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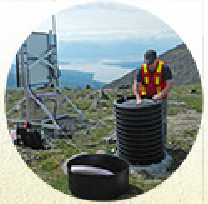


Geological Survey of Canada
Scientific Presentation 167

The geology of critical battery metals: a spotlight on Co in VMS deposits and Li in pegmatites

T.K. Cawood and J.M. Peter

2024

Canada

Presented at: Central Canada Mineral Exploration Convention

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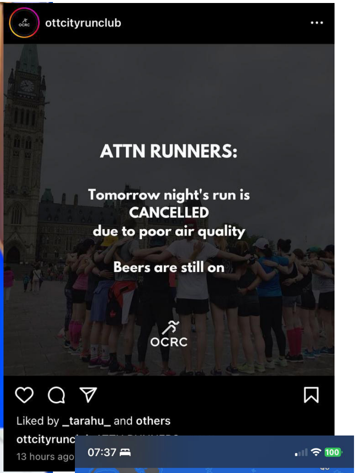
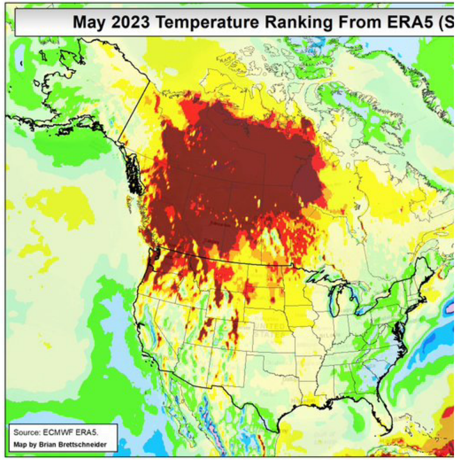
JUNE 2, 2023 Editors' note

Thousands ordered to flee advancing wildfires in Quebec

by Michel COMTE



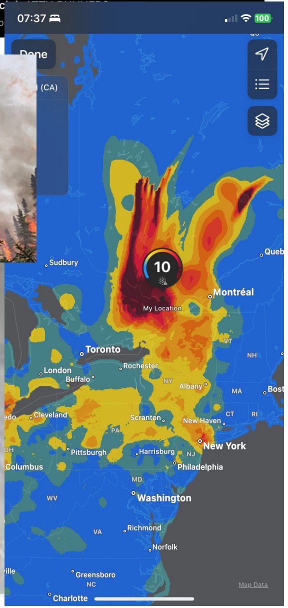


Extreme heat, wildfires wreaking havoc with hottest months still ahead

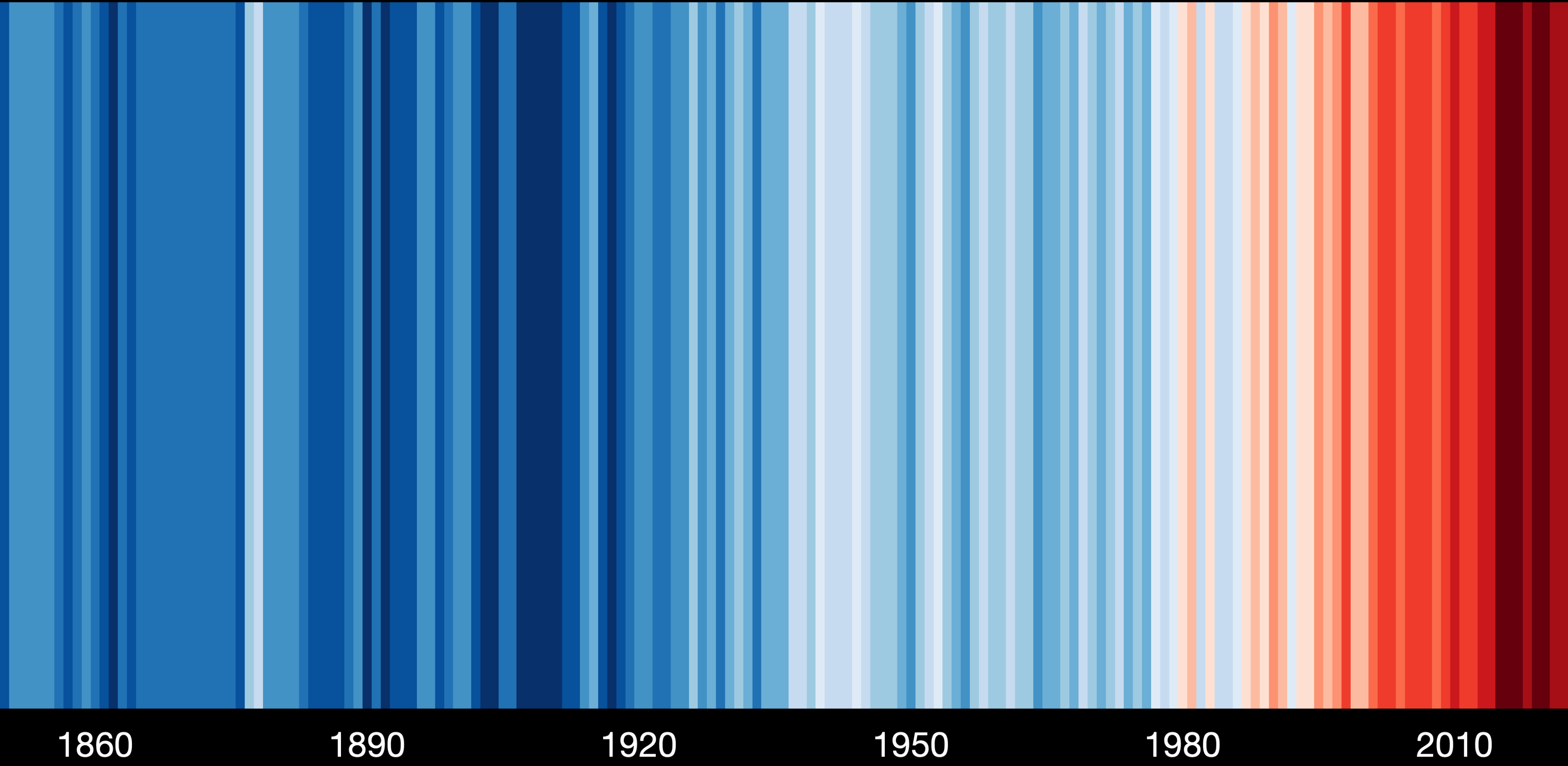
The oceans are record warm while heat waves have invaded multiple continents and ice levels are at historic lows

By Ian Livingston, Dan Stillman and Jason Samenow
June 6, 2023 at 6:00 a.m. EDT

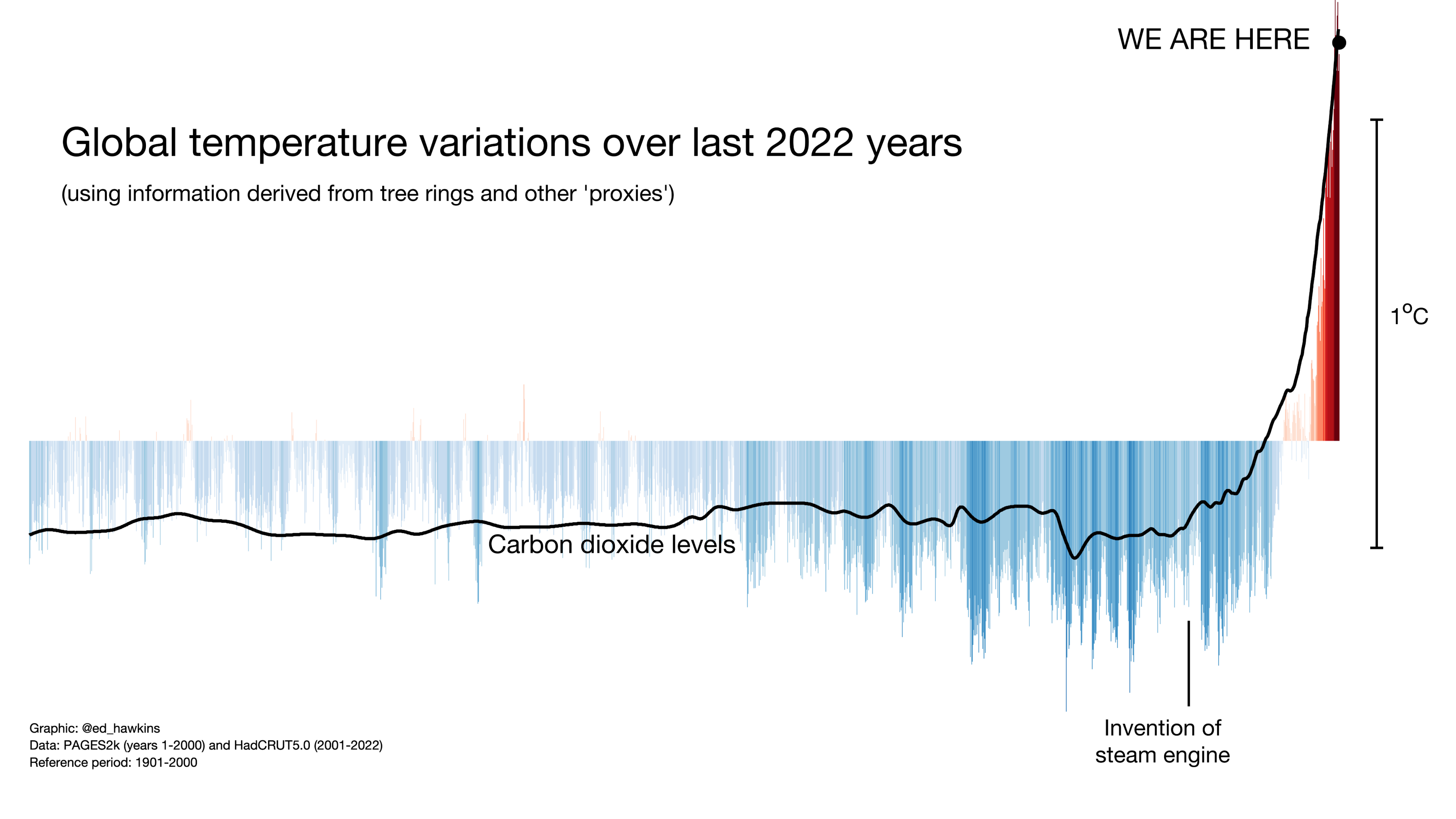
Smoke billows upward from a planned ignition by firefighters tackling the Donnie Creek Complex wildfire south of British Columbia on Saturda
(B.C. Wildfire Service/Reuters)



