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# Troilus Gold-Copper Mine Site, Québec - Updated and Corrected ML-ARD Predictions Requiring Multi-Faceted and Integrated Studies


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# Additional Contributors

- This collaborative effort involved many people who could not all be added as co-authors.  They include the following.

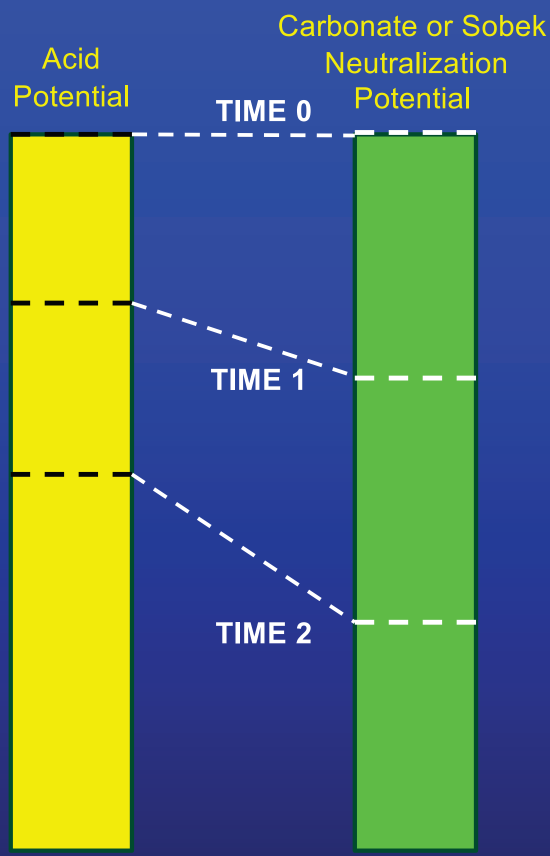
  - Troilus Gold’s team at the minesite particularly Mathieu Michaud.
  - Cheng Huang, Liang Ma, Simon Liu, Elton Gu, Colin Sun, Weimin Qian, Jianqin Zhou, and Rina Siu at NRC Canada
  - The Coalia research centre in Québec particularly Jean-François Grenier.
  - Valuable detailed technical comments and discussions were provided by Dr. Bill Price of Natural Resources Canada, by Francisco Ruiz Allén of Congeo consulting in Spain, and by anonymous ICARD conference reviewers.

# Something to Think About

- With the knowledge that standard prediction methods for ML-ARD are typically reliable when done correctly (Price, 2009), how much additional work should be done to detect the small percentage of cases where standard methods are misleading or wrong?
  - Price, W.A. 2009. Prediction Manual for Drainage Chemistry from Sulphidic Geologic Materials. Canadian Mine Environment Neutral Drainage Report 1.20.1, Natural Resources Canada, dated December 2009

- For example, if 1 to 2% of minesites have their ARD potential on large scales overestimated and exaggerated by standard methods, should a large, expensive amount of additional prediction/assessment work be done in advance to determine if a particular site is part of this 1 to 2% exception?

# "Standard" Conceptual Model for Predicting ARD with Static Testing as Acid Potential (AP) and Neutralization Potential (NP) are Consumed

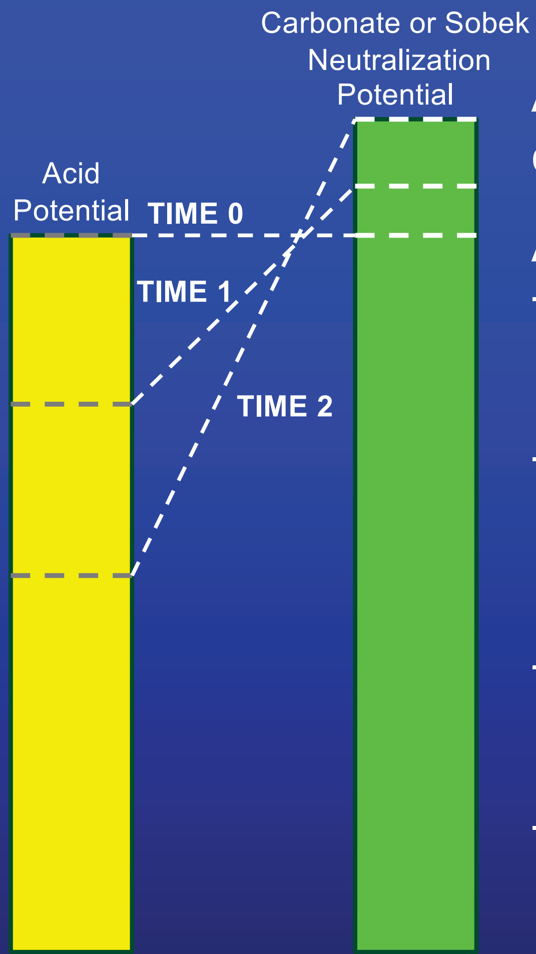



According to the "standard" conceptual model, Acid Potential generates acidity and Neutralization Potential responds by neutralizing acidity to above ~pH 6.0.

Neutralization Potential is typically consumed proportionally faster than Acid Potential (e.g., NP/AP ~ 2.0)

The one Potential that outlasts the other "wins the geochemical battle" of ARD vs. near-neutral drainage.

# Passive Capture and Storage of Atmospheric CO2 by Mine Wastes, Accompanied by Ongoing Sulphide Oxidation and Acid Generation

