How Deformation Affects the Distribution of Battery Metals:
From the Regional to the Micro Scale

Dr. Tarryn Kim Cawood
University of British Columbia – Okanagan, Canada

IASGT Accra 2026
Structural Geology in a Changing World

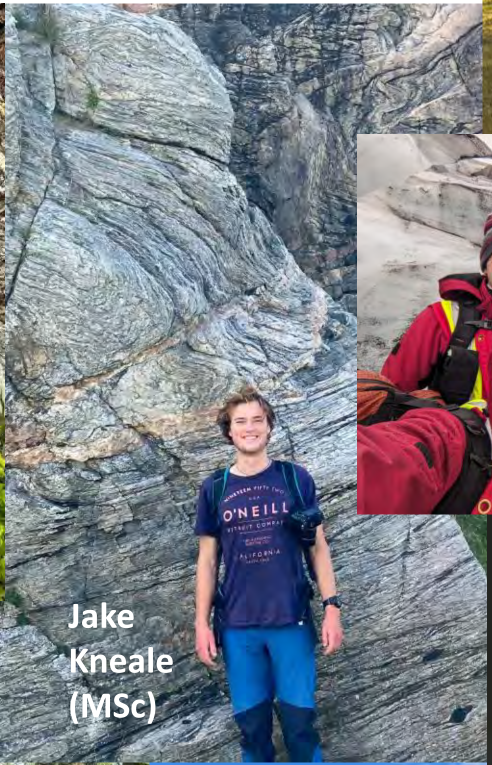
No Woman is an Island

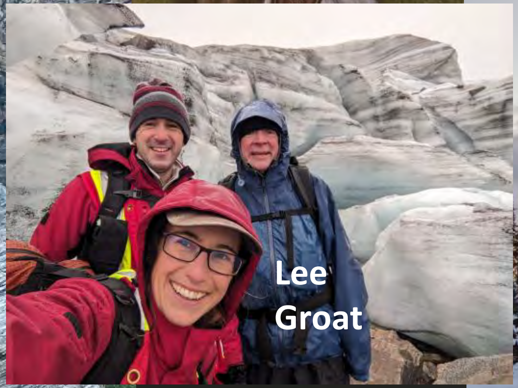
Black Mountain Mining

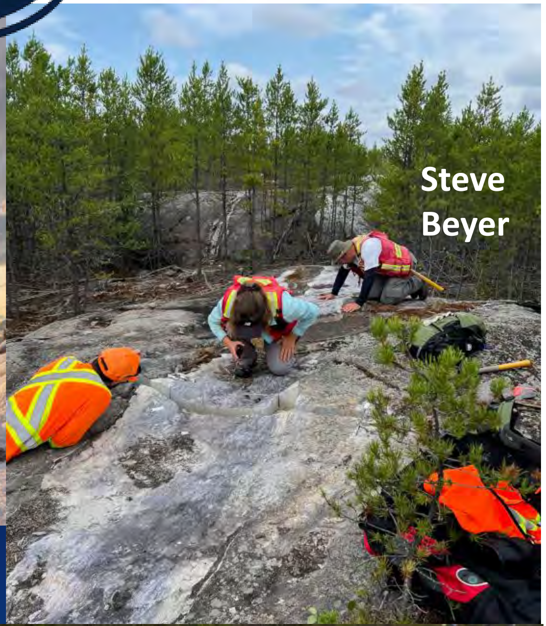
UBC

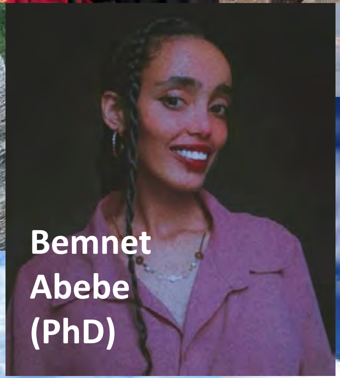
Canada

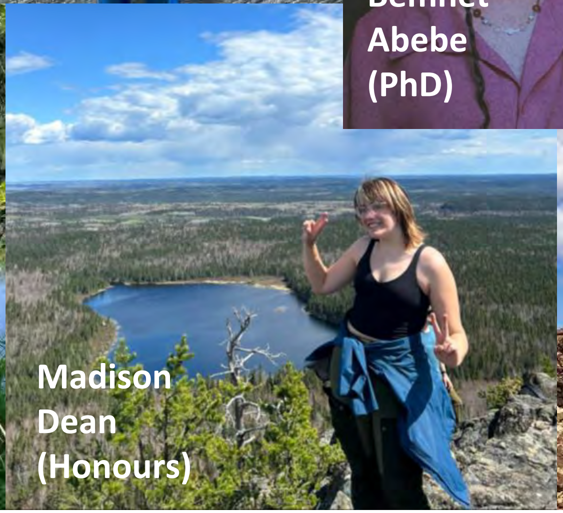
vedanta





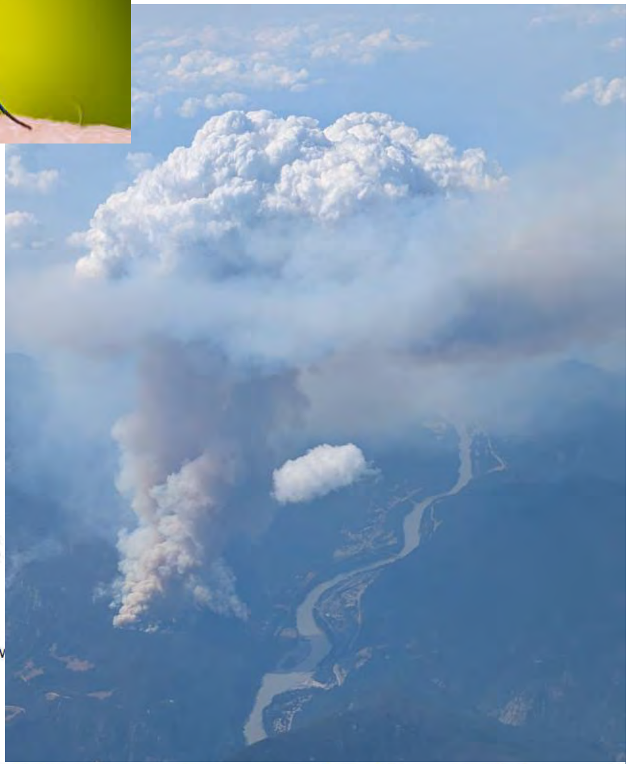







Why do we care about battery metals?

https://www.theguardian.com/commentisfree/2022/nov/05
/africa-climate-crisis-cop27-drought-flooding-support



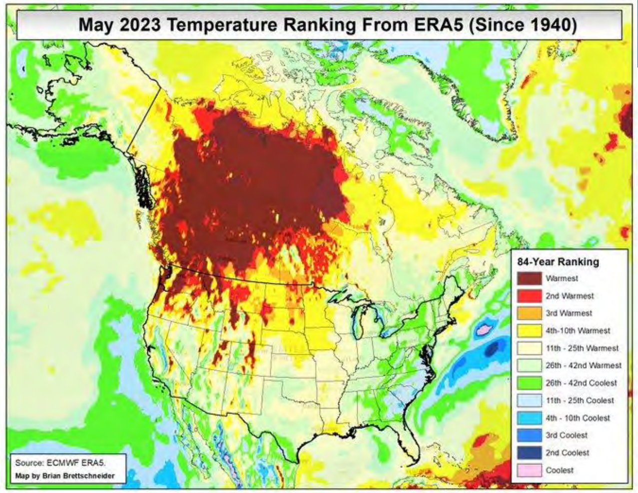
https://www.nsri.org.za/

Extreme heat, wildfires wreaking havoc with hottest months still ahead

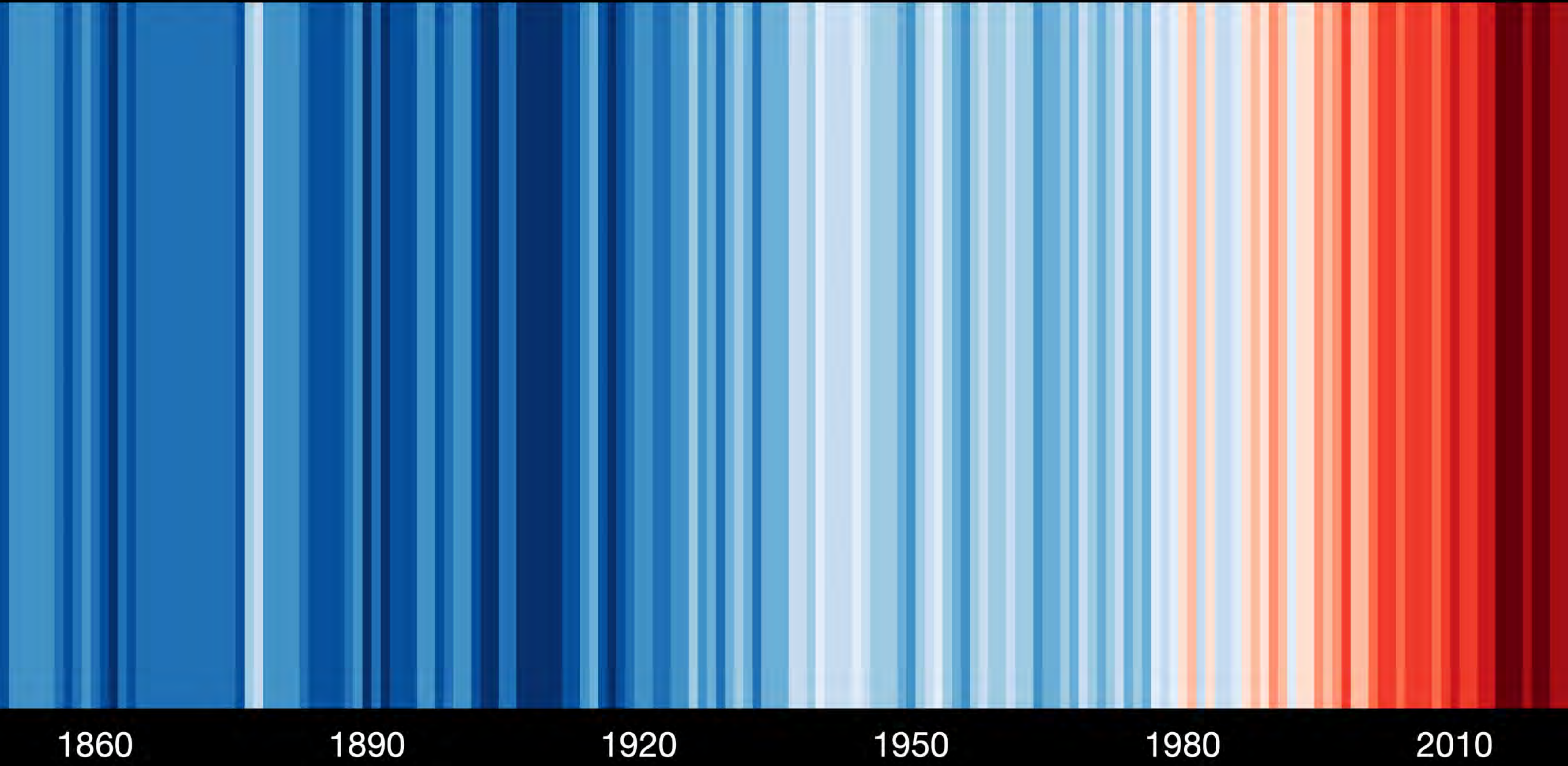
The oceans are record warm while heat waves have invaded multiple continents and ice levels are at historic low

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

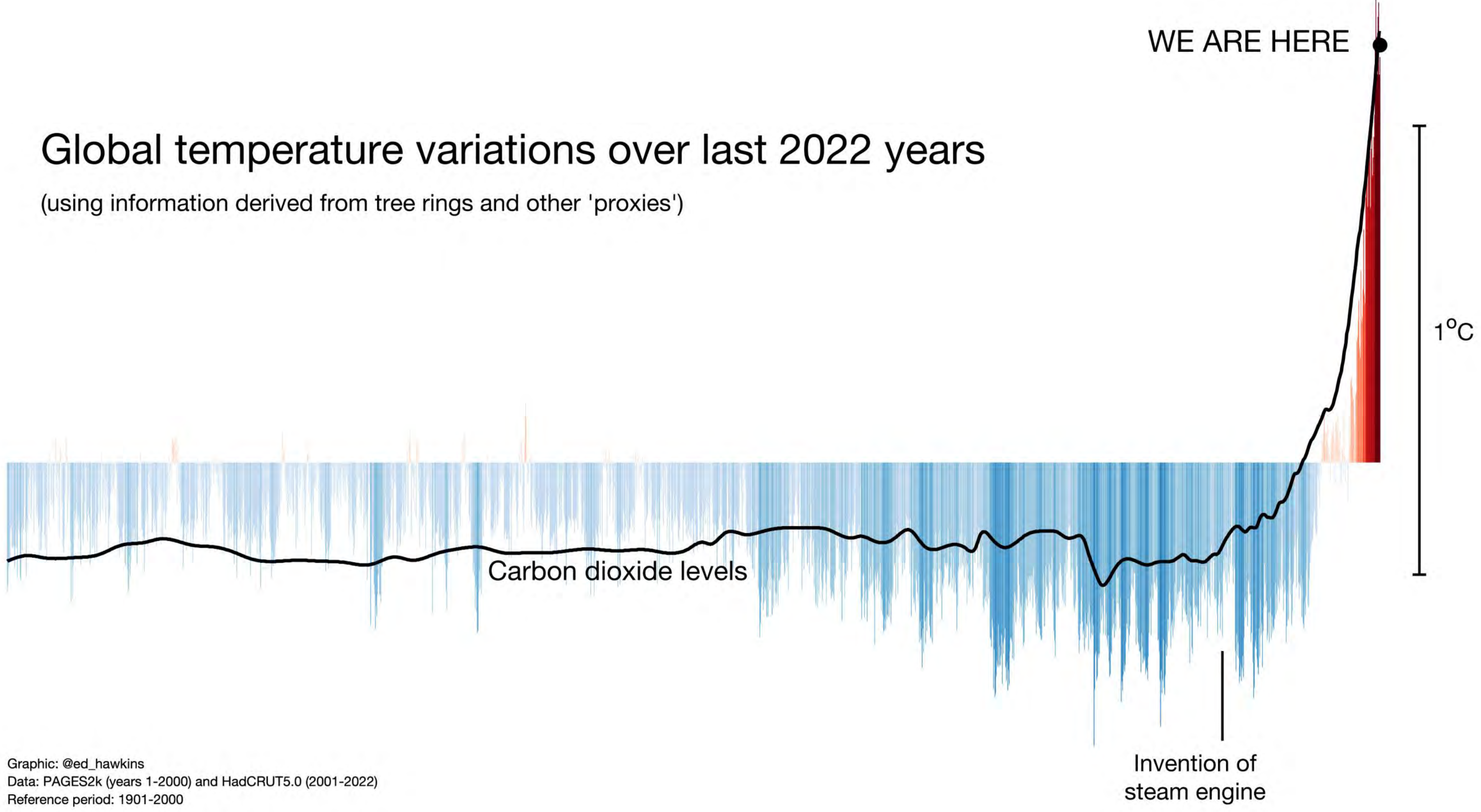
Smoke billows upward from a planned ignition by firefighters tackling the Donnie Creek Complex wildfire south of British Columbia on Saturday. (B.C. Wildfire Service/Reuters)



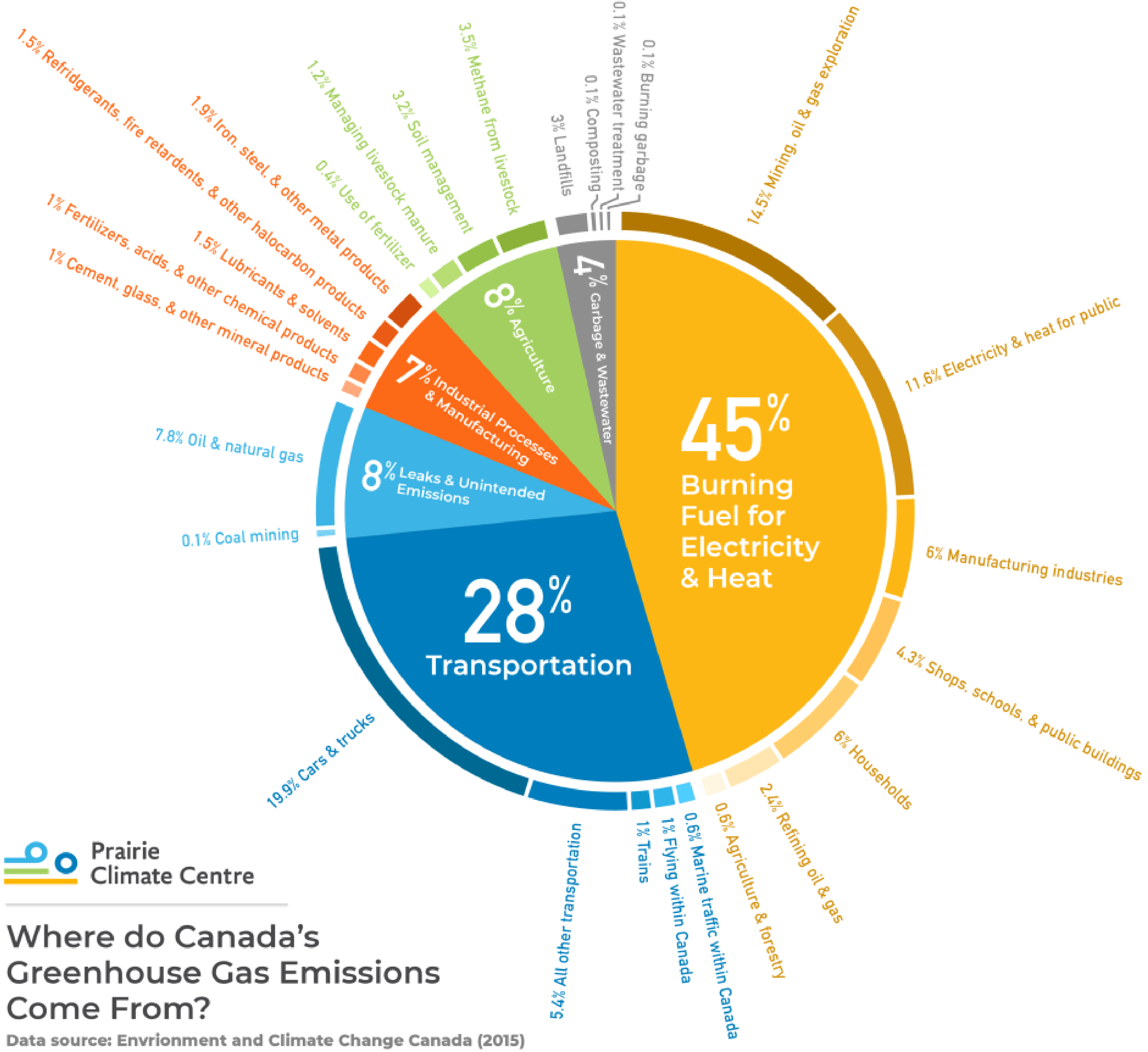
Global temperature change (1850-2022)



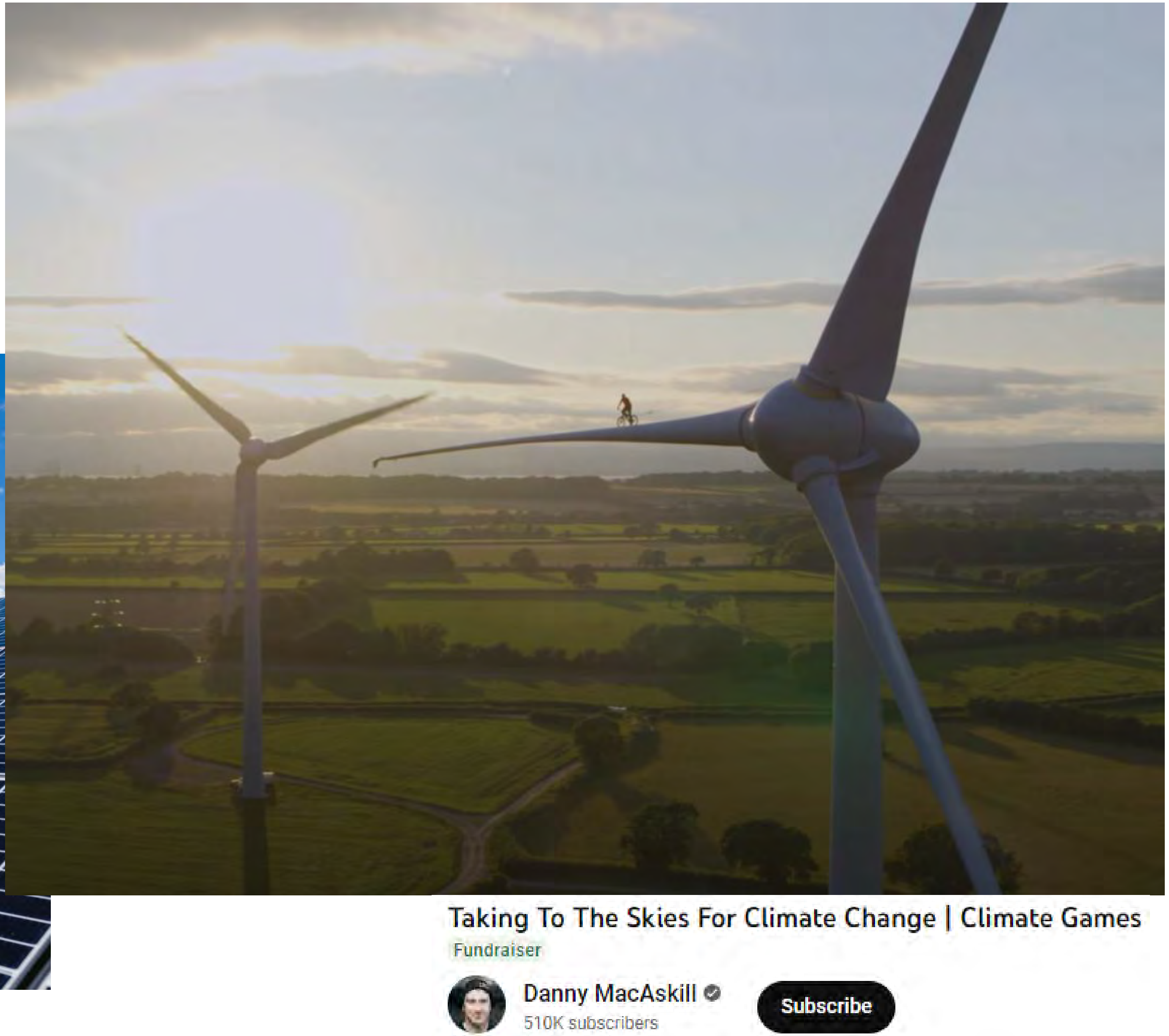
Ed Hawkins, https://ed-hawkins.github.io/climate-visuals/stripes.html


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?



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

Types of Batteries

Single-use

Lithium

Alkaline

Carbon Zinc

Silver Oxide

Rechargeable

Nickel metal hydride

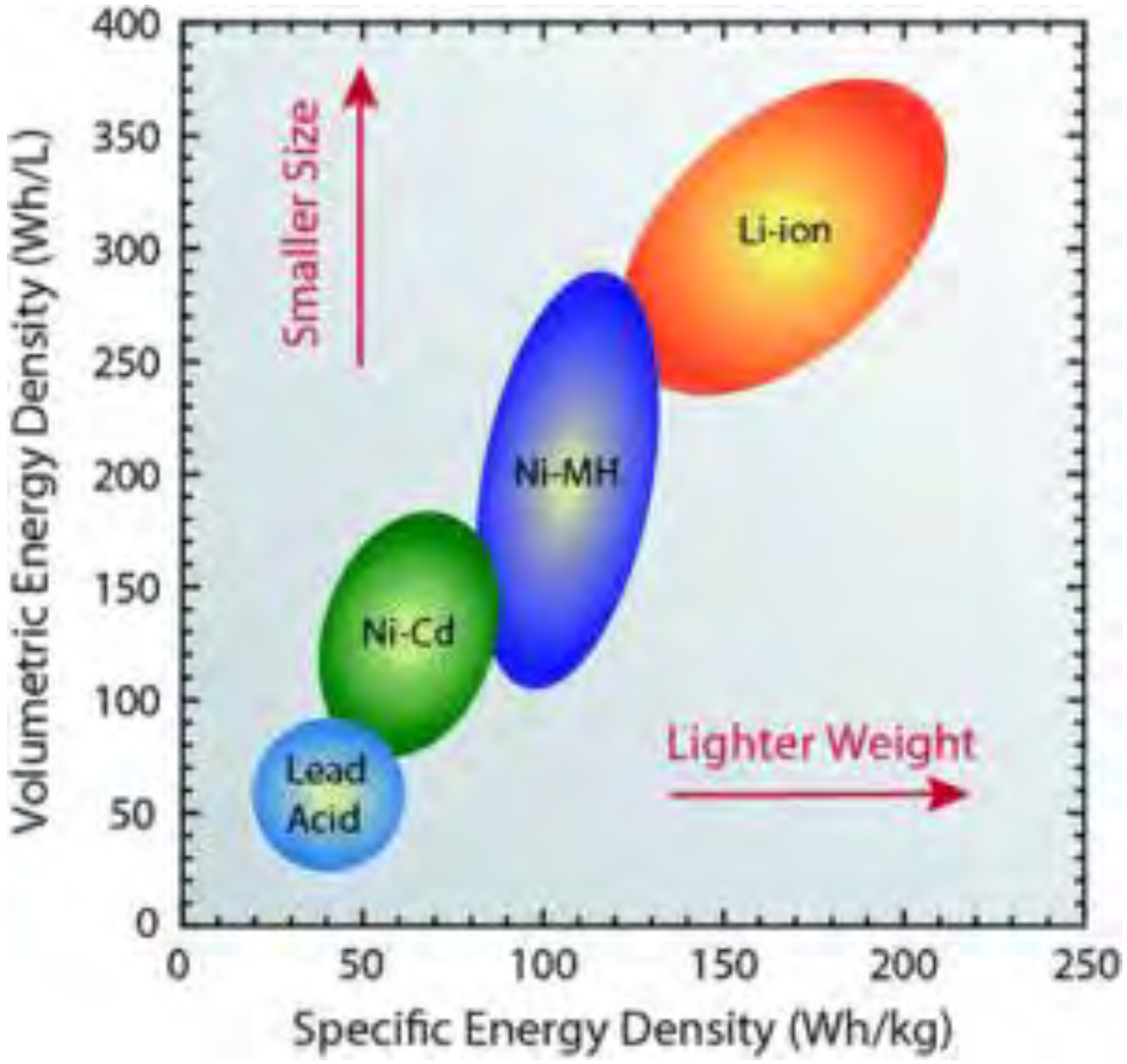
Lithium ion

Nickel cadmium

https://www.webstaurantstore.com/guide/923/batteries-buying-guide.html; https://ruchiragreenearth.com/blog/how-to-choose-the-right-lithium-ion-battery/;

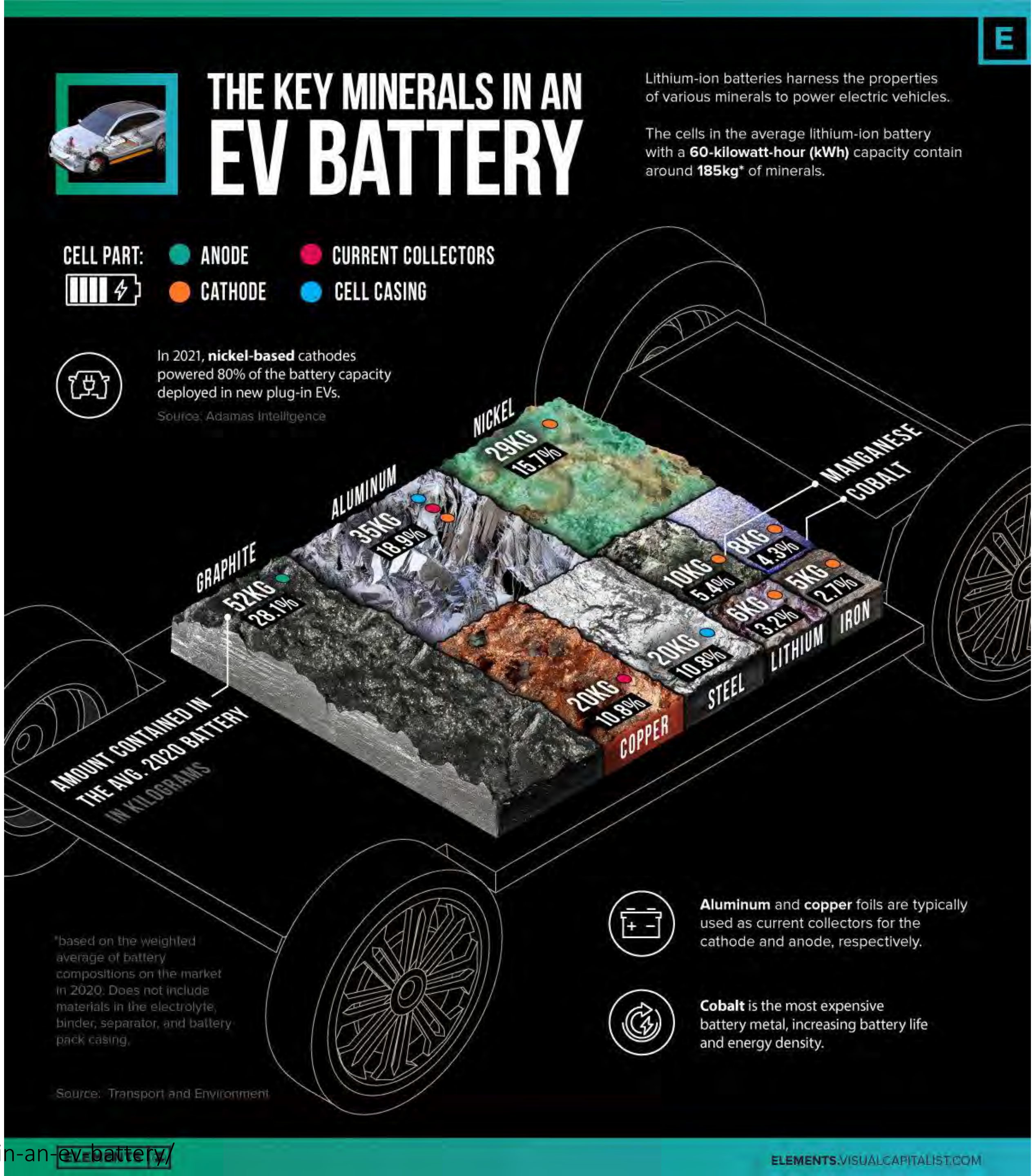
Li-Ion Batteries

- 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)



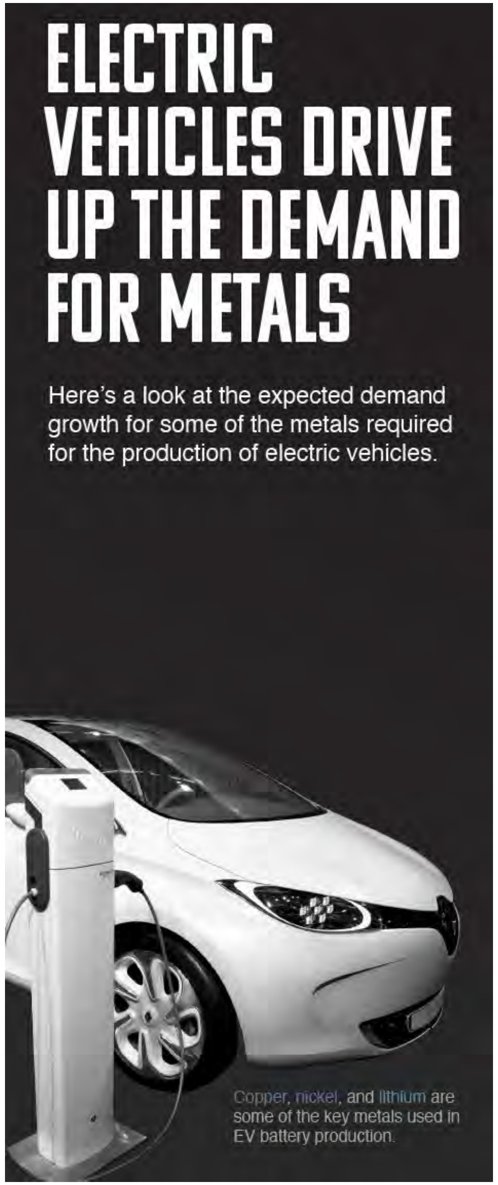
https://www.cei.washington.edu/education/science-of-solar/battery-technology/

Battery Metals

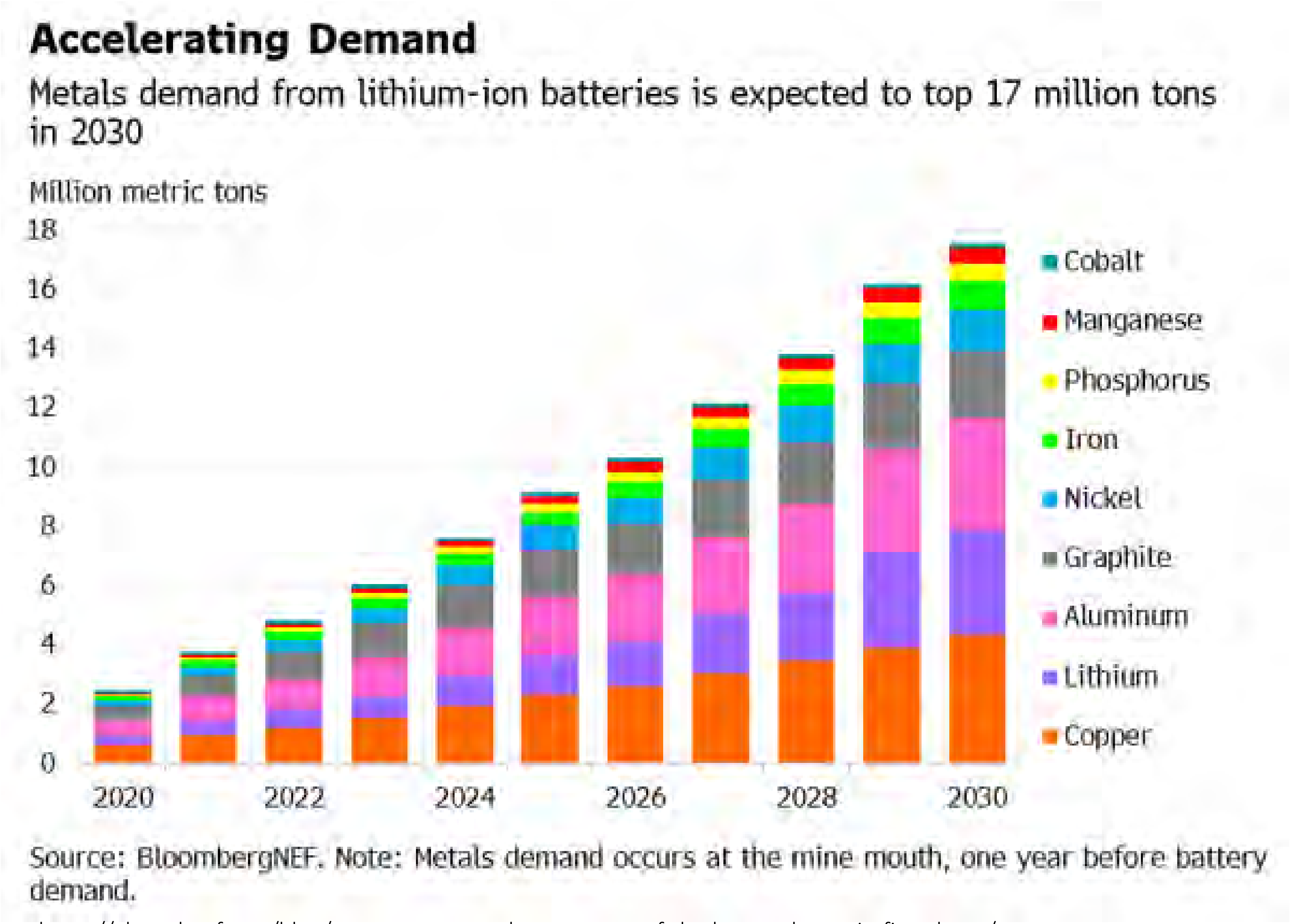


https://elements.visualcapitalist.com/the-key-minerals-in-an-ev-battery/

Battery Metals



visualcapitalist.com

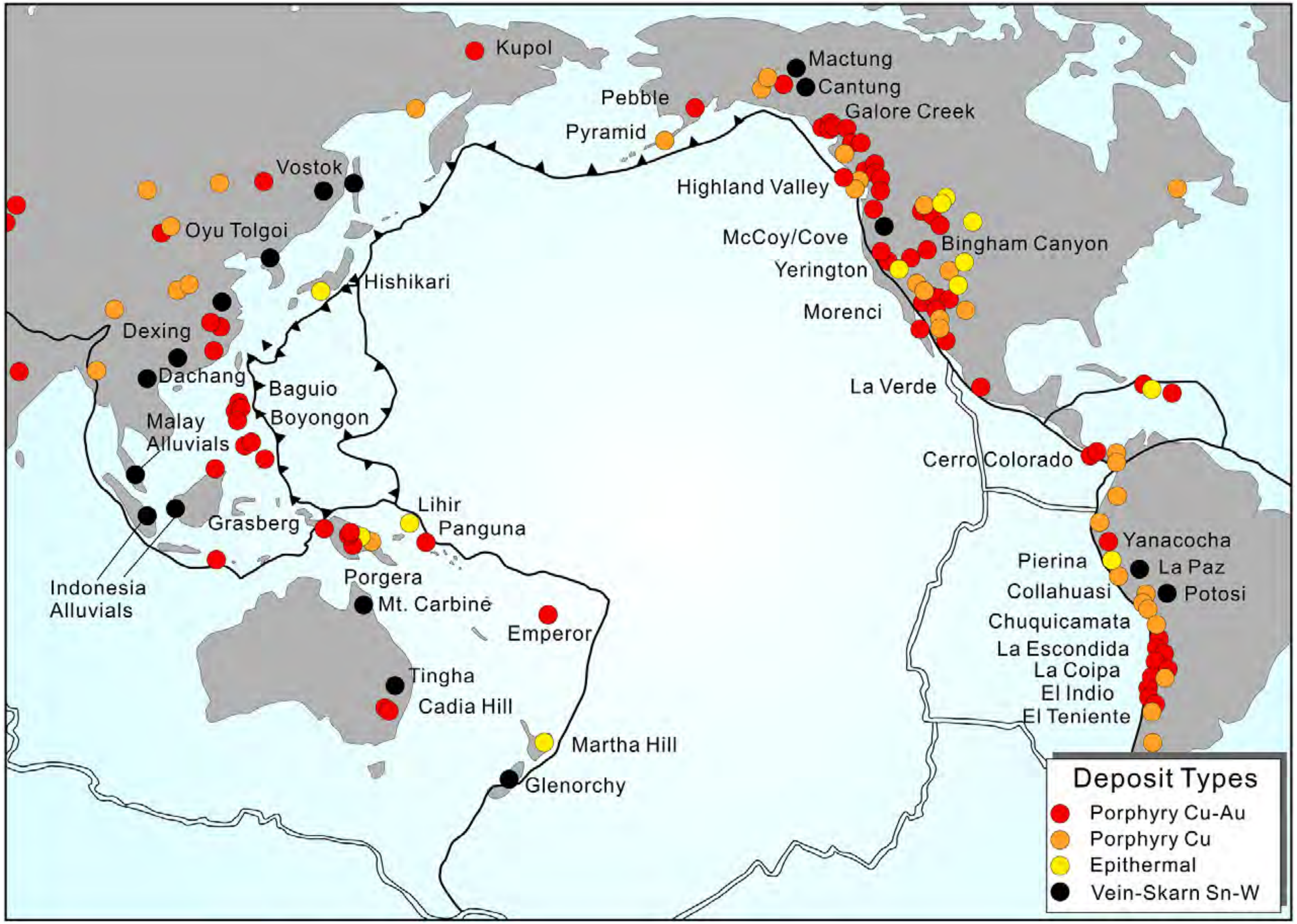


https://about.bnef.com/blog/race-to-net-zero-the-pressures-of-the-battery-boom-in-five-charts/

Where Can We Find Them?

