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Turbidite-hosted intrusion-related mineralisation in the Cobar Basin

New insights from the south

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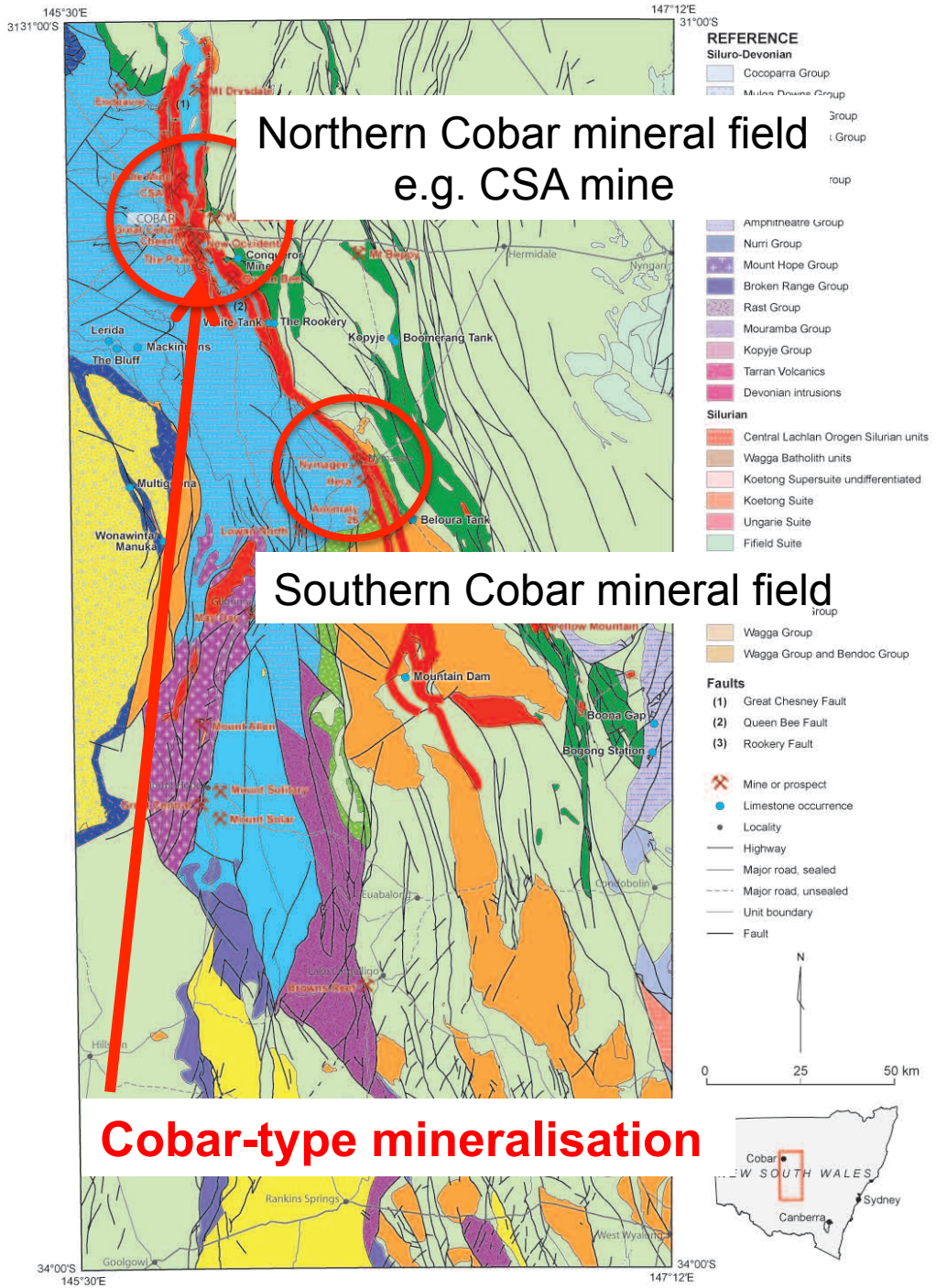
Contents

Cobar Basin

- Ordovician basement
- Intruded by Silurian granite
  - Exhumed prior to…
- Siluro-Devonian Basin
  - Sedimentary basin
  - Volcanogenic troughs/centers
  - Western shelf
  - Eastern drowned shelf/volcanic belt
  - Early Devonian intrusions (420-415 Ma)
- Overlain by middle-late Devonian
- **Major fault systems active in**
  - **Basement**
  - **Basin opening**
  - **Basin inversion**

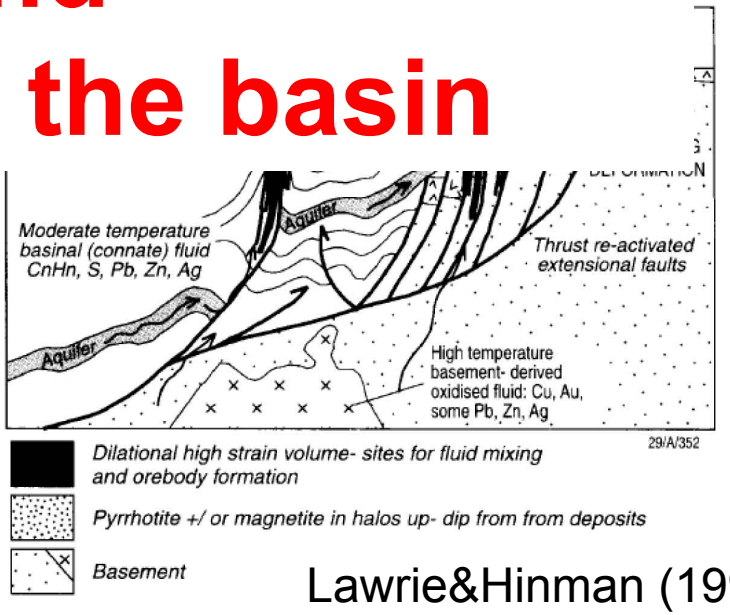


Cobar-type

- Described in the NE
  - CSA, Peak, Great Cobar, Chesney
- Geo
  - Mult
  - Shoi
  - Larg
- Dep
  - Meta
    - W
  - Mas
    - M
  - Broadly stratabound, but cross-cut bedding at **deposit-scale**
- Genesis
  - Syn-deformation - developed during basin inversion c. 380 Ma
  - Mixing of basin Pb-Zn and basement Cu-Au-rich fluids
  - Remain enigmatic. Variously attributed in the past
    - VMS, epithermal, subhalative-exhalative…

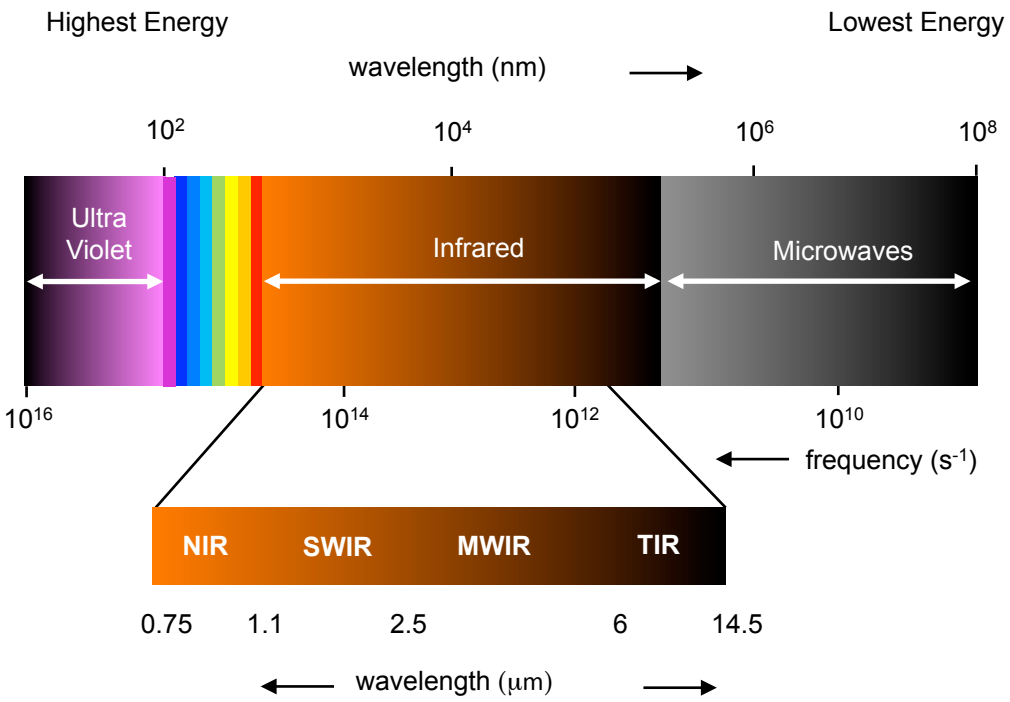
If structural/metamorphic model then…

Need to understand metamorphism in the basin



Lawrie&Hinman (1998)

GSNSW HyLogger



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Digging up heat in the Cobar Basin

Metamorphism

- **Diagenetic: 0-200°C**
- **Anchizone: 200-300°C**
- **Epizone: 300-350°C**
- **Biotite zone: 350-400°C**
- **Amphibolite facies/pyroxene hornfels >400°C**

Number of methods to determine burial metamorphic grade in very low grade pelitic rocks.

- Illite crystallinity (Kübler index)
- Vitrinite reflectance
- **CAI (Conodont Alteration Index)**

Facies zone	Metapelitic zone (depth, km)	Temperature (°C)	Illite crystallinity	Vitrinite reflectance R_o%	Conodont Alteration Index (CAI)
Zeolite (sub-greenschist)	Early diagenetic zone				1 yellow
	3.5–4	100	~1.0	0.5	
	Late diagenetic zone			0.75	2 light brown
			~0.60	1.35	3 brown
	6.5–8	200	~0.42	2.00	
	Low anchizone			2.50	4 dark brown
				3.00	
	High anchizone		~0.3		5 black
	10–12	300	~0.25	4.00	5.5
Greenschist	Epizone				
		350			
	Biotite-zone				6 grey
		400			
Amphibolite					

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vironment

Mapping heat in the Cobar Basin

R. Mawson, J.A. Talent,
D. Mathieson and A.J. Simpson

- **CAI**
- Unaltered conodonts exhibit a pale yellow colour and a smooth surface with silky brightness (CAI 1). Exposure to increasing temperatures results in carbonization of conodont matter that produces a progressive colour sequence of light to dark brown (CAI 1.5–4) to black (CAI 5), then grey (CAI 6) and white (CAI 7).

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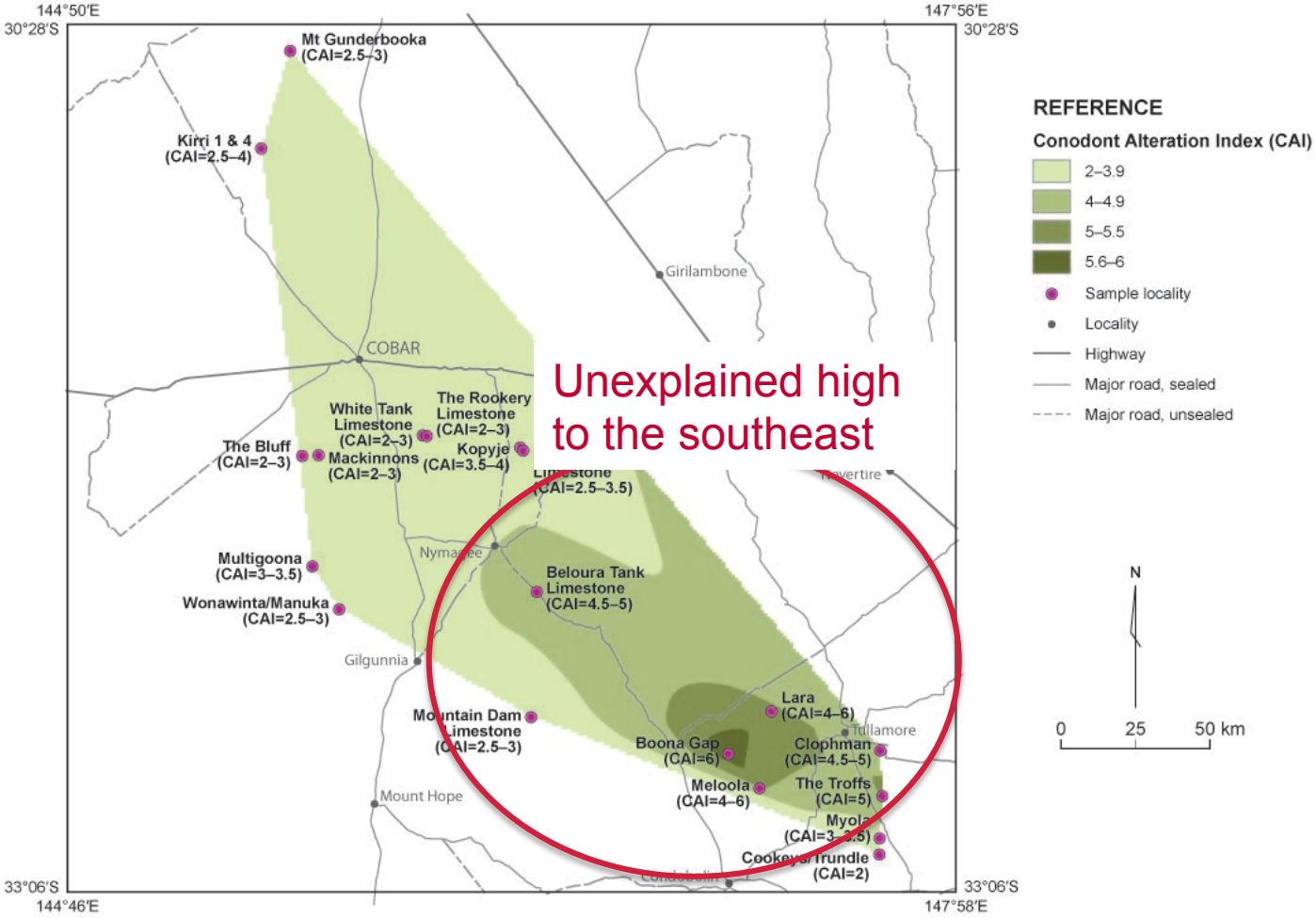
1) Virgin Hills (0-100°C)

2) The Rookery (100-150°C)

3) Manuka (150-200°C)

5) Beloura Tank (250-300°C)

Mapping heat in the Cobar Basin



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Greenschist	Epizone				
		350			
	Biotite-zone				6 grey
		400			
Amphibolite					

Mapping heat in the Cobar Basin

Distal to mineralisation

- Illite crystallinity (Δ°2θCu-Kα) values
  - Kyne (2014) – CSA mine (0.24–0.27)
  - Brill (1988) – Endeavor mine (0.24–0.27)
- Fluid inclusions
  - Seccombe (1990) – Endeavor mine (170-225°C)
  - Giles (1993) – Manuka mine (~150°C)
- Chlorite thermometry
  - Bush (1980) – Mineral Hill mine (~150°C)
- Vitrinite reflectance
  - Robertson and Taylor (1987) – CSA mine (3.3–3.4)

Proximal to mineralisation

- Illite crystallinity (Δ°2θCu-Kα) values
  - Brill (1988) - CSA mine (0.25-0.21), Chesney mine (0.26-0.18) Queen Bee mine (0.21-0.19), The Peak mine (0.29-0.21)
- Fluid inclusions
  - Giles & Marshall (2004) – CSA mine (350–380°C)
  - Sun & Secombe (2000) – Endeavor mine (286-374°C)
  - Forster & Secombe (2000) – Mackinnons mine (270-340°C)
- Chlorite thermometry
  - Page (2011) – Hera mine (270-365°C), Nymagee (292-394°C)
  - Bush (1980) – Mineral Hill mine (~300°C)

Temperatures of 150-250°C distal to mineralisation

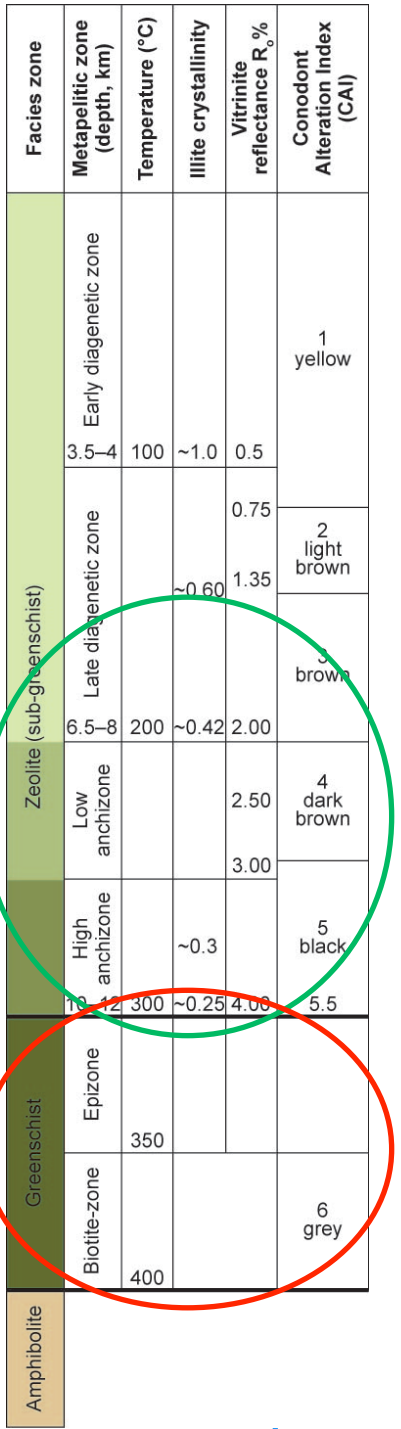
↑

Localised nature of heat

↓

Temperatures of 300-380°C proximal to mineralisation.

