Workshop on CO₂ Mineralization for ENERGY RELEVANT MINERAL EXTRACTION

Can our production of metals lead to negative emissions?

Held July 13 and 15, 2021
Geological mineralization as a route to Carbon Dioxide Removal and liberation of energy-essential minerals

Why?

- The US has vast deposits of mafic and ultramafic that is capable of sequestering CO₂

- These deposits contain minerals critical to our economy at concentrations below current commercial interest that can be more efficiently extracted via the addition of CO₂. e.g.: Nickel, Cobalt, Chrome
It takes a tribe to surround a topic
Some old NEWS for this crowd - All paths to 2°C go through zero
But you may not have considered...

Sustainable Energy is Powered by Minerals

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>1</td>
<td>Aluminum</td>
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<tr>
<td>2</td>
<td>Chromium</td>
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<tr>
<td>3</td>
<td>Cobalt</td>
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<td>4</td>
<td>Copper</td>
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<td>5</td>
<td>Graphite</td>
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<td>6</td>
<td>Indium</td>
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<td>7</td>
<td>Iron</td>
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<td>8</td>
<td>Lead</td>
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<td>9</td>
<td>Lithium</td>
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<tr>
<td>10</td>
<td>Manganese</td>
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<tr>
<td>11</td>
<td>Molybdenum</td>
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<td>12</td>
<td>Neodymium</td>
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<tr>
<td>13</td>
<td>Nickel</td>
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<td>14</td>
<td>Silver</td>
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<tr>
<td>15</td>
<td>Titanium</td>
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<tr>
<td>16</td>
<td>Vanadium</td>
</tr>
<tr>
<td>17</td>
<td>Zinc</td>
</tr>
</tbody>
</table>
But you may not have considered...

**Sustainable Energy is Powered by Minerals**

| 1 | Aluminum | 10 | Manganese |
| 2 | Chromium | 11 | Molybdenum |
| 3 | Cobalt | 12 | Neodymium |
| 4 | Copper | 13 | Nickel |
| 5 | Graphite | 14 | Silver |
| 6 | Indium | 15 | Titanium |
| 7 | Iron | 16 | Vanadium |
| 8 | Lead | 17 | Zinc |
| 9 | Lithium |

**Growth of selected minerals in the SDS, 2040 relative to 2020**

- Lithium: 42
- Graphite: 25
- Cobalt: 21
- Nickel: 19
- Rare earths: 7

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These metals do not come without baggage

Average GHG emissions intensity for production of selected commodities

IEA. All rights reserved.

Notes: Includes both Scope 1 and 2 emissions of all GHGs (the majority of which are CO₂) from primary production. The values for lithium carbonate refer only to CO₂ emissions based on the weight average of brine and hard-rock production (denoted on a lithium carbonate equivalent basis).

Sources: IEA (2020b) and Rio Tinto (2020) (steel); Nuss and Eckelman (2014) (zinc); data received from Skarn Associates (copper and nickel); Roskill (2020) and S&P Global (2021) (lithium); IEA (2020b) and Tost et al. (2018) (aluminium); Argonne National Laboratory (2019) (cobalt); Marx et al. (2018) (neodymium).
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The Role of Critical Minerals in Clean Energy Transitions

Sustainable and responsible development

Changing patterns of demand and types of resource targeted for development are set to exert upward pressure on emissions.

GHG emissions intensity for production of selected commodities

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The Role of Critical Minerals in Clean Energy Transitions

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Metal Science

- Mafic/Ultramafic ore bodies
  - Will mineralize CO₂
  - Contain energy relevant metals
- Olivine example at right
  - Potential to mineralize 400 kg/ton
    - Based on Ca/Mg content
  - If processed for the 0.7wt% nickel
    - 143 tons ore/ton of nickel
    - Mineralizing 57.2 ton CO₂/ton of Ni

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**Table 1. Chemical composition of the investigated olivine and magnesia**

<table>
<thead>
<tr>
<th>Components</th>
<th>Olivine</th>
<th>Magnesia</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>46.43</td>
<td>0.32</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>2.55</td>
<td>0.20</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>10.88</td>
<td>0.58</td>
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<tr>
<td>TiO₂</td>
<td>0.11</td>
<td>0.05</td>
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<tr>
<td>CaO</td>
<td>2.16</td>
<td>0.75</td>
</tr>
<tr>
<td>MgO</td>
<td>35.57</td>
<td>97.56</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.39</td>
<td>0.02</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.17</td>
<td>0.10</td>
</tr>
<tr>
<td>MnO</td>
<td>0.17</td>
<td>0.24</td>
</tr>
<tr>
<td>Cr₂O₃</td>
<td>0.45</td>
<td>0.00</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>ZrO₂</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>SO₃</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>BaO</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>ZnO</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>NiO</td>
<td>0.89</td>
<td>0.09</td>
</tr>
<tr>
<td>Co₃O₄</td>
<td>0.08</td>
<td>0.00</td>
</tr>
<tr>
<td>CuO</td>
<td>0.06</td>
<td>0.00</td>
</tr>
<tr>
<td>Total</td>
<td>100.00</td>
<td>100.00</td>
</tr>
</tbody>
</table>

