Refining the Cobar-type mineral system:

New insights spawned from direct dating of mineralisation

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Discoveries in the Tasmanides, September 2019

Presentation outline

1. *When? – examples of direct dating of Cobar mineralisation*
2. *What? – attempting to understand key characteristics*
3. *Why? – what's happening in the Central and East Lachlan Orogen*
4. *Summary*

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The Cobar Conundrum

Cobar-type deposits:

Deformed, fault-controlled, sometimes broadly stratabound, polymetallic sulfide +/- Au orebodies with similar geometries that are isolated in basin turbidite sequences.

Not only do we have the blinkers of structural complication on, but we are missing a plausible genetic link.

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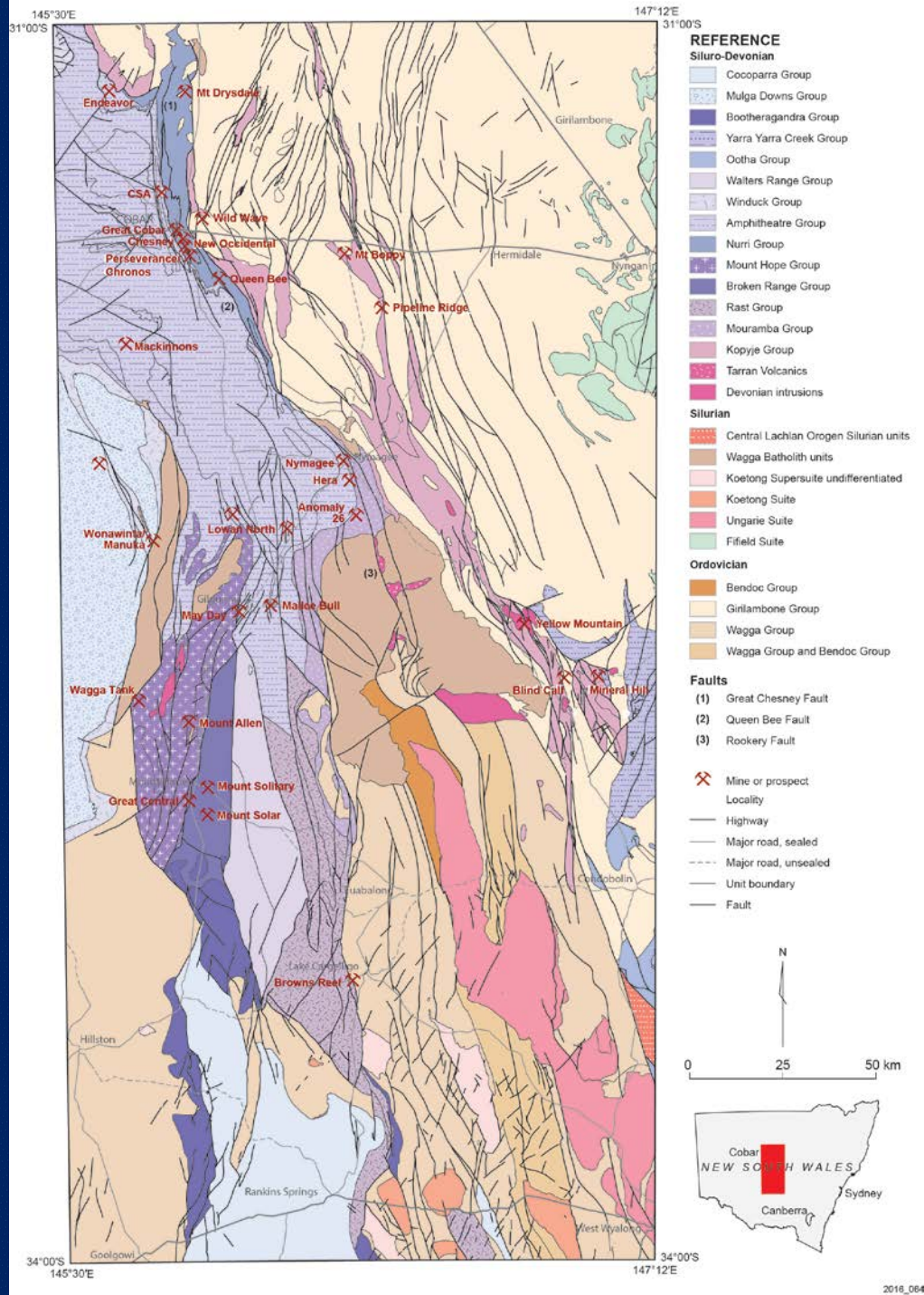
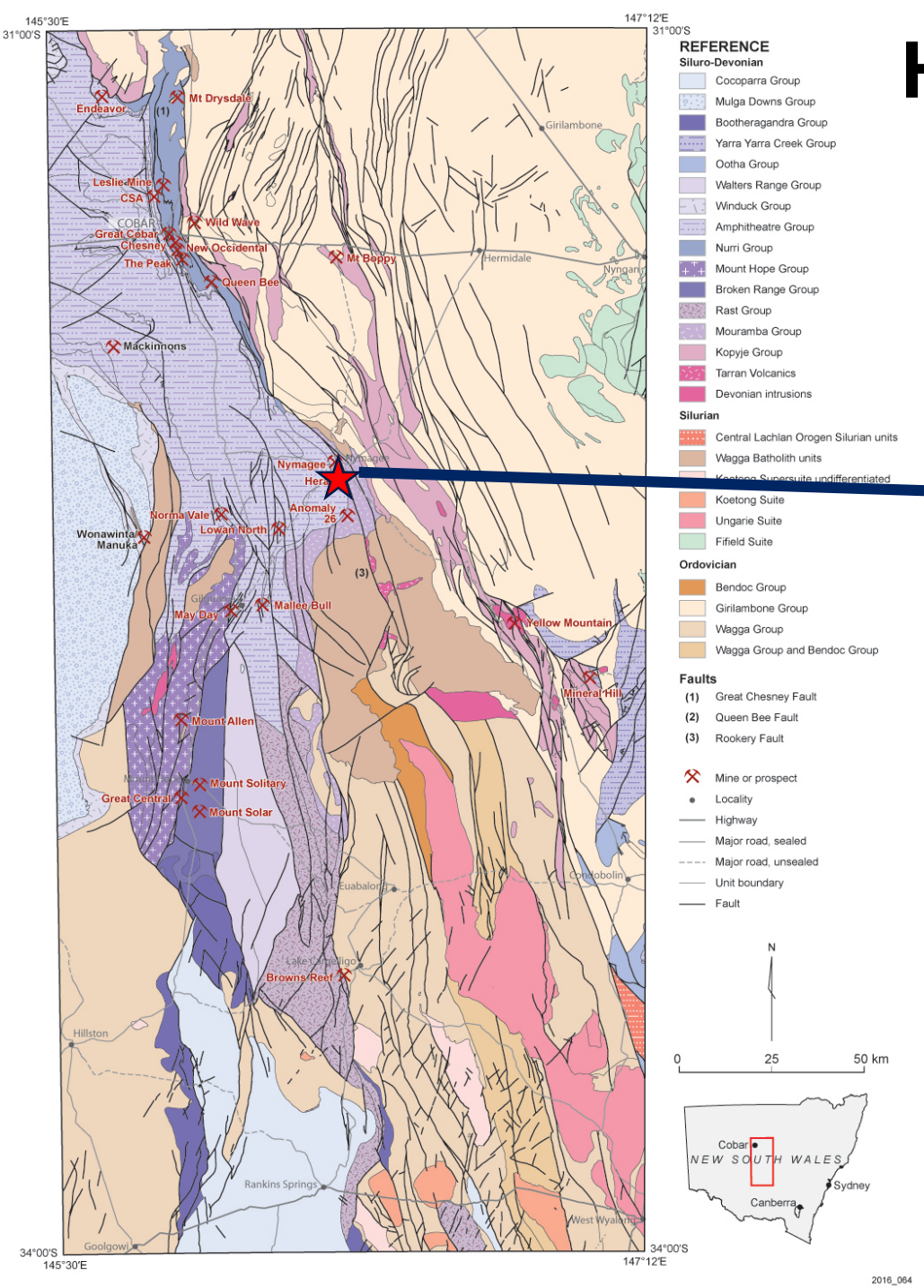
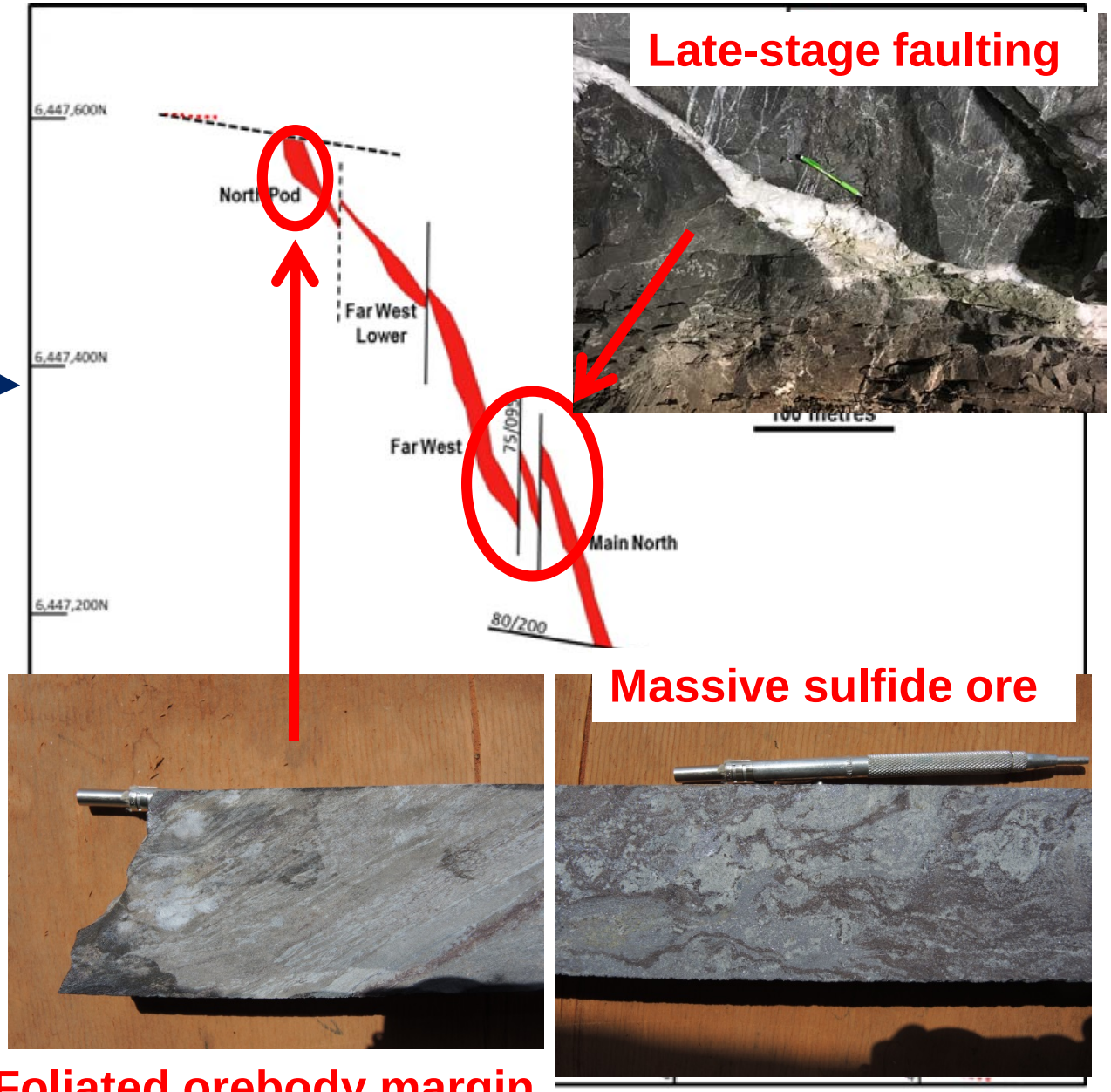
When? – examples of direct dating of Cobar mineralisation