Within 100's of meters



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Mapping heat

Basement

- Lower greenschist east of Gilmore
- Sub-greenschist west of Gilmore

Western Shelf

- Diagenetic zone

Deep water basin

- Sedimentary – anchizone
- Contact metamorphism

Eastern shelf

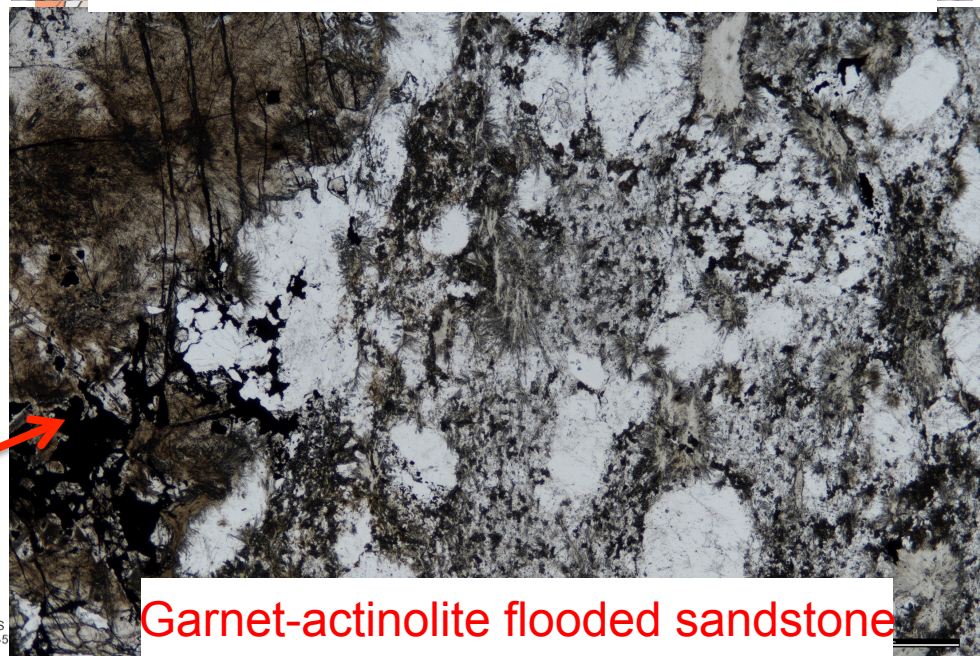
- Anchizone-middle greenschist

Hydrothermal metamorphism

- Close to major faults
- Northeast – greenschist (biotite)
- **South – pyroxene hornfels facies**

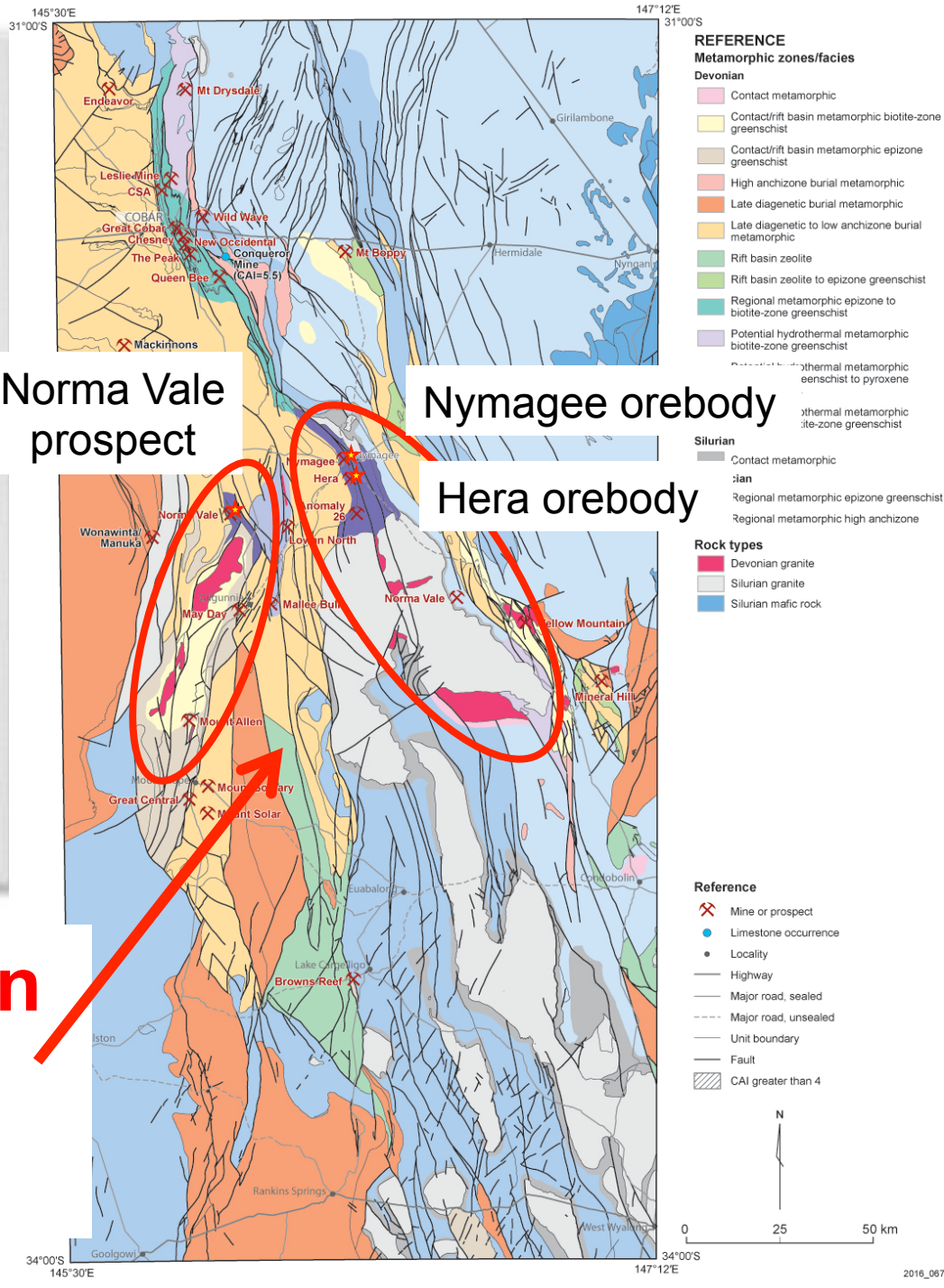
Important!
Hydrothermal heat is very localised
100's of meters around orebodies
Not a regional field gradient

Anchizone
detrital biotite/muscovite-rich sandstone



Garnet-actinolite flooded sandstone

Tour mineralisation in Hydrothermal ‘Hot Zone(s)’



Hera orebody

Au-Ag-Zn-Pb

- Steeply west-dipping
- Short strike length
- Sulfide vein/breccia zones
- Similar to other Cobar type deposits

Mineralisation hosted within intensely silicified siliciclastic turbidite

Gold associated with sulfide zones, but not always within the sulfides

Intensely silicified turbidite

Sulfide breccia

Sulfide breccia

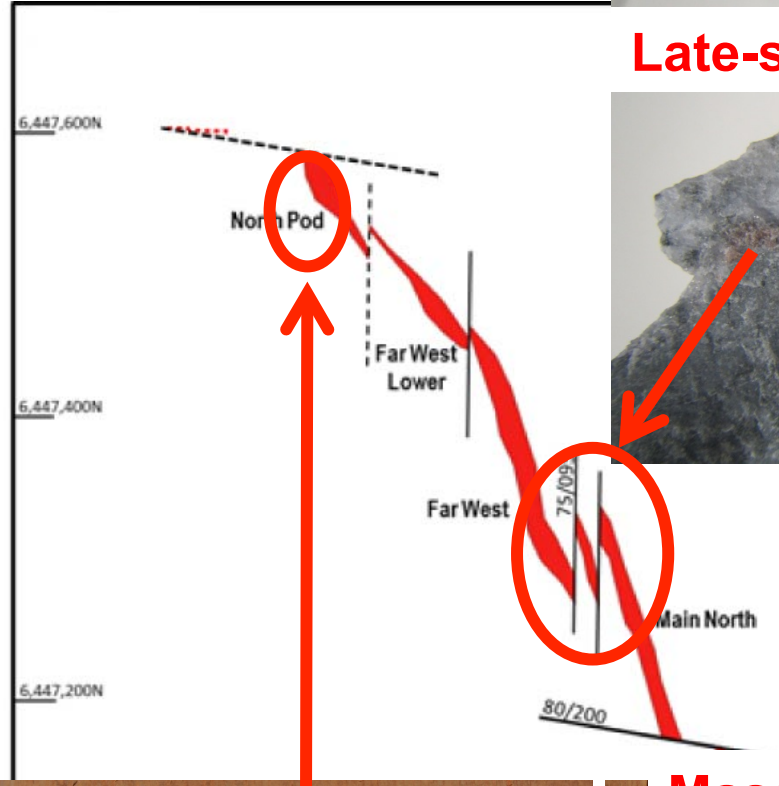
Gold in foliation

Gold and sphalerite

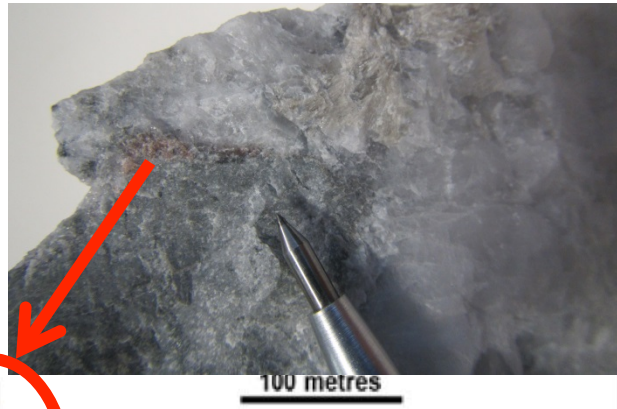
High-T minerals have been described

Hera orebody

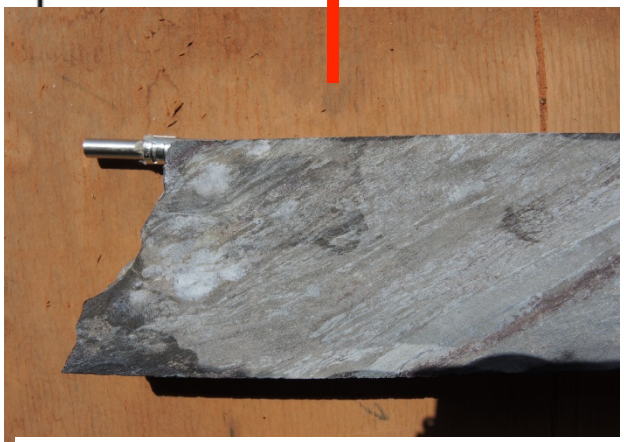
- Orebody interpreted as a single ?horizon
- Orebody enveloped by steeply west-dipping foliation
- Late (post-foliation) steeply east dipping thrust repartition



Late-stage titanite vein



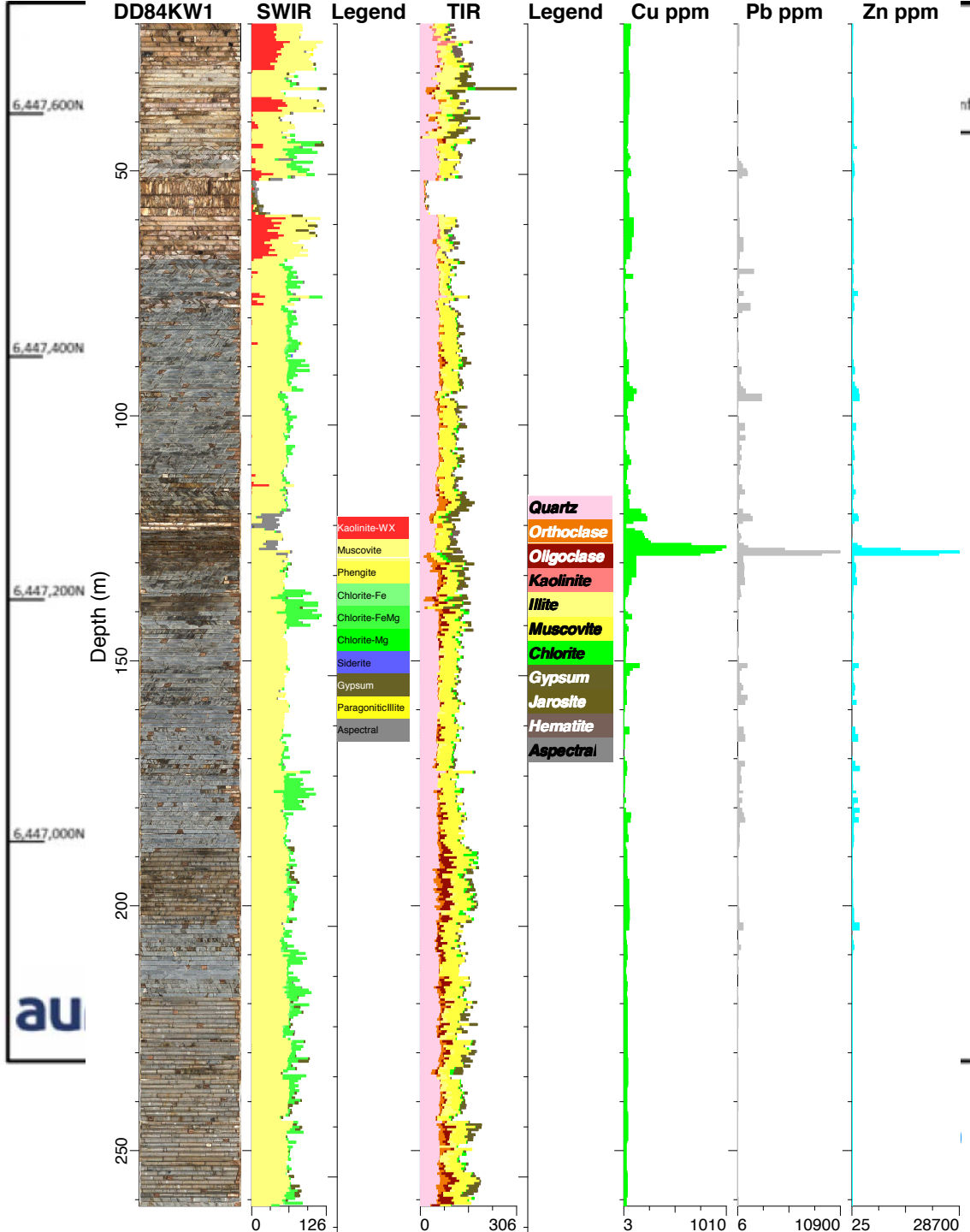
Massive sulfide core



foliated orebody margin

Hera orebody

- Nymagee Hylogger study.. Downes et al (2016)
- Drill holes from above Main South
- Chlorite–phengitic muscovite-albite dominant alteration.
- Chlorite becomes Mg-rich
- Sniff of K-feldspar
- But no signs of anything abnormal for Cobar



