

1.Mineralogical Sobek NP:

1. Generally similar to mineralogical carbonate NP.
2. Modified Sobek NP consistent with calculated mineralogical NP (except S3 samples).
3. S3 samples influenced by unique mineralogical characteristics

4. This check triggered us to perform a more in depth exploratory data analysis regarding the effects of talc and serpentine using the modified Sobek method, which I'll address in the final insight.



Insight #3 was related to the effect of temperature and particle size. We had made some inherent assumptions related to the effect of particle size and temperature at the start of these tests, and unfortunately we didn't see as clear as distinction in the results as we had assumed.

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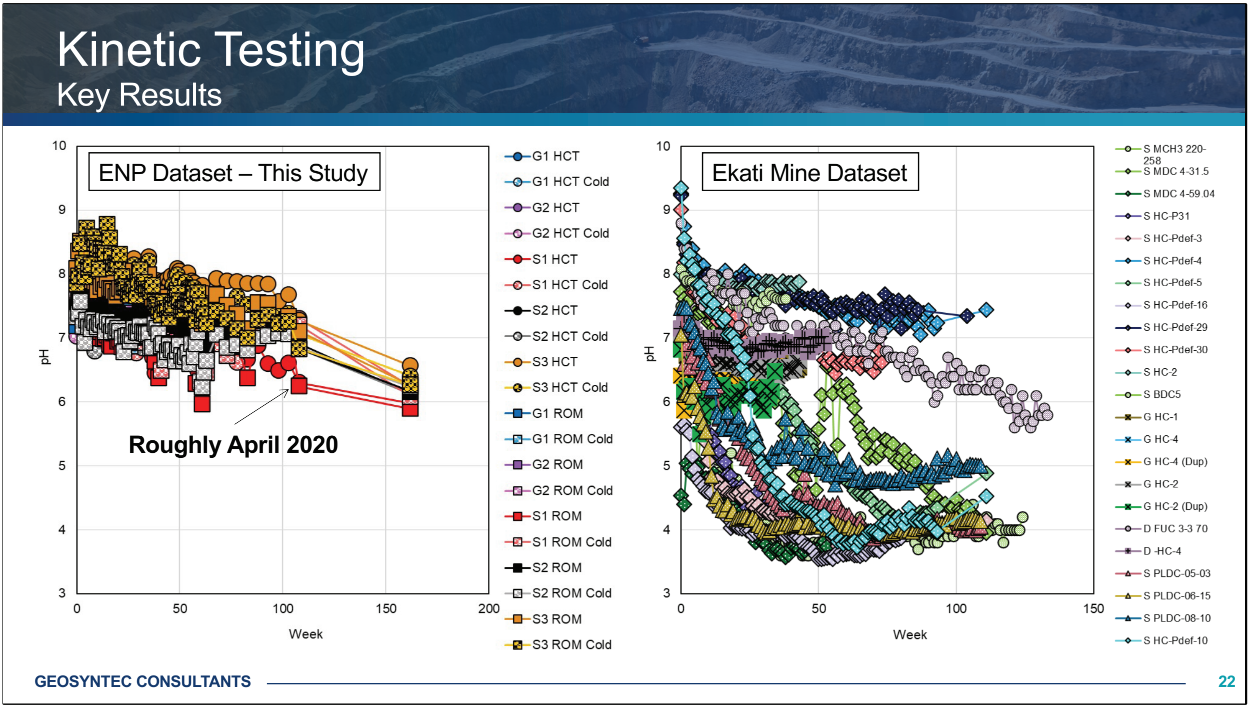
I'm going to head this off at the pass, a lot of effort was invested in the column study program, and while we did see differences in the results, they were not as broad as we had hoped.



Because you might be sick of talking about mineralogy, here's some kinetic test results.

Moving on.