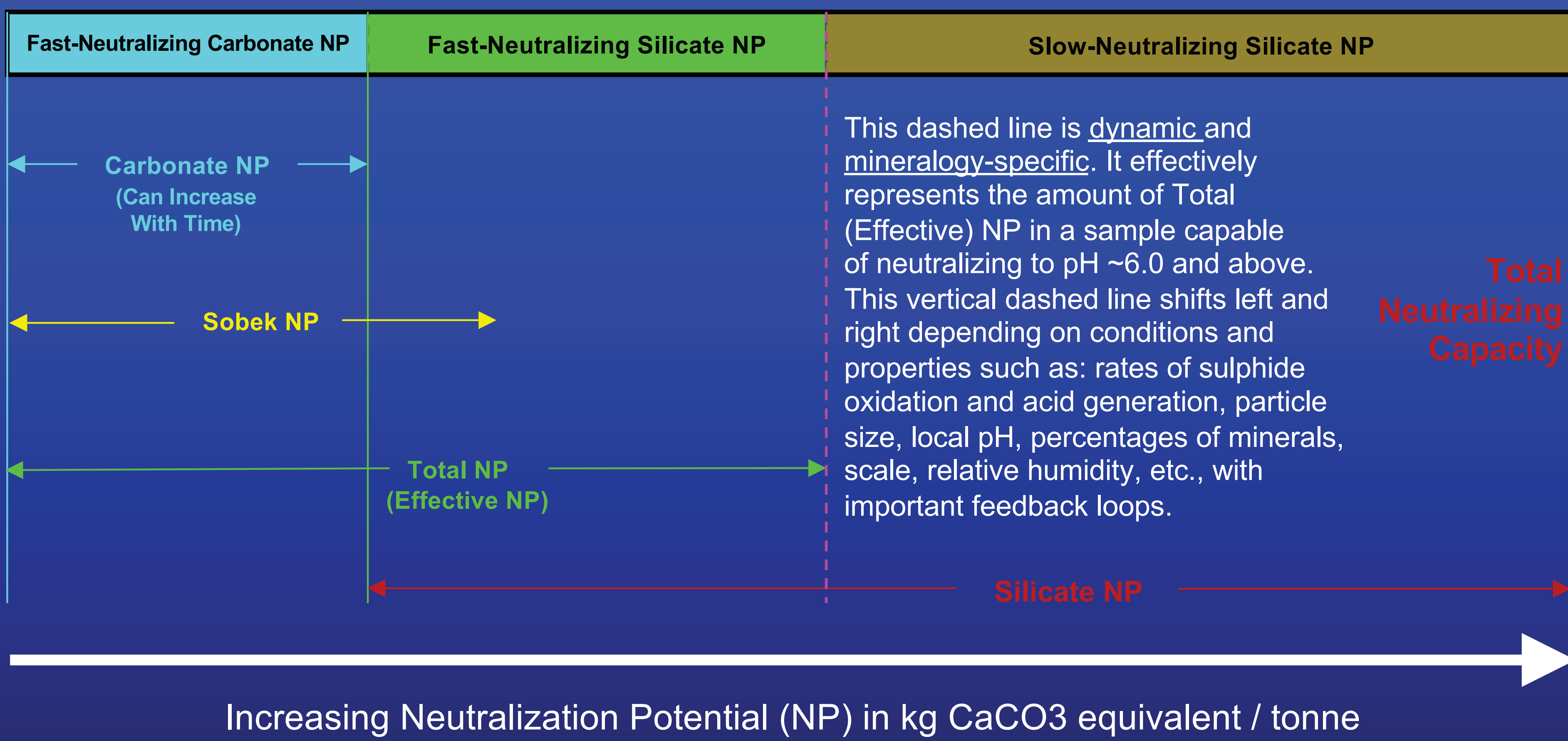



A less common conceptual model exists for a small percentage of minesites, perhaps only 1% to 2% (not a verified estimate).

As a kinetic generalization, we have found:

- There is a site-specific “moderate” rate of sulphide oxidation that stimulates and accelerates dissolution of certain silicate minerals, which in turn creates carbonate NP.
- There is a site-specific “higher” rate of sulphide oxidation that exceeds the dissolution rate of the site-specific silicate minerals. This leads to the consumption of carbonate minerals and thus possibly to ARD after a lag time. This is the “standard” situation for most sulphidic minesites.
- There is a site-specific “lower” rate of sulphide oxidation that can either (1) be too low to activate silicate neutralization and thus can allow ARD or (2) remain sufficient to neutralize and to maintain carbonate NP.
- Thus, sulphide oxidation can be a hindrance or a benefit to the capture of CO2 and the formation of carbonate NP. This is not recognized in many passive-CO2 capture studies of mine rock and tailings.

# ML-ARD Systems with Significant Silicate Neutralization Potential (NP) – Conceptual Model and Terminology adjusted to Static Testing



# Anomalous ARD Predictions and Occurrences at Minesites in the Past – a Literature Review

## Literature Review

- In summary, ARD characteristics of these rare, anomalous minesites include:
  - ABA results indicate ARD should appear quickly and be widespread, but no full-scale ARD is detected at sites over decades.
  - Small-scale kinetic tests produce ARD within a year or two, although no full-scale ARD is detected on site after decades.
  - Calcite and carbonate minerals represent a minor portion of Total (Effective) NP, with ongoing weathering of rock apparently producing small amounts of carbonate detected by ABA.
  - Laboratory-measured Neutralization Potentials (NP) such as by the U.S. EPA 600 (Sobek) method are relatively the same among samples and do not change significantly after years to decades of weathering.
  - Aqueous alkalinity can be accounted for by ingassing of atmospheric carbon dioxide (atmospheric CO2 capture).

# Literature Review

- (Continued) In summary, characteristics of these rare, anomalous minesites include:
  - Minerals like biotite, magnetite, and epidote theoretically contribute substantially to Silicate NP, but apparently are not reacting sufficiently fast to provide much Fast-Neutralizing Silicate NP.
  - Plagioclase series minerals provide much of the Fast-Neutralizing Silicate NP. Calcium released from plagioclase is proportionally more effective at CO2 capture as less-soluble calcite than more-soluble magnesite and dolomite from non-plagioclase magnesium silicate minerals.
  - Acid-generating sulphide minerals are primarily pyrite and pyrrhotite with some chalcopyrite and molybdenite, and their levels range from relatively small amounts (<~0.1%S) up to ~5%S.
  - Rates of sulphide oxidation and acid generation at these sites are low based on (1) aqueous sulphate concentrations and (2) comparisons to approximately 700 humidity cells at 90 sites in the International Kinetic Database.

