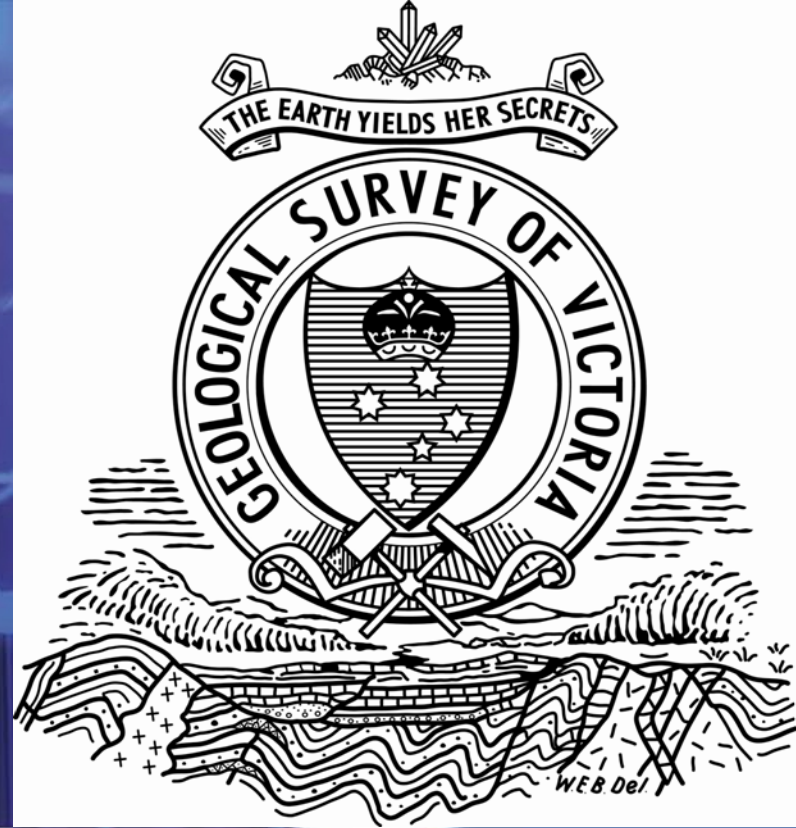




Emerging geological concepts, and how they are changing Victorian gold and base metals prospectivity

Prepared by Ross Cayley, on behalf of the combined GA and GSV team:
Geoscience Australia
Geological Survey of Victoria

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Presentation outline

- **Challenges for the State**

- Multi-disciplinary, cross-agency collaboration – the firepower needed to grapple with some tricky problems
- Arcs – What are they? Why are they important? How can you tell when you've found one?
- Oroclines – Giant folds of whole mountain ranges. So what?
- A paradigm shift for Victorian gold and base-metals prospectivity – rhetoric or reality?

Victoria: some current perceptions

(areas of focus in this presentation in black)

- Large historic gold production – ‘old-style’ high-grade Au deposits are huge, but less suited to modern development and difficult to predict.
- World class Gippsland Basin energy resources
- Emerging Heavy Minerals Sands sector; world class, some technical hurdles (grainsize, geochemistry)
- Some other deposits (eg. Benambra Cu), and others of interest to smaller producers

But Victoria does have predictable deposit types, proven to be suited to modern development....

Stawell — 5 M oz+ Au total endowment from a single greenstone-hosted shear system mined continuously since the early 1980's; currently mined

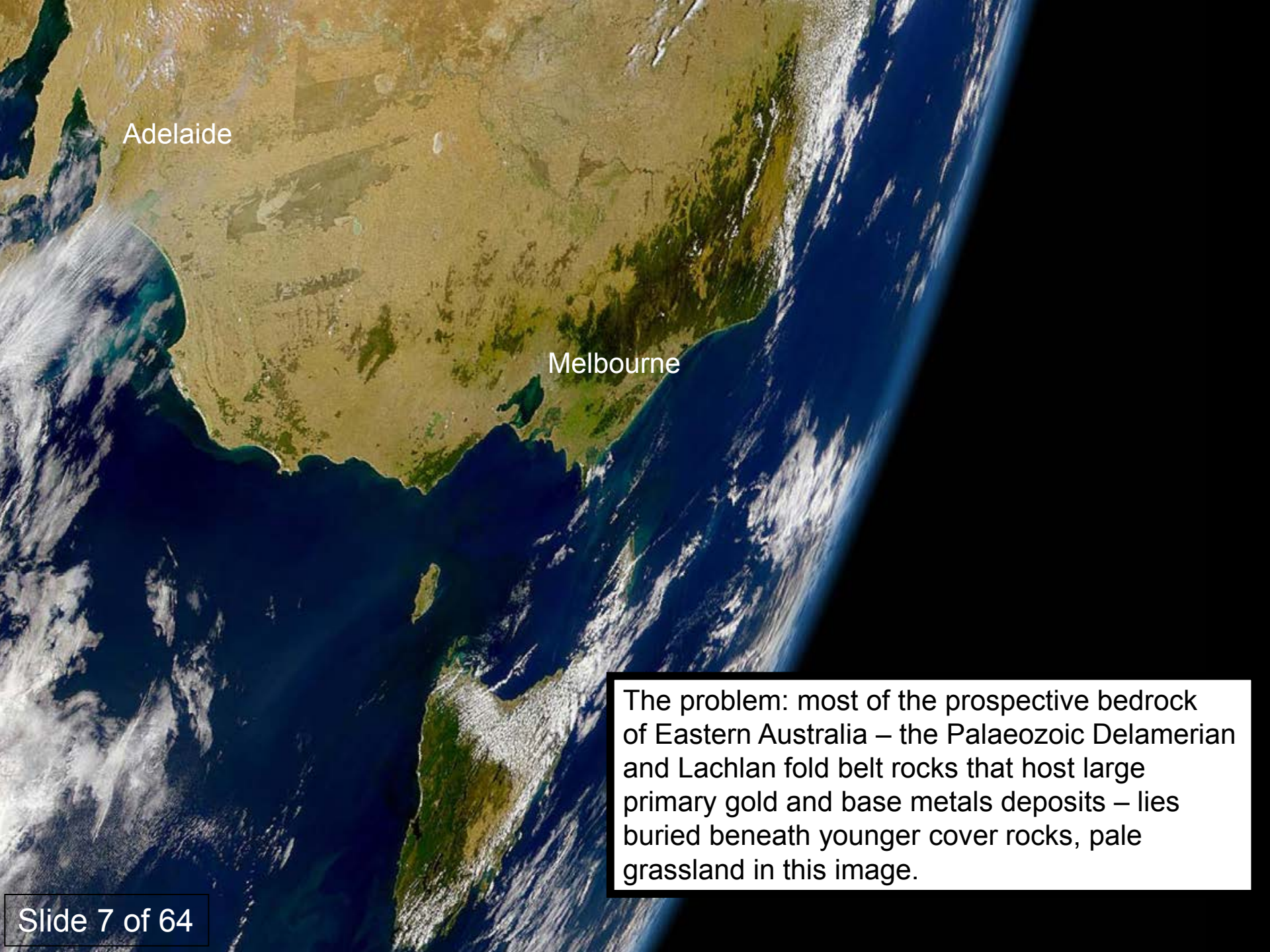
Fosterville — multi-million oz Au total endowment from a metasediment-hosted fault system; currently mined.

Benambra (Cu) — VHMS — undergoing redevelopment

GSV predicts that improved geological understanding will help find more of these and new deposit styles to boot.....

Talk outline

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A satellite image of Eastern Australia, showing the coastline and inland regions. The land is a mix of green and brown, indicating vegetation and bare ground. The ocean is dark blue with white clouds. The labels 'Adelaide' and 'Melbourne' are placed over the land. The text box is in the bottom right corner.

