Victoria

A spotlight on Cambrian – Devonian Victorian geology –

the Delamerian and Lachlan orogens and the formation of a world class gold (+Critical Minerals) province

Ross Cayley

April 29 2024

GEOLOGICAL SURVEY OF VICTORIA

About the Geological Survey of Victoria

The Geological Survey of Victoria (GSV) is the State's geoscience agency. It sits within the Department of Energy, Environment and Climate Action.

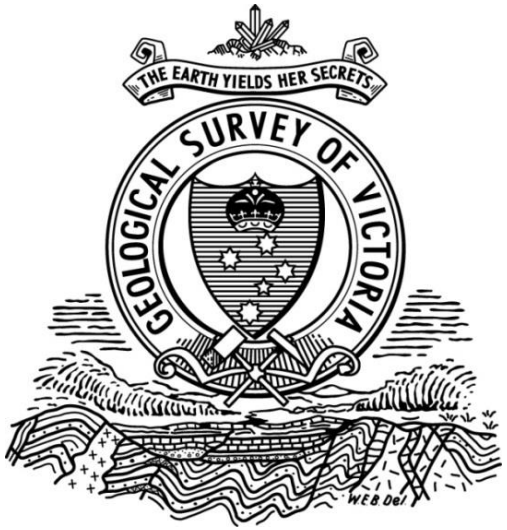
The GSV is responsible for understanding Victoria's geological framework through regional geoscientific investigations, particularly to enable the informed and integrated management of State-owned resources.

For over 170 years, GSV has studied and mapped the surface and sub-surface of Victoria. Today, it provides evidence-based knowledge and information to Government, industry, academia and the community, using the latest geoscience technologies and methods.

GSV staff come from a range of geoscientific disciplines, providing an authoritative and in-depth knowledge of our dynamic planet.

Australian Government

Geoscience Australia



GEOLOGICAL SURVEY OF VICTORIA

ANSIR NATIONAL RESEARCH FACILITY FOR EARTH SOUNDING

AuScope

Significant Drill Intersections of 2017

rank	country	company	project	hole	intersection
1		**Kirkland Lake Gold Ltd.** (TSX, OTCQX)	**Fosterville**	UDH1817	15.15m @ 1429g/t Au from 345.55m

Australian Mining

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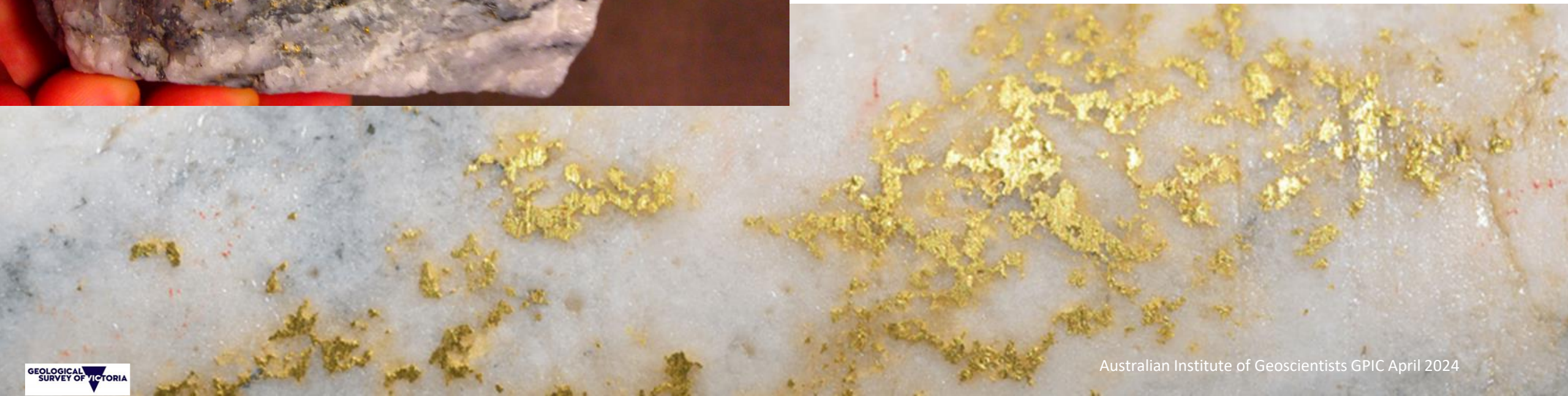
Fosterville record drives Kirkland Lake's 'best year ever'

January 10, 2020 News Salomae Haselgrove



FOSTERVILLE – Approaching ~12.5 Moz

Production 2020

Gold produced (oz) 640,467

Ore processed (tonnes) 593,343

Gold grade (g/t) 33.9

Recovery (%) 98.9

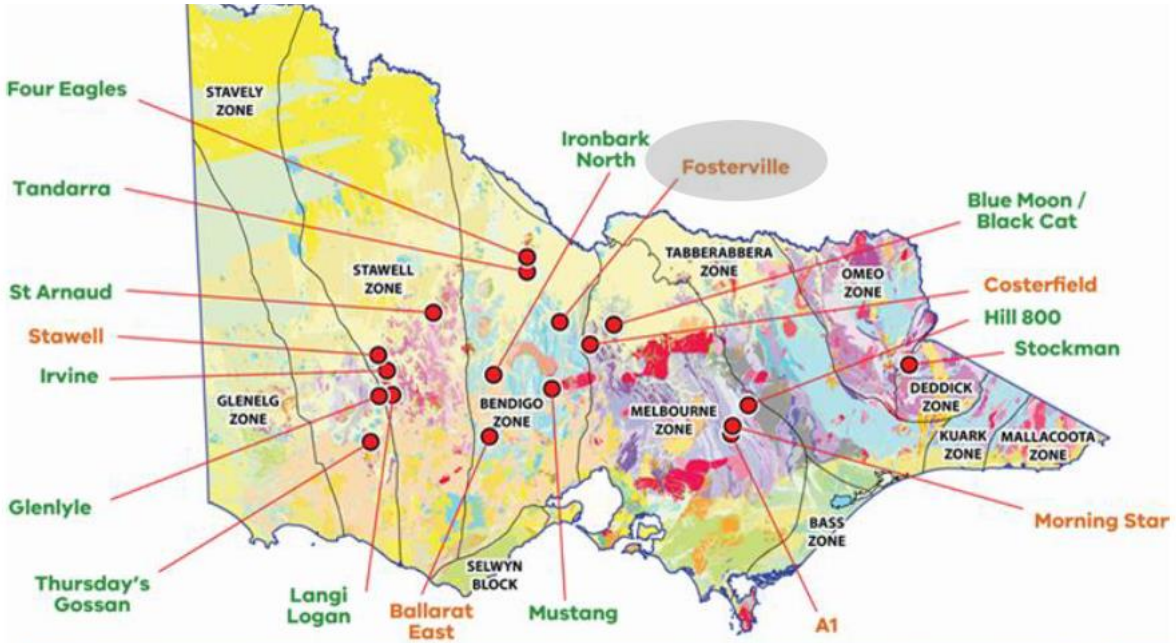
Operating: $139/oz

AISC: $312/oz

Exploration 2021

$85-$95M

Robbins Hill



Source: https://www.kl.gold/news-and-media/press-release-details/2021/Kirkland-Lake-Gold-Reports-Record-Results-in-Q4--FY-2020/default.aspx

Highest-grade underground gold mines in the world – Victoria dominates

	Mine	Country	Major owner	Q1 2020 Au milled grade, g/t
1	Fosterville	Australia	Kirkland Lake	42.4
2	Nevada Operations	United States	Hecla	35.9
3	Macassa	Canada	Kirkland Lake	19.7
4	Segovia Operations	Colombia	Gran Colombia	14.9
5	Eagle River	Canada	Wesdome	14.0
6	Costerfield / Augusta	Australia	Mandalay	12.6
7	Hope Bay	Canada	TMAC	11.9
8	Island Gold	Canada	Alamos Gold	11.7
9	Bambanani	South Africa	Harmony Gold	10.7
10	Seabee	Canada	SSR Mining	10.3

Source: Mines and Metals

SELECT DRILL RESULTS **Sunday Creek** (as of April 2024)

Hole SDDSC107	455.3 m @ 7.2 g/t Au (uncut) from 413.6 m
Hole SDDSC077B	404.4 m @ 5.1 g/t Au (uncut) from 374.0 m
Hole SDDSC082	331.5 m @ 6.8 g/t Au (uncut) from 588.0 m
Hole SDDSC091	20.0 m @ 62.7 g/t Au from 430.0 m

Top gold producers based on production 2020

	Property	Location	Operating Owner	Work Type	2020 Production (koz)	2020 Costs (USD/oz)
1.	Olimpiada	Russia	Polyus	Open-Pit	1,200	532
2.	Pueblo Viejo	Dominican Republic	Barrick Gold	Open-Pit	899	661
3.	Grasberg	Indonesia	Freeport-McMoRan	Underground	848	1,279
4.	Cadia Valley	Australia	Newcrest Mining	Underground	822	104
5.	Kibali	Dem. Republic of the Congo	Barrick Gold	Open-Pit/Underground	807	778
6.	Cortez	United States	Barrick Gold	Open-Pit/Underground	798	1,000
7.	Lihir	Papua New Guinea	Newcrest Mining	Open-Pit	772	1,308
8.	Loulo Gounkoto	Mali	Barrick Gold	Open-Pit/Underground	680	1,001
9.	Boddington	Australia	Newmont	Open-Pit	670	1,091
10.	Fosterville	Australia	Kirkland Lake Gold	Underground	640	313

Source: Miningintelligence

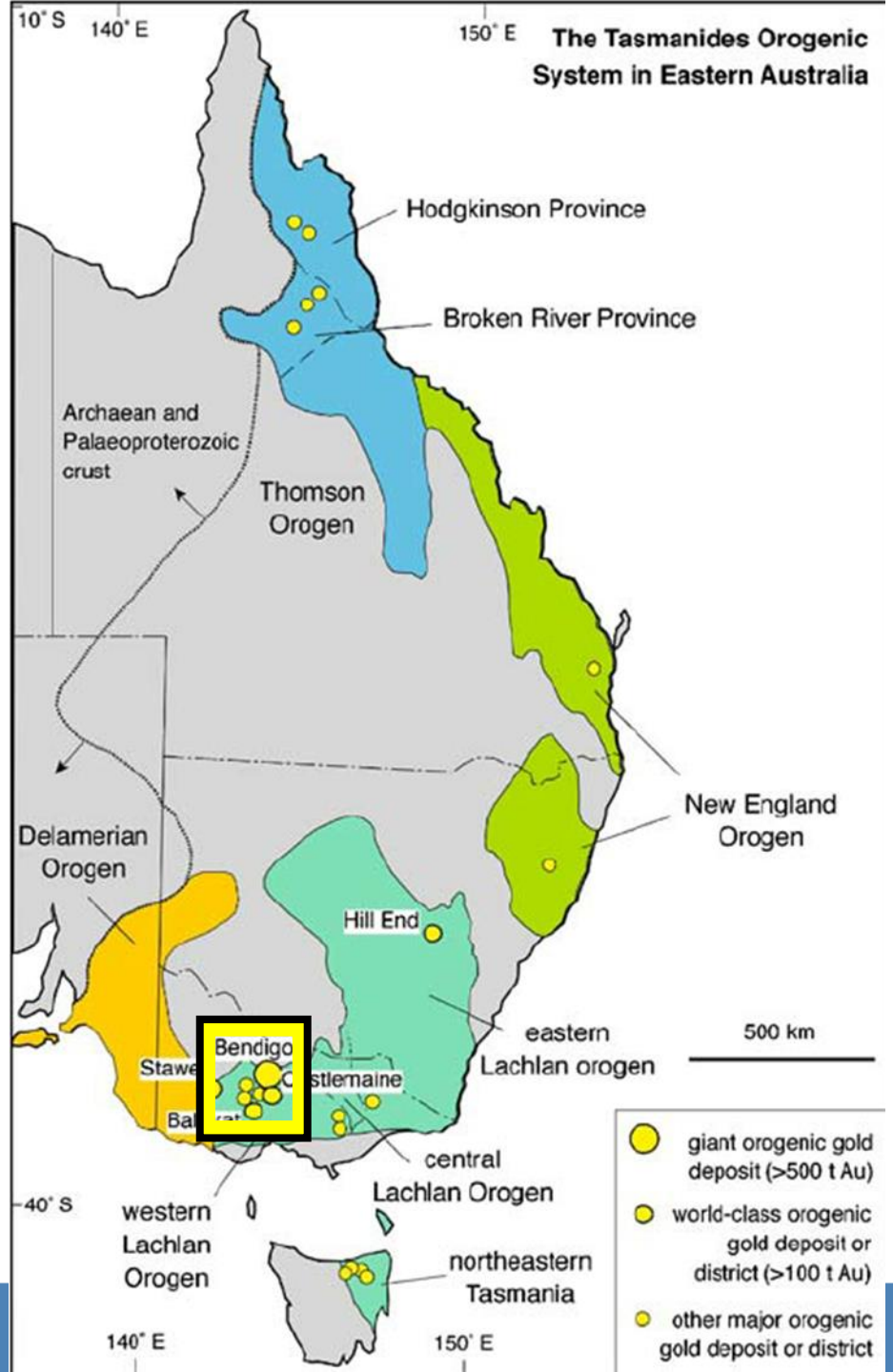
mining intelligence data

***Costerfield (Mandalay) Global Top 5 for antimony**

GEOLOGICAL SURVEY OF VICTORIA

Talk outline

- **Geological setting for Victorian orogenic (and intrusion related) gold**
- Competing tectonic models for the Early Palaeozoic – confusing for gold explorers
- Structural / stratigraphic mapping + potential field geophysics: powerful tools…
- …but Deep Seismic Reflection data drives systems-scale understanding
- Application to mineral systems models at crustal scale…
- Constrained retrodeformation scenarios – critical to take geological systems analysis from crustal scale to lithospheric scale
- Towards a Unifying Theory for Eastern Australian Early Palaeozoic geology and mineral systems
- Wrapping up

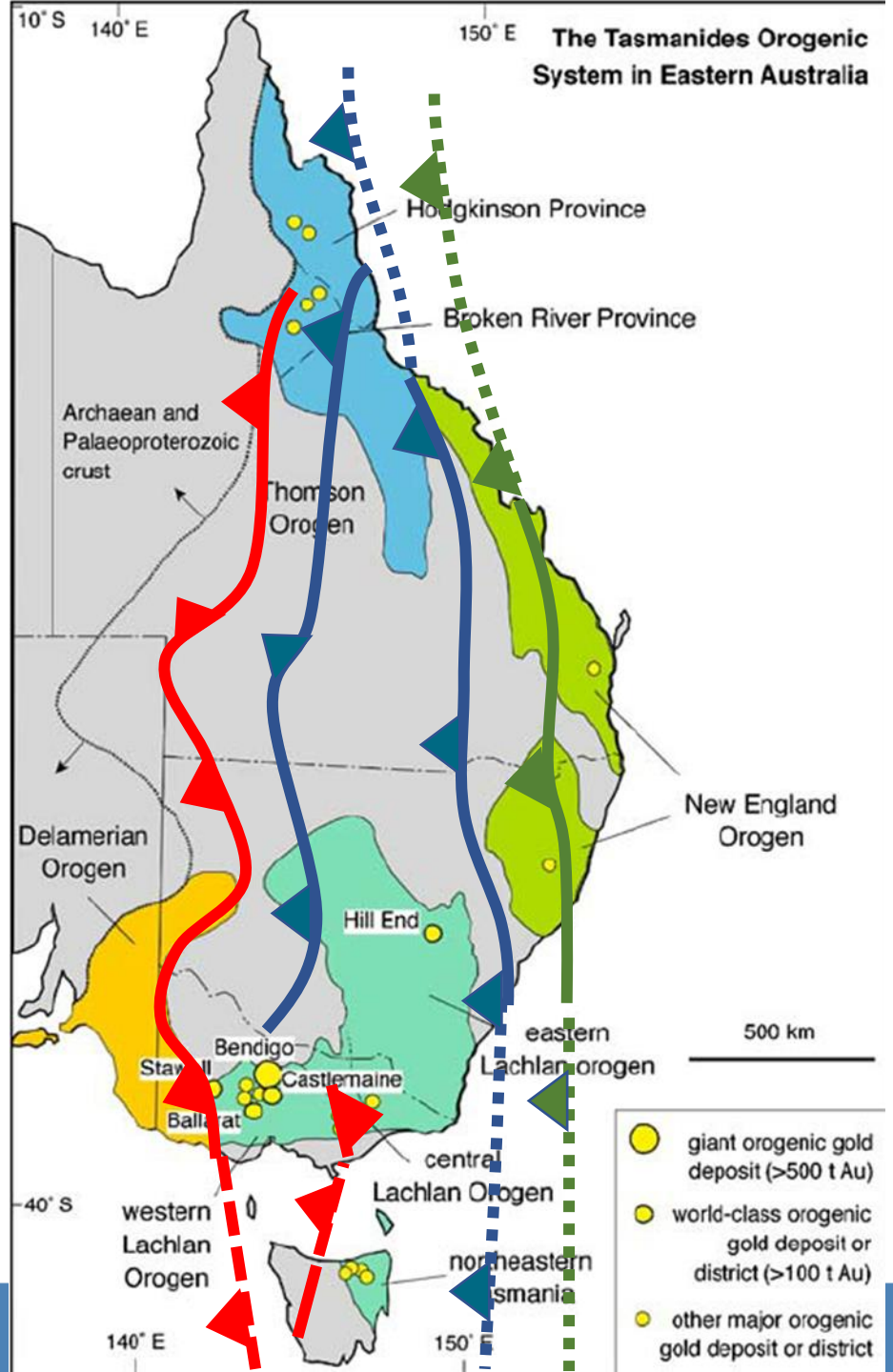


Early Palaeozoic rocks of similar age, provenance and appearance, with similar structural history, widespread throughout Eastern Australia but:

only central-west Victoria has a cluster of proven giant orogenic gold deposits.

Why?

Are there other areas potentially as good, but not yet discovered?



The Tasman Fold Belt System –

3-4 cycles of Early-Mid Palaeozoic subduction-accretion that progressively built eastern Australia….

(Personally I think most were continent-dipping, but debate continues……)

Delamerian / Tyennan - Cambrian

Lachlan – Ordovician – Siluro-Devonian

New England – Carboniferous -

Convergent margin key elements and systematics

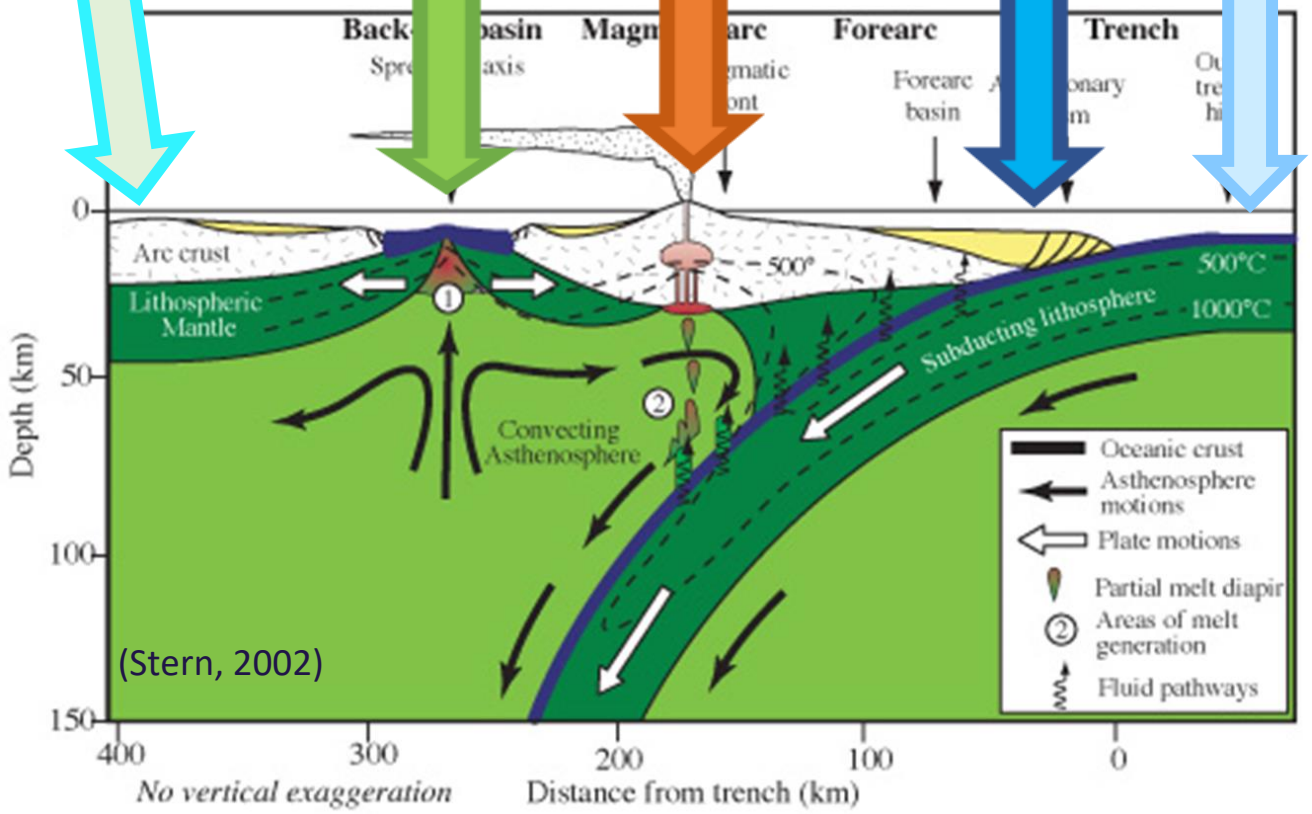
Distal back-arc: transition to intraplate

Back-arc basin: hot, syn-sediment magmatism, extension weak/strong deformation

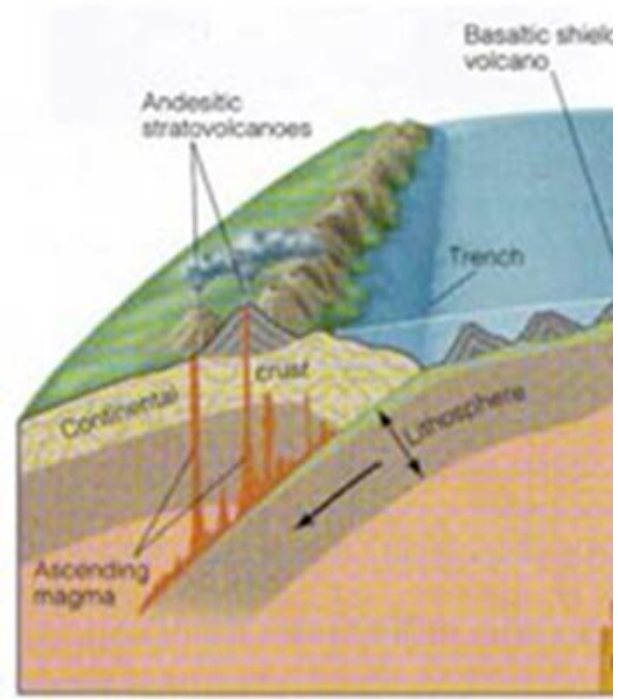
Magmatic arc: hot, igneous-dominated

Accretionary wedge: cold, inherent strong syn-sedimentary shortening deformation, amagmatic (thickening crust)

Intraplate: cold, undeformed, amagmatic

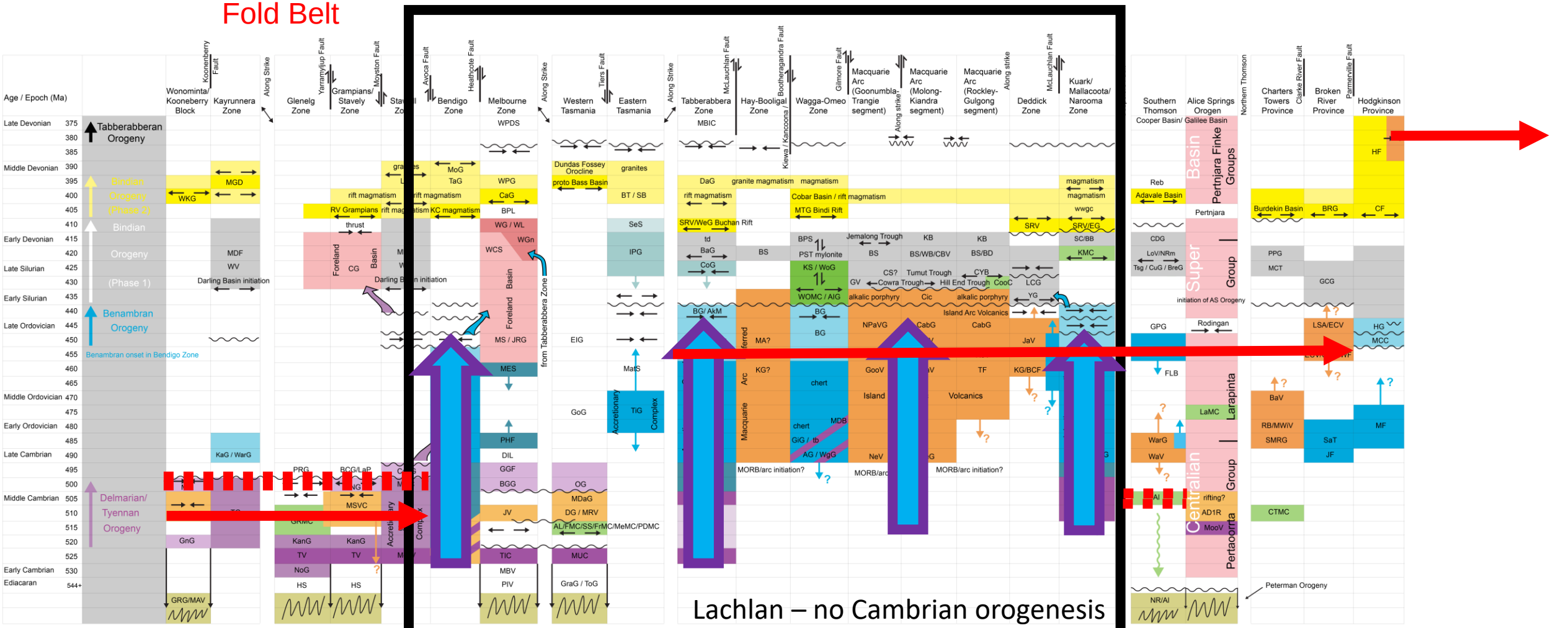


(Stern, 2002)



Delamerian Fold Belt

Lachlan Fold Belt



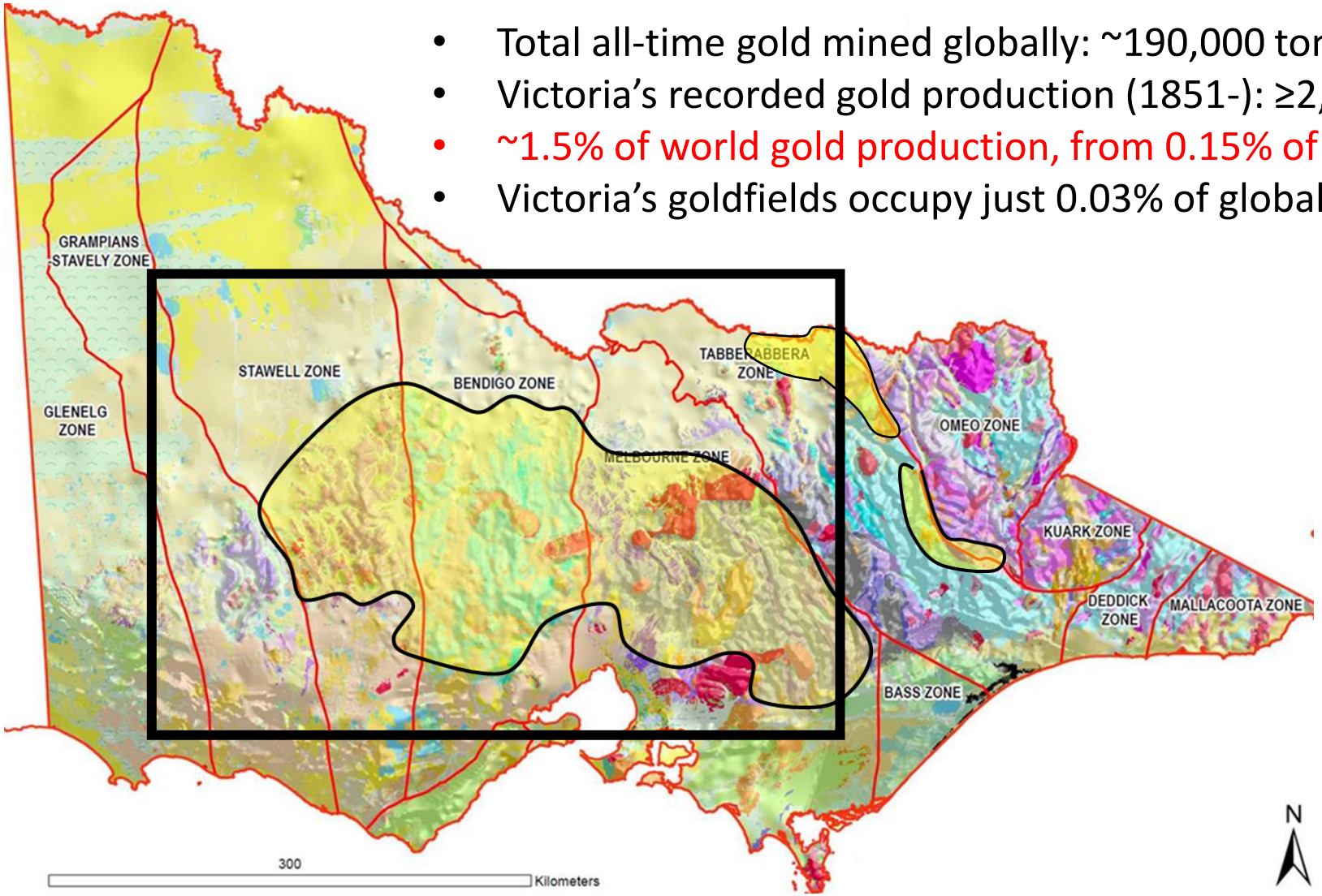
Convergent margin systems young eastward →

Time-space plot : Eastern Australia

Cayley & Musgrave, in prep

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



Victoria's goldfield geology has already produced: **2 Orders of Magnitude (100x)** more gold / area than the global continental average (at least!)

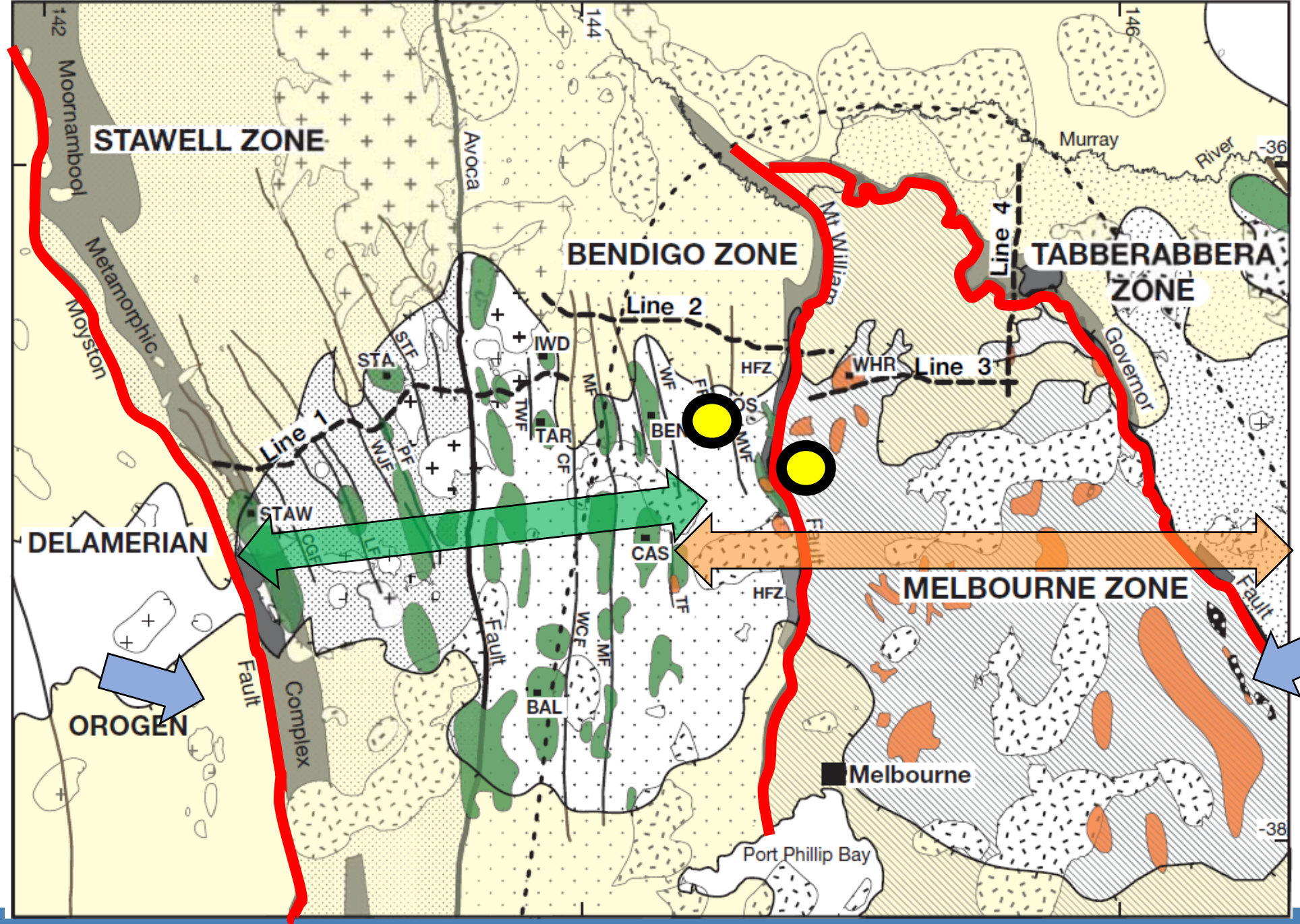
*World Gold Council 2019

Orogenic gold

~450-440 Ma

Intrusion-related Cu / Au

~500 Ma

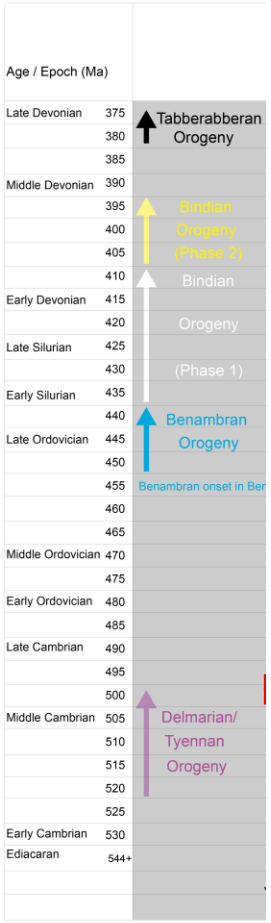


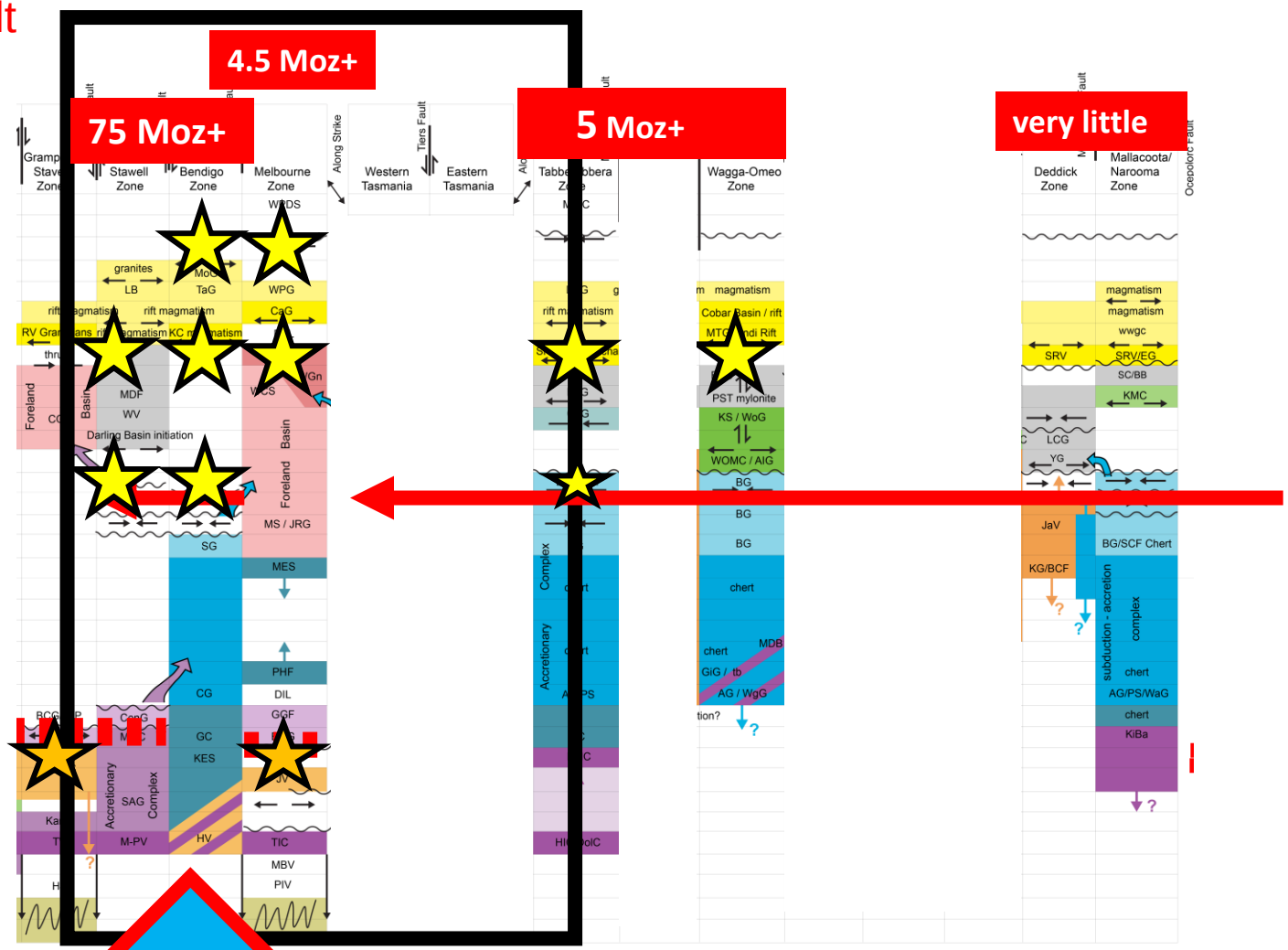
Orogenic gold

~410-380 Ma

Delamerian Fold Belt

Lachlan Fold Belt





Time-space plot : Victoria

Cayley & Musgrave, in prep

Orogenic gold

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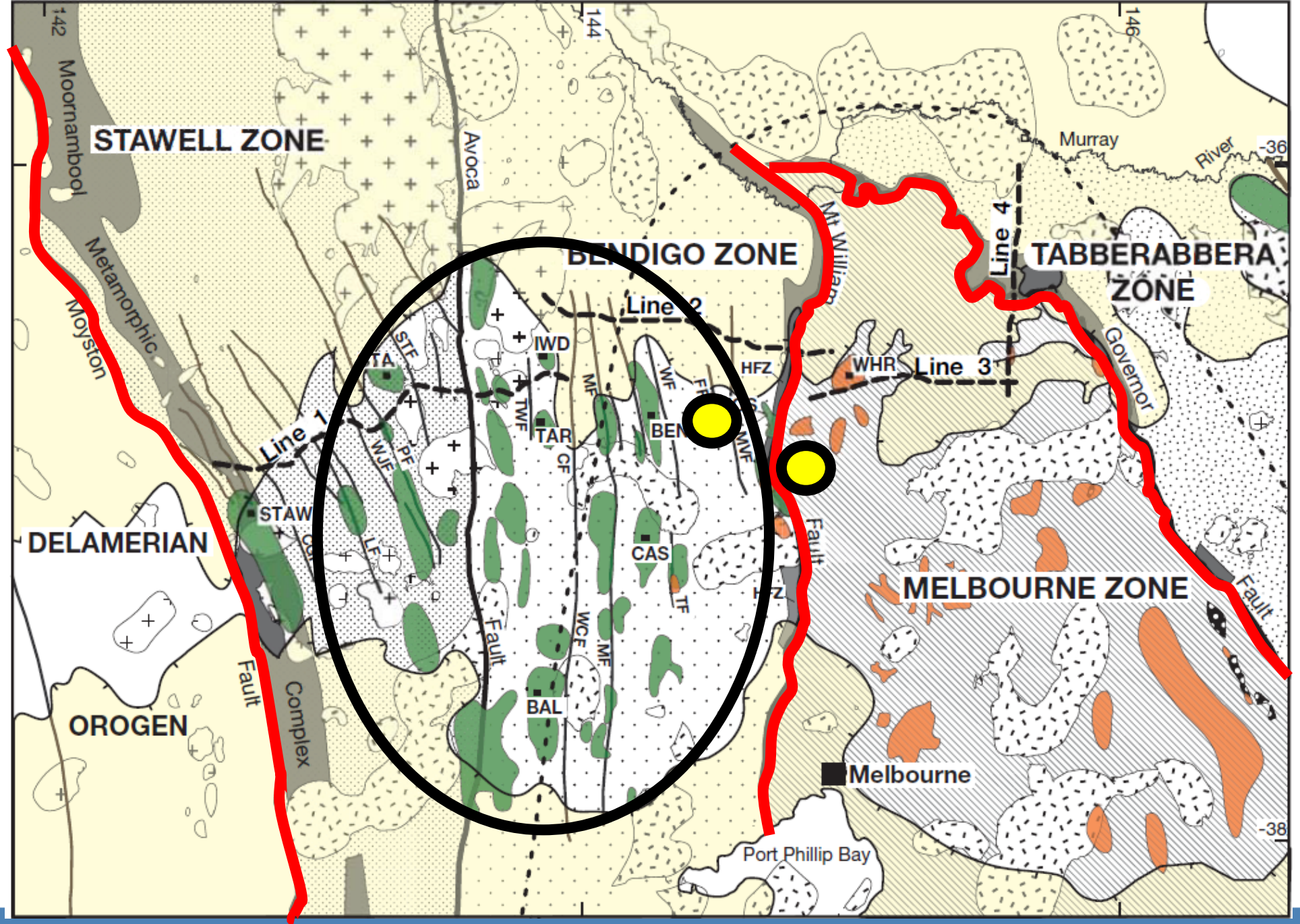


Orogenic gold

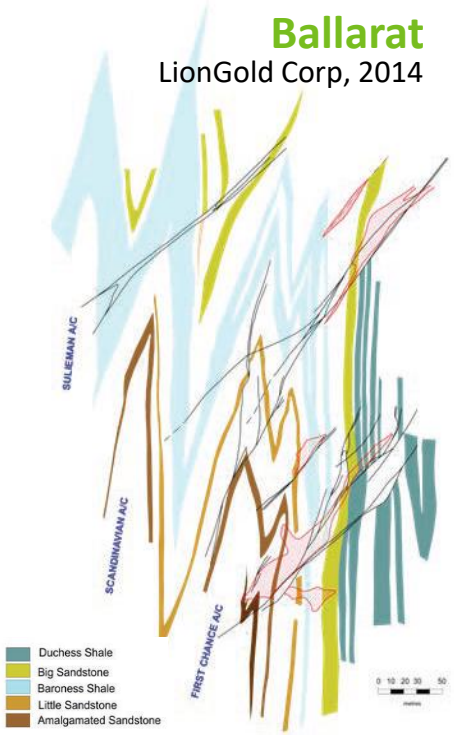
~410-385Ma

Cambrian – Ordovician (- Early Devonian) Lachlan Supergroup

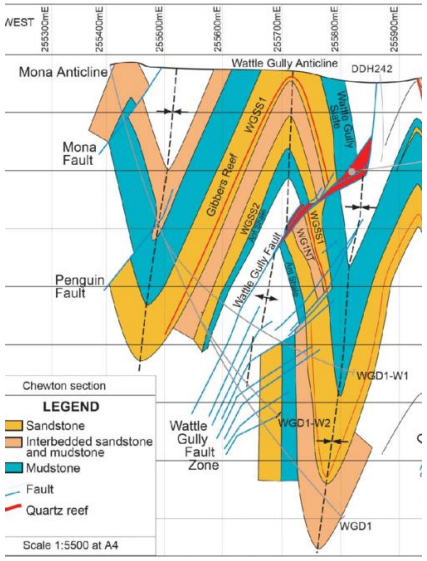
The most common host rock for Victoria's orogenic gold deposits is the most common rock –

folded and faulted, quartz-rich deep marine metasediments

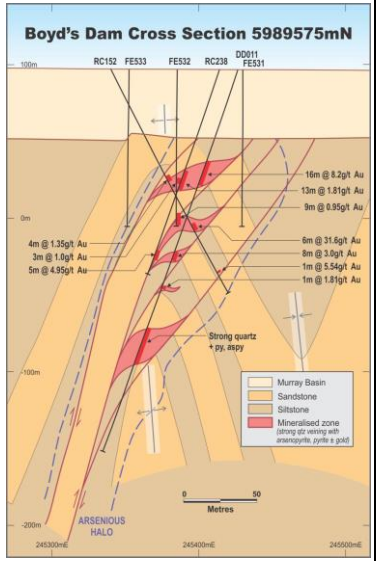
Ballarat
LionGold Corp, 2014



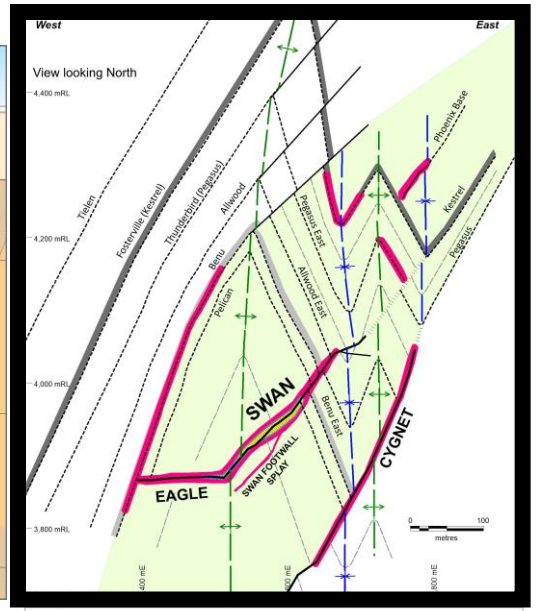
Wattle Gully
Arne et al., 2016 AJES



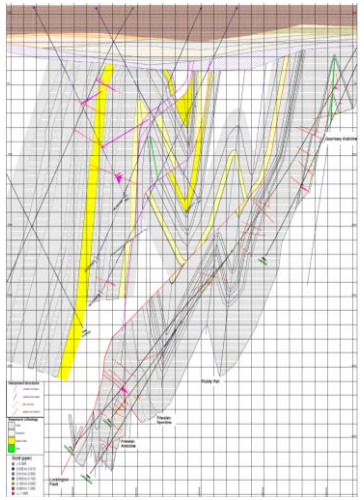
Four Eagles
Charlton, 2019

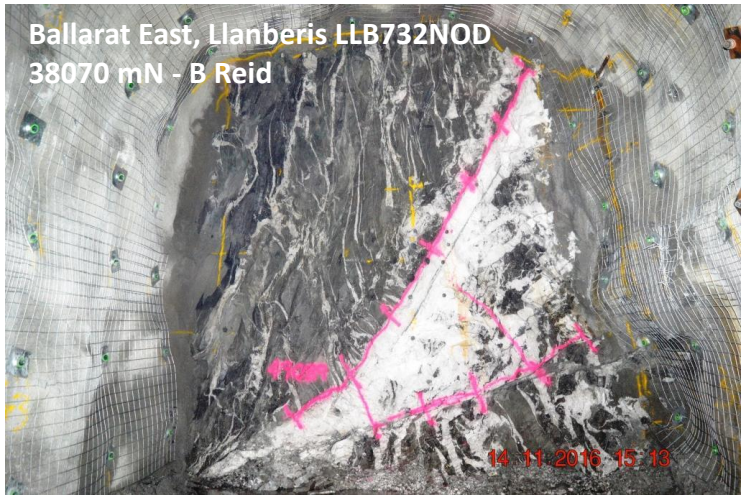


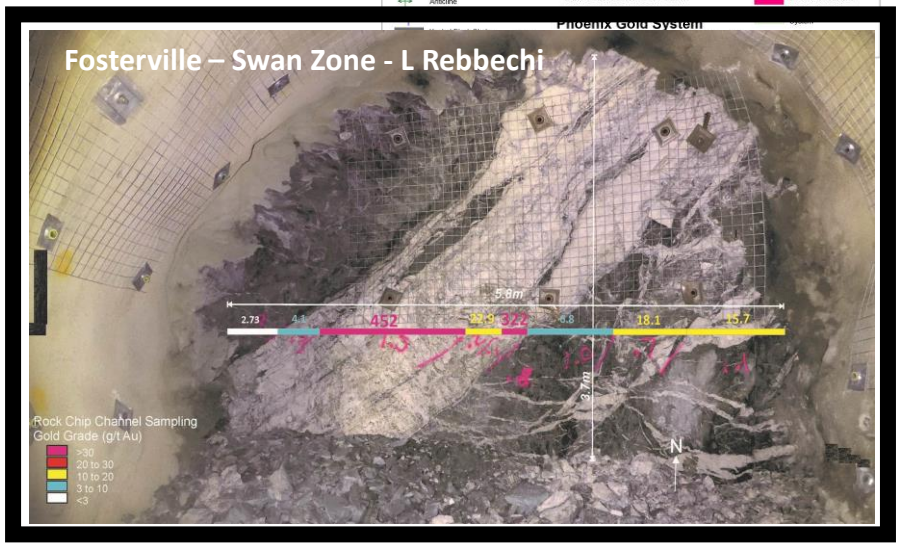
Fosterville
Kirkland Lake Gold, 2018



Lockington
Goldfields, 2007







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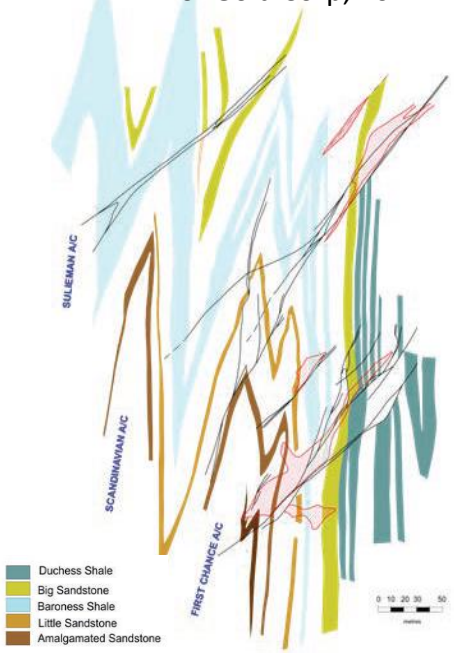
LionGold Corp, 2014



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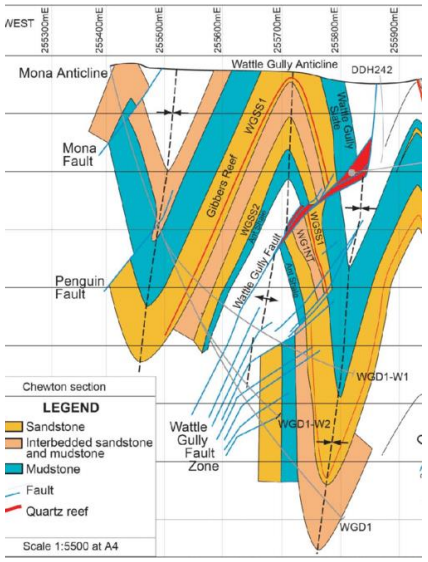
Arne et al., 2016 AJES



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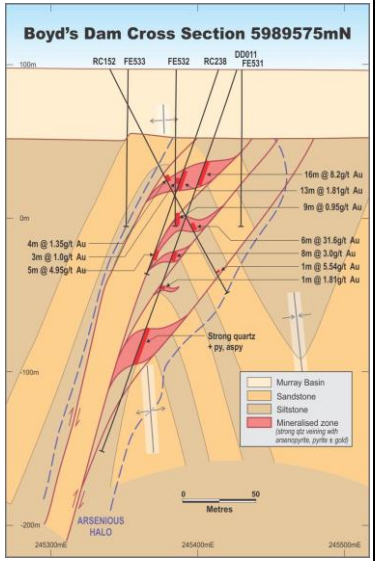
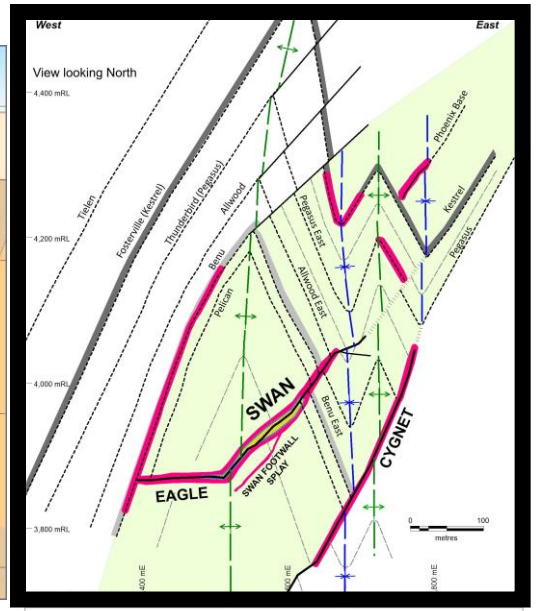
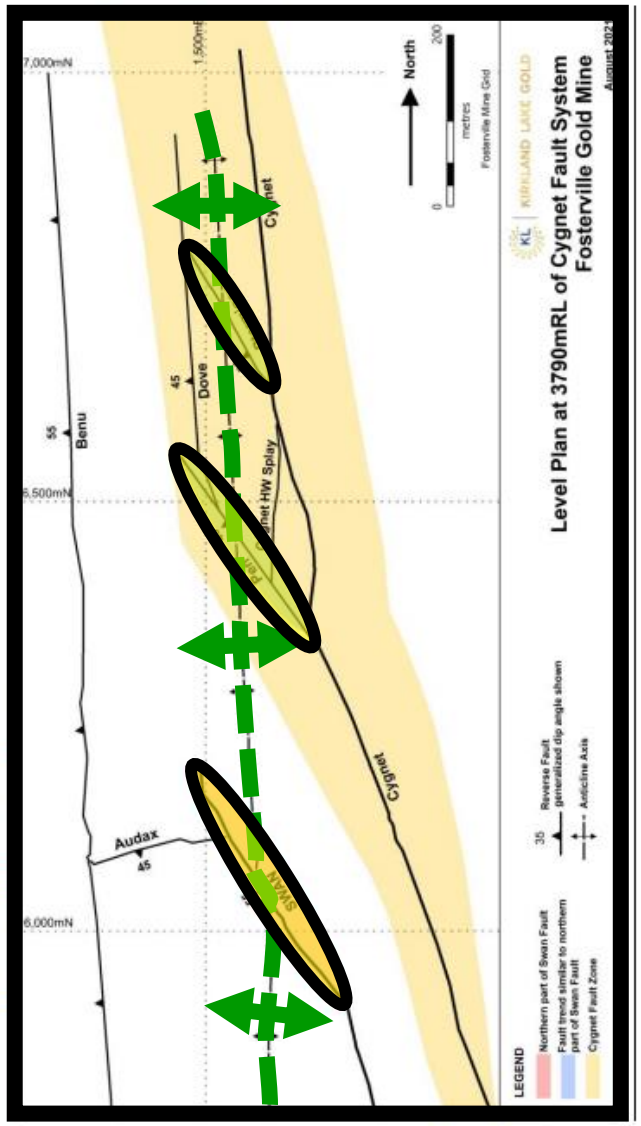
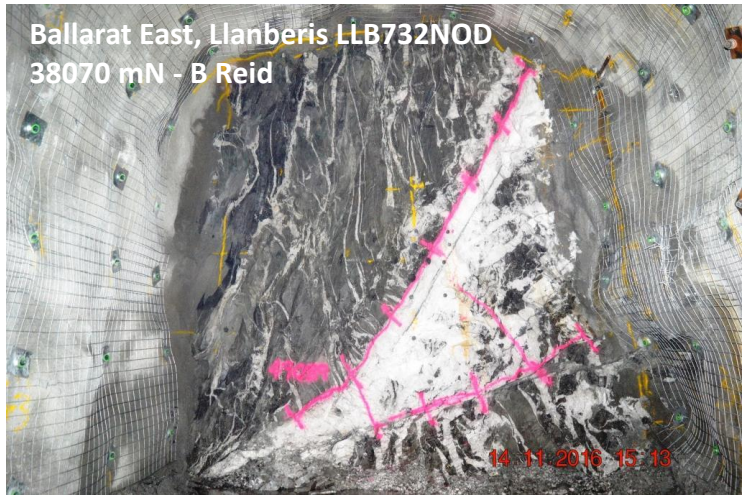


Fosterville
Kirkland Lake Gold, 2018



Fosterville





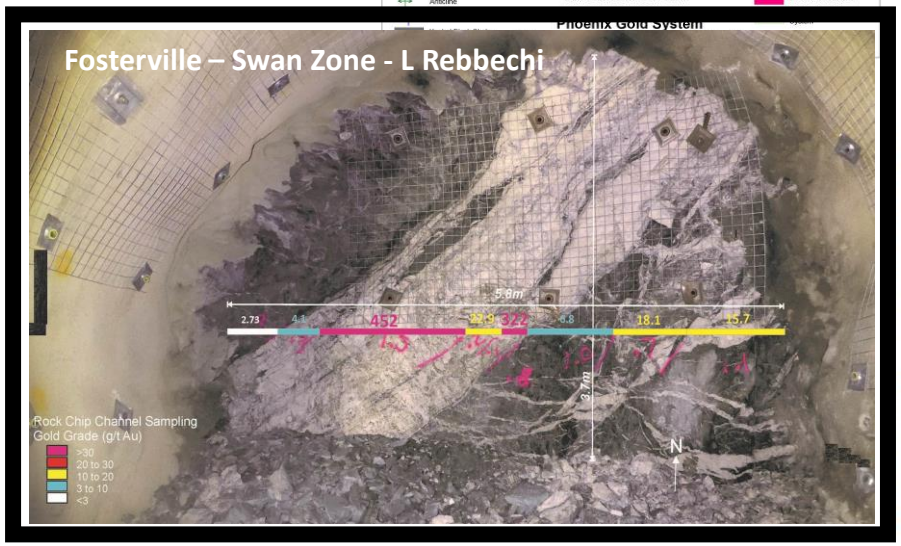
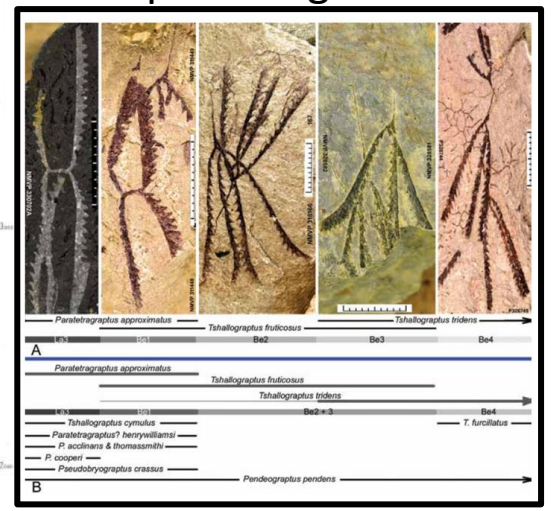


Figure 3. Plan View – Cygnet Fault System

0 5km

Major, deeply tapping fault

Graptolite age control



Bendigo goldfield:

disconnects between major structures and gold

Willman, 1992

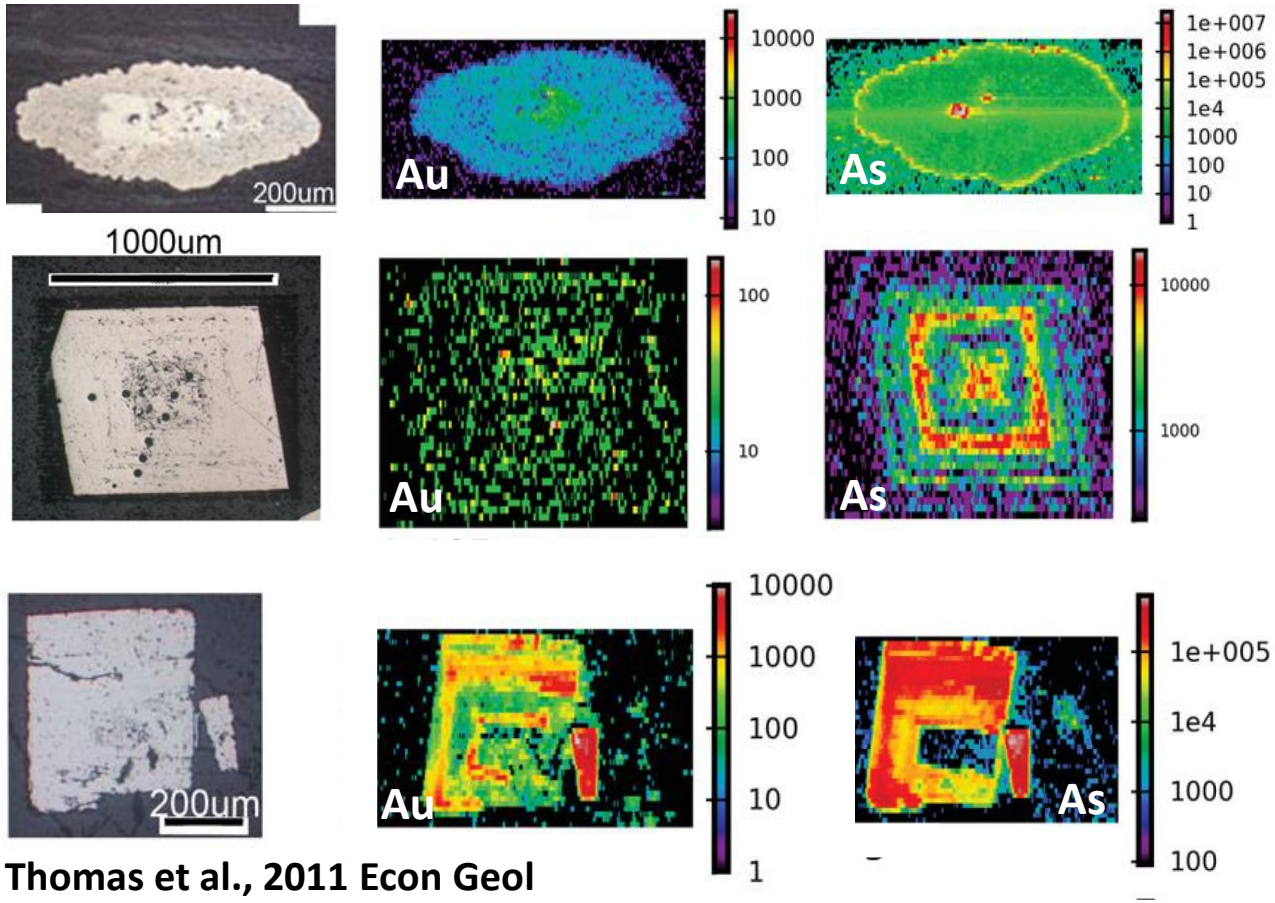
What is controlling gold distribution?