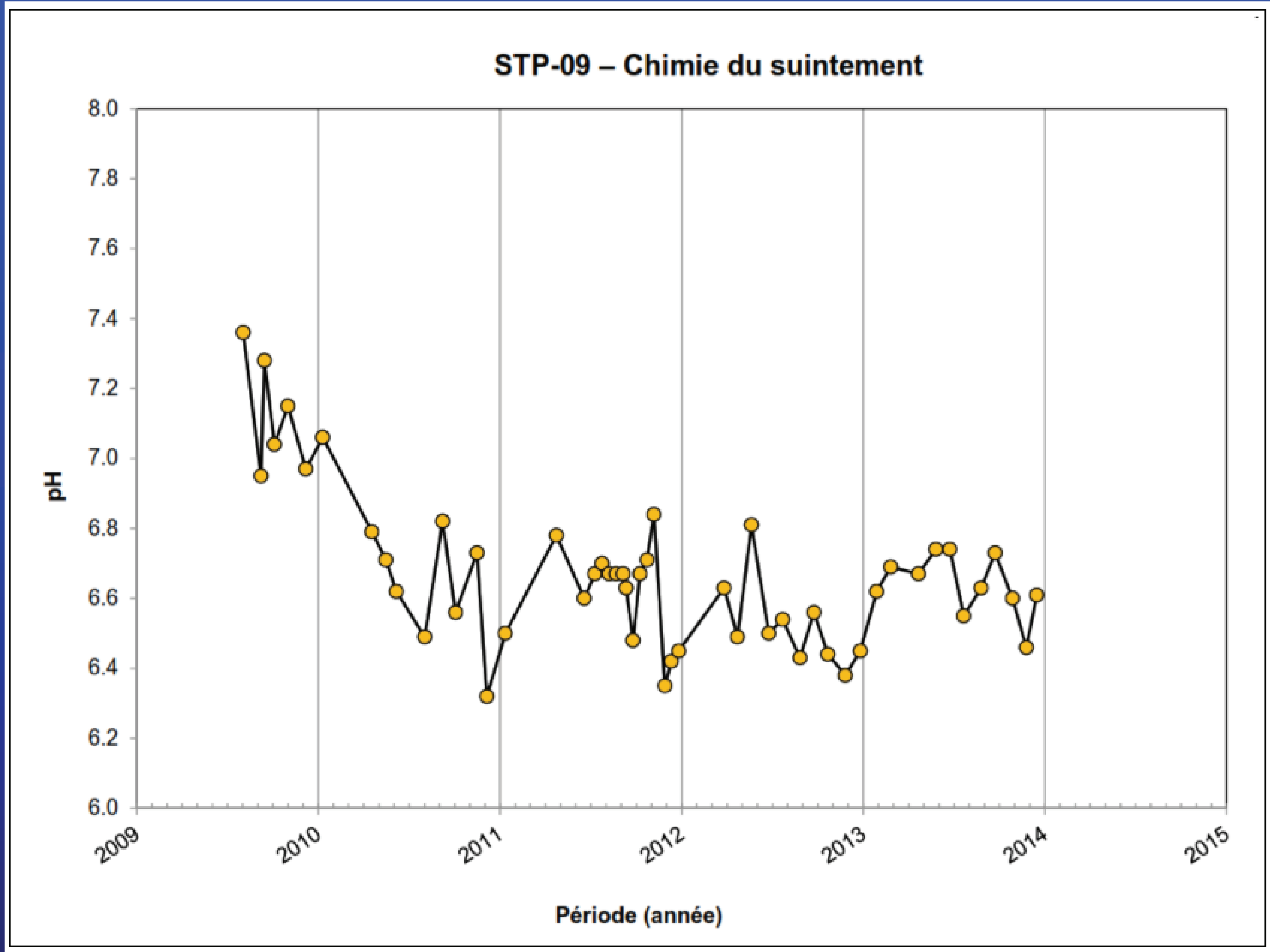
# The Troilus Gold Site


# The Troilus Site

- The currently inactive Troilus gold-copper-silver minesite is located near Chibougamau, Québec.
- From 1996 to 2010, Inmet Mining mined two ore zones known as “J4” and “87”, producing approximately 77 million tonnes of ore/low-grade ore, 135 million tonnes of waste rock, and 18 million tonnes of overburden.
- Troilus Gold Corp. purchased and intends to re-open the mine, with major expansions of the J4 and 87 Zones plus the addition of two new zones named Southwest or “SW” and X22.
- Gold-copper mineralization occurs mainly on the physical boundary of the Troilus Diorite (metadiorite, also reportedly appearing as gabbro), and within breccias, amphibolite, and quartz - chlorite (±tourmaline) felsic vein swarms.

# The Troilus Site

- When mining at Troilus stopped in 2010, full-scale drainage pH decreased quickly from ~7.4 down to ~6.4. ARD was expected in a year or so. An ARD management plan was created after effluent pH decreased.
- In 2011, the pH stopped decreasing.
- In 2024, there is no ARD and pH remains around 6.5.



# The Troilus Site

- At Troilus, many decades of pre-mining, intra-mining, and post-mining ARD studies using standard predictive criteria have predicted:
  - ARD from nearly all rock after lag times of a few to several years, and
  - ARD from some rock after a lag time of up to 1,500 years, and
  - no ARD at any time.

- Decades later, no full-scale ARD is detected, and only limited ARD drains from a few smaller-scale kinetic tests at Troilus. This is like other case studies where ARD on a small scale can be detected, but ARD is not detected on a full scale even after many decades.

- Such past ambivalent and even contradictory ARD predictions are not acceptable for re-opening Troilus, especially in a jurisdiction where basal liners can be required before mining starts, for mine materials expected to release ARD at any time (even after 1,500 years). Our co-authors, Jacqueline and Ann, decided a few years ago that research was needed to resolve and clarify this.

# The Troilus Research Study for Reliable ML-ARD Predictions

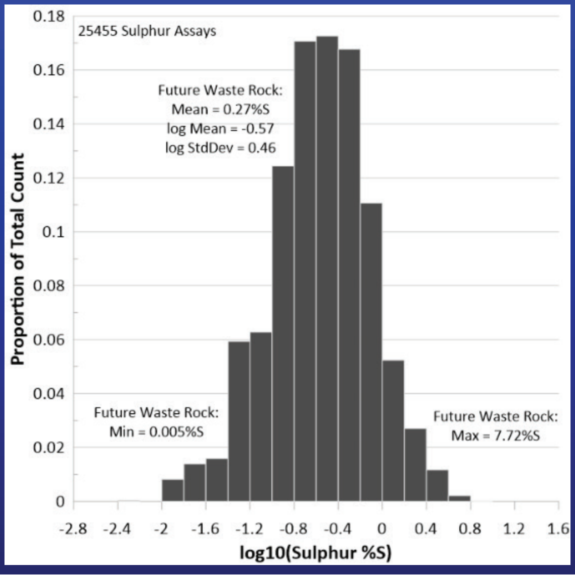
# The Troilus Research Study for ML-ARD

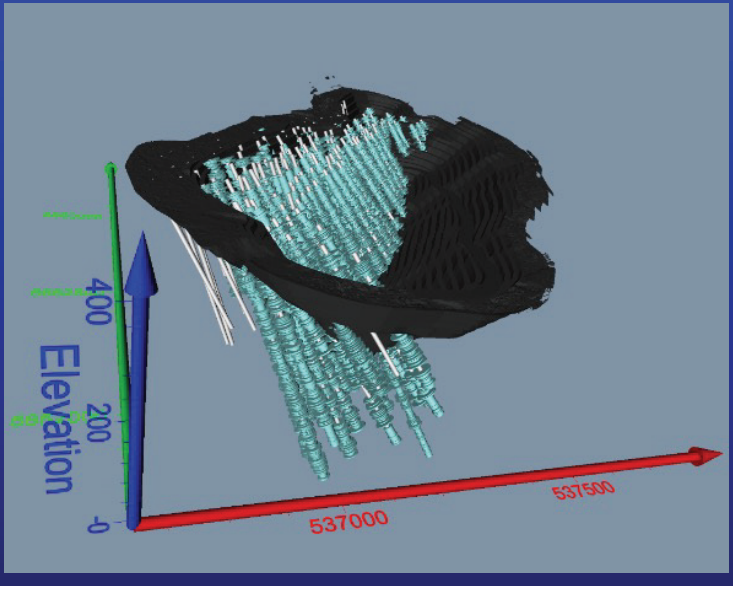
- This table shows the methods and results for predicting ARD at Troilus since 1990. As shown in the bottom row, the resolution of the contradictory ARD predictions at Troilus has required integrated research-level studies since 2021, including many major test methods.