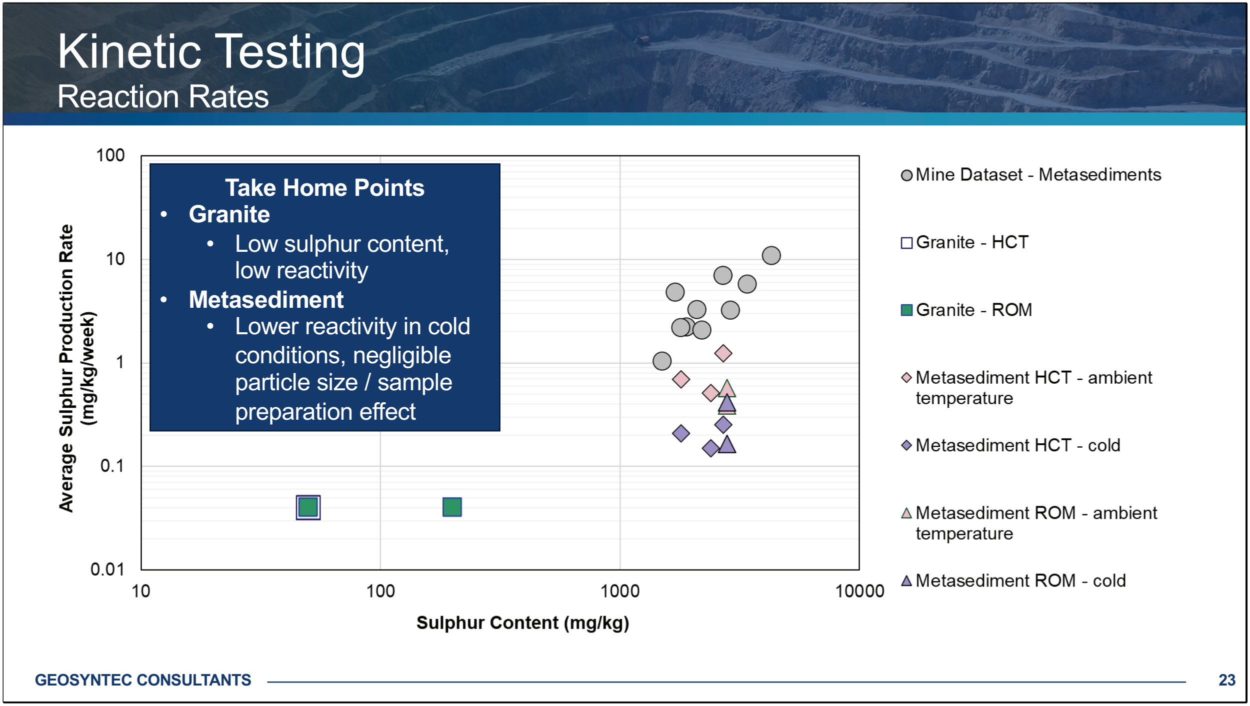
Just kidding – these are the results of the ENP study HCTs and columns in comparison to the results realized in the Ekati Mine dataset HCTs.

The testing program continued at a regular frequency for about two years. April 2020 happened and the mine had an ownership transition. As a cost savings measure for the program, the samples were put into storage.

At the point they were discontinued, the tests had been ongoing for about 3 years. While the samples in the ENP dataset were starting to see a downward trend, they were discontinued before acidic conditions were realized.

The samples were slower reacting than those in the existing dataset. Made an informed decision to discontinue based on loading rates, estimated depletion times, and the interpretation of available data – did we have enough information to answer our key questions.

We used a comparison of loading rates to confirm a few things, like how CMR compared to NP/AP ratio, and if we saw a material difference in loading rates of key factors like sulphate that demonstrated differences in reactivity.



This plot shows our sulphate production rates as a proxy for sulphide depletion – these average rates after the first flush

No correlation between S concentration and sulphate production in granite HCTs
Positive correlation in metasediment HCTs

In general – temperature influenced reaction rates – difference between the purple and pink symbols
Did not see a huge effect related to how the samples were prepared, which as you recall, is related to using ROM samples as is vs. using crushed samples for HCT

And as we might infer from the pH trends I showed on the previous slides, this set of samples is slower reacting than the samples in the mine dataset