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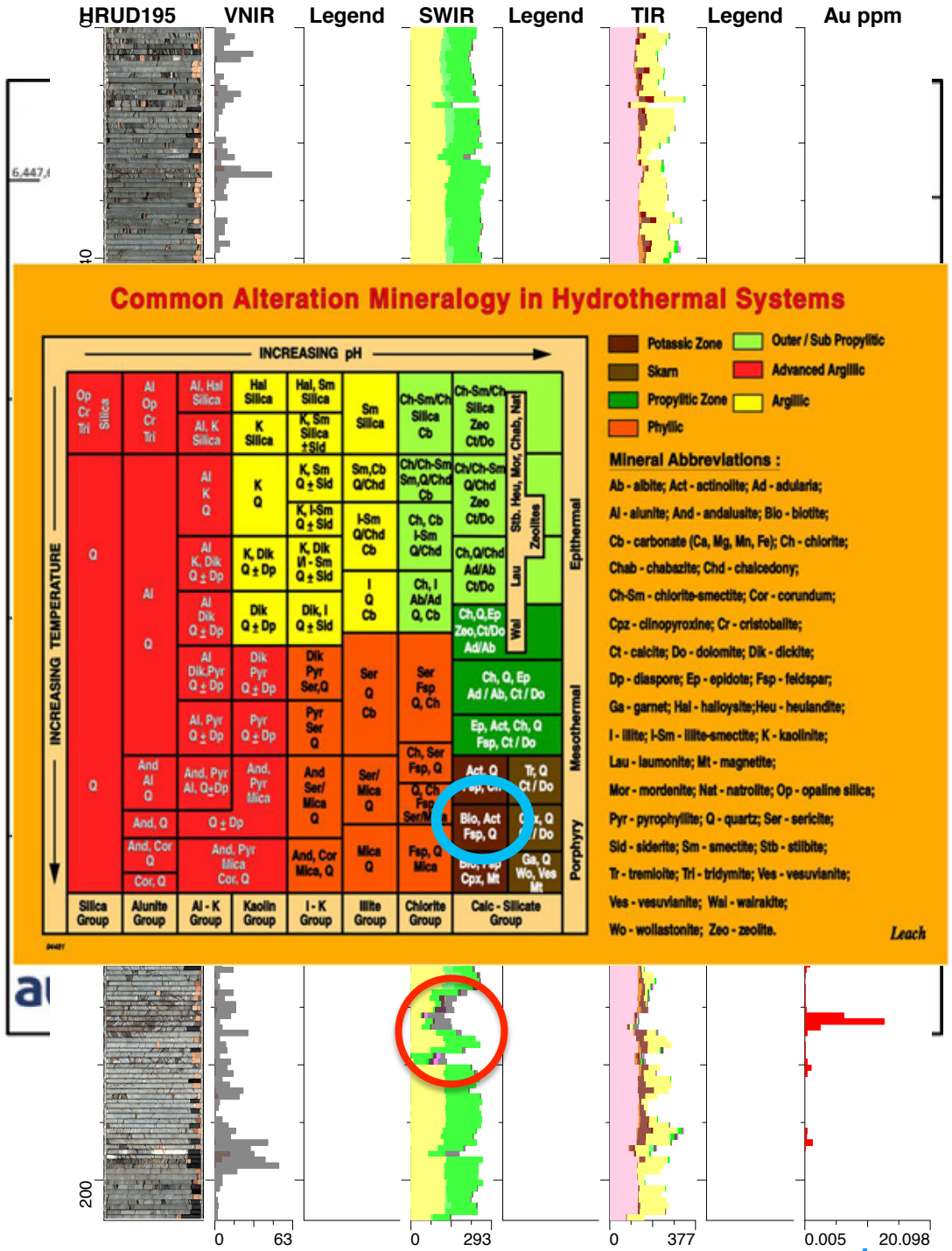
Hera orebody

- A drill hole through Main North and the top of Far West
- K-feldspar-biotite-actinolite
- Strongly chlorite-albite overprint
- Suggestion of potassic, calc-potassic alteration



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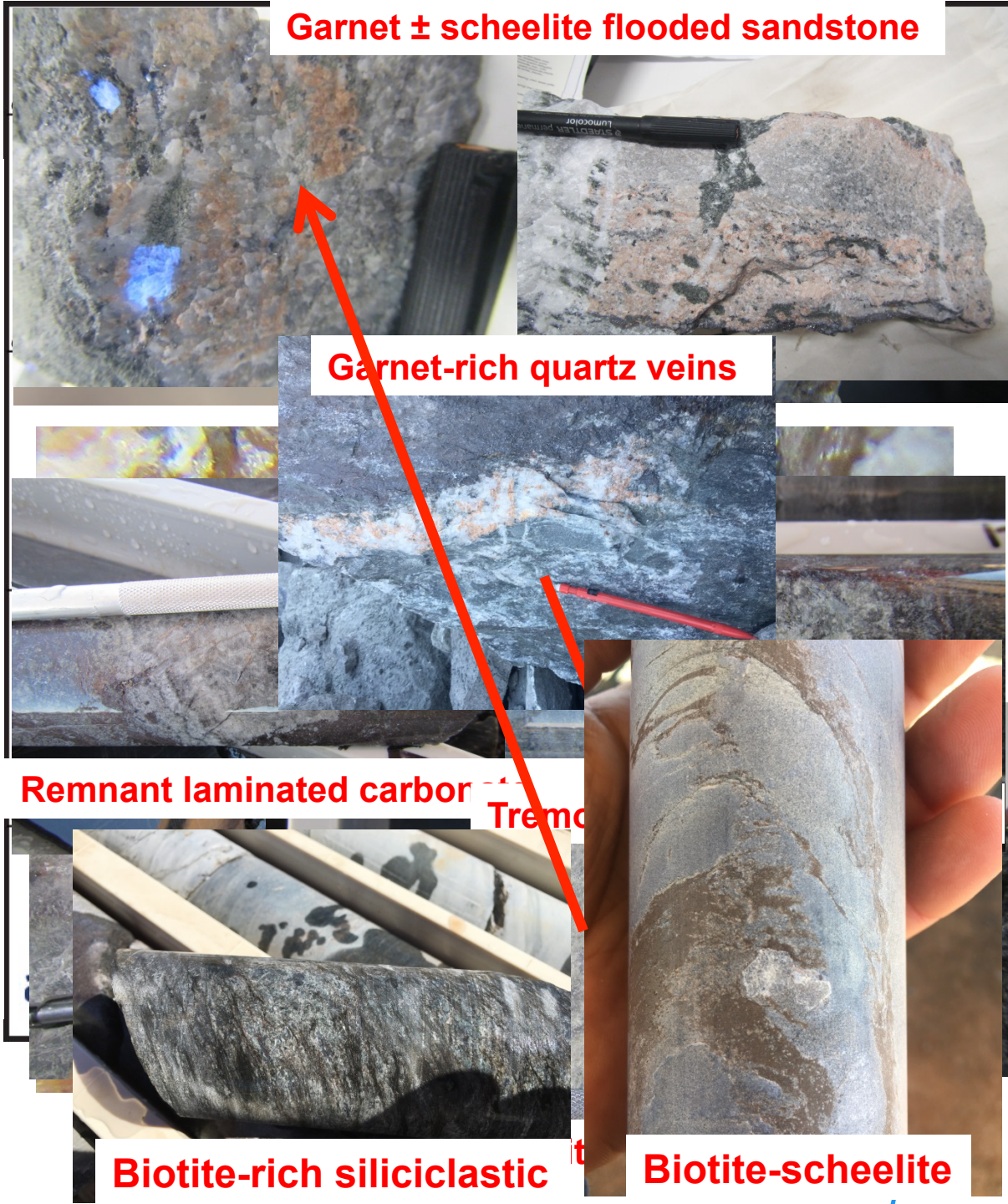
Hera Orebody - Digging deeper

Hera orebody

- Into the skarn
  - Far West/North Pod
- Remnant high-T skarn and carbonate clasts
  - South to north zonation
  - Garnet-rich
  - Pyroxene-rich
  - Anorthite-tremolite (remnant carbonate)
- Siliciclastic-hosted skarn alteration and veins
  - South to north zonation
    - Garnet (±scheelite)
    - Biotite (±scheelite)



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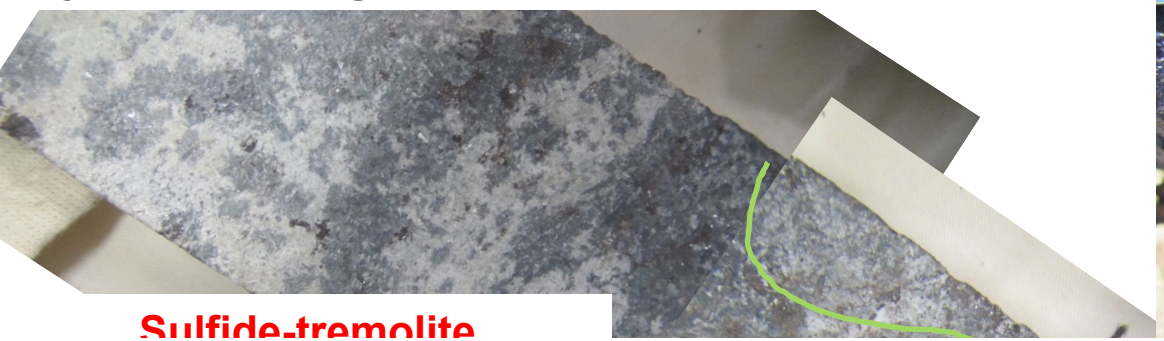
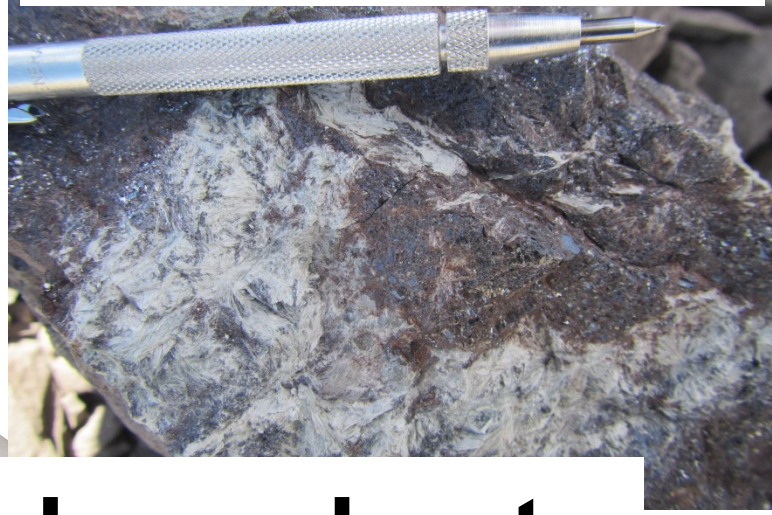
Hera orebody

Hydrous retrogression & mineralisation



Sulfide-tremolite

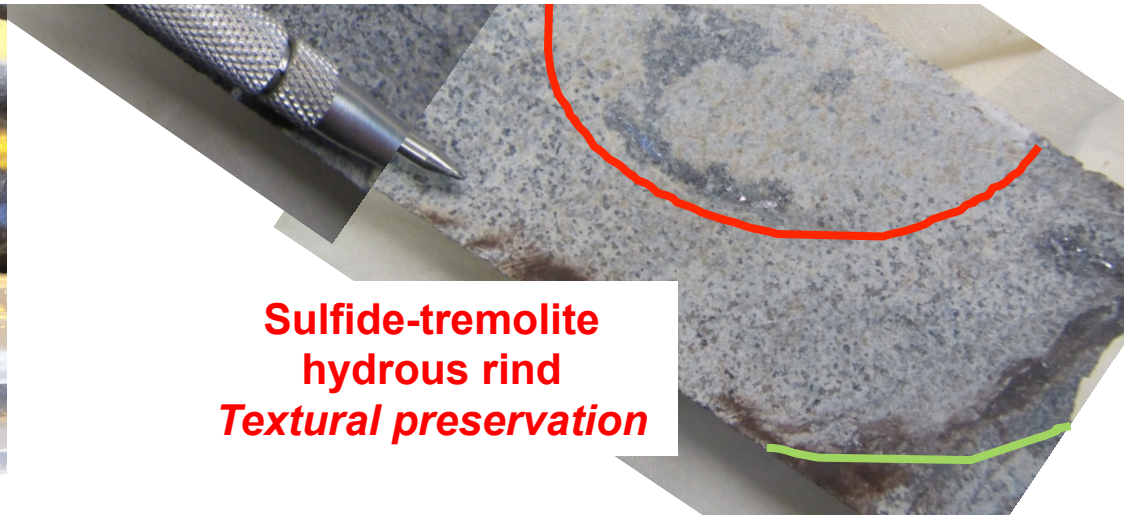
Complete tremolite replacement



Cor

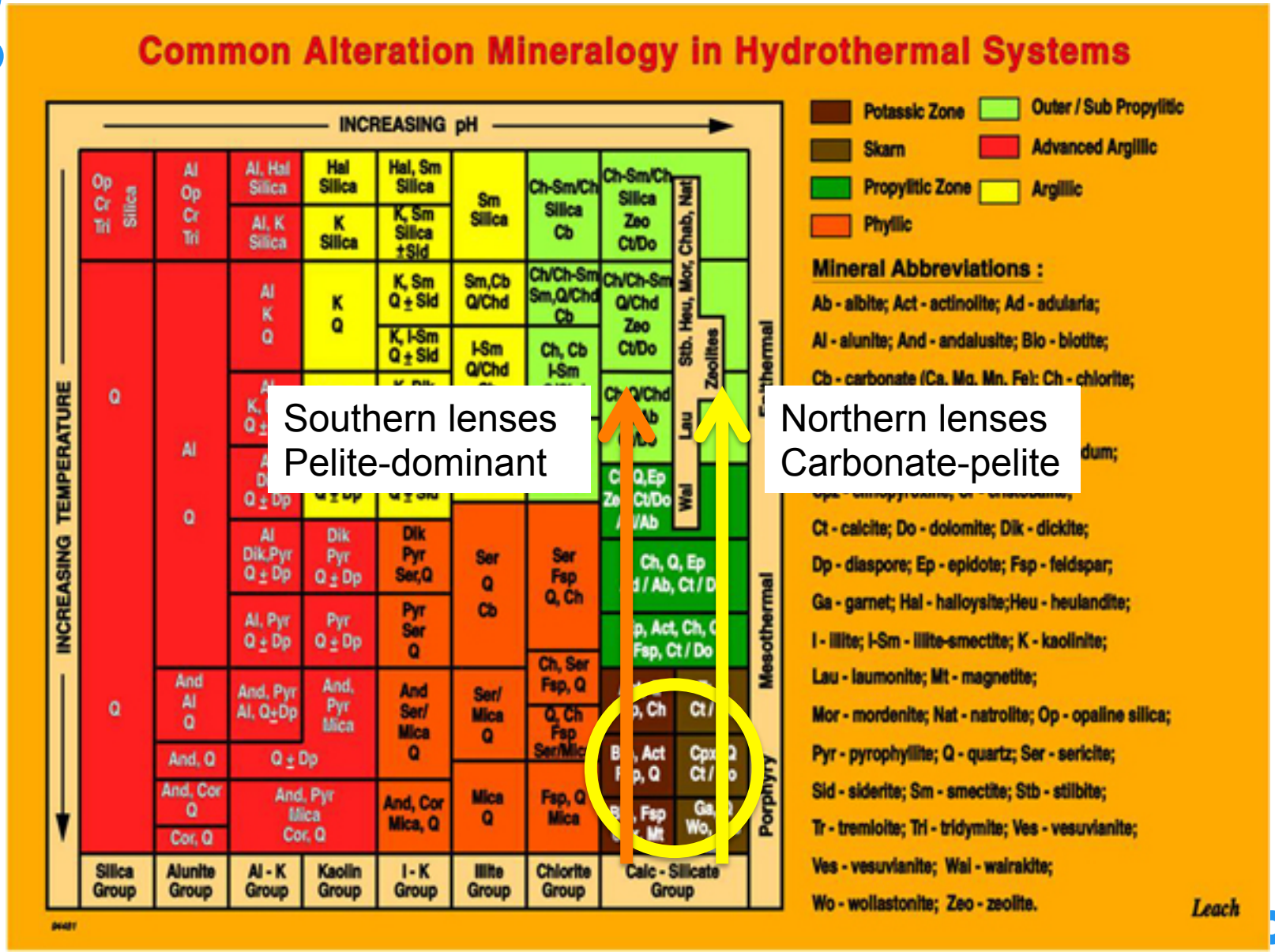
Rare to find high-T skarn due to pervasive retrogression and mineralisation