| Year | # Samples | Predicted ARD? | ABA | Total Element | Mineralogy | NAG | Leach /Flask | Lab Kinetic | Field Kinetic | Full-Scale Monitoring |
|---|---|---|---|---|---|---|---|---|---|---|
| 1990-1992 | 68 | Some; uncertain | Y | Y | | | | | | |
| 1993 | 123 | None | Y | | | | Y | | | |
| 1995 | 191 | Minor | Y | | | | | | | |
| 1998 | 36 | Major | Y | | | | | | | |
| 1998– 2000 | 37 | Major, after 8 years | Y | Y | | | | Y | | |
| 2003 | 4 | Minor | | | | | | | | |
| 2004 | 12 | Minor | Y | | | | | | | |
| 2004-2005 | 106 | Significant, after decades | Y | Y | | Y | | | | |
| 2011 | 72 | Uncertain; some | Y | Y | | | | | | |
| 2019– 2021 | 56 | After 1500 years | Y | | | | | Y | | Y |
| **2021– 2025** | **120 + 158,000 core intervals** | **Minor** | **Y** | **Y** | **Y** | | **Y** | **Y** | **Y** | **Y** |

# The Troilus Research Study for ML-ARD

- Interpretations of decades of on-site monitoring of full-scale water chemistry.
- On-site kinetic tests holding up to about 300 kg of various rock units. This includes 11 columns containing fresh drill core, and two columns of existing 13- to 26-year-old J4 waste rock with one quickly releasing ARD and one releasing ~pH 6.0 to 7.0.
- Dozens of carefully selected core intervals based on sulphur geostatistics from ~158,000 sulphur assays, the dominant rock units, and 3D spatial distributions.
- Several types of laboratory kinetic tests including 23 past and recent humidity cells. In most kinetic tests, aqueous calcium was the major cation released on a molar basis.



# The Troilus Research Study for ML-ARD

- Multi-faceted and integrated mineralogy including:
  - visual mineralogy and petrographics,
  - x-ray diffraction (XRD),
  - scanning electron microscopy with energy dispersive x-ray spectroscopy (SEM-EDX),
  - microscopic Raman spectroscopy, and
  - thermogravimetric analyses (TGA).
- This mineralogical work includes the updated 2021 USGS RockJock x-ray-diffractogram library, the Raman Renishaw's Library backed up by visually assessed spectra developed for the Perseverance Rover on Mars, and mineral-specific Calcium Molar Ratios (Ca / Ca+Na) using SEM/EDX. Due to site-specific mineral imperfections and variabilities, a Troilus-specific mineral ID database was created for the above methods.

- Measurements of sulphide-oxidation rates along with $CO_2$ release and uptake by rock. This includes custom oxygen-consumption (oxycon) and $CO_2$-capture testing in sealed chambers with elaborate and special air-leak prevention due to the slow rate of sulphide oxidation in Troilus rock. Inward leaks of air, due to the consumption of $O_2$, humidity, and $CO_2$, and the resulting partial vacuums, typically lead to significant underestimations of rates for both oxidation and $CO_2$ capture, and this was given special attention for Troilus testwork.

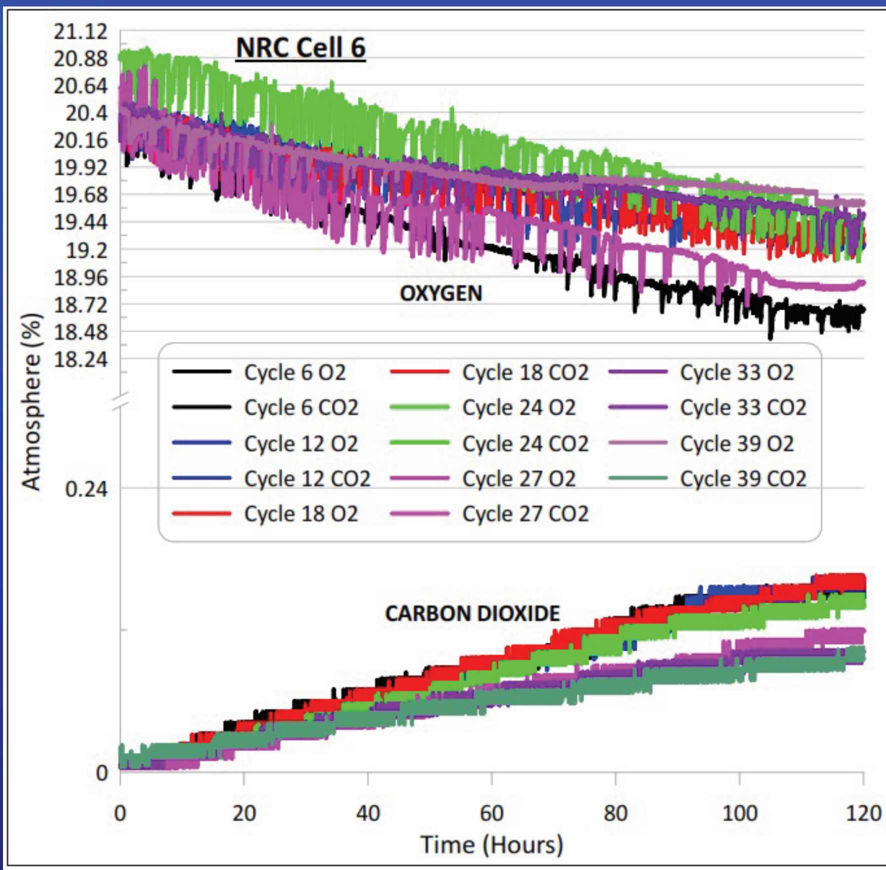
- Compilations of published silicate-mineral stoichiometry and reaction rates in various pH ranges.

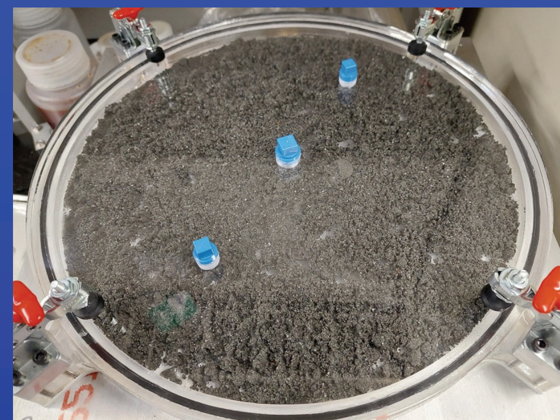
# Examples of Troilus Multi-faceted Testing

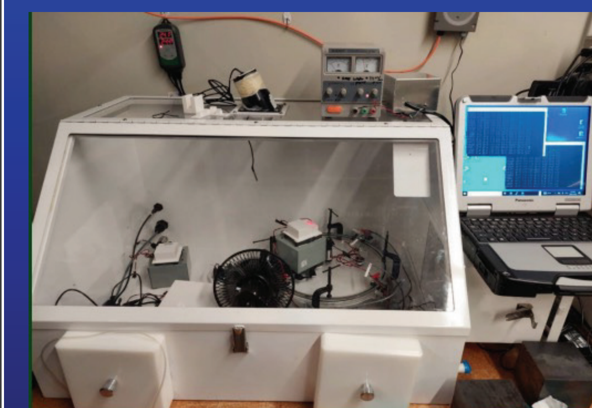
# Examples of Multi-faceted Testing – Oxycon & CO2