Cambrian – Ordovician (- Early Devonian) Lachlan Supergroup

Pyritic Black shales within the succession are a potential source of gold (and sulphur).

- S and (likely) Au sourced by pyrite to pyrrhotite transition – can occur metasediments and/or metavolcanics
- Implicates the greenschist – amphibolite transition which occurs at mid-crustal depths in collisional orogens
- S isotopes indicate either magmatic or well-mixed source
- Metamorphism of ‘pyritic metasediment’ the currently favored orogenic gold source in academia……
- **Victoria’s orogenic gold story is crustal-scale (its not just about the host rocks).**
- Intrusion related gold-sulphide association also important - but proven IRG+ is subordinate to orogenic gold

Mode of occurrence	Mean Au ppm	Mean As ppm	
Diagenetic	0.61	1300	Enriched in Mn, Zn, Mo, Cu, V, Ba, Ag, Cd, Tl, Co, Ni, Bi, Pb, Te
Pyrrhotite in base	0.04	4	Depleted in Cu, Zn, Sb, Te Enriched in Co, Ni as nodular
Hydro in turbidites	Rim 1.24 Core 0.65	Rim 1850 Core 1550	Variable enrichment usually in core (Co, Ni, Bi, V, Pb) dependent on host lithology
Hydro in LQ	4.37	4960	
Hydro in Au reef	5.65	6580	



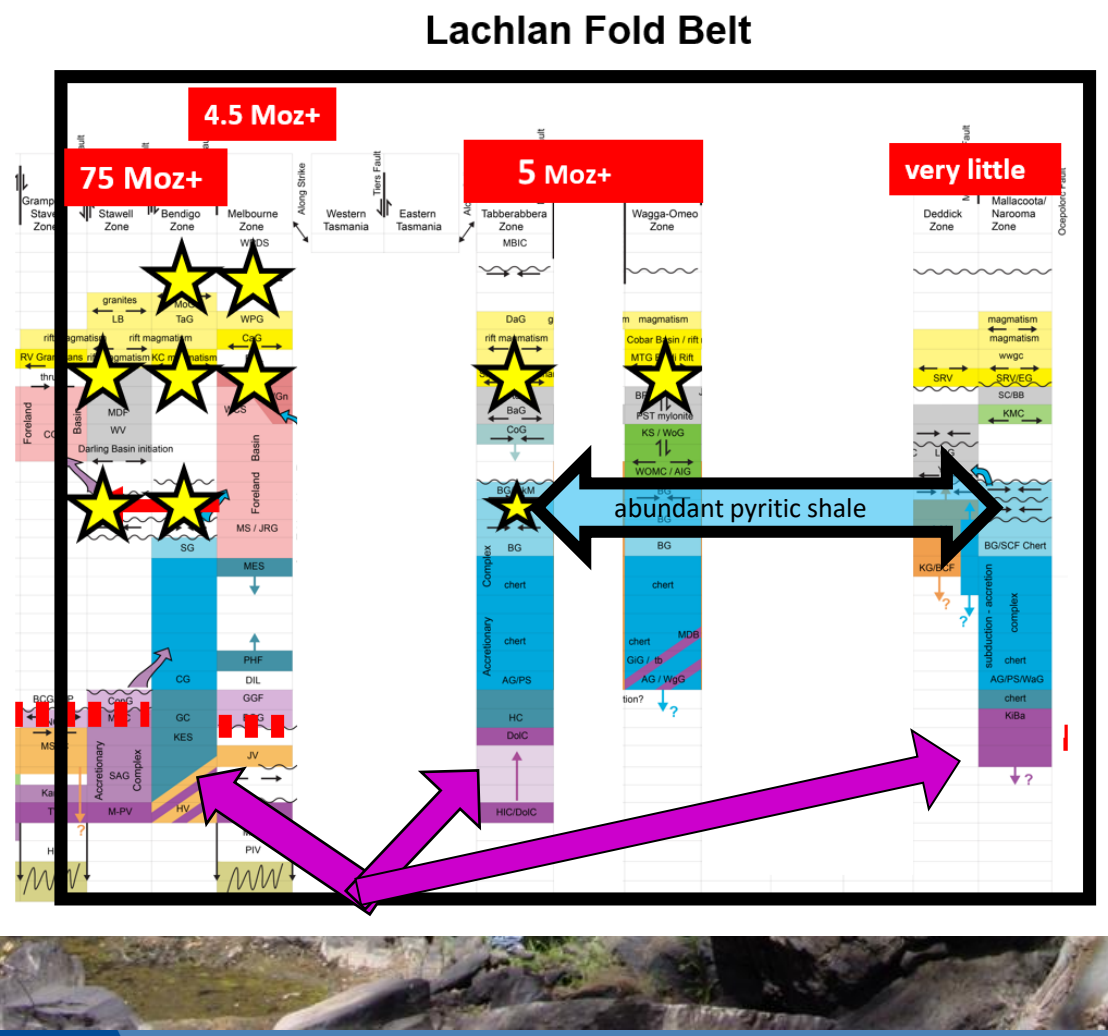
Thomas et al., 2011 Econ Geol

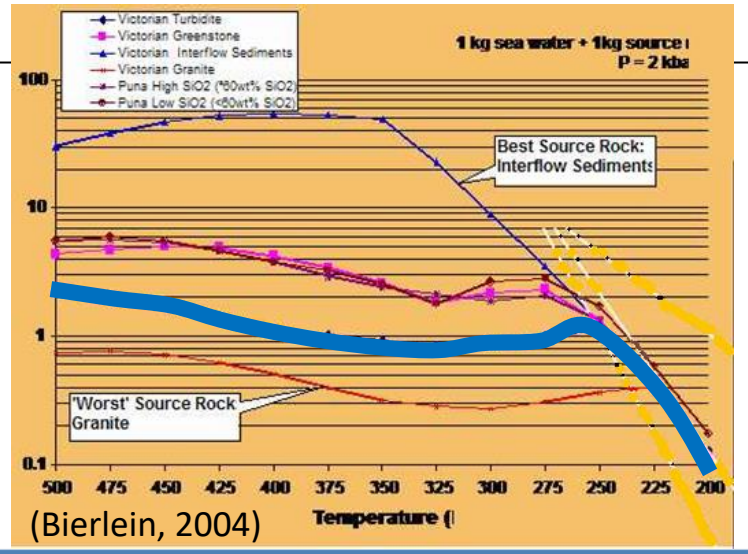
BUT…overall, the quartz-rich deep marine sediment succession is **not inherently rich in gold**
(eg Glasson & Keays, 1978; Bierlein, 2004)

AND…the relative stratigraphic abundance of pyritic black shale in Victoria is anti-correlated with orogenic gold endowment!!

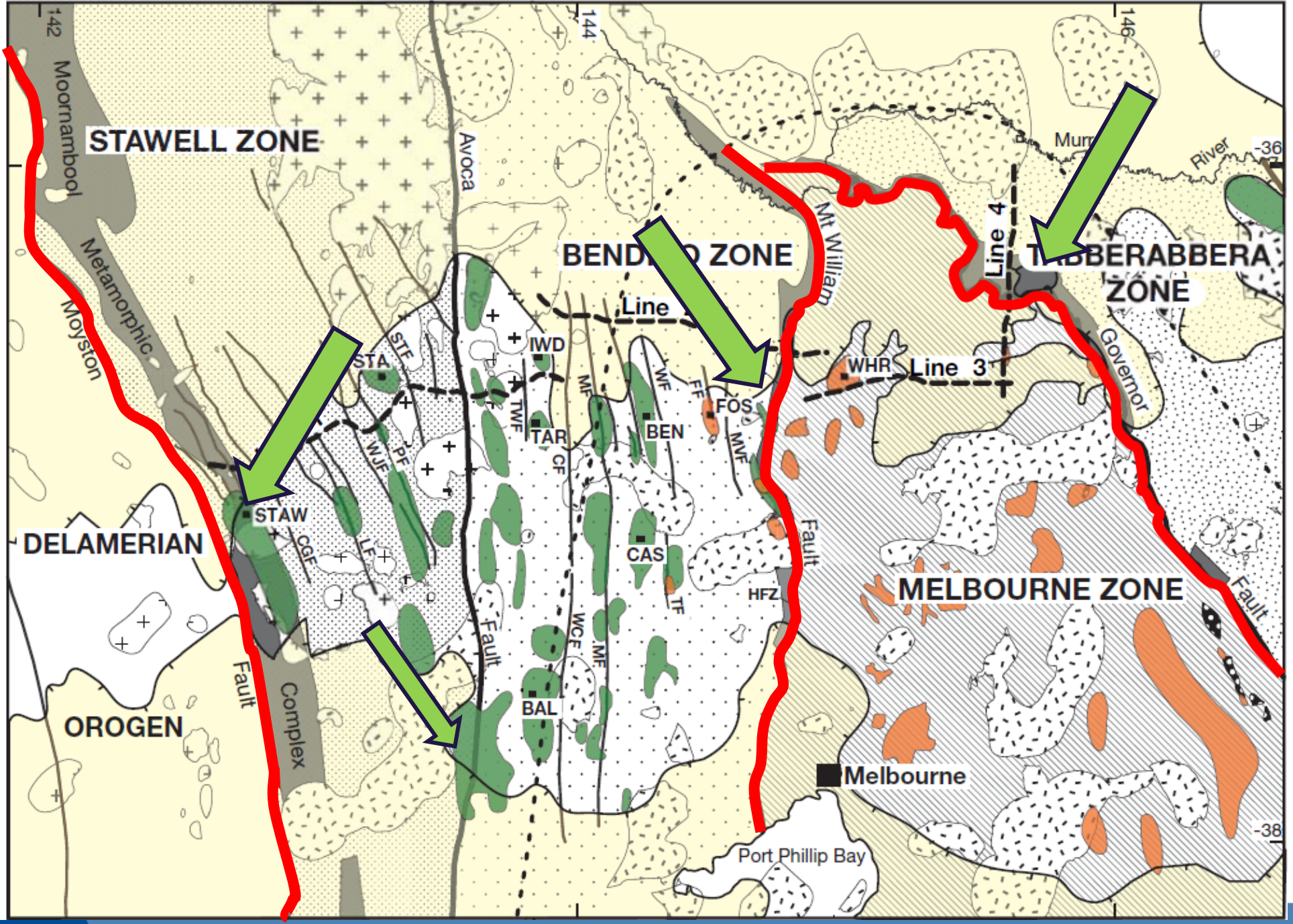
(eg: 'Bendoc Group' extensive in eastern Victoria: pyritic black shale dominant but a region with less proven orogenic gold. Bendigo-Fosterville goldfields: world class orogenic gold, but <5% / vol pyritic black shale).

Victoria's orogenic gold story **must** be more complex than just the host rocks and structures….this has been the exploration challenge





(Bierlein, 2004)


142
144
146
-36
-38
STAWELL ZONE
BENDIGO ZONE
TABBERABBERA ZONE
MELBOURNE ZONE
DELAMERIAN OROGEN
Moornambool Metamorphic Complex
Moyston Fault
Avoca Fault
Mt William Fault
Governor Fault
Line 1
Line 2
Line 3
Line 4
STA
STAW
IWD
TAR
BEN
FOS
WHR
CAS
BAL
STF
TWF
WJF
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HFZ
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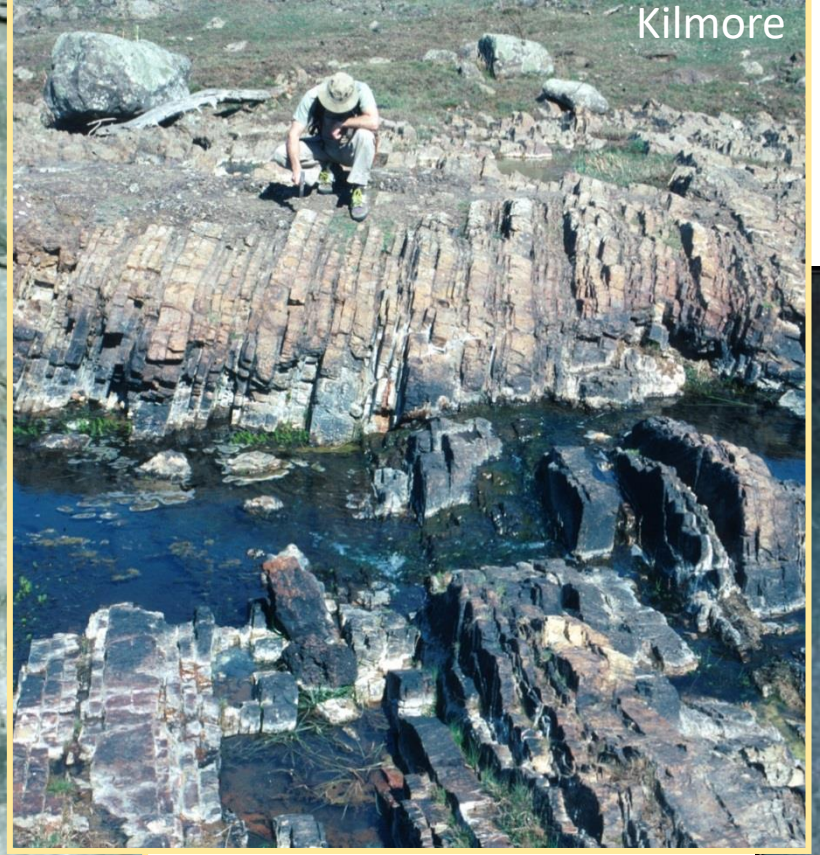
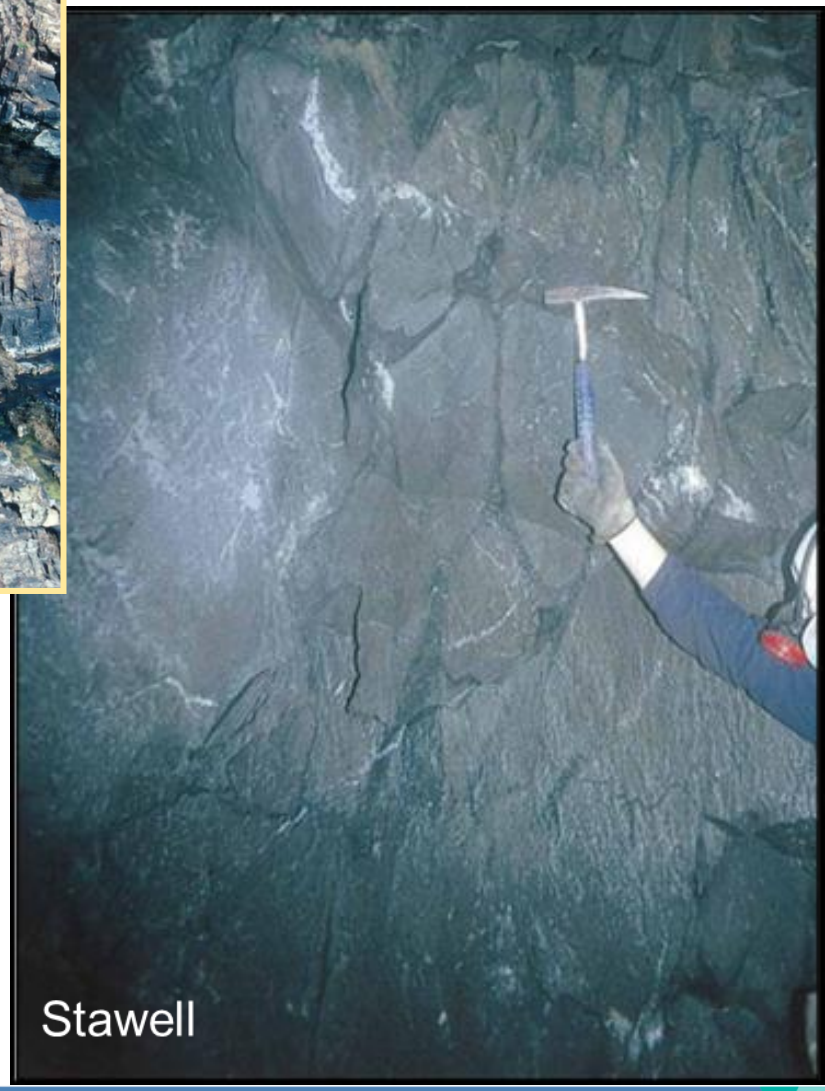
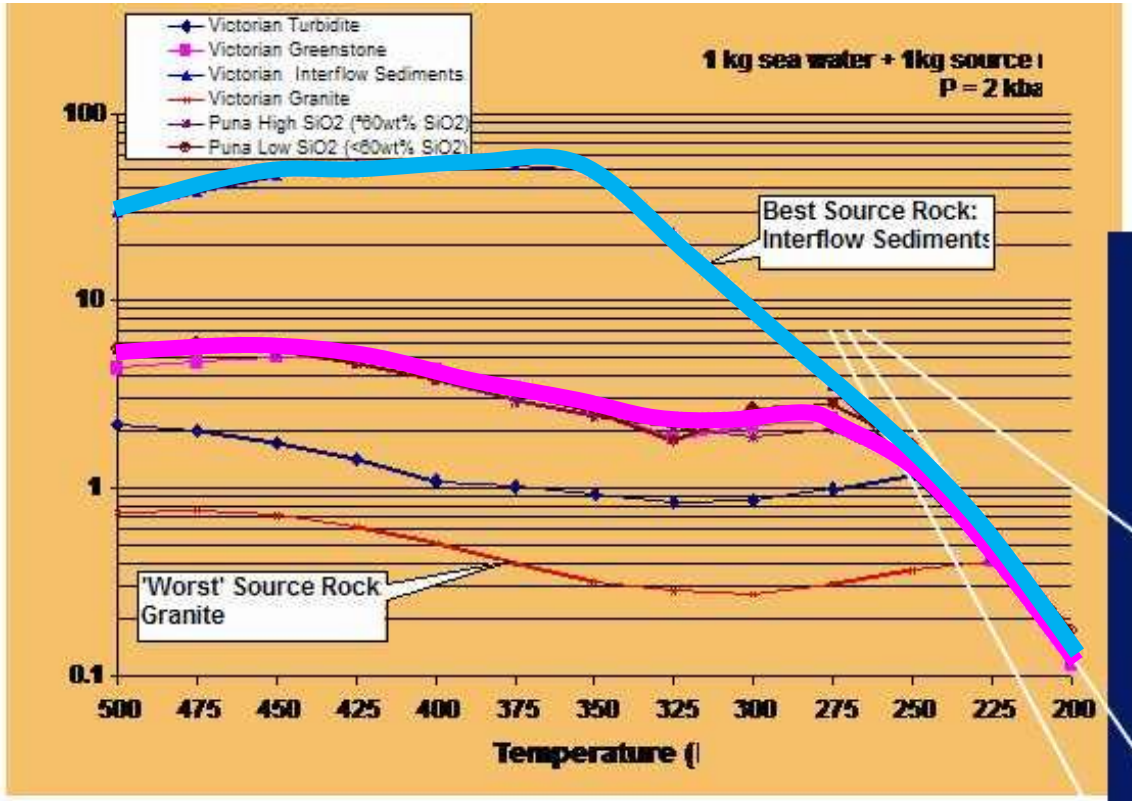
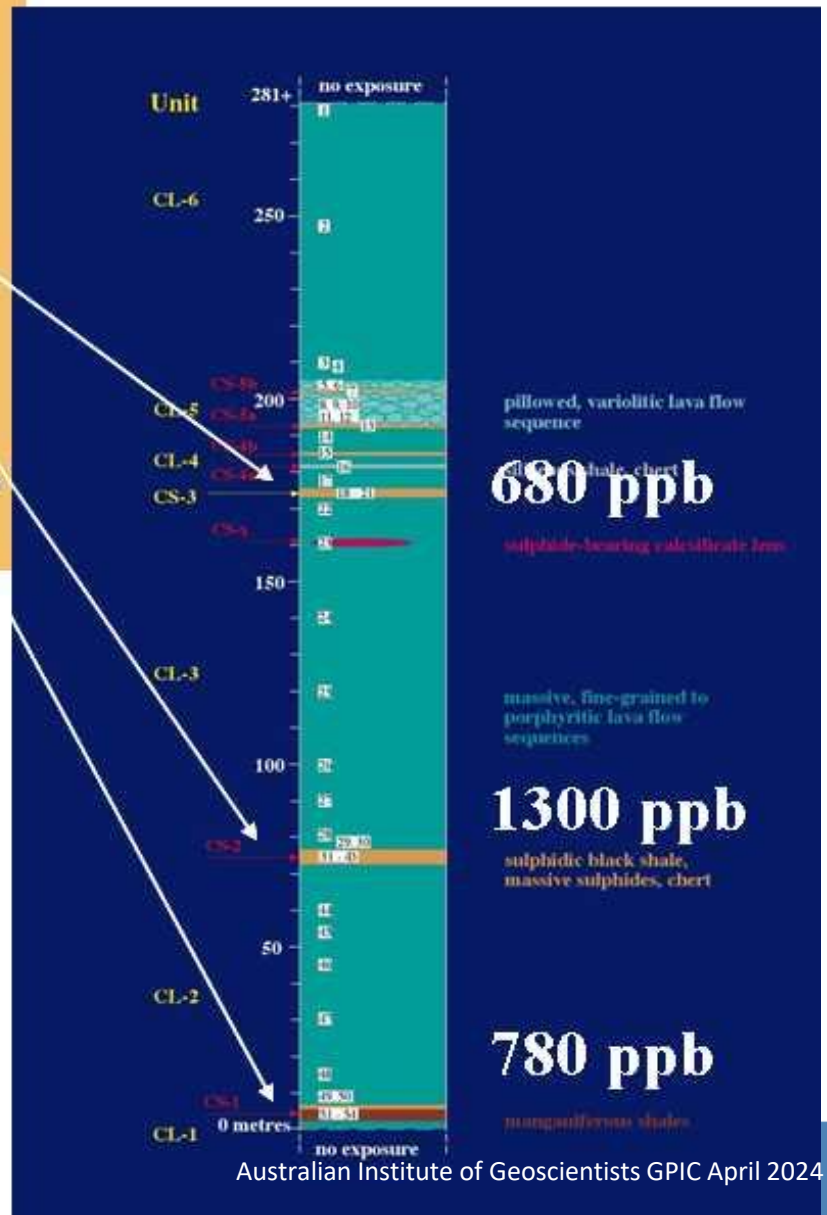
WCF
Melbourne
Port Phillip Bay
River





Major faults expose
Early Cambrian MORB,
BABB and boninite,
deep marine setting,
Cambrian pelagic chert
(Goldie Chert, Howqua Chert)



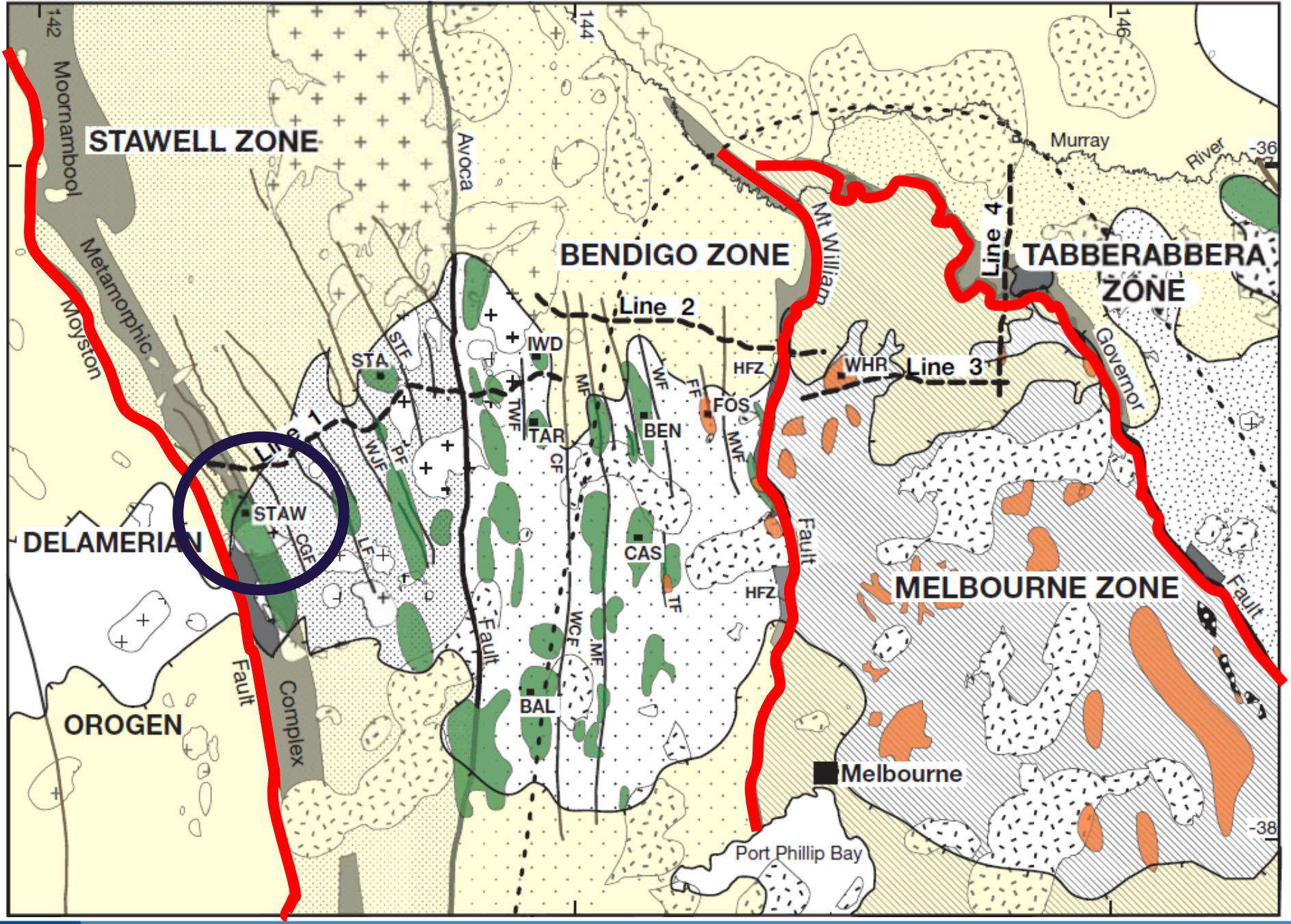


Boninite: a credible source of lots of gold (e.g. Keays, 1987):

Cambrian metavolcanics exposed in:
Moyston Fault / Moornambool Metamorphic Complex, Avoca Fault, Heathcote Fault Zone and, farther east, Governor Fault Zone –

points to oceanic / intra-oceanic arc precursor crust for lots of Victoria.

(Hamlyn et al, 1985; Bierlein, 2004;
also Pitcairn et al., 2006 in NZ for Otago Schist MORBS)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Moornambool Metamorphic Complex
Moyston Fault
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Governor Fault
Murray River
Line 1
Line 2
Line 3
Line 4
STAW
STA
IWD
TAR
BEN
FOS
WHR
CAS
BAL
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CGF
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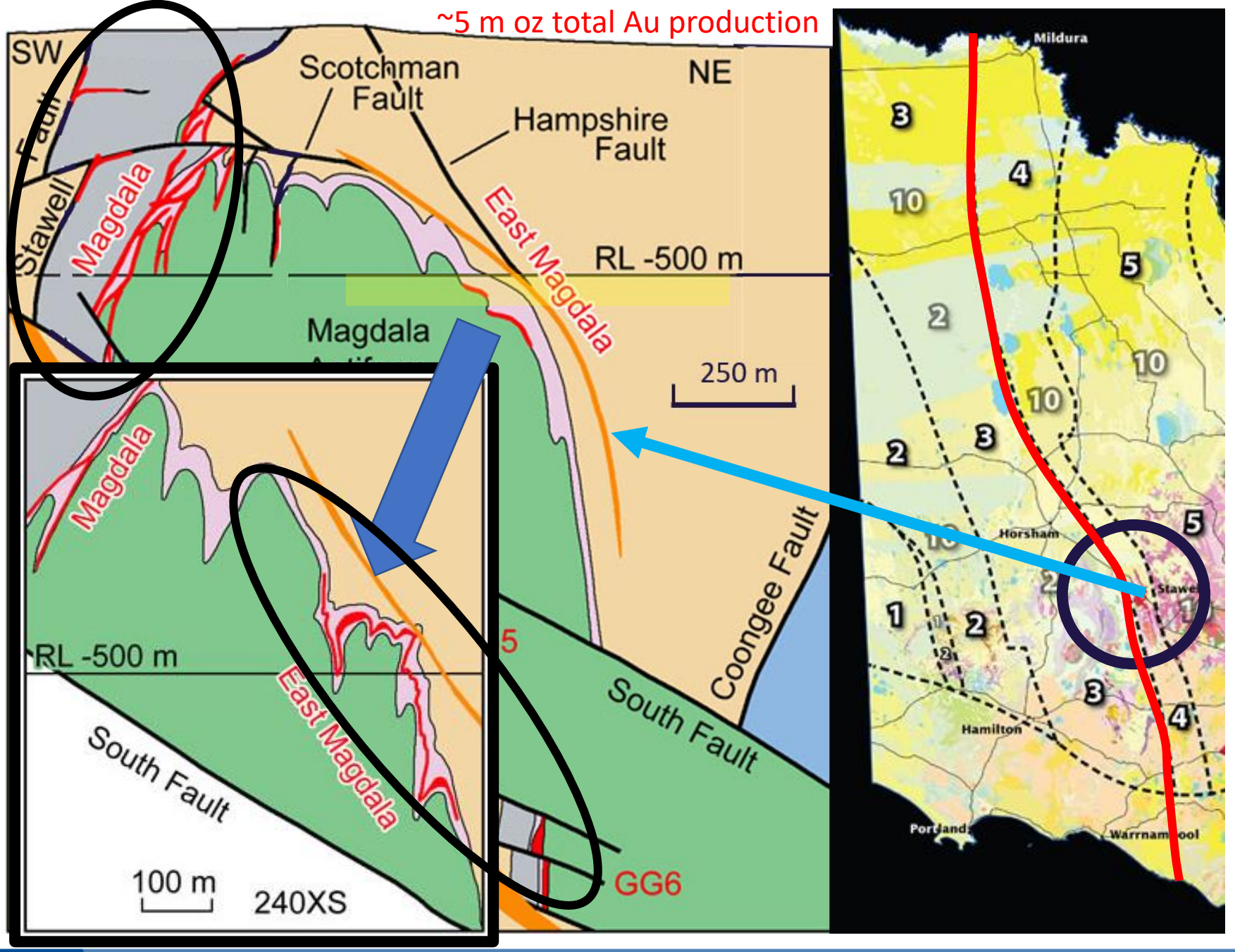
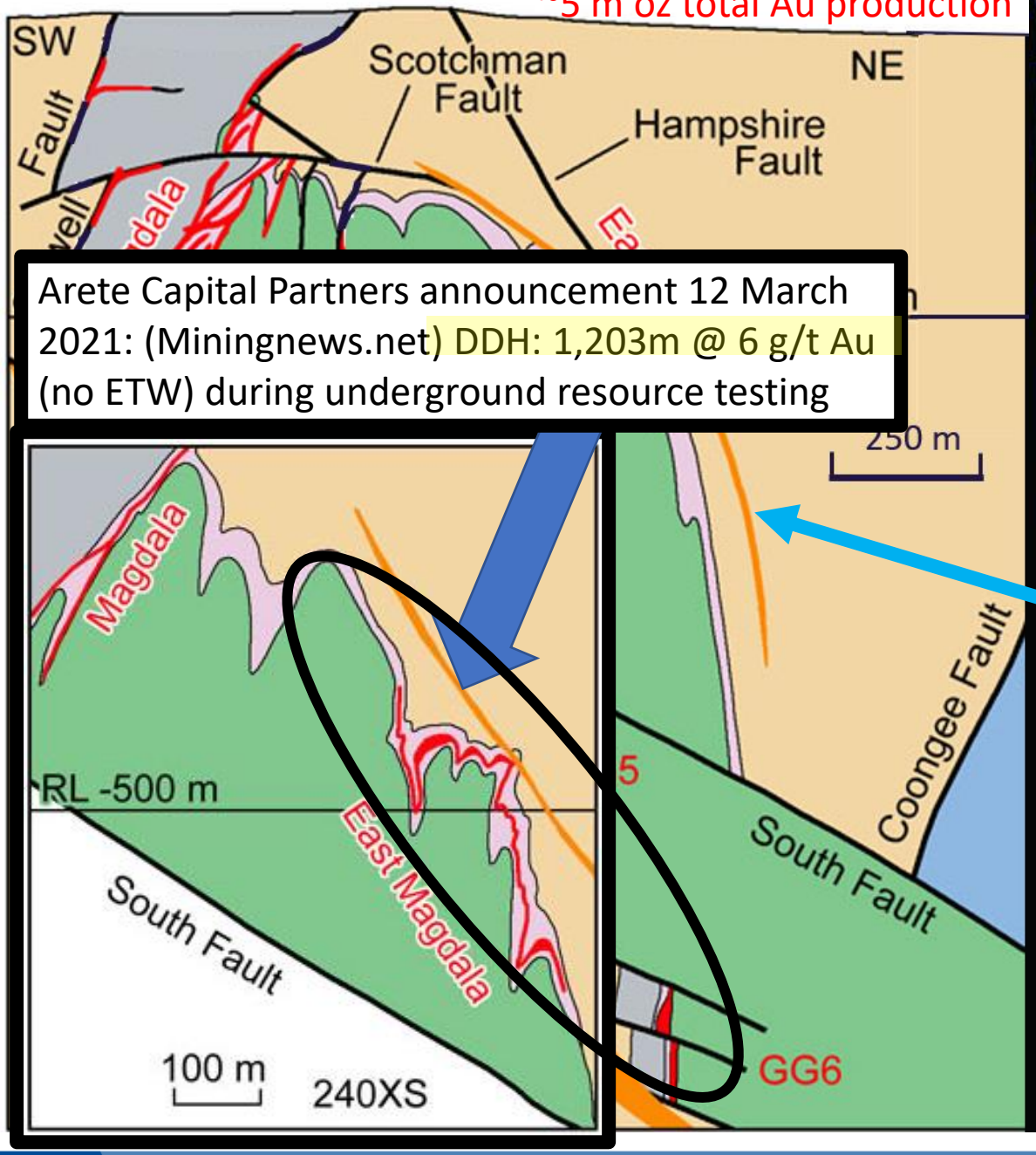
HFZ
MVF
TF
WCF
Melbourne
Port Phillip Bay

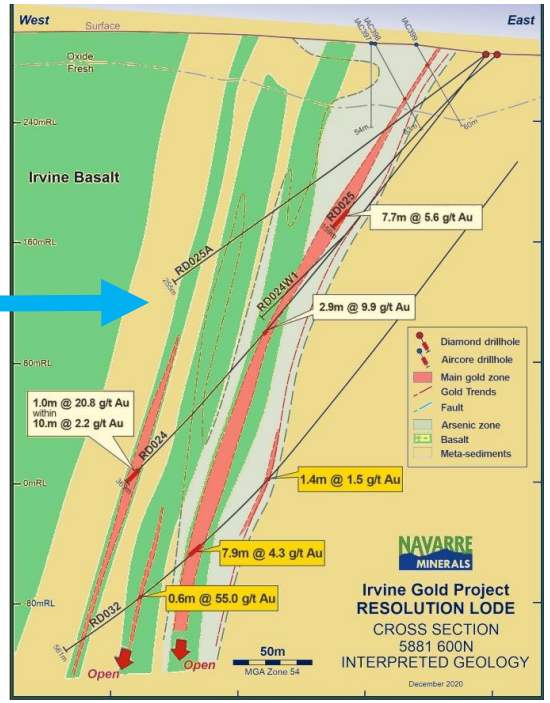

~5 m oz total Au production
SW
NE
Scotchman Fault
Hampshire Fault
Stawell
Magdala
East Magdala
RL -500 m
Magdala
250 m
Coongee Fault
South Fault
RL -500 m
East Magdala
South Fault
5
100 m
240XS
GG6
Mildura
Horsham
Hamilton
Portland
3
4
10
5
2
10
10
2
3
5
2
1
2
3
4

~5 m oz total Au production

Arete Capital Partners announcement 12 March 2021: (Miningnews.net) DDH: 1,203m @ 6 g/t Au (no ETW) during underground resource testing



Navarre Minerals Maiden Resource (Resolution, Adventure prospects 304,300 oz @ 2.43g/t Au. (30 March 2021)…this is how modern Magdala (~3Moz-) started!



Talk outline

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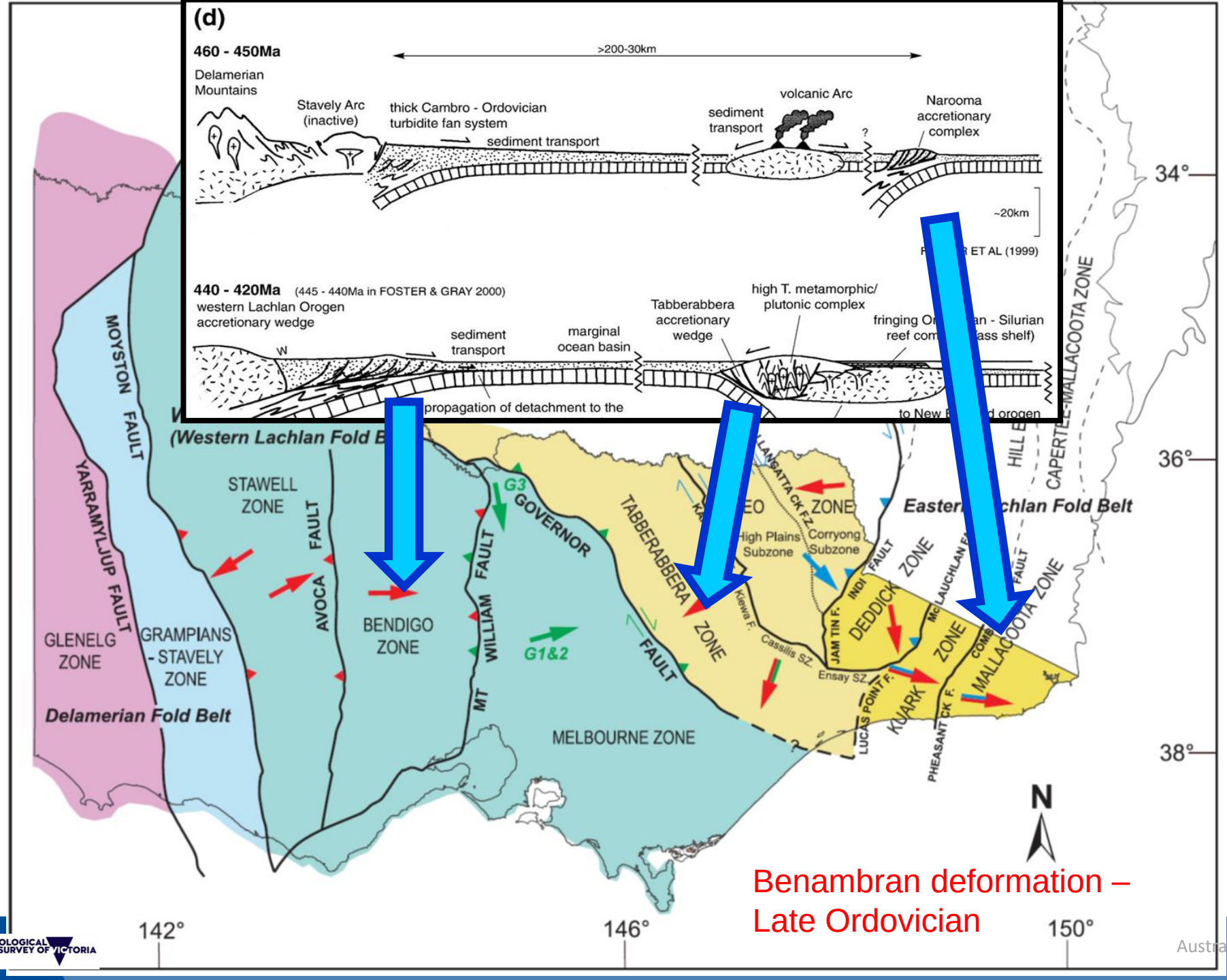


Benambran deformation – Late Ordovician

Gray & Foster, 1999, 2000:

A breakthrough tectonic model that honoured structural vergence, deformation timing, and the accretionary character of some Ordovician stratigraphy

Convergent margin key elements and systematics

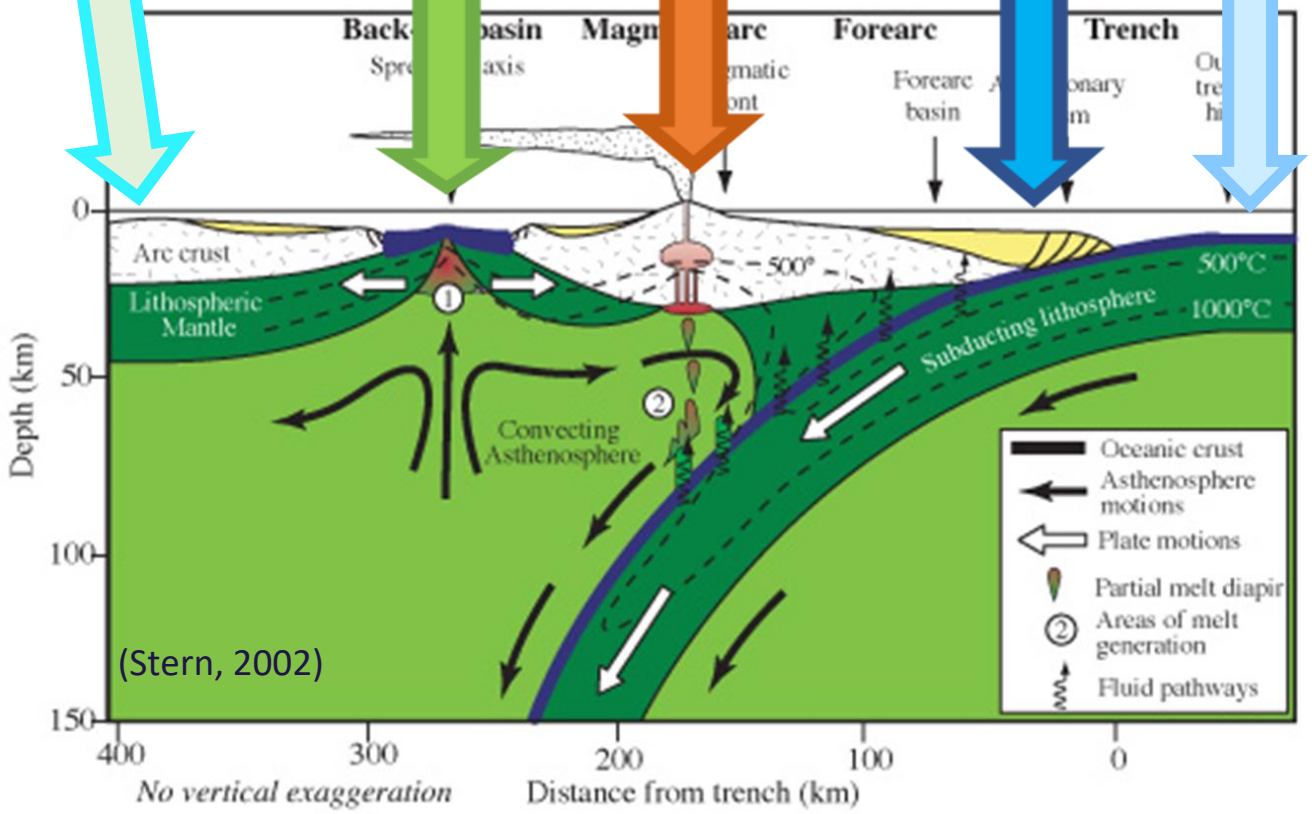
Distal back-arc: transition to intraplate

Back-arc basin: hot, syn-sediment magmatism, extension weak/strong deformation

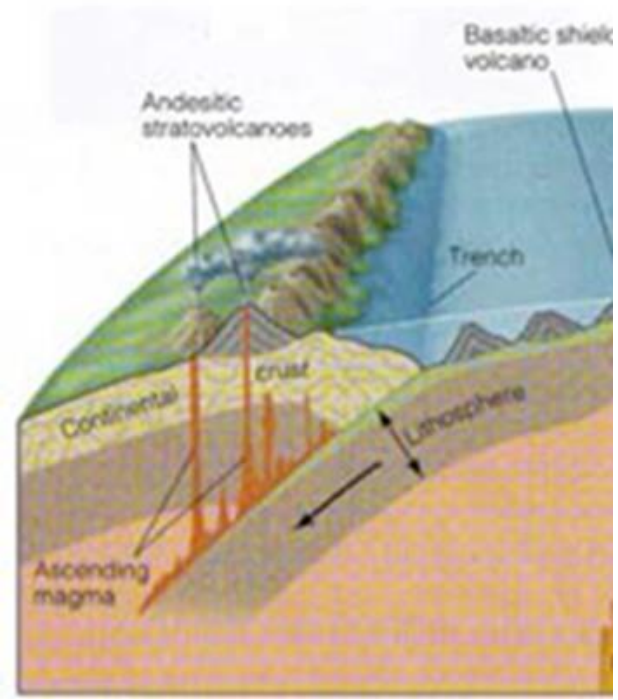
Magmatic arc: hot, igneous-dominated

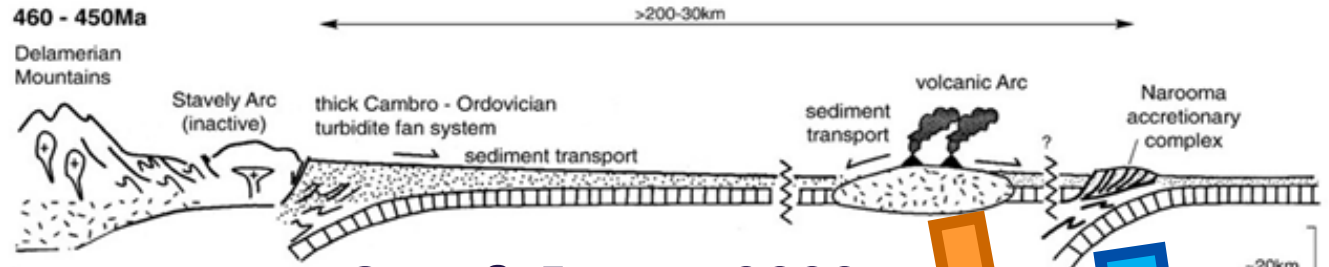
Accretionary wedge: cold, inherent strong syn-sedimentary shortening deformation, amagmatic (thickening crust)

Intraplate: cold, undeformed, amagmatic

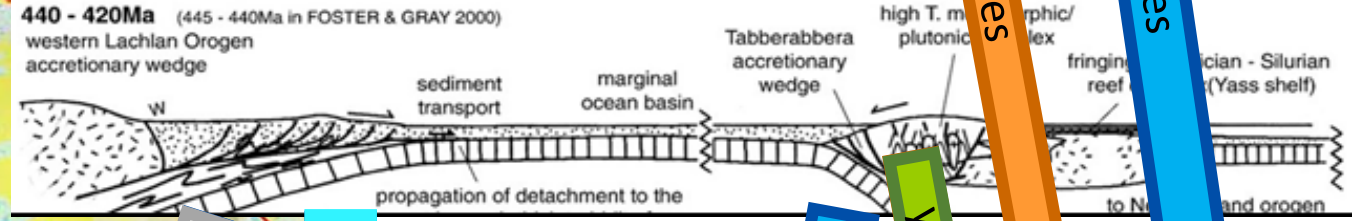


(Stern, 2002)





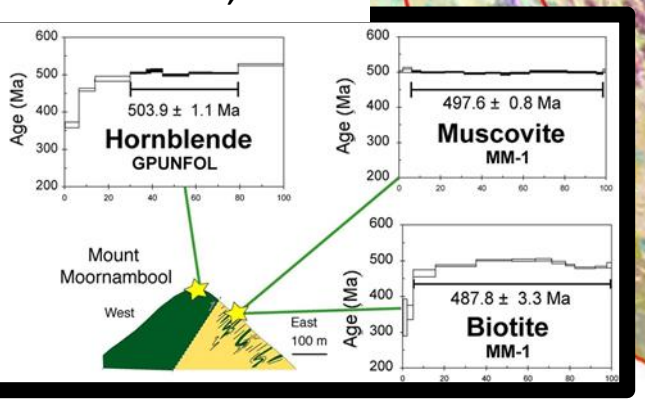
Gray & Foster, 2000

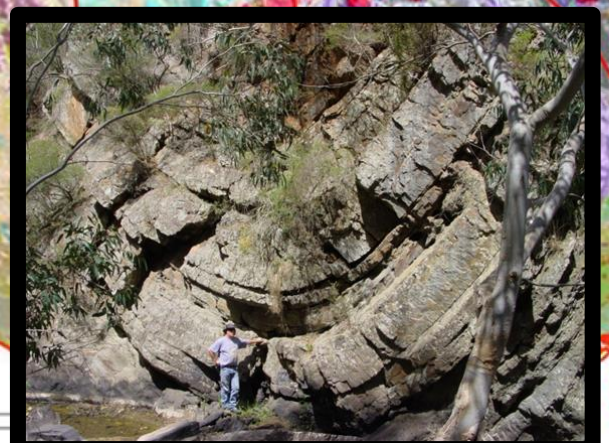


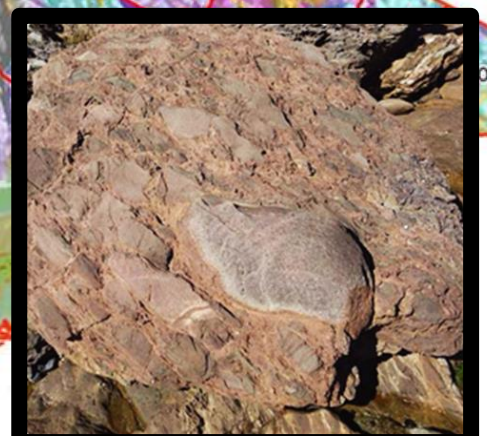
Subduction / accretion models for Late Ordovician Victoria -

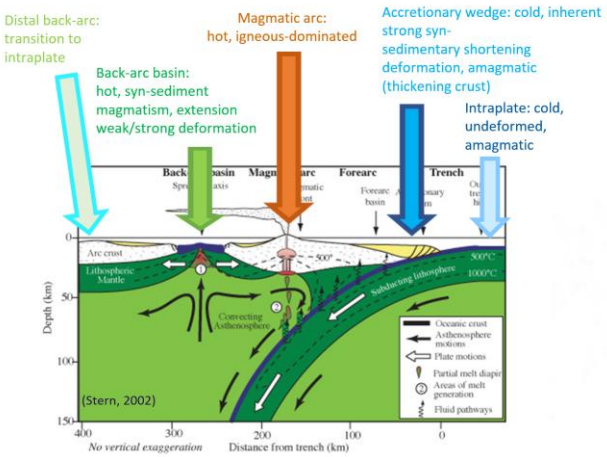
….they don't work perfectly.

Miller et al., 2003

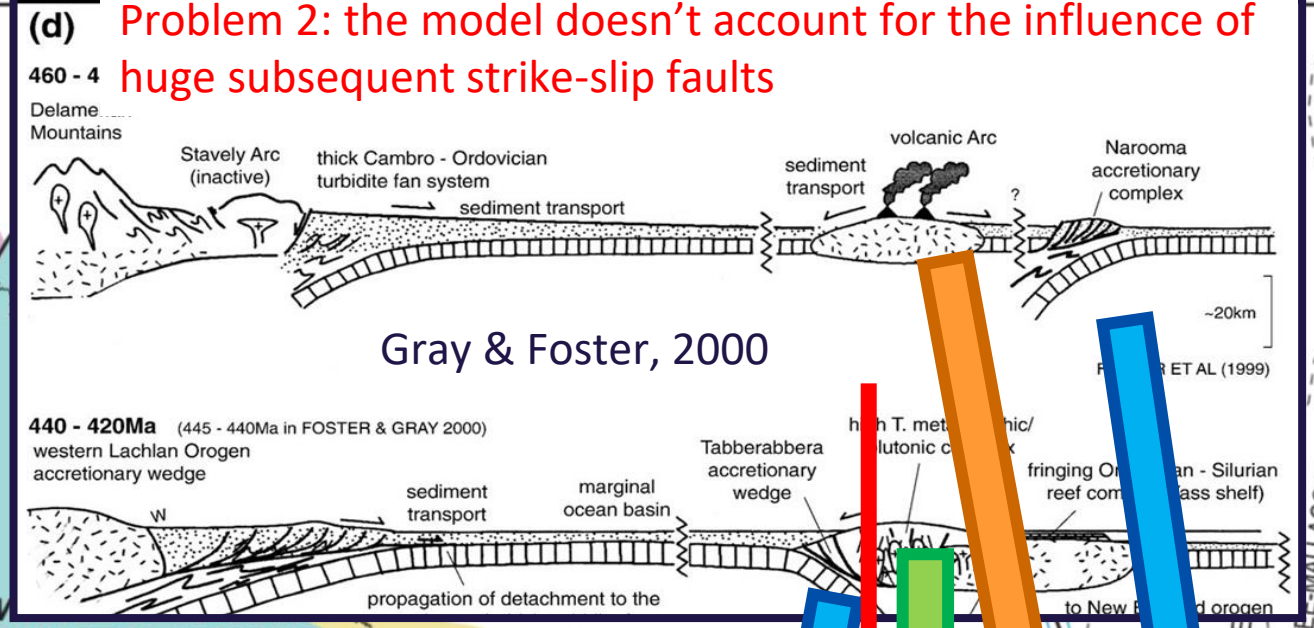




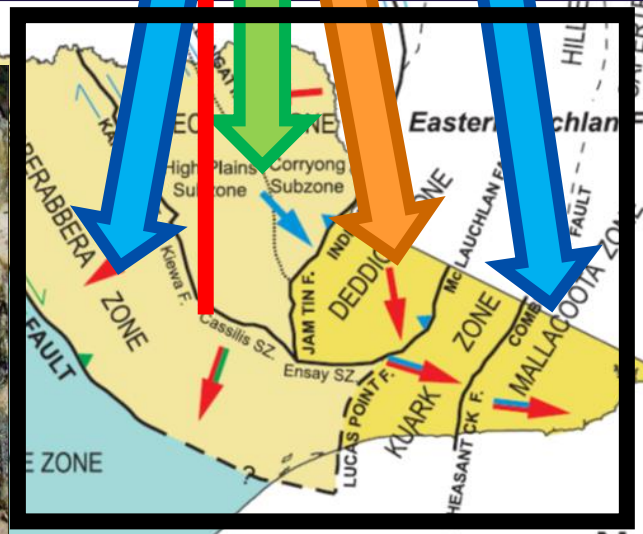




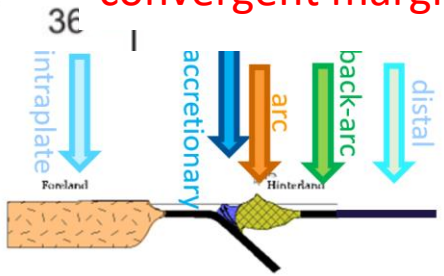
Problem 2: the model doesn't account for the influence of huge subsequent strike-slip faults



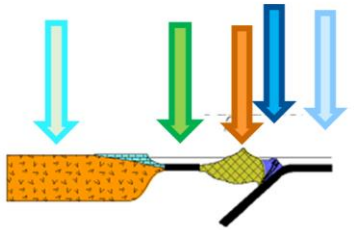
Gray & Foster, 2000

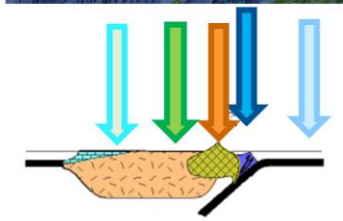


Blue (accretionary wedge) against **Green** (back arc):
a relationship not observed in simple convergent margins

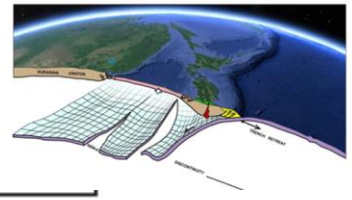


Continent-Island Arc Collision

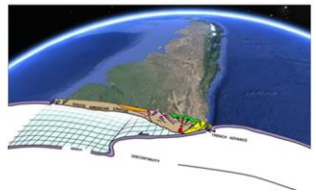


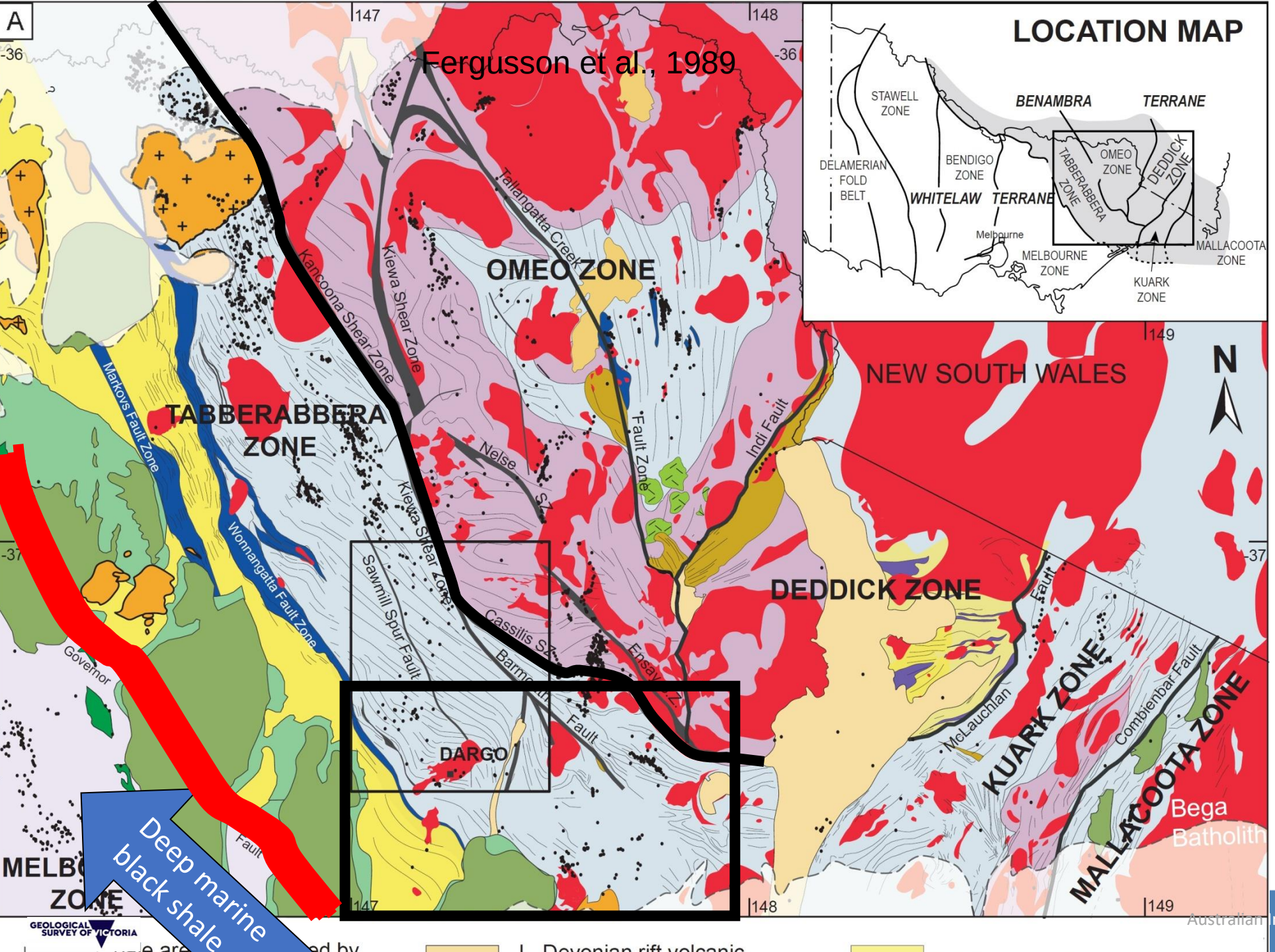


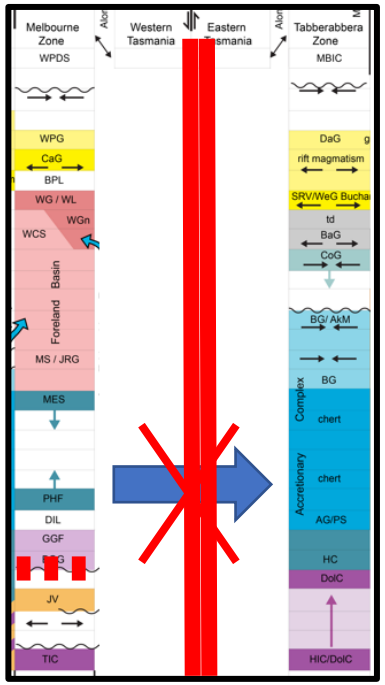
Island Arc



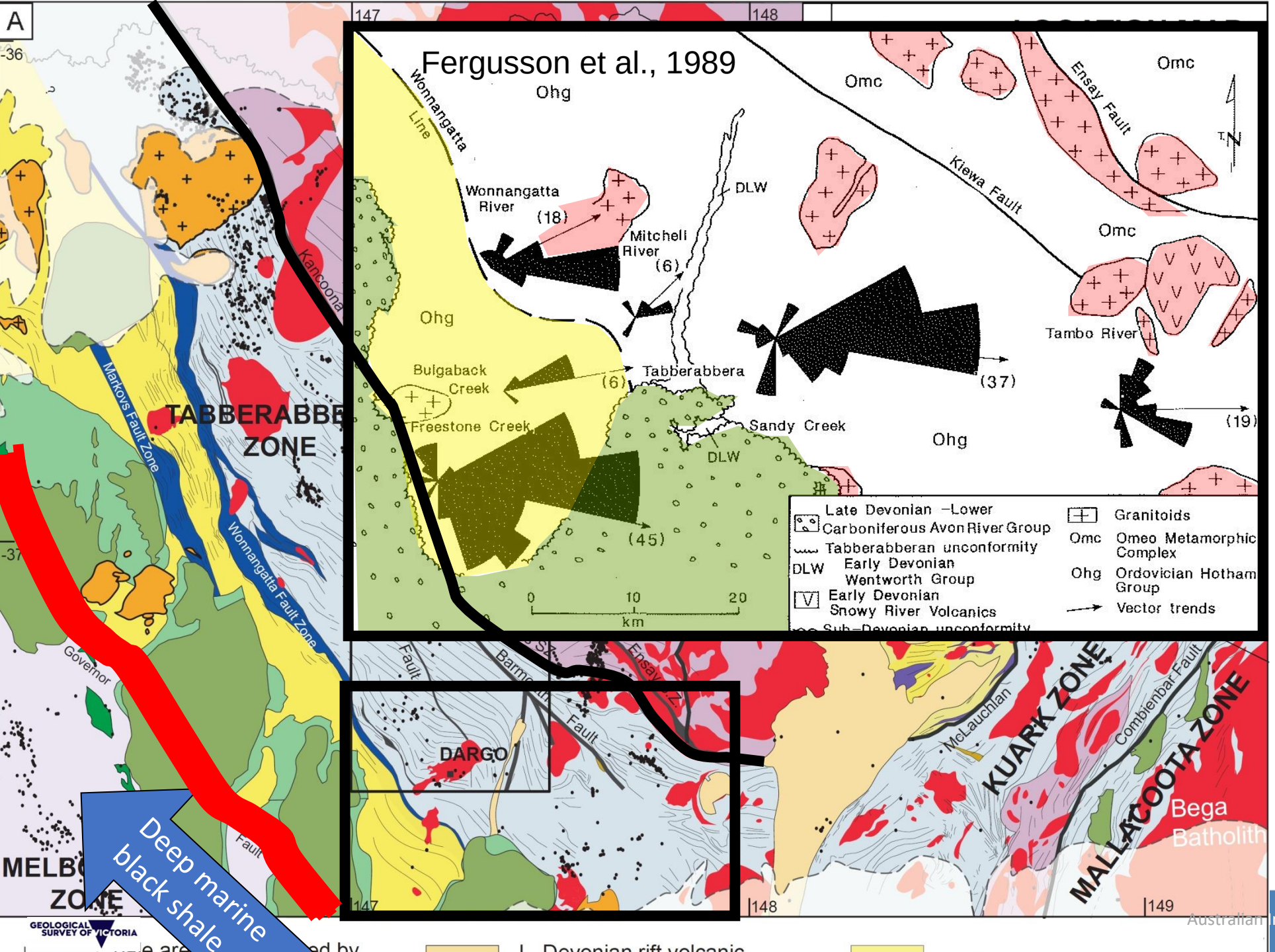
Cordilleran

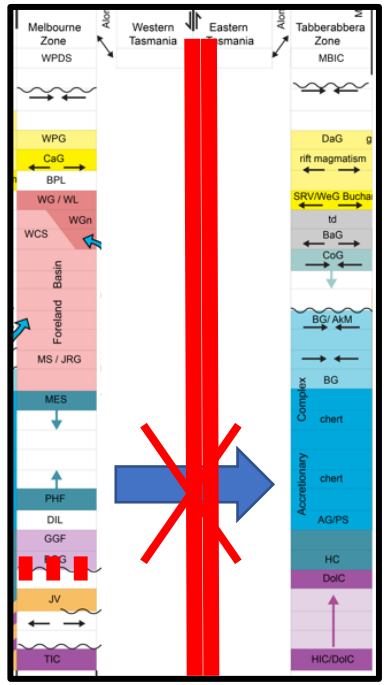






Field geology – Sedimentology, Palaeogeography can also provide critical constraints…



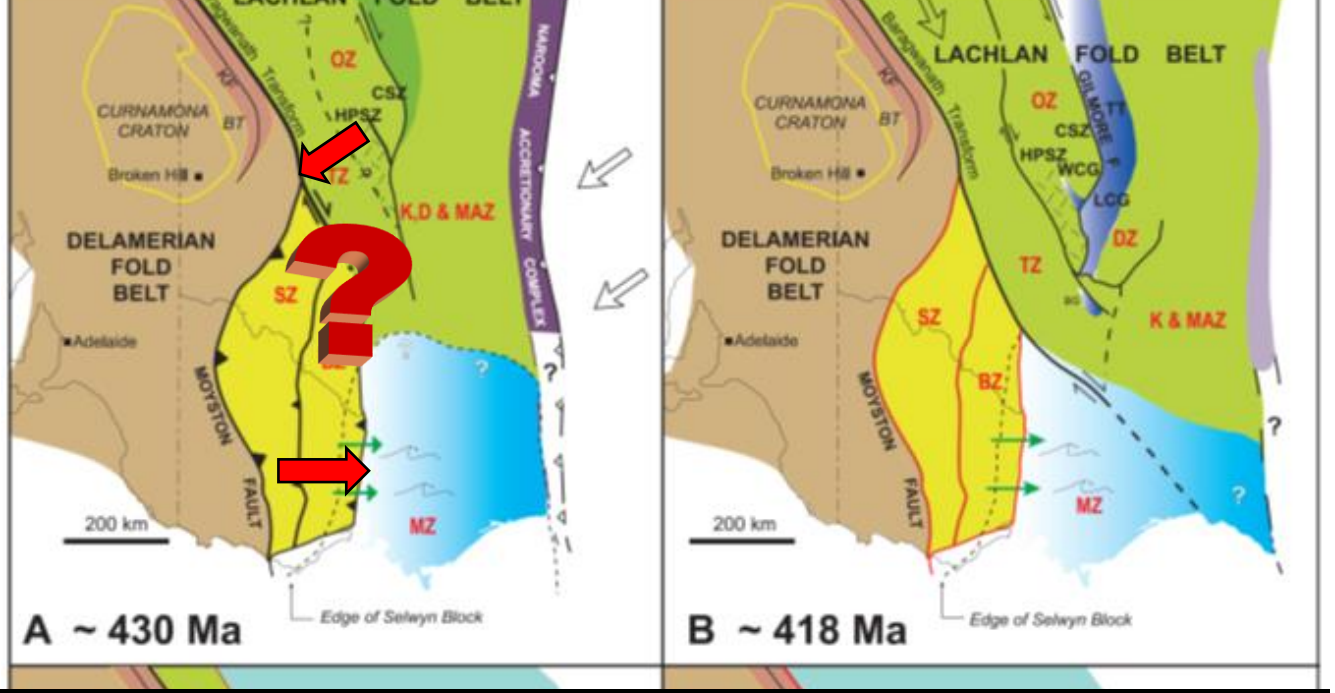


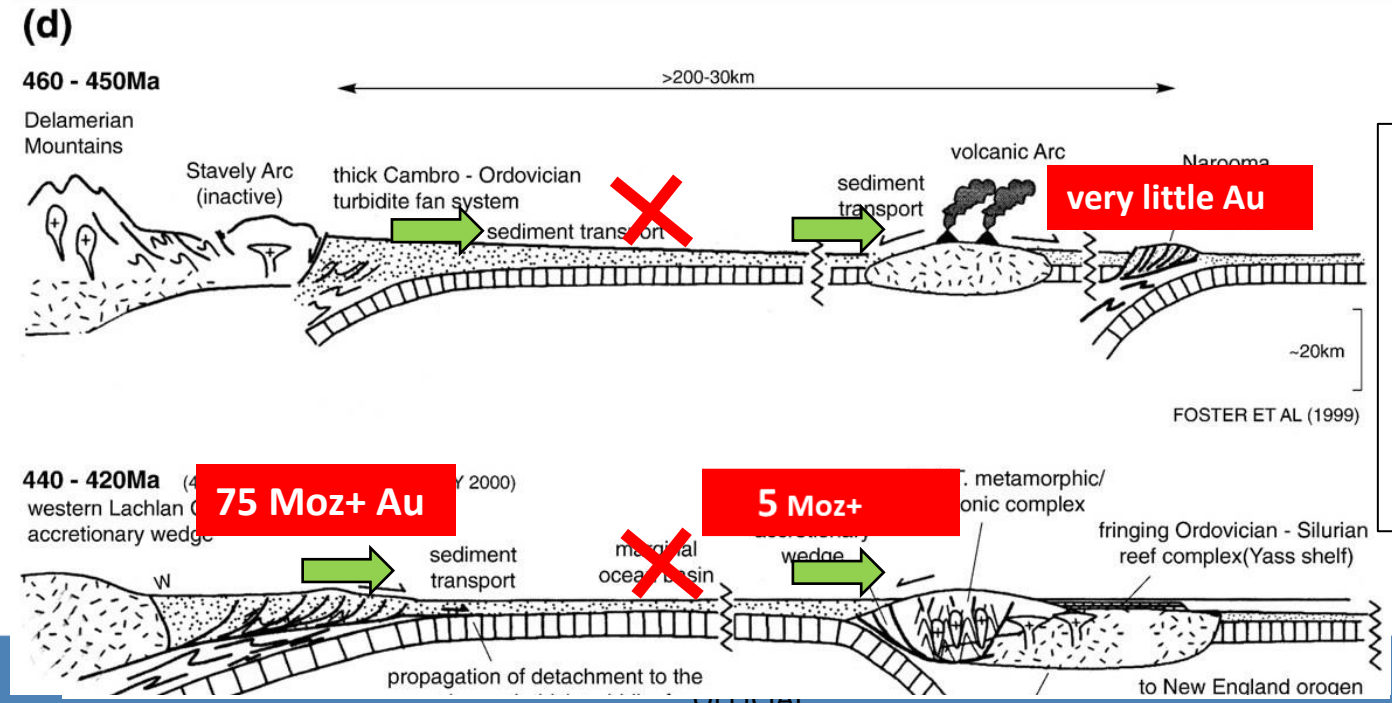
Field geology – Sedimentology, Palaeogeography can also provide critical constraints…

Models that honour paleogeographic constraints, and account for strike-slip faults…..

eg. the Baragwanath Transform concept…

(VandenBerg et al. 2000, Willman et al., 2002)





Tectonic models of the 1990's-early 2000's all have major shortcomings… and don't specifically help predict Orogenic gold location or endowment!

