Siluro-Devonian tectonics and metallogeny in Victoria: Sorting out the Bindian and Tabberabberan orogenies.

AIG Victorian Minerals Round-up

Tom Andrews

18 June 2026

RESOURCES VICTORIA

We acknowledge and respect Victorian Traditional Owners as the original custodians of Victoria's land and waters, their unique ability to care for Country and deep spiritual connection to it.

We honour Elders past and present whose knowledge and wisdom has ensured the continuation of culture and traditional practices.

Resources Victoria is committed to genuinely partnering with Victorian Traditional Owners and Victoria's Aboriginal community to progress their aspirations.

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Reference

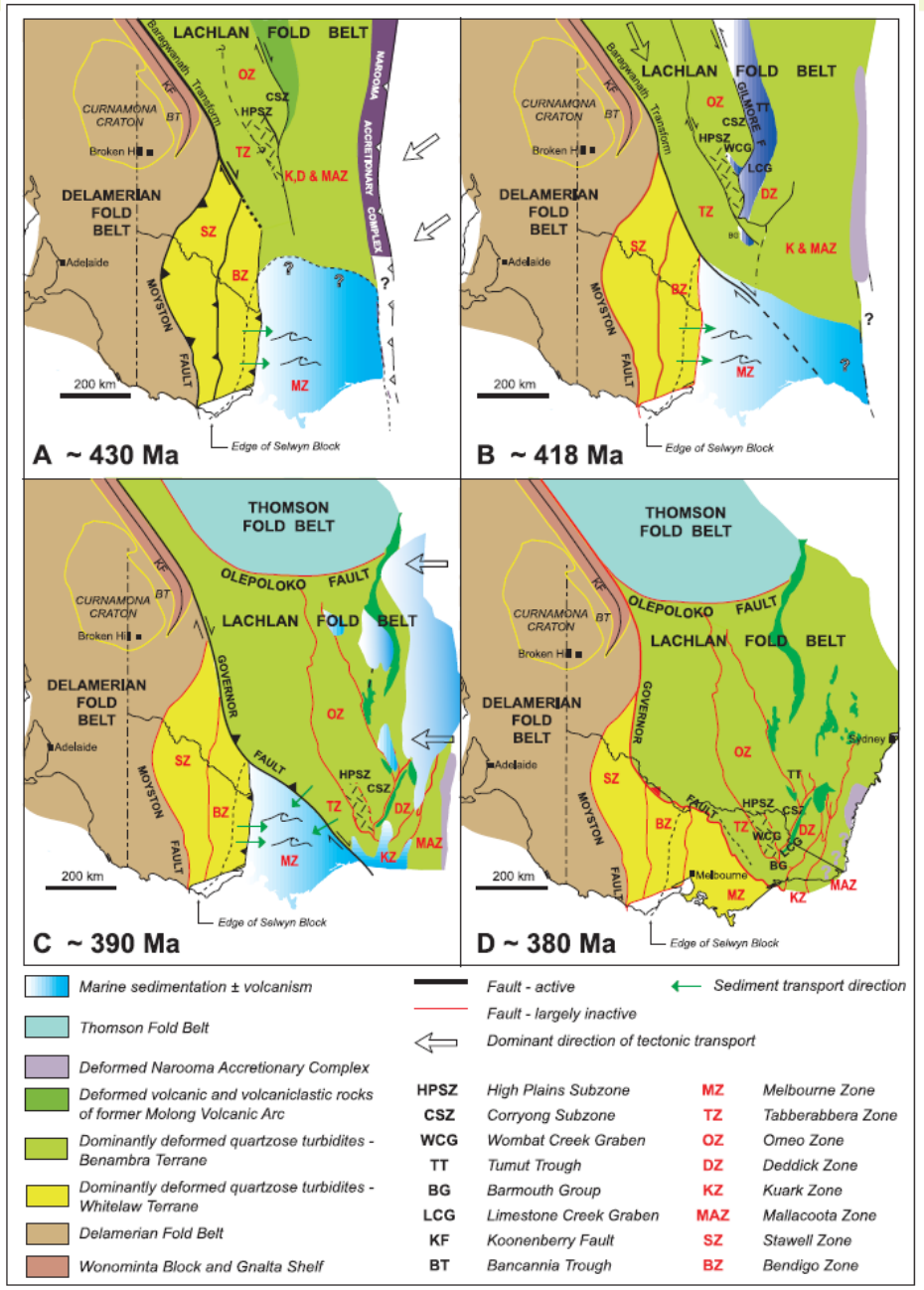
Andrews T.M., Cayley R.A., Cairns C.P., Boger S.D. 2026. Siluro-Devonian tectonics and metallogeny in Victoria: Sorting out the Bindian and Tabberabberan orogenies. AIG Victorian Minerals Round-up, Ballarat.

What happened

- Victoria was incorrectly interpreted to be a sedimentary layer cake.
- Stratigraphic relationships were incorrectly applied across the entire state.
- In the Melbourne Zone, the stratigraphy was interpreted as conformable, and the first period of deformation after the youngest unit – the Tabberabberan Orogeny
- This means that deformation histories were incorrectly extrapolated across zones, and incorrectly placed within zones

We've learned a lot

- Our understanding of the paleogeography of the Victoria and the wider Lachlan Fold belt has increased
- We know different structural zones occupied distinct paleogeographic and environmental settings – with different sedimentological histories.
- Our understanding of the complex tectonic evolution of the Lachlan Fold Belt during the Silurian to Devonian – the orocline - has increased.



(VandenBerg et al., 2000)

Recent work

- Orocline model
- Southeast Lachlan deep crustal seismic reflection survey
- Targeted studies of mineral systems and their relationship and timing wrt deformation
- New mapping/revising old mapping
- New U-Pb geochronology
- New specific mineral geochronology
  - Rb-Sr mica – in prep
  - Re-Os
  - U-Pb cassiterite, wolframite, scheelite
  - U-Pb apatite
- New modern geochemistry – igneous and sedimentary

The old paradigm – the Bindian Orogeny

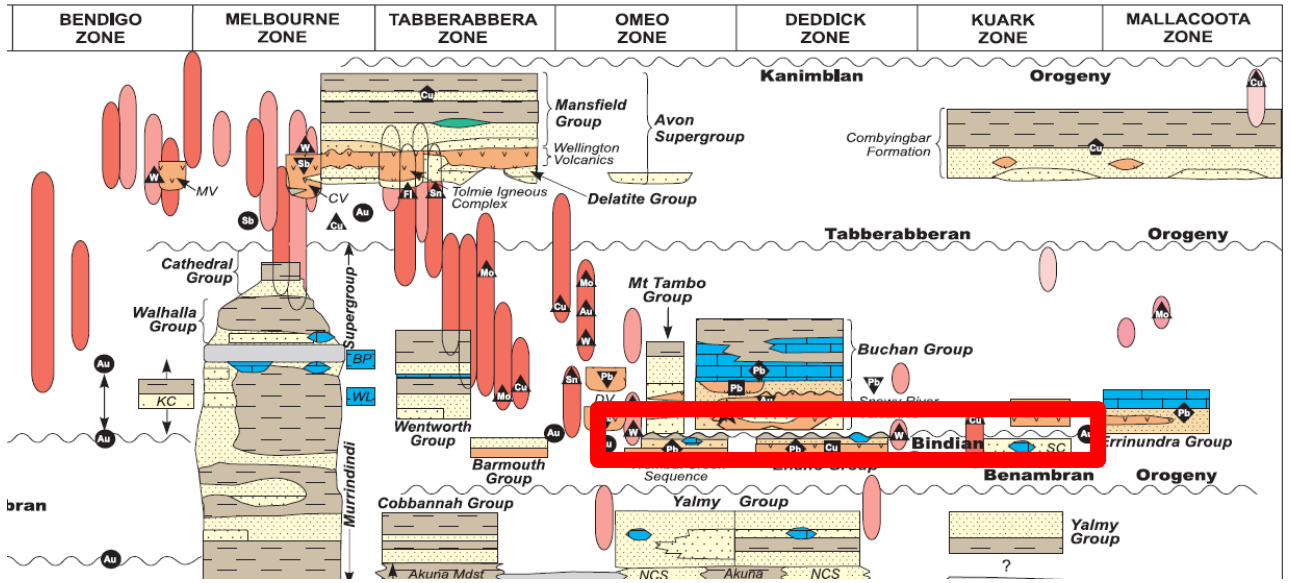
At the end of the Silurian, rocks in the Cowombat Rift were faulted and tightly to isoclinally folded parallel to the rift margins, presumably controlled by the rigid rocks on the rift flanks.

Farther west, in central Victoria, evidence of deformation is absent – indeed, it appears to have had no impact at all, even on sedimentation

Tasman Fold Belt - (VandenBerg et al., 2000)

Table 2.36 Timing constraints on the Bindian Orogeny in the Benambra Terrane

Stratigraphic constraints		Radiometric constraints		
Youngest deformed rocks	**Oldest overlying rocks**	**Metamorphic mica ages**	**Syntectonic intrusion ages**	**Post-tectonic intrusion ages**
Late Silurian Enano and Wombat Creek groups (418 Ma)	Early Devonian Snowy River Volcanics (415–400 Ma)	415–405 Ma (in fault zones)	420–405 Ma	415–395 Ma
Summary: major deformation at about 418–410 Ma, based on stratigraphic and radiometric constraints. The younger ages of syntectonic granites can be interpreted in two ways. Either the effects of the orogeny lasted until about 405 Ma or the region remained above the closure temperature for the isotopic methods used and therefore the younger ages represent a cooling age.				



The old paradigm – the Tabberabberan Orogeny

The Tabberabberan Orogeny was the first deformation that affected all parts of the Lachlan Fold Belt in Victoria.

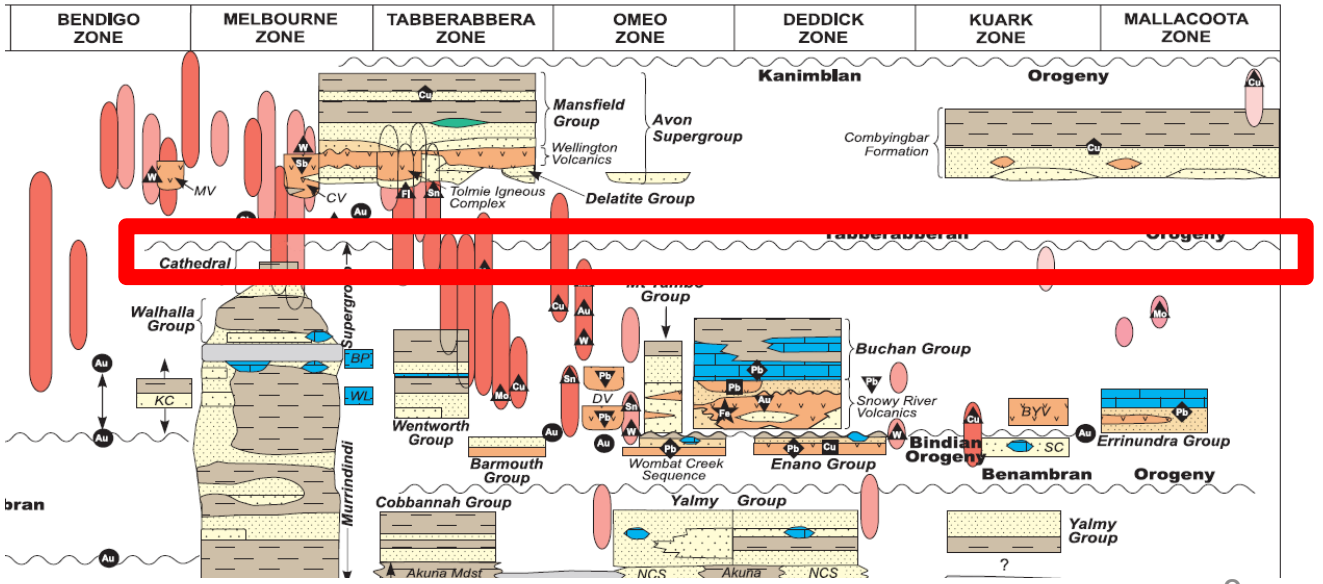
The orogeny marks the amalgamation of the Whitelaw and Benambra terranes and cessation of dextral strike-slip movement along the Baragwanath Transform.

Its effects were most strongly felt in previously undeformed regions with thick sediment fills such as the Melbourne Zone, Mitchell Syncline, Boulder "graben" and Scrubby Creek Syncline.

Tasman Fold Belt - (VandenBerg et al., 2000)

Table 2.58. Timing constraints on the Tabberabberan Orogeny in Victoria

	Stratigraphic constraints		Radiometric constraints		
	Youngest deformed rocks	**Oldest overlying rocks**	**Metamorphic mica ages**	**Syntectonic intrusion ages**	**Post-tectonic intrusion ages**
Whitelaw Terrane	Early or Middle Devonian Cathedral Group (~385 Ma)	Late Devonian caldera volcanics (370–355 Ma)	390–380 Ma (Melbourne Zone)		375–350 Ma
Benambra Terrane	Early Devonian Wentworth Group (415–400 Ma)	Frasnian (Late Devonian) Lewis Farm Conglom. (370 Ma)	385 Ma (Kancoona Fault)	385 Ma (Mudgeegonga Granite)	
Summary: Well constrained by stratigraphic and radiometric constraints to the interval between 385 and 380 Ma. Final but much weaker deformation straddles the age of the Woods Point Dyke Swarm (~376 Ma) and may have extended to about 370 Ma.					



What are the Bindian and Tabberabberan orogenic cycles

Bindian

- Everything after Benambran compression finishes, slab advance stalls and rollback begins

Until

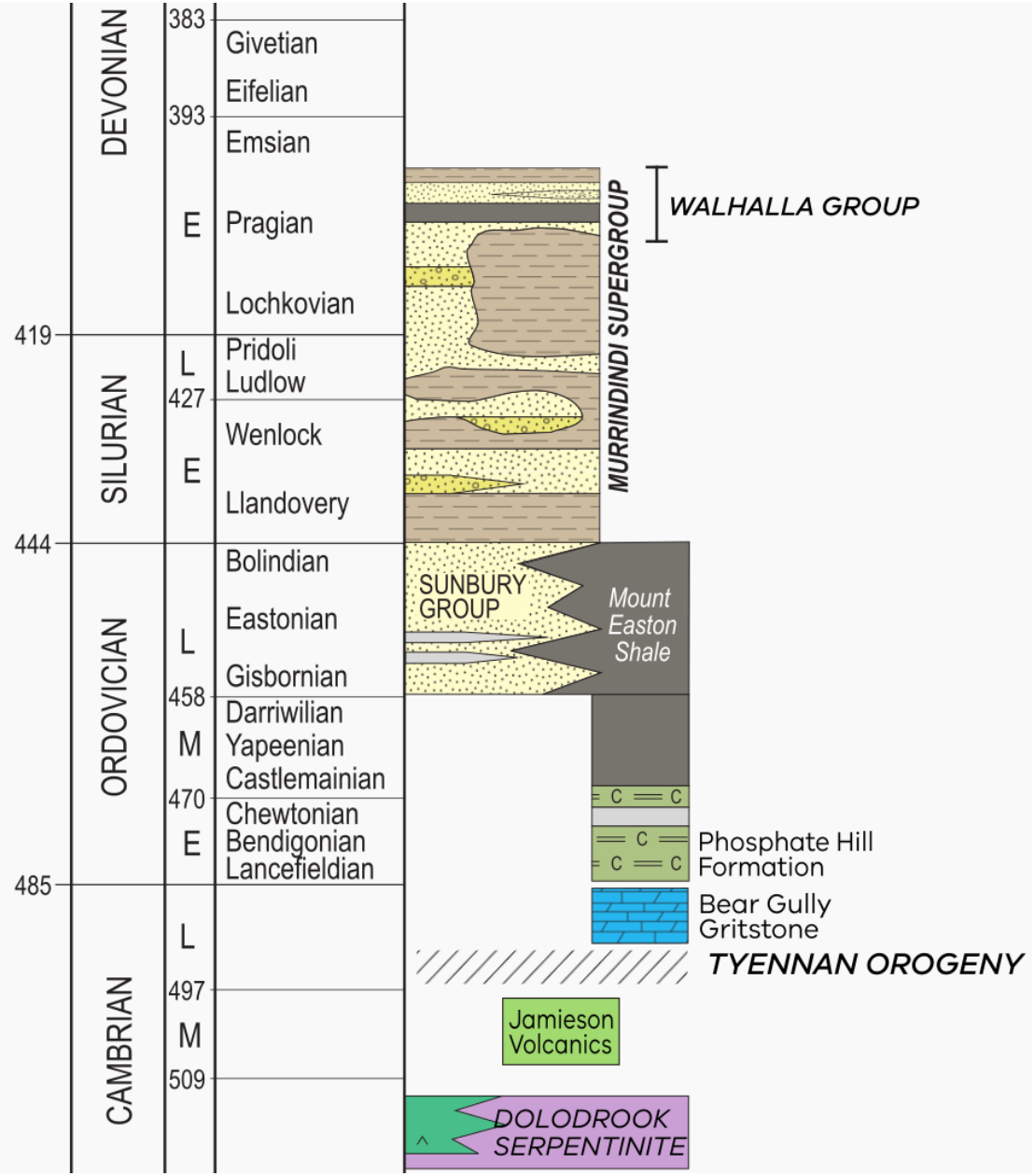
- The curved slab tears off, and the margin reestablishes as a simple, west dipping subduction zone
- The orocline

Tabberabberan

- Reestablishment of simple linear subduction zone
- Perturbated by short periods of compression

History of the Melbourne Zone

- Proterozoic continent crust
- Cambrian calc-alkaline volcanics
- Deformed in the late Cambrian – Tyennan
- Latest Cambrian continental sedimentation
- Deep to shallow water sediment started oceanic plateau through Ordovician
- Late Ordovician - early Silurian – receives sediment from uplifted Bendigo Zone post Benambran – Springfield Sandstone
- Silurian to early Devonian – conformable variable turbiditic sedimentation
- Until the early Devonian



Melbourne Zone stratigraphy

Changes - early Devonian

- First arrival of deep-water coarse mass flows with foreign provenance
  - Broadford Formation
  - Walhalla Group
- North and easterly derived paleocurrents
- Uplift of deep-water sediments to form shallow limestone reefs – Lilydale, Coopers Creek