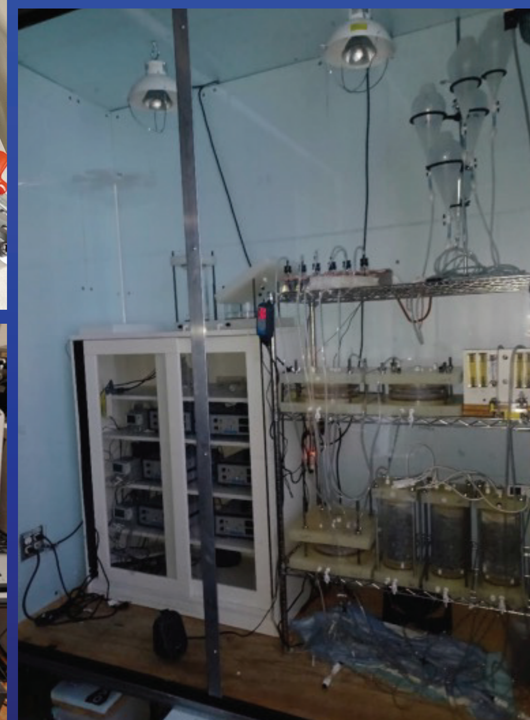
## *National Research Council Canada*

Custom-designed oxycon and CO2 testing with special leak detection, operating in cycles for more than a year.







## Examples of the Multi-faceted Testing – Mineralogy

*National Research Council Canada and Ultra Petrography and Geoscience Inc.*

- Three-dimensional optical microscopy: critical for integrating the other mineralogical techniques.
- Petrography: characterization of Troilus rock, mineralogy, composition, texture, structure, and estimated conditions of formation, using light, filters, and polarization; typically requires polished thin sections.
- X-Ray diffraction: structures of mineral crystals observed as diffraction patterns of x-rays by surface atoms; a bulk mineralogical method for non-polished samples.
- Raman microscopy: chemical-bond vibration energy observed as emitted light frequencies; can focus on individual particles that are not polished.
- SEM/EDX: atomic composition observed as intensity and energy of x-ray fluorescence by atoms.
- Thermogravimetric analysis: the mass of a sample measured over time as the temperature changes, focused on thermal decomposition of certain minerals at specific temperatures during heating.

# Examples of the Multi-faceted Testing – Mineralogy

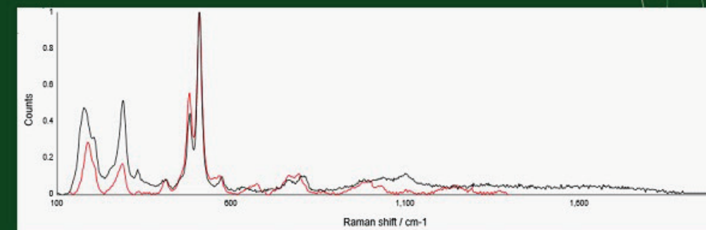
*National Research Council Canada and Ultra Petrography and Geoscience Inc.*

Several mineralogical methods were used on individual mineral particles to ensure proper identification and to build a Troilus-specific mineral ID library.

NOTE: Due to 3D variations in mineral-particle contacts, the depth of detection for each method could result in the identification of differing minerals at the same point.

## SPOT 2

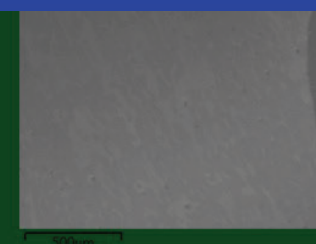

## RAMAN SPECTRA

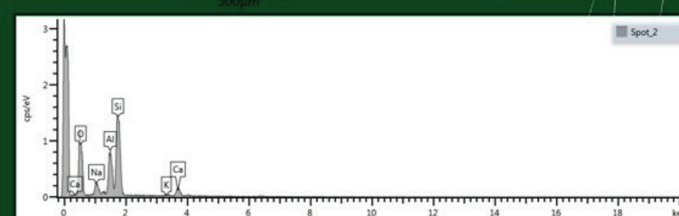



| Material index | Quality | Library name | Material name | Molecular formula | Spectrum | User controls |
|---|---|---|---|---|---|---|
| 443 | 0.805372 | Inorgan | Oligoclase (sunstone) (Feldspar group, An10-30) | | | i |
| 498 | 0.802983 | Inorgan | Oligoclase (Feldspar group - An10-30) | | | i |
| 899 | 0.744615 | Inorgan | Labradorite (Feldspar group, An50-70) | | | i |

## SEM – EDS RESULTS

| Element | Wt % | Wt% Sigma |
|---|---|---|
| O | 54.10 | 0.55 |
| Na | 4.90 | 0.26 |
| Al | 12.49 | 0.30 |
| Si | 24.80 | 0.40 |
| K | 0.42 | 0.12 |
| Ca | 3.29 | 0.17 |
| Total | 100.0 | |





# Some Major Lessons and Improved Predictions from the Integrated and Multi-Faceted ML-ARD Studies at the Troilus Site

"… emergence occurs when a complex entity has properties or behaviors that its parts do not have on their own, and emerge only when they interact in a wider whole."

# Major Geochemical Processes at Troilus Often Incorrectly Studied Separately

## Silicate-Mineral Dissolution

Silicate minerals dissolve into water at highly variable rates, from very fast to very slow, and neutralize from large amounts of acidity to none depending on their stoichiometry and solid-phase concentration. Most studies of this dissolution are done under controlled laboratory conditions using single and pure minerals. This is not representative of most multi-mineral waste rock and tailings.

Positive ("good") and negative ("bad") feedback loops and interactions

All Three Combined: e.g.,

**Troilus Gold-Copper Minesite**

Positive ("good") and negative ("bad") feedback loops and interactions

## Sulphide-Mineral Oxidation

Sulphide minerals like pyrite and pyrrhotite can oxidize under near-surface conditions at variable rates from fast to slow e.g., due to spatial zonation and impurities, resulting in acid generation. Most ARD studies focus on neutralization by carbonate minerals and the related measurements like Sobek Neutralization Potential (NP). This is correct for most minesites, but not all.