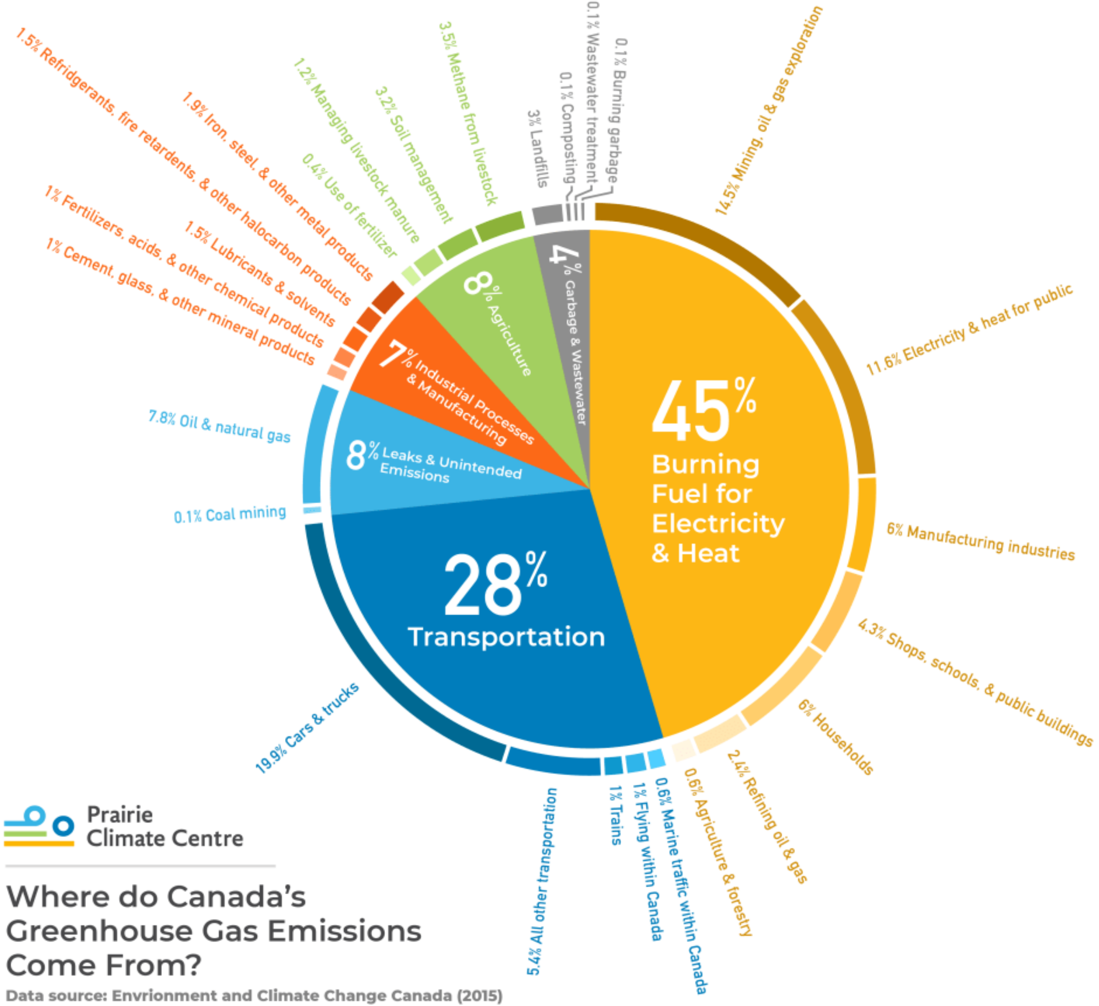
Global temperature change (1850-2022)



Ed Hawkins, https://ed-hawkins.github.io/climate-visuals/stripes.html


WE ARE HERE
Global temperature variations over last 2022 years
(using information derived from tree rings and other 'proxies')
1°C
Carbon dioxide levels
Invention of steam engine
Graphic: @ed_hawkins
Data: PAGES2k (years 1-2000) and HadCRUT5.0 (2001-2022)
Reference period: 1901-2000

Major Emitters



Why Batteries?

Taking To The Skies For Climate Change | Climate Games

Fundraiser

Danny MacAskill

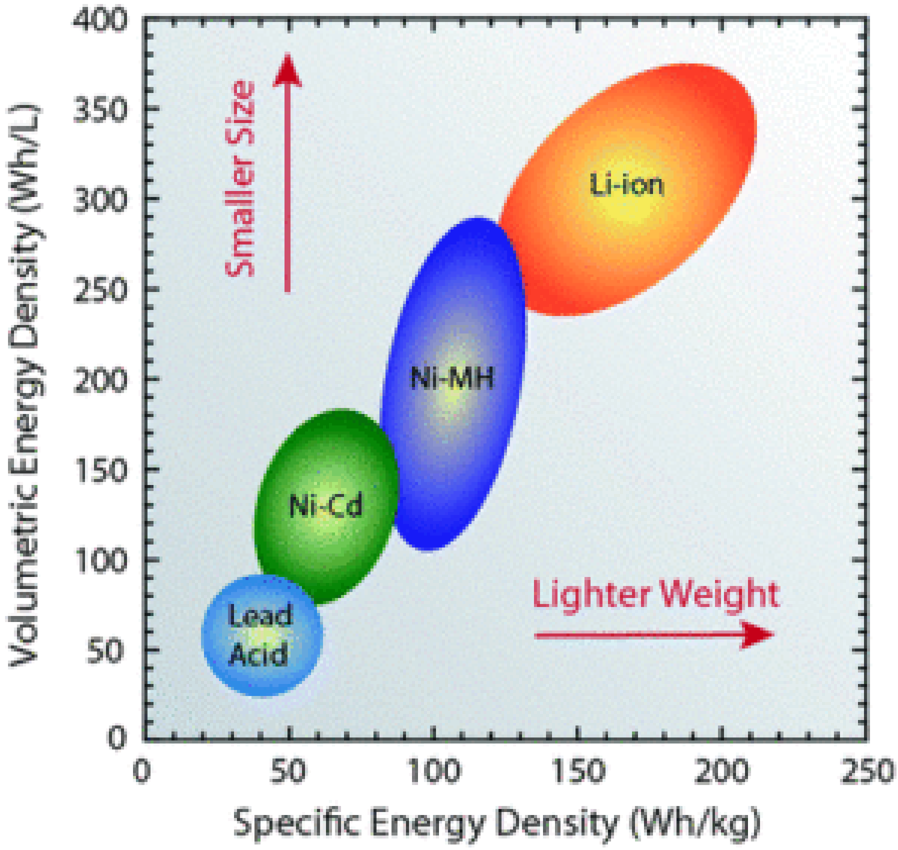
510K subscribers

Subscribe

https://www.livezeno.com/; https://www.youtube.com/watch?v=XR4maEf-eCY

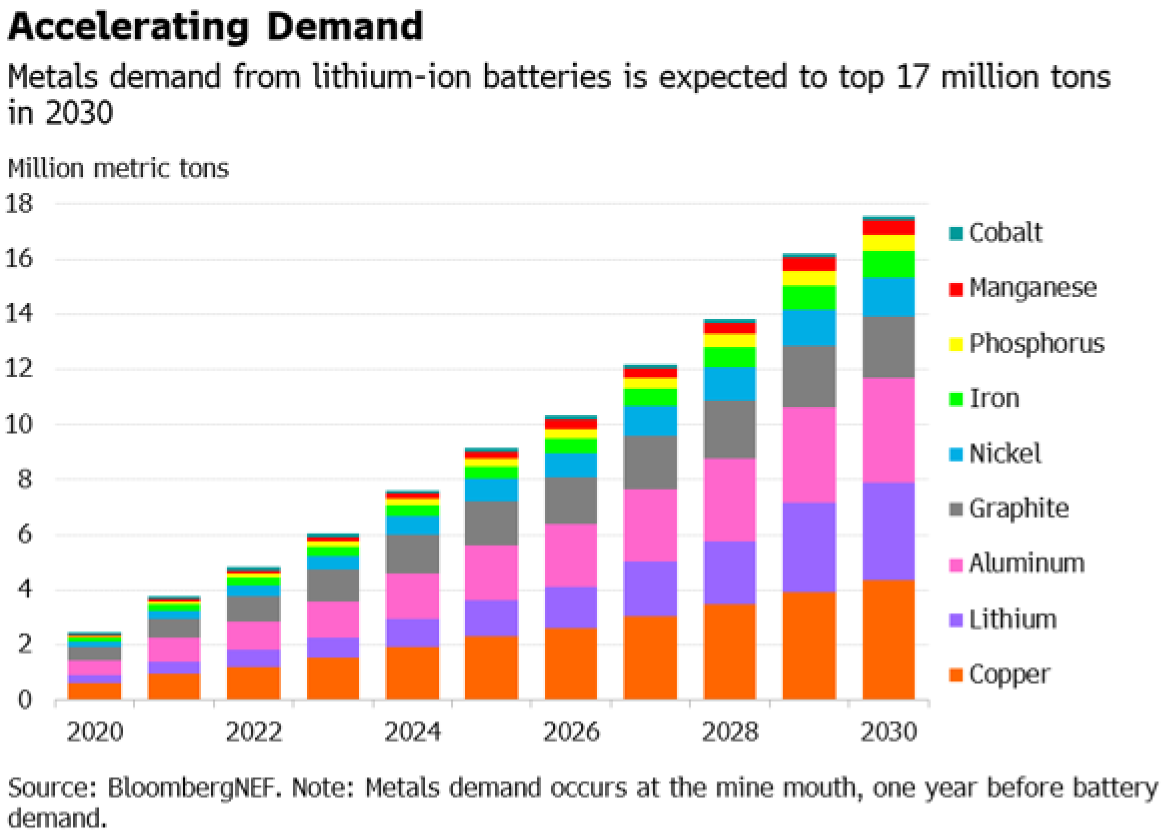
Li-Ion Batteries

- High energy density
  = ***small & light***
- High voltage
  = ***good for high-power applications***
- Low maintenance
- No memory effect (which can lower capacity over time)
- Non-toxic (no cadmium)



https://www.cei.washington.edu/education/science-of-solar/battery-technology/

Increasing Demand for Metals



https://about.bnef.com/blog/race-to-net-zero-the-pressures-of-the-battery-boom-in-five-charts/