Adelaide

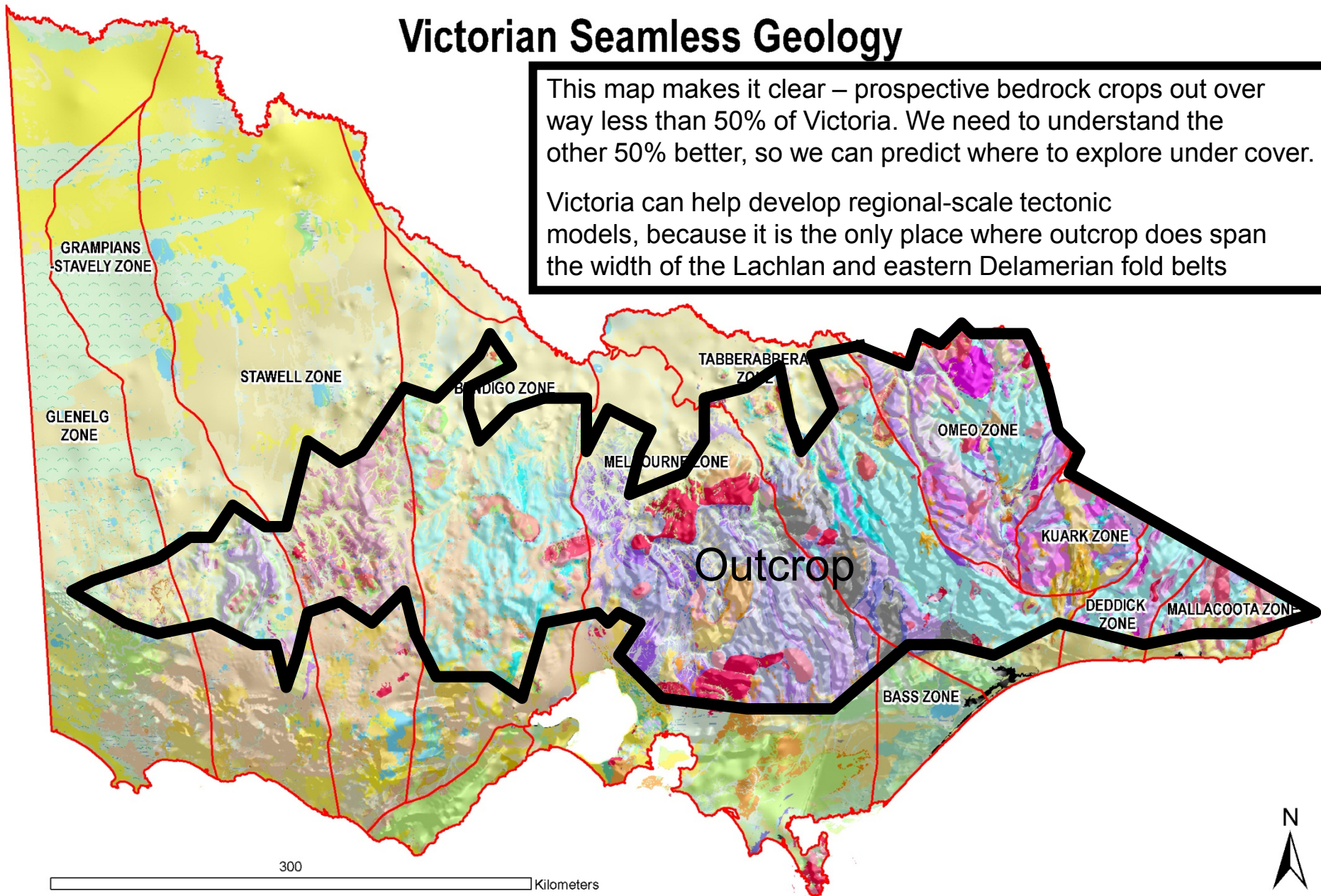
Melbourne

The problem: most of the prospective bedrock of Eastern Australia – the Palaeozoic Delamerian and Lachlan fold belt rocks that host large primary gold and base metals deposits – lies buried beneath younger cover rocks, pale grassland in this image.

Victorian Seamless Geology

This map makes it clear – prospective bedrock crops out over way less than 50% of Victoria. We need to understand the other 50% better, so we can predict where to explore under cover.

Victoria can help develop regional-scale tectonic models, because it is the only place where outcrop does span the width of the Lachlan and eastern Delamerian fold belts



Collaboration is key, and the following geoscience data and concepts could not have happened without a dedicated collaborative effort between scientist working for the organisations below, and others. This work is ongoing....



Australian Government
Geoscience Australia



MONASH University

ANSIR NATIONAL RESEARCH
FACILITY FOR
EARTH SOUNDING



AuScope

pmd*crc

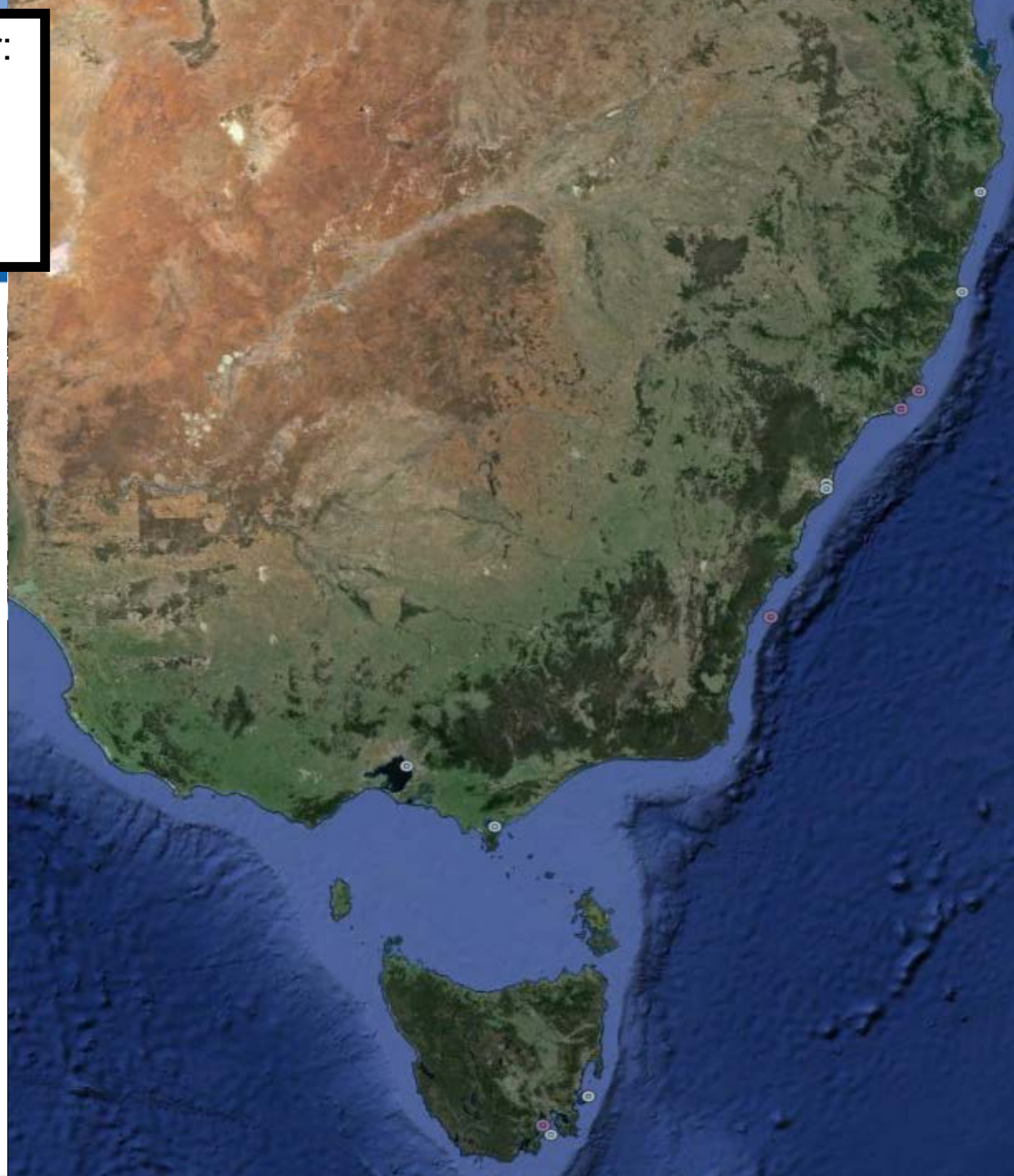


DEPARTMENT OF
STATE DEVELOPMENT
BUSINESS AND
INNOVATION



Defeating the tyranny of cover:
complete aeromagnetic data
coverage across the nation.

Turning this.....