Positive ("good") and negative ("bad") feedback loops and interactions

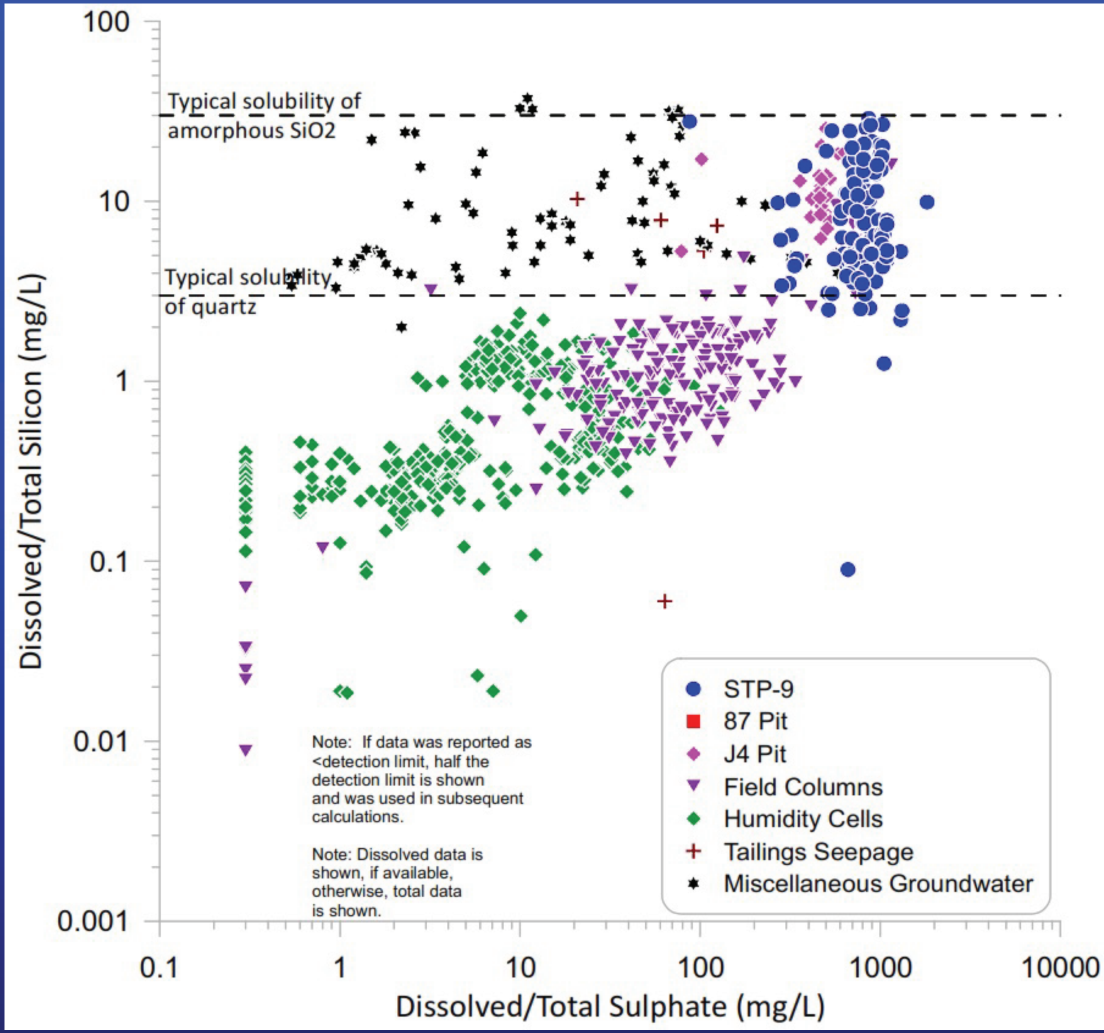
## Passive CO2 Capture

Certain silicate minerals and certain combinations can quickly capture gas-phase CO2 and store it as carbonate minerals. However, nearly all such studies are done in laboratories, using pure silicate minerals which is incorrect for most multi-mineral waste rock and tailings. Calcium minerals are more effective at CO2 capture than magnesium. The FluidFlower research program in Norway shows that CO2 capture involves some mechanisms not yet well understood.

# Major Lessons and Improved Predictions

- At scales up to ~100 kg, analyses of aqueous silicon indicated dissolution of the silicate minerals was relatively slow, rarely reaching the solubility of quartz at ~3 mg Si/L.

- Most full-scale monitoring locations at Troilus produce aqueous silicon between the solubility of quartz and amorphous SiO2, up to ~30 mg/L, indicating silicon on the full site scale is more active.