Near complete sulfide replacement



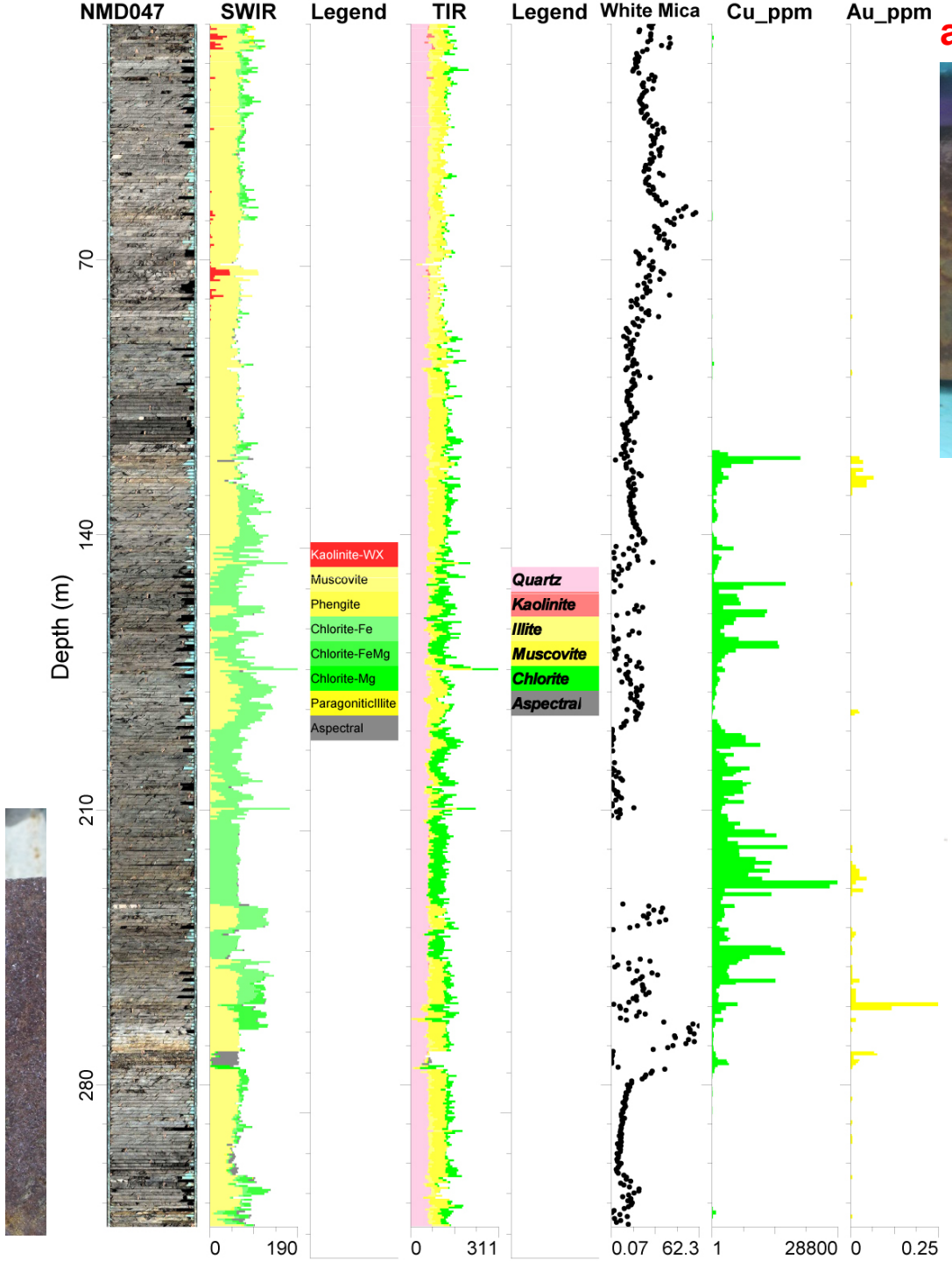
Sulfide-tremolite
hydrous rind
Textural preservation

Hera alteration



Nymagee Orebody

- Cu-Zn-Pb-Ag mineralisation in steeply west-dipping sulfide vein/breccia zones similar to other Cobar-type deposits
- Foliation envelopes orebody
  - Preliminary evidence of same bulky white quartz cross veins terminating ore lenses
- Metals zoned between lenses
  - Western zone is Zn-Pb-rich
  - Eastern zone is Cu-rich
- Initial magnetite-rich mineralisation overprinted by sulfides



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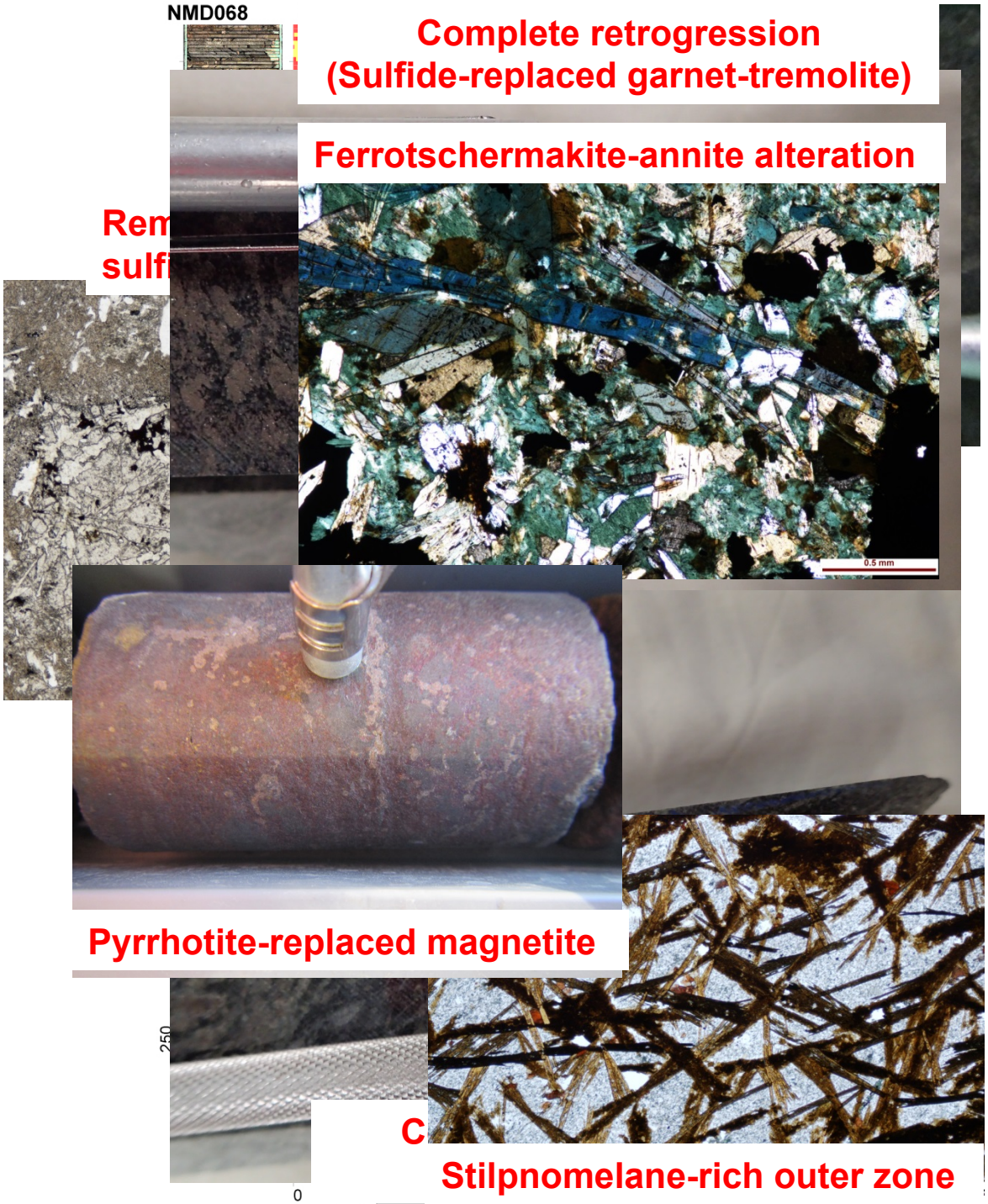
Nymagee Orebody - Digging deeper

Nymagee Orebody

- Garnet-anorthite-zoisite-tremolite skarn
  - Coincident with mineralisation
- Pervasive retrograde evolution
  - Initial tremolite-sulfide
  - Pervasive chlorite-talc-muscovite-sulfide
    - Particularly Cu lodes
- Ferrotschermakite-annite-magnetite-rich skarn
  - Fe-pelite-hosted



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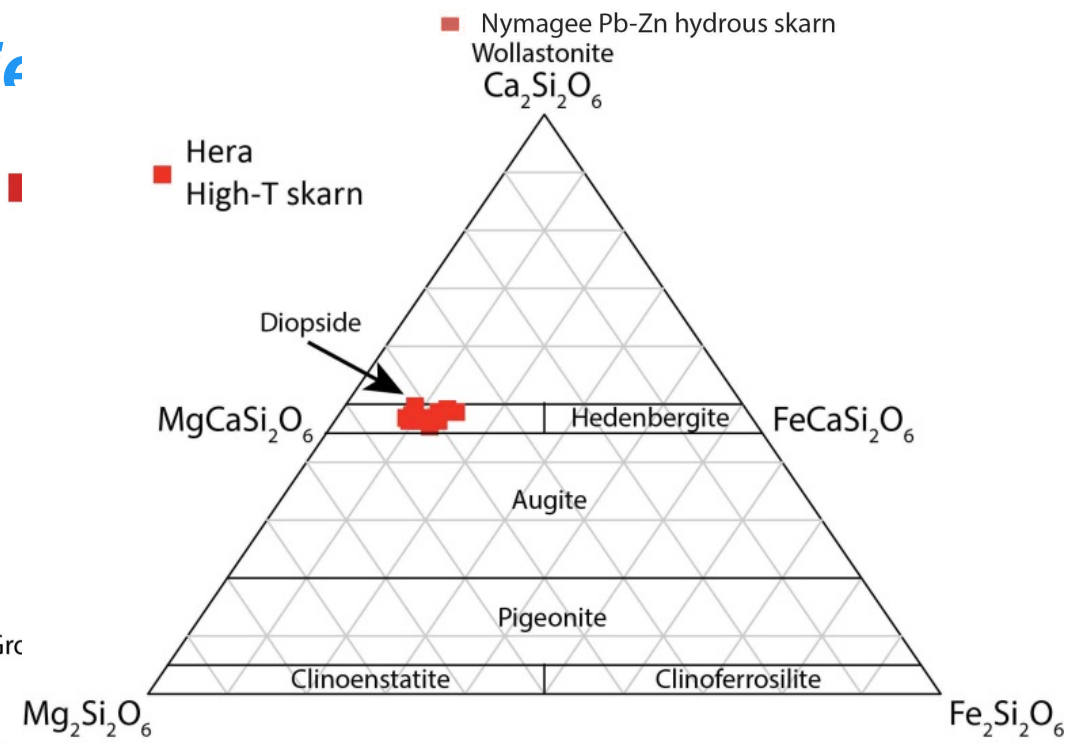
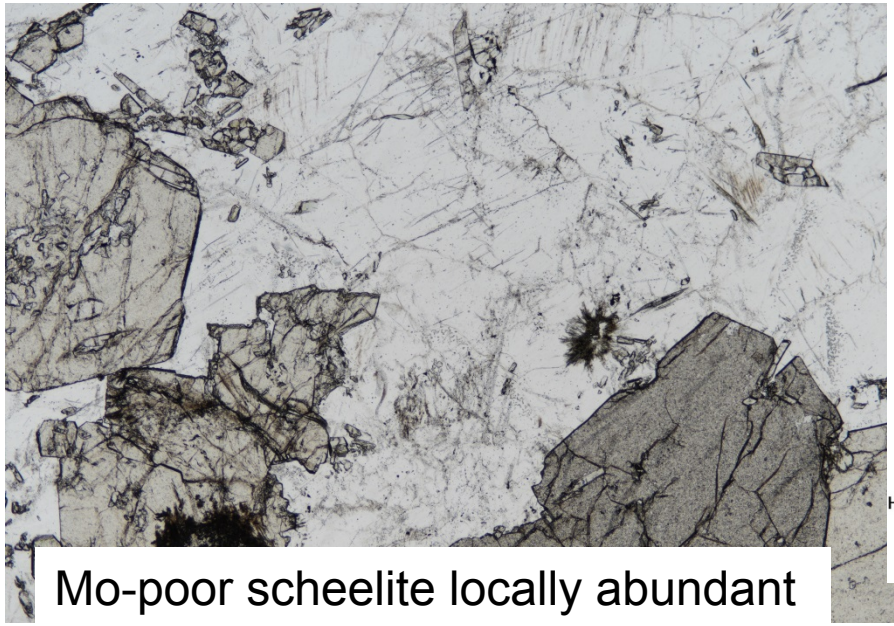
Hera-Nymagee Orebodie

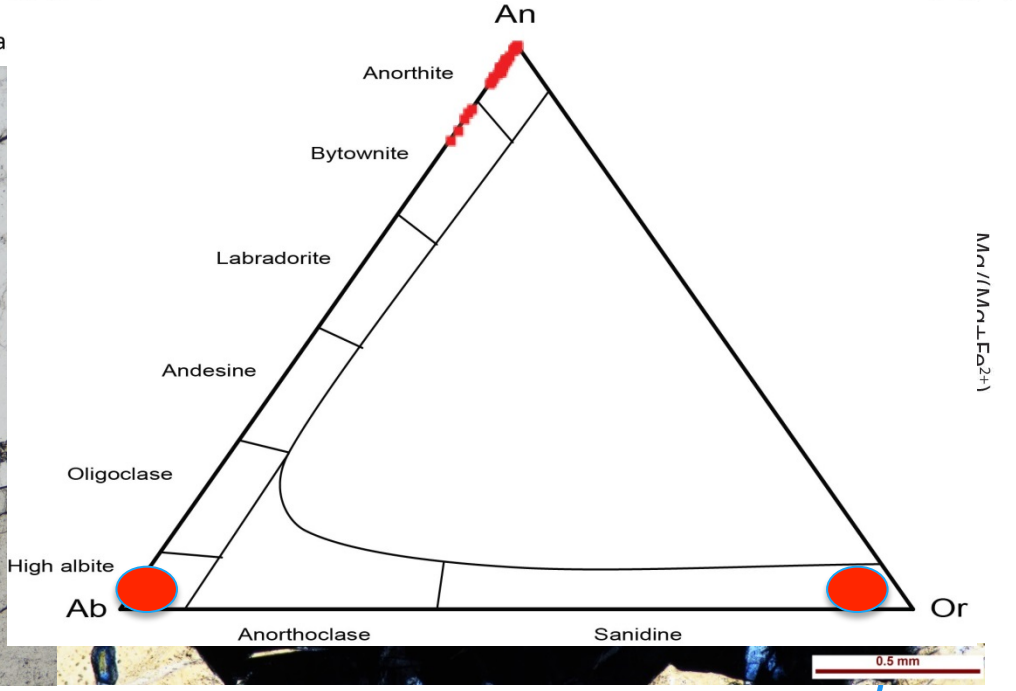
Silicate mineral chemistry

- Garnet = sub-calcic
  - Siliciclastic = spessartine
  - Carbonate = grossular
  - **Reduced skarn**
- Initial carbonate → zoisite
  - **CO_2-poor skarn**