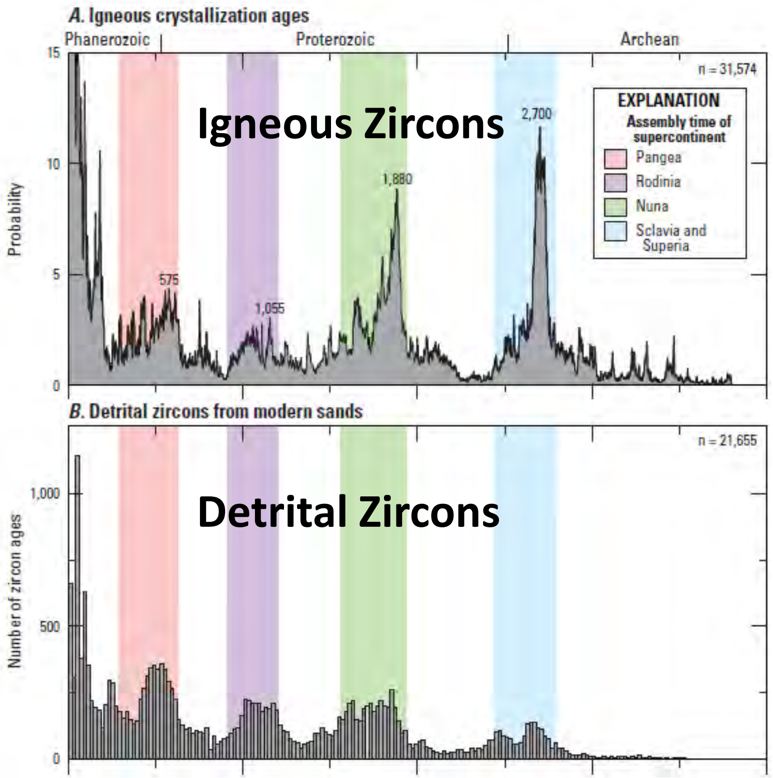
The Global Scale

Mineral Deposits: Global-Scale Distributions



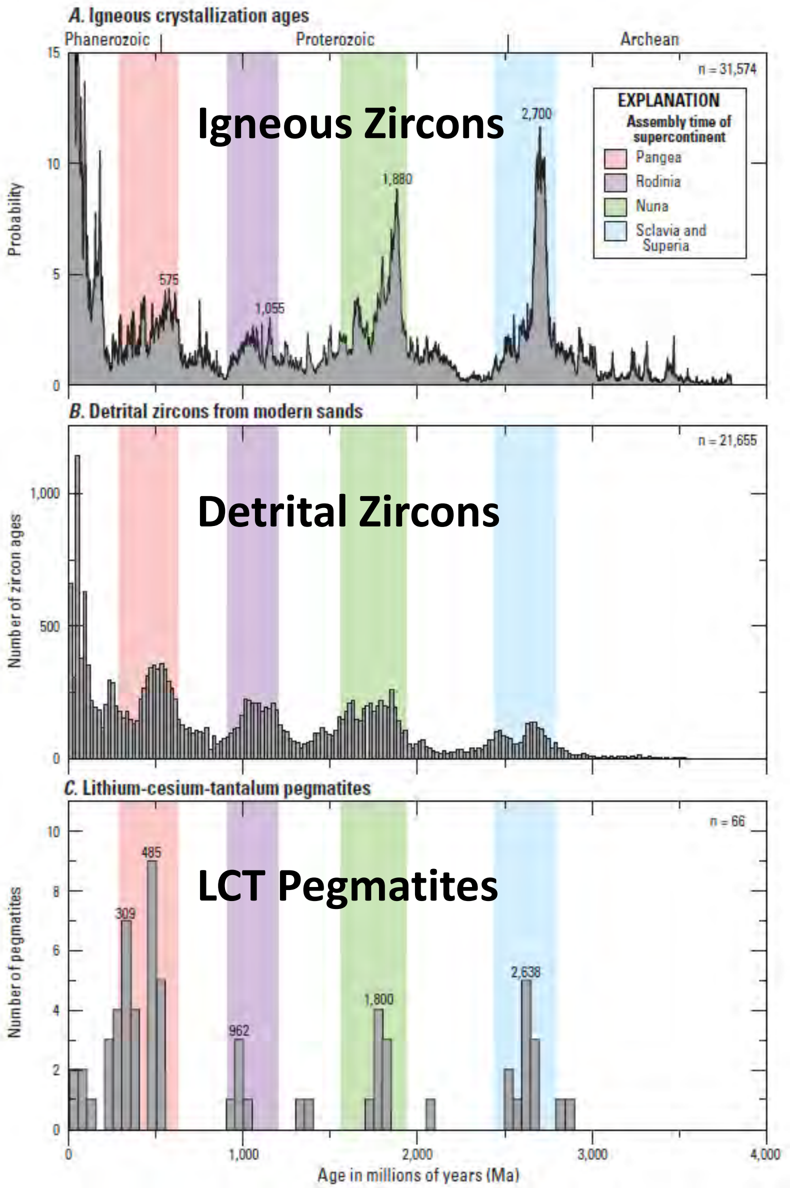
Groves et al., 2005, Ore Geology Reviews

Mineral Deposits: Global-Scale Distributions *Through Time*



Bradley et al., 2010, USGS report

Mineral Deposits: Global-Scale Distributions *Through Time*



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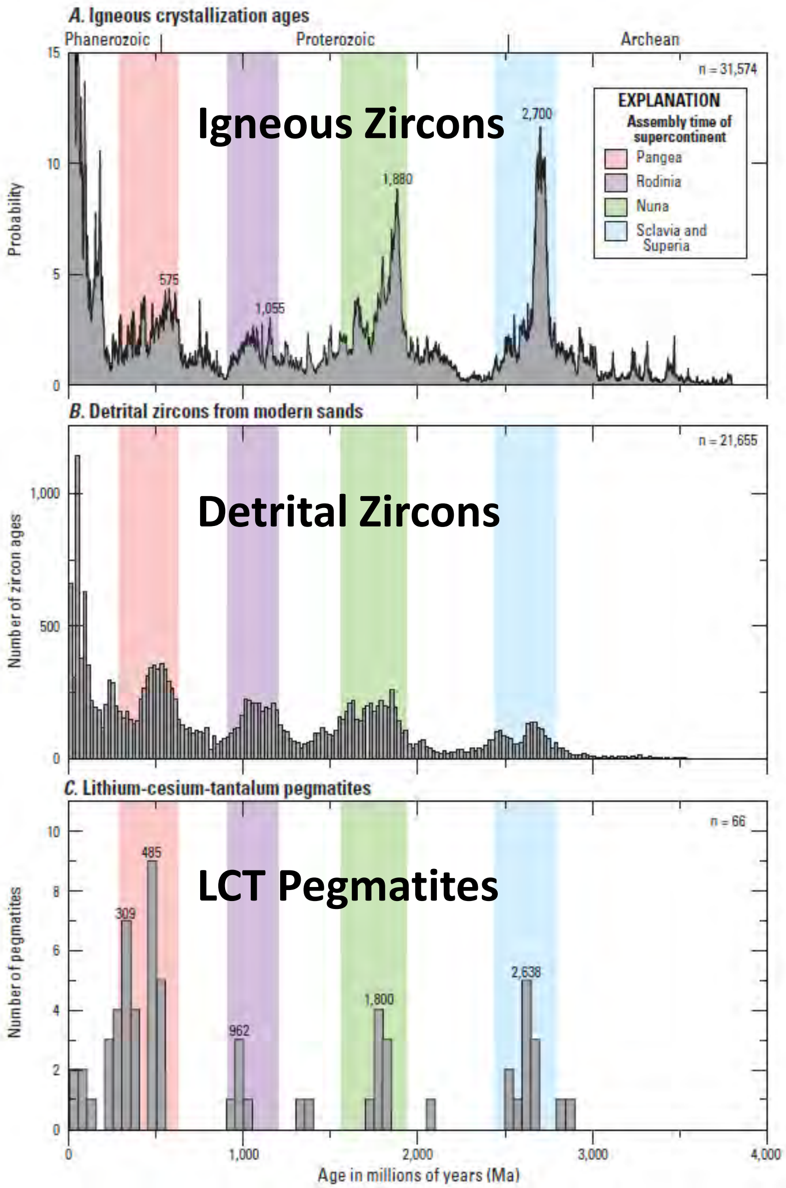

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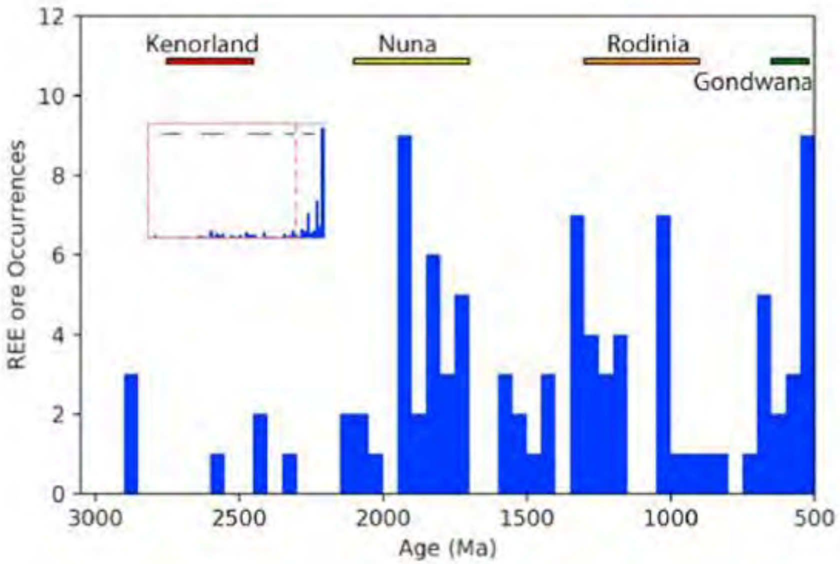
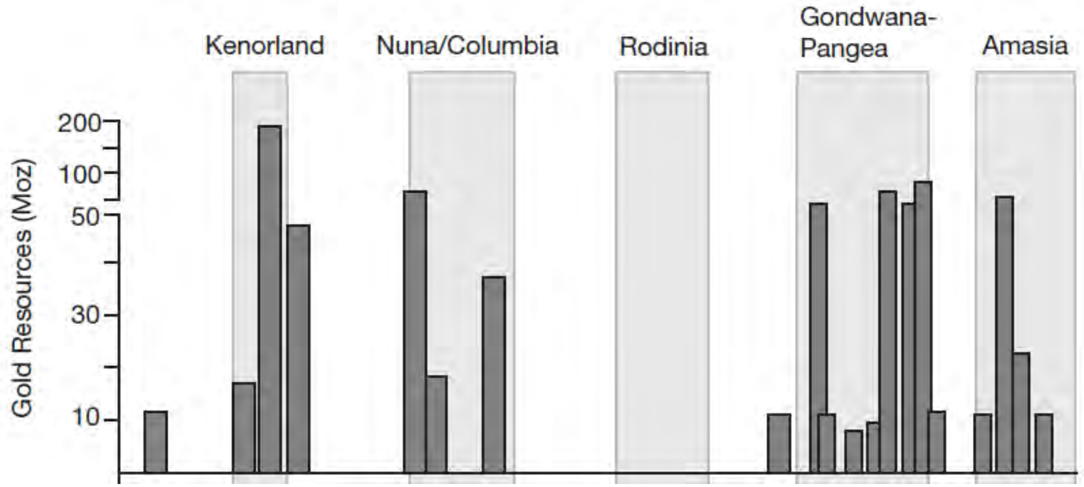
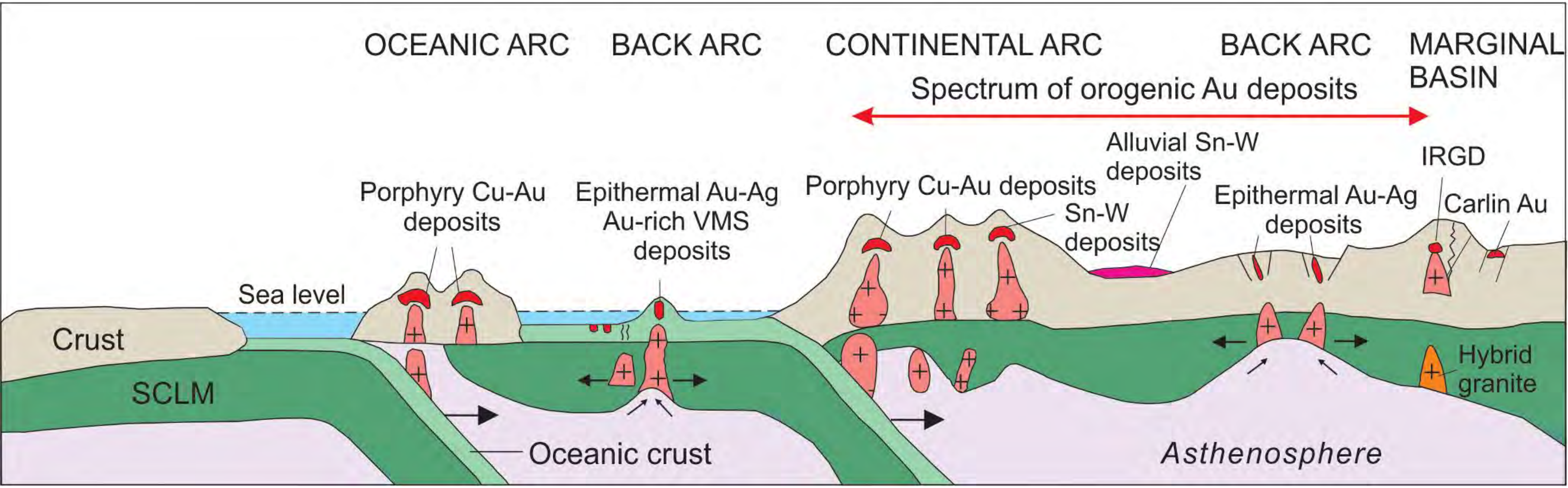


Liu et al., 2019, Earth-Science Reviews



Goldfarb et al., 2010, Economic Geology

Mineral Deposits: Global-Scale Distributions



Groves et al., 2021, Ore Geology Reviews

The Regional Scale
with a focus on lithium

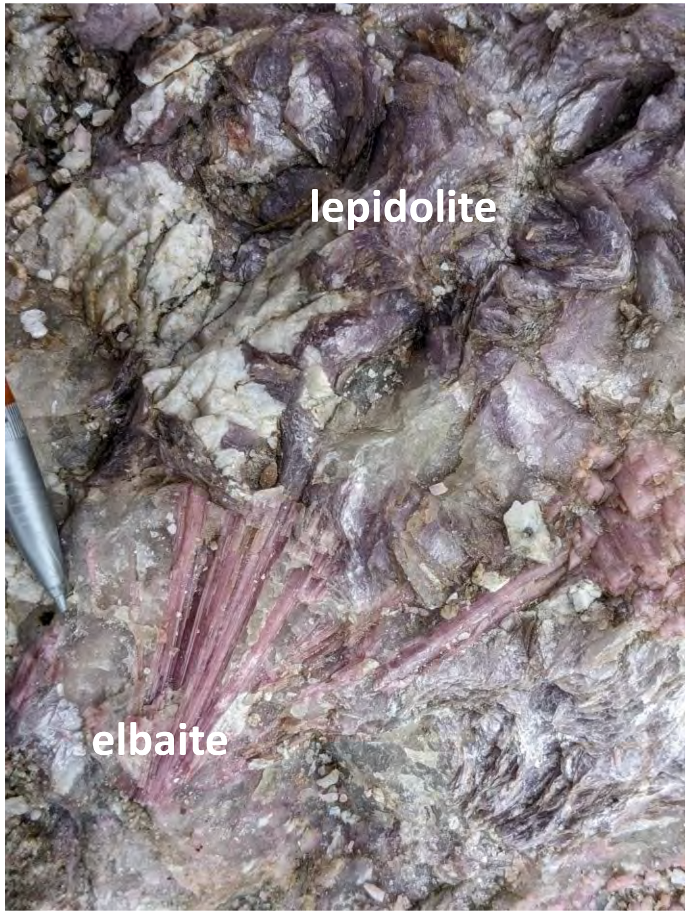
Sources of Lithium

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

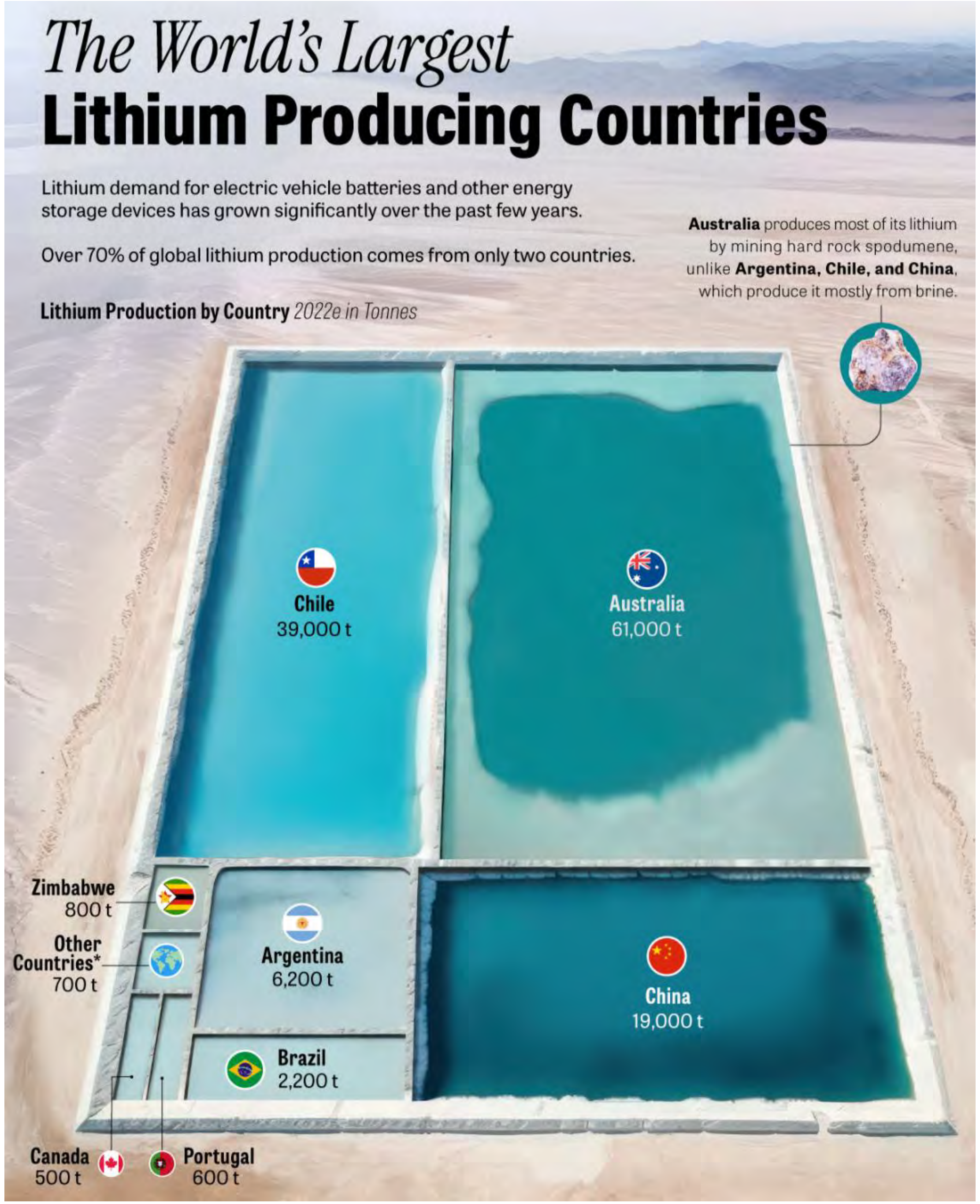
Sources of Lithium

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

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

- **Li clays**
  Thacker Pass, Nevada

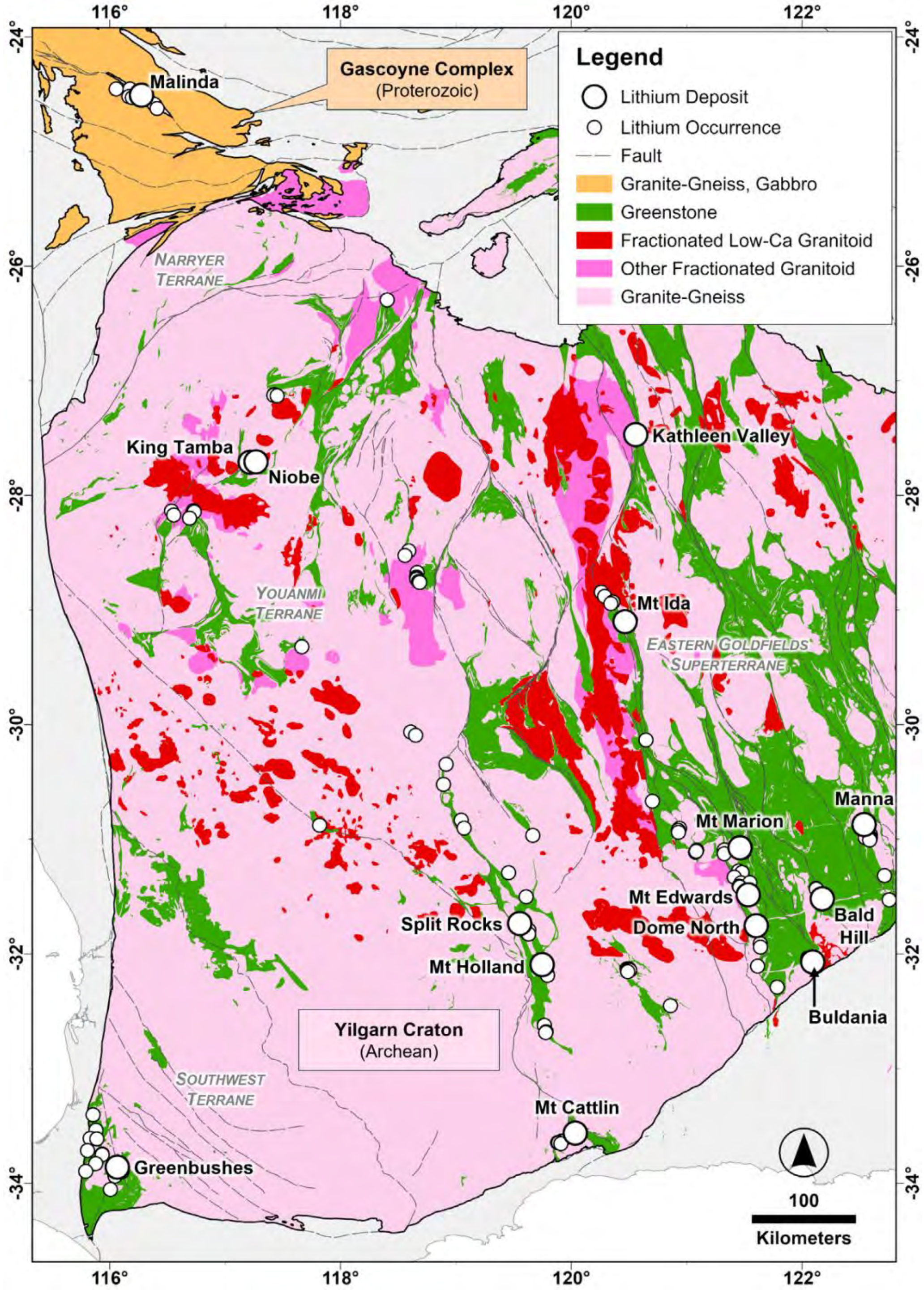
- **Other Li brines**
  Geothermal brines – Salton Sea, California
  Oilfield brines - Alberta



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

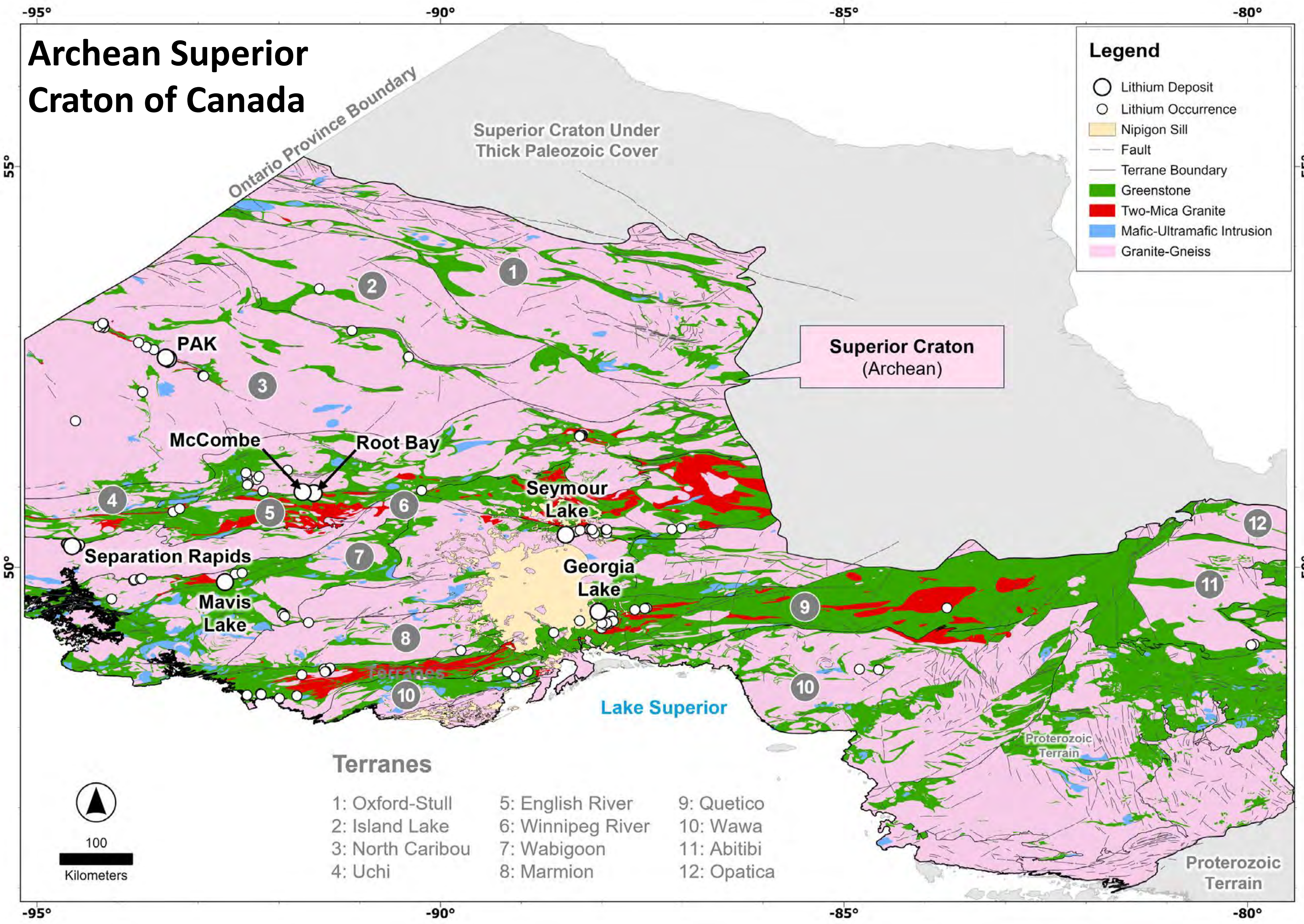
Regional Scale Distributions: Lithium-Bearing Pegmatites

Archean Yilgarn Craton of Australia



Kreuzer & Roshanravan 2025. Minerals

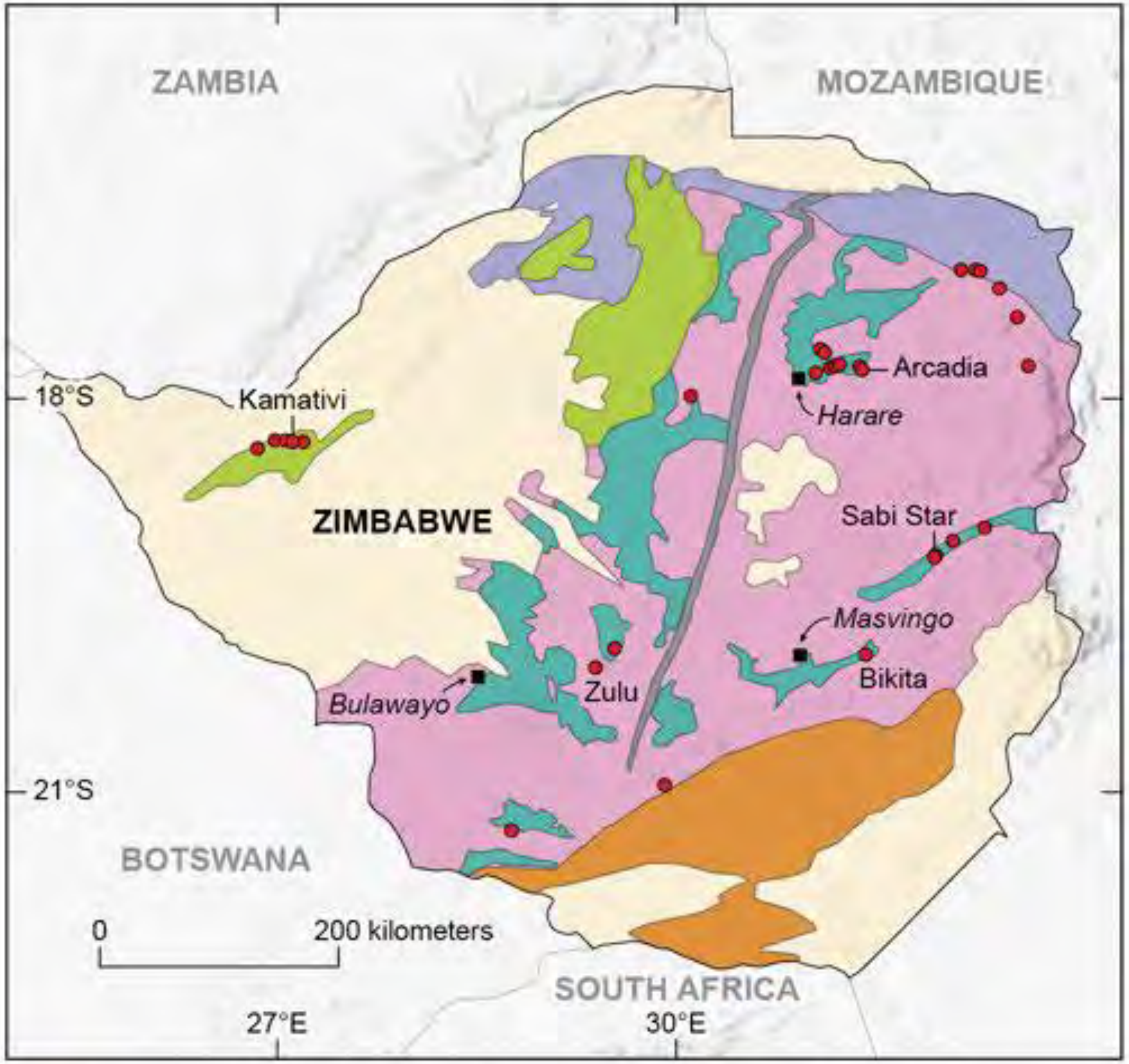
Regional Scale Distributions: Lithium-Bearing Pegmatites



Kreuzer & Roshanravan 2025. Minerals

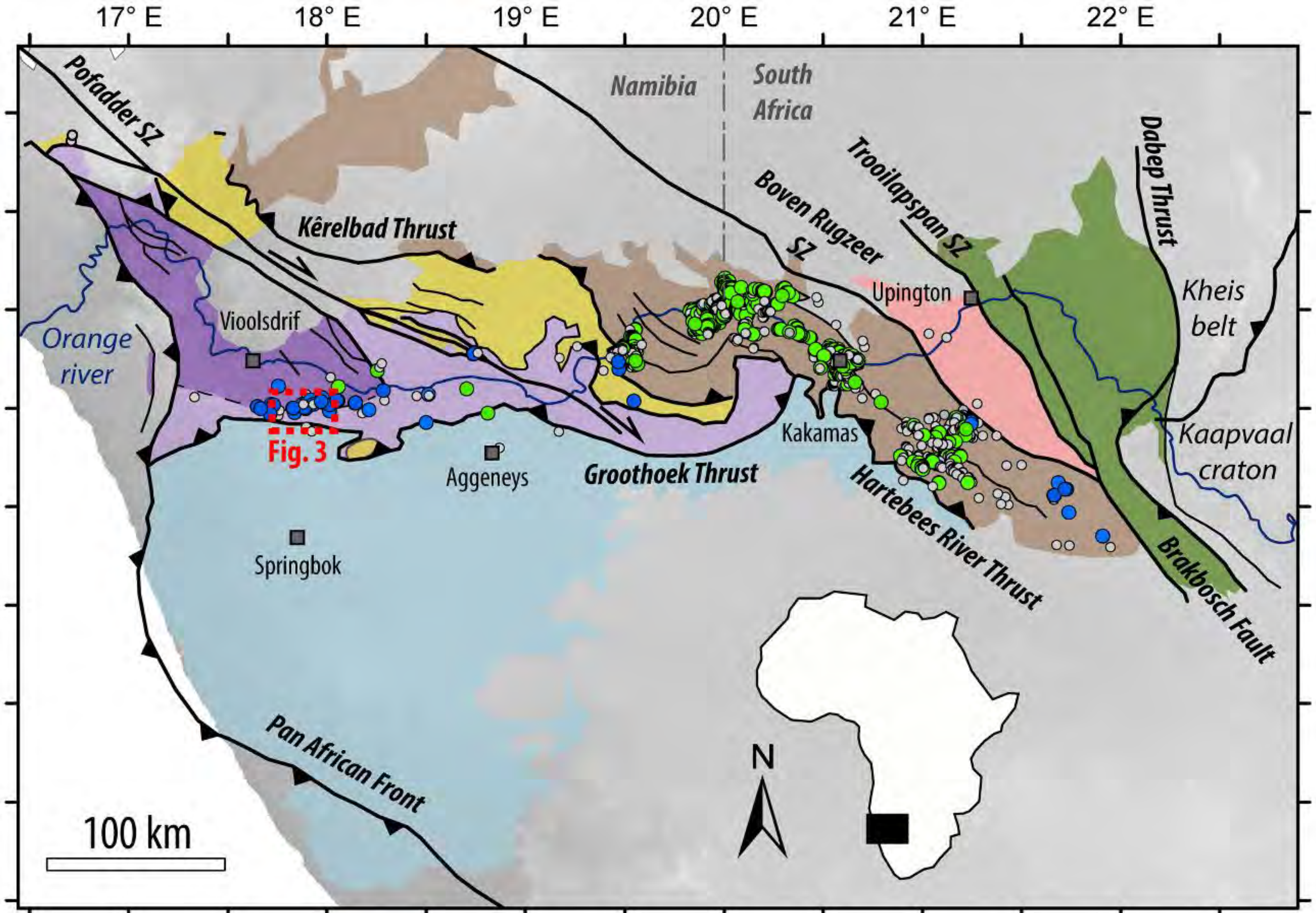
Regional Scale Distributions: Lithium-Bearing Pegmatites

Archean Zimbabwe Craton of Africa



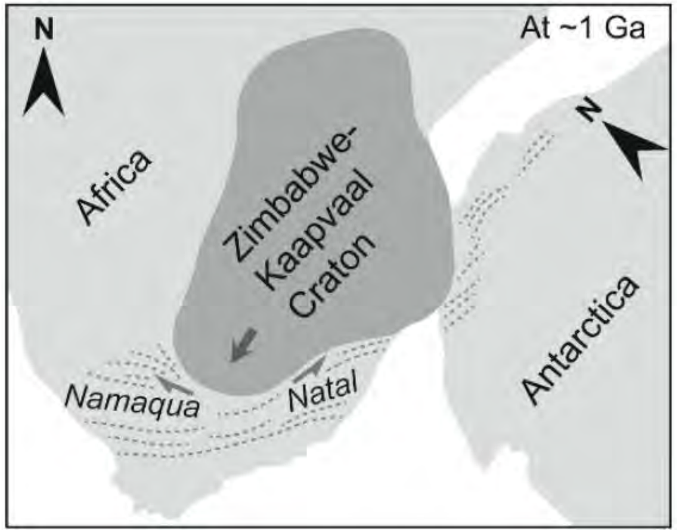
Goodenough et al. 2025. Econ. Geol.