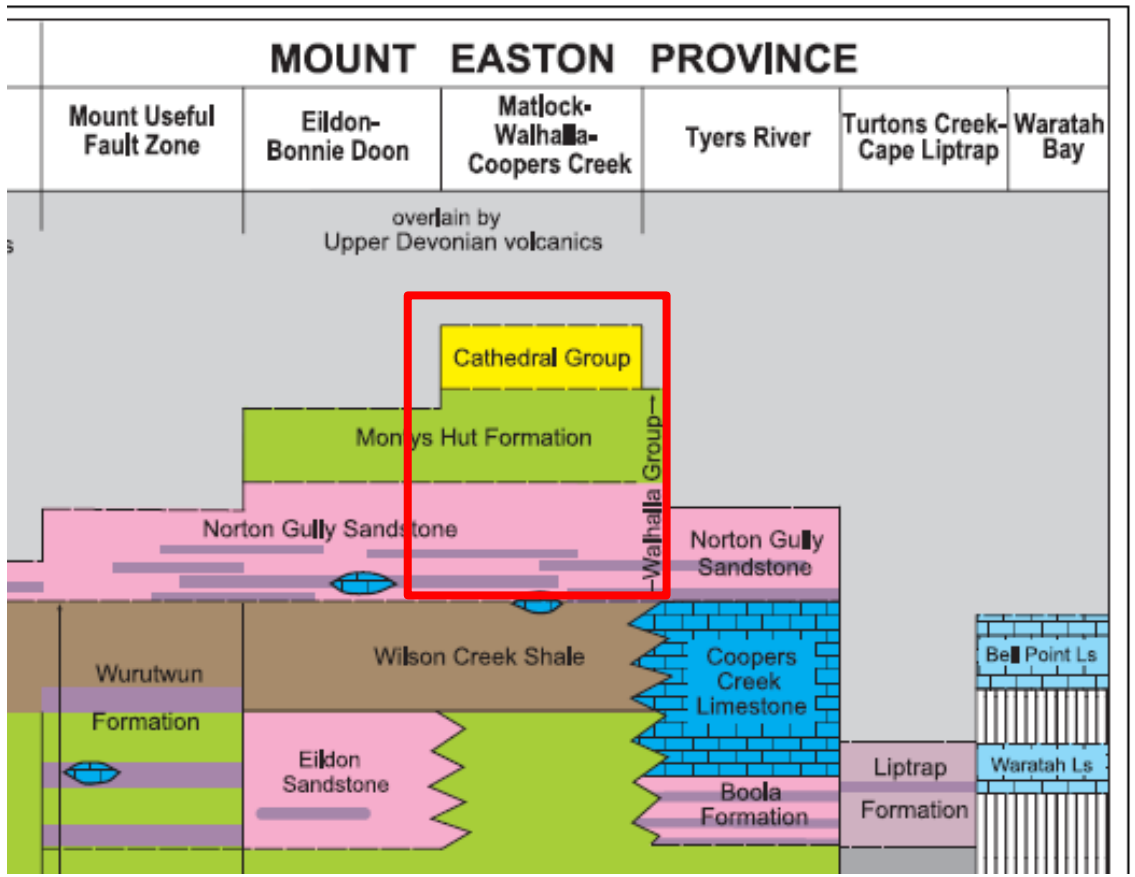
Walhalla Group deep water mass flow conglomerate with rhyolite clasts (VandenBerg et al., 2006)

The key relationship – the Cathedral Group

- Continental subaerial fluvial to lacustrine sediments straddling the Cerberean Cauldron
- Interpreted as conformable with the Walhalla Group **– not mapped**
- Implies all deformation is younger, and therefore the Melbourne Zone was deformed in the Tabberabberan.

& Gray, 1992; Edwards *et al.*, 1998). The Cathedral Group, which outcrops on both sides of the Cerberean–Acheron cauldron complex, is the youngest of the Murrindindi Supergroup units. Contacts with the underlying Walhalla Group are largely covered but are probably conformable in the Cathedral Range. The group is subdivided into two formations with a total thickness of about 2500 m in the Cathedral Range and about 1900 m at Koala Creek. The lower unit, Koala Creek

(VandenBerg, 2003)



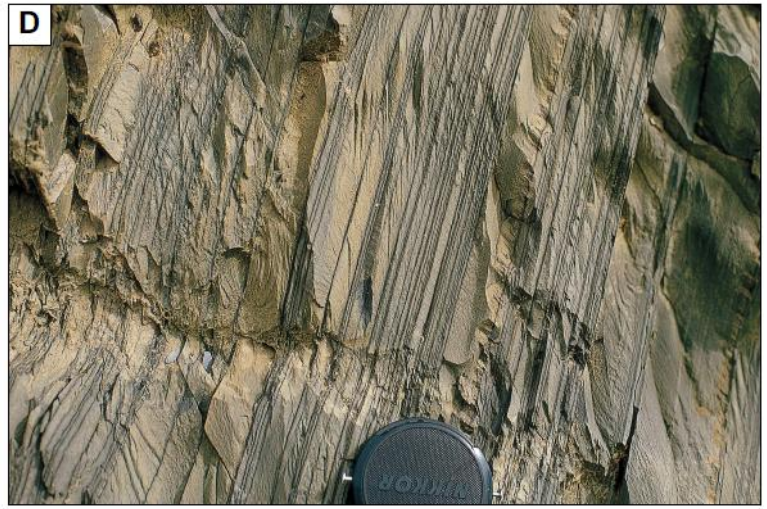
(VandenBerg et al., 2000)

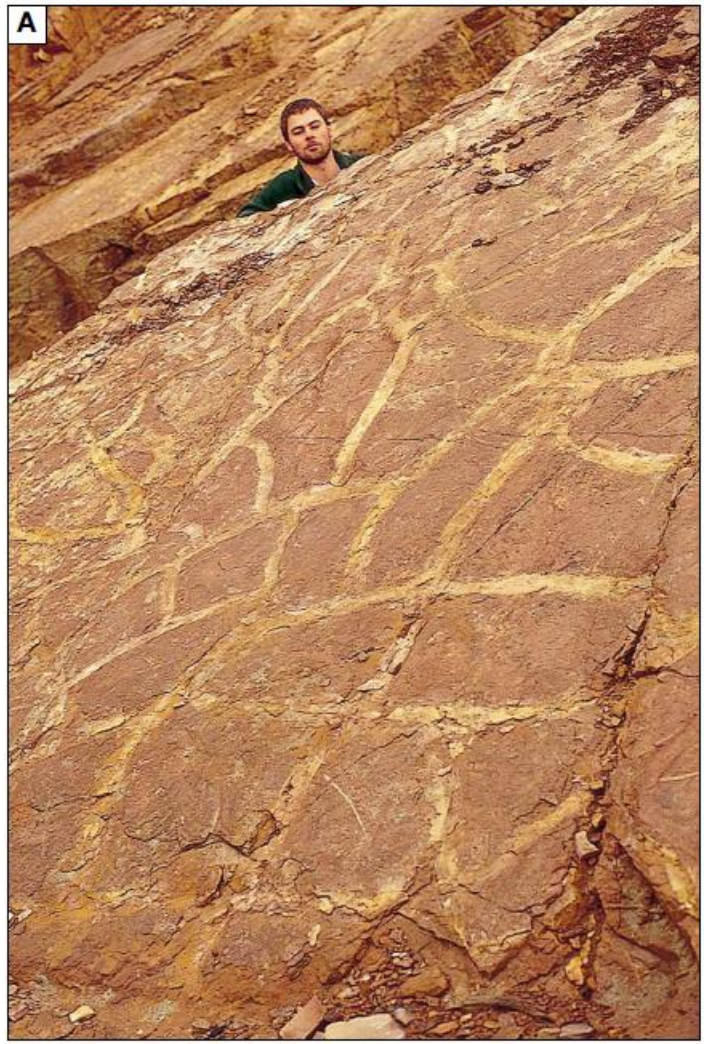
Lithology and depositional environment

- **Walhalla Group** – deep marine fine siliciclastic sediments containing mass flow conglomerates derived from uplifted Tabberabberan highlands to the east and north

- **Cathedral Group** - oxidized, fluvial sandstones, braided rivers, raindrop casts and desiccation cracks – subaerial

Dramatic change – no transitional facies





(VandenBerg et al., 2000)

Structural history

Cathedral Group

- Open cylindrical syncline

“Siltstones in Knobby Spur Member display no strain in the axis of the syncline”

Underlying Walhalla group

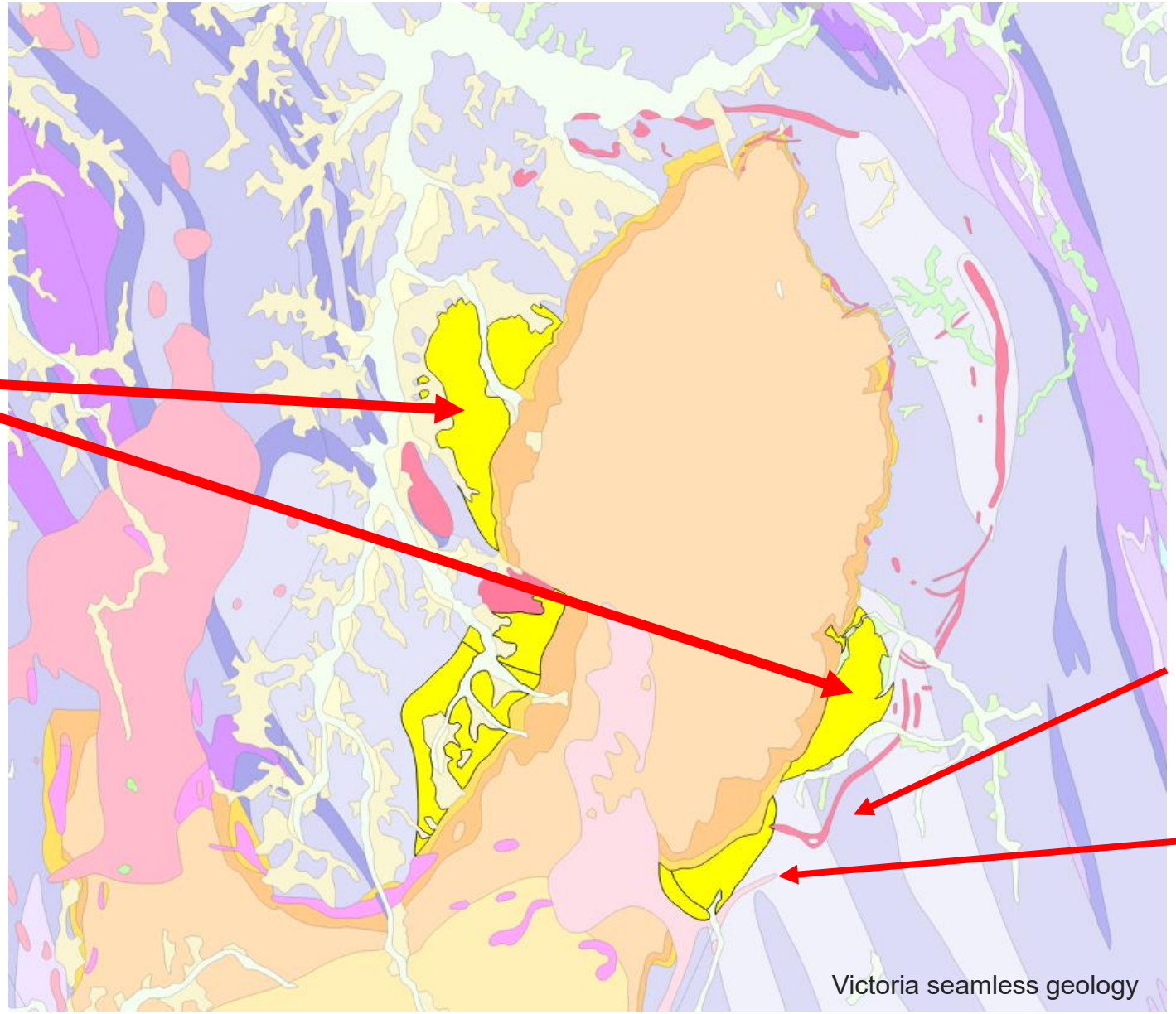
- Parasitic folding
- En echelon tension gashes
- Chaotic bedding
- Mesoscopic sinistral and dextral parasitic folds with en echelon quartz filled veins which themselves are folded.

“The presence of this isolated deformation only in the Walhalla Group and not in the overlying Cathedral Formation is likely to be a reflection of the changes in rock types”

(Ryan, 1992).

(VandenBerg et al., 2006)

The map pattern is all wrong

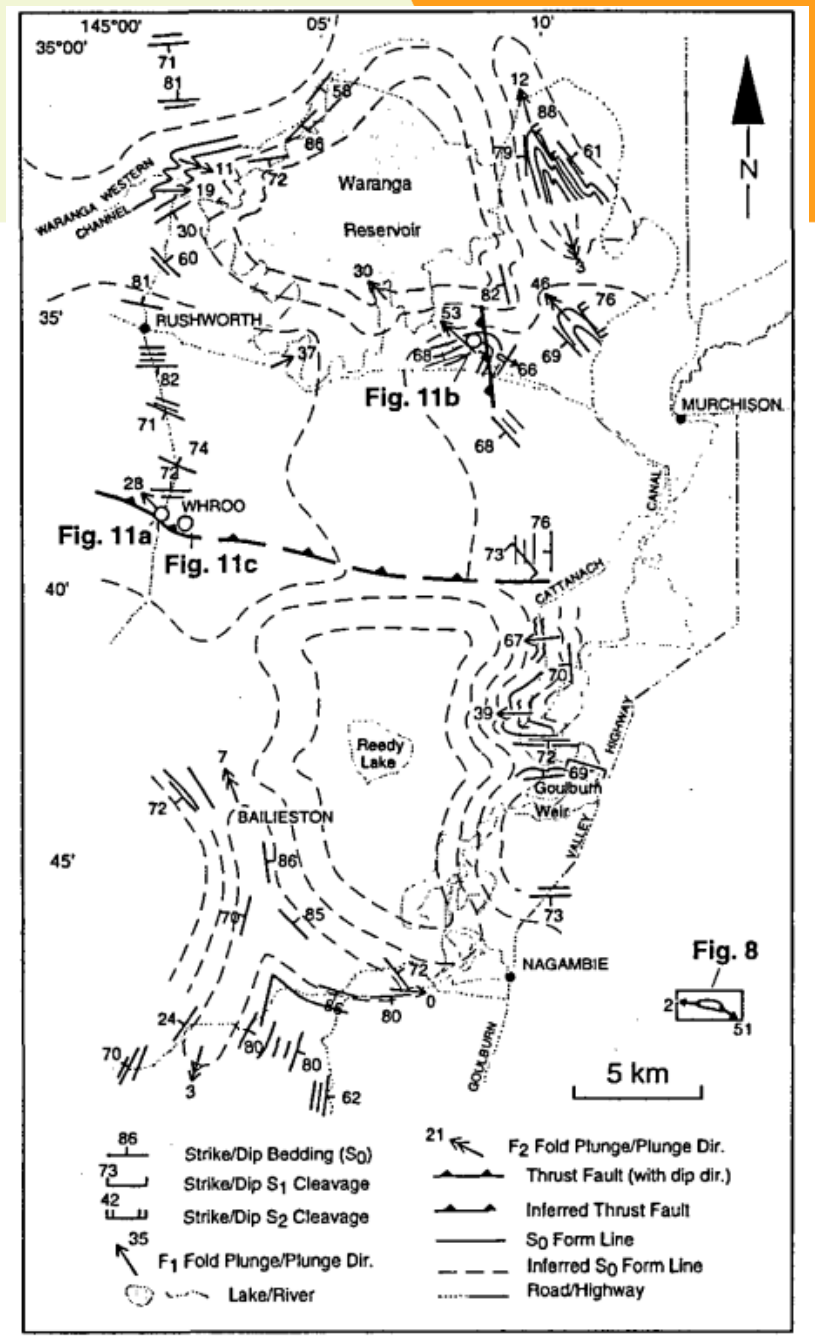


Alternate interpretation

- The Melbourne Zone was deformed prior to the deposition of the Cathedral Group
- Cathedral Group sits unconformably on deformed deep marine sediments
- Deformation is not Tabberabberan - ???

So, what is it?

Bindian



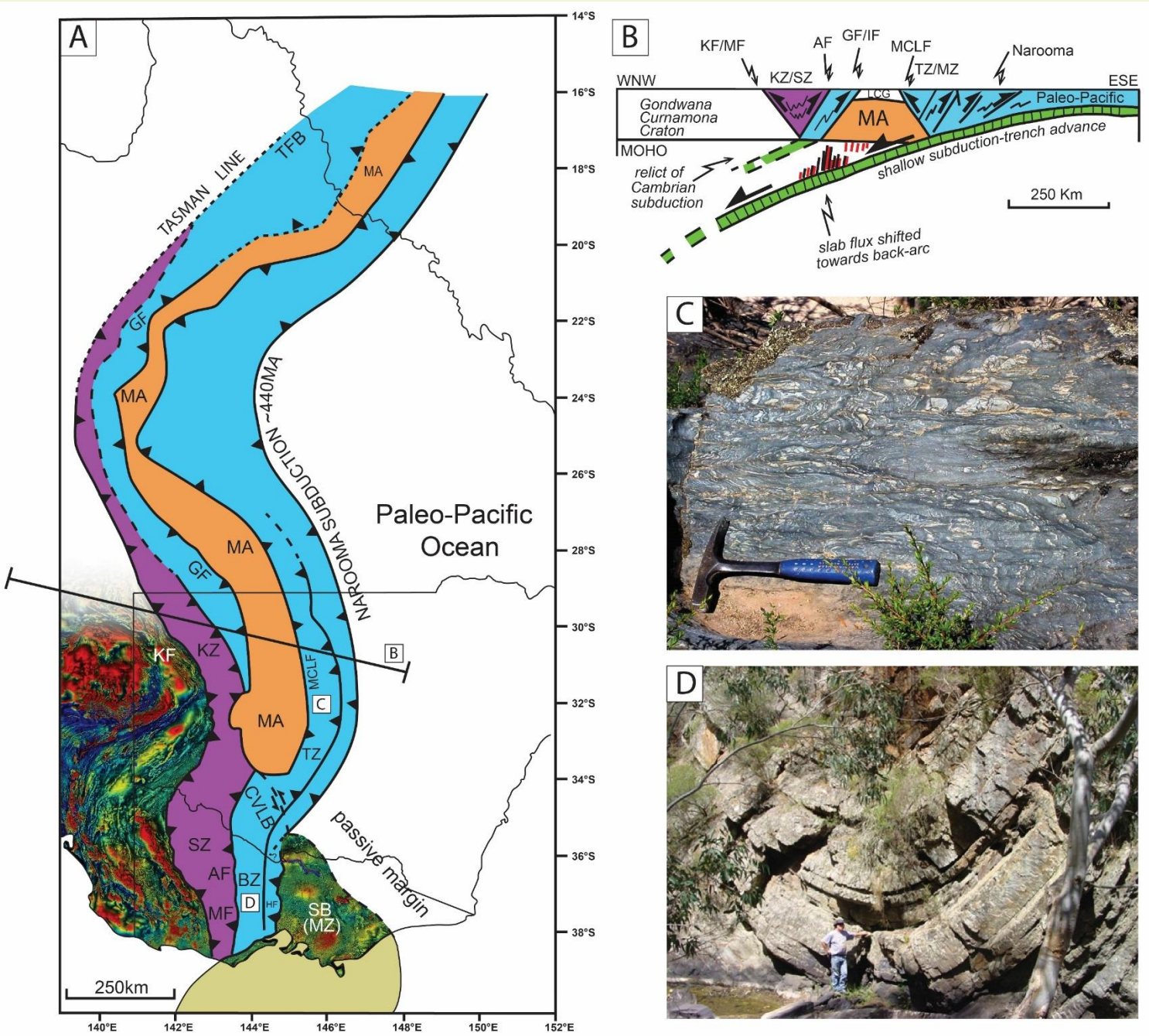
Fold interference patterns Nagambie - (Gray & Mortimer, 1996)