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*Metals 2018, 8, 993*
It’s Pretty Simple Chemistry

‣ One just needs rock, CO₂ and perhaps a little water...
‣ Thermodynamically favorable (15-22 kcal/mol)
‣ Basically innocuous reaction products
‣ But...

Wollastonite
Olivine
Pyroxenes
Serpentine polytypes
Brucite

CaSiO₃
Mg₂SiO₄
CaMgSi₂O₆
Mg₃Si₂O₅(OH)₄
Mg(OH)₂

CO₂
2CO₂
2CO₂
3CO₂
CO₂

CaCO₃
2MgCO₃ + SiO₂
CaMg(CO₃)₂ + 2SiO₂
3MgCO₃ + 2SiO₂ + 2H₂O
MgCO₃ + H₂O

CO₂ and Extraction
It’s Pretty Simple Chemistry

- One just needs rock, CO₂ and perhaps a little water...
- Thermodynamically favorable (15-22 kcal/mol)
- Basically innocuous reaction products
- But...

\[
\text{Wollastonite:} \quad \text{CaSiO}_3 + \text{CO}_2 \rightarrow \text{CaCO}_3 + 0.38 \text{ per t of rock}
\]
\[
\text{Olivine:} \quad \text{Mg}_2\text{SiO}_4 + \text{CO}_2 \rightarrow 2\text{MgCO}_3 + 0.62 \text{ per t of rock}
\]
\[
\text{Pyroxenes:} \quad \text{CaMgSi}_2\text{O}_6 + \text{CO}_2 \rightarrow \text{CaMg(CO}_3)_2 + 0.41 \text{ per t of rock}
\]
\[
\text{Serpentine polytypes:} \quad \text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4 + \text{CO}_2 \rightarrow 3\text{MgCO}_3 + 0.48 \text{ per t of rock}
\]
\[
\text{Brucite:} \quad \text{Mg(OH)}_2 + \text{CO}_2 \rightarrow \text{MgCO}_3 + 0.75 \text{ per t of rock}
\]
But, in the wild this is a SLOW Process

Key to the erosion process that takes mountains into molehills!

Nature’s way:
- Wind, rain, ice, freeze thawing, biology and seismic events all contribute to the process
- Removes about 1 gigaton of CO$_2$/yr
- It takes time – literal eons

http://butane.chem.uiuc.edu/pshapley/Environmental/L29/2.html
Is there an Industry Big Enough to Deploy?

The global scale of mining is almost Incomprehensible

Yearly mineral production - 19 Billion tonnes
Coal/limestone/aggregate dominate

Yearly mining waste produced - 50 Billion tonnes
Coal/limestone/aggregate do not dominate

Production will drop but waste will increase
7 Billion tons of coal annually will stay in the ground

For Mineral Extraction – 3 Stages open to CO₂ Reaction

**Pre-treatment**
- Before extraction
- During extraction

**During processing**
- Comminution
- Flotation
- Extractive step

**Post processing**
- Before the tailings pile
- Process residue
- Overburden
Concept illustration from a vanadium deposit in Australia

- **TMT Limited Projections**
  - Total $V_2O_5$ to be mined = 225 kt
  - Total ore processed = 35 Mt
  - Total overburden moved = 150 Mt
    - Primarily mafic gabbro!

- **Inferred CO$_2$ Mineralization Potential**
  - SWAG of 1 ton CO$_2$/10 tons of gabbro
  - Potential > -100 ton CO$_2$/ton of V metal

- **Current CO$_2$e emissions of V**
  - +63.4 ton/ton of metal
    
https://amg-v.com/sustainability/

In-situ CO$_2$ Pretreatment (Incorporating in Mine Planning?)

