Using Mineralogy to Calculate Field Sulphide Oxidation Rates and Delay to ARD for Weathered PAG Rock at the Ulu Project, Nunavut, Canada

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Outline

- Ulu project background
- Concept for using mineralogy to calculate field sulphide oxidation rate and delay to ARD
- Mineralogy
- Sulphide oxidation reaction rate constant calculation
- Delay to ARD calculation inputs and results
- Validation
- Conclusions

Ulu Project Background

- Legacy gold project in Nunavut, Arctic Canada

- Currently undergoing reclamation and exploration

- Location is cold and dry:

  – Continuous permafrost

  – Mean annual snowfall = 138 cm, rainfall = 160 mm

  – Mean annual air temperature = –11ºC

  – Mean July air temperature of +12ºC

- Few days of +20 to +30ºC

- Active layer thaws each summer, 2 to 5 m deep

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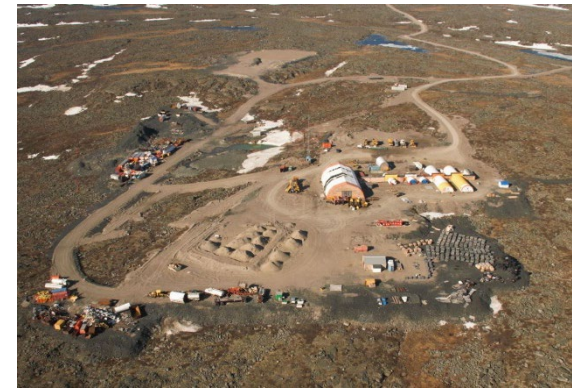
Ulu Project Background

- Archean lode gold deposit

  – Sulphides include arsenopyrite, pyrrhotite, pyrite, sphalerite, chalcopyrite

  – Trace calcite

  – Waste rock is metabasalt

- Advanced underground exploration in 1996

  – Bulk ore sample processed off-site

  – 40,000 to 45,000 m^3 of waste rock at surface in 1 to 2 m thick infrastructure pads and a small waste rock stockpile

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Concept for using mineralogy to calculate field sulphide oxidation rate and delay to ARD

- Delay to ARD needed for reclamation planning

- One historical waste rock HCT but not representative, and data had high DL's

- The infrastructure pads themselves may have recorded the weathering history if a primary mineral weathered to a secondary mineral that was not flushed away

- Field oxidation rate could be calculated if it were possible to quantify the iron oxyhydroxides that had precipitated due to iron sulphide oxidation, on particle surfaces between exposure in 1996 and sample collection in 2020

Concept for using mineralogy to calculate field sulphide oxidation rates and delay to ARD

Conceptually, t(onset) is a function of the rate at which sulphide minerals are oxidized and acid generation occurs (determined from k and AP), the available reactive carbonate minerals (TIC), and how effectively carbonate minerals are utilized in response to acid generation $(TIC/AP)_{crit}$.

- Delay to ARD simplified equation (detailed in Day and Marquez, in press):

