Workshop on CO_2 Mineralization for ENERGY RELEVANT MINERAL EXTRACTION

Can our production of metals lead to negative emissions?

Held July 13 and 15, 2021

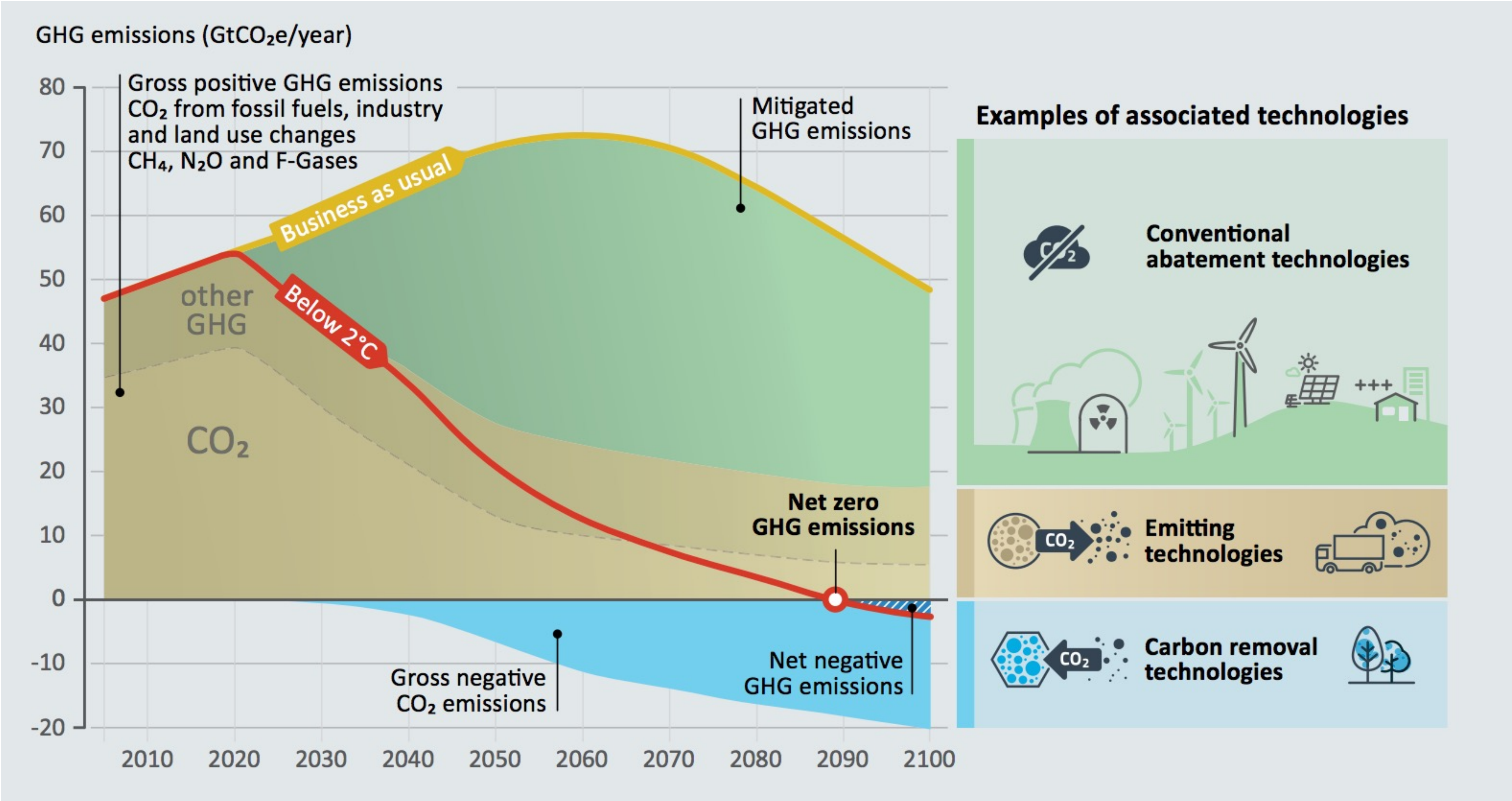
Topic Introduction

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 CO_2
  - These deposits contain **minerals critical to our economy** at concentrations below current commercial interest that can be more efficiently extracted via the addition of CO_2. *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



National Academy of Sciences. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda.* 2019. p. 3