What is the Bindian

- Everything that happens between when the slab goes into rollback, and reestablishes as a single linear, continent dipping subduction zone
- Very dynamic
- ‘Orogeny’ difficult to define because of contrasting structural histories across zones

The start of the Bindian: end Benambran

- Simple, stalled quasi linear congested subduction zone
- Ordovician stratigraphy variably deformed



Cayley and Musgrave – in prep

Bindian: early Silurian - 440 - 430

Transtension

Arc:

- Macquarie Arc
  - Cadia, Northparkes
- Deddick Zone
  - Rifting and felsic volcanism - Limestone Creek Graben – Thorkidaan Volcanics

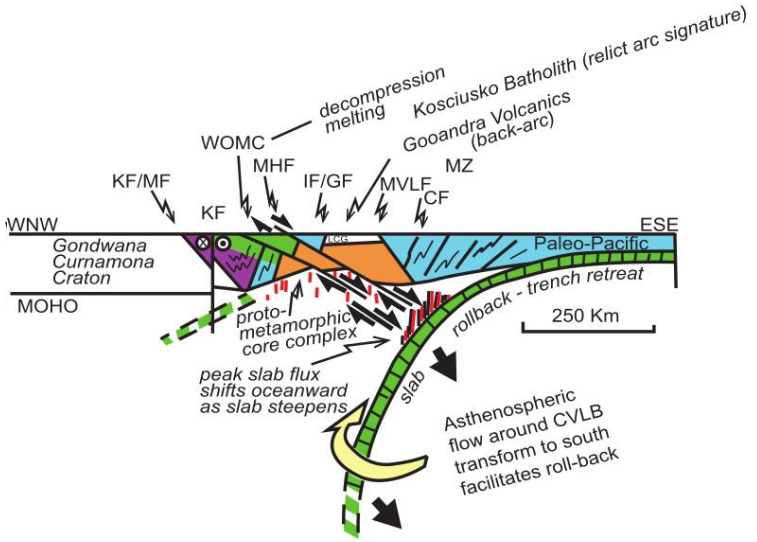
Back arc:

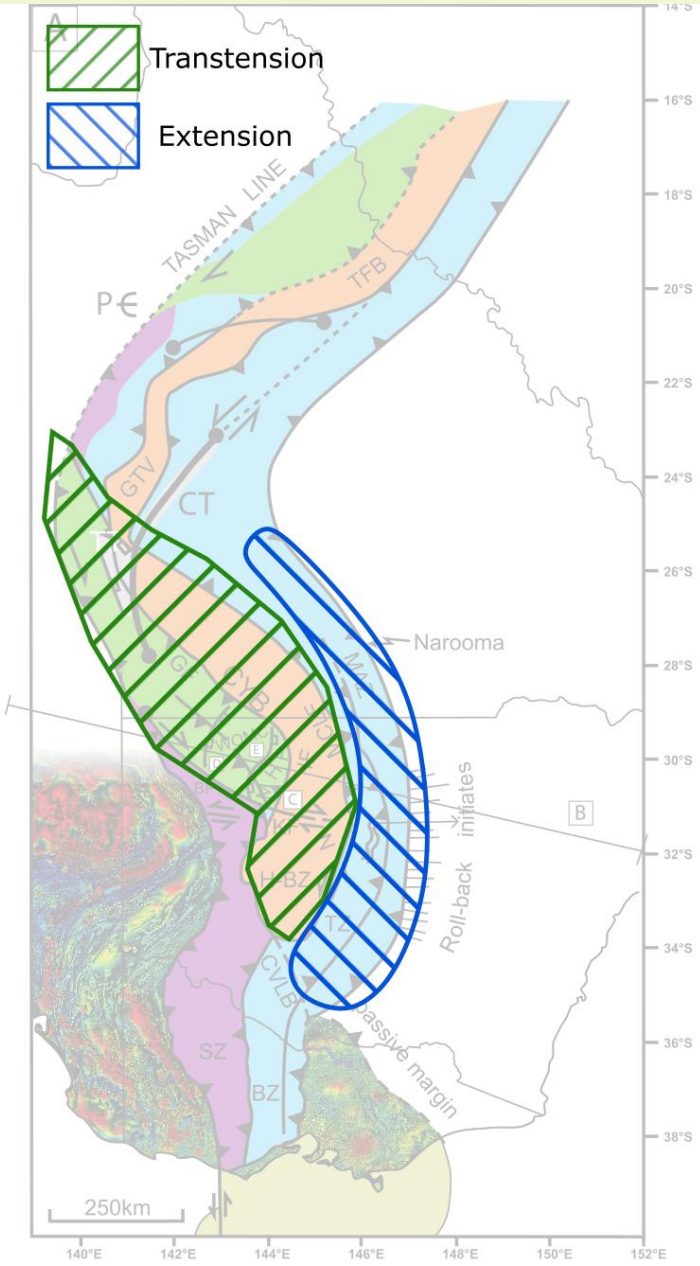
- Wagga - Omeo Zone
  - HTLP metamorphism – Wagga Omeo Metamorphic Complex
  - Rifting and felsic volcanism Omeo Zone – Wombat Creek Graben

Extension

Forearc:

- Kuark, Mallacoota Zones
- NSW – Dripstone Formation, Douro Group – Hawkins Volcanics, Tannabutta Group





Cayley and Musgrave – in prep

Bindian: late Silurian - 430 - 420

Transtension

Arc - Junee-Narromine Belt

- Jemalong trough – rift volcanism
- Deddick Zone - Enano Group rift sedimentation

Back Arc

- Omeo Zone – rampant S-type magmatism

Extension

Arc – Molong Belt

- Hill End Trough

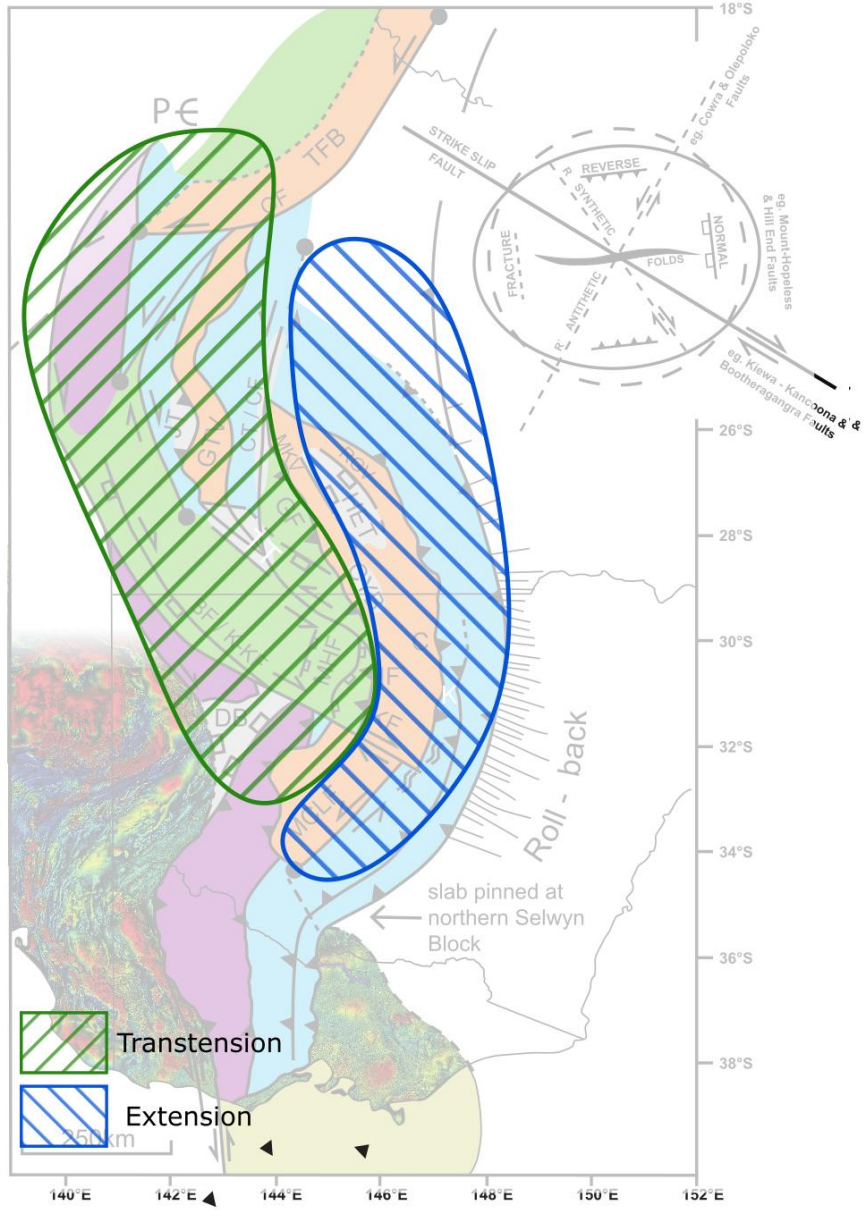
Forearc

- Kuark Zone – Sardine Graben
- NSW – Kohinoor Volcanics

Strike Slip

Western Victoria

- Dismemberment of Stavely Arc
- Grampians Group deformation



Cayley and Musgrave – in prep

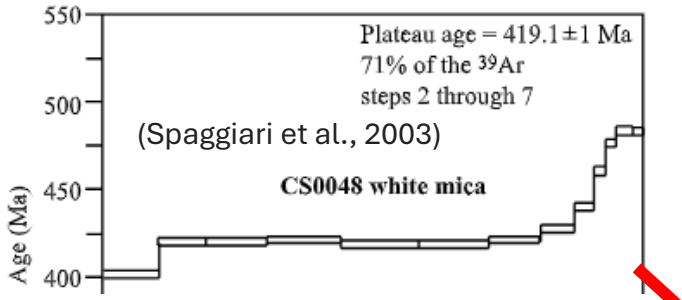
Bindian: Early Devonian - 420 - 415 – things start to get crazy

Classic Bindian Orogeny – Deddick Zone deformed as it is overthrust by the Ome Zone

Transtension:

Backarc:

- Omeo Zone - Bindi Graben
- NSW: Junee-Narromine Belt



Extension

Forearc:

- NSW – volcanic basins everywhere: Bredbo Group, Hoskinstown Group
- Kuark and Mallacoota Zones: magmatism

Compression:

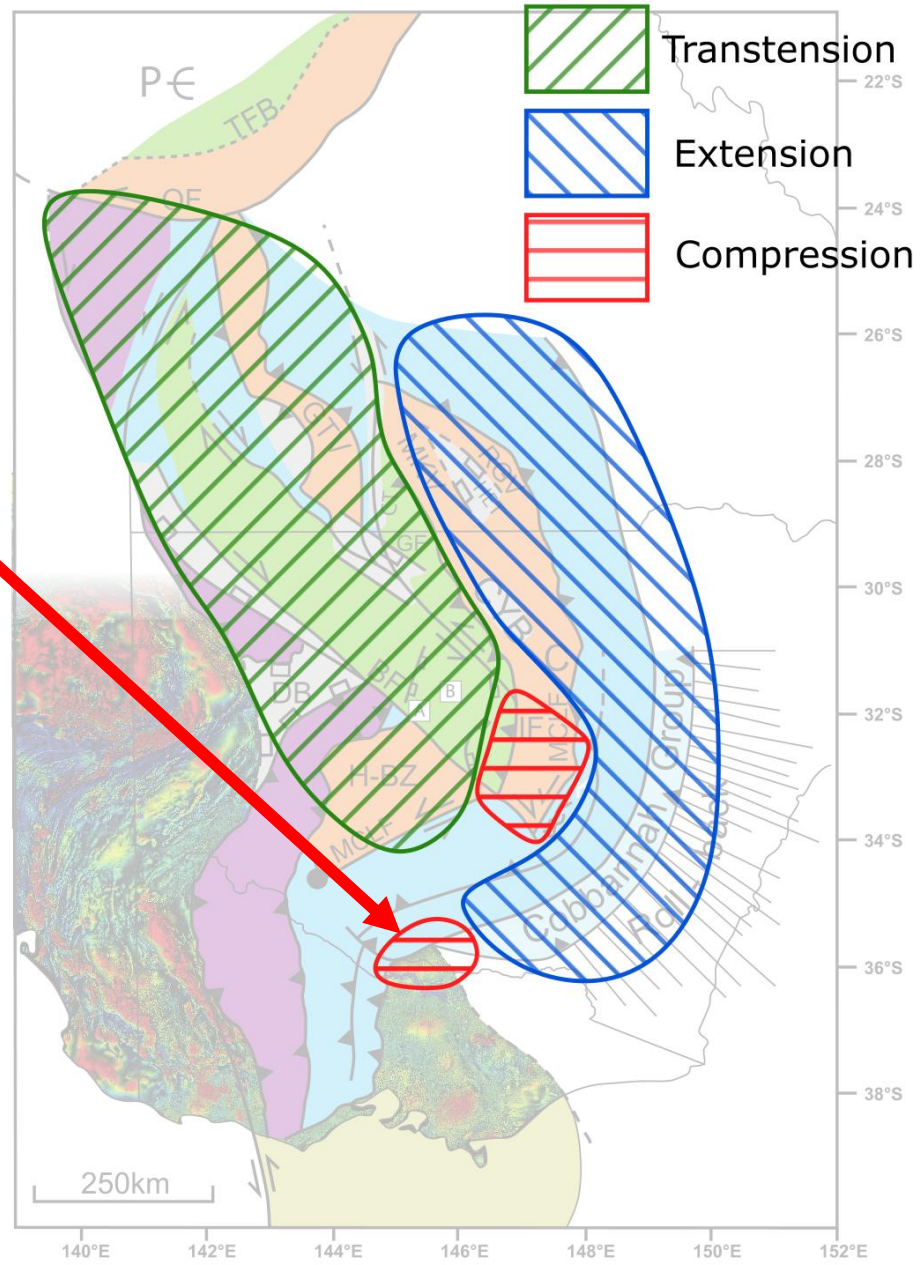
Arc:

- Deddick Zone, Indi Fault, Enano Group – classic Bindian Orogeny

Forearc:

- Northern Melbourne Zone - Mt Useful Slate Belt

- The classic Bindian is an isolated area of compression within an overall extensional/transtensional system
- Related to space problems in the hinge of a fold, not stress imposed from plate margin



Cayley and Musgrave – in prep

Bindian: middle Devonian: 415 - 410

Transtension

Arc

- NSW: Junee-Narromine Belt: Jemalong Trough

Backarc

- Omeo Zone: Bindi Graben
- NSW: Cobar

Extension:

Arc

- Deddick Zone: Snowy River Volcanics
- NSW: Molong/Rockley Gulgong: Hill End Trough

Forearc

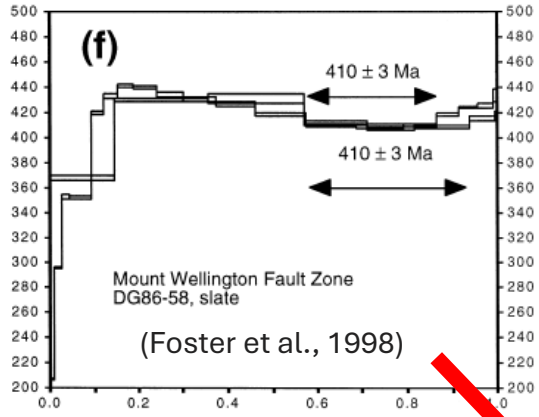
- Mallacoota Zone: Boulder Graben
- NSW – Bindook group, Gundary Volcanics, Mares Forest Volcanics

Compression:

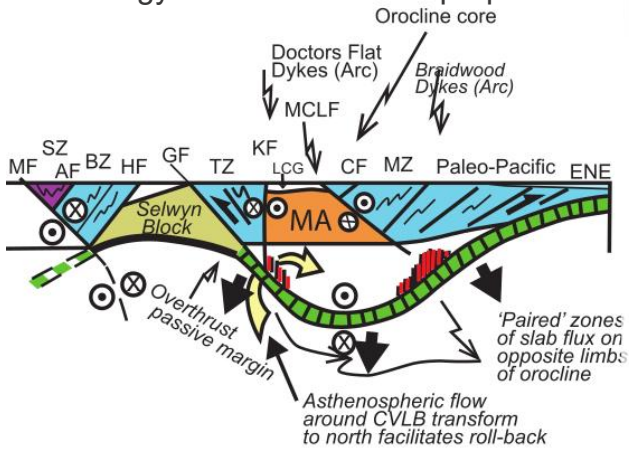
- Northern Melbourne Zone, Mt Useful Slate Belt and Tabberabbera Zone

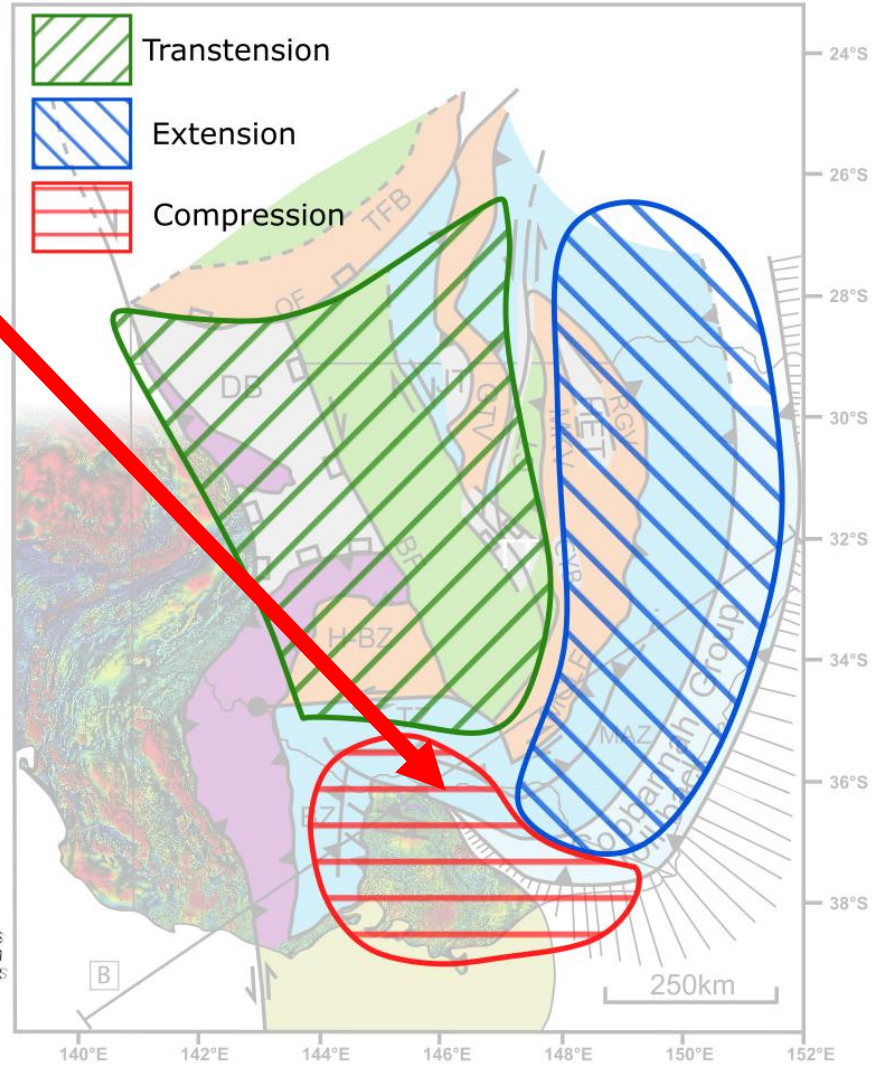
Binary either side of orocline hinge

- **East** – free to extend. **West** – no space, compression.