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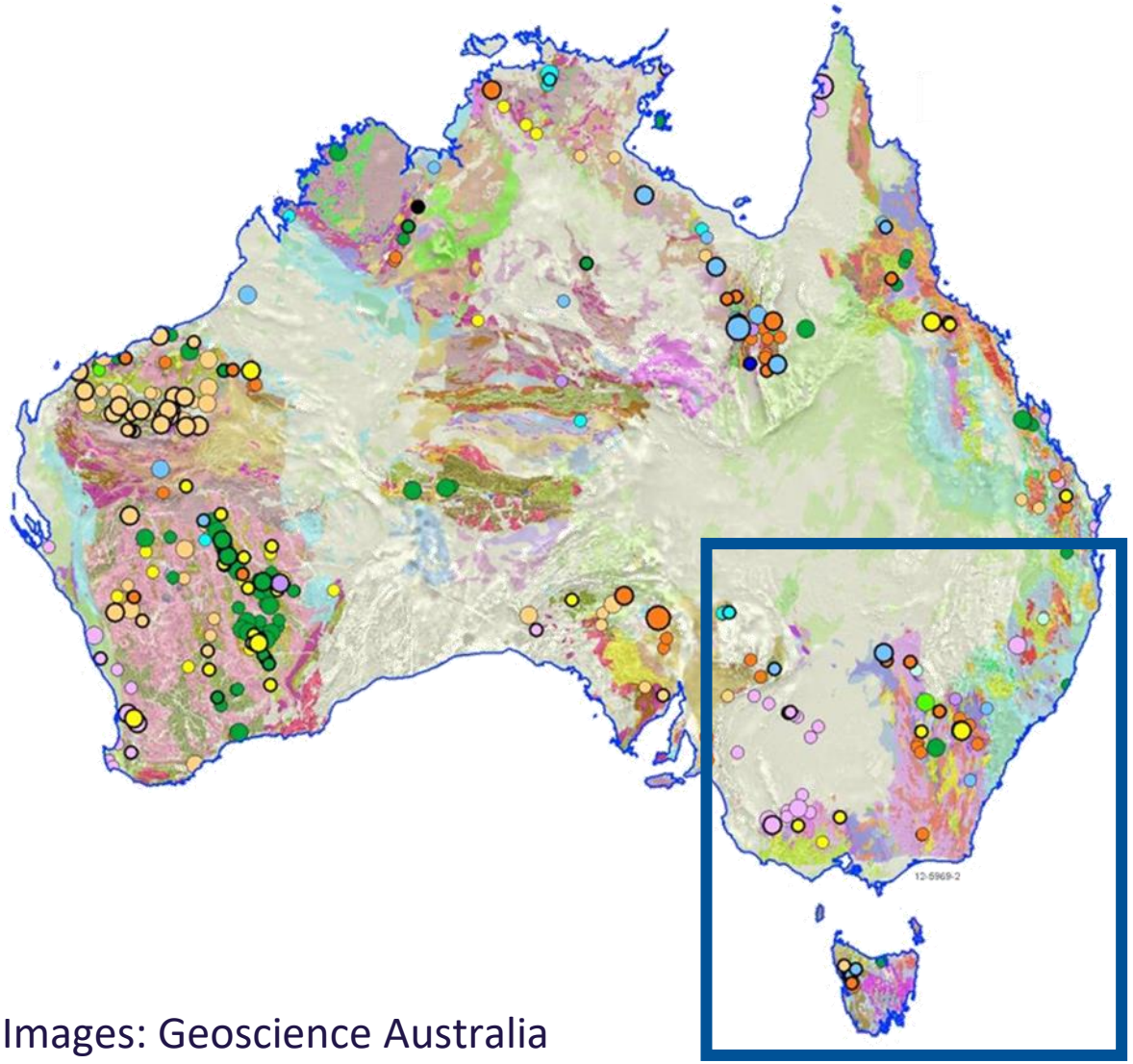


Images: Geoscience Australia

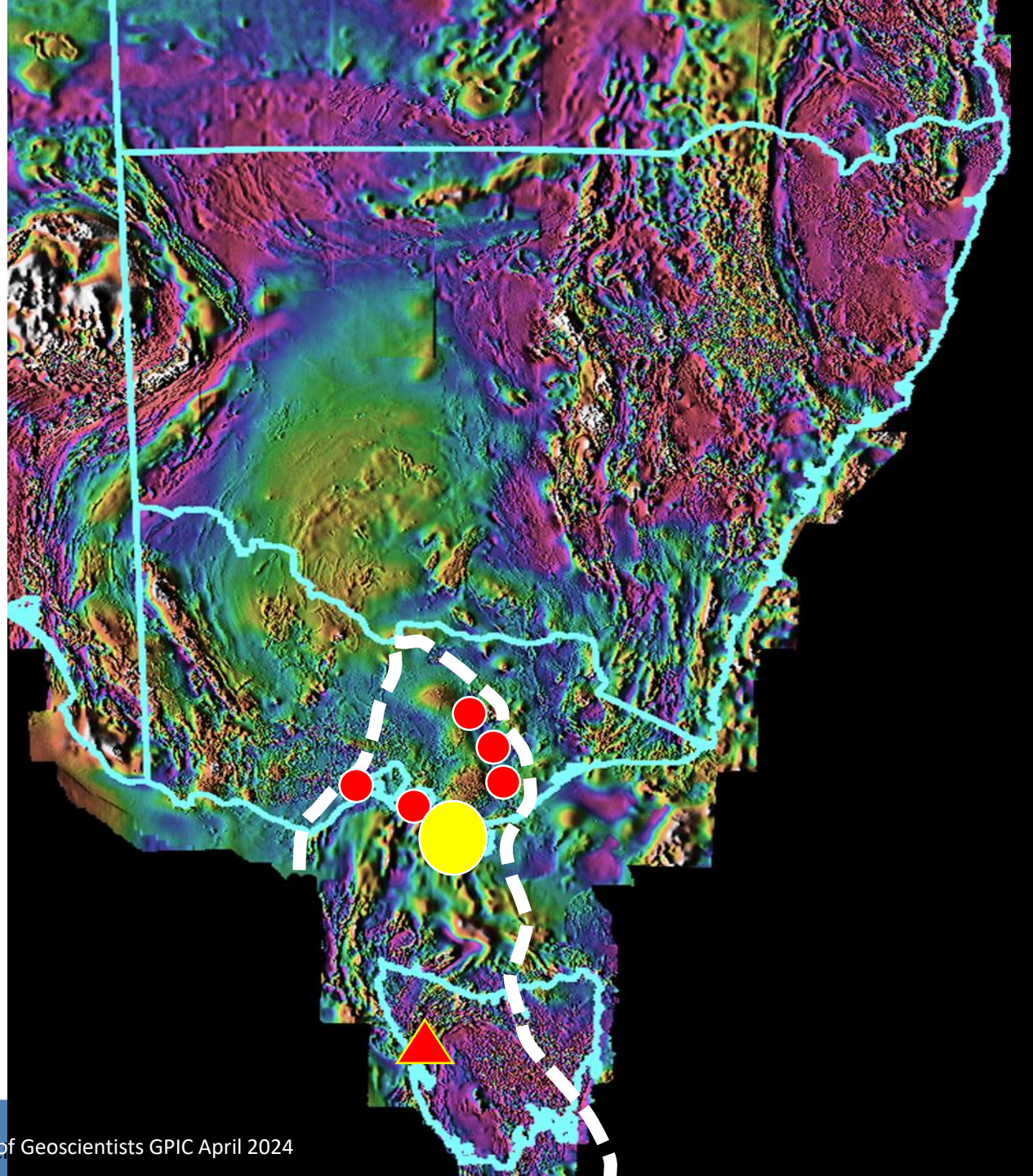
Google Earth TM

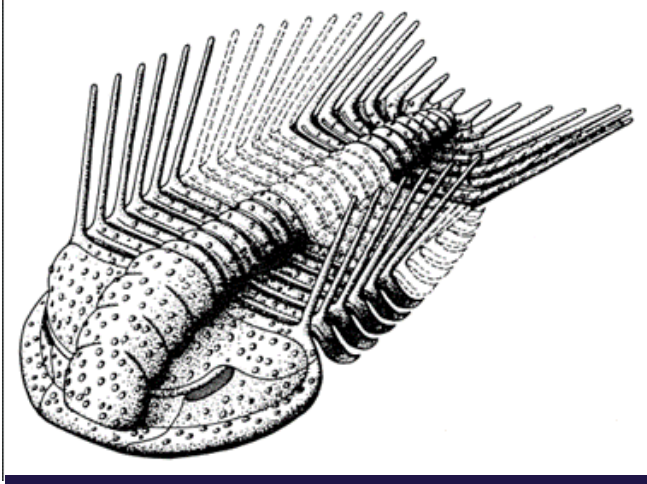
Western Tasmania and its northern extension…
the Selwyn Block.
(Cayley et al., 2002)

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

Cambrian Jamieson Volcanics (Vic)

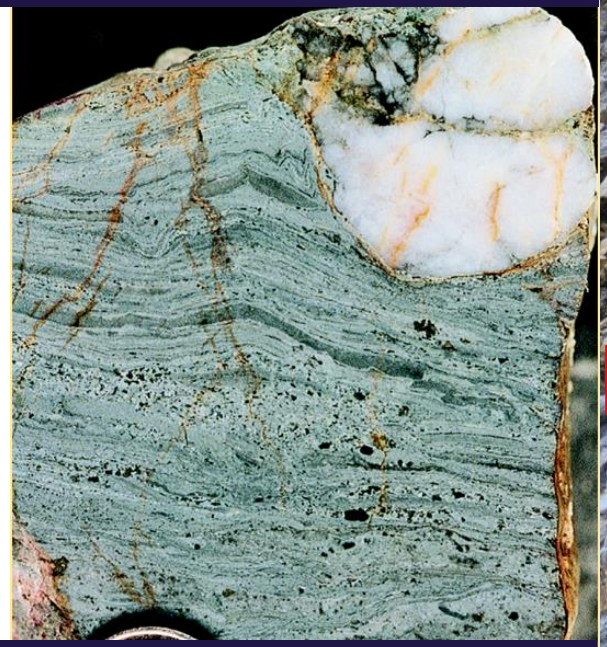
coeval with (and along strike from)
Mount Read Volcanics
Dundas ‘Trough’ (Tas) ▲





Waratah Bay

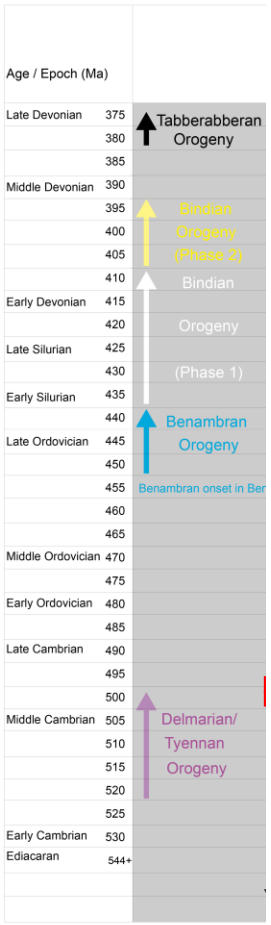
Early Lancefieldian – ~490Ma+

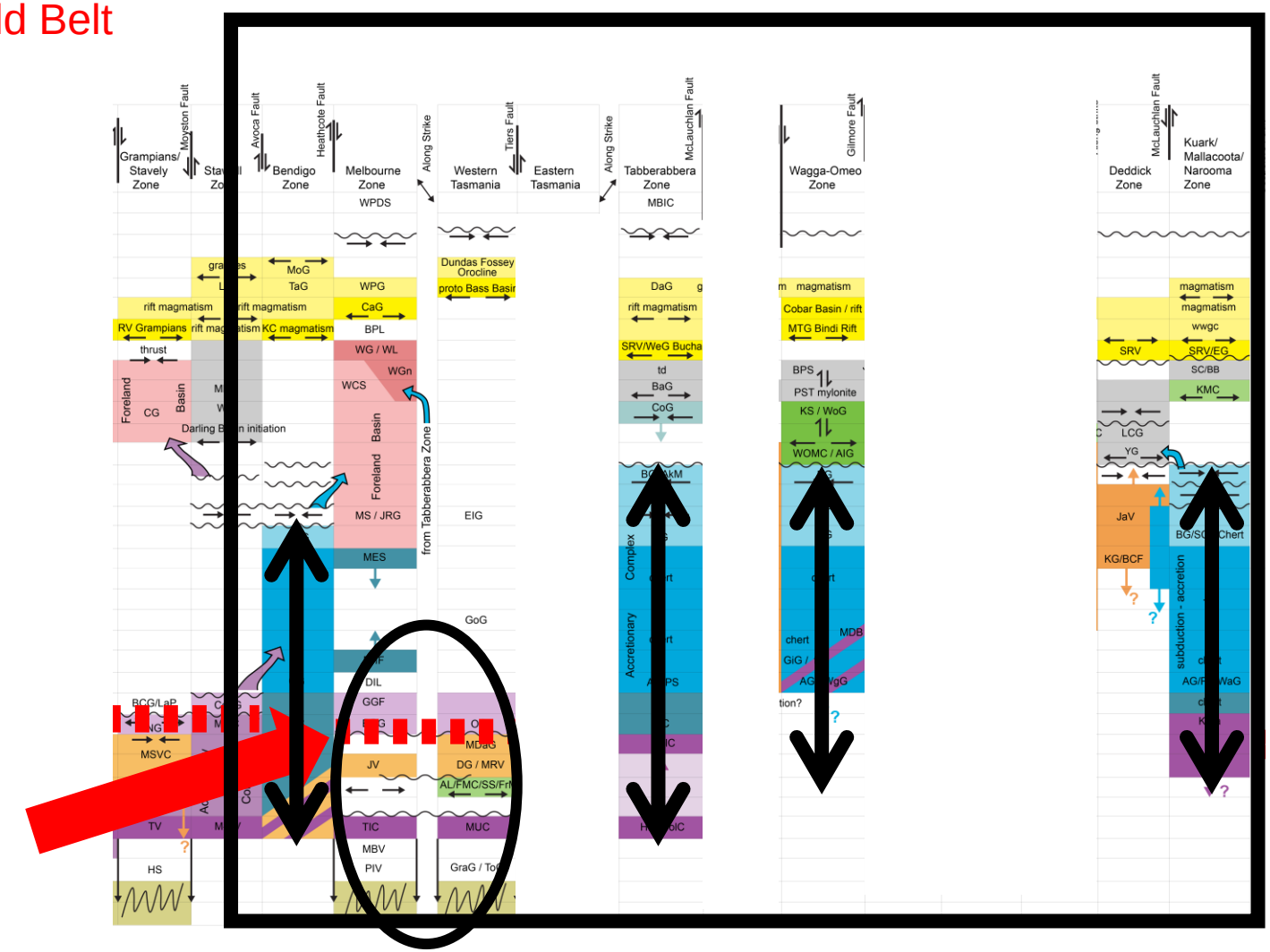


Bear Gully Gritstone

Delamerian Fold Belt

Lachlan Fold Belt

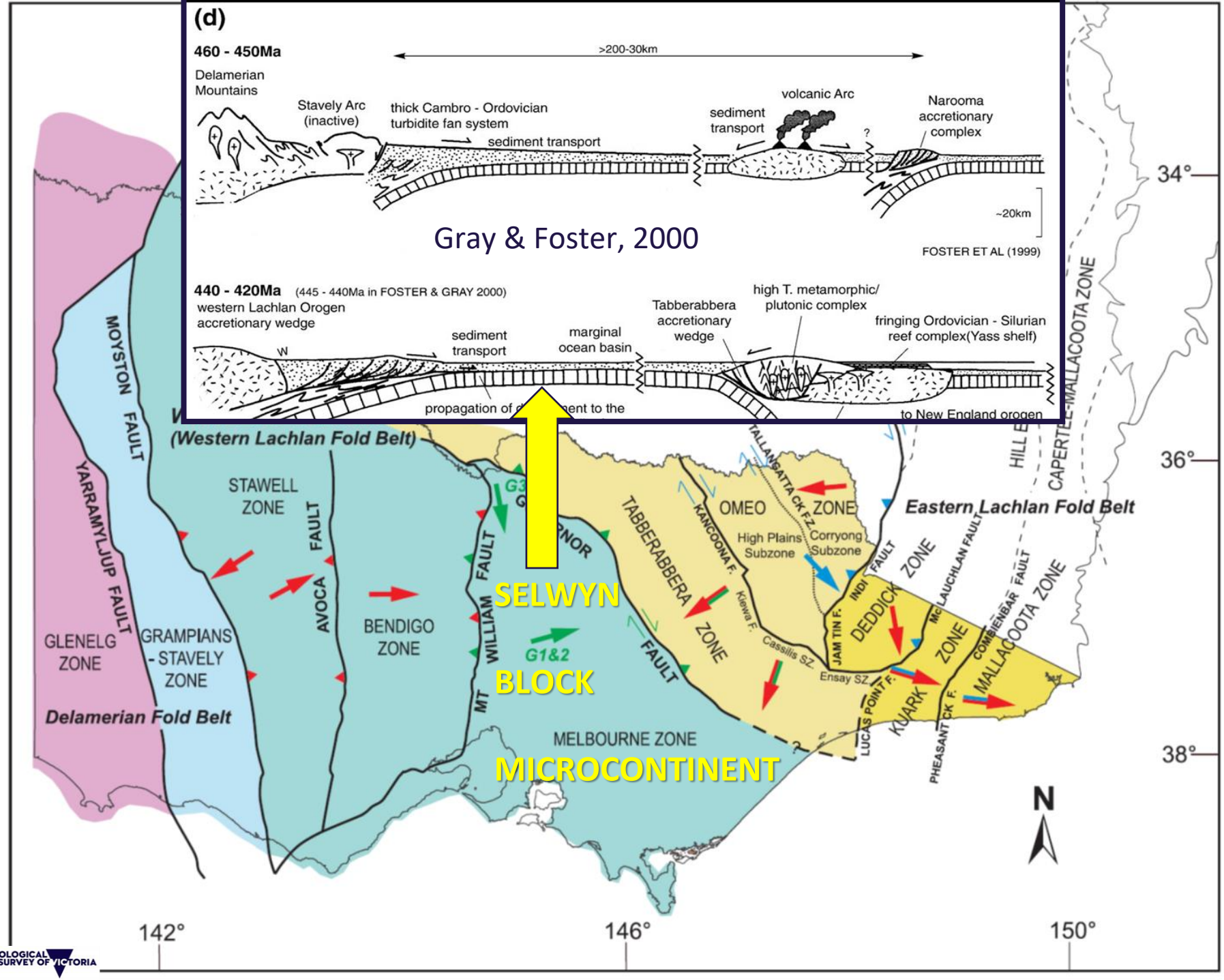




the Selwyn Block:
a region with Cambrian orogenesis,
surrounded by zones that
don't have Cambrian orogenesis:

Time-space plot : Victoria

Cayley & Musgrave, in prep



The Selwyn Block model – alternative explanation for some observed changes in Lachlan Fold Belt sedimentation and deformation timing (particularly overlying Melbourne Zone)

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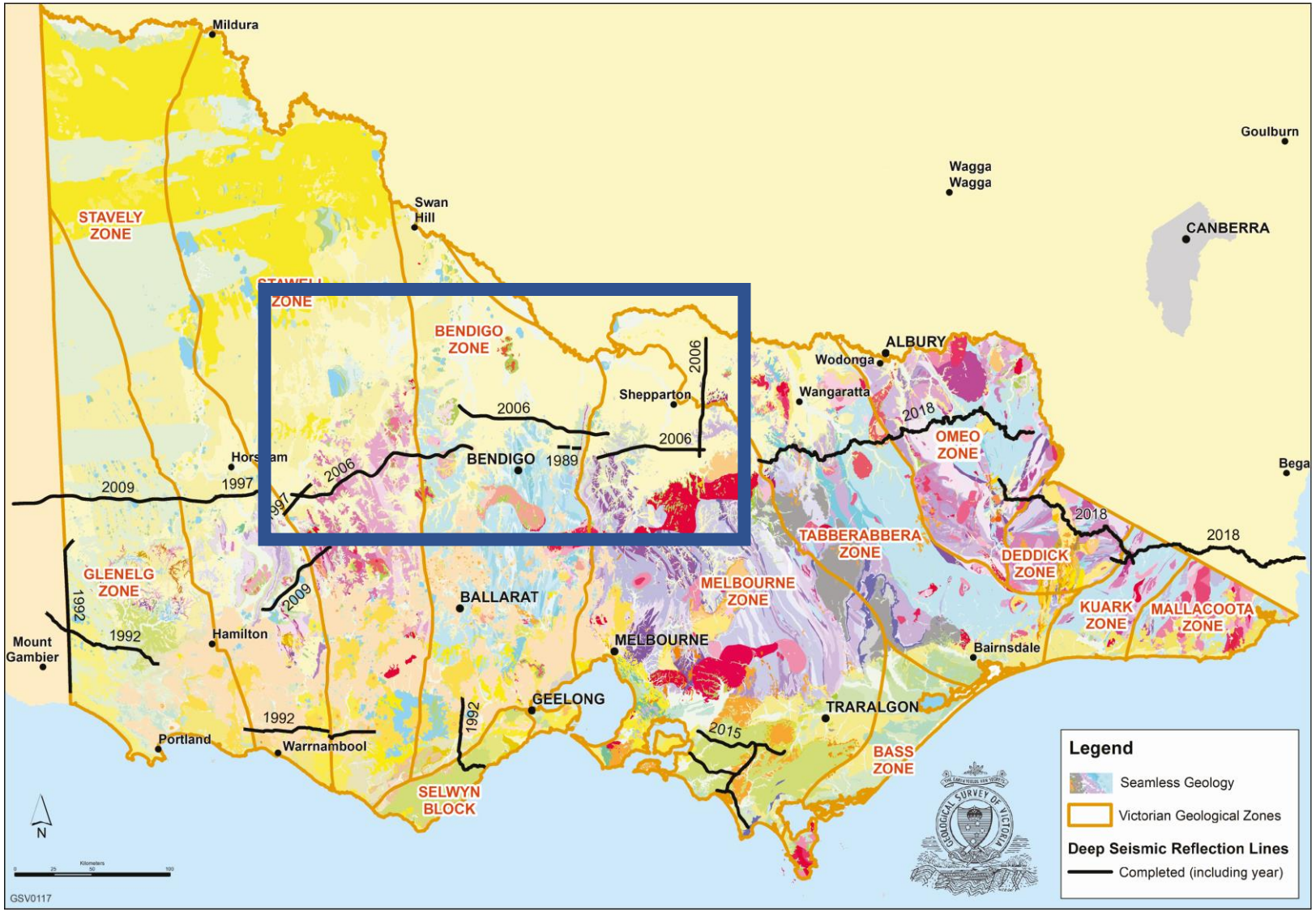
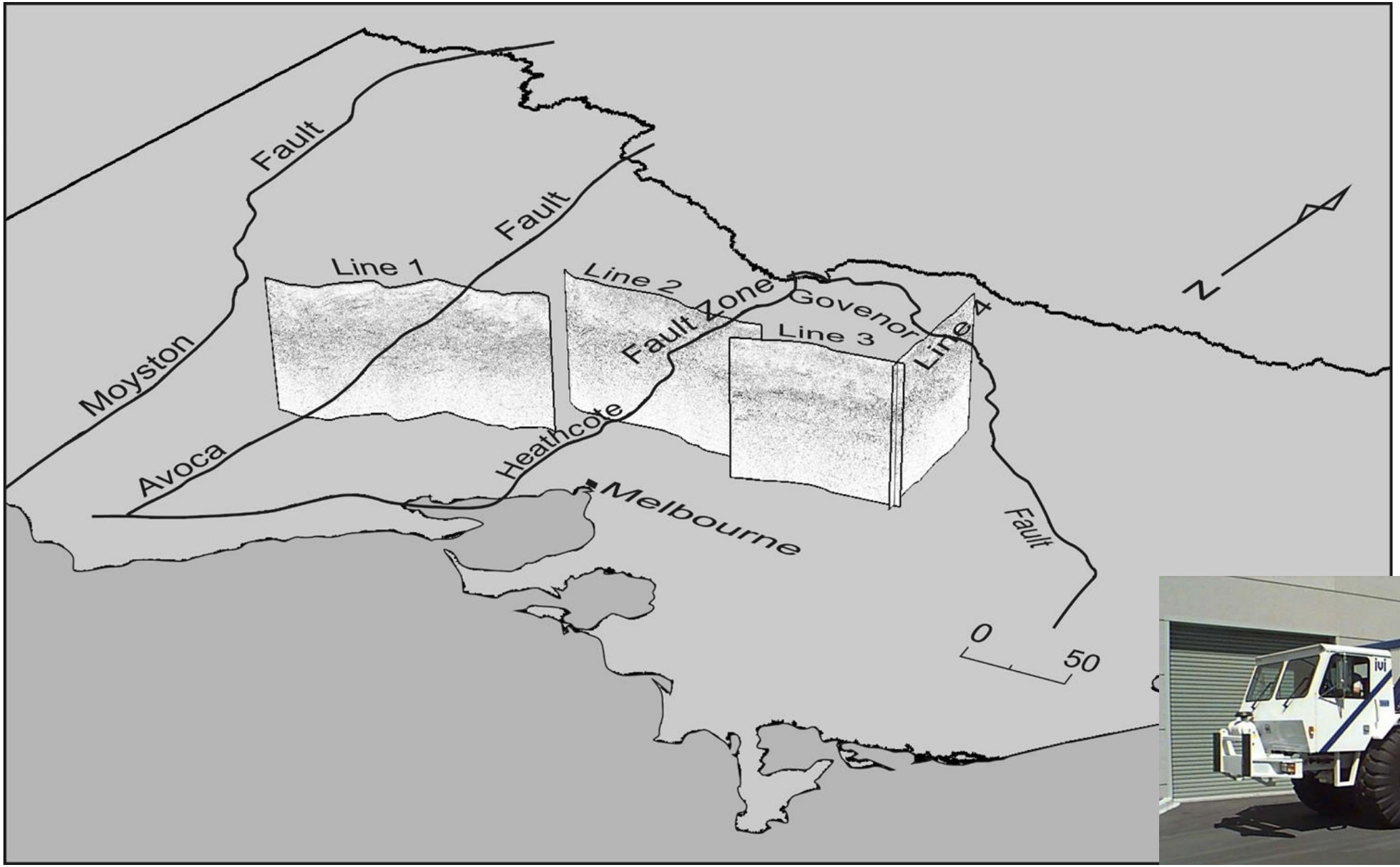
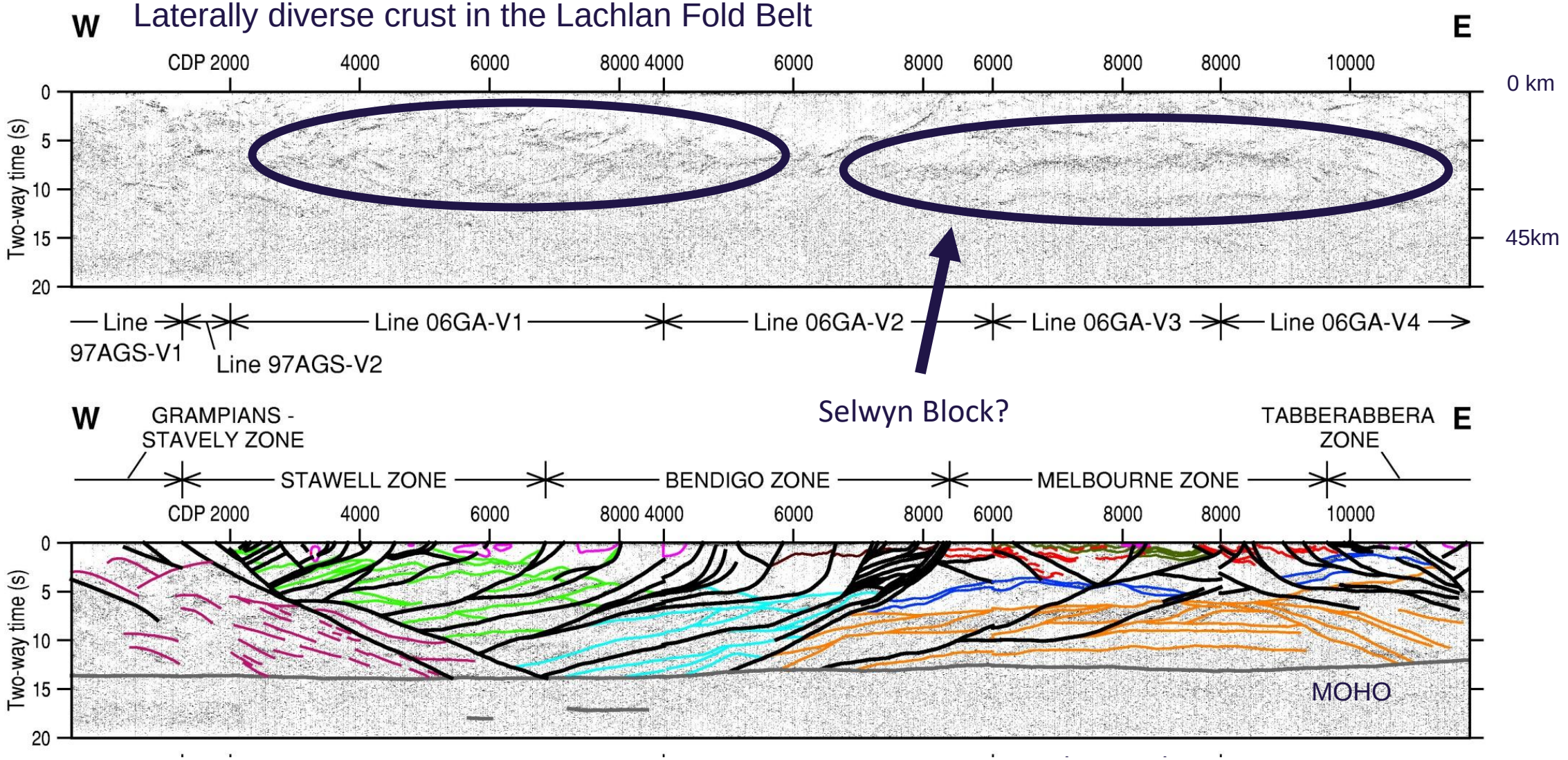
Deep Seismic Reflection

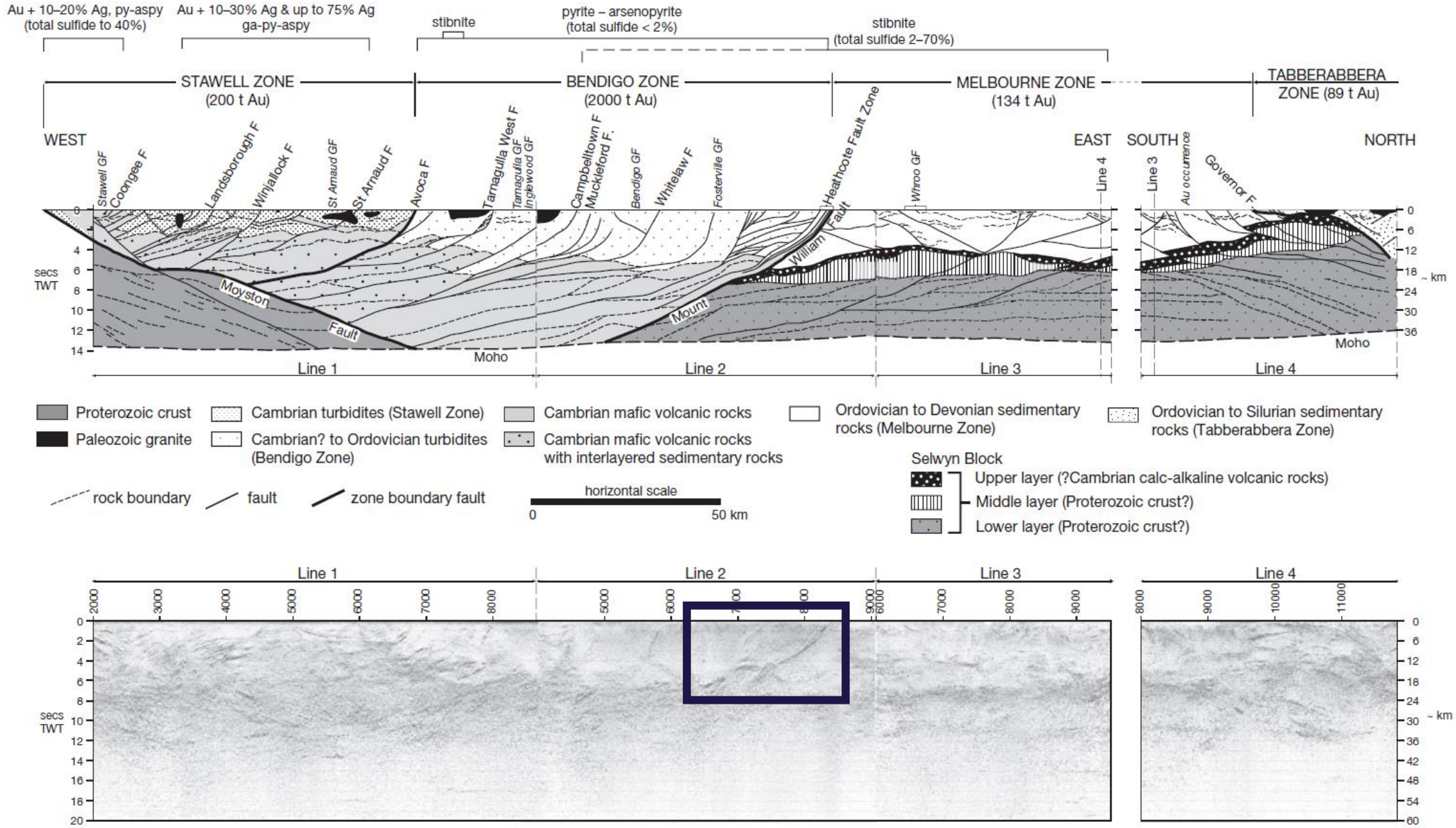




2006 regional deep seismic transects: GA, pmd*crc

Laterally diverse crust in the Lachlan Fold Belt




Au + 10–20% Ag, py-aspy (total sulfide to 40%)
Au + 10–30% Ag & up to 75% Ag ga-py-aspy
stibnite
pyrite – arsenopyrite (total sulfide < 2%)
stibnite (total sulfide 2–70%)
STAWELL ZONE (200 t Au)
BENDIGO ZONE (2000 t Au)
MELBOURNE ZONE (134 t Au)
TABBERABBERA ZONE (89 t Au)
WEST
EAST
SOUTH
NORTH
Stawell GF
Coongee F
Landsborough F
Winjallock F
St Arnaud GF
St Arnaud F
Avoca F
Tarnagulla West F
Tarnagulla GF
Inglewood GF
Campbelltown F
Muckleford F.
Bendigo GF
Whitelaw F
Fosterville GF
Heathcote Fault Zone
Whroo GF
Line 4
Line 3
Au occurrence
Governor F.
secs TWT
~ km
Moyston Fault
William Fault
Mount
Moho
Line 1
Line 2
Line 3
Line 4
Proterozoic crust
Paleozoic granite
Cambrian turbidites (Stawell Zone)
Cambrian? to Ordovician turbidites (Bendigo Zone)
Cambrian mafic volcanic rocks
Cambrian mafic volcanic rocks with interlayered sedimentary rocks
Ordovician to Devonian sedimentary rocks (Melbourne Zone)
Ordovician to Silurian sedimentary rocks (Tabberabbera Zone)
rock boundary
fault
zone boundary fault
horizontal scale
0
50 km
Selwyn Block
Upper layer (?Cambrian calc-alkaline volcanic rocks)
Middle layer (Proterozoic crust?)
Lower layer (Proterozoic crust?)

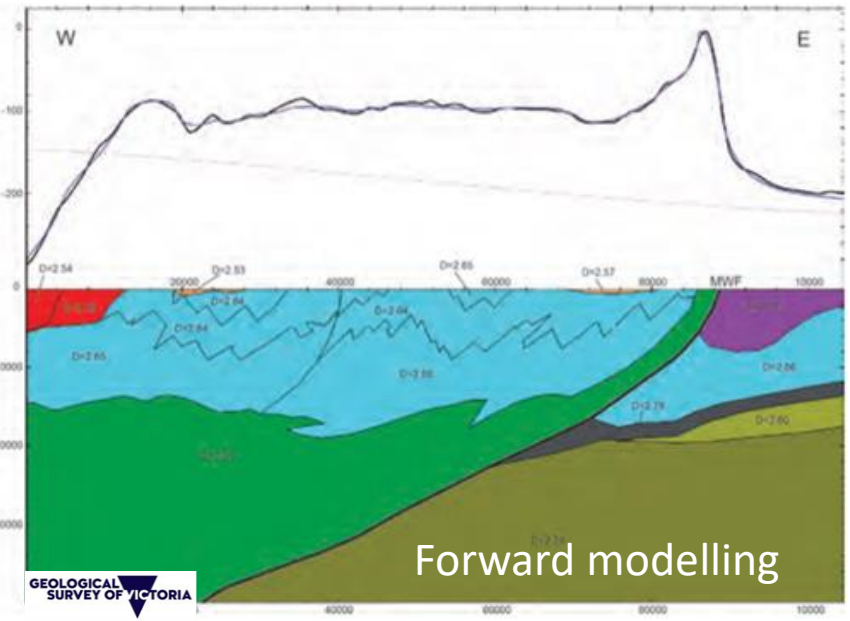
Line 1
Line 2
Line 3
Line 4
secs TWT
~ km

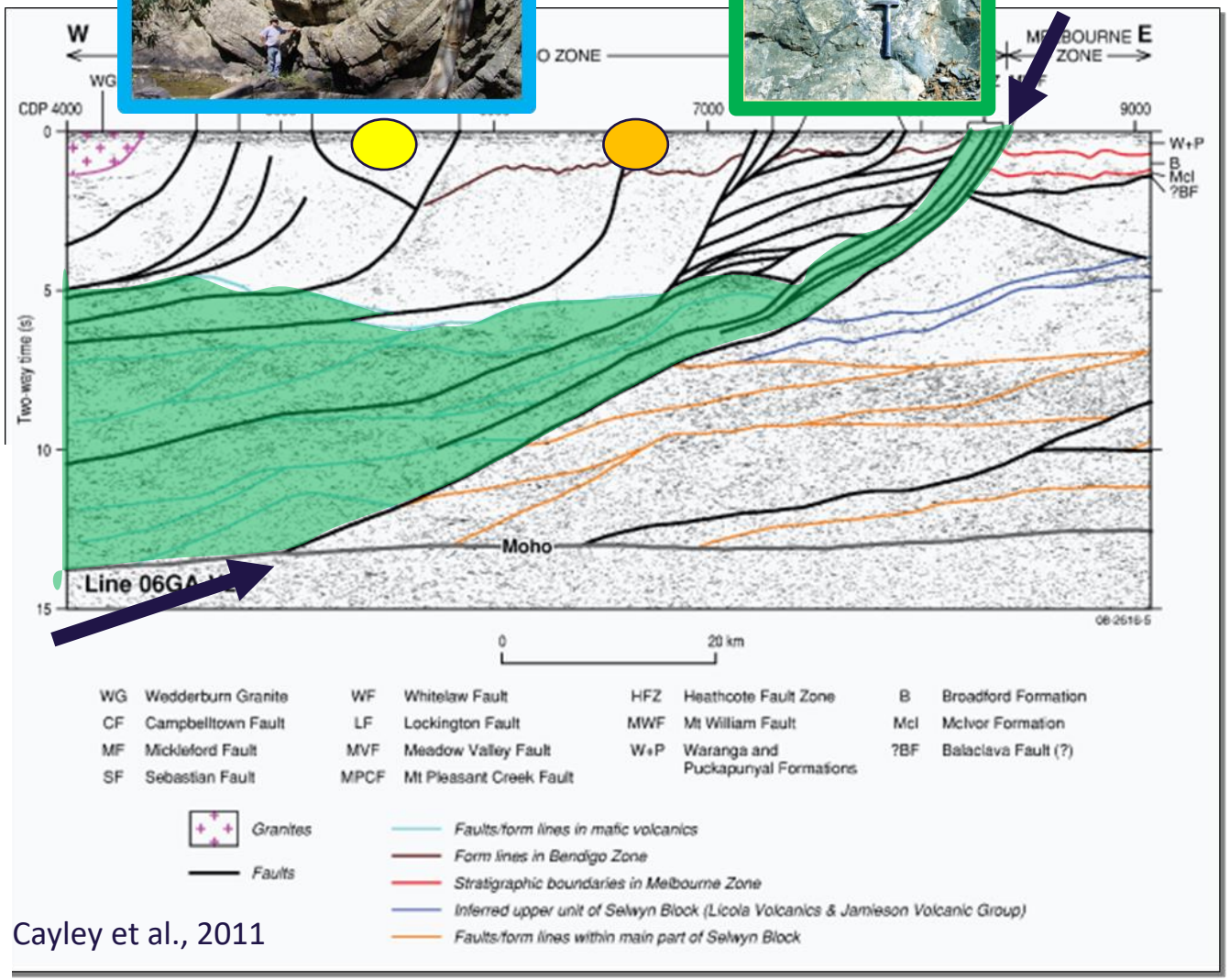
Detail of the Heathcote Fault Zone

This research shows that tens of thousands of cubic kilometres of Cambrian metavolcanic rocks underlie the Bendigo goldfields

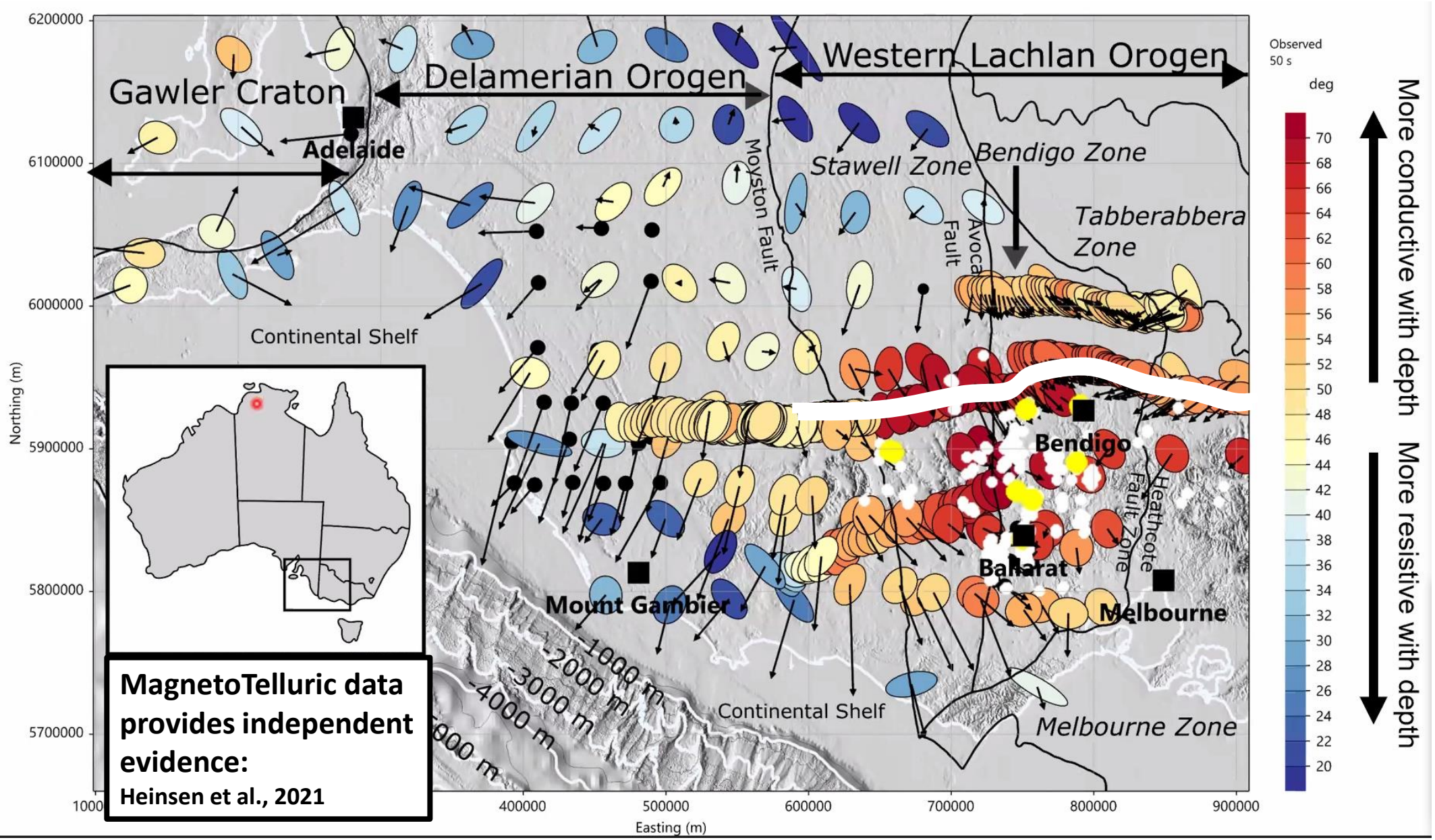
– a source for gold?

Goldfields geology is thick-skinned!





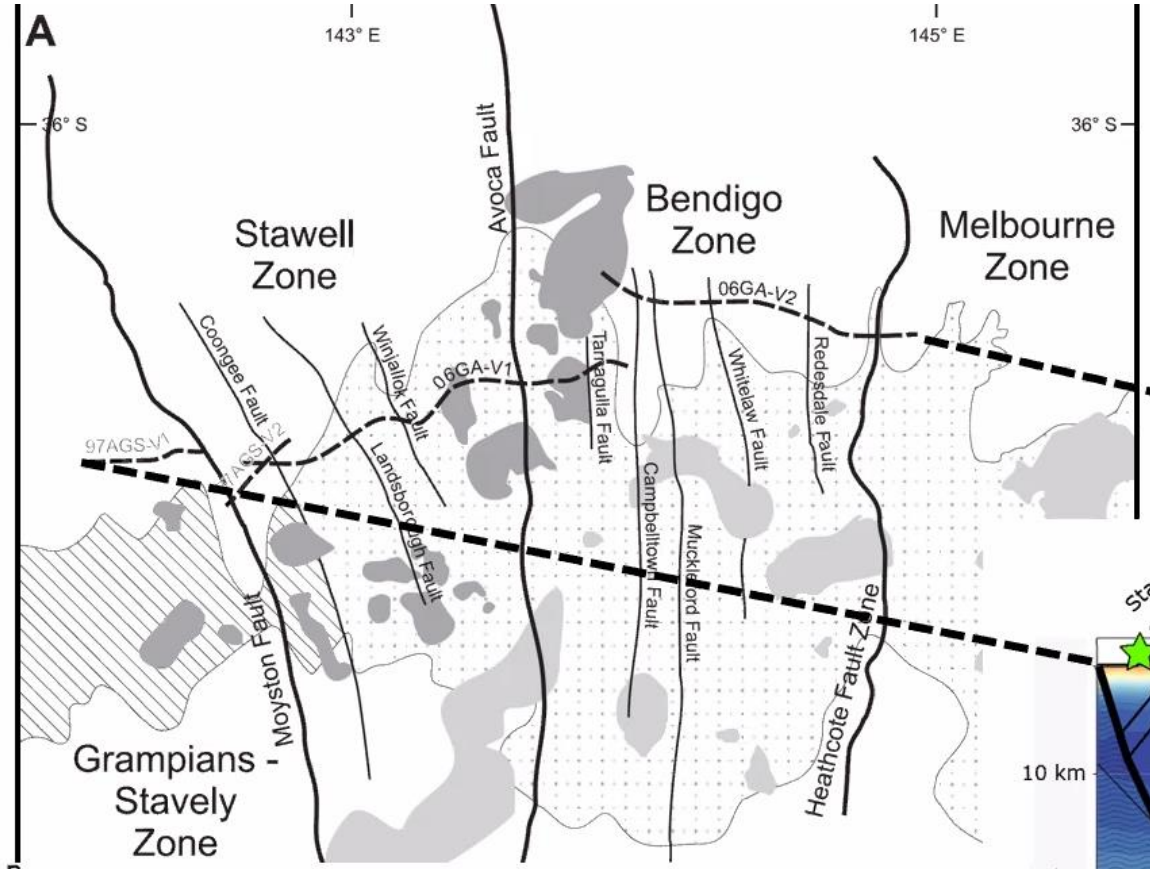
Cayley et al., 2011

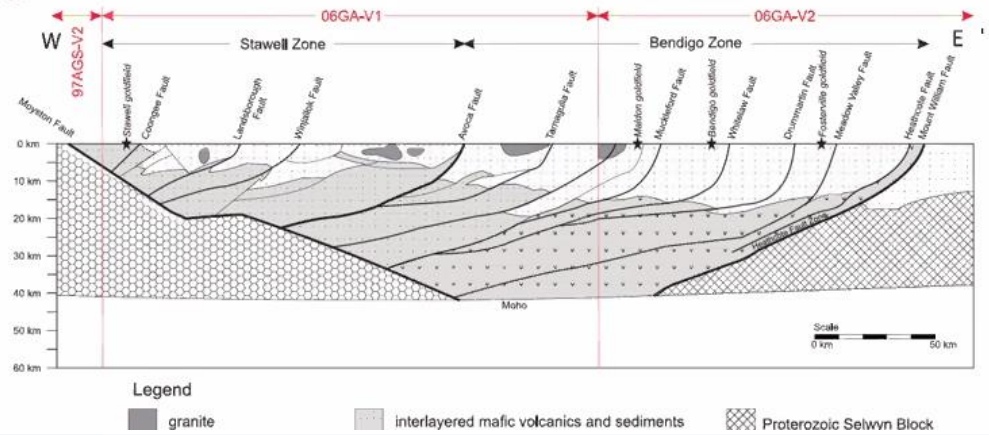


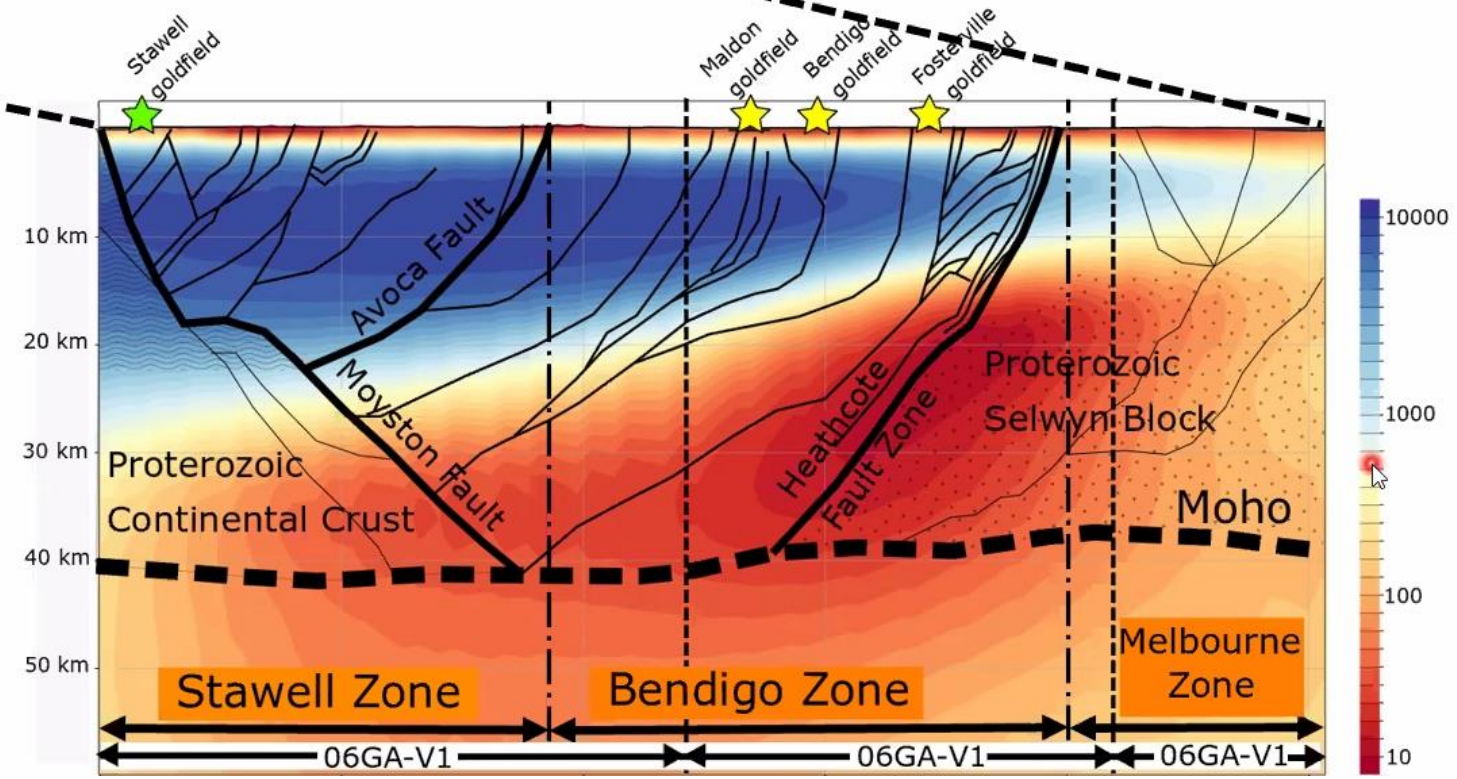
MagnetoTelluric data provides independent evidence:

Heinsen et al., 2021

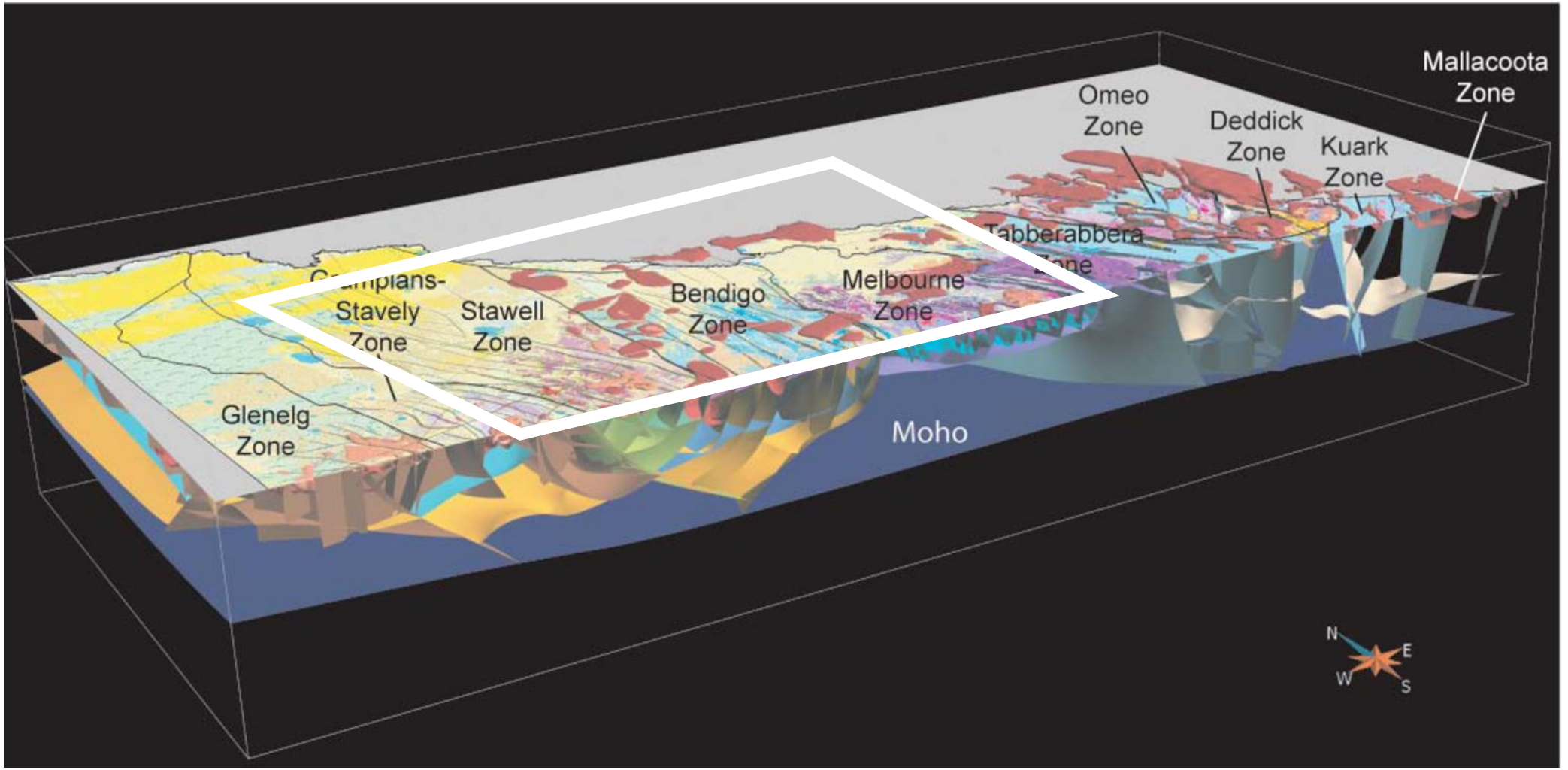
Heinsen et al., 2021: MT data shows the region imaged as dominated by Early Cambrian mafic igneous rocks in Seismic Reflection data is also less electrically resistive.
The overlying interlayered and metasediment-dominated successions are highly resistive.