arpa·e
CHANGING WHAT'S POSSIBLE

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		

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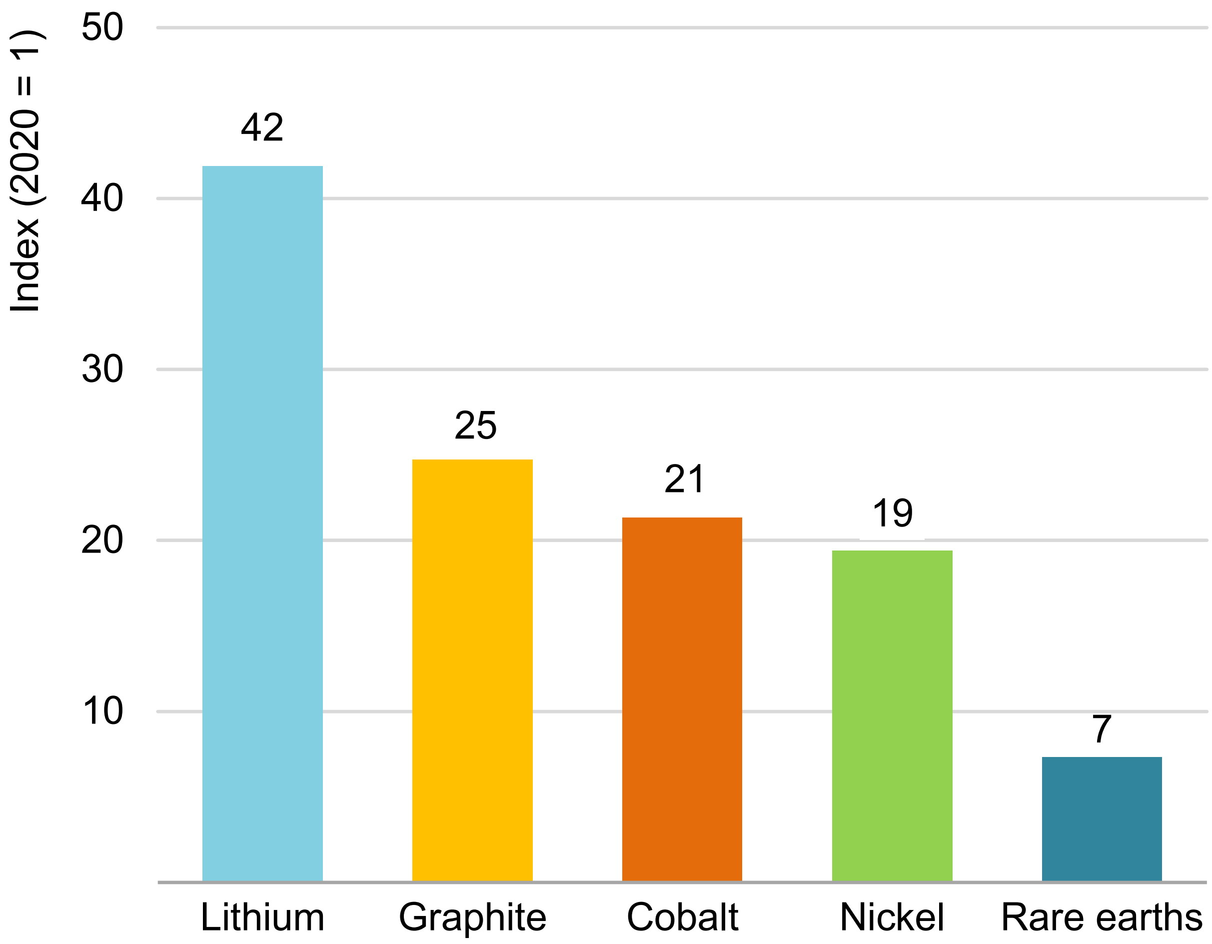
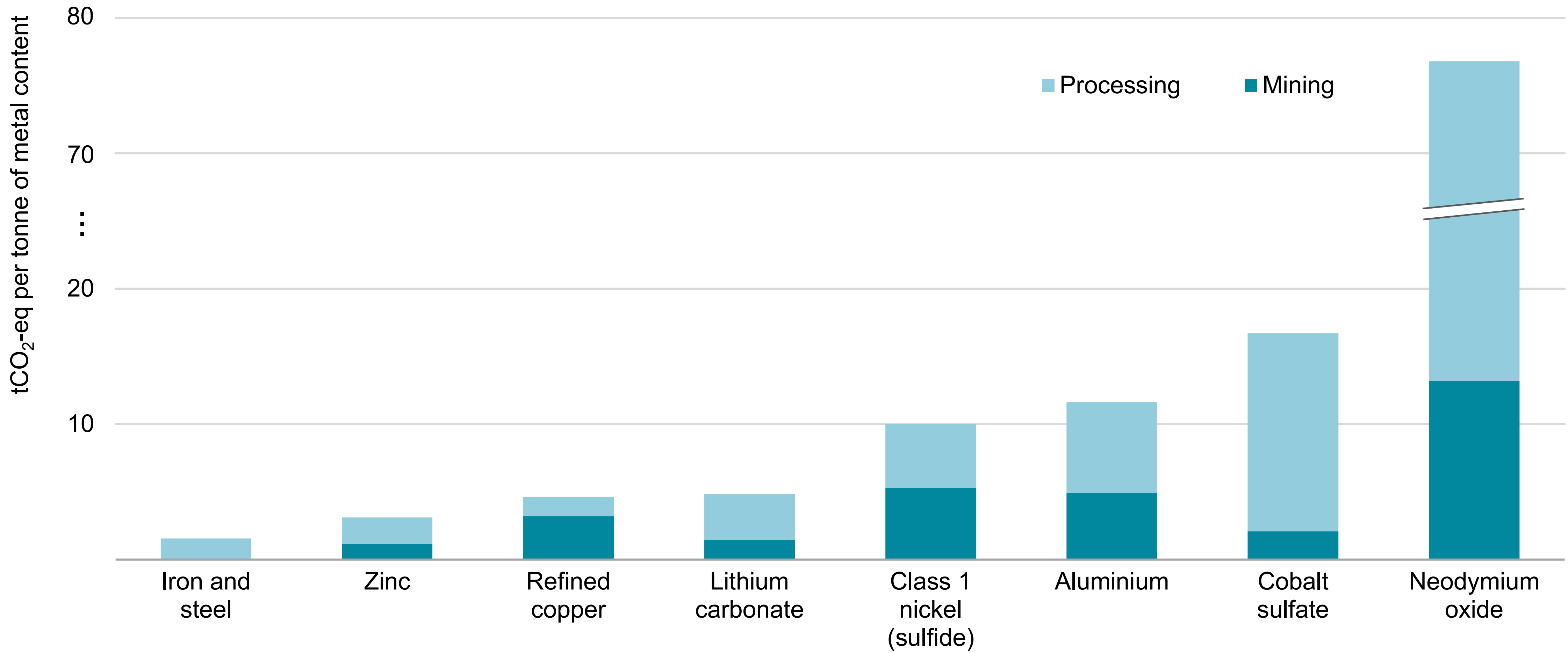
Growth of selected minerals in the SDS, 2040 relative to 2020