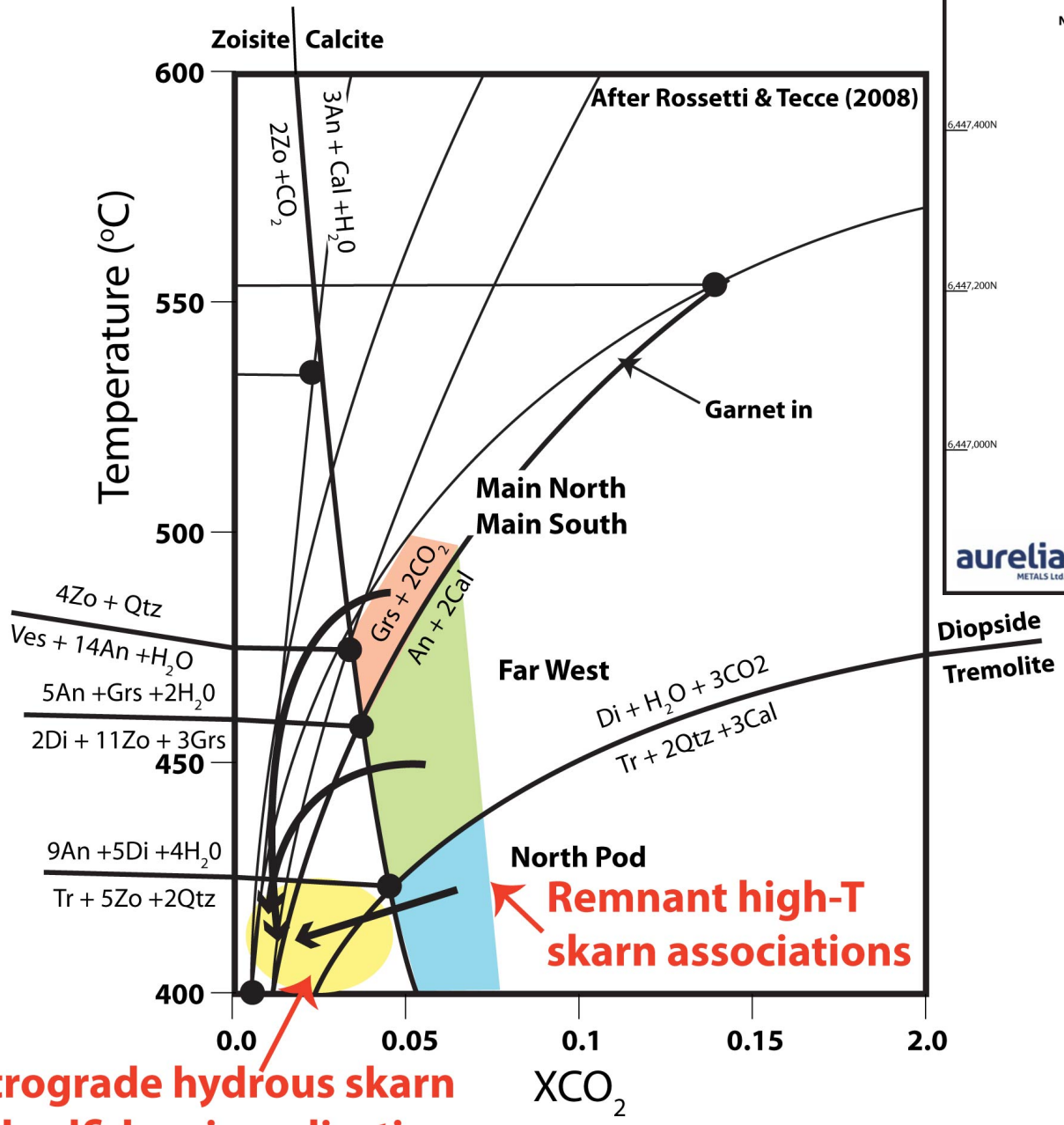


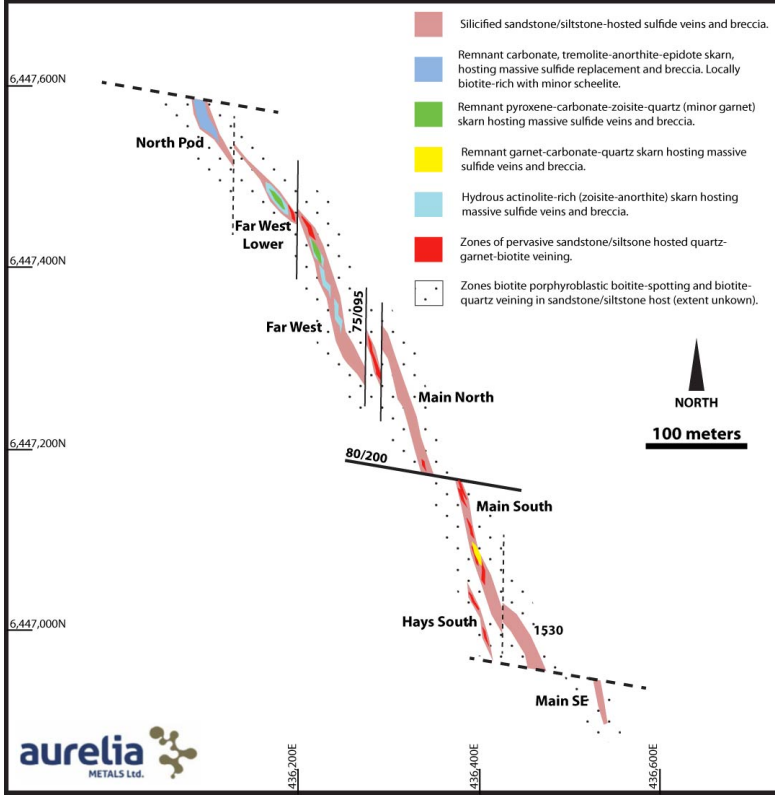


Mo-poor scheelite locally abundant



Schematic T-XCO_2 at 1.5 Kbar
CaO-MgO-Al2O3-SiO2-H2O-CO2



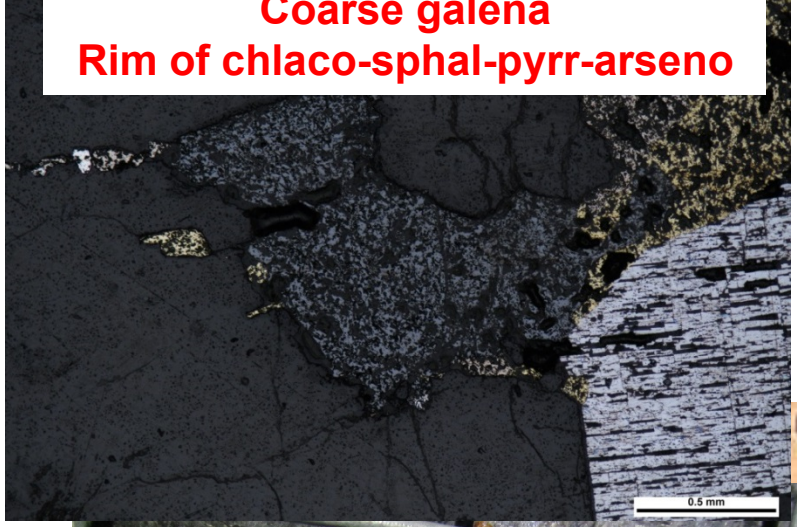


~~The black arts~~ Isotopes

- **Pb^{20this} over Pb^{20that} Hera and Nymagee:**
  - Crustal lead isotopic signature with a lead model age of (Downes et al 2016)
    - ~420 Ma and 420-428 Ma respectively
    - More recently model ages of 400 Ma
  - **Consistent with age of basin deposition and igneous activity, Maybe younger?**

- **S Hera and Nymagee**
  - $\delta^{34}S$ (‰) multiple sulfides range of 3-10
    - Downes (2016)
    - paragenetically unconstrained
  - Sulfides constrained from single lens hydrous skarn only Hera orebody
    - $\delta^{34}S$ (‰) ranges from 3-5

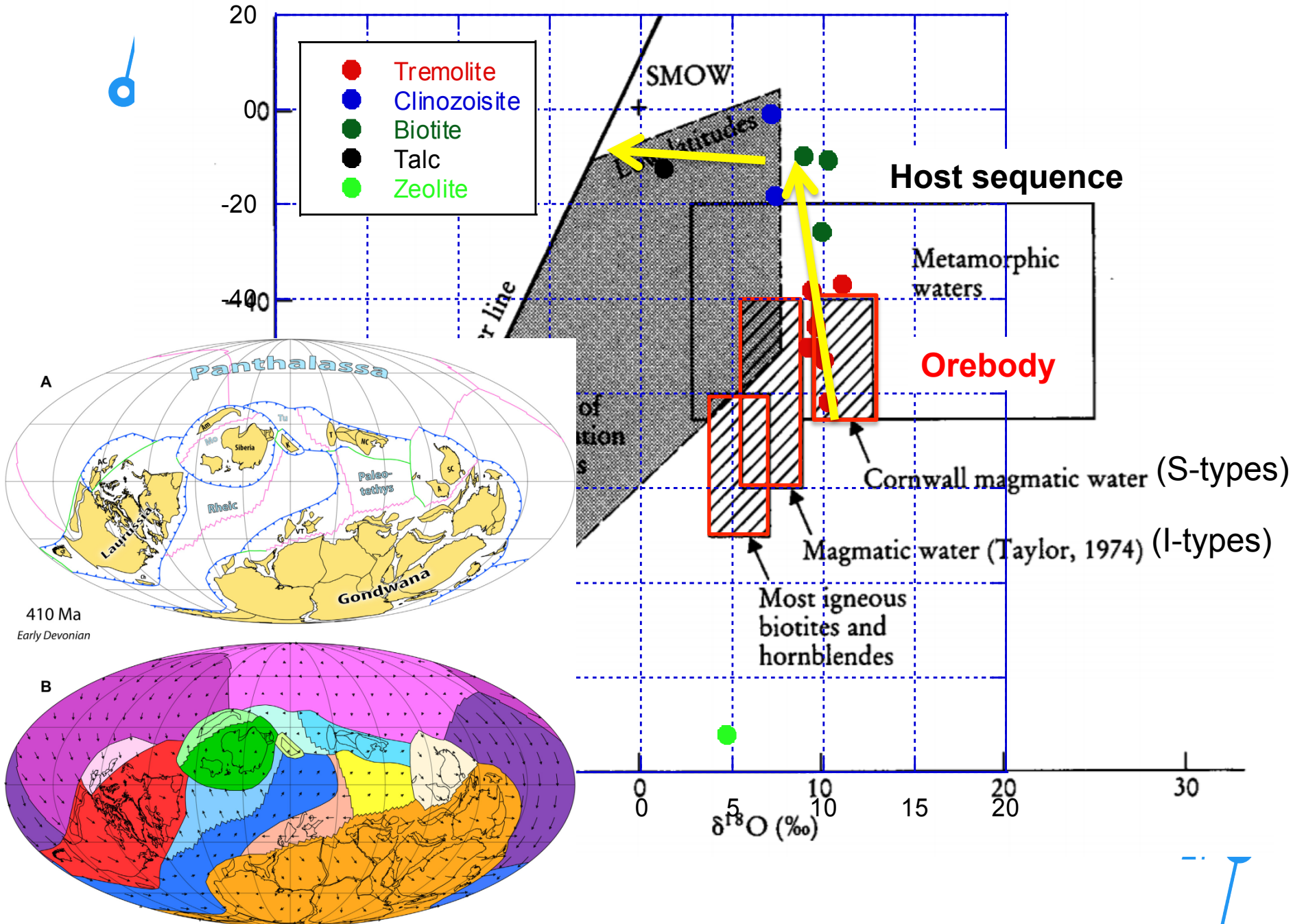
Low numbers consistent with magmatic S input, mixed with formational



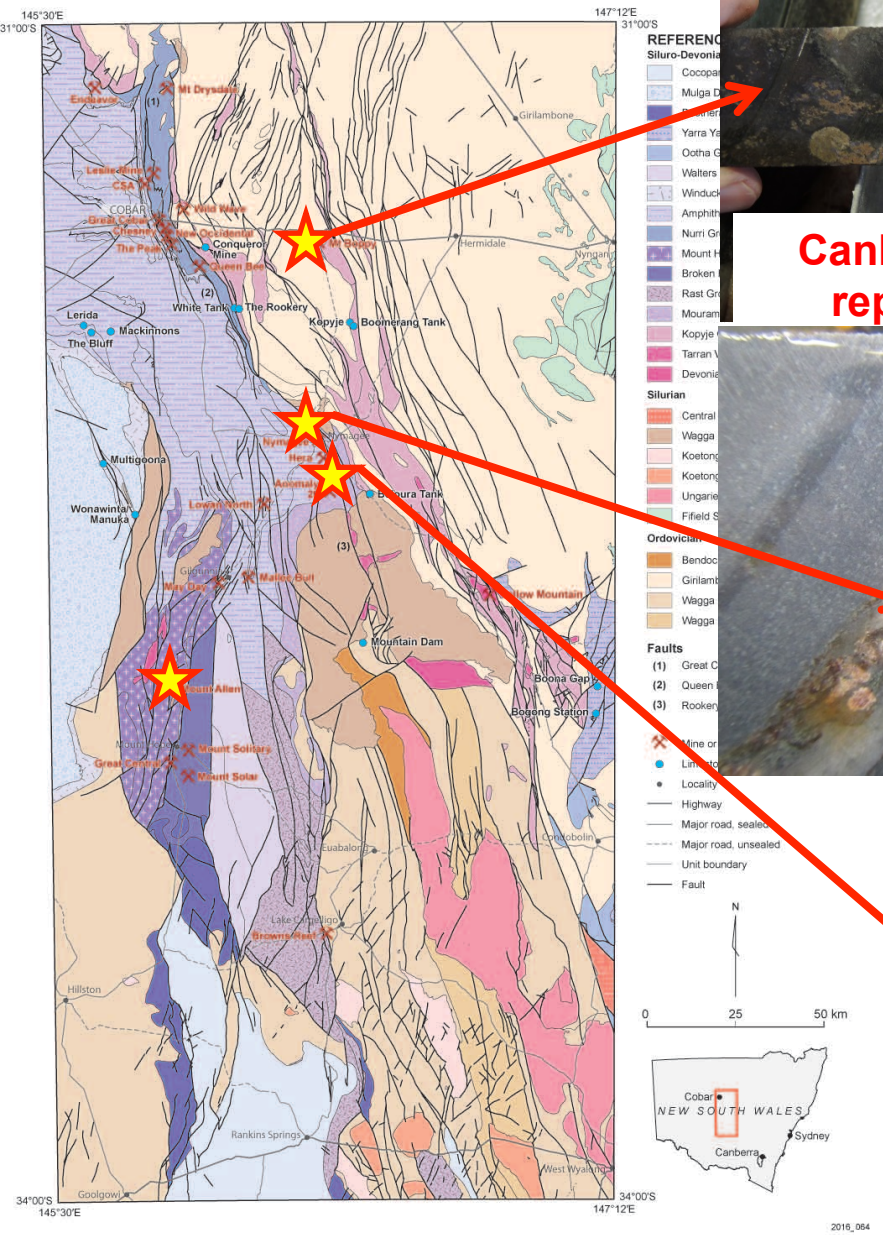
Coarse galena
Rim of chlaco-sphal-pyrr-arseno

Late massive galena (post foliation)

Hydrous skarn galena

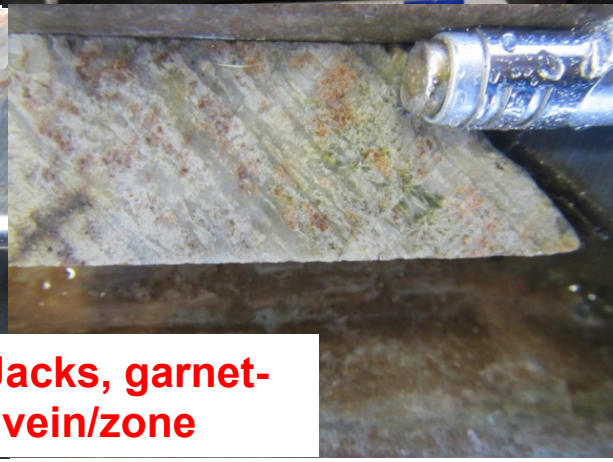

Tremolite
Clinozoisite
Biotite
Talc
Zeolite
SMOW
Host sequence
Metamorphic waters
Orebody
Cornwall magmatic water (S-types)
Magmatic water (Taylor, 1974) (I-types)
Most igneous biotites and hornblendes
20
00
-20
-40
0
5
10
15
20
30
δ18O (‰)
A
Panthalassa
Laurussia
Gondwana
Siberia
Rheic
Paleo-tethys
410 Ma
Early Devonian
B

One off?