Victoria – State-wide 3D geological model



Rawling et al., 2011

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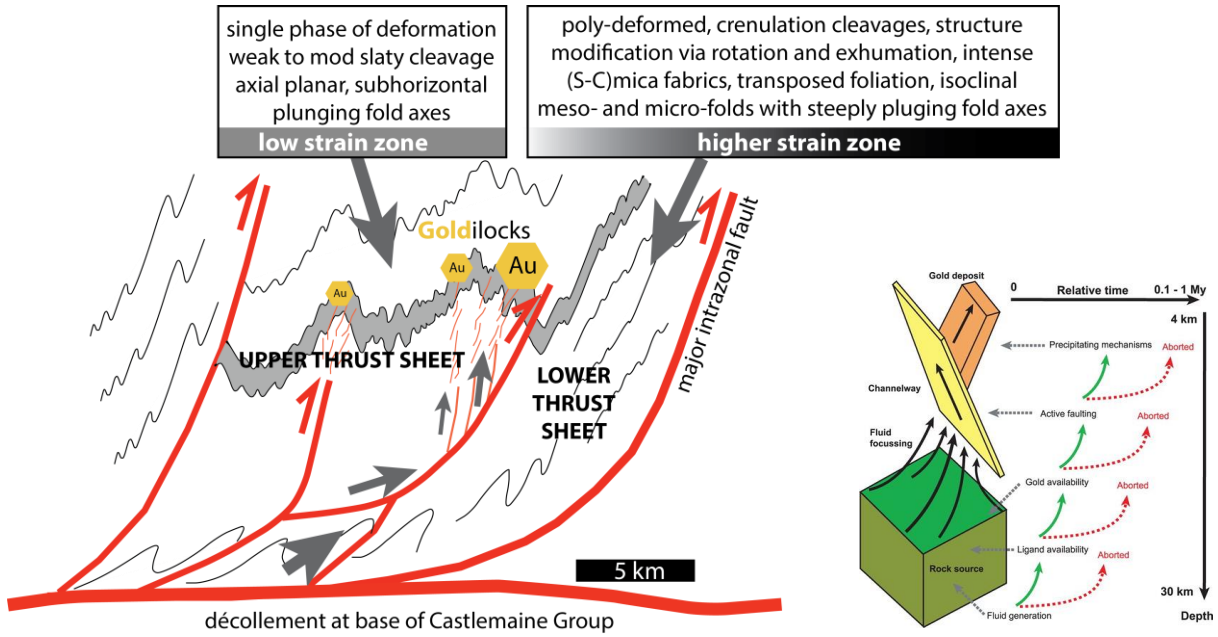
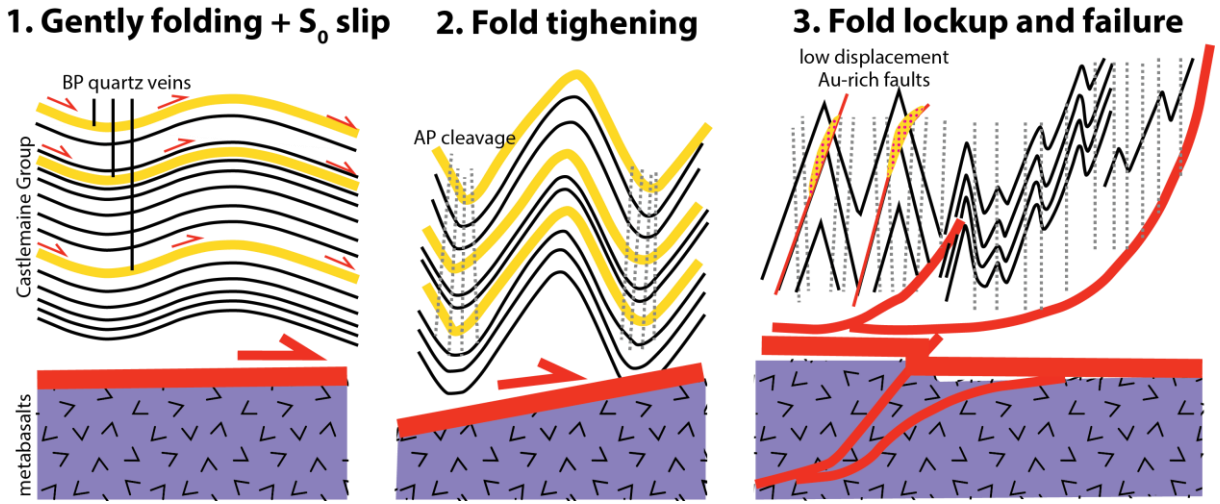
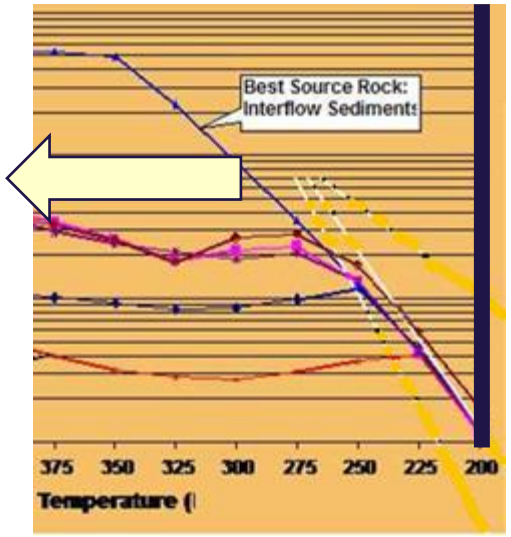


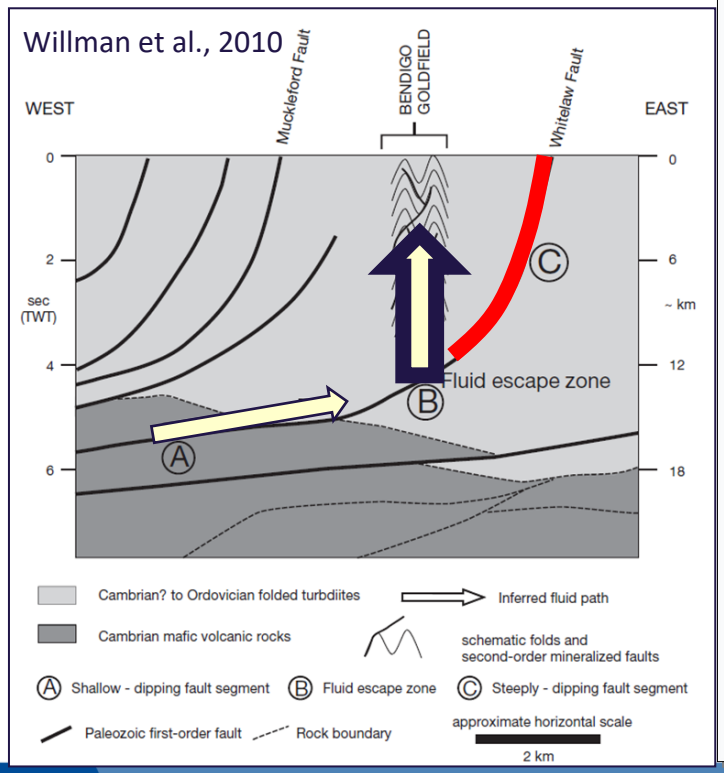
Eg: Willman 2007 Min Dep

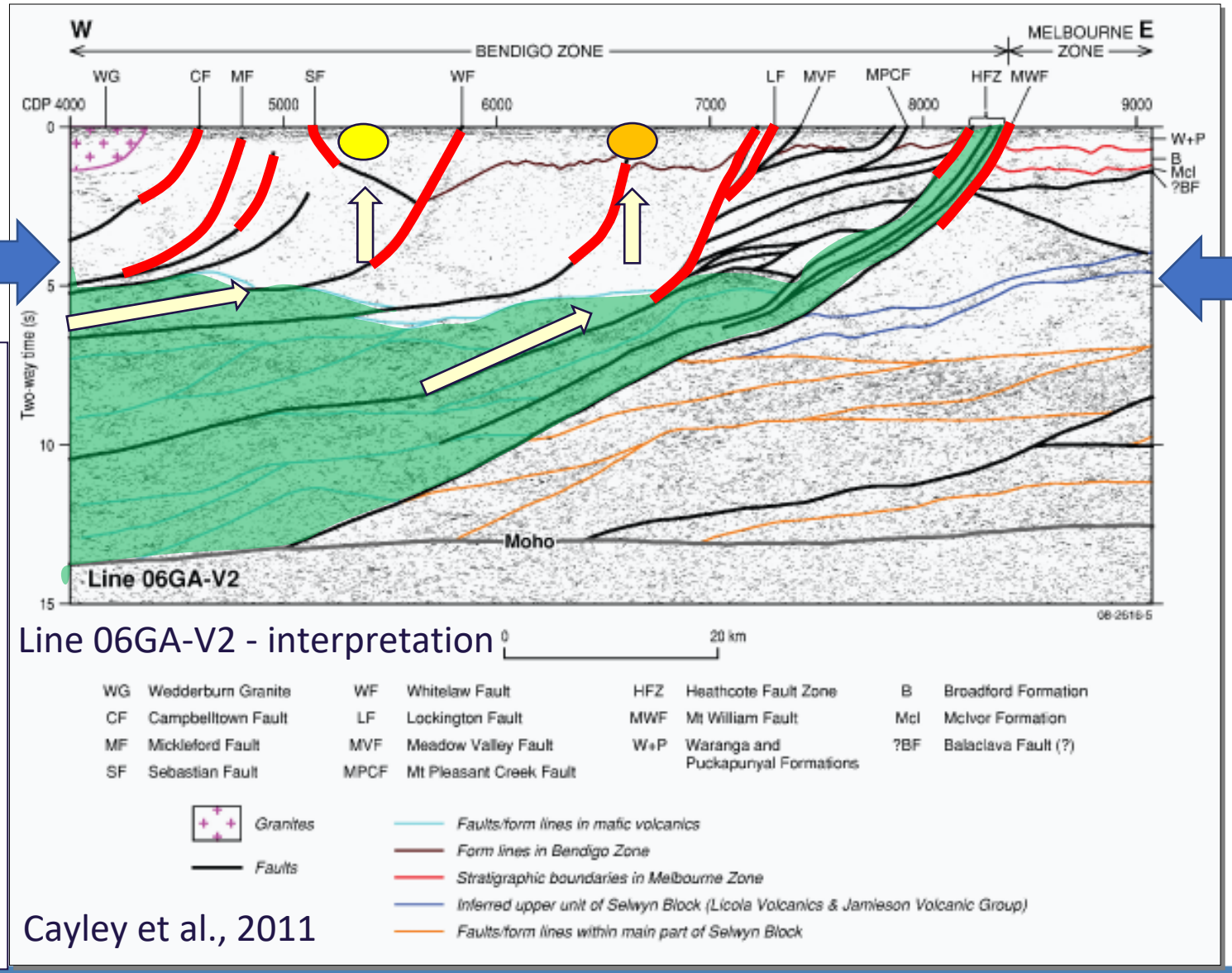


Minerals Systems Models:

This process need not be efficient – the data indicates tens of thousands of cubic km of potential mafic igneous source rocks

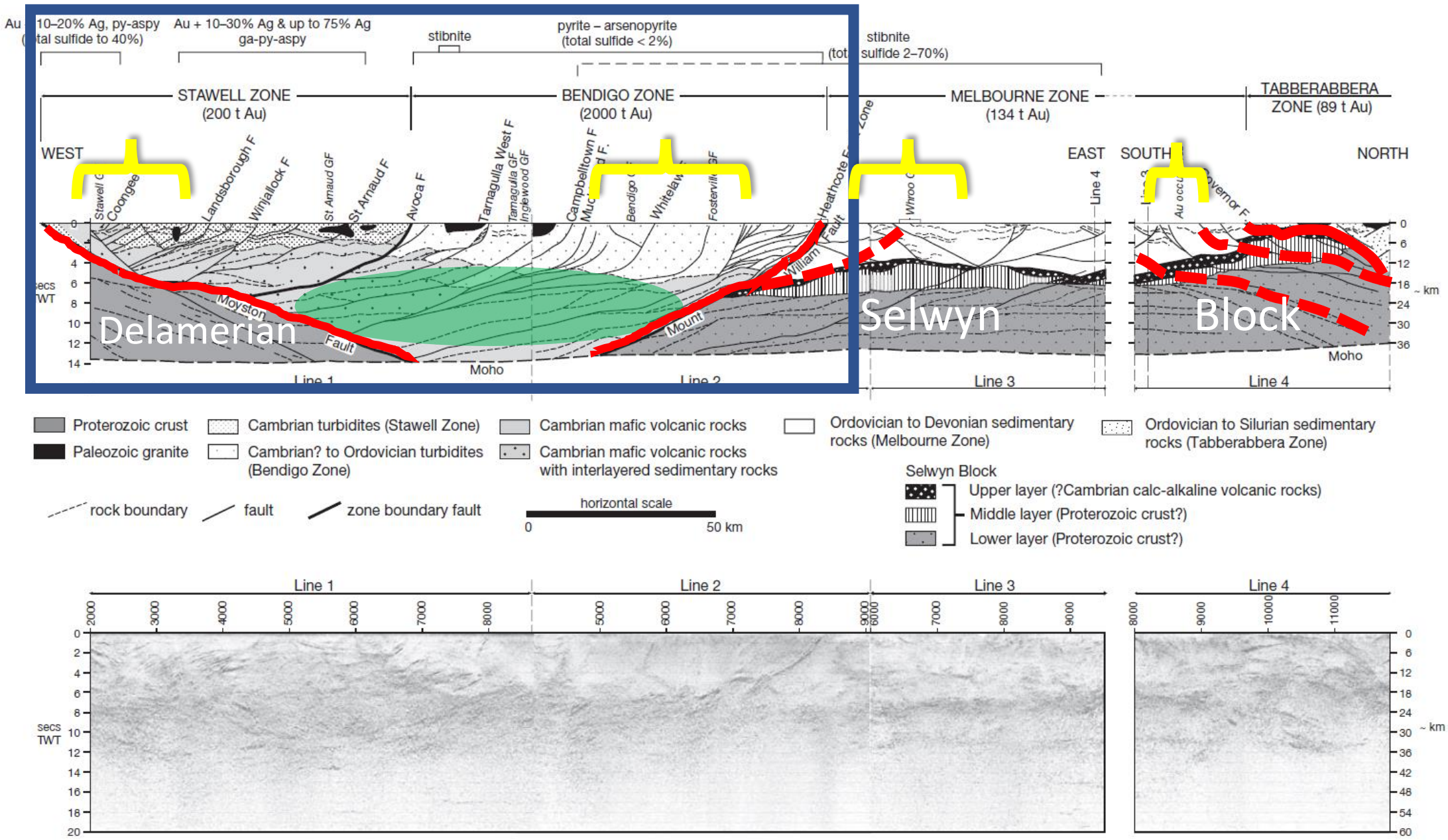




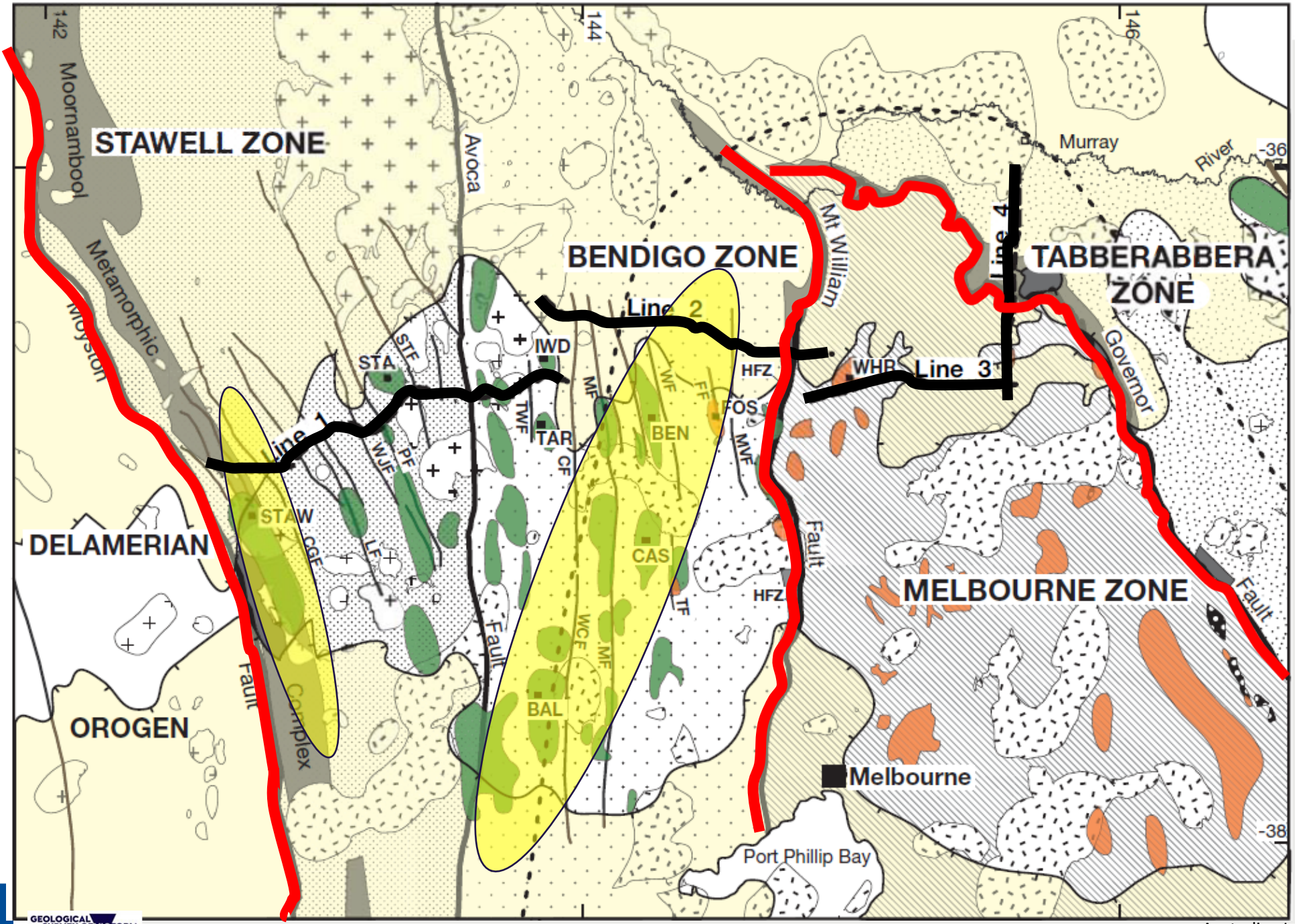


Line 06GA-V2 - interpretation

Cayley et al., 2011



Cayley et al., 2011

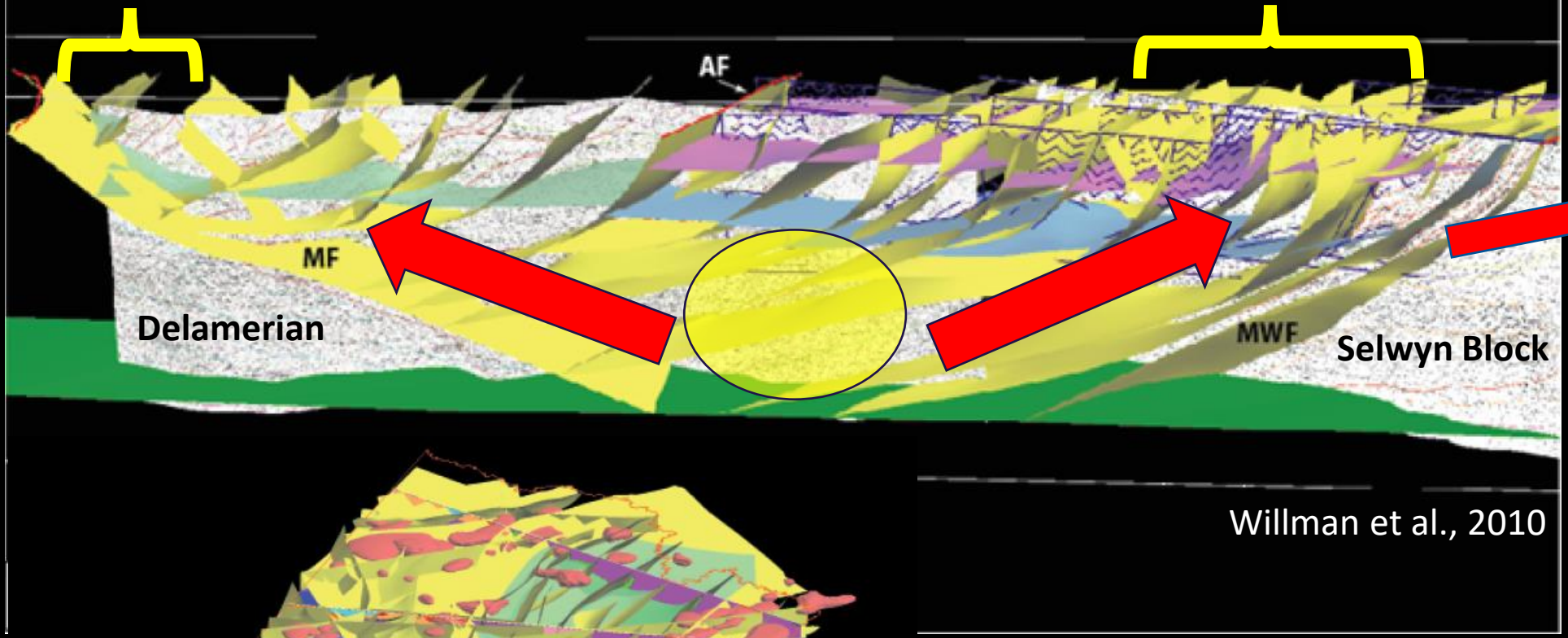


One hypothesis:

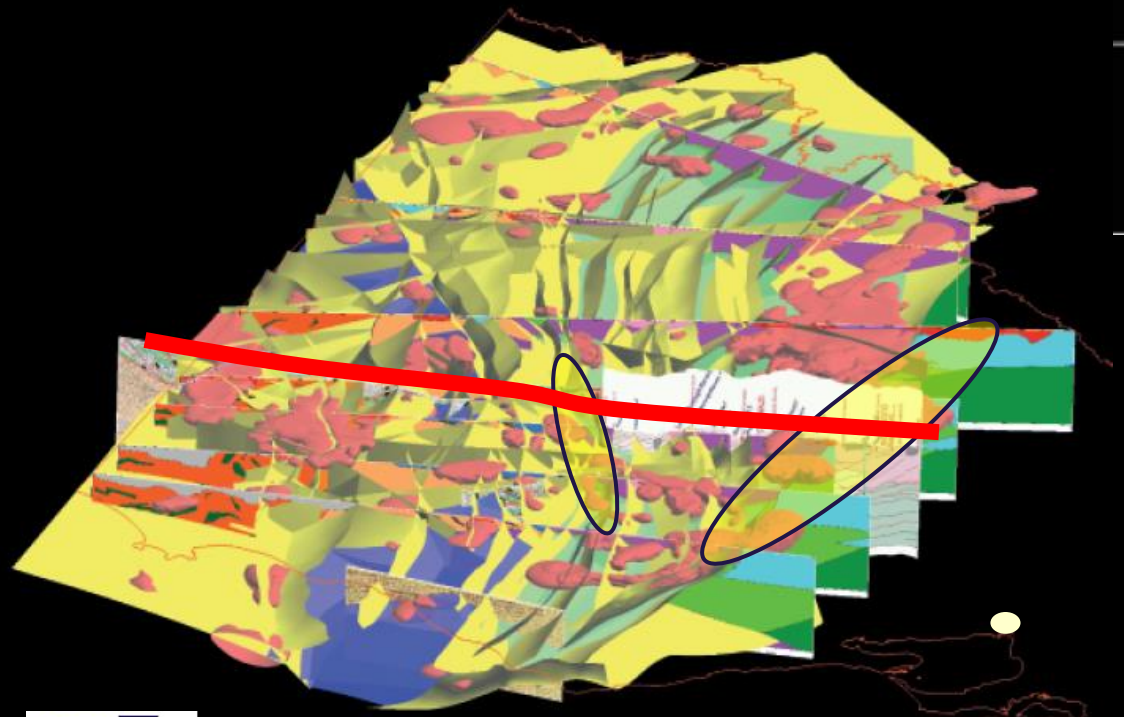
'Corridors' of gold prospectivity, aligned above the buried margins of the Selwyn Block and, further west, pre-Ordovician Gondwana

Stawell, Ararat

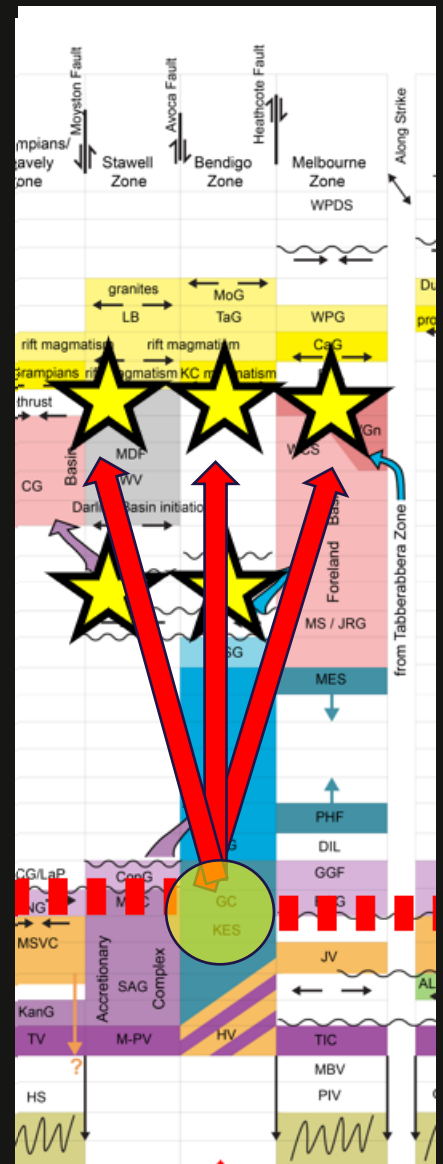
Bendigo, Fosterville

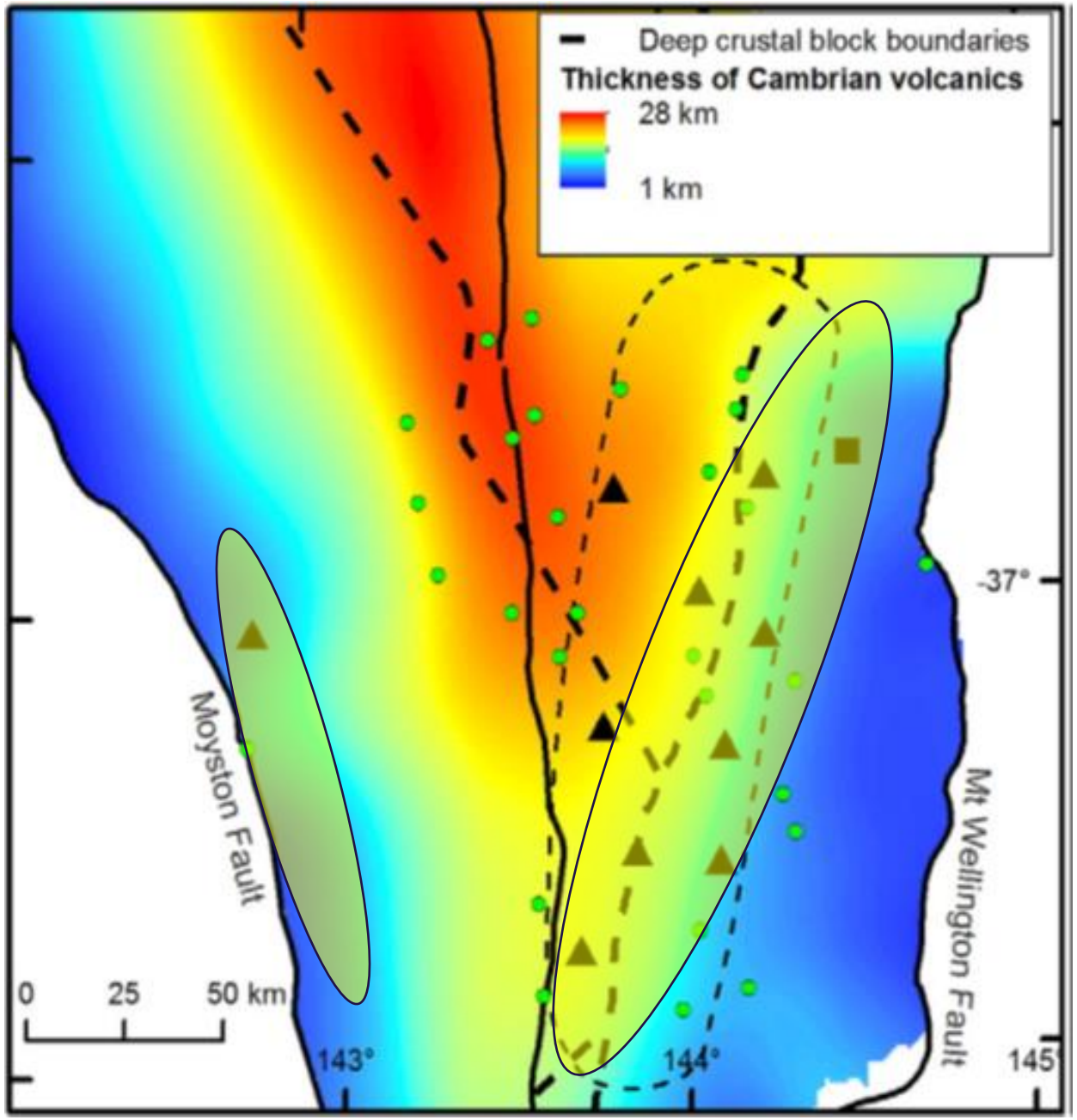


Willman et al., 2010



Rawling et al., 2011

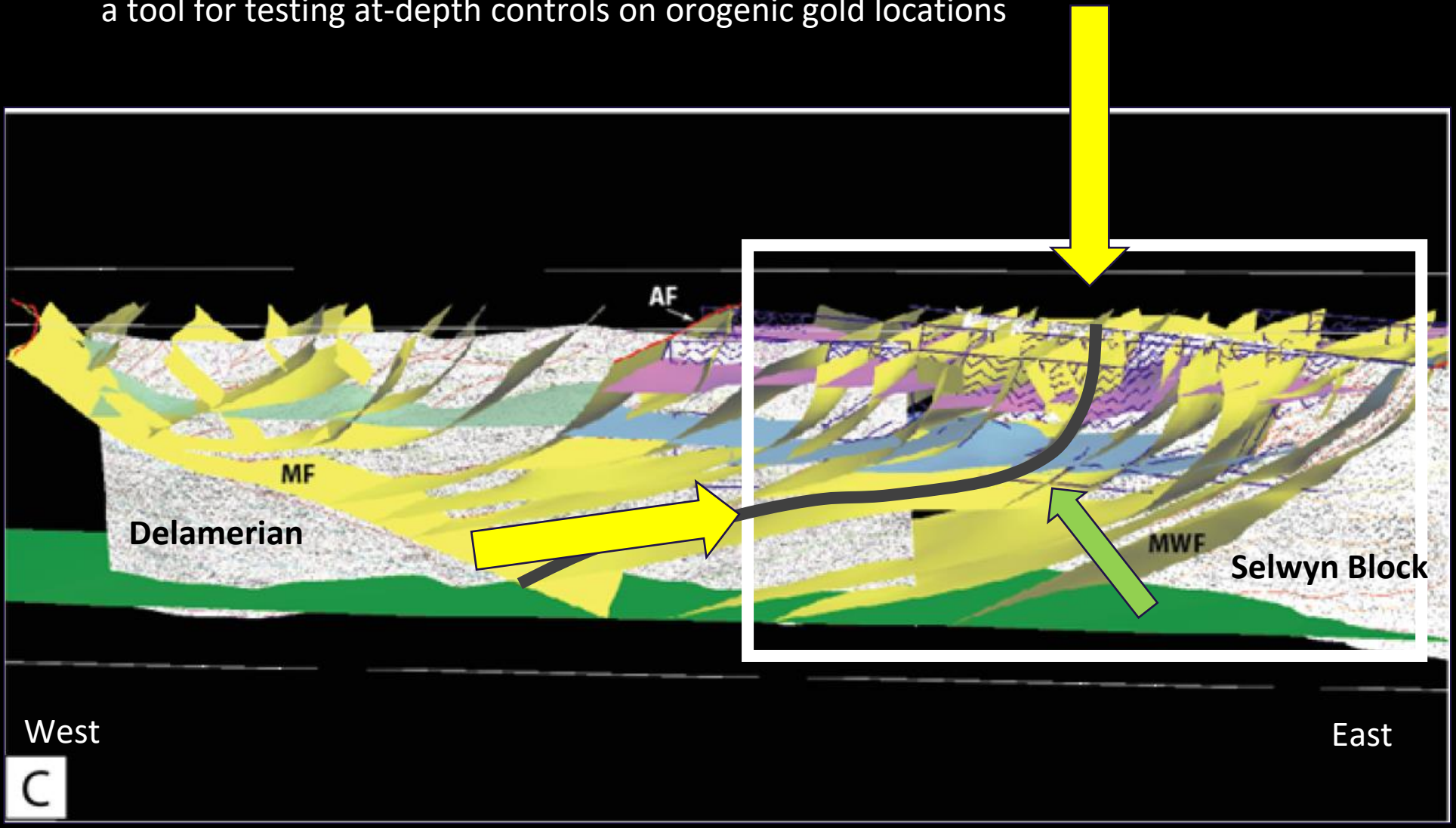


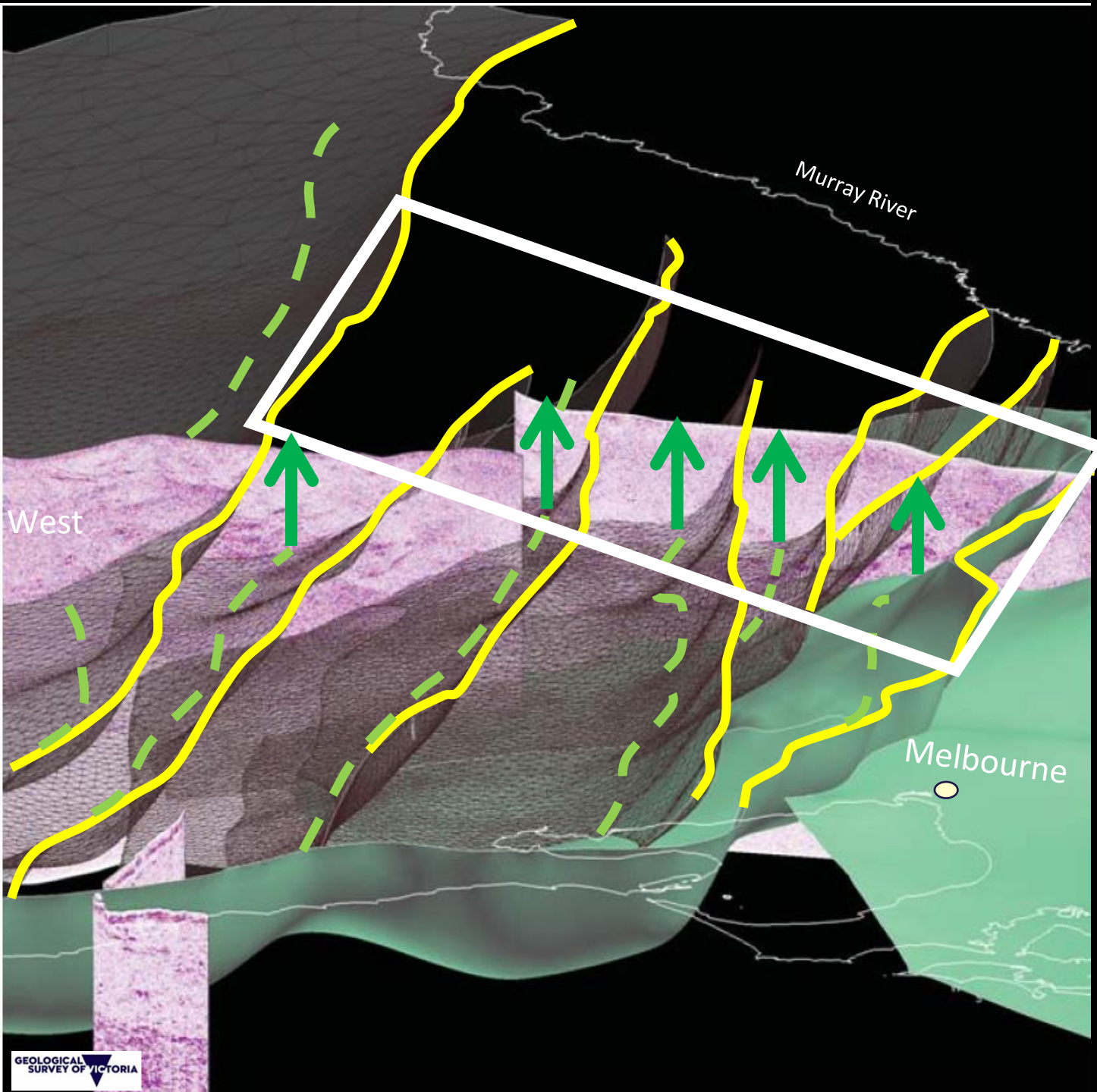


This model can explain the lateral Offsets between the regions of highest historical gold production (yellow ellipses), and the regions where gravity modelling suggests the most Cambrian mafic igneous crust occurs in the lower crust…..

Rawling et al., 2007 GSV 3D Vic

Full crustal section, Stawell and Bendigo zones –
a tool for testing at-depth controls on orogenic gold locations





Inflection-point mapping, using the Victorian crustal-scale 3-D model

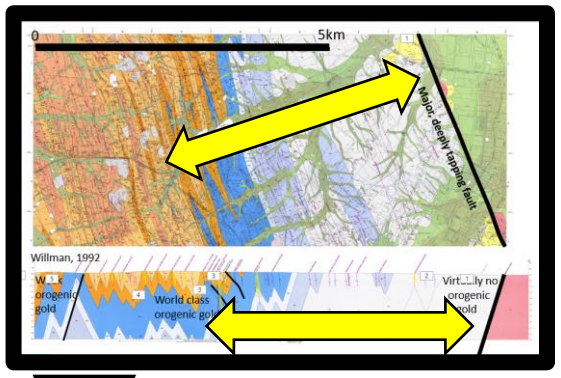
1500 metre buffer…..around mapped surface fault trace positions (yellow around red):
Captures 41% known Au deposits, 27% intermediate-large size Au deposits

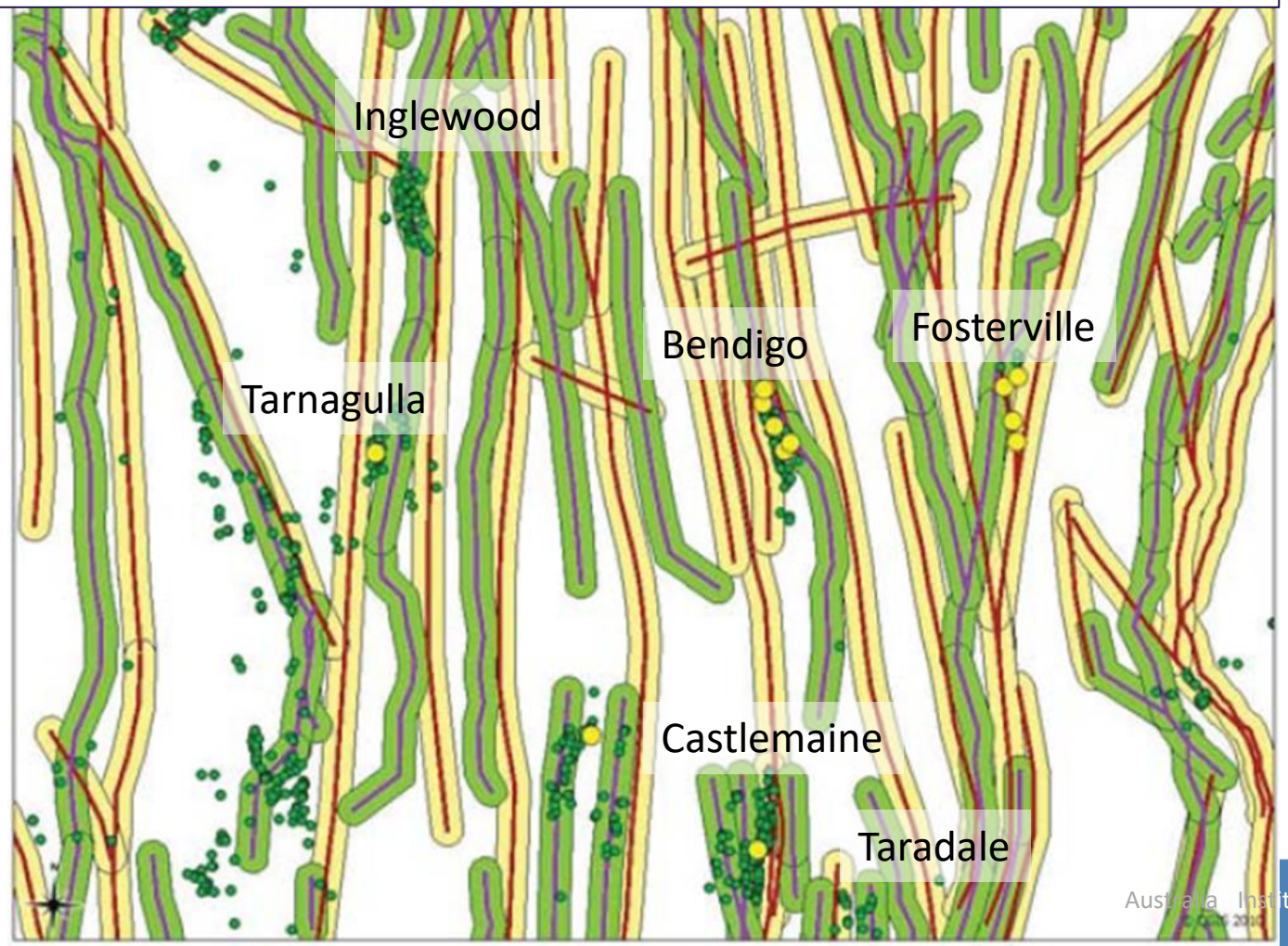
1500 metre buffer…around interpreted 3D model fault dip inflections projected to surface (green around purple): Captures 67% known Au deposits, 60% intermediate-large size Au deposits + 30% smaller buffer area

Fault dip inflection projections win as a predictor of significant goldfields locations!

Is **THIS** why its been so hard to understand the controls localising Victorian Orogenic Gold at goldfield scale?

A key control is 15km down!





calibrating hypotheses against known goldfield distribution

Rawling et al., 2011

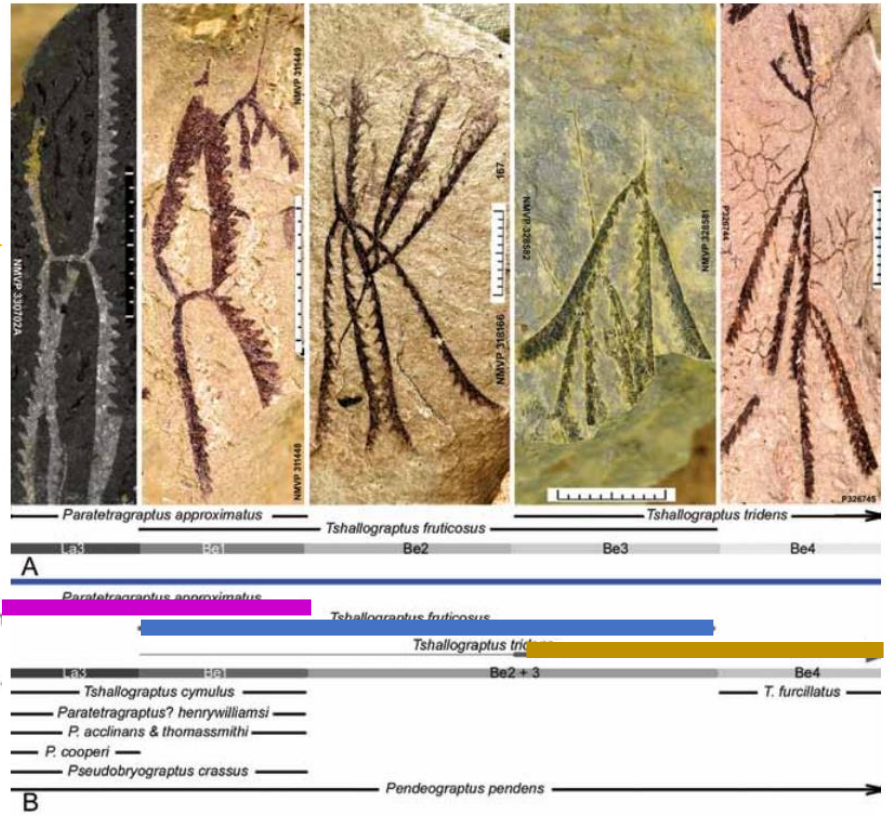
Once calibrated, large mappable fault positions CAN be used to predict the offset locations of orogenic gold deposits!

Including undercover (Tandara, Four Eagles!)

VICTORIA State Government Australia

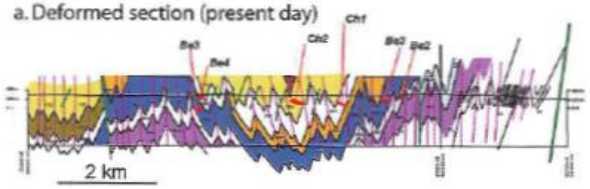
Talk outline

- Geological setting for Victorian orogenic (and intrusion related) gold
- Competing tectonic models for the Early Palaeozoic – confusing for gold explorers
- Structural / stratigraphic mapping + potential field geophysics: powerful tools…
- …but Deep Seismic Reflection data drives systems-scale understanding
- Application to mineral systems models at crustal scale…
- **Constrained retrodeformation scenarios – critical to take geological systems analysis from crustal scale to lithospheric scale**
- Towards a Unifying Theory for Eastern Australian Early Palaeozoic geology and mineral systems
- Wrapping up



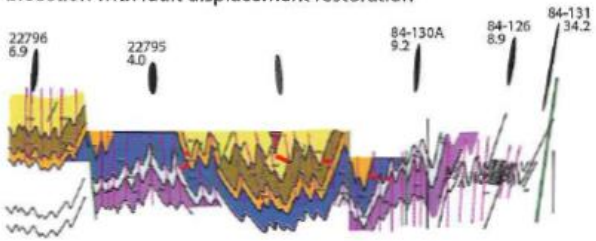
STRAIN REVERSAL (RETRODEFORMATION) OF THE BENDIGO SECTION

a. Deformed section (present day)

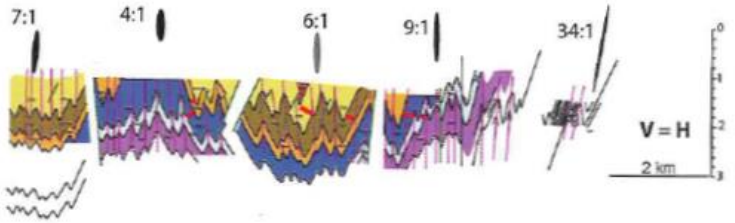


e. stratigraphic thicknesses from retrodeformed section

b. section with fault displacement restoration

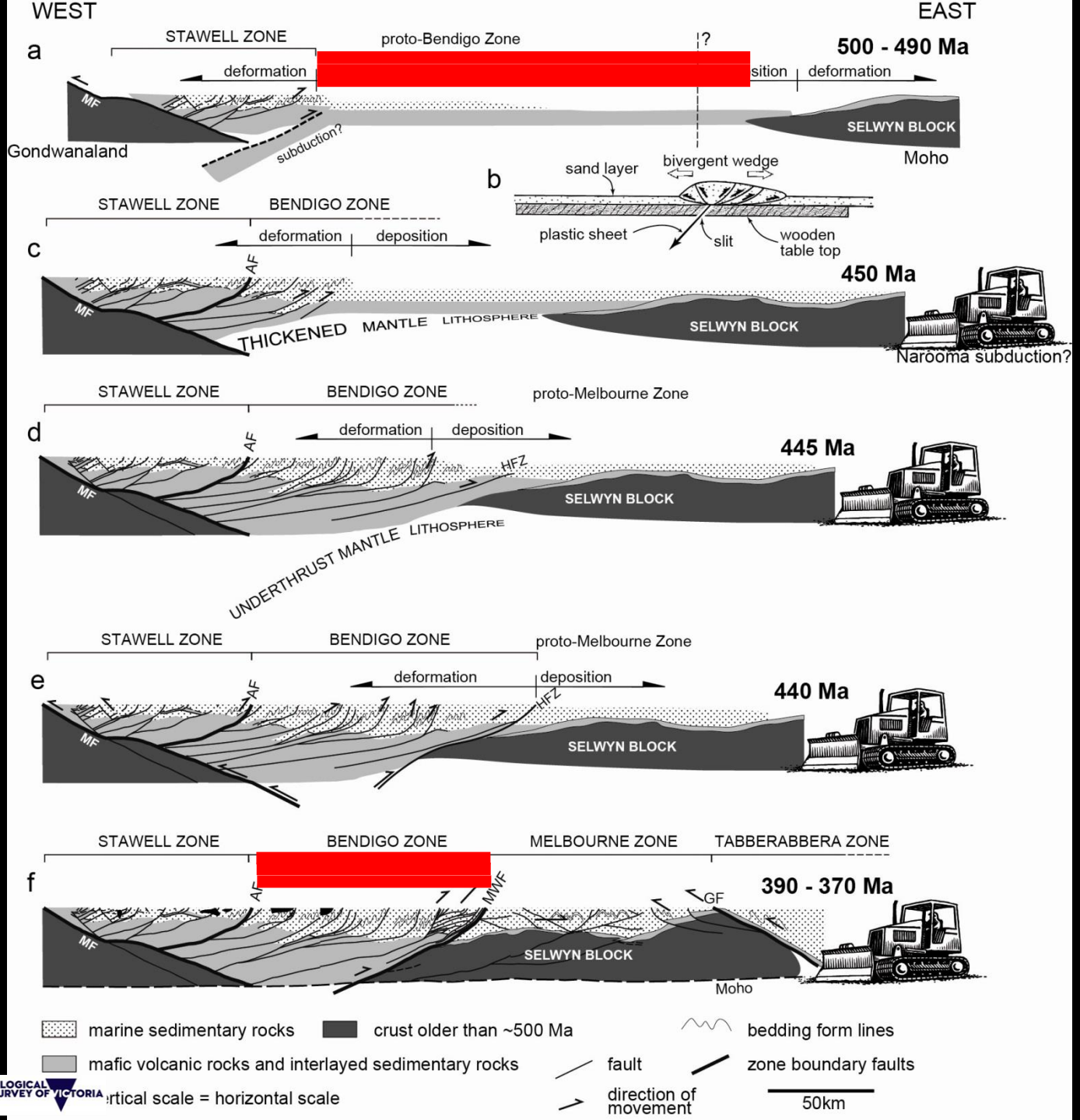


c. profile segments and "average" strain for unstraining

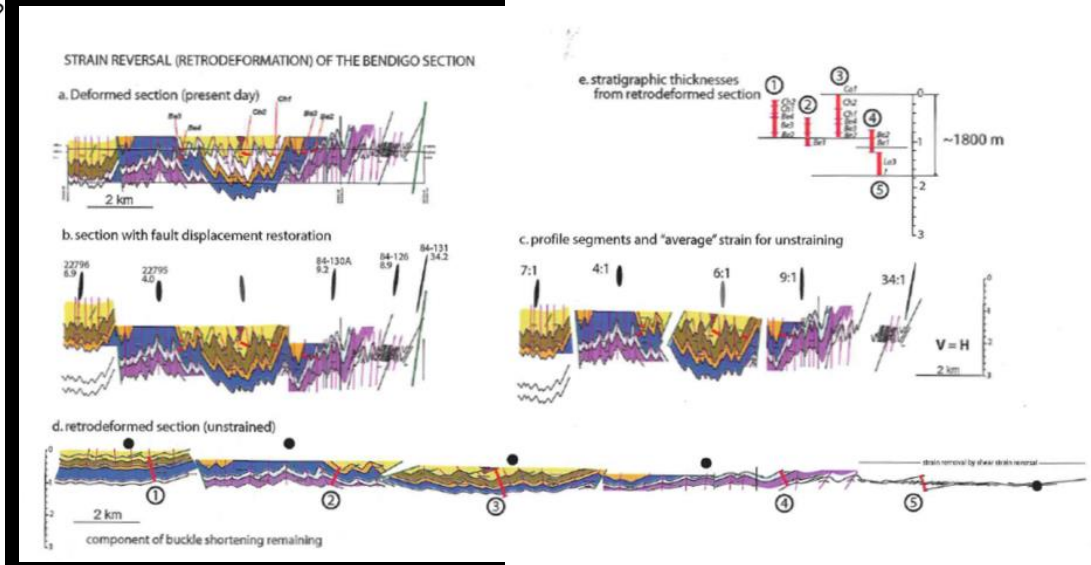


eg VandenBerg, 2017

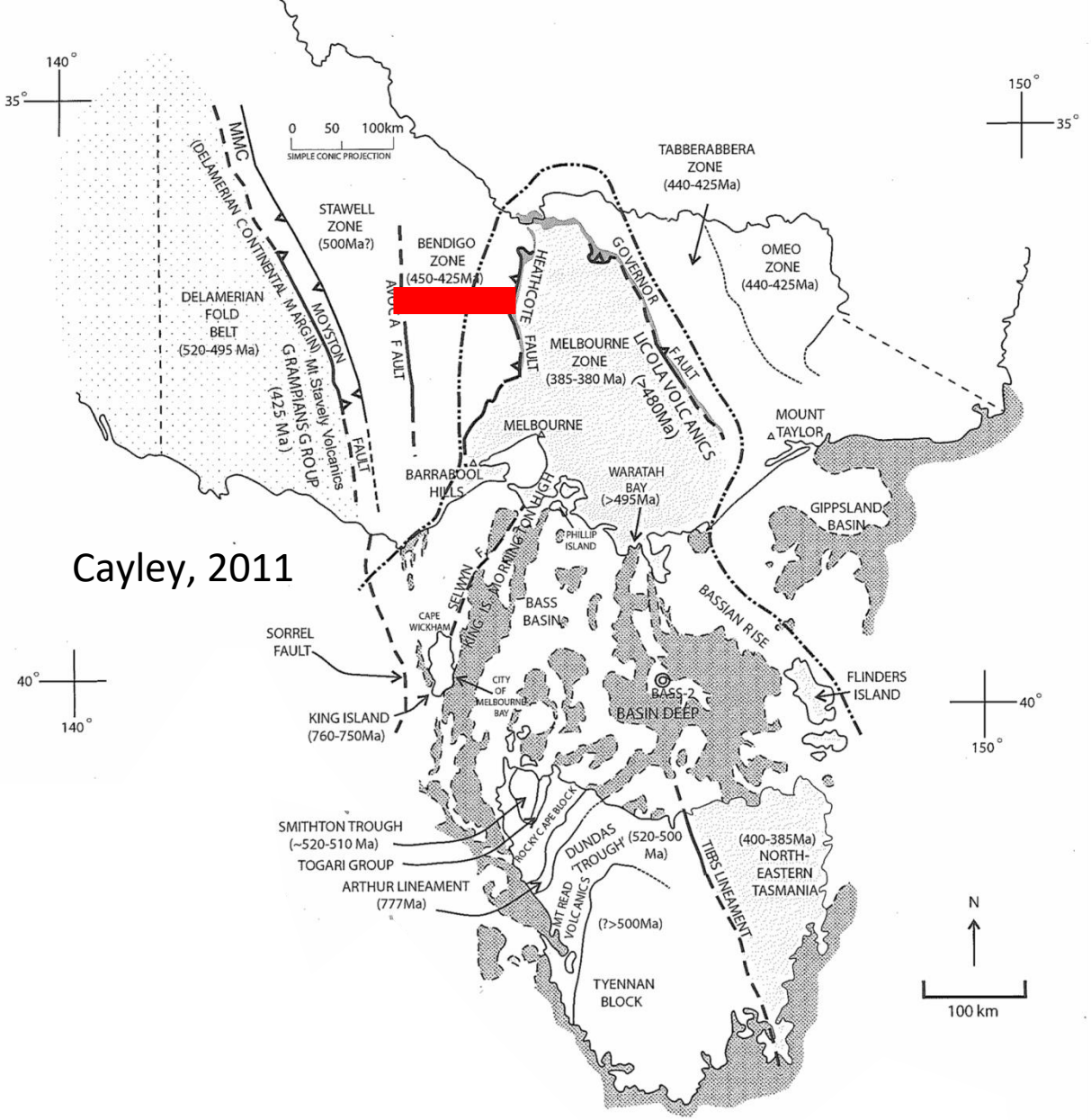
(Gray et al., 2006: restoration of Victoria's uppermost crust)



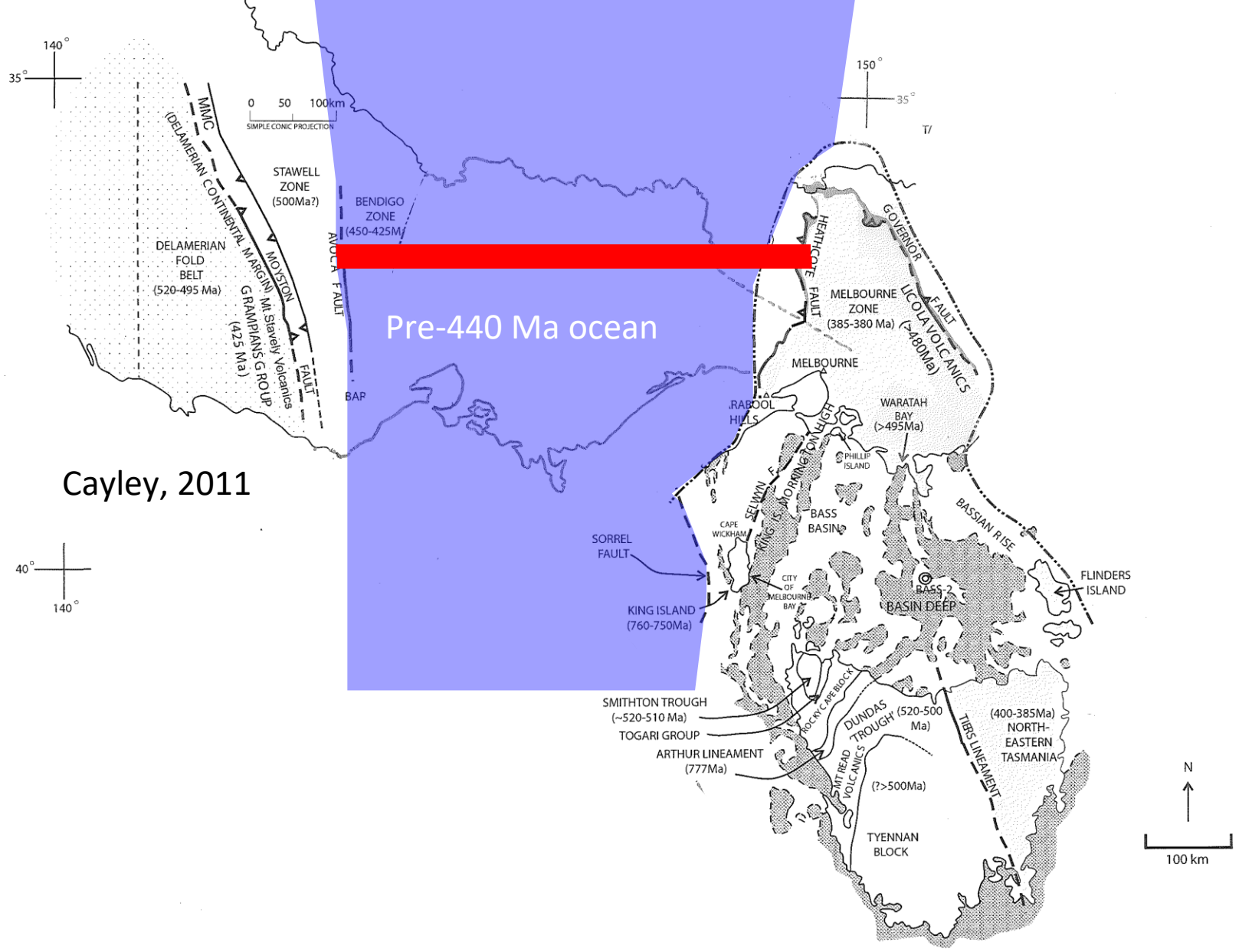
Cayley et al., 2011



Gray et al, 2006


140°
35°
0 50 100km
SIMPLE CONIC PROJECTION
MMC
(DELAMERIAN CONTINENTAL MARGIN)
DELAMERIAN FOLD BELT (520-495 Ma)
MOYSTON FAULT
GRAMPIANS GROUP (425 Ma)
Mt Stavely Volcanics
STAWELL ZONE (500Ma?)
BENDIGO ZONE (450-425Ma)
ANUA F AULT
HEATHCOTE FAULT
GOVERNOR FAULT
TABBERABBERA ZONE (440-425Ma)
OMEO ZONE (440-425Ma)
MELBOURNE ZONE (385-380 Ma)
LICOLA VOLCANICS (>480Ma)
MELBOURNE
MOUNT TAYLOR
BARRABOOL HILLS
WARATAH BAY (>495Ma)
GIPPSLAND BASIN
PHILLIP ISLAND
SELWYN F.
MORNINGTON HIGH
BASS BASIN
CAPE WICKHAM
KING I.
BASSIAN RISE
SORREL FAULT
CITY OF MELBOURNE BAY
BASS-2
BASIN DEEP
FLINDERS ISLAND
KING ISLAND (760-750Ma)
SMITHTON TROUGH (~520-510 Ma)
TOGARI GROUP
ARTHUR LINEAMENT (777Ma)
ROCKY CAPE BLOCK
DUNDAS TROUGH (520-500 Ma)
TIBRS LINEAMENT
(400-385Ma) NORTH-EASTERN TASMANIA
MT READ VOLCANICS
(?>500Ma)
TYENNAN BLOCK
150°
35°
40°
140°
40°
150°
N
100 km

