Goldey Rocks and the Vee'd pairs –

why deep seismic reflection profiles across central Victoria suggest external origins for Melbourne Zone 'orogenic' gold, and provide a predictive pathway to places we think might be just right for new discovery

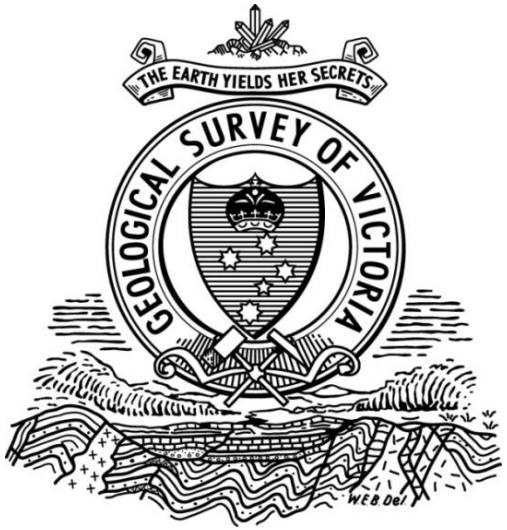
Ross Cayley

February 2023

GEOLOGICAL SURVEY OF VICTORIA

Australian Government

Geoscience Australia



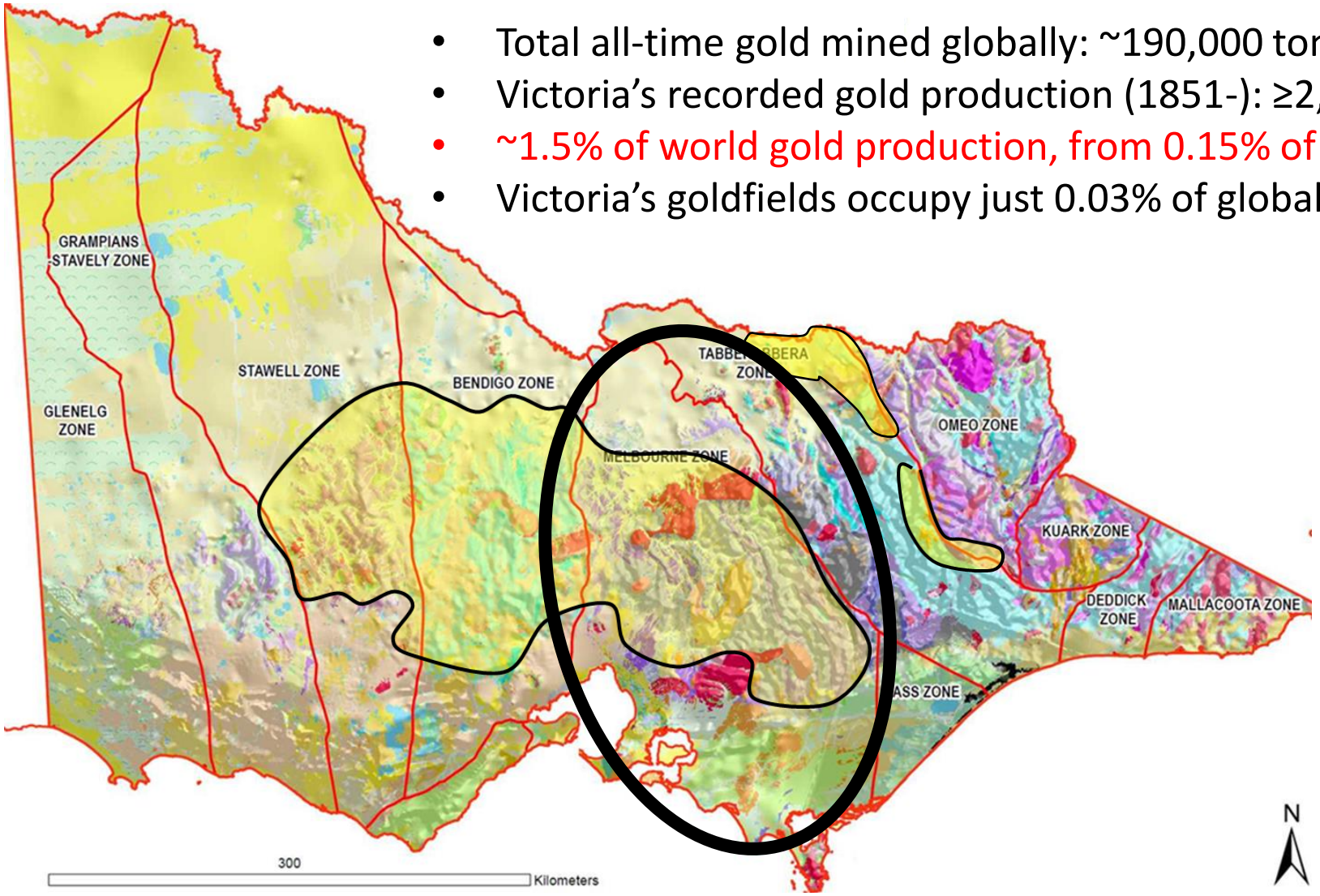
GEOLOGICAL SURVEY OF VICTORIA

ANSIR NATIONAL RESEARCH FACILITY FOR EARTH SOUNDING

AuScope

Gold in Victoria

- Total all-time gold mined globally: ~190,000 tonnes*
- Victoria's recorded gold production (1851-): ≥2,600 tonnes+
- ~1.5% of world gold production, from 0.15% of global land area
- Victoria's goldfields occupy just 0.03% of global land area



The Melbourne Zone

*World Gold Council 2019

Talk outline

- ‘Orogenic gold’ – what is it and how to recognize the it?
- Central Victoria (the ‘Melbourne Zone’) is different to adjacent parts of Victoria.
- The western Melbourne Zone - mapping and deep seismic reflection data both suggest fluid plumbing system linkage into adjacent Bendigo Zone orogenic gold systems
- The eastern Melbourne Zone – 5 M oz+ of gold endowment with a different (intrusion-related) association.
- Previous internally-sourced models to explain Walhalla-Woods Point gold mineralization
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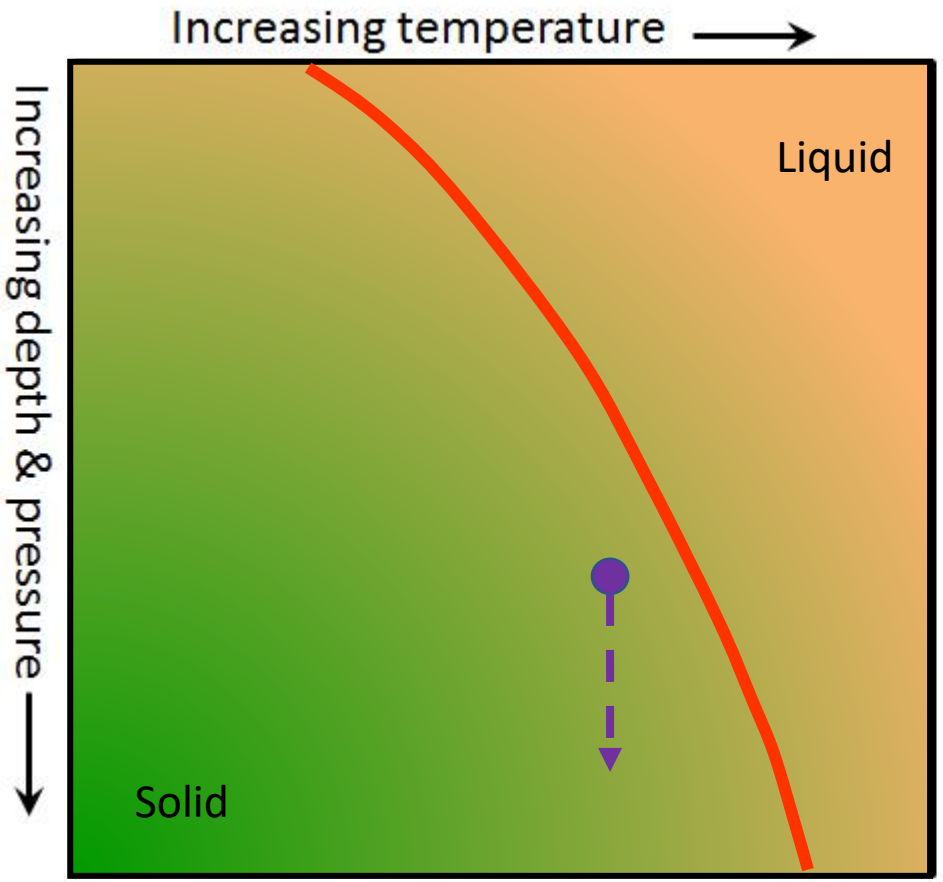
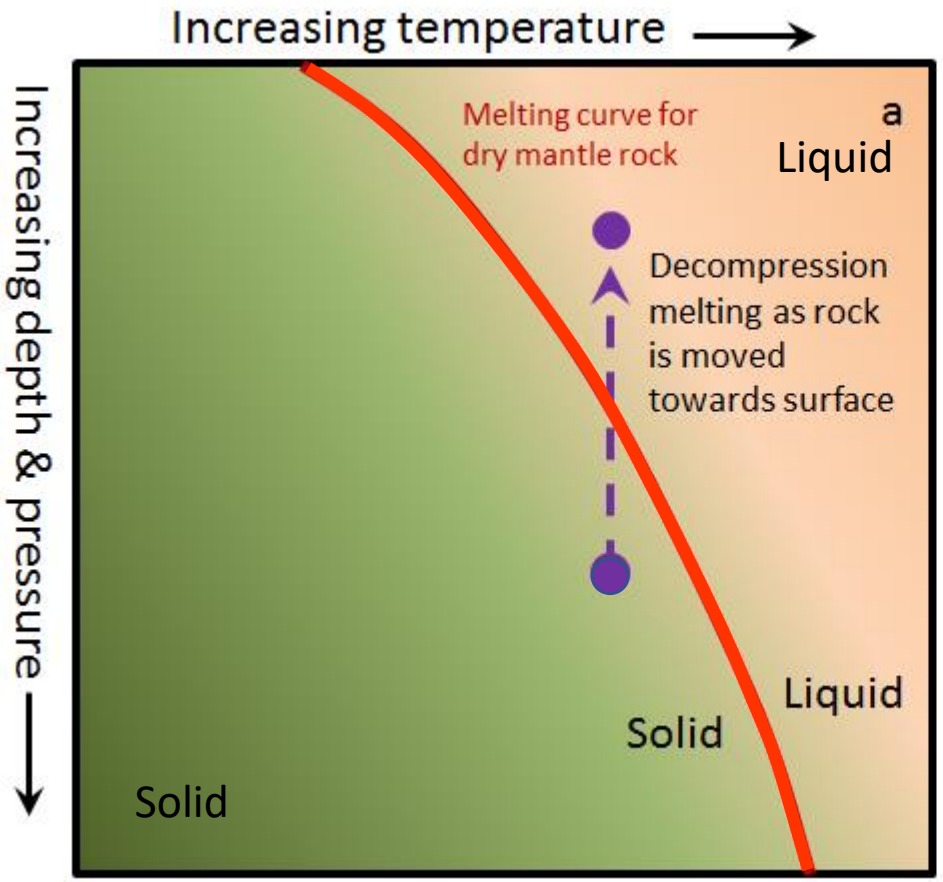


Crustal thickening (folding, thrust faulting, Barrovian-style prograde metamorphism – things familiar to Victorian orogenic gold buffs).
Drives crust to depth, leading to increasing pressure, devolatilization and fluid generation.
On its own, ***incompatible*** with the generation of mantle and crustal melts.
(rock moves away from the liquidus).

Gold deposits like Bendigo, Ballarat, Stawell, formed around 450—440 Ma, fit this association – for example: there is no local magmatism within 30 million years either before or after this large, regional scale mineralisation event.

Figure adapted from: Stephen Earle, 2019.

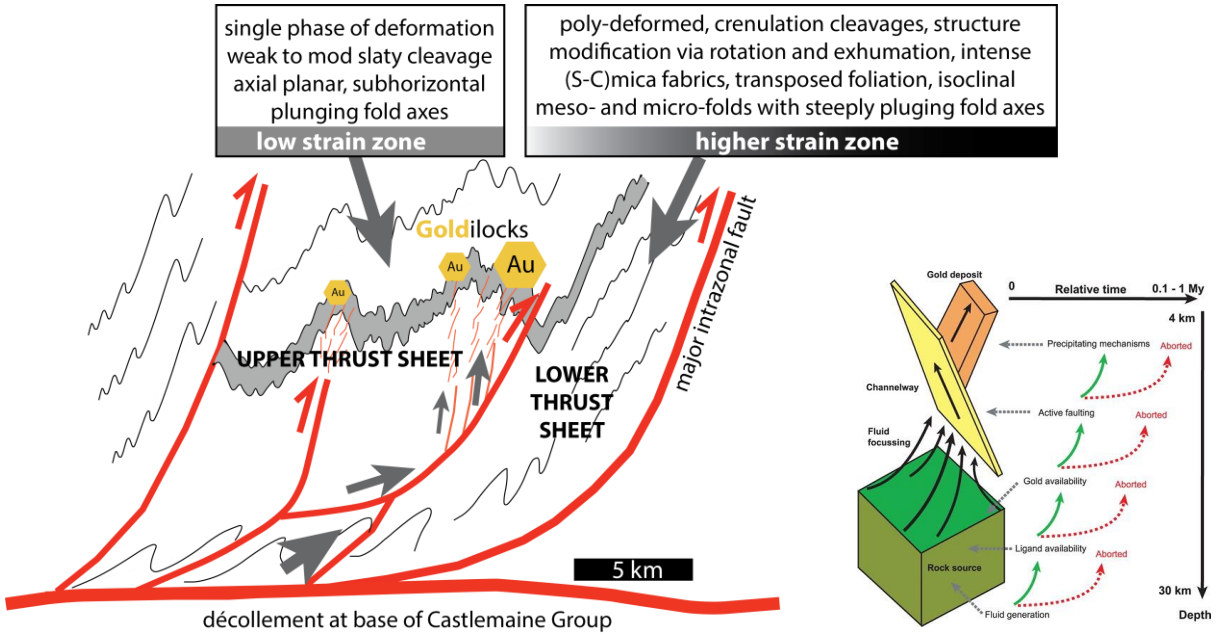


Crustal thinning (extension, rifting, Buchan-style metamorphism.
Lifts crust towards surface, leading to decreasing pressure.
Conditions typically associated with the generation of mantle and crustal melts (rock moves towards the liquidus).

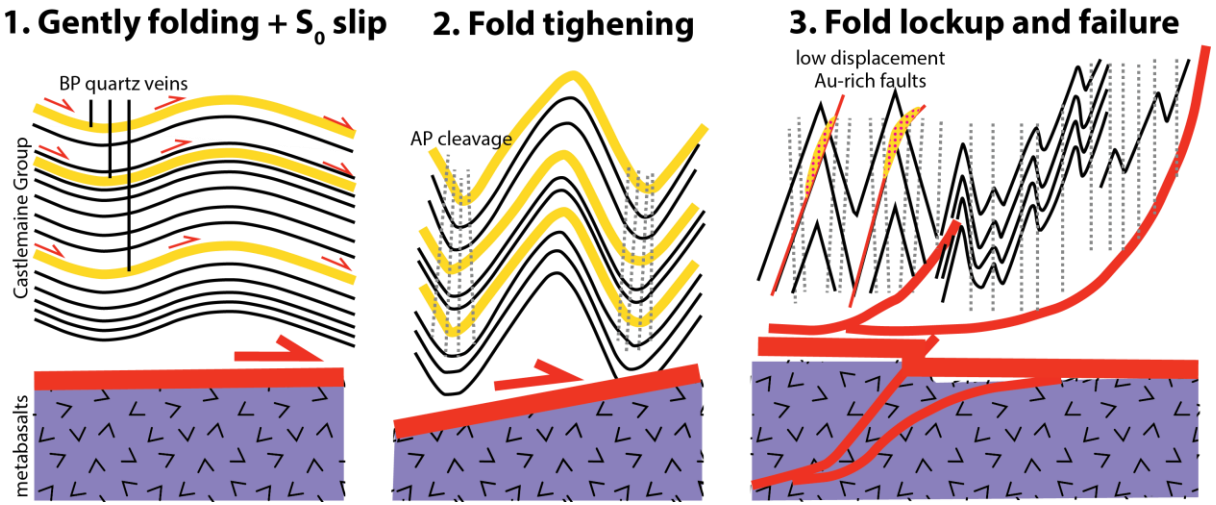
Possibility of advective heat addition to crust due to magma introduction - leading to devolatilisation and fluid generation – might result in deposits that look similar to classic 'orogenic' deposits anyway – but with a temporal association with magmatism.

How many Victorian gold systems fit this association?

Figure adapted from: Stephen Earle, 2019.



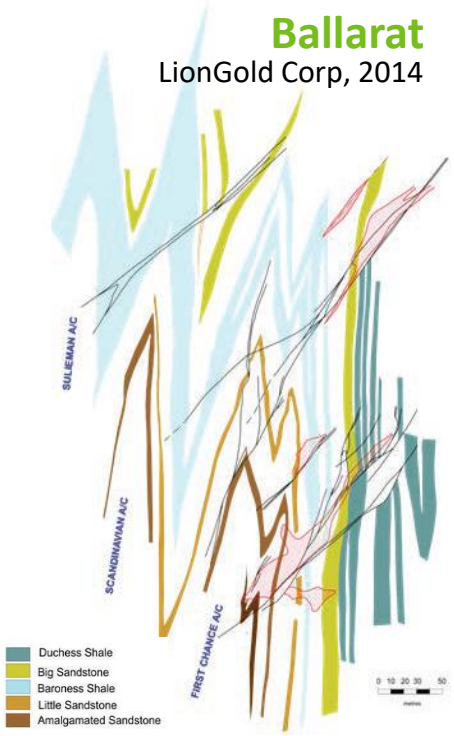
Eg: Willman 2007 Min Dep



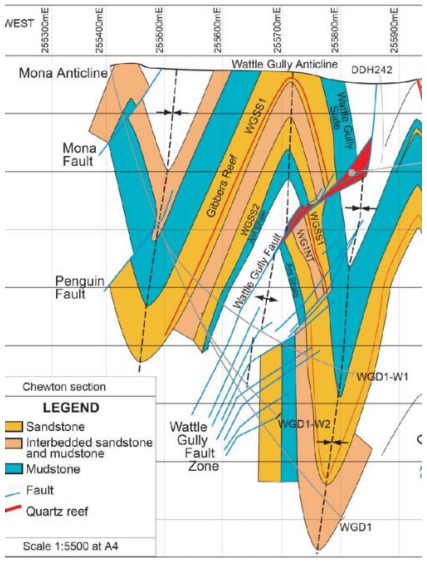
Minerals Systems Models:

‘Classic’ orogenic gold system models for western/central Victoria: an crustal thickening association, that is inherently amagmatic: results in similar looking deposits across the Bendigo Zone for example:

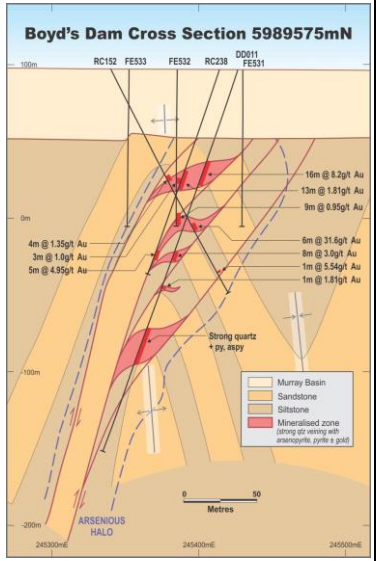
Ballarat
LionGold Corp, 2014



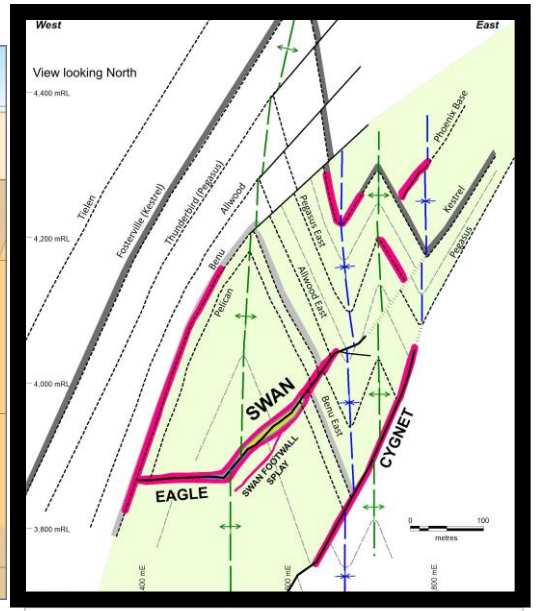
Wattle Gully
Arne et al., 2016 AJES



Four Eagles
Charlton, 2019



Fosterville
Kirkland Lake Gold, 2018



No associated magmatism

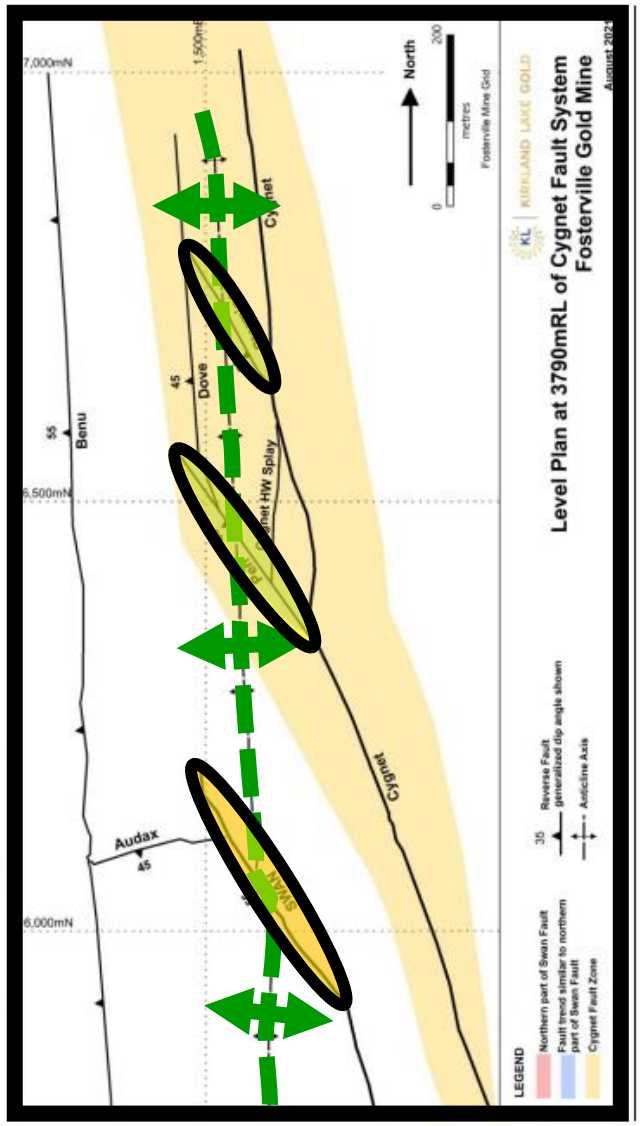
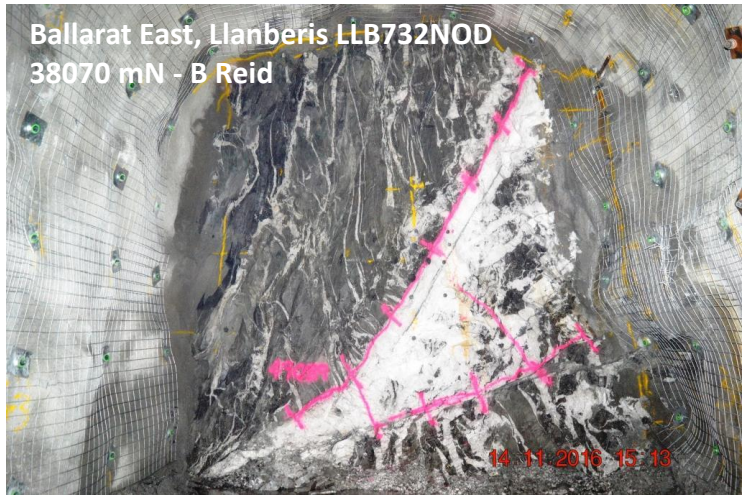
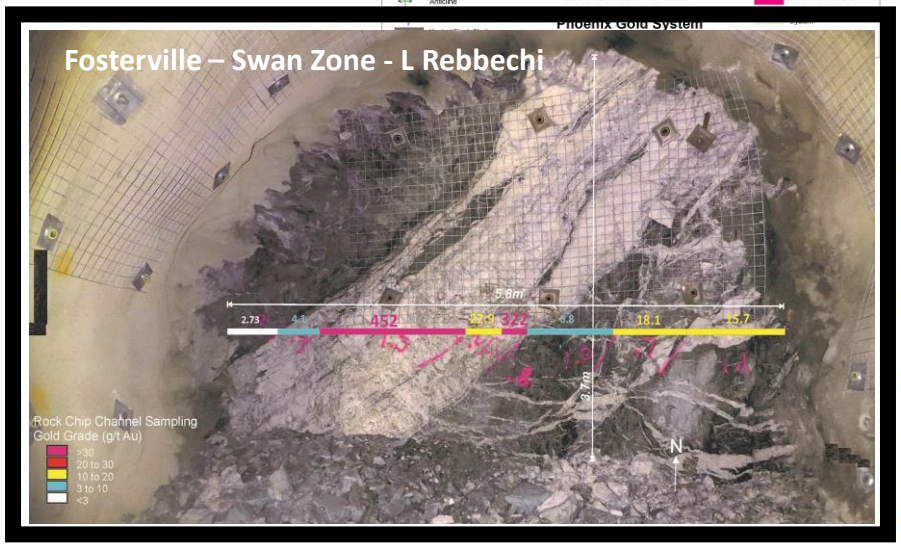


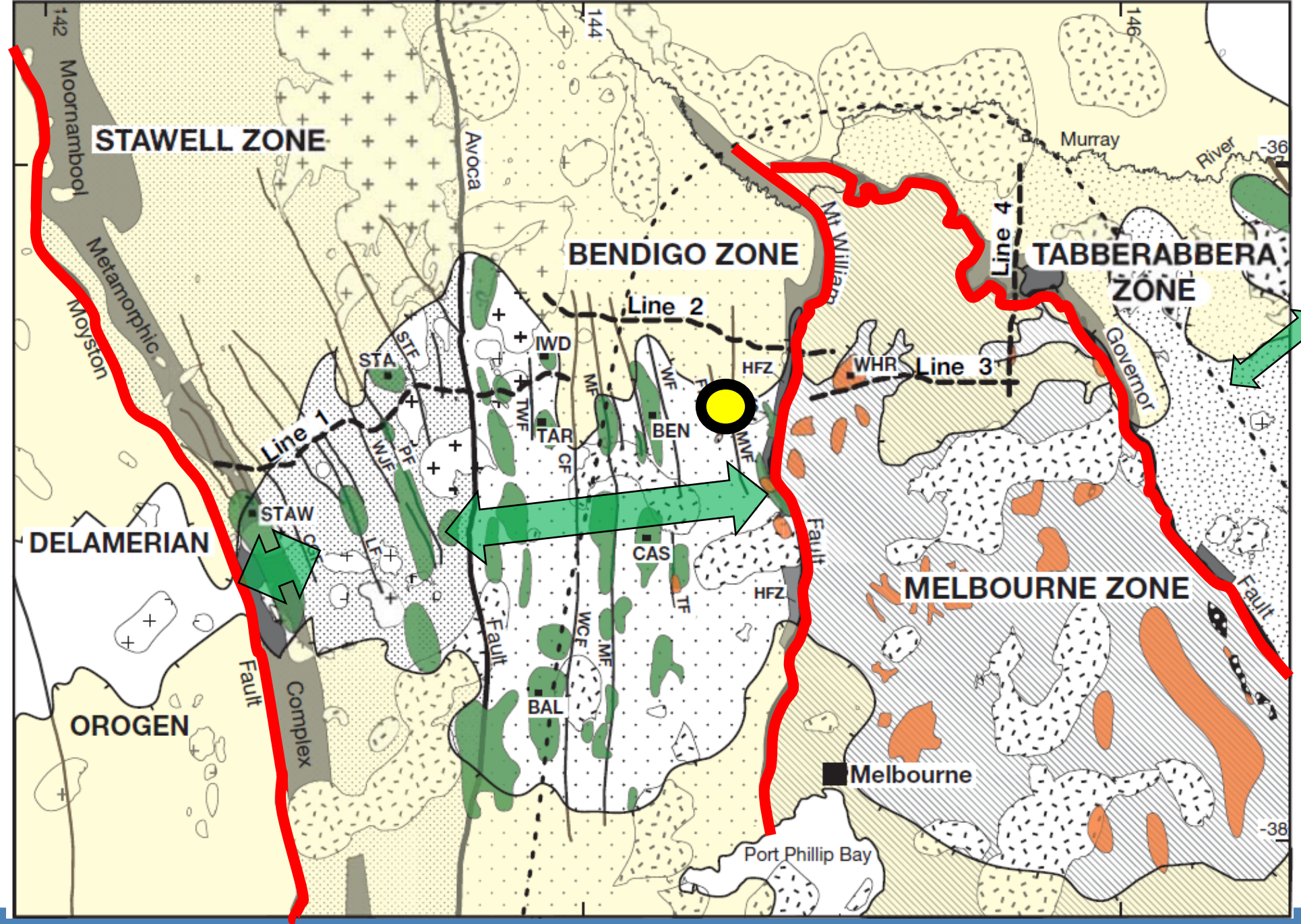
Figure 3. Plan View – Cygnet Fault System