Regional Scale Distributions: Lithium-Bearing Pegmatites



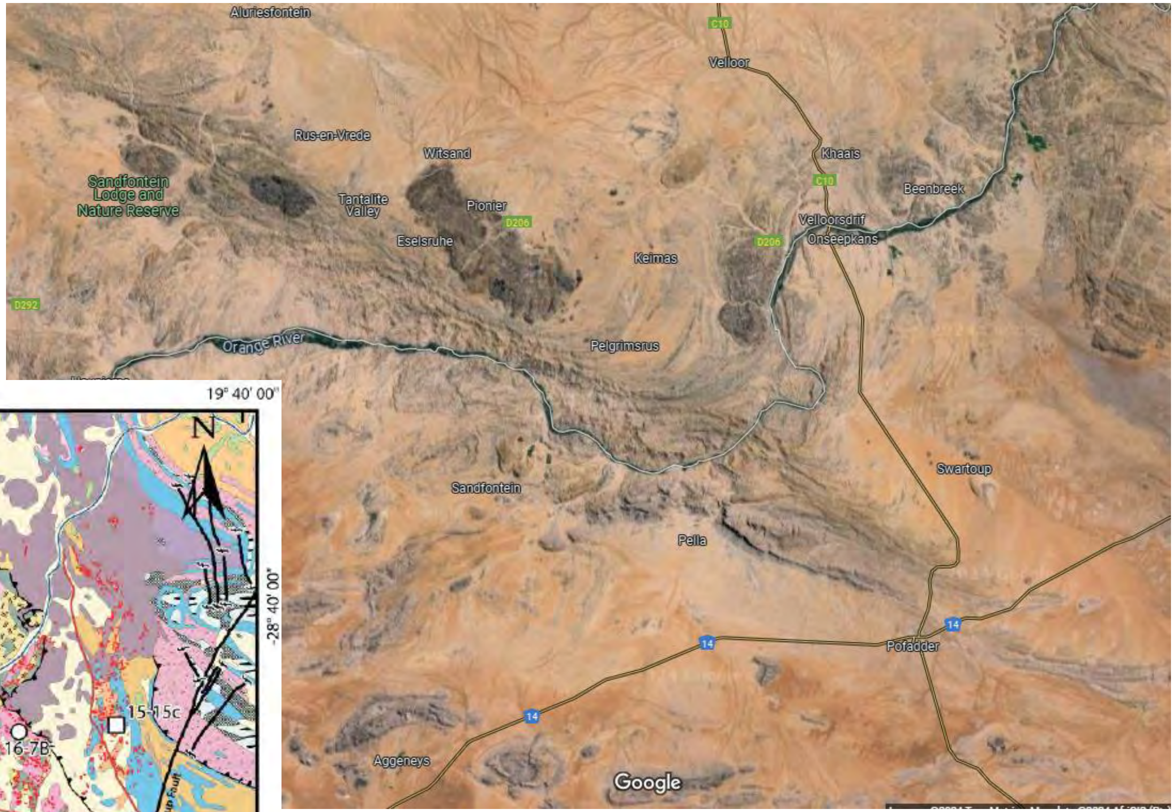
Ballouard et al. 2020. Ore Geology Reviews

Mesoproterozoic Orange River Pegmatite Belt, South Africa & Namibia

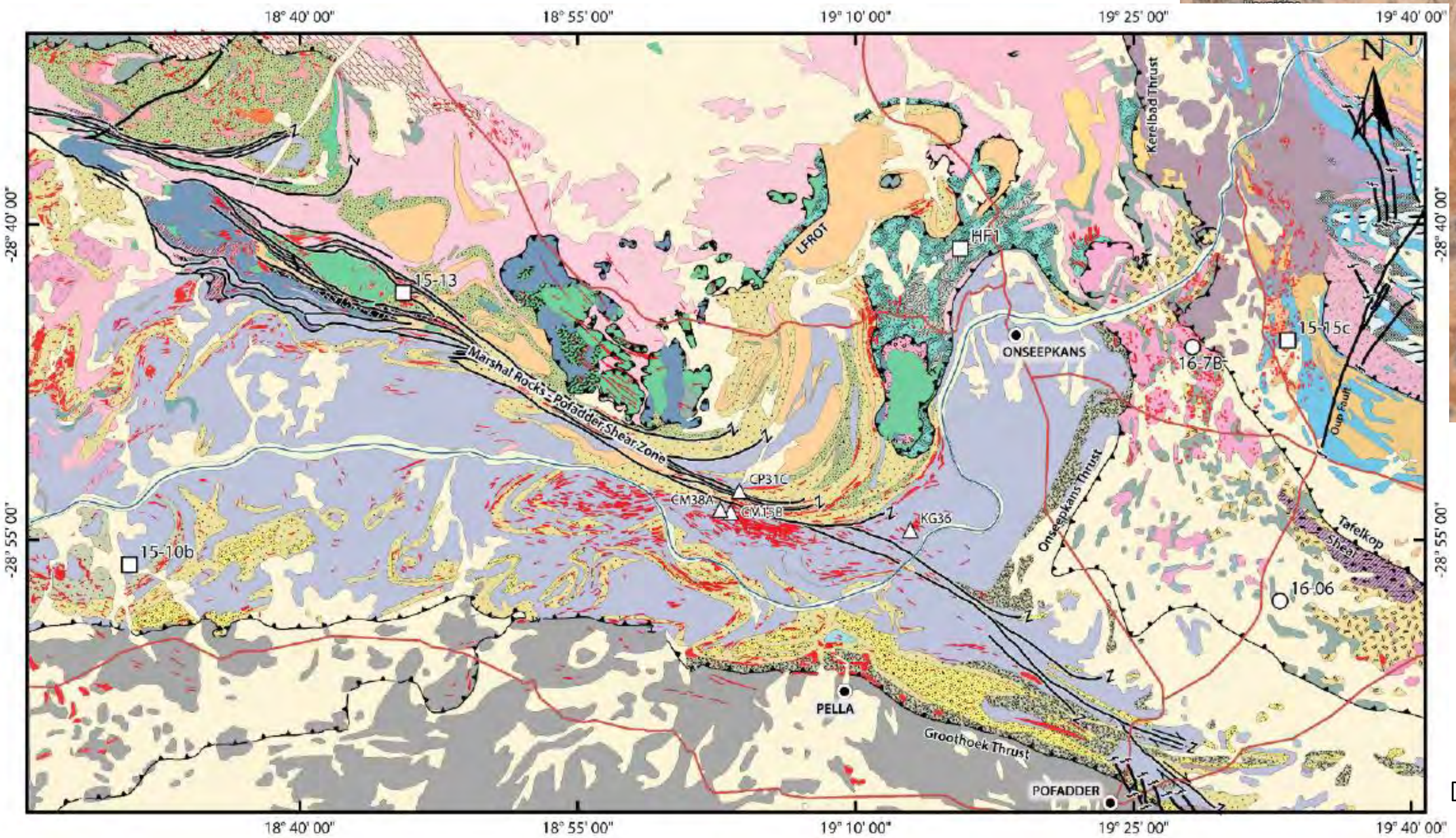


Cawood et al., 2023, Ore Geology Reviews; after Jacobs et al., 1993, Geology

Regional Scale Distributions: Lithium-Bearing Pegmatites

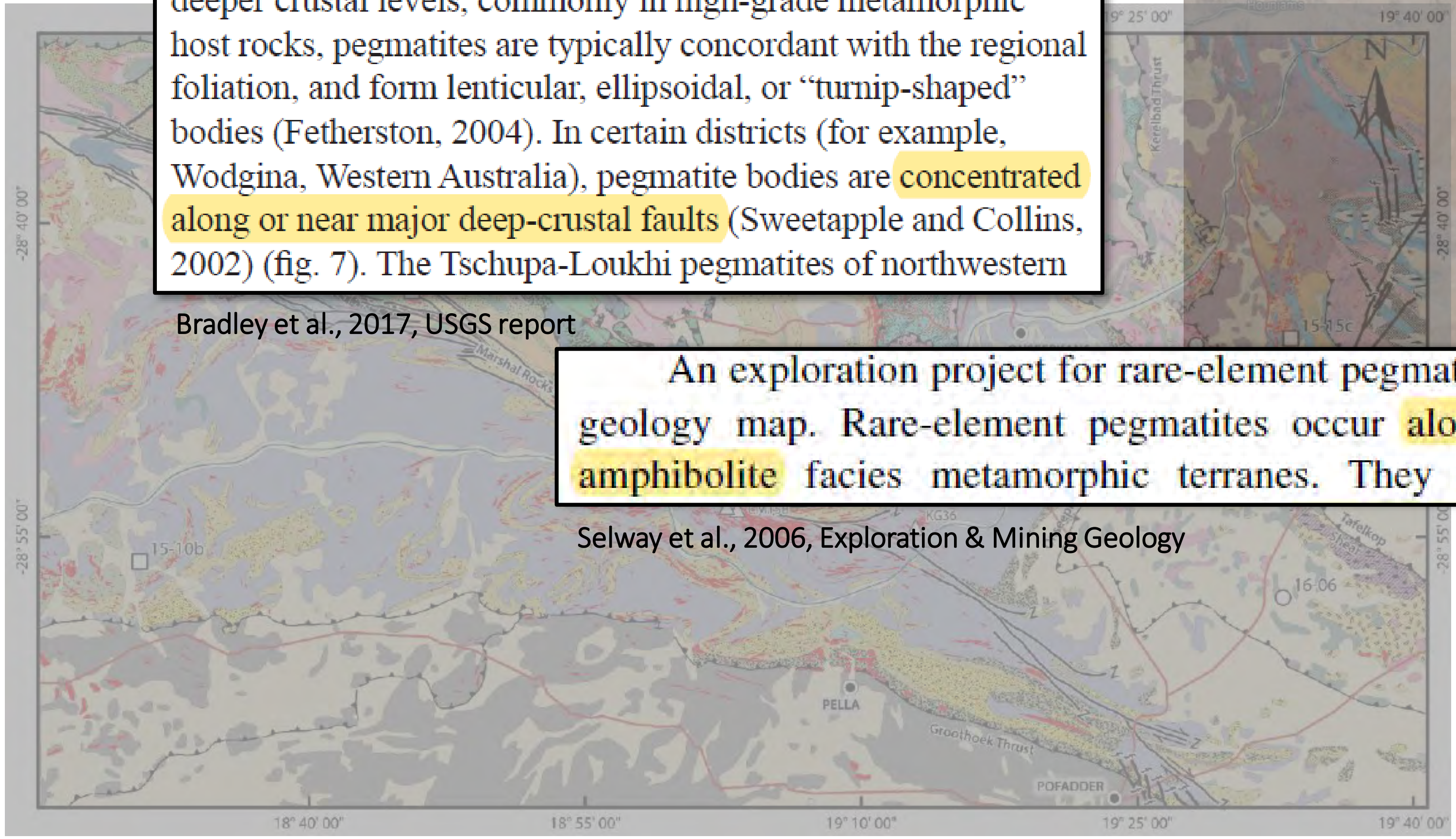


Google Maps, 2024



Doggart, 2019, M.Sc.

Regional Scale Distributions: Lithium-Bearing Pegmatites



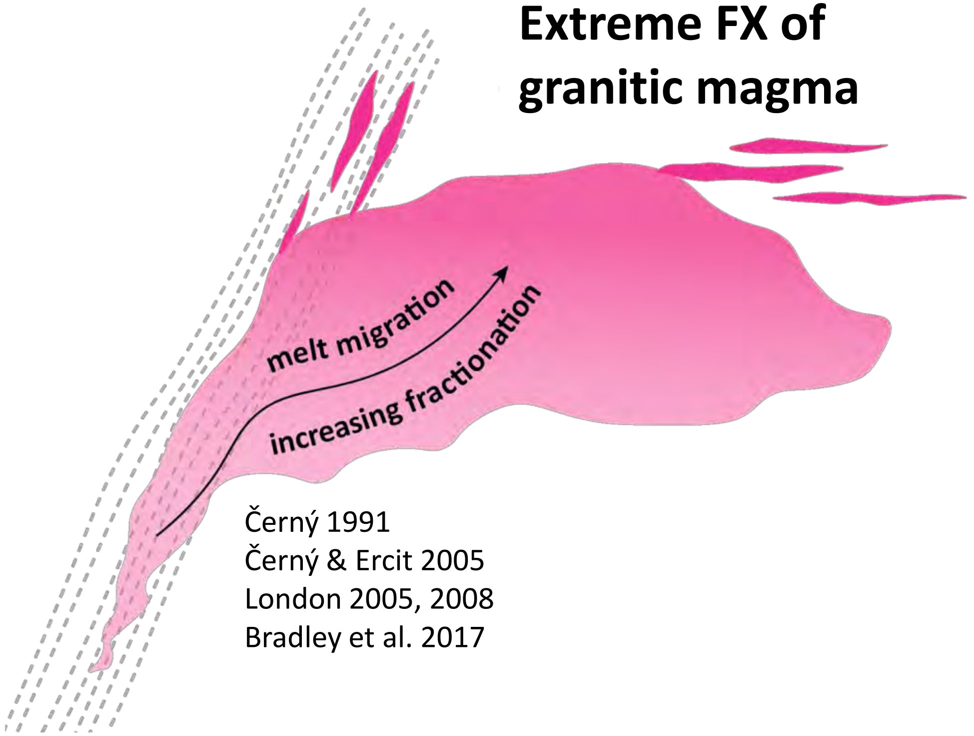
Most LCT pegmatite bodies show some structural control, with the specifics being a function of depth of emplacement and varying from district to district. At shallow crustal depths, pegmatites tend to be intruded along anisotropies, such as faults, fractures, foliation, and bedding (Brisbin, 1986). At relatively deeper crustal levels, commonly in high-grade metamorphic host rocks, pegmatites are typically concordant with the regional foliation, and form lenticular, ellipsoidal, or "turnip-shaped" bodies (Fetherston, 2004). In certain districts (for example, Wodgina, Western Australia), pegmatite bodies are concentrated along or near major deep-crustal faults (Sweetapple and Collins, 2002) (fig. 7). The Tschupa-Loukhi pegmatites of northwestern

Bradley et al., 2017, USGS report

An exploration project for rare-element pegmatites should begin with an examination of a regional geology map. Rare-element pegmatites occur along large regional-scale faults in greenschist and amphibolite facies metamorphic terranes. They are typically hosted by mafic metavolcanic or

Selway et al., 2006, Exploration & Mining Geology

Formation of Li-Pegmatites

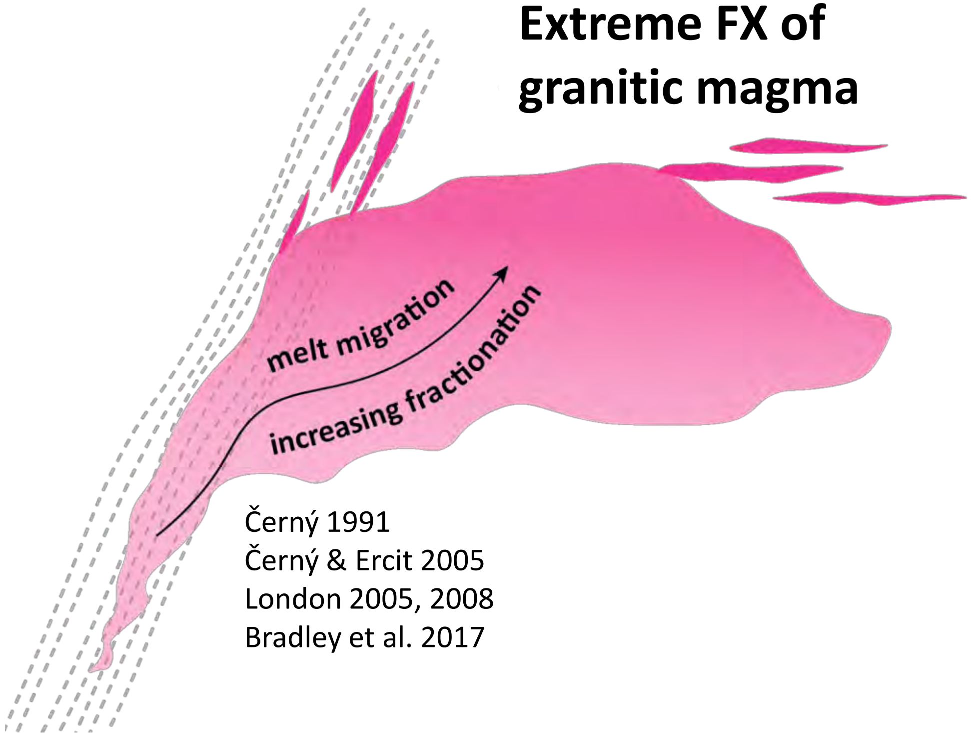


Extreme FX of granitic magma

Černý 1991
Černý & Ercit 2005
London 2005, 2008
Bradley et al. 2017

Formation of Li-Pegmatites

Extreme FX of granitic magma



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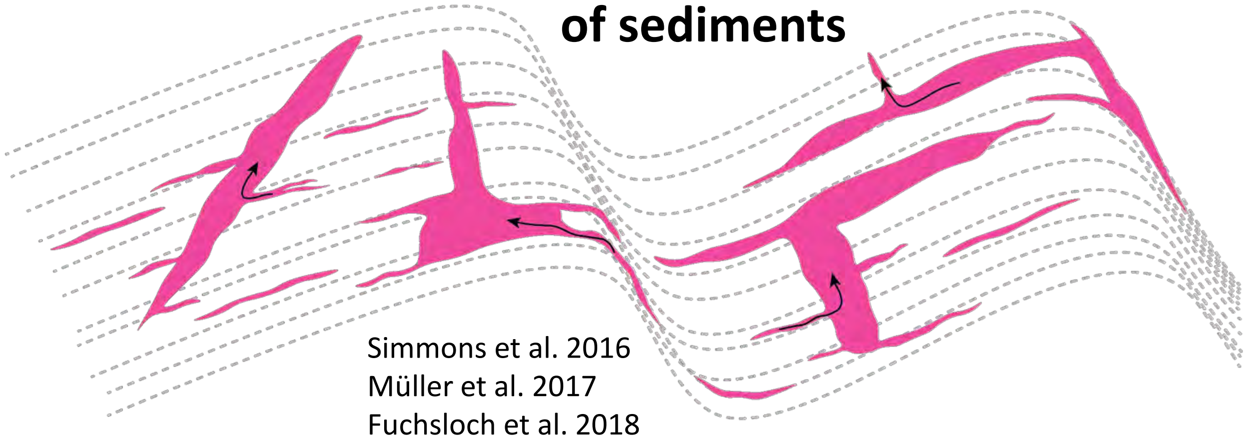
Low-degree partial melting of sediments



Simmons et al. 2016
Müller et al. 2017
Fuchsloch et al. 2018
Doggart 2019

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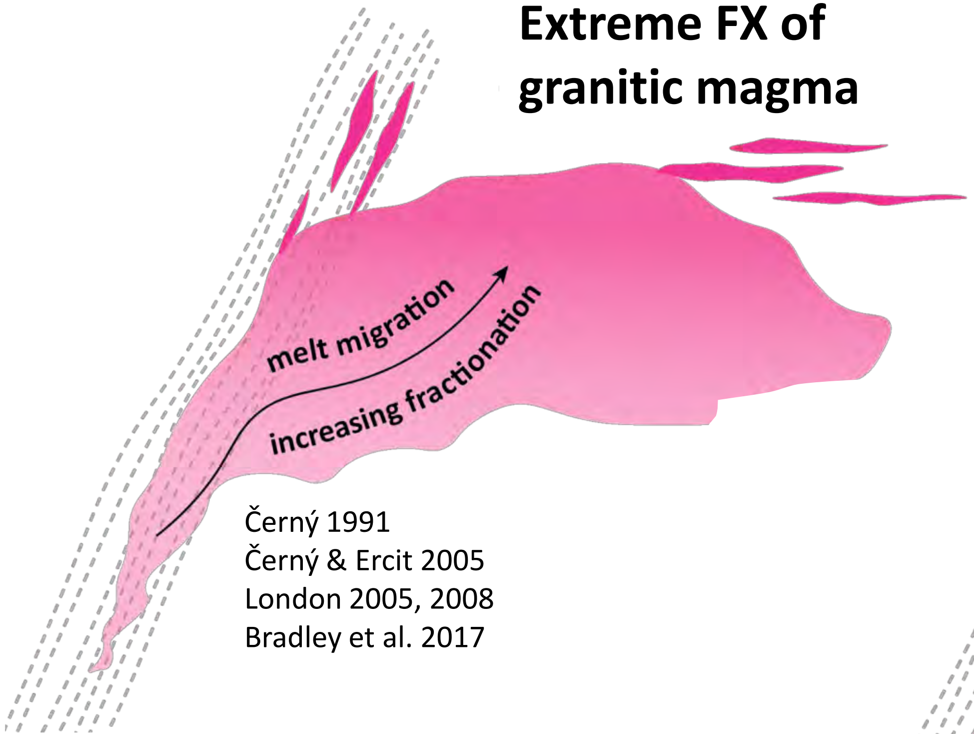

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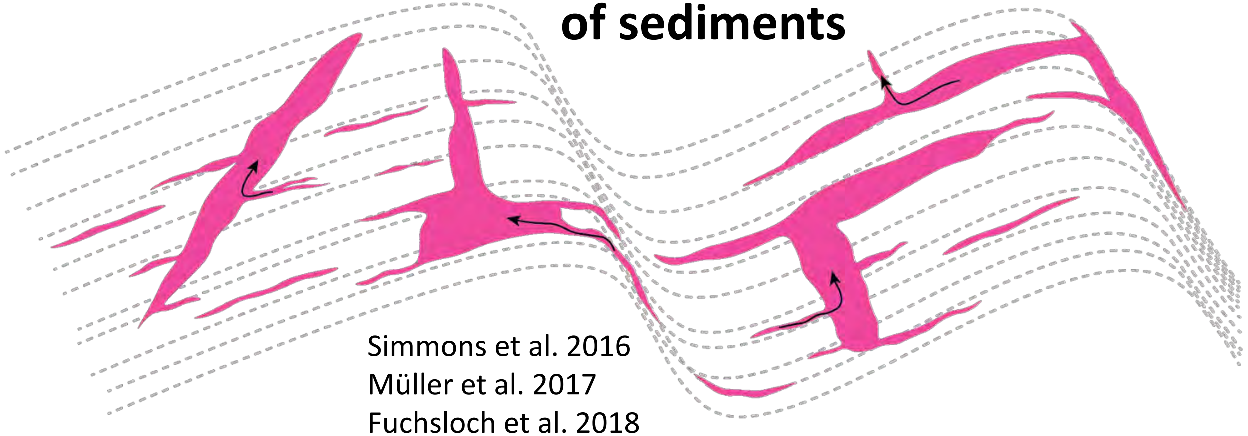
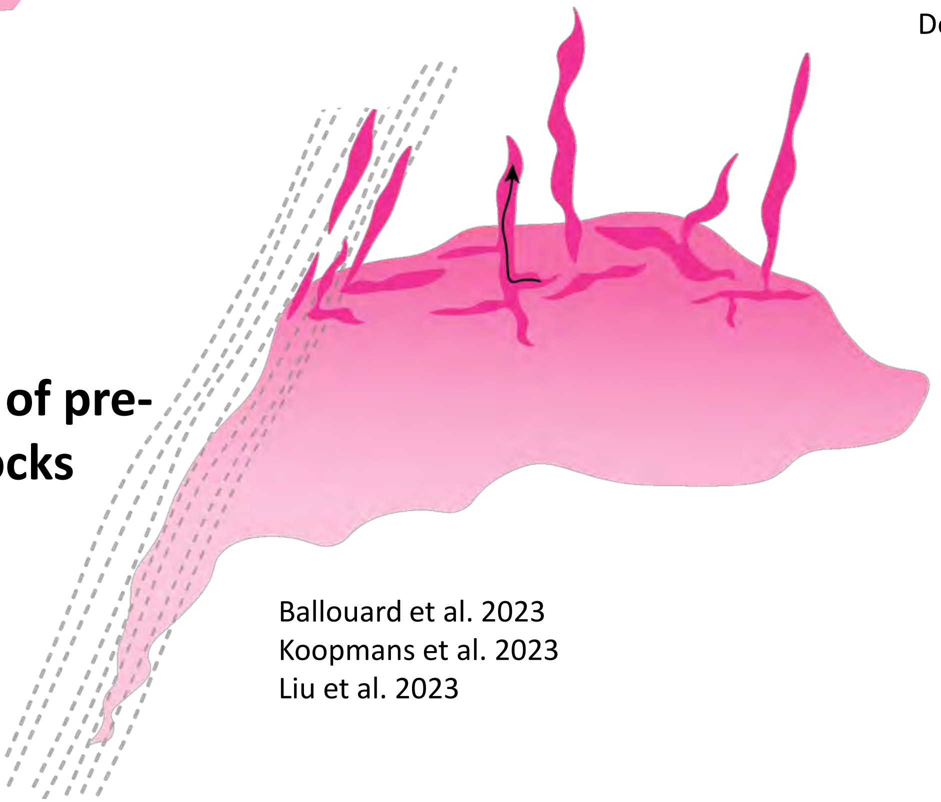


Simmons et al. 2016
Müller et al. 2017
Fuchsloch et al. 2018
Doggart 2019

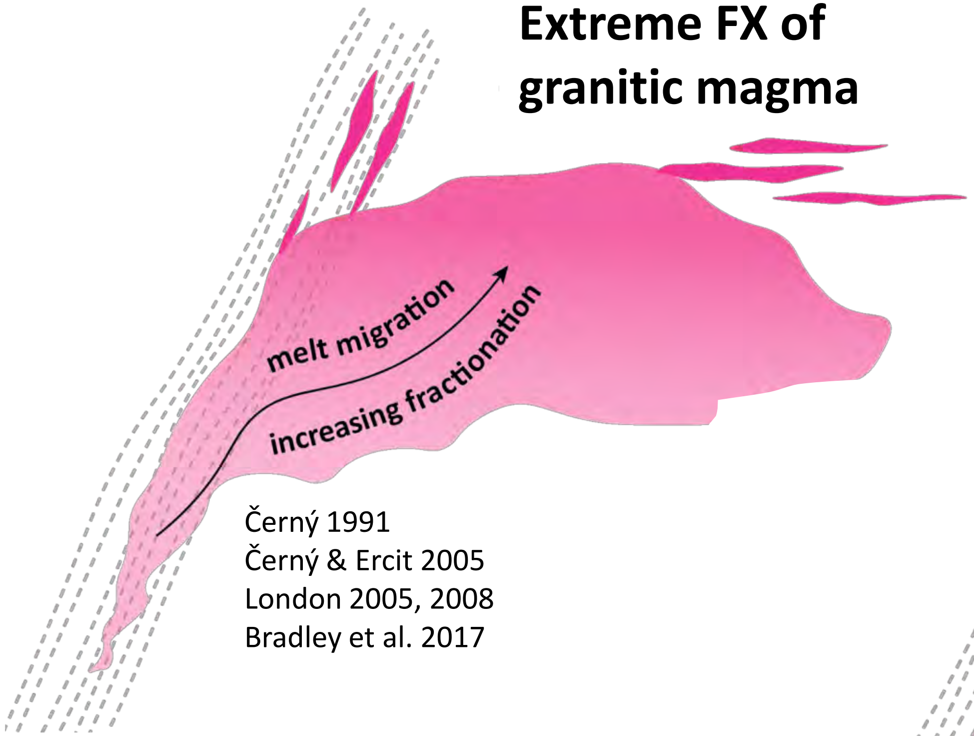
Re-melting of pre-enriched rocks



Ballouard et al. 2023
Koopmans et al. 2023
Liu et al. 2023

Formation of Li-Pegmatites

Extreme FX of granitic magma



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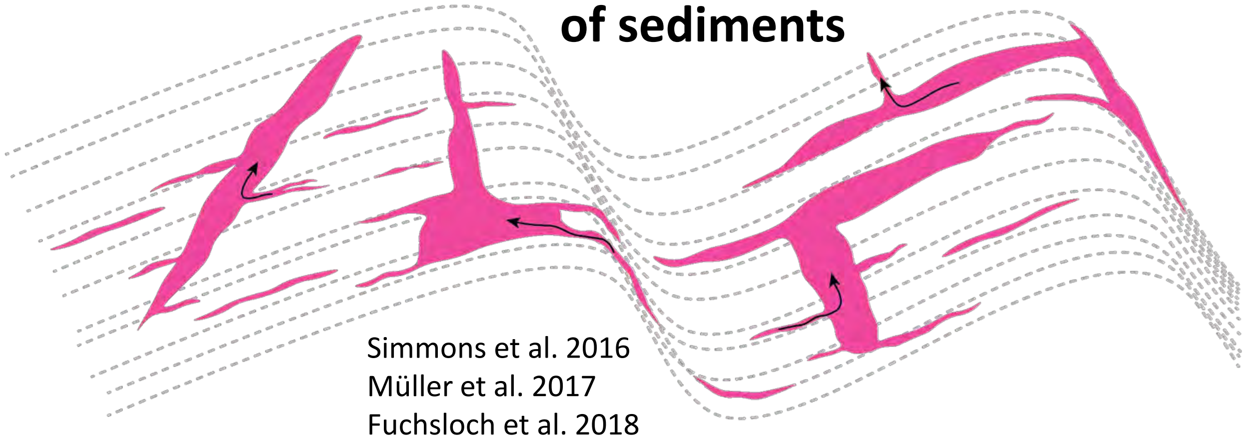

Simmons et al. 2016
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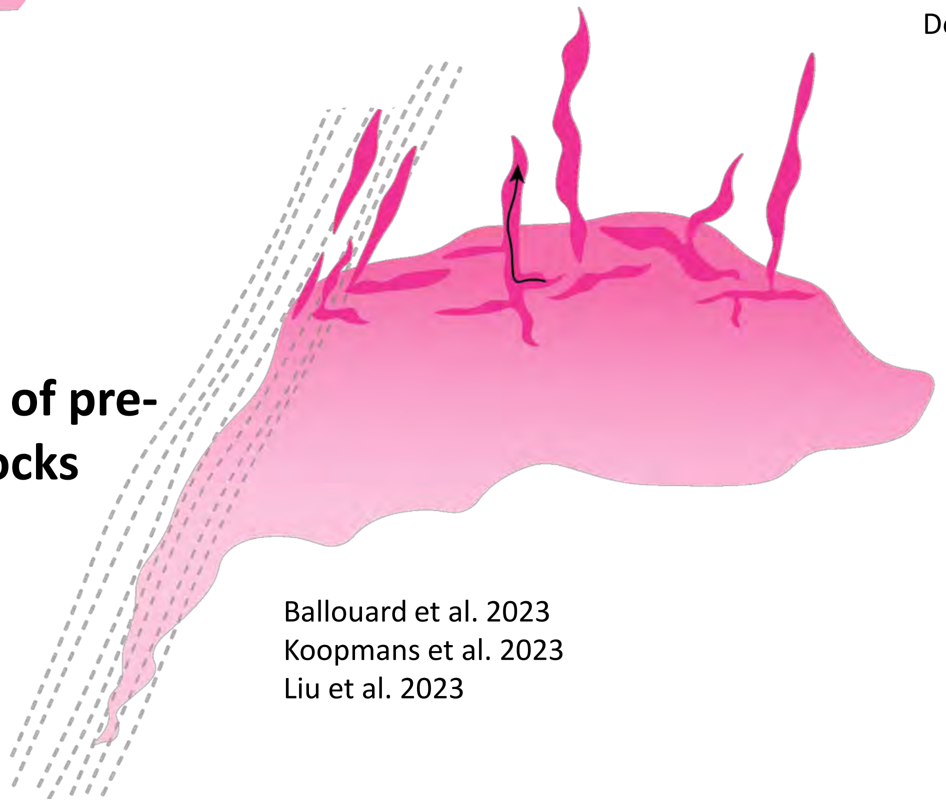


Re-melting of pre-enriched rocks

Ballouard et al. 2023
Koopmans et al. 2023
Liu et al. 2023

How to Induce Partial Melting:

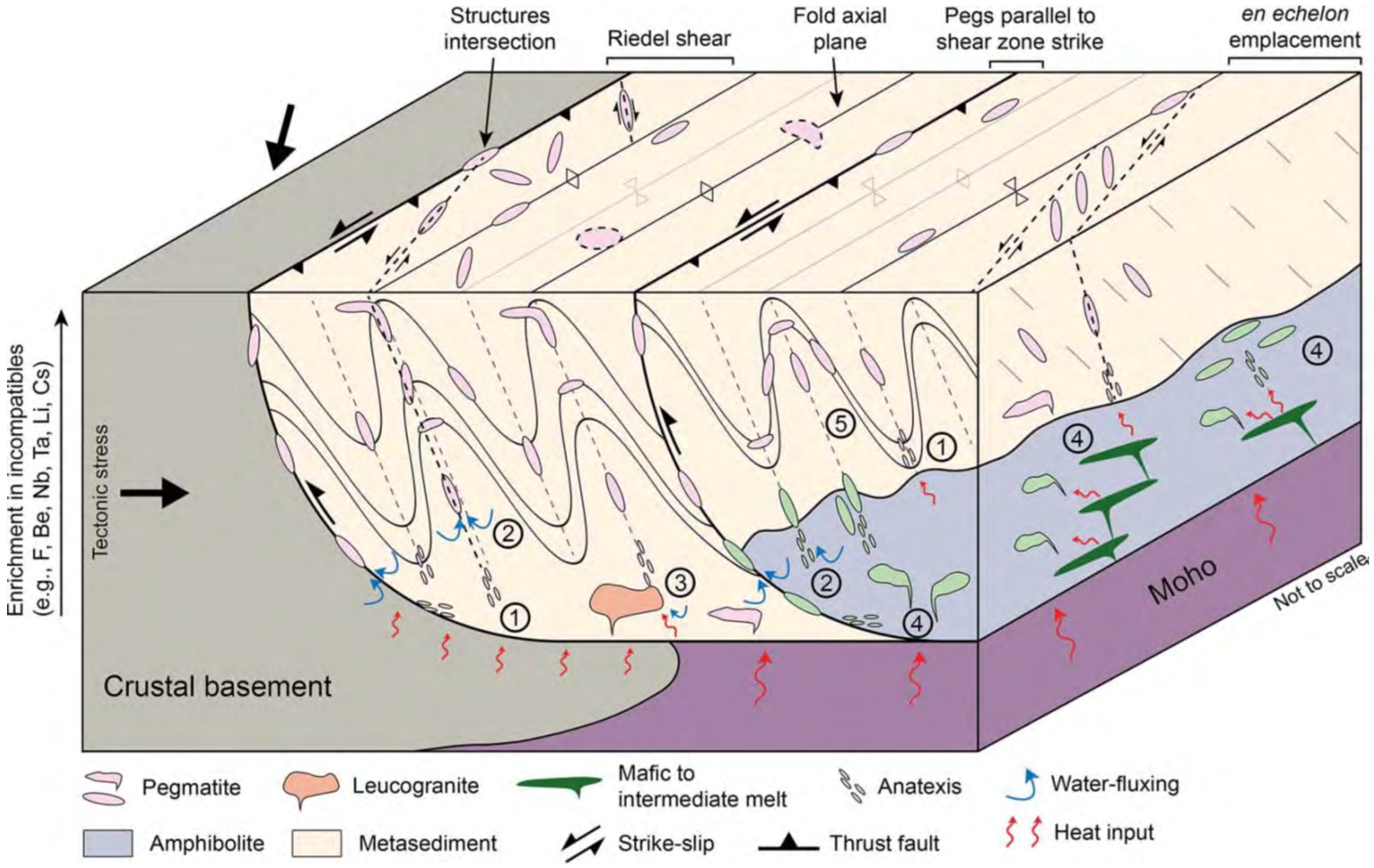
↑ T

↓ P

+ fluids

Silva et al. 2024

But Why?



Silva et al. 2023, Canadian Journal of Min & Pet; Goodenough et al. 2025, Economic Geology

But Why?