Mt Useful Slate Belt – in situ Rb-Sr cleavage geochronology – Andrews et al in prep





Cayley and Musgrave – in prep

Bindian: Devonian (~Pragian) - 410 - 405

Transtension:

Backarc:

- Omeo Zone: Dartella Volcanics
- NSW: Trundle Group - Cobar

Arc:

- Junee-Narromine Belt: Jemalong Trough

Extension:

Arc

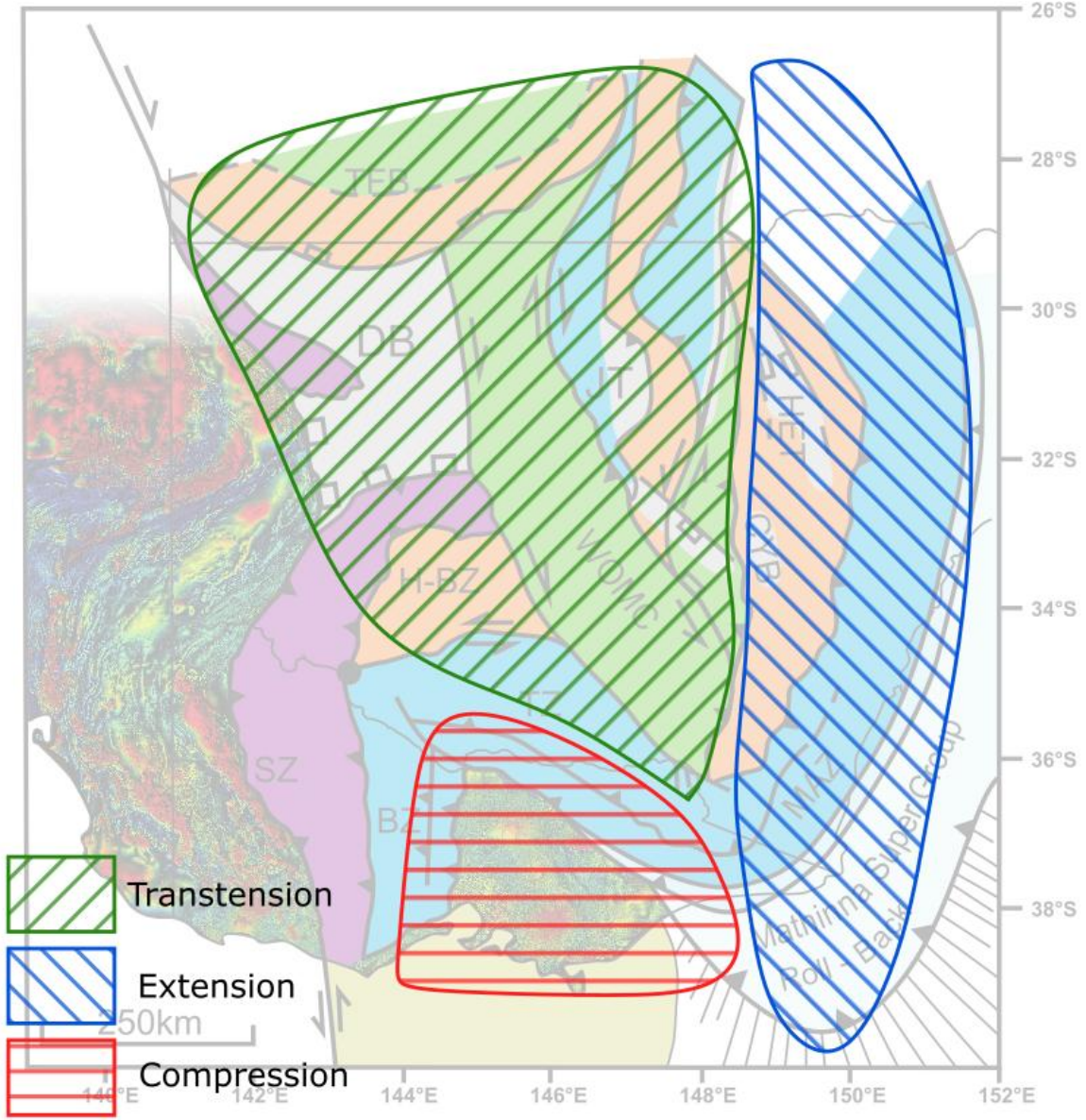
- Deddick Zone: Snowy River Volcanics
- Molong/Rockley Gulgong: Hill End Trough

Forearc

- NSW: Quialigo Volcanics

Compression:

- Deformation of entire Melbourne Zone stratigraphy – syn sedimentary – coeval with deposition of Walhalla Group



Cayley and Musgrave – in prep

Bindian: Devonian (early Emsian) - 405 - 400

Extension

Arc:

Rockley-Gulgong: Queens Pinch Group, Dungaree Volcanics

Backarc:

- Omeo Zone: Bedsford Ignimbrite

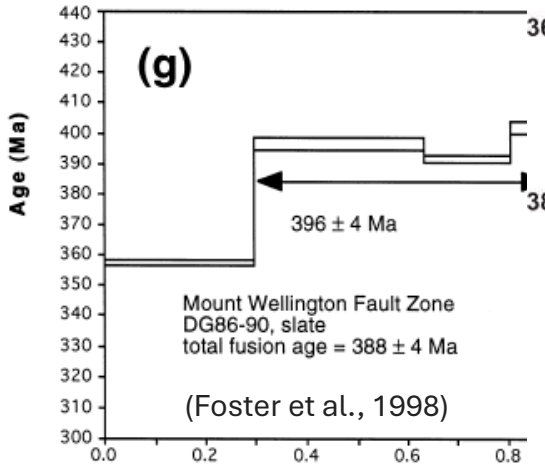
Forearc:

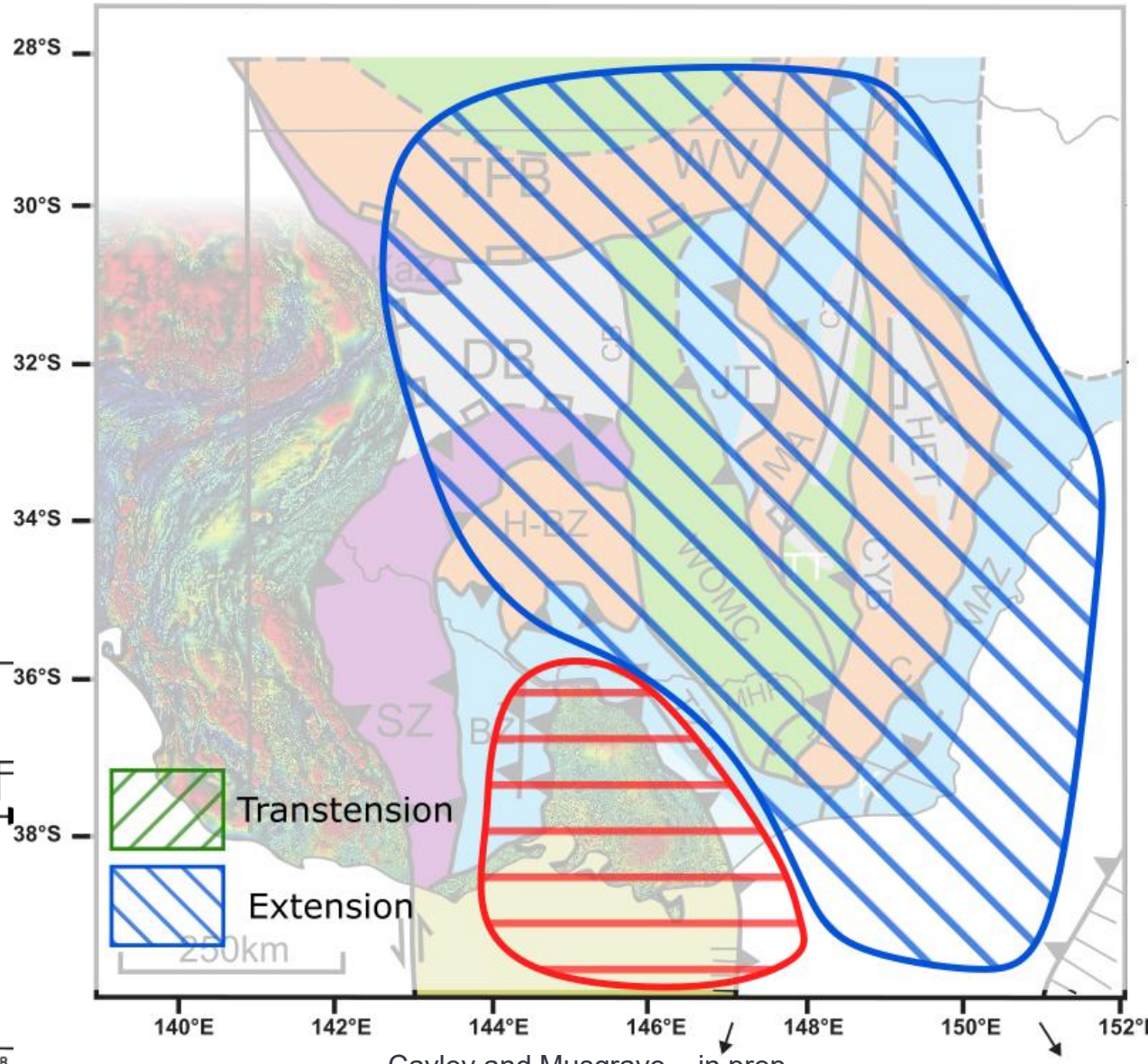
- Mallacoota Zone: Bega Batholith

Compression:

- Culmination of

Melbourne Zone deformation

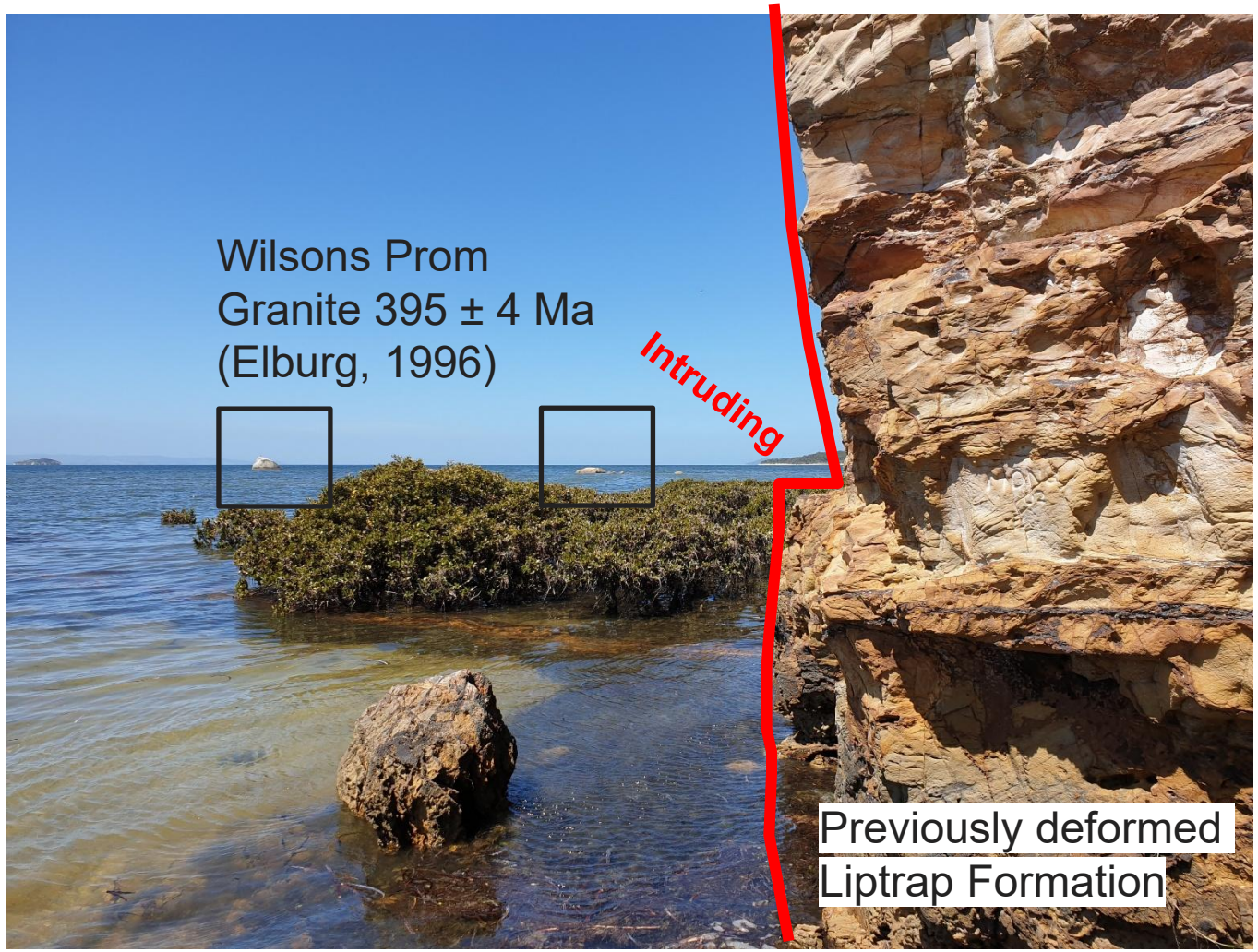




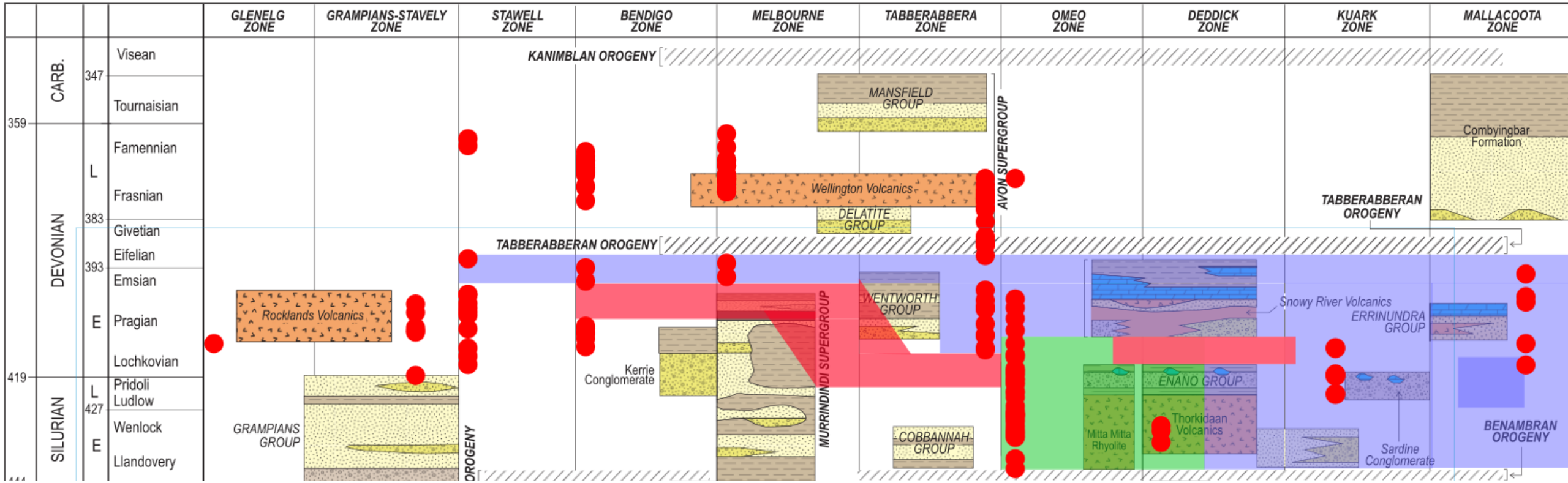
Cayley and Musgrave – in prep

The end of the Bindian: Devonian (late Emsian) - 400 - 395

- Statewide extension
- Post tectonic granites emplaced into already deformed Melbourne Zone stratigraphy – Bulla, Wilsons Prom ~ 395 Ma (Bierlein et al., 2001; Elburg, 1996)
- This is the Bindian - Tabberabberan transition – the margin has reorganized as a single subduction zone



Bindian time space plot



Dominantly compression

Dominantly transtension

Dominantly extension

U-Pb zircon magmatic age

Bindian Metallogenesis

- Spatially and temporally diverse
- Crucially, rollback through the Bindian means **subduction continues and subduction fertilised magmas are generated**
- But it doesn't look like a classic arc

Hematite altered Demon Ridge Andesite Porphyry (Andrews et al., in prep)

Polymictic IRG breccia – Shippen Gully (Andrews et al., in prep)

Pseudoacicular carbonate boiling textures – Nelson Creek (Andrews et al., in prep)

Bindian: early Silurian 440 - 425

HTLP metamorphism associated lithophile granite-pegmatite LCT mineralisation

Dorchap tin greisen – 7.5% Sn: 432 ± 2 (Waugh et al., 2024b)