These metals do not come without baggage

Average GHG emissions intensity for production of selected commodities



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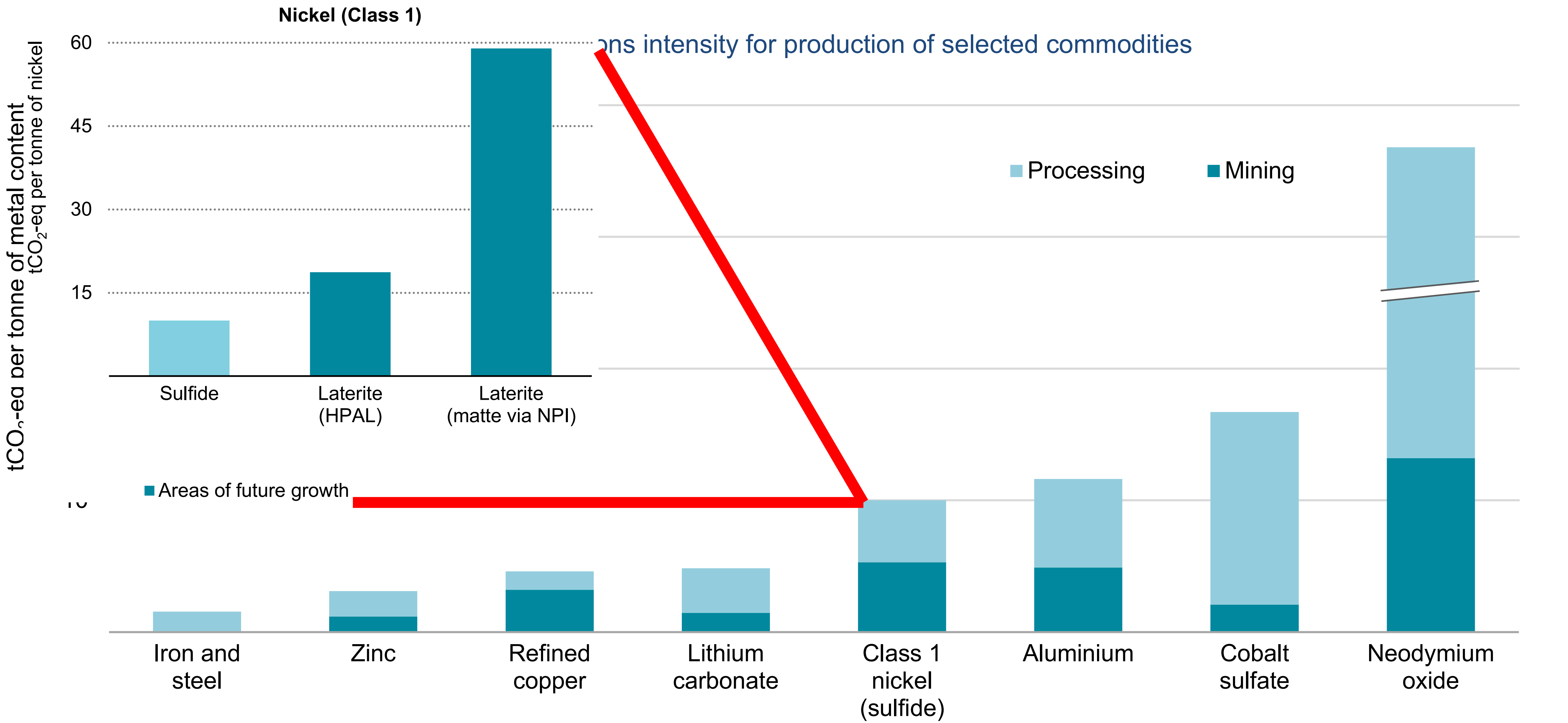


CHANGING WHAT'S POSSIBLE

Hard Rock Science

- **Mafic/Ultramafic ore bodies**
  - Will mineralize CO_2
  - 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 CO_2/ton of Ni

Table 1. Chemical composition of the investigated olivine and magı

Components	Olivine	Magnesia
SiO_2	46.43	0.32
Al_2O_3	2.55	0.20
Fe_2O_3	10.88	0.58
TiO_2	0.11	0.05
CaO	2.16	0.75
MgO	35.57	97.56
K_2O	0.39	0.02
Na_2O	0.17	0.10
MnO	0.17	0.24
Cr_2O_3	0.45	0.00
P_2O_5	0.00	0.00
ZrO_2	0.02	0.03
SO_3	0.00	0.00
BaO	0.00	0.00
ZnO	0.08	0.08
NiO	0.89	0.09
Co_3O_4	0.08	0.00
CuO	0.06	0.00
Total	100.00	100.00

Metals **2018**, *8*, 993

It's Pretty Simple Chemistry

+ CO_2 →

Wollastonite	$CaSiO_3$	+	CO_2	→	$CaCO_3$
Olivine	Mg_2SiO_4	+	$2CO_2$	→	$2MgCO_3 + SiO_2$
Pyroxenes	$CaMgSi_2O_6$	+	$2CO_2$	→	$CaMg(CO_3)_2 + 2SiO_2$
Serpentine polytypes	$Mg_3Si_2O_5(OH)_4$	+	$3CO_2$	→	$3MgCO_3 + 2SiO_2 + 2H_2O$
Brucite	$Mg(OH)_2$	+	CO_2	→	$MgCO_3 + H_2O$