Sources of Cobalt

Co^{2+} is compatible:

Concentrates into olivine in the mantle
Only released to magma after high degree of partial melting
Highest in ultramafic (+ mafic) magmas

Co is mobile in aqueous fluids, as Co^{2+} but especially as chloride species:

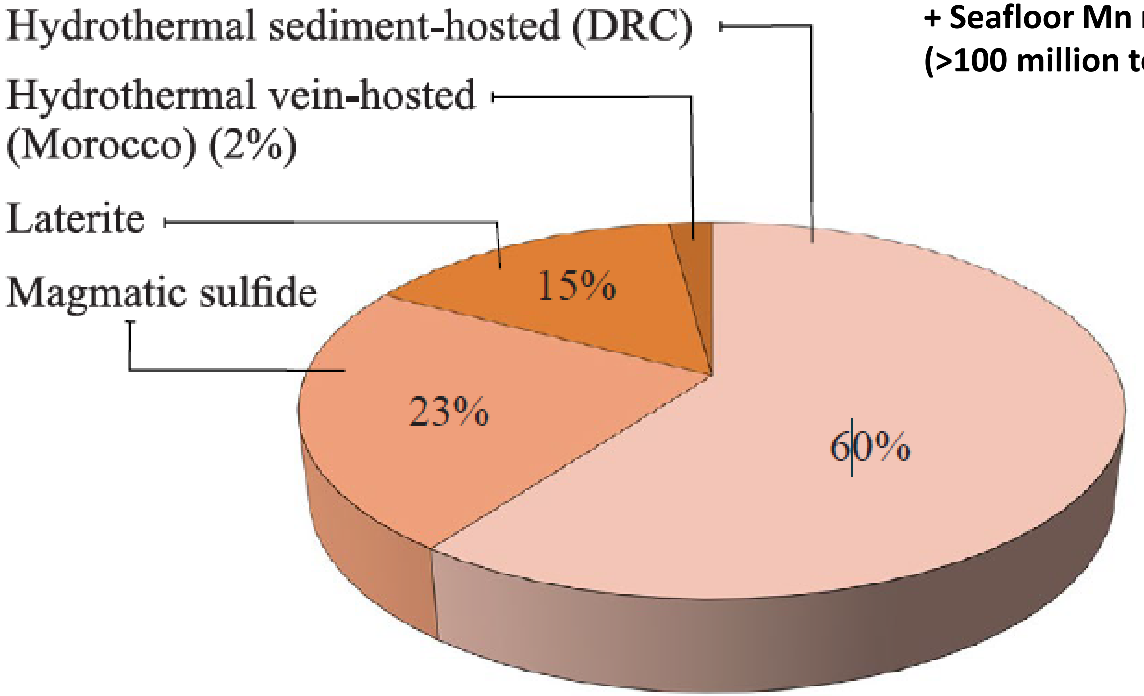
Mobilized by oxidized high-salinity brines

Williams-Jones & Vasyukova 2022. Part I. *Economic Geology;* Vasyukova & Williams-Jones 2022. Part II. *Economic Geology.*

Sources of Cobalt

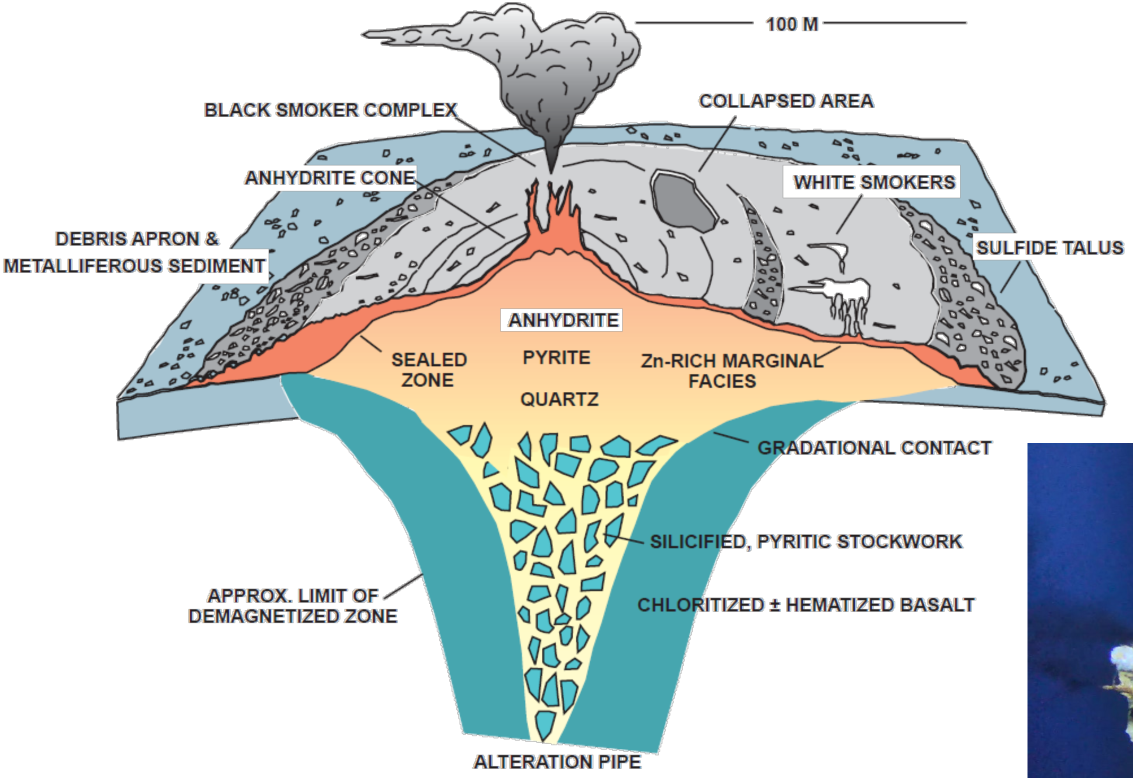
+ VMS deposits
(e.g. Windy Craggy, ~190 000 tonnes Co)

+ Seafloor Mn nodules & Fe-Mn crusts
(>100 million tonnes Co)



Williams-Jones & Vasyukova 2022. Part I. *Economic Geology;* Petersen et al. 2016 *Marine Policy*

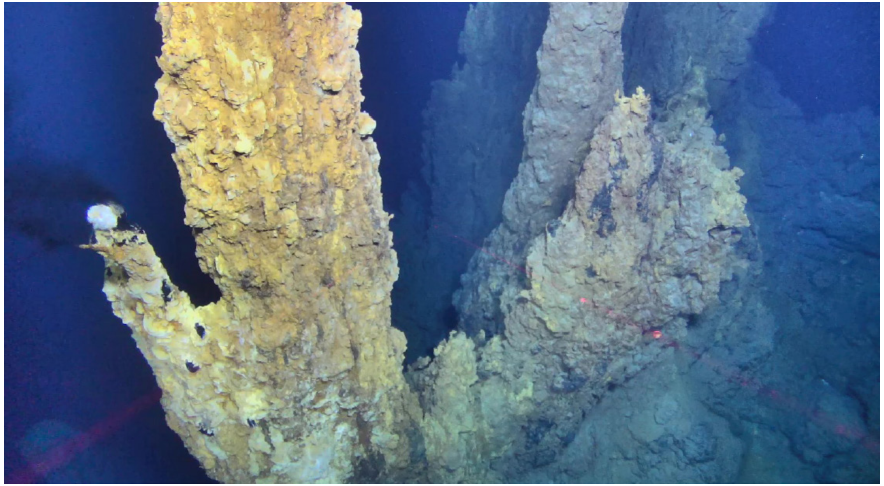
Sources of Cobalt: VMS Deposits



Fåvne seafloor massive sulfide deposit, Arctic Mid-Ocean Ridge:

- Up to 0.98 wt% Co in whole-rock samples
- In pyrrhotite, (isocubanite, sphalerite, magnetite) in high-T zones

→ Ultramafic/mafic source rocks
→ High-salinity Cl- fluids
→ Focused high-T venting