Dorchap lithium pegmatite – 1.11 % Li_2O

VMS in arc shoulder volcanic rift – Limestone Creek Graben – Wilga - Currawong

Wilga ore. Top: 20+% Cu, 1.9% Zn, 70 ppm Ag (Bend 23, 116.9 m). Bottom13.4% Cu, 0.7% Zn, 0.2% Pb, 50 ppm Ag (Bend 19, 103 m). (VandenBerg et al., 2000. Photo by D. Barr)

Bindian: late Silurian 425 - 420

Transition from metamorphic peraluminous lithophile mineralisation to:

Granitic, vein hosted sulphur rich Sn-W

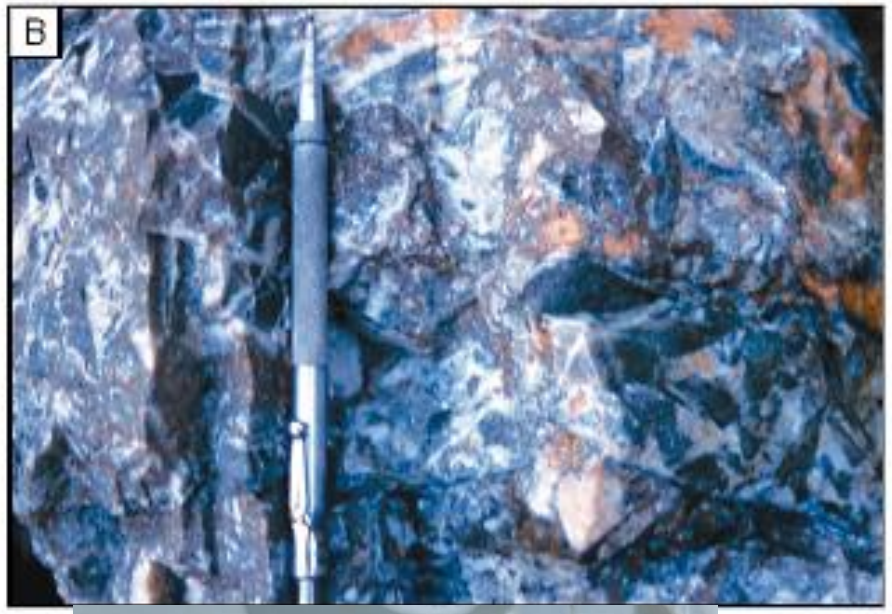
e.g. Koetong, Fainting Range, Mt Murphy

Arsenopyrite, cassiterite, schorl vein - Koetong

Wolframite in quartz vein – Mt Murphy - 426 ± 4 (Waugh et al., 2024b)

Bindian: Early Devonian 420 - 415

- Porphyry Cu-Mo-Au
  - Unicorn, Gentle Annie, Mowamba
- Low-Intermediate sulphidation epithermal
  - Granite Flat 414 ± 3 Ma (Waugh et al., 2024a)
  - Mt Wills
  - Omeo Goldfield - Forsyths-Comstock-Gambetta-Polar Star



Low sulphidation breccia with bladed carbonate boiling textures – Banimboola - (Morand et al., 2005)

Low sulphidation breccia – Gambetta – 3.07 g/t Au

Arsenopyrite-sphalerite cemented intermediate sulphidation breccia – Gambetta – 15.4 g/t Au, 1.69 g/t Ag, 1,360 ppm Zn, 17.5 % As

Bindian: 410 - 405

- Snowy River Volcanics - VMS Cu-Pb-Zn-Fe
- Tabberabbera + Kuark zone: Porphyry-epithermal
  - Nelson Creek, Dogwood, Booths Fancy, Double Bull Creek
  - Porphyry Cu-Mo veins, USTs, epithermal veins, boiling textures, altered volcanic shoulders
  - Pluton cupola IRG breccia Ag-Au-Te – Shippen Gully

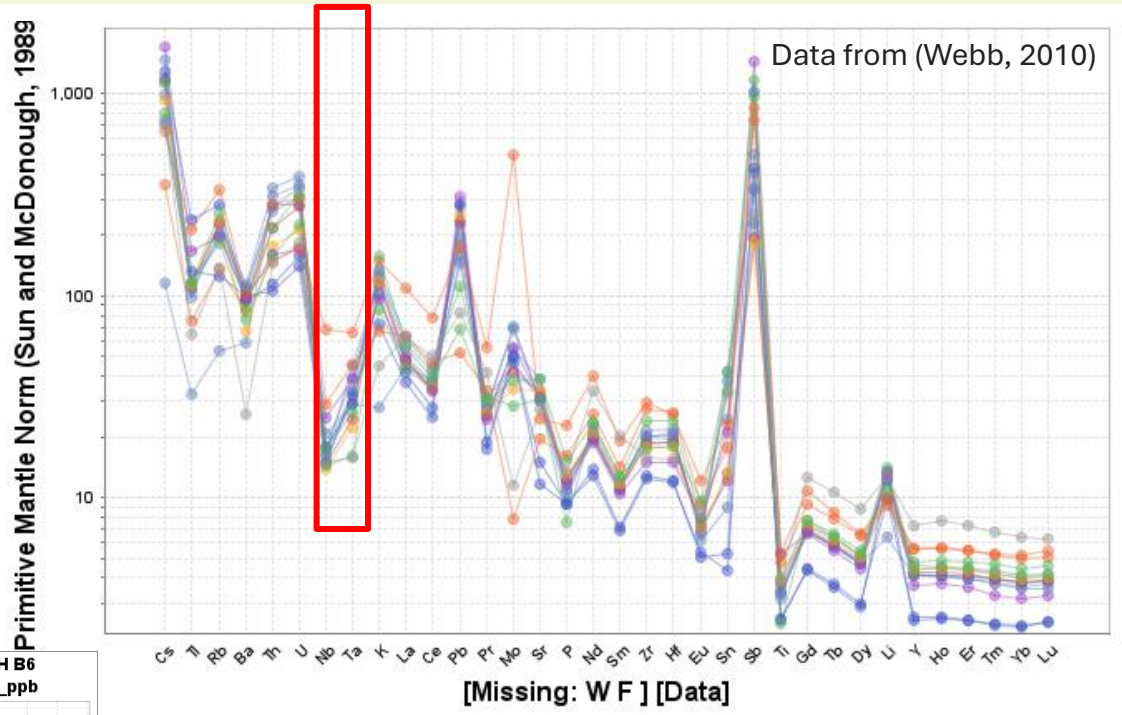
Low sulphidation breccia, moss, colloform & chalcedonic quartz, ginguro banding – Nelson Creek - 2.69 g/t Au

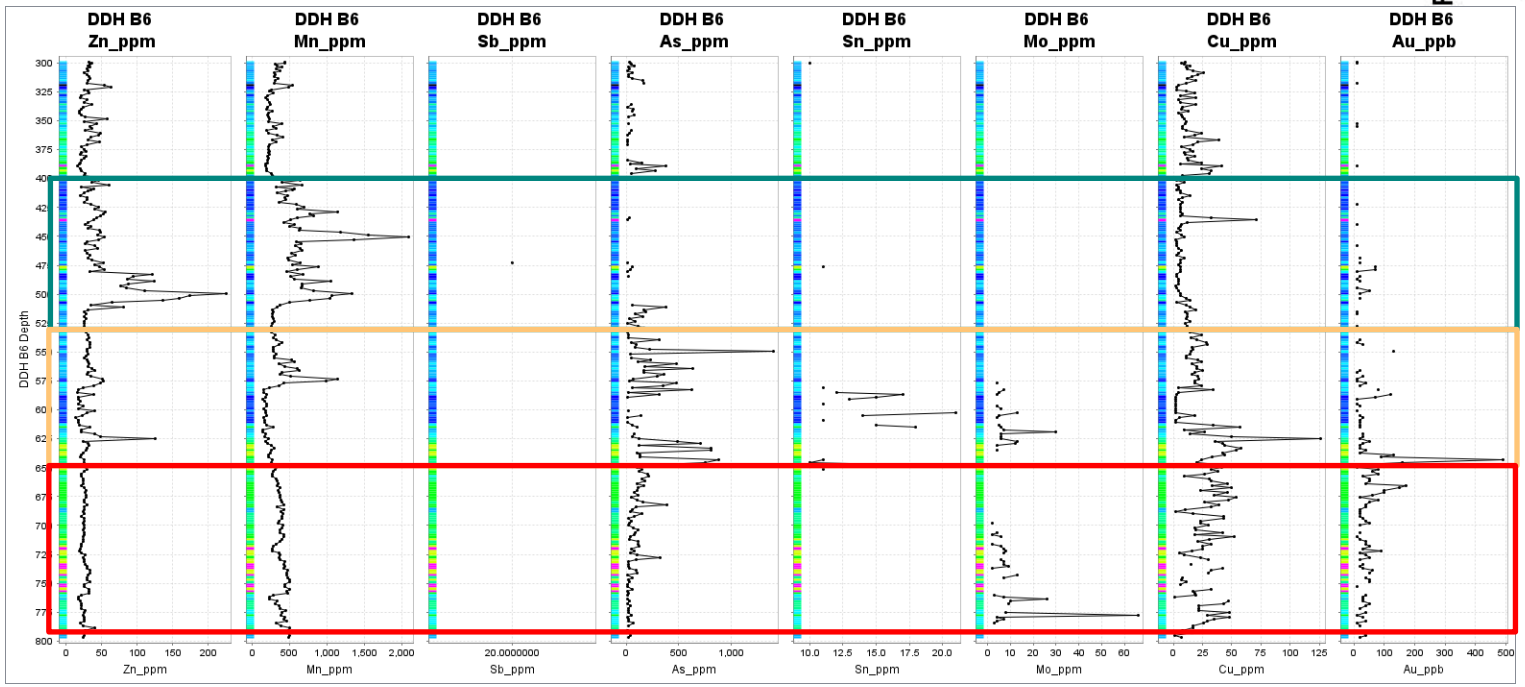
Intensely phyllic altered UST rich qtz porphyry intruding barren silicified rhyolite shoulder

Overprinting

Bindian: 405 – 400 Ma

- Continued rifting – Cu-Au mineralisation in Ovens Graben – Boorhaman Complex
- Arc like geochemistry, porphyry like alteration

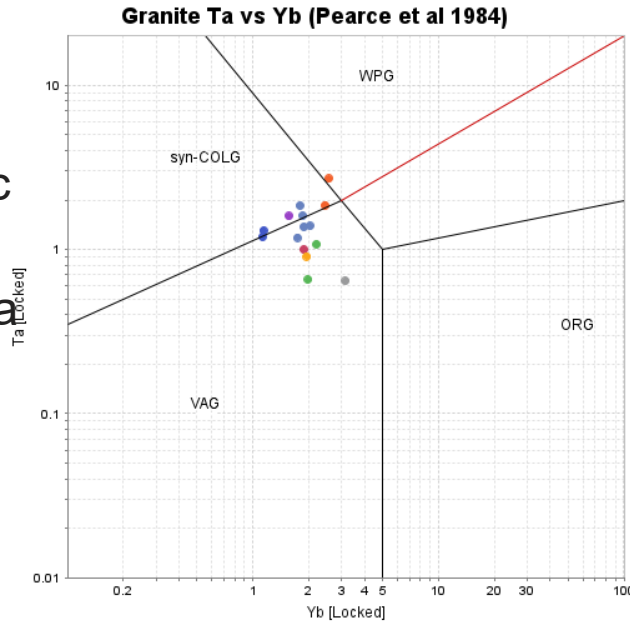




Zn – Mn propylitic

Mo-Sn-As in mica outer phyllic

Cu-Au hot pyrite rich phyllic



Data from (Highlake Resources, 2009)

OFFICIAL

Data from (Webb, 2010)

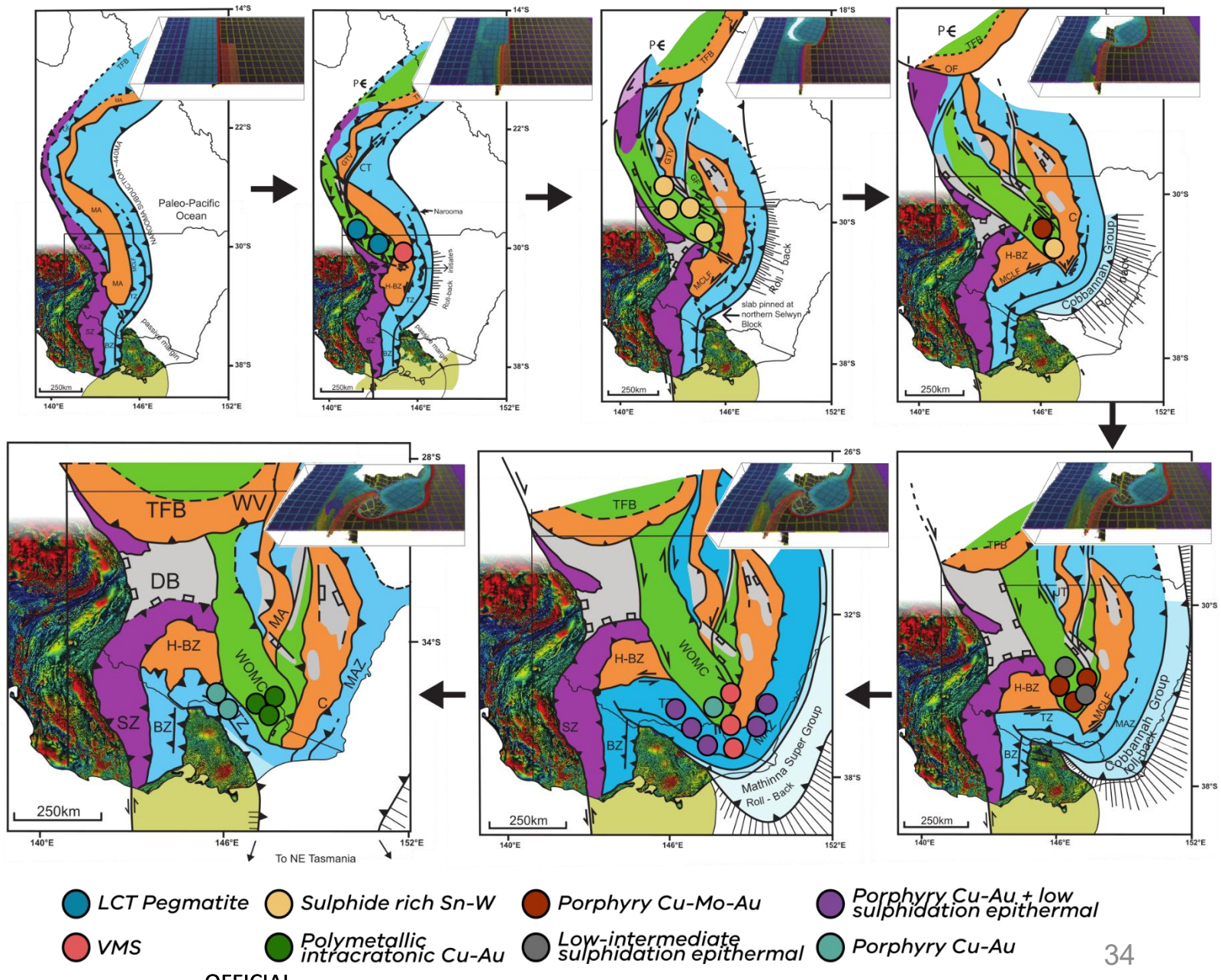
Bindian: ~395 Ma

- Mantle contribution, high-temperature intracratonic Cu-Au (Brauhart & Groves, 2026)
- Polymetallic Cu-W-Mo-Bi-Sn + S + F + Se
- Highly oxidized, acidic, fluorine rich alteration
- Womobi, Pine Mountain, Reward Copper

Quartz – molybdenite vein cutting intensely silicified granite with disseminated chalcopyrite – Womobi – 322316 - 1.65 % Mo, 1,265 ppm Cu, 4,520 ppm W, 4,470 ppm Sn, 3,390 ppm Bi

Bindian summary

- Everything between Benambran collision and reestablishment of simple subduction zone
- Incredibly diverse
- Affects all of Victoria, not to mention NSW and TAS
- Varied significant metallogenesis
- Progression from early peraluminous lithophile mineralisation to increasingly arc like, metaluminous, chalcophile mineralisation
- Radiates from core of orocline outward with retreating slab



So, what is the Tabberabberan?