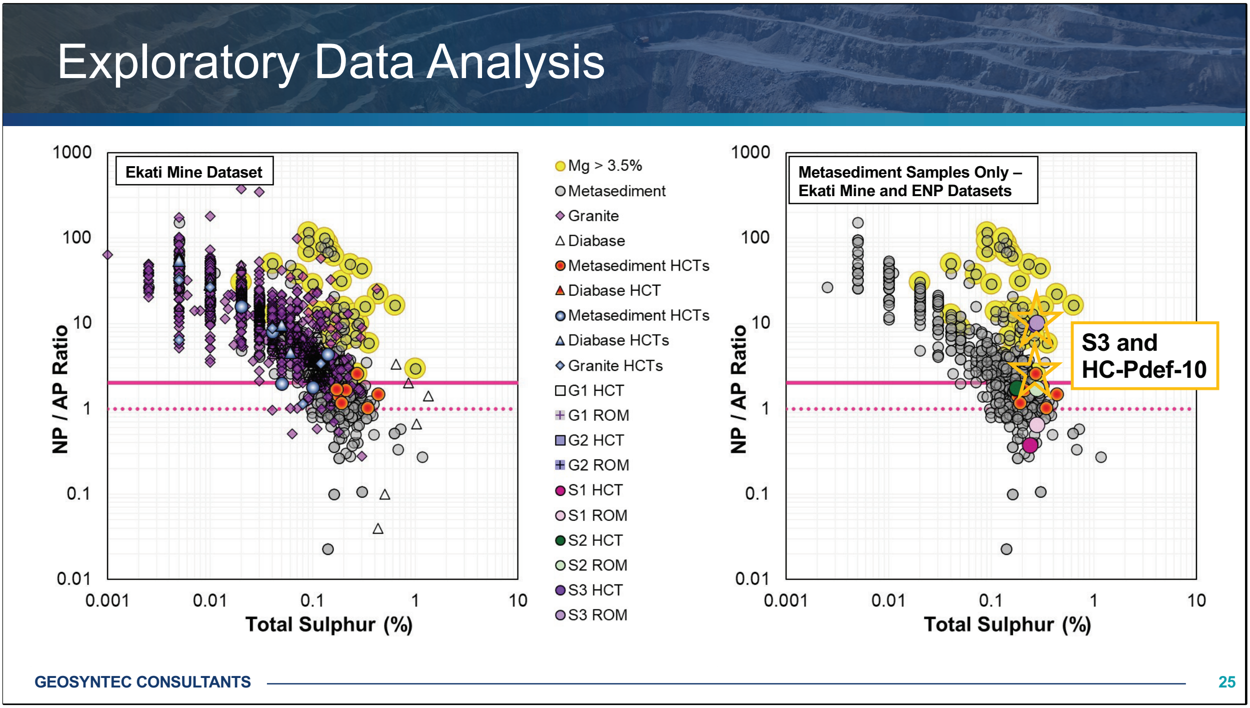
Insight #4: New data should be used to reinterpret original conclusions.

Metasediment Sample Pigeon HC-Pdef-10 – NP/AP 2.67 – generated acidity during humidity cell testing.

- Exploratory data analysis was performed to investigate this sample's solid phase characteristics.
- This led to an investigation of potential bias in analytical results using data the mineralogical results from the ENP dataset.

And the last insight, which if you were paying attention as we go, you might have seen coming.

As we developed our conceptual model for ENP, and assimilated all the mineralogical and kinetic testing data related to each of the ENP factors, we realized that we had an anomaly to investigate, and that anomaly was indeed the sample that informed the original comments related to the ENP study.