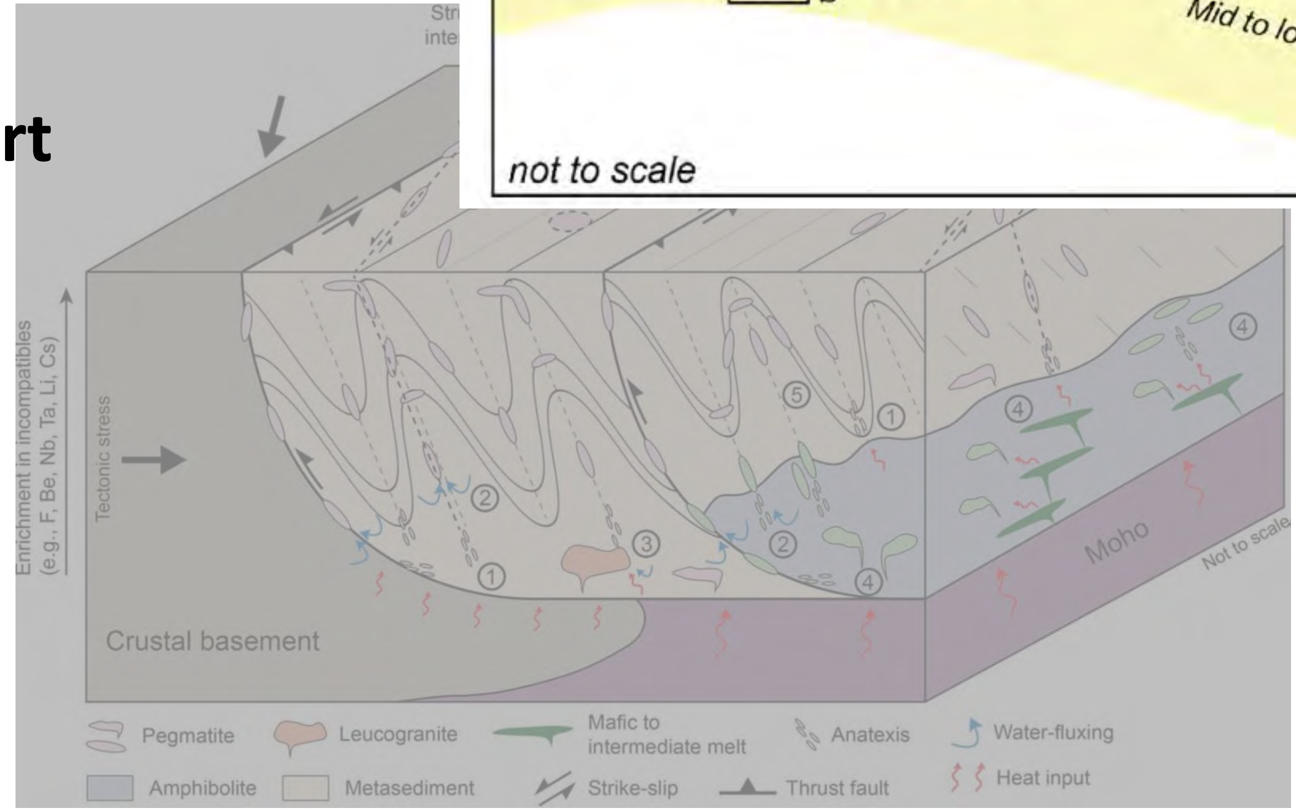
Trap

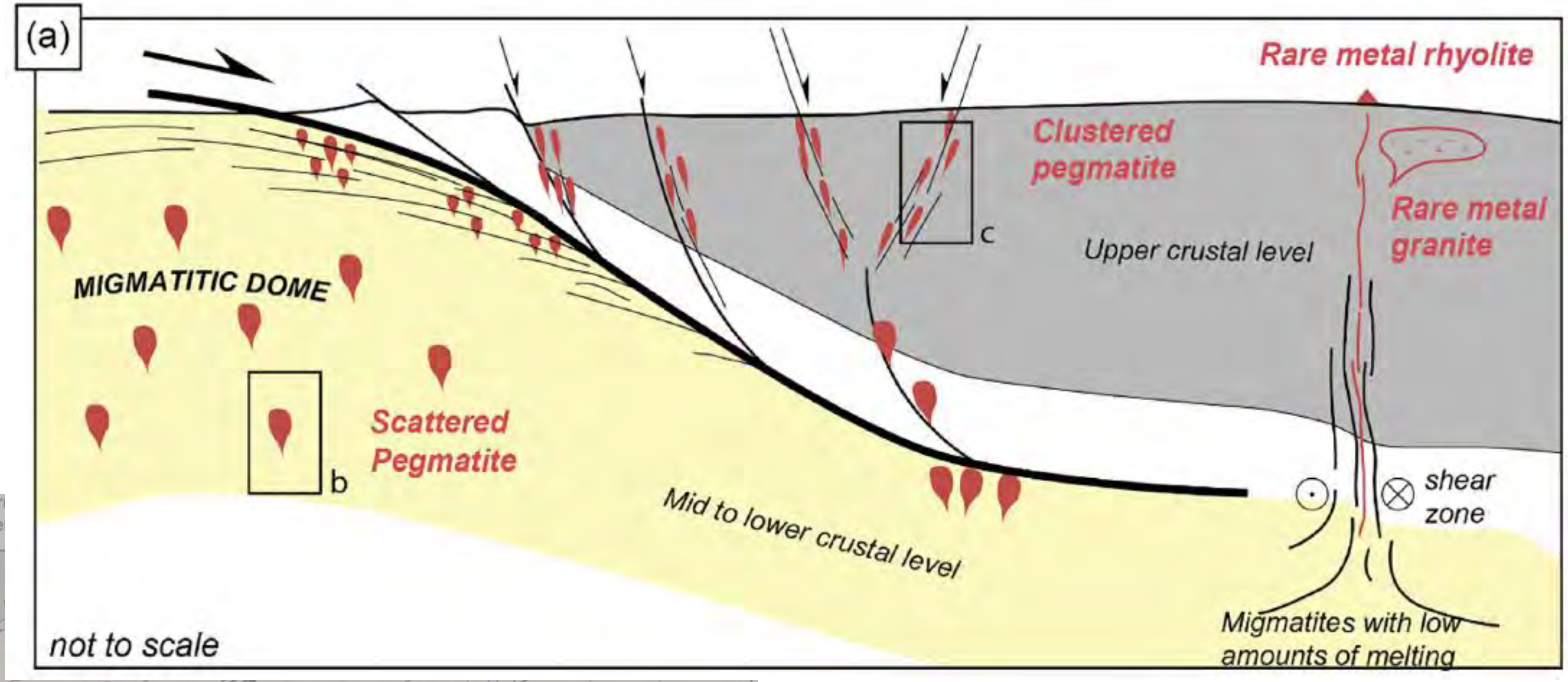
↑

Transport

↑

Source





Plunder et al., 2022, Lithos

Silva et al. 2023, Canadian Journal of Min & Pet; Goodenough et al. 2025, Economic Geology

The District- to Local Scale
with a focus on lithium

Li-Pegmatites Emplaced Along (Cryptic) Faults

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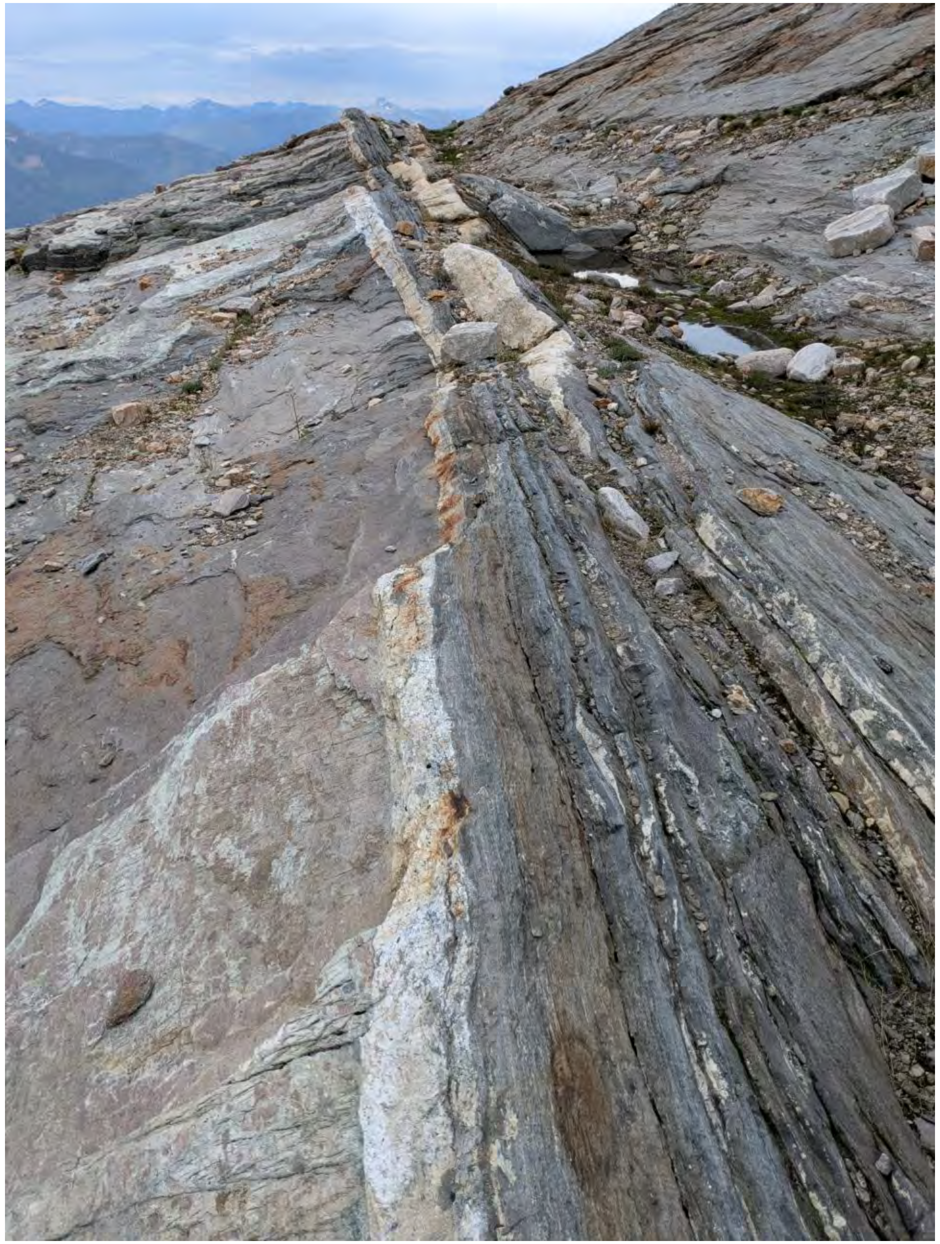


Li-Pegmatites Emplaced Along (Cryptic) Faults

Variety of Shapes & Sizes…

Variety of Shapes & Sizes…

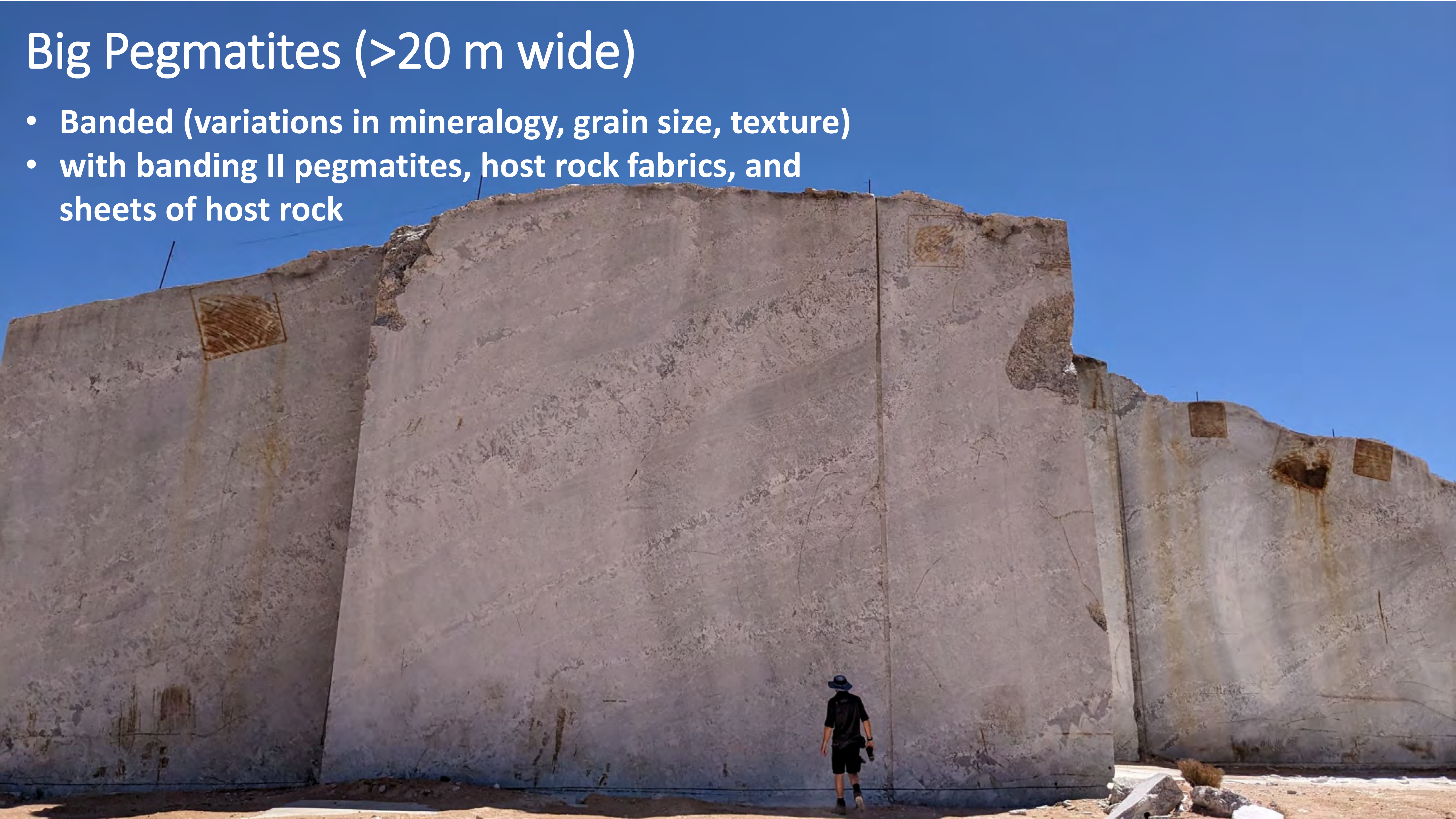
Orange River Peg. Belt, Southern Africa

Variety of Shapes & Sizes…

Uis V12 pegmatite, Namibia

Big Pegmatites (>20 m wide)

- **Banded (variations in mineralogy, grain size, texture)**
- **with banding II pegmatites, host rock fabrics, and sheets of host rock**



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→ *Multiple melt injections*

(e.g., Miller & Paterson 2001)

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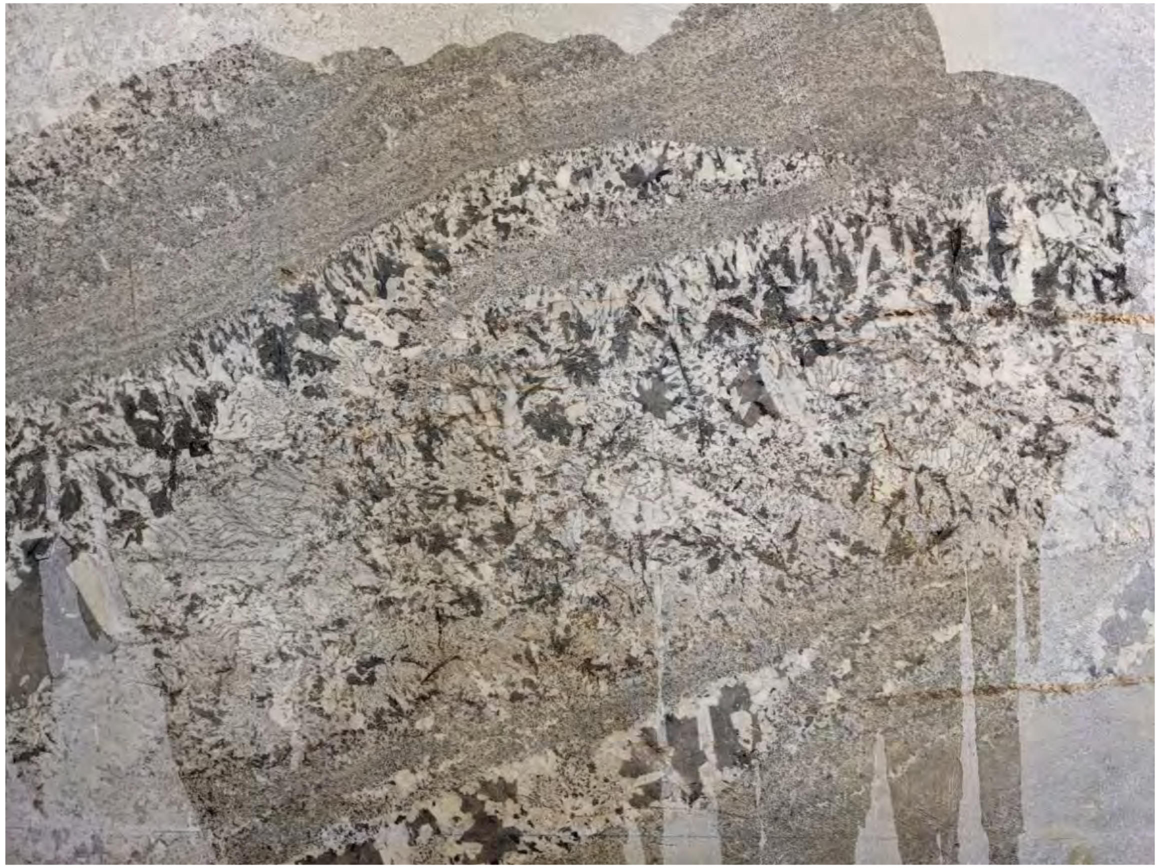
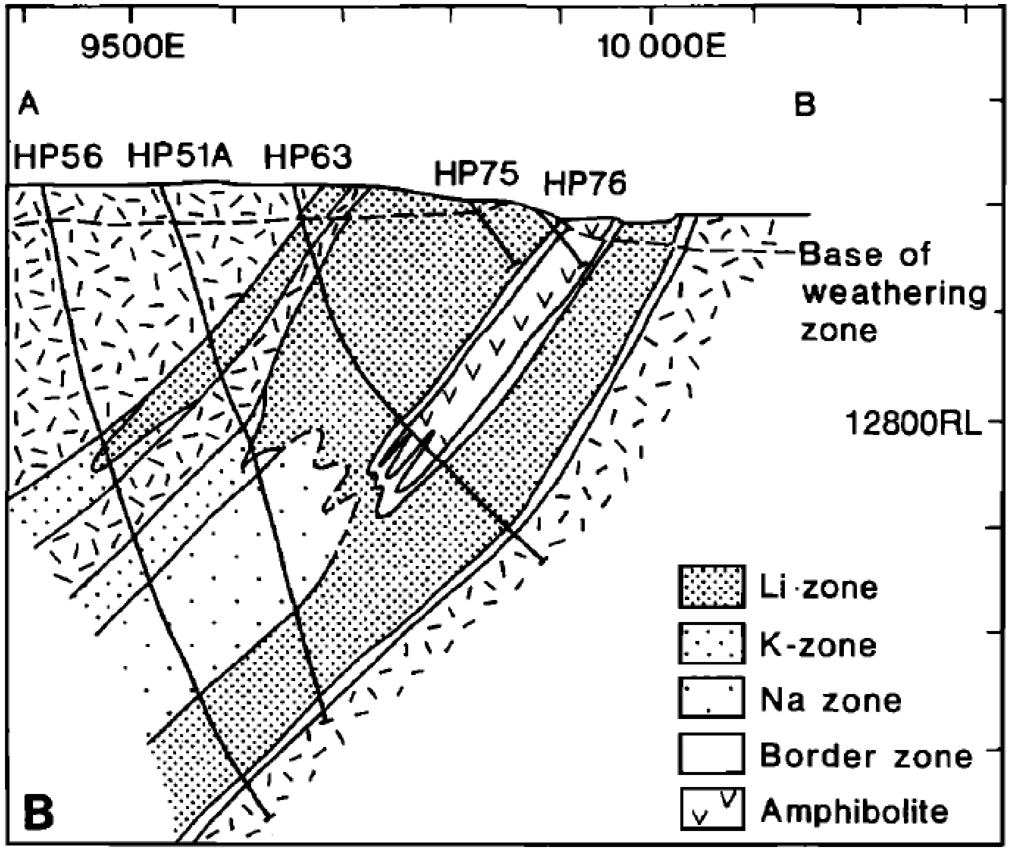
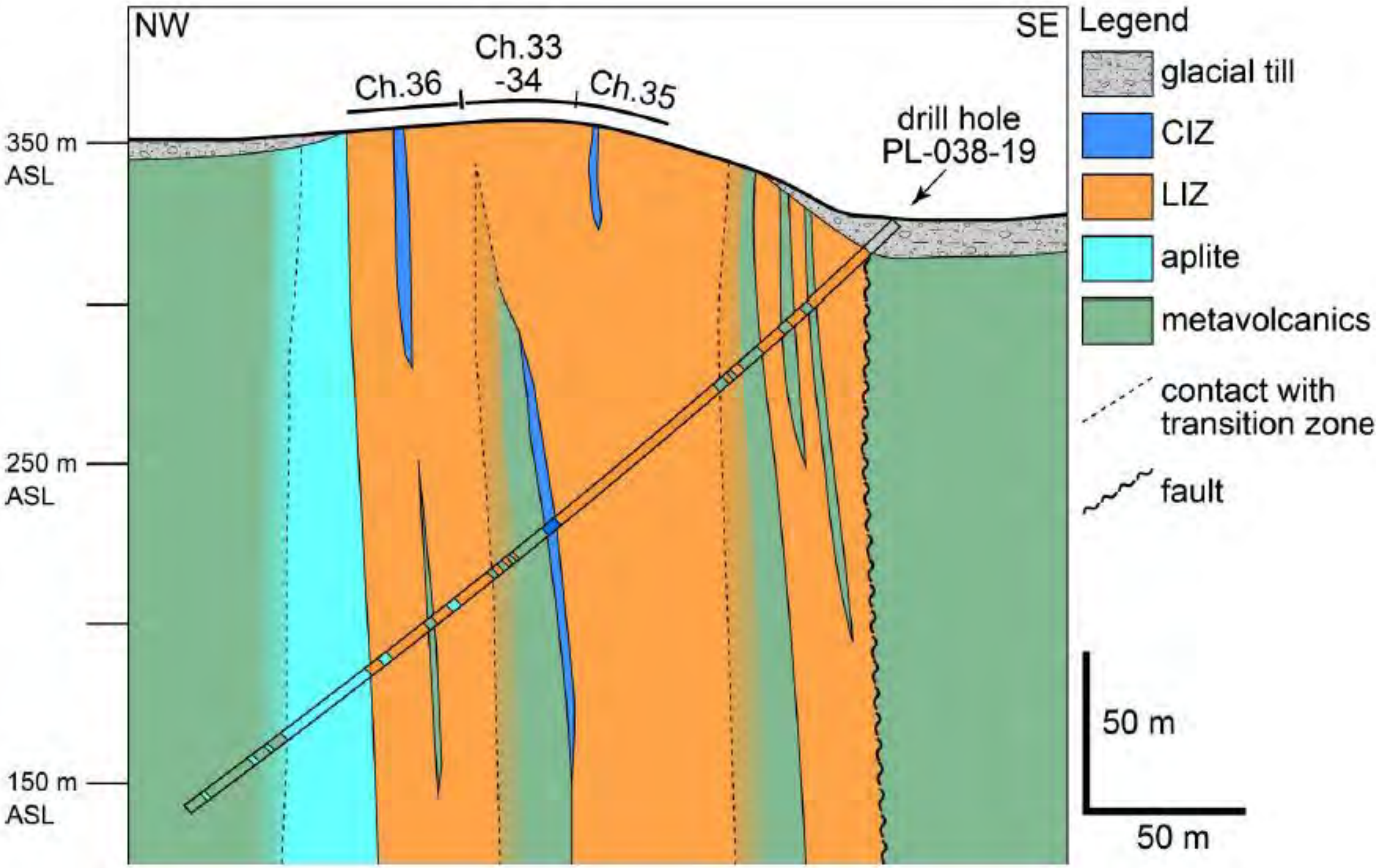


Big Pegmatites (>20 m wide)

- **Single large pegmatite**
- **With narrow sheet-like host rock xenoliths**



Greenbushes, Australia: Partington et al. (1995)



Spark, Ontario: Beyer et al. (2024)

Big Pegmatites (>20 m wide)

- **Single large pegmatite**
- **With narrow sheet-like host rock xenoliths**
- **Some grade outwards into narrow dykes**

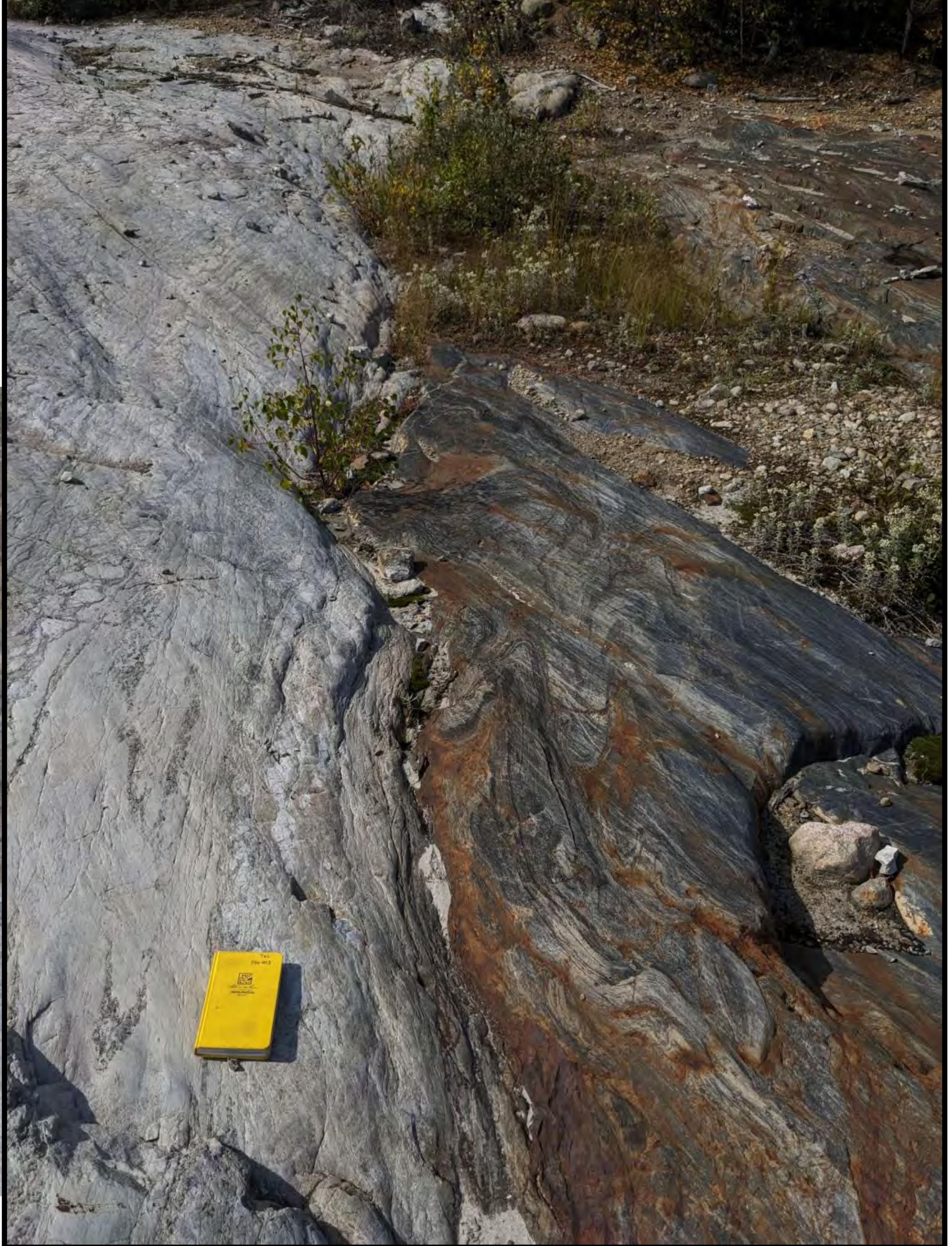
Cawood et al. (2025) SGA abstract

Big Pegmatites (>20 m wide)

- **No concentric internal zonations**
- **although some individual bands do have USTs & quartz cores**

Big Pegmatites (>20 m wide)

- **Pegmatites ~planar, ~II host rock fabric..**
- **but locally cross-cut it…**
- **and are also overprinted by it**



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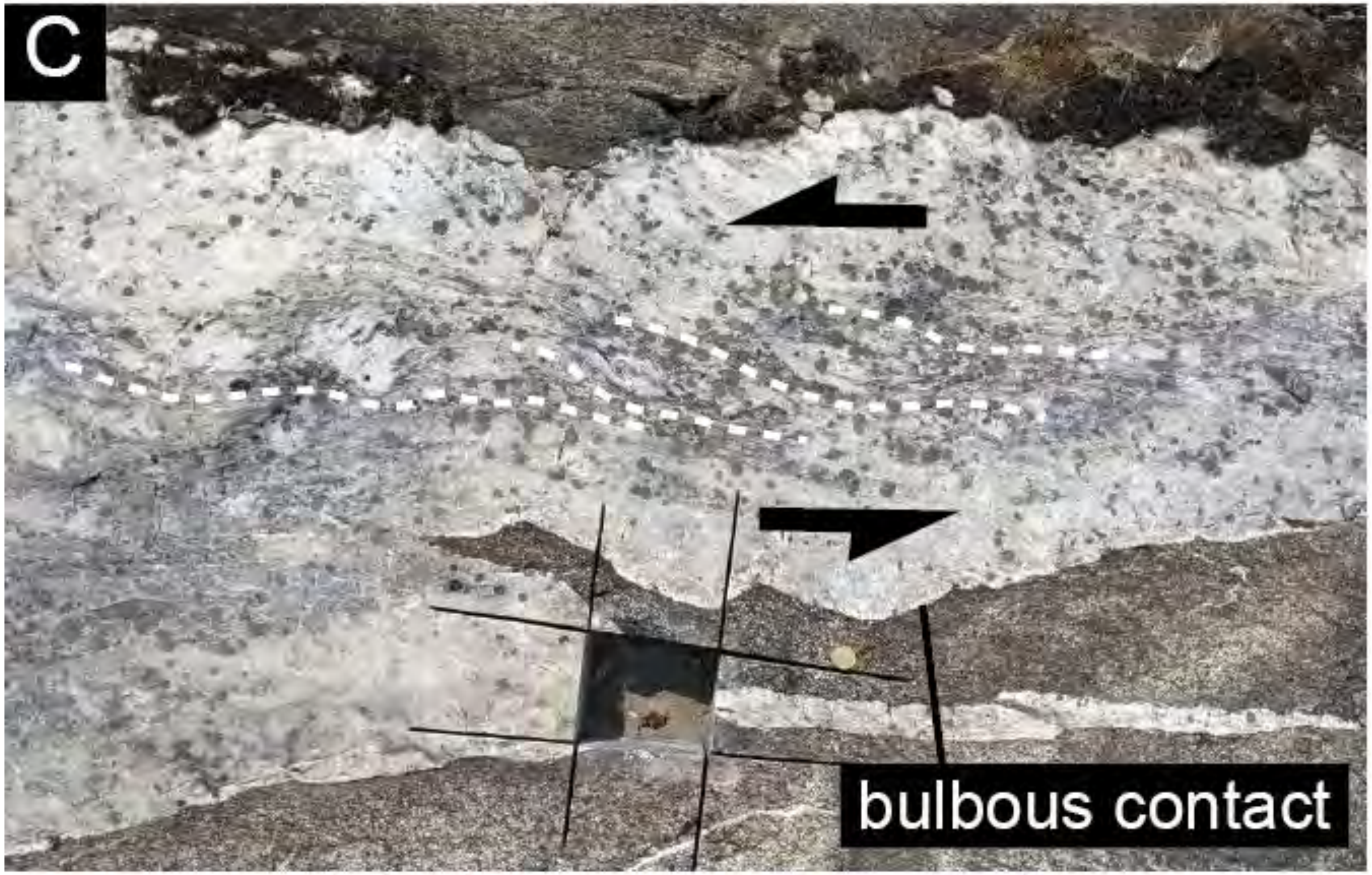
- **but locally cross-cut it…**
- **and are also overprinted by it**

→ *Emplaced during ductile shearing*

Big Pegmatites (>20 m wide)

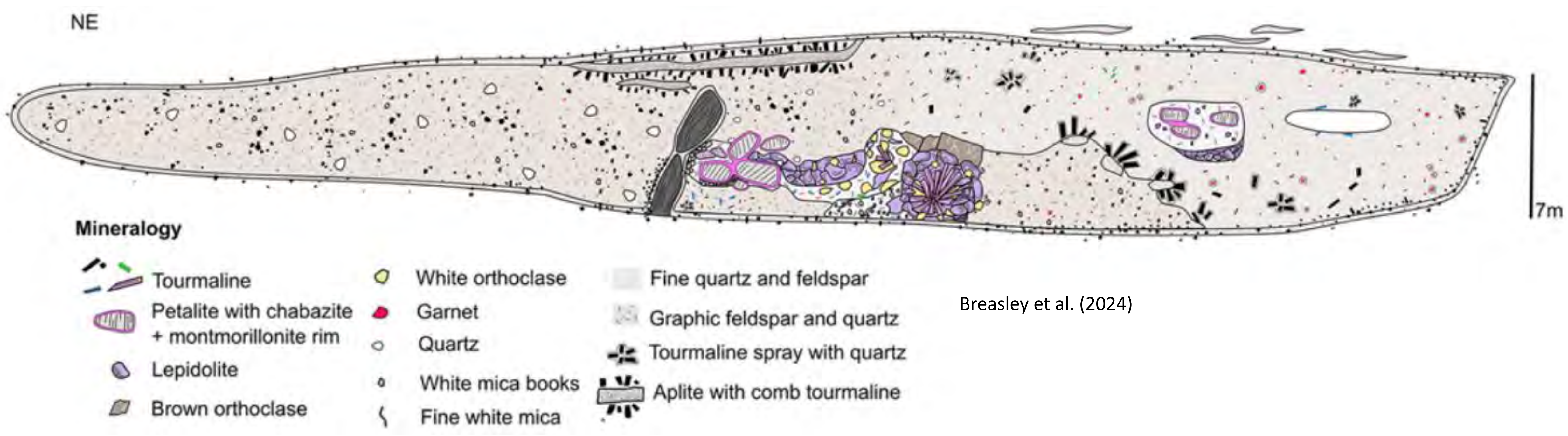
- **Curved to irregular contacts**
  → *Emplaced into ductile host rocks*
  (e.g., Brisbin 1986, Ching 2024)



Small Pegmatites (<15 m wide)

- **May have concentric internal zonations**
- **No banding or internal fabrics**
- **No sheets of host rock**

  → *Single melt injection*



Breasley et al. (2024)

Small Pegmatites (<15 m wide)

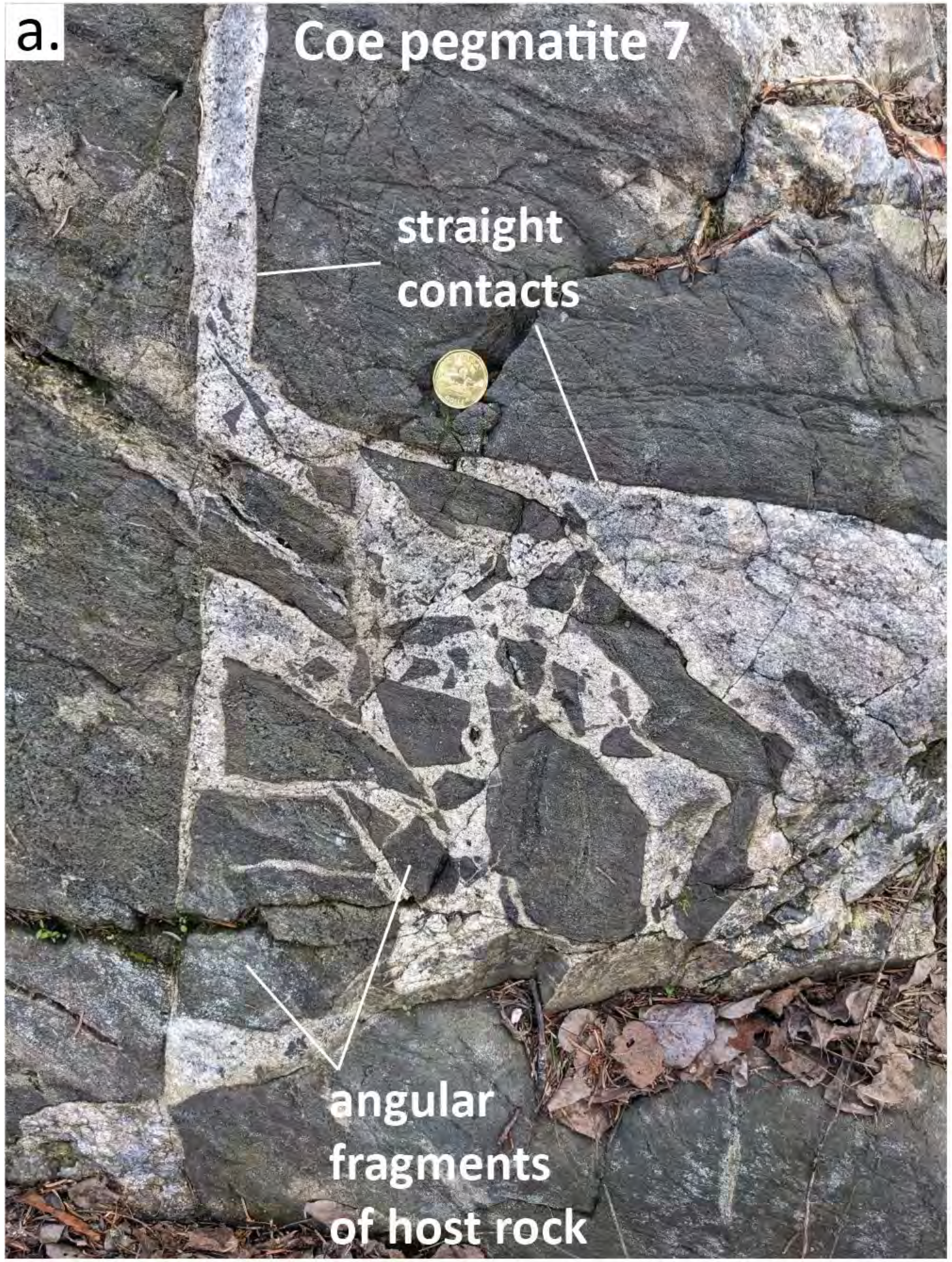
- **Typically not deformed**
- **Don't always have a close spatial association to major structures**