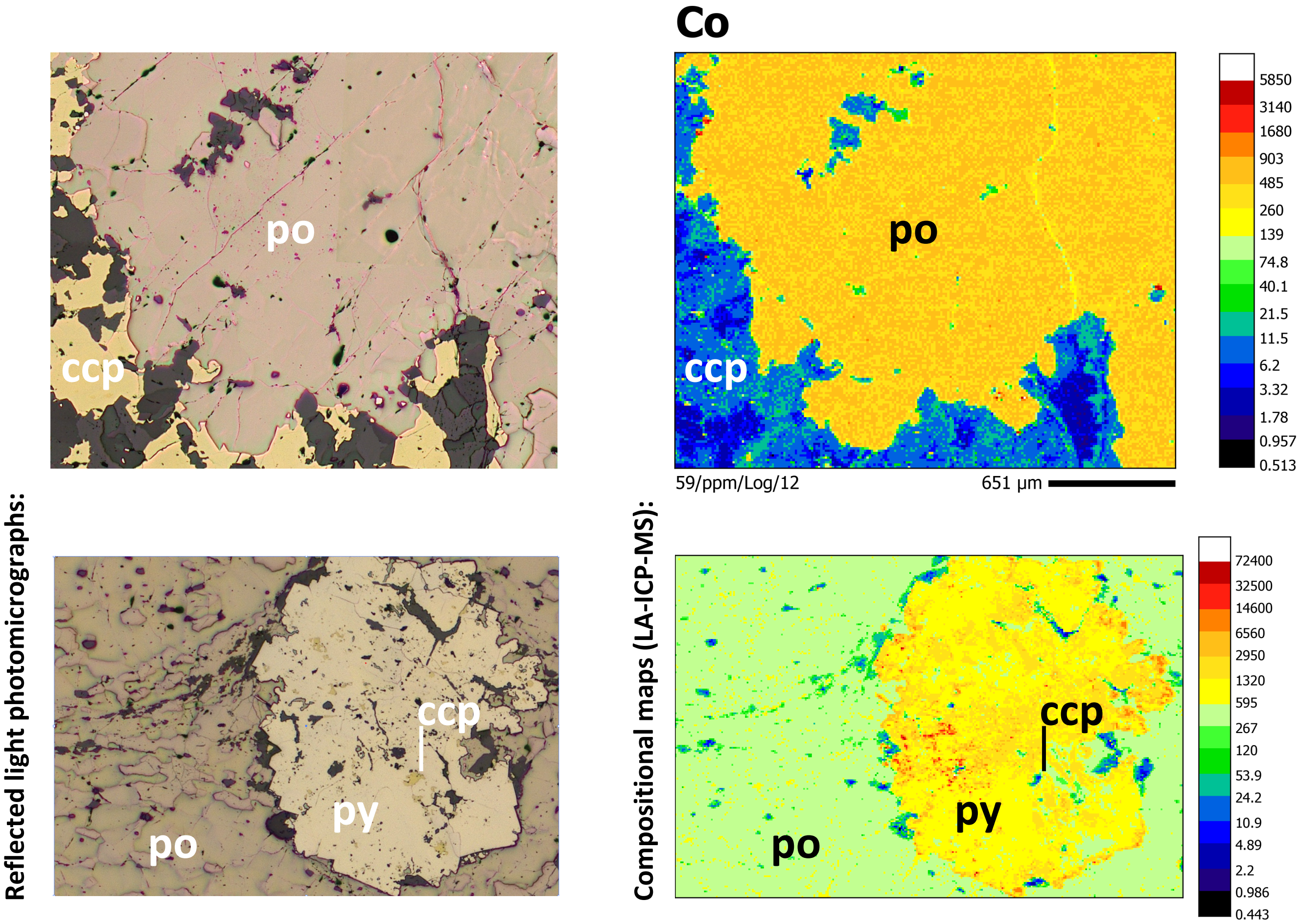
Galley et al. 2007 *Mineral Deposits of Canada;* Sahlström et al. 2023 *Ore Geology Reviews*

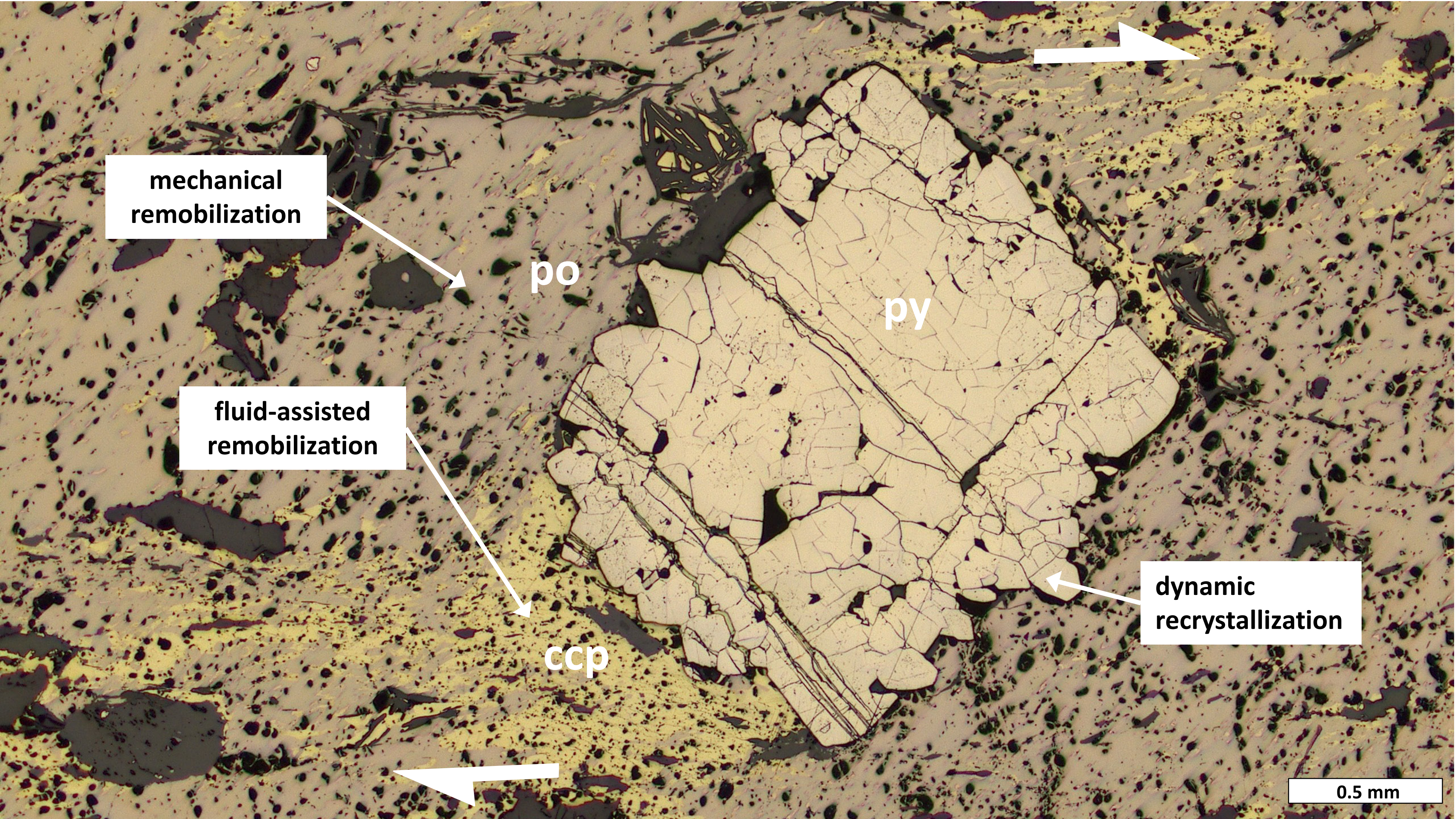
The Windy Craggy VMS deposit

272 Mt @ 0.07% Co =
~190 000 tonnes Co

Peter & Scott, 1993. *Resource Geology Special Issue, no. 17;* photo by Jan Peter

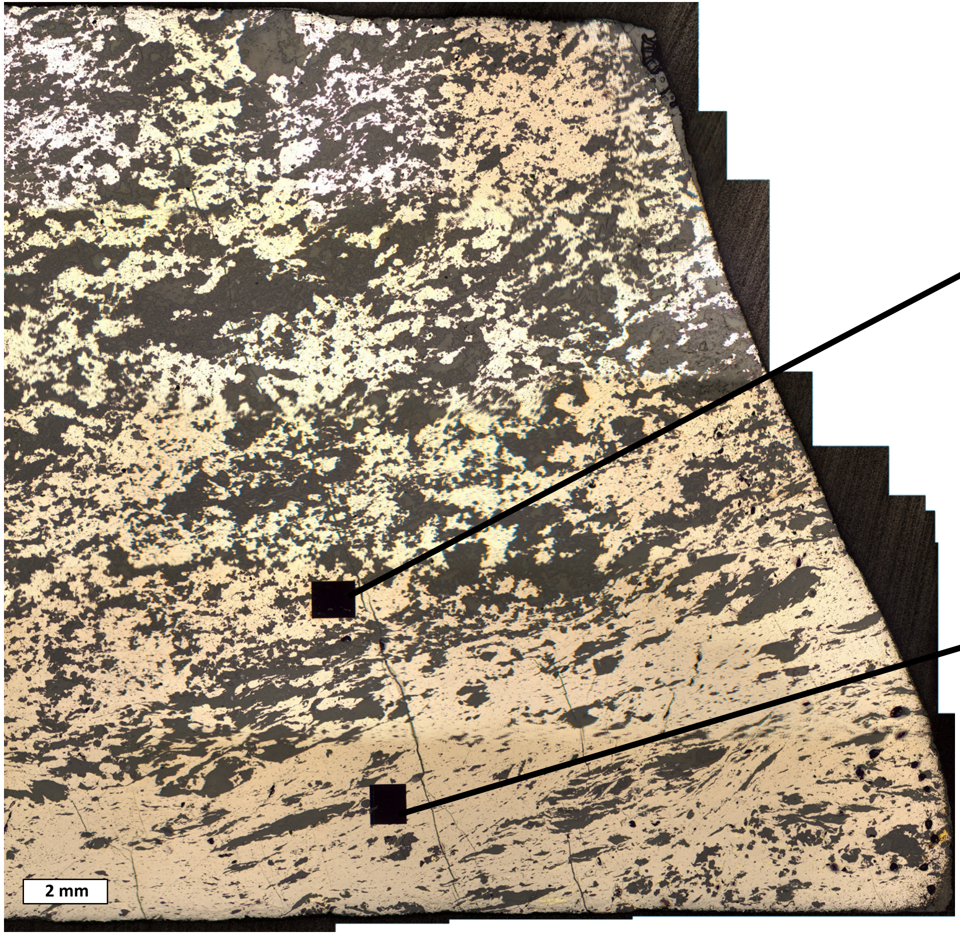
Main Hosts of Co



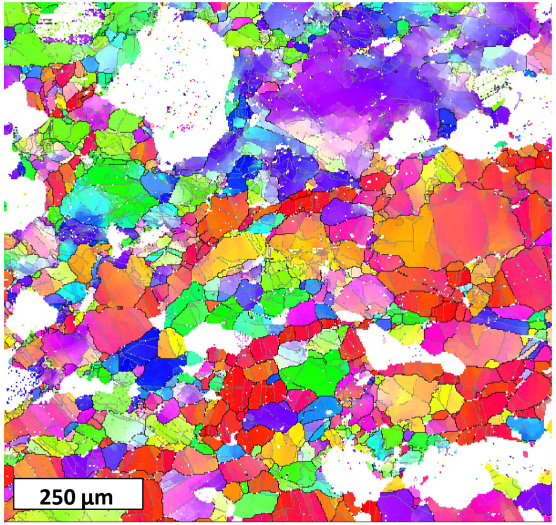

mechanical remobilization
po
py
fluid-assisted remobilization
ccp
dynamic recrystallization
0.5 mm