Field oxidation rate, usually from kinetic data but here from mineralogy

ABA dataset

Kinetic dataset or seepage data

$$t_{(onset)} = \frac{(TIC/AP)_{current}}{k \, (TIC/AP)_{crit}}$$

Where:
- $(TIC/AP)_{current}$ is the current TIC/AP (total inorganic carbon/acid potential) of the waste rock (unitless)
- k is the sulphide oxidation reaction rate constant (units of year^{-1})
- $(TIC/AP)_{crit}$ is the critical TIC/AP value indicating how effectively carbonate minerals neutralize the acid generated by sulphide oxidation (unitless)
- t(onset) is expressed in years
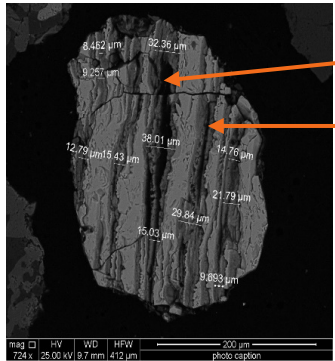
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Broader ML/ARD Characterization
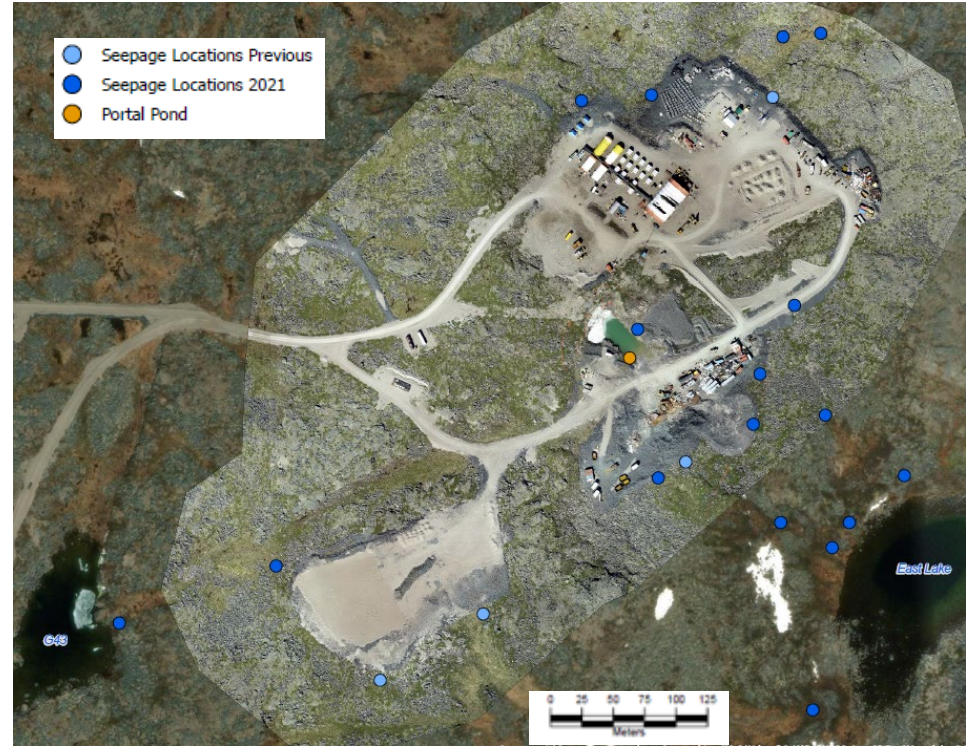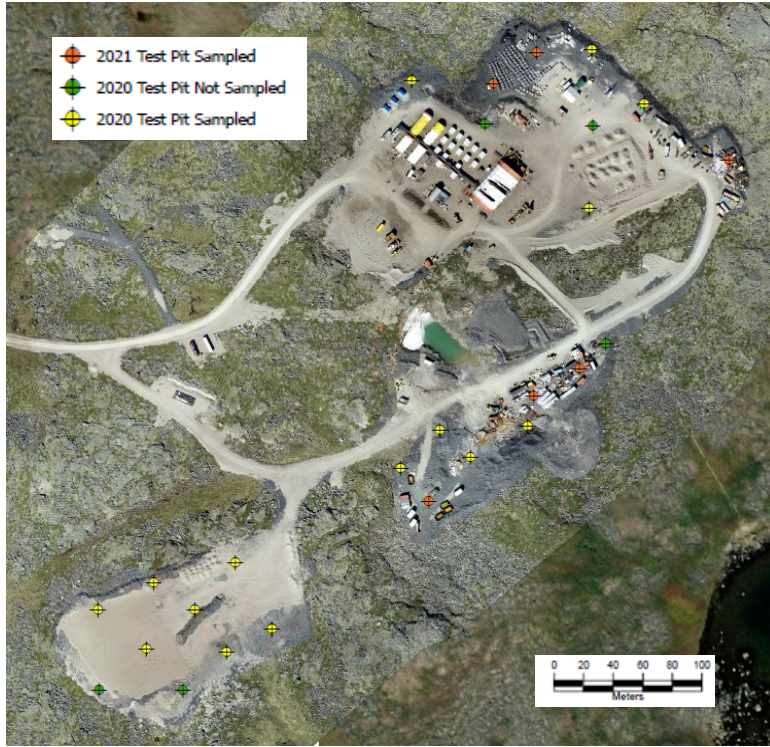
- Test pitting for static samples

- Seepage monitoring

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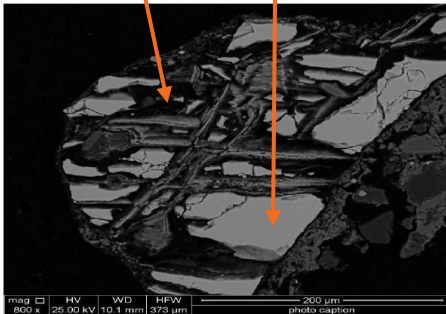
Mineralogical Characterization

- QEMSCAN on 7 samples (some near-surface, some 1m depth, some with/without overlying esker sand)