Hera





Late-stage faulting

Foliated orebody margin

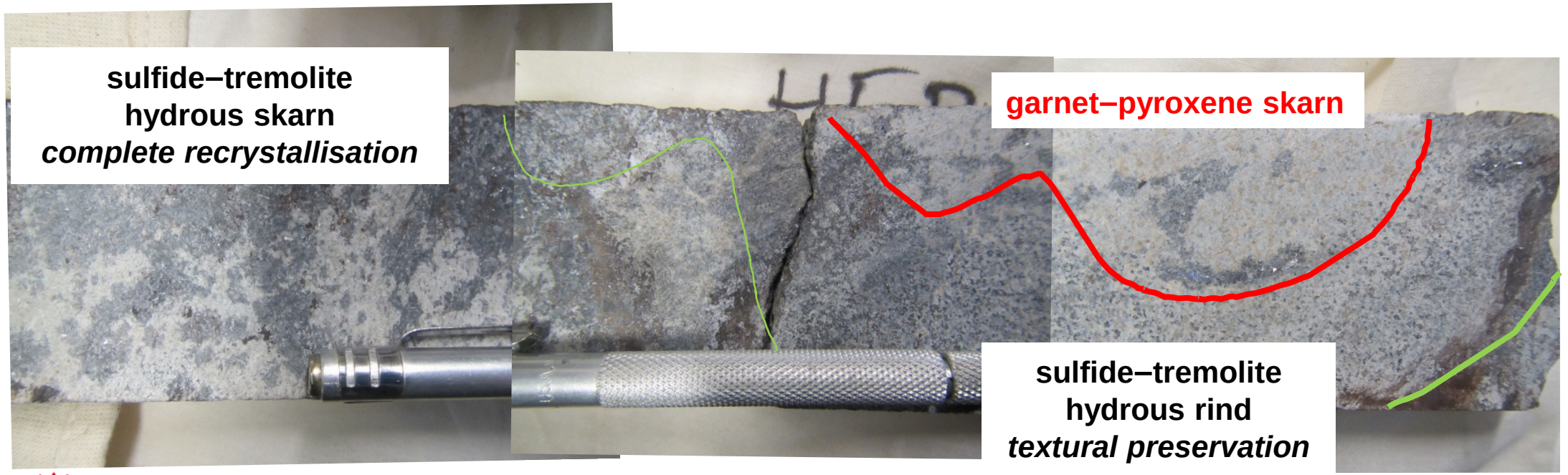
Massive sulfide ore

Orebody paragenesis – prograde skarn and retrograde Zn–Pb sulfide mineralisation

Tremolite-rich hydrous retrogression
– main sulfide mineralising stage

⟵

Prograde skarn, peak temperature
– reduced, low-CO_2 Ca–Mn distal skarn



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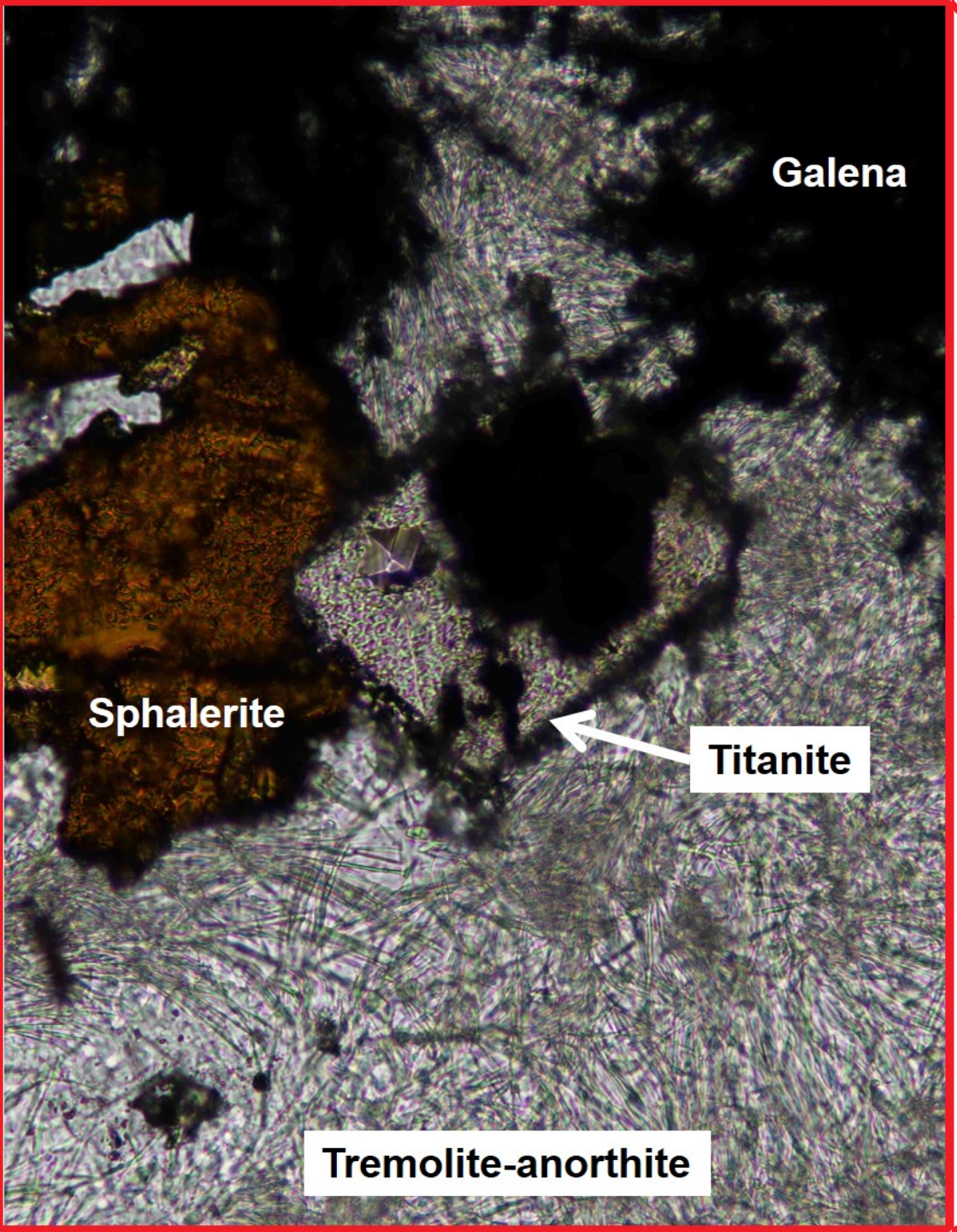
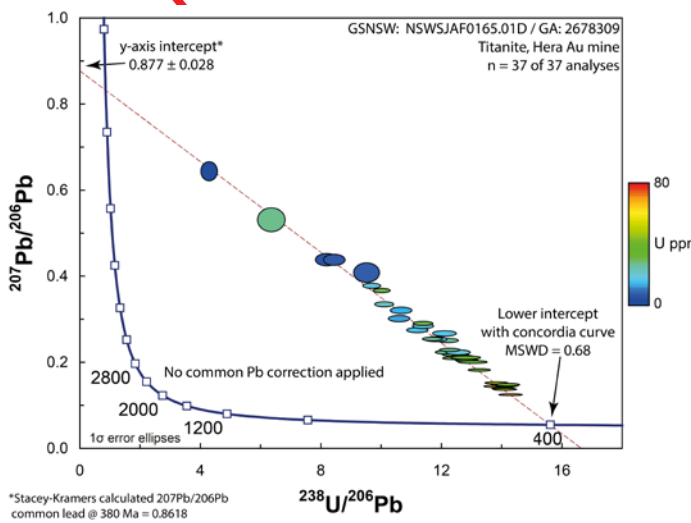
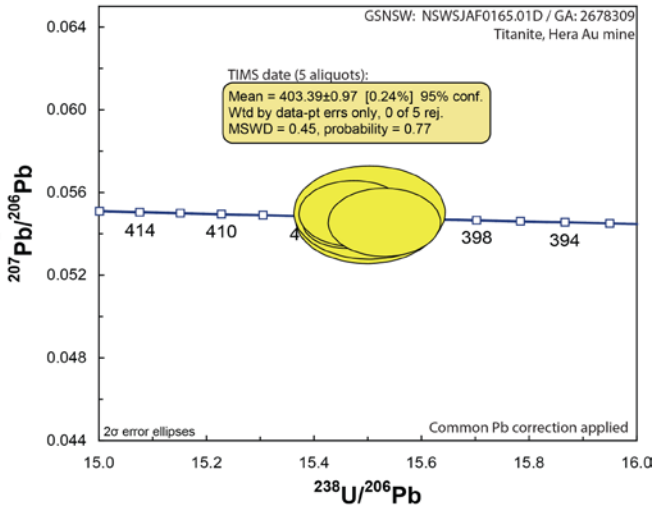
Orebody paragenesis – Au

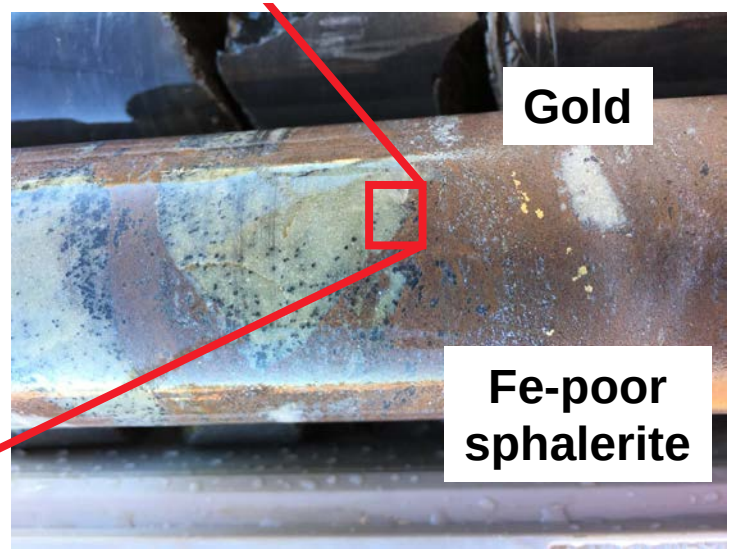


Titanite (SHRIMP) 400.3 ± 4.6 Ma, (TIMS) 403.39 ± 0.97 Ma

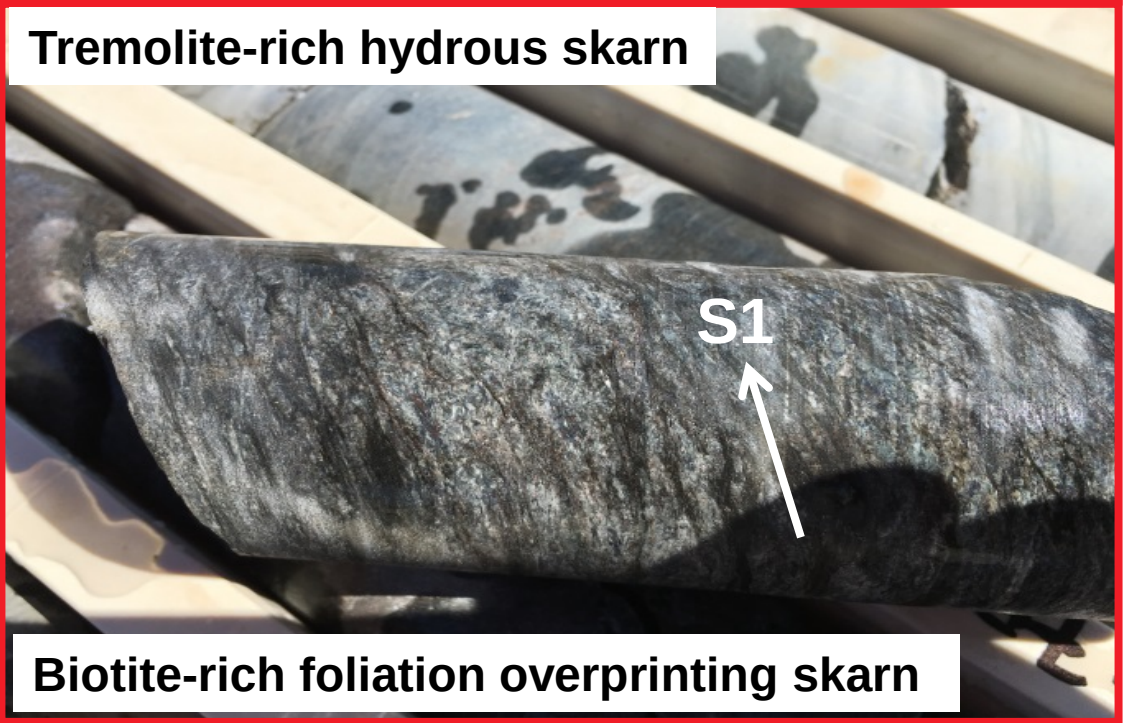




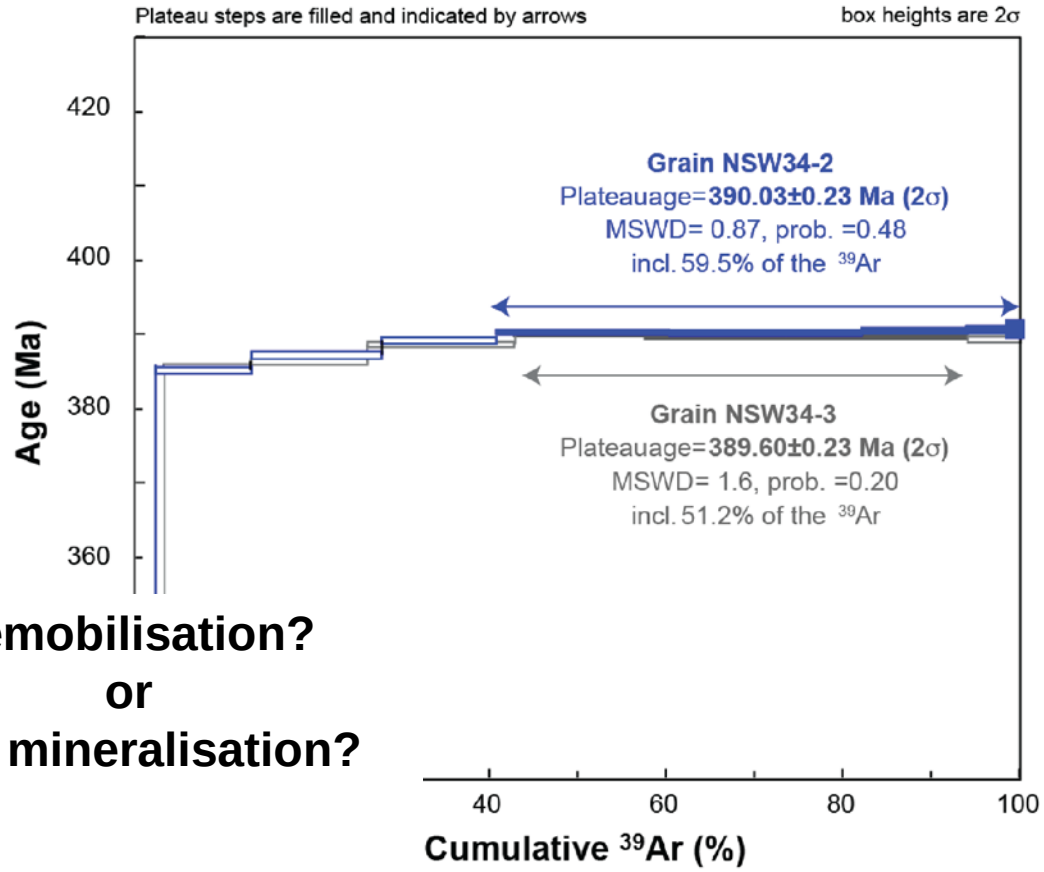
- Au – low Fe sphalerite mineralisation
- appears to overprint skarn
  - K-feldspar replacement.