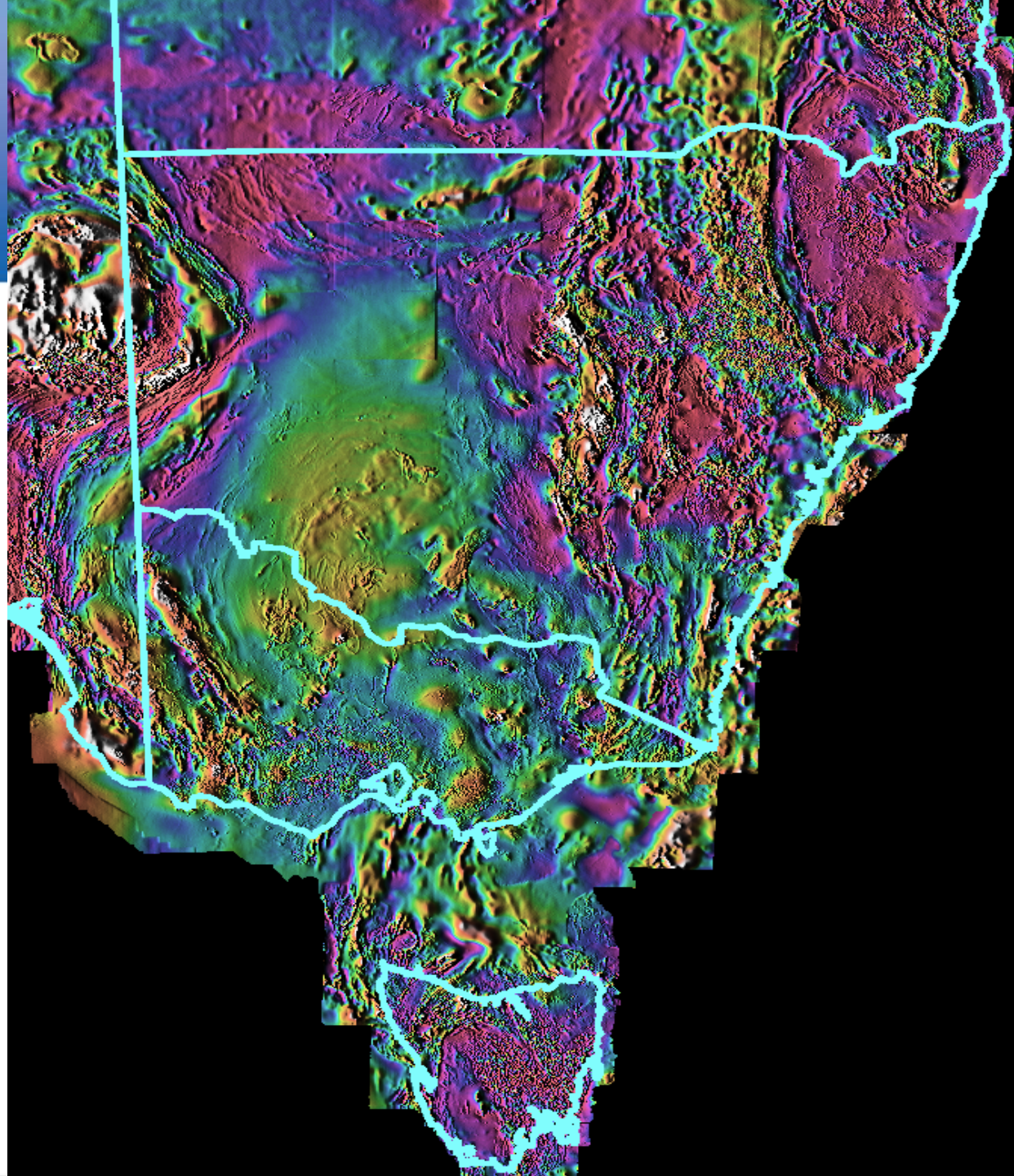


...into this.....

Regional

Total Magnetic Intensity

a window to the underworld

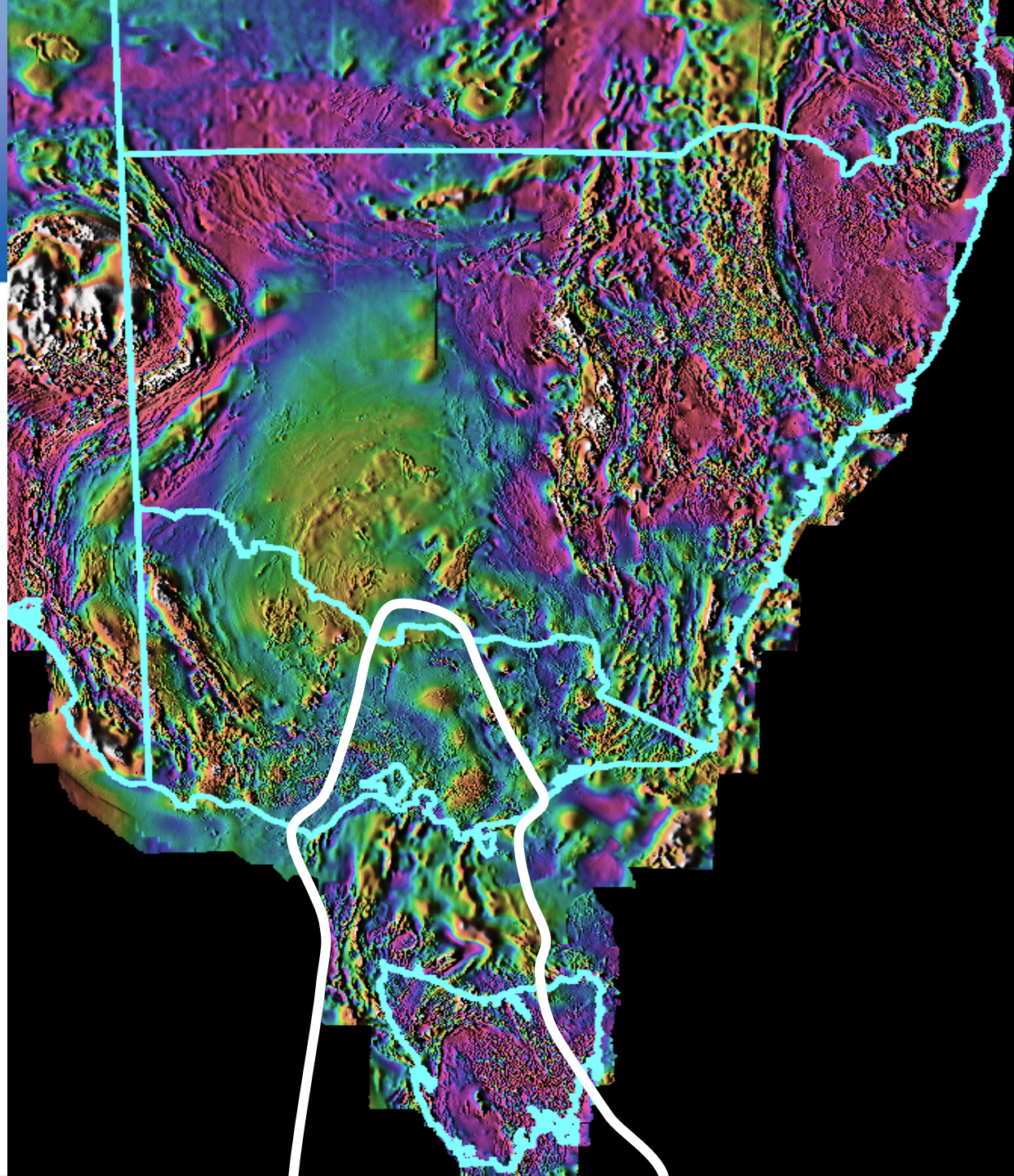


Vandieland (Cayley, 2010, G.R)