  → *Emplaced into low-displacement, once-off structures*

Small Pegmatites (<15 m wide)

- **Cross-cut host rock fabrics**
- **Or emplaced into non-foliated host rocks**
- **With sharp, planar to angular contacts**

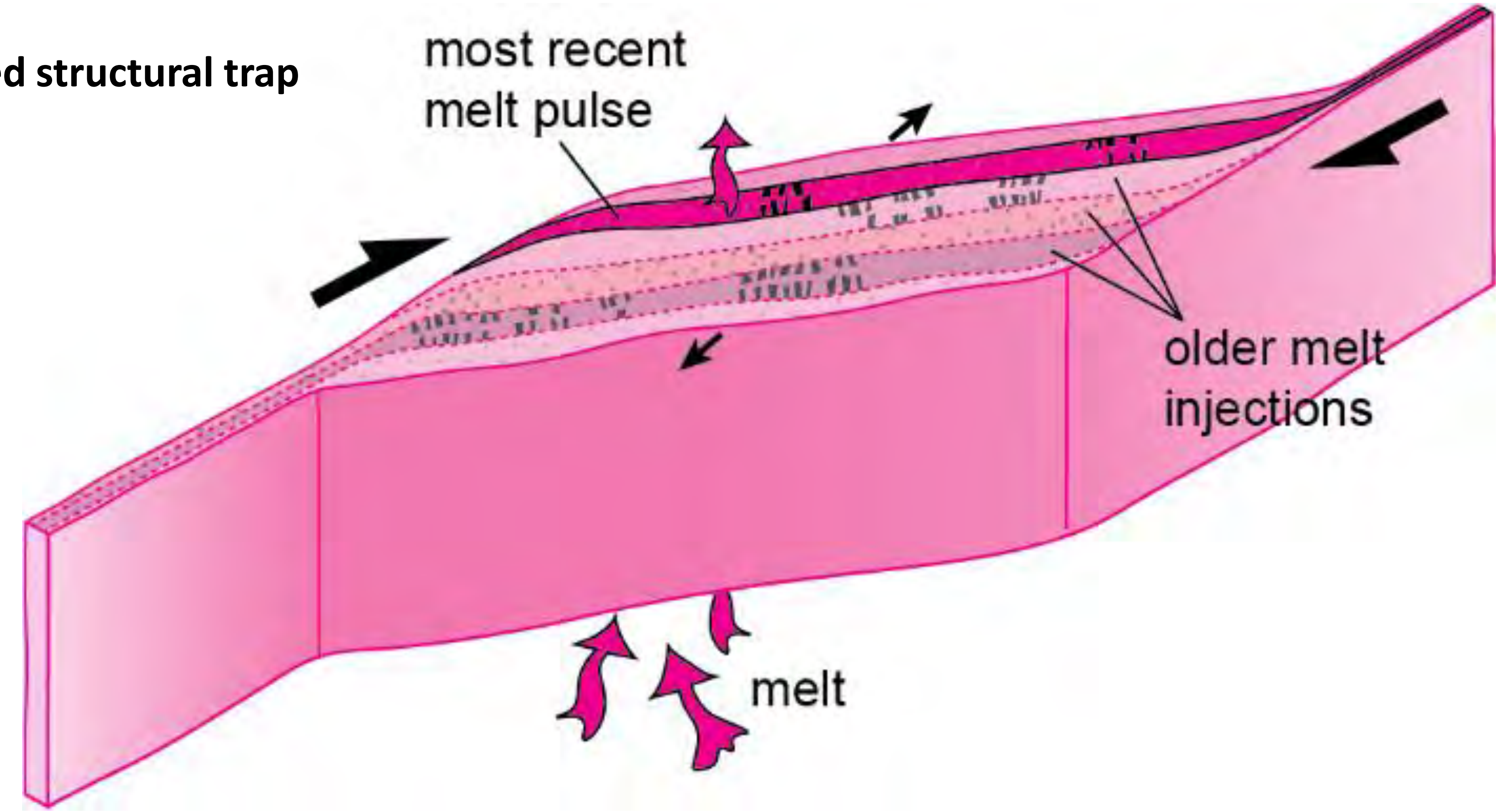
  → *Emplaced into brittle structures, in shallow crust*



Emplacement Controls on Pegmatite Size

<u>Big Pegmatites (>20m)</u>

- **multiple melt injections**
- **into a multiply-reactivated structural trap**



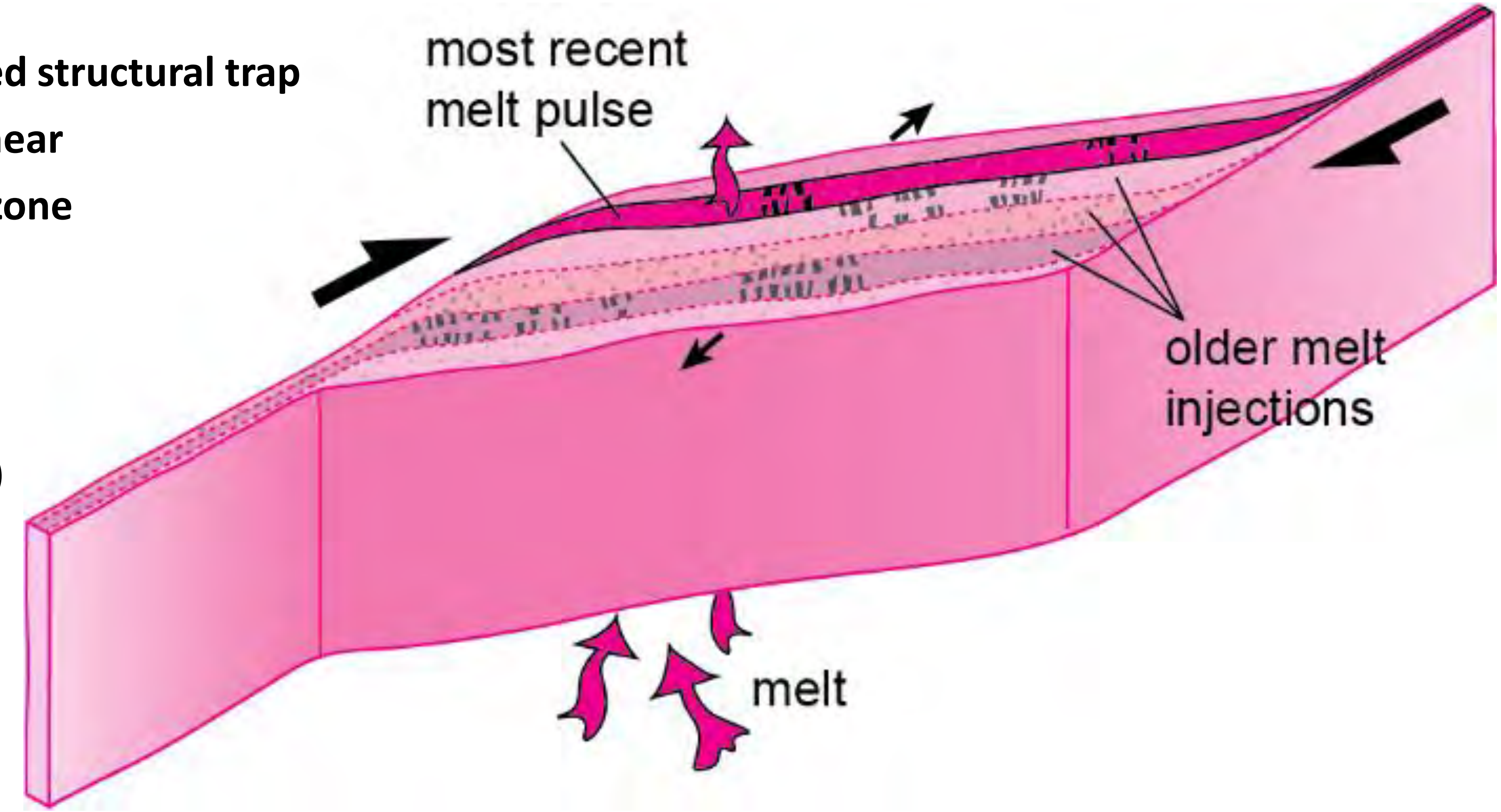
Adapted from Lambert (2013)

Emplacement Controls on Pegmatite Size

<u>Big Pegmatites (>20m)</u>

- **multiple melt injections**
- **into a multiply-reactivated structural trap**
- **during ongoing ductile shear**
- **along a long-lived shear zone**
- **in warm mid-deep crust**

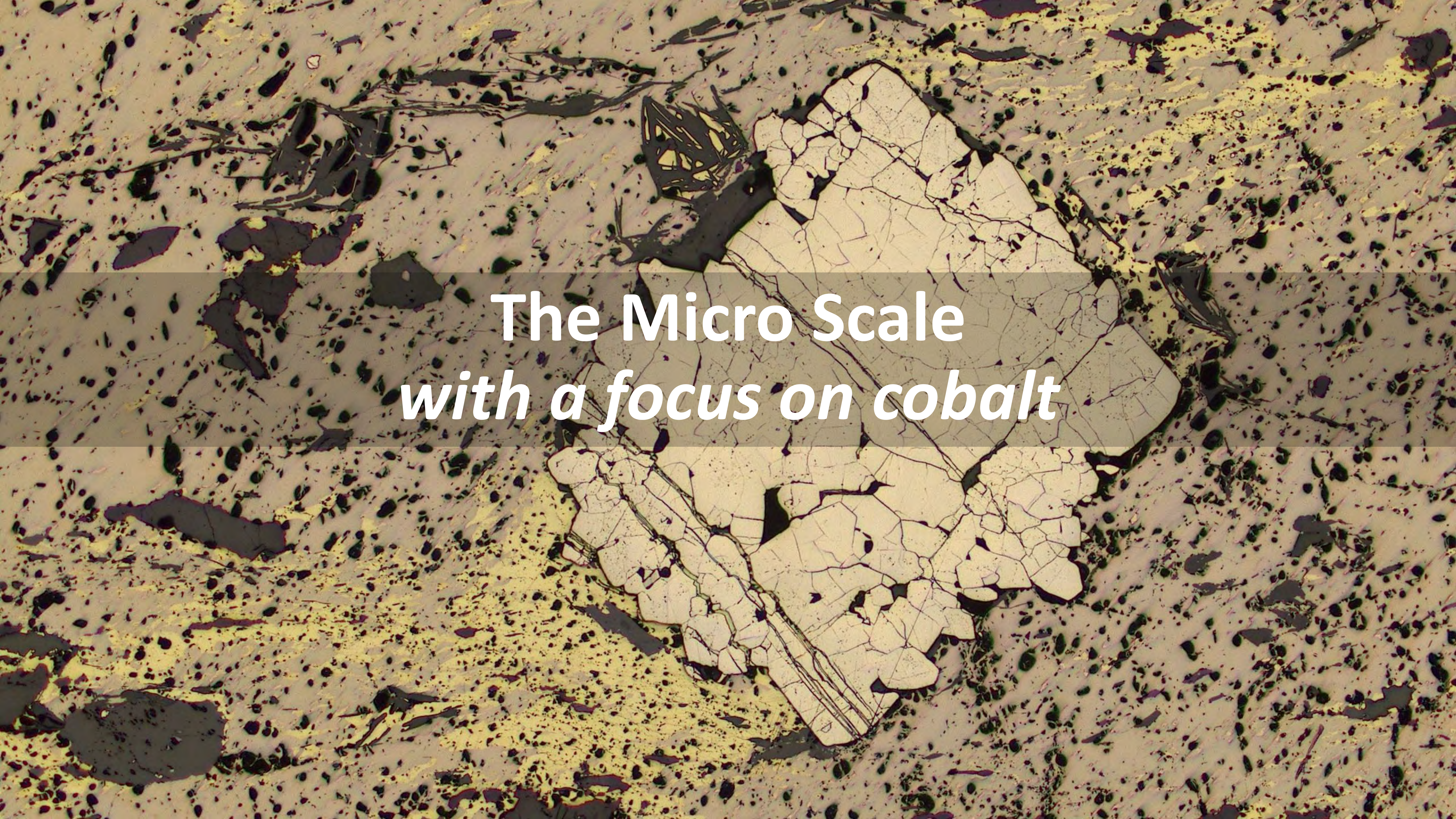
Possibly Manono-Kitotolo
(Rodriguez-Ardila et al. 2025)



Adapted from Lambert (2013)

The Micro Scale

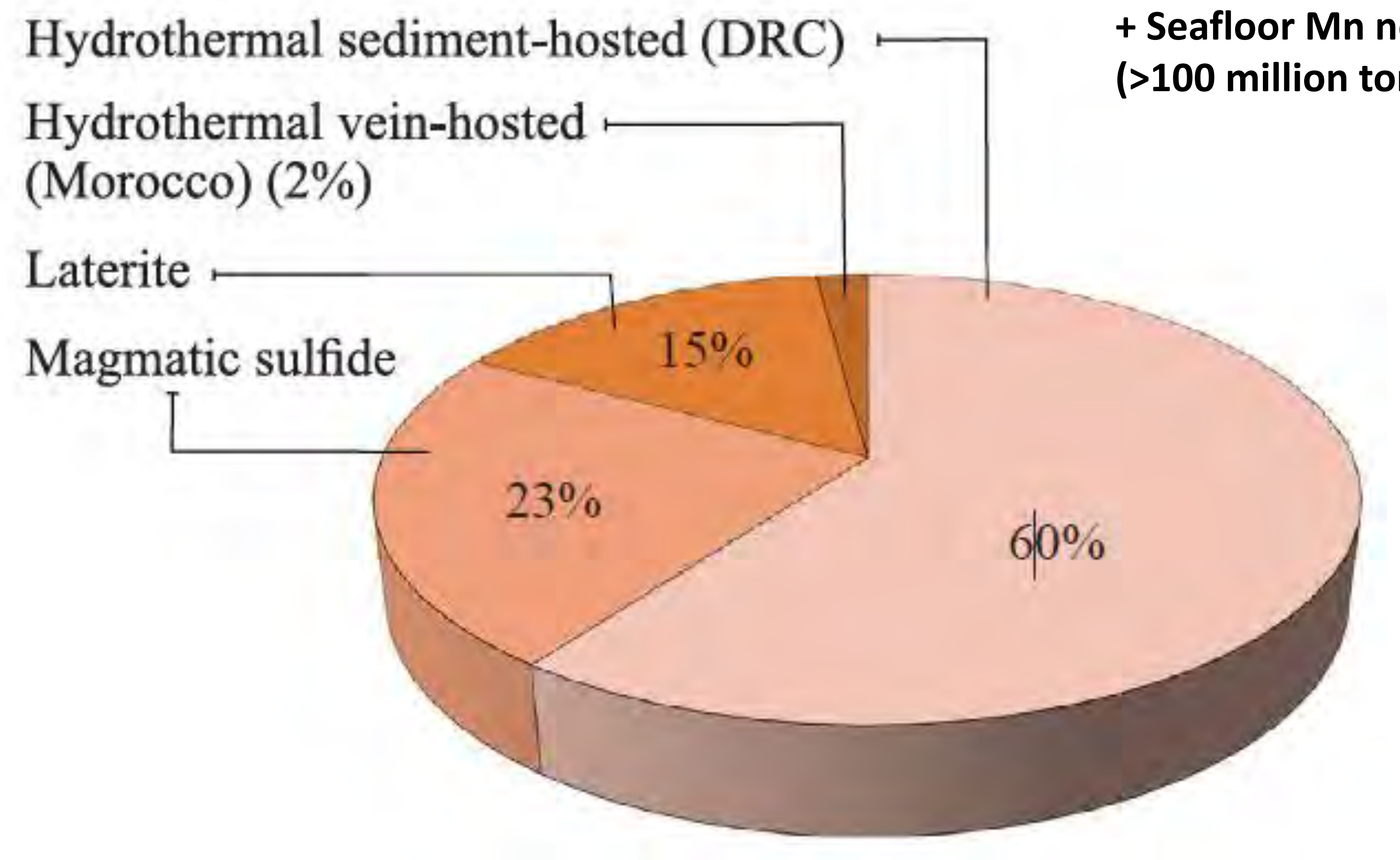
with a focus on cobalt



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*

Case study: The Windy Craggy VMS Deposit

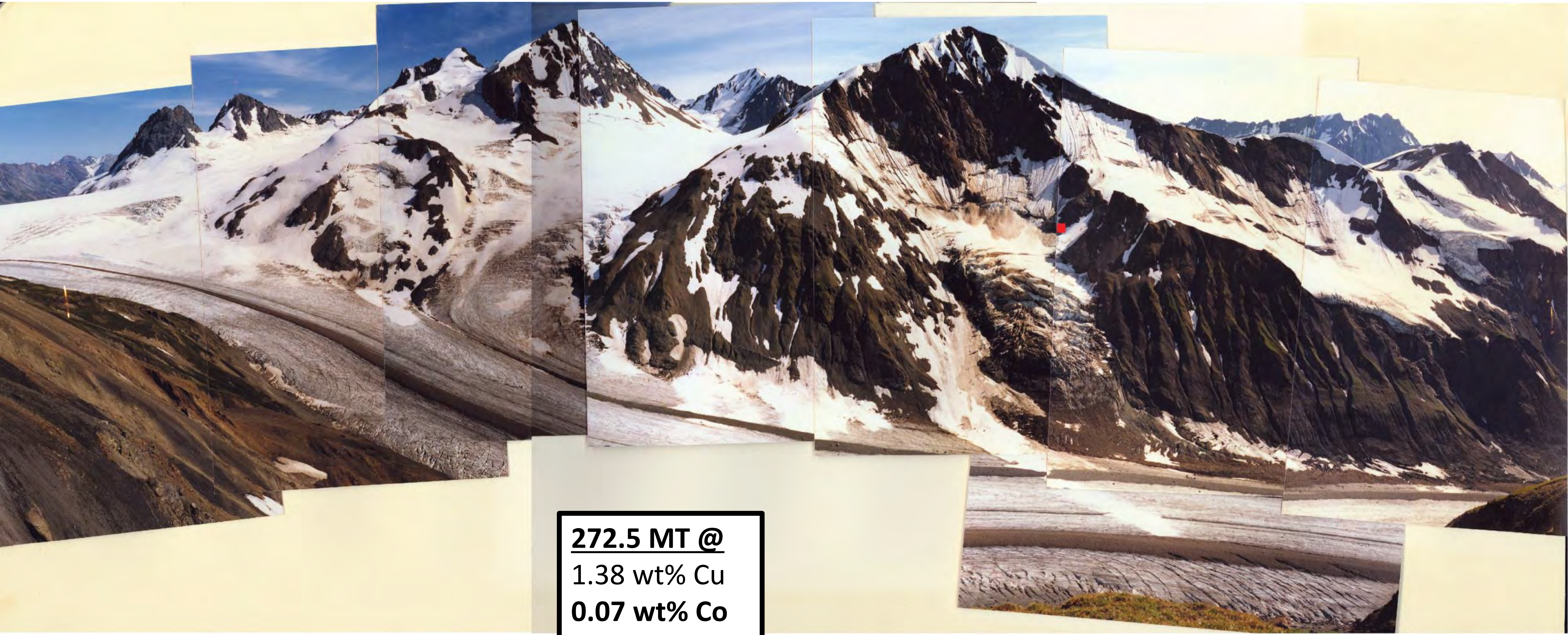


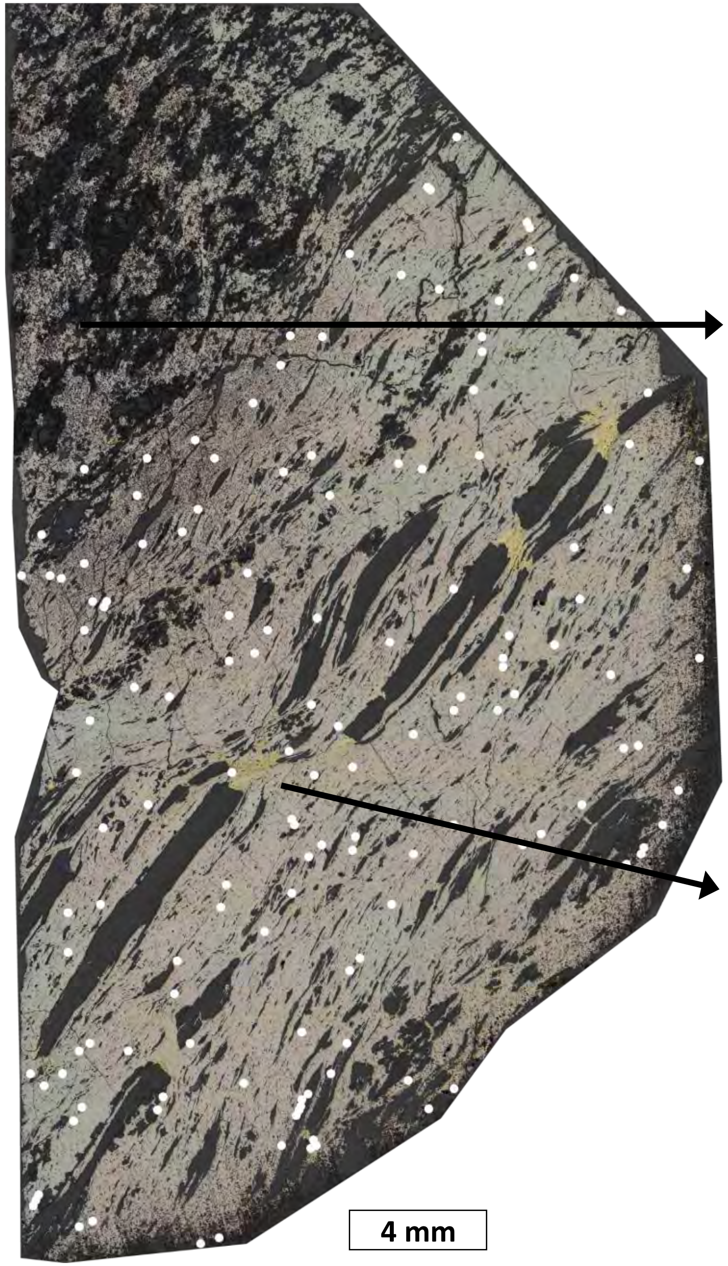
Photo: Jan Peter

<u>272.5 MT @</u>
1.38 wt% Cu
0.07 wt% Co
0.2 g/t Au
3.83 g/t Ag

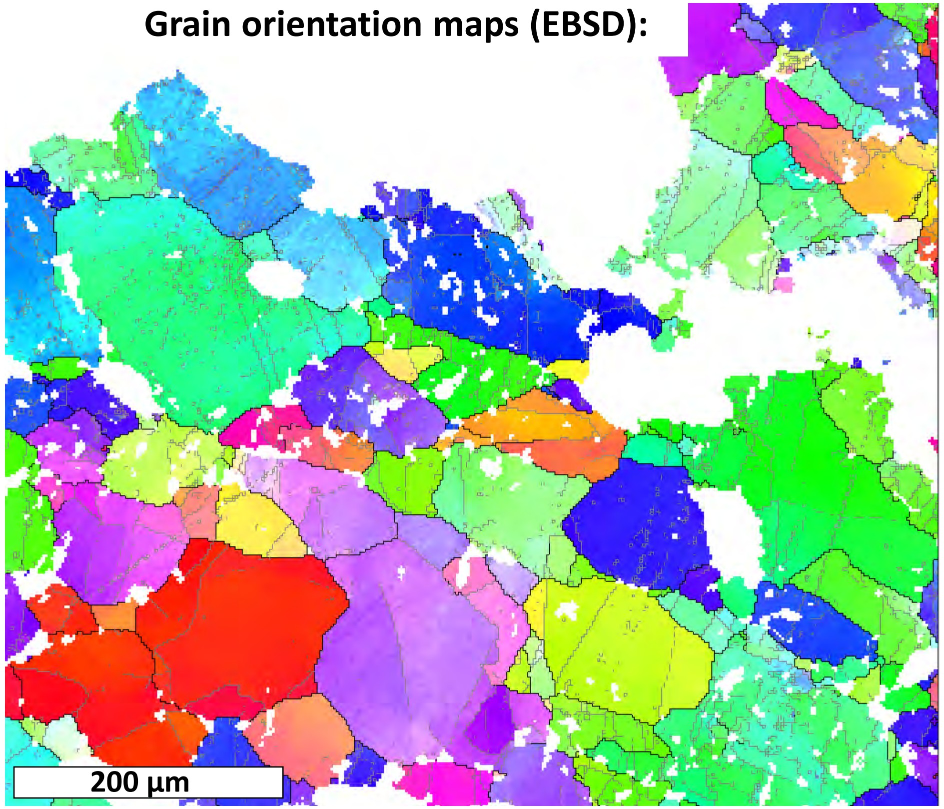
Giroux, 1991

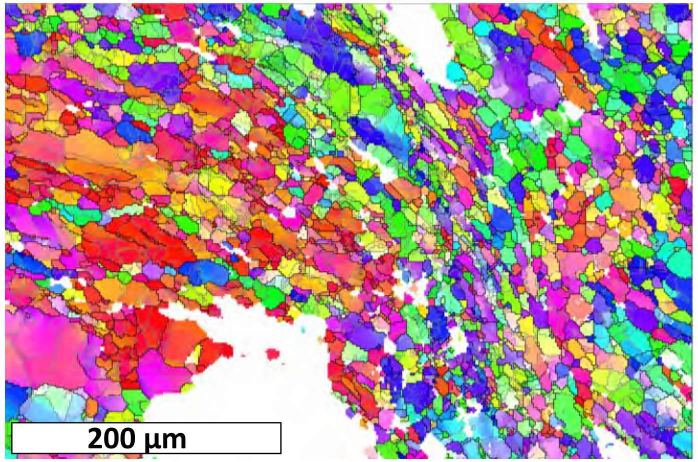
Pyrrhotite: Mechanical Remobilization

Reflected light photomicrograph:



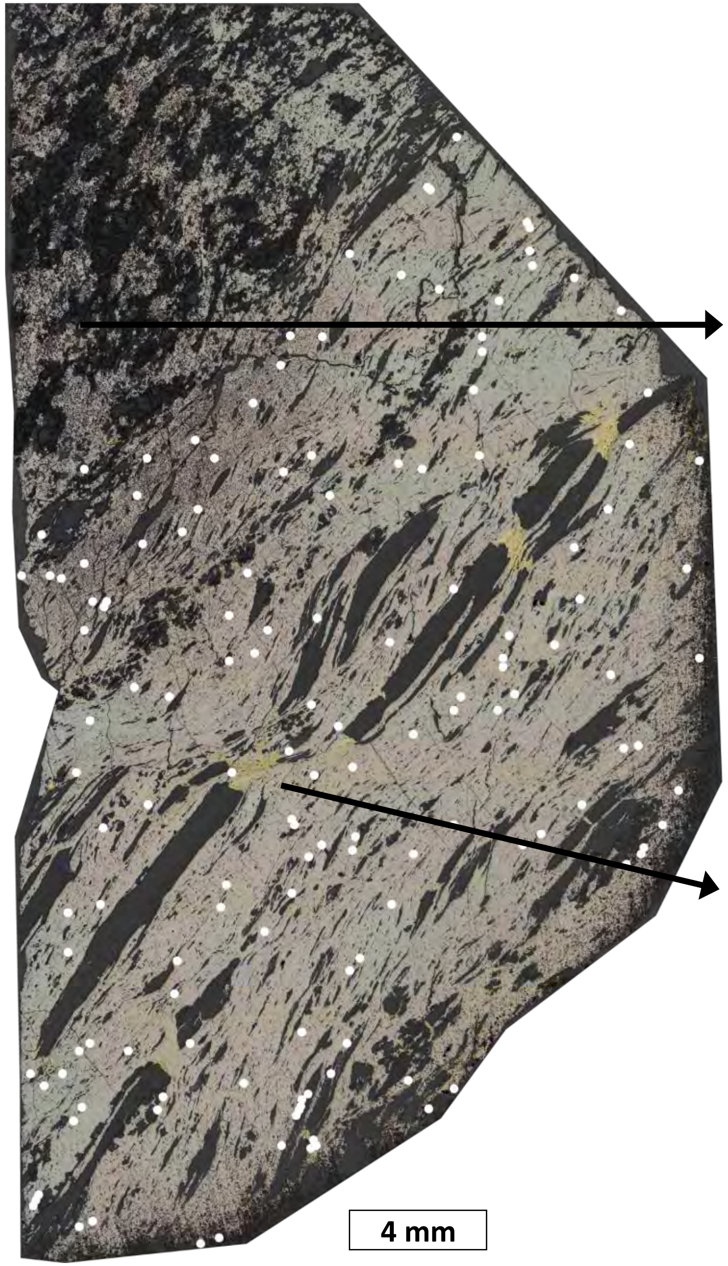
Grain orientation maps (EBSD):



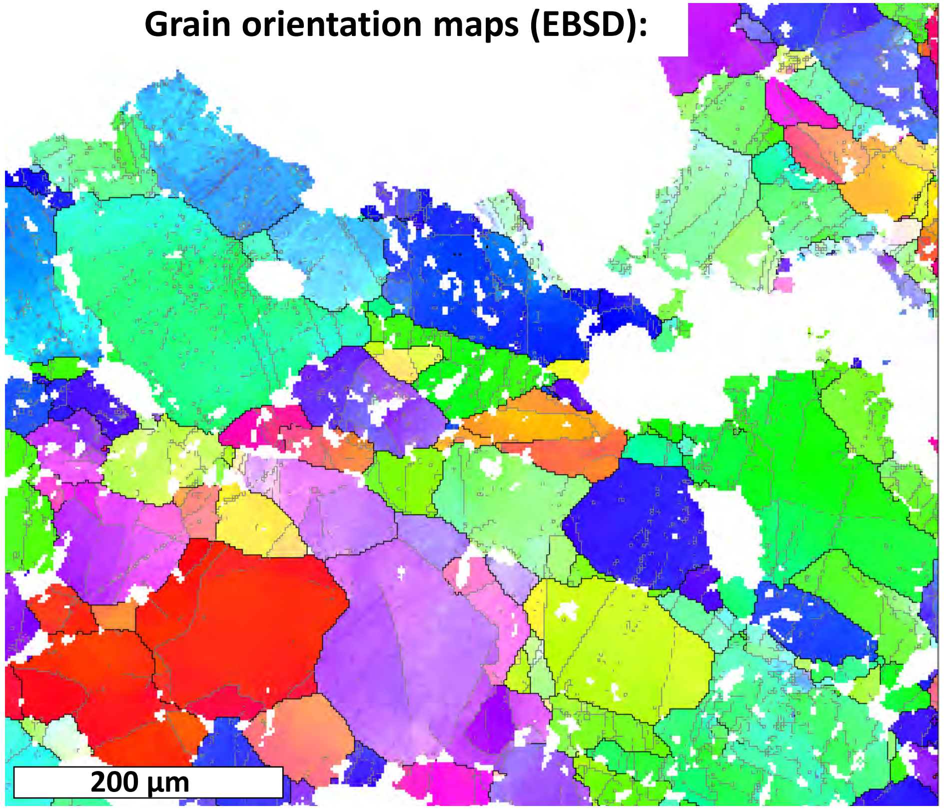


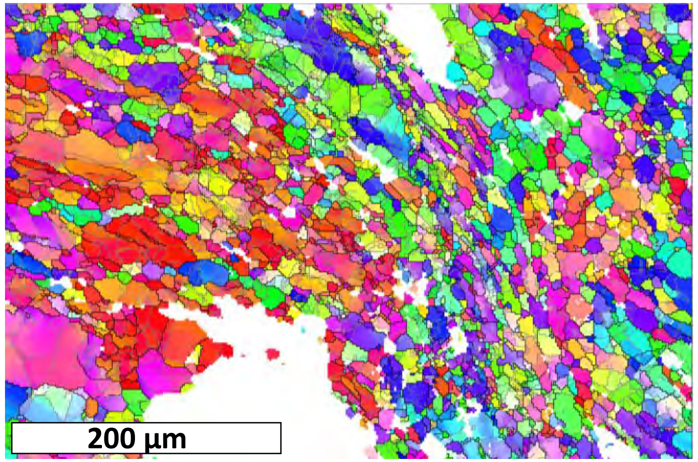
Pyrrhotite: Mechanical Remobilization

Reflected light photomicrograph:



Grain orientation maps (EBSD):

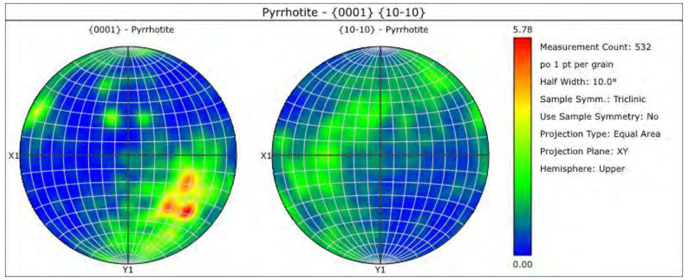


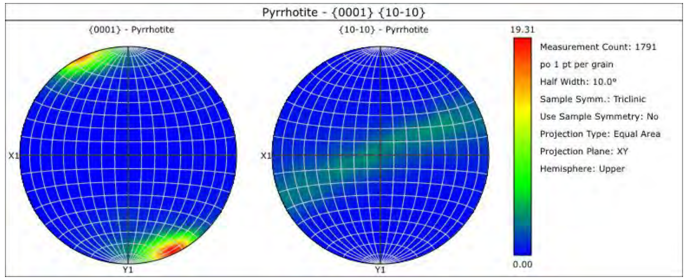


- internal grain distortion
  = dislocation creep

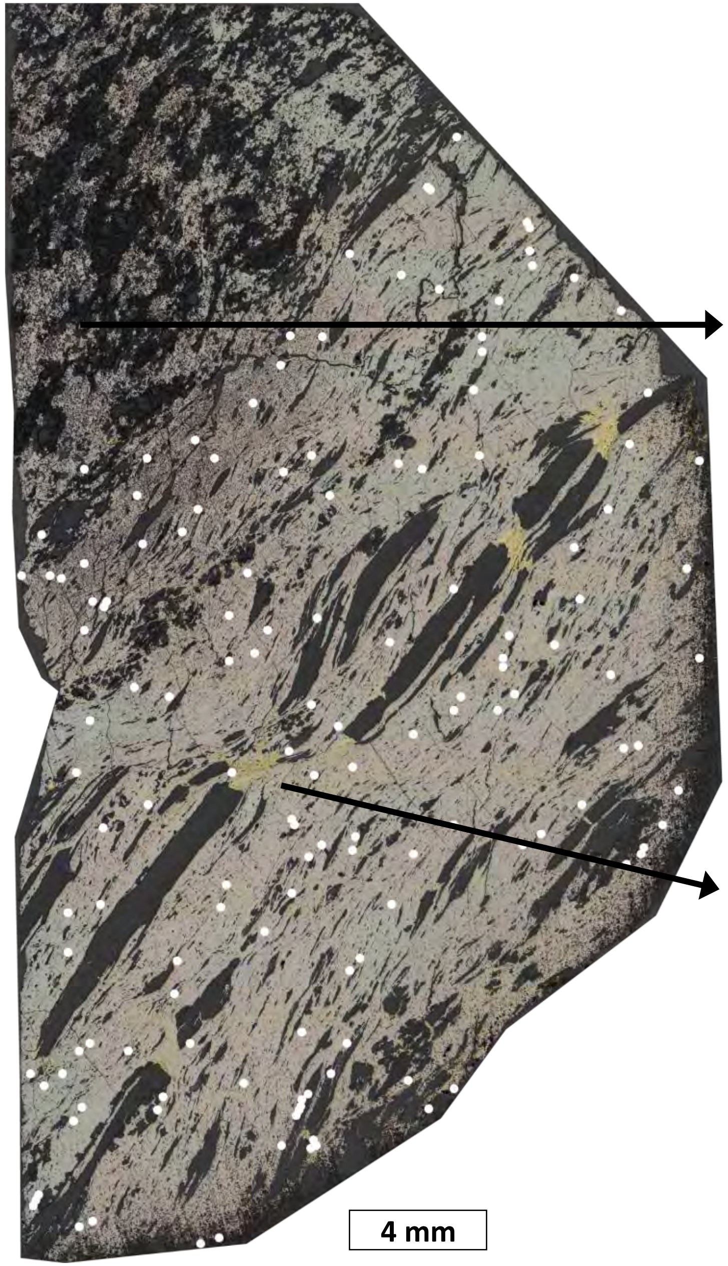
- finer grain size & stronger preferred orientation for foliated pyrrhotite
  = dynamic recrystallization

Grain orientation pole figures (EBSD):

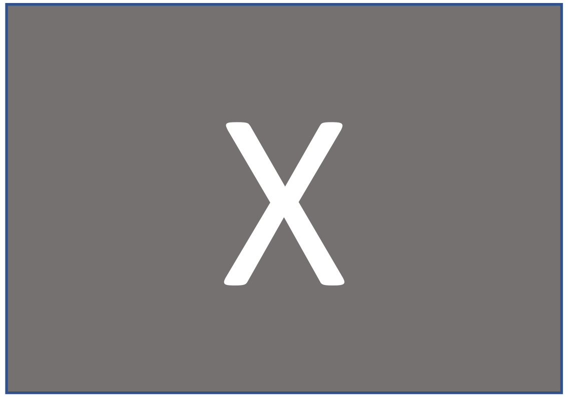




Pyrrhotite: and Cobaltite!