Cayley, 2011


Pre-440 Ma ocean
Cayley, 2011
140°
35°
0 50 100km
SIMPLE CONIC PROJECTION
MMC
(DELAMERIAN CONTINENTAL MARGIN)
STAWELL ZONE (500Ma?)
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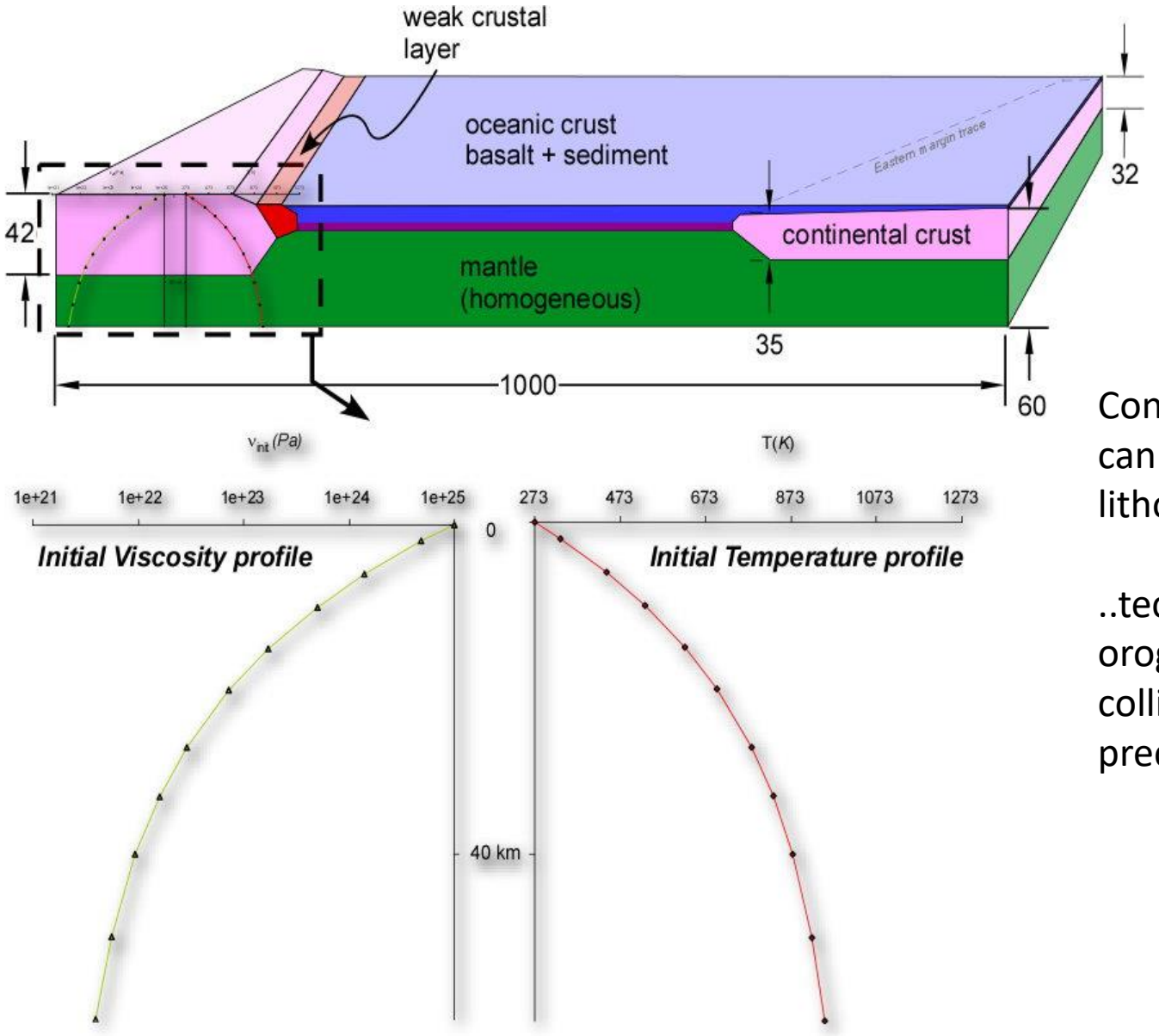
TIERS LINEAMENT
(400-385Ma) NORTH-EASTERN TASMANIA
MT READ VOLCANICS
(?>500Ma)
TYENNAN BLOCK
40°
140°
N
100 km

Gale simulations of basin closure (continental collision)

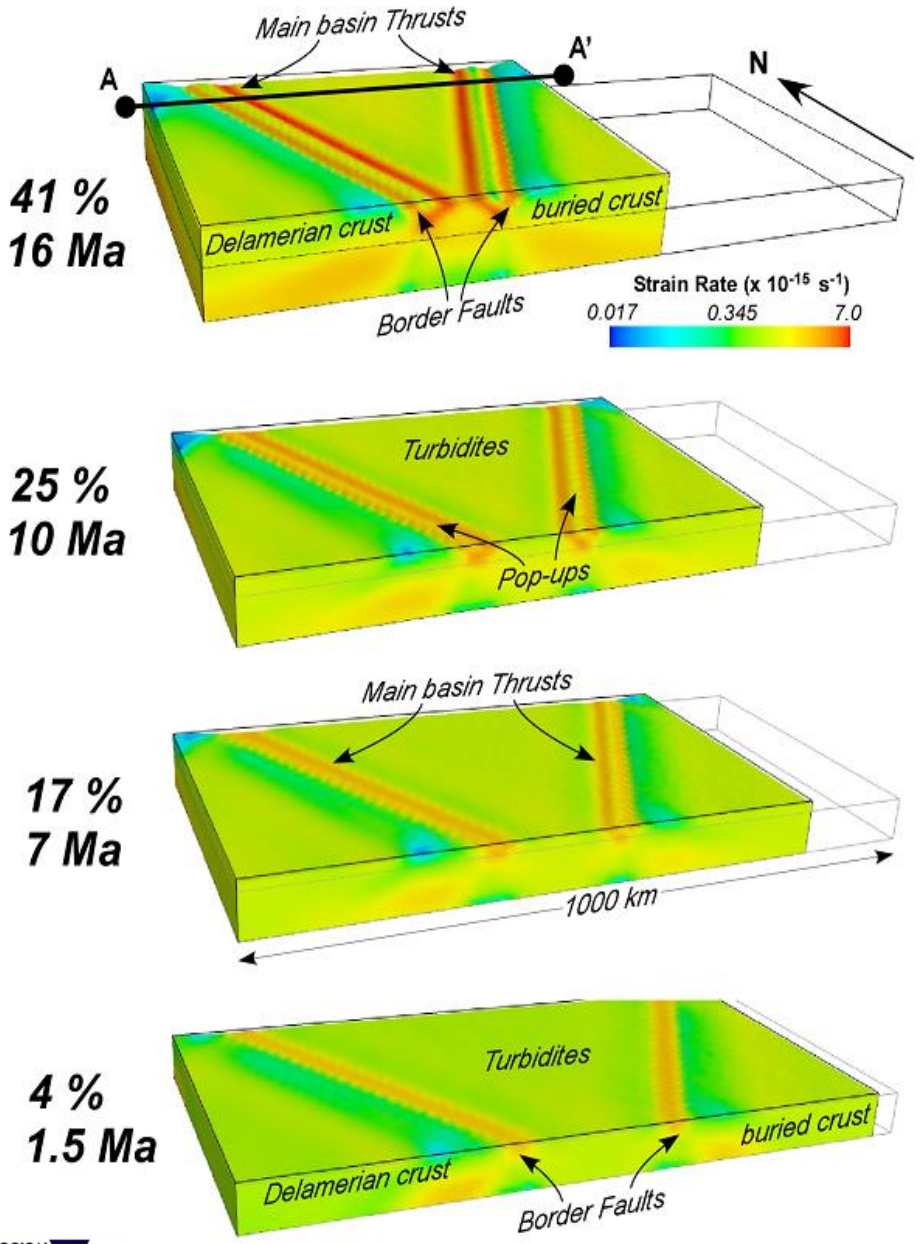


Constrained crustal-scale retrodeformations can give geometrical start-points for lithospheric-scale modelling of…

..tectonic scenarios that potentially formed orogenic-gold –laden continental crust from collisional thickening of an oceanic crust precursor (ie: no local crust subduction)

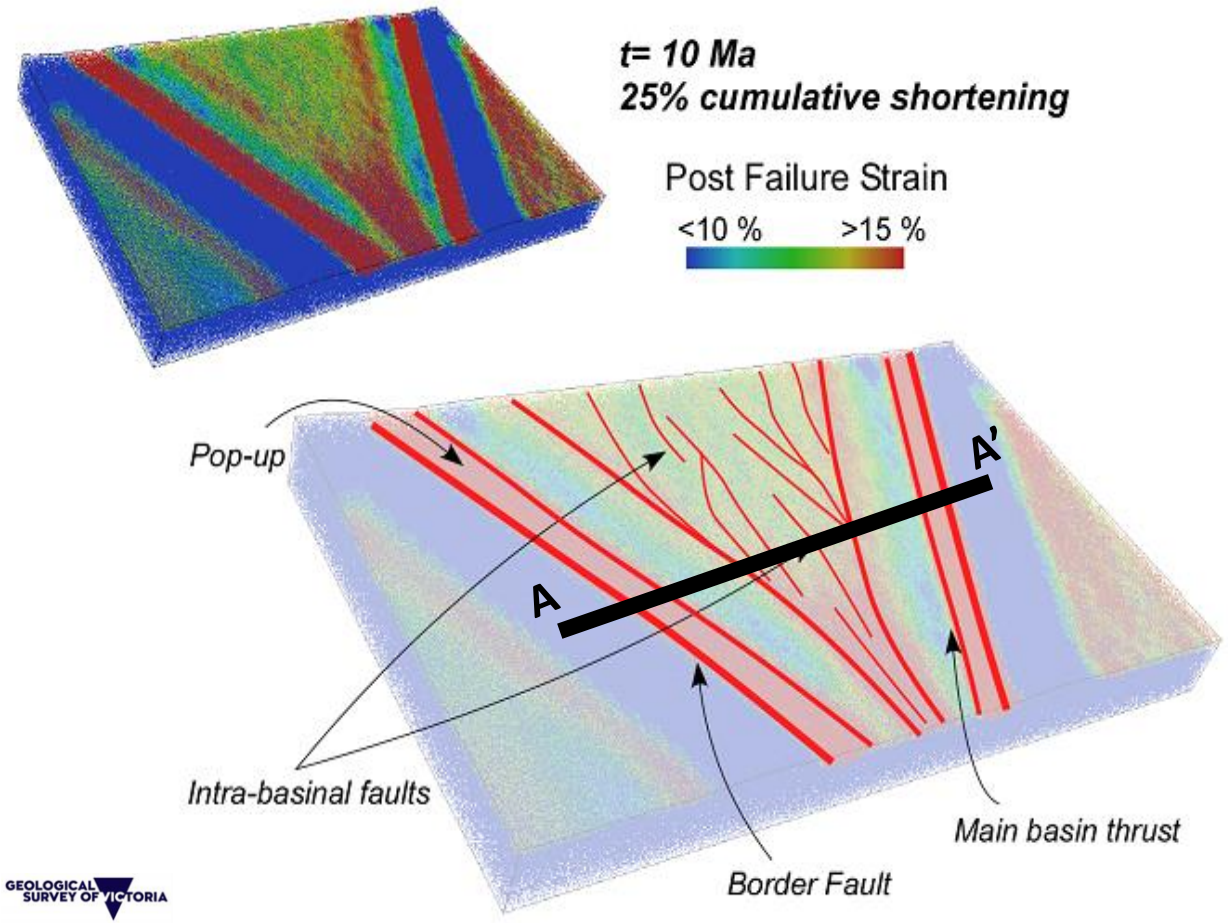
Gale simulations carried out by Guillaume Duclaux – CSIRO

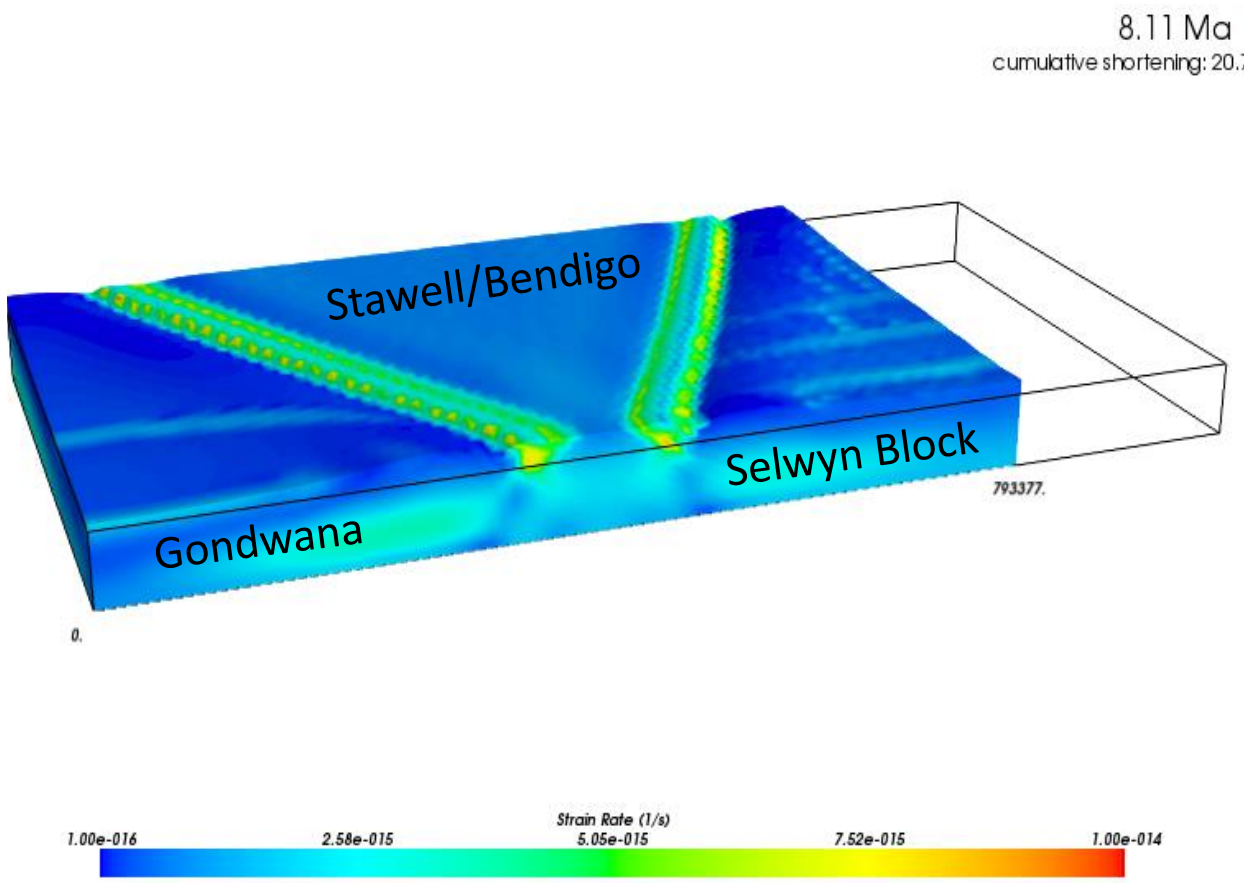
Gale simulations of basin closure



- Initial formation of basin-dipping bounding faults
- Moyston F., Heathcote F.
- Subsequent development of back thrusts
- High strain zones within the basin

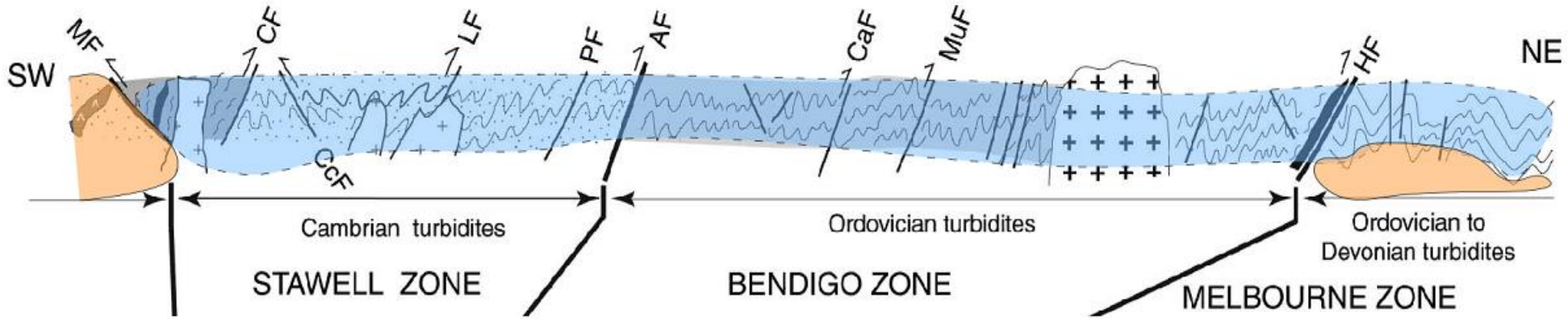
Recreates large bounding faults….
and a network of internal faults reminiscent of what is observed
in map-view in the Stawell and Bendigo zones

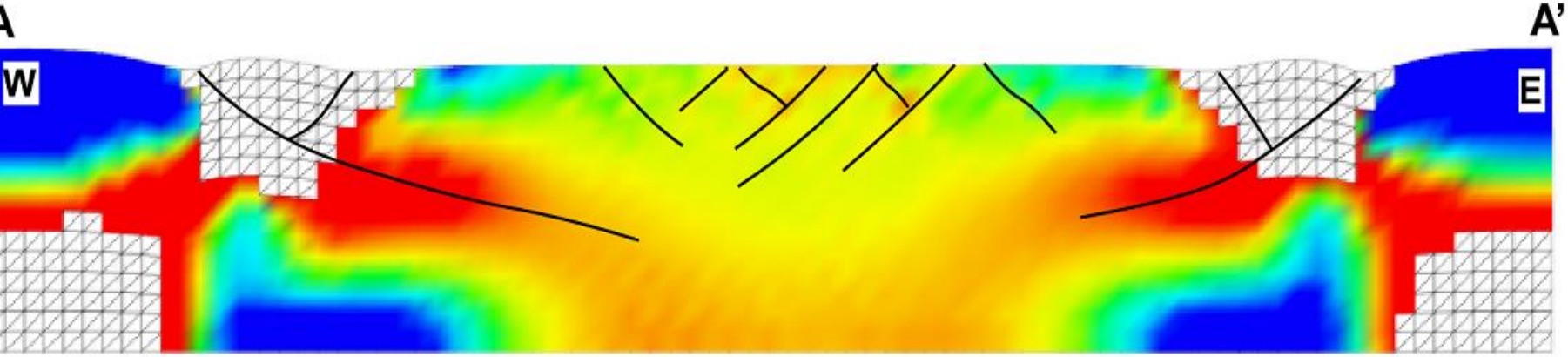




See: Rawling et al., 2011

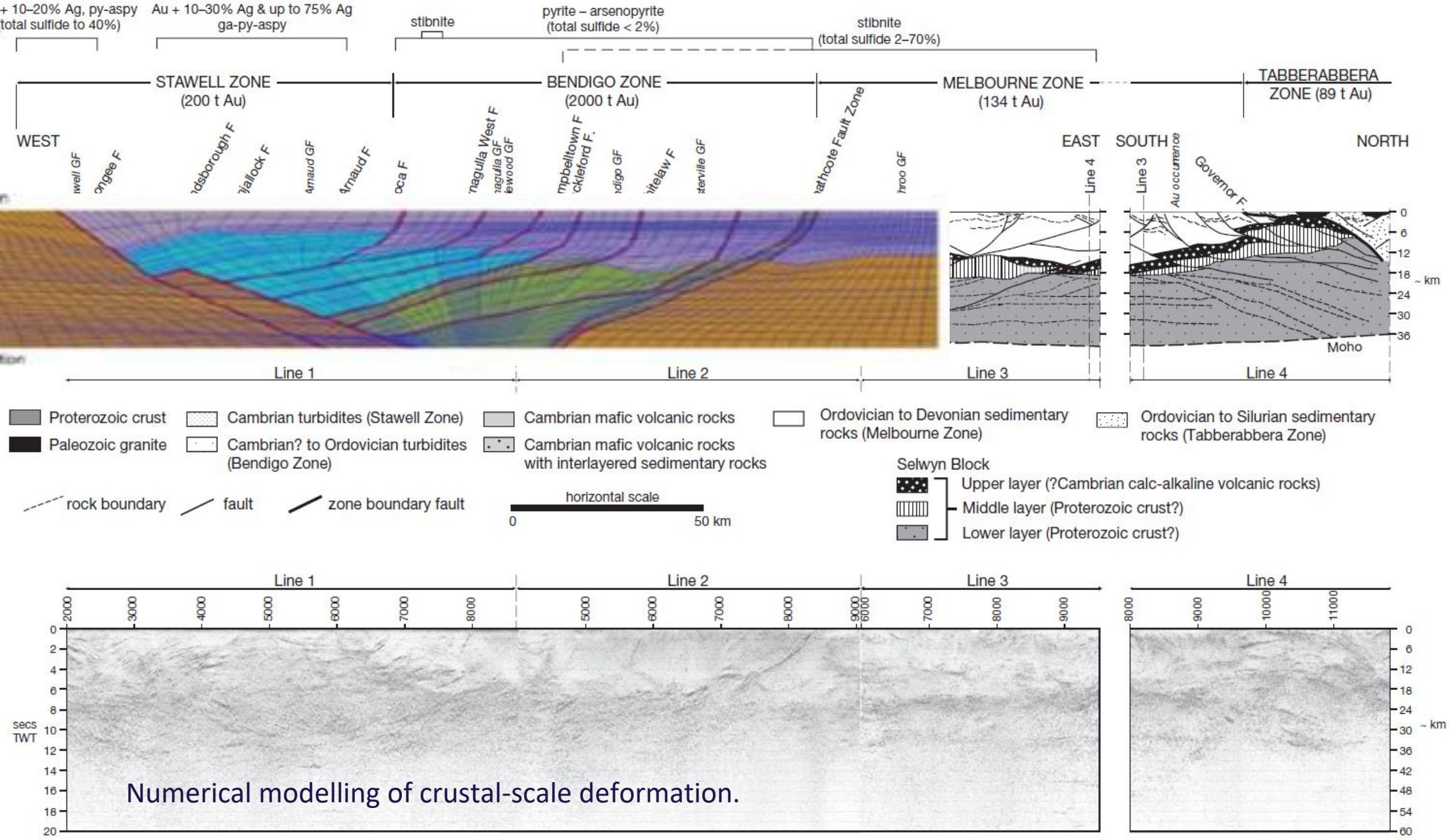
…and reminiscent of what is observed
in cross-section in the Stawell and Bendigo zones…..





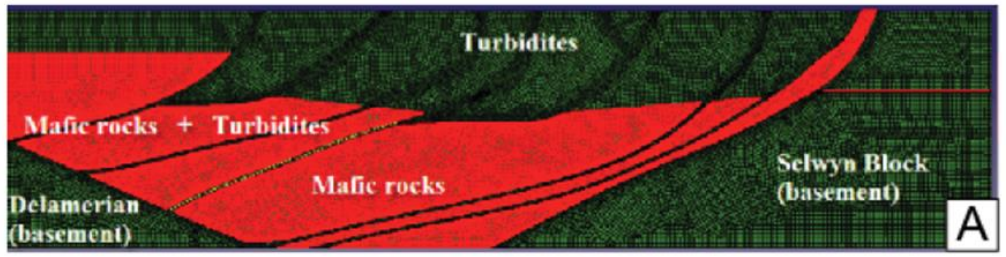
See: Rawling et al., 2011

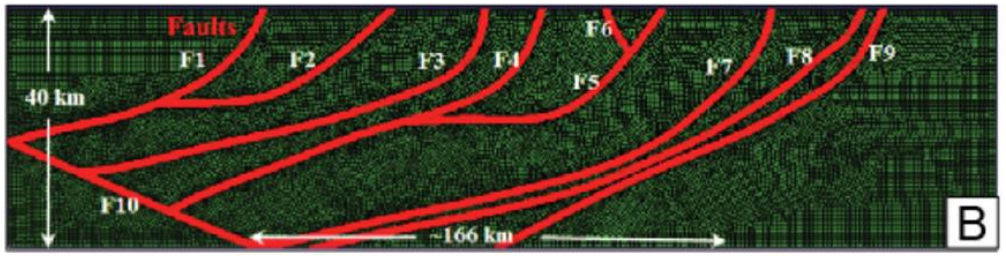
As these models are refined, improved predictive capacity for orogenic gold is sure to follow…..

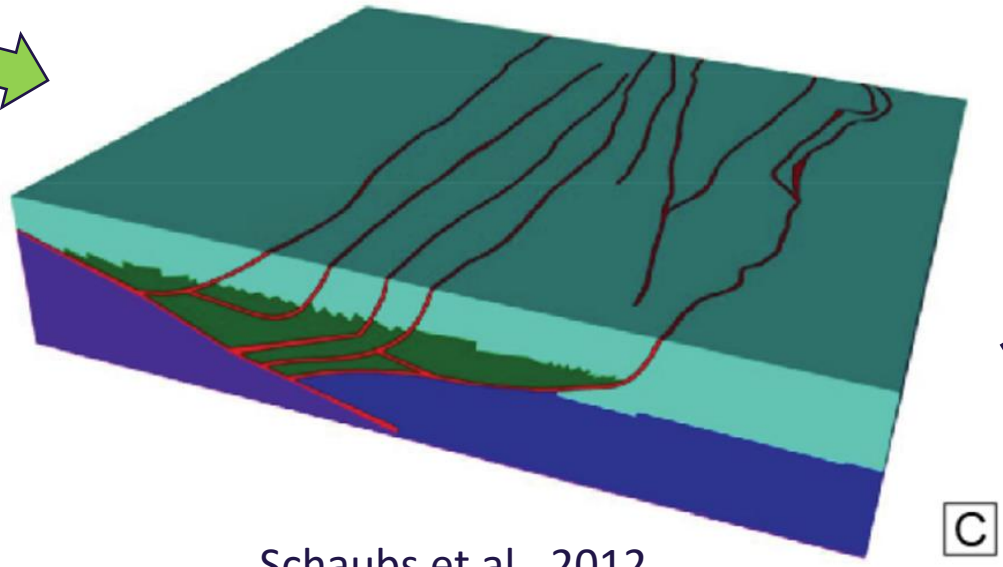


Numerical modelling of crustal-scale deformation.

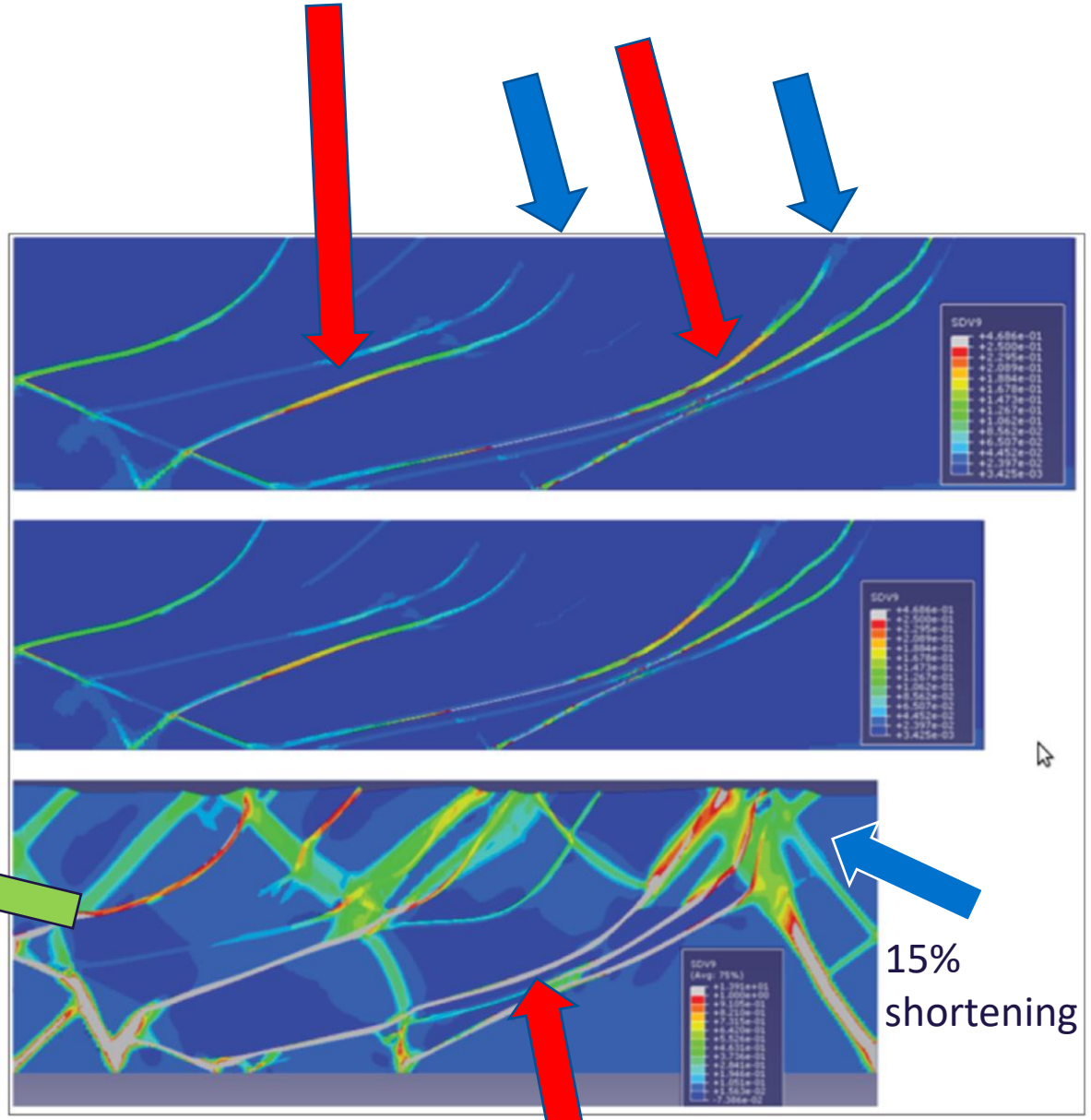
Eg. Leader & Wilson, 2010, Cayley et al., 2011







Schaubs et al., 2012



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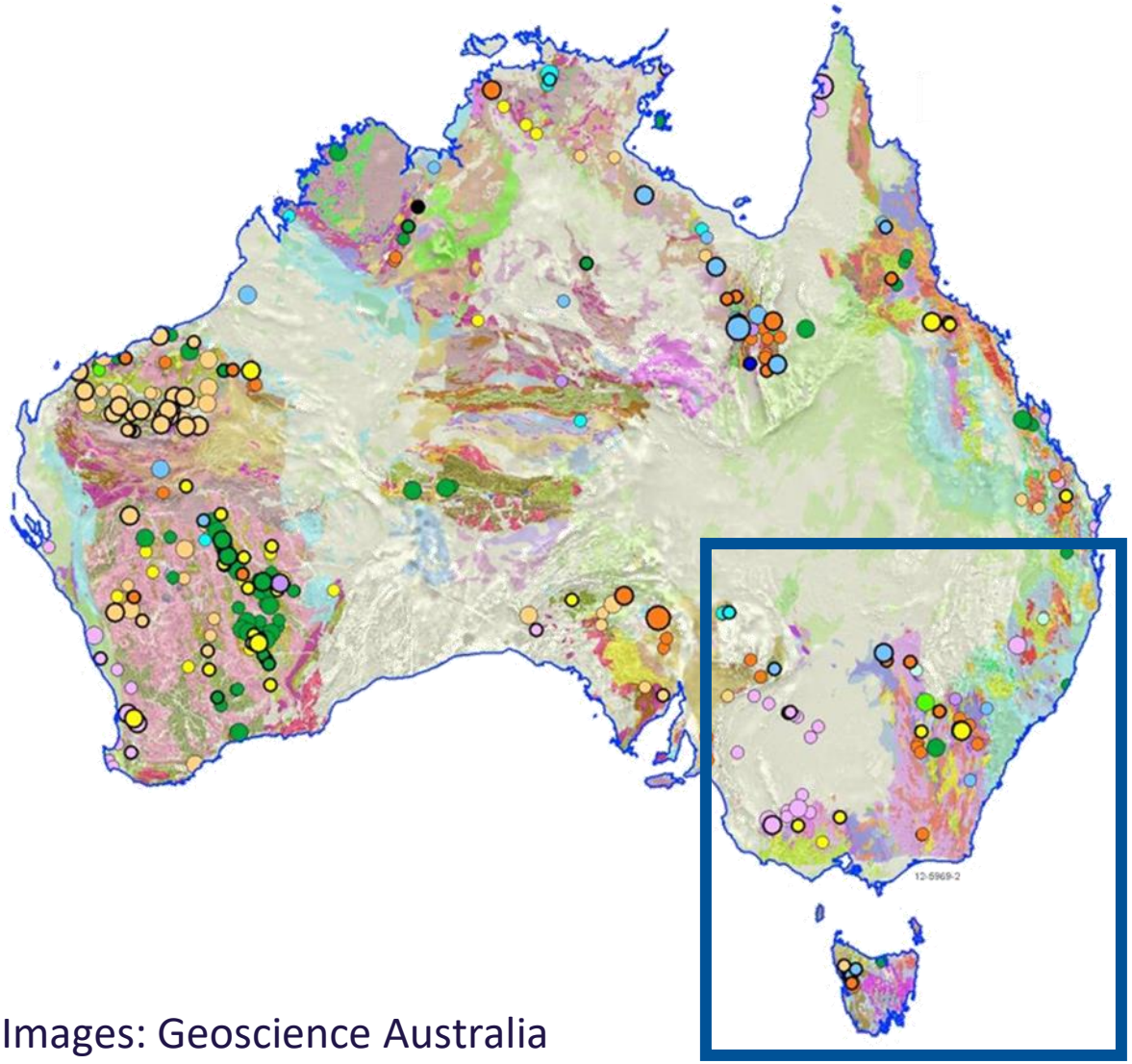
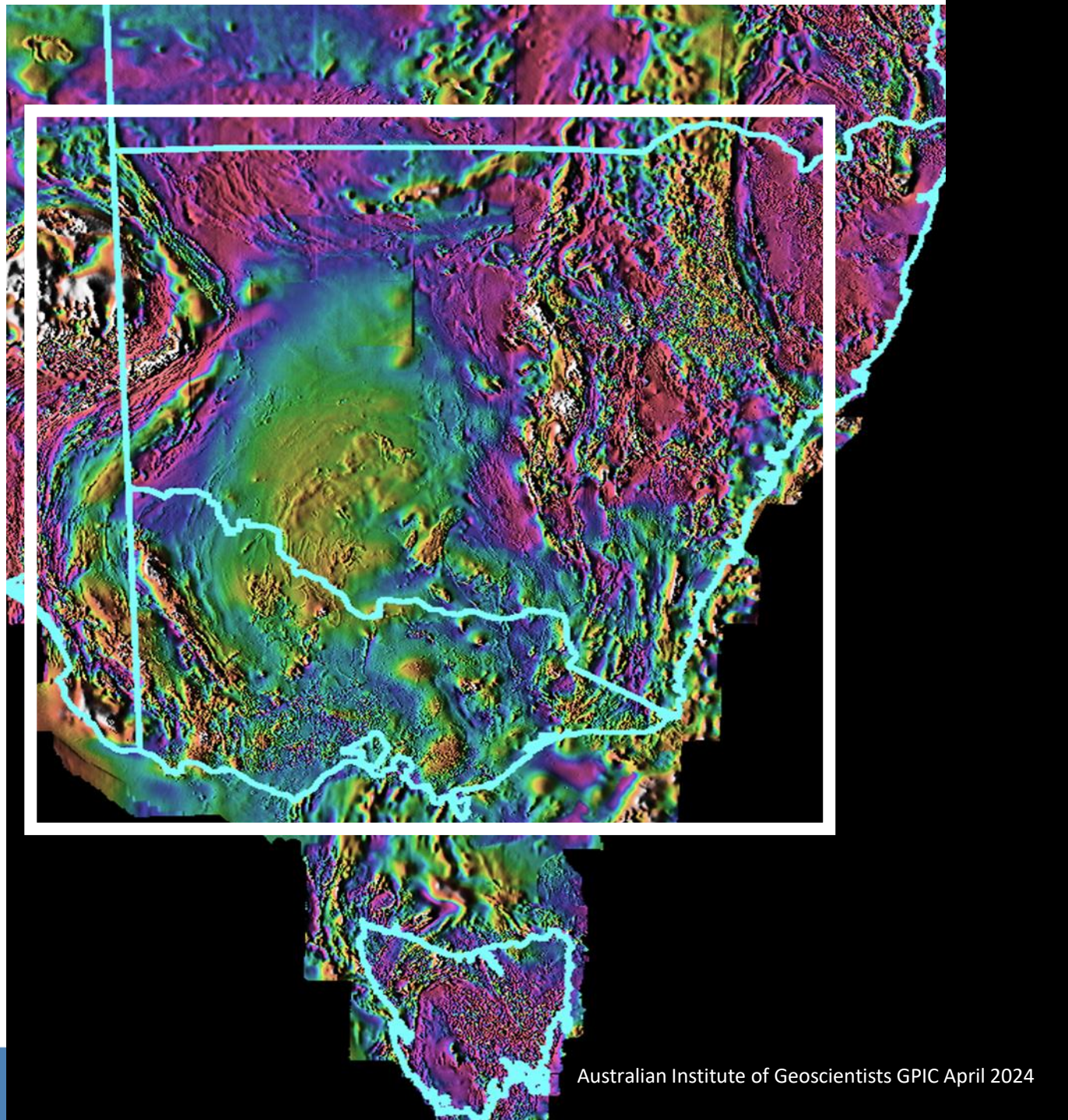
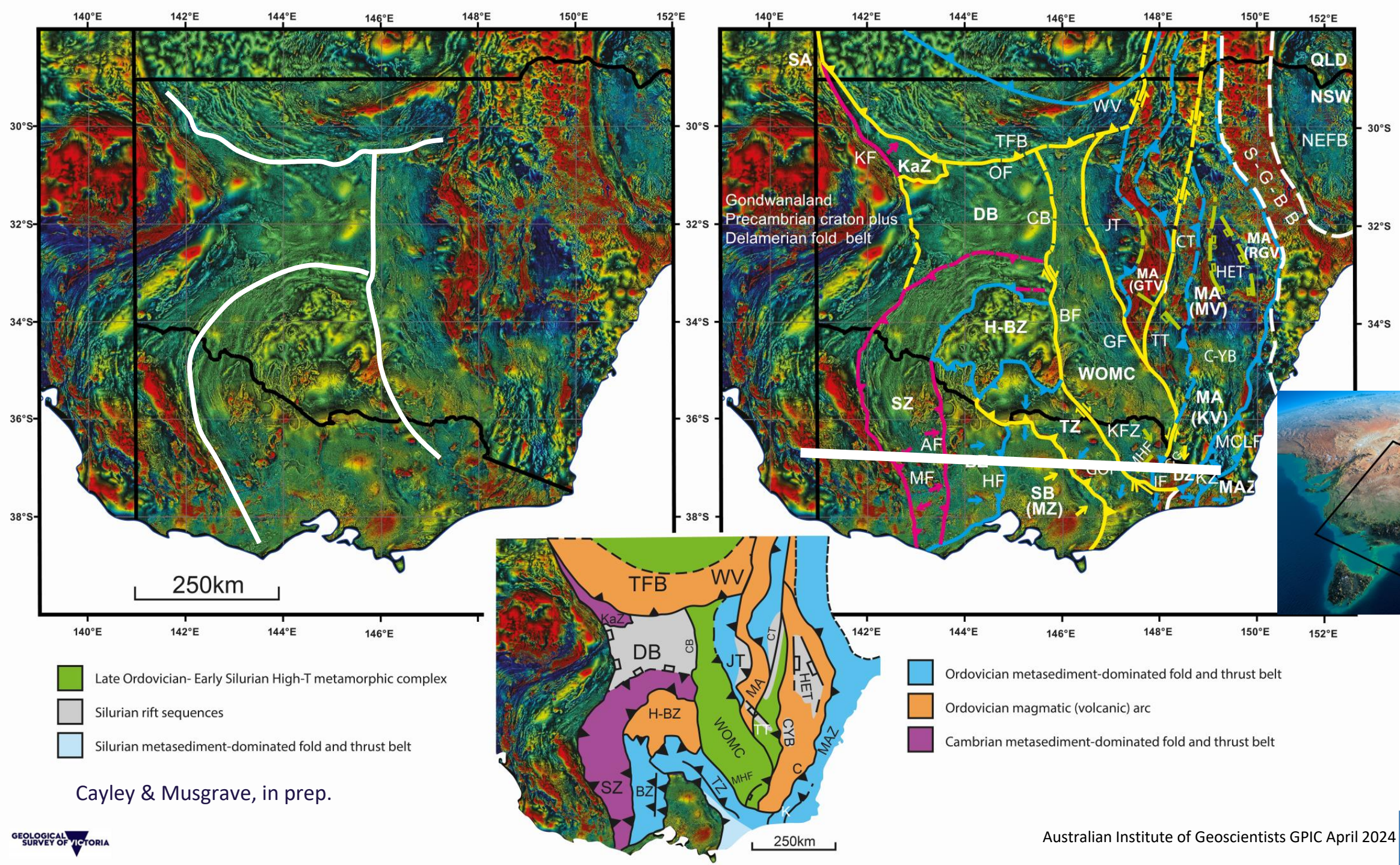
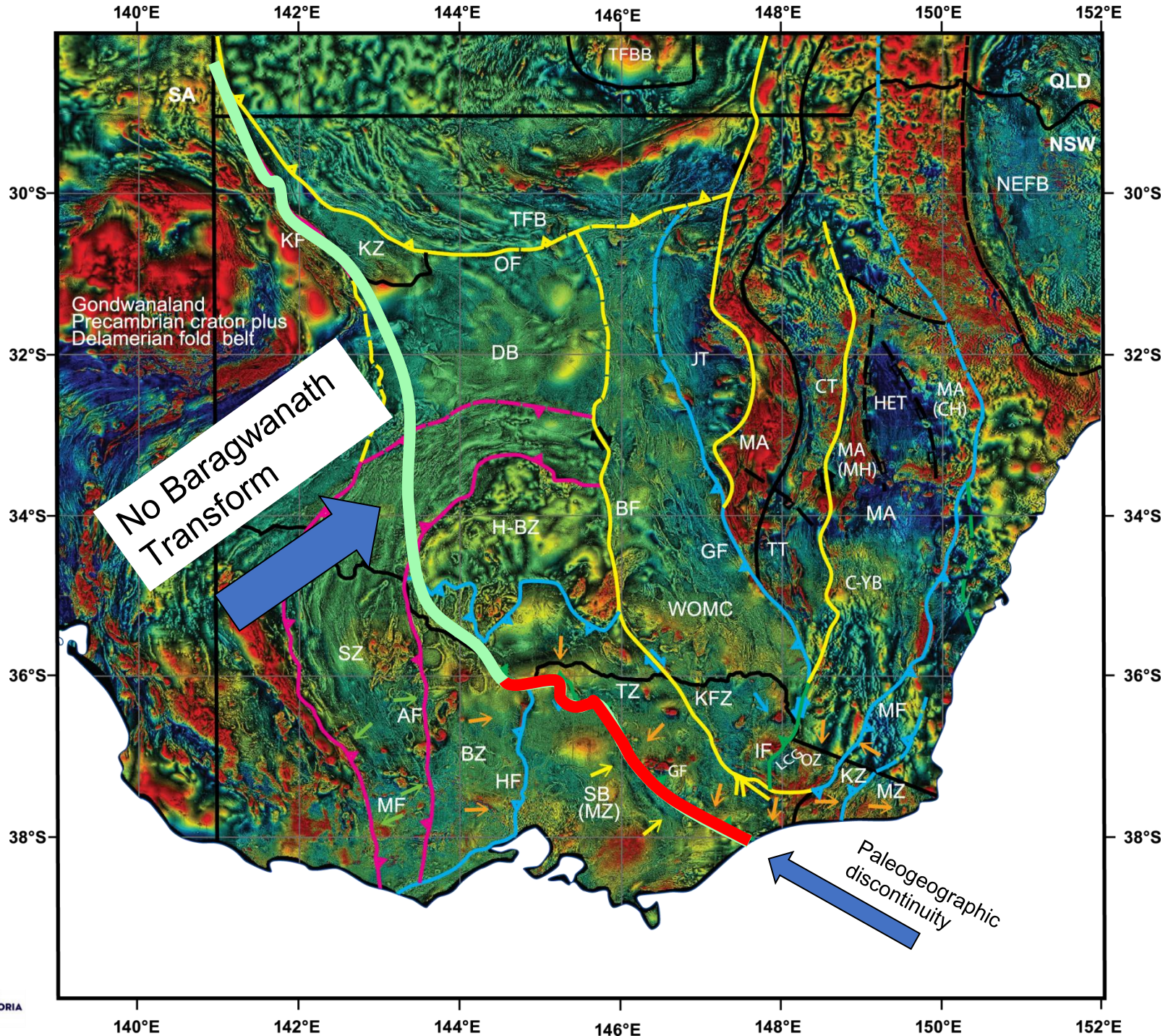


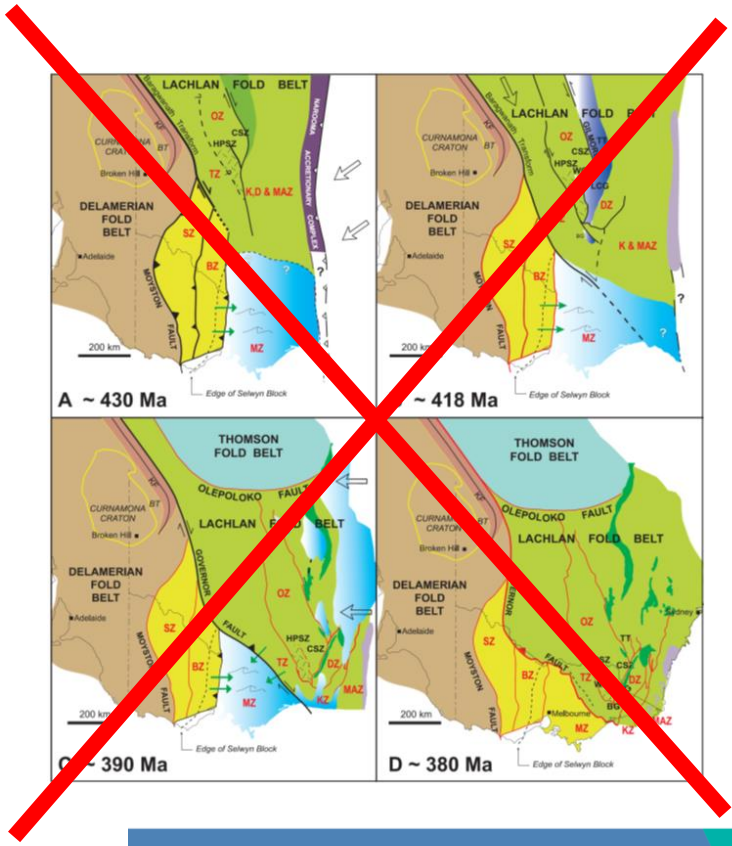
Images: Geoscience Australia

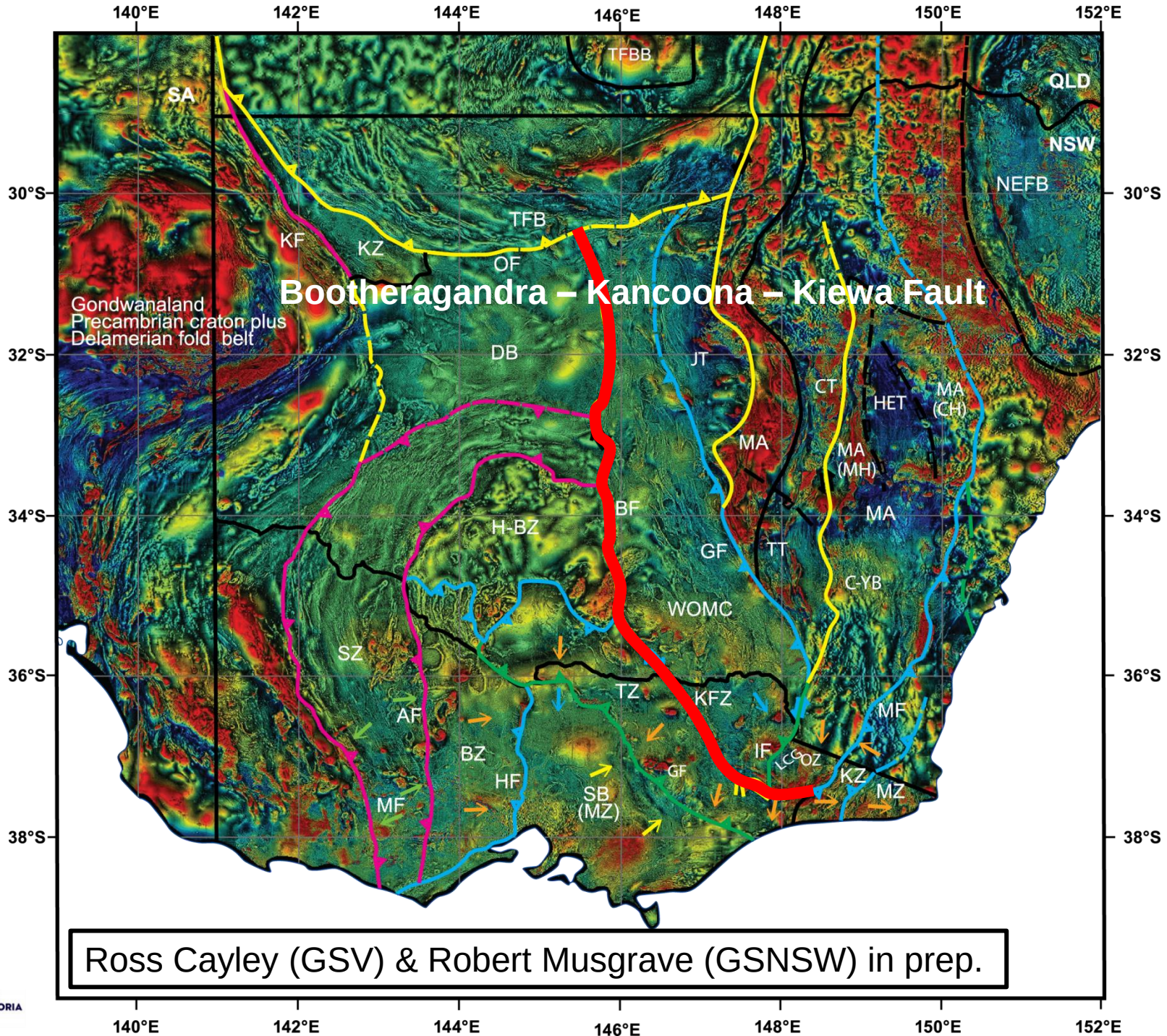




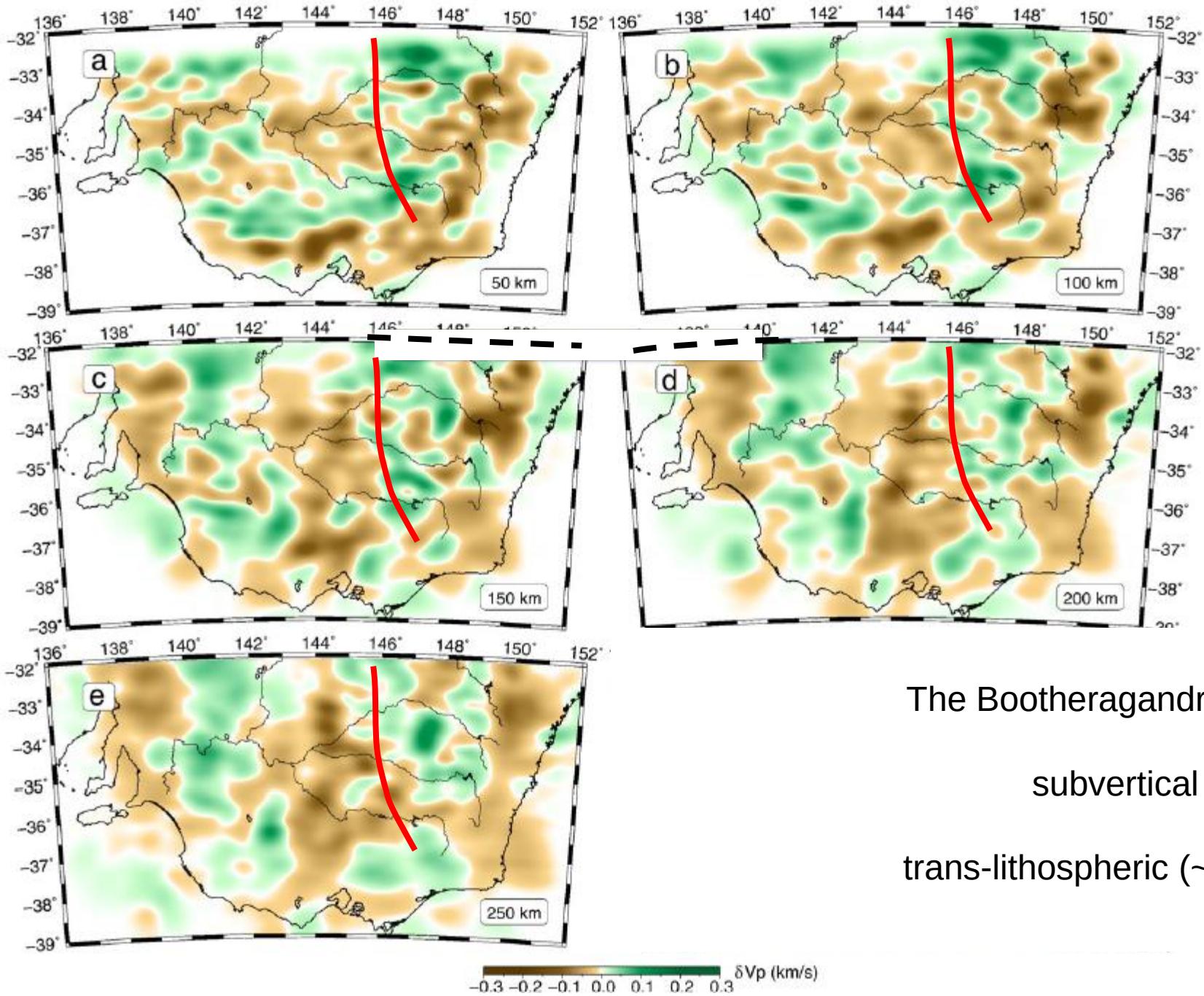
Cayley & Musgrave, in prep.


140°E
142°E
144°E
146°E
148°E
150°E
152°E
30°S
32°S
34°S
36°S
38°S
SA
QLD
NSW
NEFB
TFBB
TFB
OF
KF
KZ
Gondwanaland
Precambrian craton plus
Delamerian fold belt
No Baragwanath
Transform
DB
JT
CT
HET
MA
(CH)
MA
MA
(MH)
MA
BF
H-BZ
GF
TT
C-YB
WOMC
SZ
TZ
KFZ
AF
BZ
HF
MF
SB
(MZ)
GF
IF
LCC
OZ
KZ
MZ
MF
Paleogeographic
discontinuity


LACHLAN FOLD BELT
DELAMERIAN FOLD BELT
A ~ 430 Ma
~ 418 Ma
THOMSON FOLD BELT
OLEPOLOKO FAULT
~ 390 Ma
D ~ 380 Ma



Ross Cayley (GSV) & Robert Musgrave (GSNSW) in prep.

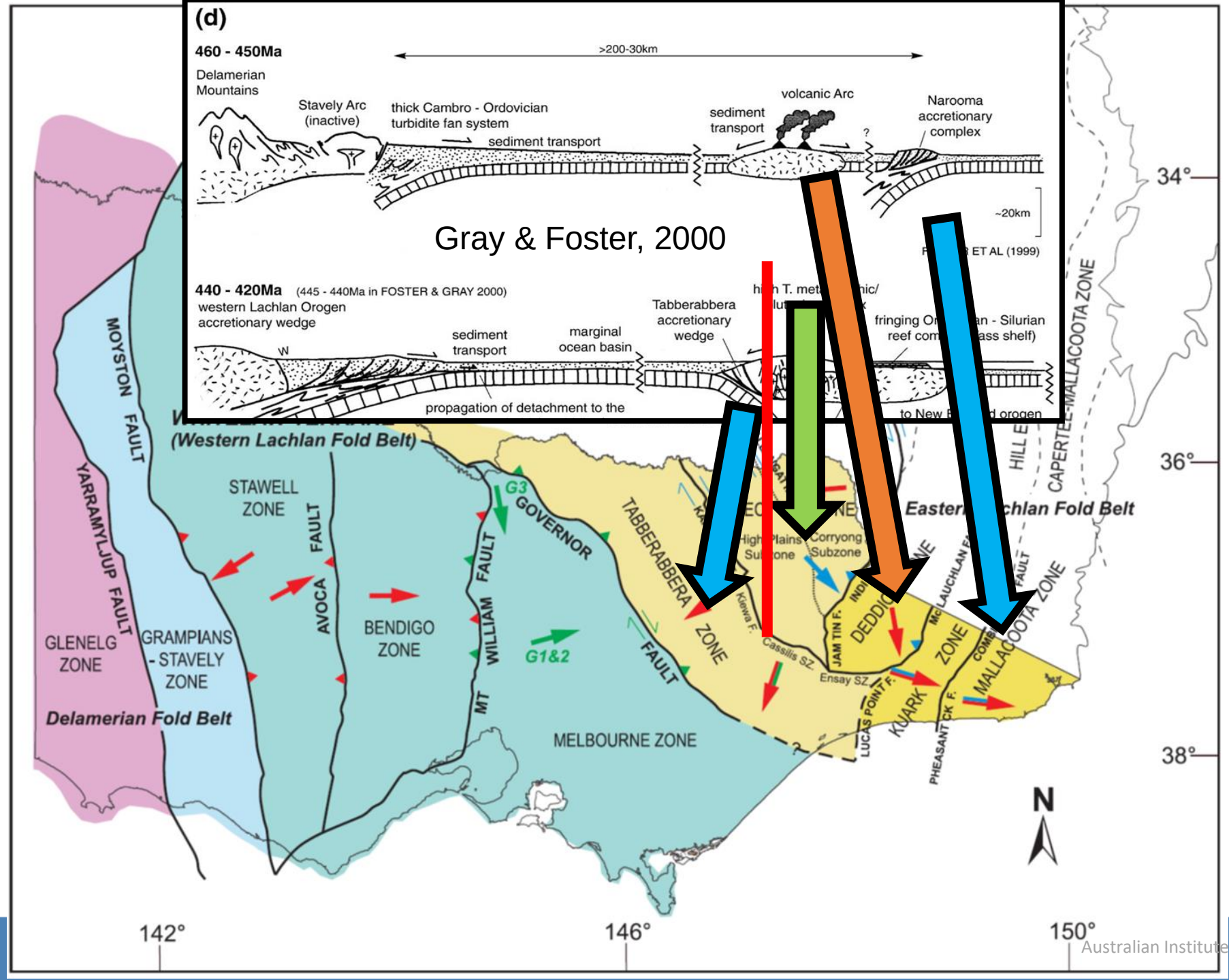


WOMBAT passive seismic experiment:
time arrival residuals
(Rawlinson, et al, GR, 2011)

The Bootheragandra Fault:

subvertical

trans-lithospheric (~200km)



This strike slip fault is big enough to explain the bits of Victorian geology that don't make sense in their current positions..