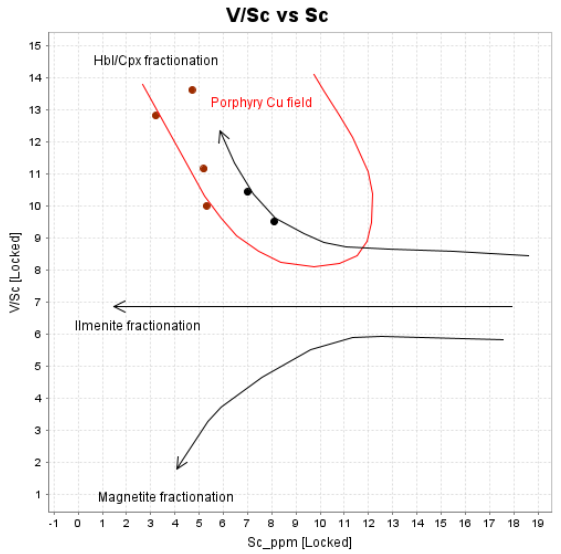
- Largely unchanged
- Compression confined to approx. 382 Ma – statewide
- Followed by a period of statewide transtension - extension
- Expression in eastern Victoria unchanged – refolding of folds, faulting of faults, deformation of E limb rift basins e.g Boulder Graben
- The main change is that it is a minor event in the Melbourne Zone – faulting of dykes, refolding of folds and Bindian cleavages

Steep Bindian axial planar cleavage refolded into vertically plunging kink folds – Murrindindi Supergroup (Andrews et al., in prep)

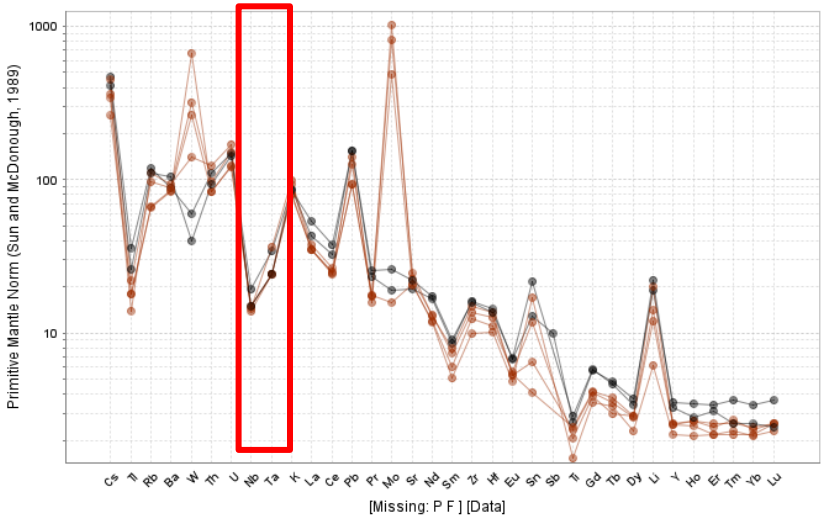
Tabberabberan metallogenesis

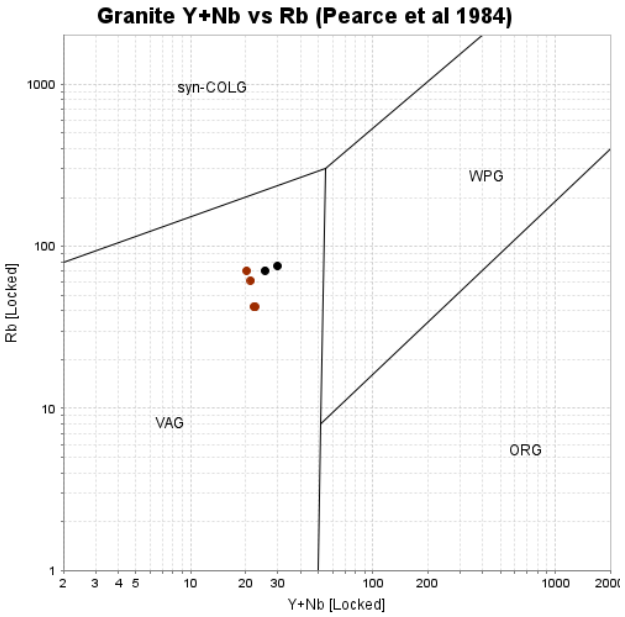
Tabberabbera Zone

- Post collisional fertilized mantle melts
- Magmas stalled during compression – high pressure fractionation
- S-type magmas cause tin mineralisation at Beechworth
- I-type magmas cause porphyry Mo mineralisation at Everton – ultra high grade Re
- Magmas with arc like, fertile geochemistry



Molybdenite USTs - Everton





Tabberabberan metallogenesis - Melbourne and Bendigo zones

- Orogenic Au-Sb
- Intrusion related Au
- Intrusion related W-Mo-Sn: Wilks Creek, Monkey Gully, Brittania Creek
- Tin: Beenak, Bunyip, Latrobe River, Buxton
- Fluorite - lead: Warby Range
- Cu-Ni-PGE: Coopers Creek

Late stibnite breccia overprinting laminated-stylolitic quartz - Costerfield

Polymictic granite – siltstone IRG breccia – Mt Piper

Fluorite – Warby Range

Tabberabberan metallogenesis - Melbourne and Bendigo zones

- Orogenic Au-Sb
- Intrusion related Au

We’ve seen the what, and the where – now some ideas on the how

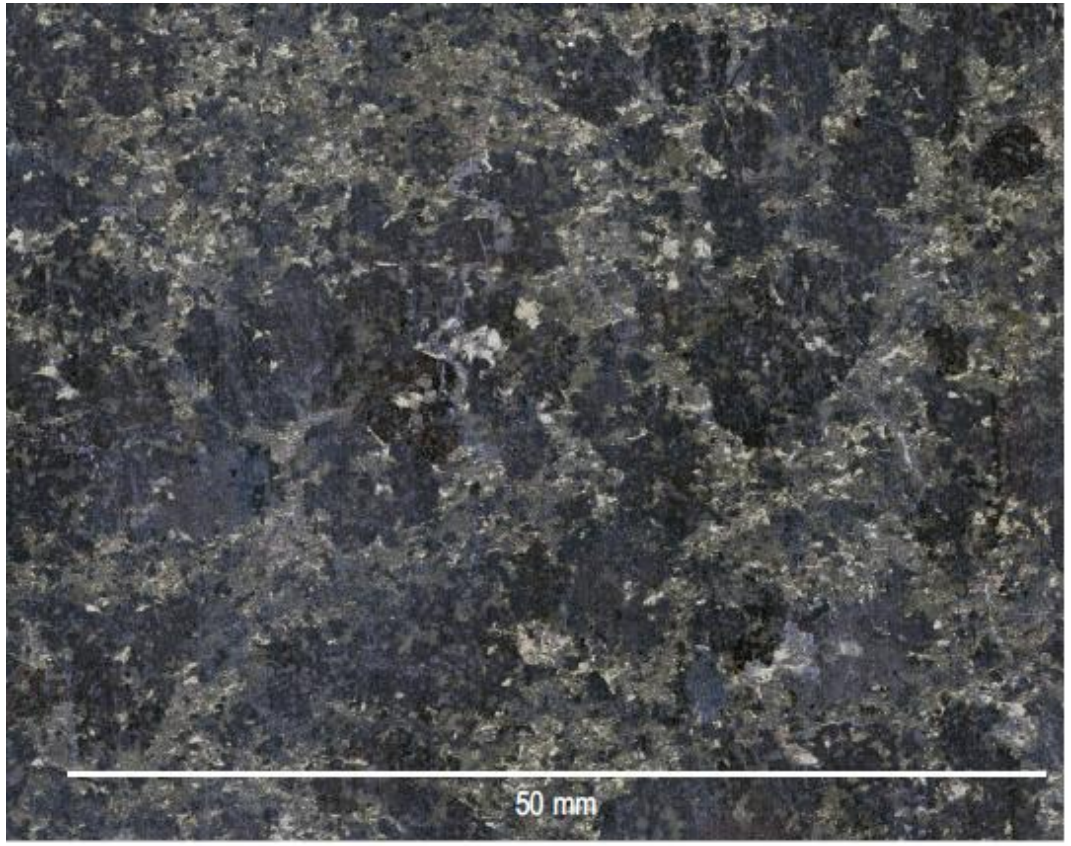
Late stibnite breccia overprinting laminated-stylolitic quartz - Costerfield

Polymictic granite – siltstone IRG breccia – Mt Piper

Fluorite – Warby Range

Prograde metamorphism and gold deposits in intraplate settings

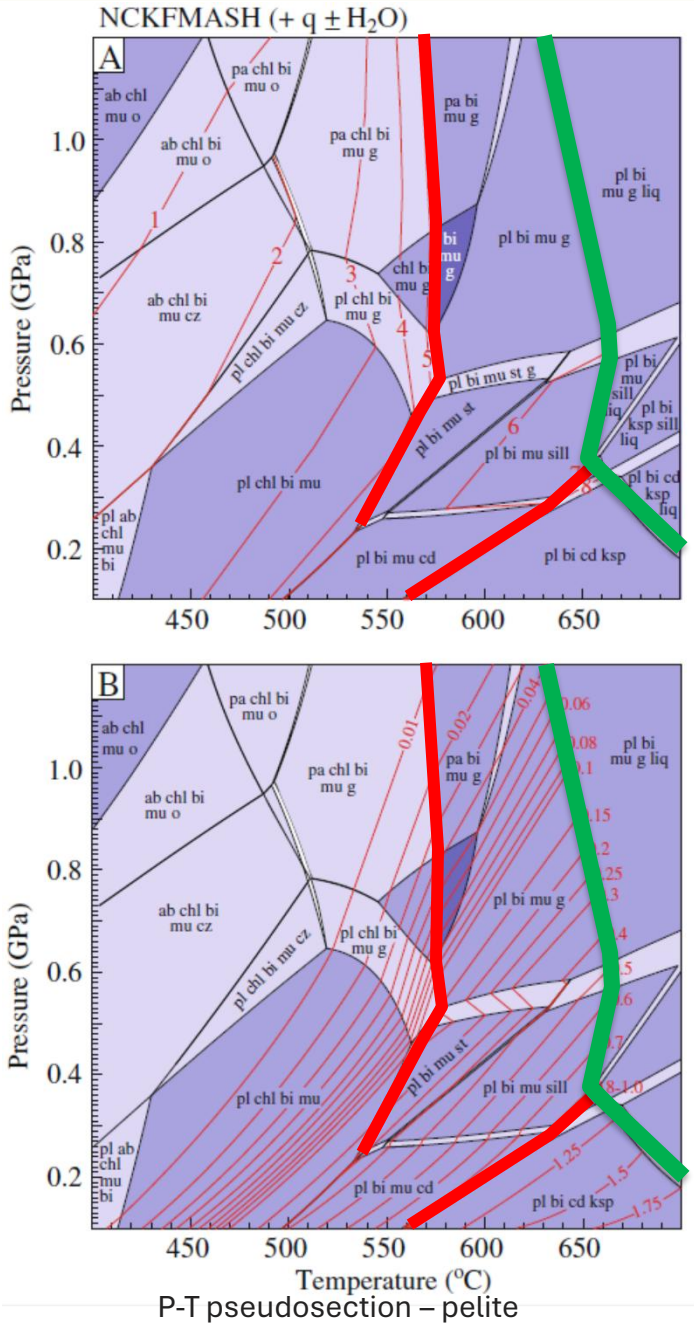
- For rocks to melt in intraplate settings, they must take a prograde metamorphic path through the windows which liberate H_2O, H_2S, Au, Sb and As.
- We know the Melbourne Zone basement took this path, because we have the result - ~374 Ma magmatic event
- The posited driver of this advective heat input and prograde metamorphism in Victoria is magmatic underplating
- Great observation in Boger et al. (2025) that PGEs will only be extracted from the mantle after extensive melting causes complete sulphur depletion
- PGEs at Coopers Creek confirm this occurred – causing magmatic underplating and massive advective heat input into the crust



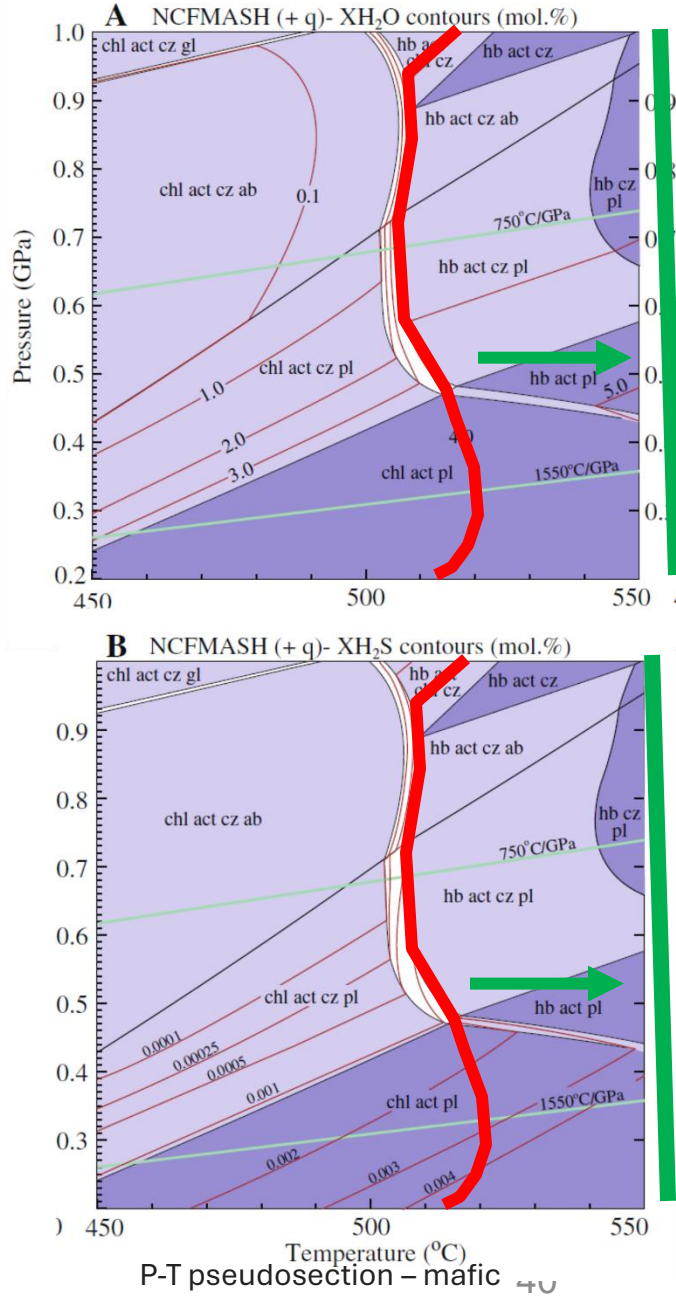
Net-textured Ni-Cu-PGE sulphides – Coopers Creek (Boger et al., 2025)

H_2O, H_2S and the wet solidus

- Most H_2O and H_2S are liberated during chlorite and/or muscovite breakdown - (Tomkins, 2010)
- Simultaneously, 93% of **Au** and ~75% of As; and ≥90% of Mo, Cd, Pb, **Sb**, W, Cu, Bi, Te, and Tl are released from pyrite - (Latheef Thathrampally et al., 2025)
- This occurs well before the wet solidus (melting)
- We know the Melbourne Zone basement rocks passed the wet solidus, as we have the granites
- Therefore, by the magmatic event, fertile Melbourne Zone basement rocks had already passed through the most productive H_2O, H_2S, Au, Sb, As generation window



P-T pseudosection – pelite



P-T pseudosection – mafic

(Tomkins, 2010)

The natural progression of this geotherm

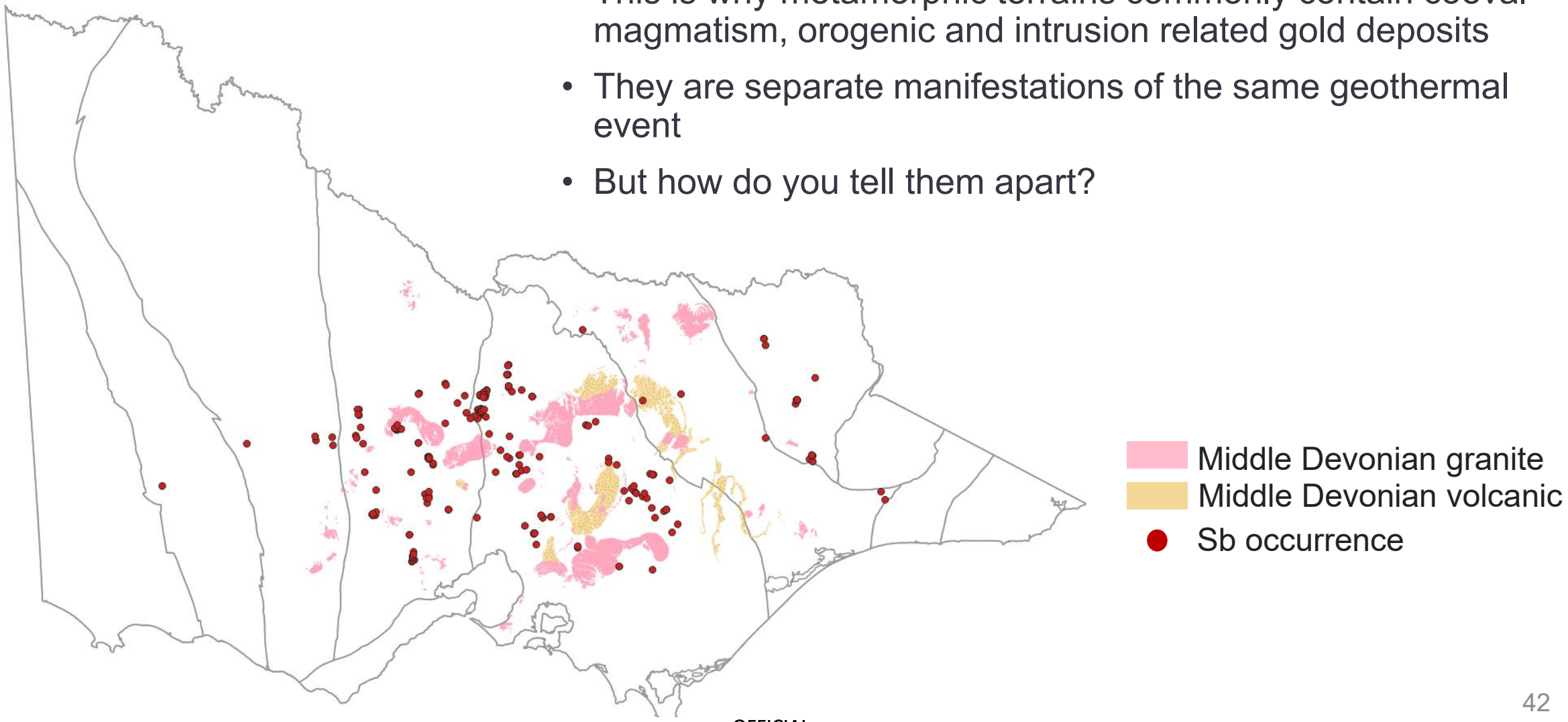
1. Breakdown of chlorite, muscovite and pyrite releases > 90 % of Au and TEs, plus H_2O and H_2S into metamorphic fluid – prior to any melting – this fluid forms orogenic deposits
2. Metamorphism progresses past the wet solidus –TEs in remnant fluids flux silicate melting
3. Some of these melts fractionate to form IRGs
4. Most coalesce to form massive, barren siliceous batholiths and calderas

Late quartz stibnite veinlet overprinting magmatic hydrothermal breccia – Mt Piper

Sheeted veins overprinting UST rich cupola – Belltopper Hill

Granites and gold in metamorphic terrains

- This is why metamorphic terrains commonly contain coeval magmatism, orogenic and intrusion related gold deposits
- They are separate manifestations of the same geothermal event
- But how do you tell them apart?