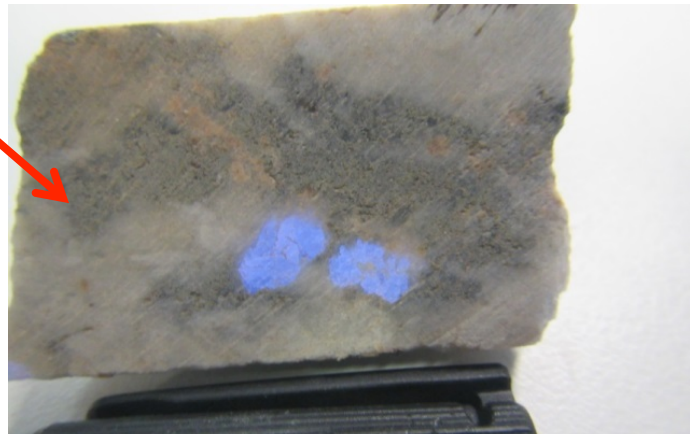


Canbelego magnetite replaced dolomite

Garnet-veins in dolomite

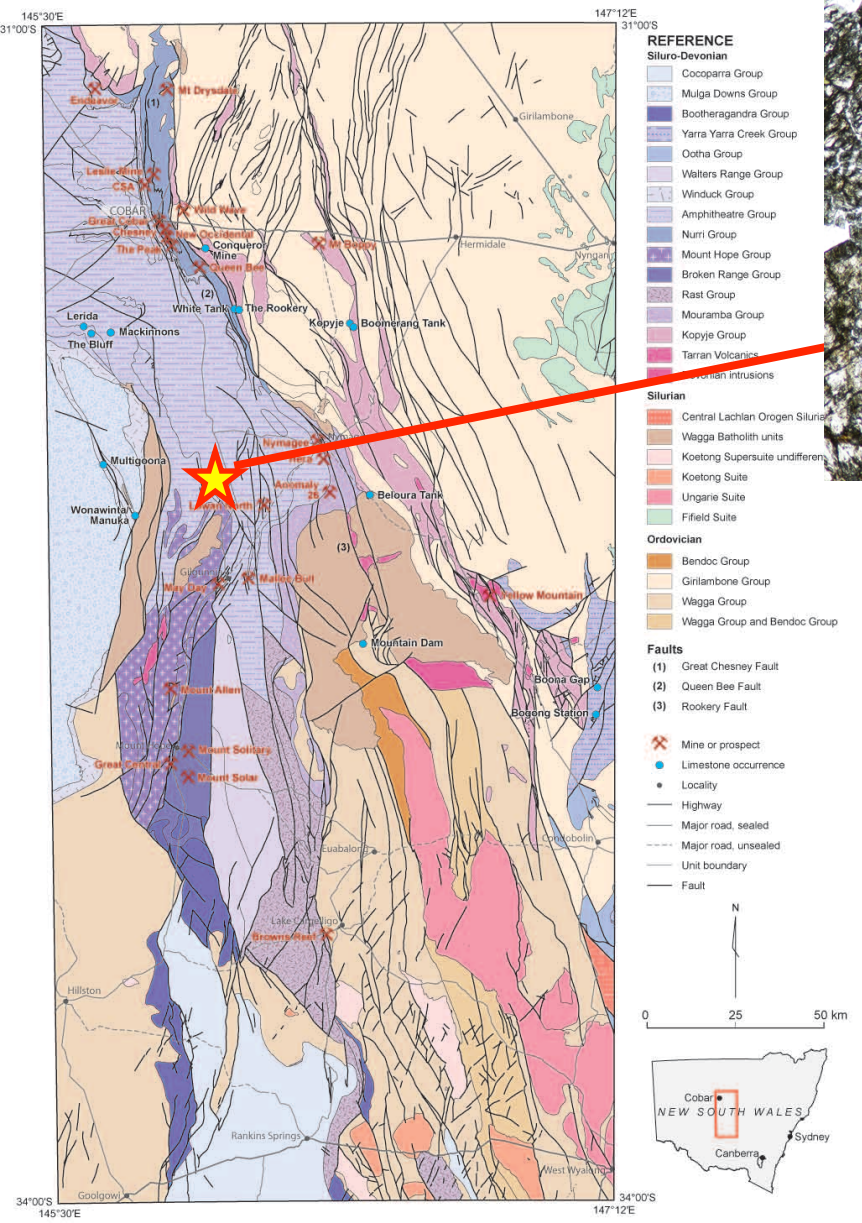


Happy Jacks, garnet-rich vein/zone

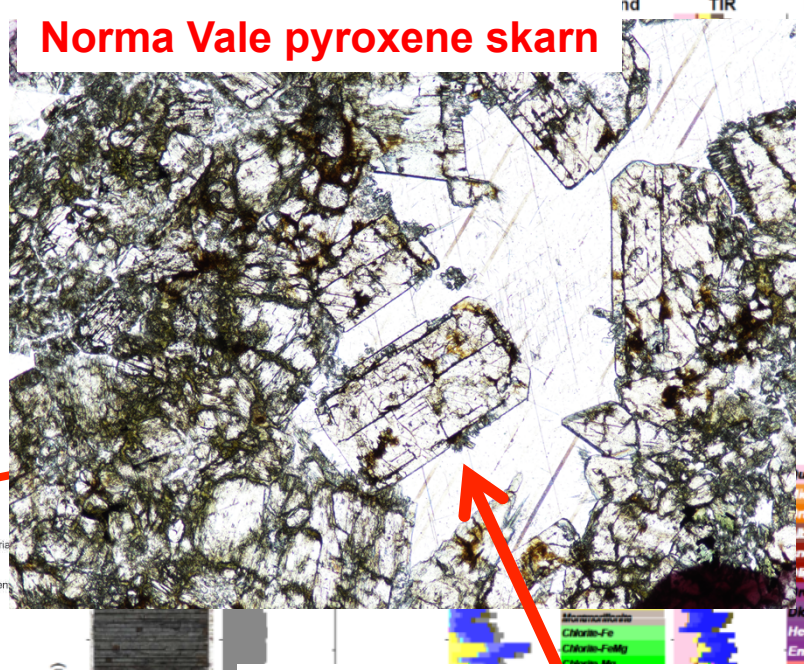


Hebe quartz-garnet-scheelite veins

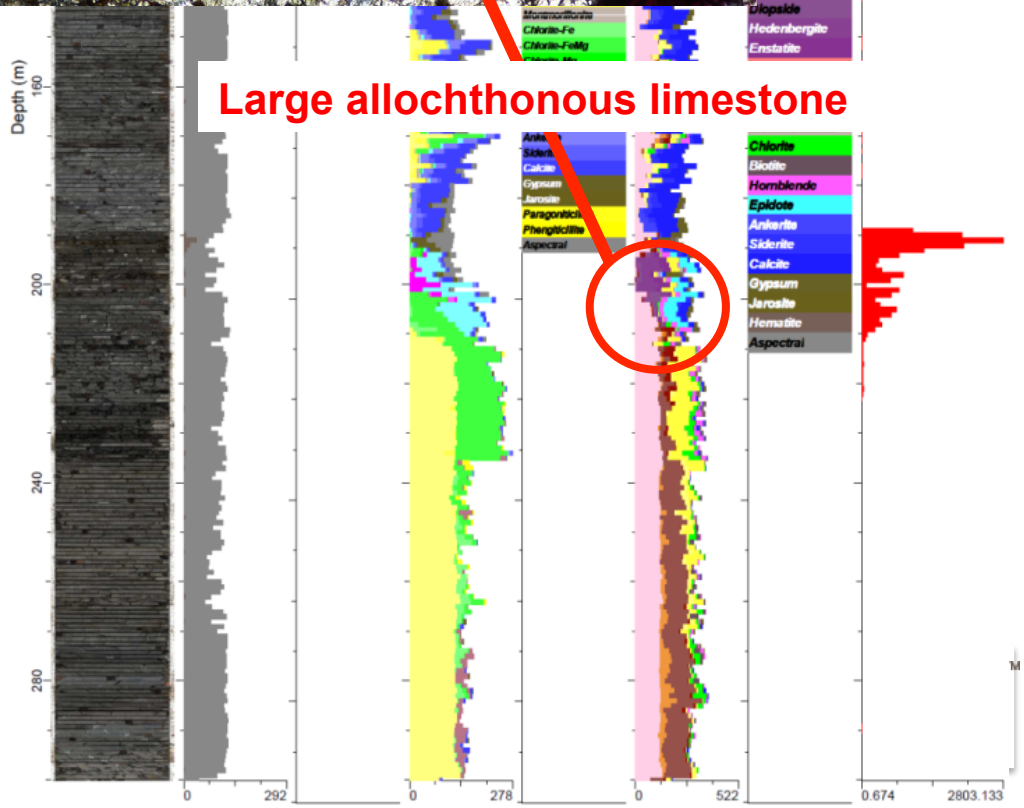
Norma Vale



Norma Vale pyroxene skarn



Large allochthonous limestone



Norma Vale

Silicate mineral chemistry

- Garnet = sub-calcic
  - **Reduced**
- Carbonate-rich skarn
  - Much larger block
- Pyroxene = Hedenbergite
  - **Fe-rich skarn**
- Sulfide phase
  - Fe-rich stilpnomelane
  - Fe-rich epidote
  - Amphibole = actinolite
  - **$\delta^{34}S$ (‰) ranges from 8-10**

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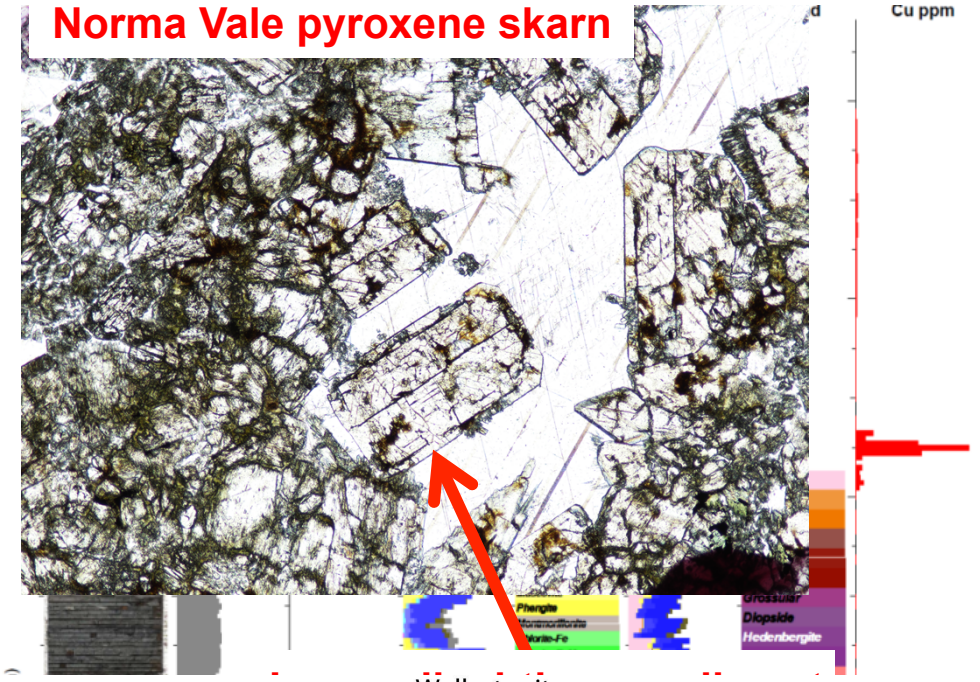
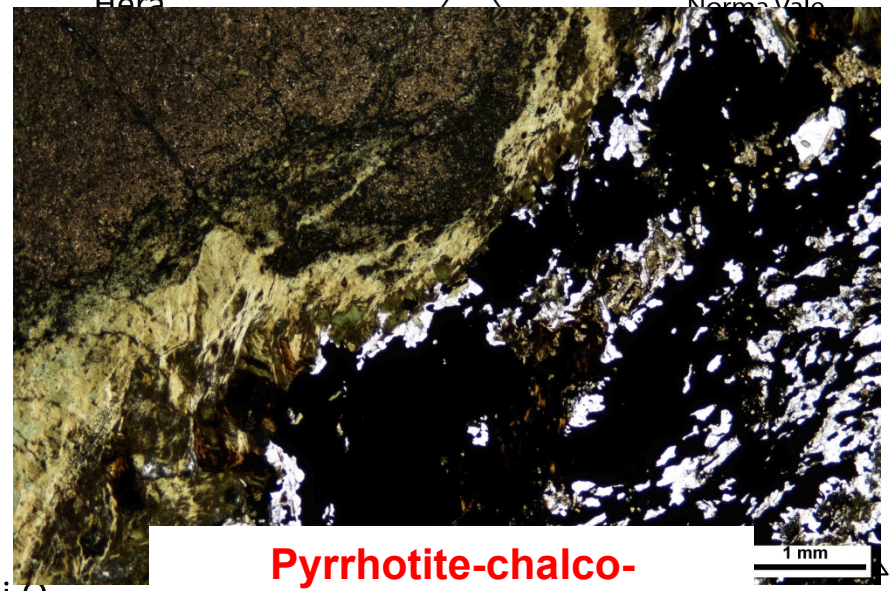


Wollastonite
$Ca_2Si_2O_6$



Pyrrhotite-chalco-stilpnomelane

$Mg_2Si_2O_6$

$Fe_2Si_2O_6$

Recipe for a southern Cobar-type?

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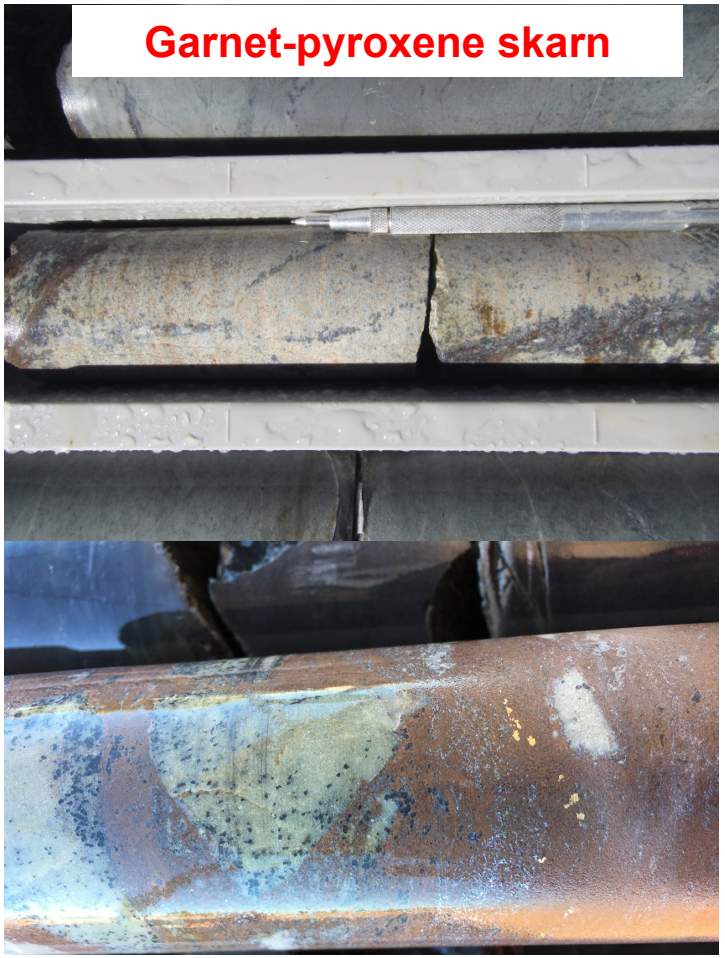
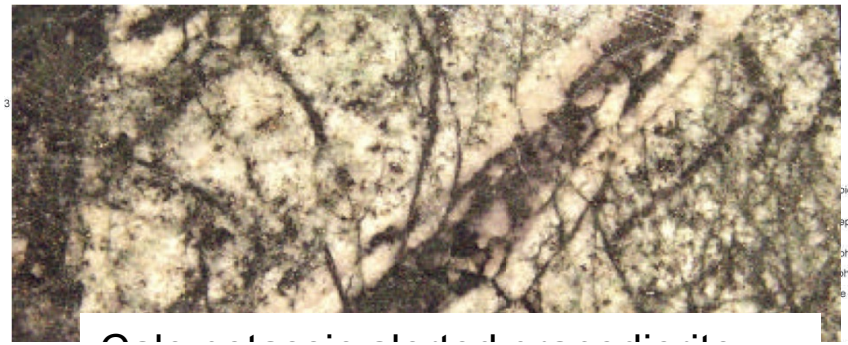
Recipe for a southern Cobar-type?