- One just needs rock, CO_2 and perhaps a little water…
- Thermodynamically favorable (15-22 kcal/mol)
- Basically innocuous reaction products
- But…

It’s Pretty Simple Chemistry

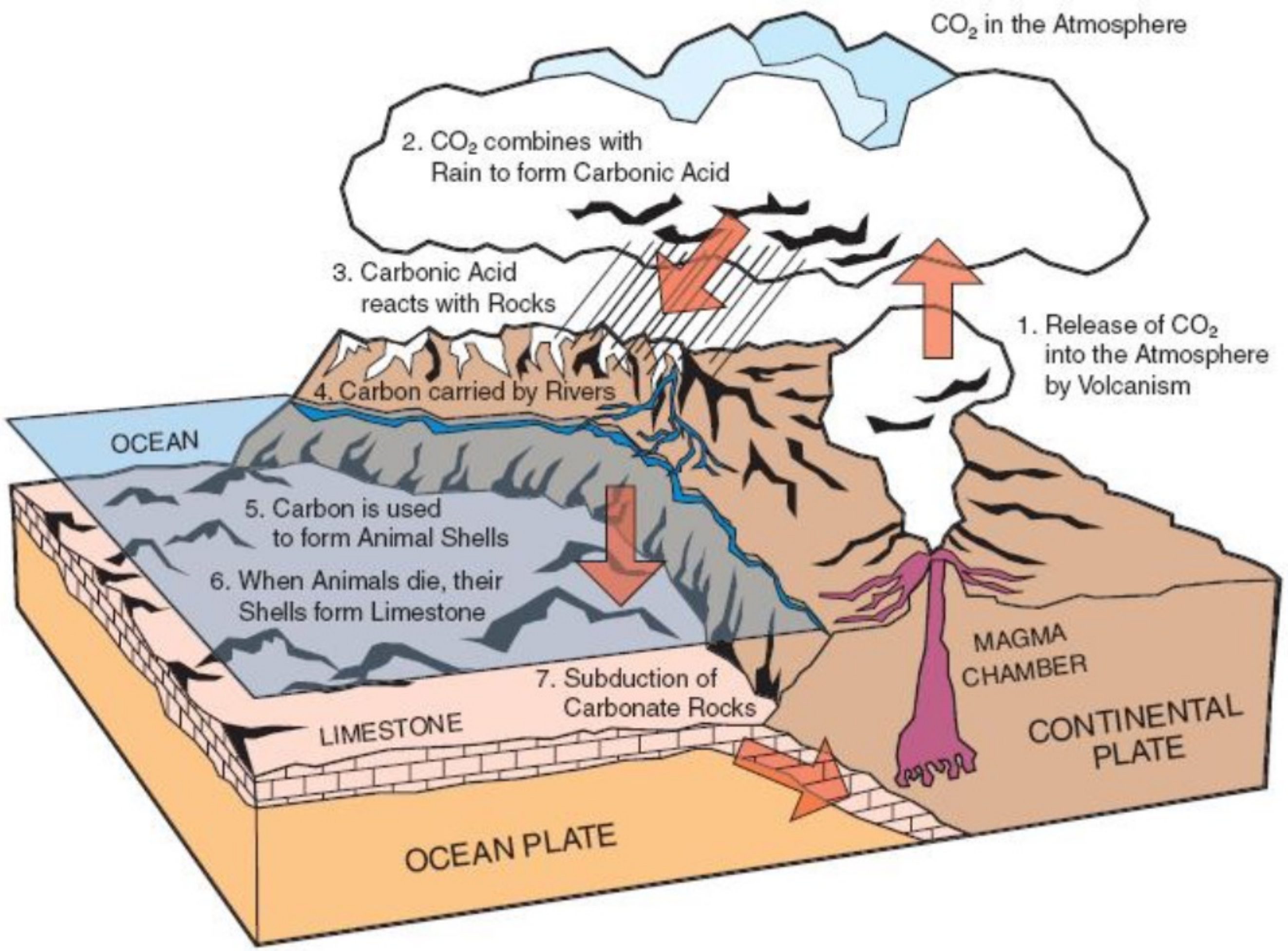
+ CO_2

per t of rock

Wollastonite	$CaSiO_3$	0.38	$CaCO_3$	
Olivine	Mg_2SiO_4	0.62	$2MgCO_3$	$+ SiO_2$
Pyroxenes	$CaMgSi_2O_6$	0.41	$CaMg(CO_3)_2$	$+ 2SiO_2$
Serpentine polytypes	$Mg_3Si_2O_5(OH)_4$	0.48	$3MgCO_3$	$+ 2SiO_2 + 2H_2O$
Brucite	$Mg(OH)_2$	0.75	$MgCO_3$	$+ H_2O$

- One just needs rock, CO_2 and perhaps a little water…
- Thermodynamically favorable (15-22 kcal/mol)
- Basically innocuous reaction products
- But…

But, in the wild this is a SLOW Process



http://butane.chem.uiuc.edu/pshapley/Environmental/L29/2.html

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***

Is there an Industry Big Enough to Deploy?