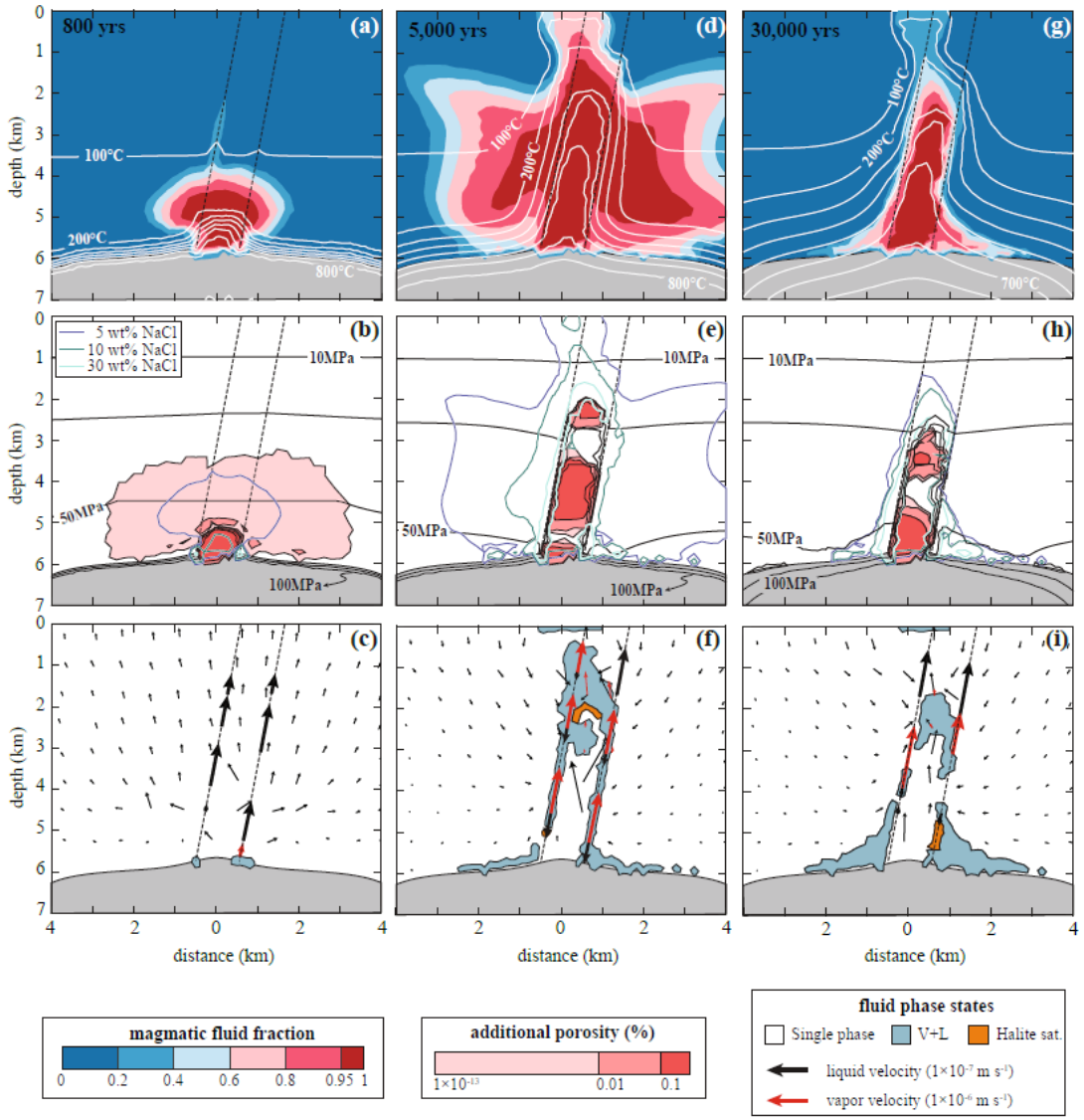
So, how do you tell orogenic from intrusion related gold

Exactly as described in Hart & Goldfarb (2005)

- “Most mineral deposits are classified according to numerous empirically-derived characteristics. However, IRGS and orogenic gold systems share a large number of similar features (i.e., anomalous Bi, W, Te; reduced sulfide assemblages; low salinity, CO_2-bearing fliuids; post-peak metamorphic lodes; spatial/temporal association with granitoids) that mostly result from their formation from fluids with similar compositions, and their formation in settings that both host large amounts of felsic magma. As a result, IRGS are furthermore better recognized using a set of distinguishing features that are particular **to hydrothermal systems surrounding cooling magmatic bodies, which are distinctive from most orogenic gold systems**. “

Hydrothermal systems surrounding cooling magmatic bodies

- Volatiles are concentrated in carapace of cooling magmatic bodies – poorly focussed in large and flat-topped batholiths
- Fluids explosively escape and rise buoyantly through an incredibly steep geotherm > 500 °C/km
- Concentric zoned metal assemblages reflecting °C and pH gradients over 10s to 100s of metres – within hornfels aureole
- Characteristic textures: chaotic breccias, USTs, sheeted veins



(Codeço et al., 2022; Weis, 2014)

Hydrothermal systems surrounding cooling magmatic bodies

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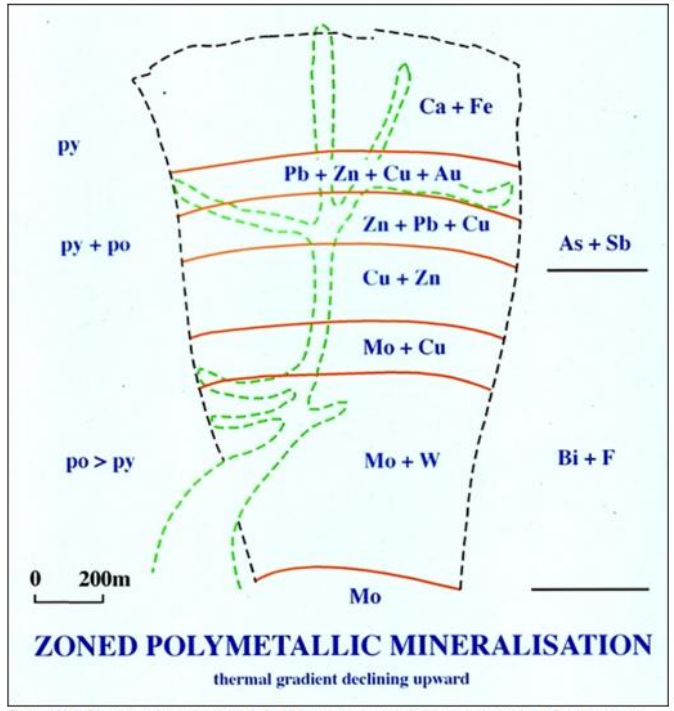


Figure 18.18: Diagrammatic section through the Kidston breccia pipe showing metal zonation reflecting upward decreasing temperature (Lisowiec and Morrison 2013, caption modified from Morrison et al. 2019)

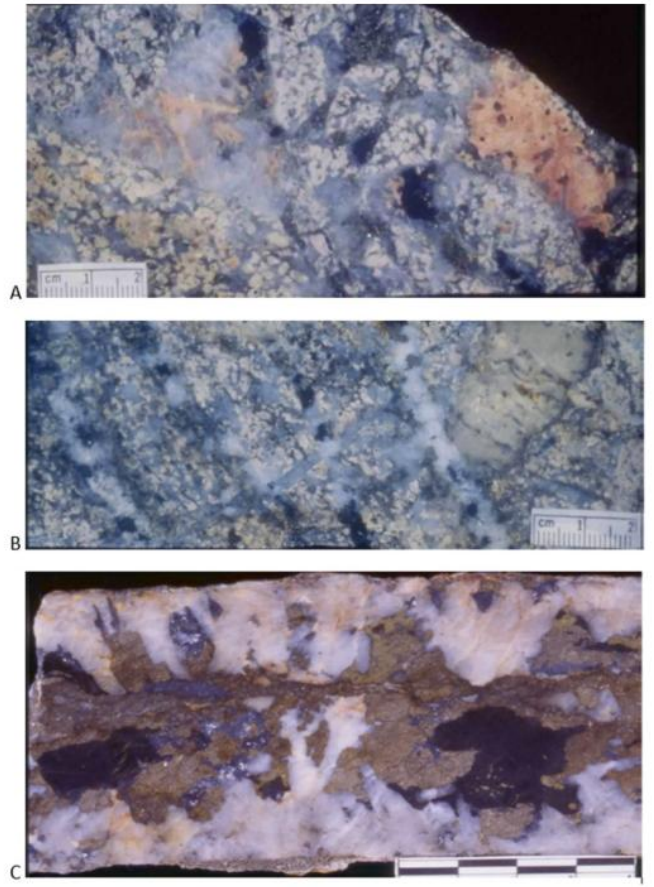
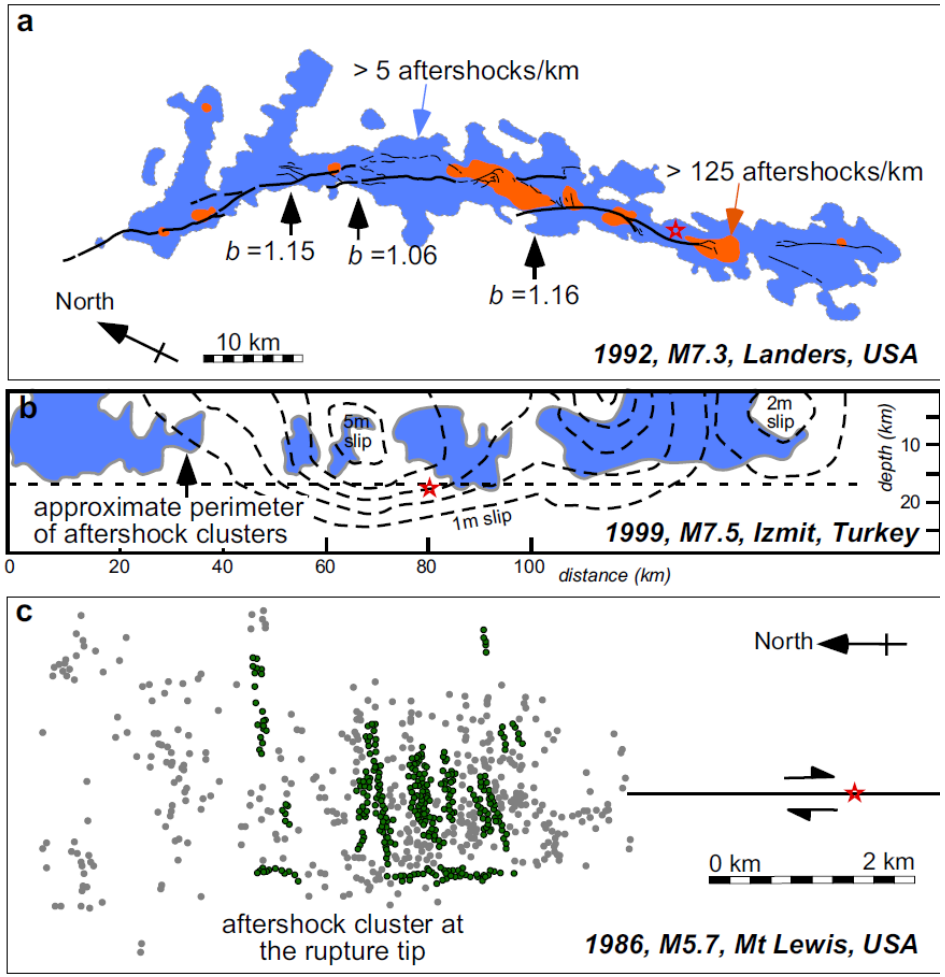


Figure 18.17: Kidston ore types. A - breccia Au ore showing stubby, medium-grained, comb textured quartz crystals lining cavity with later carbonate, pyrite and base metal sulphide filling cavity cores. B – sheeted Au ore with quartz, carbonate, and sulphide infill as breccia matrix. C – sheeted Au ore showing close-up vein of medium-grained, comb textured quartz crystals lining vein margin with later siderite, pyrite and base metal sulphide filling vein cores (taken from Morrison et al 2019, caption modified from Morrison et al 2019).

Kidston, QLD (Allan et al., 2024)

Orogenic gold deposits

- 100s to 1000s of pulses of metamorphic fluid exploiting the same structure(s) in a very similar stress field
- Earthquake aftershock maps show lateral fluid migration and propagation of fluid conduits – ore shoots
- First order control on distribution is regional scale faults
- Deposit metal zoning reflects regional geotherms e.g. 30 – 80 °C/km – presents as (dis)appearance of single isotherm characteristic elements (e.g. Sb @ ~250°C) over scale of orebody e.g. 600 – 1000m
- Characteristic textures: syntectonic laminated-stylolitic-brecciated veins in consistent orientations



Map of earthquake surface rupture trace and contours of aftershock density (Micklethwaite et al., 2010) modified from (Liu et al., 2003)

Orogenic gold deposits

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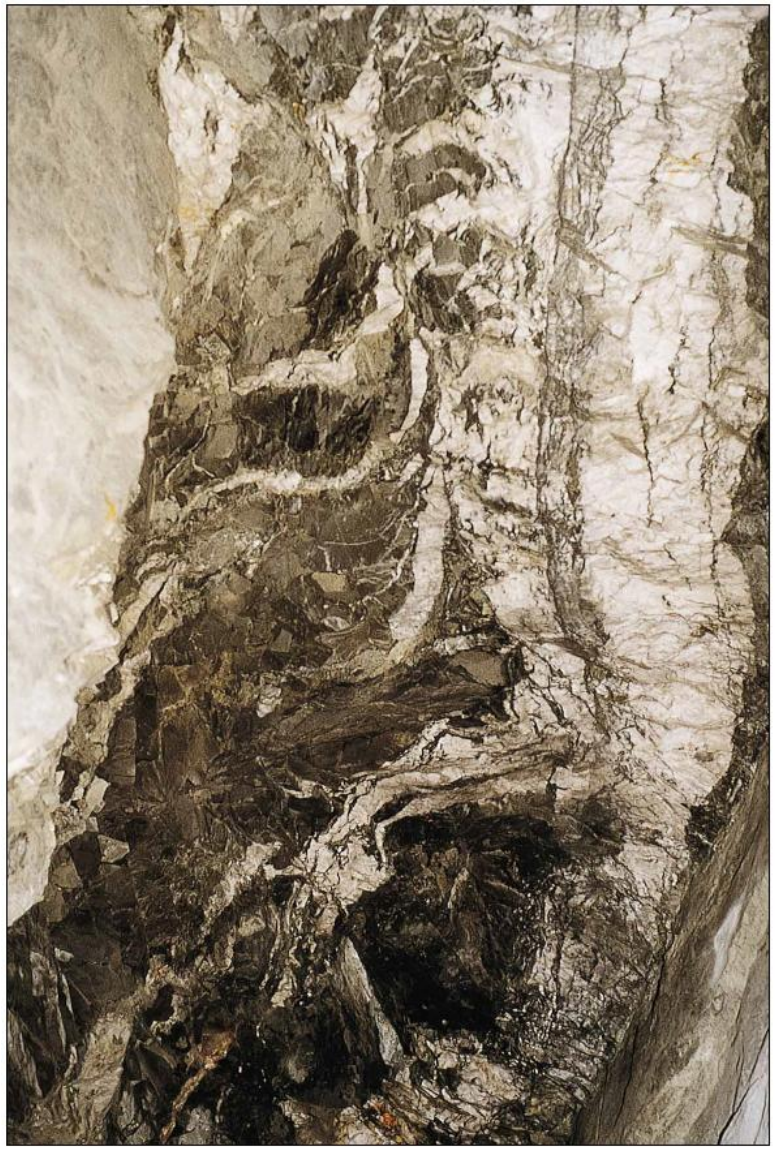


Syn deformation laminated-stylolitic quartz veins Nick O' Time shoot (VandenBerg et al., 2000)

Test empirically – be objective

Deposit	Vein textures	Alteration	Metal assemblage	Metal zoning scale	Magmatic hydrothermal transition	Sheeted veins	Location above small pluton	Distal base metal veins
	Laminated-stylolitic-brecciated	Typical orogenic	Au-Sb-As-W	Potentially crosses two isotherms, broad >500m	No	No	No	No
	Laminated-stylolitic-brecciated	Typical orogenic	As-Sb	Crosses one isotherm, broad >500m	No	No	No	No
	Laminated-stylolitic-brecciated	Intense sericite in diorite dyke, normal orogenic elsewhere	As-Sb	Crosses one isotherm, broad >500m	No	No	No	No
	Laminated-stylolitic	Typical orogenic	As-Sb	Crosses zero isotherms, broad >500m	No	No	No	No
	Laminated-stylolitic	Typical orogenic	As-Sb	Crosses zero isotherms, broad >500m	No	No	No	No
	Stibnite breccia	?	As-Sb-Cu	?	No	No	?	No
	Veins in granite	Sericite pyrite?	Au-Sb-??	?	No	No	?	No
	Laminated-stylolitic	Typical orogenic	Au-Sb	?	No	No	No	No
	Laminated-stylolitic	Typical orogenic	Au-Sb	?	No	No	No	No
	Single phase and undeformed brittle veinlets	Widespread acidic albite destruction	Au-Mo-Bi-Sb-W	Narrow, 200m from Bi-Mo to Sb	? UST, late brittle planar veins in alteration halo, single stage vein	No	In small granite	No
	Massive silica breccia	Widespread greisenisation	Au-Mo-Bi-Sb-W	Narrow, 100 m from Au only to Sb only	Yes - massive silica breccia overlying altered felsic porphyry	No	Yes	No
	Circular hydrothermal stockwork, sheeted veins	?	Au-Mo-Sb	?	Yes, USTs, sheeted veining	Yes	Yes	No

The old paradigm – the Bindian Orogeny

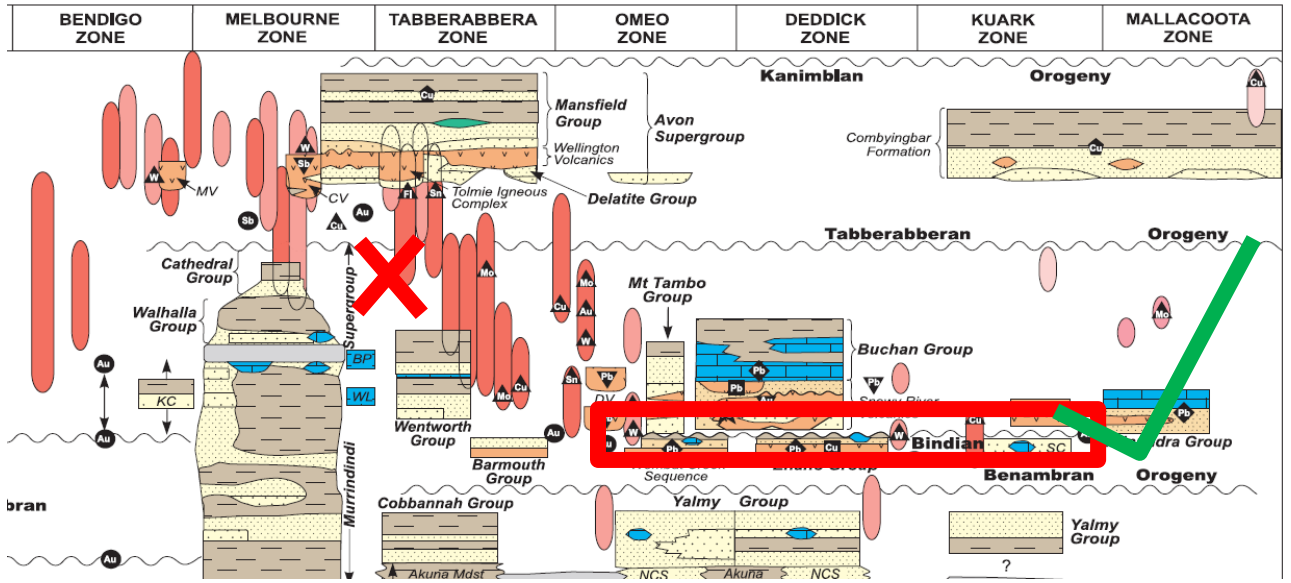
At the end of the Silurian, rocks in the Cowombat Rift were faulted and tightly to isoclinally folded parallel to the rift margins, presumably controlled by the rigid rocks on the rift flanks.