Convergent margin key elements and systematics

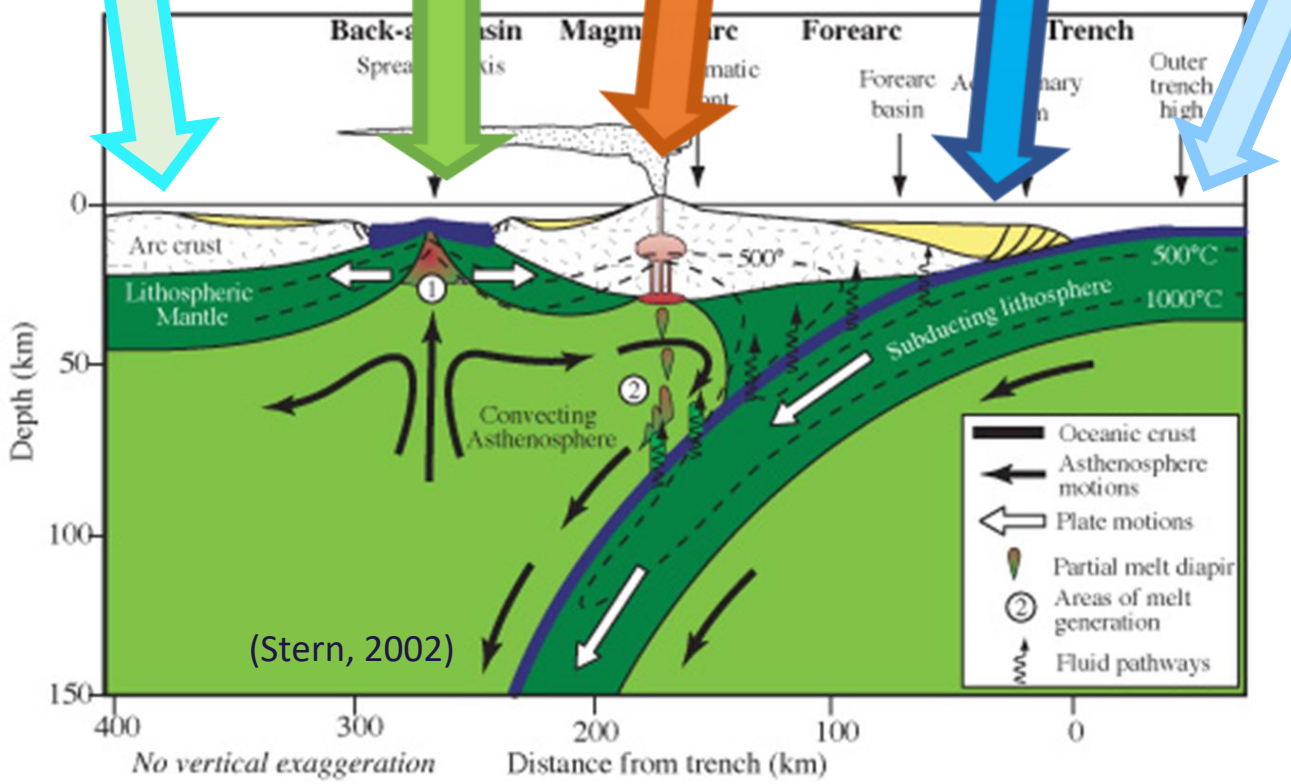
Distal back-arc: transition to intraplate

Back-arc basin: hot, syn-sediment magmatism, extension weak/strong deformation

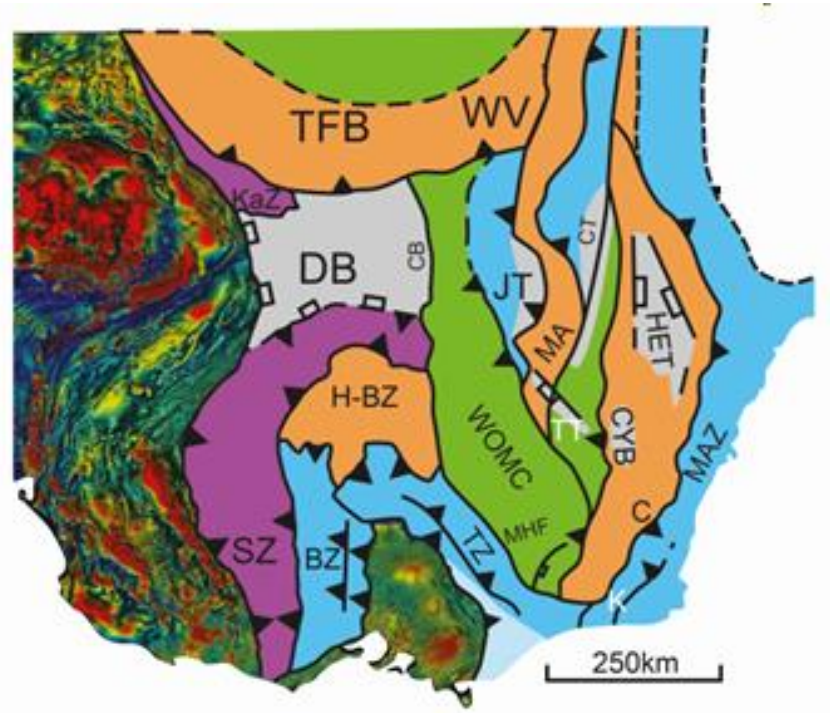
Magmatic arc: hot, igneous-dominated

Accretionary wedge: cold, inherent strong syn-sedimentary shortening deformation, amagmatic (thickening crust)

Intraplate: cold, undeformed, amagmatic

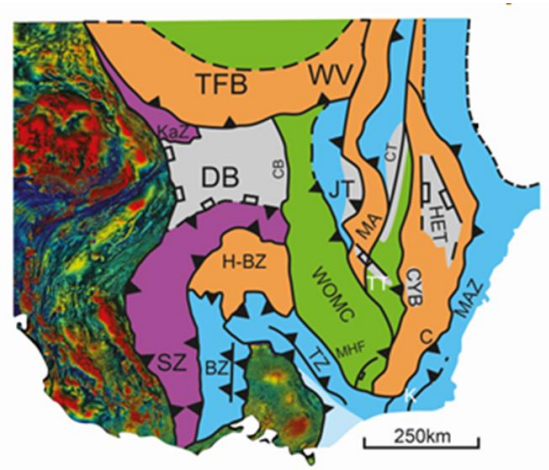


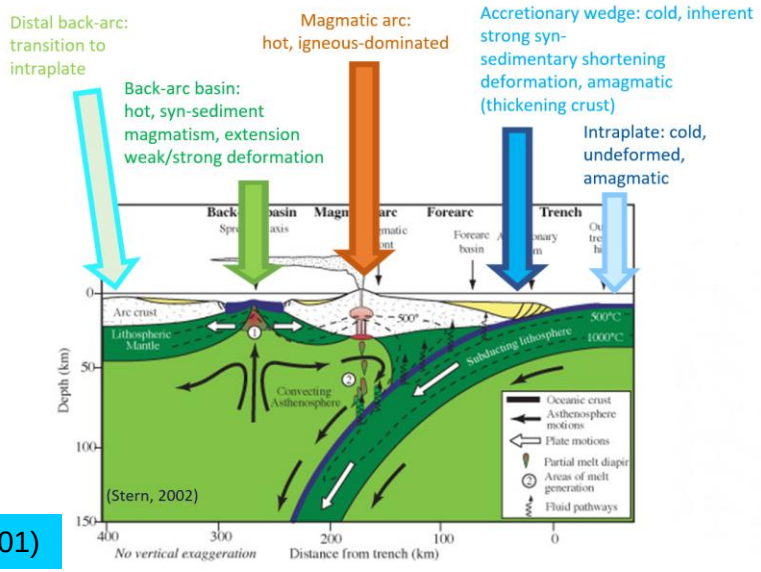
(Stern, 2002)

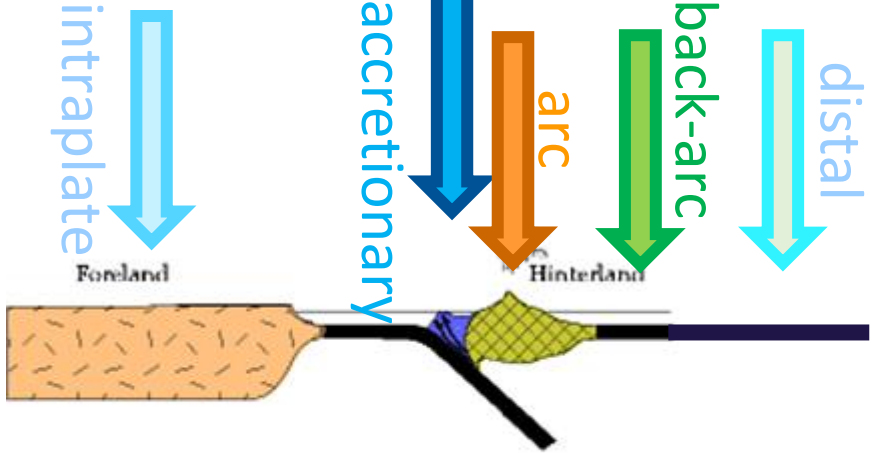


Ordovician tectonic setting

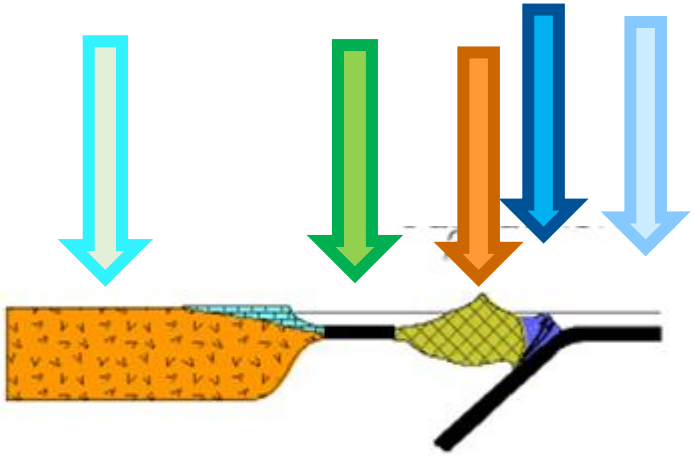
	A	B
1	**Lachlan Fold Belt Zone**	**Most likely Ordovician setting**
2		
3	Stawell Zone	Gondwana
4	Kayrunnera Zone	Gondwana (eg. Greenfield et al., 2011)
5	Bendigo Zone	Intraplate, deep marine
6	Melbourne Zone	Intraplate, marginal marine (basin)
7	Selwyn Block	Vandieland microcontinent
8	Tabberabbera Zone	accretionary wedge, marine
9	Wagga / Omeo Zone	back arc basin, deep marine
10	Macquarie Arc	island arc, marginal marine
11	Mallacoota / Narooma Zone	accretionary wedge, marine
12	Thomson Fold Belt (south)	arc, marginal marine
13	Mathinna Zone (Tasmania)	accretionary wedge, marine (eg. Reed, 2001)



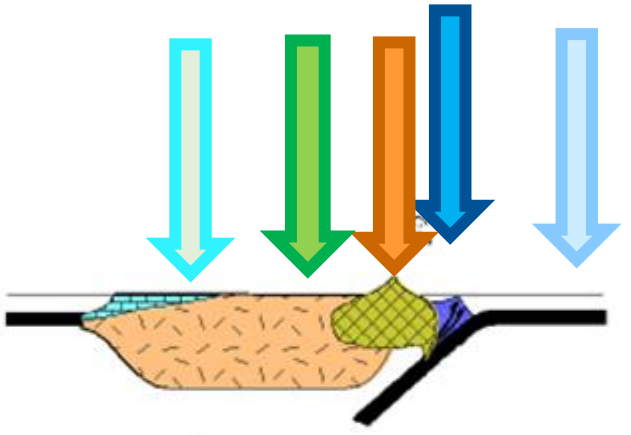




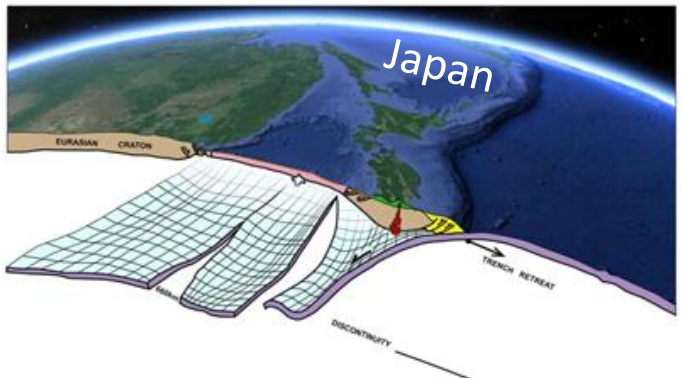
Continent-Island Arc Collision

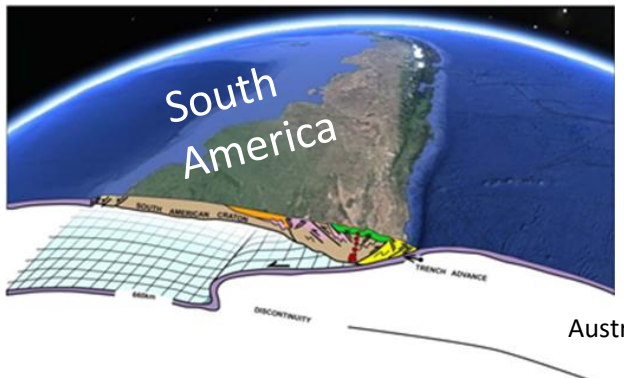


Island Arc

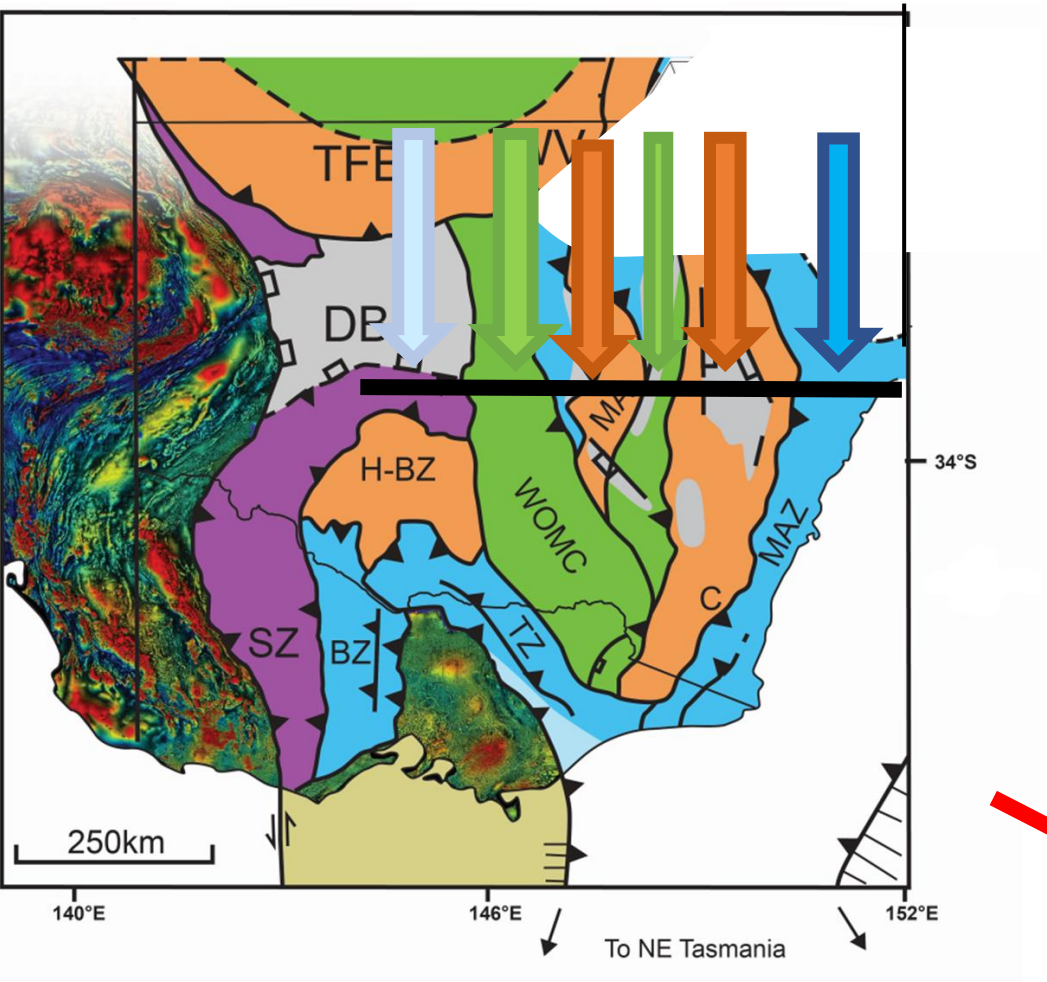


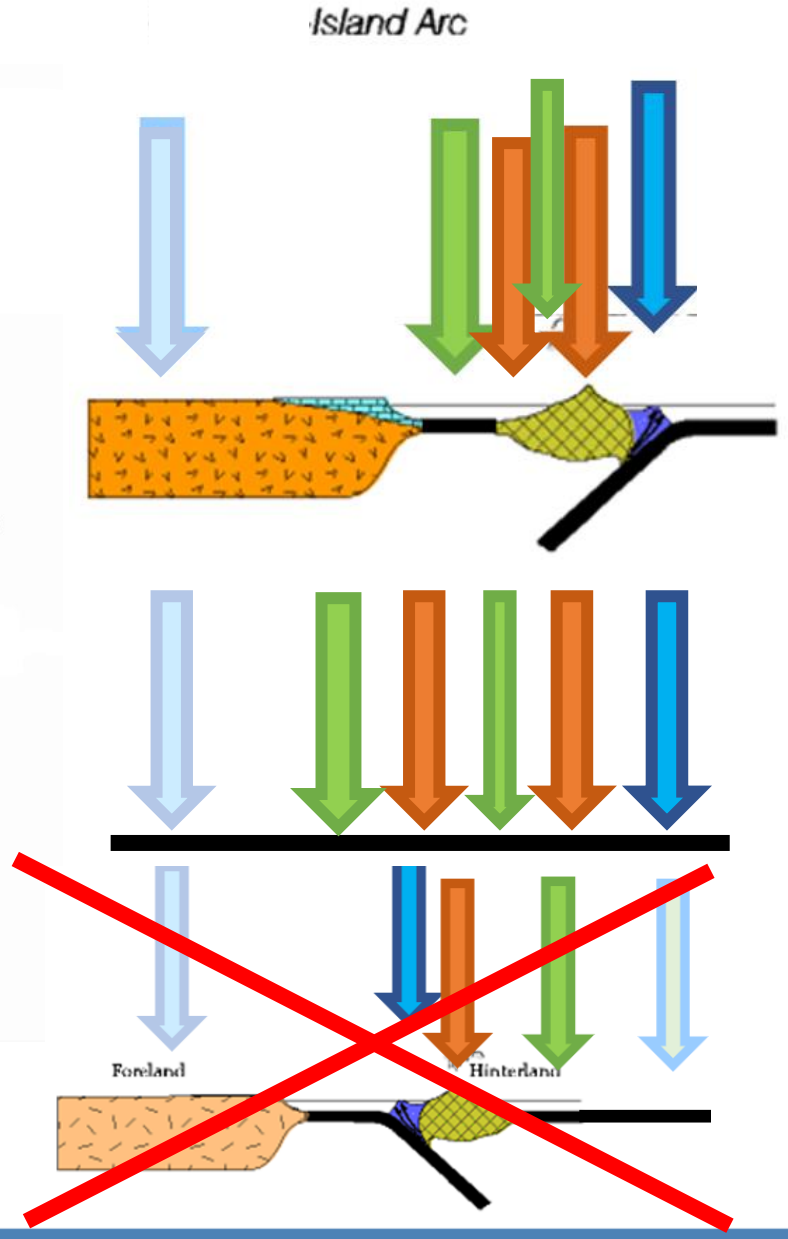
Cordilleran

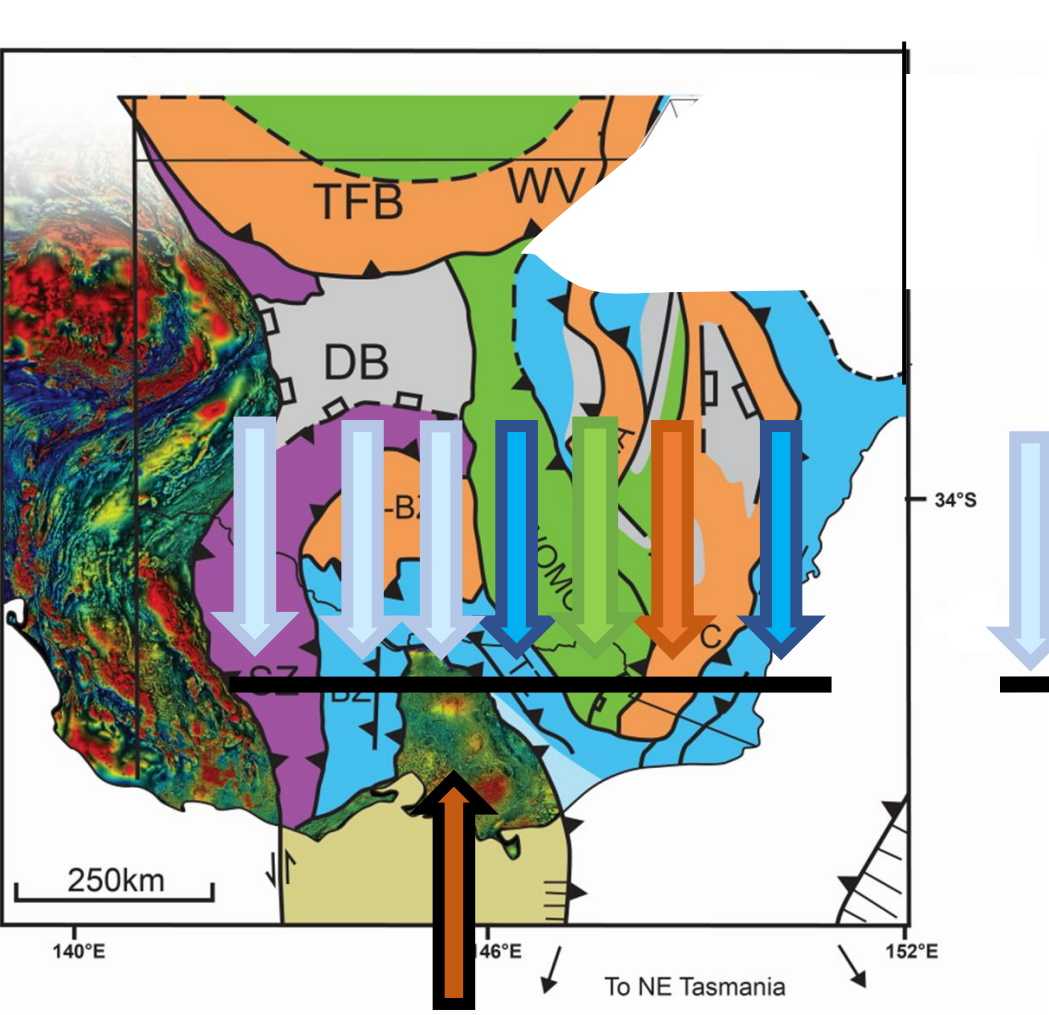


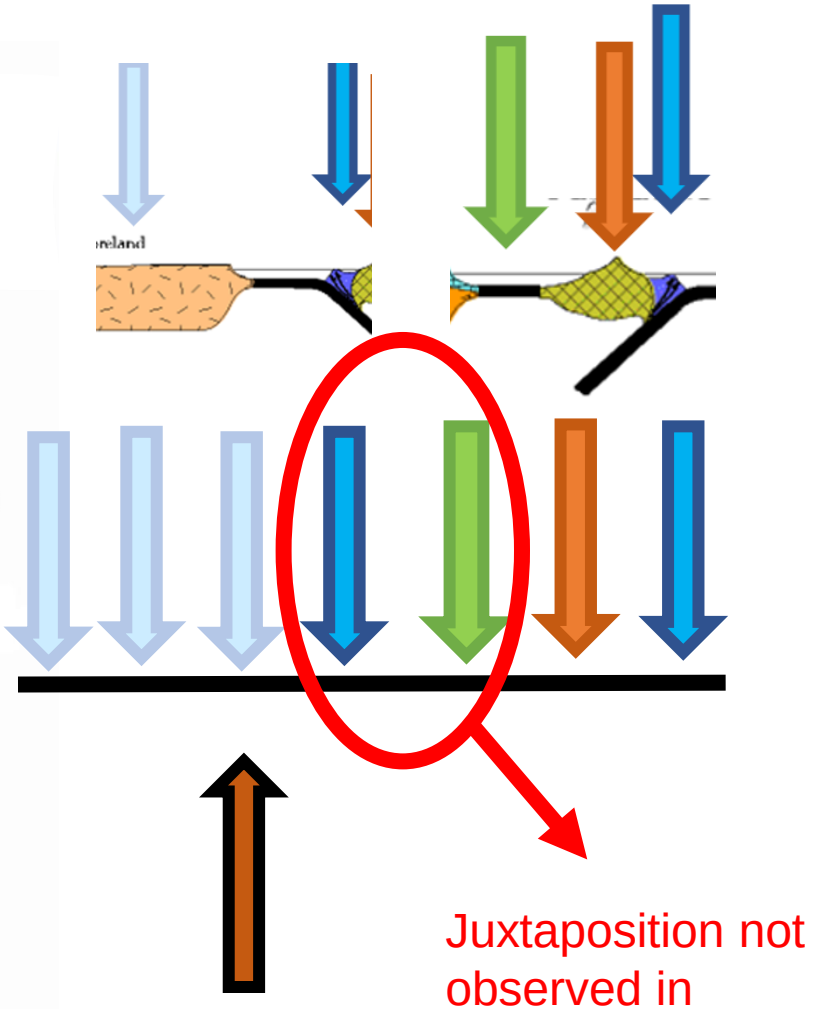


Benchmarking against modern systems

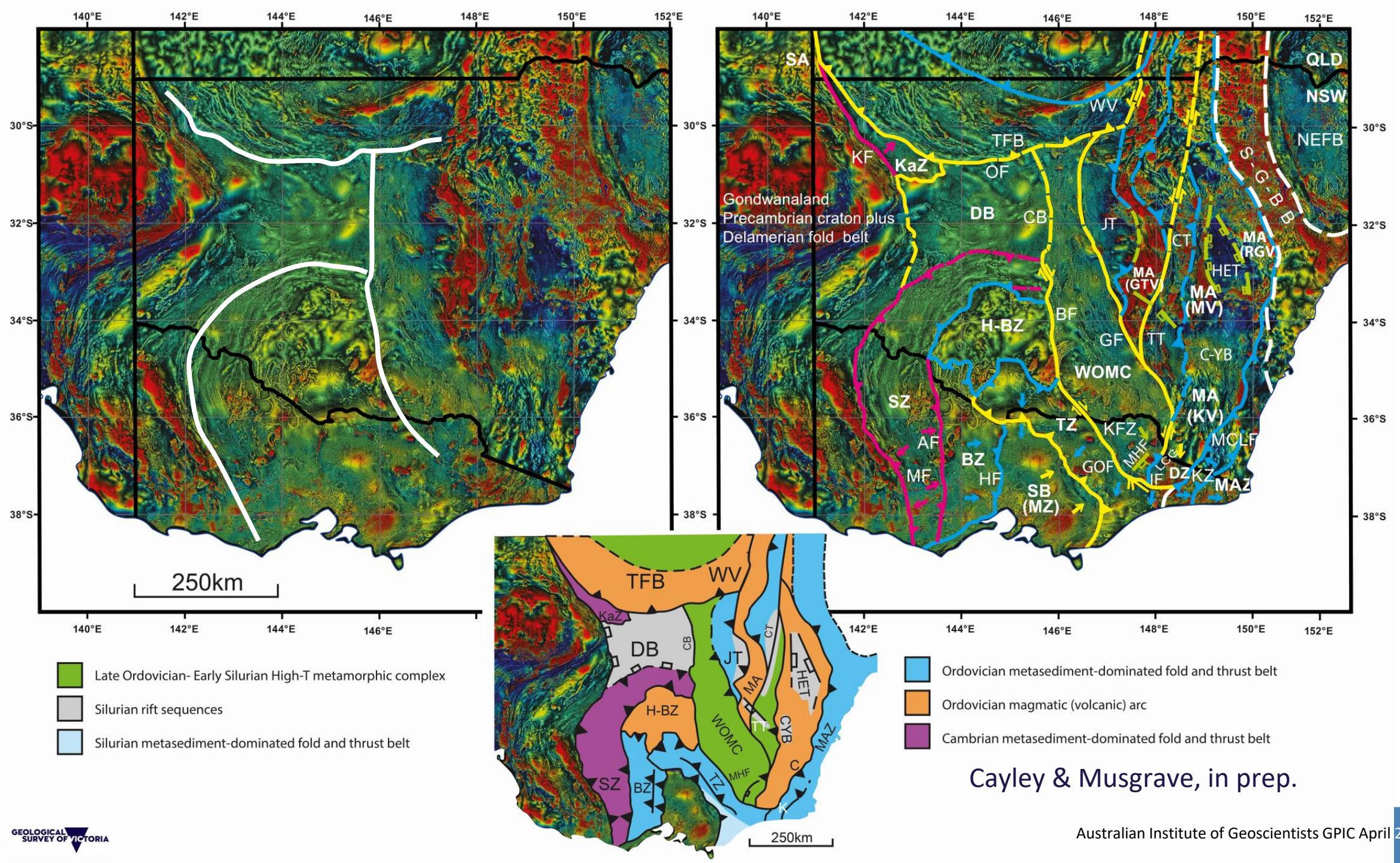

TFE
DB
H-BZ
WOMC
MA
C
MAZ
SZ
BZ
TZ
34°S
250km
140°E
146°E
152°E
To NE Tasmania


Island Arc
Foreland
Hinterland





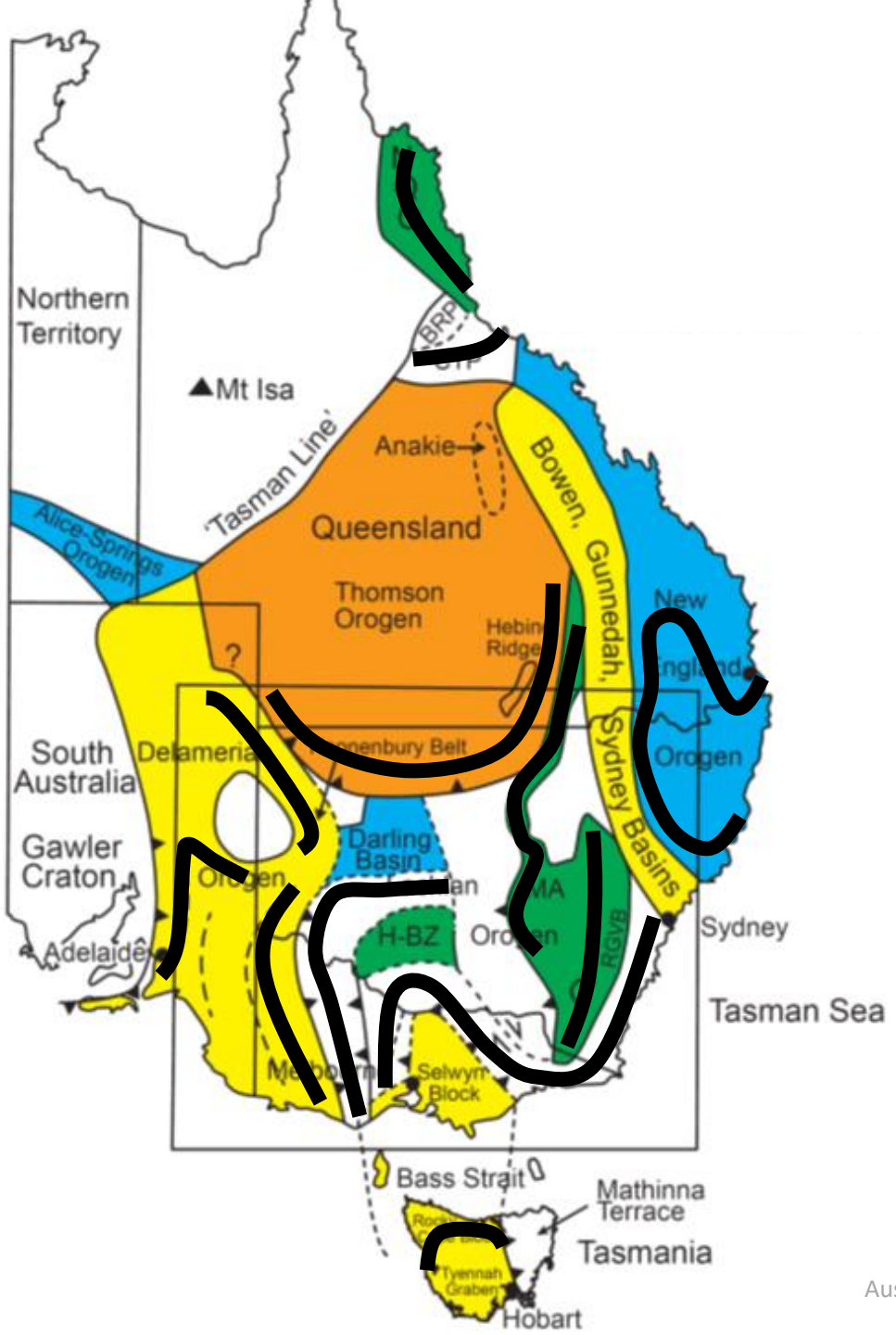
Juxtaposition not observed in active systems



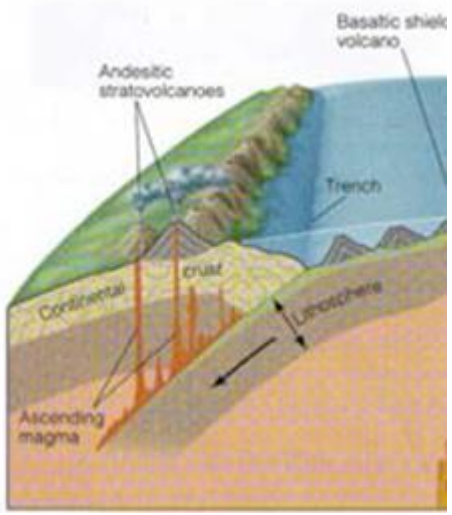
Cayley & Musgrave, in prep.

Eastern Australian Tasmanides geology…

…all screwed up….



…not like a ‘textbook’ accretionary system……



‘textbook’ accretionary systems are often depicted in ‘pseudo-3D’ – which is 2D projected to distance.

Any cross-section through it will look the same……

Analogue modelling…

Early Palaeozoic east-Australia as a rock ‘warehouse’……

lots of familiar stores,
but pretty messy…..

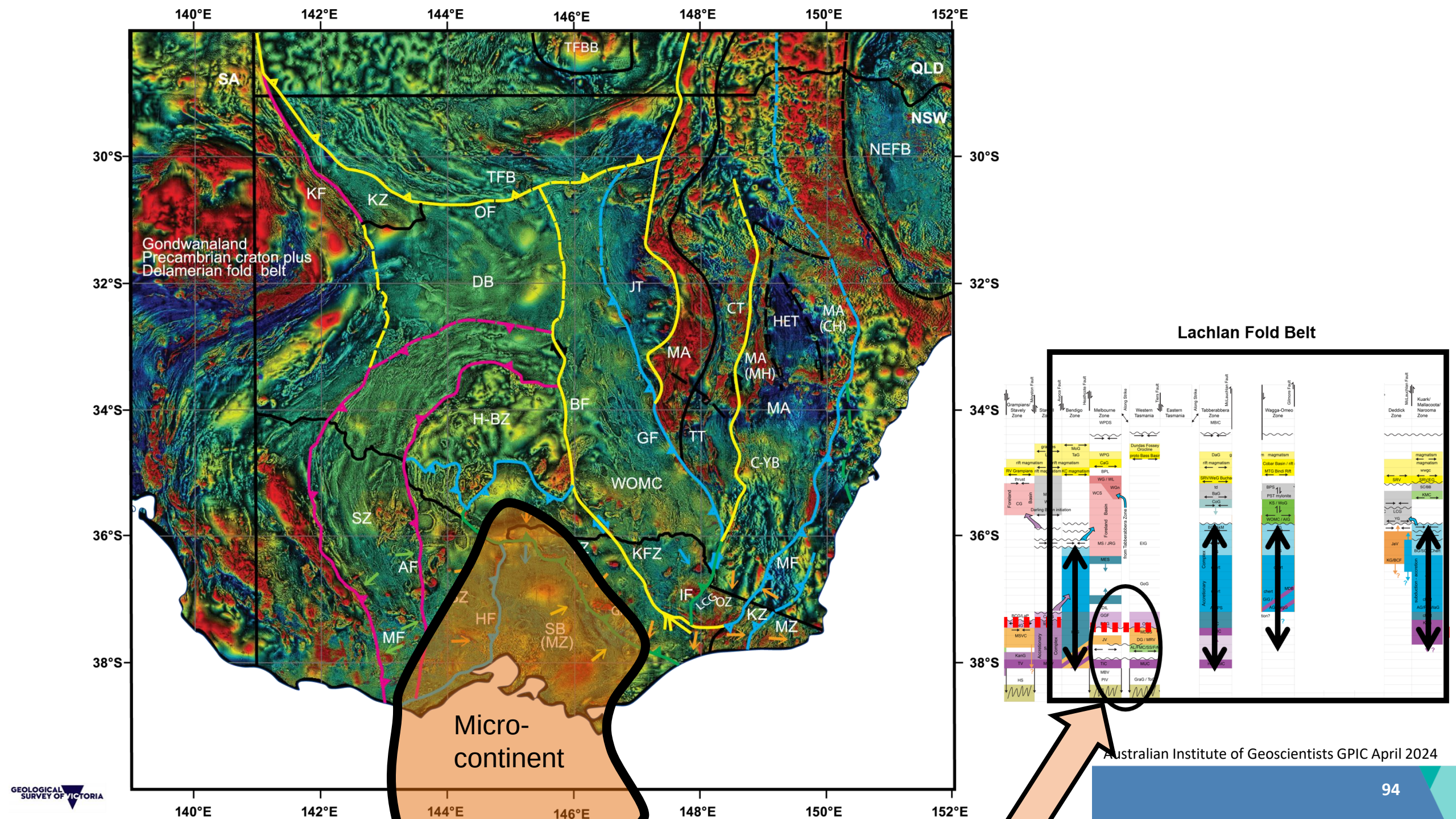
bits and pieces piled up
all over the place…

…hard to understand….

…not like the ‘textbook’ warehouse……

The difference?……

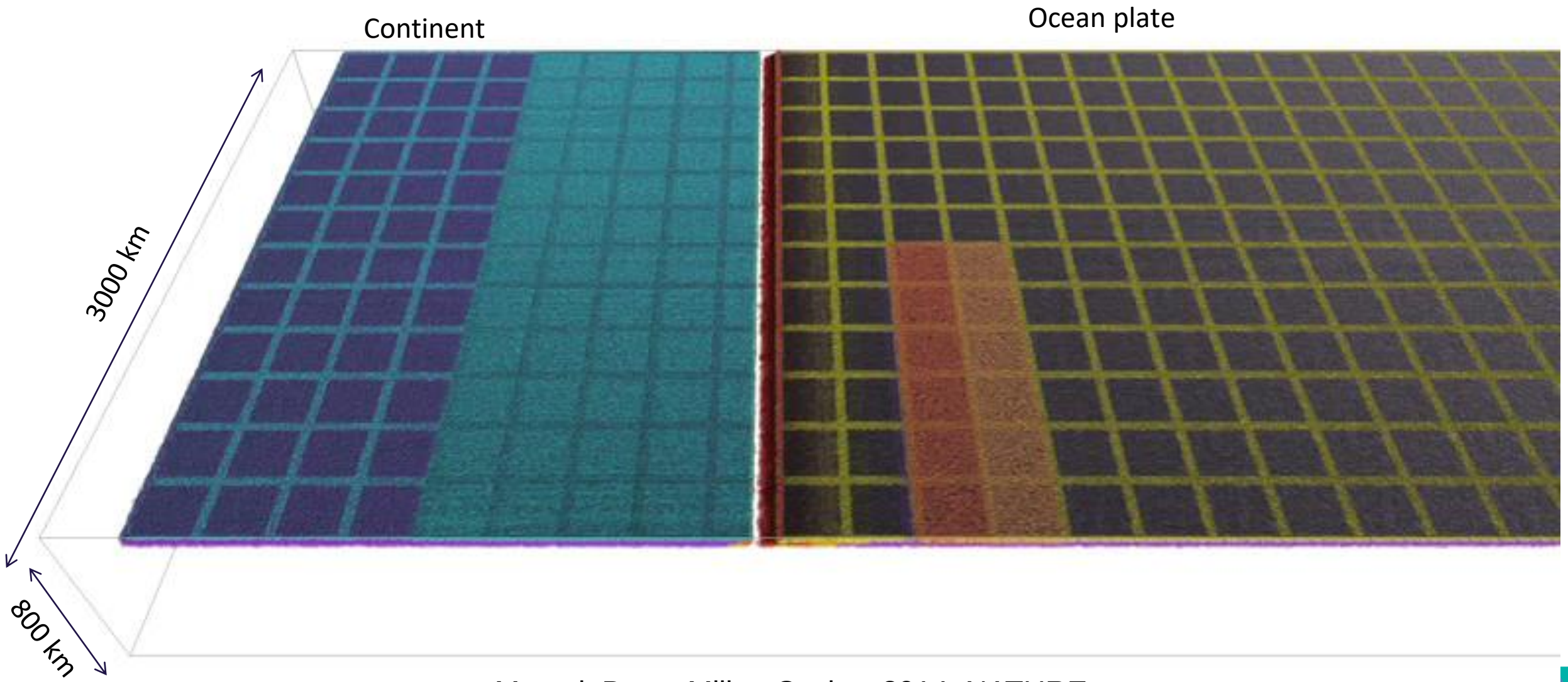
Appreciation of the **huge potential** of small colliders introduced into large, organised, but gravitationally meta-stable system
to trigger a cascade……and the rapid rate of that change…


140°E
142°E
144°E
146°E
148°E
150°E
152°E
30°S
32°S
34°S
36°S
38°S
SA
QLD
NSW
NEFB
TFBB
TFB
KF
KZ
OF
Gondwanaland
Precambrian craton plus
Delamerian fold belt
DB
JT
CT
HET
MA
(CH)
MA
MA
(MH)
MA
BF
H-BZ
GF
TT
C-YB
WOMC
SZ
KFZ
AF
MF
IF
LCG
OZ
KZ
MZ
HF
SB
(MZ)
MF
Micro-
continent
Lachlan Fold Belt

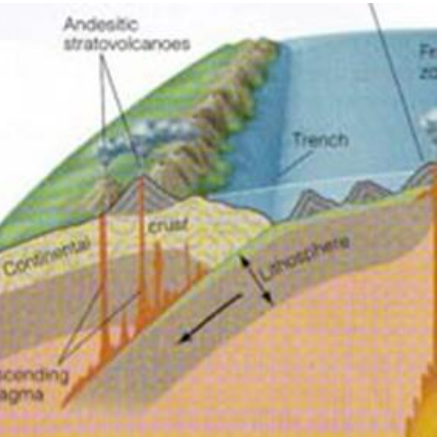
gslab

Geodynamics of congested subduction zones

Model run time = 60 Million years



Moresi, Betts, Miller, Cayley, 2014: NATURE



Geodynamics of congested subduction zones

Rifting / basins

a

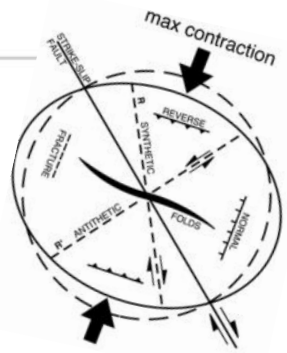
c

b

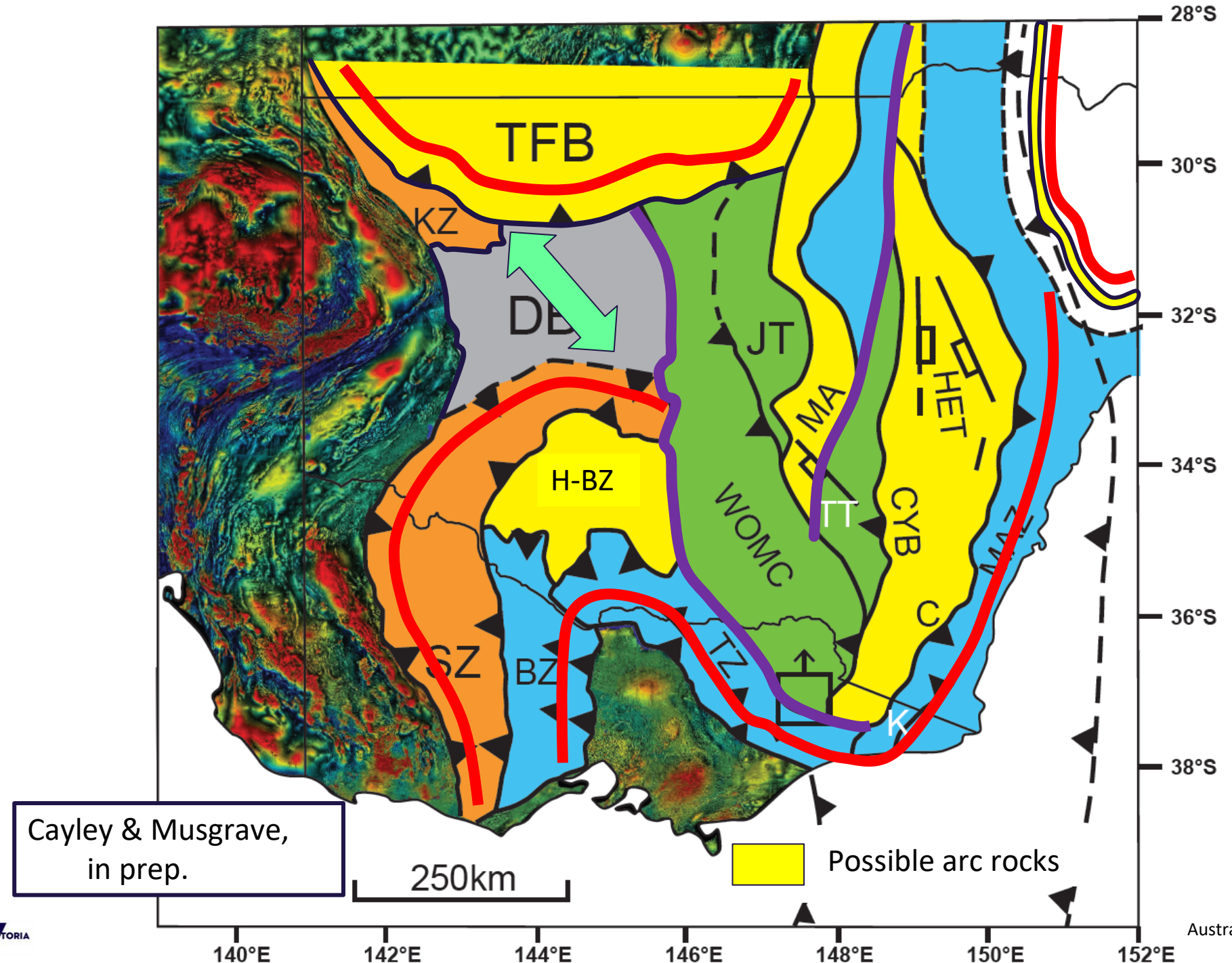
Extension!

Collision!

d

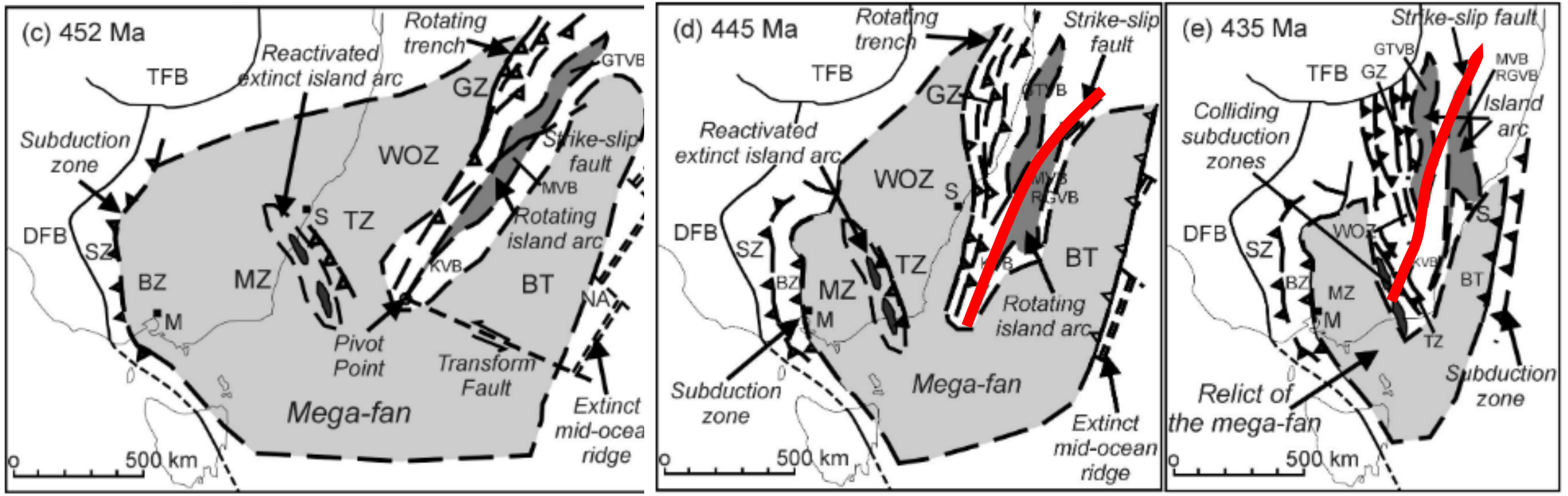


Moresi, Betts, Miller, Cayley, 2014: NATURE



Cayley & Musgrave, in prep.

Models that suggest strike-slip repetition of Macquarie Arc segments:



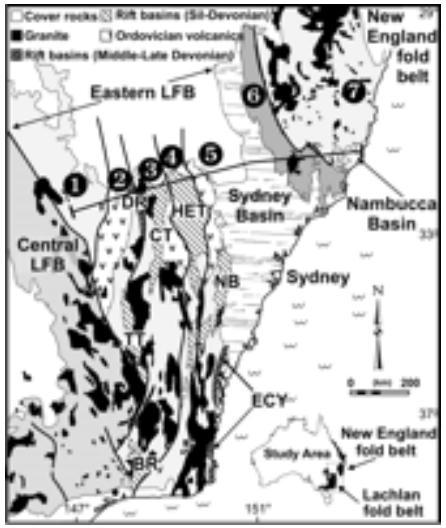
Packham, 1987 (AGU Geodynamics Series 19); Fergusson, 2009 (AJES)

New ideas for LFB geodynamics…

Recognition of the critical role of roll-back in LFB evolution….

Tectonic switching and roll-back in the LFB

Collins, 2002 (Geology)

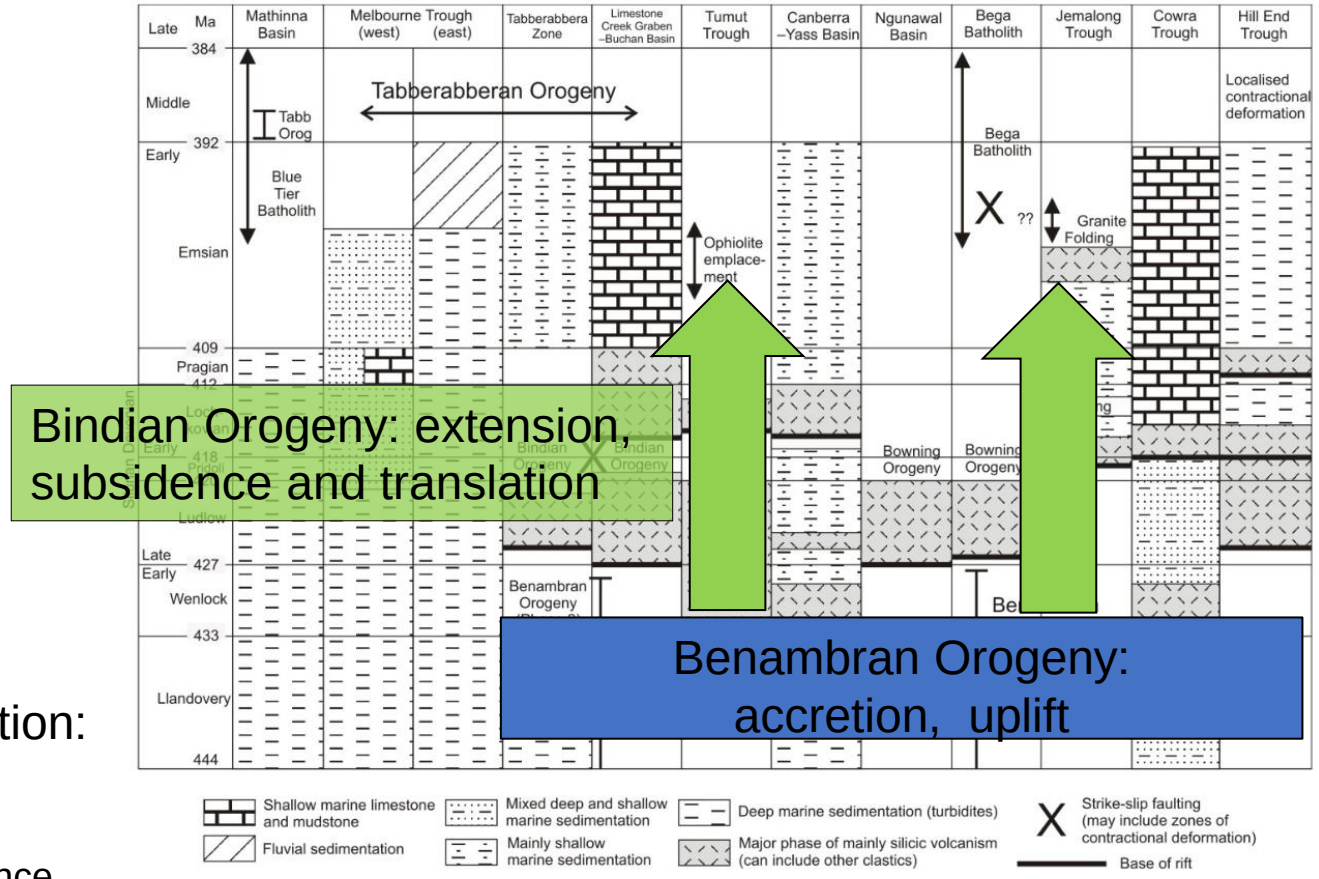


Extension and the tripartite association:

S-type granites, arcs and back-arc basins

Collins and Richards, 2008 (Geology)

Models that link extension to sedimentation in the Lachlan Fold Belt:



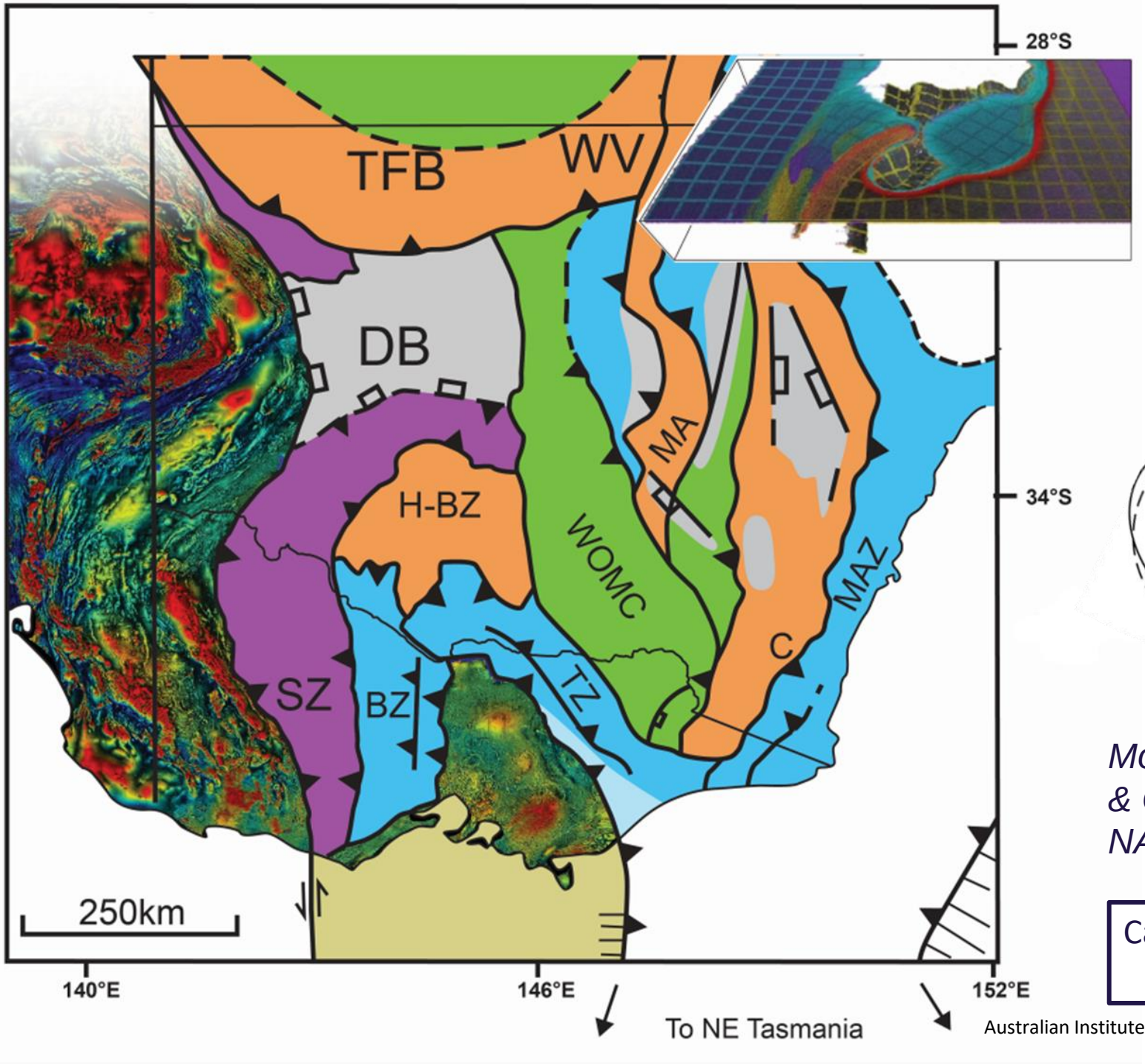
Bindian Orogeny: extension, subsidence and translation

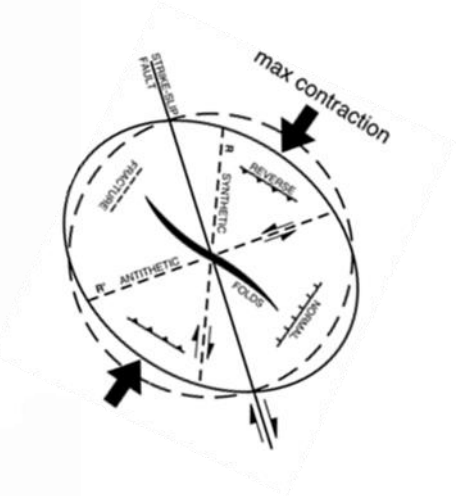
Benambran Orogeny: accretion, uplift

Fergusson, 2010: AJES:

Lachlan Fold Belt sedimentation:

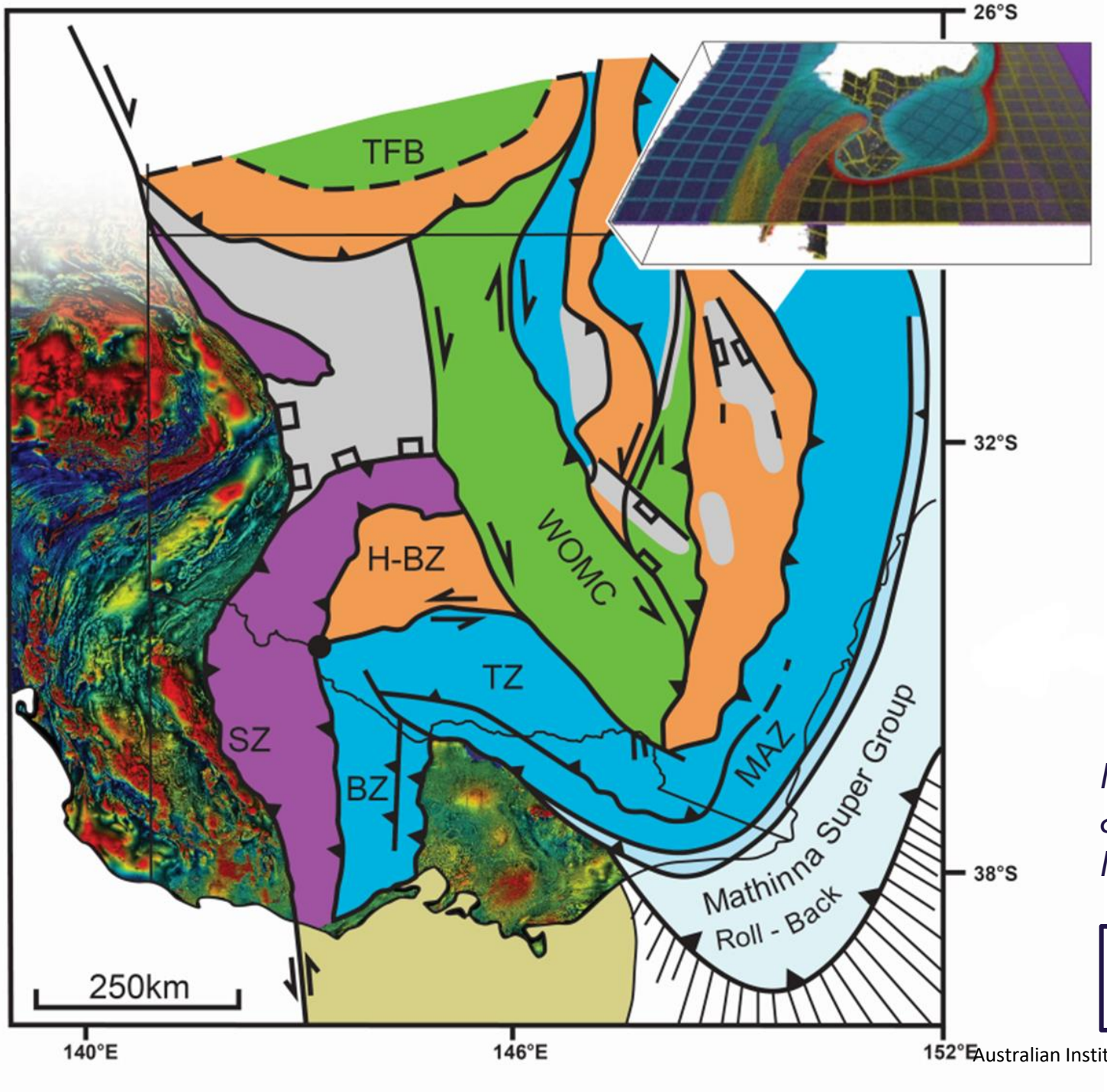
Late Silurian-Middle Devonian
plate-driven extension and convergence





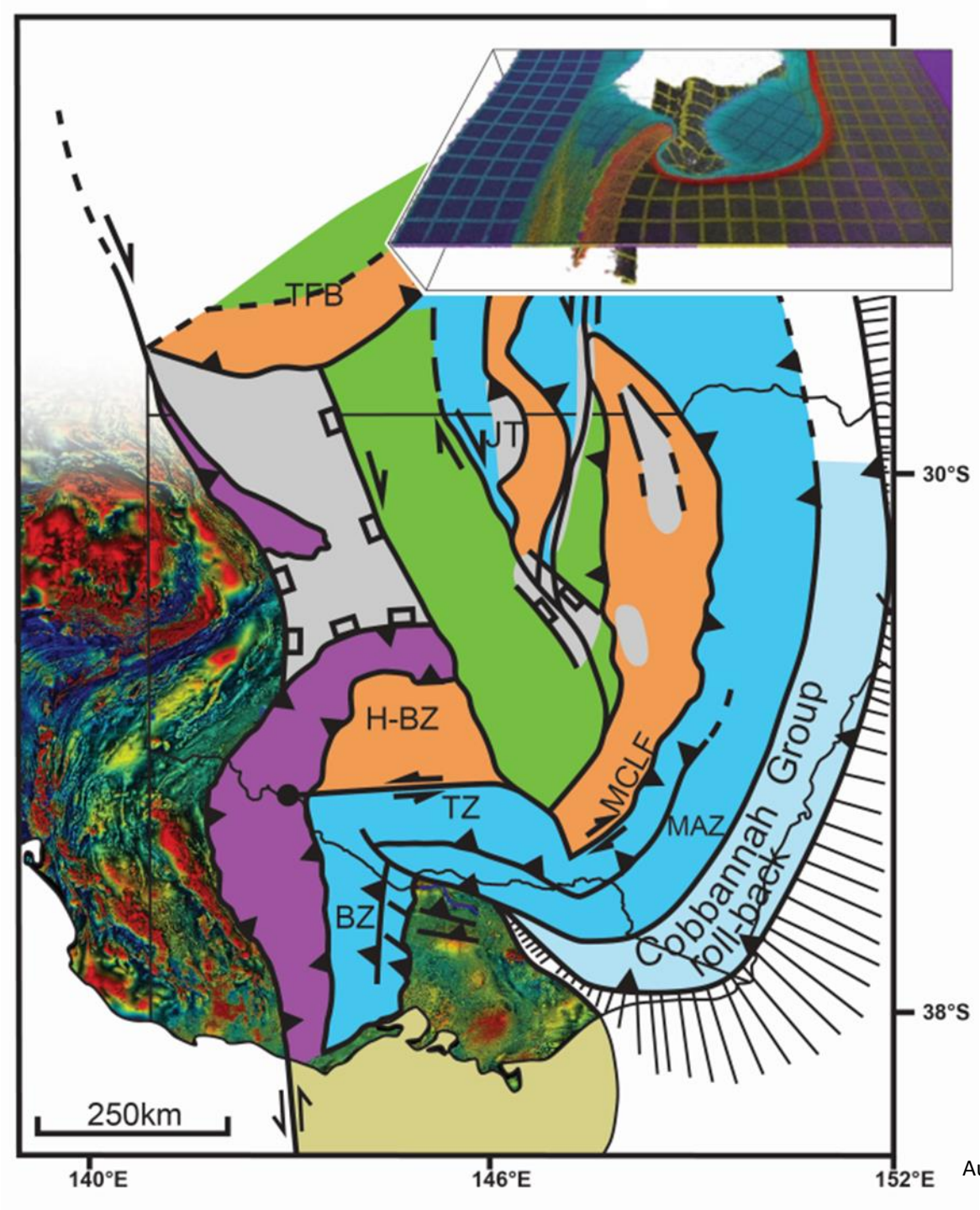
Moresi, Betts, Miller & Cayley 2014, NATURE.