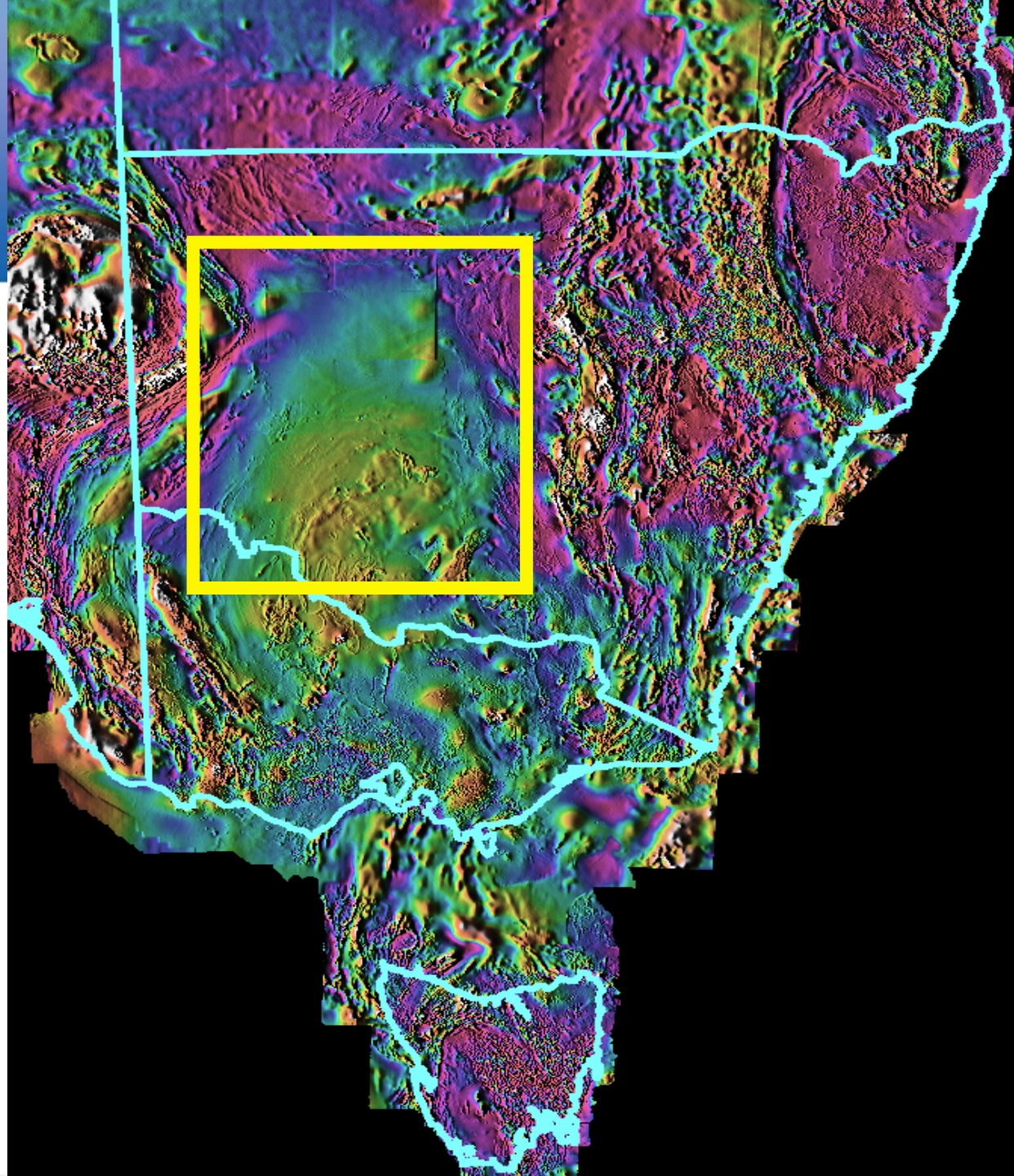
A Mesoproterozoic
microcontinent.....

includes Western Tasmania
and the 'Selwyn Block' (Cayley et
al., 2002, AJES)...

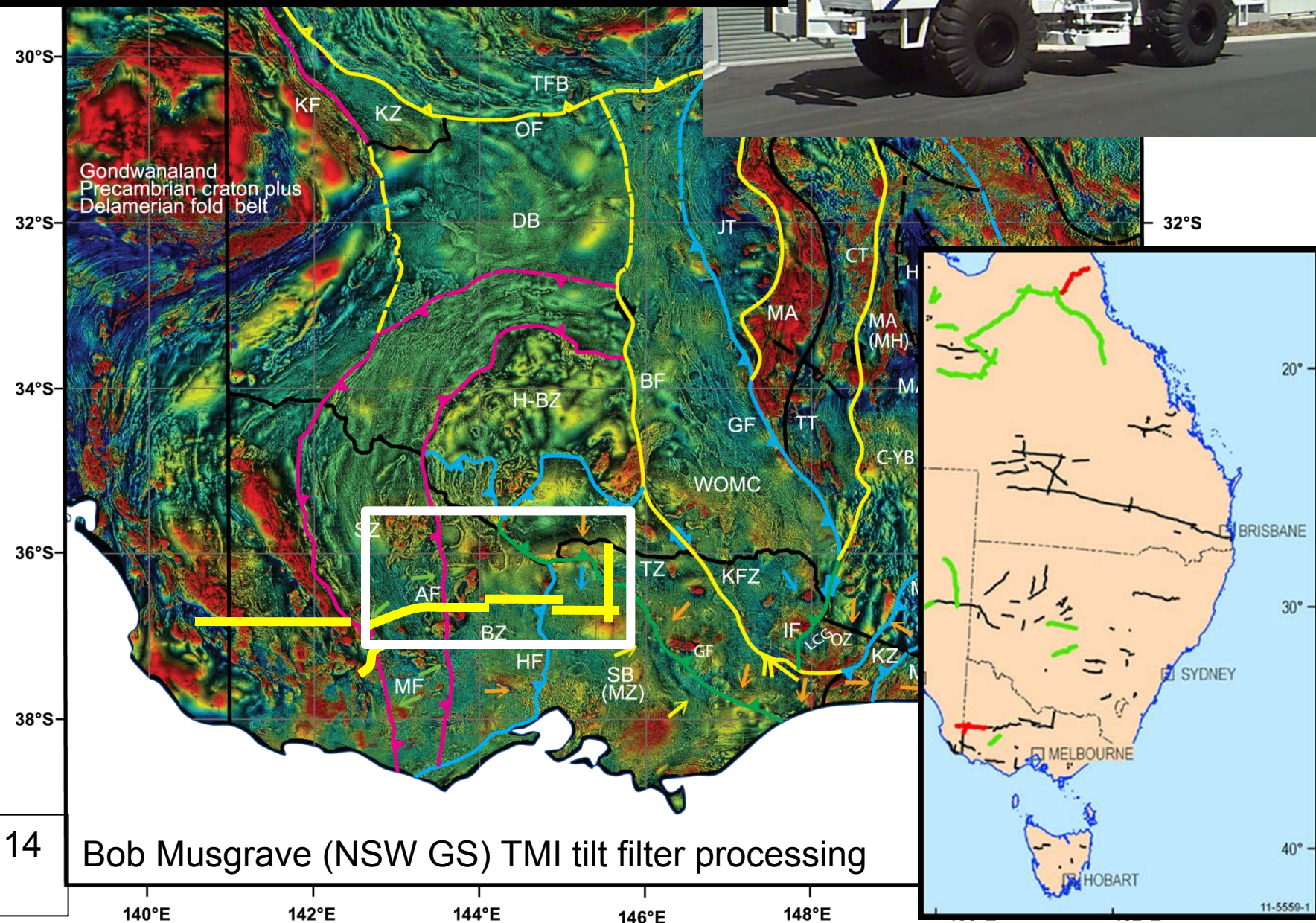
embedded within the
Paleozoic Lachlan Fold Belt...



New, high quality
Aeromagnetic data infill....
.....where it matters....



