Direct Air Capture and CO$_2$ Mineralization in Mine Tailings

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Geochemical Framework

Cation source (e.g., Mg$^{2+}$) and buffering pH

Mineral dissolution

Mineral Carbonate Precip’n

CO$_2$ supply

Permanent CO$_2$ Storage

Source of CO$_2$

(air or point source)
Carbonation of Mine Tailings

- Significant impact at scale of mine operations – GHG neutral mining
- Happening now by accident (40 kt CO$_2$/yr)
- CO$_2$-limited; CO$_2$ supply will hit mineral dissolution limits
- Labile cations = cheap storage
- Leverage inherent geological variability
- Potential for direct air capture:
  - 5-10 MT feasible at $10/T with existing mining
  - 100’s MT to GT’s by direct air capture if we mine for C sequestration ($200-$300/T)
  - 100’s MT CO$_2$ possible at $100-200/T (with point sources)
Mining’s Carbon Footprint

- Large mine: ~350,000 tonnes CO$_2$/yr GHGeq
- ~60% point source (energy generation)
- ~40% distributed (e.g., trucks)

- Energy intensive activities are crushing/moving rock
- Most mined rock is waste (waste rock and tailings)
- GHG emissions scale with waste
- Some mines have sequestration capacity 10x greater than GHG production
  - Complete GHG offsets, and more???
  - Air capture is always part of the picture because local point sources of CO$_2$ are generally insufficient
Assessing and quantifying C mineralization

1. C reservoir fingerprinting

2. Mineral abundances

3. Reactive transport modelling

Mine scale CO$_2$ sequestration rate & predictive model
Cementation of tailings originally deposited as water-sand slurry
Mt Keith Nickel Mine, WA, Australia

Hydromagnesite cementing milled tailings grains
Clinton Creek Mine, Yukon, Canada

40,000 t/year CO₂
2.4 kg CO₂/m²/year
Mt Keith Nickel Mine, WA, Australia

11 Mt tailings/yr

3 kg CO₂/m²/year
Lab-based “soil” gas flux measurements
(c.f., 4 – 10 g CO₂/m²/yr in river catchments)
Rate Limits

Lab and field carbonation rates are limited by CO$_2$ supply

- At mine sites, labile Mg is buried before reacting
- CO$_2$ “starvation” imparts distinctive kinetic $^{13}$C signature seen in lab experiments and in tailings cements
- Lab CO$_2$ draw-down rates are independent of labile Mg content (above threshold value)
- Roughening tailings surface increases drawdown rate in lab experiments (2x)
- Carbon mineralization rates during gas injection into base of tailings columns are at rate of gas injection

Overcome CO$_2$ supply limits by air/gas/tailings handling, enhanced tailings-air contact
Direct air capture in tailings

Realistic limit: normal tailings

Only need four- to five-fold increase in rate to overcome CO₂ supply rate limits.

Mineral dissolution limit for optimal tailings

Reaction Rates

Mineral Deposit Research Unit

Lamont-Doherty Earth Observatory
Columbia University | Earth Institute
Assessing Reactivity

- Mineral dissolution studies using flow-through reactors

Adjustable parameters:
- Flow rate (~0.01 mL/min to 1+ mL/min)
- Temperature with water bath (~10-80 °C)
- Sample mass (~0.05-1.5 g tailings)
- Variable eluent chemistry
Cations: Labile vs Recalcitrant

- Serp - Mg
- Mount Keith tailings - Mg
- Serp - Effluent pH
- Mount Keith tailings – Mg
- Eluent pH

**Serpentine surface Mg**

**Brucite dissolution**

5-10% Mg of total Mg leached

- Labile Mg
  - Short-term, easily extractable
  - Inexpensive

- Recalcitrant Mg
  - Long-term capacity

bulk stoichiometric mineral dissolution

**pH buffering**

Trace minerals

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surface processes

Mineral Deposit Research Unit (MDRU)
Low-cost cations = low-cost carbon

Kinetically-controlled, far-from-equilibrium mineral dissolution

MKM Tailings

$\text{labile}$

$10's$

$\text{surface processes trace minerals}$

$\text{recalcitrant}$

$\text{bulk stoichiometric mineral dissolution}$

$\text{TCO}_2/\text{Trock}/s$

$10^{-8}$

$10^{-7}$

$10^{-6}$

$0.01$  $0.1$  $1$

Fraction Reacted

$\text{CO}_2$/T

$10's$

$100's$

Serpentine

$\text{Mg pre-jump}$

$\text{Mg post-jump}$

$\text{Si pre-jump}$

$\text{Si post-jump}$

Concentration (mmol/L)