Orebody paragenesis – deformation

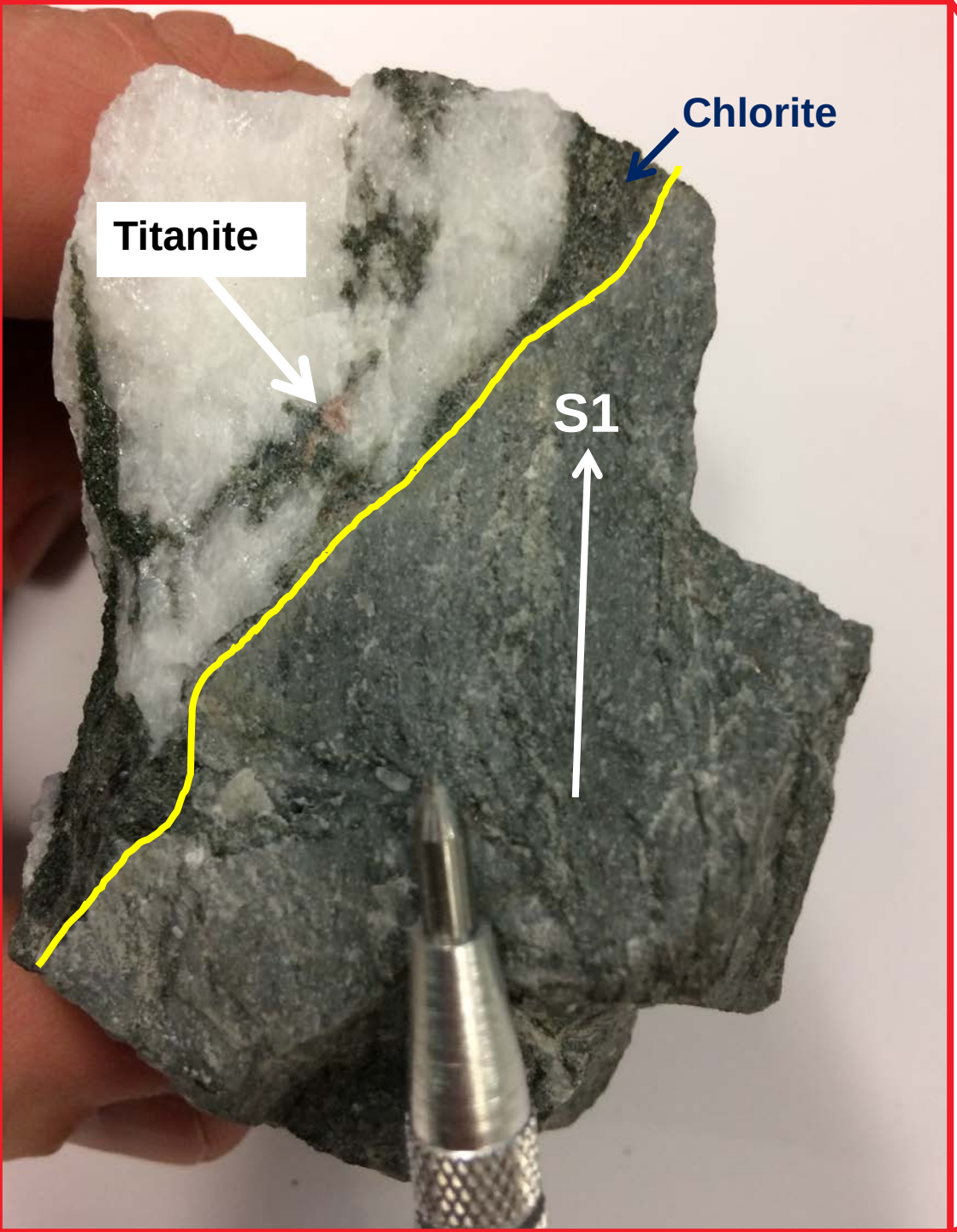


Biotite (Ar–Ar) 390.3 ± 0.23 Ma

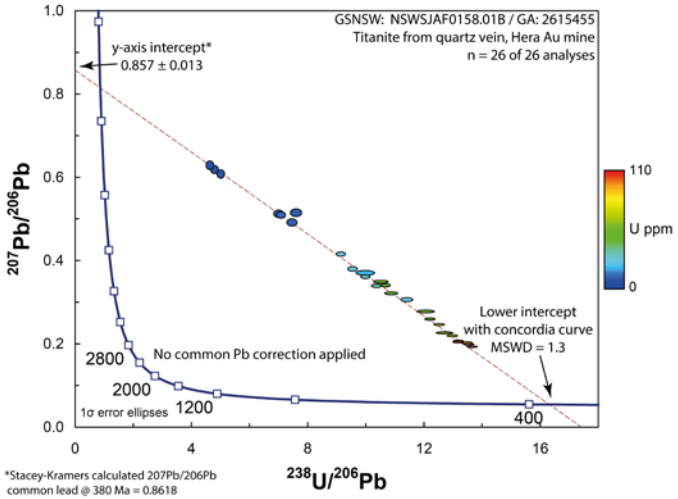


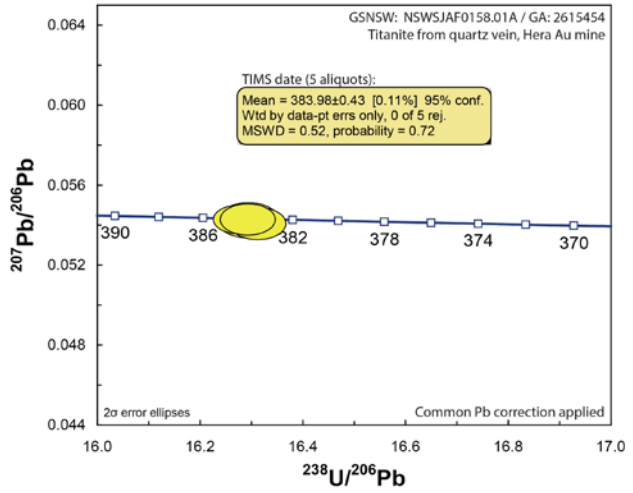
Remobilisation?
or
New mineralisation?

Orebody paragenesis – brittle faulting



Titanite (SHRIMP) 383.9 ± 2.2 Ma, (TIMS) 383.98 ± 0.43 Ma



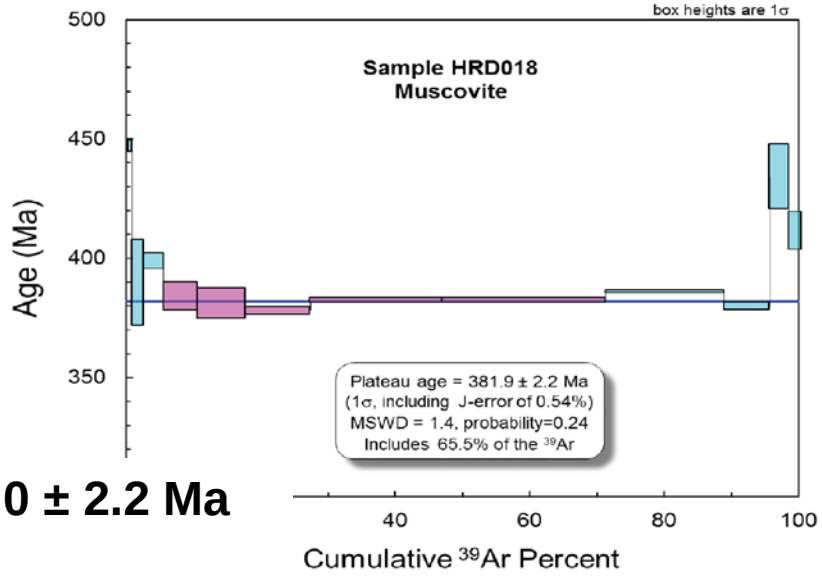


Orebody paragenesis – post-deformation

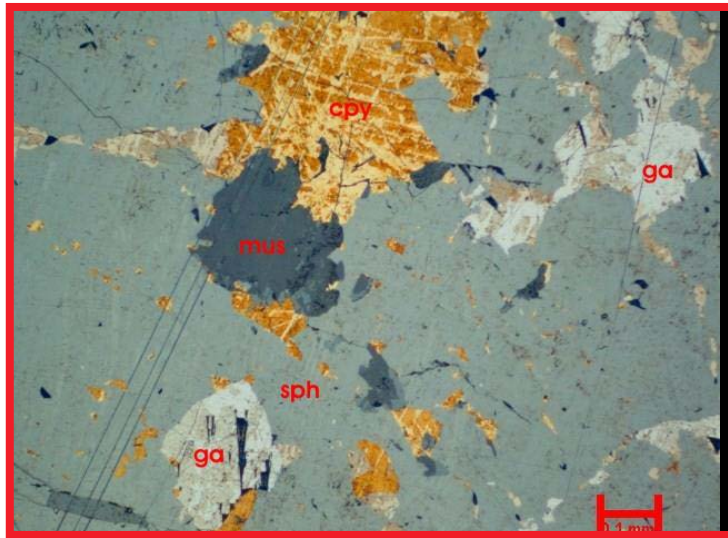
Massive galena and post-S1 folding

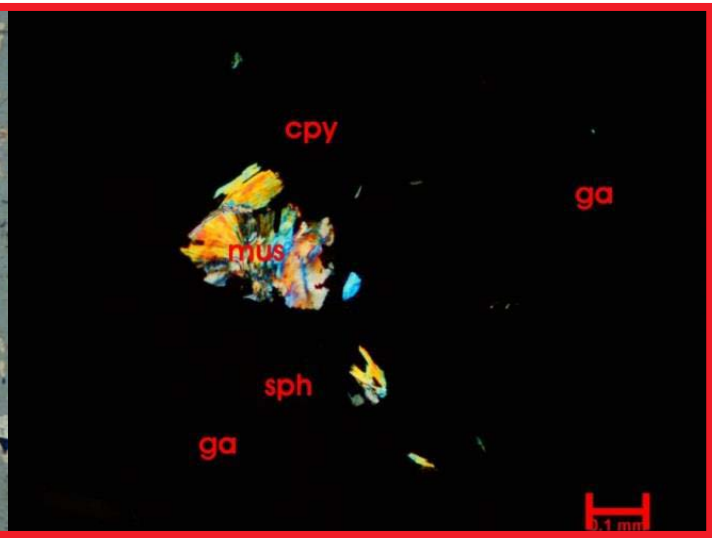
Sphalerite and post-S1 folding

- Mineralisation that crosscuts foliation.
- New or remobilised?