The global scale of mining is almost Incomprehensible

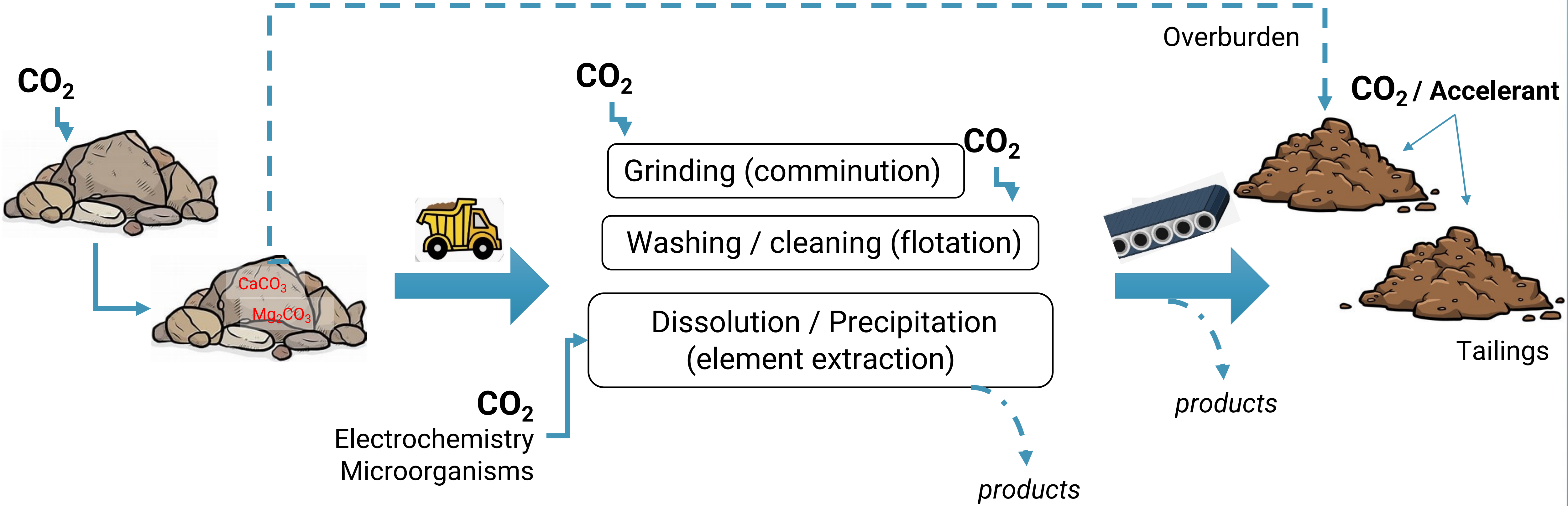
Yearly mineral production - 19 Billion tonnes
Coal/limestone/aggregate dominate

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

https://www.world-mining-data.info/wmd/downloads/PDF/WMD2020.pdf

For Mineral Extraction – 3 Stages open to CO_2 Reaction



Pre-treatment
- Before extraction
- During extraction

OR

During processing
- Comminution
- Flotation
- Extractive step

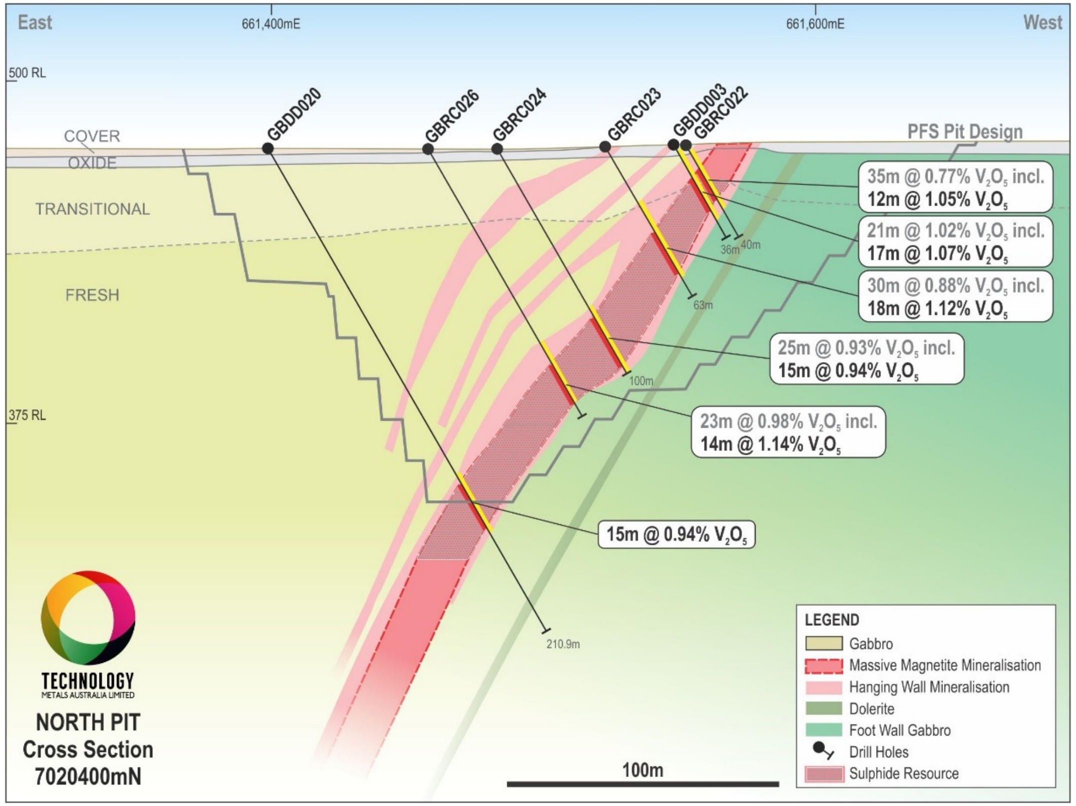
OR

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_2e emissions of V**
  - +63.4 ton/ton of metal