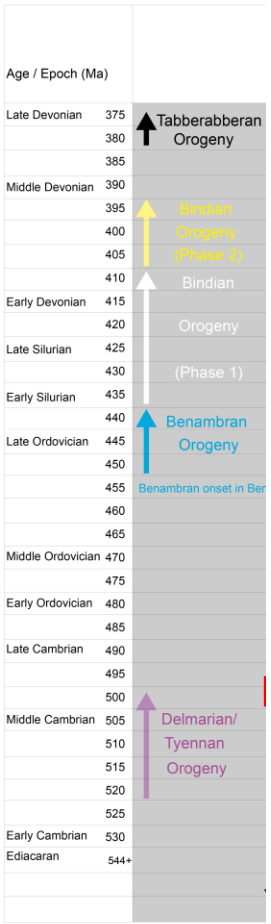
Orogenic gold

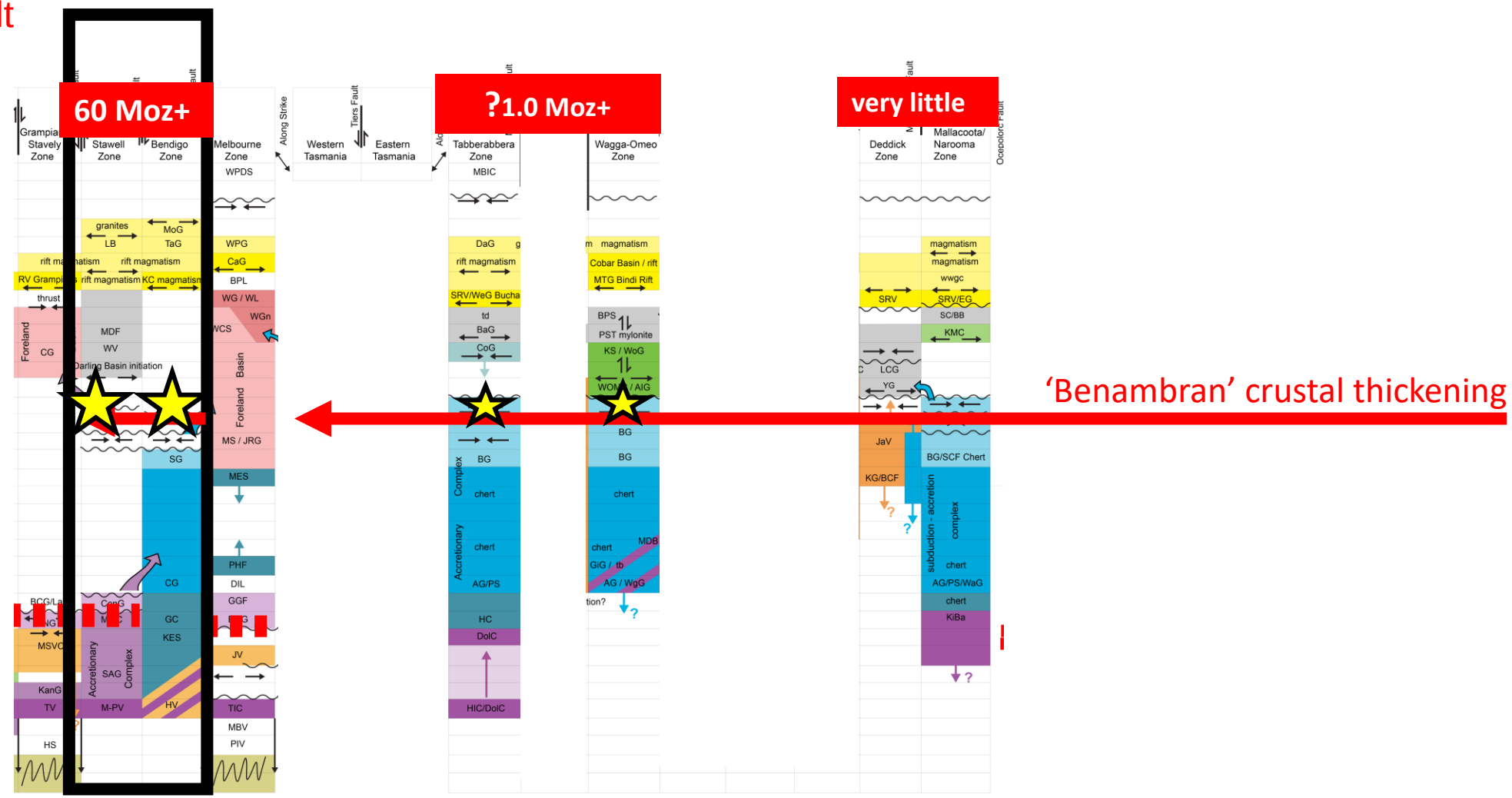
~450-440 Ma



Delamerian Fold Belt

Lachlan Fold Belt





Time-space plot : Victoria

Cayley & Musgrave, in prep

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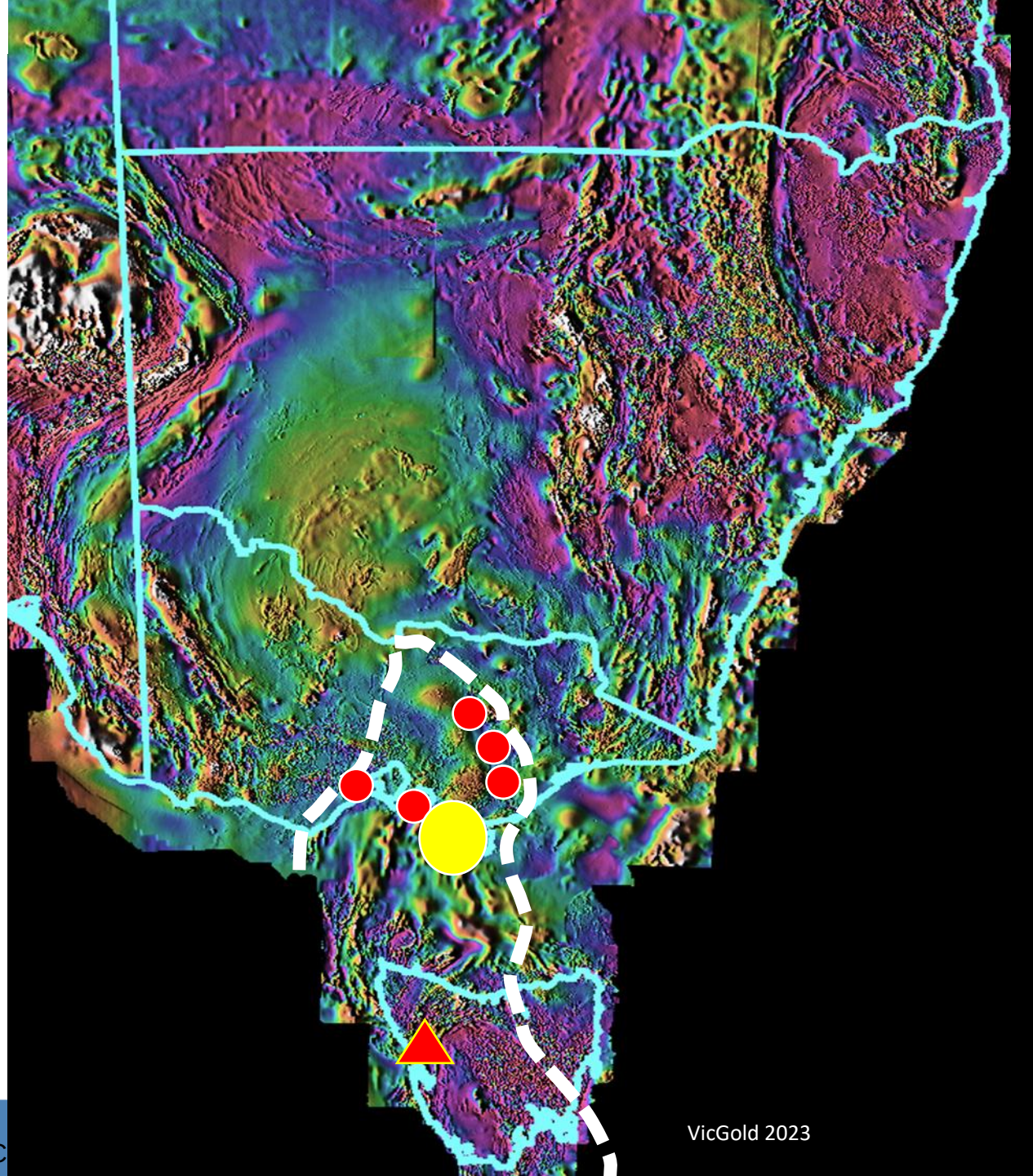
Western Tasmania and its northern extension…
the Selwyn Block.
(Cayley et al., 2002)

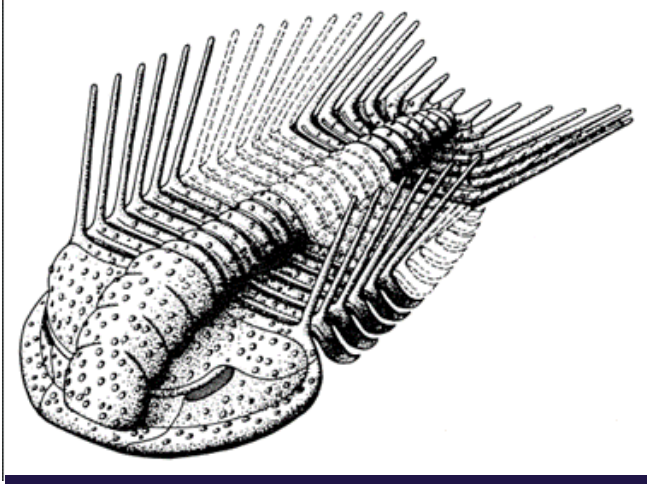
The Vandieland microcontinent –
Proterozoic crust beneath central Victoria
(Cayley, 2011)

Cambrian Jamieson Volcanics (Vic)

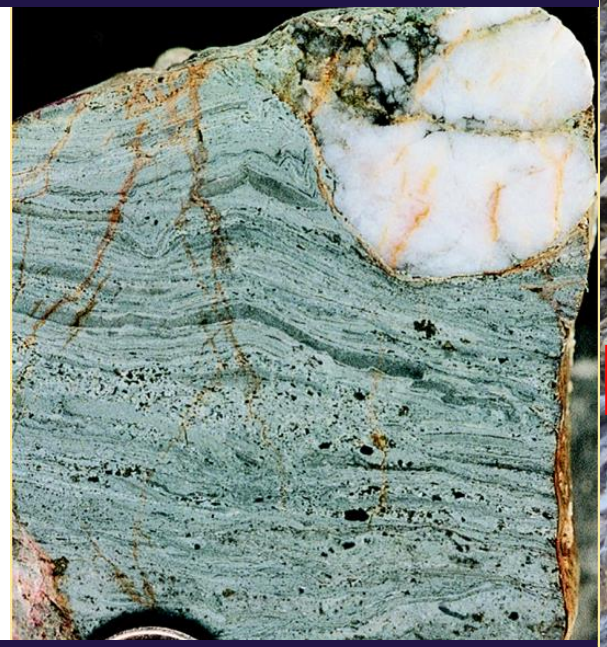
coeval with (and along strike from)
Mount Read Volcanics
Dundas ‘Trough’ (Tas) ▲



VicGold 2023



Early Lancefieldian – ~490Ma+



Bear Gully Gritstone

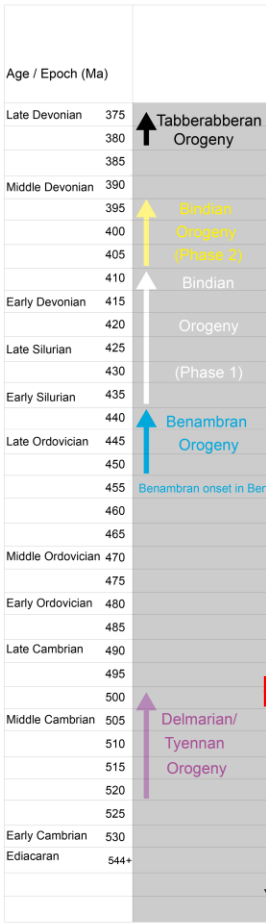
‘Tyennan’ age unconformity and western Tasmania-style rock associations well exposed at Waratah Bay (Cayley et al., 2002)

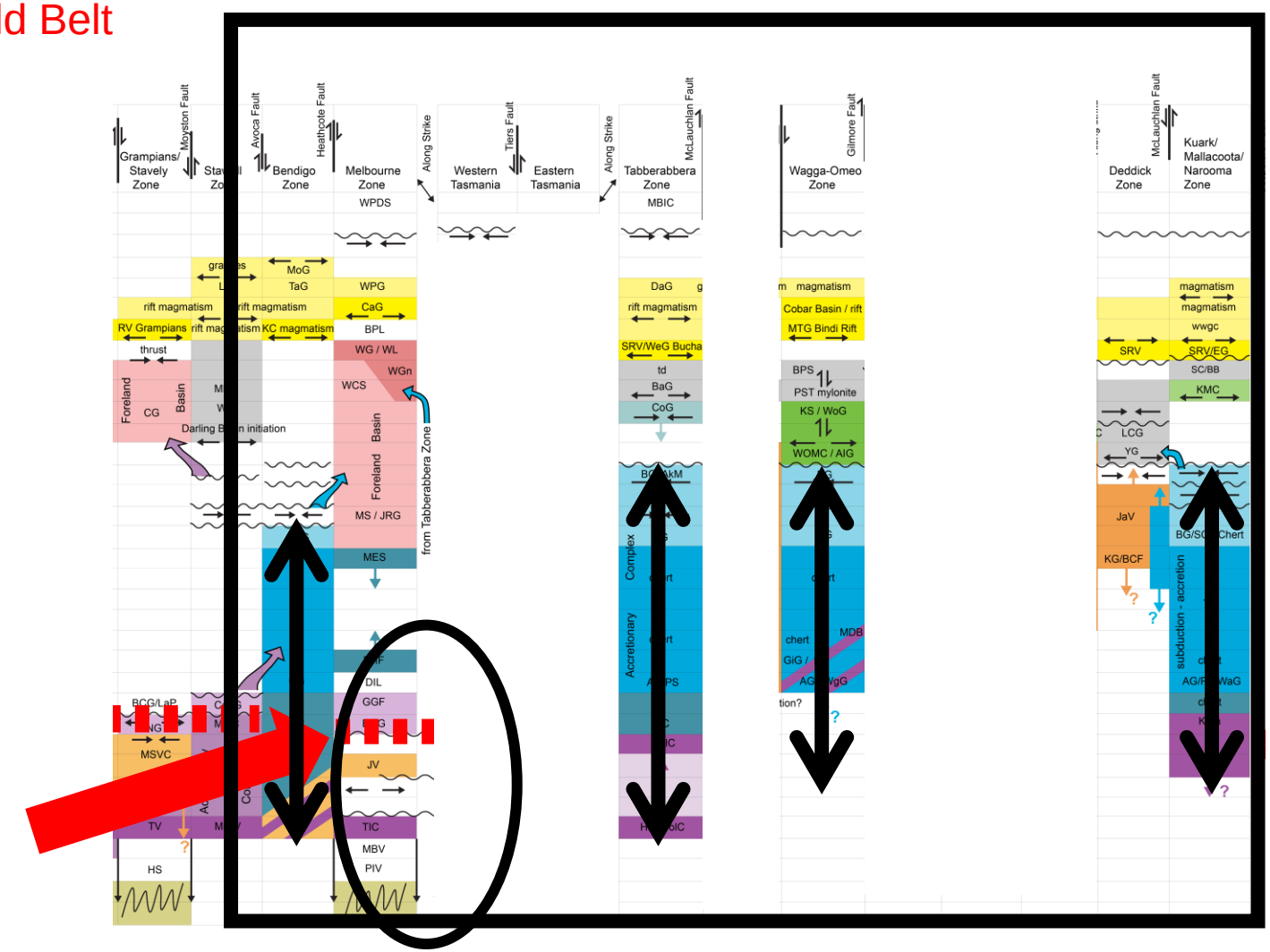
VicGold 2023

GEOLOGICAL SURVEY OF VICTORIA

Delamerian Fold Belt

Lachlan Fold Belt



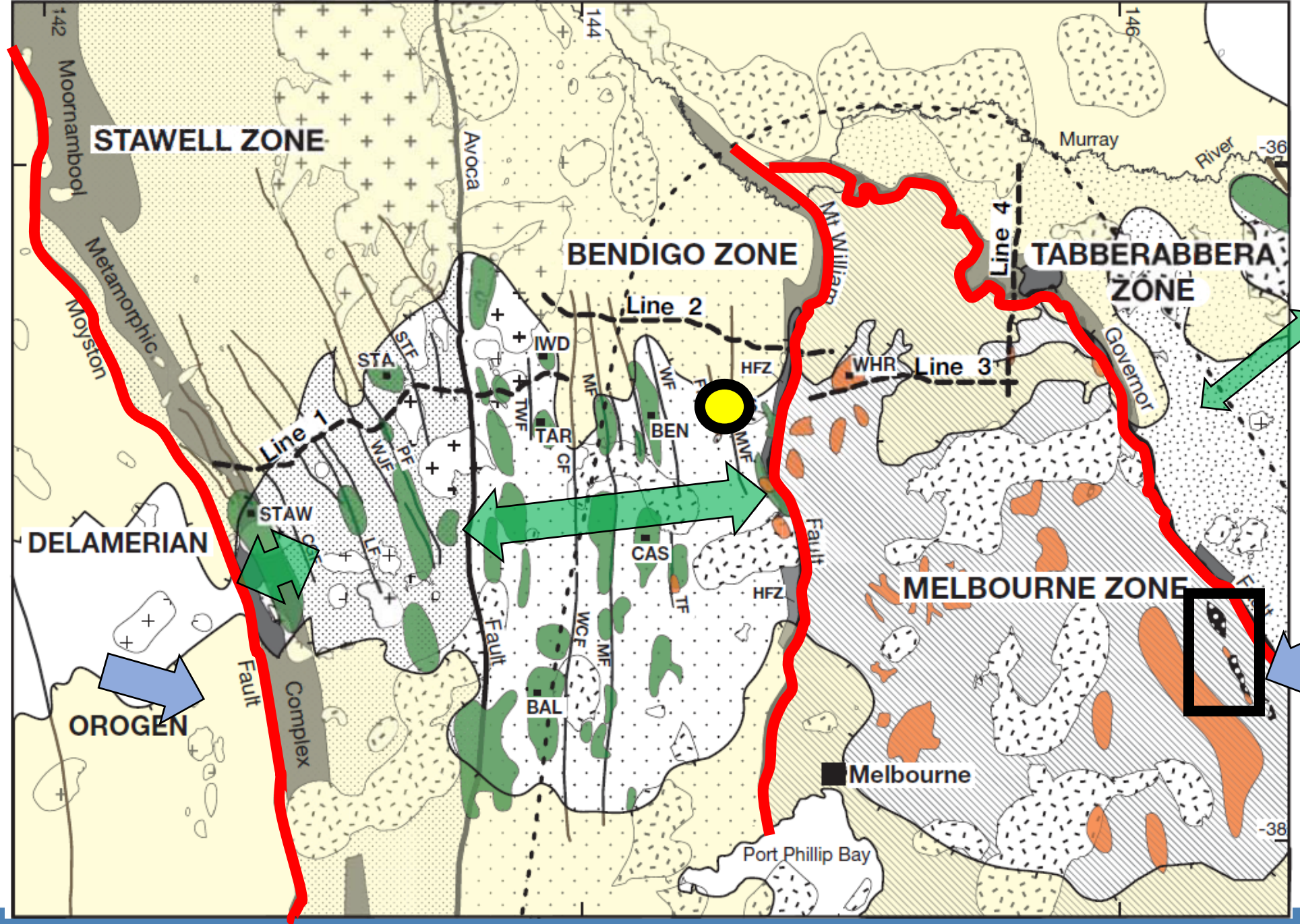


Time-space plot : Victoria

Cayley & Musgrave, in prep

Orogenic gold

~450-440 Ma



Intrusion-related Cu / Au

~500 Ma

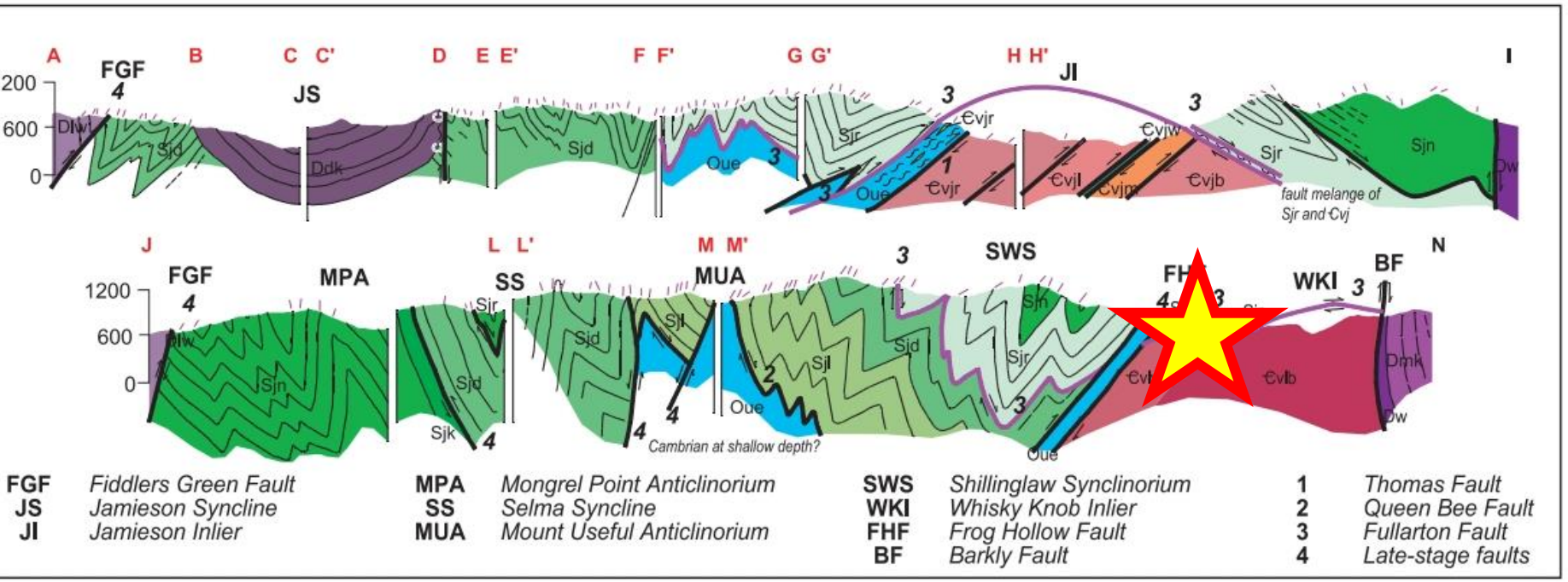
(eg 'Hill 800')

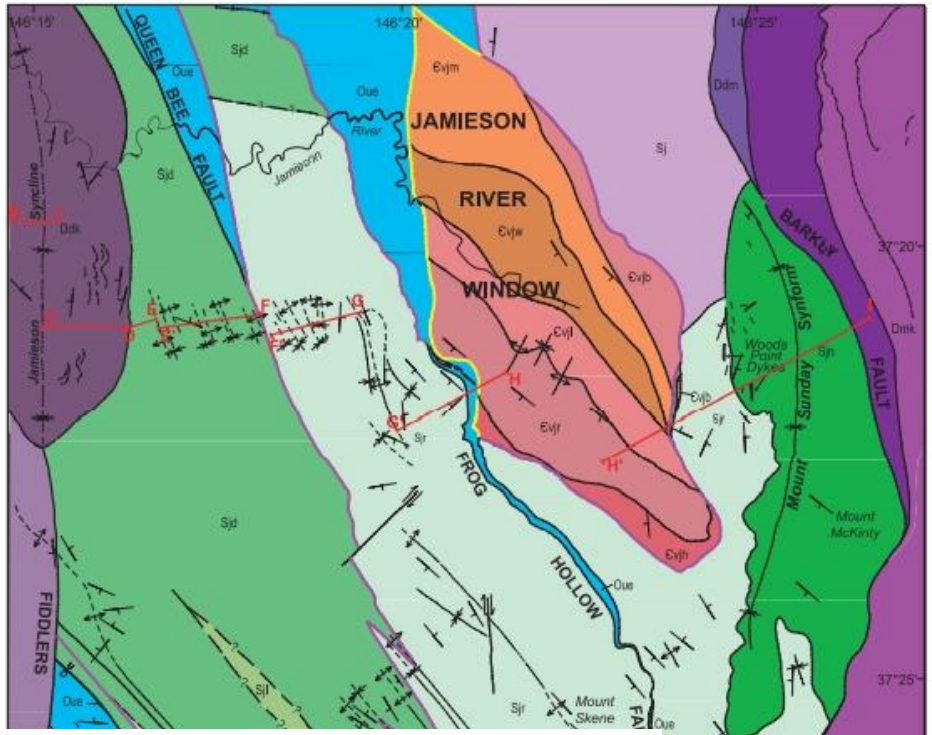
VicGold 2023

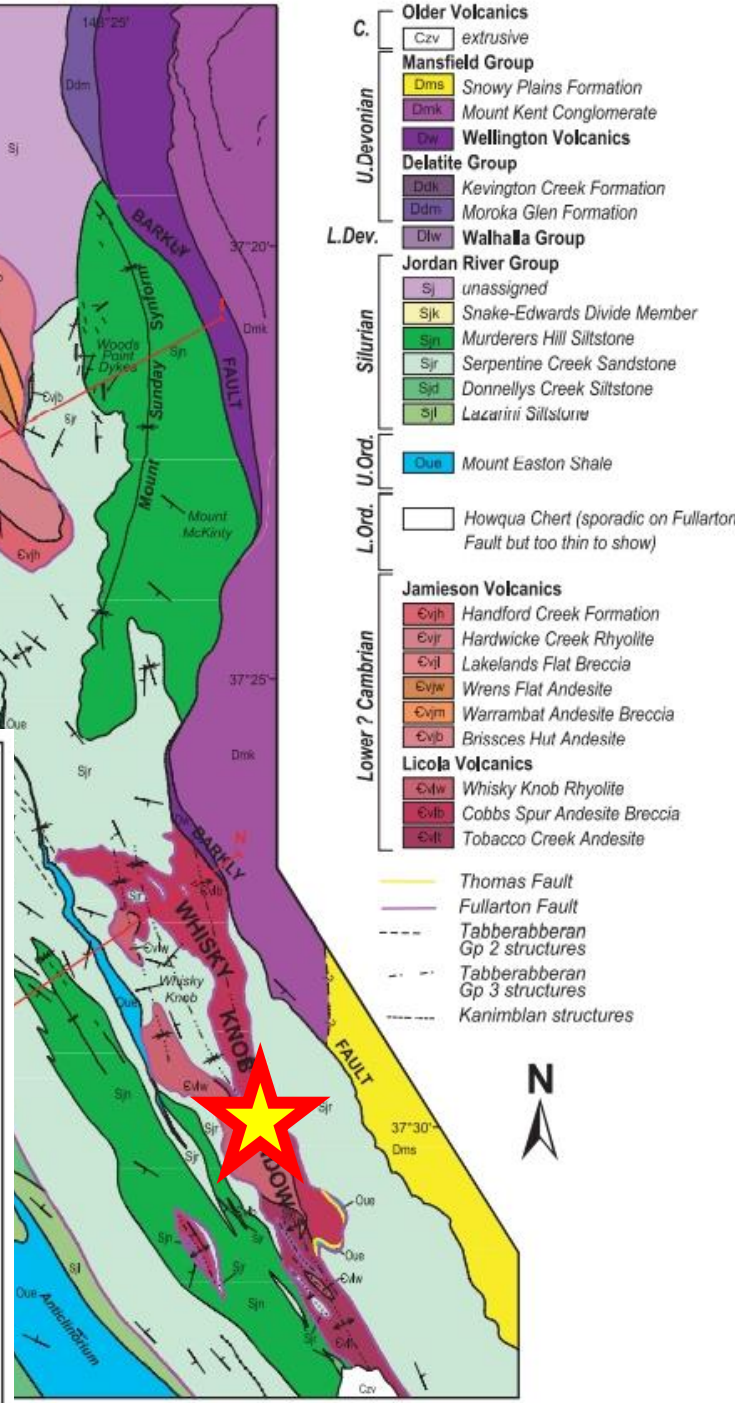
‘Windows’ of Selwyn Block crust
exposed beneath overthrust Melbourne Zone stratigraphy