Co in Pyrrhotite

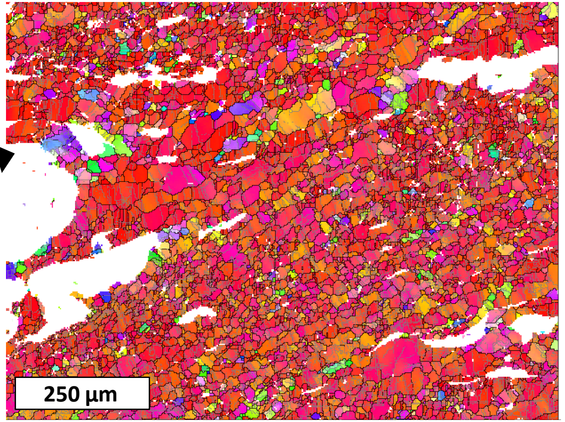
Reflected light photomicrograph:



Grain orientation maps (EBSD):



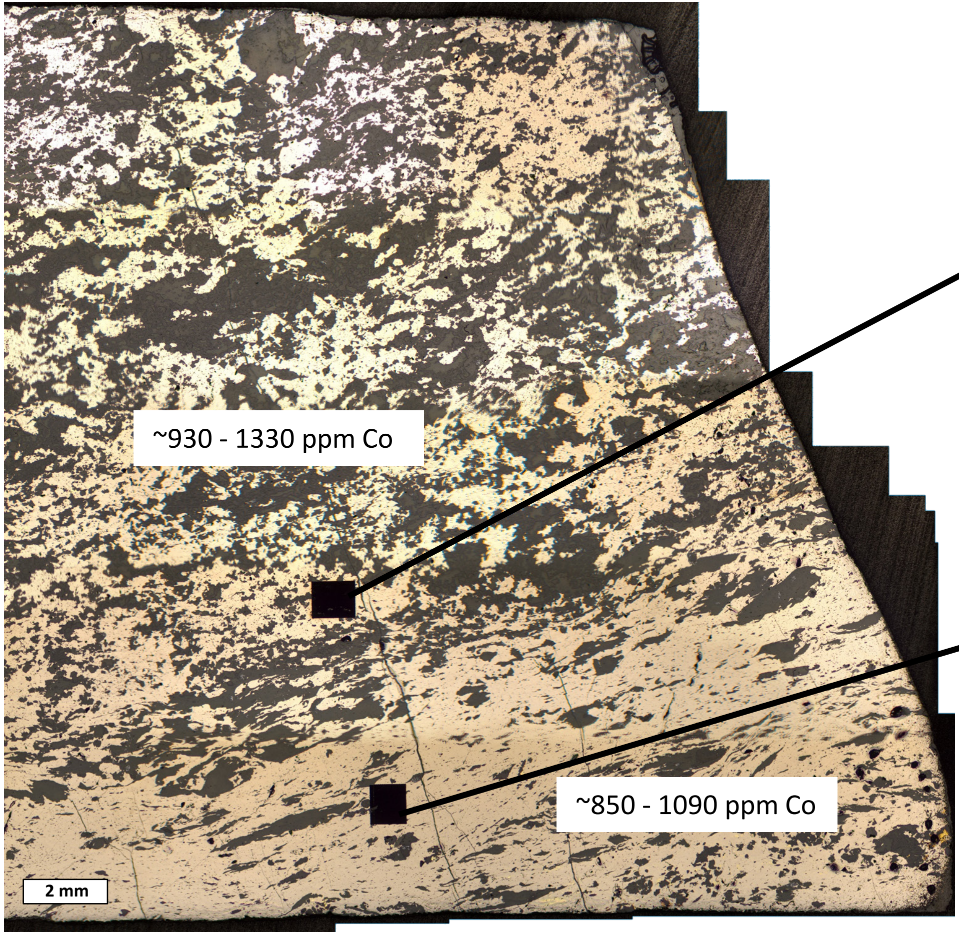
- internal grain distortion
  = dislocation creep



- finer grain size for foliated pyrrhotite
  = dynamic recrystallization

Co in Pyrrhotite

Reflected light photomicrograph:



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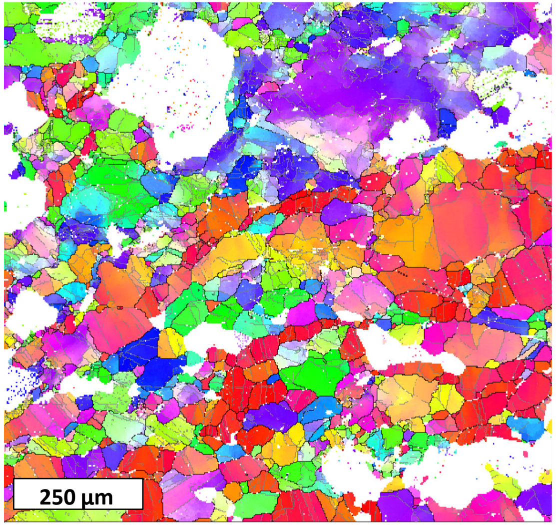

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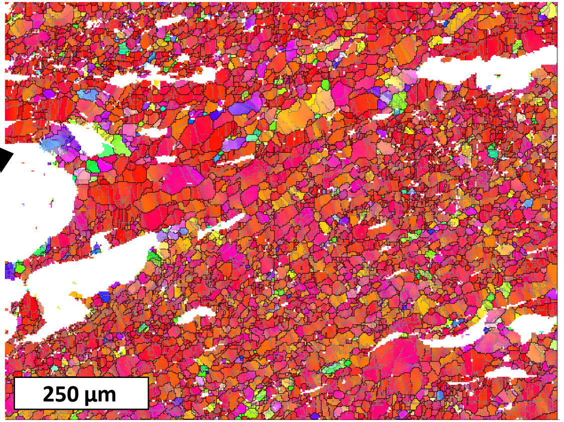
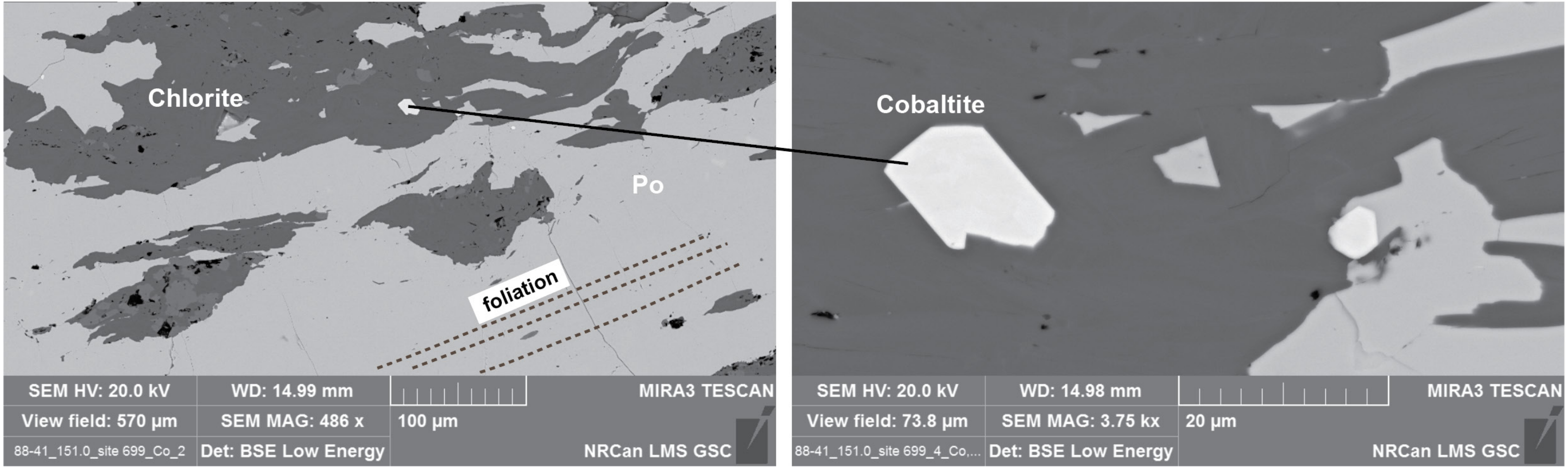