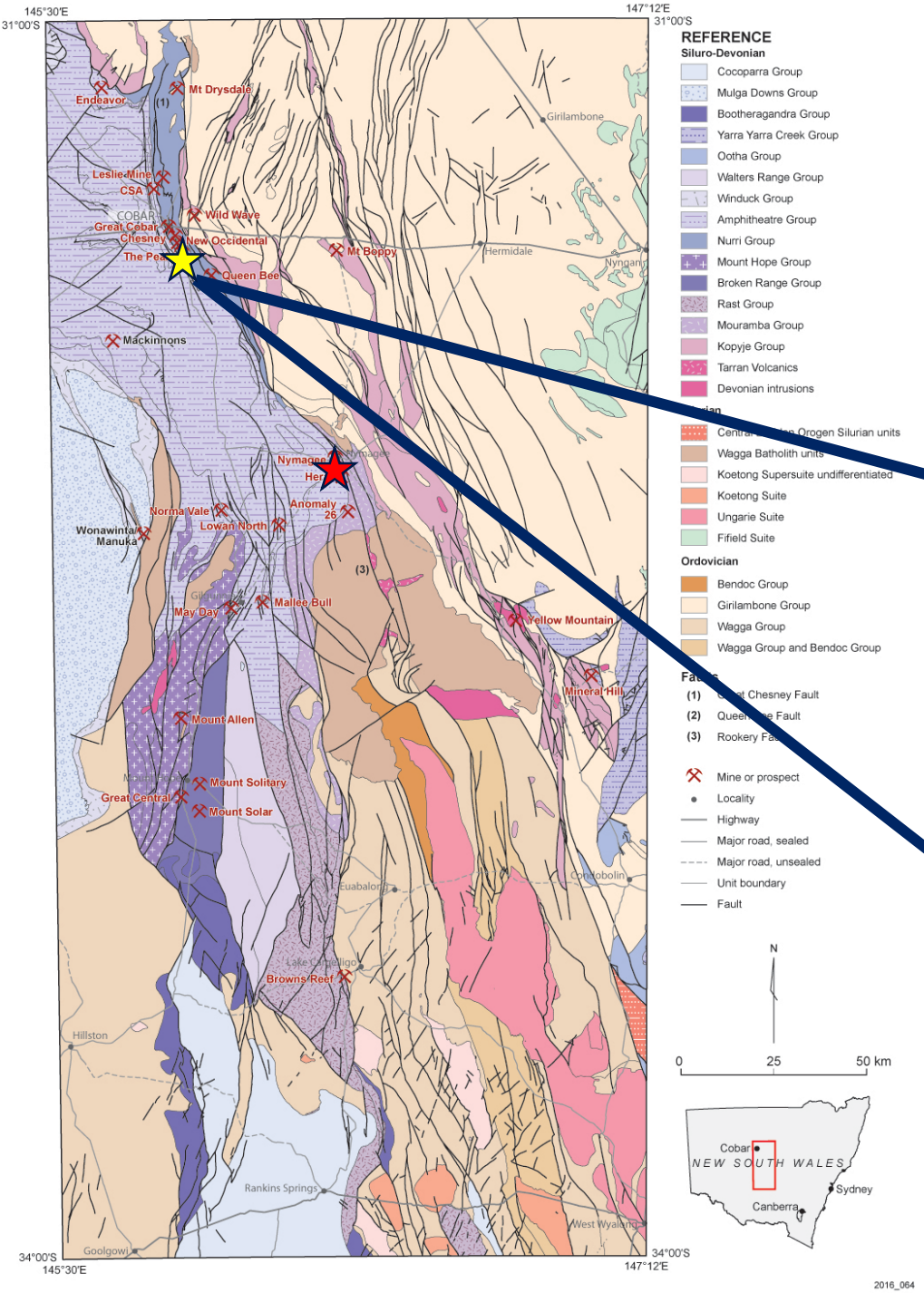


Muscovite (Ar–Ar) 381.0 ± 2.2 Ma

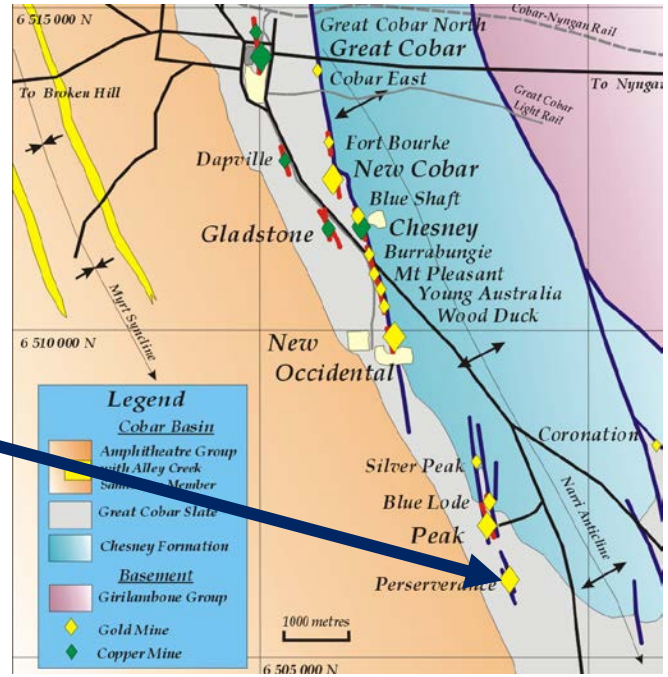


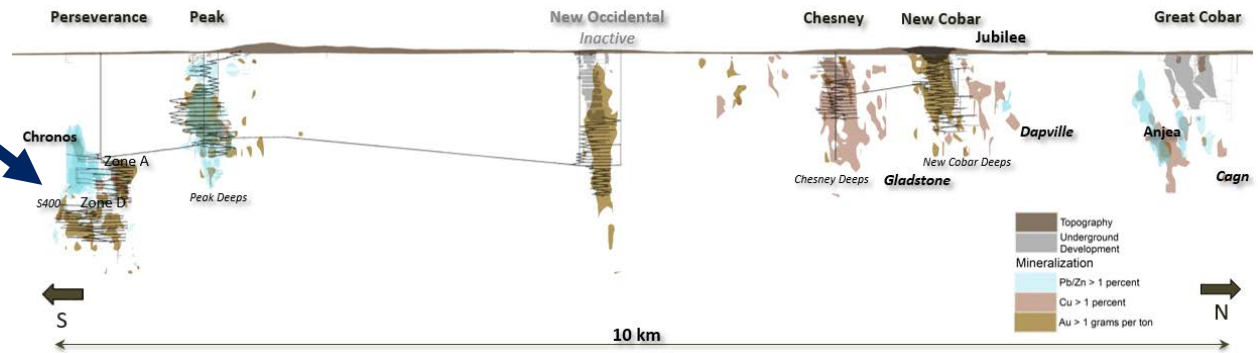


Perseverance and Chronos



Perseverance–Chronos





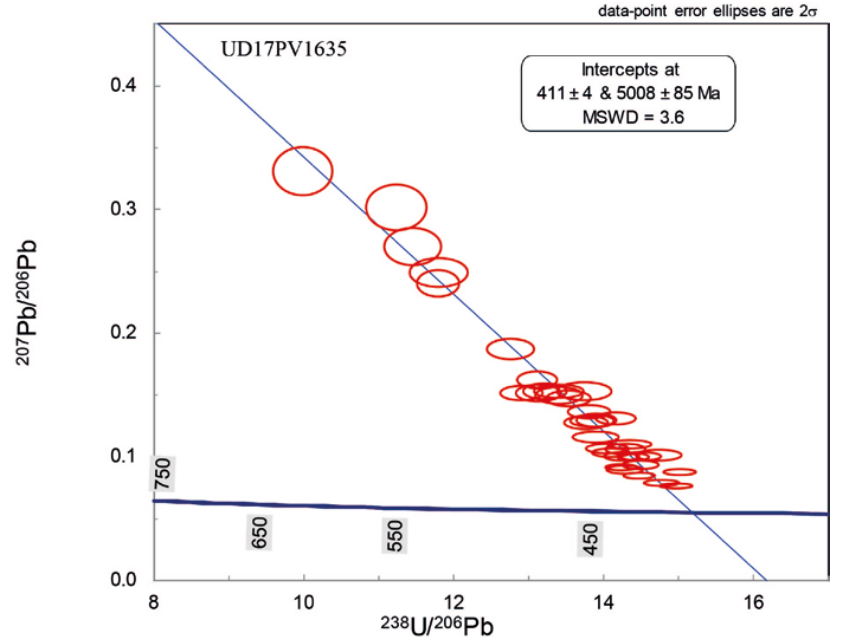
Steven et al. 2017

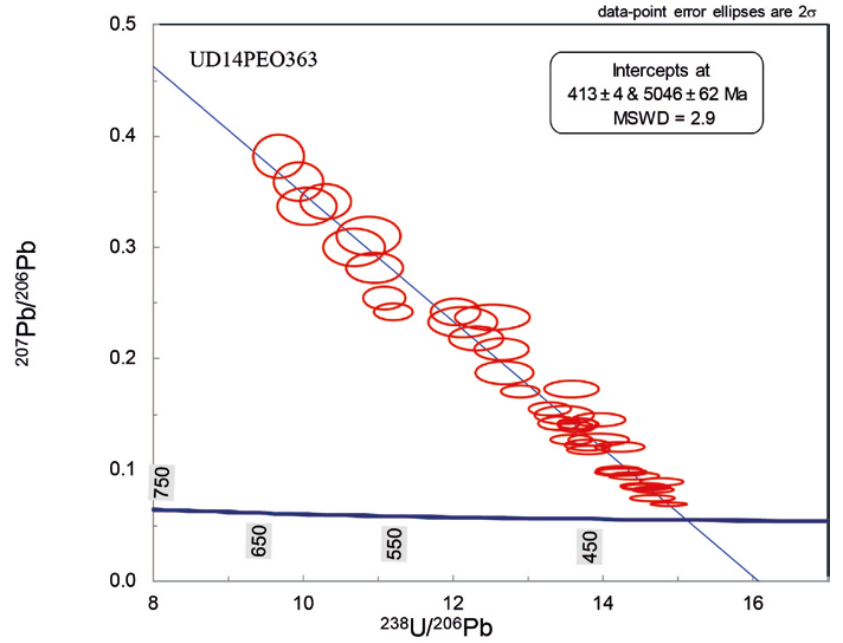
Perseverance and Chronos

- Hydrothermal veins:
  - biotite–titanite–sulfide veins
    - linear vein arrays in the mineralised rhyolite
  - chlorite–titanite–sulfide veins
    - deformed veins within sedimentary rocks.
- Titanite LA-ICPMS ages all within error:

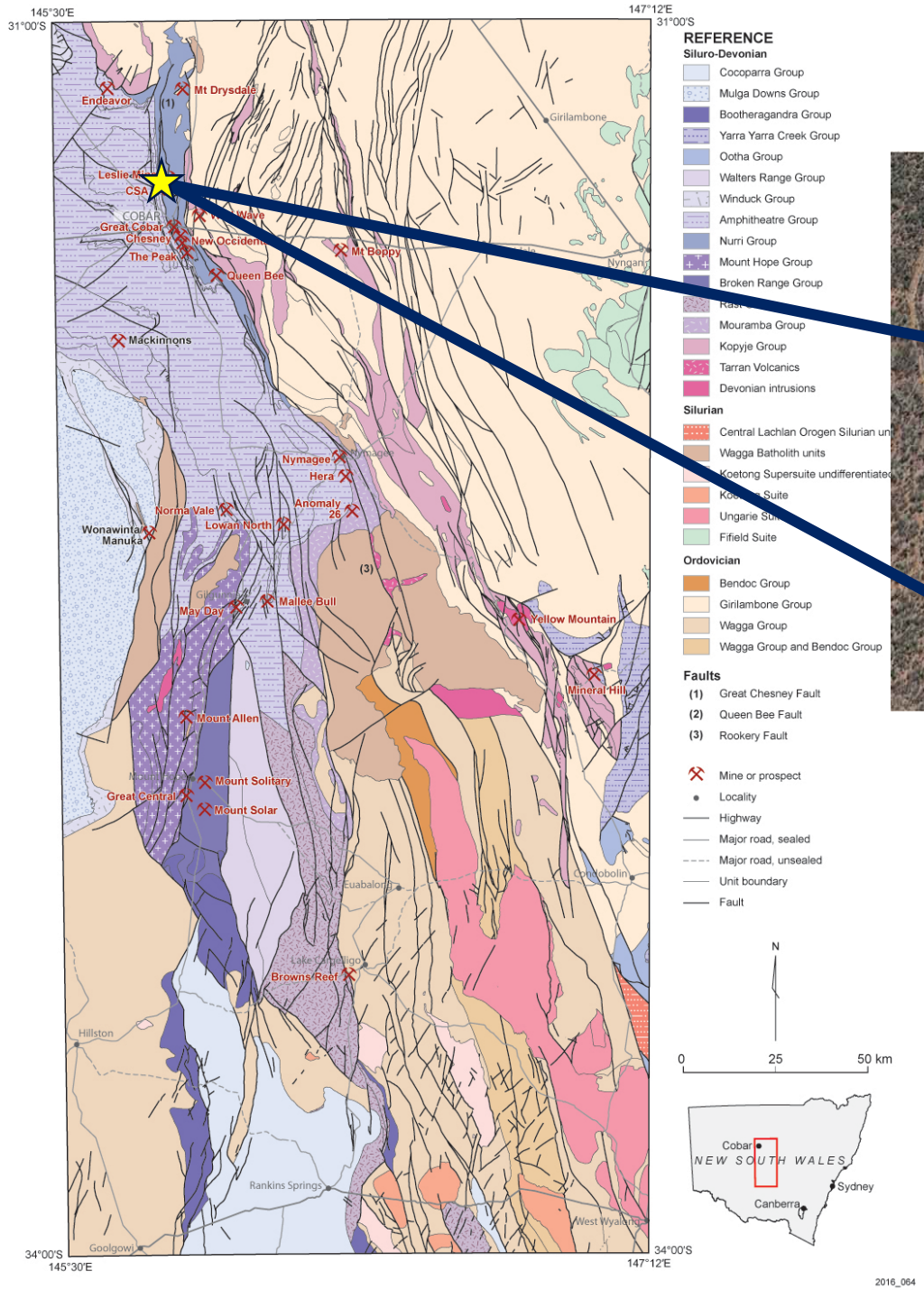
  409 ± 3.7 Ma, 411 ± 4 Ma and 413 ± 4 Ma.