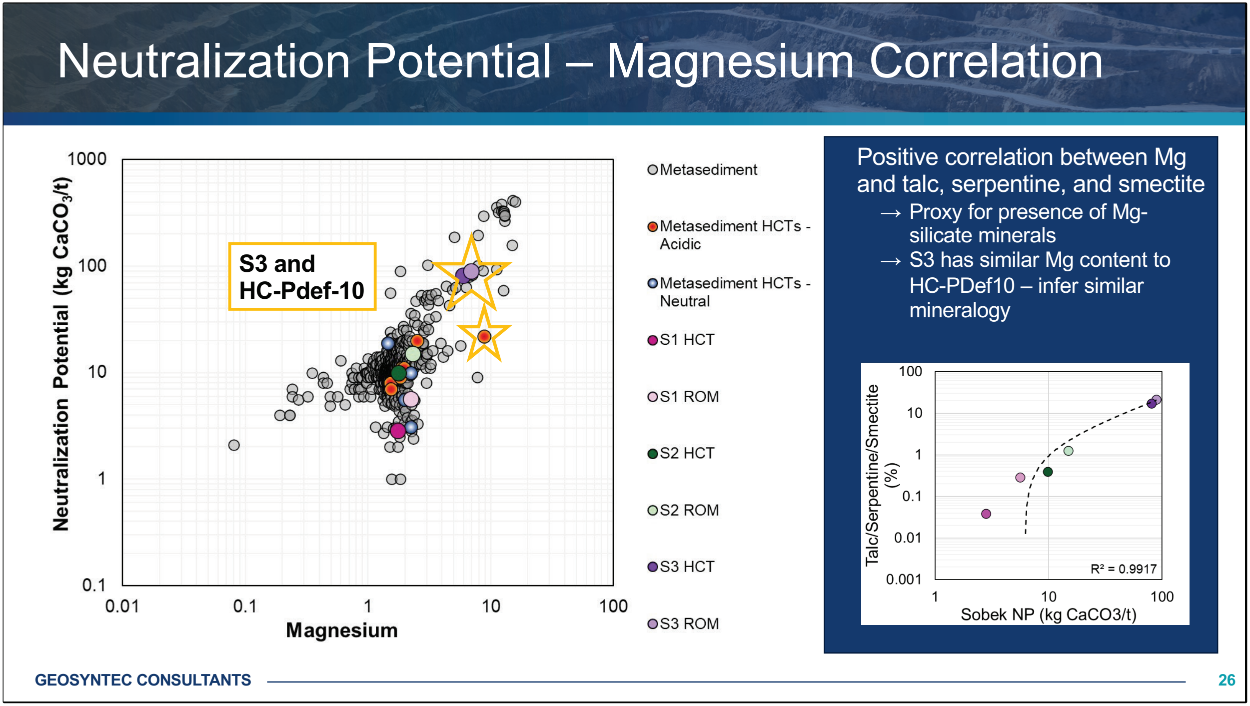


Let's point out our anti-heros on this slide…. Metasediment Sample Pigeon HC-Pdef-10 – NP/AP 2.67 – generated acidity during humidity cell testing. This sample has a higher NP than most metasediment samples. Similarly, S3 has an elevated NP within the metasediment dataset.

To make a long story short, because we are running short on time, we identified a clear trend in the metasediment dataset, where a population of samples with Mg concentrations also had high NP/AP values
This group of samples broadly didn't fall into the same data cloud as the rest of the metasediment samples. Sample PDef10 and S3 fall into this population.

To answer the obvious questions:

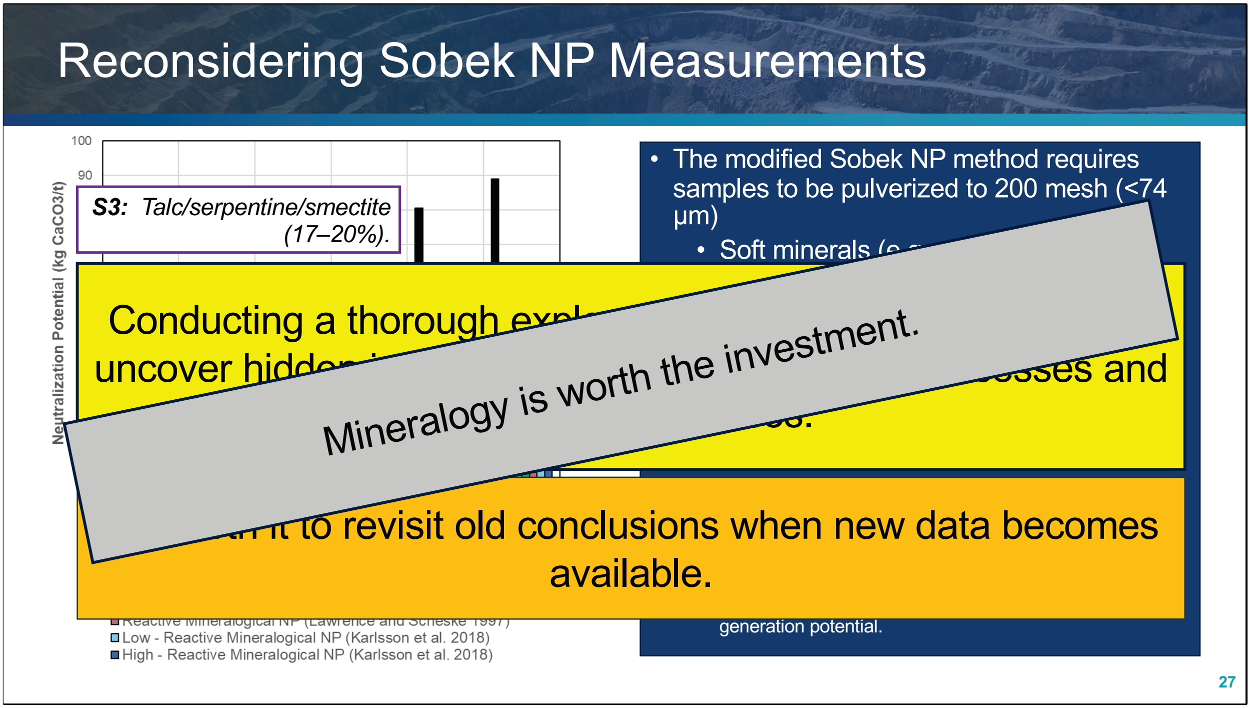
- No, there was no duplicate material of the original sample PDEF10 sample
- Yes, PDEF10 underwent mineralogical analysis, but it was XRD – bluntly not the greatest data, very poor mineral resolution, etc.