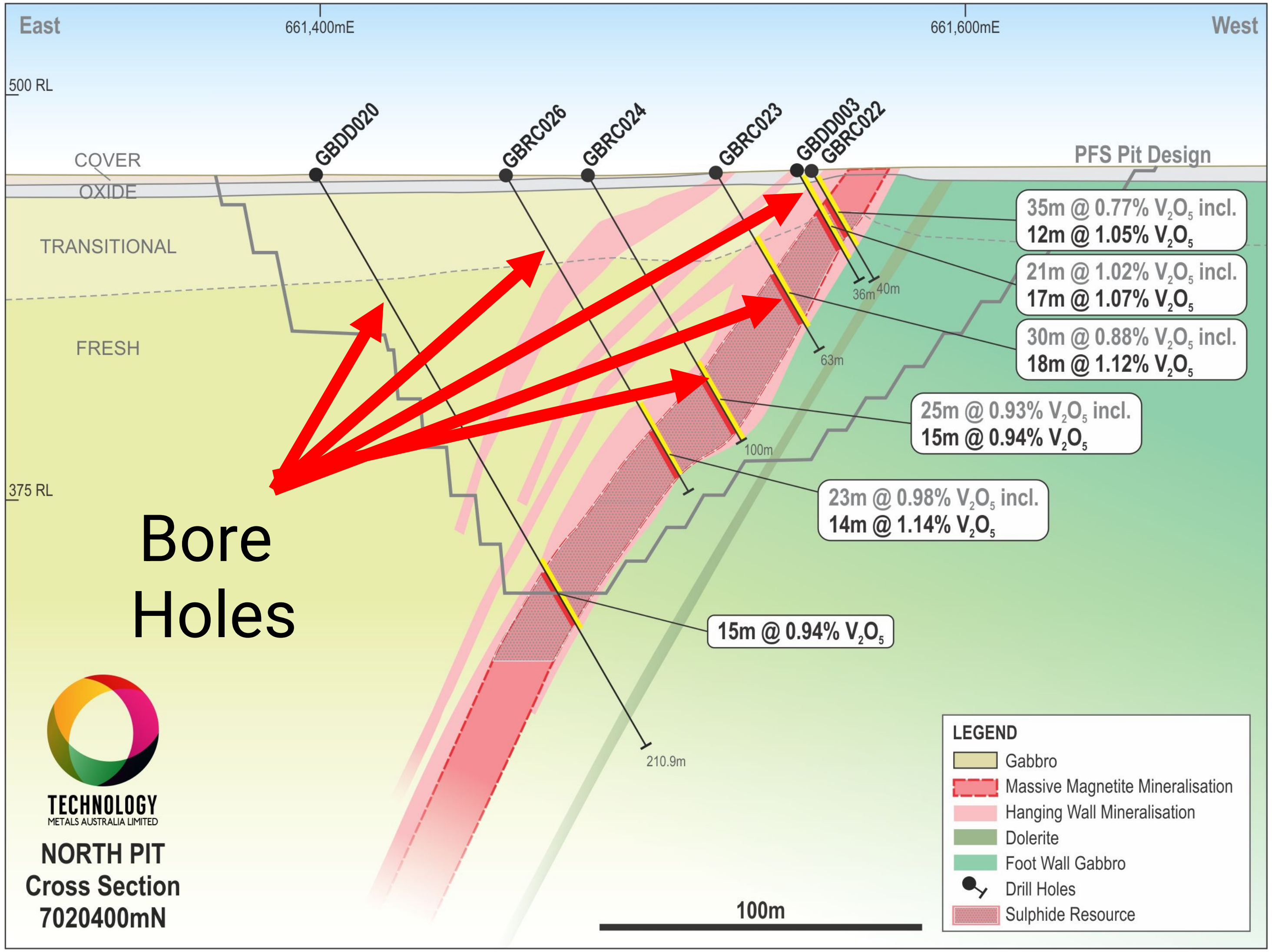
  https://amg-v.com/sustainability/



https://www.tmtlimited.com.au/geology

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



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Other Opportunities for Mineralization