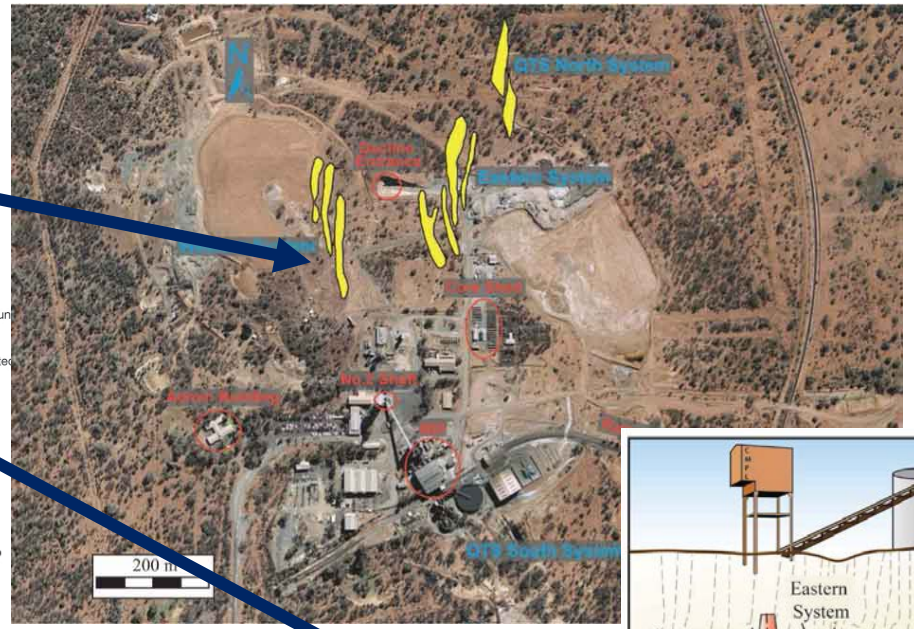
Peak rhyolite – 418.3 ± 3.0 Ma

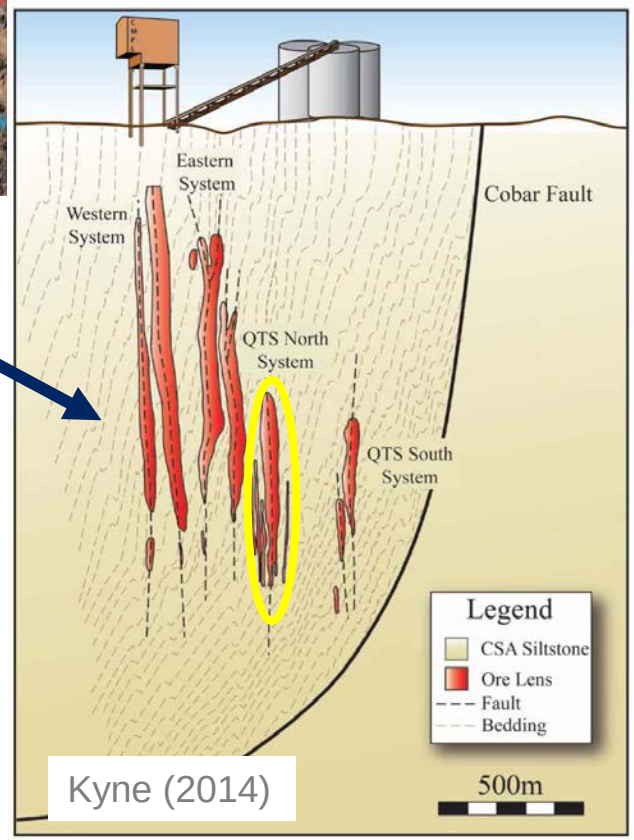




CSA

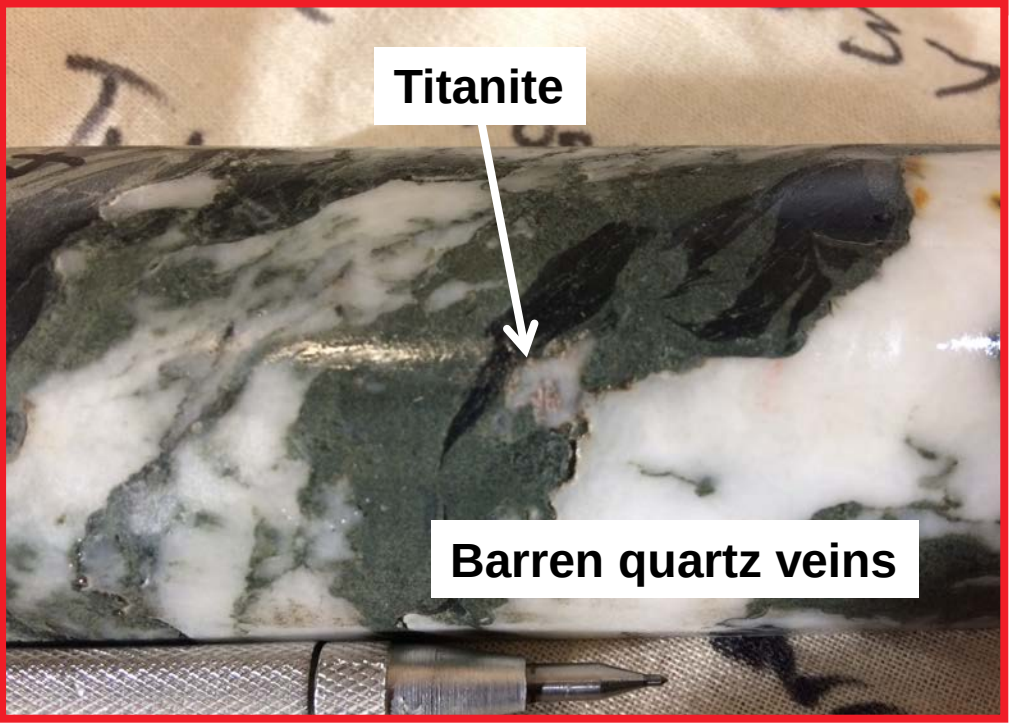






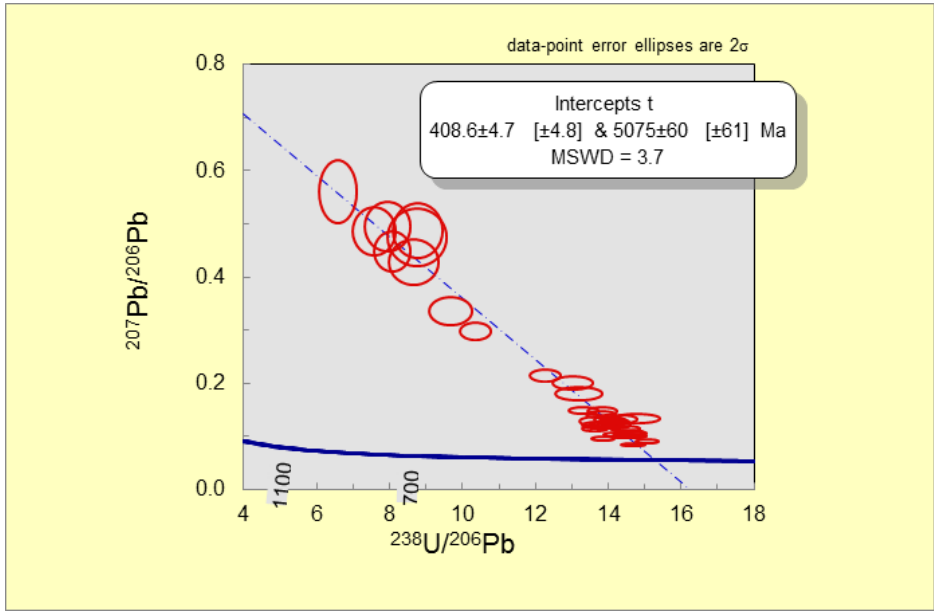
- Note the orebody geometry.
- Consider the Hera orebody model and age dating.

CSA



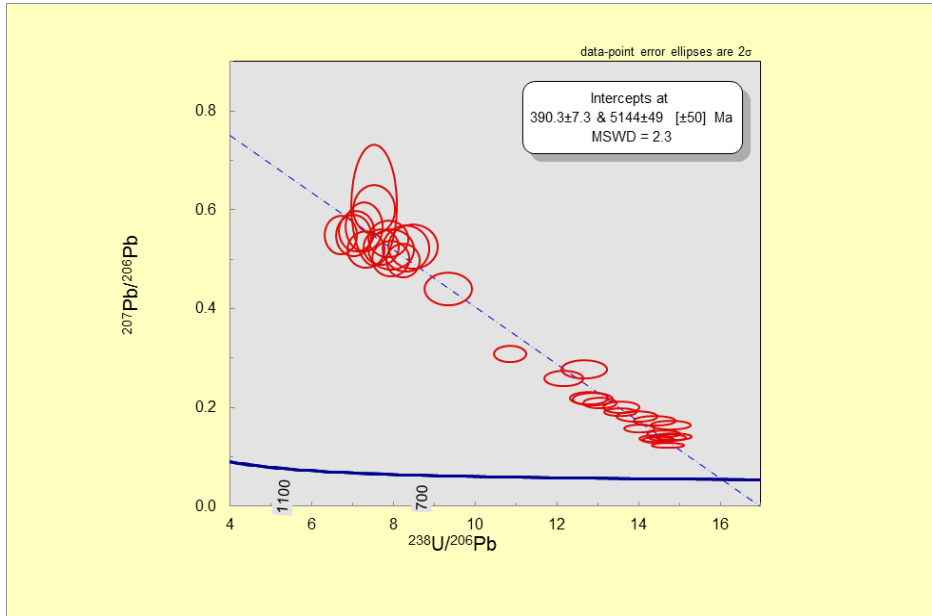
- **Two generations of hydrothermal titanite:**
  - deformed mineralised veins

    408.6 +/- 4.7 Ma

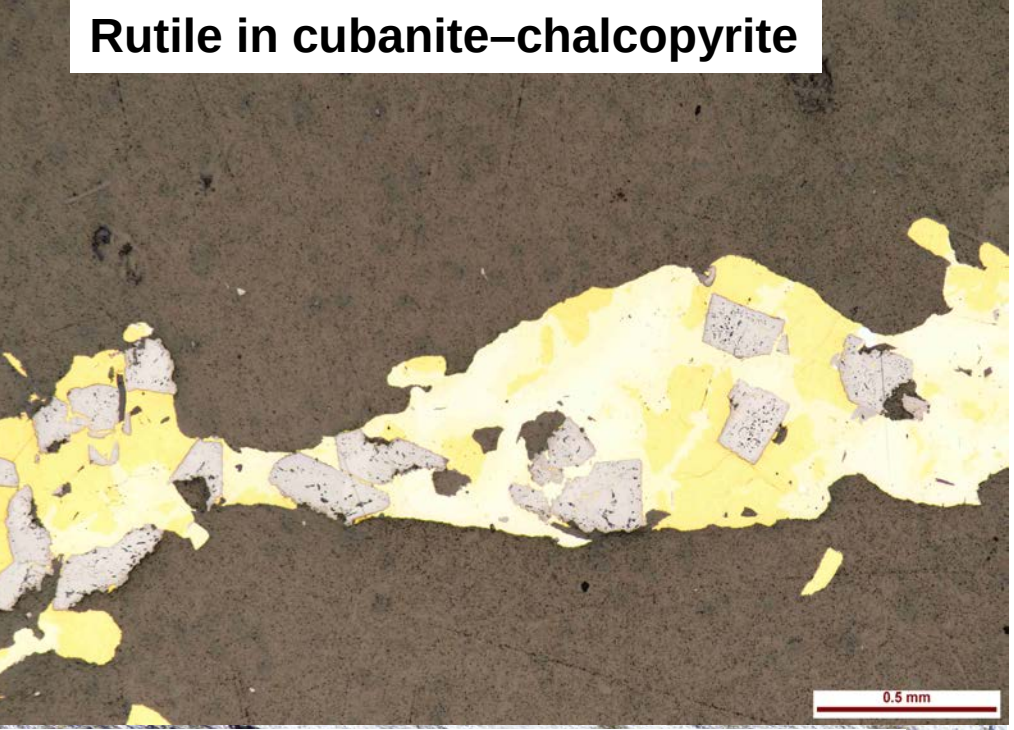


  - cross-cutting barren veins (similar to Hera)
  - located at ore lens terminations

    390.3 +/-7.3 Ma.