VandenBerg et al., 1995

https://www.youtube.com



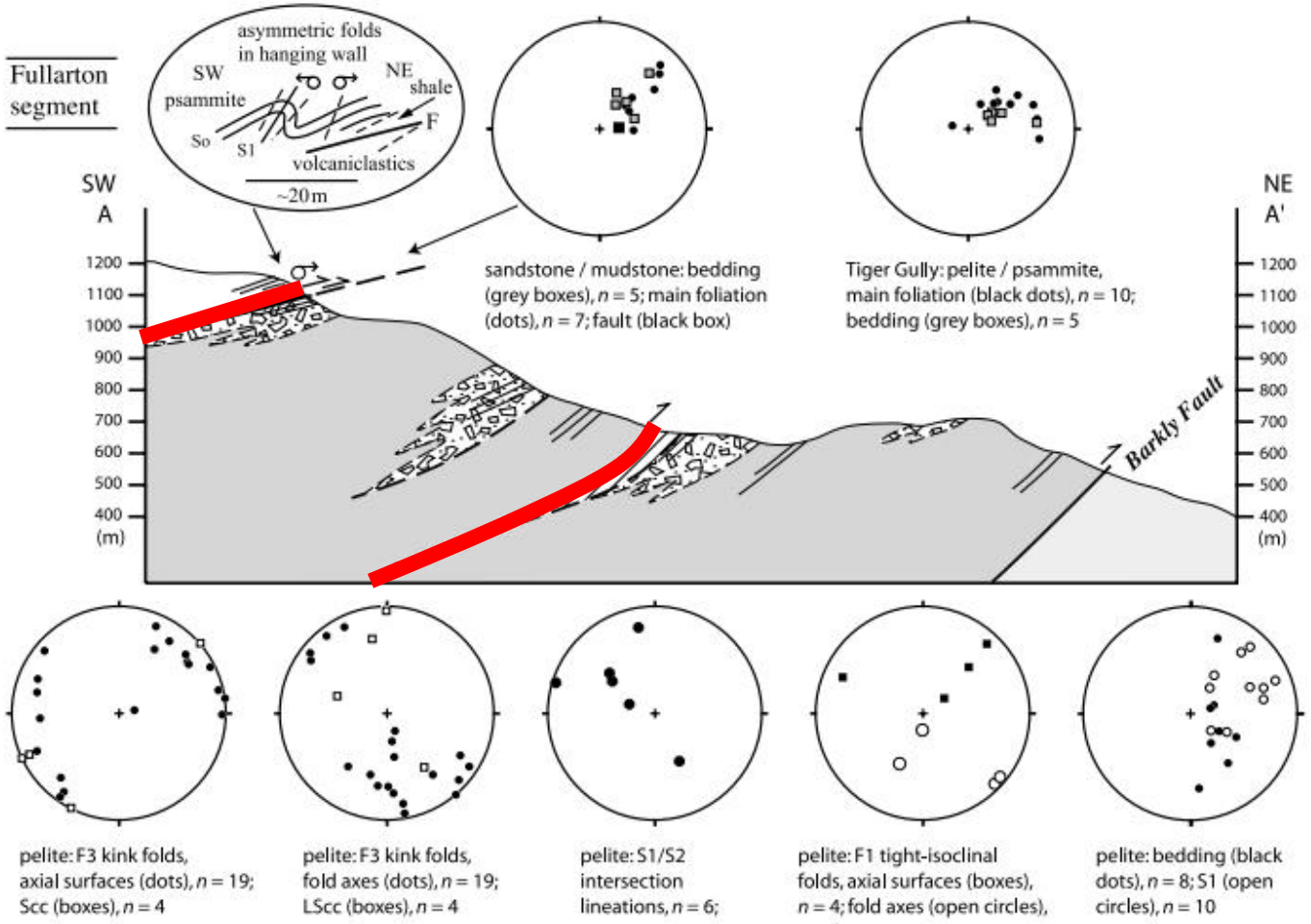


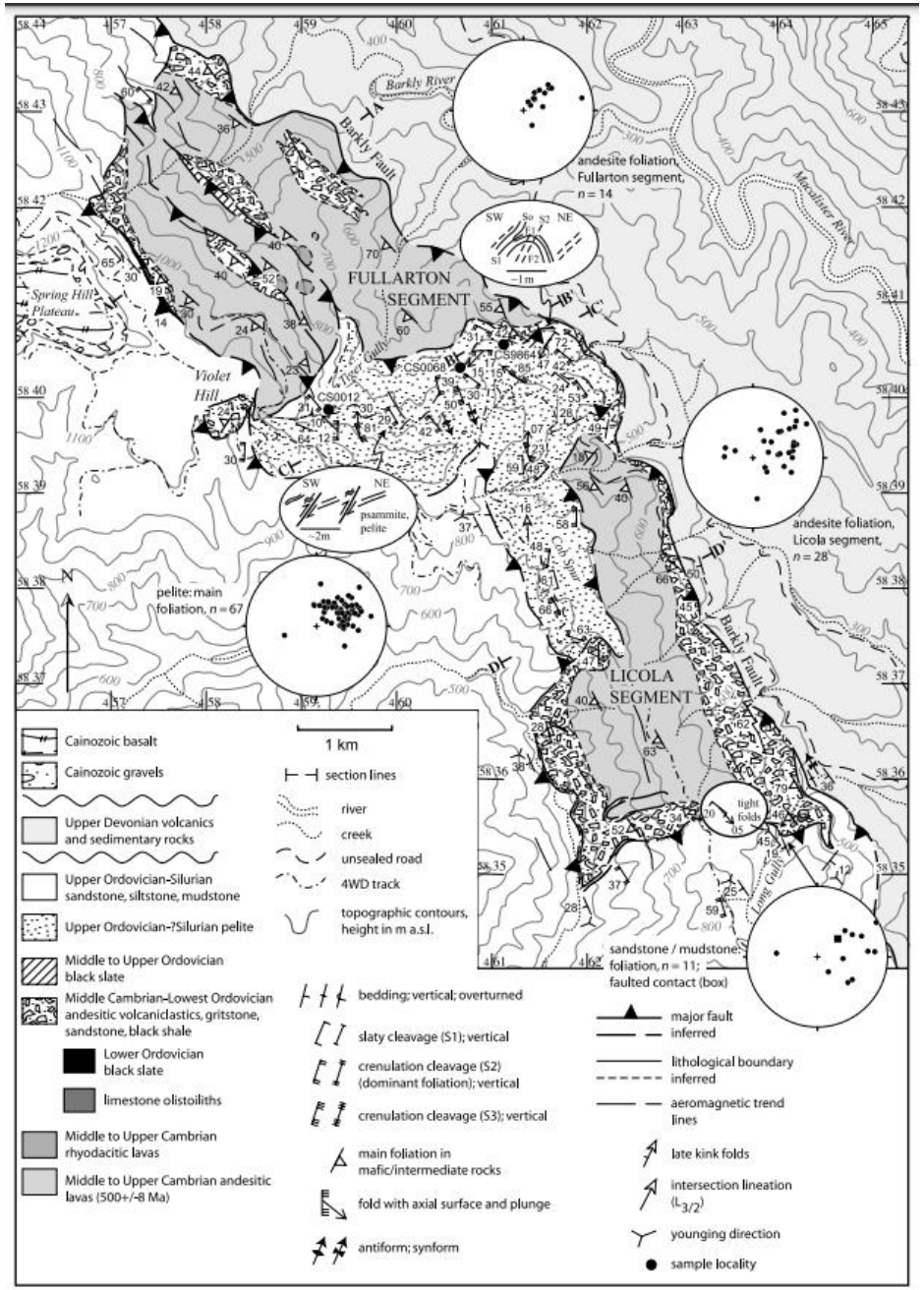


Cambrian Jamieson Volcanics at Licola

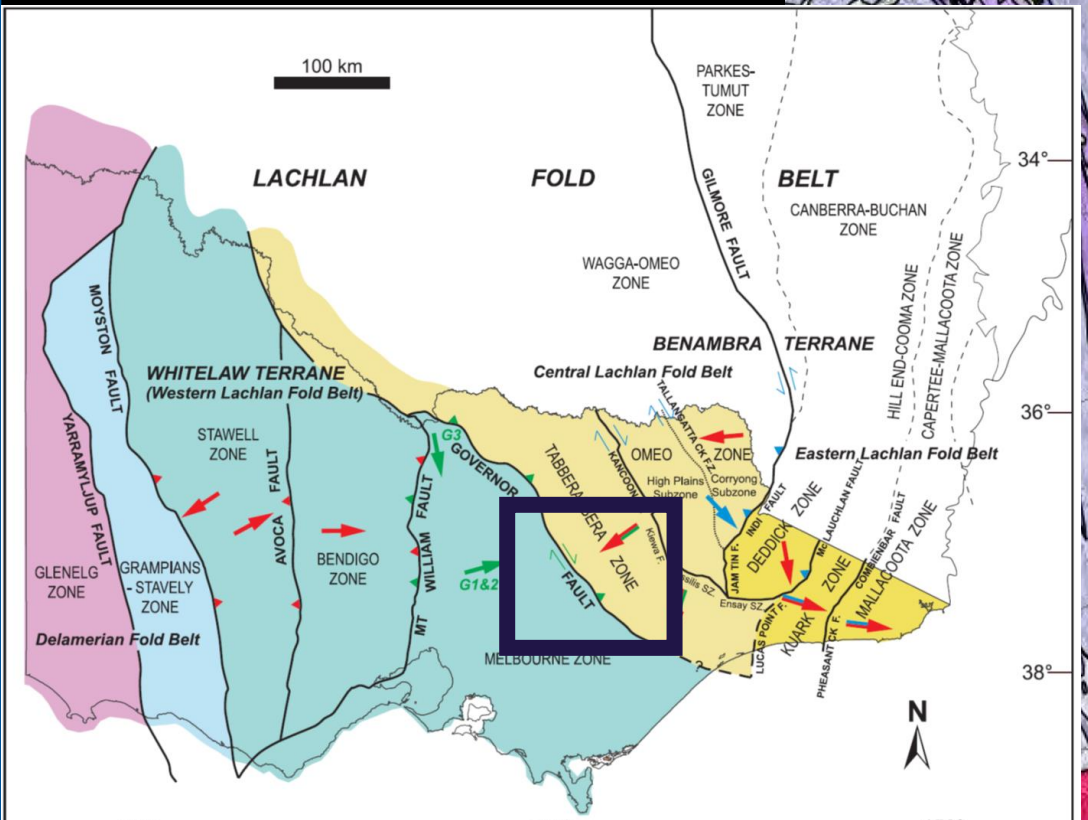
VicGold 2023


VicGold 2023

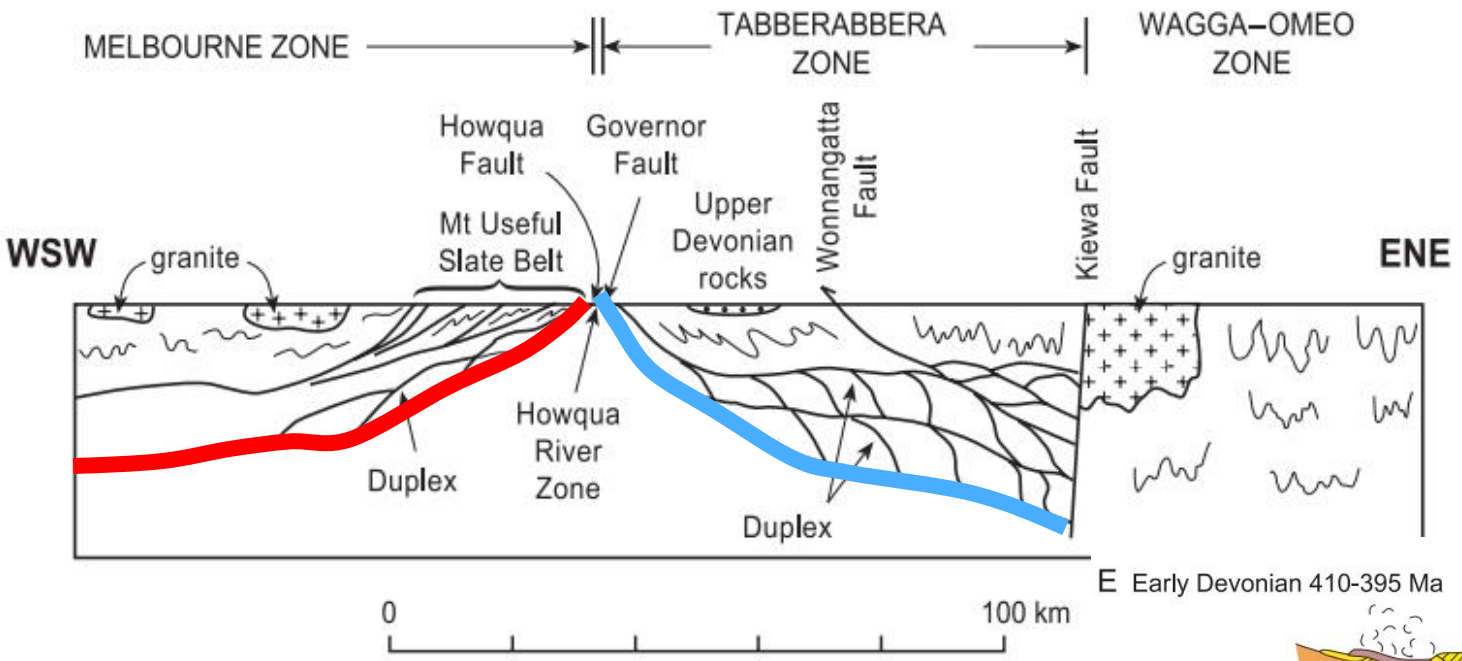




Spaggiari et al.

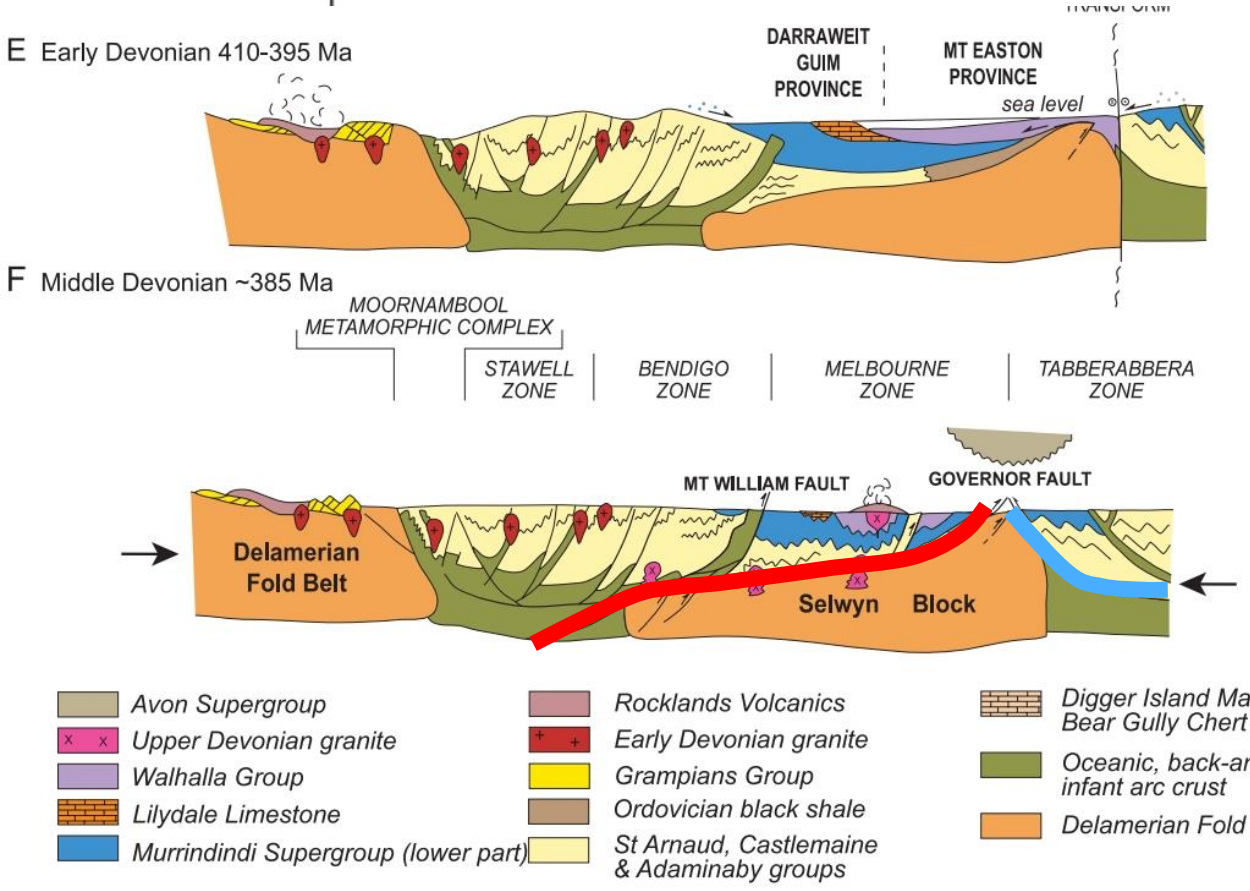

100 km
LACHLAN
FOLD
BELT
PARKES-
TUMUT
ZONE
GILMORE FAULT
CANBERRA-BUCHAN
ZONE
WAGGA-OMEO
ZONE
BENAMBRA
TERRANE
Central Lachlan Fold Belt
WHITELAW TERRANE
(Western Lachlan Fold Belt)
MOYSTON
FAULT
YARRAMYLJUP FAULT
STAWELL
ZONE
FAULT
AVOCA
BENDIGO
ZONE
WILLIAM
FAULT
MT
GLENELG
ZONE
GRAMPIANS
- STAVELY
ZONE
Delamerian Fold Belt
G3
GOVERNOR
G1&2
OMEO
ZONE
High Plains
Subzone
Corryong
Subzone
Eastern Lachlan Fold Belt
HILL END-COOMA ZONE
CAPERTEE-MALLACOOTA ZONE
DEDDICK
ZONE
MALLACOOTA
ZONE
KVARK
FAULT
MELBOURNE ZONE
34°
36°
38°
N

Bonnie Doon
Mansfield
Eildon
Jamieson
Woods Point
Mount Buller
Harrietville
Hotham Heights
Dargo
Licola
VicGold 2023

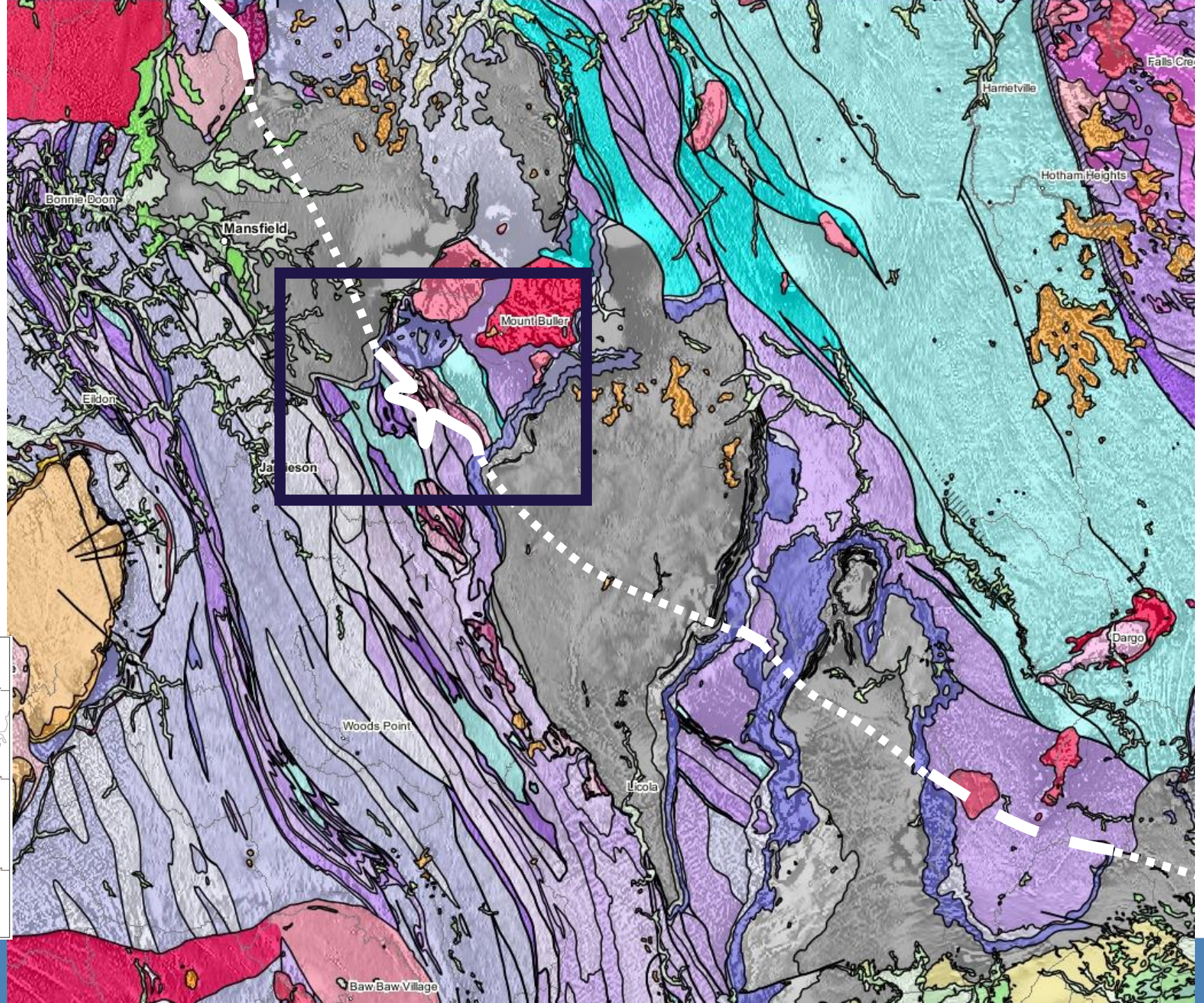


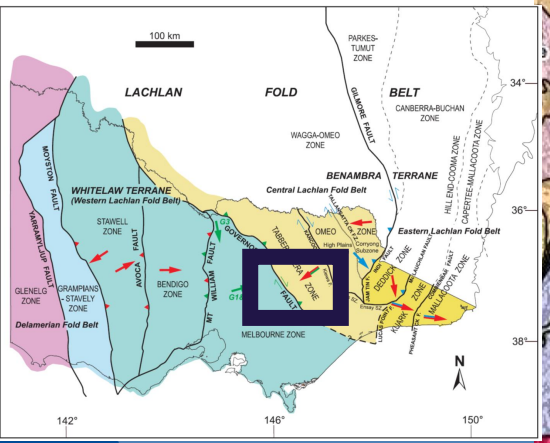
Fergusson, 2003

S



VandenBerg et al, 2000


Bonnie Doon
Mansfield
Eildon
Jamieson
Mount Buller
Harrietville
Hotham Heights
Falls Cre
Dargo
Woods Point
Licola
Baw Baw Village


100 km
LACHLAN
FOLD
BELT
PARKES-TUMUT ZONE
CANBERRA-BUCHAN ZONE
WAGGA-OMEO ZONE
GILMORE FAULT
BENAMBRA TERRANE
Central Lachlan Fold Belt
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MOYSTON FAULT
YARRAMYLUP FAULT
STAWELL ZONE
GLENELG ZONE
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AVOCA FAULT
BENDIGO ZONE
WILLIAM FAULT
MT
GOVERNOR
OMEO
MELBOURNE ZONE
HILL END-COOMA ZONE
CAPERTEE-MALLACOOTA ZONE
34°
36°
38°
142°
146°
150°
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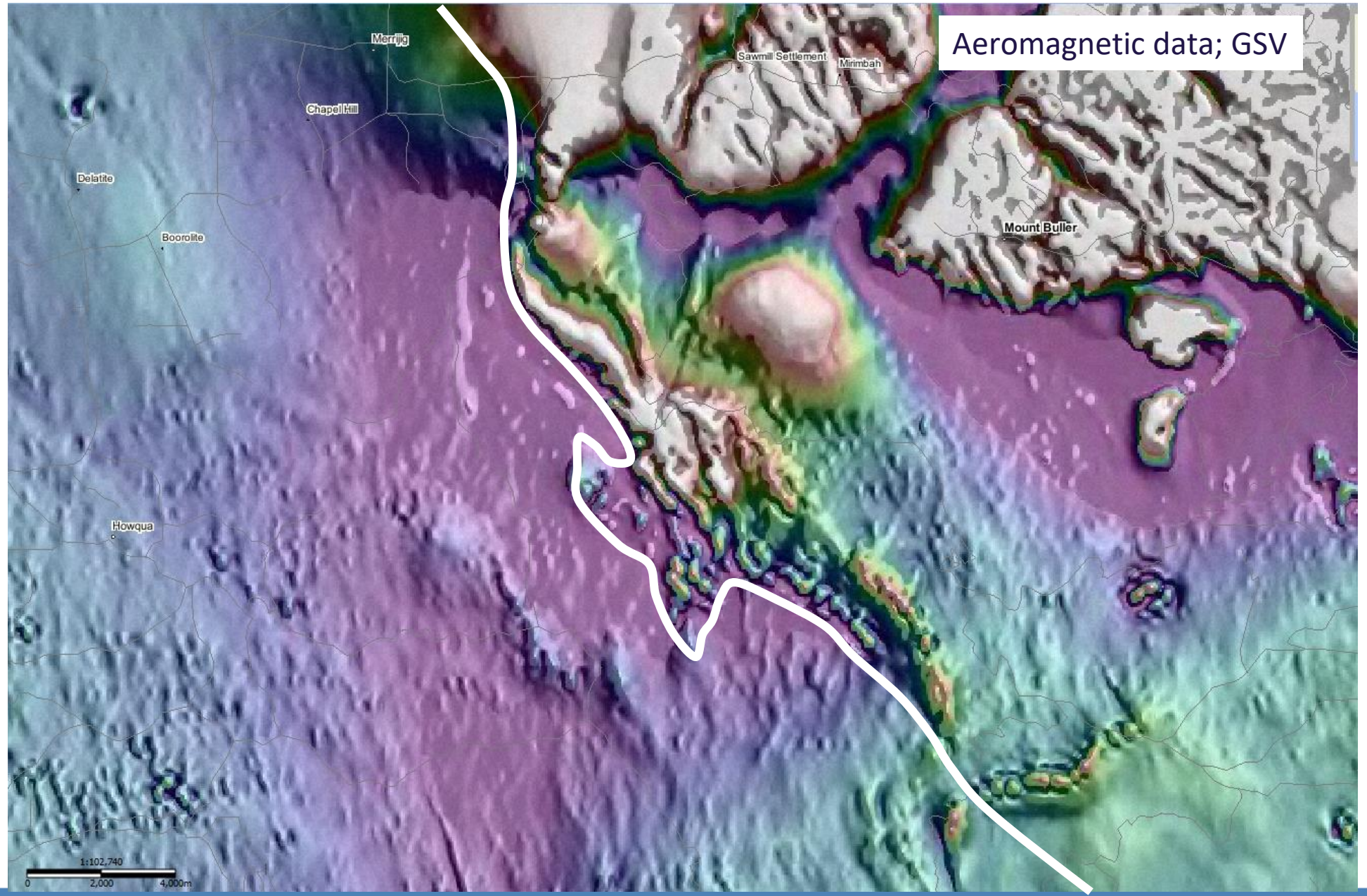
Aeromagnetic data; GSV
Merrijig
Chapel Hill
Sawmill Settlement
Mirimbah
Delatite
Boorolite
Mount Buller
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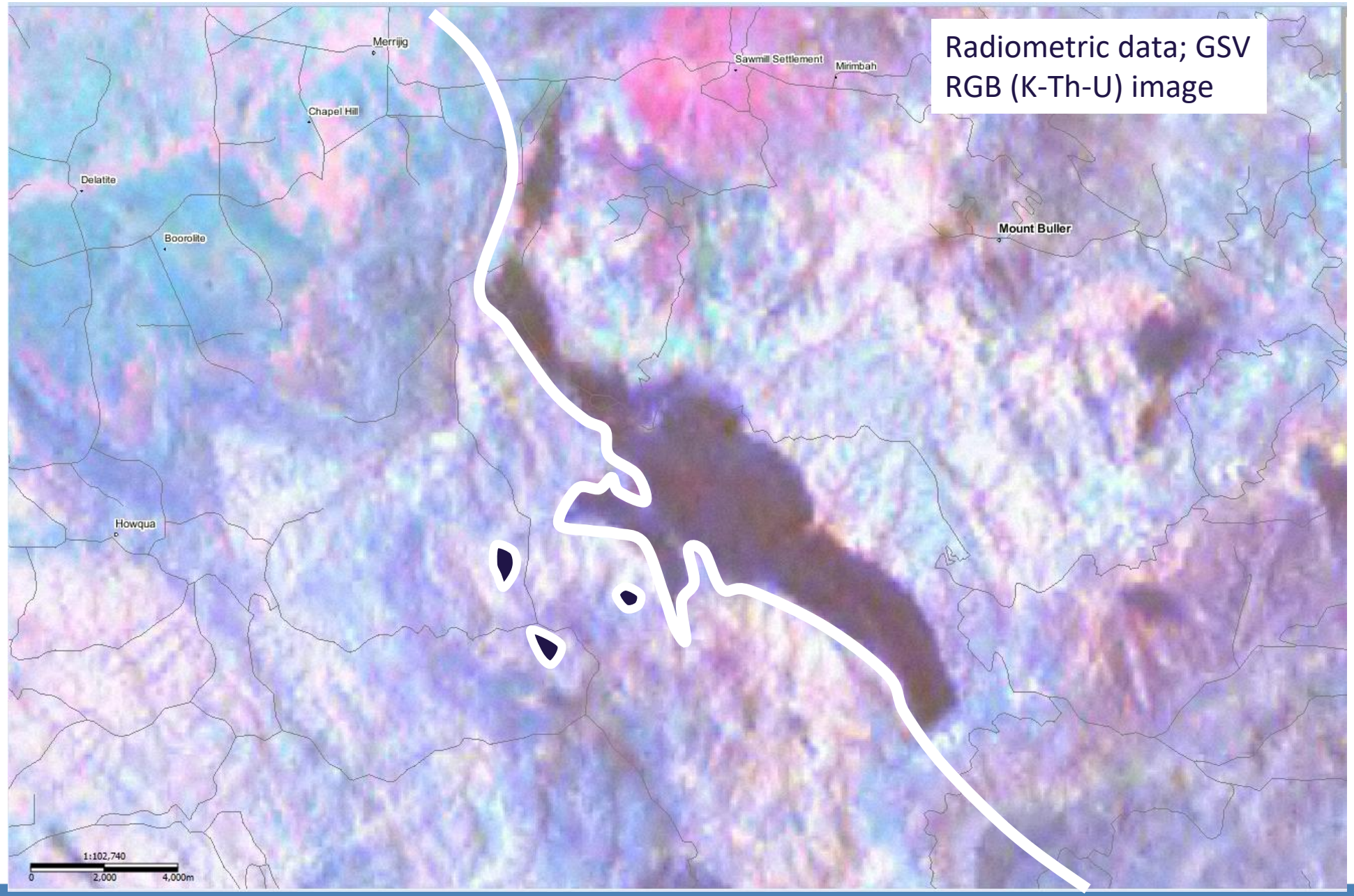
Radiometric data; GSV RGB (K-Th-U) image
Merrijig
Chapel Hill
Sawmill Settlement
Mirimbah
Delatite
Boorolite
Mount Buller
Howqua
1:102,740
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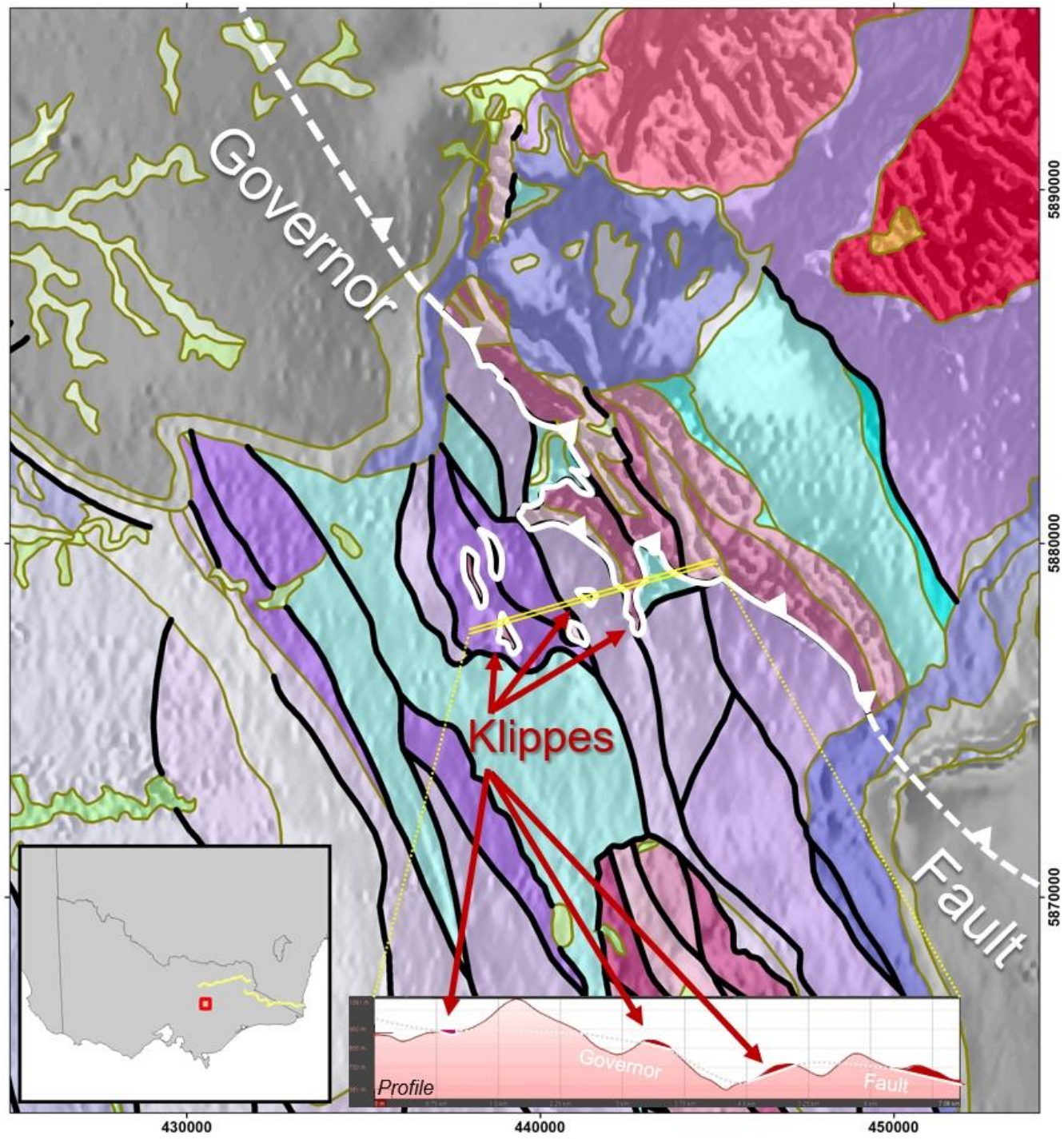
2,000
4,000m


Governor
Klippes
Fault
Profile
Governor
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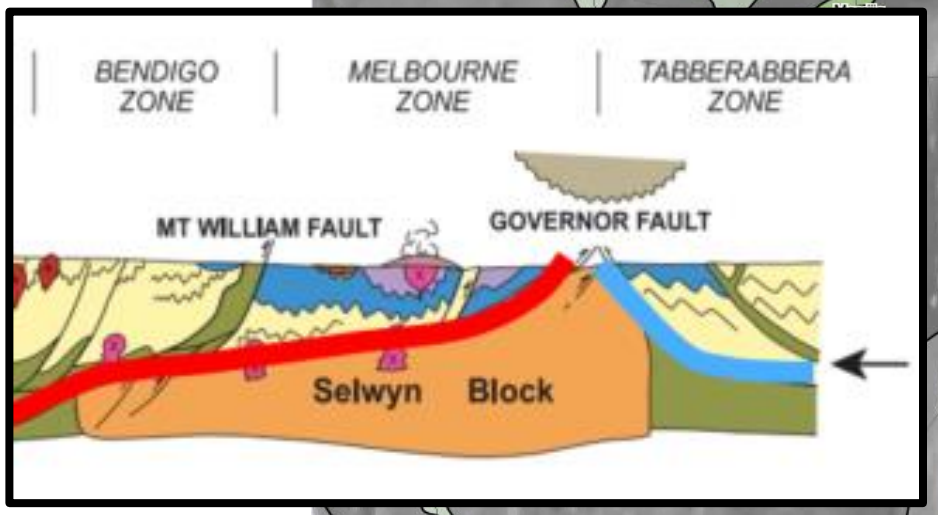
430000
440000
450000



Seamless geology layer; GSV

Structure contouring across klippen gives a averaged magnitude of ~ 15° northeast dip for the Governor Fault

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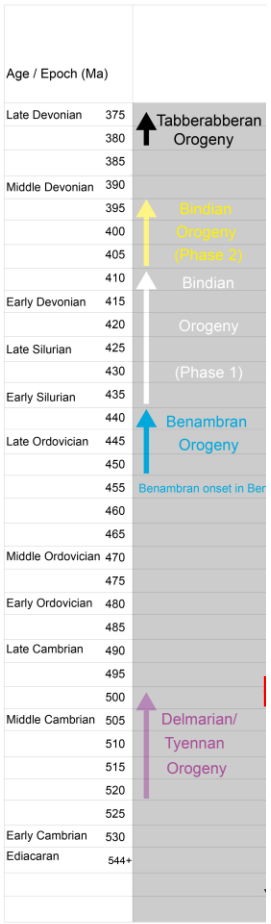
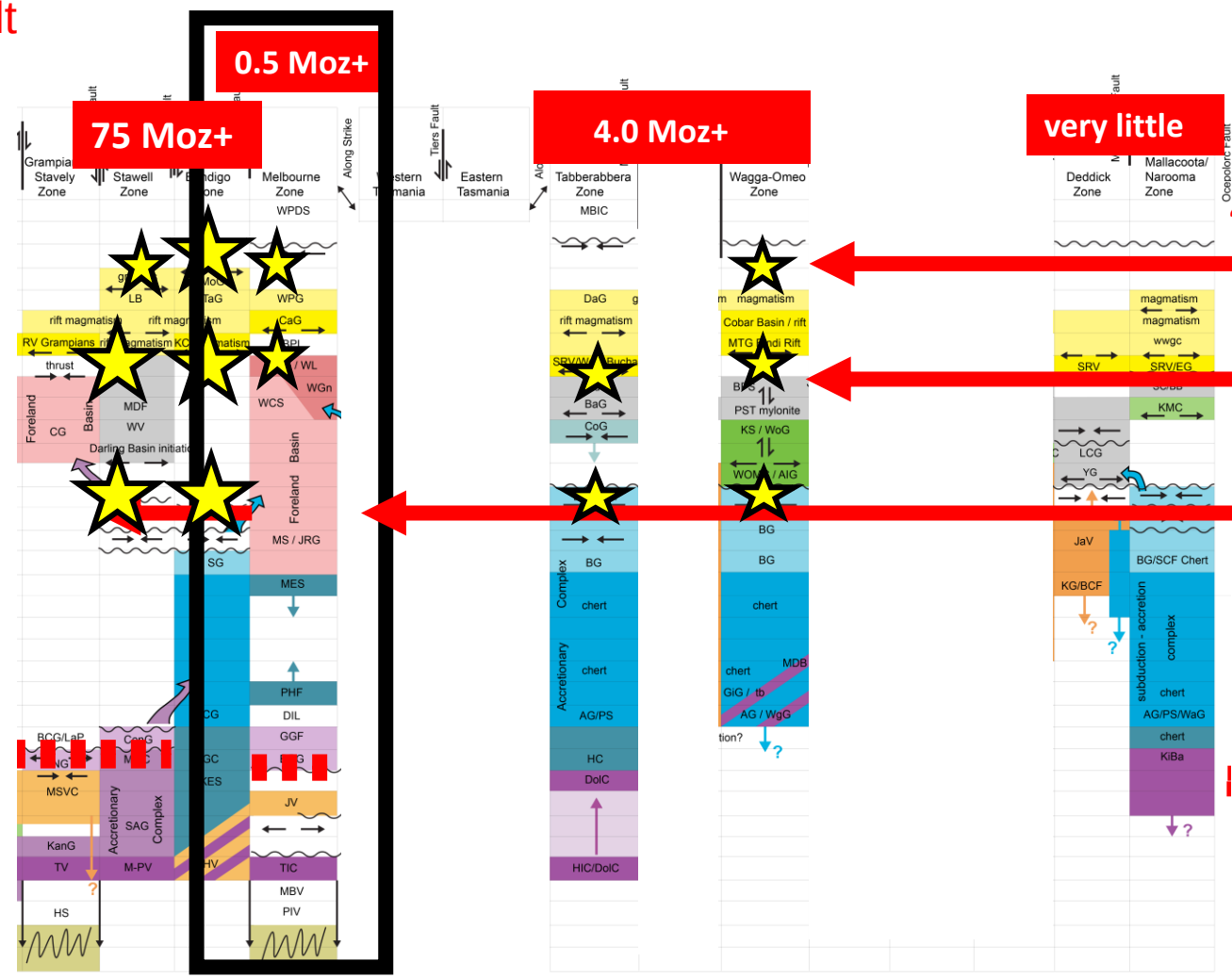
Lachlan Fold Belt