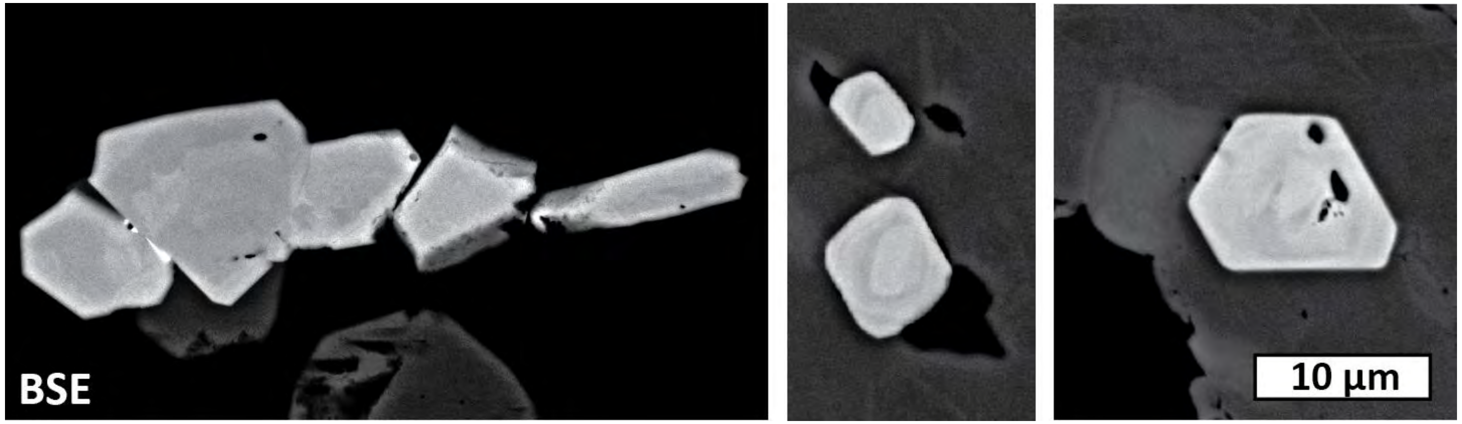


Reflected light photomicrograph:

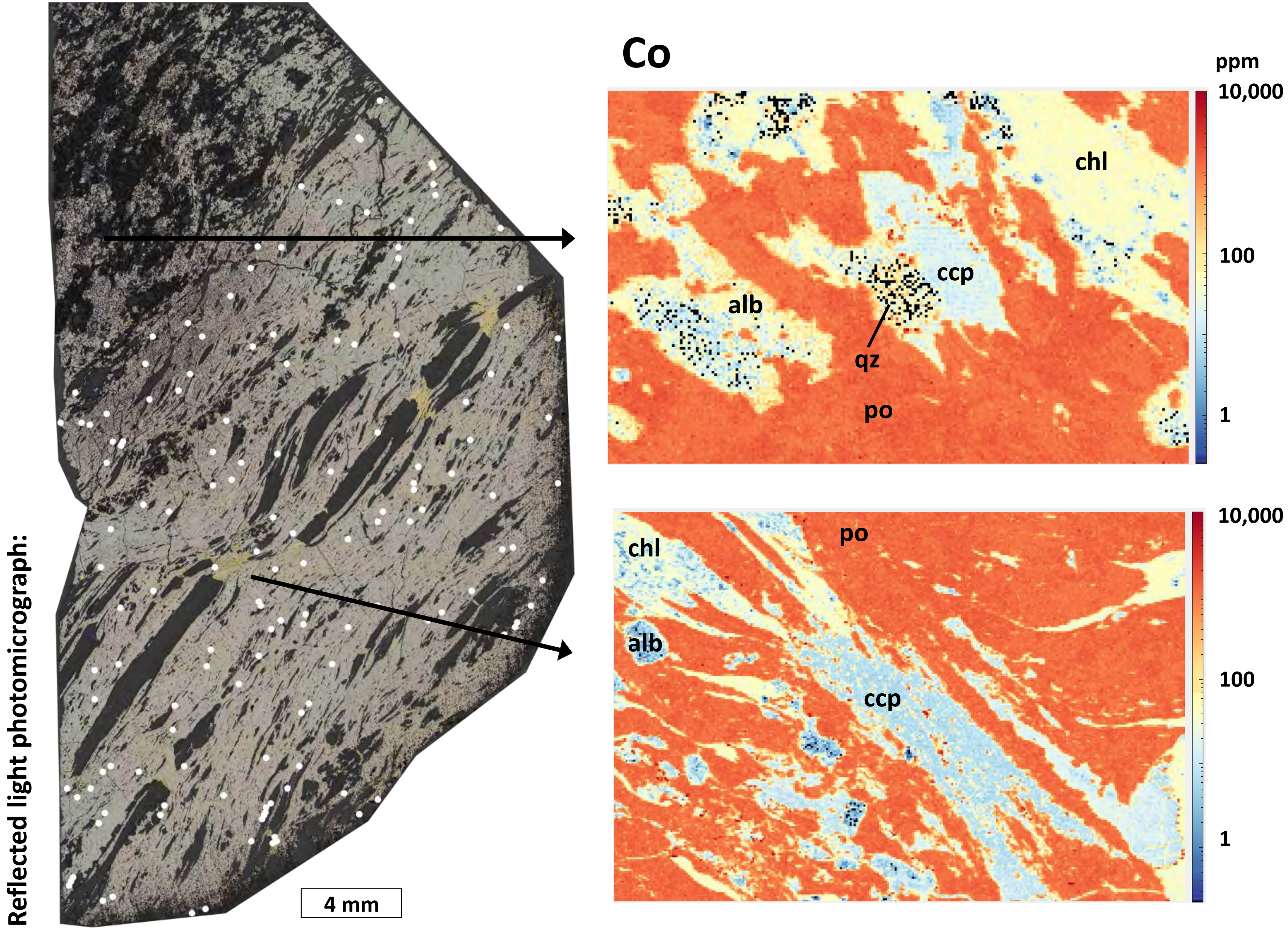


Rare, fine-grained cobaltite (CoAsS) is associated with sheared, dyn. reX po

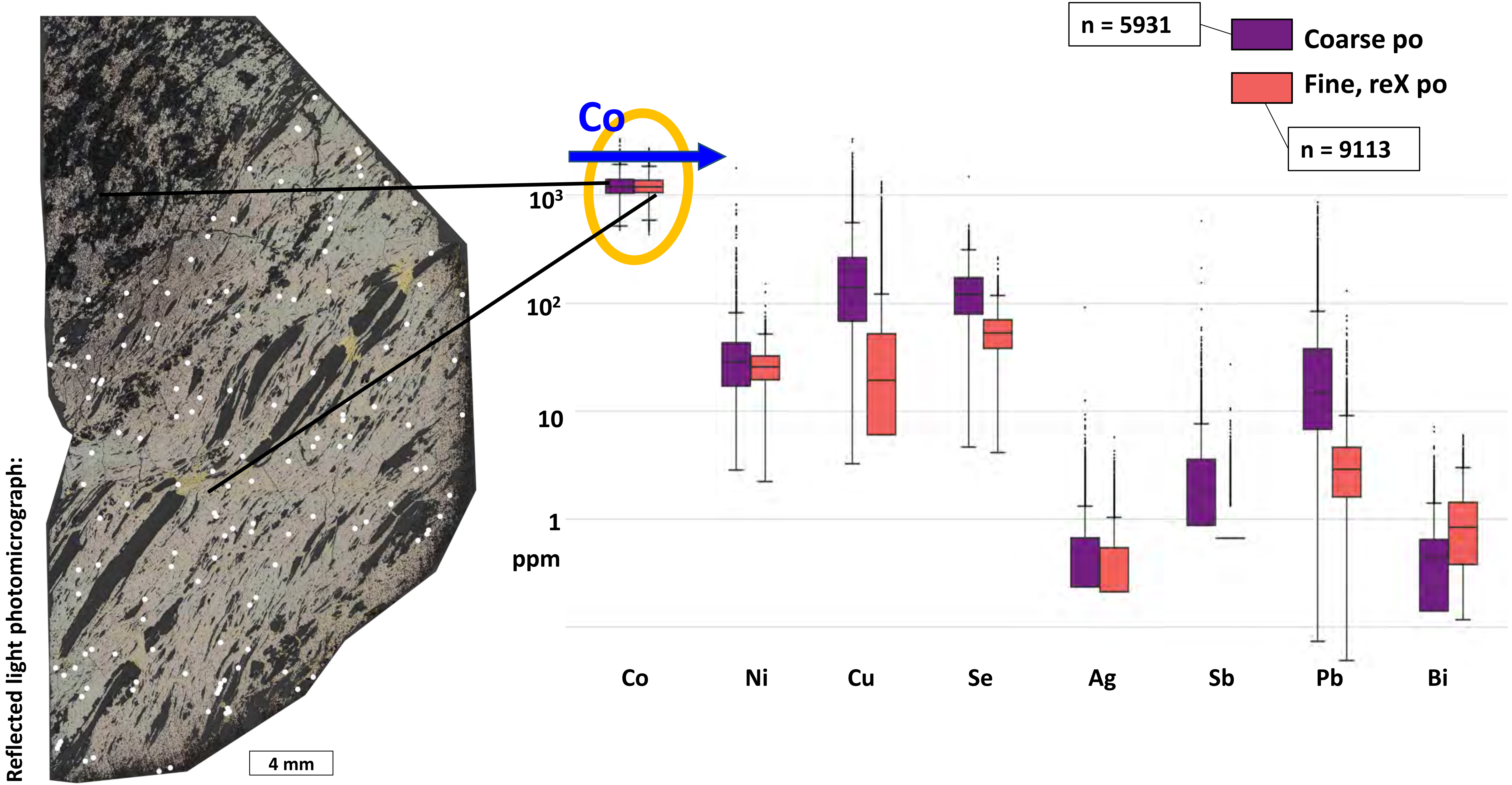
= Co released from deforming po?
= or was additional Co introduced?



Pyrrhotite: Co Content

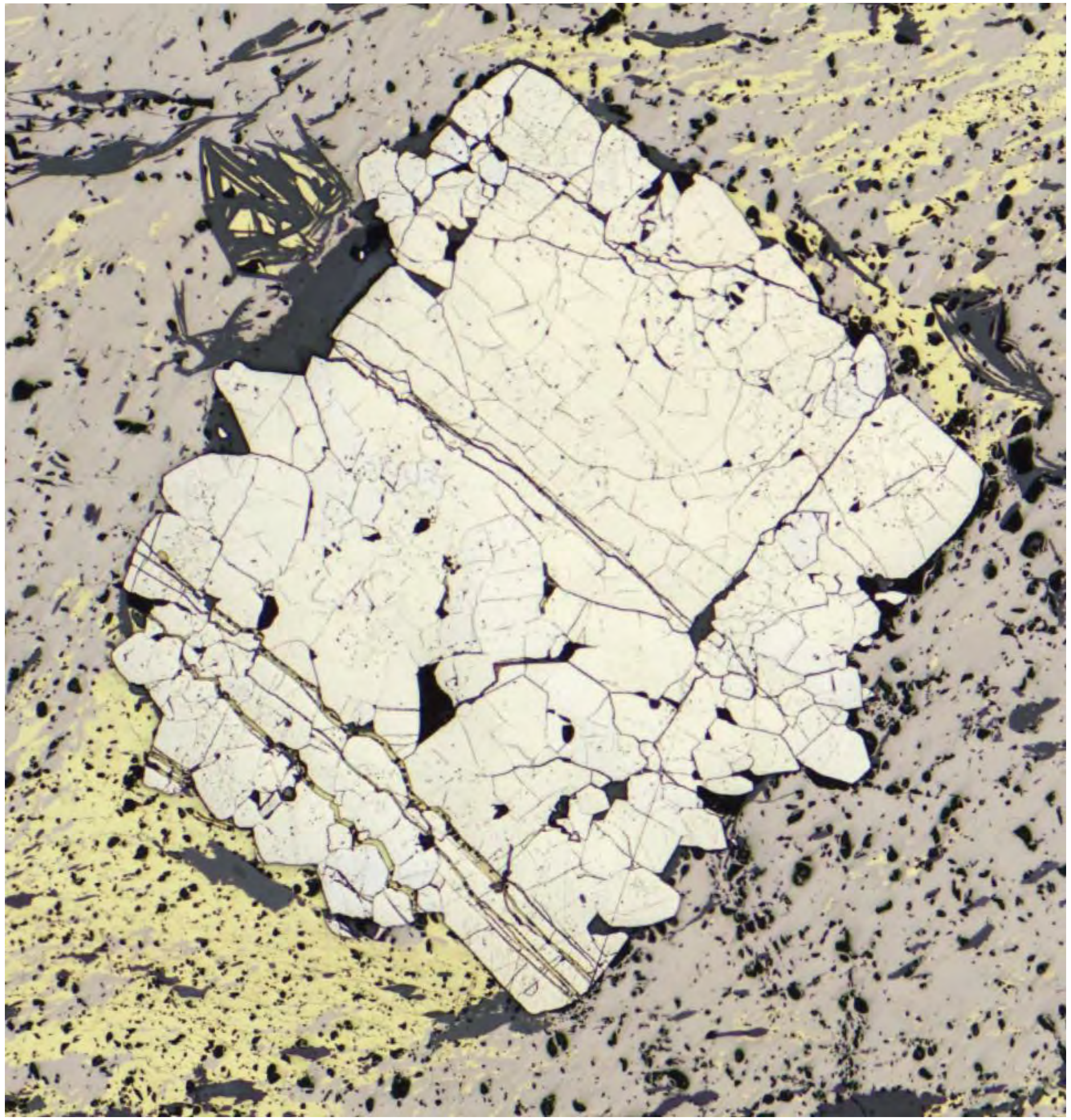


Pyrrhotite: Co Content

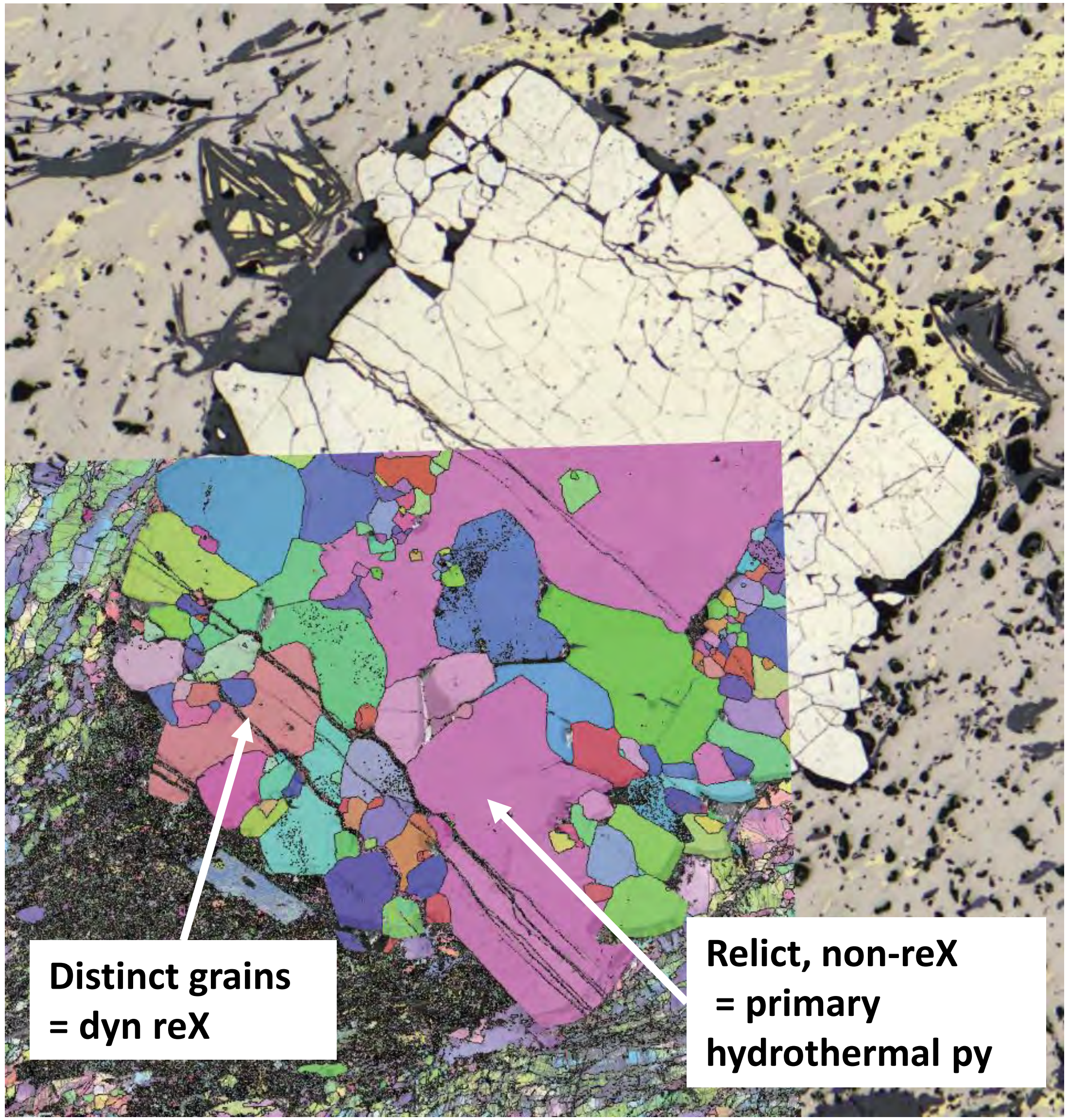


Pyrite: Limited Mechanical Remobilization

Reflected light photomicrograph

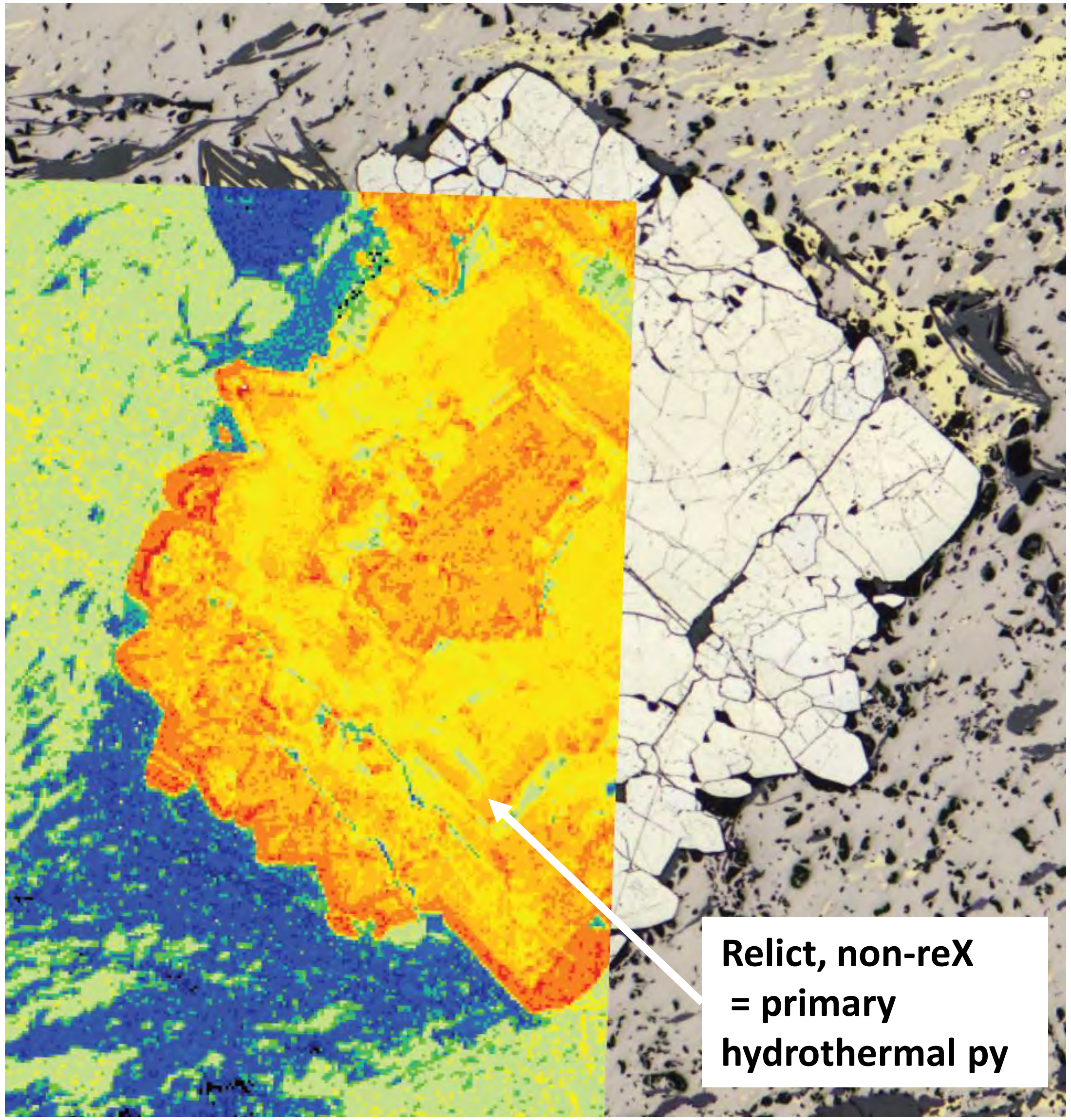


Grain orientation map (EBSD)

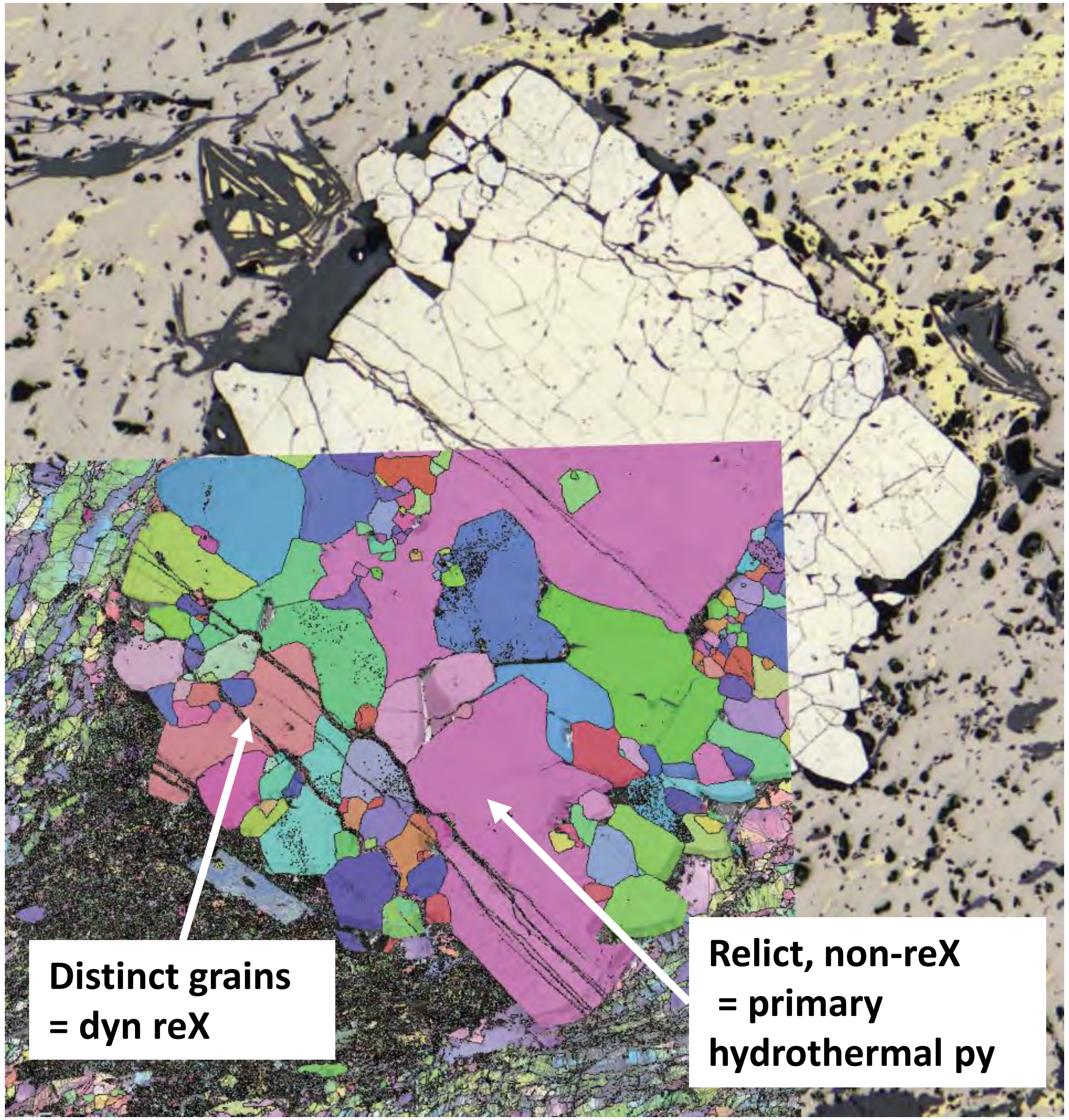


Pyrite: Co Content

Co compositional map (LA-ICP-MS)

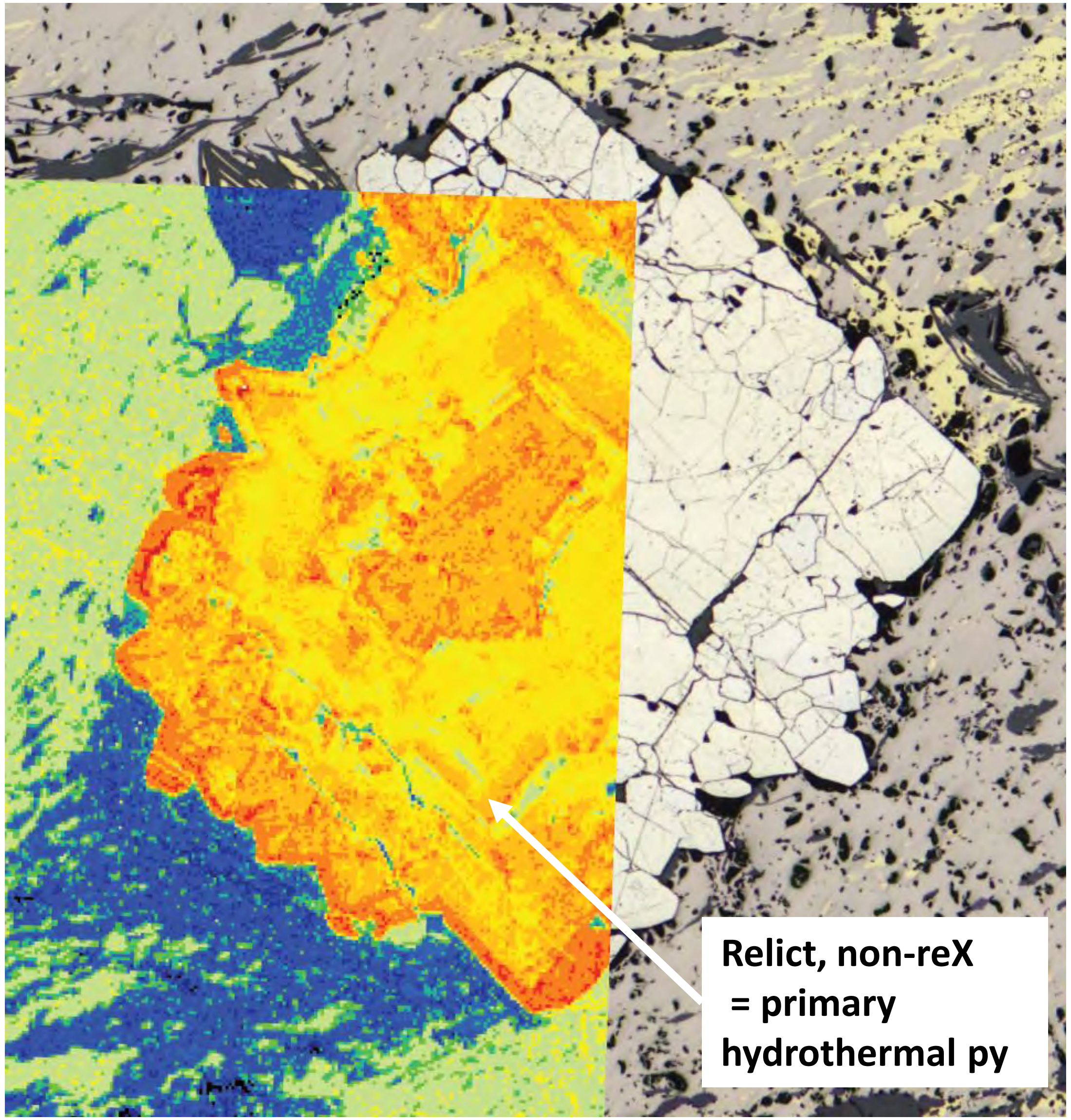


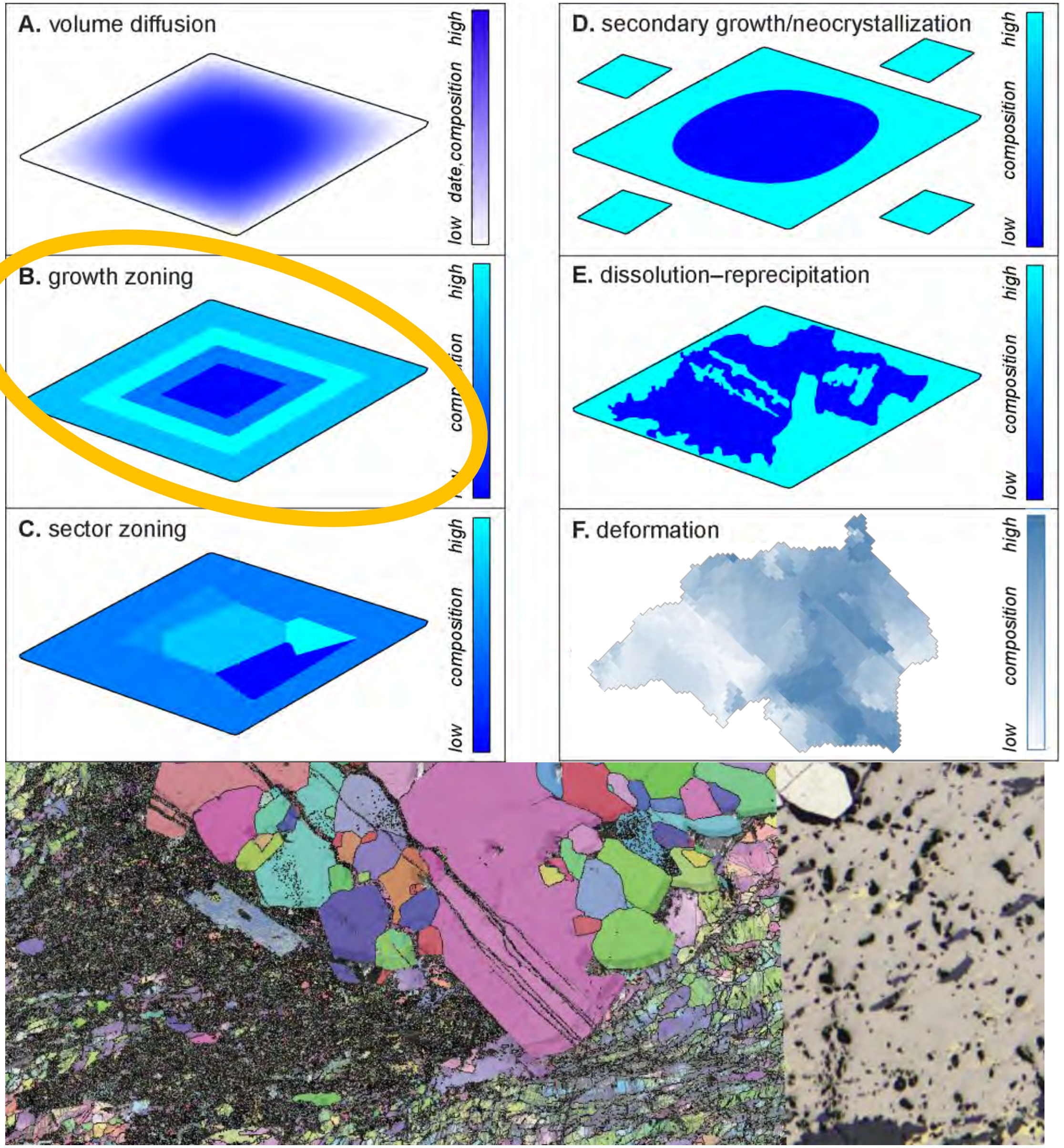
Grain orientation map (EBSD)



Pyrite: Co Content

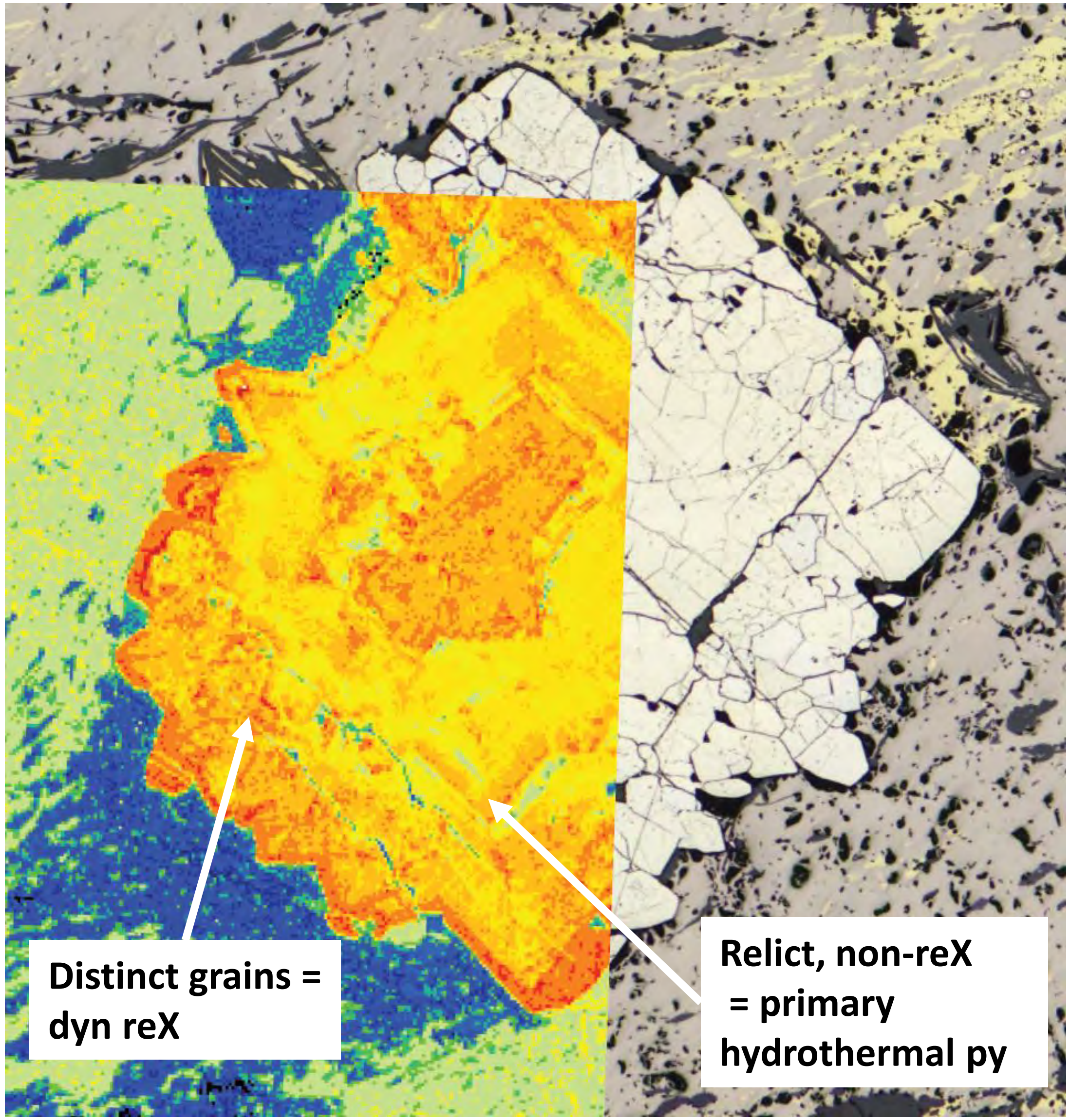
Co compositional map (LA-ICP-MS)