Taking this one step forward, we identified a nice positive correlation between talc, serpentine, and smectite minerals in the ENP samples

Why this matters is because we don't have great mineralogy data or frankly, ANY mineralogy samples for most of the samples in the Ekati Mine dataset. We wanted to identify a proxy for the presence of presence of magnesium-silicate minerals in samples without mineralogical context.

Magnesium seemed to be a good proxy for the presence of these minerals



Because we have the benefit of extensive mineralogical analysis for the ENP dataset, we know that sample S3 in particular had unique mineralogical characteristics – in particular that elevated talc / serpentine content.
ANIMATION 1

Those soft minerals are more susceptible to pulverization – in the context of the Sobek NP test, the first step of that test is a fizz test. If the soft minerals are overly pulverized, they may “overly fizz”, which will alter the amount of acid that is added during the titration step of the NP procedure… and may result in overestimates of NP.

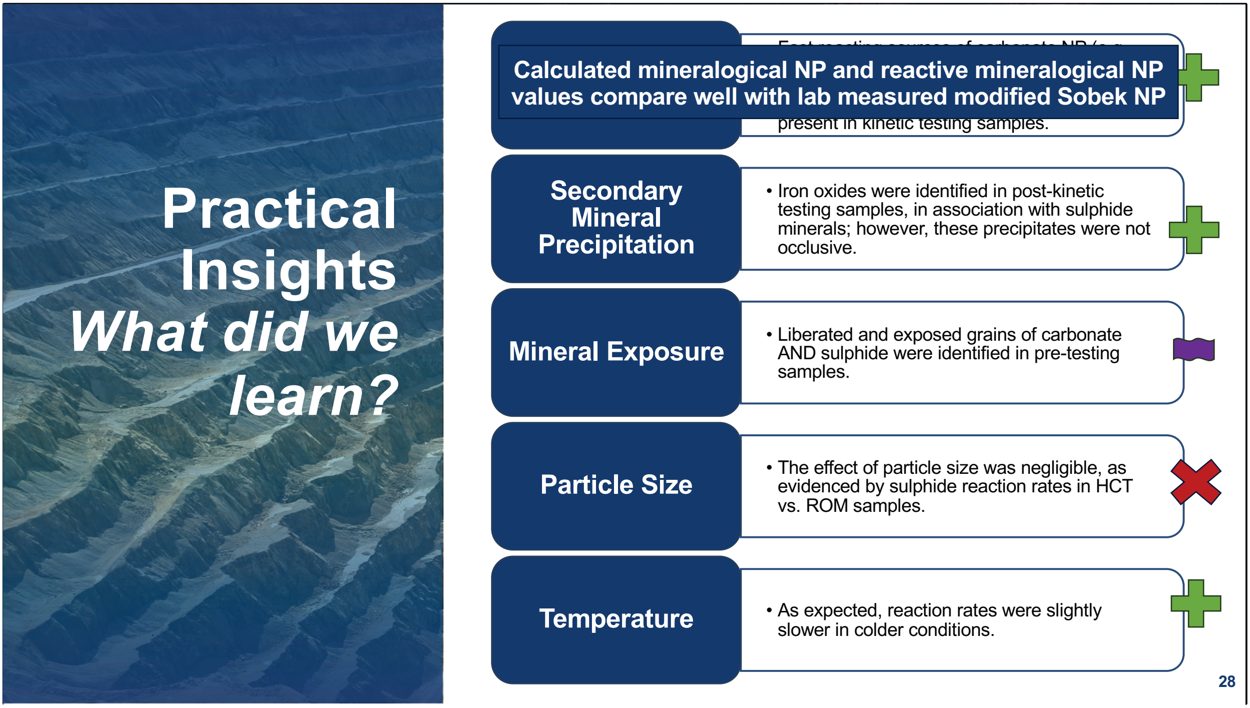
While I don’t touch on it in this presentation, we used this finding to calculate a correction factor for Sobek NP measurements in those samples in that high Mg population. When these correction factors are applied, an NP/AP of 2 is an accurate predictor of long-term acid generation potential with respect to kinetic test results.