‘Tabberabberan’ crustal thickening

‘end-Bindian’ crustal thickening

‘Benambran’ crustal thickening

Time-space plot : Victoria

Cayley & Musgrave, in prep

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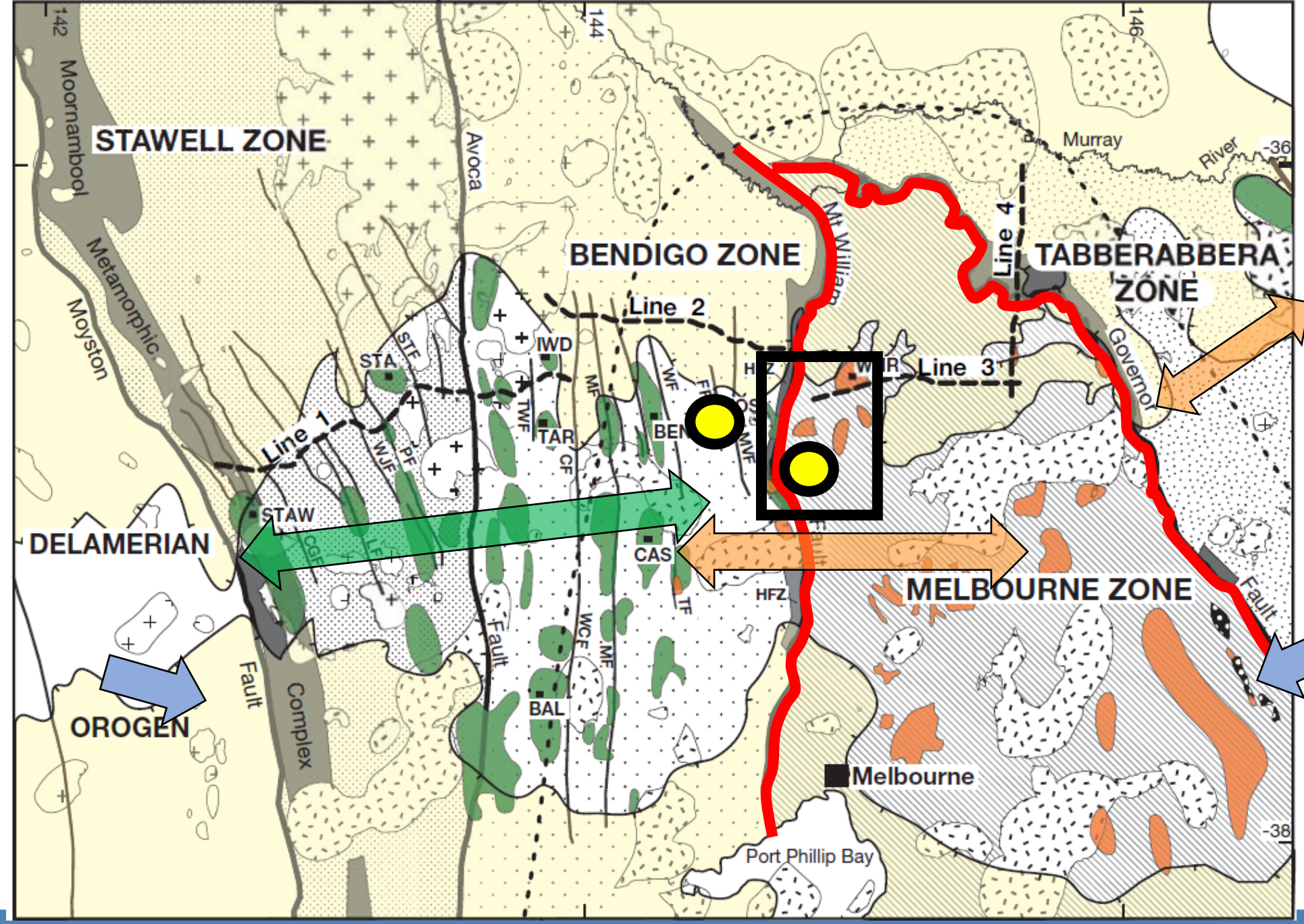
~450-440 Ma

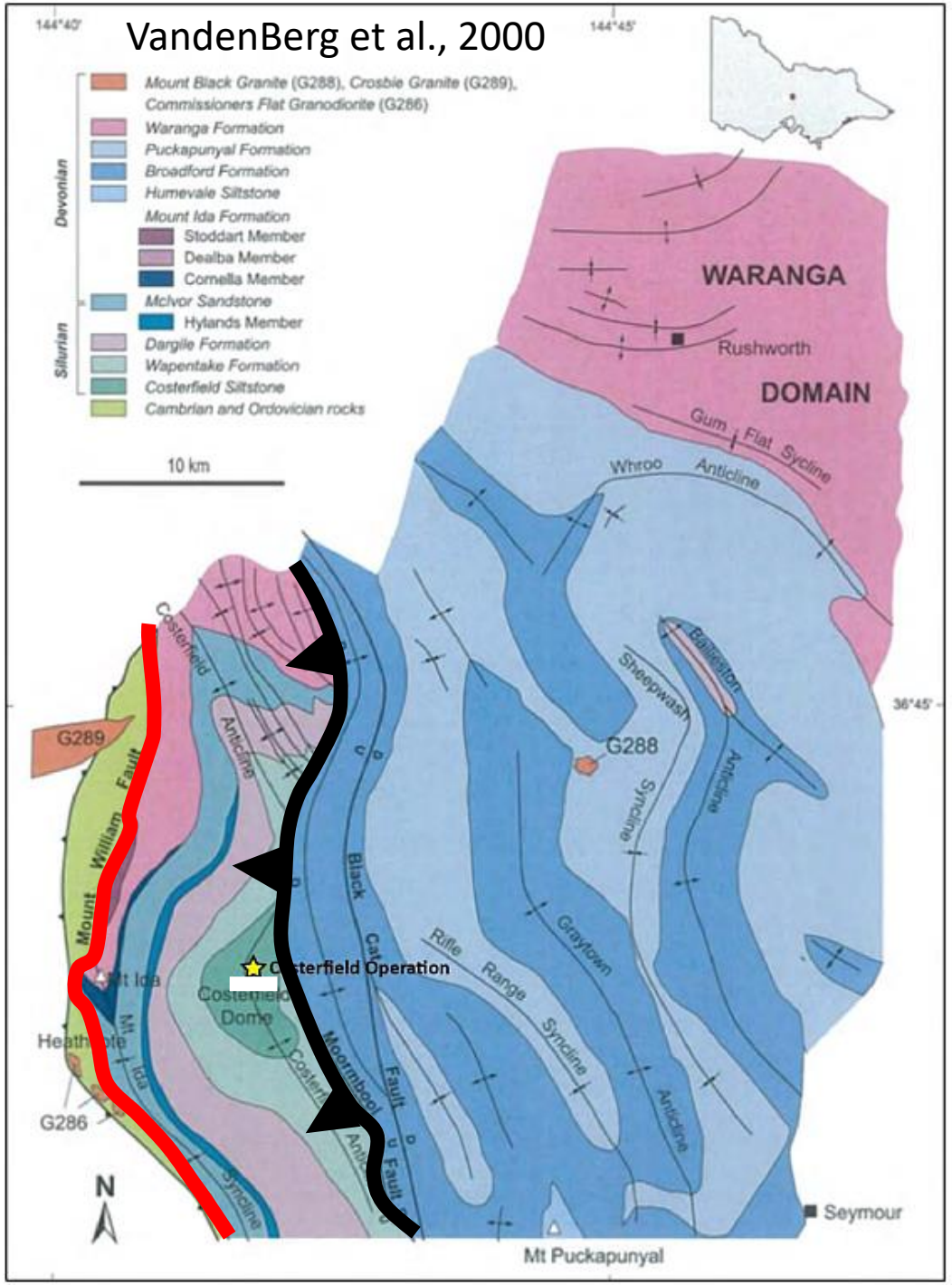
Intrusion-related Cu / Au

~500 Ma



'Orogenic' gold

~410-385Ma



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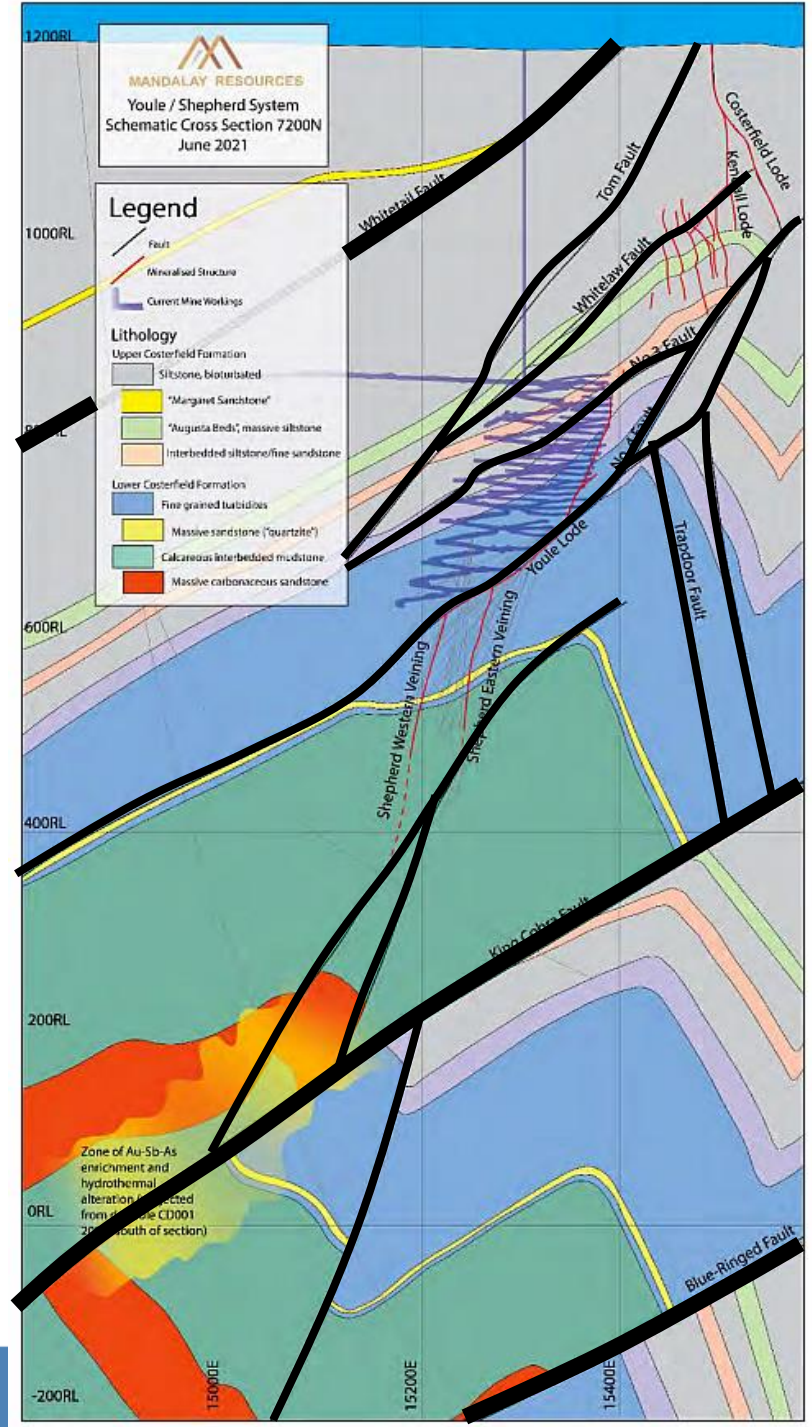
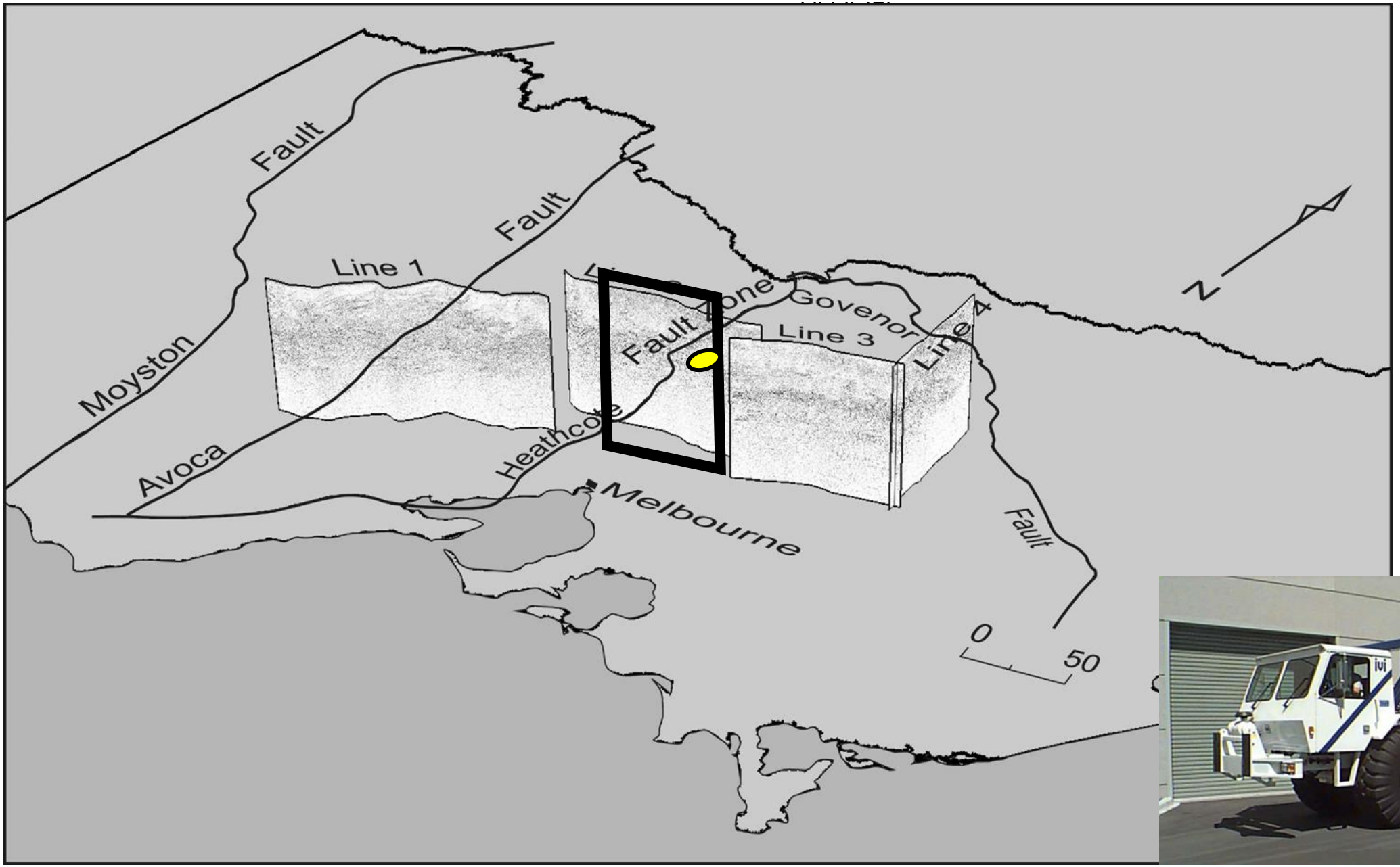
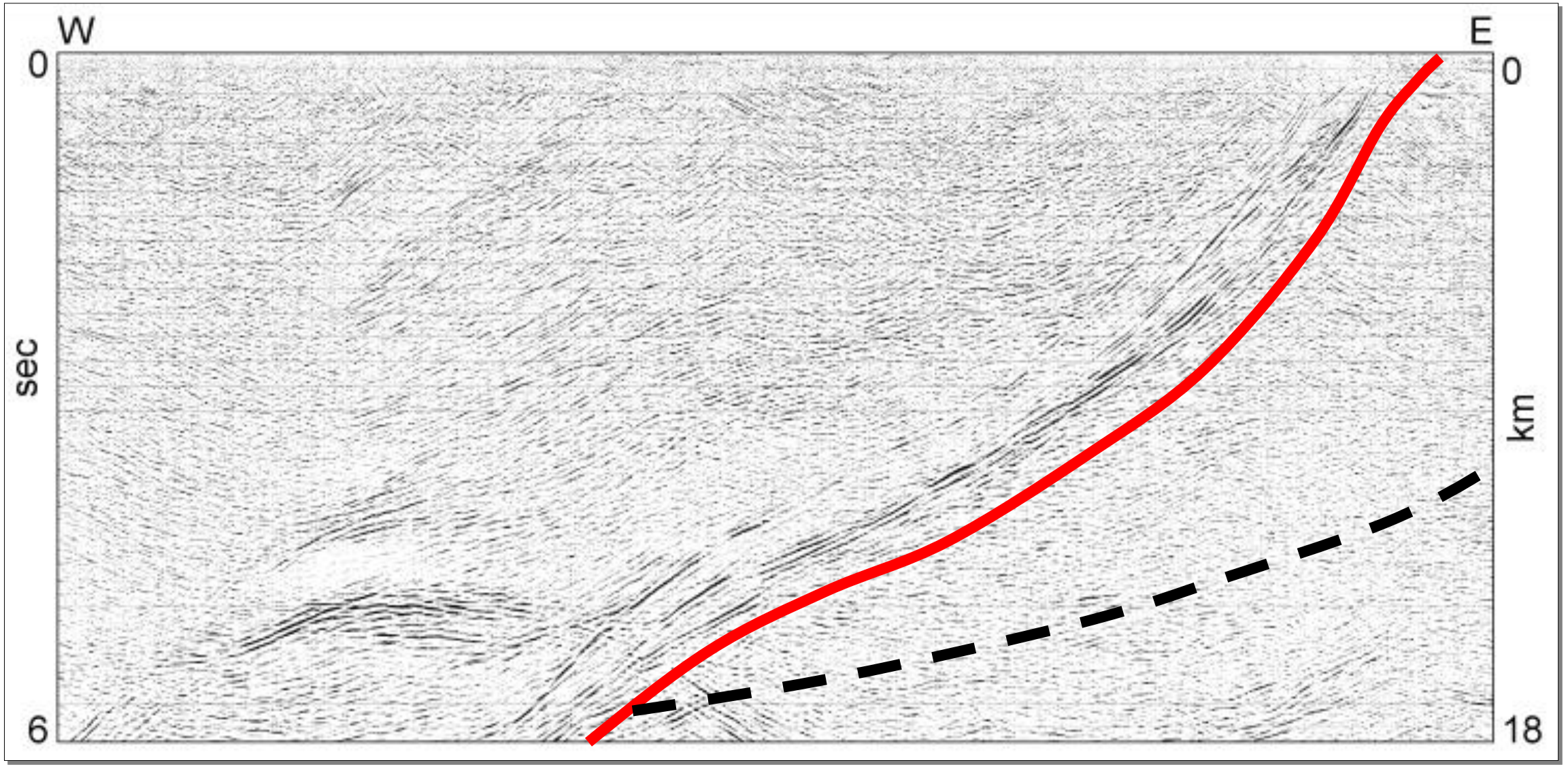


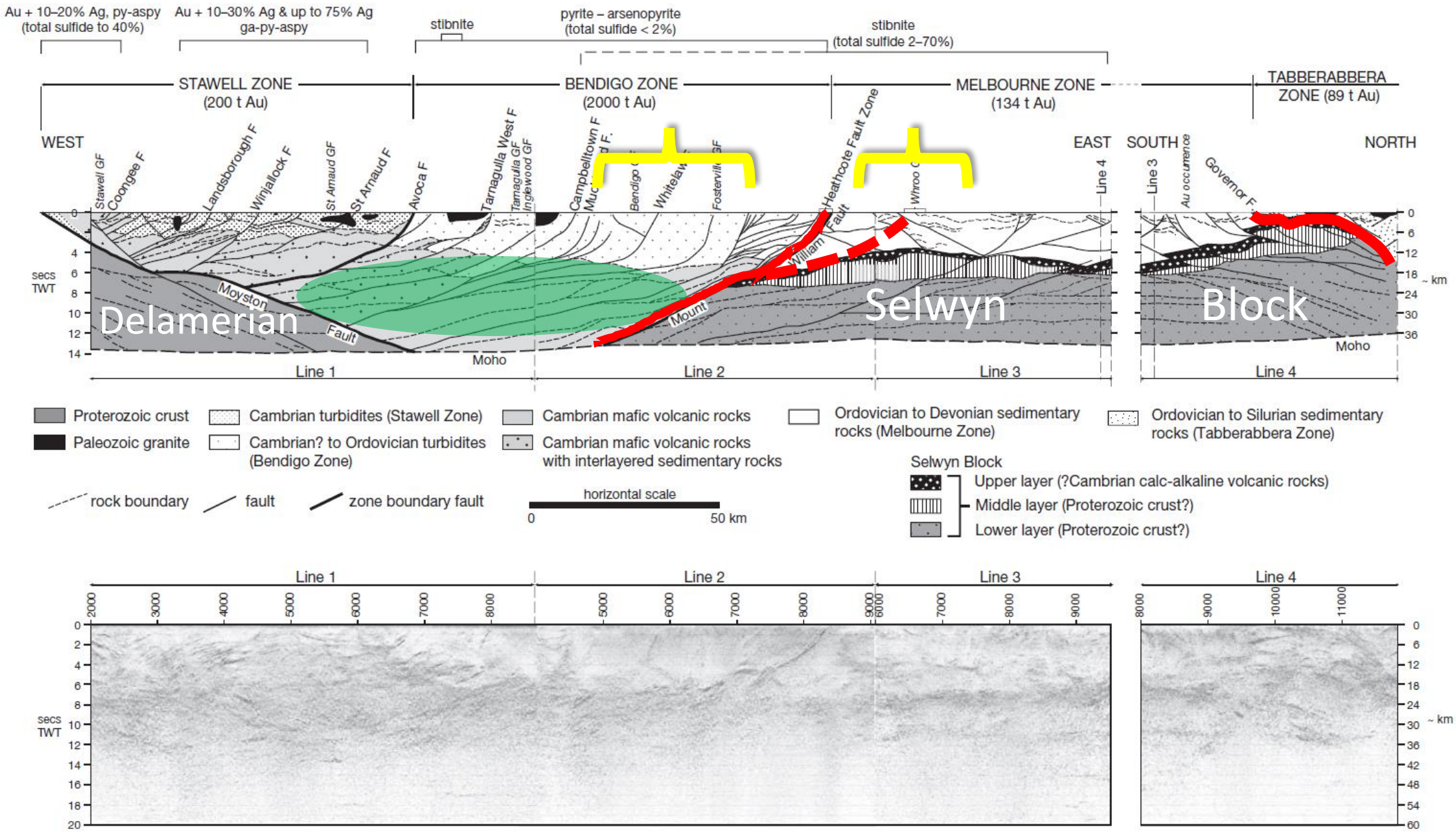
Mandalay Resources 2022

CIAL


Fault
Fault
Line 1
Moyston
Avoca
Heathcote
Fault
Line 3
Govenor
Line 4
N
Melbourne
Fault
0
50

Detail of the Heathcote Fault Zone





Cayley et al., 2011

Talk outline

- ‘Orogenic gold’ – what is it and how to recognize the it?
- Central Victoria (the ‘Melbourne Zone’) is different to adjacent parts of Victoria.
- The western Melbourne Zone - mapping and deep seismic reflection data both suggest fluid plumbing system linkage into adjacent Bendigo Zone orogenic gold systems
- **The eastern Melbourne Zone – 5 M oz+ of gold endowment with a different (intrusion-related) association.**
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VicGold 2023

- Radiometric dating of Walhalla-Woods Point gold deposits suggests mineralisation was introduced between about 370 and 376 Ma.

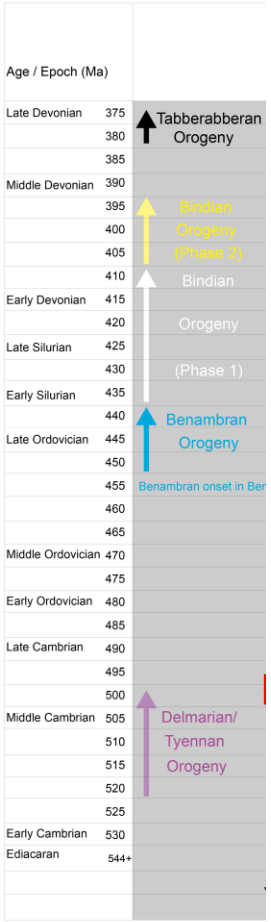
- Ar/Ar date on alteration sericite in the Morning Star dyke at Woods Point: 374 ± 2 Ma (Bierlein et al., 2001b).

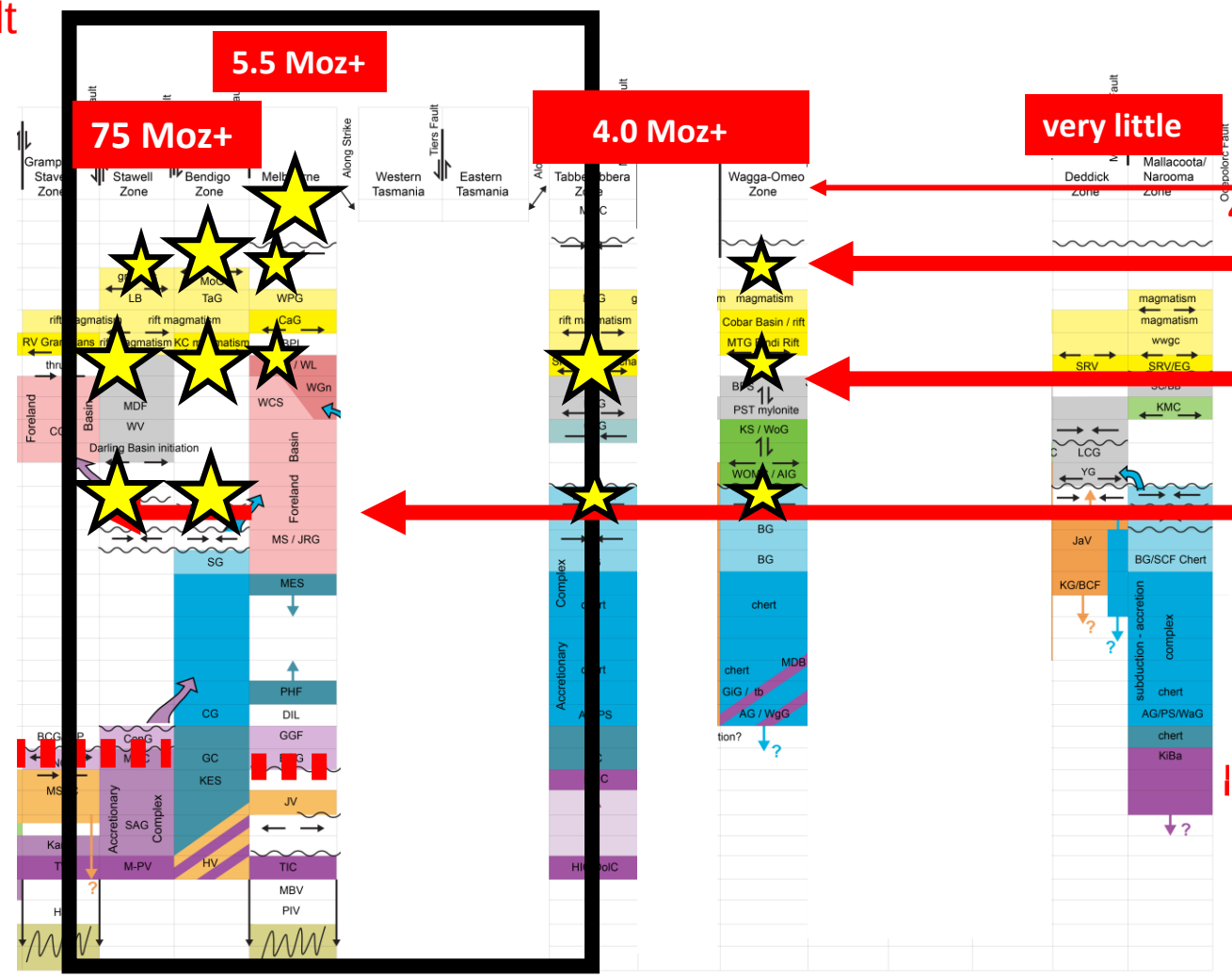
- Ar/Ar date on sericite in quartz vein at Walhalla: 372 ± 2 Ma (Foster et al. (1998)

- At Tallangallook, mineralisation was interpreted to predate intrusion of the Late Devonian Strathbogie Granite (Baldwin, 1994), but this interpretation is not supported by recent drilling.