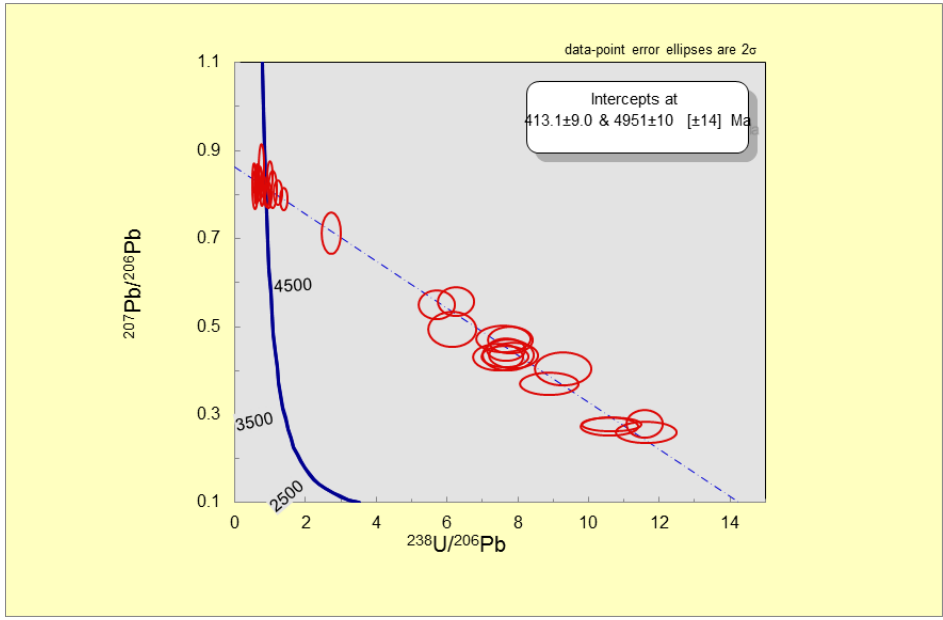


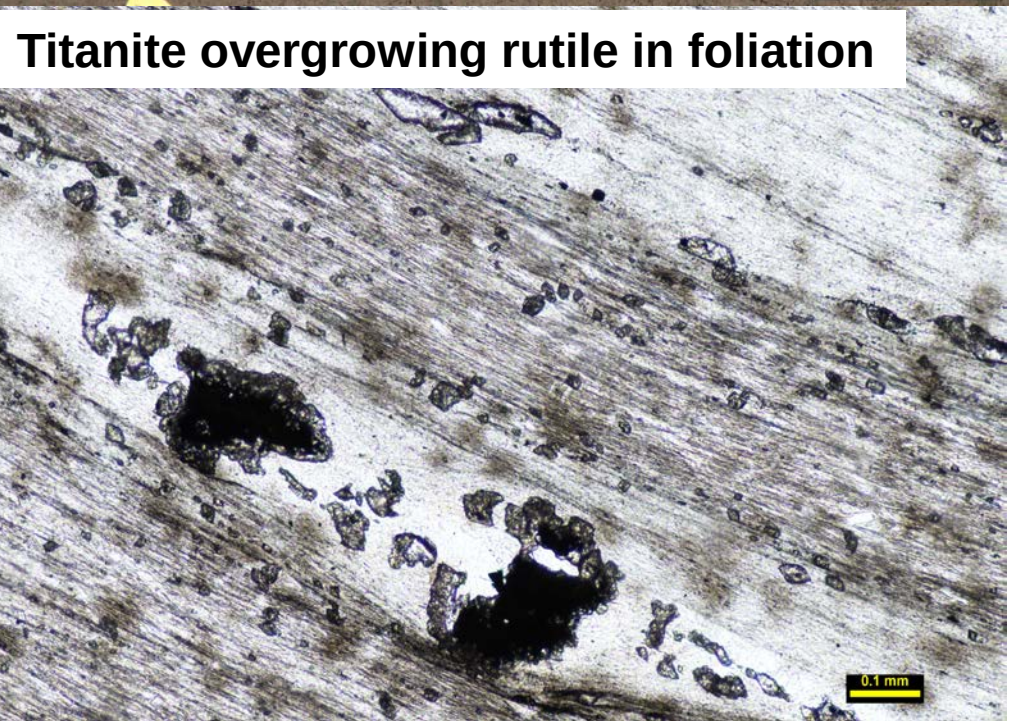
CSA – in situ dating



- **Hydrothermal rutile**
  - cubanite/chalcopyrite

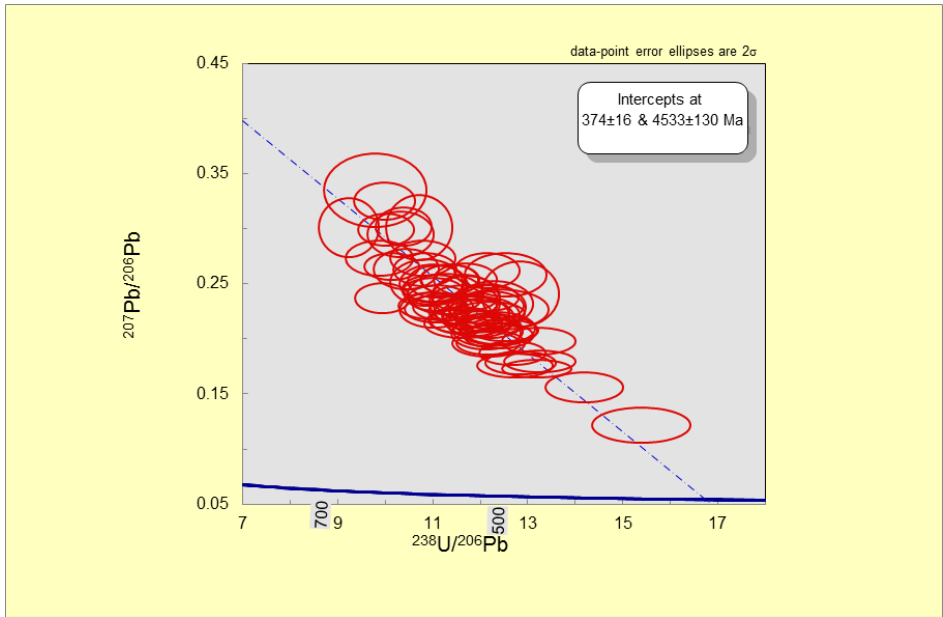
413.1 +/- 9.0 Ma



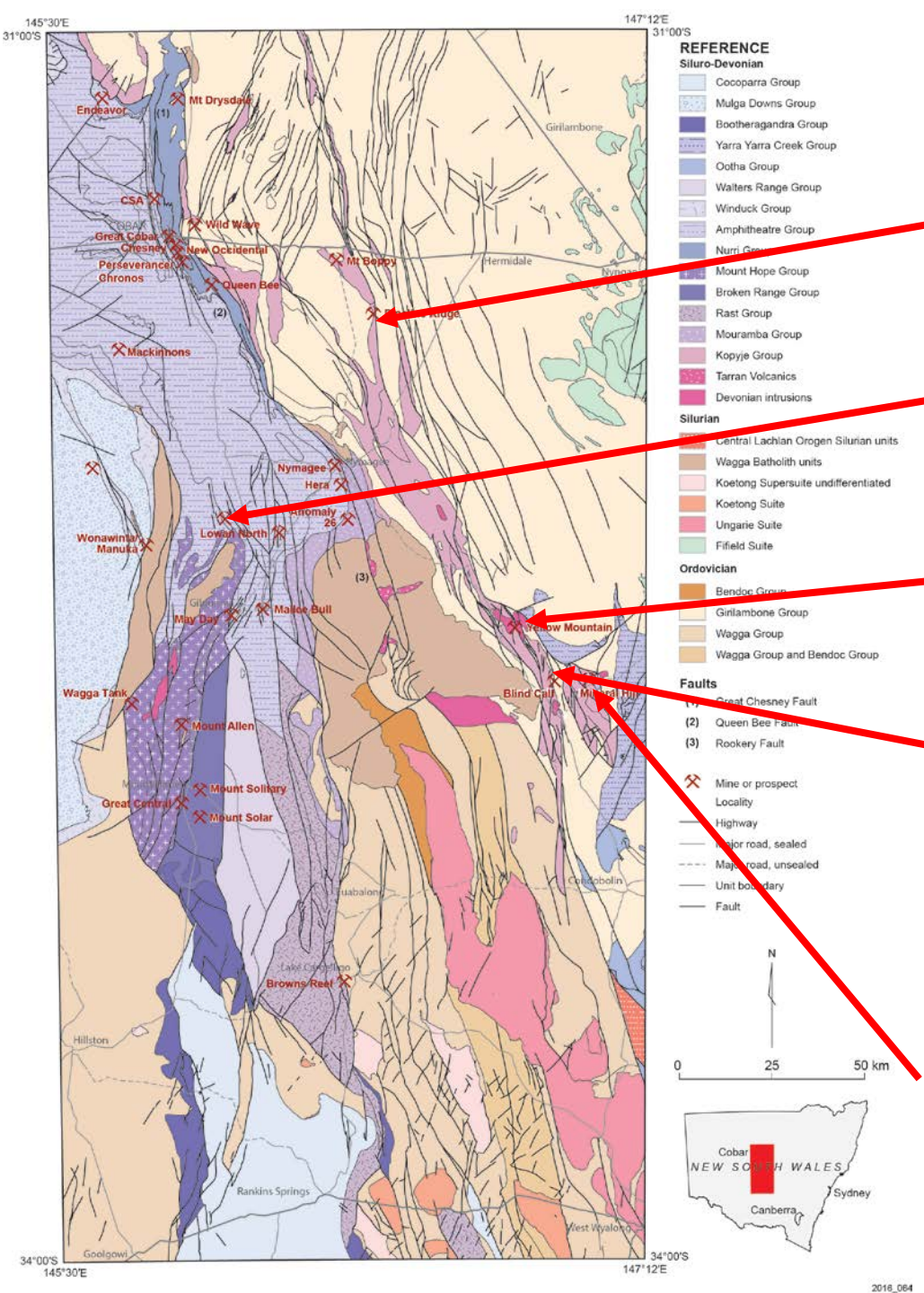


  - titanite replacing rutile in foliation

374 +/-16 Ma.



Ar–Ar dating of mineralisation



Pipeline Ridge
(408.2 ± 0.6 Ma)

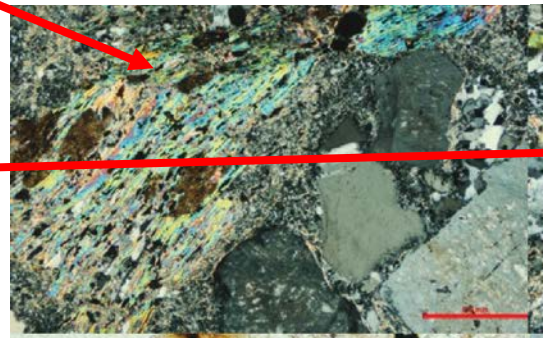
Norma Vale
(418.2 ± 0.3 Ma)

Yellow Mountain
(409–416 Ma)

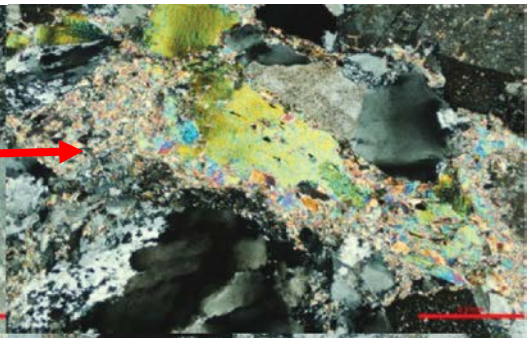
Blind Calf
(399.5 ± 0.3 Ma)

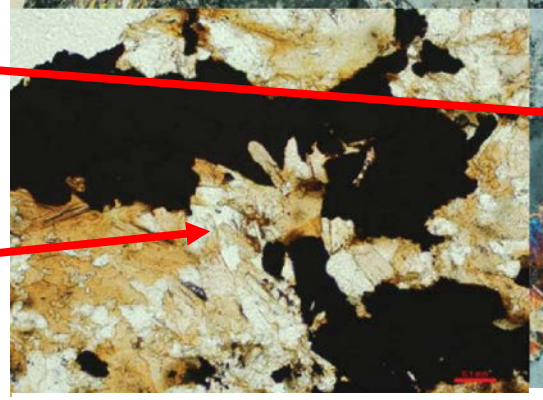
Mineral Hill
(420.5 ± 0.27 Ma)
Downes & Phillips (2018)

Hydrothermal muscovite

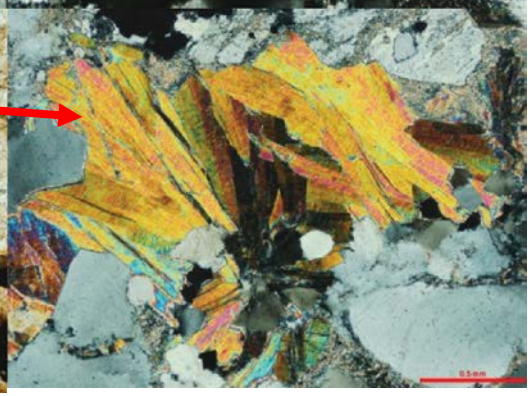


Hydrothermal muscovite



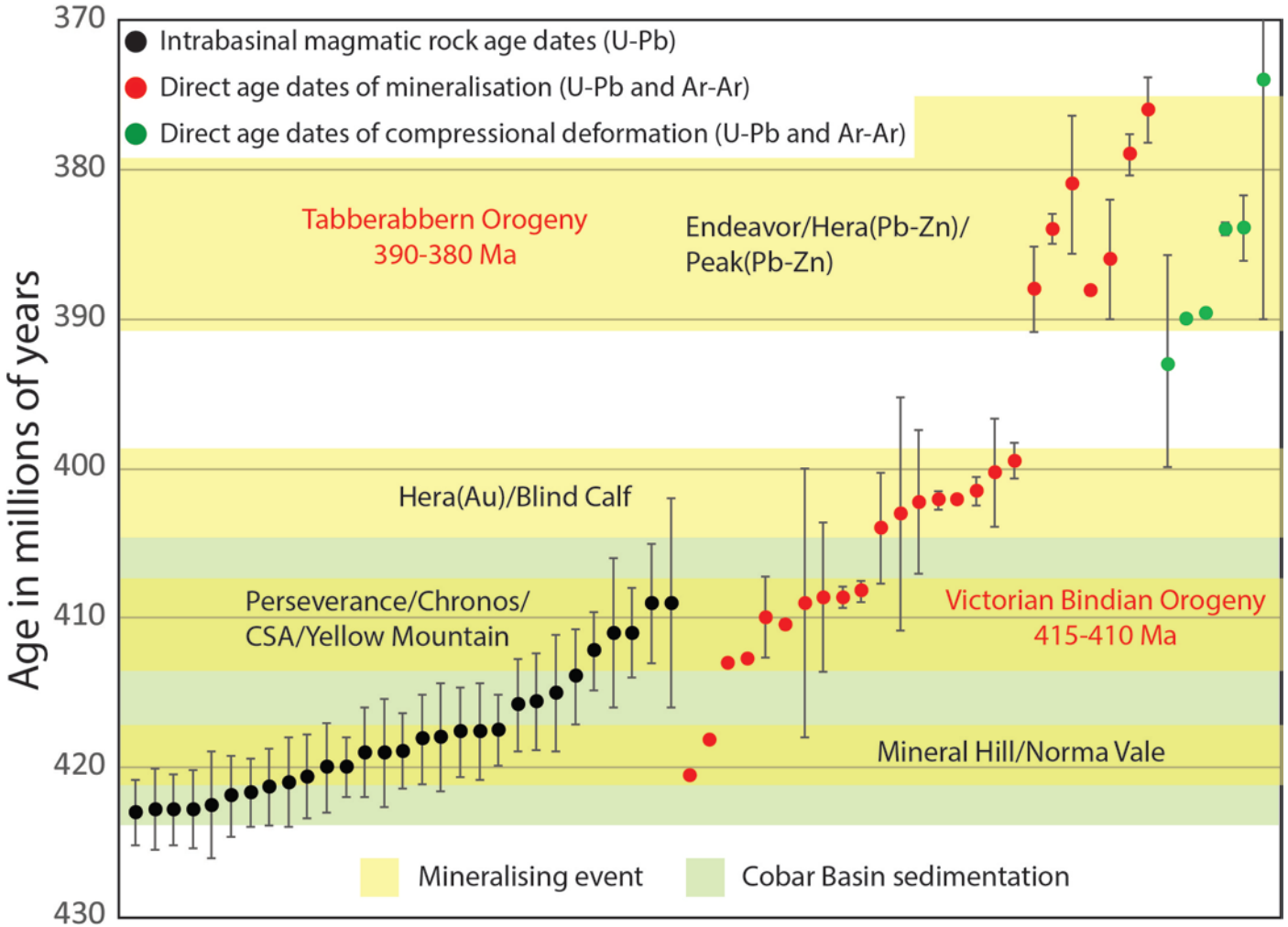


Hydrothermal biotite-sulfide



Hydrothermal muscovite

Dating summary



- **Early syn-rift mineralisation**
  - ca. 420 Ma e.g. Mineral Hill.
- **Cobar Cu–Au sweet spot @ 413–408 Ma**
  - youngest intra-basin magmatism 411 Ma
  - plot includes Yellow Mountain (Au) dated at ca. 412 Ma.
- **Hera skarn Au–Pb–Zn 405–400 Ma**
  - renewed high heat flow
  - no evidence of a genetic link
  - includes Segals and Blind Calf dated at ca. 400 Ma.
- **Foliation formation and brittle faulting at Hera @ 390 Ma**
  - there is no doubt that there is Pb–Zn mineralisation at this age as well.