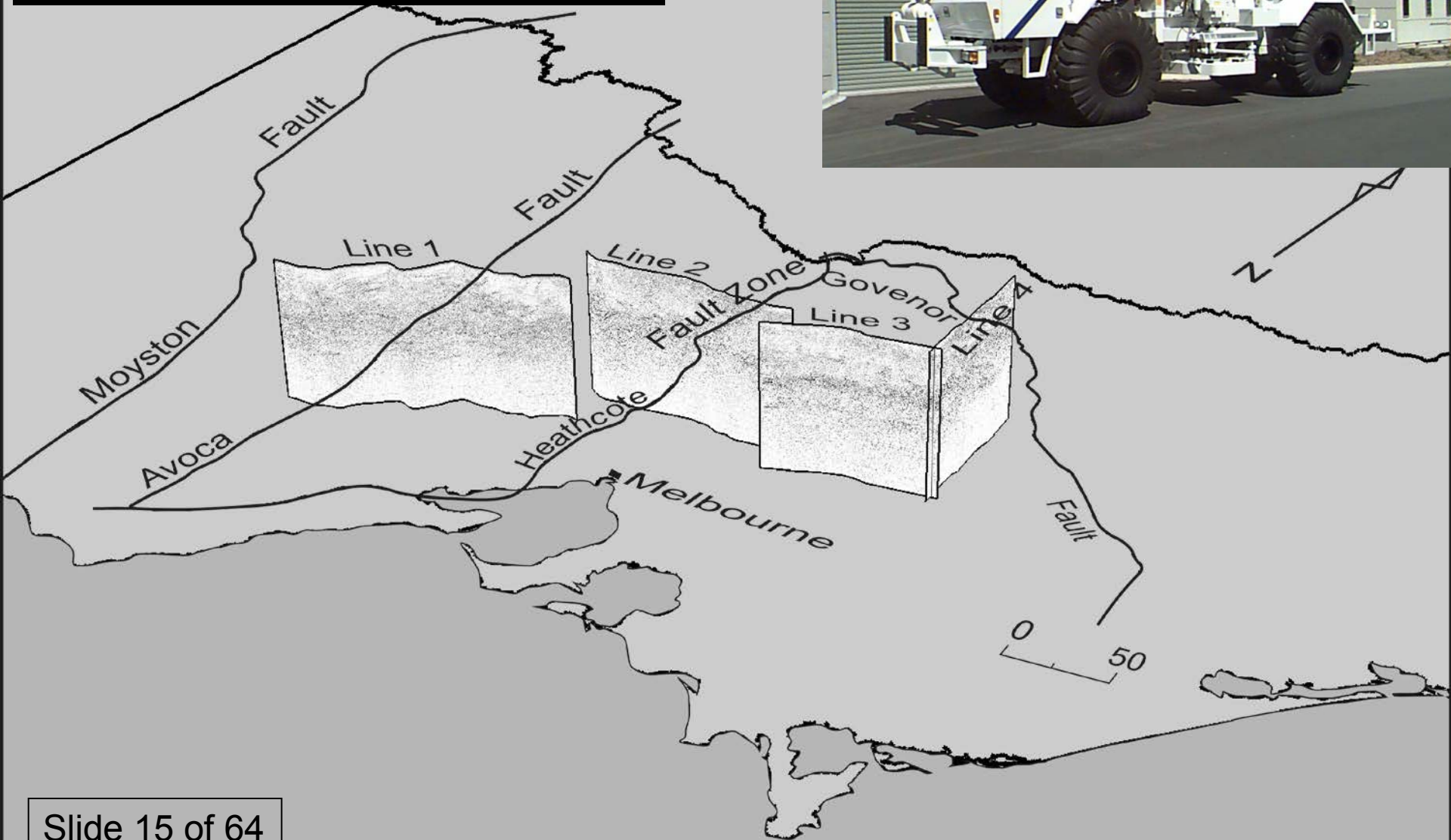
...and advances in processing quality.....and testing interpretations with regional deep seismic reflection transects (including in Victoria: yellow lines).



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of 64

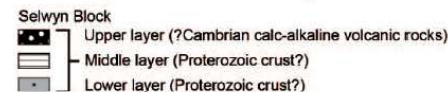
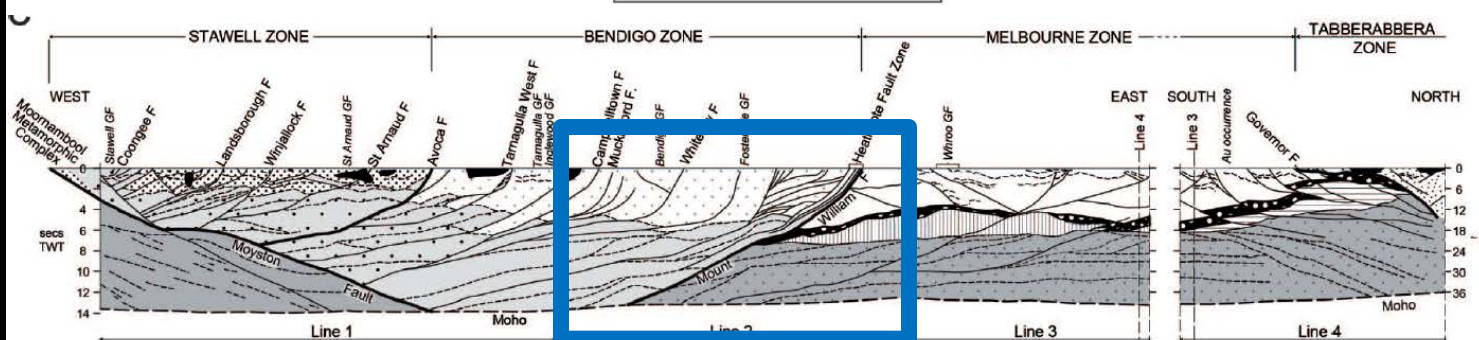
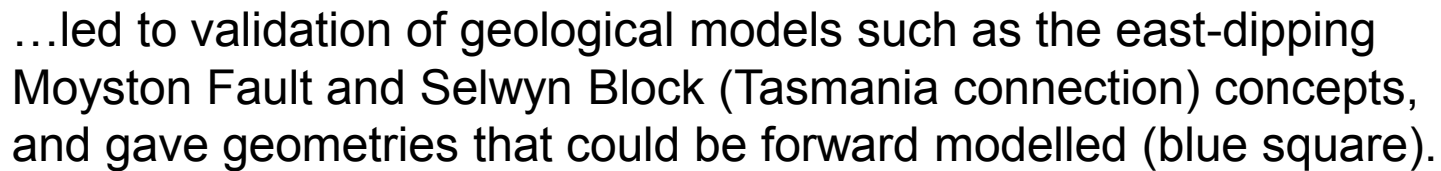
Bob Musgrave (NSW GS) TMI tilt filter processing

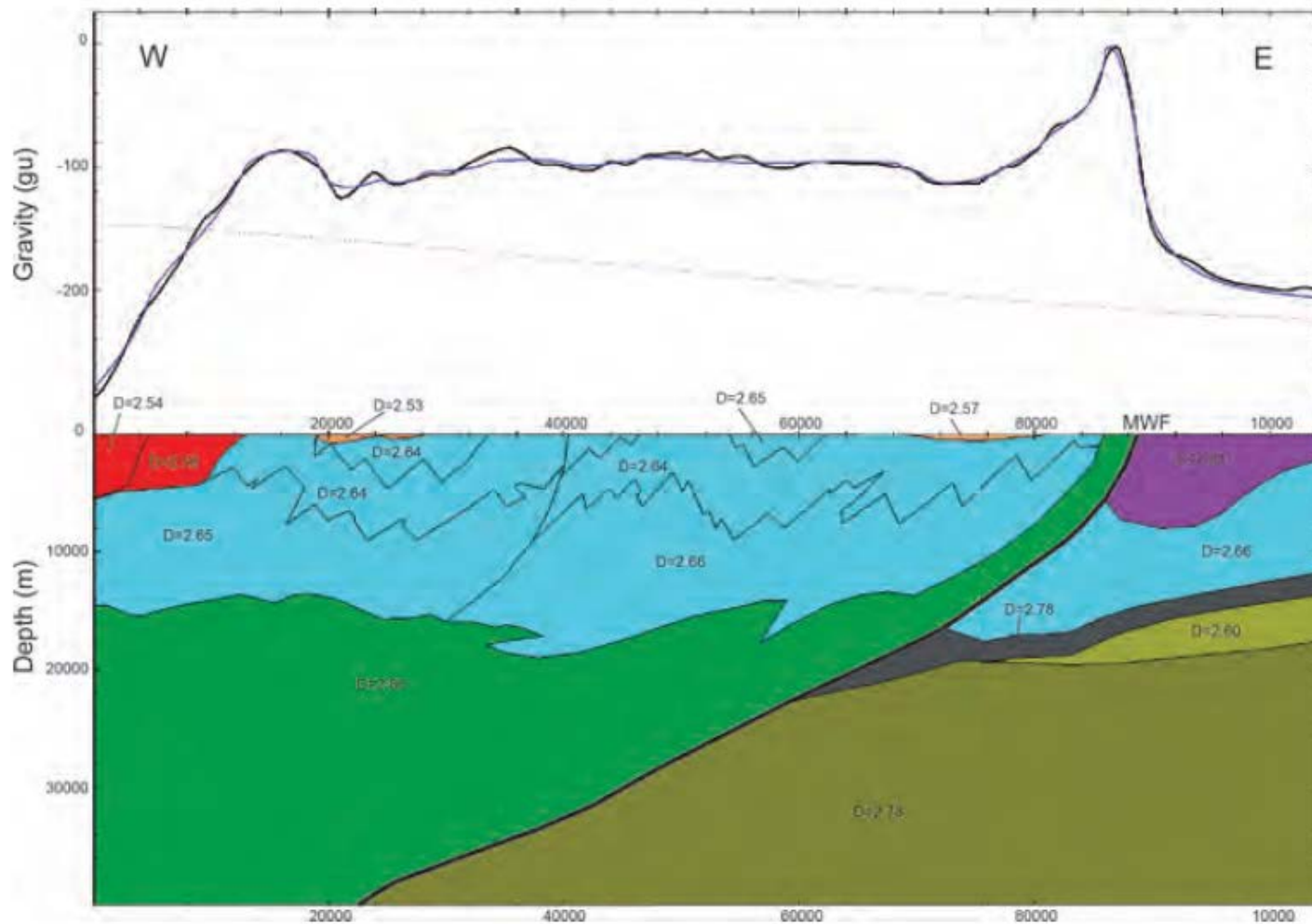
Central Victorian deep seismic data,
acquired in 2006.....