Cayley & Musgrave, in review



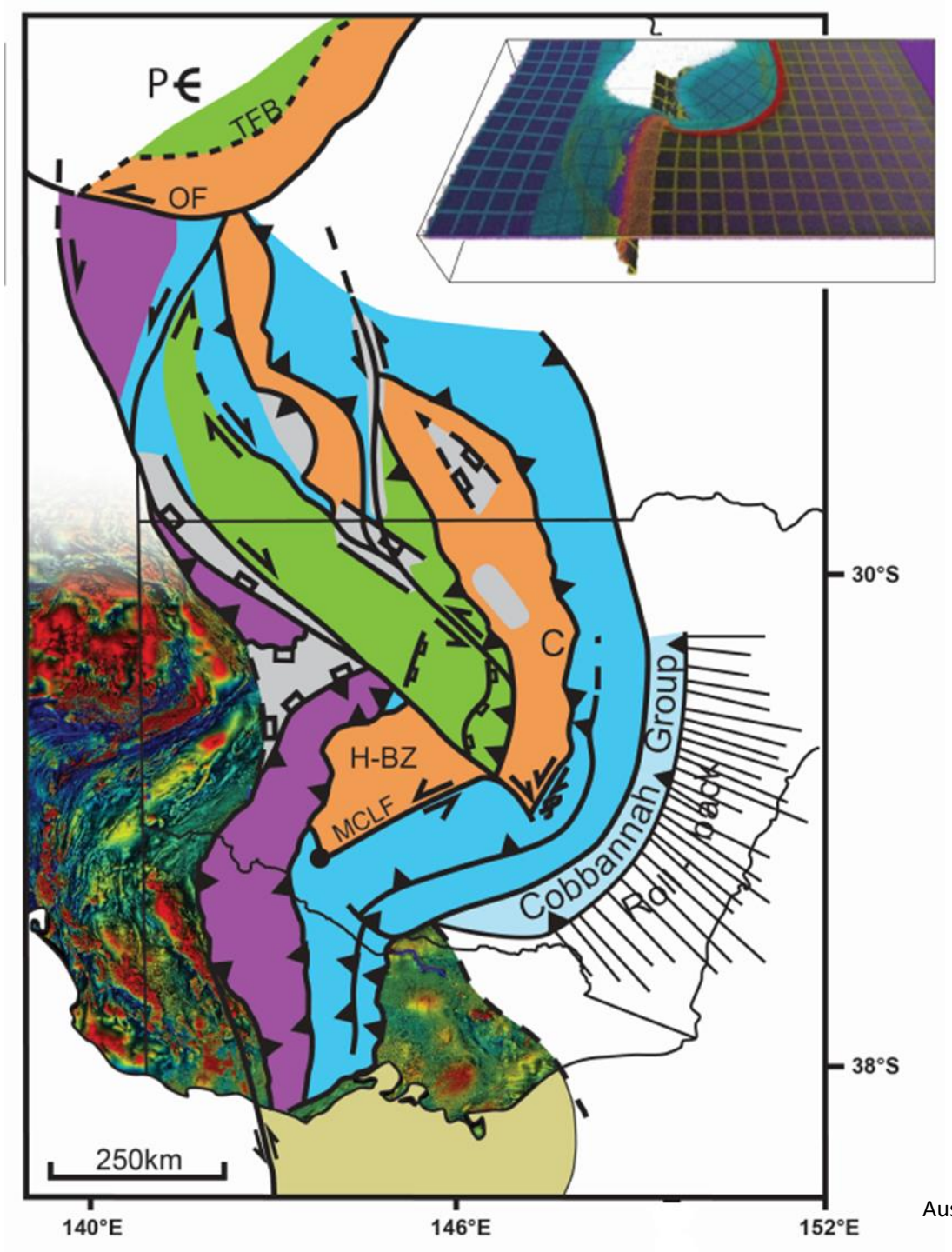
Moresi, Betts, Miller & Cayley 2014, NATURE.

Cayley & Musgrave, in review



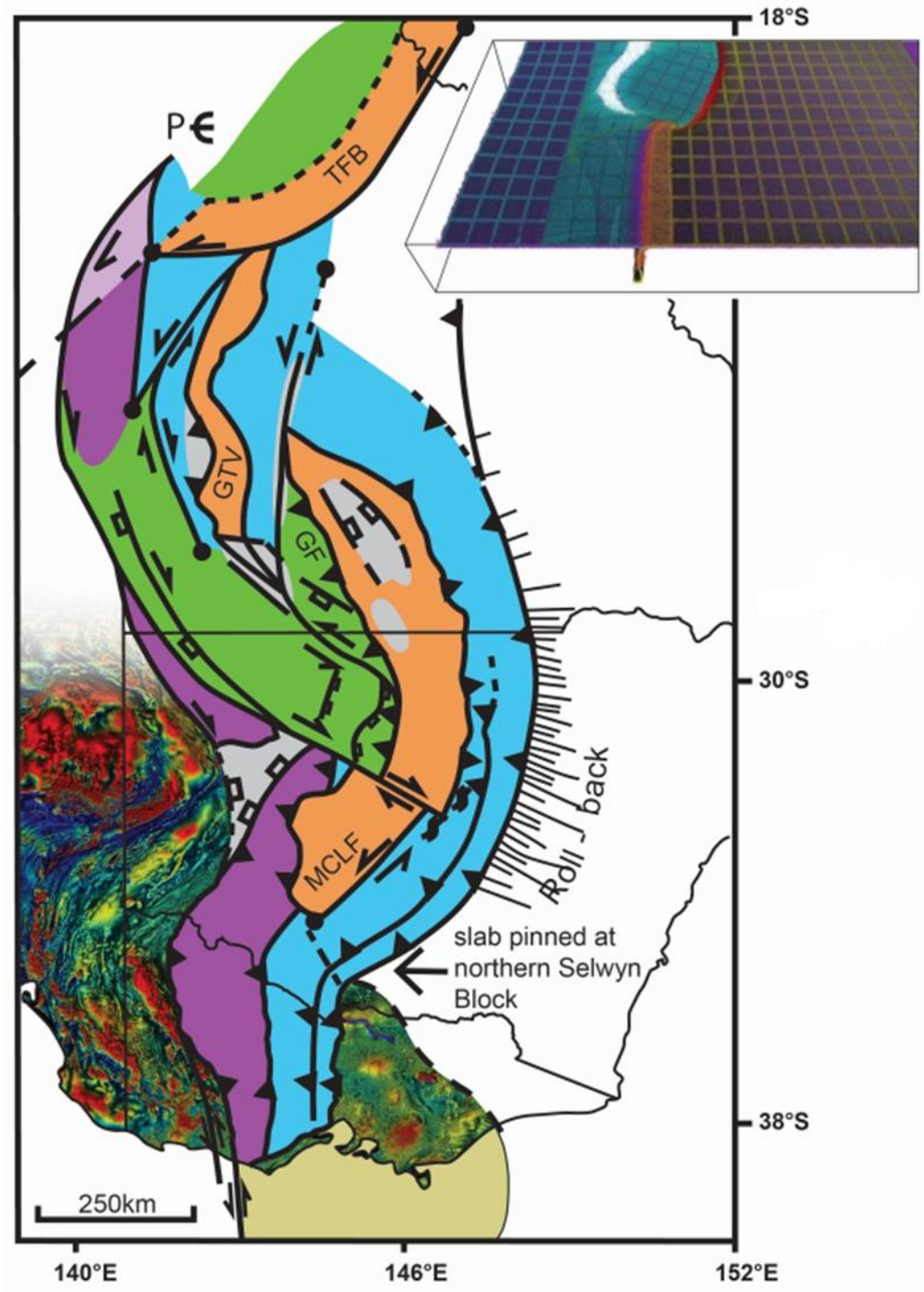
Moresi, Betts, Miller & Cayley 2014, NATURE.

Cayley & Musgrave, in review



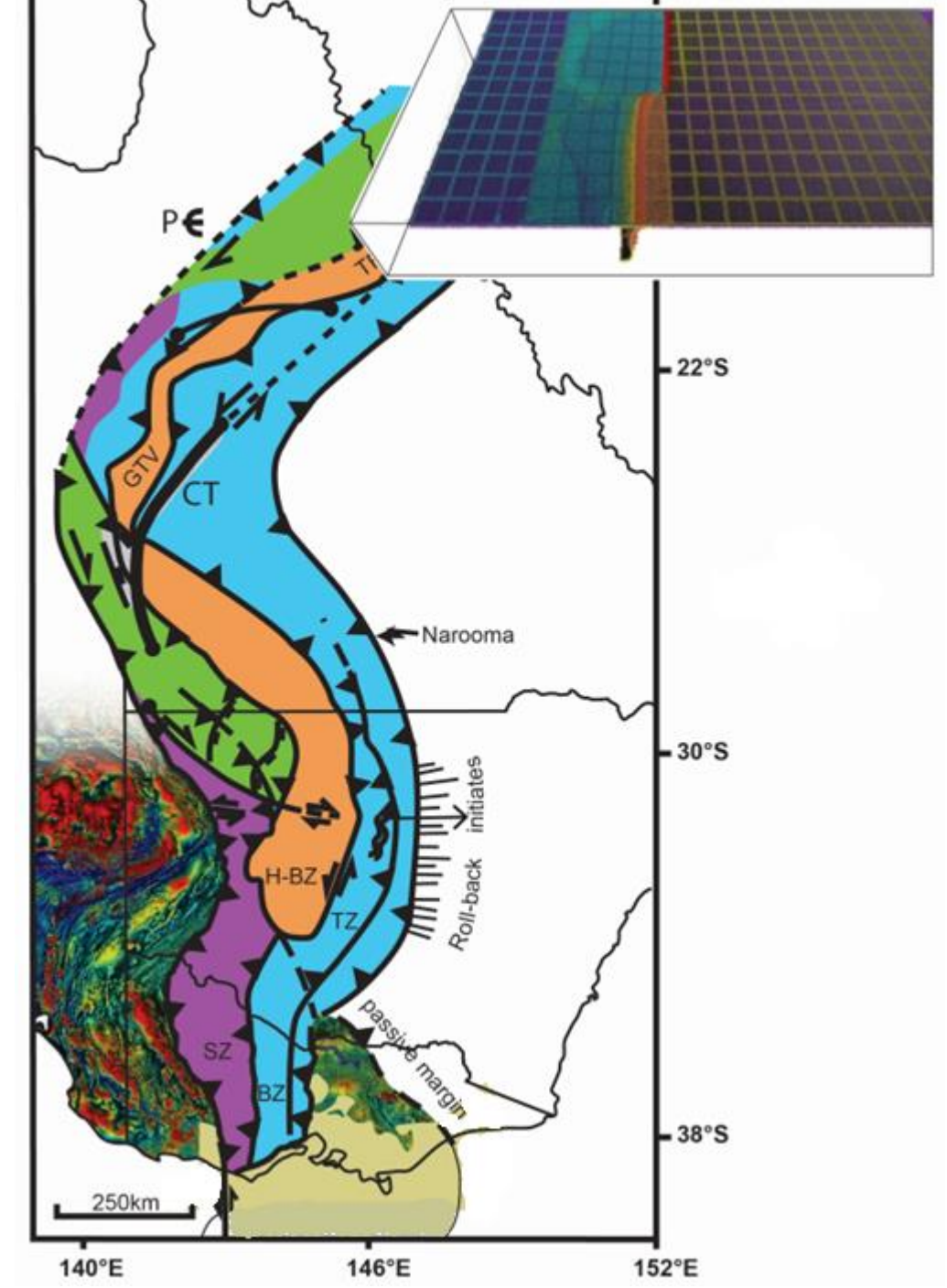
Moresi, Betts, Miller & Cayley 2014, NATURE.

Cayley & Musgrave, in review



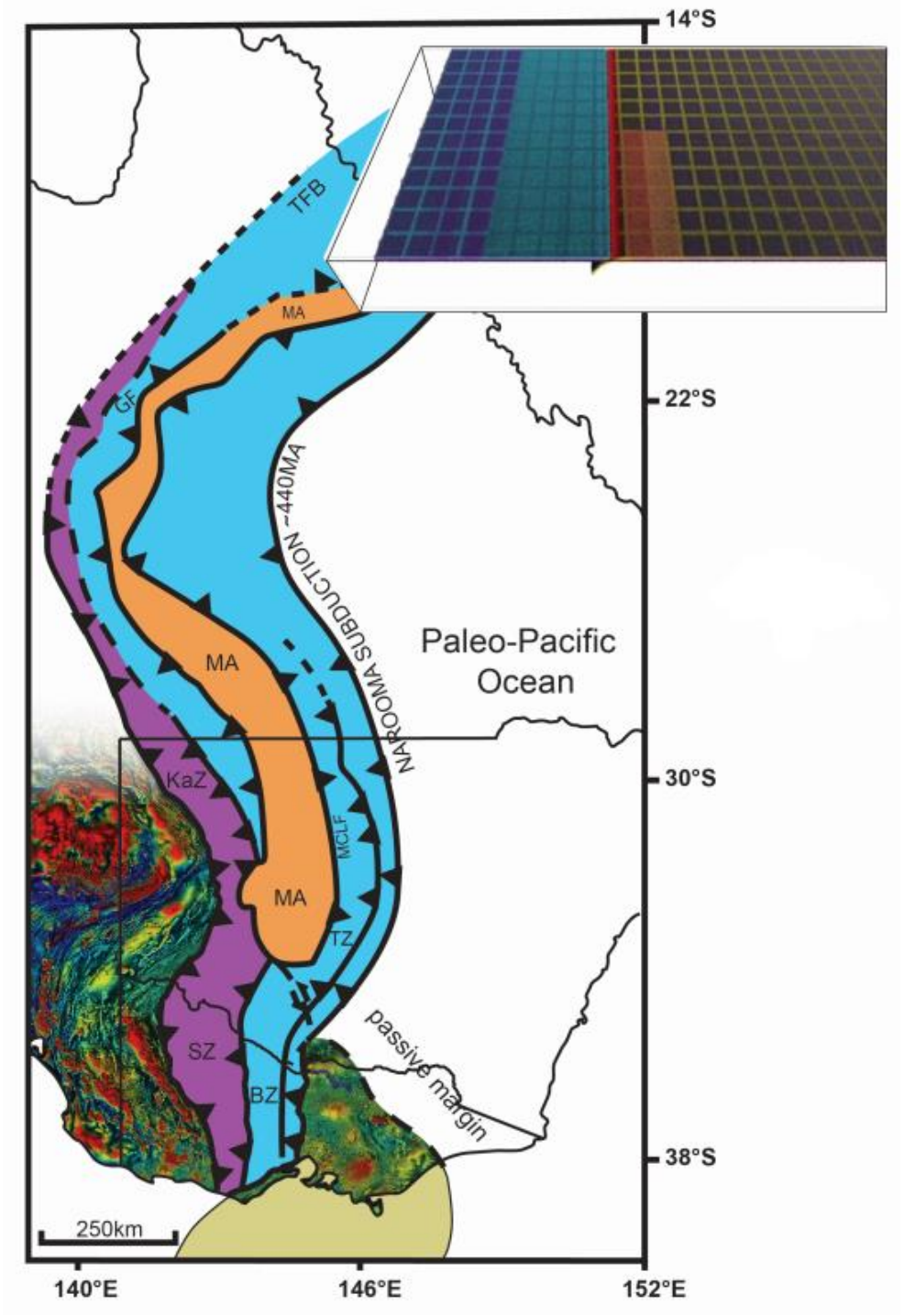
Moresi, Betts, Miller & Cayley 2014, NATURE.

Cayley & Musgrave, in review



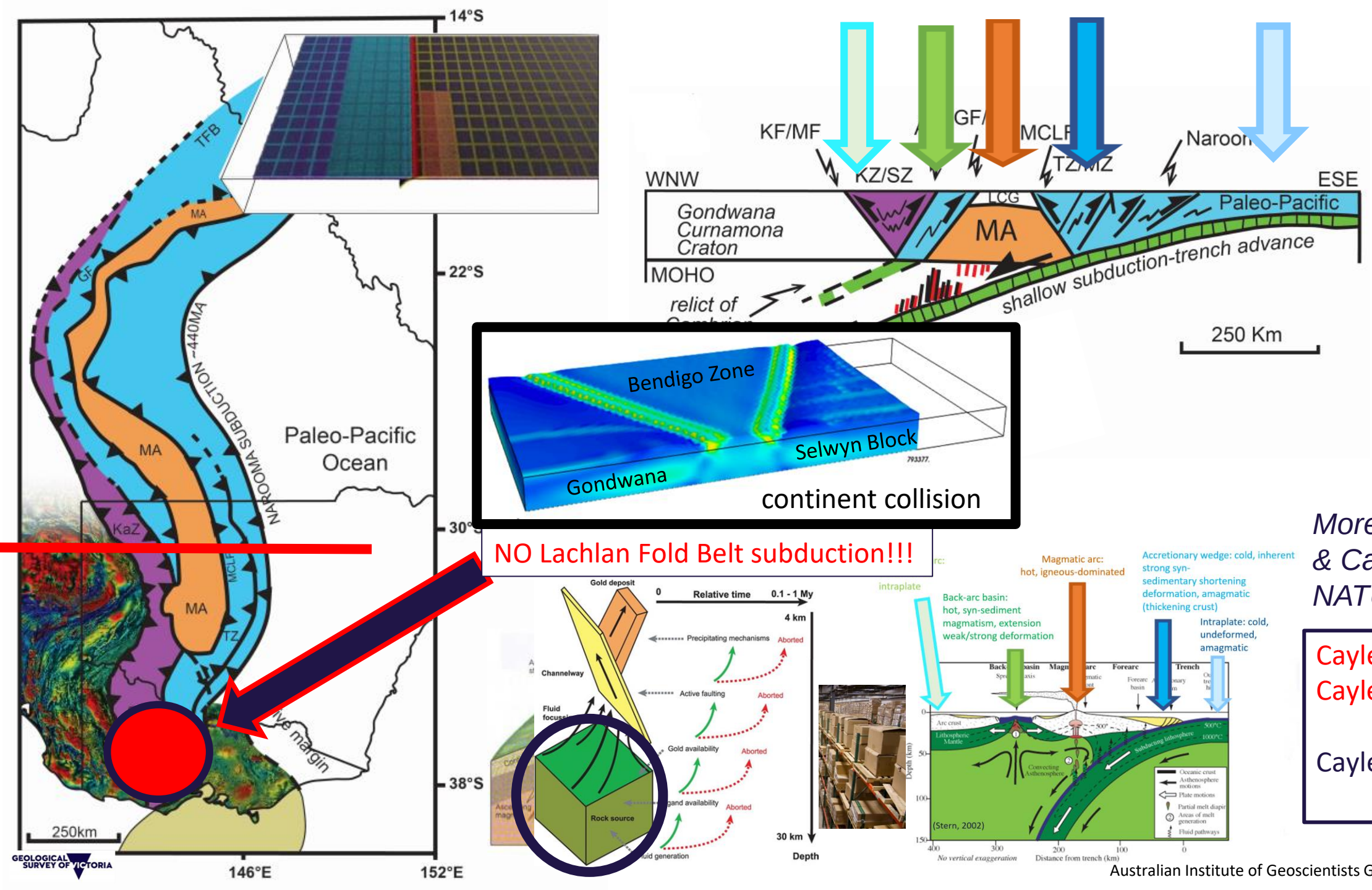
Moresi, Betts, Miller & Cayley 2014, NATURE.

Cayley & Musgrave, in review



Moresi, Betts, Miller & Cayley 2014, NATURE.

Cayley & Musgrave, in review

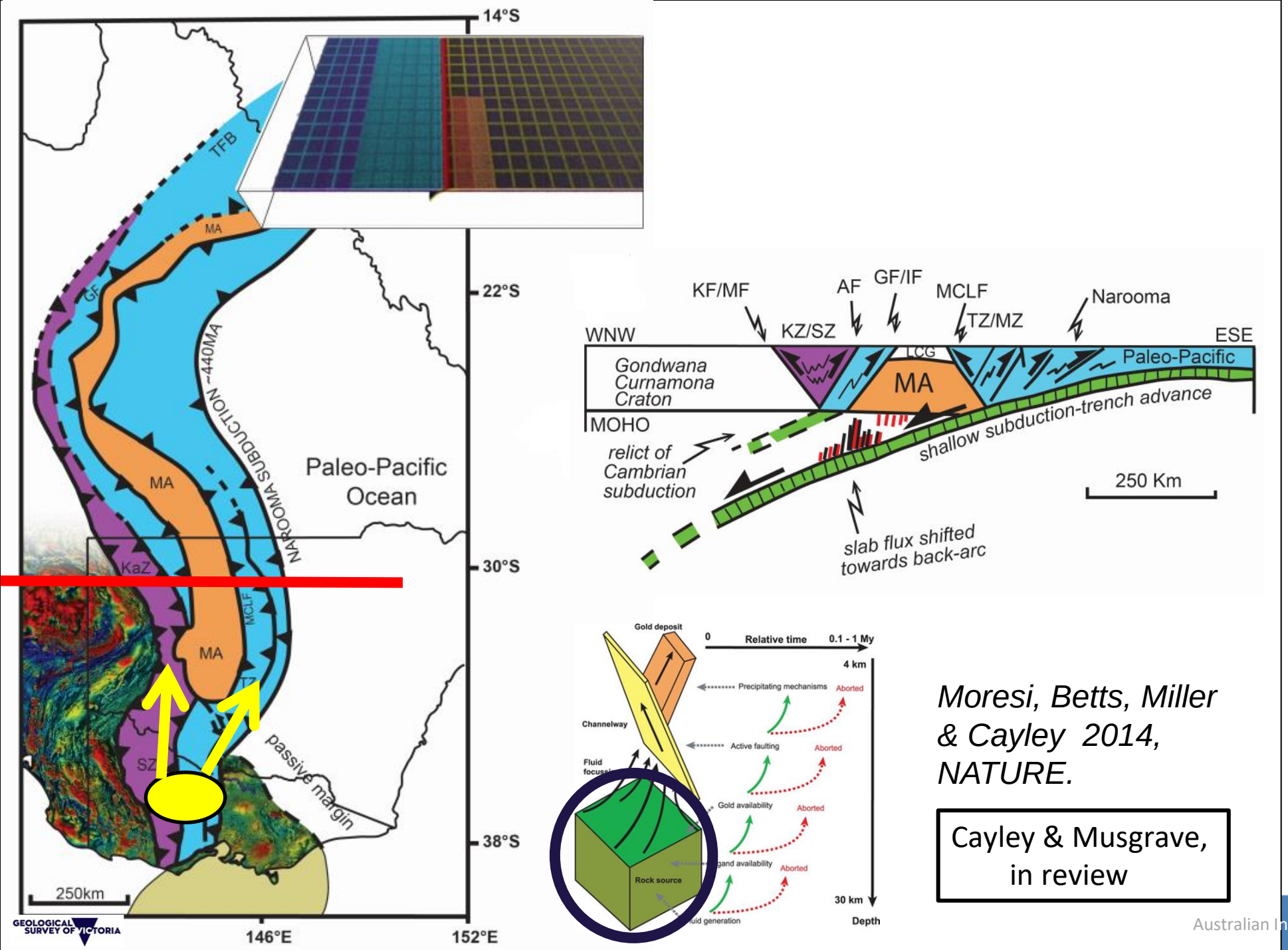


NO Lachlan Fold Belt subduction!!!

Moresi, Betts, Miller & Cayley 2014, NATURE.

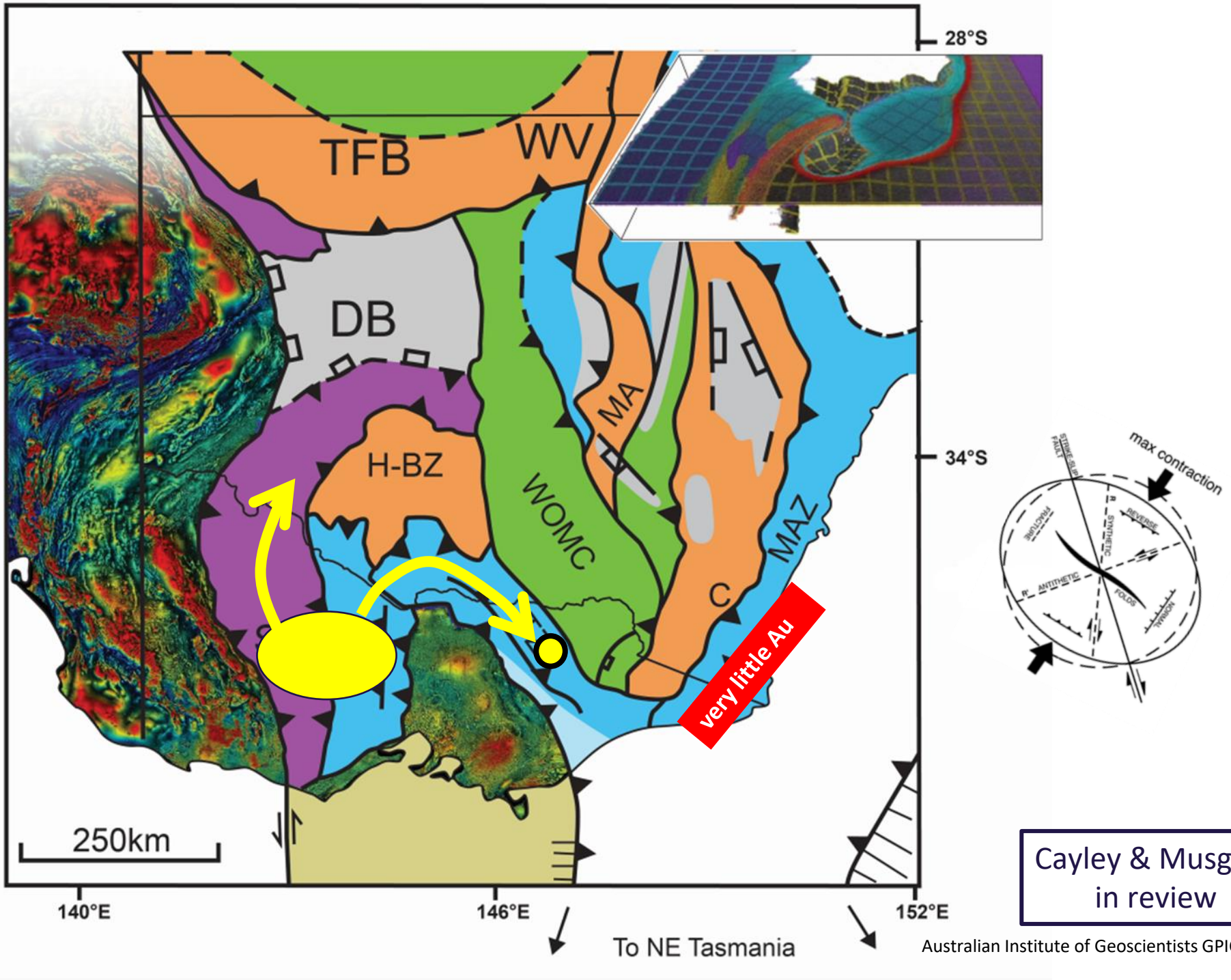
Cayley et al., 2011, Cayley 2011

Cayley & Musgrave, in review



Moresi, Betts, Miller & Cayley 2014, NATURE.

Cayley & Musgrave, in review



Cayley & Musgrave, in review

Australian Mining

Very Happy Valley with historic gold hit

June 16, 2021 News Henry Ballard

E79 Resources has hit massive gold grades at the Happy Valley gold prospect in Victoria, striking more than 100 grams of gold per tonne.

Located 280 kilometres northeast of Melbourne at Happy Valley, the Vancouver-based explorer took two drill holes to hit 160.45 grams per tonne of gold – around 32 times higher than the industry standard for "high-grade" gold.

The highlight was an intercept of 2430 grams of gold per tonne within the second drill hole, measuring 60 centimetres.

Latest News

E79 Resources 14 July 2021.

Drillhole HDV003 intersected:

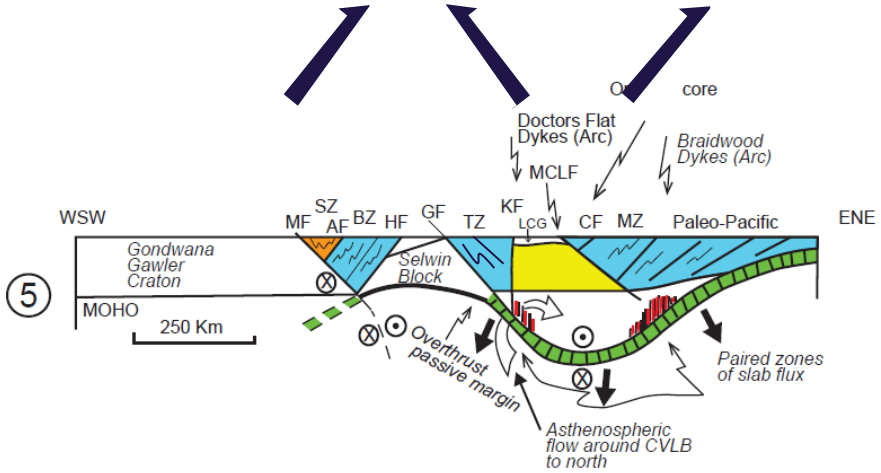
11.10m @ 160 g/t Au, including:
0.6m @ 2430 g/t Au,
0.60m @ 147 g/t Au,
0.70m @ 99 g/t Au,

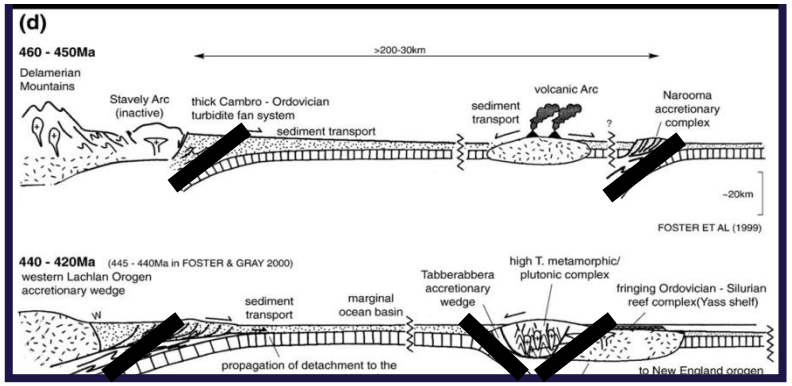
140m below historic workings.

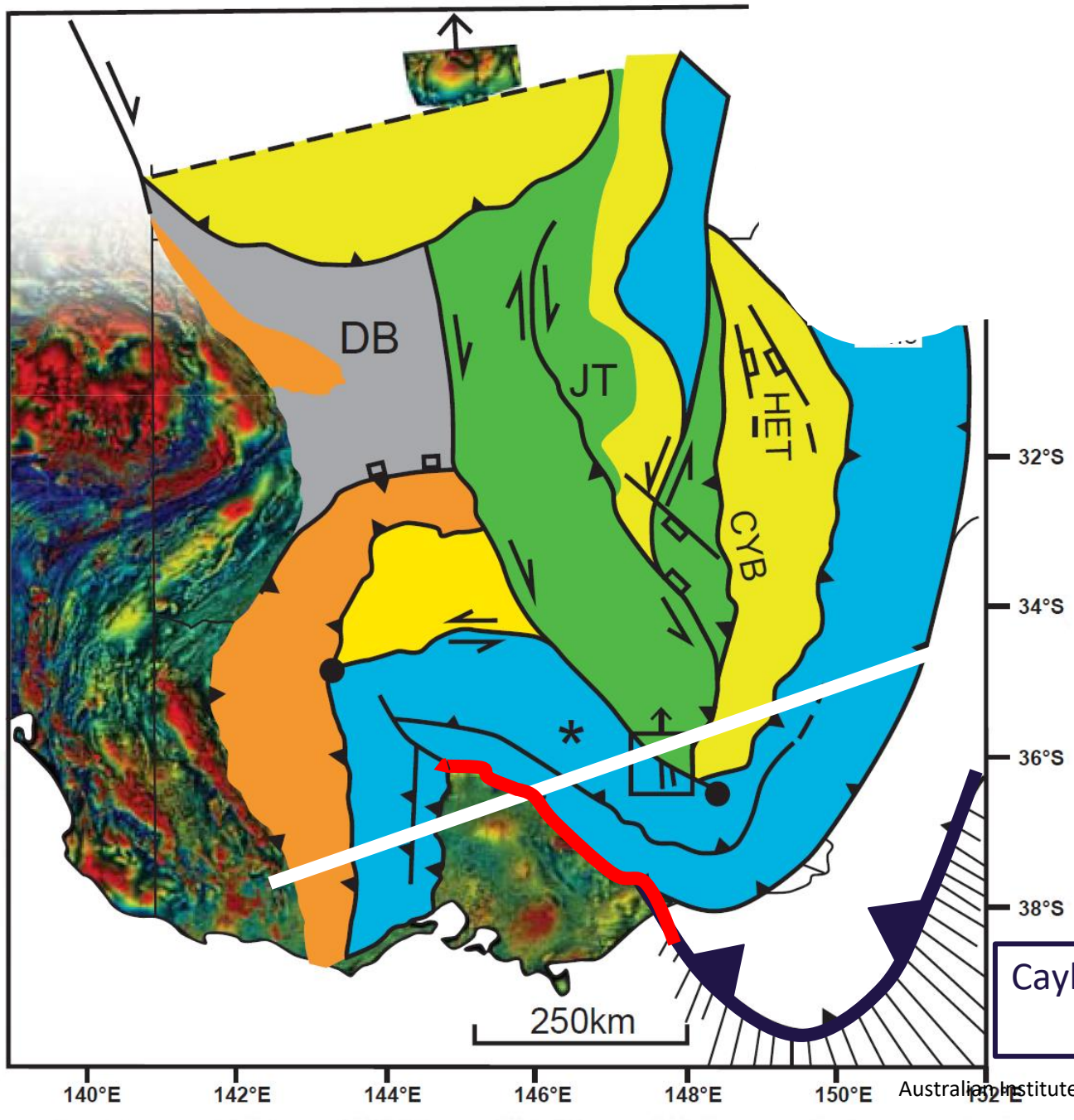
4 other intersections >3g/t Au

The Lachlan Orocline:

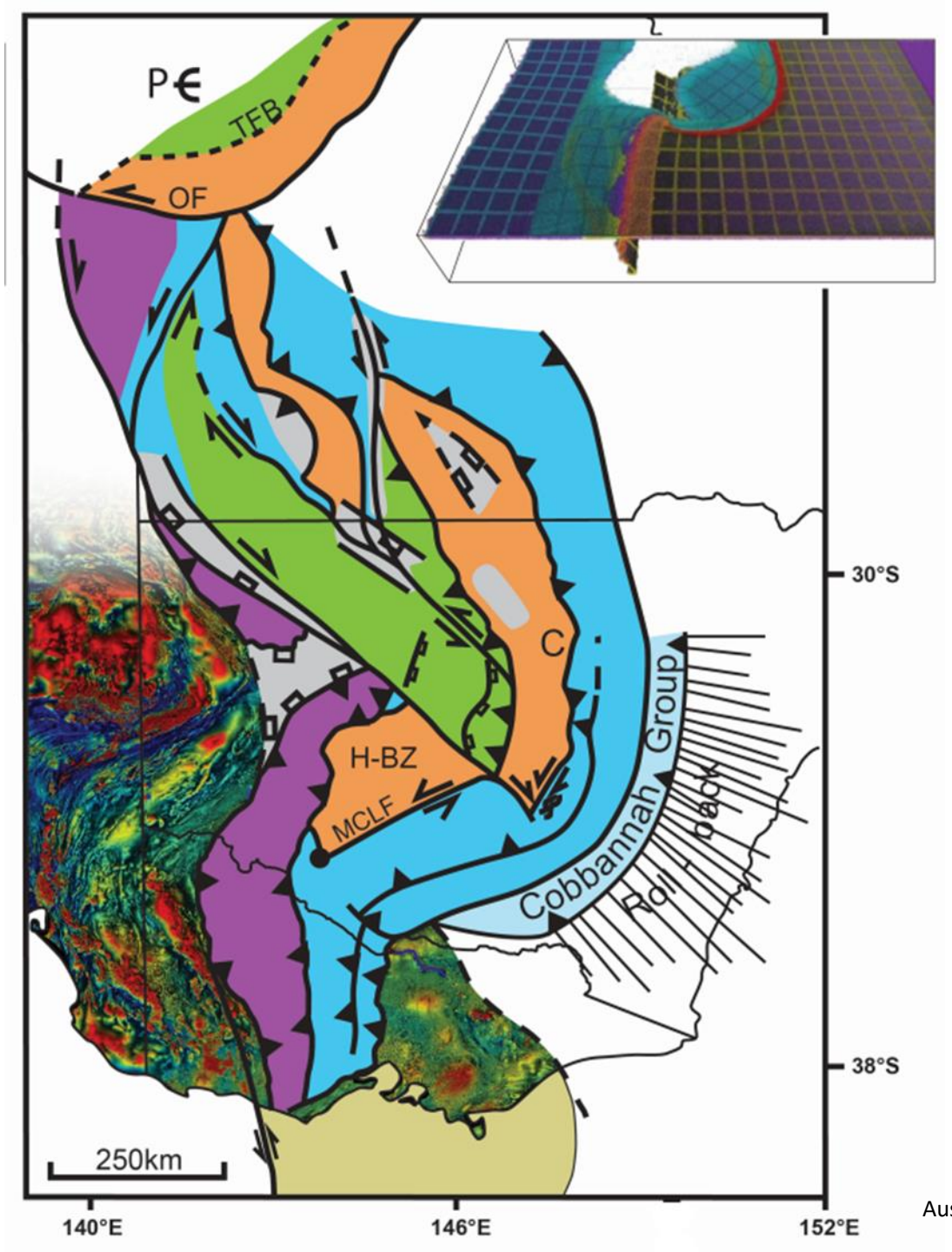
an alternative explanation of apparent vergence reversals in Ordovician LFB:







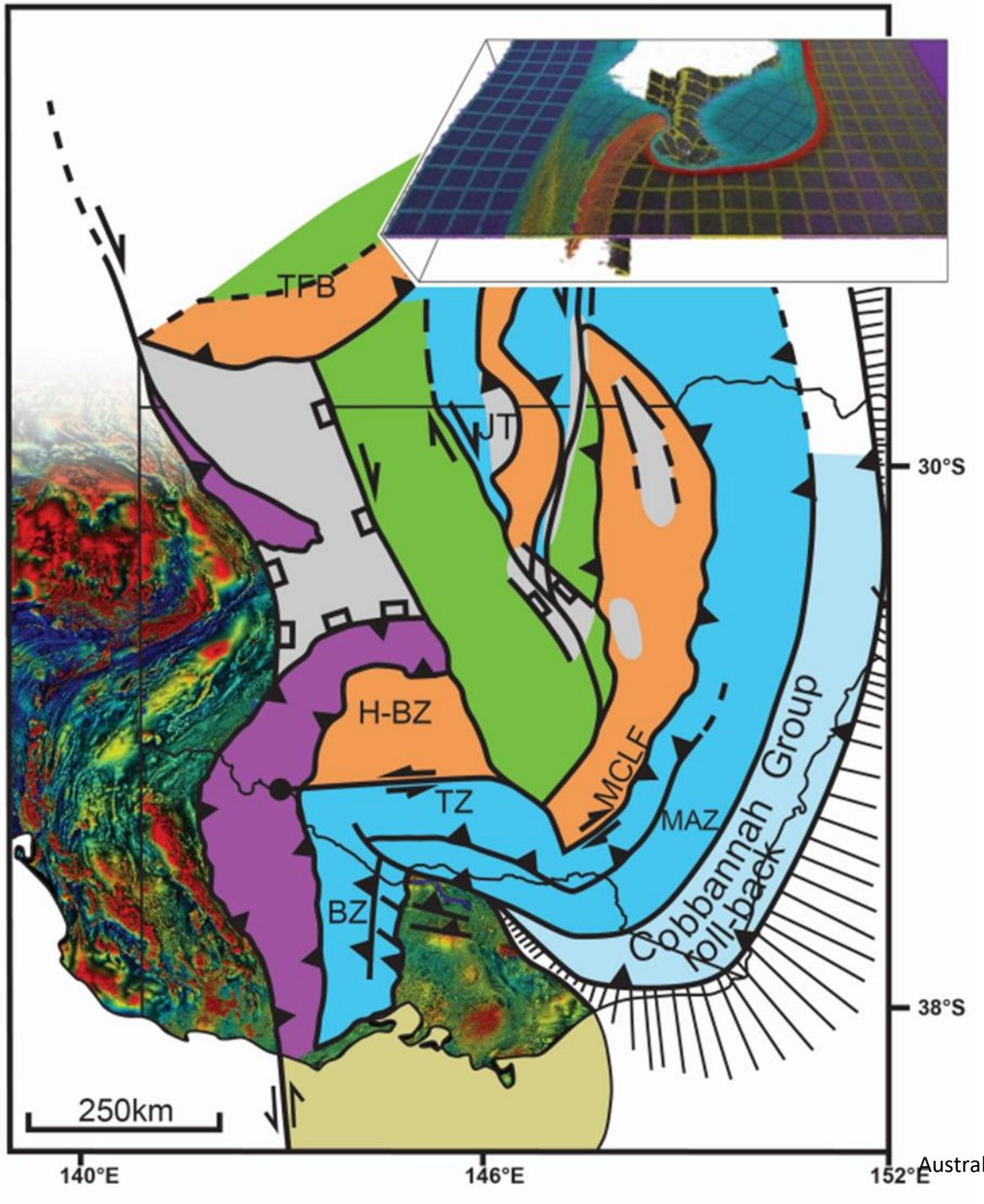
Cayley & Musgrave, in review



Moresi, Betts, Miller & Cayley 2014, NATURE.

Cayley & Musgrave, in review

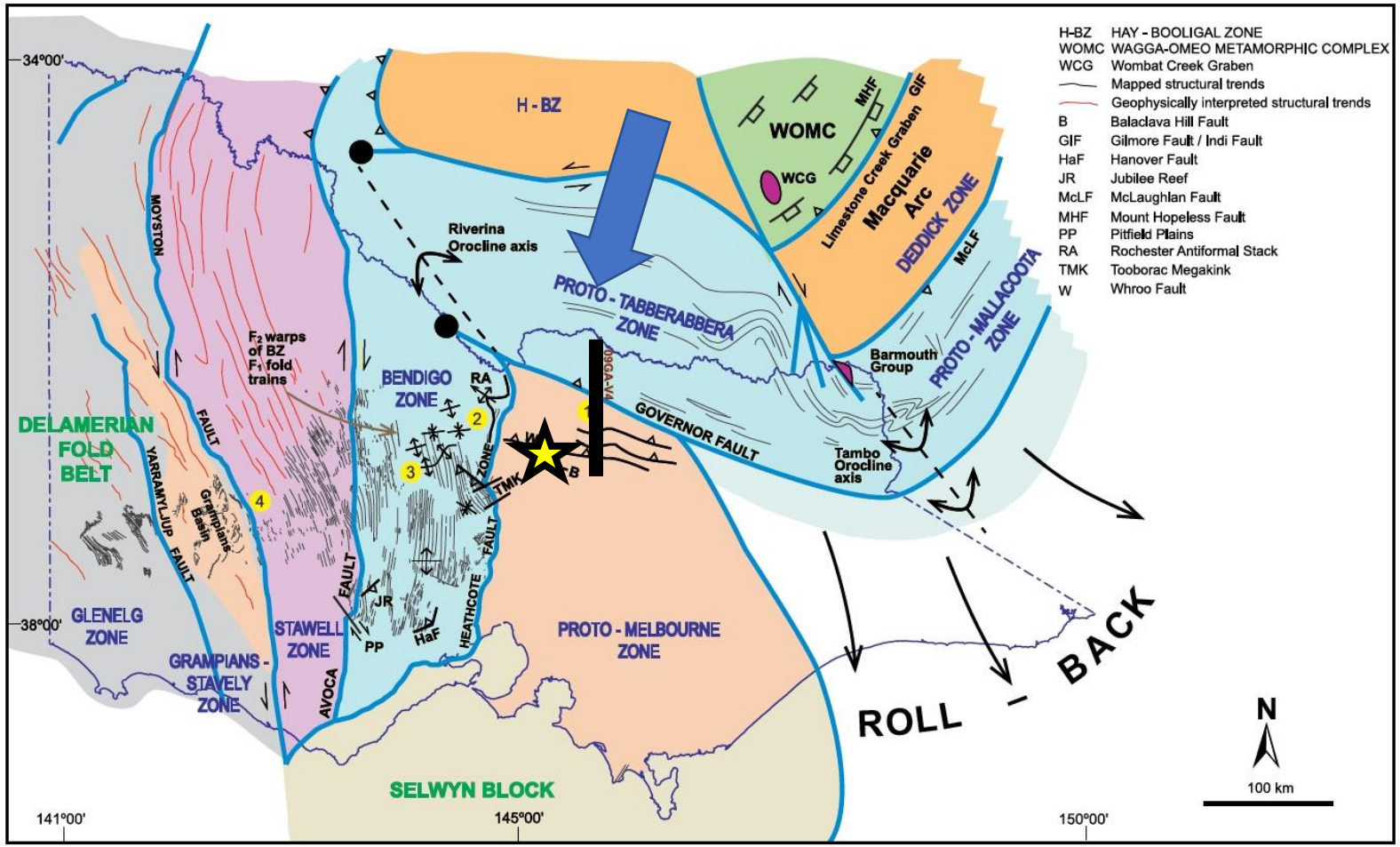
GEOLOGICAL SURVEY OF VICTORIA

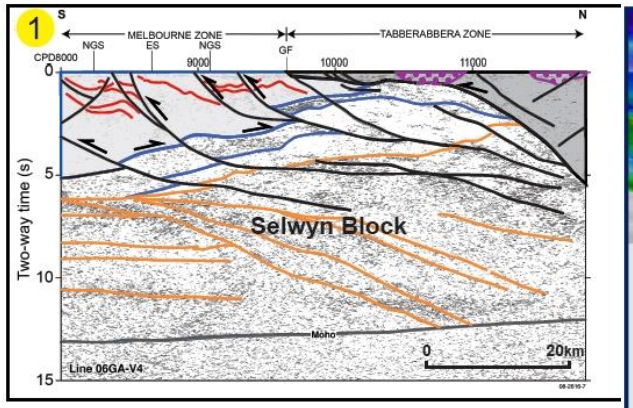


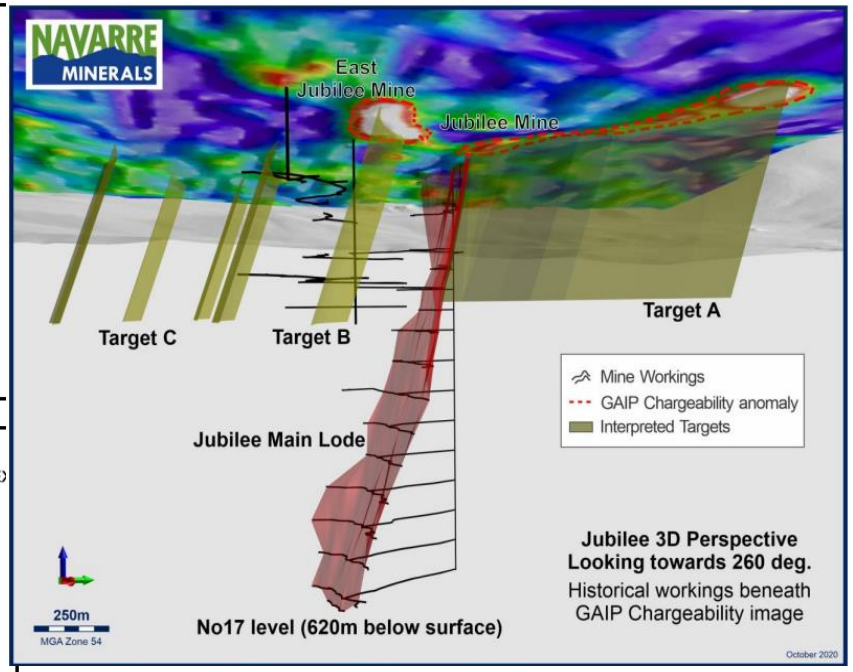
Moresi, Betts, Miller & Cayley 2014, NATURE.

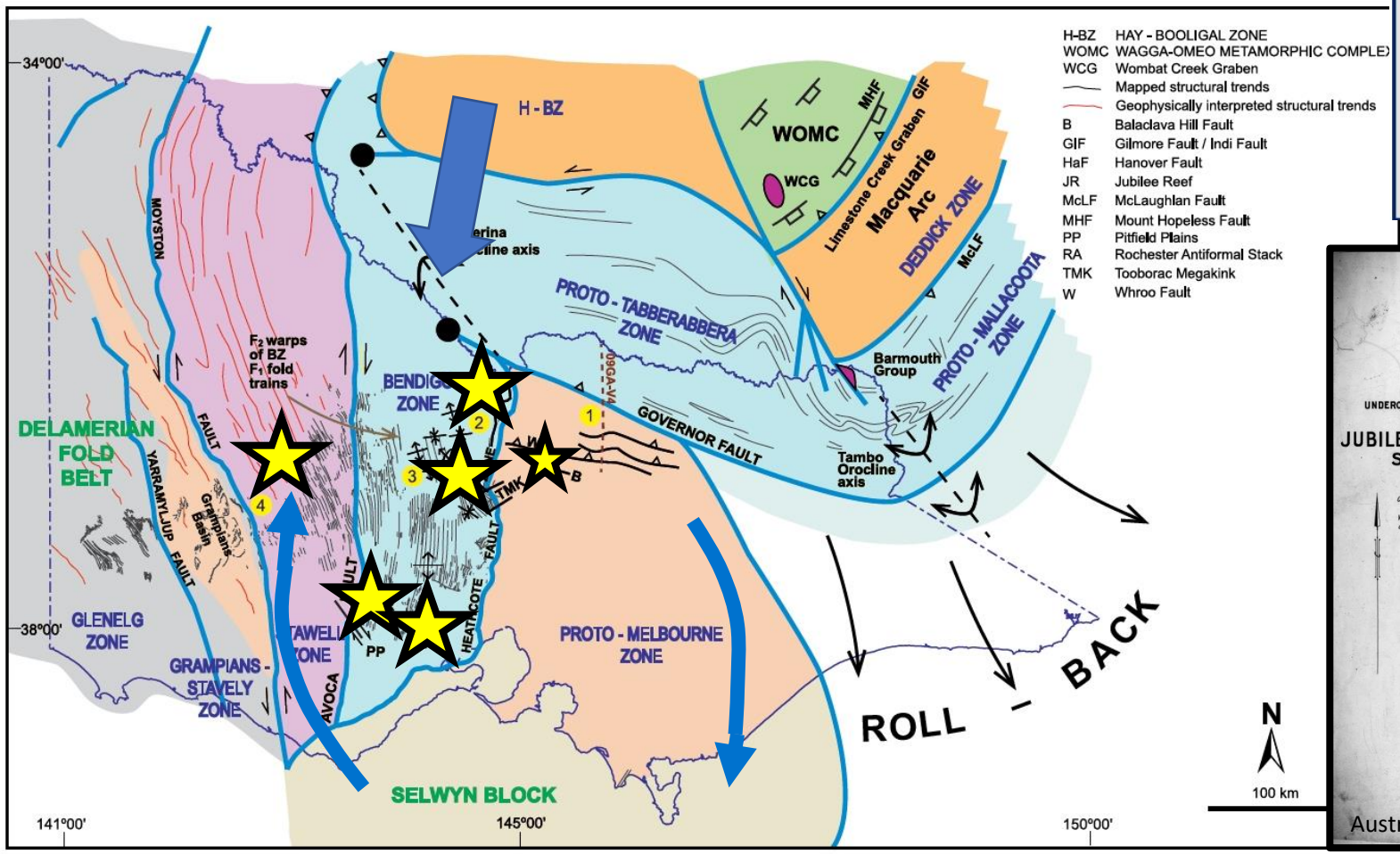
Cayley & Musgrave, in review

GEOLOGICAL SURVEY OF VICTORIA


H-BZ HAY - BOOLIGAL ZONE
WOMC WAGGA-OMEO METAMORPHIC COMPLEX
WCG Wombat Creek Graben
Mapped structural trends
Geophysically interpreted structural trends
B Balaclava Hill Fault
GIF Gilmore Fault / Indi Fault
HaF Hanover Fault
JR Jubilee Reef
McLF McLaughlan Fault
MHF Mount Hopeless Fault
PP Pitfield Plains
RA Rochester Antiformal Stack
TMK Tooborac Megakink
W Whroo Fault
34°00'
38°00'
141°00'
145°00'
150°00'
H - BZ
WOMC
WCG
MHF
GIF
Limestone Creek Graben
Macquarie Arc
DEDDICK ZONE
McLF
PROTO - MALLACOOTA ZONE
PROTO - TABBERABBERA ZONE
Riverina Orocline axis
MOYSTON
F2 warps of BZ F1 fold trains
BENDIGO ZONE
RA
TMK
GOVERNOR FAULT
Barmouth Group
Tambo Orocline axis
DELAMERIAN FOLD BELT
YARRAMYLJUP FAULT
Grampians Basin
GLENELG ZONE
STAWELL ZONE
AVOCA FAULT
JR
PP
Haf
HEATHCOTE FAULT
GRAMPIANS - STAVELY ZONE
PROTO - MELBOURNE ZONE
SELWYN BLOCK
ROLL - BACK
N
100 km


1
S
N
MELBOURNE ZONE
TABBERABBERA ZONE
NGS
ES
NGS
GF
CPD8000
9000
10000
11000
Two-way time (s)
Selwyn Block
Moho
Line 06GA-V4
0
20km


NAVARRE MINERALS
East Jubilee Mine
Jubilee Mine
Target A
Target C
Target B
Mine Workings
GAIP Chargeability anomaly
Interpreted Targets
Jubilee Main Lode
Jubilee 3D Perspective
Looking towards 260 deg.
Historical workings beneath
GAIP Chargeability image
250m
MGA Zone 54
No17 level (620m below surface)
October 2020


34°00'
38°00'
141°00'
145°00'
150°00'
H-BZ
WOMC
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Limestone Creek Graben
Macquarie Arc
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AVOCA FAULT
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F2 warps of BZ F1 fold trains
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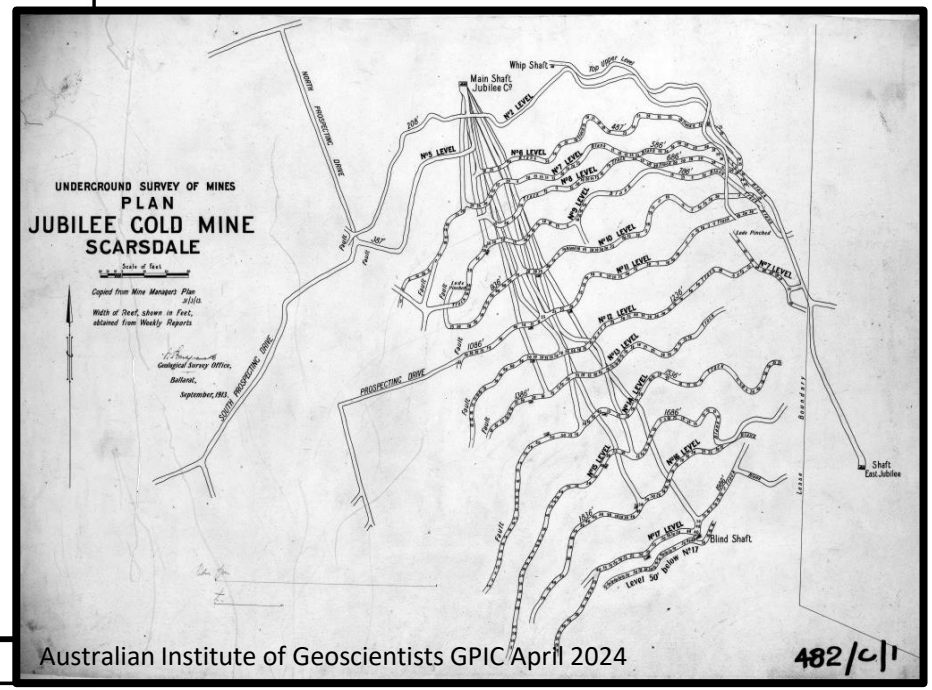
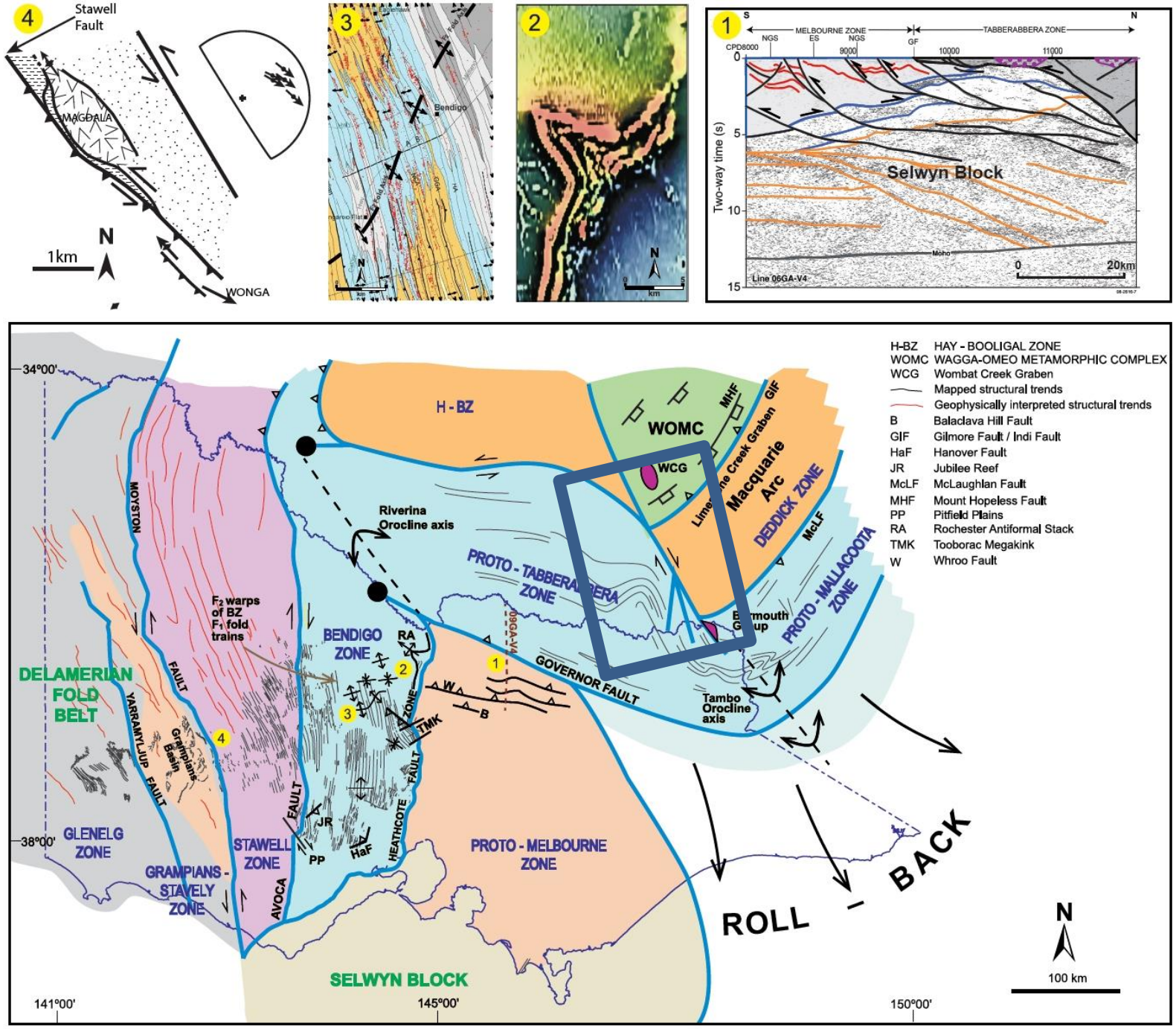
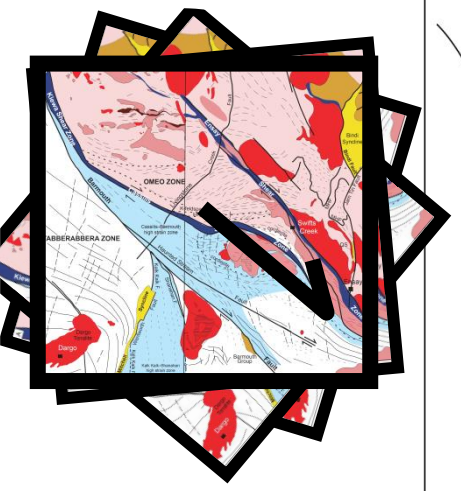
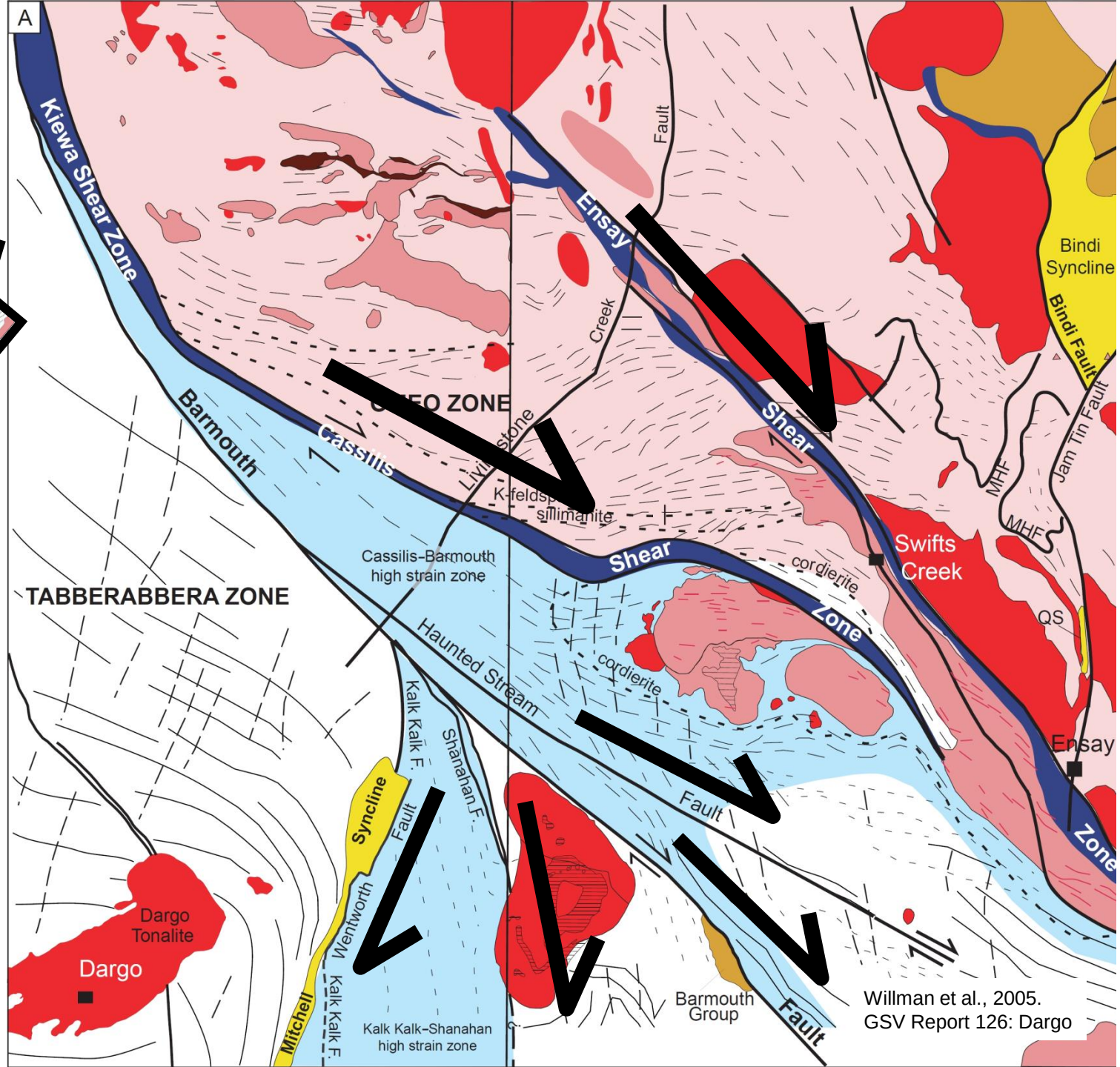
N
100 km