What? – attempting to understand key characteristics

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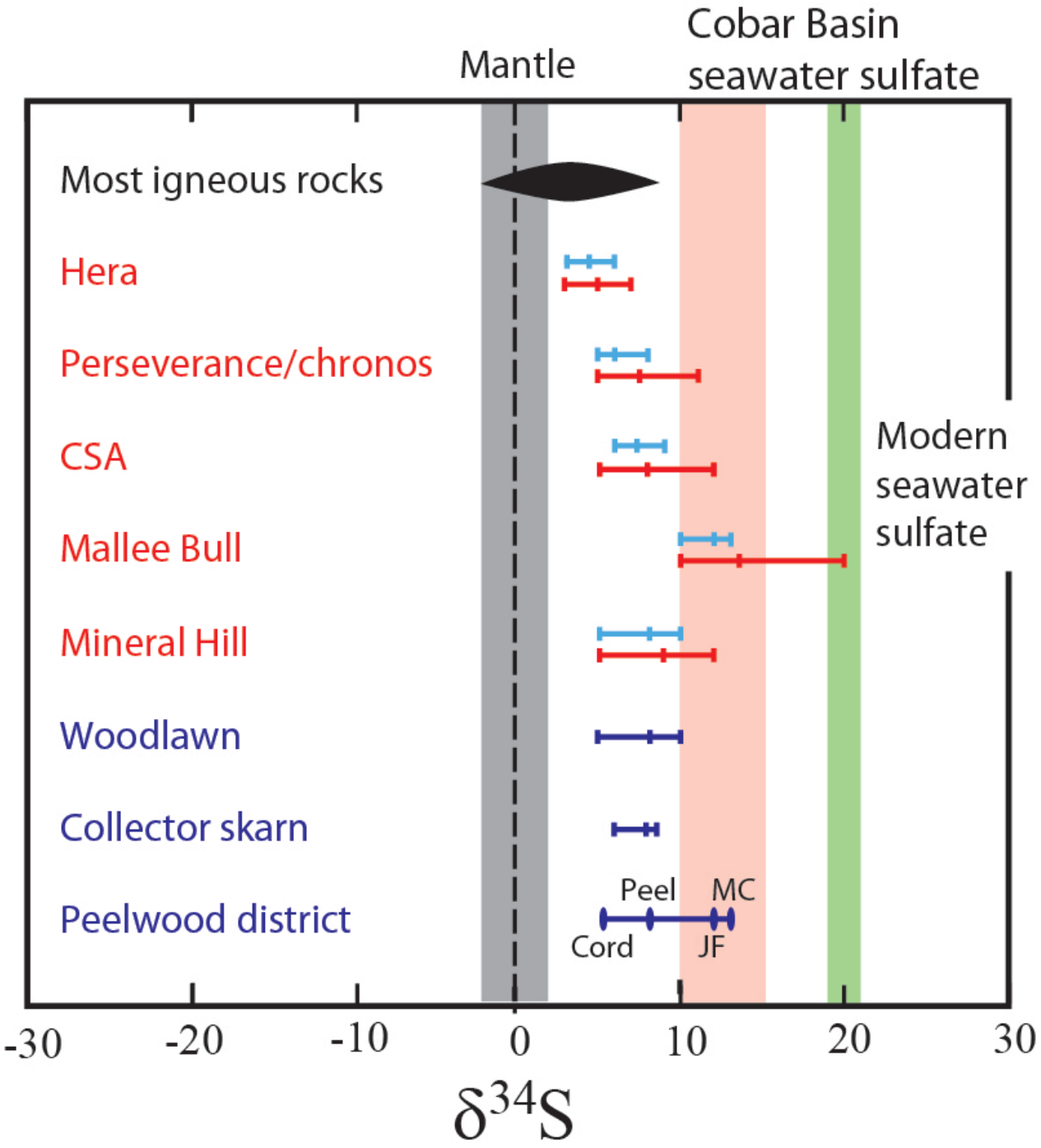
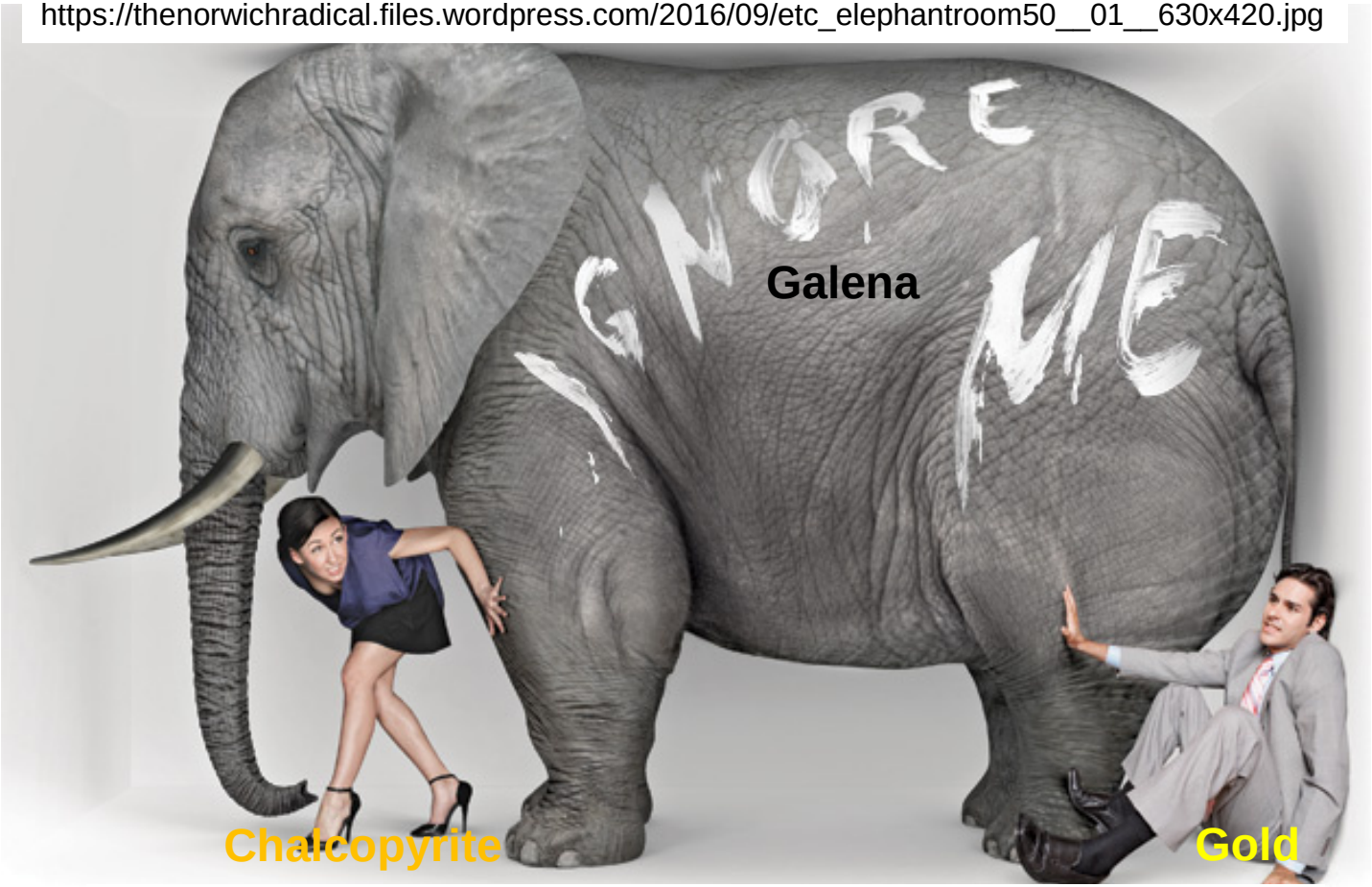


Sulfur source

- **Simple ratio of S^{34}/S^{32} ($\delta^{34}S$)**
  - **Cobar**
    - consistent $\delta^{34}S$ within deposits and marked variation between
      - Hera = most igneous-like
      - Mallee Bull = most seawater-like
    - overall, a variable sulfur source
    - Mineral Hill a ca. 420 Ma high-sulfidation epithermal orebody in Cobar
      - $\delta^{34}S$ the same as Perseverance/Chronos/CSA.
  - **HET and Goulburn basin**
    - accepted Siluro-Devonian VMS and skarn
    - Peelwood district VMS same variation as Cobar.
- **The point**
  - Cobar orebodies have an inhomogeneous sulfur source
    - variable basement source?
    - variable magmatic versus formation/sea input?

https://thenorwichradical.files.wordpress.com/2016/09/etc_elephantroom50__01__630x420.jpg



Different parents? We are exclusively using high-Pb minerals (galena) as a proxy for source in deposits with known time transgressive metallogeny like CSA

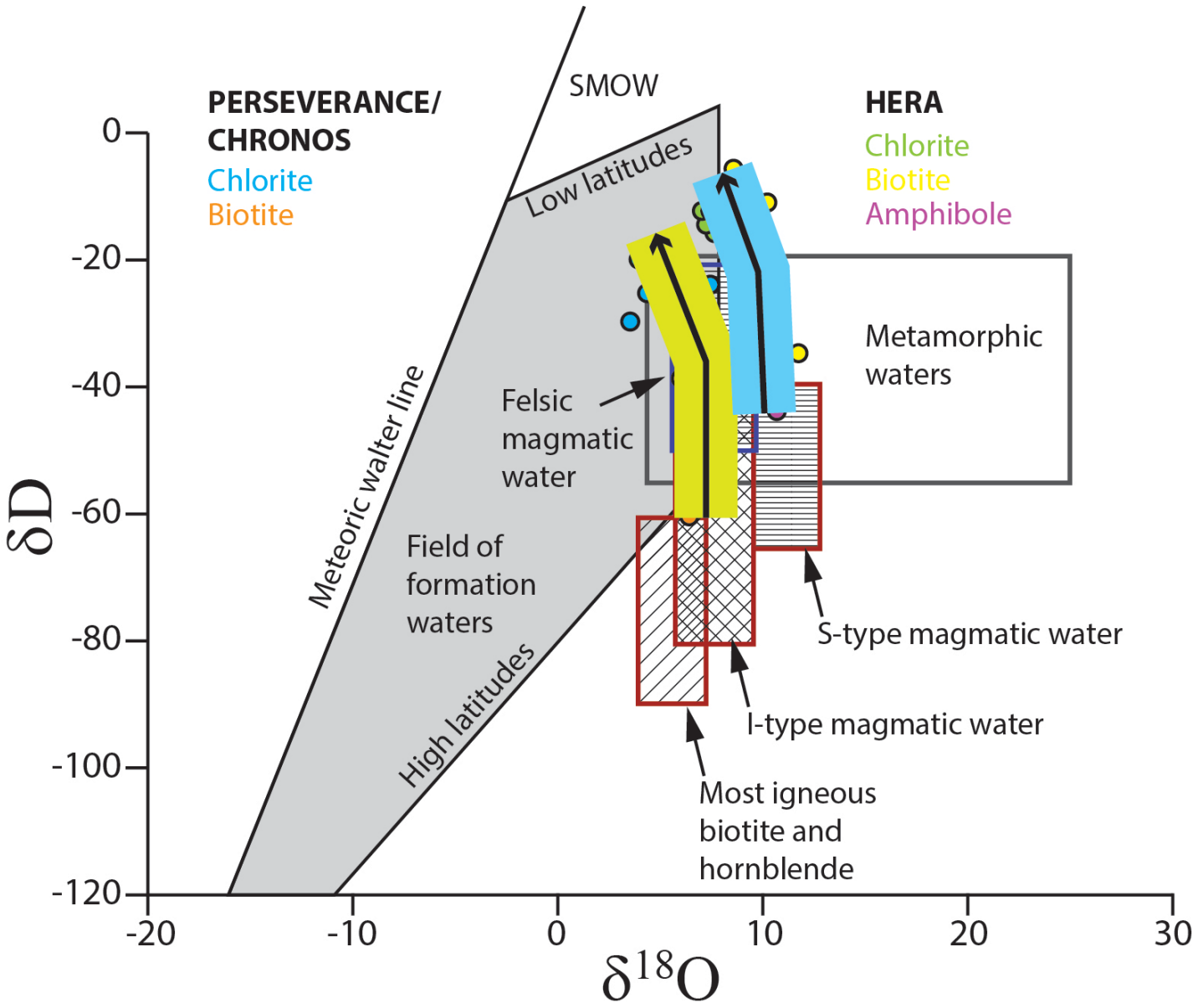
Not new Used to suggest basement Cu–Au mixed with basin Pb–Zn (Lawrie & Hinman,1998)

Pb model ages

- **End members that span the range of interest**
  - **Mallee Bull**
    - Pb model age of 432–422 Ma
    - same as some Ordovician-hosted Cu-deposits. Strong involvement of basement and basin.
  - **Hera**
    - Pb model age of ~401 Ma (412–397)
    - younger than basin, but same age as mineralisation! Now an event of this age!
  - **Endeavor–CSA (Pb)**
    - Pb model age of ~390–380 Ma
    - Tabberabberan Orogeny, basinal fluid.

- **The point: Is it mixing?**
  - Cobar deposits have a variable Pb-source
    - some old - basement source (Mallee Bull)
    - some source age = deposit age (Hera)
    - some young - Tab Orogeny (CSA-Pb, Endeavor)
    - need a good reason to have Pb-age younger than U-Pb dating
      - CSA (Pb model age) 380–390 Ma
      - U-Pb dating of CSA (Cu) ca. 410 Ma.