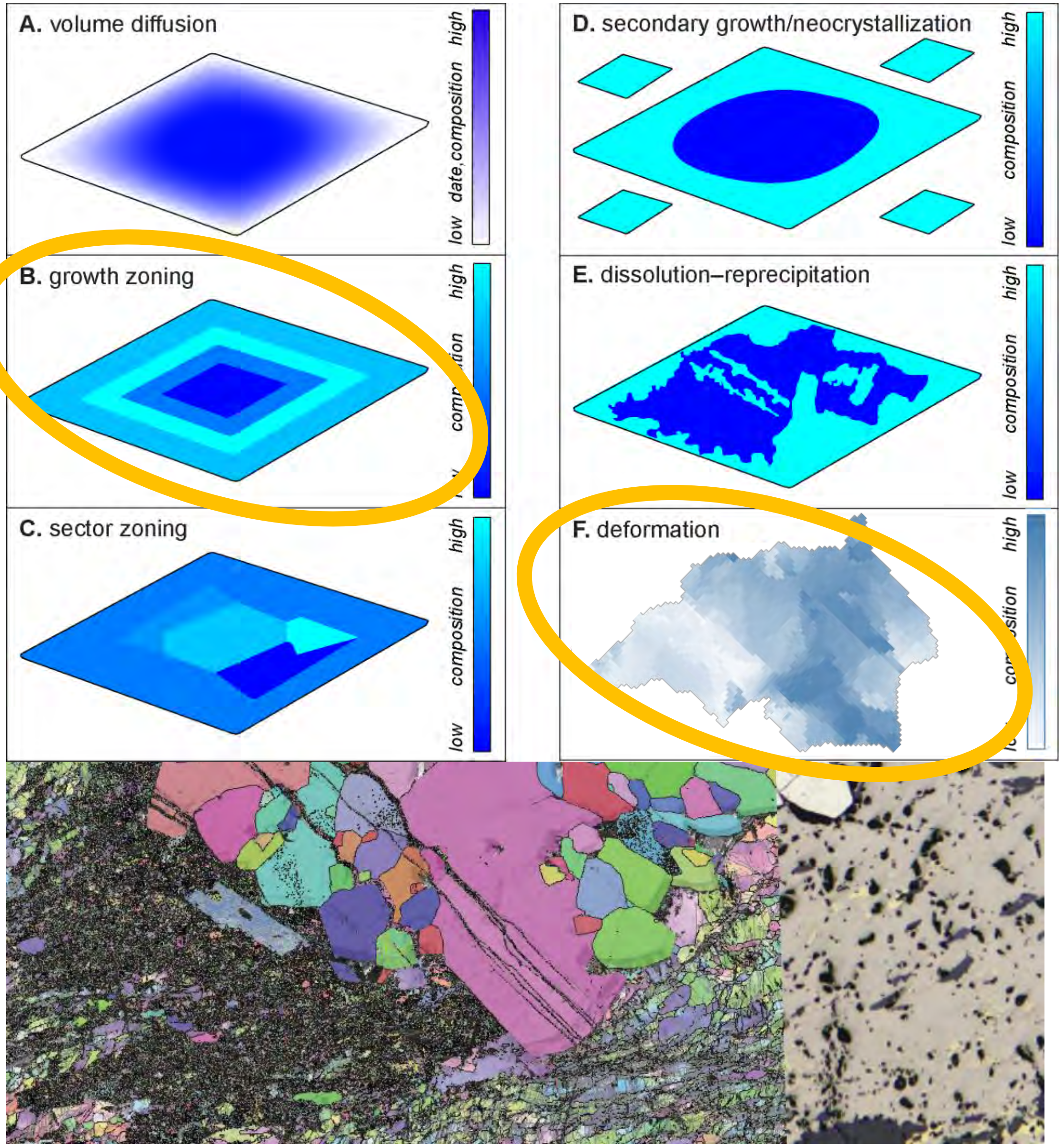




Pyrite: Co Content

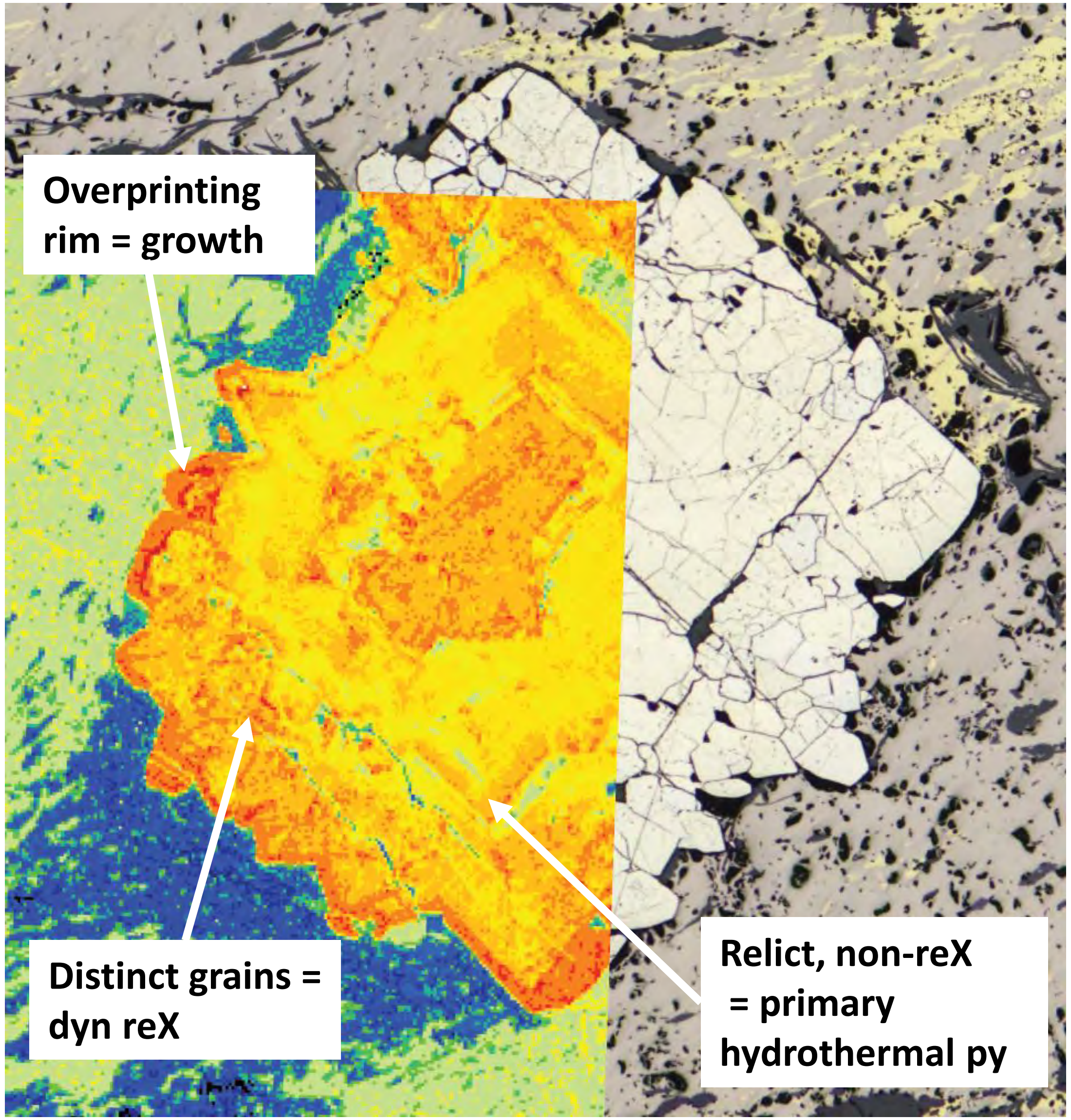
Co compositional map (LA-ICP-MS)

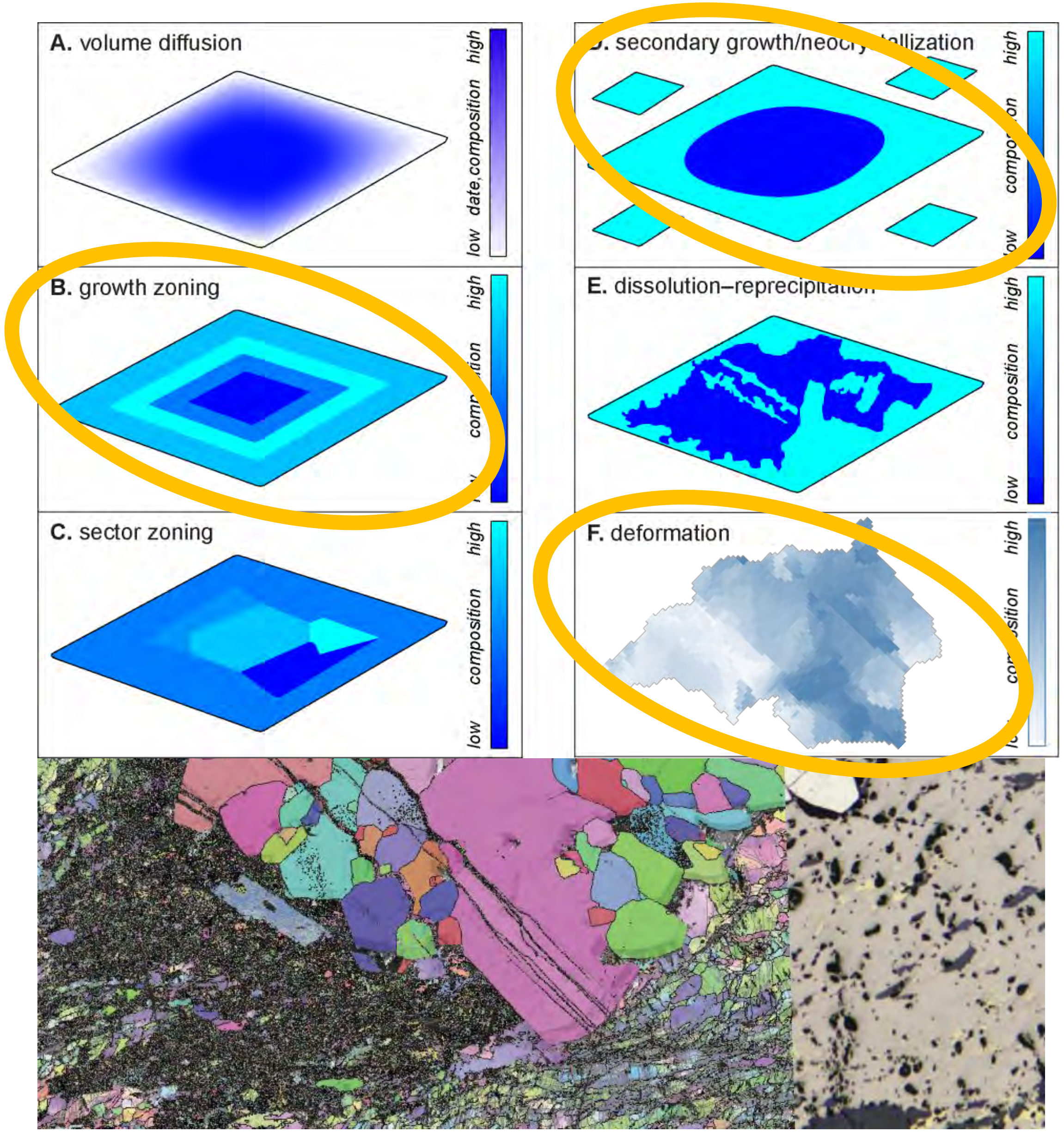




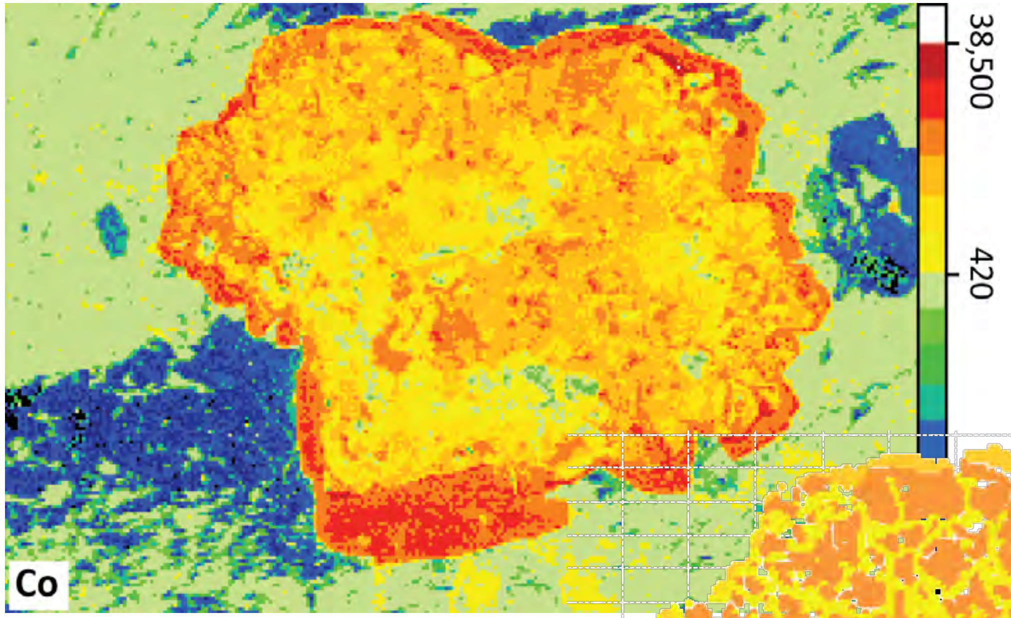
Pyrite: Co Content

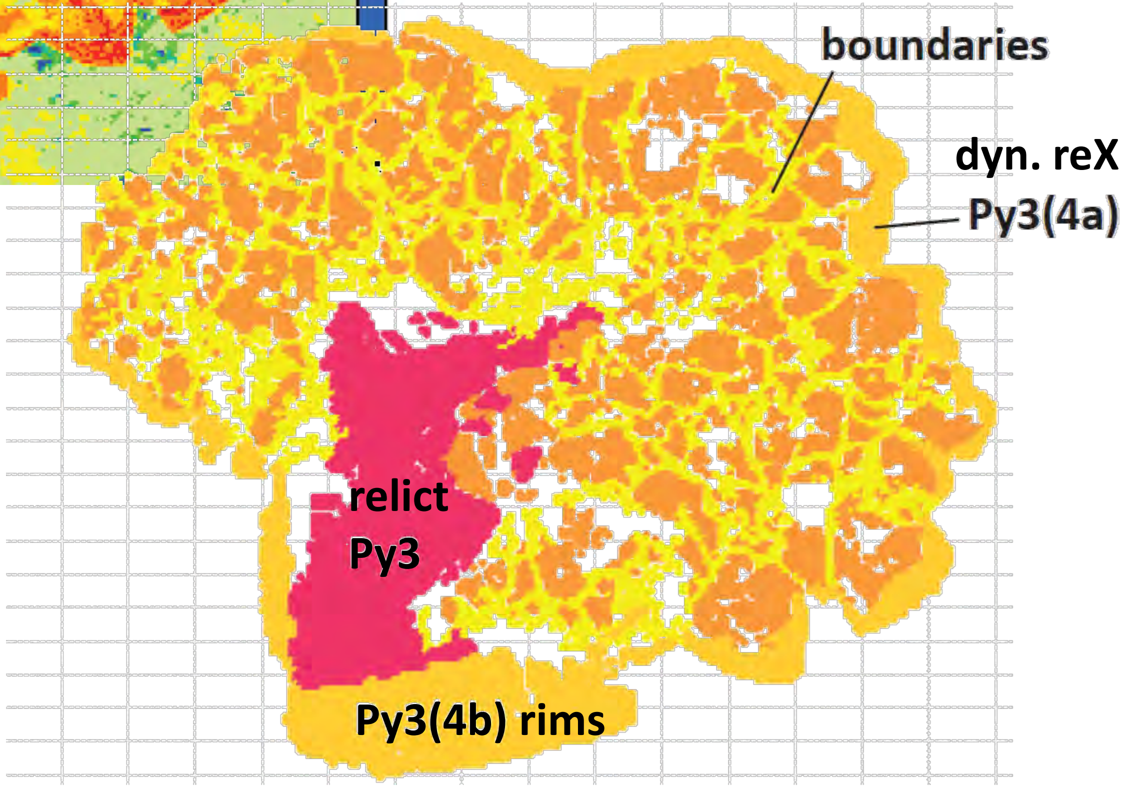
Co compositional map (LA-ICP-MS)

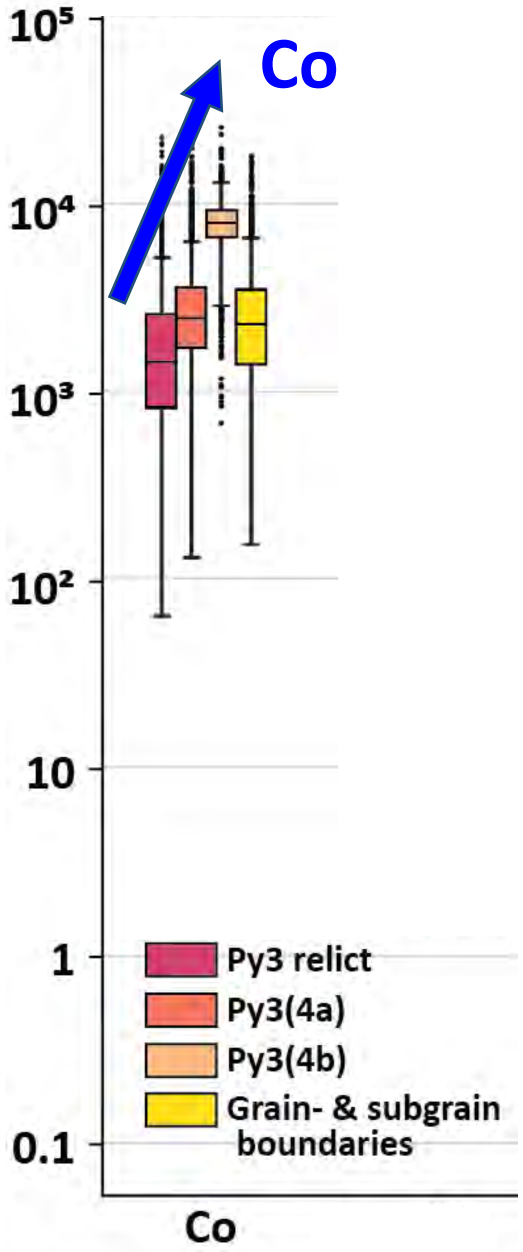




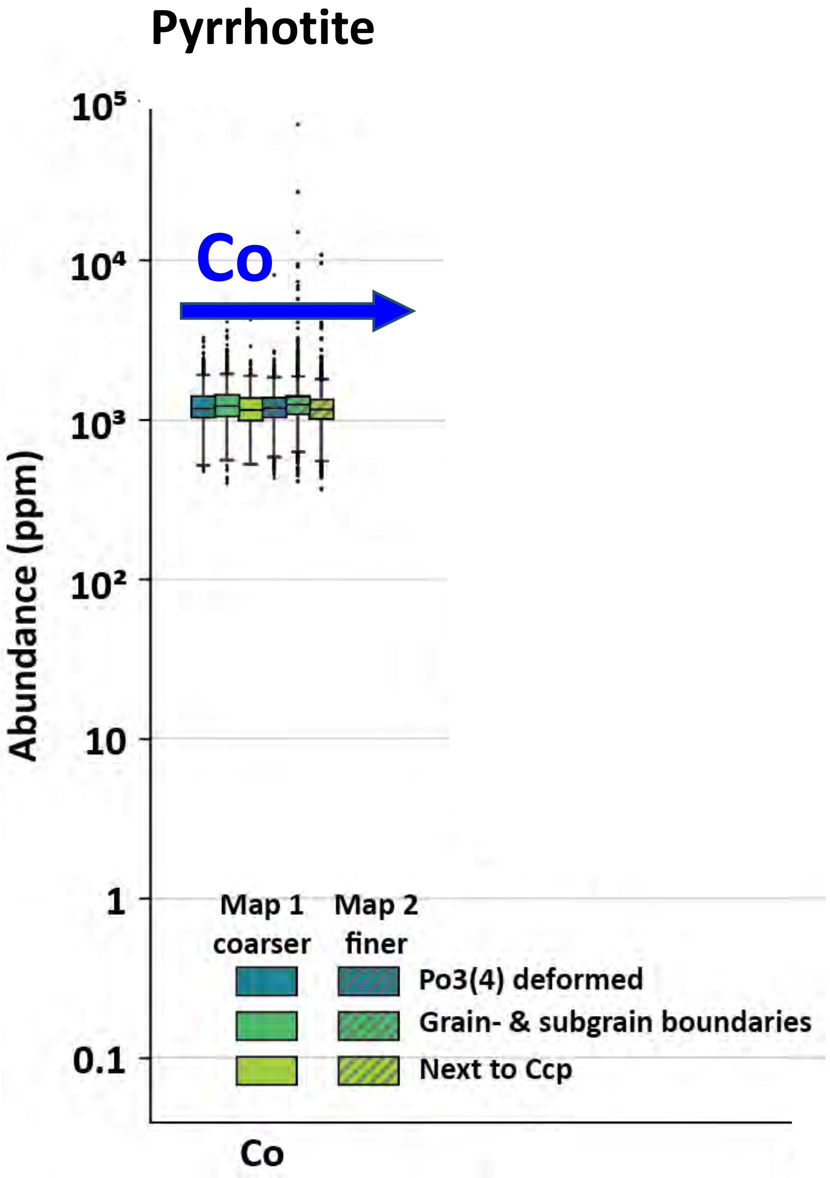
Pyrite: Co Content

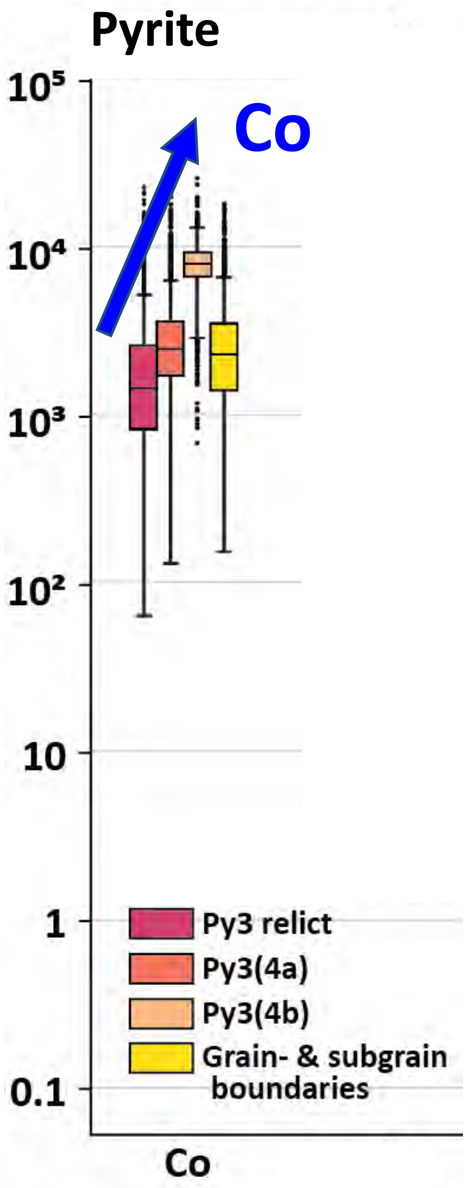


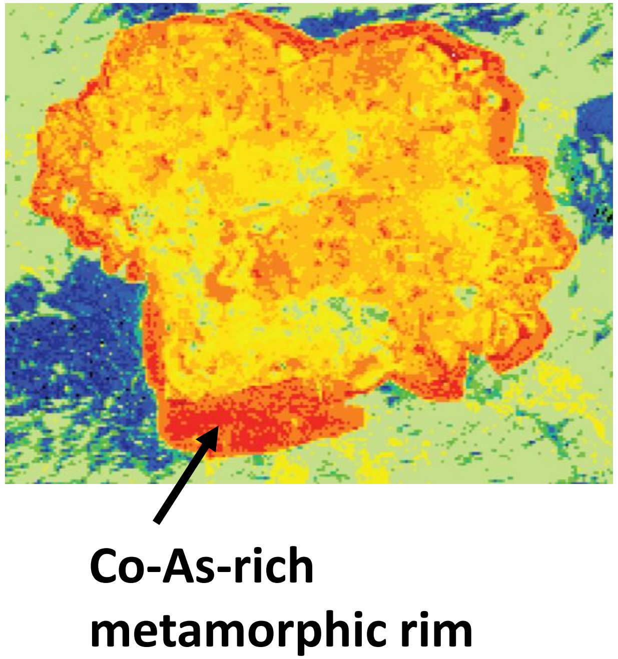




Source of the Co?



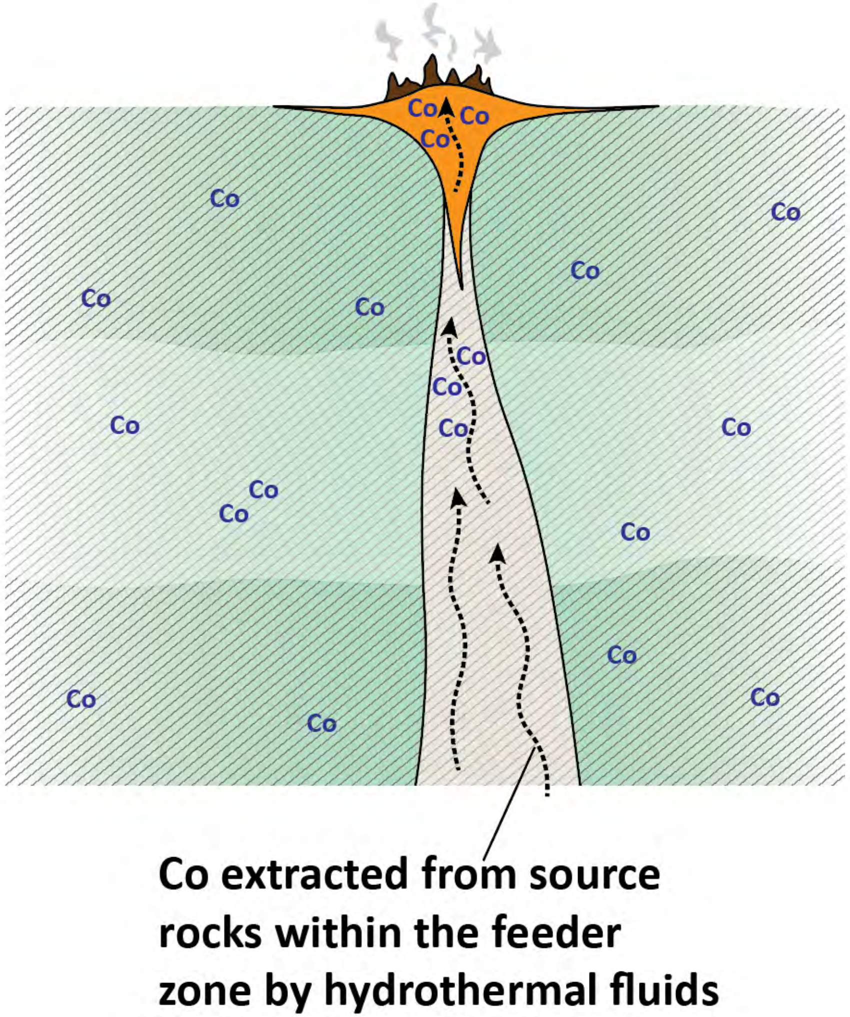


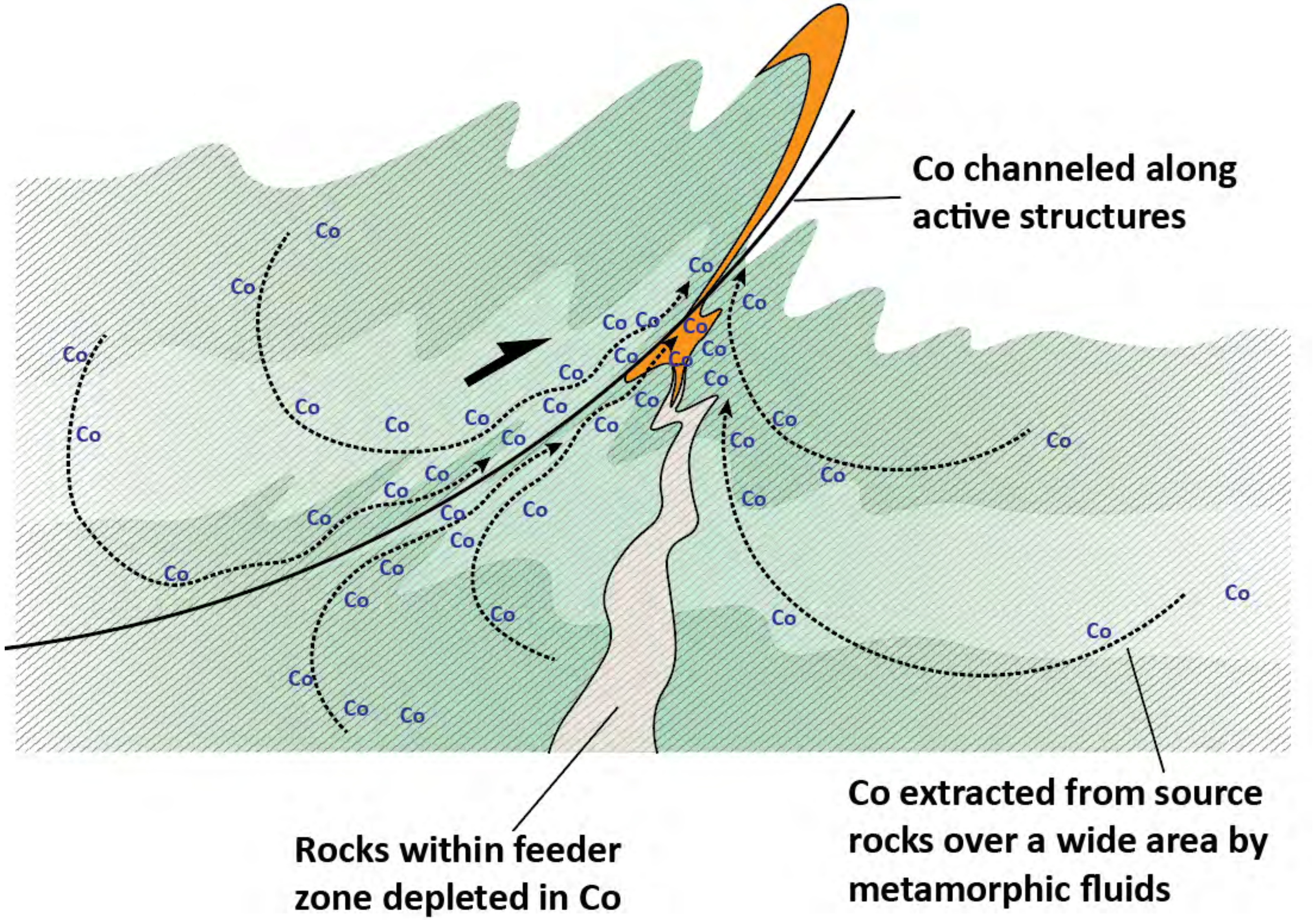


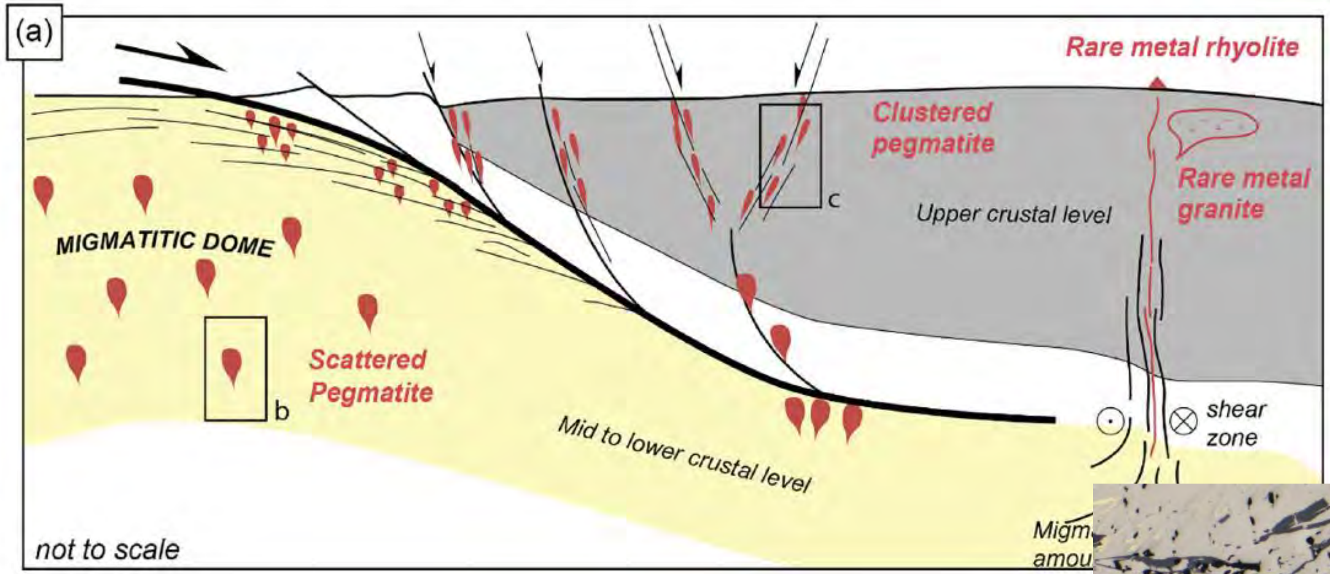
Syn-tectonic cobaltite

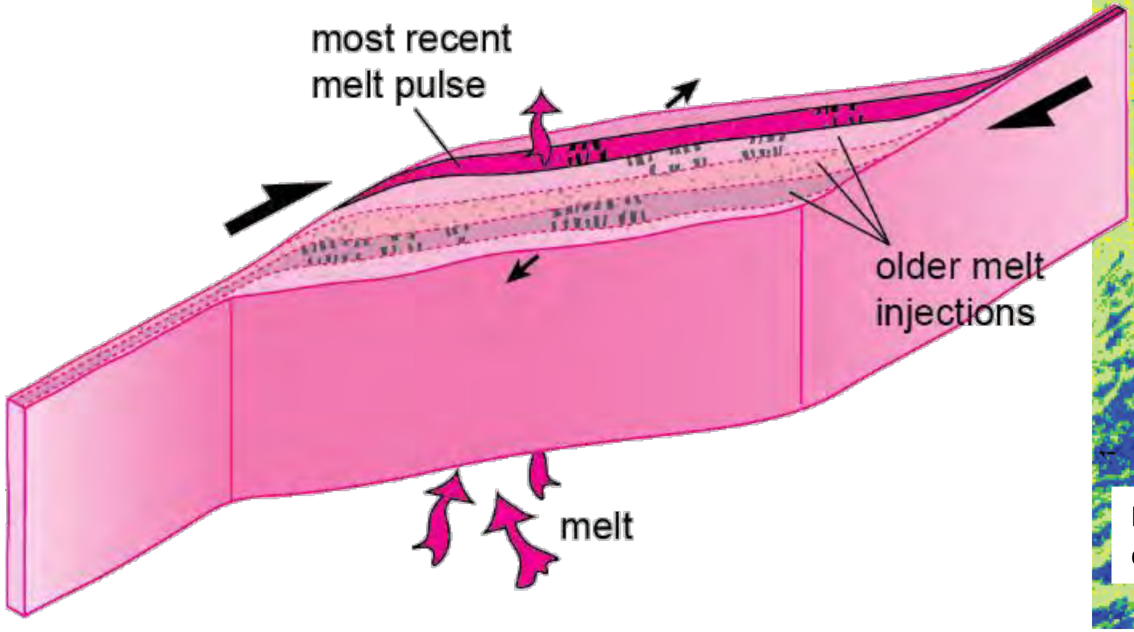
= no local Co source
= need additional external Co!

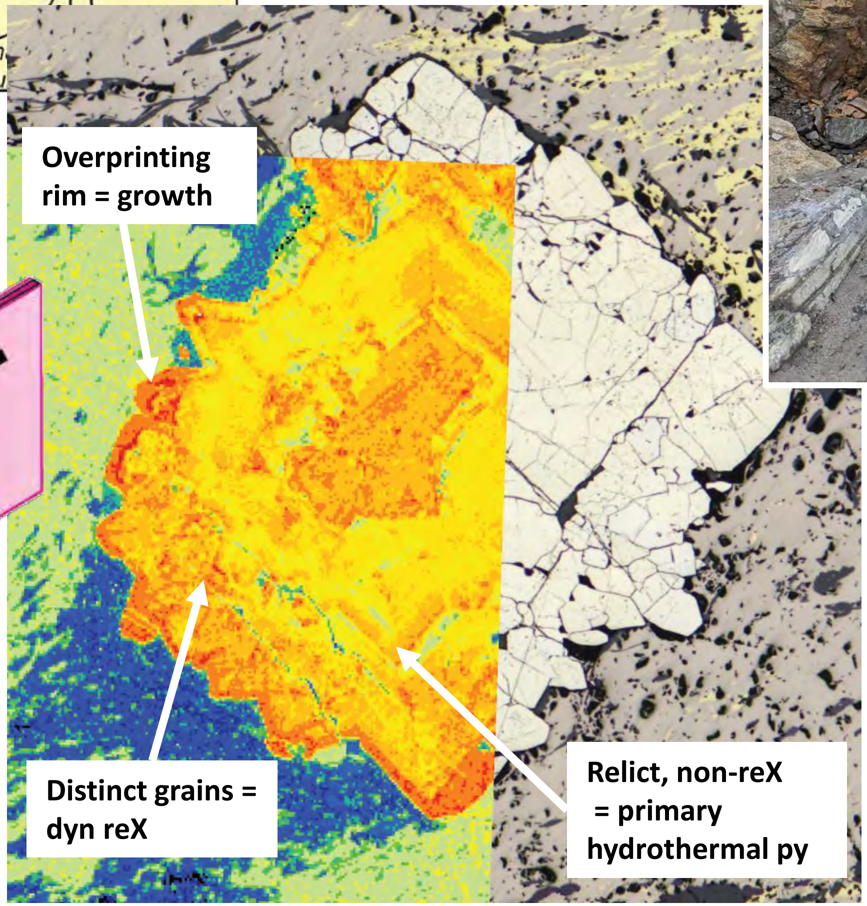
Source of the Co?