- Important not to crush/pulverize the samples and expose minerals not involved in surface weathering reactions
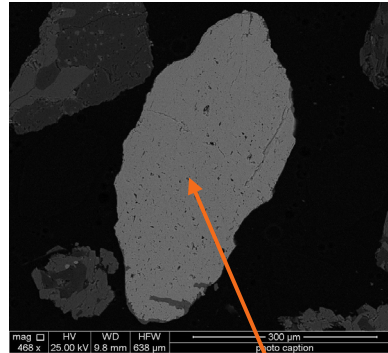

Pyrrhotite
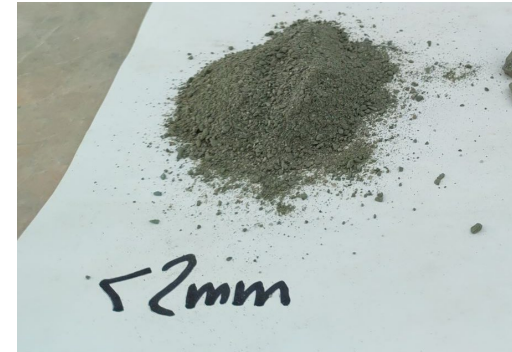
FeOOH

<425>150µm fraction

<1400>425µm

<425>106µm fraction

Pyrite

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# Mineralogical Characterization

	TP-01	TP-05B	TP-07	TP-09	TP-12	TP-14	TP-17
	Mineral abundance (wt.%) in <1400 µm size fractions						
Chalcopyrite	0.08	0.04	0.03	0.04	0.03	0.03	0.02
Sphalerite	0.00	0.39	0.00	0.00	0.01	0.02	0.00
Pyrite	1.55	0.11	0.28	0.55	0.67	0.27	0.26
Pyrrhotite	0.62	0.70	1.00	1.27	0.65	0.77	0.64
Arsenopyrite	0.00	0.00	0.00	0.01	0.05	0.01	0.02
Millerite	0.00	0.00	0.00	0.01	0.00	0.00	0.00
Total Sulphides	2.26	1.23	1.32	1.88	1.41	1.10	0.94
Goethite/Limonite	0.66	1.30	0.82	0.45	0.60	0.72	0.54
Calcite	0.59	0.02	0.29	0.49	2.10	0.69	0.45
Dolomite	0.06	0.01	0.13	0.06	0.21	0.14	0.07
Ca-sulphate	0.11	0.00	0.00	0.00	0.00	0.00	0.00

- Pyrrhotite dominant sulphide in 5 of the samples and most oxidized based on imaging

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Sulphide oxidation reaction rate constant

$$FeS+ \frac{9}{4} O_2+ \frac{3}{2}H_2O \rightarrow FeOOH+ SO_4^{2-}+2H^+$$
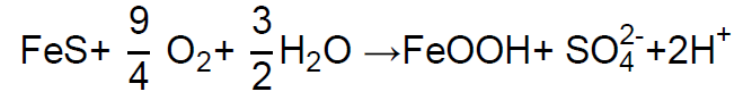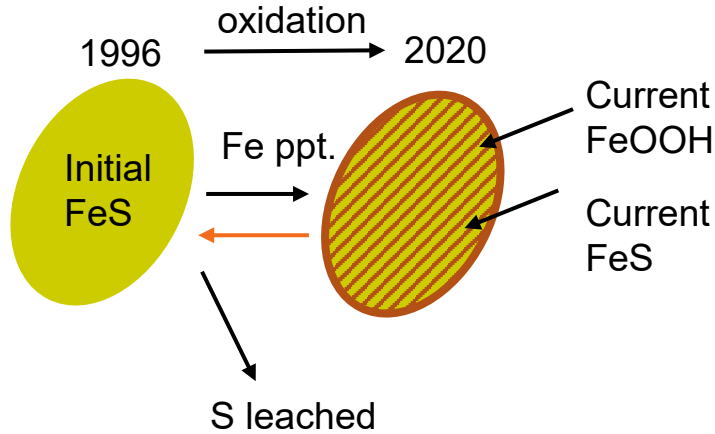
$$k \ (year^{-1})=\frac{S_{\text{leached}} \ (mg \ kg^{-1} \ year^{-1})}{S_{\text{initial}} \ (mg \ kg^{-1})}$$

Where:
- S leached is sulphur leached from a sample, measured over a period of time
- S initial is the initial sulphur content of the sample
- k is the sulphide oxidation reaction rate constant and may be calculated from an individual sample, or from several samples where k is provided by regression analysis.