Delamerian Fold Belt

Lachlan Fold Belt





‘barely any’ crustal thickening

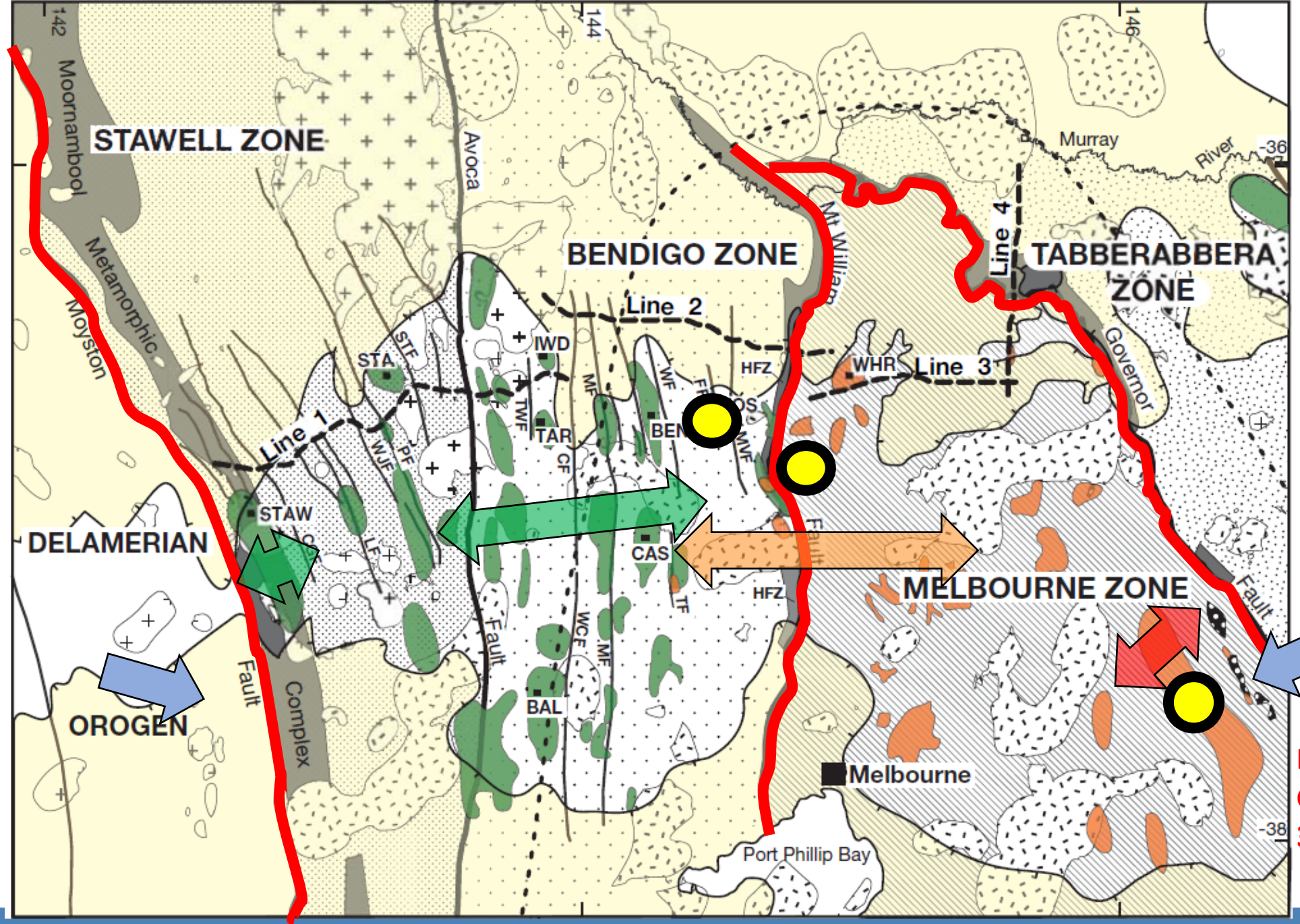
‘Tabberabberan’ crustal thickening

‘end-Bindian’ crustal thickening

‘Benambran’ crustal thickening

Time-space plot : Victoria

Cayley & Musgrave, in prep



Orogenic gold

~450-440 Ma

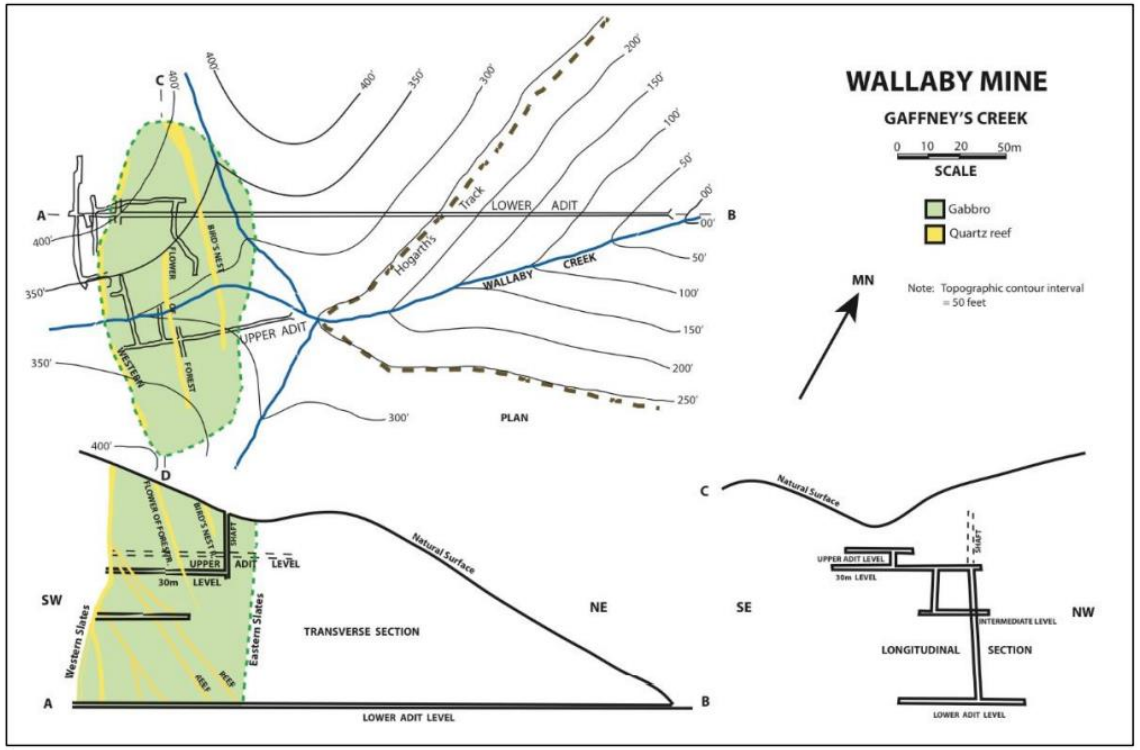
Intrusion-related Cu / Au

~500 Ma

Orogenic gold

~410-385Ma

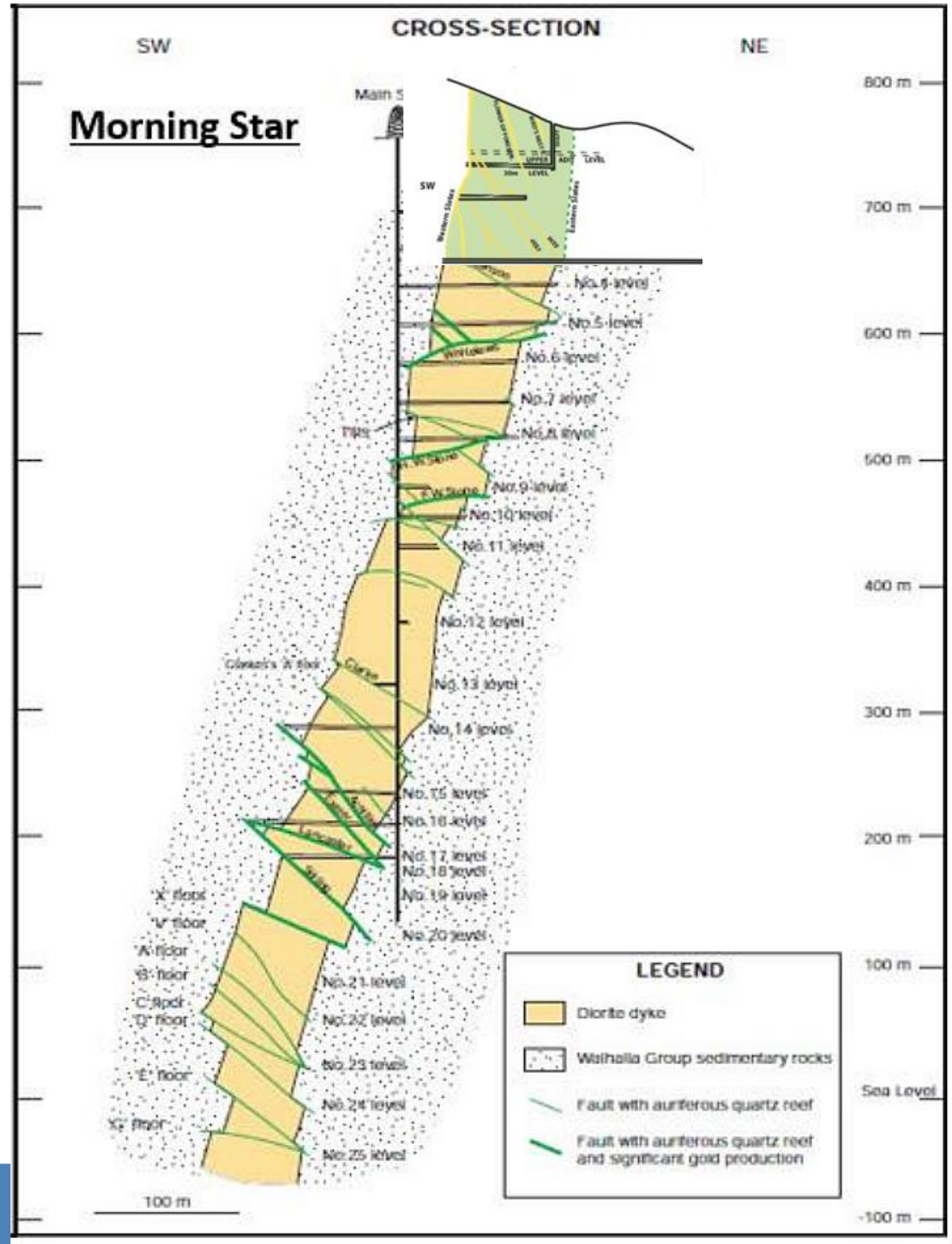
Dyke-associated Gold 375-370 Ma



Wallaby (Gaffneys Creek): 7000 oz Au @9g/t

Map and sections: Kenny 1926, P. Jackson.

Morning Star ~900 000 oz Au @ 26+g/t.



- Woods Point Dyke Swarm: hornblende peridotite (Coopers Creek), hornblende pyroxenite, hornblende gabbro, gabbroic diorite – evolved (most felsic) dyke compositions with pyrite halos seem most favourable to host gold mineralisation.

Photo: Peter Jackson

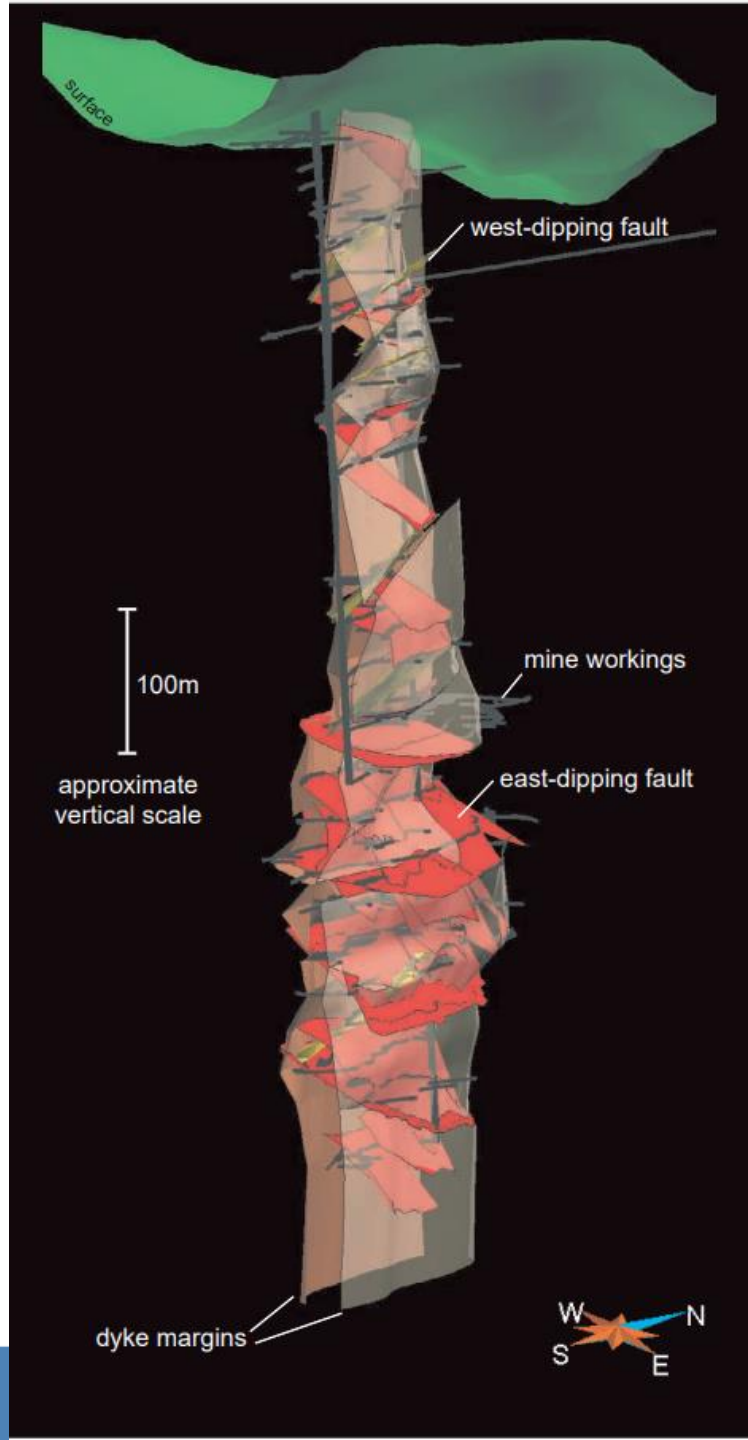
Coopers Creek –
subvertical
ultramafic dyke
(VandenBerg et al., 2006)

Intruded during
dextral transtension (Payne, 1982)

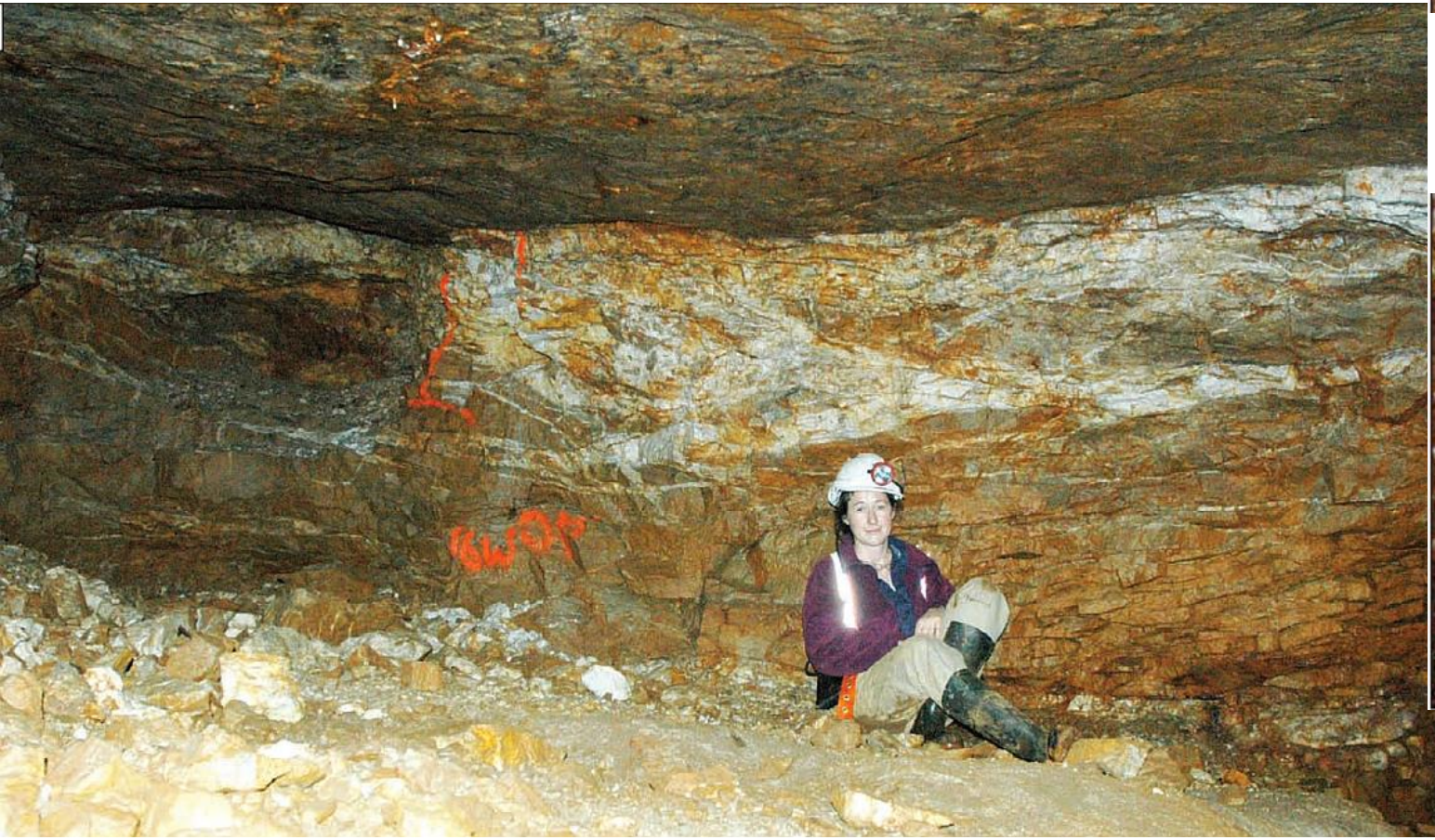
Woods Point dyke swam dominated by mantle lead isotope signatures (Andrew et al., 2002).

Chalcopyrite, pyrite (replacing pyrrhotite), pentlandite - cubanite –
PGE's hosted by sulphide and complex mineral phases (eg merenskyite - Keays & Kirkland, 1972).
Mineralisation is magmatic related, possibly sourced from ultramafic magma melt segregations (Keays, Kirkland).

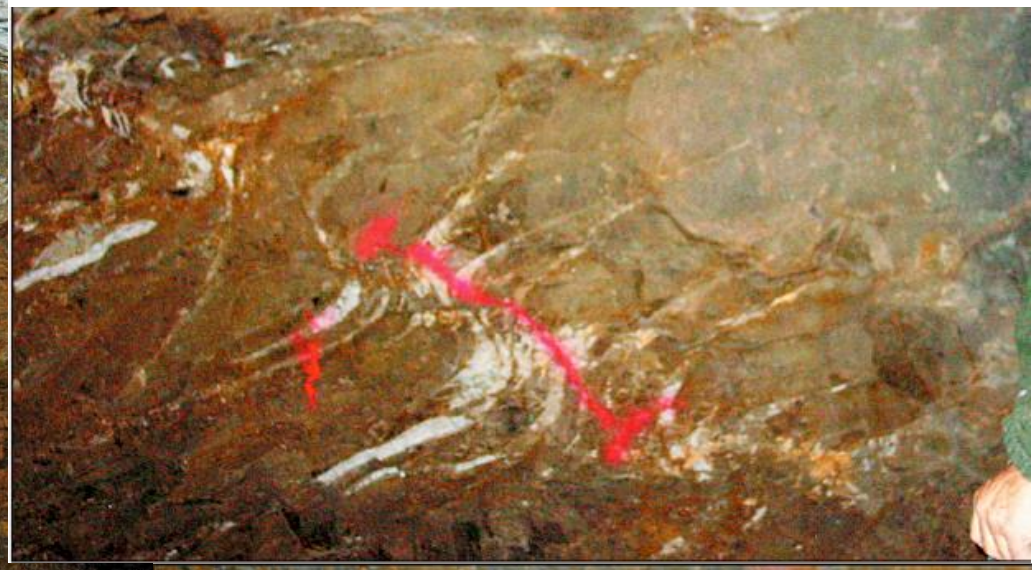
A1 dyke, Gaffneys Creek “castle reef’. Vandenberg et al., 2006.

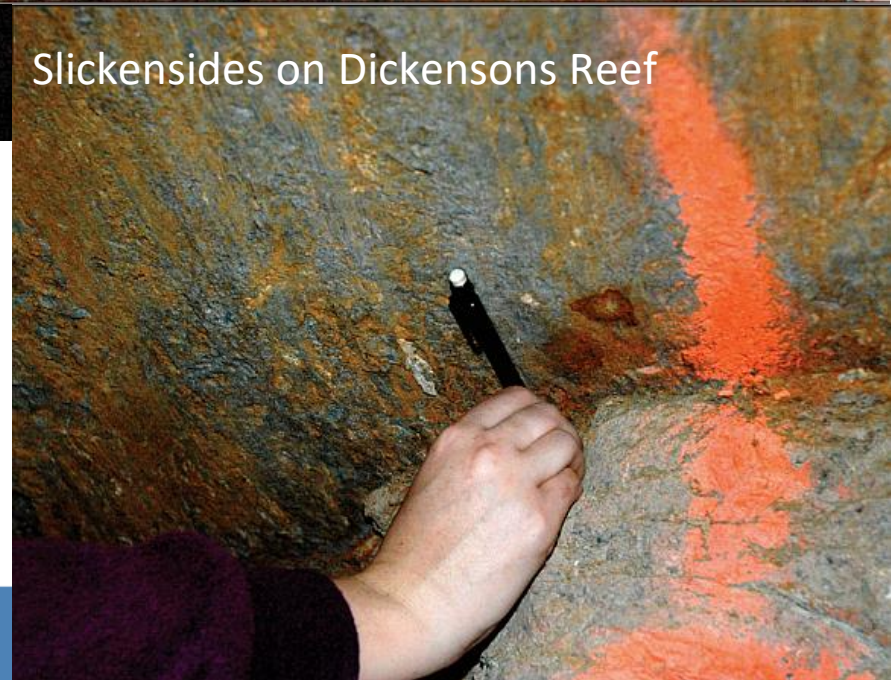


A1 gold mine – 500 000 oz gold
Photo: Kaiser Reef.



Lauraville dyke sigmoidal quartz arrays define opening under west/east reverse shear





Slickensides on Dickensons Reef

The dykes are subvertical, so intruded during transtension…but the gold mineralised veins that overprint them were emplaced during transpression.

eg: flat shoots, No 4 level in Norming Star mine – Shamrock Vein.

VicGold 2023

Golden Mountain – 77m @ 1.14g/t au. in porphyritic miarolitic granite and monzogranite. (Fosterville South). Adjacent hornfels also mineralised.

(image: Fosterville South)

At least SOME of the gold mineralising event postdates granite intrusion.

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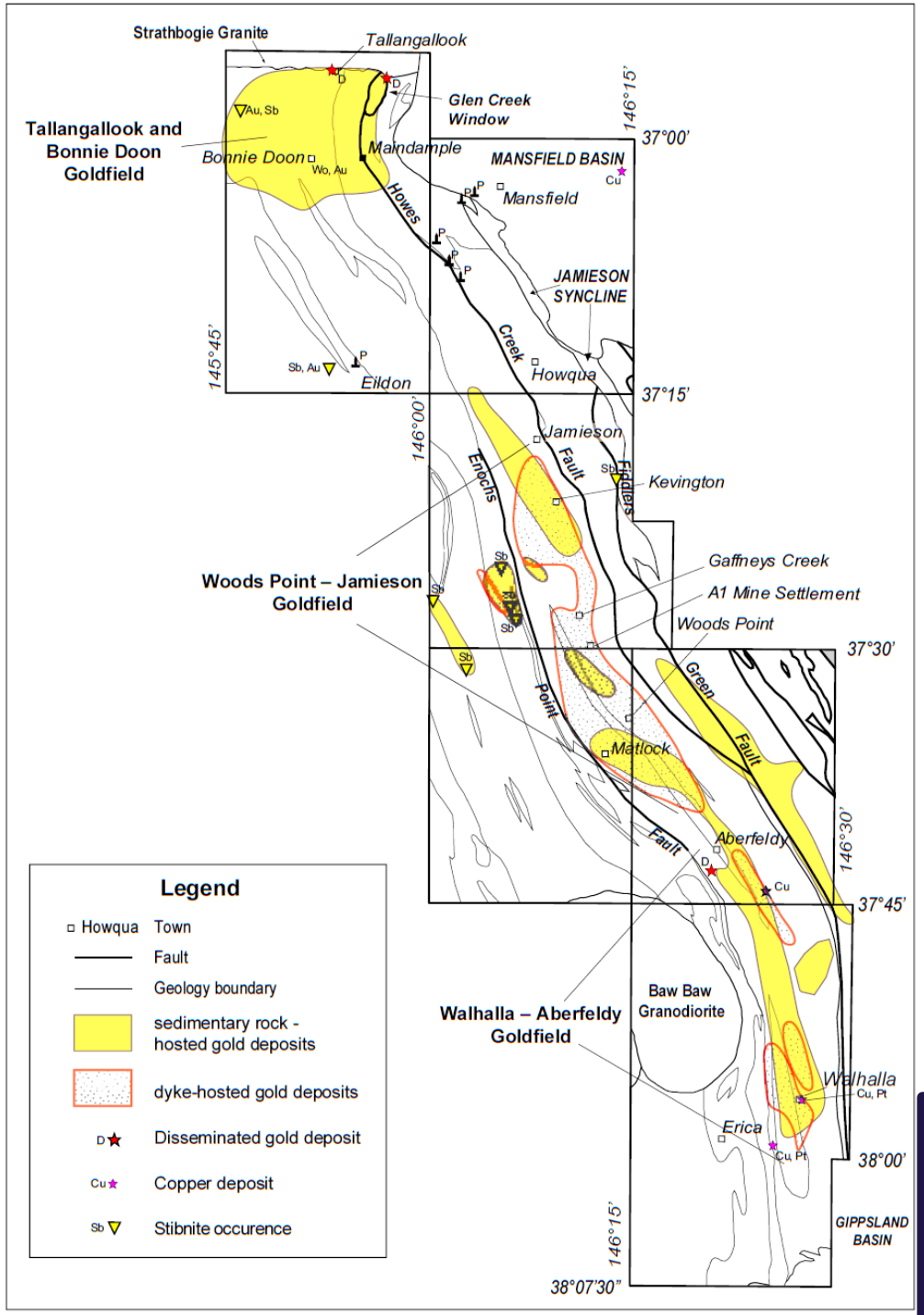
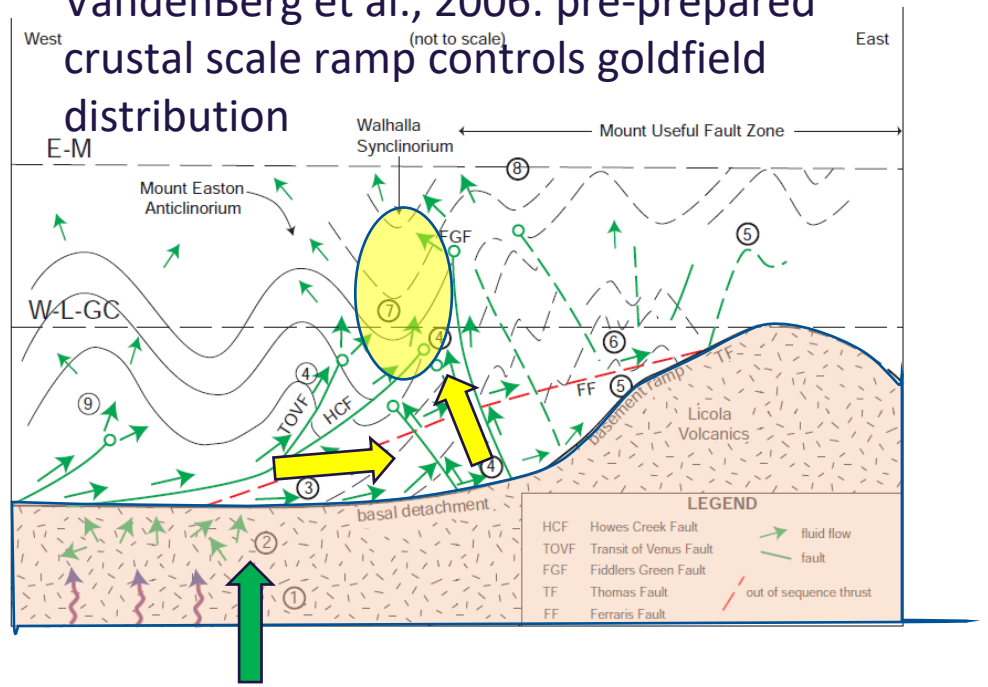
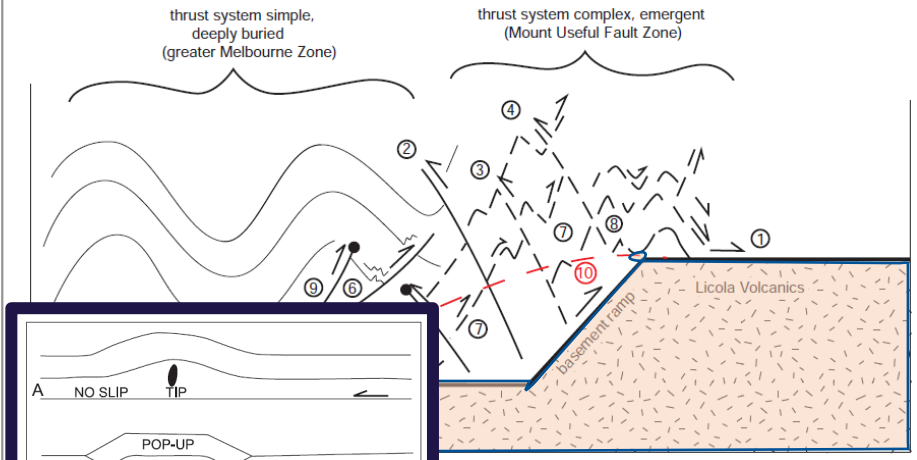
Previous model:

VandenBerg et al., 2006: pre-prepared crustal scale ramp controls goldfield distribution







eg: Butler, 1982

No significant crustal thickening anywhere nearby during the 375-370 Ma interval argues against a classic ‘orogenic’ association for gold mineralisation that overprints the Woods Point Dyke Swarm.

Instead, an intrusion-related association is implicated (common source).
Strong As association with gold, but As, Pb, Mo and Sb association in dyke hosted breccia zones are a magma-related signature (Ramsay et al., 1998).

But: numerous unmineralized Woods Point dykes occur outside the main goldfield belt – which makes the association between dykes and gold tricky to understand (eg Vandenberg et al 2006).

and – why are mantle-derived melts concentrated along the eastern Melbourne Zone? (if they came from beneath/within the Selwyn Block, why aren’t they everywhere?)