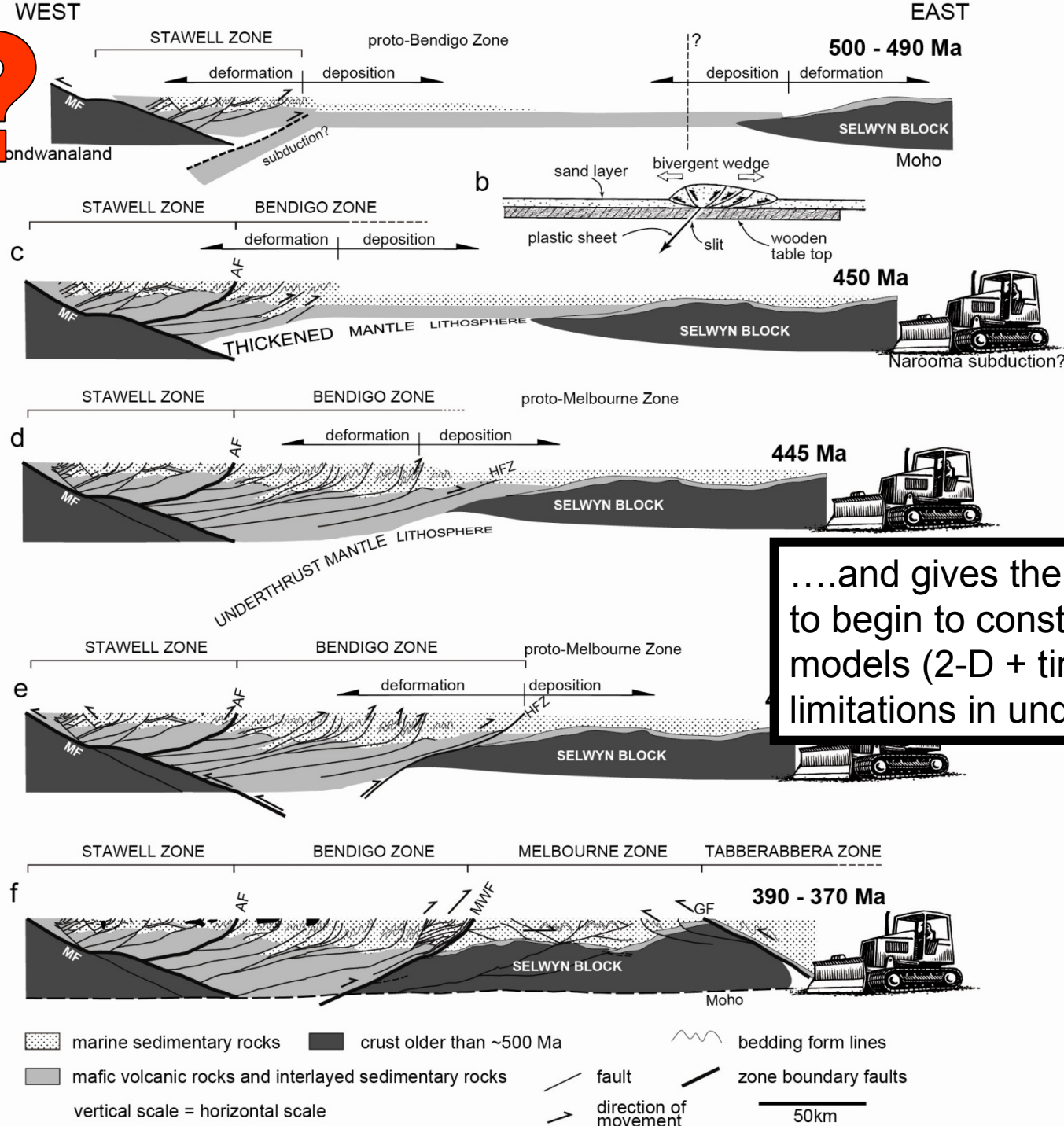
Slide 15 of 64

Regional deep seismic transects: pmd*crc, AUSCOPE



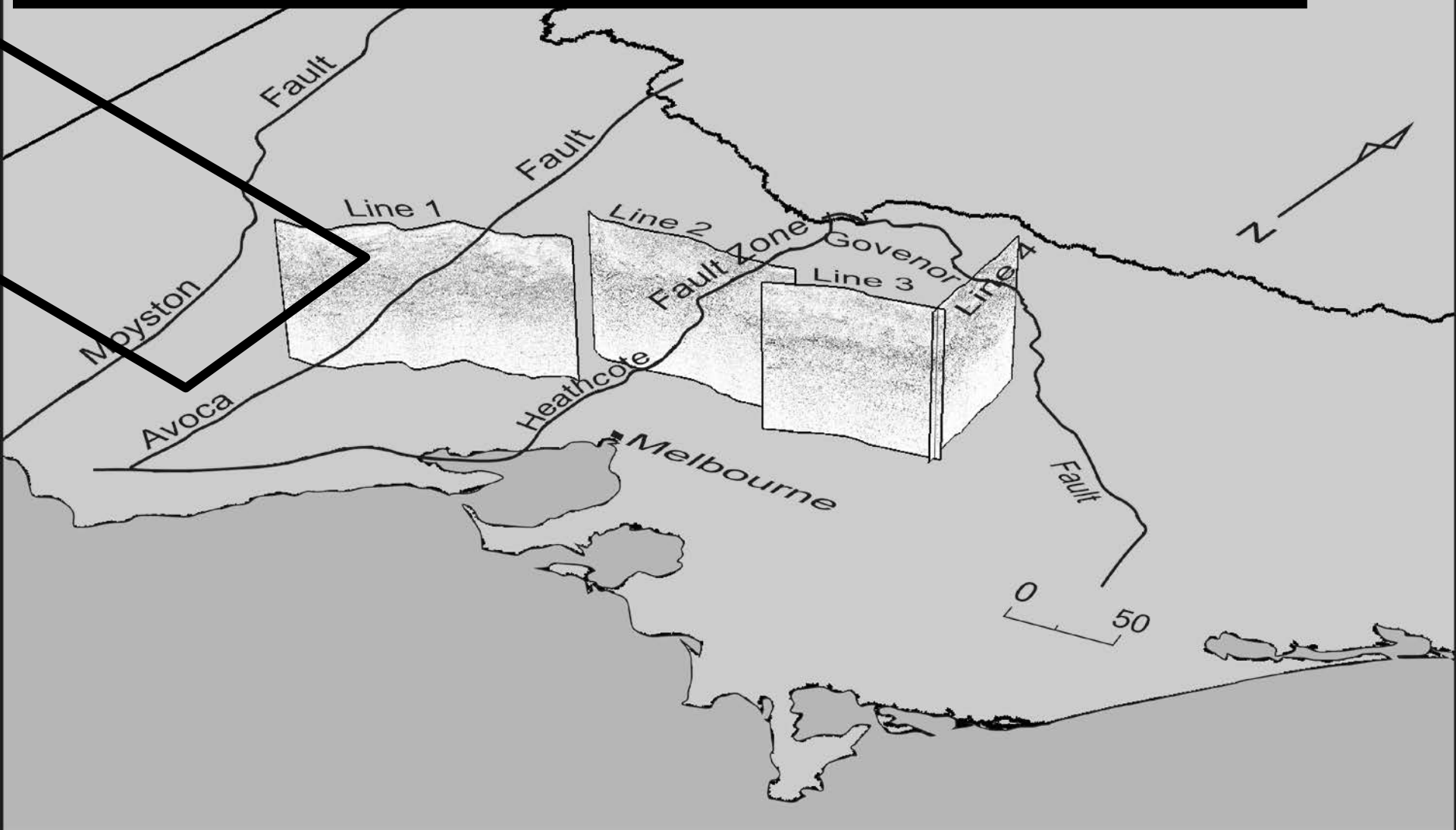


Forward model of part of Line 06GA-V2. Measured and modelled gravity profiles are a close match, using model density values measured y directly from rocks that occur along the transect (and are interpreted to depth)...shows interpretation is possible.....



....and gives the confidence needed to begin to construct 3-D geodynamic models (2-D + time). Also highlights limitations in understanding exist (?)...