Farther west, in central Victoria, evidence of deformation is absent – indeed, it appears to have had no impact at all, even on sedimentation

Tasman Fold Belt - (VandenBerg et al., 2000)

Table 2.36 Timing constraints on the Bindian Orogeny in the Benambra Terrane

Stratigraphic constraints		Radiometric constraints		
Youngest deformed rocks	**Oldest overlying rocks**	**Metamorphic mica ages**	**Syntectonic intrusion ages**	**Post-tectonic intrusion ages**
Late Silurian Enano and Wombat Creek groups (418 Ma)	Early Devonian Snowy River Volcanics (415–400 Ma)	415–405 Ma (in fault zones)	420–405 Ma	415–395 Ma
Summary: major deformation at about 418–410 Ma, based on stratigraphic and radiometric constraints. The younger ages of syntectonic granites can be interpreted in two ways. Either the effects of the orogeny lasted until about 405 Ma or the region remained above the closure temperature for the isotopic methods used and therefore the younger ages represent a cooling age.				



The new paradigm – the Bindian Orogeny

At the end of the Silurian, rocks in the Cowombat Rift were faulted and tightly to isoclinally folded parallel to the rift margins, presumably controlled by the rigid rocks on the rift flanks.

Deformation progressed west from the hinge of the orocline deforming the Tabberabbera and Melbourne Zones through the early Devonian

Extension prevailed east of the orocline hinge forming magmatic extensional rift basins

Diverse evolving metallogeny systematically reacts to deformation and magmatism

Table 2.36 Timing constraints on the Bindian Orogeny in the Benambra Terrane

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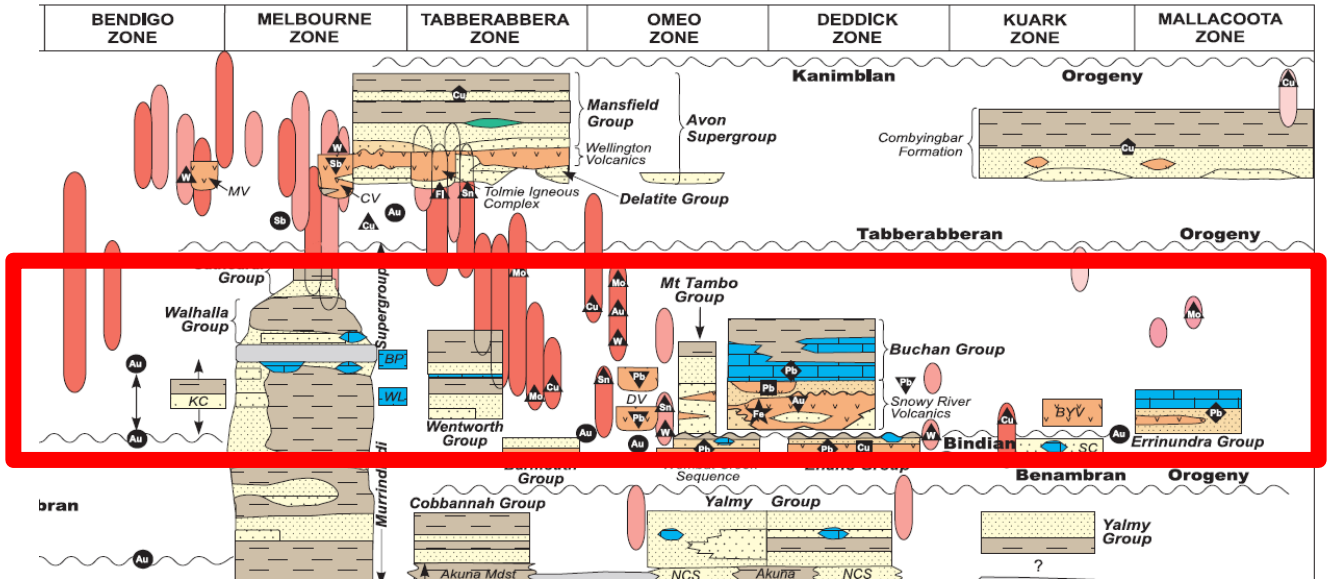


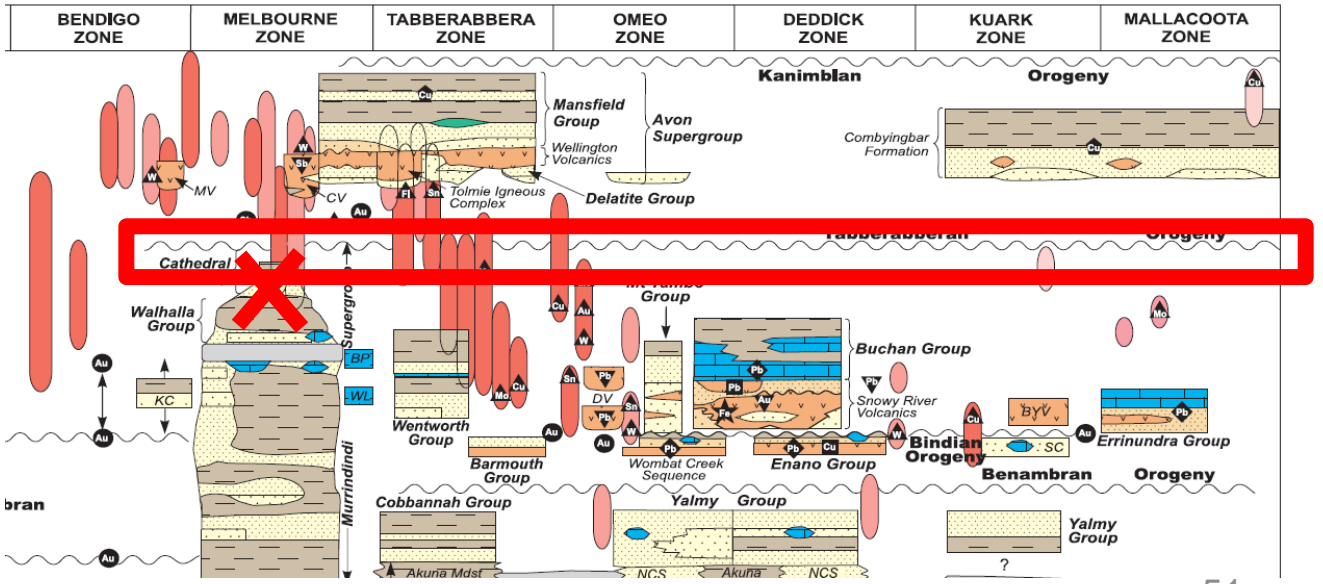
The old paradigm – the Tabberabberan Orogeny

The Tabberabberan Orogeny was the first deformation that affected all parts of the Lachlan Fold Belt in Victoria. The orogeny marks the amalgamation of the Whitelaw and Benambra terranes and cessation of dextral strike-slip movement along the Baragwanath Transform. Its effects were most strongly felt in previously undeformed regions with thick sediment fills such as the Melbourne Zone, Mitchell Syncline, Boulder "graben" and Scrubby Creek Syncline.

Tasman Fold Belt - (VandenBerg et al., 2000)

Table 2.58. Timing constraints on the Tabberabberan Orogeny in Victoria

	Stratigraphic constraints		Radiometric constraints		
	Youngest deformed rocks	**Oldest overlying rocks**	**Metamorphic mica ages**	**Syntectonic intrusion ages**	**Post-tectonic intrusion ages**
Whitelaw Terrane	Early to Middle Devonian Cathedral Group (~385 Ma)	Late Devonian caldera volcanics (370–355 Ma)	390–380 Ma (Melbourne Zone)		375–350 Ma
Benambra Terrane	Early Devonian Wentworth Group (415–400 Ma)	Frasnian (Late Devonian) Lewis Farm Conglom. (370 Ma)	385 Ma (Kancoona Fault)	385 Ma (Mudgeegonga Granite)	
Summary: Well constrained by stratigraphic and radiometric constraints to the interval between 385 and 380 Ma. Final but much weaker deformation straddles the age of the Woods Point Dyke Swarm (~376 Ma) and may have extended to about 370 Ma.					



The new paradigm – the Tabberabberan Orogeny

The Tabberabberan Orogeny was most strongly felt in previously undeformed regions with thick sediment fills such as the Mitchell Syncline, Boulder "graben" and Scrubby Creek Syncline, east of the orocline hinge

Elsewhere, it caused tightening of folds and re-faulting of faults.

Compression was followed by a period of statewide extension-transtension and granite magmatism

Metallogeny related to magmatic underplating, prograde metamorphism and melting of fertile Selwyn Block crust

Table 2.58. Timing constraints on the Tabberabberan Orogeny in Victoria

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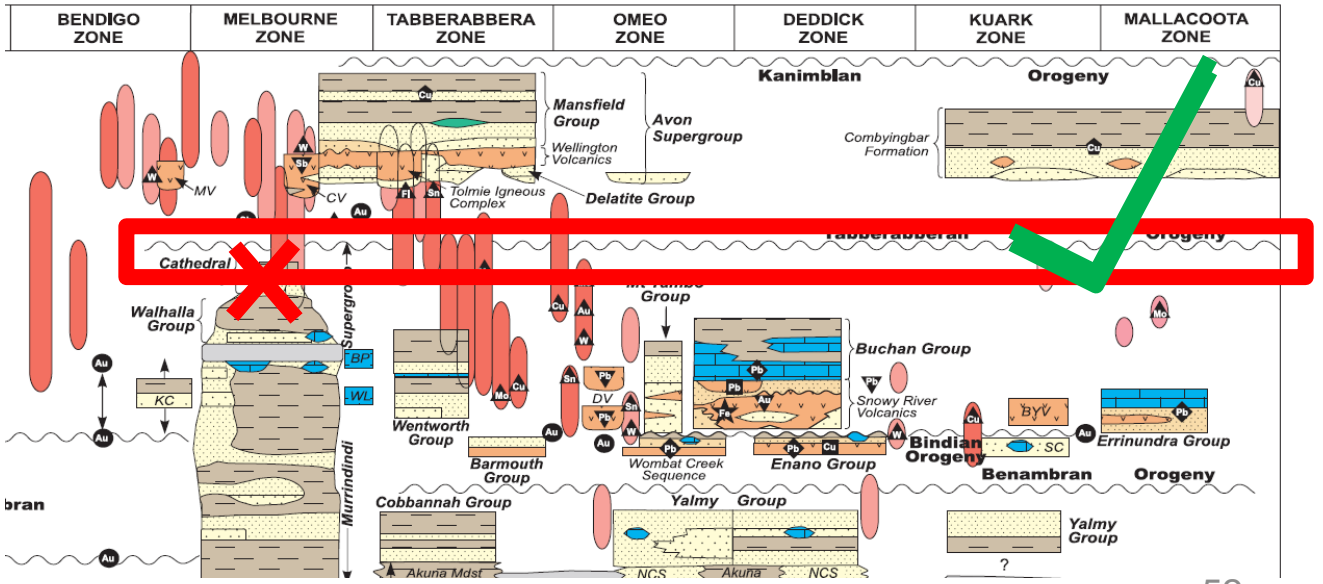

References

- Allan, S., Evans, T., & McGovern, J., 2024. Kidston (Mineral Deposit Atlas), East Queensland Mineral Deposit Atlas. *Geological Survey of Queensland*, Brisbane.
- Andrews, T.M., Cairns, C.P., Cayley, R.A., McLean, M.A., & Skladzien, P.B., in prep. MinEx phase 3 report (Geological Survey Report). *Geological Survey of Victoria*, Melbourne.
- Bierlein, F.P., Arne, D.C., Keay, S.M., & McNaughton, N.J., 2001. Timing relationships between felsic magmatism and mineralisation in the central Victorian gold province, southeast Australia. *Aust. J. Earth Sci.* 48, 883–899. https://doi.org/10.1046/j.1440-0952.2001.00907.x
- Boger, S.D., Schlegel, T.U., & Keays, R.R., 2025. Dyke-hosted copper-nickel-platinum group element mineralisation in Victoria (Geological Survey Report No. 7), Victoria's Critical Minerals and Strategic Materials. *Geological Survey of Victoria*, Melbourne.
- Brauhart, C.W., & Groves, D.I., 2026. Australian intracratonic copper-gold and allied deposits: A clan of mineral systems. *Gondwana Res.* 149, 158–182. https://doi.org/10.1016/j.gr.2025.08.011
- Codeço, M.S., Weis, P., & Andersen, C., 2022. Numerical Modeling of Structurally Controlled Ore Formation in Magmatic-Hydrothermal Systems. *Geochem. Geophys. Geosystems* 23, e2021GC010302. https://doi.org/10.1029/2021GC010302
- Elburg, M.A., 1996. U-Pb ages and morphologies of zircon in micrograniteoid enclaves and peraluminous host granite: evidence for magma mingling. *Contrib. Mineral. Petrol.* 123, 177–189. https://doi.org/10.1007/s004100050149
- Gray, D.R., & Mortimer, L., 1996. Implications of overprinting deformations and fold interference patterns in the Melbourne Zone, Lachlan Fold Belt. *Aust. J. Earth Sci.* 43, 103–114. https://doi.org/10.1080/08120099608728240
- Hart, C., & Goldfarb, R., 2005. Distinguishing intrusion-related from orogenic gold systems. *Proc. Sci. Conf. Miner. N. Z.*
- Highlake Resources, 2009. EL4743, Boorhaman (Annual technical report). Victoria.
- Latheef Thathrampally, A., Chakravarti, R., Laflamme, C., & Olin, P., 2025. Gold and Trace Element Release From Pyrite During Prograde Metamorphism of Carbonaceous Metapelites: Implications for Orogenic Gold Formation. *Econ. Geol.* https://doi.org/10.5382/econgeo.5168
- Liu, J., Sieh, K., & Hauksson, E., 2003. A Structural Interpretation of the Aftershock "Cloud" of the 1992 Mw 7.3 Landers Earthquake. *Bull. Seismol. Soc. Am.* 93, 1333–1344. https://doi.org/10.1785/0120020060
- Micklethwaite, S., Sheldon, H., & Baker, T., 2010. Active fault and shear processes and their implications for mineral deposit formation and discovery. *J. Struct. Geol. - J STRUCT GEOL* 32, 151–165. https://doi.org/10.1016/j.jsg.2009.10.009
- Miles, A.J., Woodcock, N.H., & Hawkesworth, C.J., 2016. Tectonic controls on post-subduction granite genesis and emplacement: The late Caledonian suite of Britain and Ireland. *Gondwana Res.* 39, 250–260. https://doi.org/10.1016/j.gr.2016.02.006
- Morand, V.J., Simons, B.A., Taylor, D.H., Wholt, K.E., Cayley, R.A., Maher, S., Wohlt, K.E., & Radojkovic, A.M., 2005. Bogong 1:100,000 map area geological report. (Technical Report No. 125). *Geological Survey of Victoria*.
- Ryan, S.M., 1992. The sedimentology of the Cathedral Formation, Cathedral Range, north-central Victoria (Honours). *La Trobe University*, Melbourne.
- Sibson, R.H., 1990. Conditions for fault-valve behaviour. *Geol. Soc. Lond. Spec. Publ.* 54, 15–28. https://doi.org/10.1144/GSL.SP.1990.054.01.02
- Spaggiari, C.V., Gray, D.R., Foster, D.A., & McKnight, S., 2003. Evolution of the boundary between the western and central Lachlan Orogen: implications for Tasmanide tectonics. *Aust. J. Earth Sci.* 50, 725–749. https://doi.org/10.1111/j.1440-0952.2003.01022.x
- Tomkins, A.G., 2010. Windows of metamorphic sulfur liberation in the crust: Implications for gold deposit genesis. *Geochim. Cosmochim. Acta* 74, 3246–3259. https://doi.org/10.1016/j.gca.2010.03.003
- VandenBerg, A.H.M., 2003. Silurian to Early Devonian, in: Birch, W.D. (Ed.), Geology of Victoria, Geological Society of Australia Special Publication. *Geological Society of Australia (Victoria Division)*, pp. 117–155.
- VandenBerg, A.H.M., Cayley, R.A., Willman, C.E., Morand, V.J., Seymon, A.R., Osborne, C.R., Taylor, D.H., Haydon, S.J., McLean, M., Quinn, C., Jackson, P., & Sandford, A.C., 2006. Walhalla – Woods Point – Tallangallook special map area geological report. (Technical Report No. 127). *Geological Survey of Victoria*.
- VandenBerg, A.H.M., Willman, C.E., Maher, S., Simons, B.A., Cayley, R.A., Taylor, D.H., Morand, V.J., Moore, D.H., & Radojkovic, A.M. (Eds.), 2000. The Tasman fold belt system in Victoria : geology and mineralisation of proterozoic to carboniferous rocks. *Geological Survey of Victoria, Dept. of Natural Resources and Environment,* East Melbourne, Vic.
- Waugh, S.A.F., Creaser, R.A., Cairns, C.P., Duncan, R.A., & Cayley, R.A., 2024a. Re-Os geochronology of Victorian mineral occurrences (Geological Survey Report No. 5), Victoria's Critical Minerals and Strategic Materials. *Geological Survey of Victoria*, Melbourne.
- Waugh, S.A.F., Holm-Denoma, C.S., Wintzer, N.E., & Cairns, C.P., 2024b. U-Pb cassiterite, scheelite and wolframite ages from Victorian tin and tungsten occurrences (Geological Survey Report No. 6), Victoria's Critical Minerals and Strategic Materials. *Geological Survey of Victoria*, Melbourne.
- Webb, K.L., 2010. The Boorhaman Intrusive Complex, Victoria: geology, geochemistry, geochronology and potential for porphyry-style mineralisation (Honours). *University of Tasmania*, Hobart.
- Weis, P., 2014. The Physical Hydrology of Ore-Forming Magmatic-Hydrothermal Systems, in: Kelley, K.D., & Golden, H.C. (Eds.), Building Exploration Capability for the 21st Century. *Society of Economic Geologists*, p. 0. https://doi.org/10.5382/SP.18.04

Thank you

Tom Andrews

Senior Geoscientist – Minerals

Geological Survey of Victoria

tom.andrews@deeca.vic.gov.au