Process Plant

Tailing Pond

Overburden Pile

Overburden Pile

Ore Stockpile

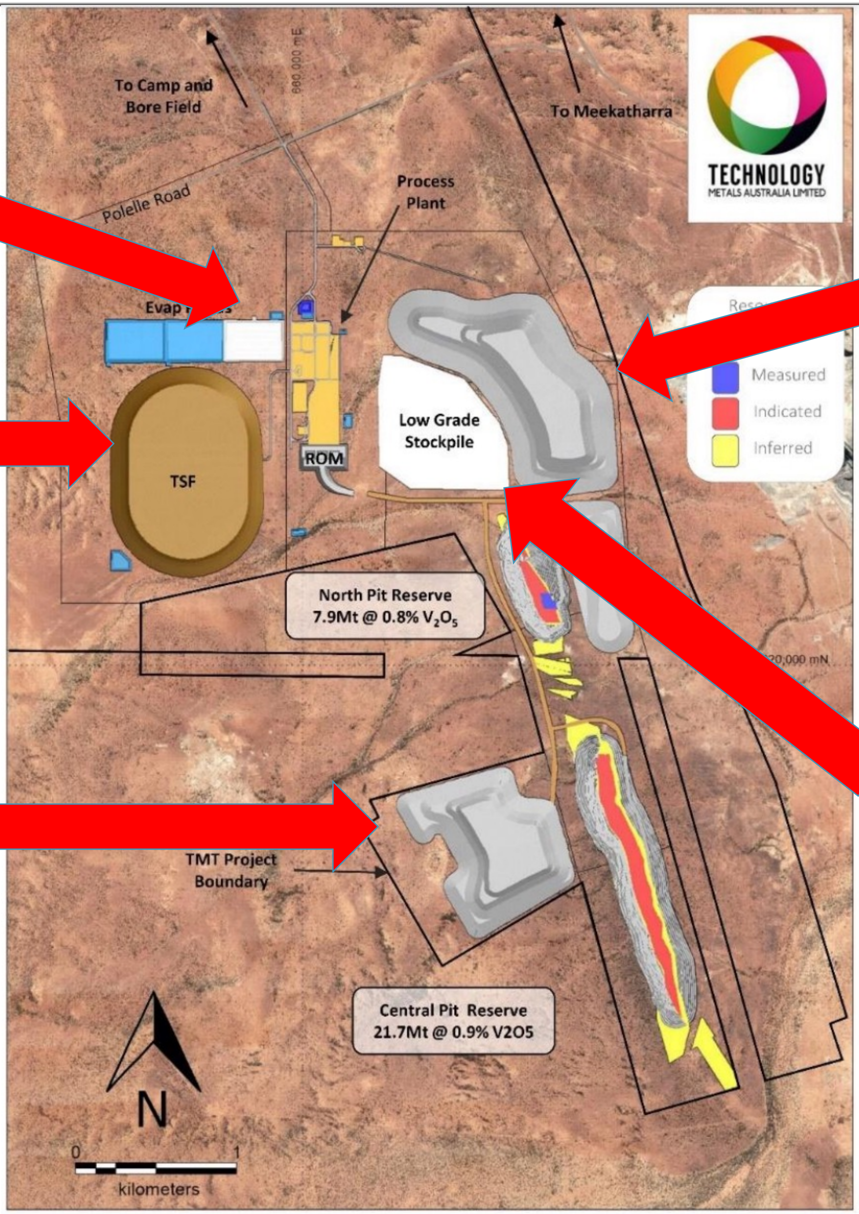


Figure 3: Gabanintha Project – Site Layout

https://www.tmtlimited.com.au/geology

Let’s look at Nickel

- **Current Global Ni**
  - Annual production = 2.5 million tons
  - [Ni] between 0.5 and 2.0%
  - Emit >50 million tons of CO_2e/yr
- **Projected global demand for EV’s**
  - Annual production = 12 million tons
  - Unabated CO_2e > 250 million tons
  - [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