- **Basic Mine Planning**
  - Drill holes to obtain core samples
  - Determine chemistry
  - Map out approach

- **Combine w/Pretreatment**
  - Flood the hole with CO$_2$ cocktail
  - Cap then allow overburden and target ore to react
  - Excavate and measure

Other Opportunities for Mineralization

Figure 3: Gabanintha Project – Site Layout


CO2 and Extraction 17
Let’s look at Nickel

- **Current Global Ni**
  - Annual production = 2.5 million tons
  - $[\text{Ni}]$ between 0.5 and 2.0%
  - Emit >50 million tons of CO$_2$e/yr

- **Projected global demand for EV’s**
  - Annual production = 12 million tons
  - Unabated CO$_2$e > 250 million tons
  - $[\text{Ni}]$ < 1.0%

- **If wishes do come true**
  - Electrify to abate existing process
  - Mineralize > 500 million tons
So, we held a Workshop: Mineralization and Enhanced Mineral Recovery

CO₂ Mineralization

**In Situ Mineralization**
- Subterranean storage methods
- Ore body pretreatment
- Acceleration of rock dissolution rates
  - Catalysis
  - Water & pressure management

**Mineralization w/ Extraction**
- Reactive extraction from ore
- Active mineralization in tailings
- Redeployment of tailings

**Common Ground**
- Geology & petrology
- Identification and mapping
- Reaction chemistries
  - Thermochemical
  - Biochemical
- Metrology
Who shows interest in the CO2/Metal Nexus?

- **100+ External Registrants**
  - >100 attendees first day, >90 second day
  - Industry, finance, academia, labs
  - NRCan, NRC, CNRS
- **6 Speakers**
- **Breakouts around process**
  - Thermochemical/Electrochemical
  - Biochemical/Phytomining
- **22 Participant fast intros or pitches at the end**
- **Many follow-up one on one calls**
What did we hear?
An aspiration to integrate across mining process

Concept illustration of how to sequester CO₂ with ultramafic mine waste

Reactivity of Rocks and Tailings to CO₂

Tailings Legend:
- poorly reactive fine (low permeability) tailings
- highly reactive coarse (high permeability) tailings
- tailings stabilized by carbonate cement formation

Summarized CO₂ Sequestration Reaction:
CO₂ + Magnesium from reactive tailings + H₂O → hydrated magnesium carbonate
(e.g. MgCO₃·3H₂O)

from Vanderzee et al. (2019), S.

Martin Turenne
President & CEO
FPX Nickel Corp.
mturenne@fpxnickel.com
What did we hear?

Electrochemistry, biochemistry, mechanochemistry approaches

High strength carbonate-reinforced recycled concrete through carbon mineralization

Next-generation built environments with low carbon building materials

Ca$_{x}$SiO$_{2+x}$ for use in cement manufacturing

CaCO$_{3}$ \ra \ Ca^{2+} + 2e^{-} + O$_2$ + CO$_2$,

\( x \text{ Ca}^{2+} + 2x \text{ e}^{-} + \text{SiO}_2 + \frac{x}{2} \text{O}_2 \ra \text{Ca}_x\text{SiO}_{2+x} \)

The research projects in the lab, from understanding how microbes adapt to the extreme starvation of caves, the evolution of antibiotics, and even the rock-eating microbes that form caves.

Hazel Barton, U Akron
What did we learn?

‣ Great Interest in the concept!
  – Major mining companies
  – Investment community
  – Carbon capture companies

‣ Lots of ideas!
  – Many approaches that could work
  – Mineralization may lead to lower mining cost and improve yield

‣ Impure CO$_2$ will be a benefit
  – H$_2$O facilitates the reaction
  – NOx, SOx and O$_2$ can be a plus
Challenges to be met

- **Chemistry and Engineering**
  - Major enhancement to reaction rates
  - New comminution approaches
  - Integration with metallurgy

- **Geology/Metrology/Petrology**
  - Identification of potential deposits
  - Correlation of ore structure with reactivity

- **Lifecycle and TEA**
  - Driving down $\text{H}_2\text{O}$ usage
  - **Impact of CO$_2$ credits on mine economics**
  - Impact on mine waste
Potential Targets for Performers

For: Ni, Cu, Co, Mn, V, P, Fe, Al, Mg, REE, PGM...

Make energy mineral production carbon negative
More carbon sequestered than emitted downstream

Quantify and monetize fast
Quantified sequestration in short order

Makes money at scale
Process cost $15-20/ton CO₂ mineralized
Additional Information

‣ Workshop Website

‣ Background Videos
  – https://youtu.be/6EVwNm22Pc0
  – https://youtu.be/NBVELH40EaE
  – https://youtu.be/1BlhmCaDHPU
  – https://youtu.be/Yf0uW9BG8E0