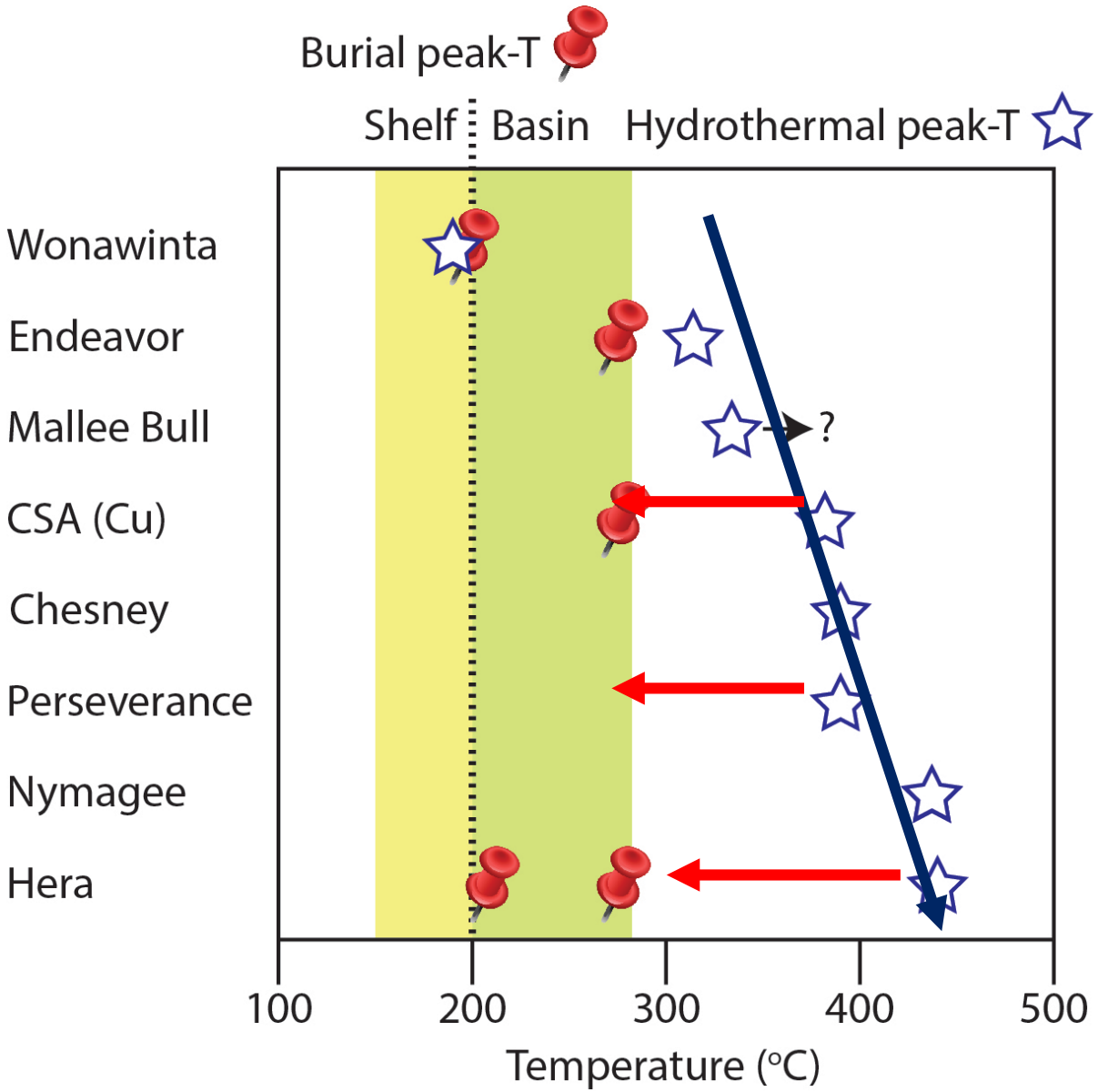
Drowning in isotopes – fluid δD-δ^{18}O



- **What are water δD-δ^{18}O values?**
  - determined using measured ratios of D_2O/H_2O (δD) and O^{18}/O^{16} (δ^{18}O) for biotite, amphibole and chlorite
  - adjusted for temperature of formation and mineral composition to calculate the isotopic composition of the last fluid that equilibrated with each mineral.

- **The point**
  - as temperature decreases the fluid evolves from a field consistent with I-type/felsic magmatic water (or metamorphic) into the field of low latitude formation waters
  - fluid source changes character through time and during orebody cooling
    - **thermal disequilibrium** between 2 different fluids, hot ore fluid and cold low-latitude formational fluid.

Burial versus hydrothermal heat



- **Burial metamorphic T based on**
  - Conodont Alteration Index (CAI), white mica crystallinity (Kubler).
- **Peak hydrothermal T based on**
  - mineral thermometry, white mica crystallinity, fluid inclusion entrapment T.
- **Timing**
  - orogenic model burial/hydrothermal = synchronous
  - some orebodies older than 390 Ma foliation!
- **The point (if we assume synchronicity)**
  - the exposed mineralised levels (all in the lower half of the basin fill) experienced fairly uniform burial ($\Delta T \sim$ 50°C east to west)
    - **large thermal disequilibrium** between orebody and host rocks results in cooling, retrograde evolution and mineralisation. Hera, Perseverance, CSA (Cu)
    - **close to thermal equilibrium** between orebody and host rocks. Endeavor and Wonawinta.

Why? – what is happening in the Central and East Lachlan Orogen

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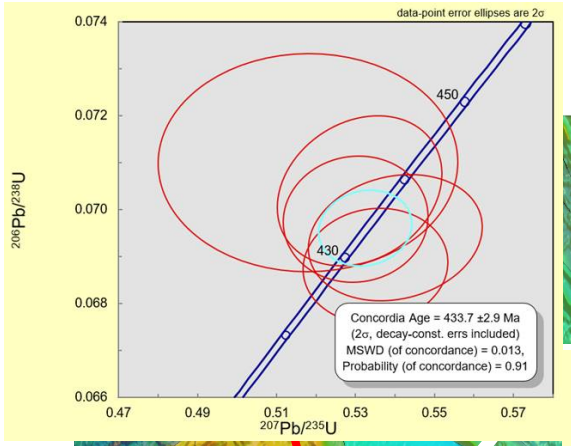
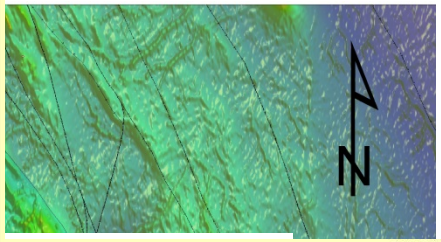
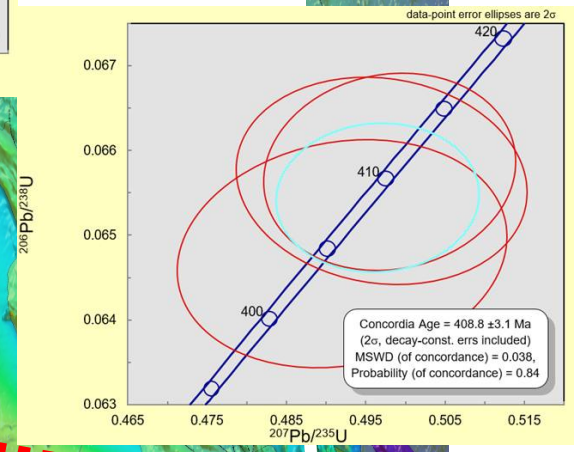
What of our genetic link?







Hot off the Laser
Tollingo Granodiorite

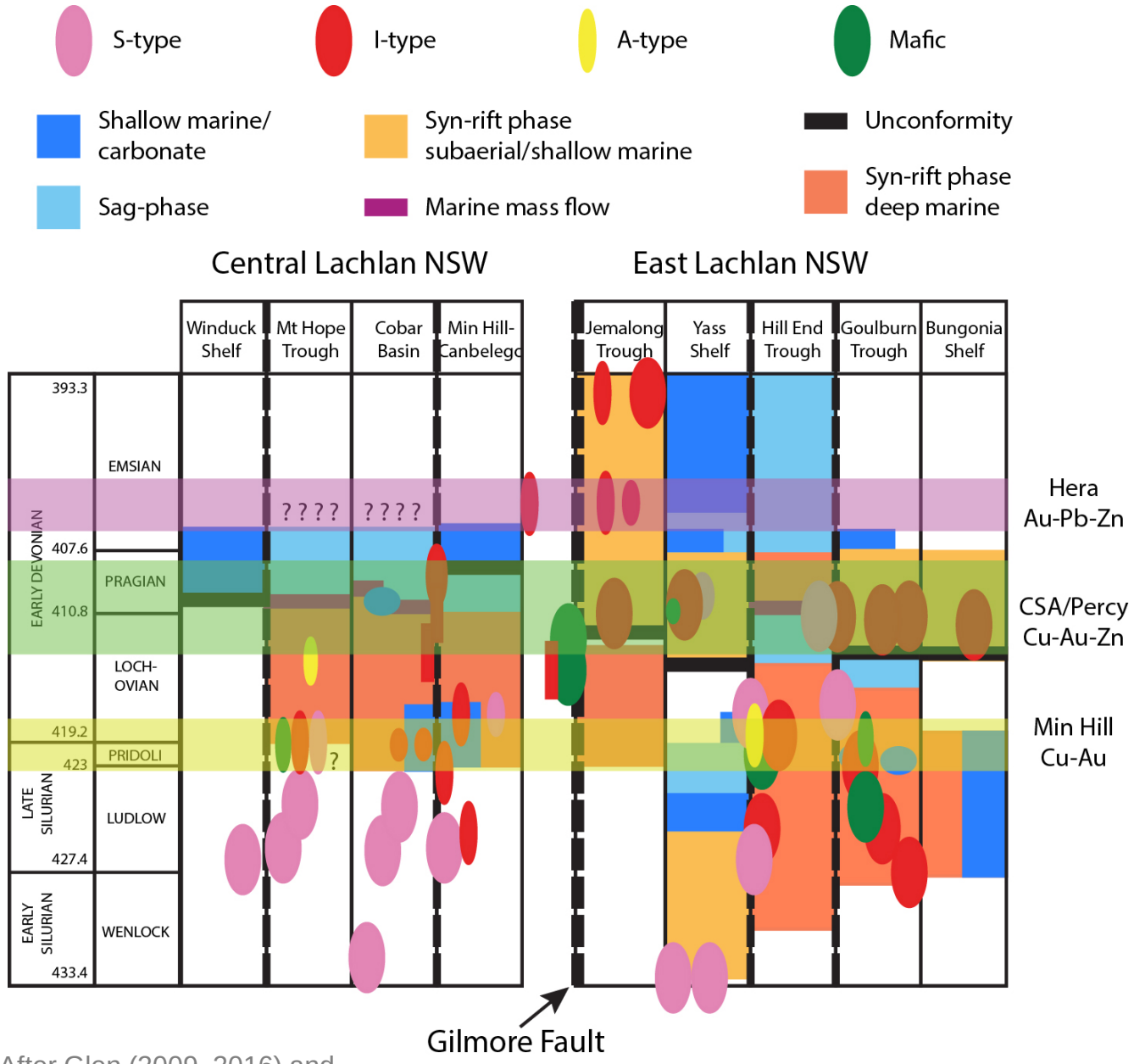
Concordant ~408 Ma zircon population

Tollingo magnetic high

413 and 403 Ma within and around the Cobar Basin?

- **U–Pb geochronology of intrusive rocks**
  - entire deep-water basin deposited between 423–418 Ma. Age differences unresolvable throughout basin
  - Yarra-Yarra Creek and Winduck groups record shallow-water deposition into the Emsian ca. 408 Ma
  - I- and A-type dykes intrude Rookery Fault system at 415–411 Ma. Boolabone Granite 415 Ma @ Mt Hope
  - isolated deep-water volcanism in Rast Trough to 412–409 Ma.
- **Age of fossils and mass flows (Mathieson et al. 2017)**
  - end Lochkovian–Pragian (415–407 Ma) instability
  - switch from rift to sag
  - Pragian outrunner blocks – Lerida (Biddibirra Fm)
  - allochthonous packages – Shume Fm
    - limestone and volcanic blocks?
  - conglomerates/olistoliths – Shume Fm
  - abundant sand influx (Alley Sandstone etc…).

What of our genetic link?



After Glen (2009, 2016) and Fergusson (2010)

What's happening between 413 and 403 Ma in the greater Lachlan Orogen?

- **Cobar Basin** – shallow marine shelf **AND** deep water mass flow
  - Pragian limestones Shume/Biddibirra formations, Pragian to Emsian shelf.
- **Jemalong Trough** (and Buchan in Vic) – immediately east of the Gilmore Fault have the youngest-lived rifting and subaerial volcanism.
  - Pragian to end Emsian 410–400 Ma. Intrusions at 405–400 Ma
- **Rest of the East Lachlan** – major rift-related high-T magmatic event
  - Late Lochkovian–Pragian. Extensive plutonism and subaerial volcanism. Mass flows in deep water.
  - Calming, shallow marine carbonate deposition and sag-phase deeper marine deposition during the Emsian Quiescence.
- **Bindian Orogeny (south) 415–410 Ma.**

Summary

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Summary - Part 1

- **Time transgressive mineralisation. Some orebodies are manifold in nature.**
  - **420 Ma – Volcanic belts (e.g. Mineral Hill)**
    - early rift phase. Most people happy with this one.
  - **413–408 Ma – North Cobar Cu–Au mineral field (e.g. CSA (Cu), Perseverance, Pipeline ridge)**
    - basin instability OR just late sag phase? Continuing magmatism until 408 Ma
  - **405–403 Ma – South Cobar Pb–Zn–Cu–Au mineral field (e.g. Hera, Nymagee, Blind Calf)**
    - Renewed extension? Poor timing on high-T skarn phase
  - **390–380 Ma – Pb–Zn(Ag) systems (Wonawinta, Endeavor, ?CSA(Pb–Zn)**
    - Tabberabberan Orogeny inversion.
- **Isotopes and heat source for 405–403 and 413–408 Ma orebodies**
  - inhomogeneous sulfur source – consistent with magmatic to basinal sulfur
  - variable Pb source – basement, basin, unknown, orogeny? Depth and age control
  - cooling to isotopically heavier fluid dominance – consistent with mixing of magmatic-formational fluid
  - thermal disequilibrium and injection of heat along faults into relatively cool basin

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All consistent with involvement of magmatism 413–400 Ma.

Recently dated magmatic activity to 408 Ma.

Summary - Part 2

- **Late Lochkovian–Pragian in the greater Lachlan – a time of active rifting and magmatism**
  - rifting and extensive magmatism followed by Emsian quiescence (East Lachlan)
  - rifting into the Emsian ca. 400 Ma in the western East Lachlan (Jemalong)
  - Victoria: Bindian Orogeny ca. 415–410 Ma followed by rift to sag (Buchan Trough) ca. 410–400 Ma
  - Cobar orebodies located over major strike-slip fault system(s) with the Gilmore Fault as the master
    - small observed movements can have big results on this crustal-scale structure
      - Fault focused magmatic activity recorded to ca. 408 Ma (Tollingo etc.)
  - The Central Lachlan is tectonically quiet, **BUT…**
    - Lachlan-wide tectonics can be the trigger to reactivate basin during rift-sag transition, syn-sag phase or even post-sag phase
    - look to far-field tectonics– renewed extension (East Lachlan), Bindian compression (ca. 415–410 Ma) or even post-Bindian relaxation
    - no doubt that the basin does provide Pb–Zn(Ag) from deep aquifers during inversion in the Tabberabberan (ca. 390–380 Ma), **BUT…**
      - Cu–Au–Pb–Zn mineralisation synchronous with older Lachlan-wide tectonic events and associated with thermal perturbation and involvement of magmatic rocks as the energy and likely metal source.

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Successive basin tapping and periodic magmatic input along large-scale basin faults.

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