- **Never deeply buried**
  - Anchizone basin (250°C) with very local zones of thermal perturbation up to ?500°C
- **Carbonate-bearing stratigraphy**
  - Allochthonous horizon?
- No direct link to intrusive rocks
  - But, high heat flow, skarn development and…
- **Hera** Zn(W)-Au skarn
  - Consistent with strongly reduced, low CO_2 Zn-skarn
    - Low-Mo scheelite, sub-calcic garnet
    - Zoisite-anorthite-rich skarn
    - Mn-enriched calc-silicate mineralogy
- **Nymagee** Fe-Cu and Pb-Zn-(Cu) skarn
  - Early Fe-Oxide evolving to pyrrhotite-chalcopyrite
    - Unsual ferrotschermakite hydrous skarn
  - Zn-Pb lodes consistent with low CO_2 Zn-Skarn
    - Zoisite-anorthite-rich
    - Mn-enriched calc-silicate mineralogy
- **Norma Vale**
  - Reduced Calci-Fe(Cu) skarn
    - Pyroxene to stilpnomelane-epidote-actinolite alteration

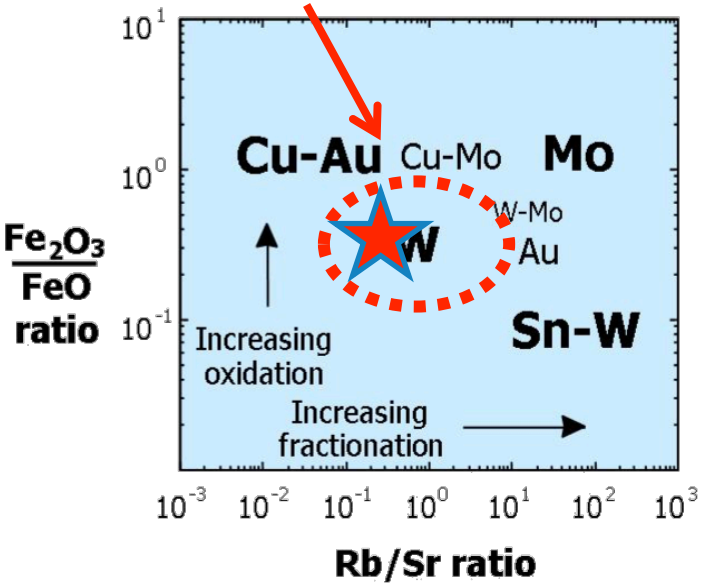


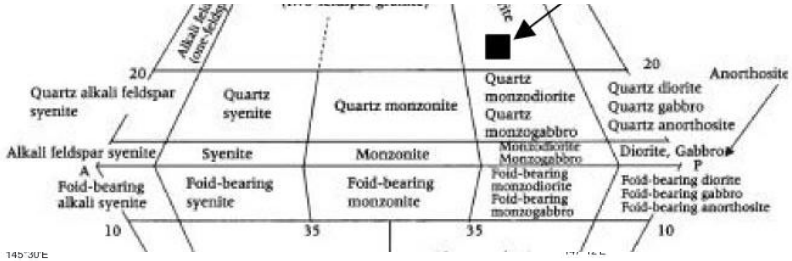
Gold-sphalerite replacement and tremolite-anorthite skarn

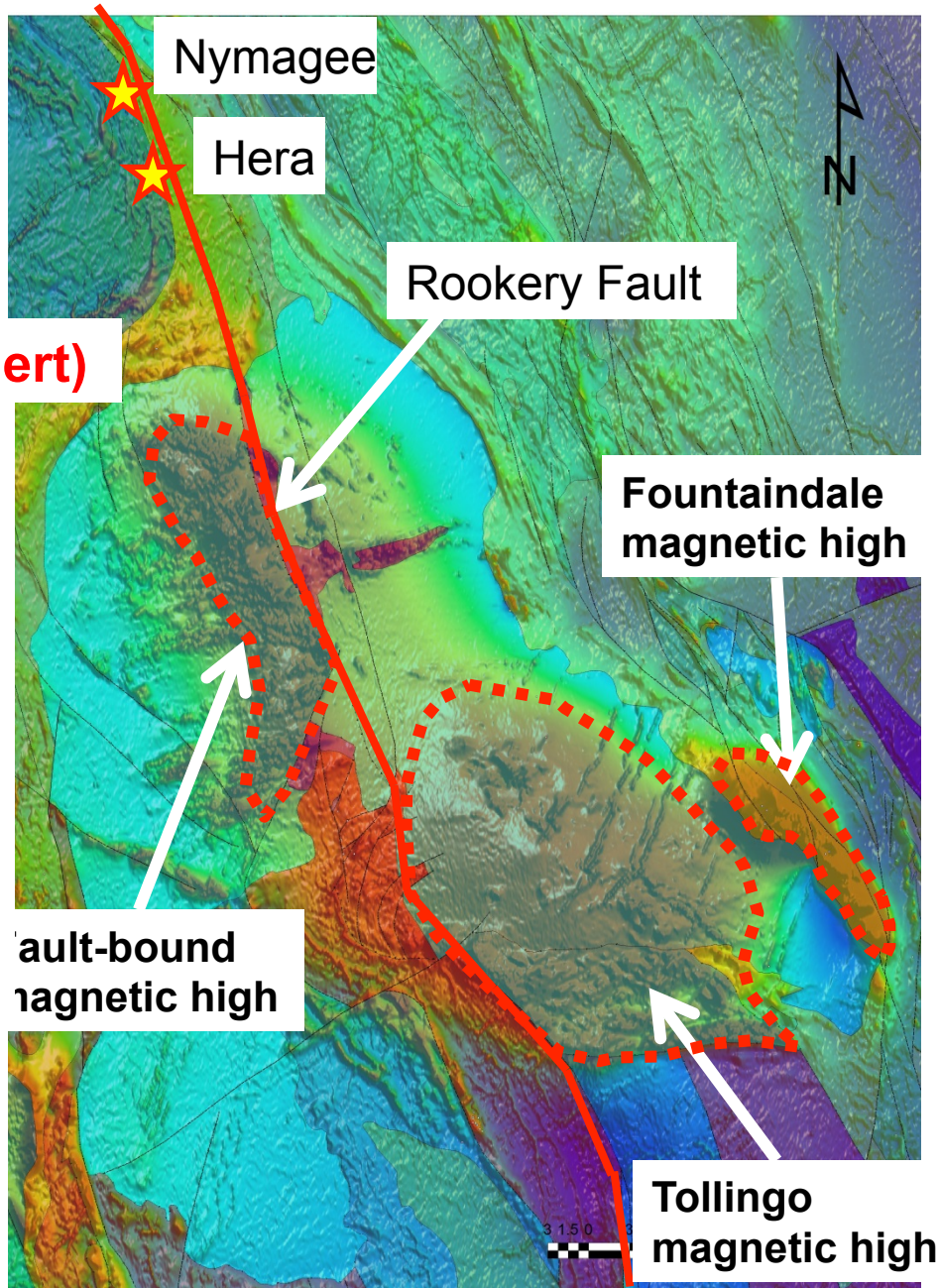
c. 420 Ma I-type magmatism - a link?



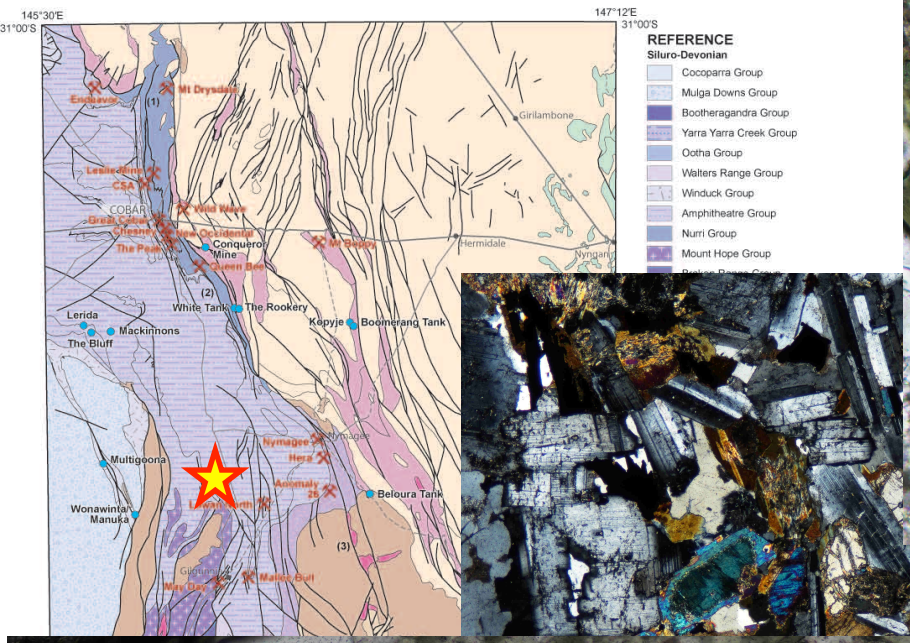
Field of Cu, Zn and W skarns (Meinert)

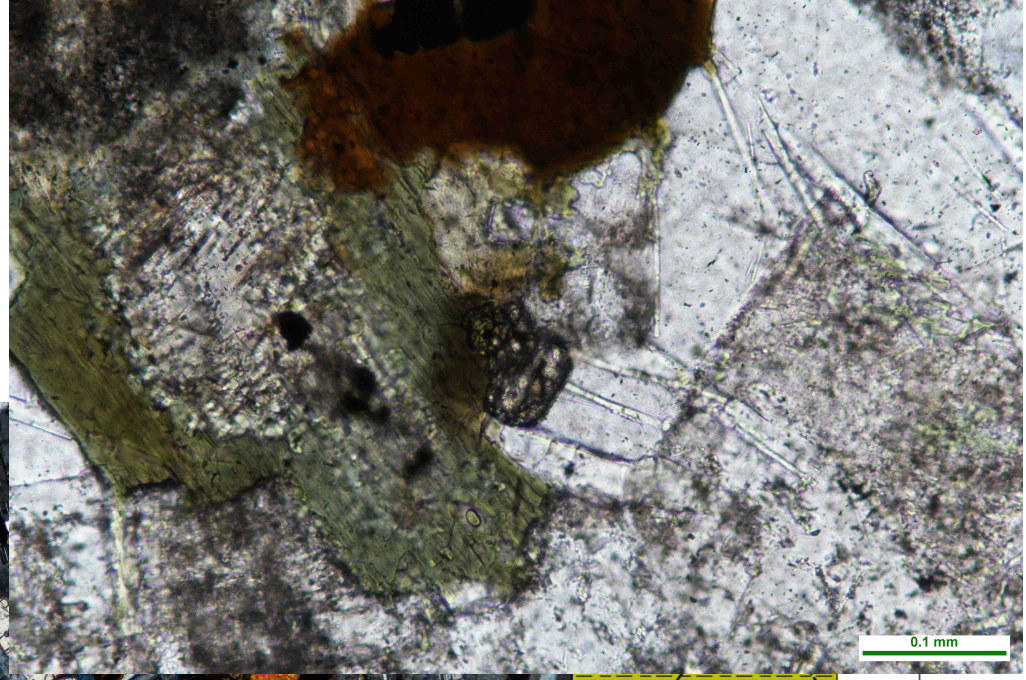


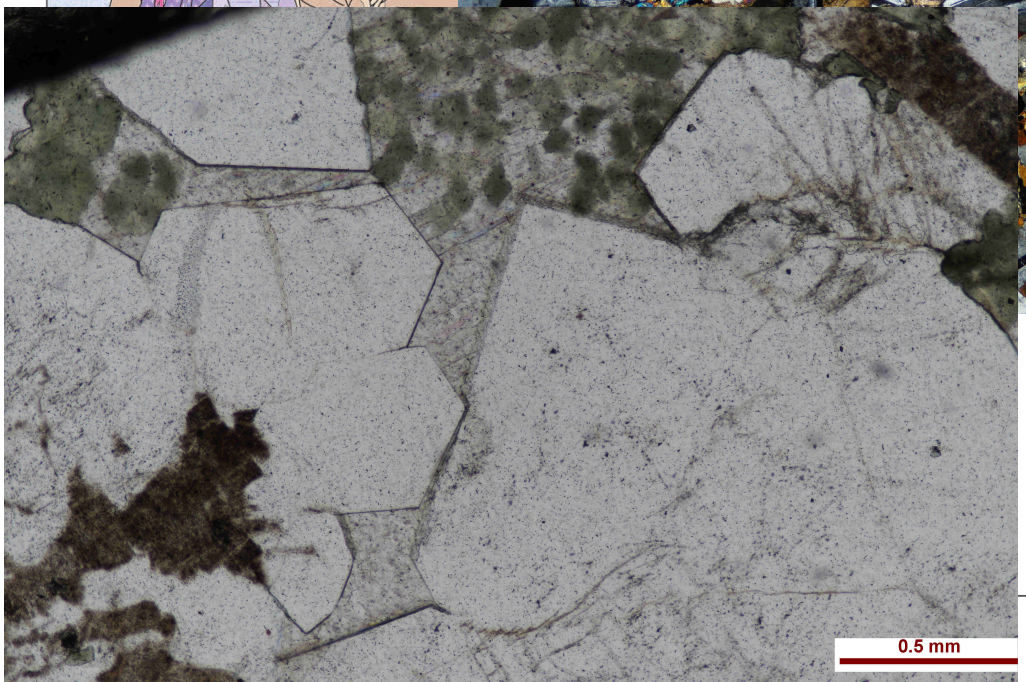




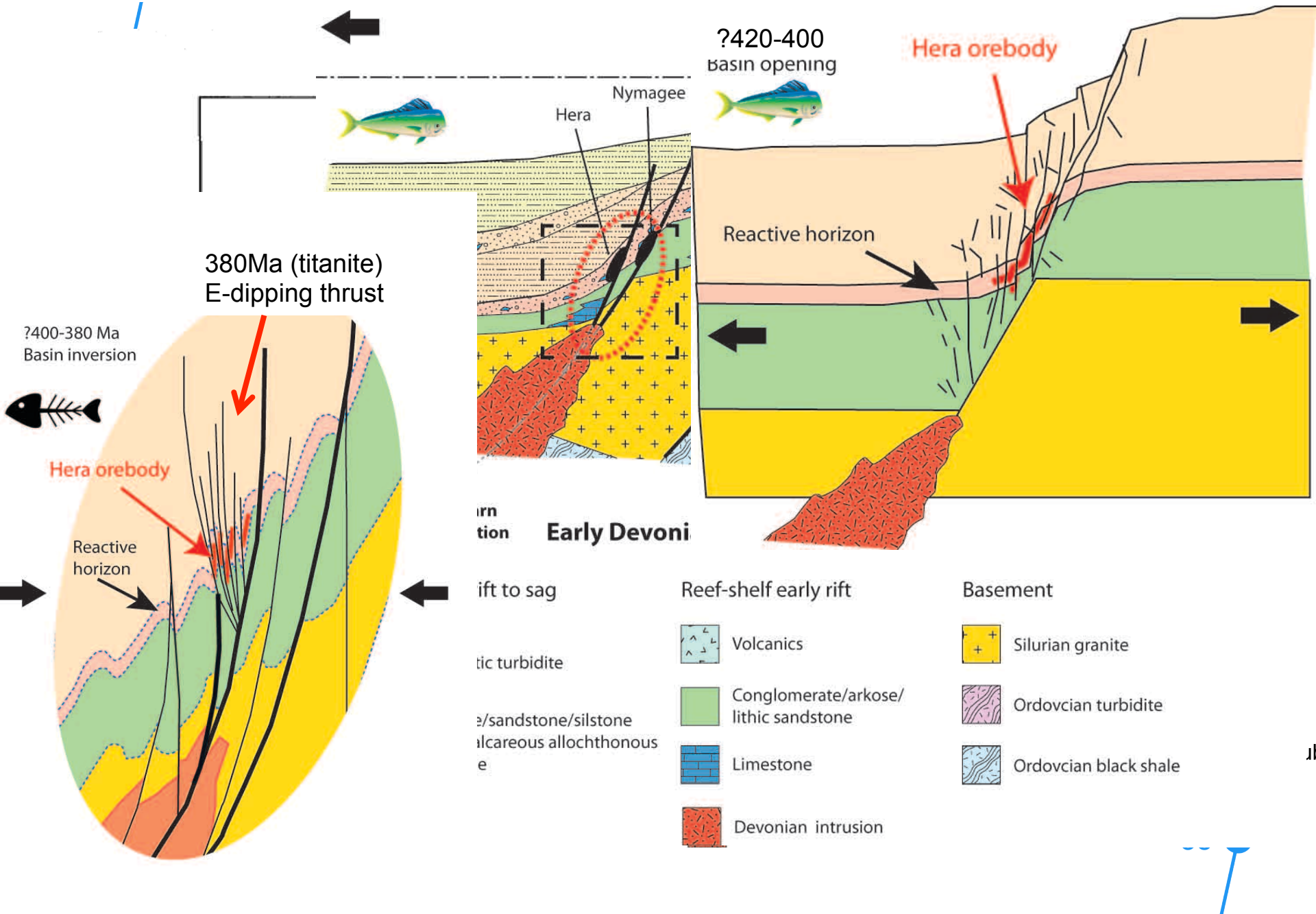
Norma Vale, mafic link..