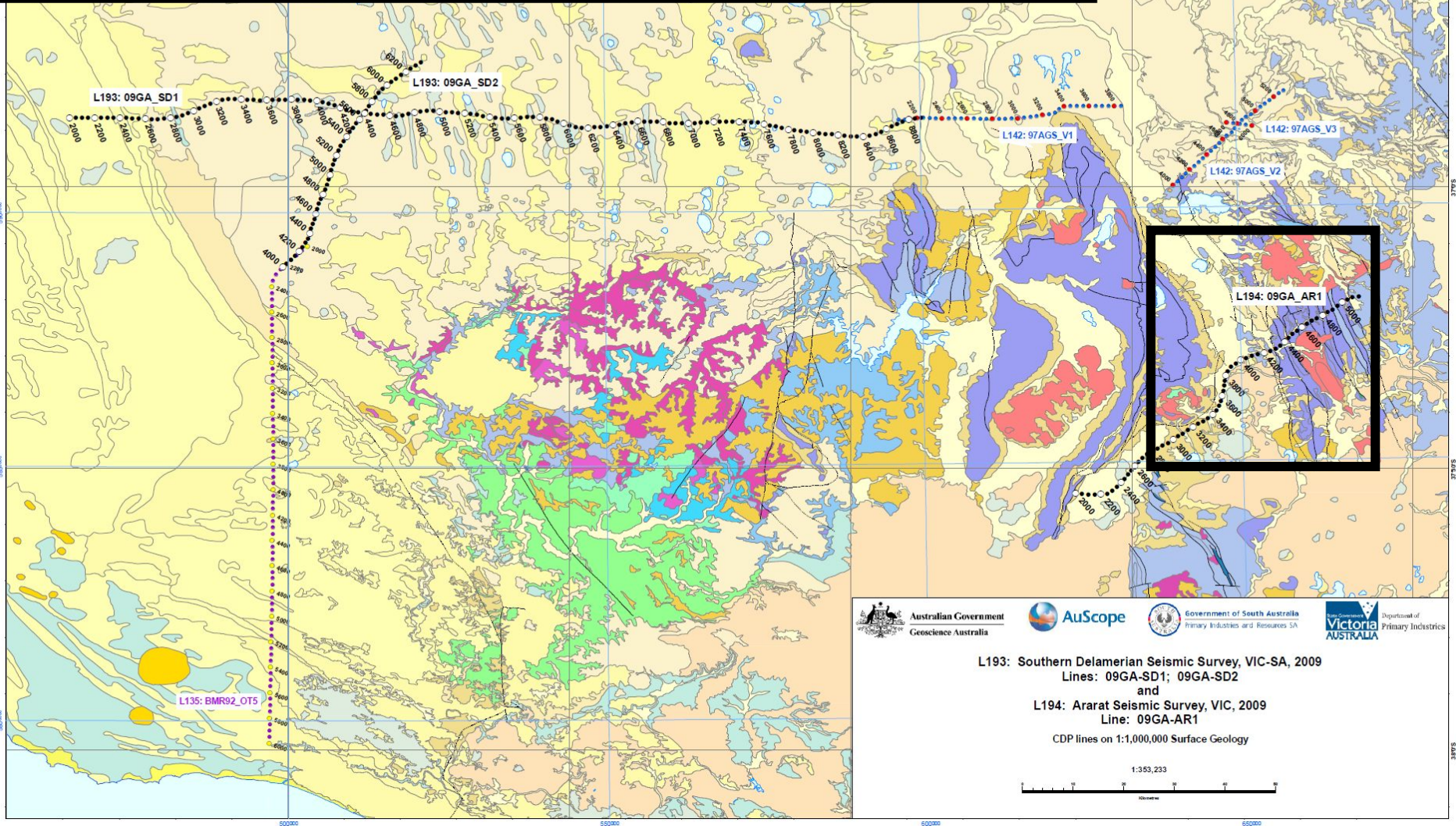
...which were addressed by extending the deep seismic transect into western Victoria, to test/develop models for the Delamerian Fold Belt – the Southern Delamerian project, 2009 -.



Southern Delamerian deep seismic project, 2009, line locations.

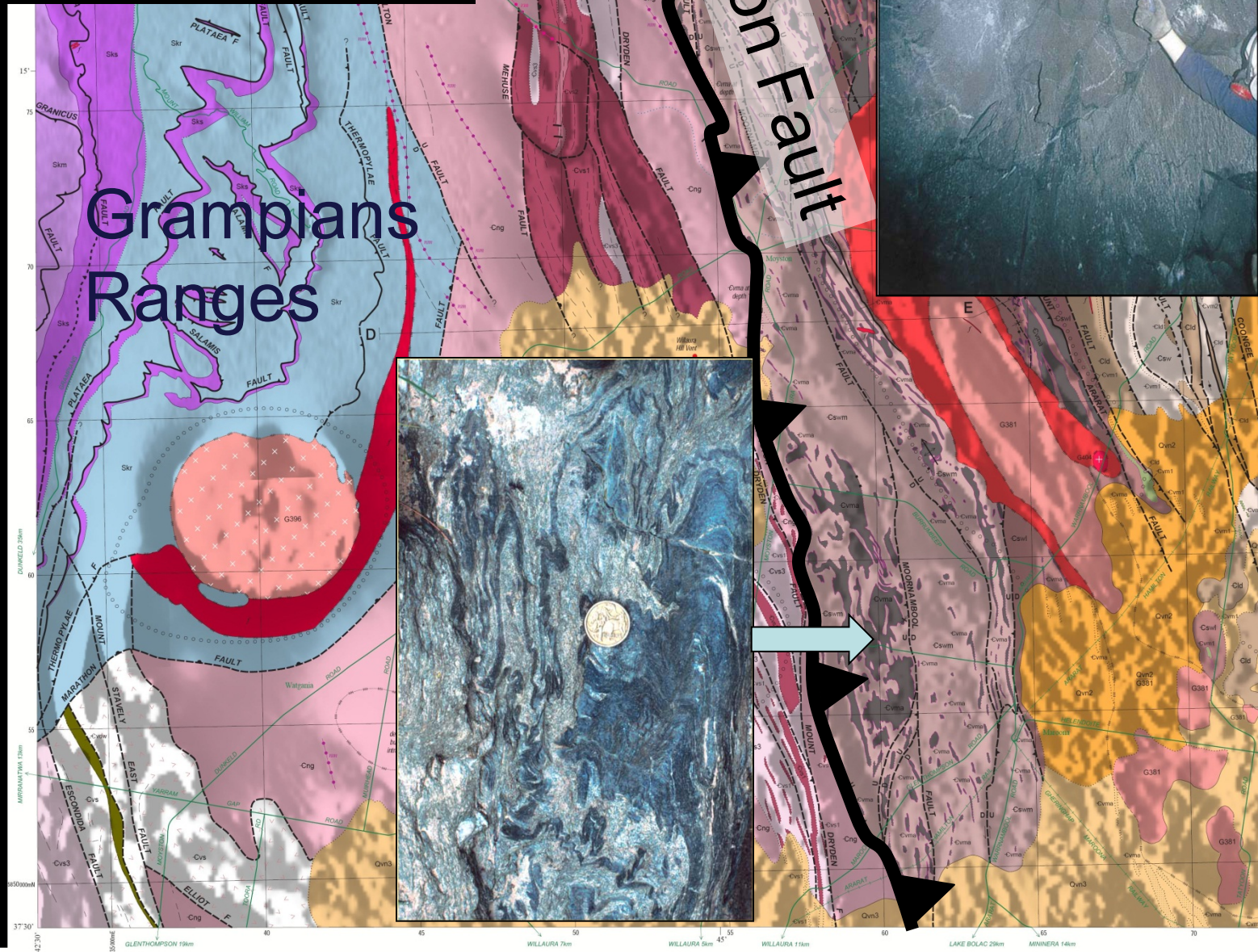
(<http://dpistore.efirst.com.au/product.asp?plD=1079&clD=6>)

Note inset square, where one line tests geological concepts from past GSV mapping...