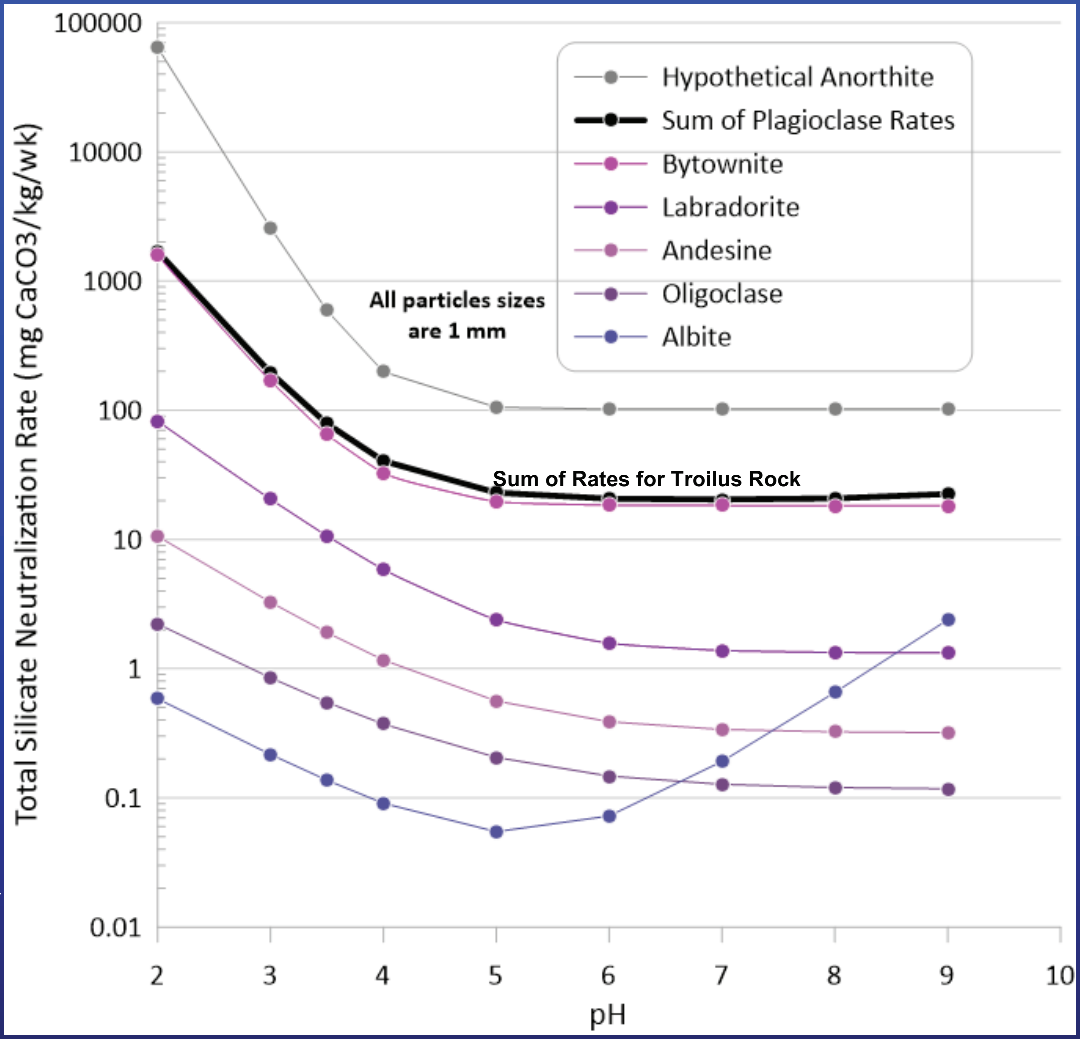


# Major Lessons and Improved Predictions

- The plagioclase series of minerals, from sodium-rich albite to calcium-rich anorthite, make up more than 50% of the dominant waste rock at Troilus, although anorthite is not regularly detected in Troilus rock.

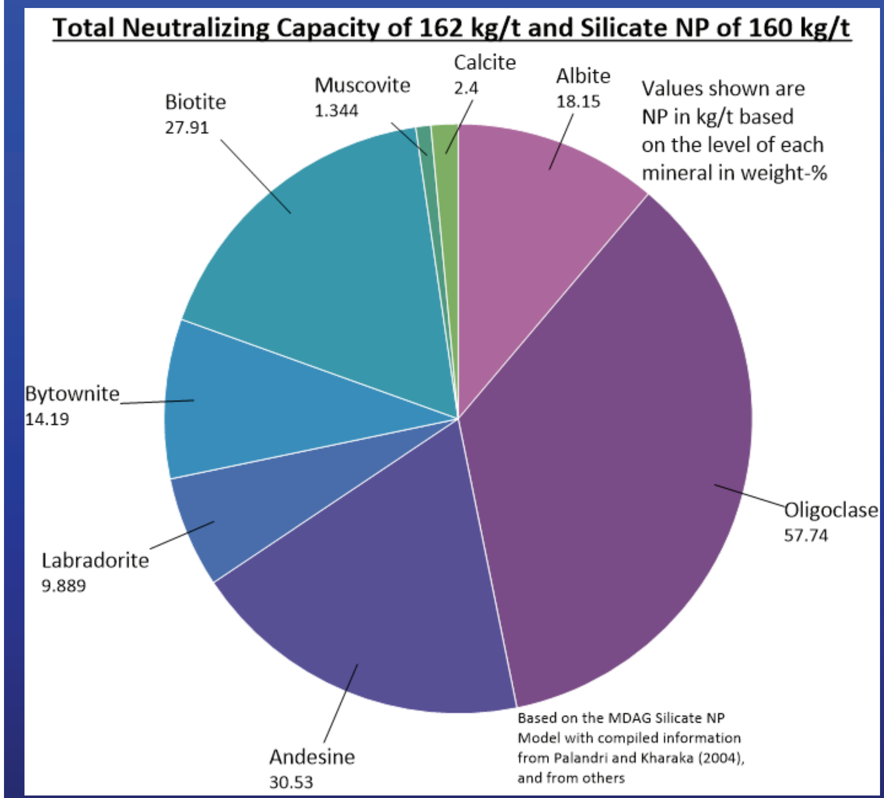
- Usage of one member for the entire plagioclase series, or of a single average value for calcium:sodium, can lead to ARD prediction errors.

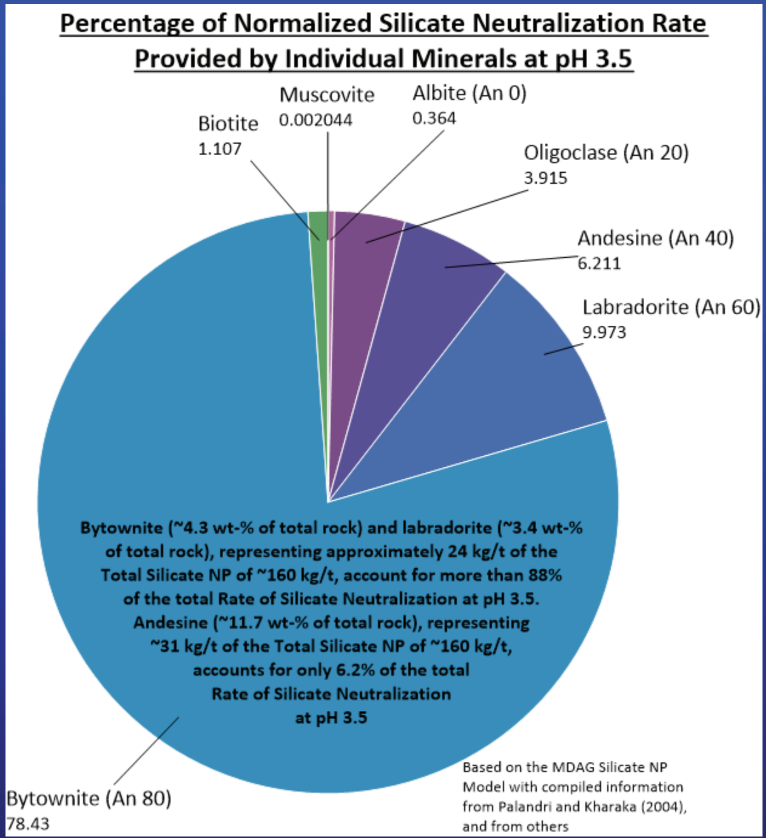
- Although the plagioclase series is typically divided into six minerals or elemental ranges, it is (1) a near-continuum of sodium to calcium with heterogeneities like spatial zonation and alternating lamellae, (2) relatively slow to relatively fast dissolving and neutralizing, and (3) pH dependent with lower acidic pH leading to faster neutralization.



# Major Lessons and Improved Predictions

- Therefore, it is not the solid-phase amounts (left diagram) that directly determine Fast-Neutralizing Silicate NP. Instead, the orders-of-magnitude variations in reaction/neutralization rates, adjusted for the solid-phase levels of each, primarily determine the Fast-Neutralizing Silicate NP (right diagram). Thus, bytownite accounts for 78% of the rate and the Fast-Neutralizing Silicate NP, and labradorite accounts for 10%.



# Major Lessons and Improved Predictions

- This Troilus rock has a Carbonate-NP-based Net Potential Ratio (NPR = NP/AP) of only 0.3 and is thus normally predicted to release ARD.  This is why some ARD studies at Troilus predicted widespread ARD.

- However, when the Fast-Neutralizing Silicate NP is added to obtain Total NP, the resulting NPR is 1.9 relative to the Troilus NPR criterion of 1.0 for ARD based on kinetic testing.  Thus, no ARD is predicted from this rock.