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Sulphide oxidation reaction rate constant

Delay to ARD Inputs

$$t_{(onset)} = \frac{(TIC/AP)_{current}}{k(TIC/AP)_{crit}}$$
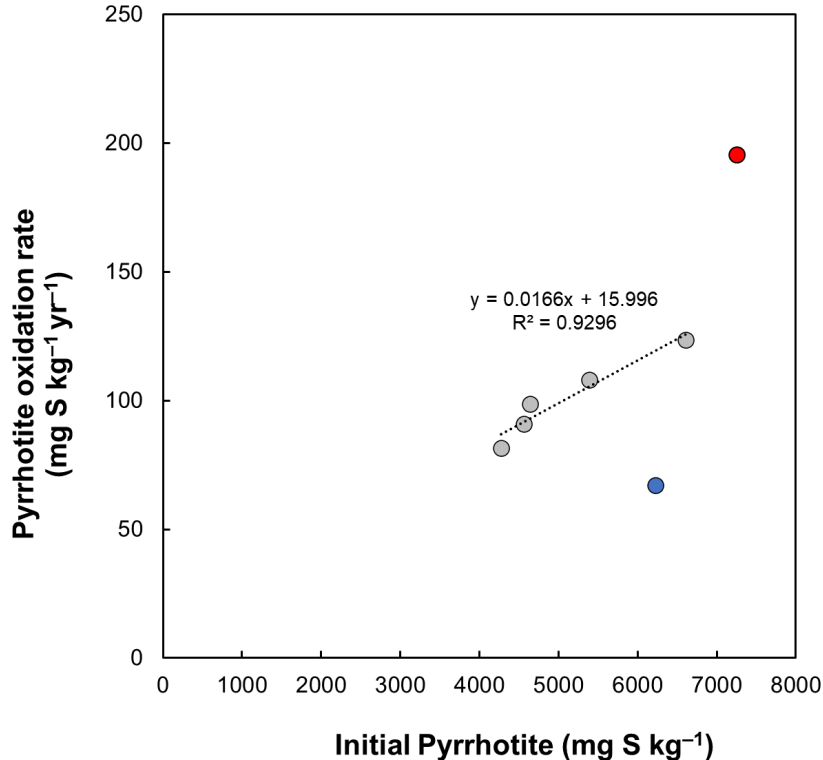
k (year^{-1}) = 0.027   Near-surface, no esker sand cover

k (year^{-1}) = 0.017   1 m depth, plus 0 to <0.5 m esker sand cover

k (year-^{1}) = 0.011   1 m depth, with 0.5 to 1 m esker sand cover

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Delay to ARD Inputs
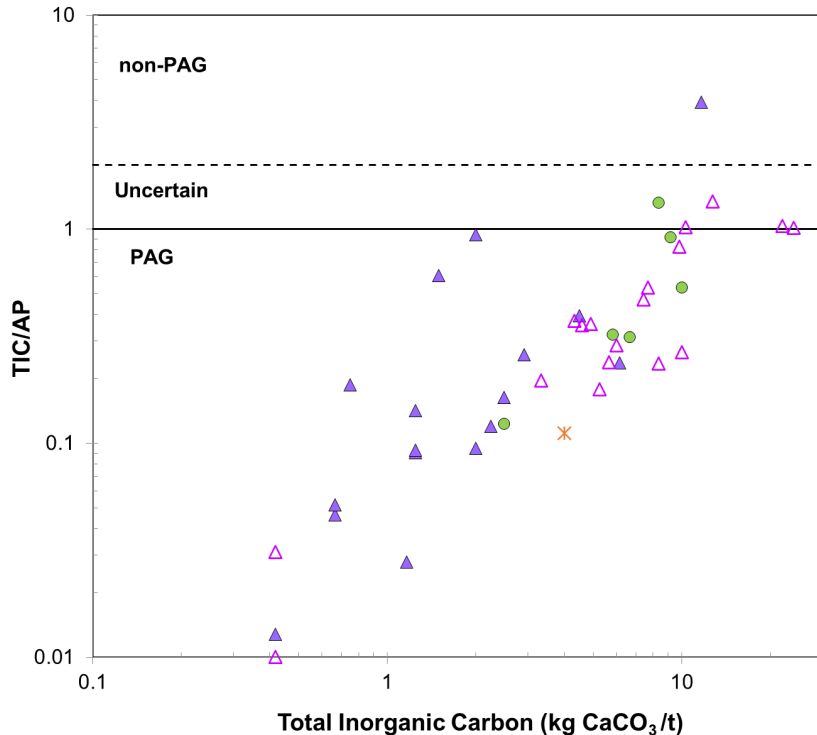
$$t_{(onset)} = \frac{(TIC/AP)_{current}}{k\,(TIC/AP)_{crit}}$$