Southern skarn formation



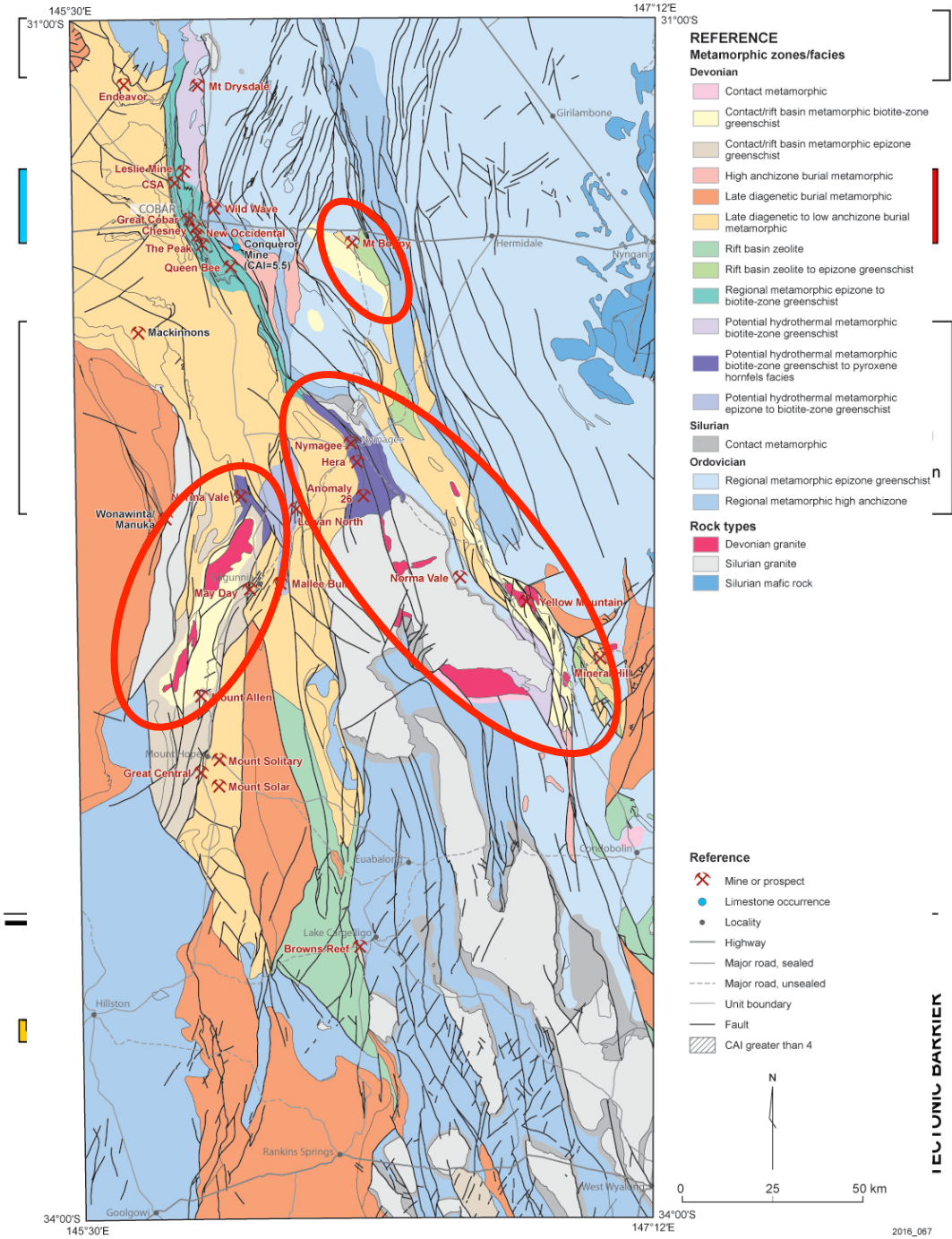
Cobar described in terms of east to west

But…. south to north

Higher Intrusion level in volcanic troughs/ belts and in the SE basin flank

Greater exhumation in the south-east?

Intrusion proximal mineralisation



Northern sister deposits

Twins?

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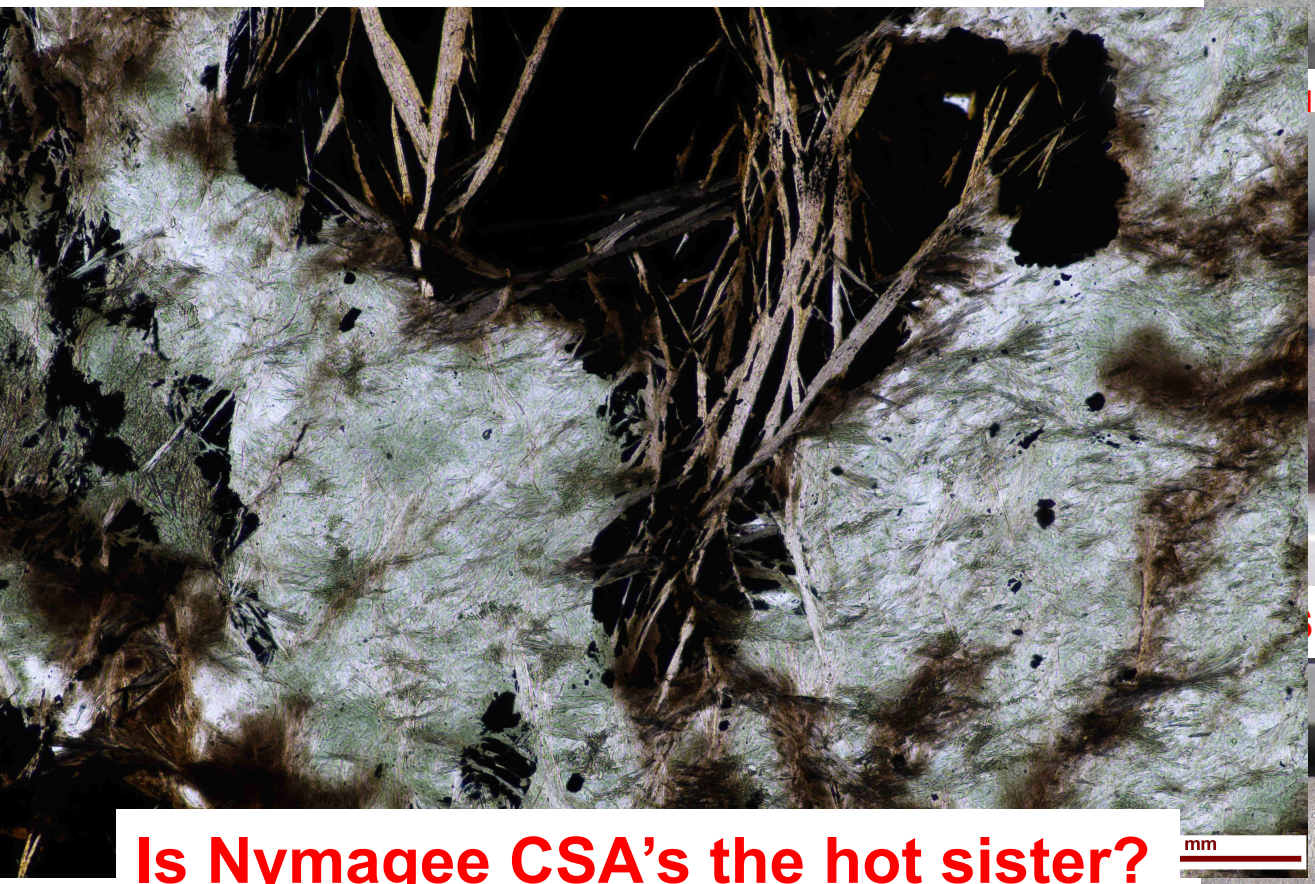
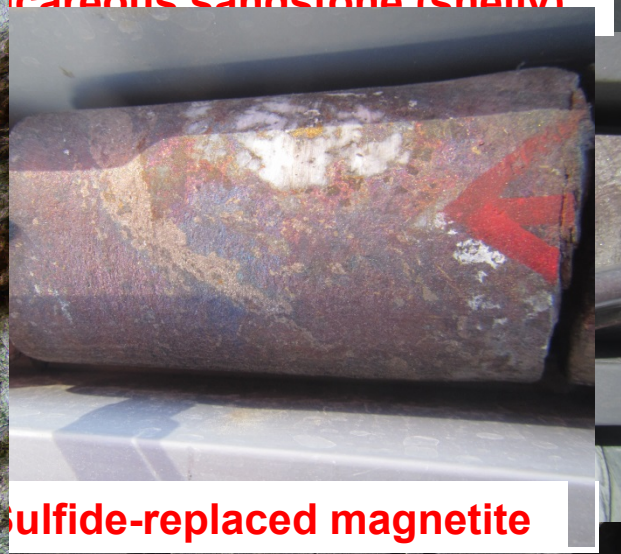
An example – CSA

Undoubtedly plenty of structurally-controlled ore… but





ulfide-replaced magnetite

Is Nymagee CSA's the hot sister?

CSA colder, intrusion distal

Another example

- **Great Cobar (FeO-Cu-Au)**
  - **Early oxide phase**
    - Magnetite replacement
    - Magnetite breccia
    - Quartz-magnetite-veins
  - **Sulfide phase**
    - Syn-deformation
    - Brecciation/vein
  - **Orebody proximal alteration**

    Early (oxide)
    - Green stilpnomelane
    - Fe-biotite (annite)
    - Fe-Chlorite (T~430°C)
    - Locally apatite-titanite-rich

Is Norma Vale GC's hot cousin?

Great Cobar colder, intrusion distal

Conclusions

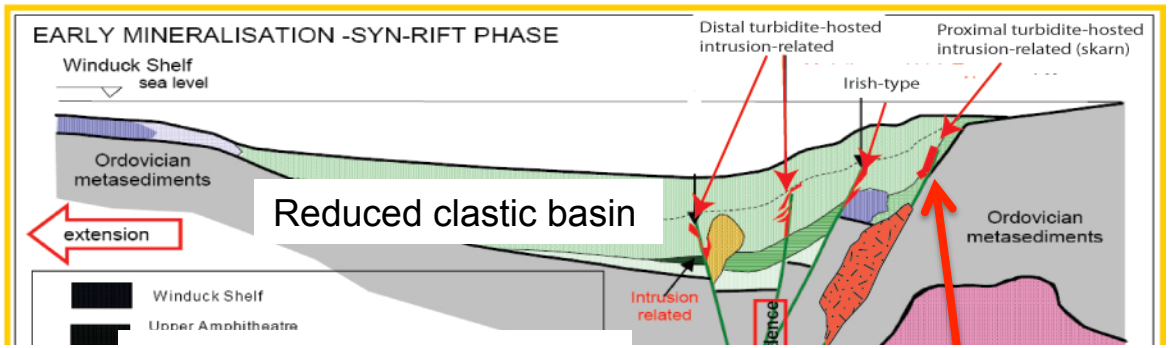
Importance of…

- Syn-rift faults
- **Permeable/reactive horizons (carbonate)**
  - Proximal = skarn
  - Distal = Lower-T lithological control
- Devonian intrusions?
  - Thermal driver
  - Fluid/metals
  - Mafic intrusions – Norma Vale
- **Intrusion proximal – south**
- **Intrusion distal - north**
- **Partly exhumation level?**
- Inversion, remobilisation or continued mineralisation?

Implications…

- Potential for metal trapping at several stratigraphic levels in the basin
  - Norma Vale Shume Formation
  - Nymagee-Hera deeper
- Skarn? in drowned, early-rift carbonate sequences…

David (2005)

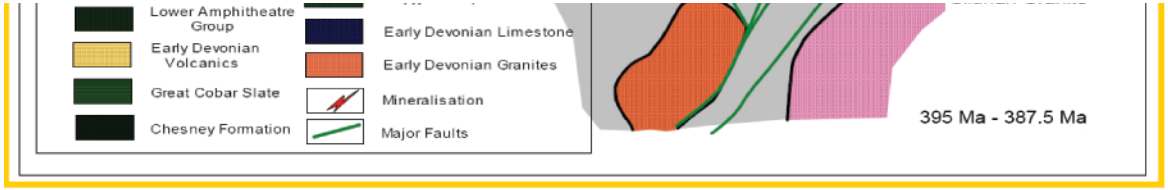


But… age of intrusive rocks?

Is intrusion diachronous?

Are there younger intrusive rocks?

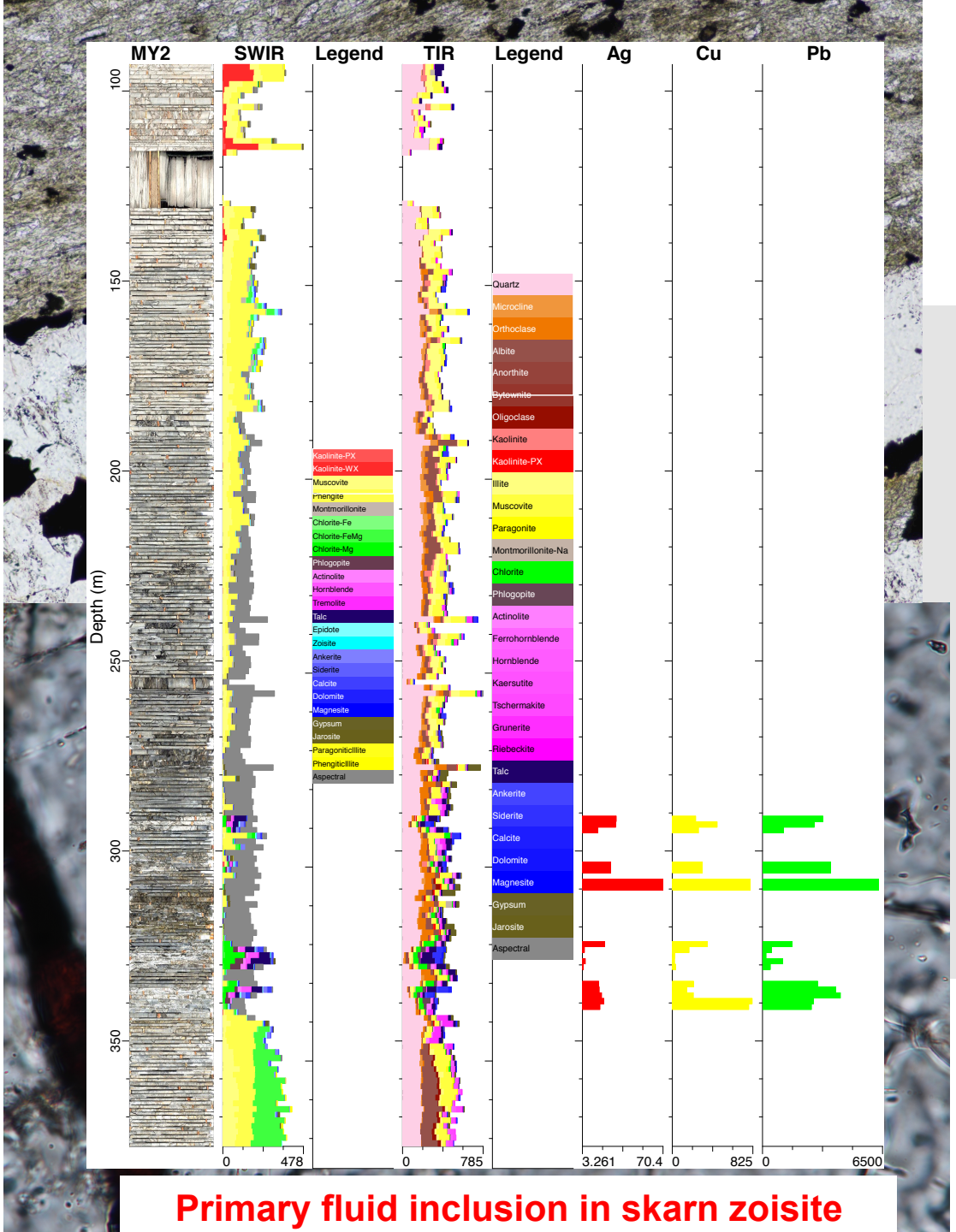
Age of mafic intrusive rocks?



What's next?

- Great Cobar
  - O-H isotopes on early oxide phase
  - Titanite dating
- Perseverance
  - O-H isotopes on early potassic alteration
  - Titanite dating
- CSA
  - O-H isotopes on early oxide phase
  - Systematic S-isotope studies
  - Titanite dating
- Nymagee-Hera
  - Scheelite REE-studies
  - Apatite dating
  - Titanite dating
  - VR-C-isotopes
  - Whole rock O
  - Fluid inclusions
- Norma Vale – NE Cobar
  - 8x SHRIMP dates on I-type

  Intrusive rocks and porphyries
- Hylogging
  - Mallee Bull et al...



Primary fluid inclusion in skarn zoisite

Thanks

Crossed polars photomicrograph garnet-pyroxene skarn (Hera orebody)

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