- finer grain size for foliated pyrrhotite
  = dynamic recrystallization

Co in Pyrrhotite… and Cobaltite

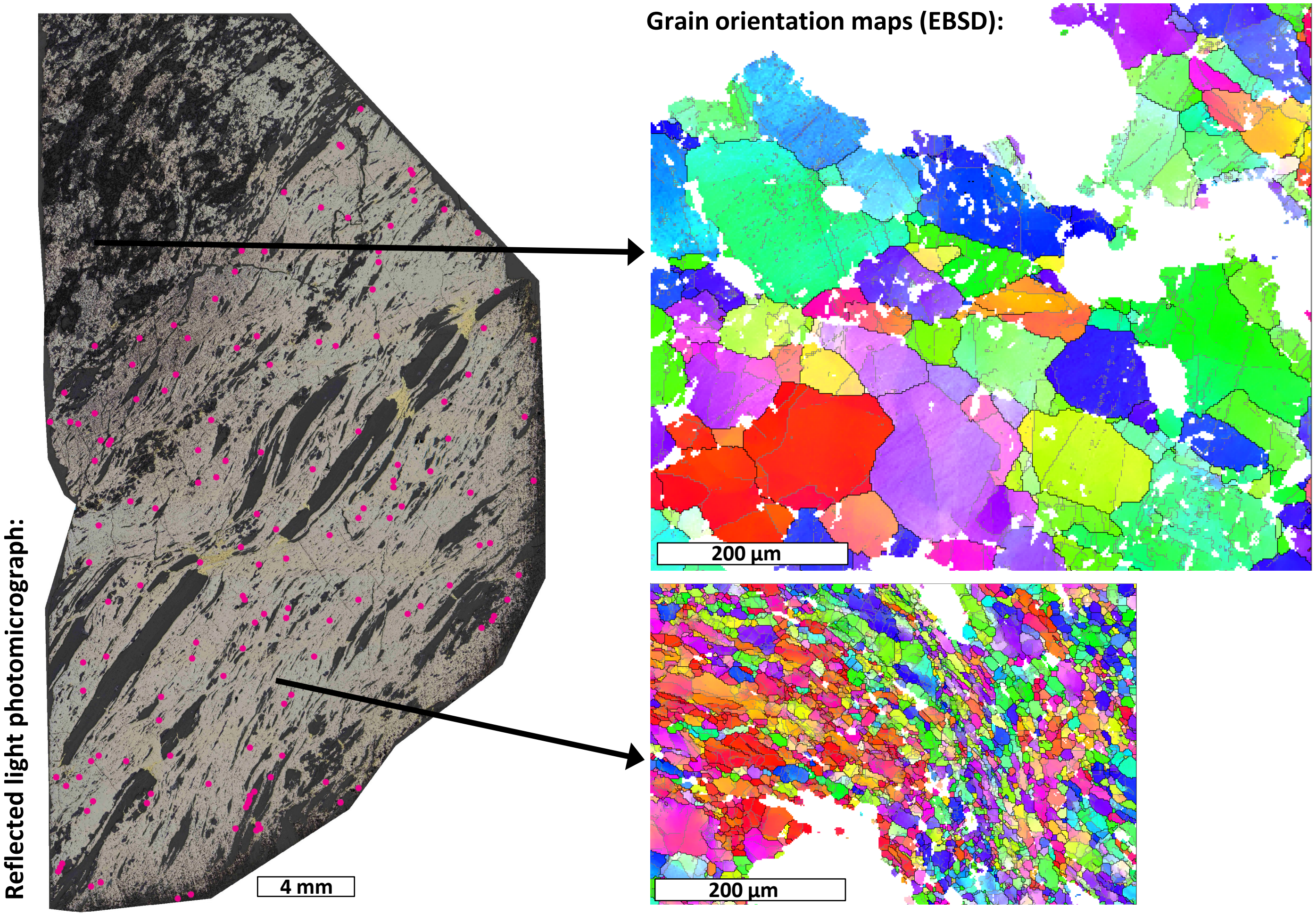
Backscattered electron (BSE) images



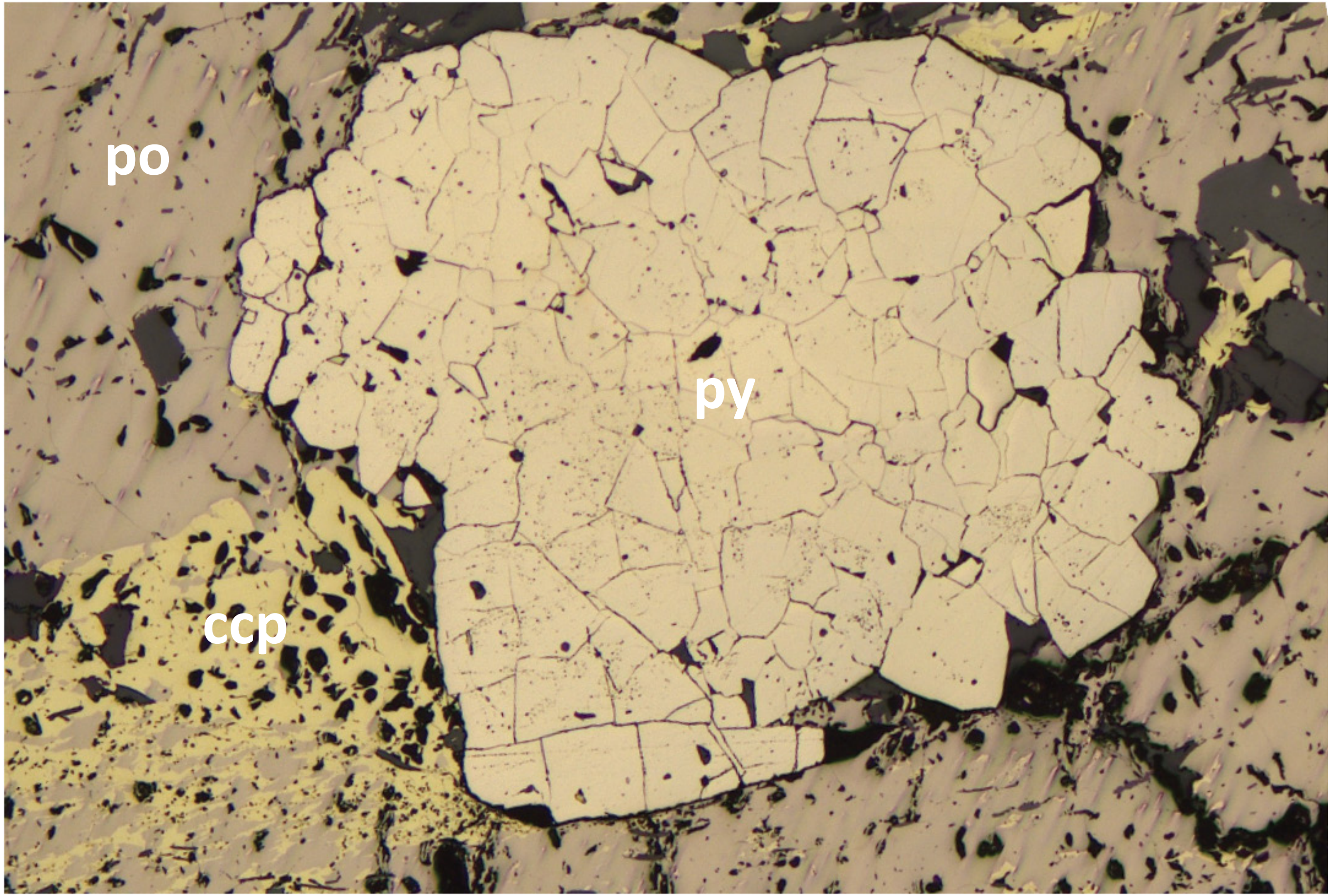
- Rare, fine-grained cobaltite (CoAsS) appears to be associated with sheared, dynamically recrystallized pyrrhotite

= suggests that (some) Co is released from Po during dynamic recrystallization, contributing to formation of cobaltite

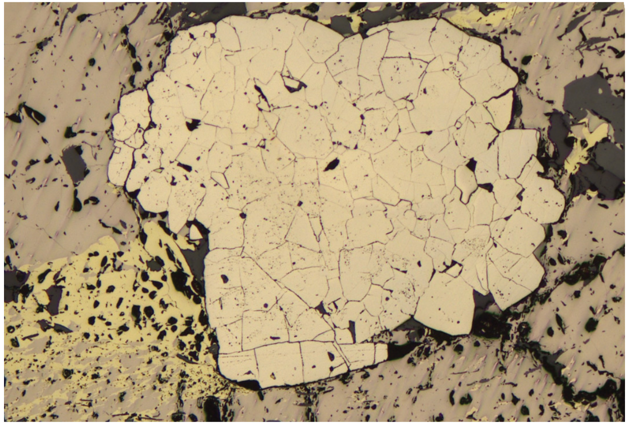
Co in Pyrrhotite… and Cobaltite



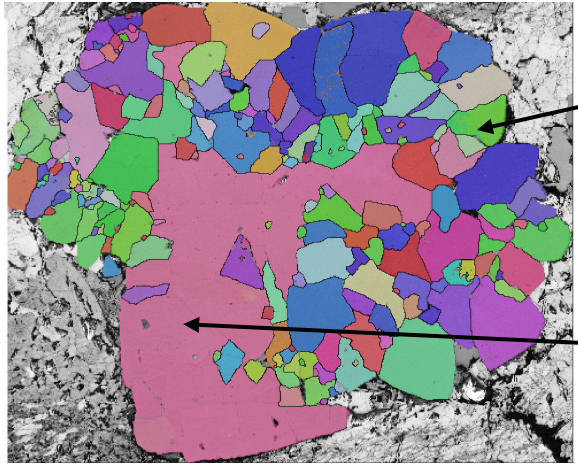
Co in Pyrite



Co in Pyrite



Reflected light photomicrograph



Grain orientation map (EBSD)

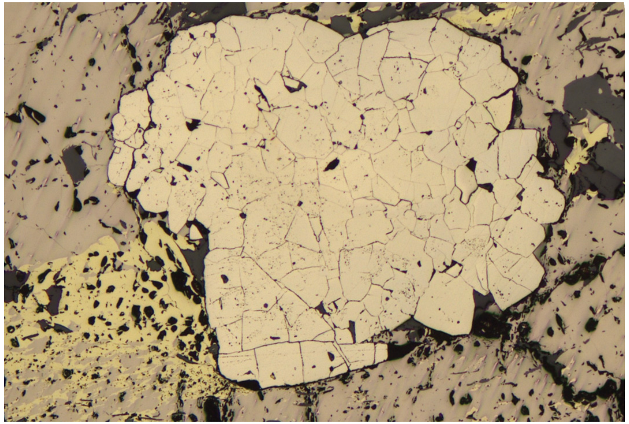
Distinct grains
= reX

Relict, non-reX
= primary
hydrothermal py

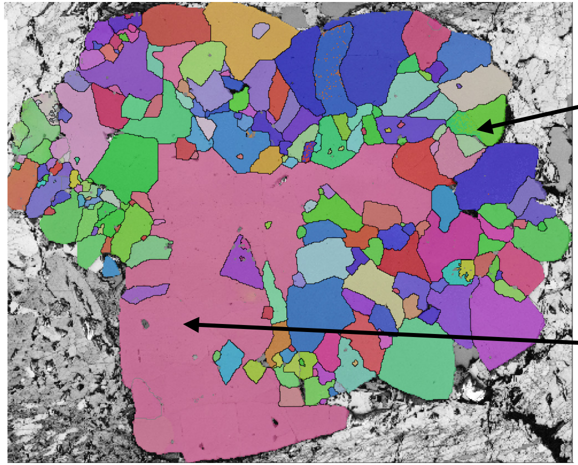
Cawood, Peter et al in prep.