$0.05$  $0.1$  $0.15$  $0.2$  $0.25$

$0$  $100$  $200$  $300$  $400$  $500$  $600$

Time (hours)

$\text{pH = 2.0}$

$\text{pH = 4.4}$

(Thom et al., 2013, Appl. Geochem.)
Predicting Labile Mg Release

Predicting labile Mg content from trace mineral abundance and mineral surface properties.
Deposit-Scale Variability of Labile Mg

- Labile Mg content of geologic deposits inherently variable
- Focus carbon mineralization on highly reactive ore types
- Co-benefits include metal encapsulation, dust reduction, tailings stabilization

MTonnes Ore

Labile Mg (Wt. % MgO)

Highly reactive ore types could generate co-benefits
Carbon Mineralization Rates

On-site CO$_2$
Tails air capture

Mine emissions

Labile Mg
$100$/Tonne

passive fixation

Diavik

Clinton Ck

Mount Keith

Off-site CO$_2$
Direct air capture

$10^{-4}$

$10^{-3}$

$10^{-2}$

$10^{-1}$

$10^1$

Tonnes CO$_2$ / Tonne Tailings / Yr

capacity
felsic

mafic
u-mafic
DAC with Tailings; Labile Mg Only

- Capacity: likely GT range (0.1% of $10^5$ GT; Lackner, 2003)
- Base labile content needed to offset mining emissions
- Carbon revenue ($/TCO2) to offset mining costs ($10/T rock)

![Graph showing carbon revenue to offset mining costs](image)

**Graph Details:**
- X-axis: Labile Mg (Wt. % MgO)
- Y-axis: MTonnes Ore
- CO$_2$ Mineralized/CO$_2$ Emitted

**Carbon Revenue to Offset Mining Cost**
- $101/TCO_2$
- $150/TCO_2$
- $300/TCO_2$
- $10,600/TCO_2$
DAC with Tailings; Labile Mg Only

- Base is previous slide
- Renewable E: 60% of point source energy from hydro (B.C.) or green
- Co-products: cover $5/Tonne with Ni recovery
Modest acceleration of current passive rates ($10^{-6}$ T/T/s; 12 kg/m$^2$/yr)

On Mount Keith Ni Mine Tailings (9 wt. % labile MgO)

- 14 MT/yr = 1.4 MT; 1 MT net. (currently 11-12 MT/yr)
- Footprint: 83 km$^2$
  - 2 km$^2$ Carbon Engineering
  - 400 km$^2$ forest
  - 20 km$^2$ current tailings storage facility
One vs Two-stage

- Tailings stability
- Dust mitigation
- Metal encapsulation

- Flame retardant
- Building materials
- C storage/delivery
Labile Mg: Best Tailings & Pre-Treatment

Kinetically-controlled, far-from-equilibrium mineral dissolution

MKM Tailings

Best Tailings; Pretreatment

Reaction Rate (T/CO₂/Trock/s)

Fraction Reacted

$10's

$100's

$T CO₂

Recalcitrant

Surface processes trace minerals

Bulk stoichiometric mineral dissolution

labile
Carbonation of Mine Tailings

• Pilot with operating mines – industry interest is building
• Confidence and know-how applies elsewhere
  – (enhanced-weathering, peridotite carbonation, etc.)
• Challenges and Opportunities:
  – better tools for labile cations
  – mineral pretreatment
  – enhancing air capture; air-water circulation
  – land-use vs other ways of delivering carbon
  – solution mining
  – subsurface mineralization
  – verification protocols
  – regulatory framework to allow experimentation