- TIC/AP$_{current}$
  - Recent ABA data
  - < 2mm fraction
  - Samples subdivided by depth (surface/near-surface and 1m depth)
  - Used P10 TIC/AP to indicate initial onset of ARD
  - Median TIC/AP to indicate widespread ARD

Delay to ARD Inputs

$$t_{(onset)} = \frac{(TIC/AP)_{current}}{k \, (TIC/AP)_{crit}}$$

i.e. how effectively carbonate minerals are utilized in response to acid generation

- TIC/AP$_{critical}$

  – 2 typically used based on 2 moles calcite required to neutralize acid from 1 mole of pyrite at pH >6.3

  – Site specific values usually derived from HCT data where it can be interpreted to represent iron sulphide oxidation with acid generation, and neutralization by calcite/dolomite

  – For Ulu waste rock, seepage data was used, due to lack of representative waste rock HCT's

  – TIC/AP$_{crit}$ represented by (Ca+Mg)/SO$_4$ (mol/mol) calculated from Ca, Mg, SO$_4$ concentrations in waste rock contact water seepage

  – Ratio of 1.8 selected for input to t$_{(onset)}$

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Delay to ARD Results

Depth within rock pads	Surface/near-surface		1 m		1 m	
Approximate sand cover thickness	none		0 to <0.5 m		>0.5 to <1 m	
k (year^{-1})	0.027		0.017		0.011	
Statistic	TIC/AP	Delay to ARD (years from 2020)	TIC/AP	Delay to ARD (years from 2020)	TIC/AP	Delay to ARD (years from 2020)
P10	0.03	<1	0.20	7	0.20	10
Median	0.32	7	0.47	10 to 20	0.47	20 to 30

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Validation of Results

<2mm Test Pit Samples
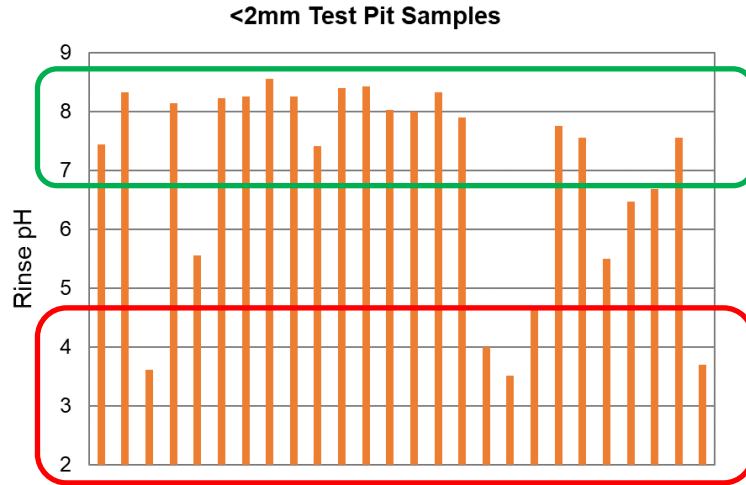
- Rinse pH results from test pits support the short delay to initial onset of ARD

- Several additional surface locations also had acidic rinse pH's

- Rinse pH results from test pits support that there is a rather longer timeframe to widespread ARD

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Delay to ARD Results

- Have not yet encountered acidic drainage at Ulu after 25 years of exposure

- Where acidic surface rock is underlain by rock with longer delay to ARD, the underlying materials may provide a source of alkalinity for neutralization

- Acidic surface material at the edge of the pads is most at risk of generating ARD due to minimal flow paths within the pads to provide neutralization

- A seepage monitoring program is in place to help determine areas at most risk of developing ARD

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Conclusions

- Predictions of the delay to onset of ARD incorporating ABA data, mineralogical data, and seepage data are consistent with current pH weathering conditions.

- Mineralogical results from samples collected within the infrastructure pads, were used to calculate field sulphide oxidation rates from 24 years of exposure

  - This may provide an improvement over relatively short duration kinetic test methods to calculate weathering rates; however, assumptions made to simplify the calculations should be considered in applying the results

  - The calculations are site specific and can be modified based on the sulphide mineralogy present

  - The calculations as presented could be refined with more detailed mineralogical work

  - The calculation method is considered of value for legacy sites or other projects with weathered waste rock

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