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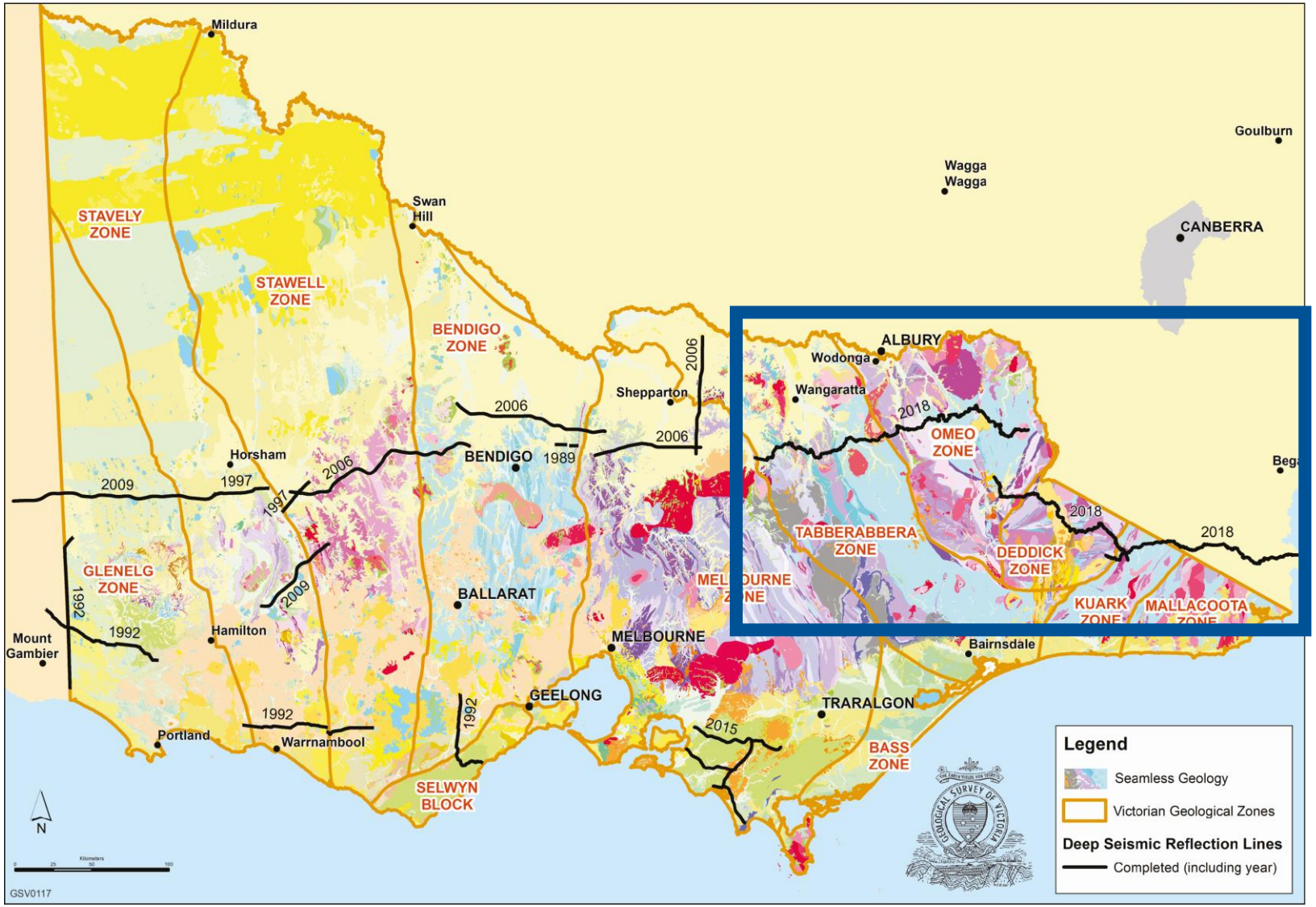
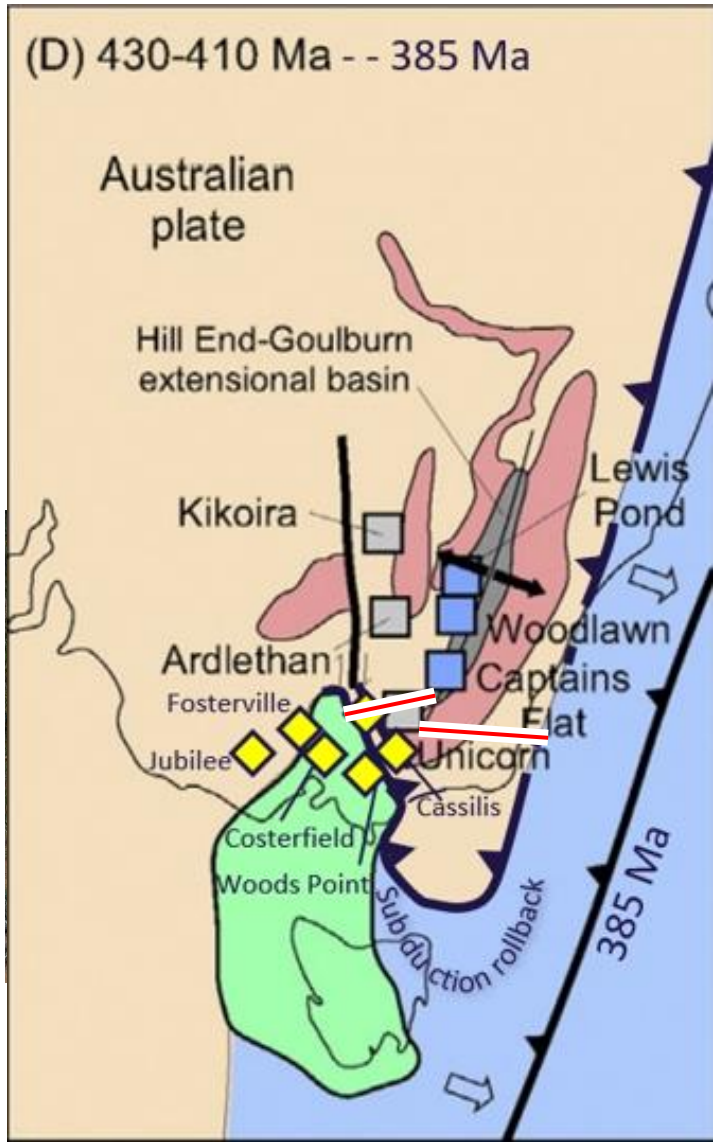
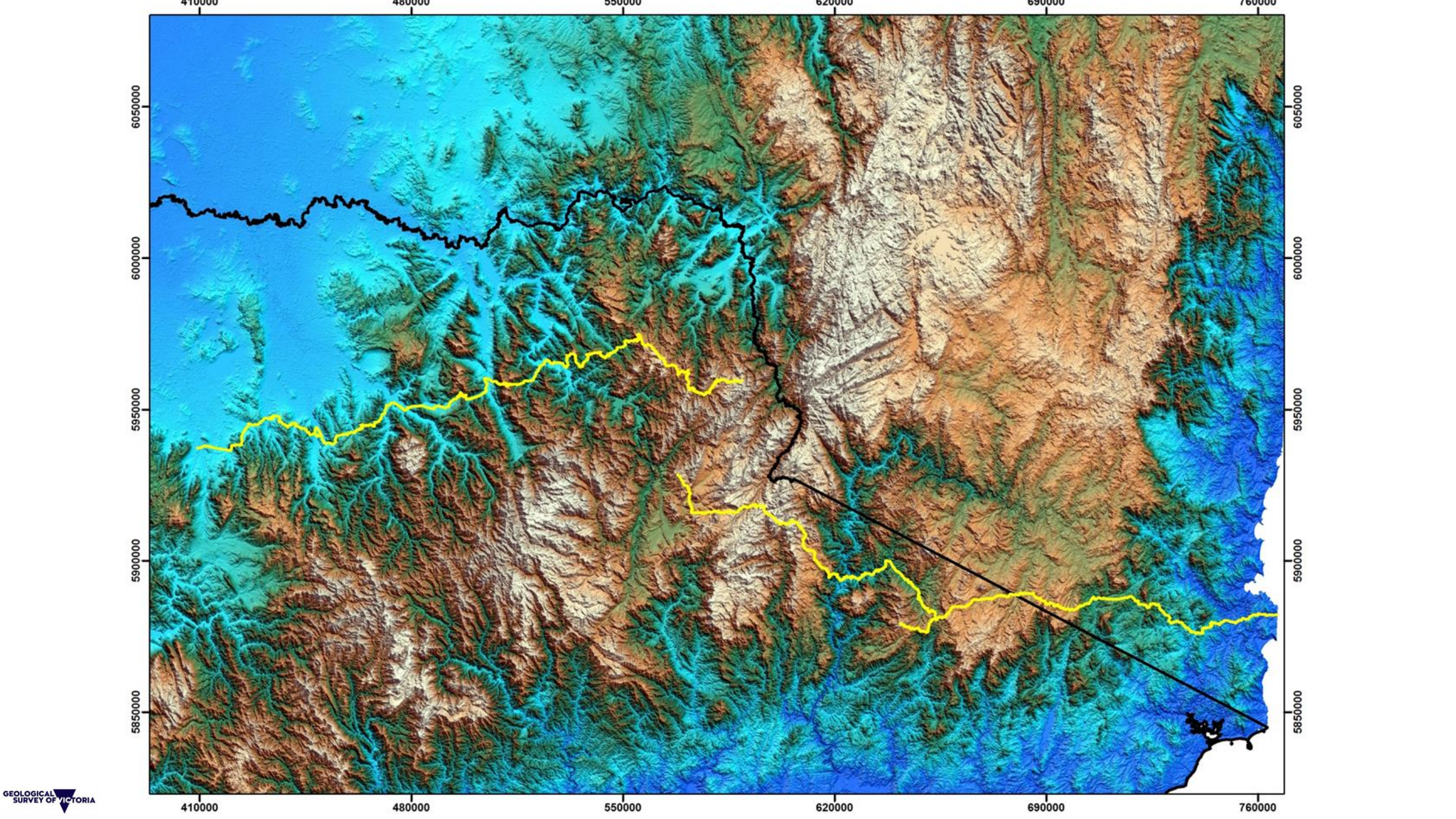
Deep Seismic Reflection

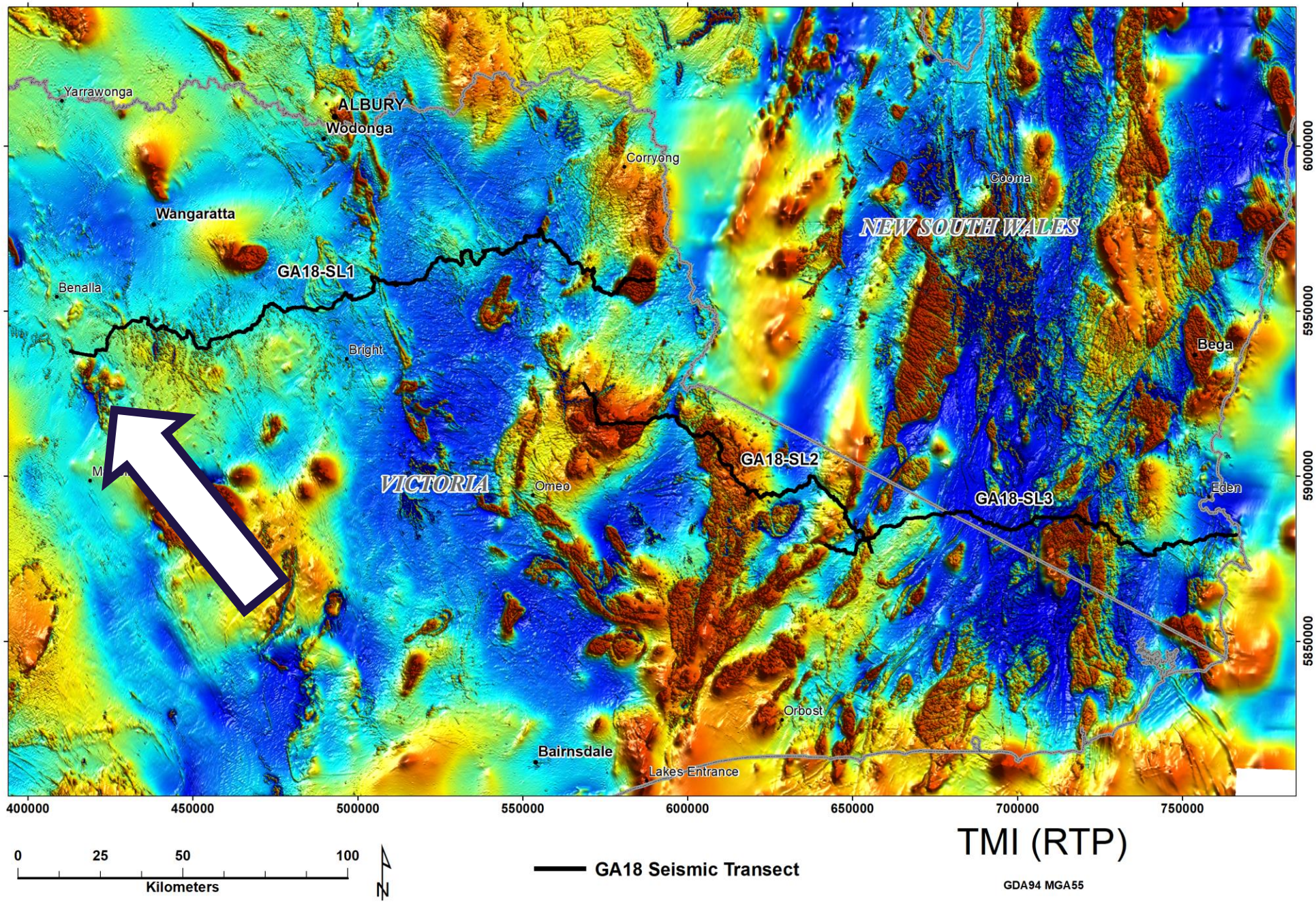


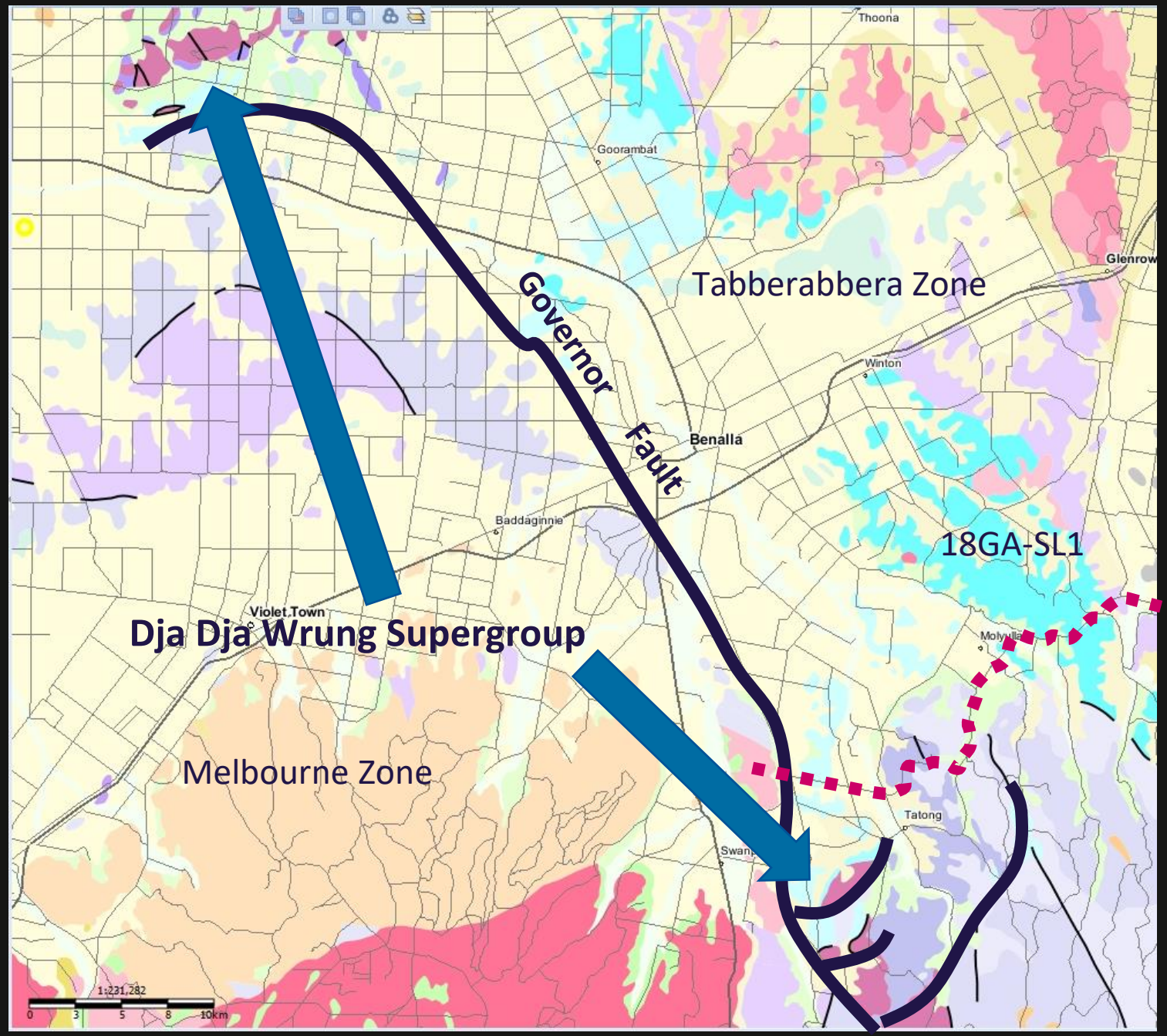
Modified from: Huston et al., 2016

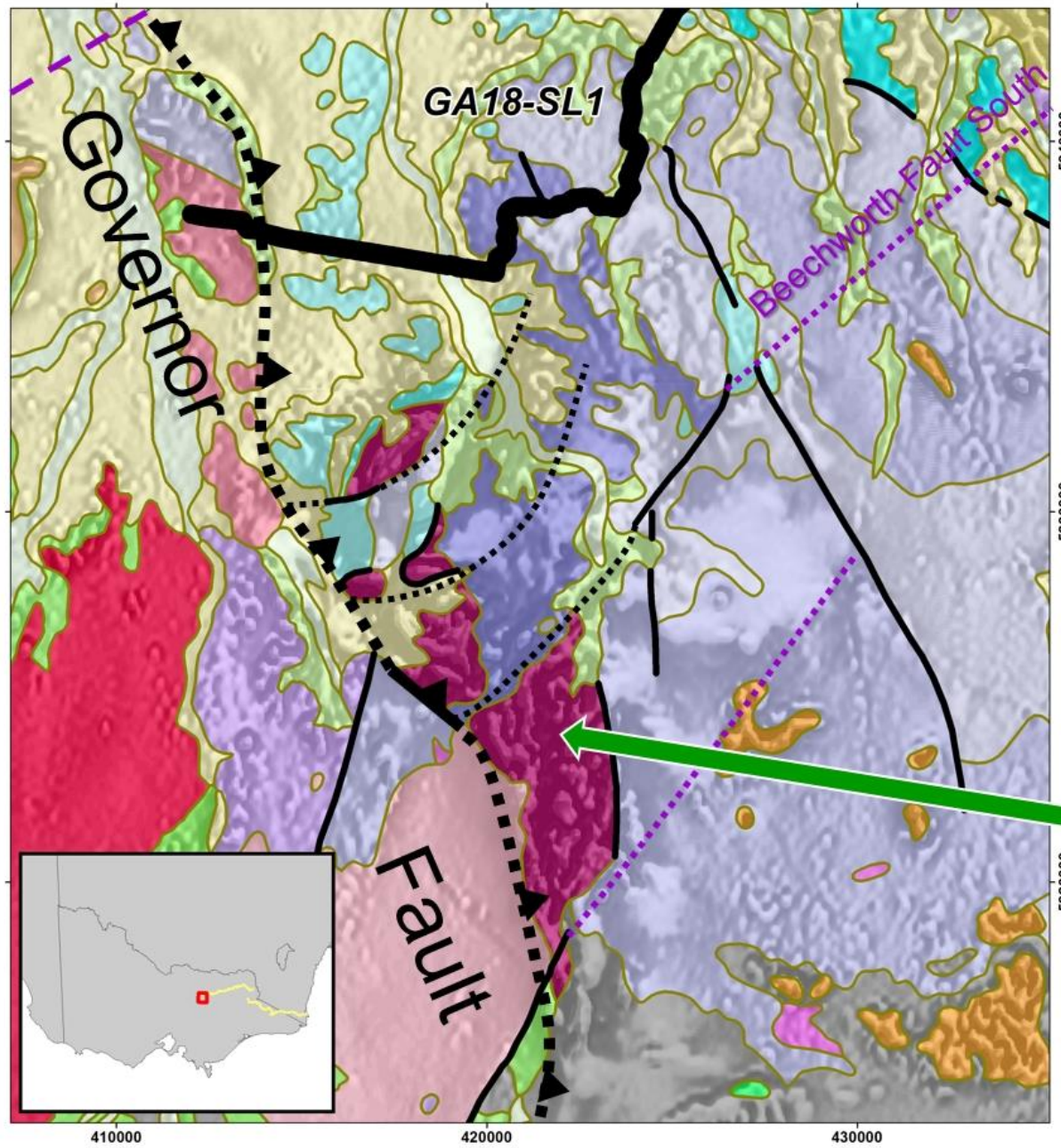




GEOLOGICAL SURVEY OF VICTORIA


Yarrawonga
ALBURY
Wodonga
Corryong
Cooma
Wangaratta
NEW SOUTH WALES
GA18-SL1
Benalla
Bright
Bega
VICTORIA
Omeo
GA18-SL2
GA18-SL3
Eden
Orbost
Bairnsdale
Lakes Entrance
6000000
5950000
5900000
5850000
400000
450000
500000
550000
600000
650000
700000
750000
0
25
50
100
Kilometers
N
GA18 Seismic Transect
TMI (RTP)
GDA94 MGA55


Thoona
Goorambat
Glenrow
Tabberabbera Zone
Governor
Fault
Winton
Benalla
Baddaginnie
18GA-SL1
Violet Town
Dja Dja Wrung Supergroup
Melbourne Zone
Tatong
1:231,282
0 3 5 8 10km

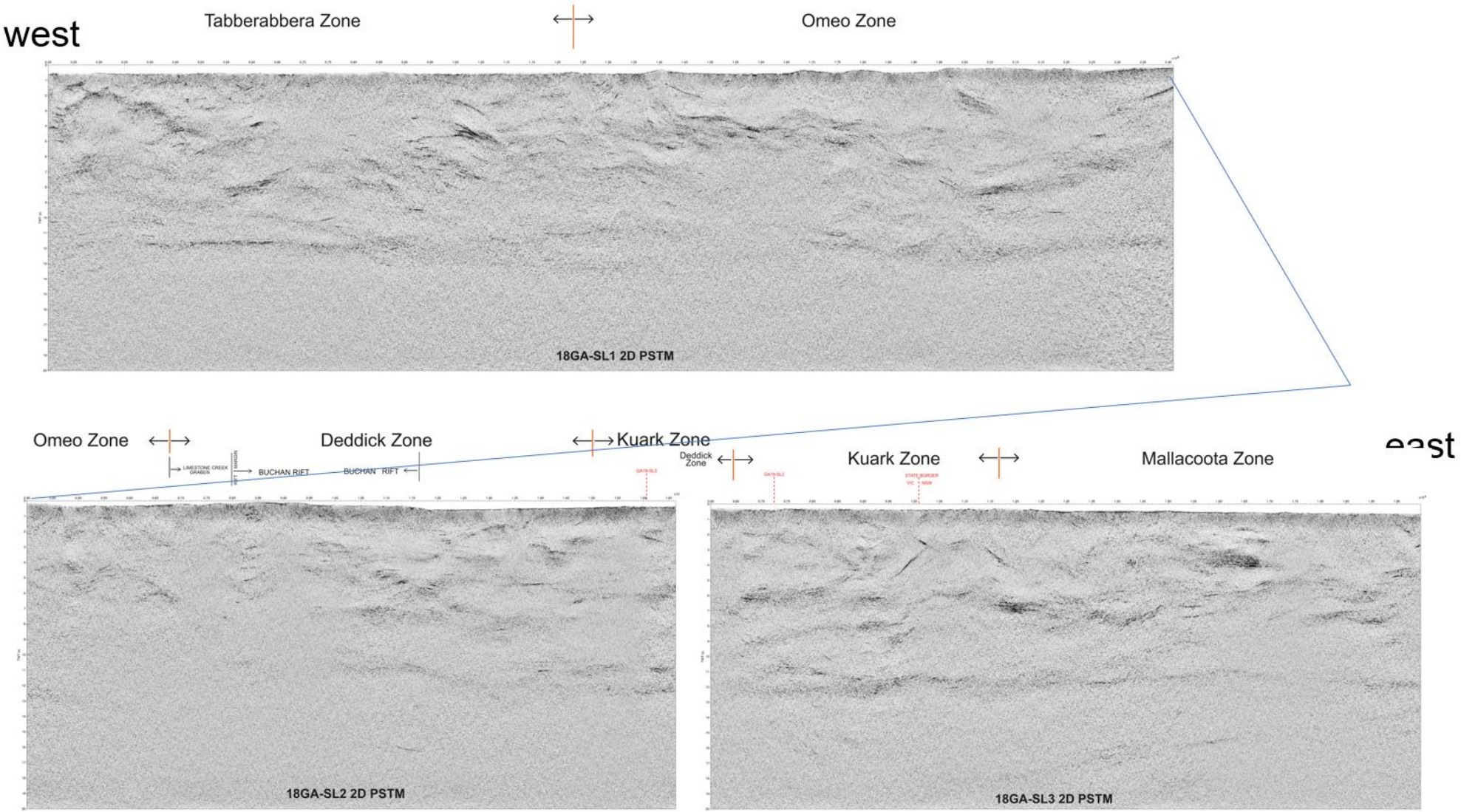


Dja Dja Wrung Supergroup:

Cambrian mafic meta-igneous rocks


VicGold 2023

SLaCT transects – migrated and stacked 20s TWT profiles



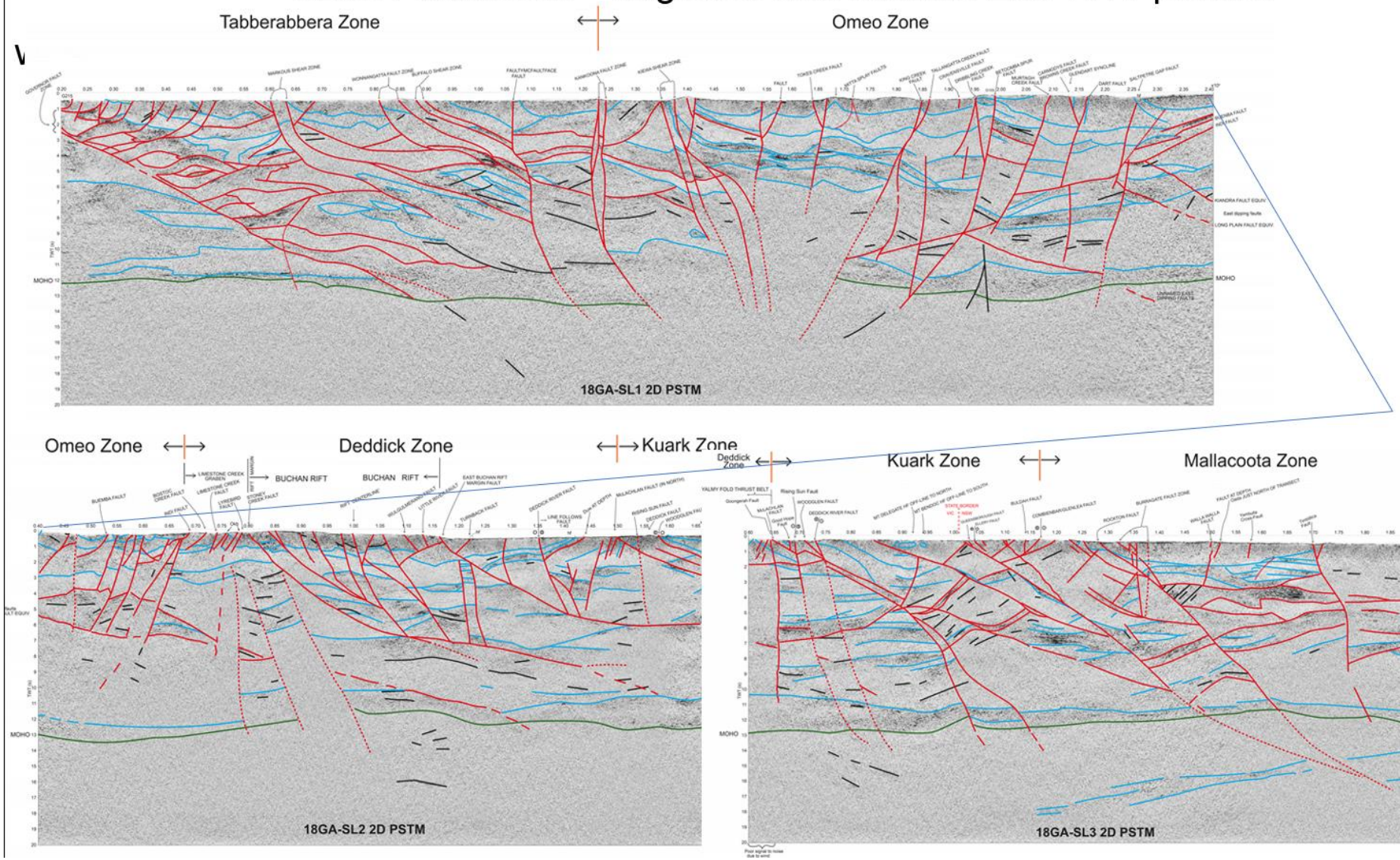
Australian Government
Geoscience Australia

GEOLOGICAL SURVEY OF NEW SOUTH WALES

GEOLOGICAL SURVEY OF VICTORIA

AuScope

SLaCT transects – migrated and stacked 20s TWT profiles



Preliminary interpretation subject to change

Australian Government
Geoscience Australia

GEOLOGICAL SURVEY OF NEW SOUTH WALES

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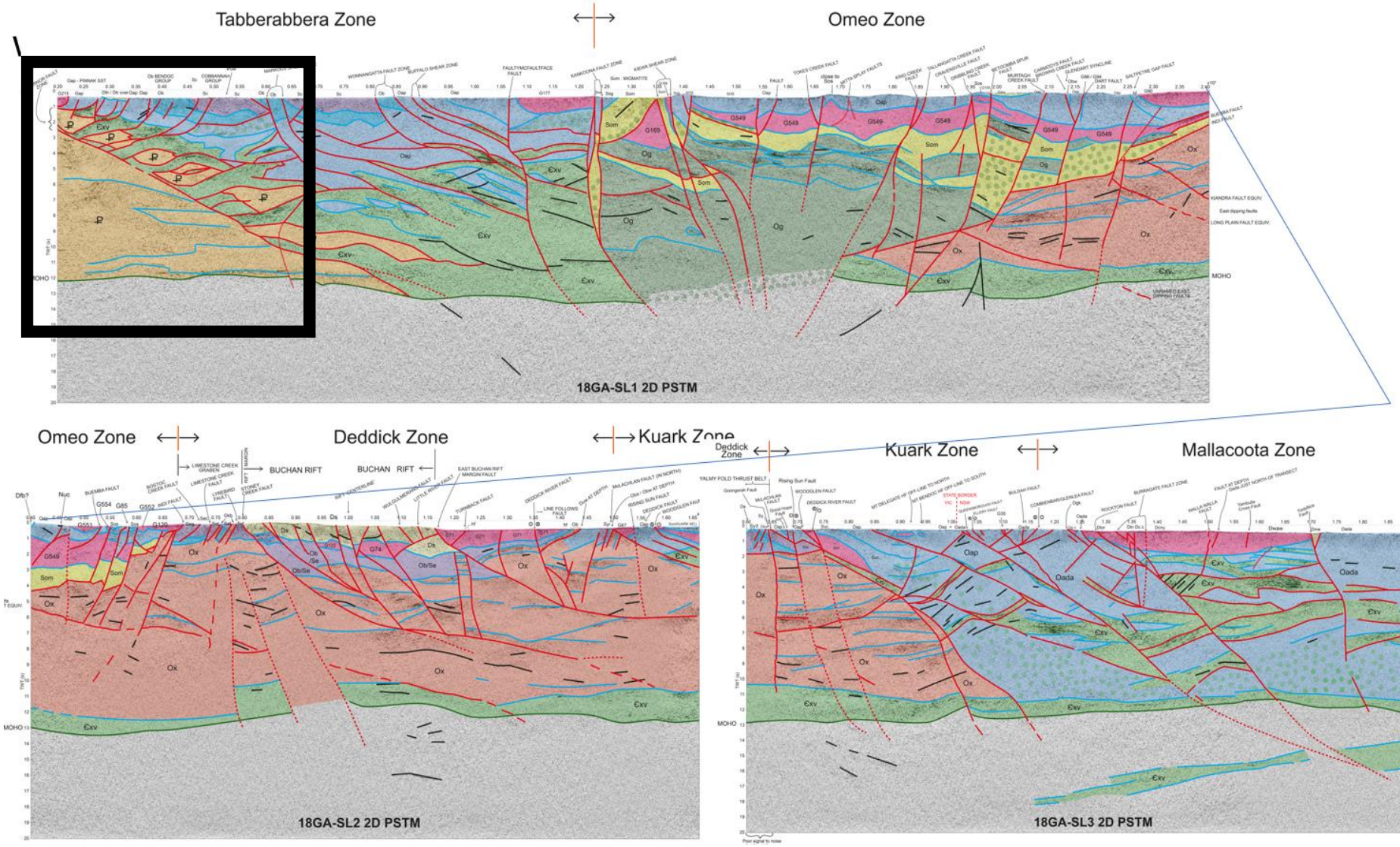

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GEOLOGICAL SURVEY OF NEW SOUTH WALES

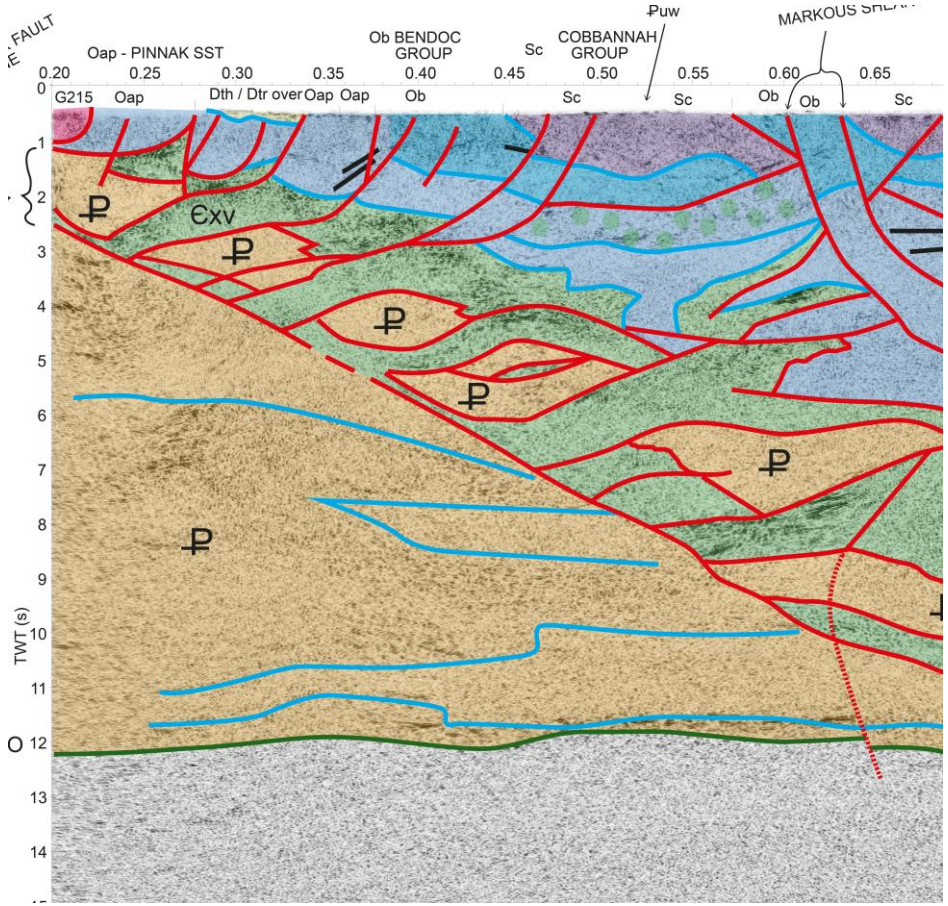
GEOLOGICAL SURVEY OF VICTORIA

AuScope

Governor Fault position at surface

Cambrian-age MORB metavolcanics (DDW Supergroup) and shale at surface

Ordovician-Silurian metasediments

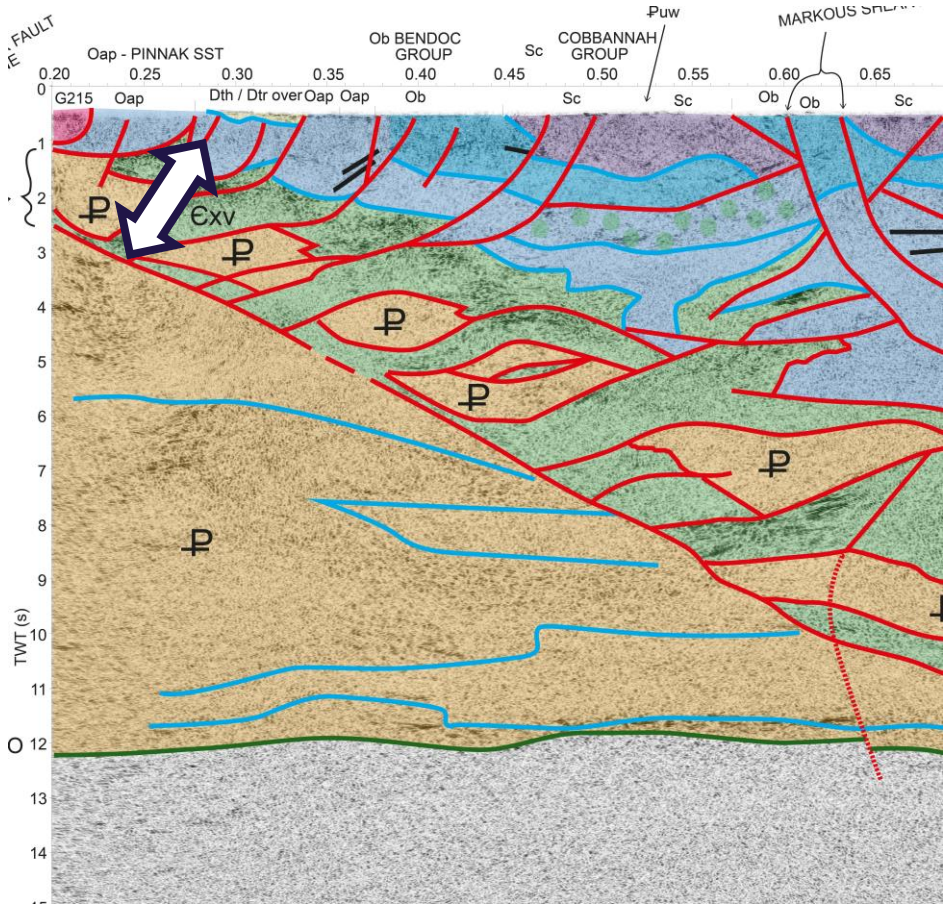


- Governor Fault – overthrusts east flank of Selwyn Block, dips east overall
- Tabberabbera Zone – mid-upper crust dominated by low reflectivity metasediments.
- Reflectors at depth and along western margin – crop out as Cambrian Dja Dja Wrung SG.
- But: crazy alternating reflectivity arranged en-echelon along the fault-plane…..
- Behaviour too coherent to be Pinnak Sandstone or equivalent. Must be crystalline.