Co in Pyrite

Reflected light photomicrograph



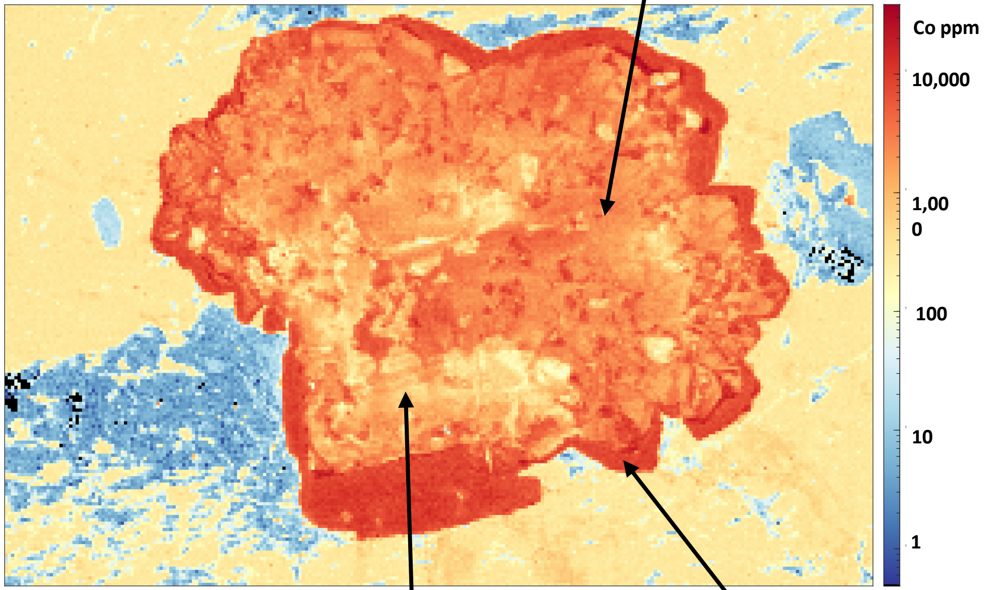
Grain orientation map (EBSD)



Distinct grains = reX

Relict, non-reX = primary hydrothermal py

Compositional map: Co (LA-ICP-MS)



~3,060 ppm
~area of reX subgrains

~185 – 1,390 ppm
Primary zoned py

~9,000 ppm
Rim must post-date reX
= diffusion during peak metamorphism

Cawood, Peter et al in prep.

Sources of Lithium

Li is incompatible

Behaves as a Large-Ion Lithophile element
Enriched in melts > crystals,
felsic > mafic > ultramafic

Li is highly mobile

Small ionic radius
High electropositivity (Li^+)
Water soluble (esp. + chlorine)
Least dense of all solids (~pine wood!)

Bunker 2022 From mines to brines, *GeoHug;* Bunker et al. 2022 *Geoconvention*; https://twitter.com/BMPMetals/status/1048264055369216000

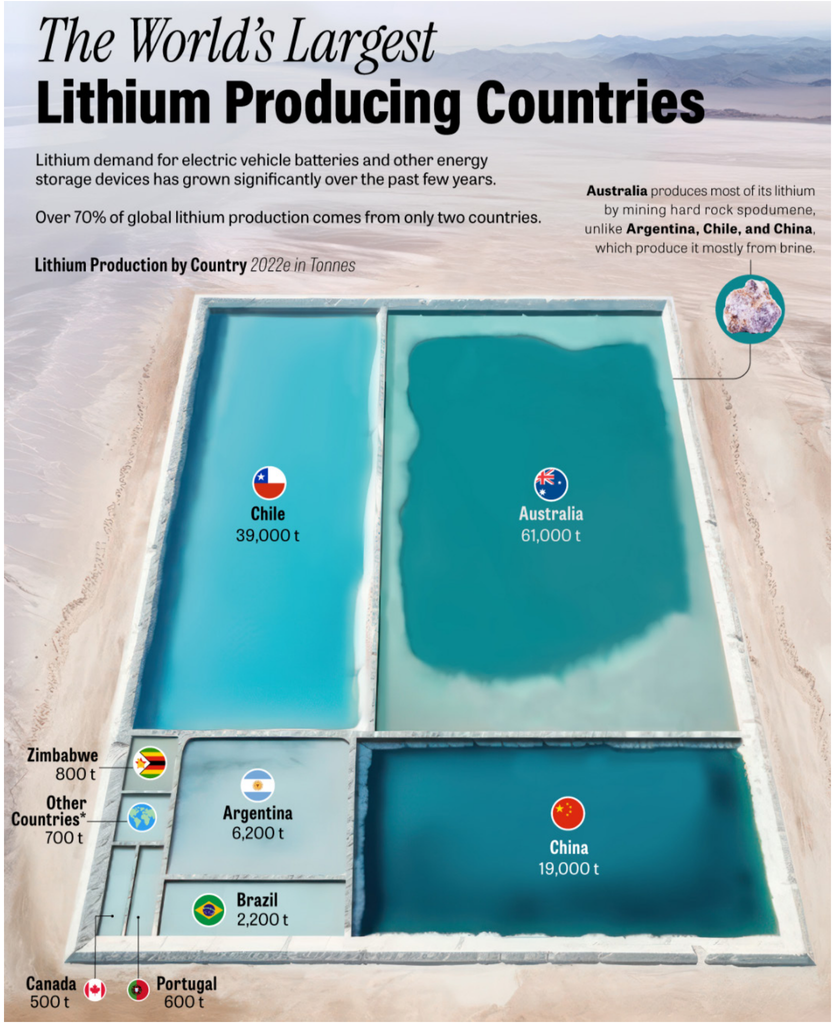
Sources of Lithium

- **Li-rich granites & pegmatites**
  Tanco Mine, MB; Greenbushes, Australia; Bikita, Zimbabwe

- **Li clays**
  Thacker Pass, Nevada

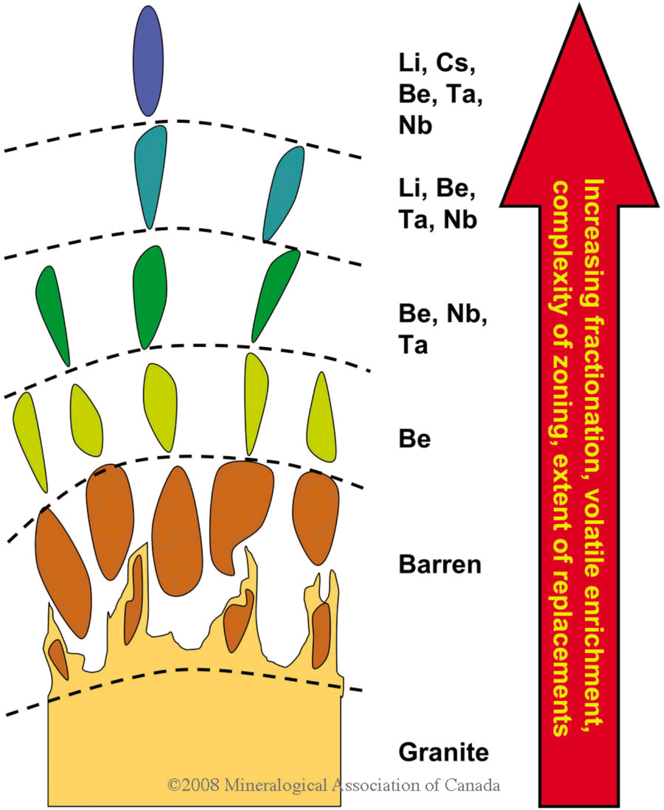
- **Salars (evaporative brines)**
  Salar de Atacama, Chile; Bolivia; Argentina

- **Other Li brines**
  Geothermal brines – Salton Sea, California
  Oilfield brines - Alberta



Bunker 2022 From mines to brines, *GeoHug,* Youtube; https://elements.visualcapitalist.com/visualizing-the-worlds-largest-lithium-producers/

Sources of Lithium: Rare Metal Pegmatites

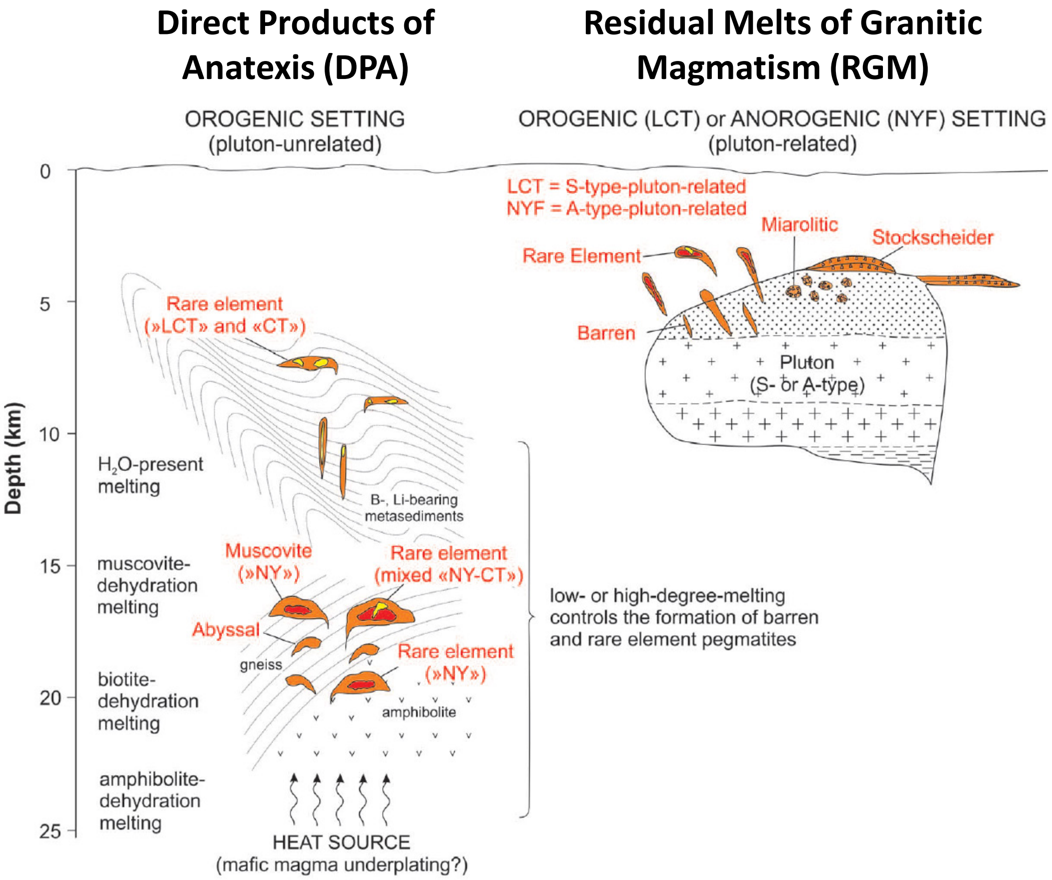


Ore Deposit Model:
Residual Melts of Granitic Magmatism (RGM)