(a)
Rare metal rhyolite
Clustered pegmatite
c
Upper crustal level
Rare metal granite
MIGMATITIC DOME
Scattered Pegmatite
b
Mid to lower crustal level
shear zone
not to scale

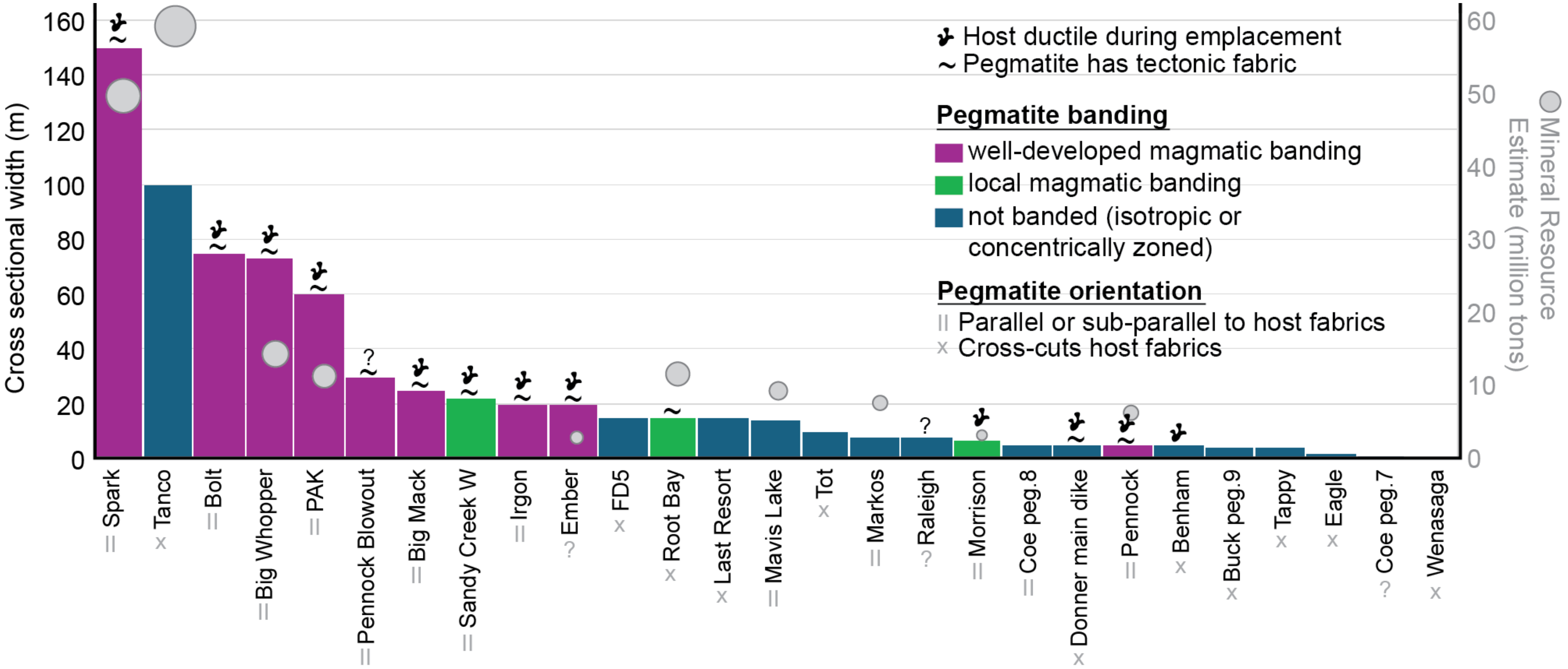

most recent melt pulse
older melt injections
melt


Overprinting rim = growth
Distinct grains = dyn reX
Relict, non-reX = primary hydrothermal py

Thank You!

Questions?

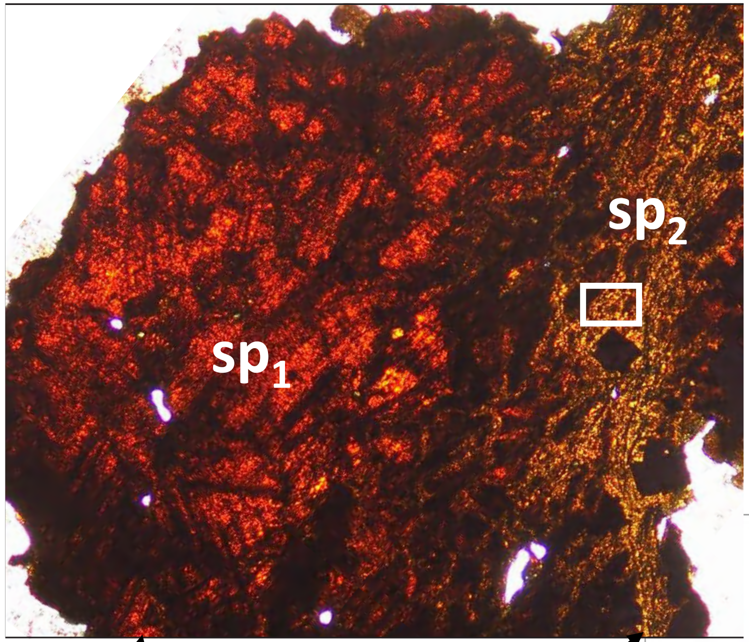
Li-Pegmatites from the western Superior Province



Cawood et al. (2025) SGA abstract

Sphalerite: Dislocation Creep & Dynamic ReX

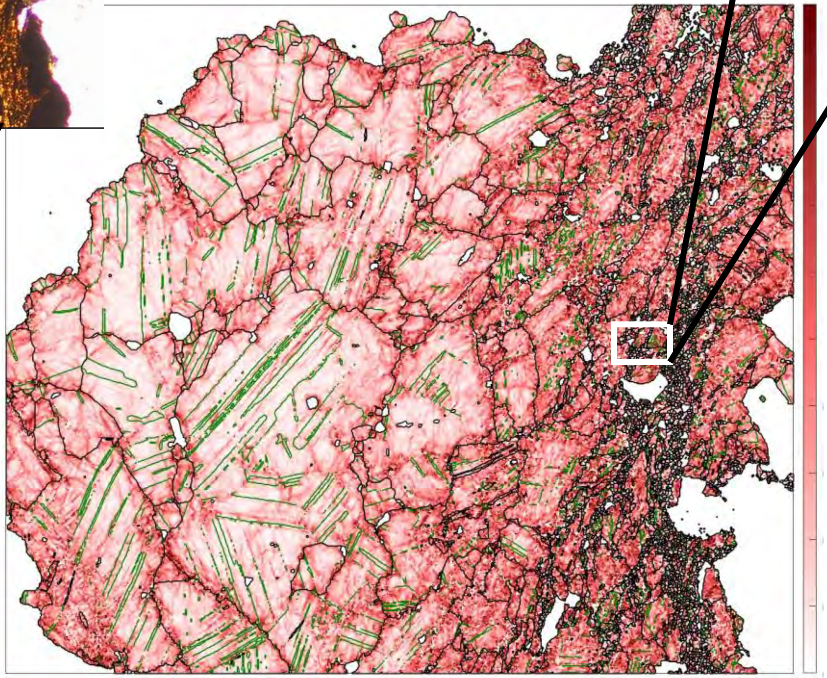
Transmitted light photomicrograph:



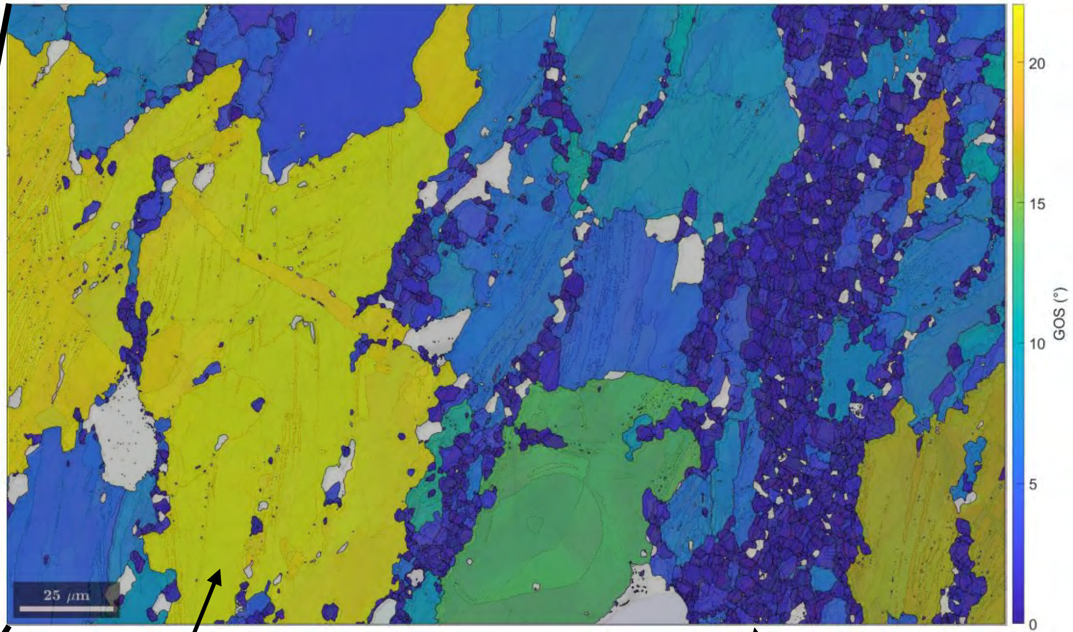
Coarse Sp$_1$
= hydrothermal

Fine Sp$_2$
= dynamic recrystallization

Local misorientation (EBSD):



Grain orientation spread (EBSD):

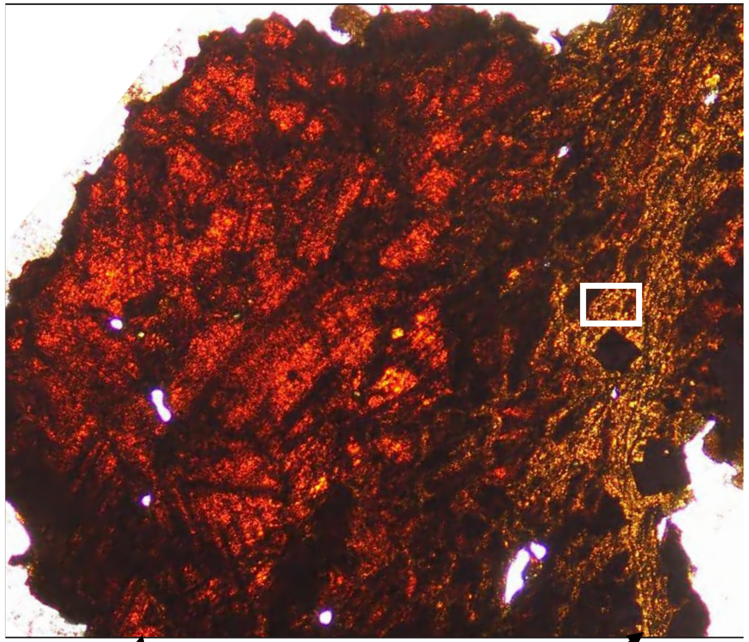


Coarser grains
High internal distortion
= dislocation creep

Fine grained
Low internal distortion
= dynamic recrystallization

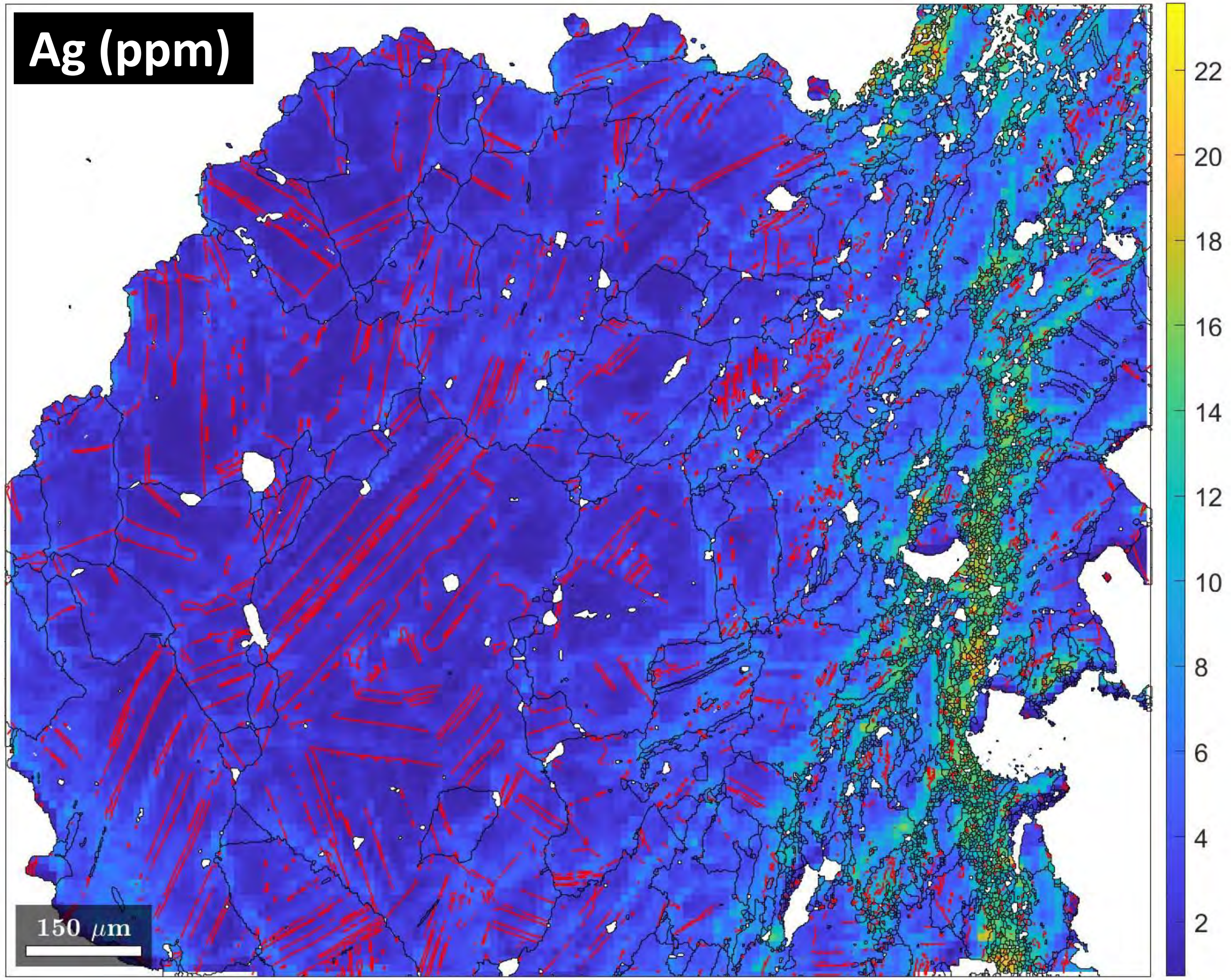
Sphalerite: Composition

Transmitted light photomicrograph:



Coarse Sp_1
= hydrothermal

Fine Sp_2
= dynamic recrystallization

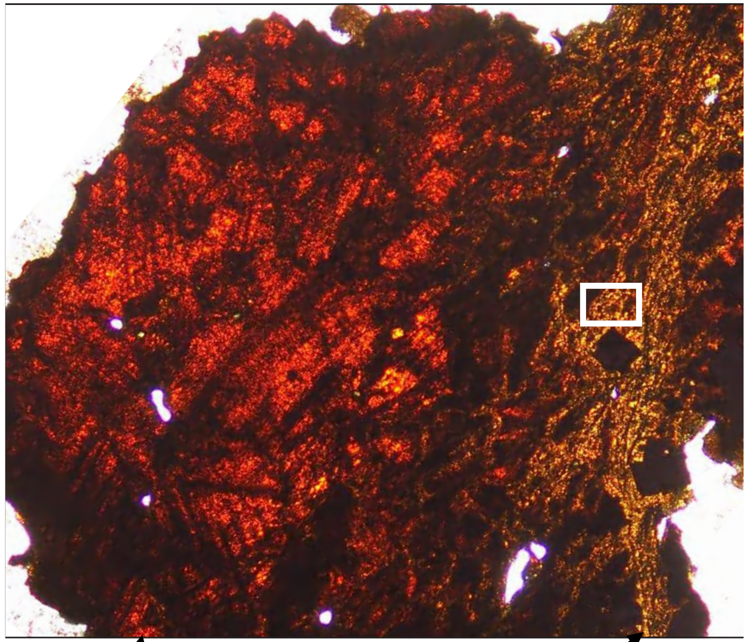


Ag along grain boundaries

= highly mobile

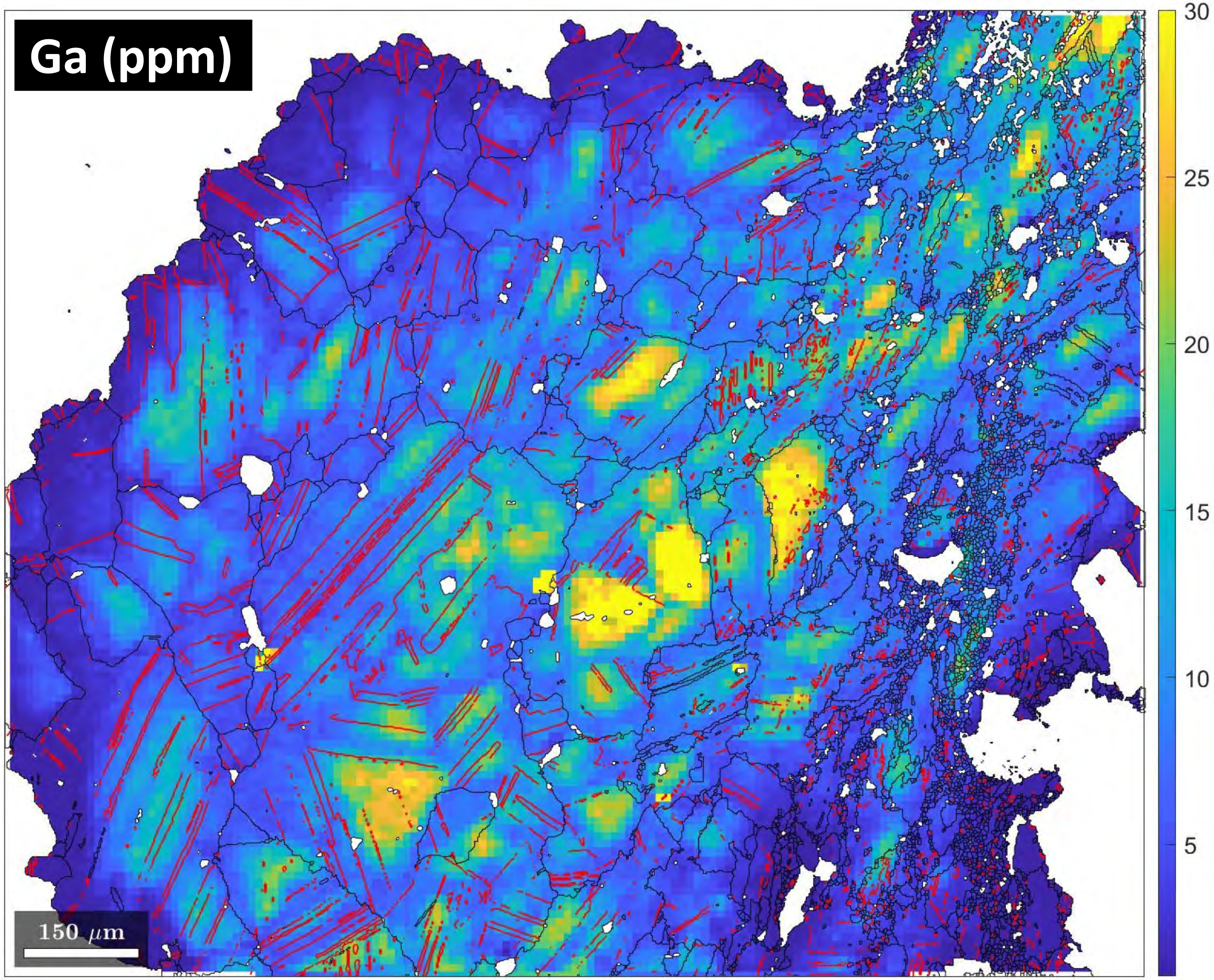
Sphalerite: Composition

Transmitted light photomicrograph:



Coarse Sp_1
= hydrothermal

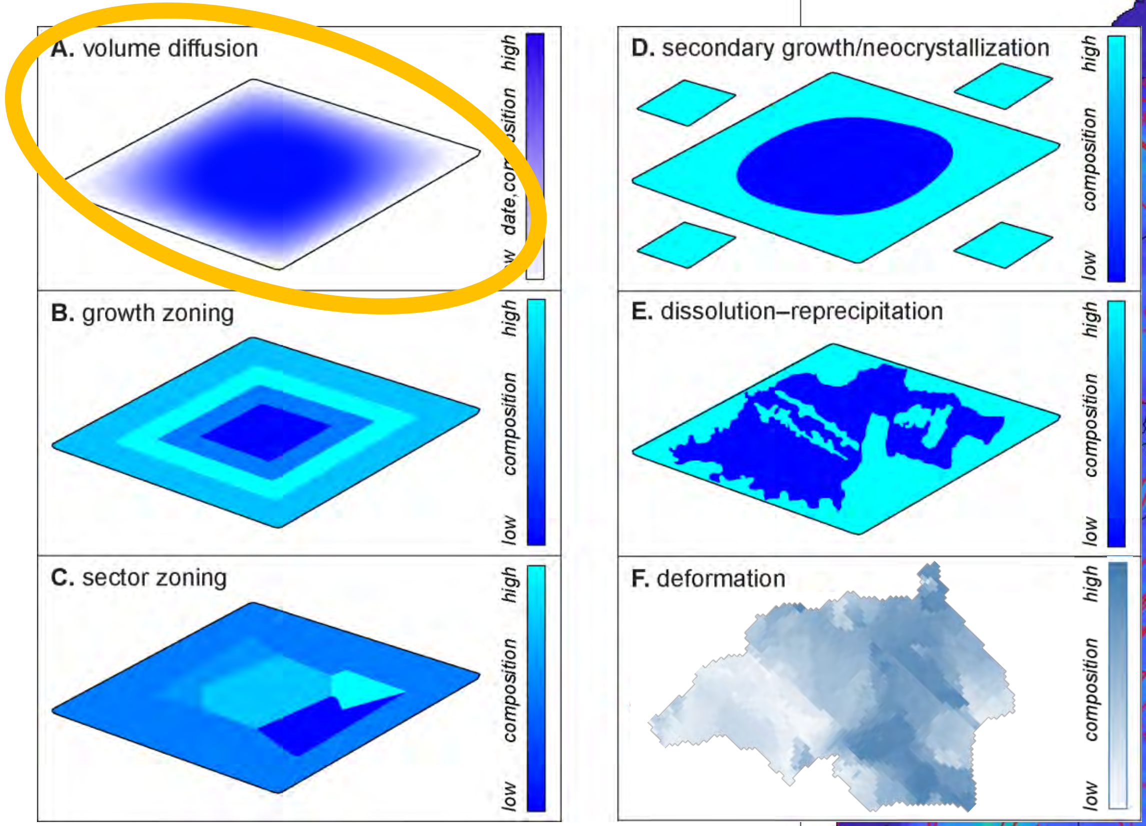
Fine Sp_2
= dynamic
recrystallization

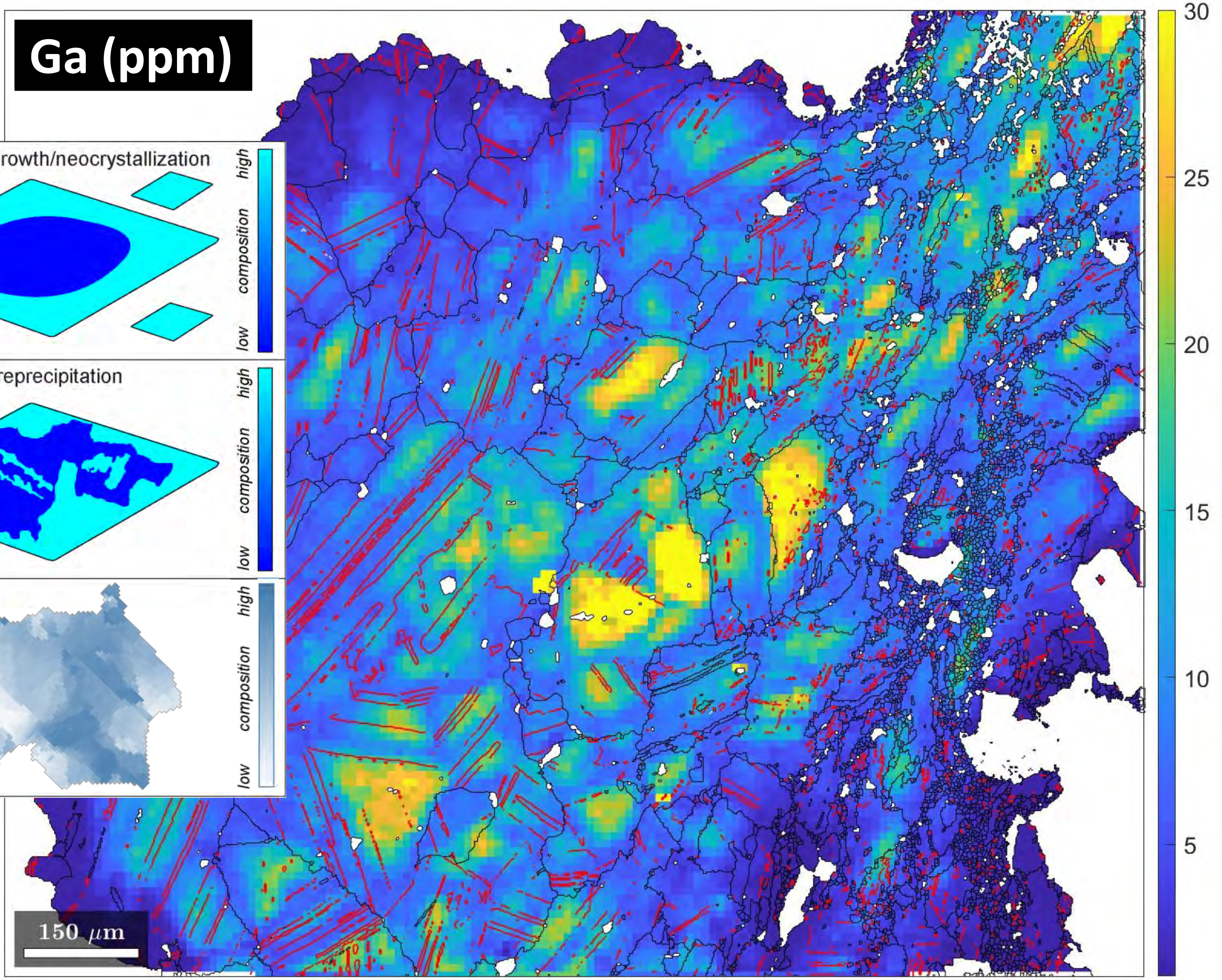


Ga in grain cores

= lost by grain boundary diffusion

Sphalerite: Volume Diffusion

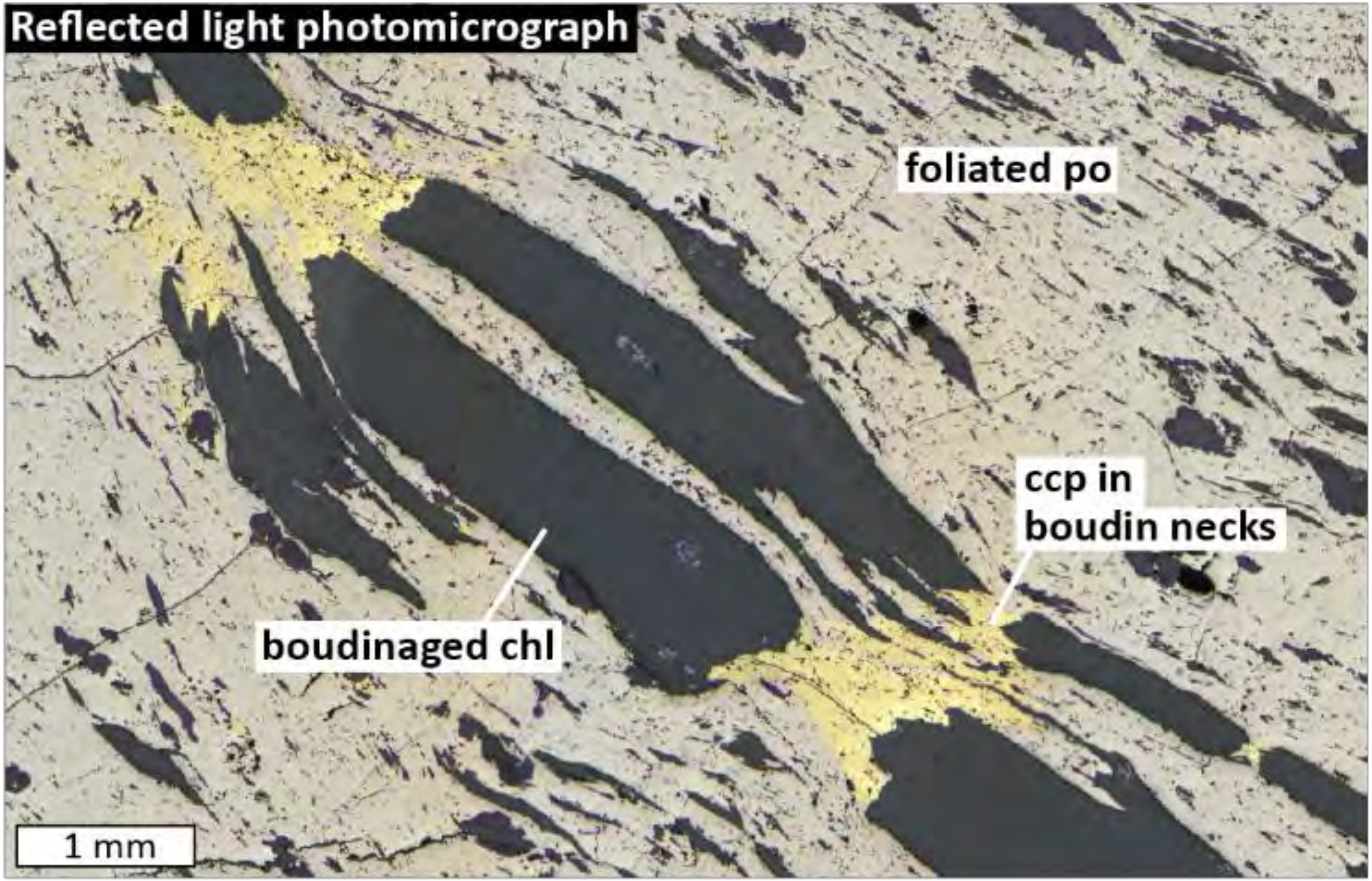




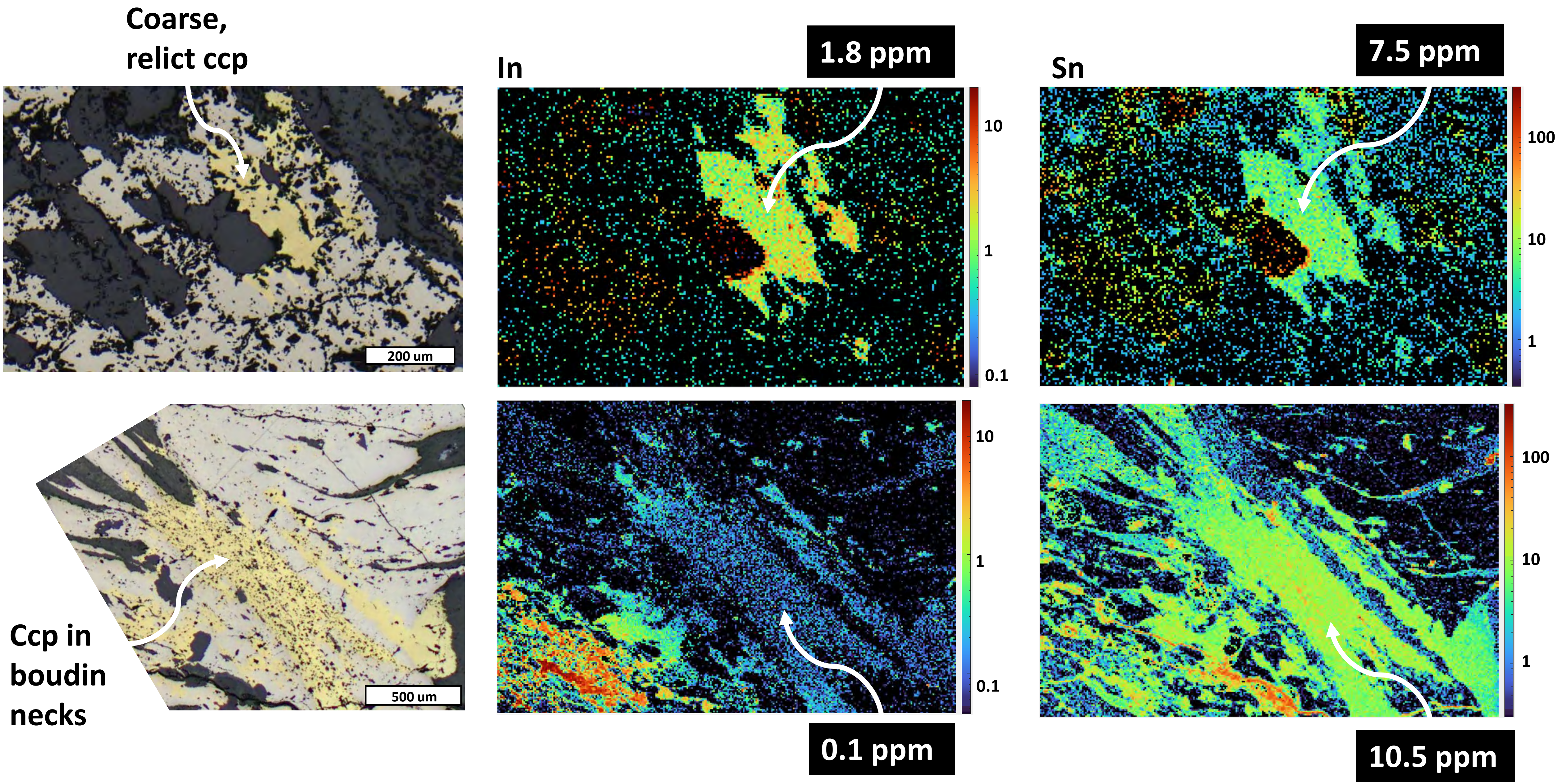
Ga in grain cores

= lost by grain boundary diffusion

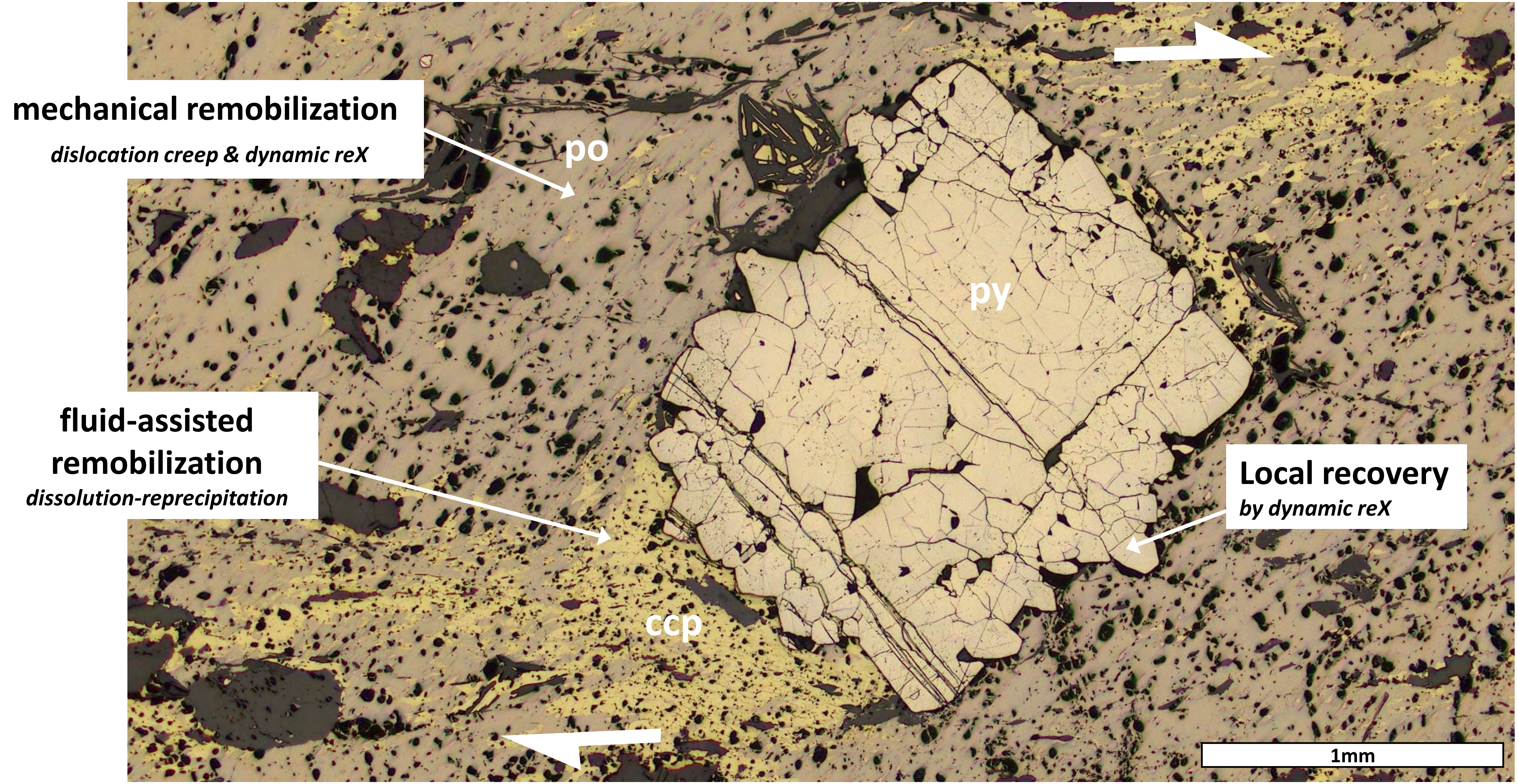
Chalcopyrite: Dissolution-Reprecipitation



Chalcopyrite: Dissolution-Reprecipitation



Deformation & Metamorphism of Sulfides



Deformation & Metamorphism of Sulfides: Effect on Chemistry