Governor Fault position at surface

Cambrian-age MORB metavolcanics (DDW Supergroup) and shale at surface

Ordovician-Silurian metasediments

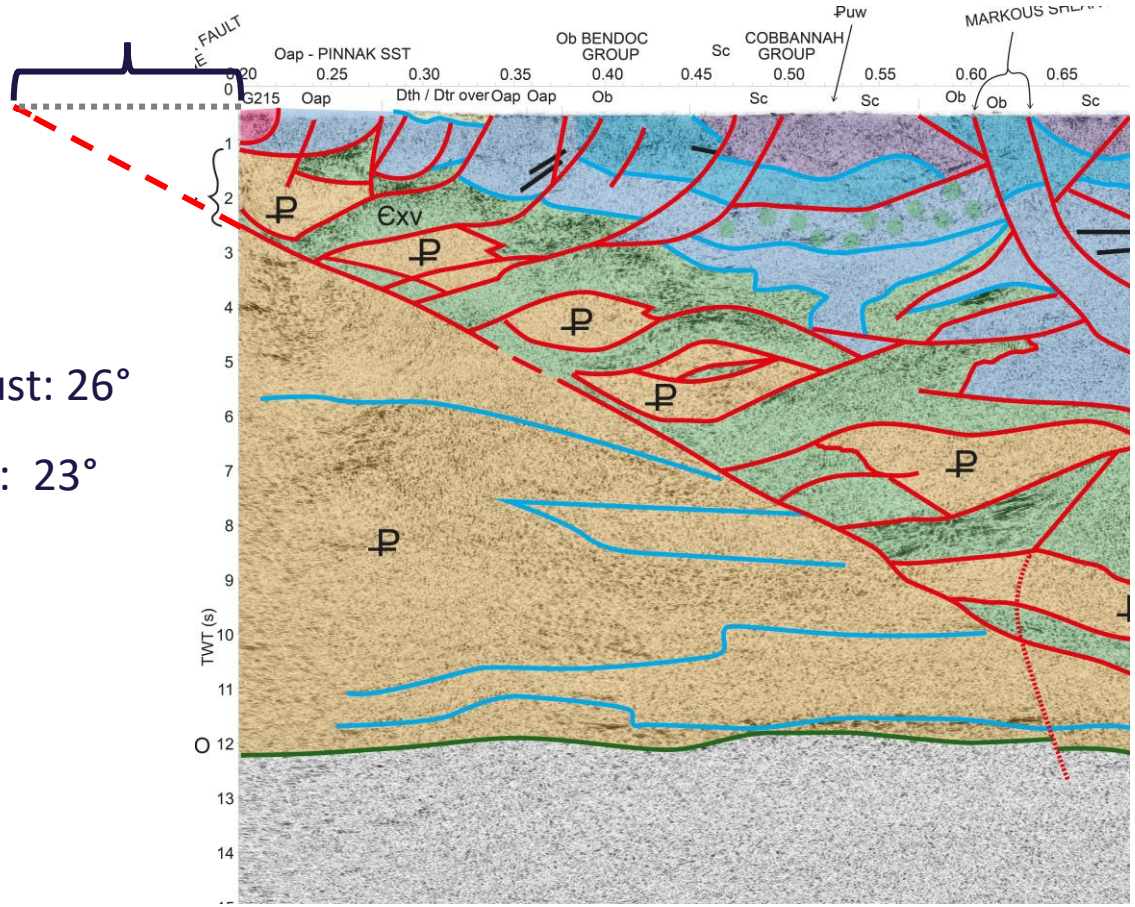


- Seismic data reveals the Governor Fault Zone is 1.5 – 2 s TWT thick (= ~4.5 - 6 km thick)
- Filled with a mix of crystalline crust inliers and abundant Cambrian mafic metavolcanics
- Only the upper part of the fault zone is exposed.

Governor Fault Zone footwall projects to surface 12 to 15 km west across strike within Melbourne Zone

Average Fault Zone dip to base of crust: 26°

Average FZ dip from ~ 4 to 2.5 s TWT: 23°



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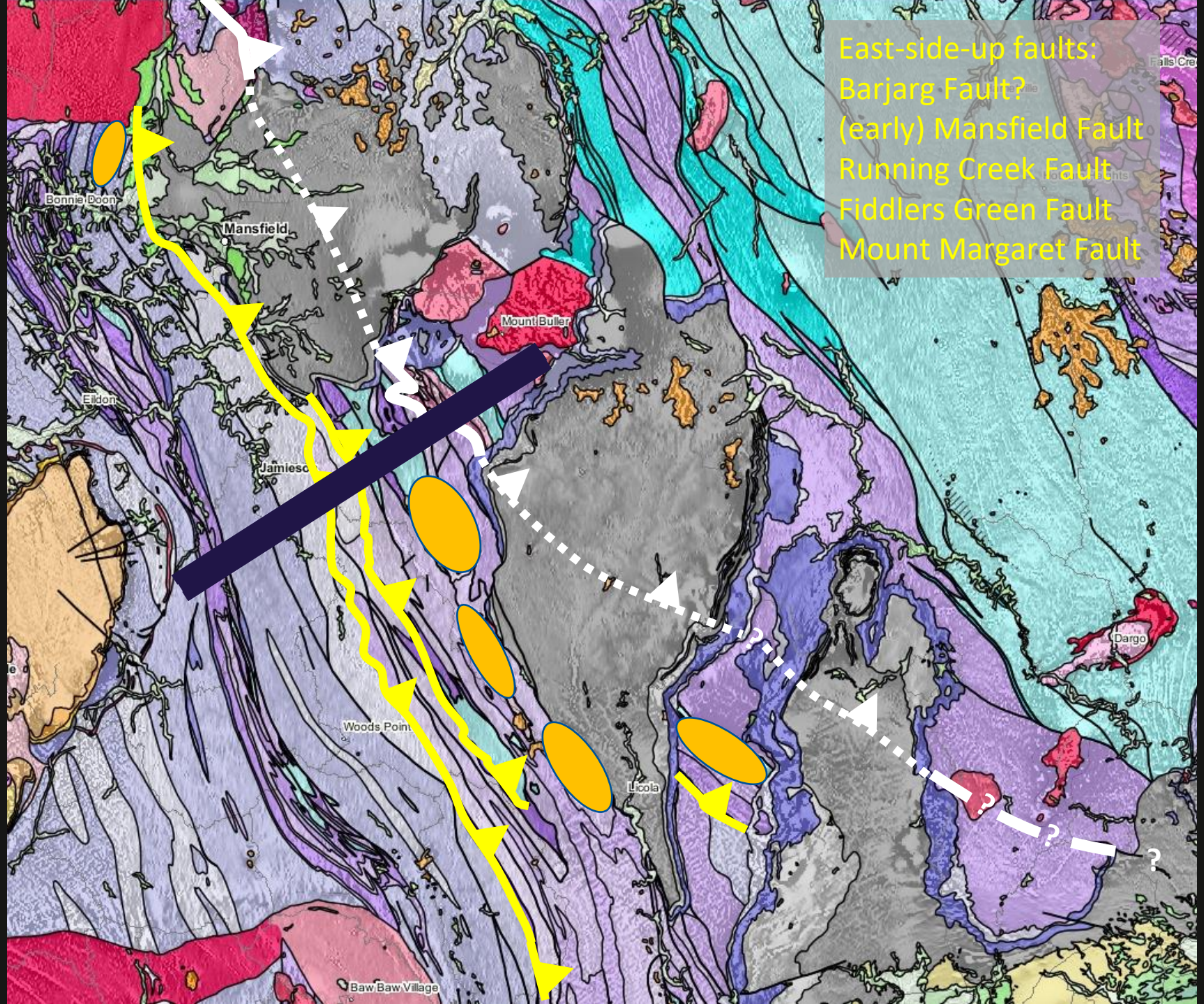
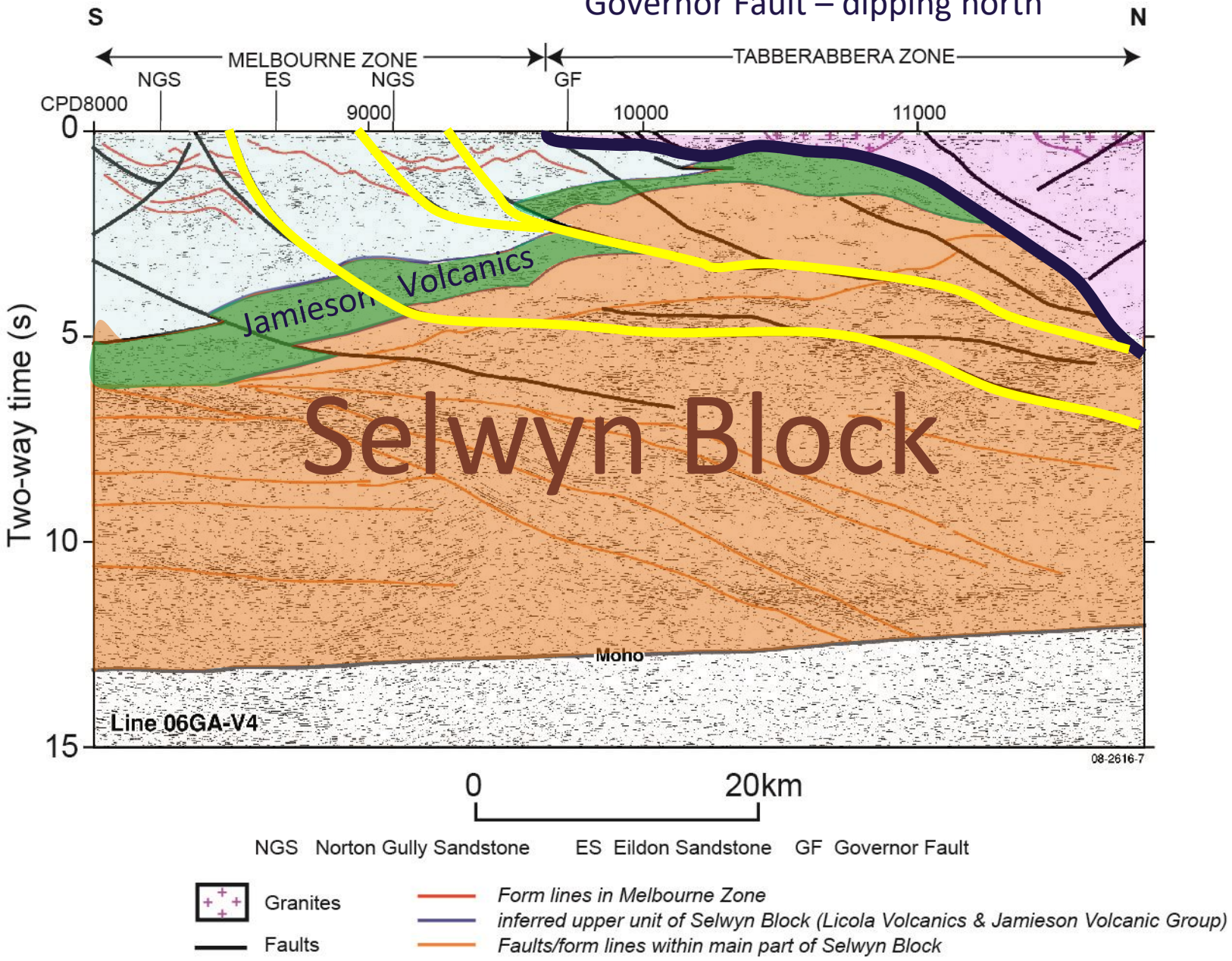


VicGold 2023

Governor Fault – dipping north

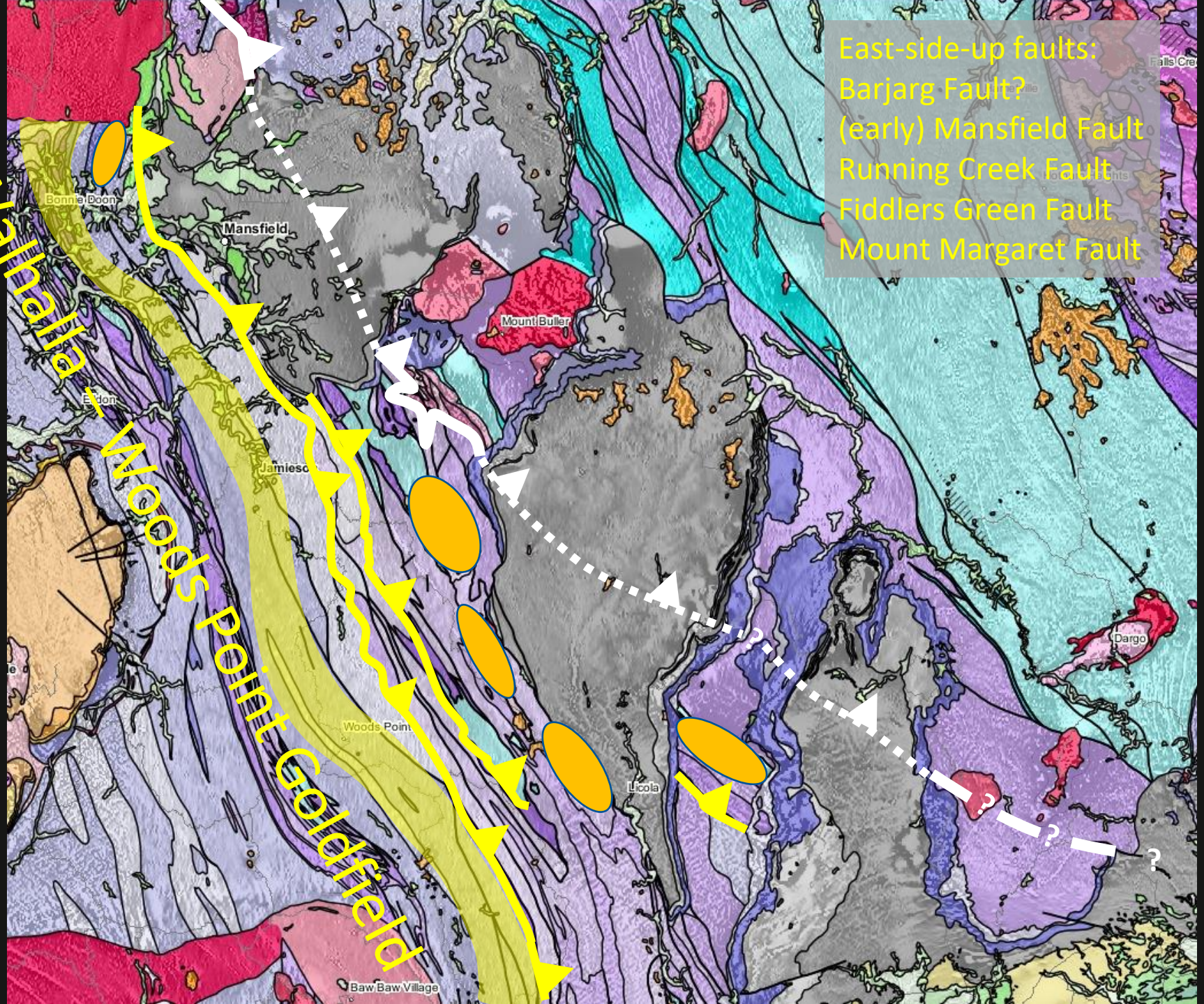
d



Cayley et al, 2011

Tracing the limits and the geometry of the Selwyn Block at depth

Regional deep seismic transects: pmd*crc, AUSCOPE



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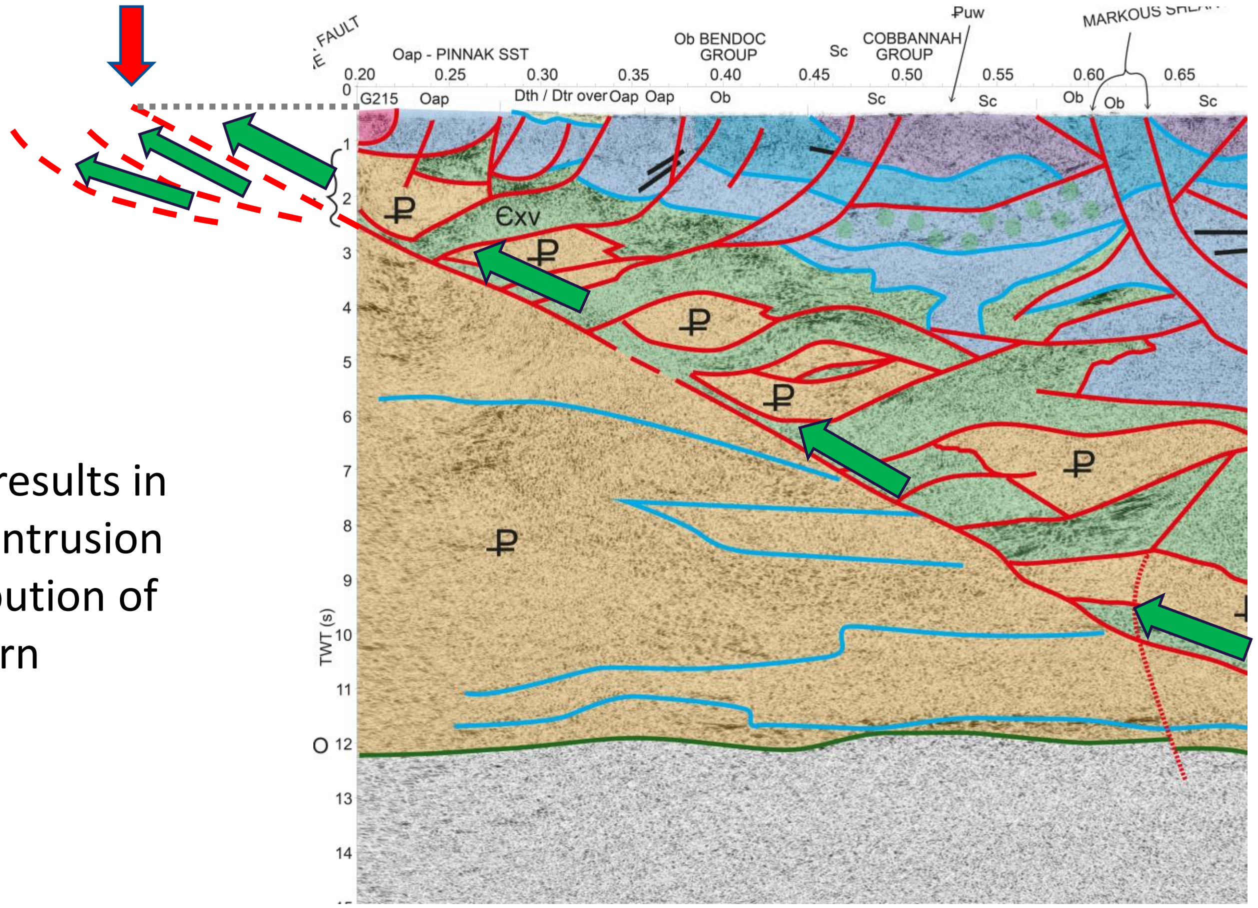
Governor Fault Zone footwall daylights

12 to 15 km across strike within Melbourne Zone – Woods Point Dyke Swarm

Crustal (lithospheric) scale fault zone – a conduit for mantle-derived (peridotite, lamprophyre) WPDS melts?

Crust is weak in tension / transtension, which results in distributed dilational strain – lots of potential intrusion pathways – might explain wide mapped distribution of Woods Point Dyke Swarm magmatism in eastern Melbourne Zone (eg VandenBerg et al., 2006)



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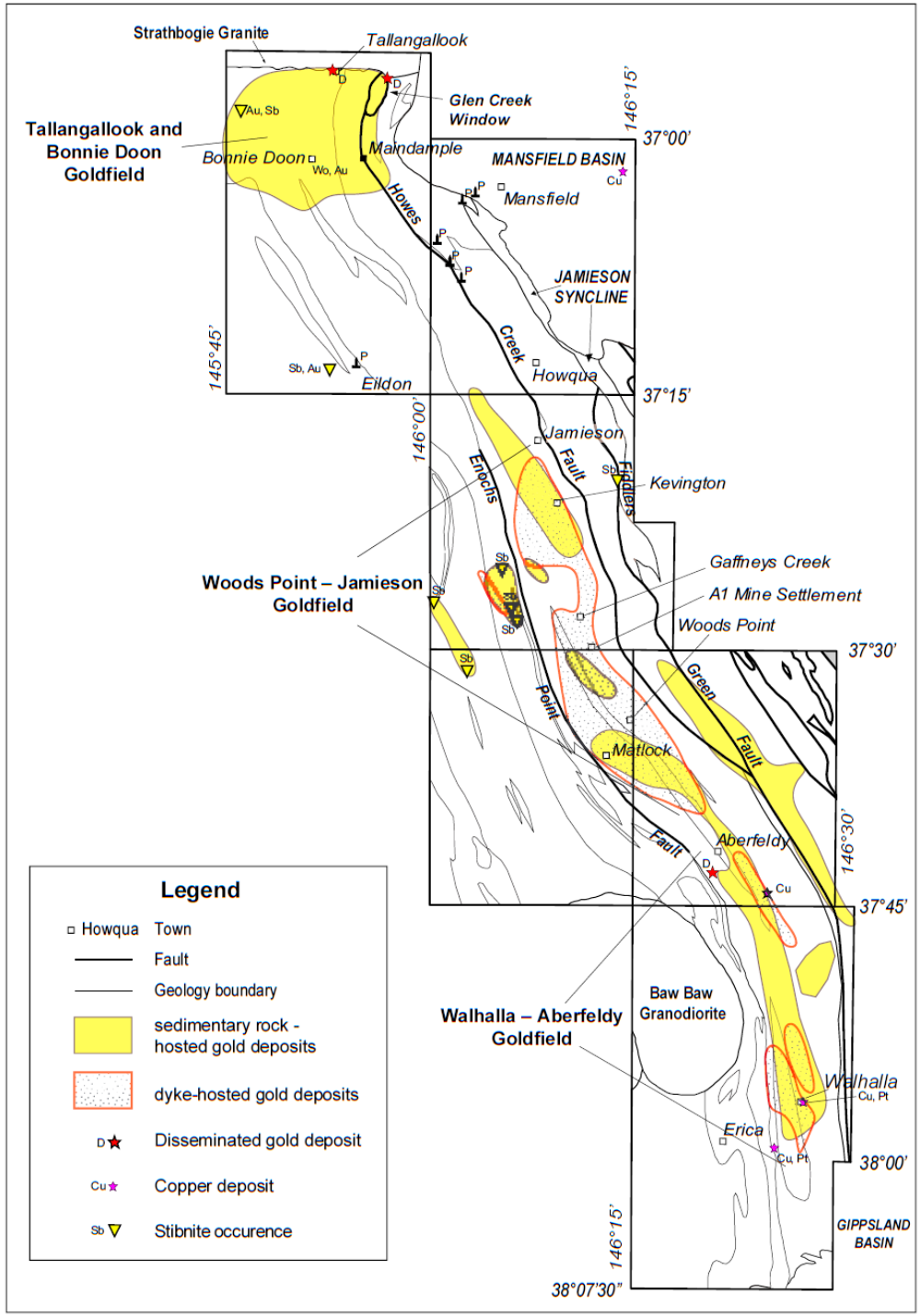
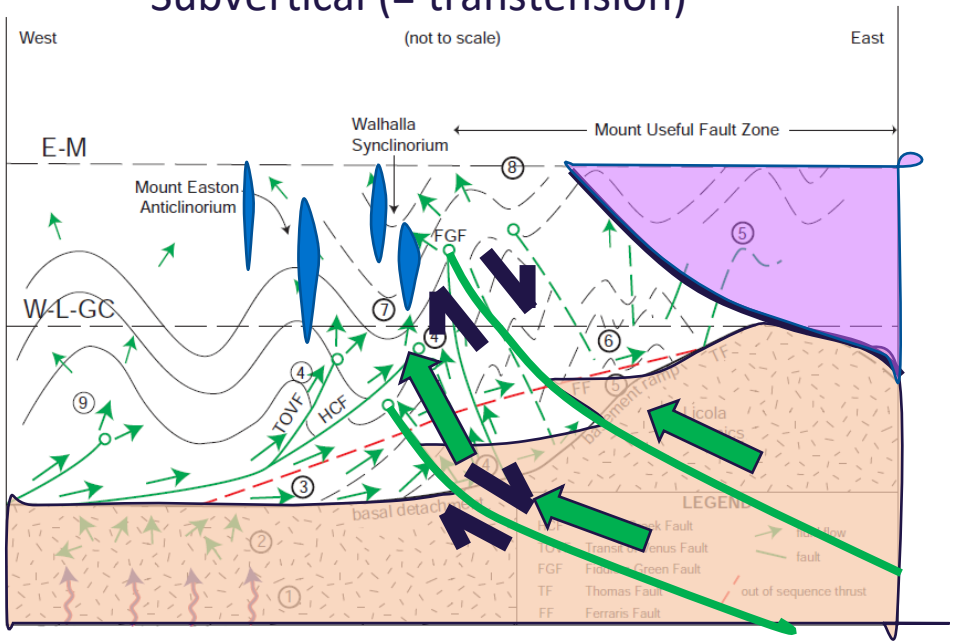
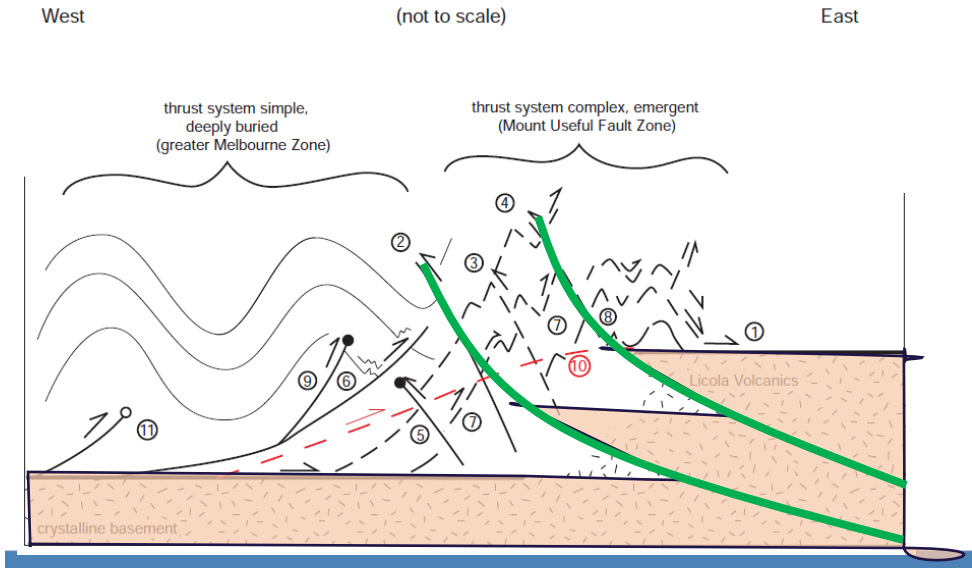
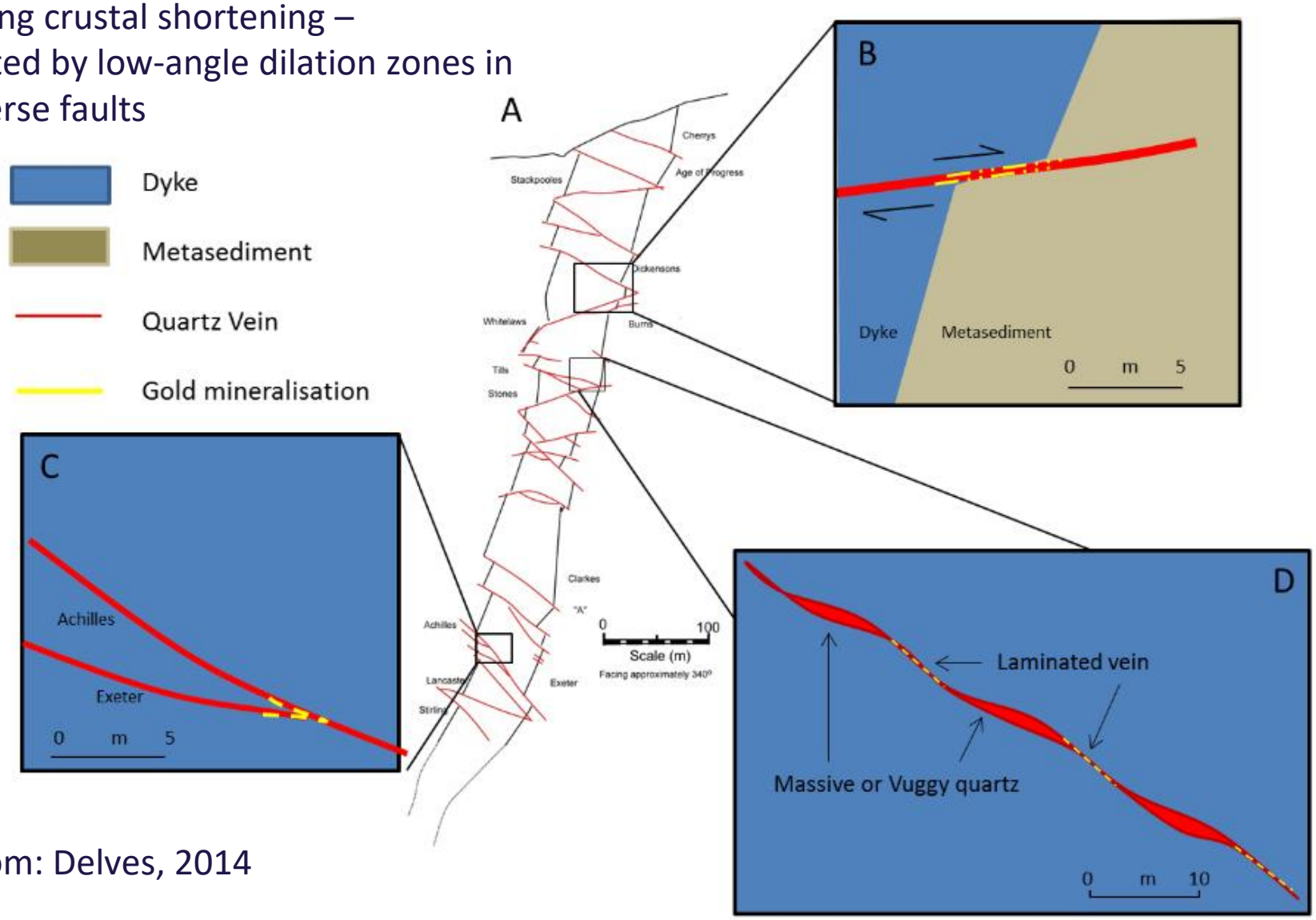
Woods Point Dyke Swarm: Subvertical (= transtension)