So… what did we learn?

Animation 2

Or… Animation 3

Or… Animation 4



So, lets wrap this up.

What did we learn?

Waste Rock Properties and Testing:

- Waste rock properties are influenced by complex processes.
- Laboratory tests help accelerate testing and simplify understanding.
- Acid neutralizing potential (ENP) tests serve as a guide but may not be precise.
- Mineralogical controls play a significant role

•Mineralogical Composition:

- Comparing mineralogy between Ekati Mine and ENP datasets is challenging due to different measurement methods, but we were able to use the available information to confirm the conceptual model for ENP.
- Fast-reacting carbonate minerals (calcite, dolomite) and slower-reacting silicate minerals (albite, amphibole, etc.) are observed.

1.Secondary Mineral Precipitation:

1. We confirmed that Iron oxide, clays, and sericite may form during sample reaction or weathering.
2. Iron oxides were detected in post-kinetic testing samples, and they occurred alongside sulphide minerals.
3. While iron oxides could potentially slow sulphide reactions if they fully encapsulate sulphide minerals, their influence on ENP is unlikely due to their mineral association.

1.Mineral Exposure:

1. Pre- and post-kinetic testing mineralogy results confirmed the reaction of liberated and exposed carbonate grains.

2.Particle Size:

1. Laboratory modified Sobek NP measurements did not correlate with particle size and we did not see a particle size effect in kinetic test results.

3.Temperature:

1. Sulphide reaction rates were lower in cold temperature kinetic tests compared to room temperature tests.
2. Temperature plays a role in mineral weathering and reactivity.

Key Findings

Detailed mineralogical analysis is recommended for comprehensive interpretation of kinetic test results.

- Pre-testing mineralogical analysis identified the presence of high Mg, minerals that influenced the interpretation of laboratory measured modified Sobek neutralization potential.

Silicate minerals play an important role in ENP in low-carbonate rocks with low sulphide content.

- Low-sulphide rocks can generate net acidity when NP is insufficient.
- Slowly reacting silicate minerals are capable of neutralizing acid production from low-sulphide rocks.

Understanding the relationship between sulphide mineral reaction rates and carbonate/silicate NP is crucial.

- Geochemical classification criteria should be site-specific and suitable for the environmental goals of the ML/ARD management plan.

For this dataset, after NP measurements were corrected, NP/AP = 2 accurately predicted outcomes in the context of kinetic test results.

Mineralogy needs to be performed as a road map for kinetic test results. For this project, we performed extensive mineralogical analysis because we had to answer complex questions. For most projects, a comprehensive quantitative analysis of bulk mineralogy should be sufficient.

Silicate minerals can be an important component of ENP in low sulphide rocks. BUT being able to QUANTIFY and EXPLAIN that relationship in a clear and concise manner is necessary, particularly when you are trying to defend site specific conceptual models of reactivity.

And for this dataset, after we used the various lines of evidence to correct data that had anomalous laboratory NP measurements, an NP/AP of 2 indeed accurately predicted outcomes in the context of kinetic testing results.

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Thank you!