# Major Lessons and Improved Predictions

- These observations lead to several complex observations and predictions due to (1) the three main geochemical processes and their positive and negative feedback loops and (2) the highly nonlinear pH-dependent neutralization rates of the plagioclase series.

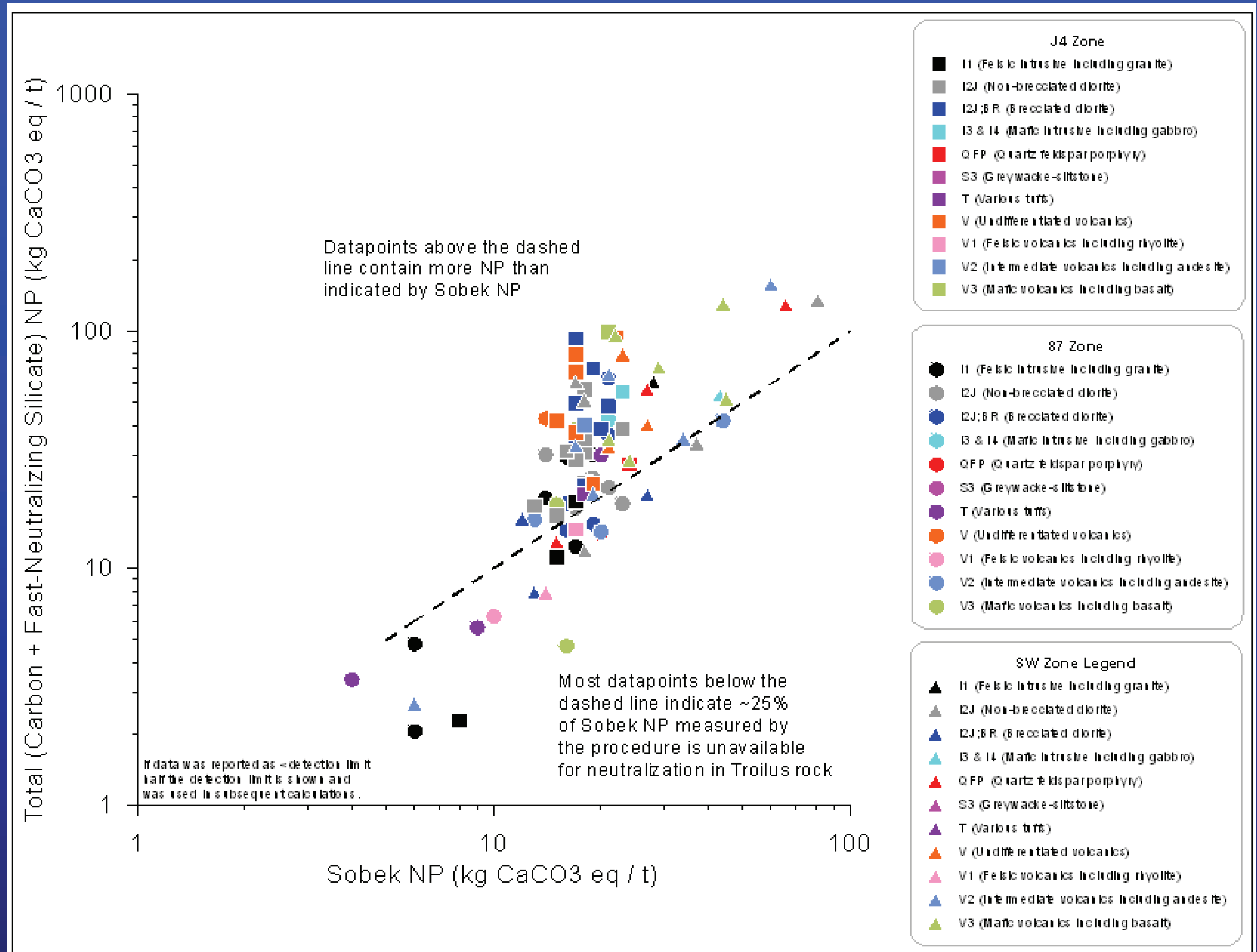
- Here is an example. If sulphide oxidation in Troilus rock resulted in a lower internal, particle-scale pH, then the Silicate Neutralization Rate would increase because the dissolution rates of all the plagioclase would accelerate. In turn, the amount of Fast-Neutralizing Silicate NP and the Net Potential Ratio (NPR=NP/AP) would increase to neutralize the lower-pH ARD. For example, andesine dissolving faster at a lower particle-scale pH could add another 31 kg/t of Fast-Neutralizing Silicate NP and increase the rock's NPR to 4.0.

- As another example, sulphide oxidation leads to significant weight gain for a solid-phase sample, and also creates partial vacuums in the gas phase and depletes water contents. Thus, a decreasing solid-phase dry-weight-% or ppm (that is, the weight ratio of the component to total sample weight) of carbonate through time could mean the mass of carbonate is actually steady or slightly increasing as the mass of the sample increases. Thermogravimetric analyses can help with this.

# Major Lessons and Improved Predictions

In Troilus rock, Sobek NP rarely rises above 30 kg/t, mostly due to the “fizz test” that assumes only the carbonate neutralizes. However, many Troilus samples have much more Total NP than 30 kg/t due to Fast-Neutralizing Silicate NP calculated from a site-specific six-step procedure.

In turn, this causes Total-NP-based TNPR in Troilus rock to be higher than Sobek TNPR for most <u>but not all samples</u>.



# Something to Think About

- Because this is a Workshop, we have a forum to raise and discuss important issues.

- With the permission of Dr. Bill Price, this presentation raises the question: *how much additional ML-ARD work should be done at a site*
  - *to determine if standard ML-ARD prediction rules do or do not apply to it, and*
  - *to ensure ML-ARD predictions are reliable on all scales?*

- Many thanks to Troilus Gold Corp. for allowing us to use their site and research study as a case study!

## Additional Sources of Information

- For more technical and scientific information, please see:
  - The 2024 ICARD paper, *Predictions of ARD Potential Dominated by Silicate Neutralization Potential at the Troilus Gold-Copper Mine Site*, Québec, Canada, and
  - *Prédiction du drainage minier acide contrôlé par le potentiel de neutralisation des silicates à la mine Troilus, Québec, Canada*. Québec Mines + Énergie 2024, Novembre 18-21, et
  - The following free Case Studies and documents at www.MDAG.com:
    - *#81: The Complex Nexus of Sulphide Oxidation, Silicate-Mineral Dissolution, and Passive CO2 Capture*
    - *#80: Silicate Neutralization Potential Focussing on Plagioclase, and the MDAG Silicate NP Model.*
    - *a draft version of the 2024 ICARD paper with additional figures and tables not in the final version.*
    - *a greatly expanded, draft version of the 2024 ICARD PowerPoint presentation with additional figures, tables, and explanations not in the final version.*
- About custom testing equipment and procedures, contact the National Research Council of Canada, with an office located at the University of British Columbia.

THE END