- "Fertile" granites (S-type, 2-mica, peraluminous…) form from partial melting of metasediments
- Fractional crystallization (FX) within pluton → more evolved compositions
- Extreme FX → melt rich in incompatible elements (Li, Cs, Ta, Nb…), fluxes & volatiles (water, B…), lower viscosity & solidus → form pegmatites
- Mineralogical/chemical zonation around parent granite

London 2008, after Cerny 1989, 1990; Simmons & Webber 2008. *European Journal of Mineralogy*; Wise et al. 2022 *The Canadian Mineralogist*

Genetic Models for Rare Metal Pegmatites



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- Mineralogical/chemical zonation around parent granite

Direct Products of Anatexis (DPA)

- Low degrees of partial melting → form pegmatites directly
- Still need some FX to concentrate rare metals?
- Maybe not – melt pre-enriched rocks (like earlier granites, Ballouard et al. 2023, Koopman et al. 2023)

Simmons et al. 2016, *The Canadian Mineralogist;* Doggart 2019, *MSc;* Müller et al. 2017 *The Canadian Mineralogist;* Wise et al. 2022 *The Canadian Mineralogist*;

Rare Metal Pegmatites from Direct Anatexis

Work in progress, with Dr. Danny Hnatyshin (GSC), and Prof. Lee Groat & Cat Breasley (UBC)

Rare Metal Pegmatites from Direct Anatexis

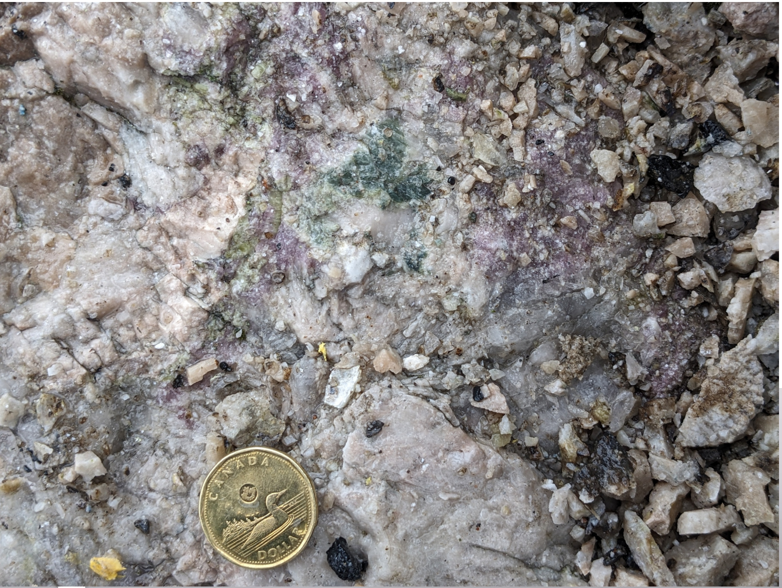
- lepidolite
- green tourmaline
- beryl
- lithiophilite
- columbite

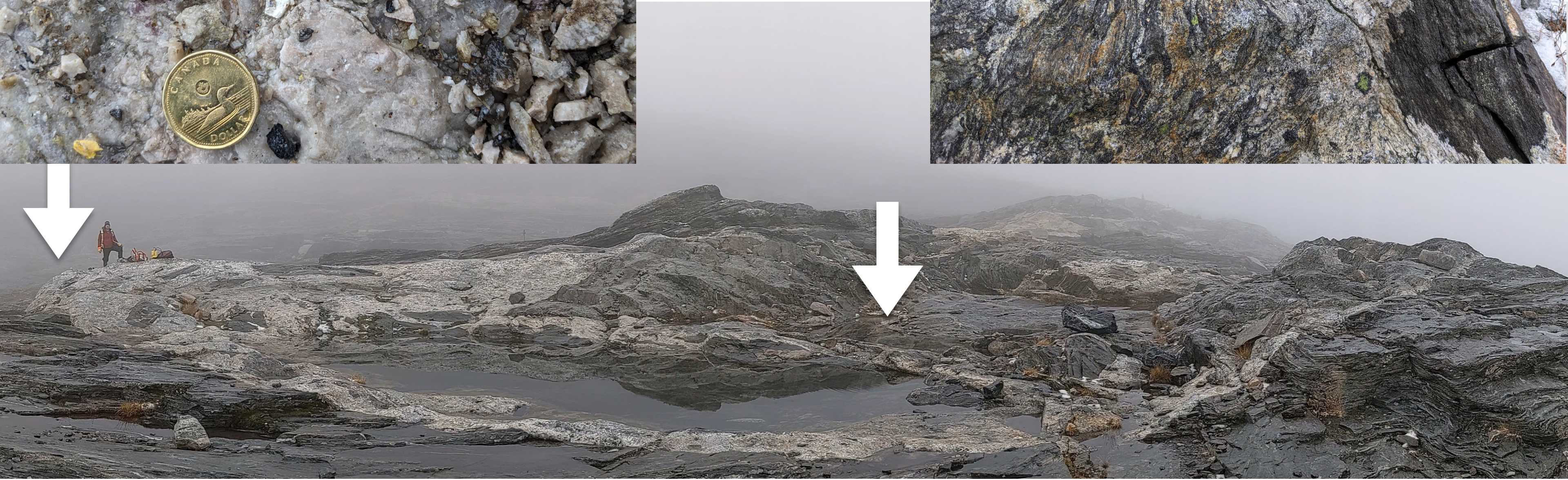
Dixon et al. 2014. *The Canadian Mineralogist*

Rare Metal Pegmatites from Direct Anatexis

- diatexite migmatite
- transitional into pegmatite
- same dyke as Li-bearing zone

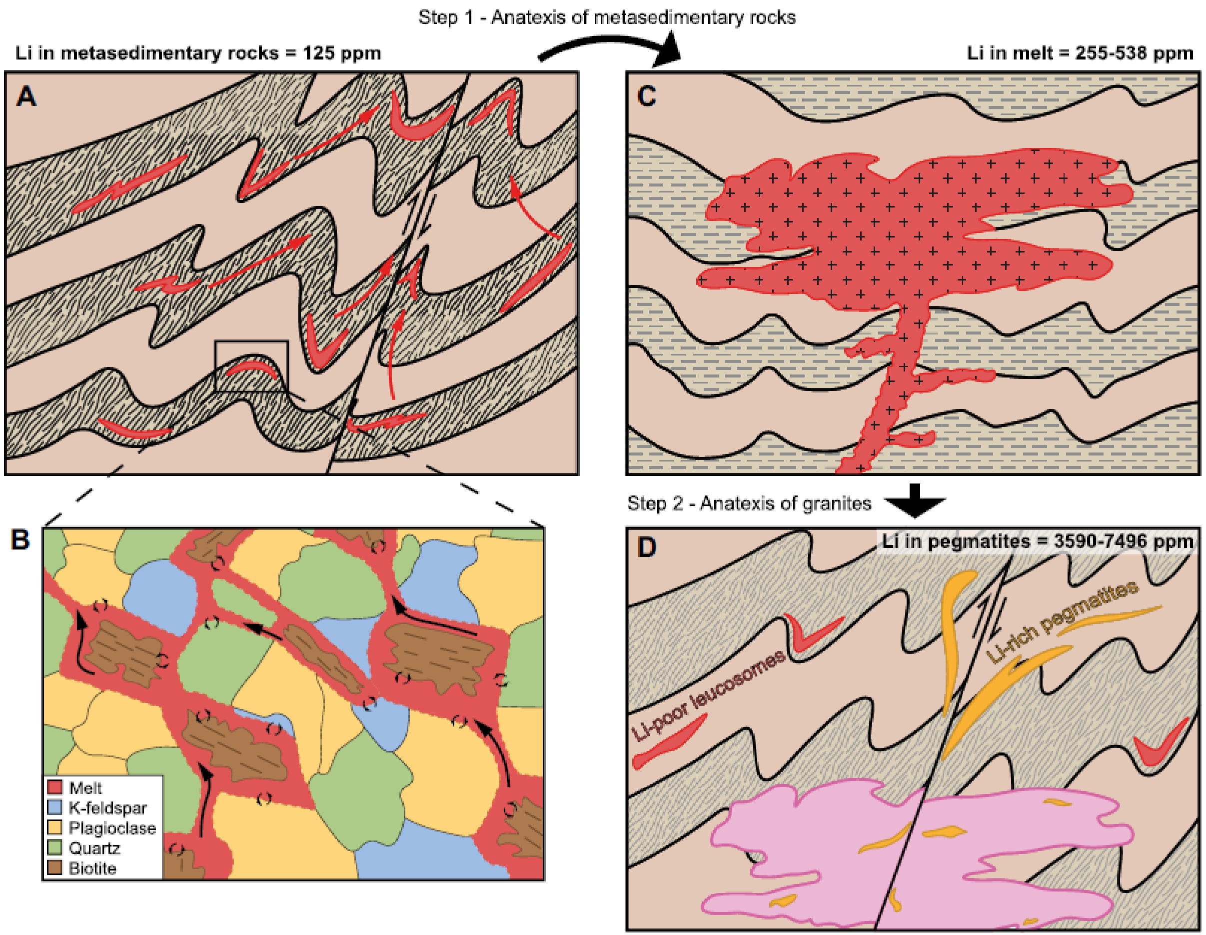
Rare Metal Pegmatites from Direct Anatexis





Rare Metal Pegmatites from Direct Anatexis

Rare Metal Pegmatites from Direct Anatexis… of Granites



Koopmans et al. 2023 *Geology,* also see Ballouard et al. 2023 *Contrib. to Min. & Petr.*

Questions?

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