UNDERGROUND SURVEY OF MINES
PLAN
JUBILEE GOLD MINE
SCARSDALE
Main Shaft, Jubilee Co
Whip Shaft
Blind Shaft
Shaft East Jubilee
PROSPECTING DRIVE

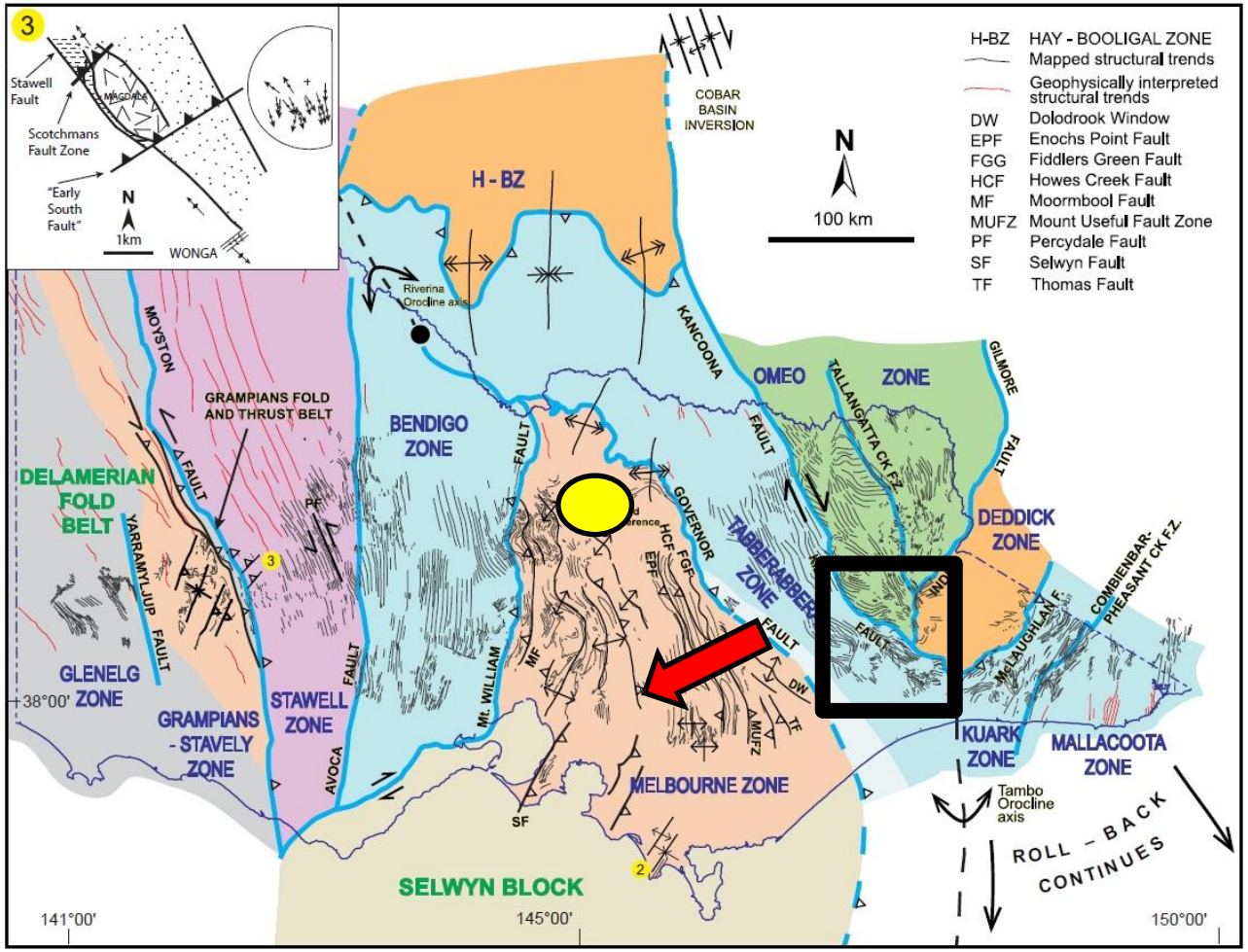

4
Stawell Fault
MAGDALA
1km
N
WONGA
3
Bendigo
2
1
S
N
MELBOURNE ZONE
TABBERABBERA ZONE
NGS
ES
NGS
GF
CPD8000
9000
10000
11000
Two-way time (s)
Selwyn Block
Moho
0
20km
Line 06GA-V4
H-BZ HAY - BOOLIGAL ZONE
WOMC WAGGA-OMEO METAMORPHIC COMPLEX
WCG Wombat Creek Graben
Mapped structural trends
Geophysically interpreted structural trends
B Balaclava Hill Fault
GIF Gilmore Fault / Indi Fault
HaF Hanover Fault
JR Jubilee Reef
McLF McLaughlan Fault
MHF Mount Hopeless Fault
PP Pitfield Plains
RA Rochester Antiformal Stack
TMK Tooborac Megakink
W Whroo Fault
34°00'
38°00'
141°00'
145°00'
150°00'
H - BZ
WOMC
WCG
MHF
GIF
Macquarie Arc
DEDDICK ZONE
McLF
PROTO - MALLACOOTA ZONE
Riverina Orocline axis
PROTO - TABBERABBERA ZONE
Tambo Orocline axis
GOVERNOR FAULT
MOYSTON FAULT
DELAMERIAN FOLD BELT
YARRAMYLJUP FAULT
Grampians Basin
BENDIGO ZONE
RA
TMK
HEATHCOTE FAULT
AVOCA FAULT
JR
PP
HaF
STAWELL ZONE
GLENELG ZONE
GRAMPIANS - STAVELY ZONE
PROTO - MELBOURNE ZONE
SELWYN BLOCK
ROLL - BACK
N
100 km

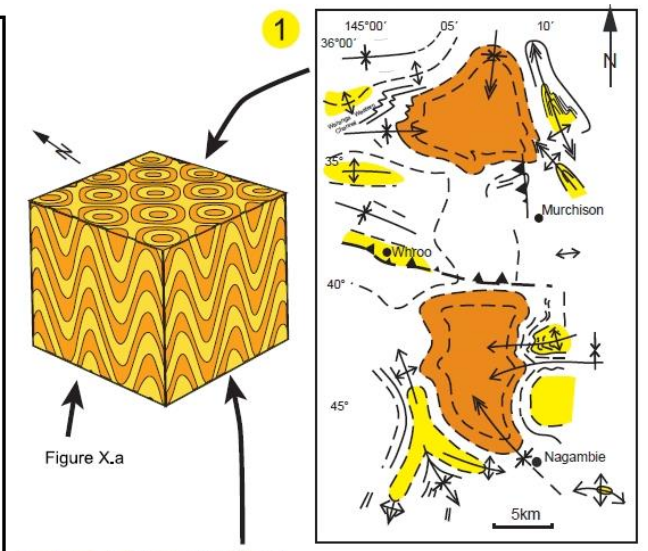


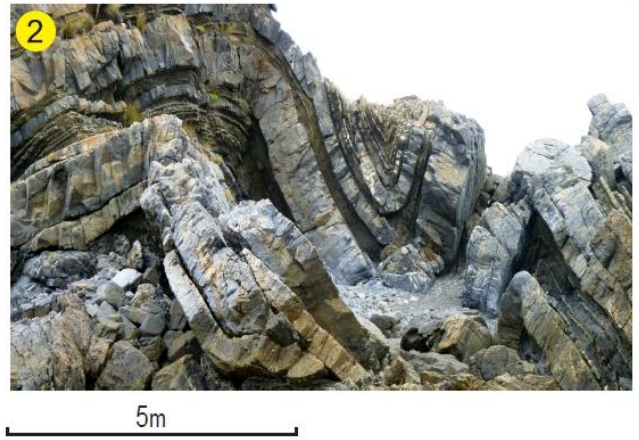
420 [illegible] (Barmouth Group)

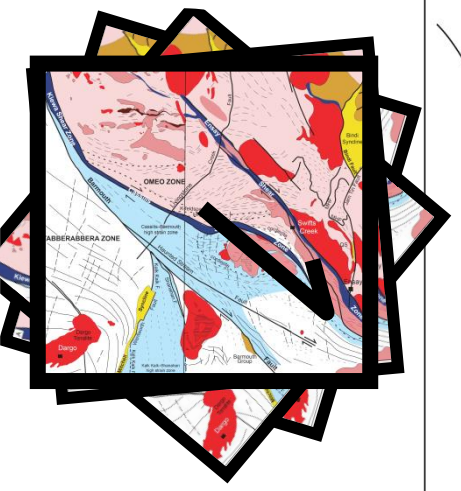


Willman et al., 2005.
GSV Report 126: Dargo

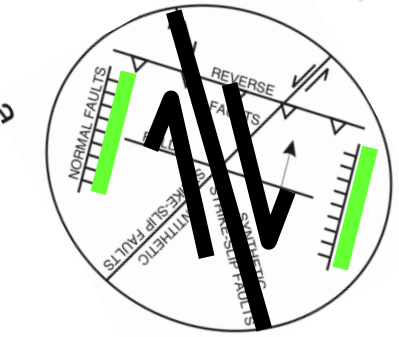

3
Stawell Fault
Scotchmans Fault Zone
"Early South Fault"
N
1km
WONGA
COBAR BASIN INVERSION
H-BZ HAY - BOOLIGAL ZONE
Mapped structural trends
Geophysically interpreted structural trends
DW Dolodrook Window
EPF Enochs Point Fault
FGG Fiddlers Green Fault
HCF Howes Creek Fault
MF Moormbool Fault
MUFZ Mount Useful Fault Zone
PF Percydale Fault
SF Selwyn Fault
TF Thomas Fault
N
100 km
H - BZ
Riverina Orocline axis
KANCOONA FAULT
OMEO ZONE
TALLANGATTA CK F.Z.
GILMORE FAULT
MOYSTON FAULT
GRAMPIANS FOLD AND THRUST BELT
BENDIGO ZONE
DELAMERIAN FOLD BELT
YARRAMYLJUP FAULT
PF
3
GOVERNOR FAULT
HCF FGF EPF
TABBERABBERA ZONE
DEDDICK ZONE
COMBIENBAR-PHEASANT CK F.Z.
McLAUGHLAN F.
GLENELG ZONE
38°00'
GRAMPIANS - STAVELY ZONE
STAWELL ZONE
AVOCA FAULT
Mt. WILLIAM FAULT
MF
DW
TF
MUFZ
KUARK ZONE
MALLACOOTA ZONE
MELBOURNE ZONE
SF
2
Tambo Orocline axis
ROLL - BACK CONTINUES
SELWYN BLOCK
141°00'
145°00'
150°00'


1
Figure X.a
145°00'
05'
10'
36°00'
35°
Murchison
Whroo
40°
45°
Nagambie
5km
N

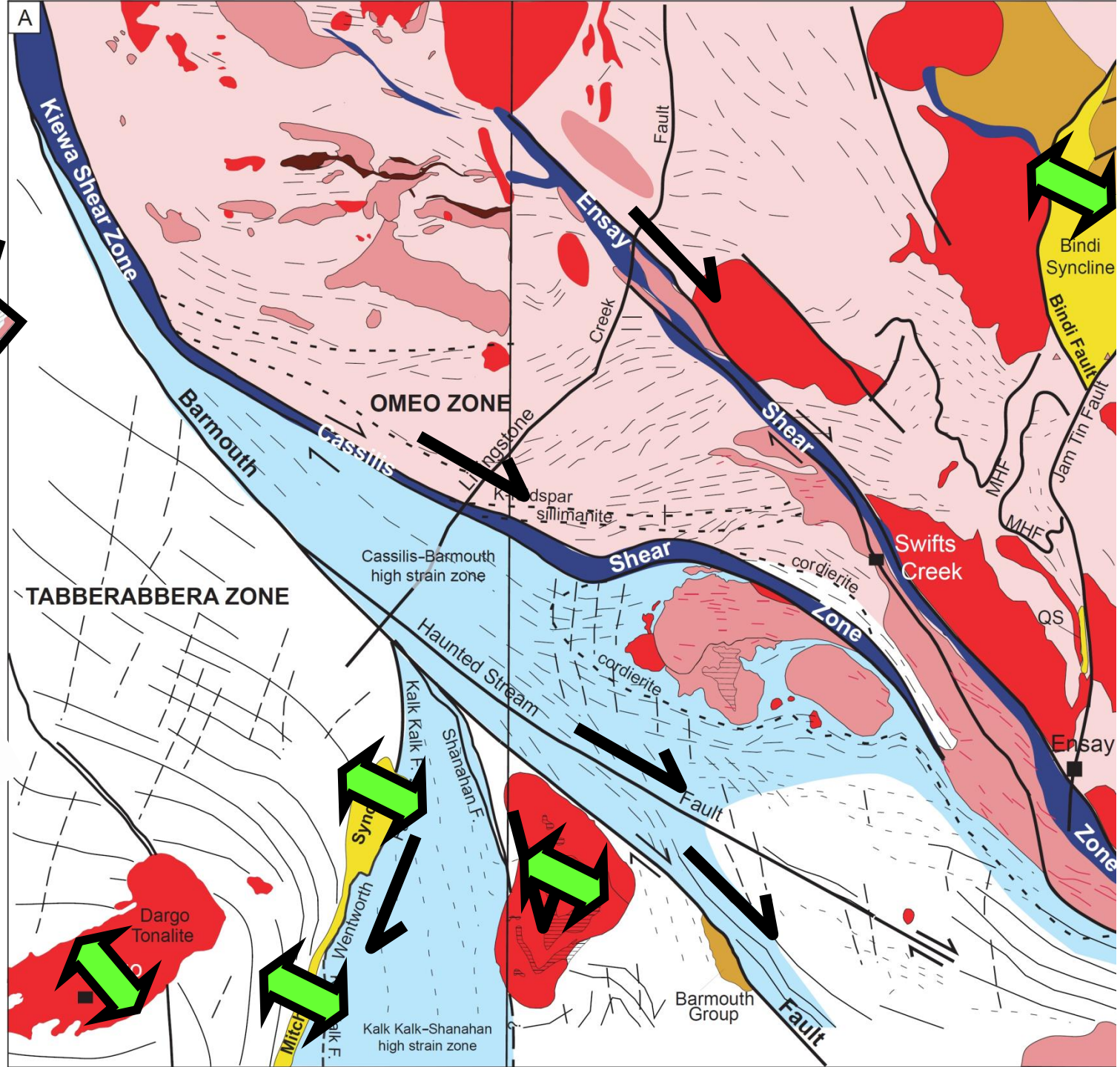

2
5m

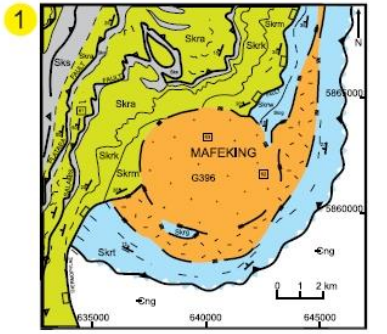


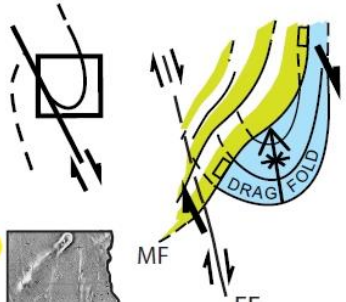
415-410 Ma
Wentworth Group

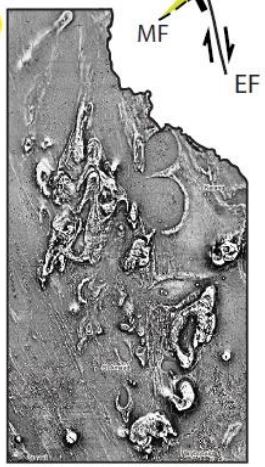


Willman et al., 2005.
GSV Report 126: Dargo

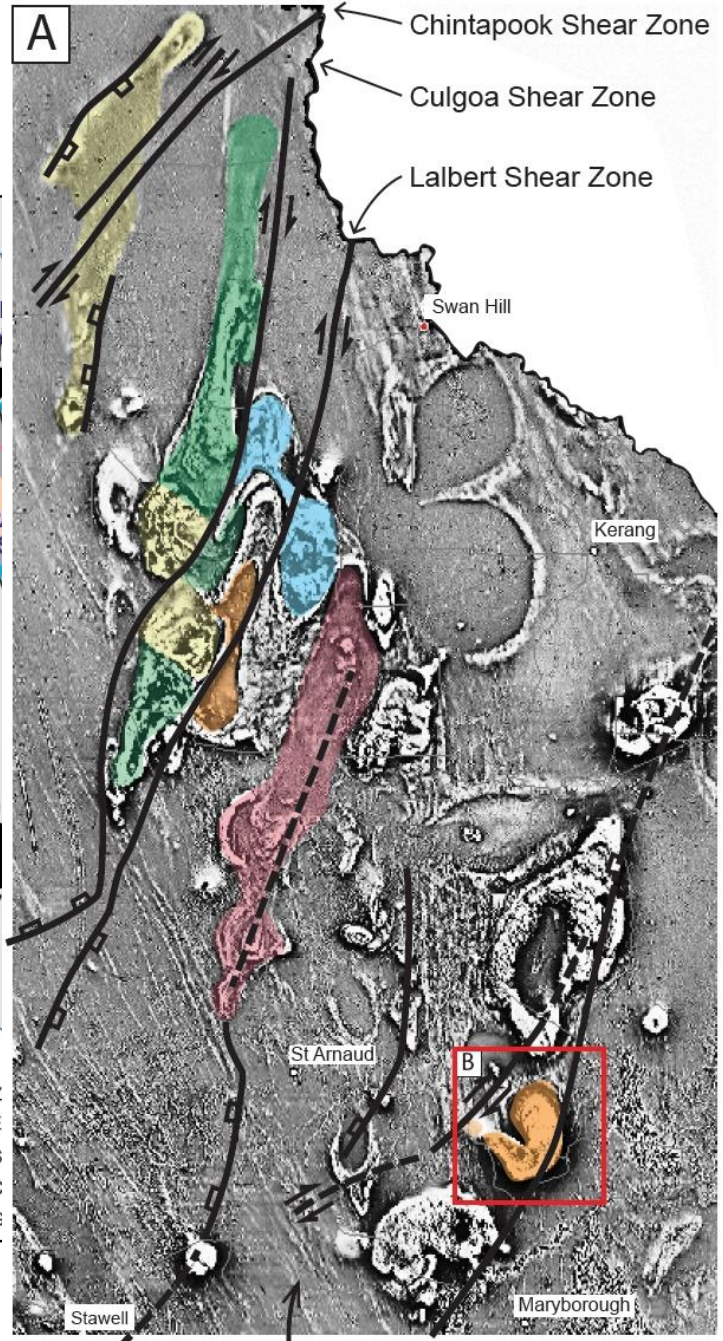


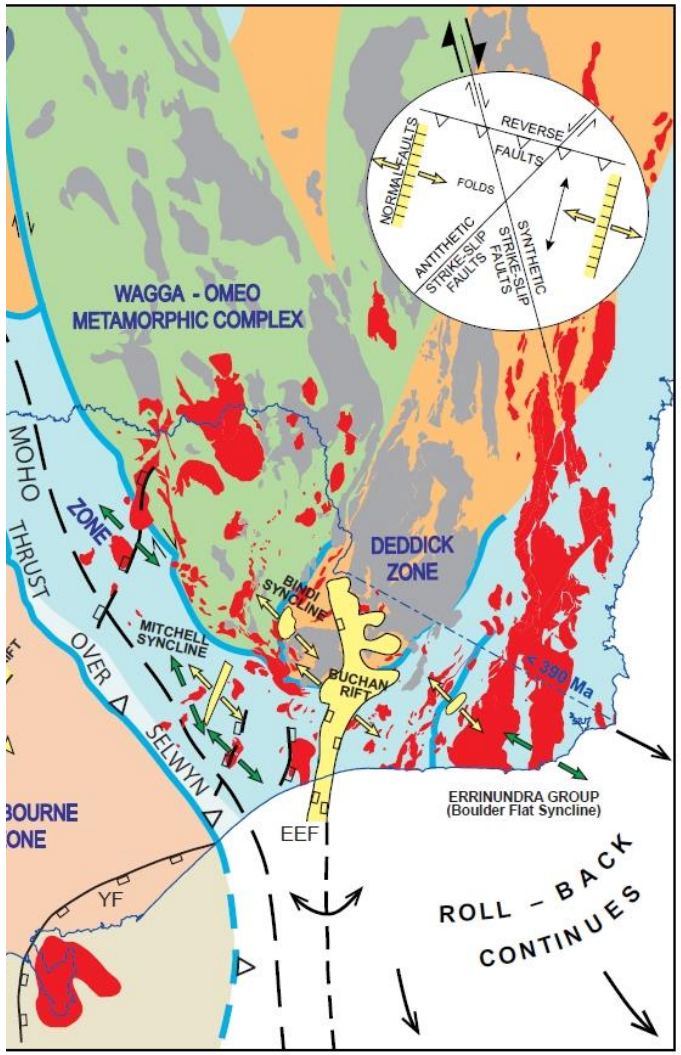


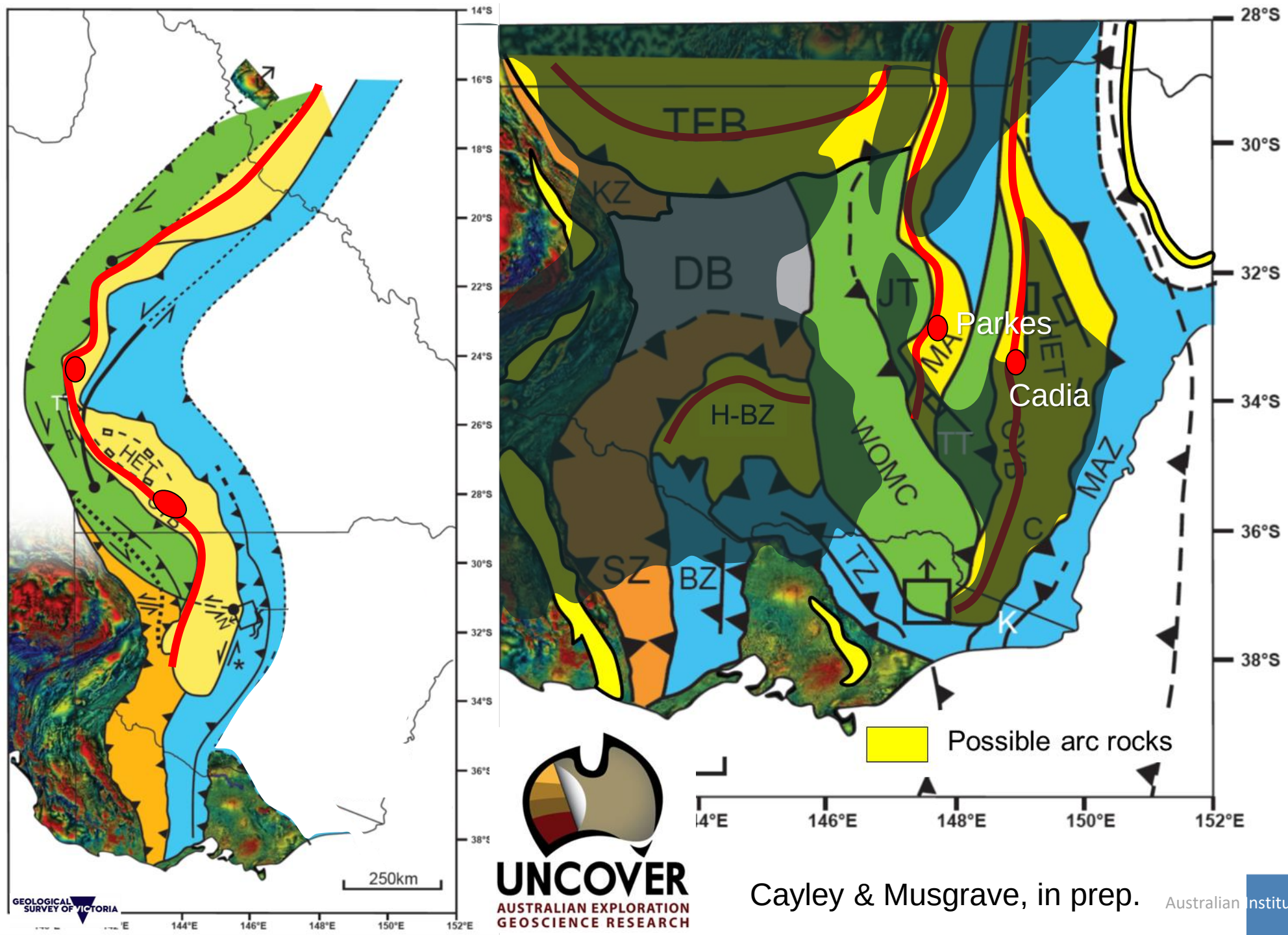




See also figure x.

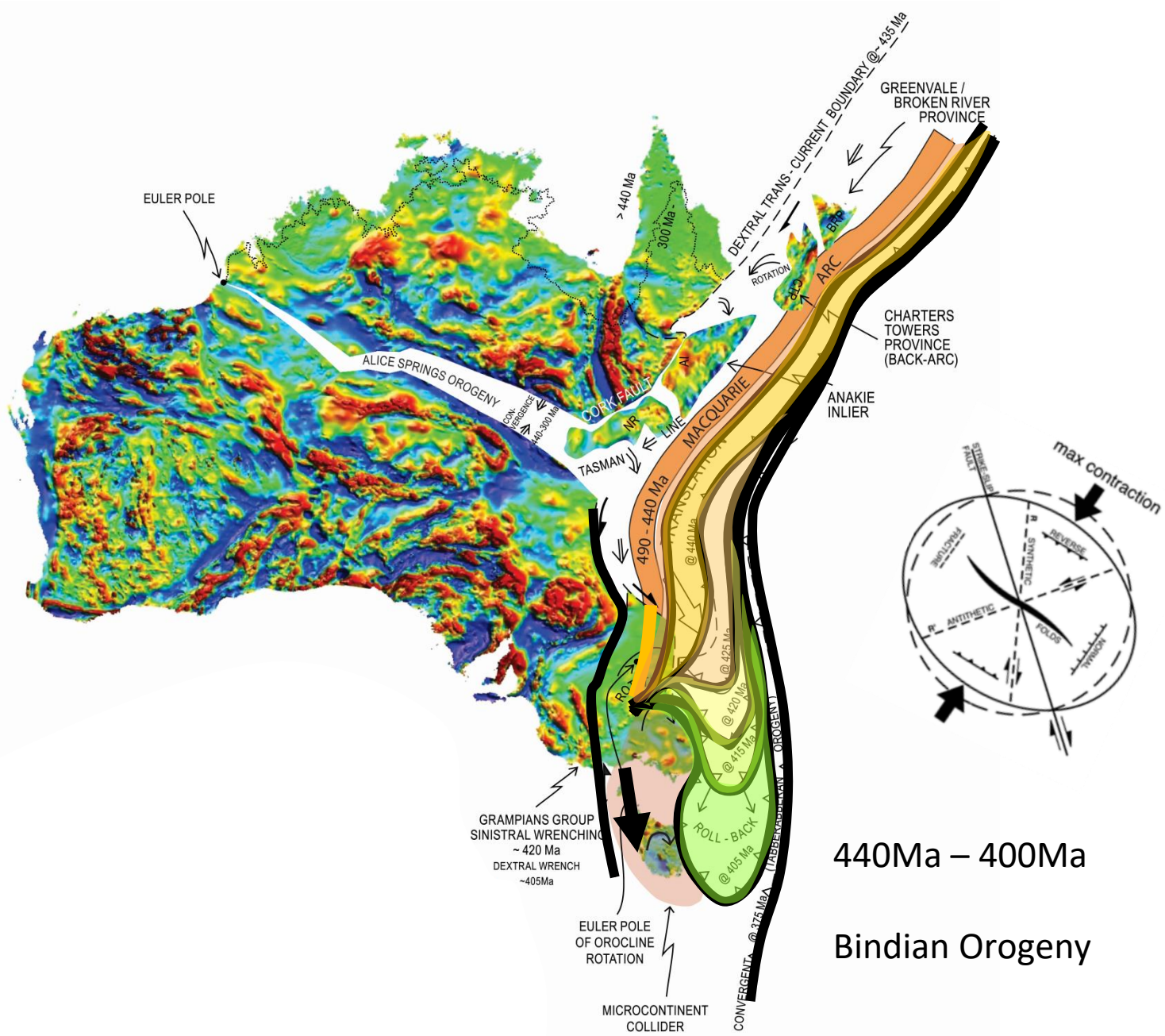






UNCOVER
AUSTRALIAN EXPLORATION GEOSCIENCE RESEARCH

Cayley & Musgrave, in prep.



Cayley & Musgrave, in review

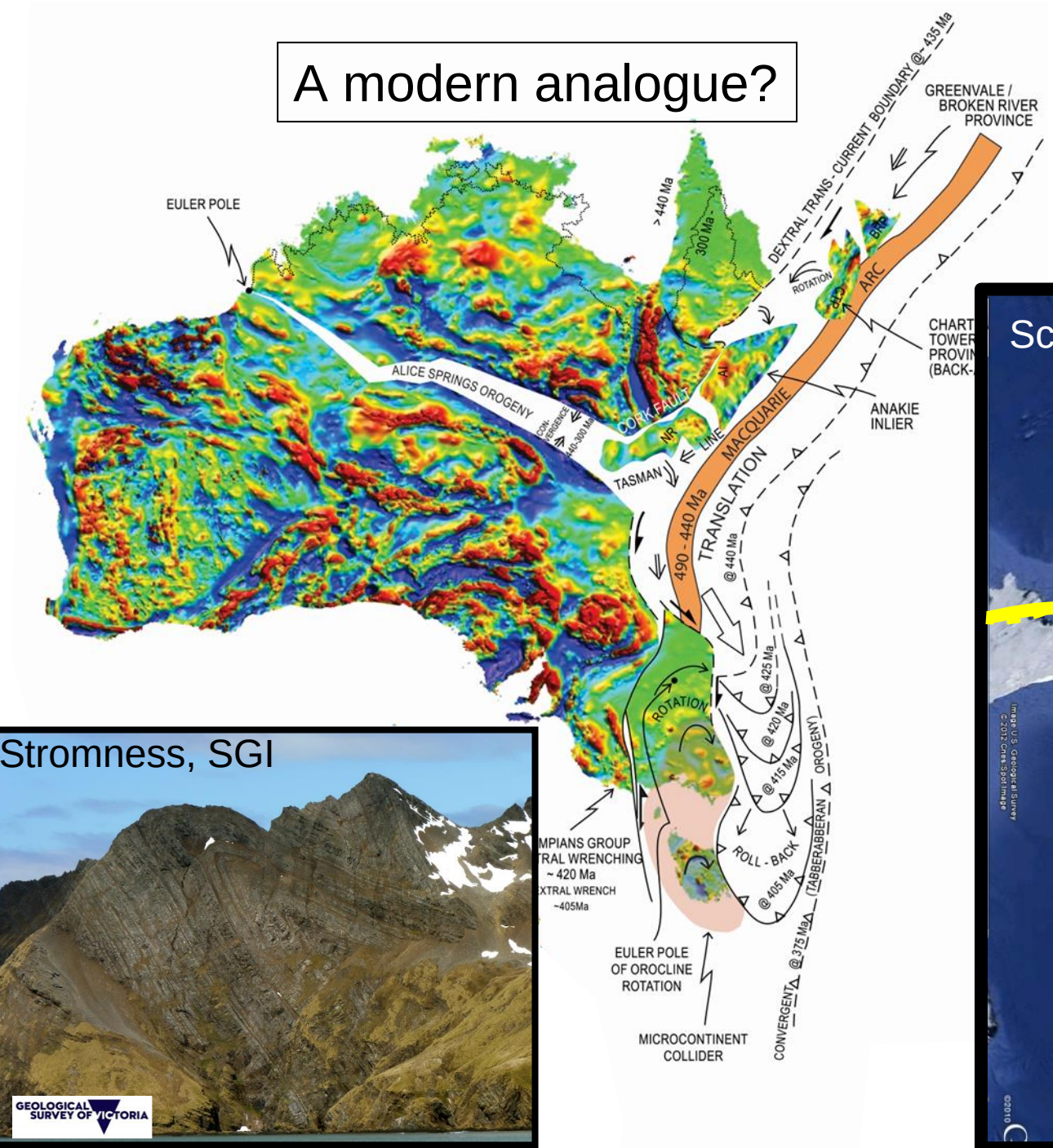
440Ma – 400Ma

Bindian Orogeny

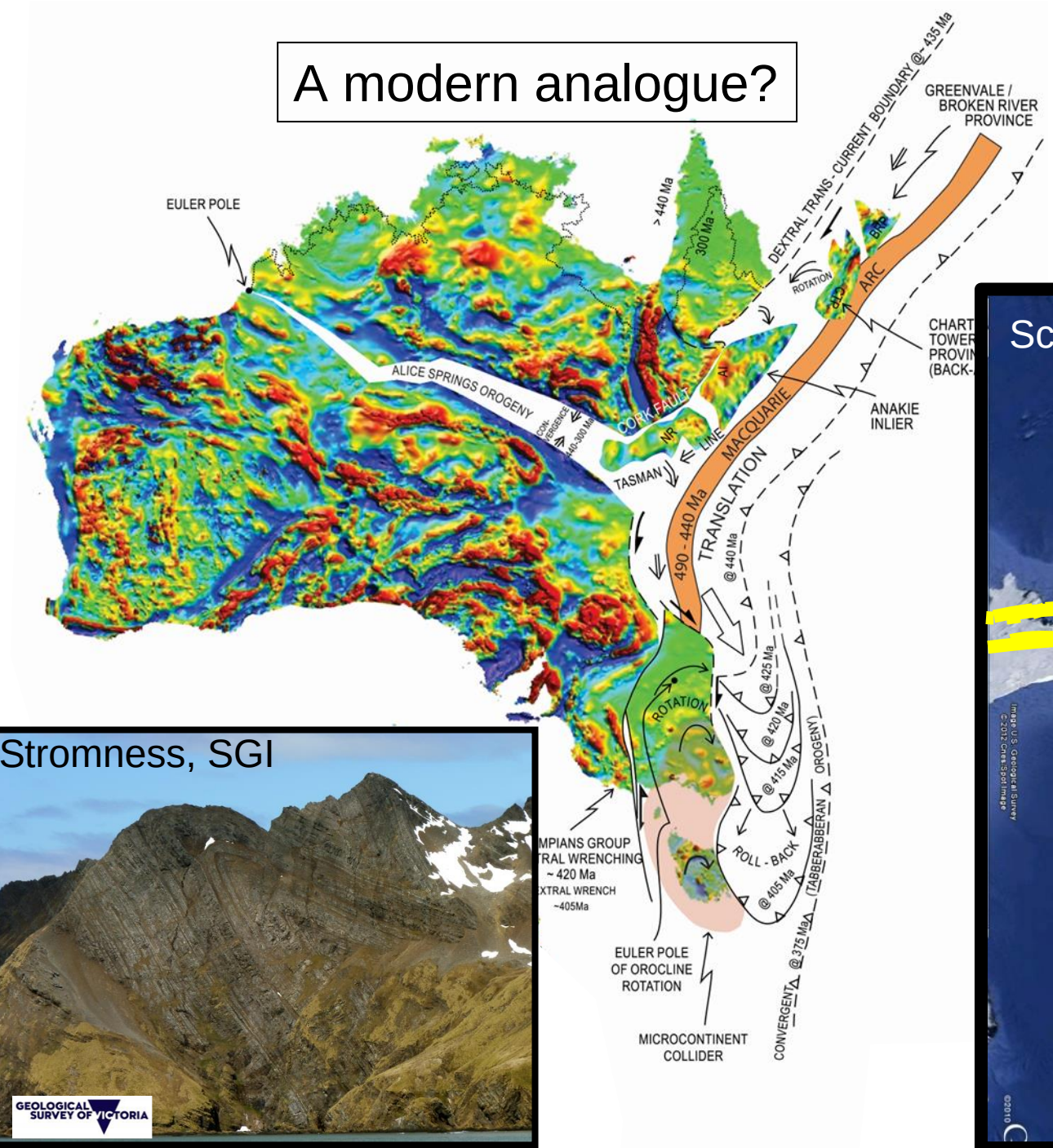
The Scotia Arc:

A modern analogue
for Lachlan Orocline growth

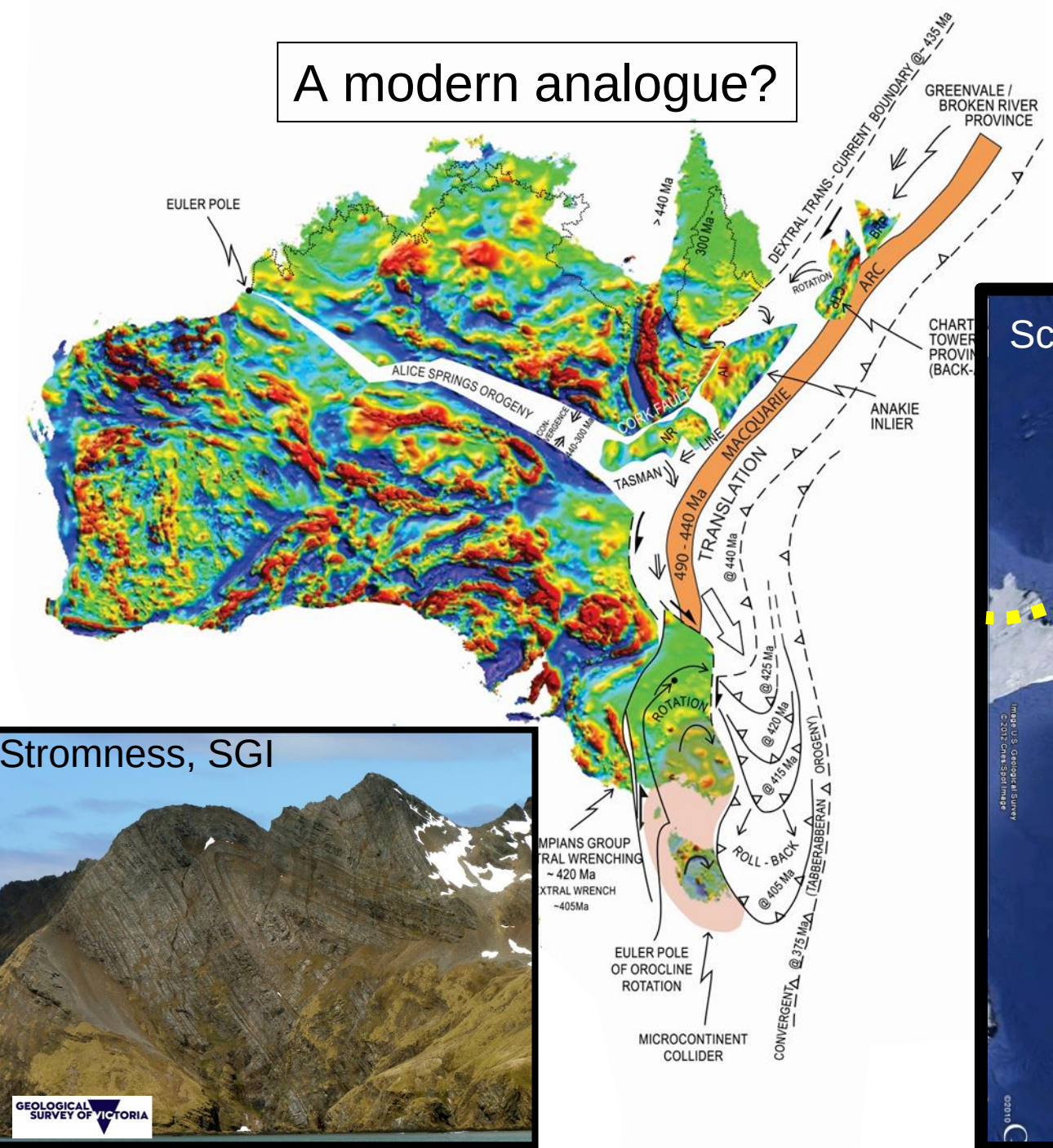
A modern analogue?

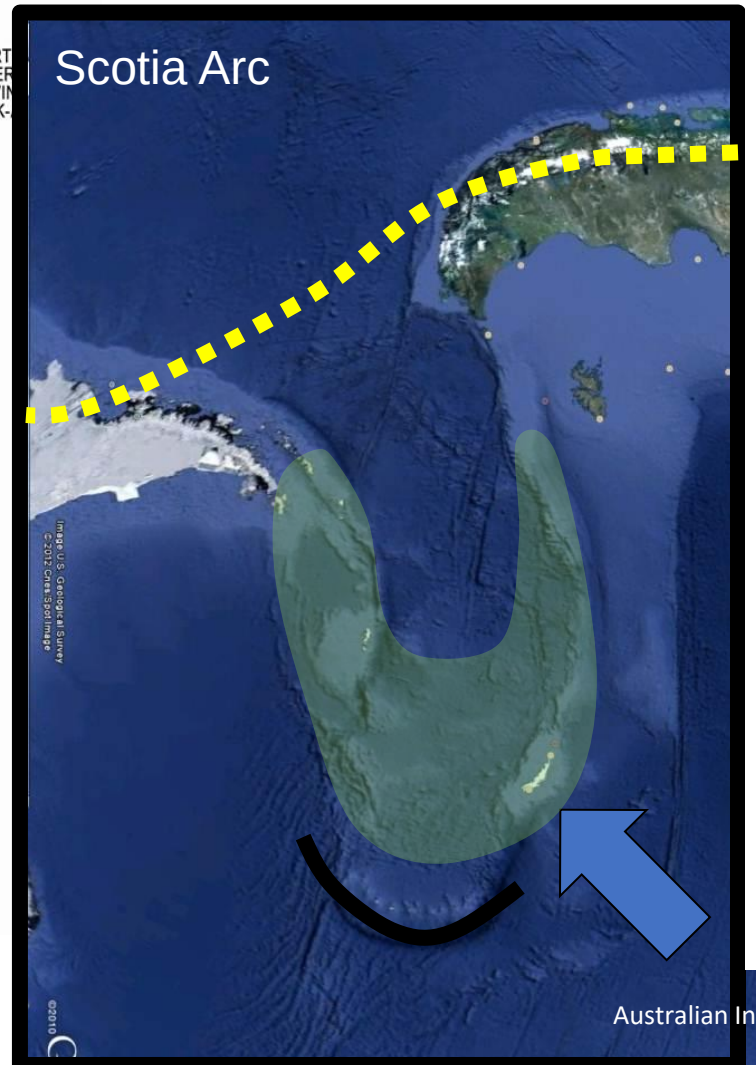


A modern analogue?



A modern analogue?



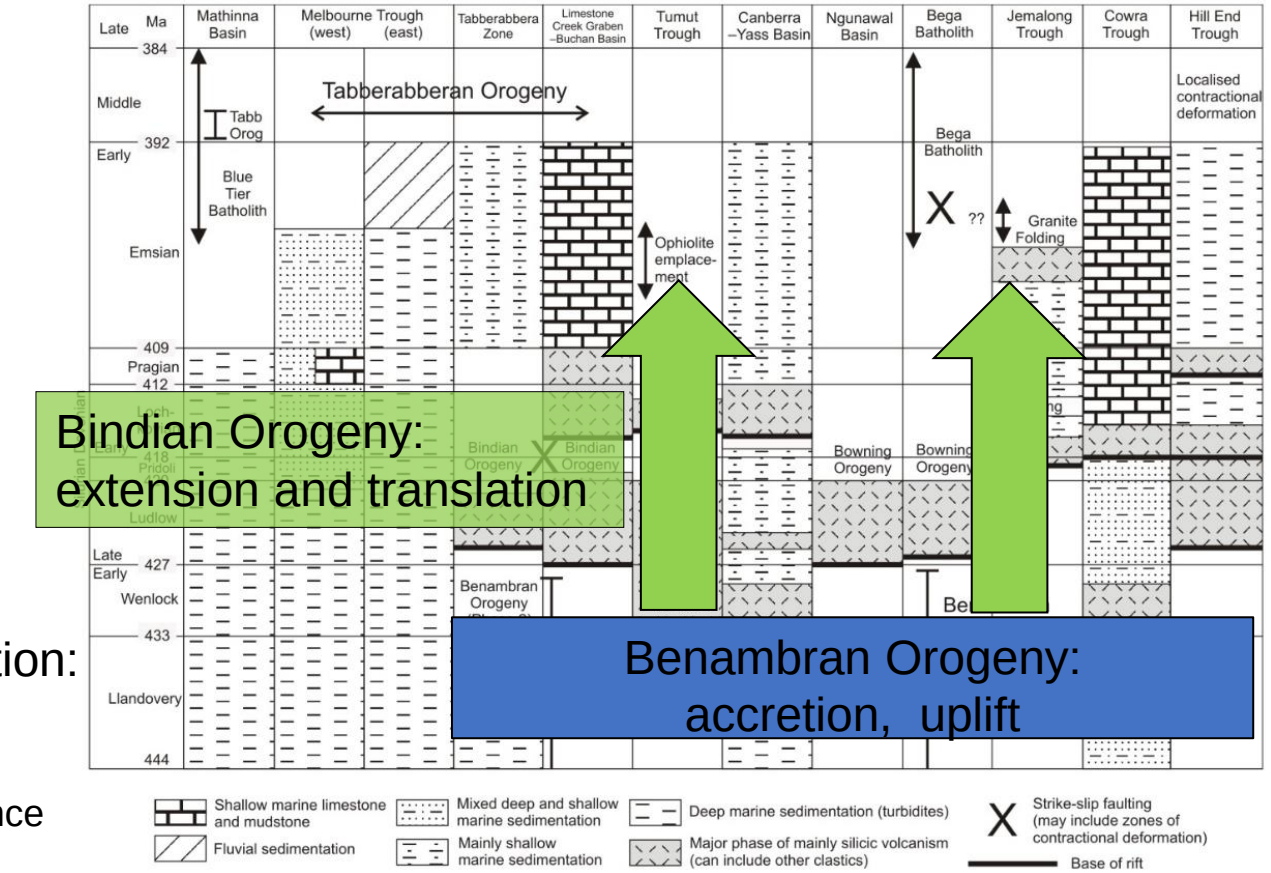


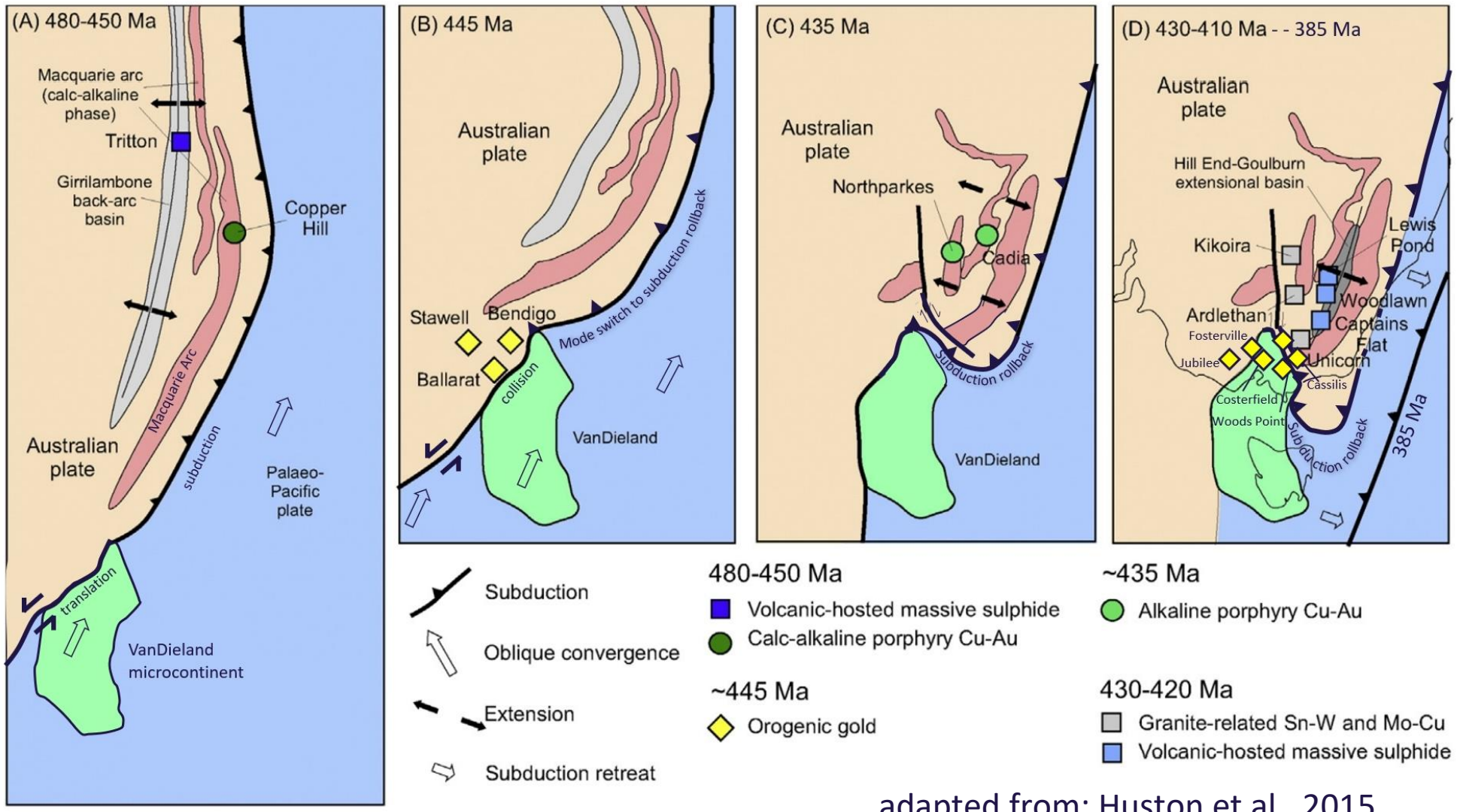
Models that link extension to sedimentation in the LFB:

Fergusson, 2010: AJES:

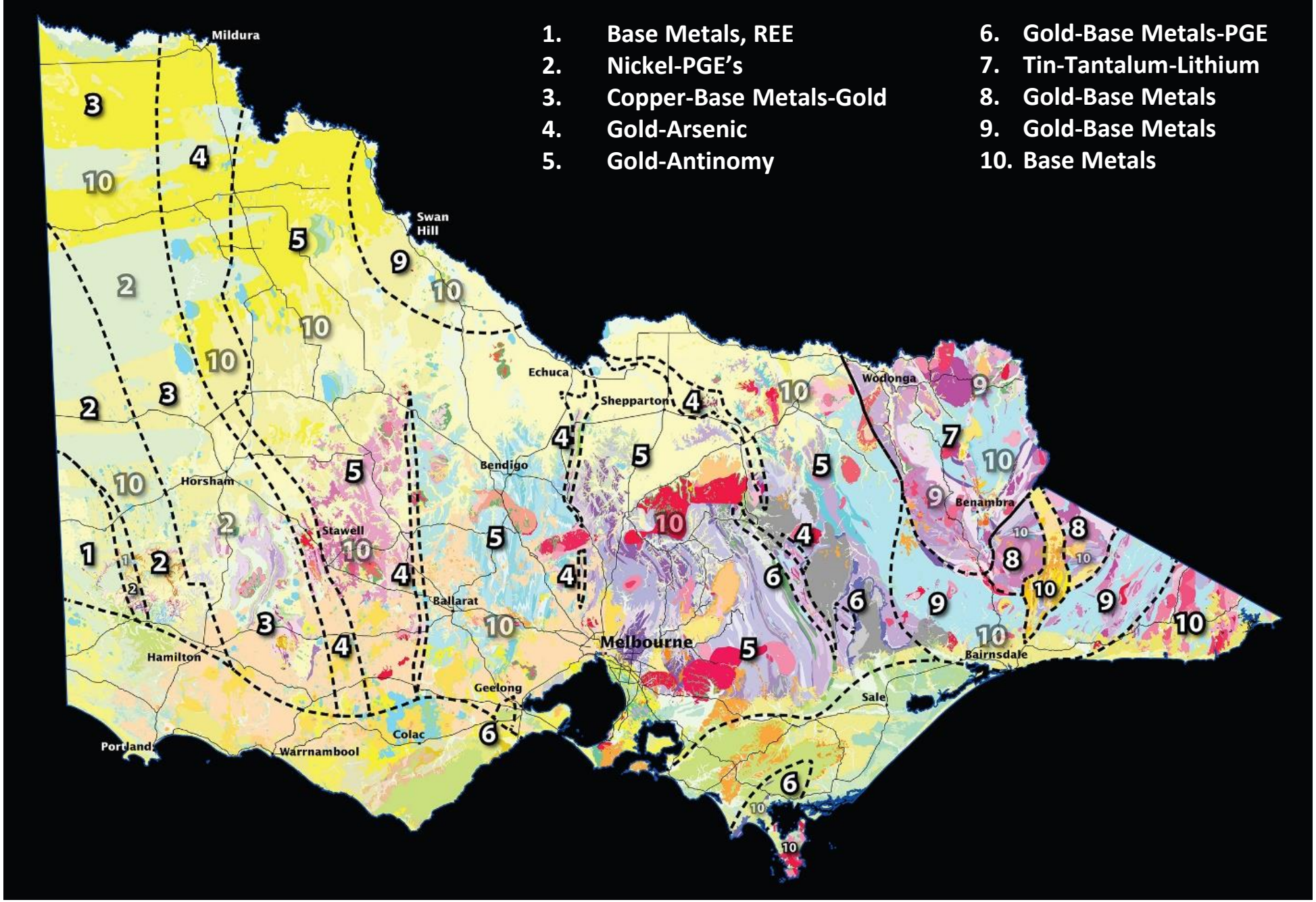
Lachlan Fold Belt sedimentation:

Late Silurian-Middle Devonian
plate-driven extension and convergence





adapted from: Huston et al., 2015



The value add:

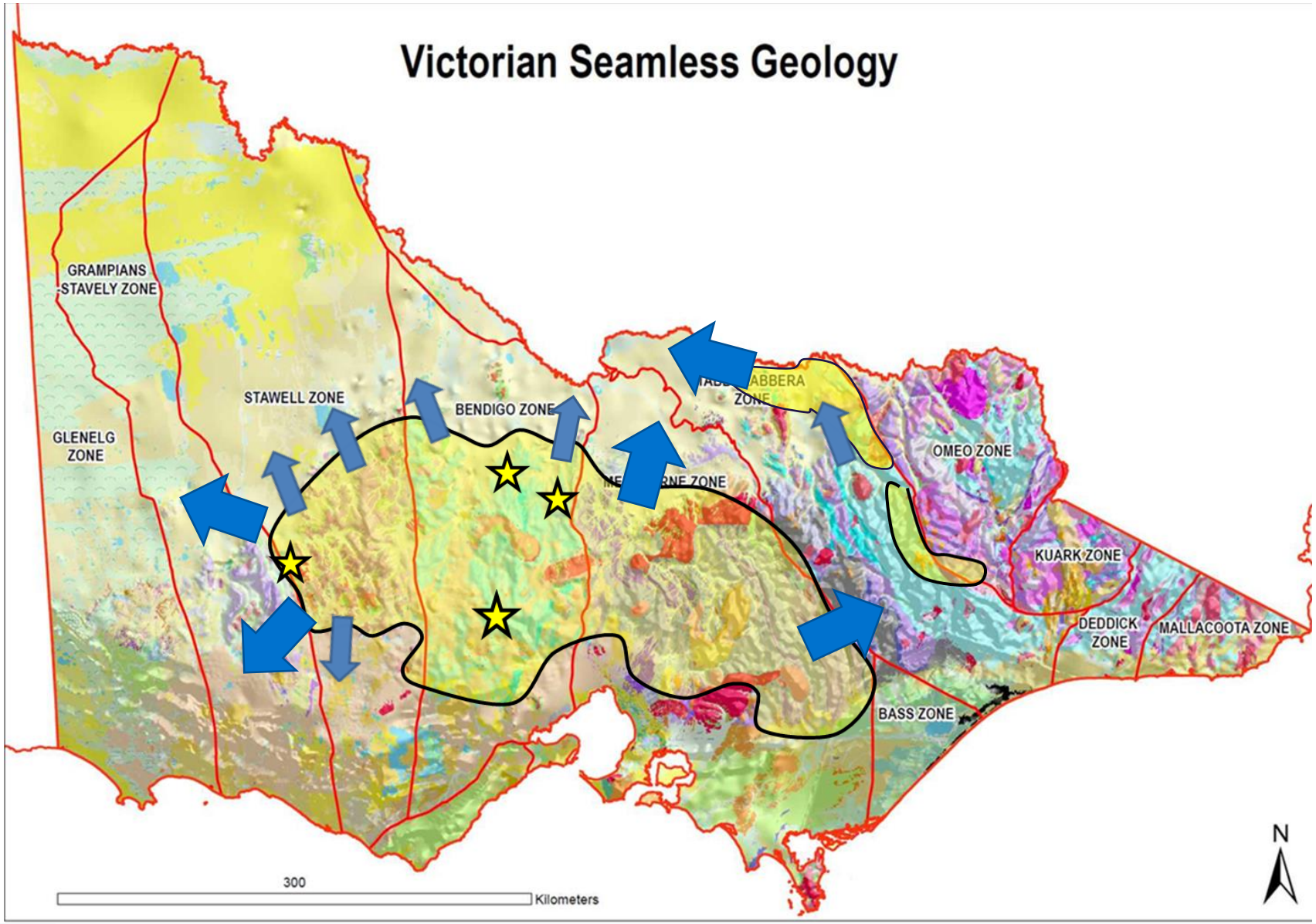
Mineral Systems map

– Key Commodities

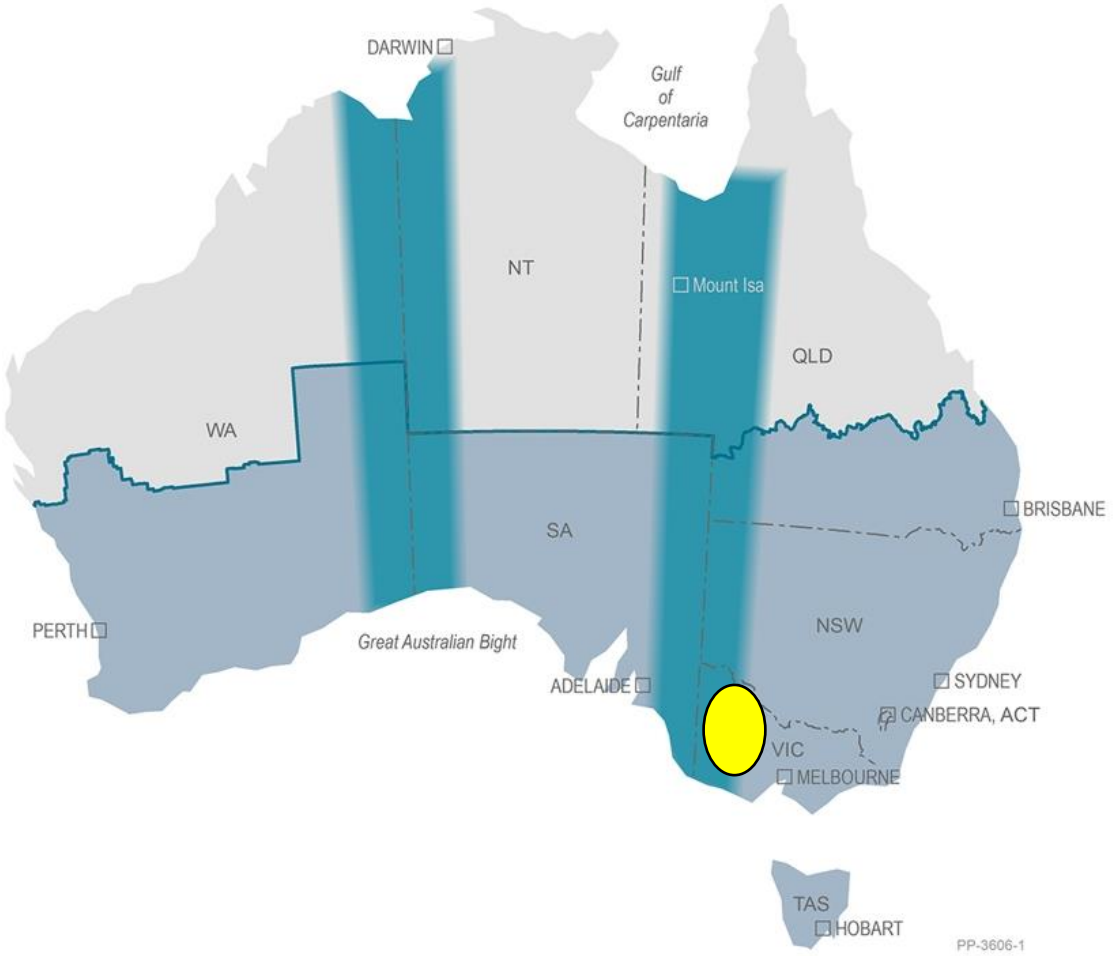
Talk outline

- Geological setting for Victorian orogenic (and intrusion related) gold
- Competing tectonic models for the Early Palaeozoic – confusing for gold explorers
- Structural / stratigraphic mapping + potential field geophysics: powerful tools…
- …but Deep Seismic Reflection data drives systems-scale understanding
- Application to mineral systems models at crustal scale…
- Constrained retrodeformation scenarios – critical to take geological systems analysis from crustal scale to lithospheric scale
- Towards a Unifying Theory for Eastern Australian Early Palaeozoic geology and mineral systems
- **Wrapping up**

Victorian gold: new opportunities



Exploring for the Future



The Exploring for the Future program will collect regional-scale geoscience data across southern Australia, and along two corridors with potential for new discoveries of groundwater, mineral and energy resources.

$125m of new funding announced, August 2020
New deep seismic reflection transect Pinnaroo- Swan Hill acquired 2022, interpreted 2023-24.
Delamerian mineral system characterisation 2023-24

The long, fruitful research collaboration that the GSV has had with Geoscience Australia continues!

Additional collaborative research underway in the Golden Triangle and Stavely Arc terranes, and elsewhere.

Wrapping up….

- Data, technology, concept and confidence advance: a new dawn for Victorian orogenic gold exploration…but the big practical lesson for success is: **Drill, drill often, and drill DEEP**.

- One virtually blind world-class discovery (Fosterville) has added ~12 m OZ+ to Victoria's gold inventory. How may others can there be? (the geology suggests several – Sunday Creek?, Rochester? others?)

- The Stavely Arc – new opportunities for primary and epigenetic base metals + gold in a swath of western Victoria, most undercover and untested. Hill 800 – ditto in the Selwyn Block in Central Victoria.

- The Lachlan Orocline hypothesis: a constrained and testable tectonic concept for Early Palaeozoic Australia – potentially explains full diversity of observed orogenic gold and base/critical metal styles**. Explains epic Bendigo Zone gold endowment + linkages**

- Predictive capacity for the styles and locations of gold (and base/critical metals) systems, including under cover – and more precompetitive research is underway!

- GEOLOGICAL SURVEY OF VICTORIA
  .

Victoria has crossed a threshold of data and understanding to what looks like sustained success