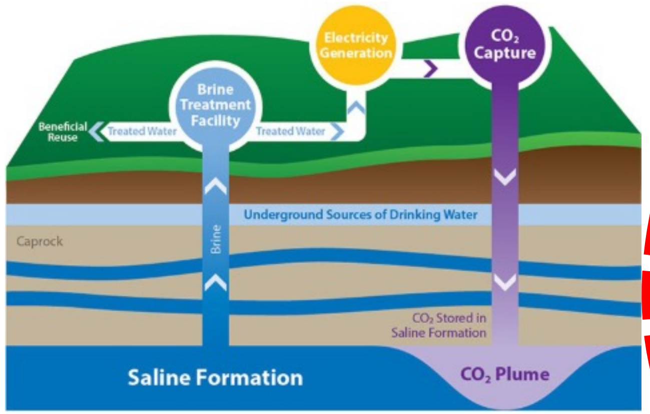
CO_2 Mineralization

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



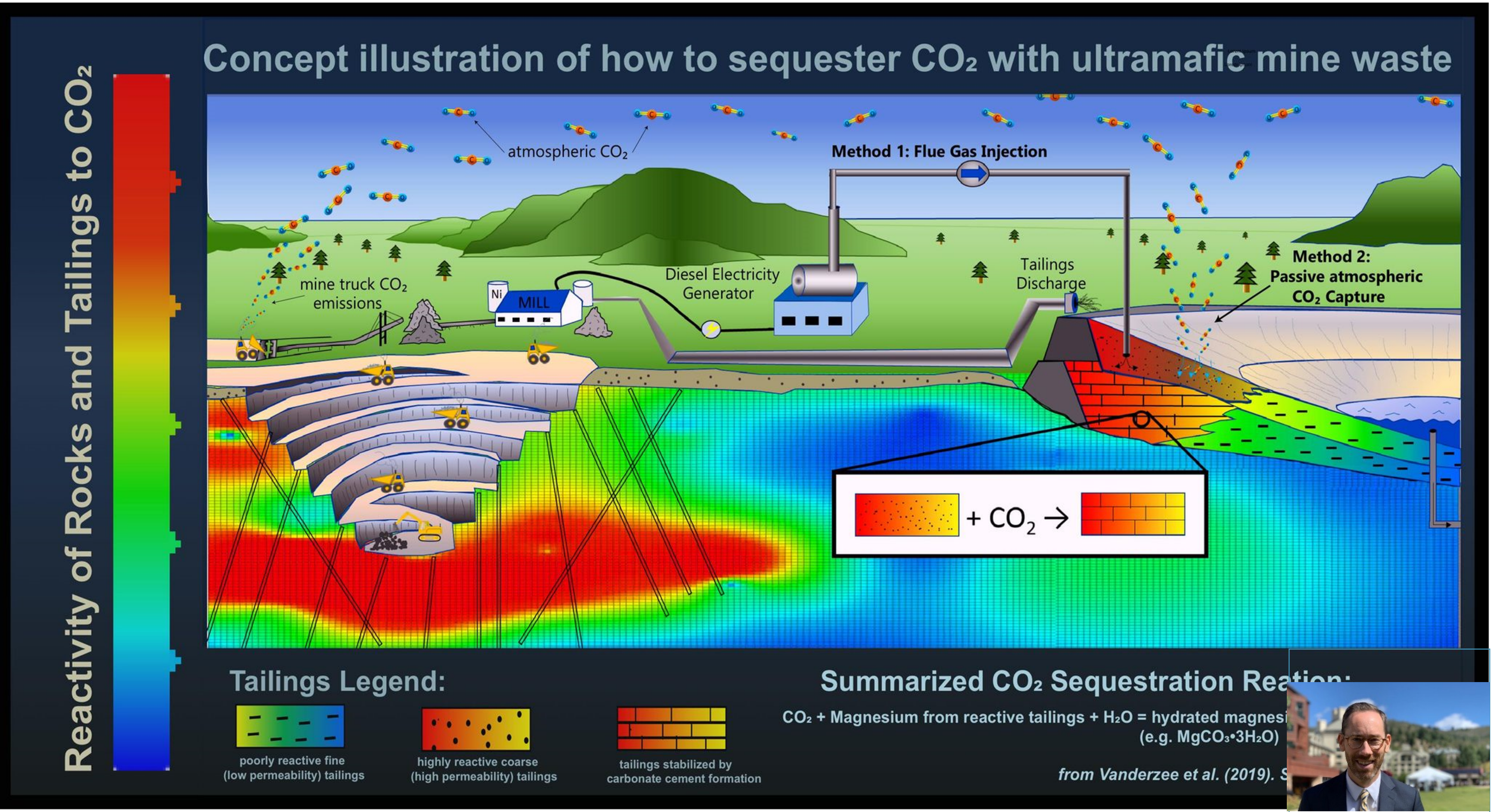
Common Ground

- 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



FPX Nickel Corp.
TSX-V:FPX

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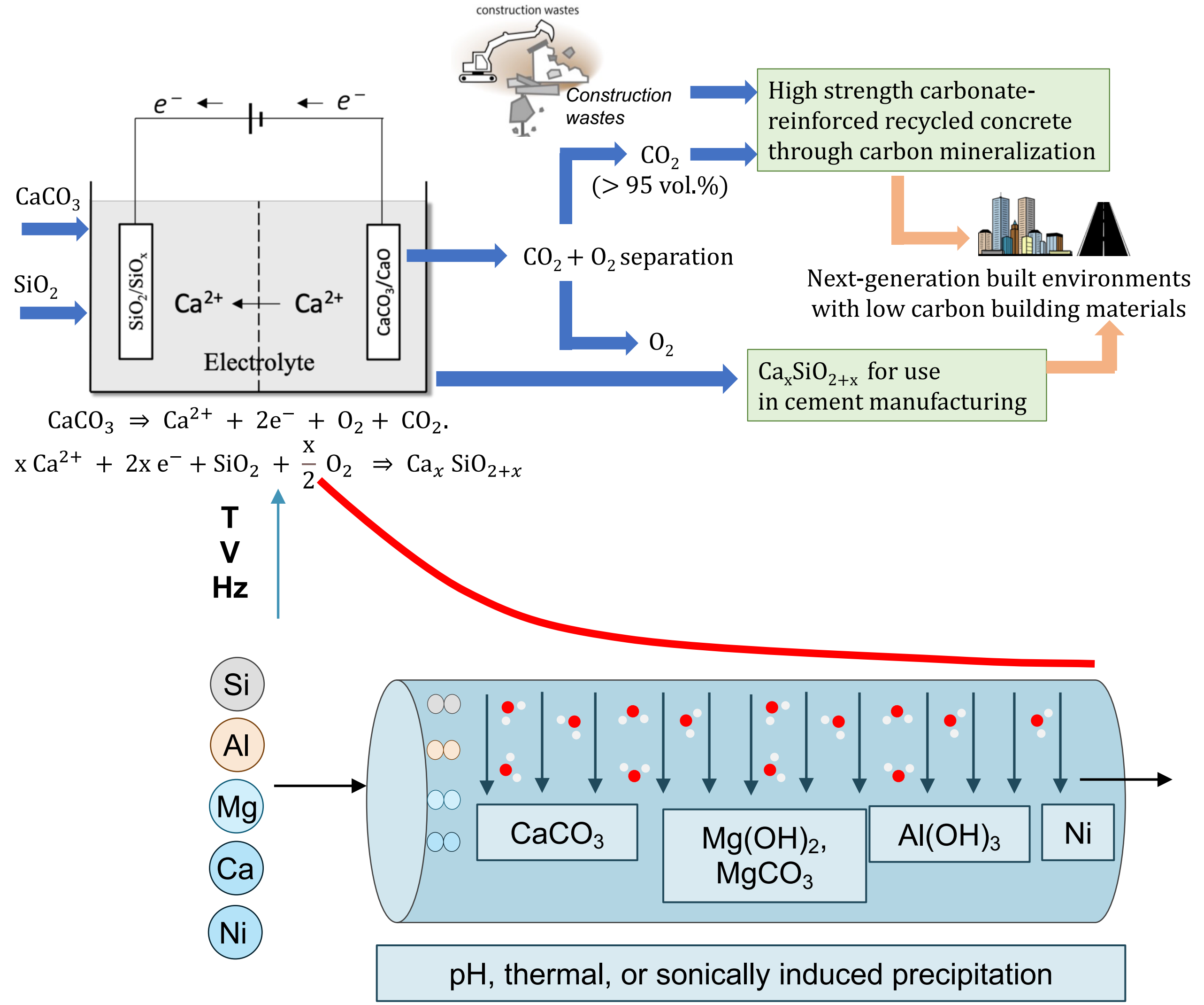
What did we hear?
Electrochemistry, biochemistry, mechanochemistry approaches



RESEARCH

We have a number of 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_2O 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 H_2O 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 CO_2 mineralized

Additional Information

- **Workshop Website**
  - https://arpa-e.energy.gov/events/co2-mineralization-for-in-situ-storage-and-ex-situ-enhanced-metals-recovery-workshop
- **Background Videos**
  - https://youtu.be/6EVwNm22Pc0
  - https://youtu.be/NBVELH40EaE
  - https://youtu.be/1BlhmCaDHPU
  - https://youtu.be/YfOuW9BG8E0