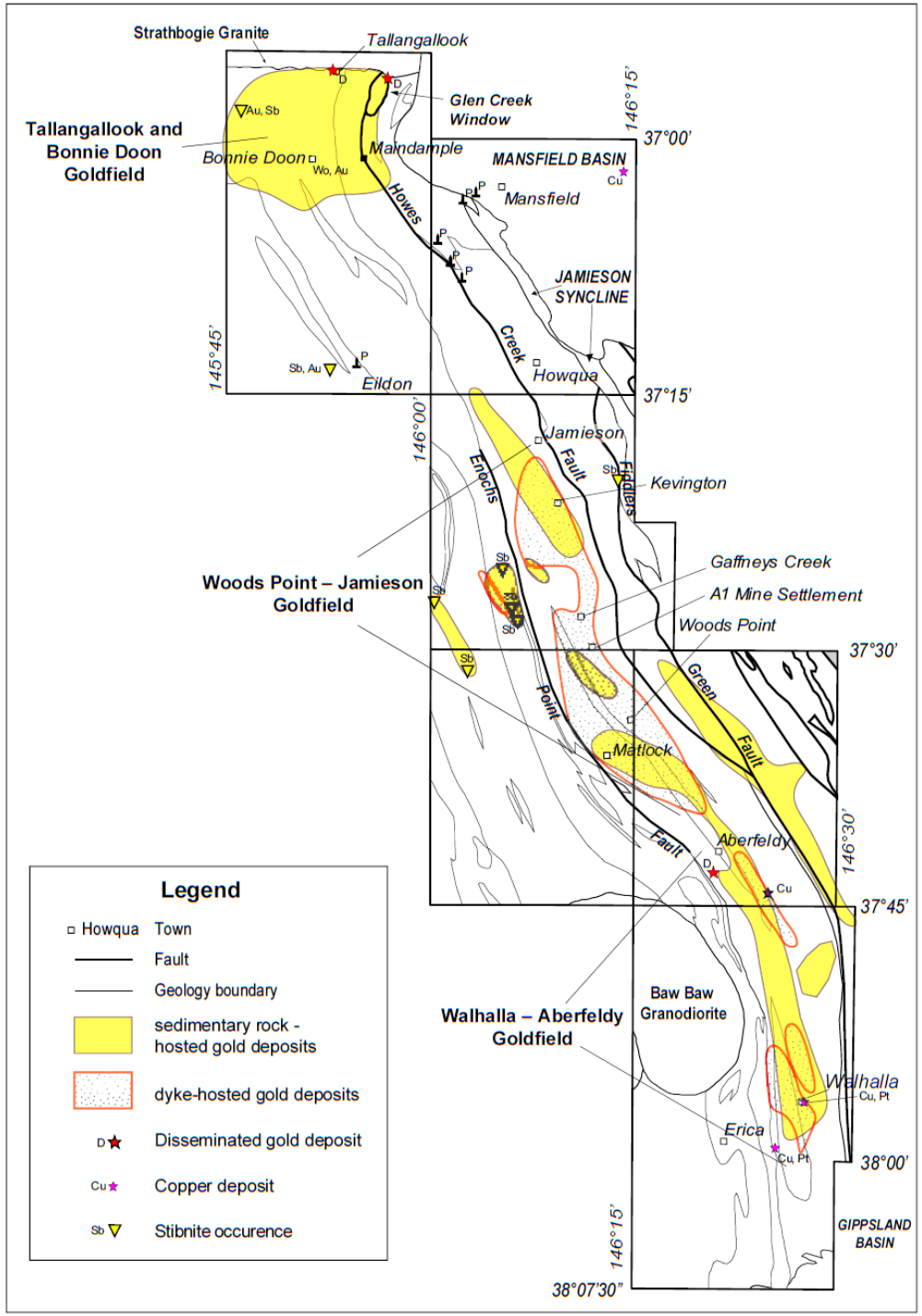


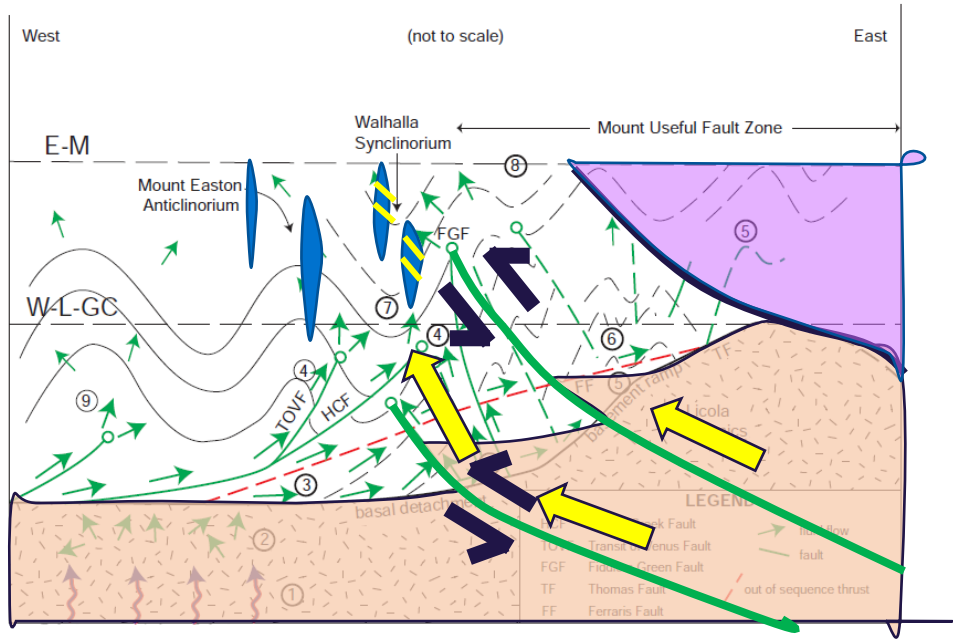
Gold and quartz introduced subsequently, during crustal shortening – hosted by low-angle dilation zones in reverse faults

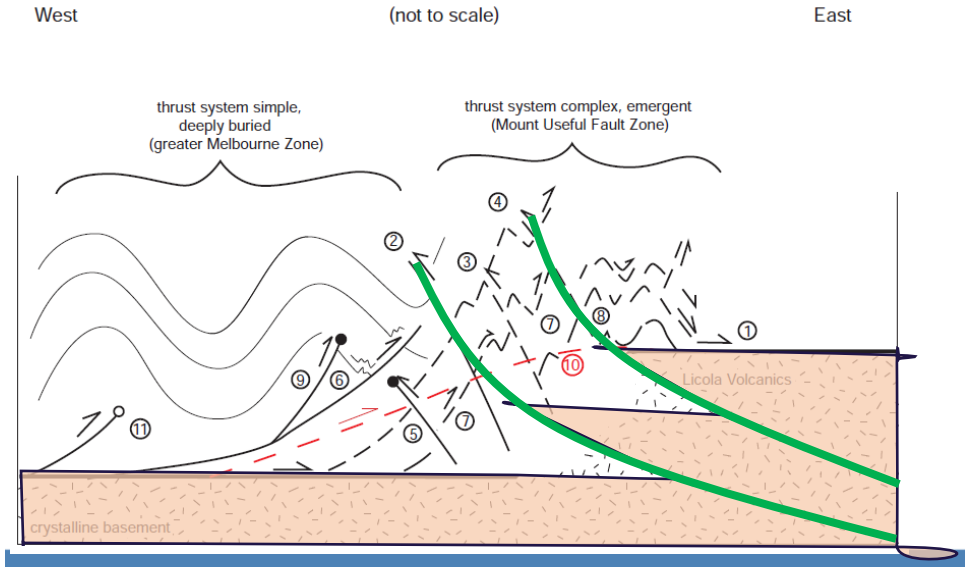


From: Delves, 2014

Figure 3.22 Localised occurences of high grade gold mineralisation in relation to their structural association using (A) the Morning Star Mine to illustrate (B) Dyke over sediment inflection (C) Quartz vein intersections (D) intermittent vein morphologies

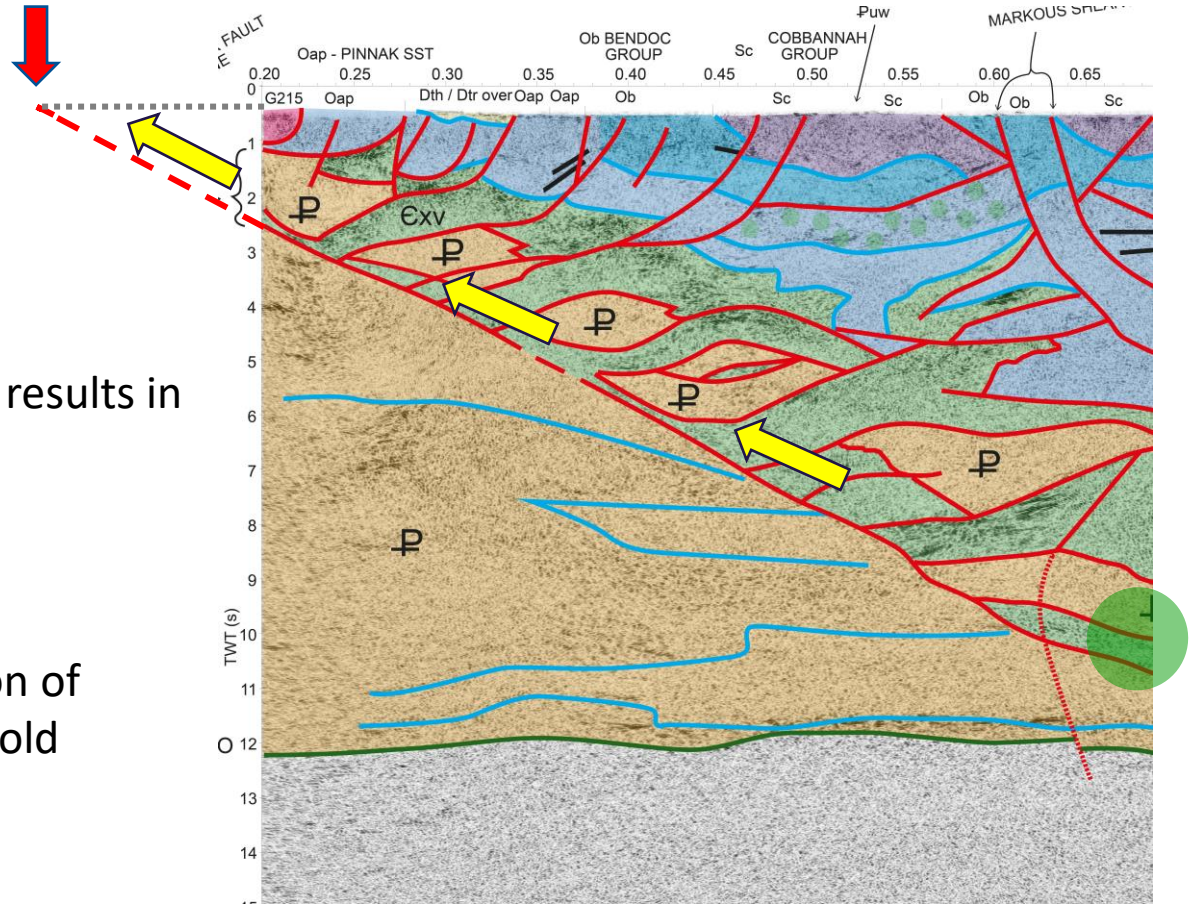

Strathbogie Granite
Tallangallook
Glen Creek Window
Tallangallook and Bonnie Doon Goldfield
Bonnie Doon
Mandample
MANSFIELD BASIN
Mansfield
Howes
JAMIESON SYNCLINE
Howqua
Eildon
Jamieson
Fault
Enochs
Flanders
Kevington
Gaffneys Creek
A1 Mine Settlement
Woods Point
Woods Point – Jamieson Goldfield
Green
Point
Matlock
Aberfeldy
Walhalla – Aberfeldy Goldfield
Baw Baw Granodiorite
Walhalla
Erica
GIPPSLAND BASIN
146°15'
37°00'
145°45'
37°15'
146°00'
37°30'
146°30'
37°45'
38°00'
38°07'30"
Legend
Howqua Town
Fault
Geology boundary
sedimentary rock - hosted gold deposits
dyke-hosted gold deposits
Disseminated gold deposit
Copper deposit
Stibnite occurence


West
(not to scale)
East
E-M
W-L-GC
Walhalla Synclinorium
Mount Useful Fault Zone
Mount Easton Anticlinorium
FGF
TOVF
HCF
basal detachment
LEGEND


West
(not to scale)
East
thrust system simple, deeply buried (greater Melbourne Zone)
thrust system complex, emergent (Mount Useful Fault Zone)
Licola Volcanics
crystalline basement

Governor Fault Zone footwall daylights
12 to 15 km across strike within Melbourne Zone – WP-W Goldfield

Crustal (lithospheric) scale fault zone –
a conduit for magmatic-derived
gold-bearing hydrothermal fluids?



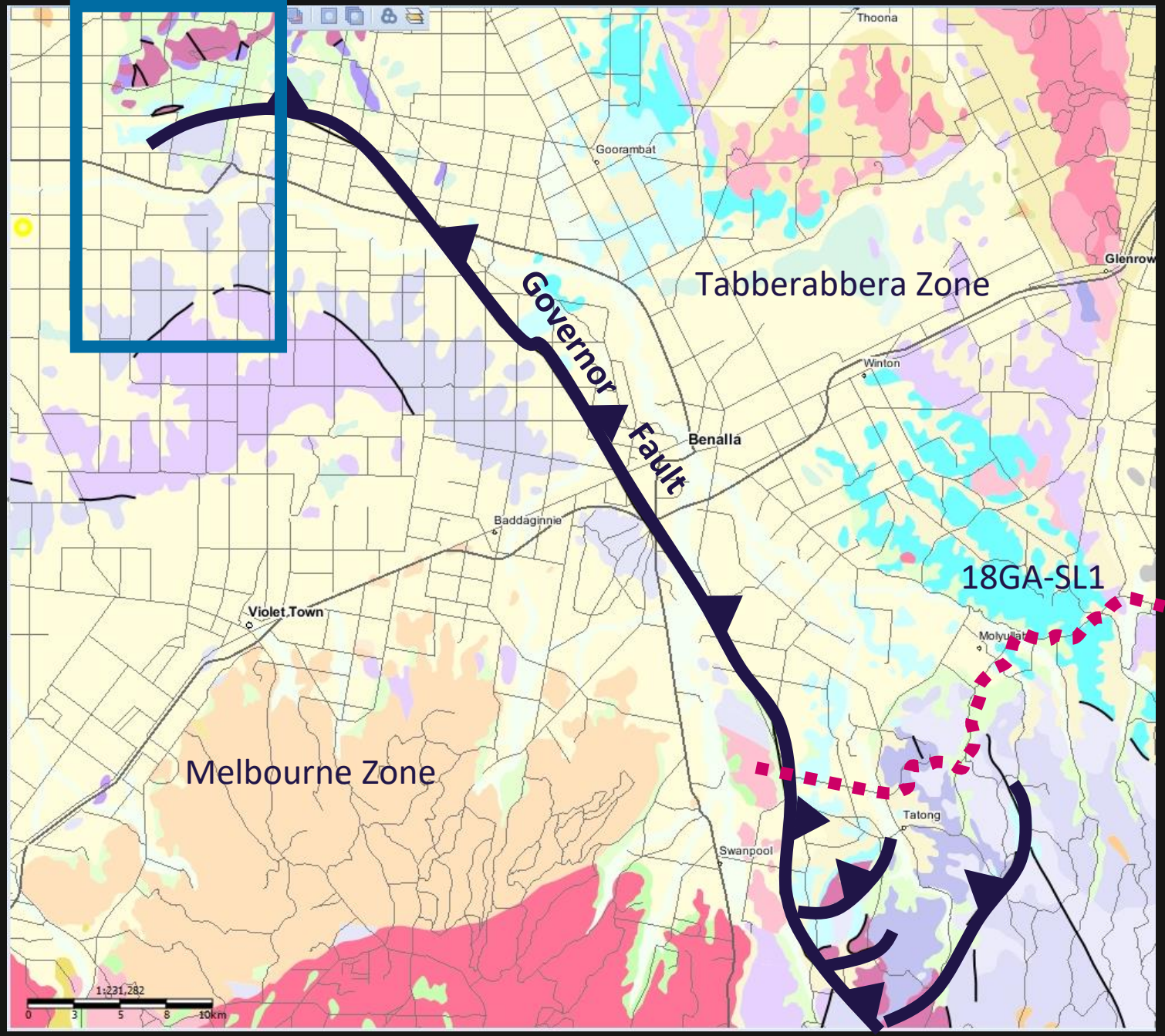
Crust is strong in compression / transpression, which results in strain localisation along/adjacent major structures
(eg Fiddlers Green F.)

Strain localisation = fluid plumbing localisation –
might explain the much narrower mapped distribution of Walhalla - Woods Point-Tallangallook hydrothermal gold mineralisation that overprints just some of the dykes
(eg VandenBerg et al., 2006)

- Seismic data reveals the Governor Fault Zone as 1.5 – 2 s TWT thick (= ~4.5 - 6 km)
- Only the upper part of the fault zone is exposed.

Talk outline

- ‘Orogenic gold’ – what is it and how to recognize the it?
- Central Victoria (the ‘Melbourne Zone’) is different to adjacent parts of Victoria.
- The western Melbourne Zone - mapping and deep seismic reflection data both suggest fluid plumbing system linkage into adjacent Bendigo Zone orogenic gold systems
- The eastern Melbourne Zone – 5 M oz+ of gold endowment with a different (intrusion-related) association.
- Previous internally-derived models to explain Walhalla-Woods Point gold mineralization
- Results of the Southern Lachlan Crustal Transect – a new externally-derived model for Walhalla-Woods Point gold mineralization (and mafic magmatism)
- **Implications for explorers.**

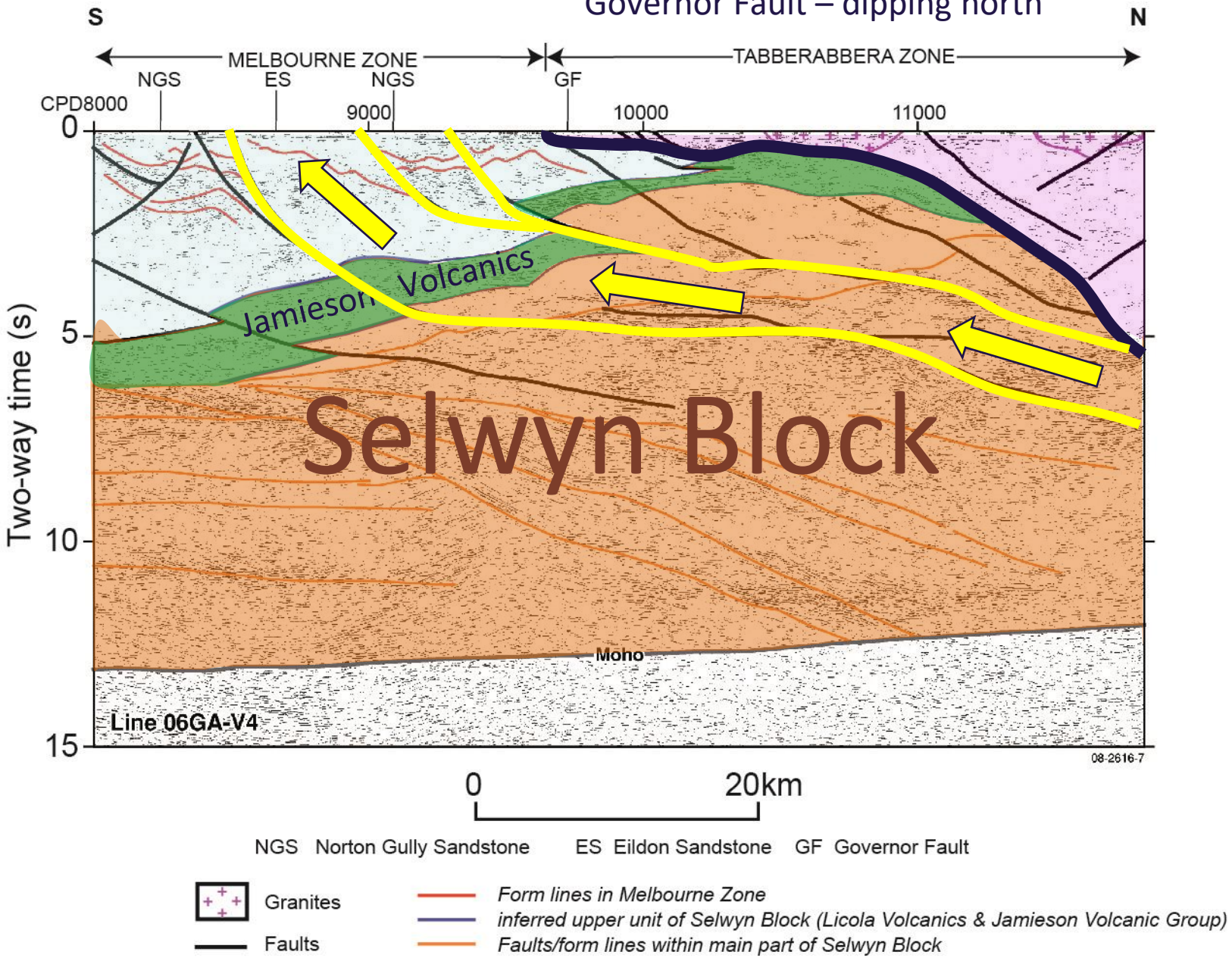

Thoona
Goorambat
Glenrow
Tabberabbera Zone
Governor
Fault
Winton
Benalla
Baddaginnie
18GA-SL1
Violet.Town
Melbourne Zone
Tatong
Swanpool
1:231,282
0 3 5 8 10km

This northernmost part of the Melbourne Zone is concealed beneath younger cover rocks, not properly prospected for IRG.

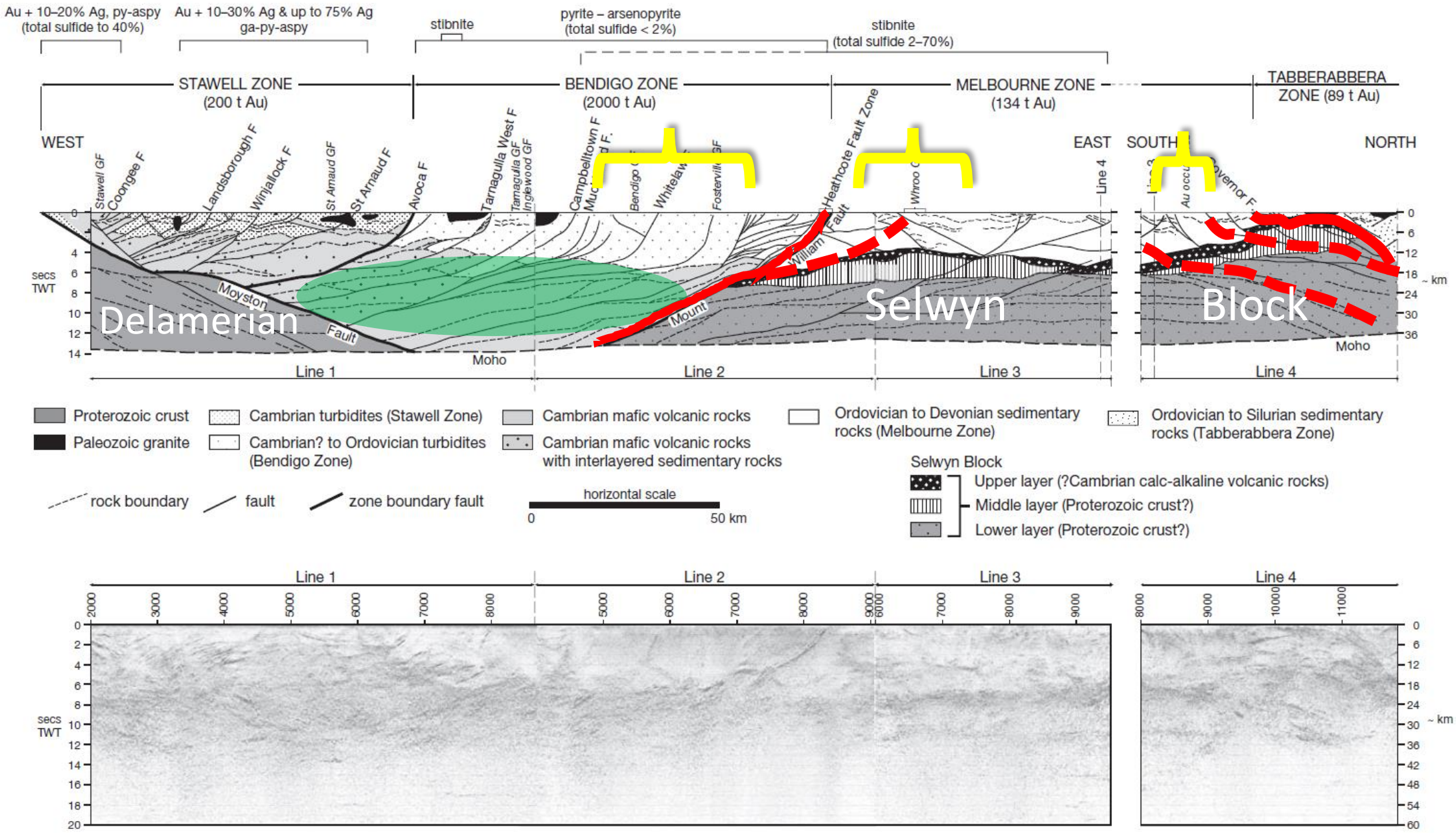
Could there be a ‘Benalla west’ and / or ‘Shepparton Goldfield’?

The GSV is currently undertaking work to test these ideas.

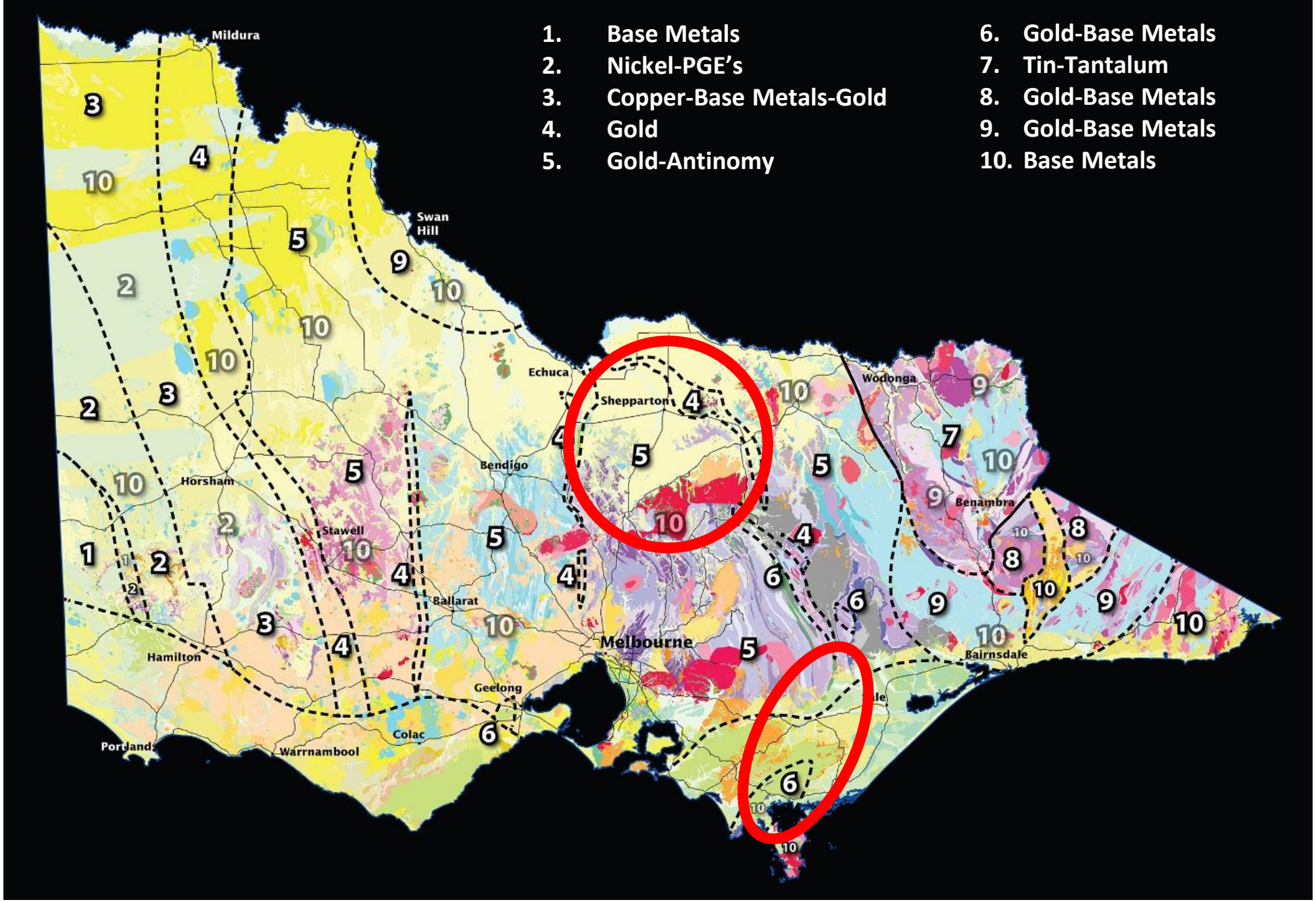
Governor Fault – dipping north



Cayley et al, 2011



Cayley et al., 2011



Time to add to the

GSV

Mineral Systems map

Conclusions

- Most Melbourne Zone gold mineralisation appears to be externally derived, from the Bendigo Zone (west) or from the mantle / Tabberabbera Zone (east, north)
- Deep seismic reflection datasets supported by modern structural mapping show how the structural linkages work
- SLaCT data: images a lithospheric scale megathrust – the perfect structure to tap mantle-derived melts (and, potentially intrusion-related gold and other metals)
- Most (ie 5M oz) Melbourne Zone gold endowment (to date) is magmatic, NOT orogenic. Opportunities elsewhere (including beyond the Melbourne Zone)?
- A hybrid intrusion-related but structurally controlled mineralisation model for the Walhalla-Woods Point-Tallangalook goldfield can be chased under cover in the northern and southeastern Melbourne Zone.