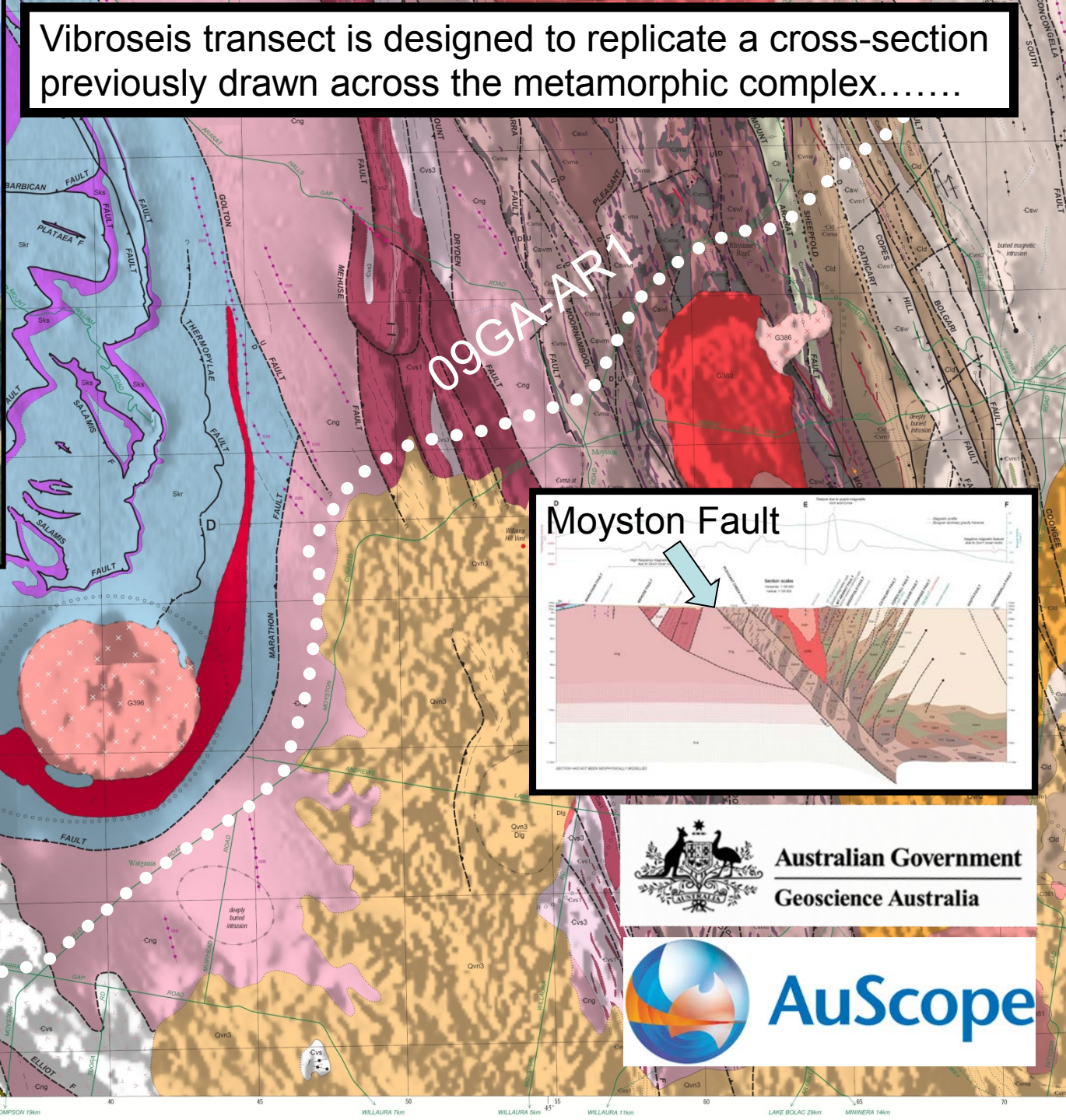
Testing existing concepts, Moyston Fault, Moornambool Metamorphic Complex wedge 'pop-up' geometry.....

(<http://dpistore.efirst.com.au/product.asp?plD=507&cID=39>)



Cayley & Taylor, 2000

Vibroseis transect is designed to replicate a cross-section previously drawn across the metamorphic complex.....



Cayley & Taylor, 2000



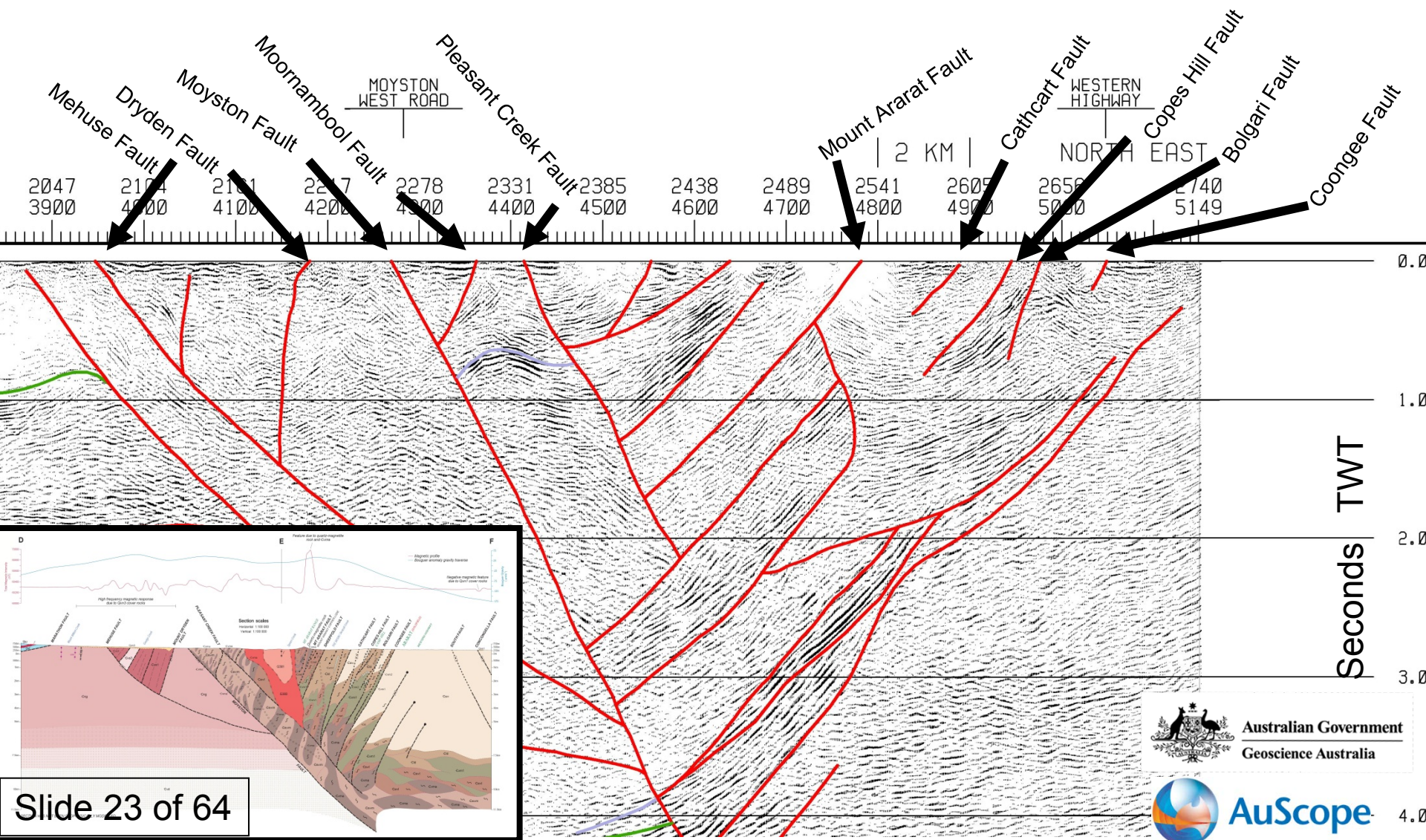
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AuScope

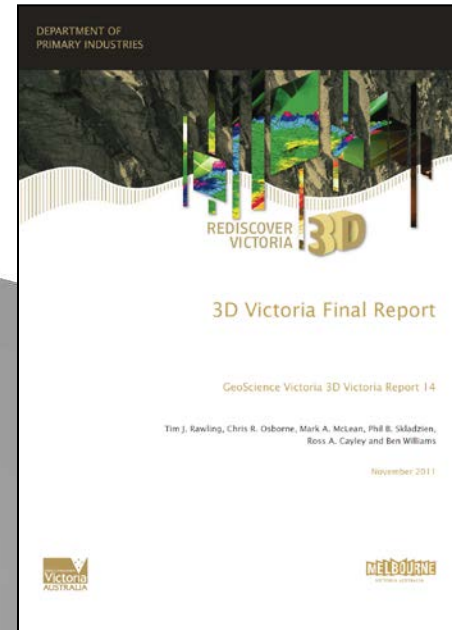
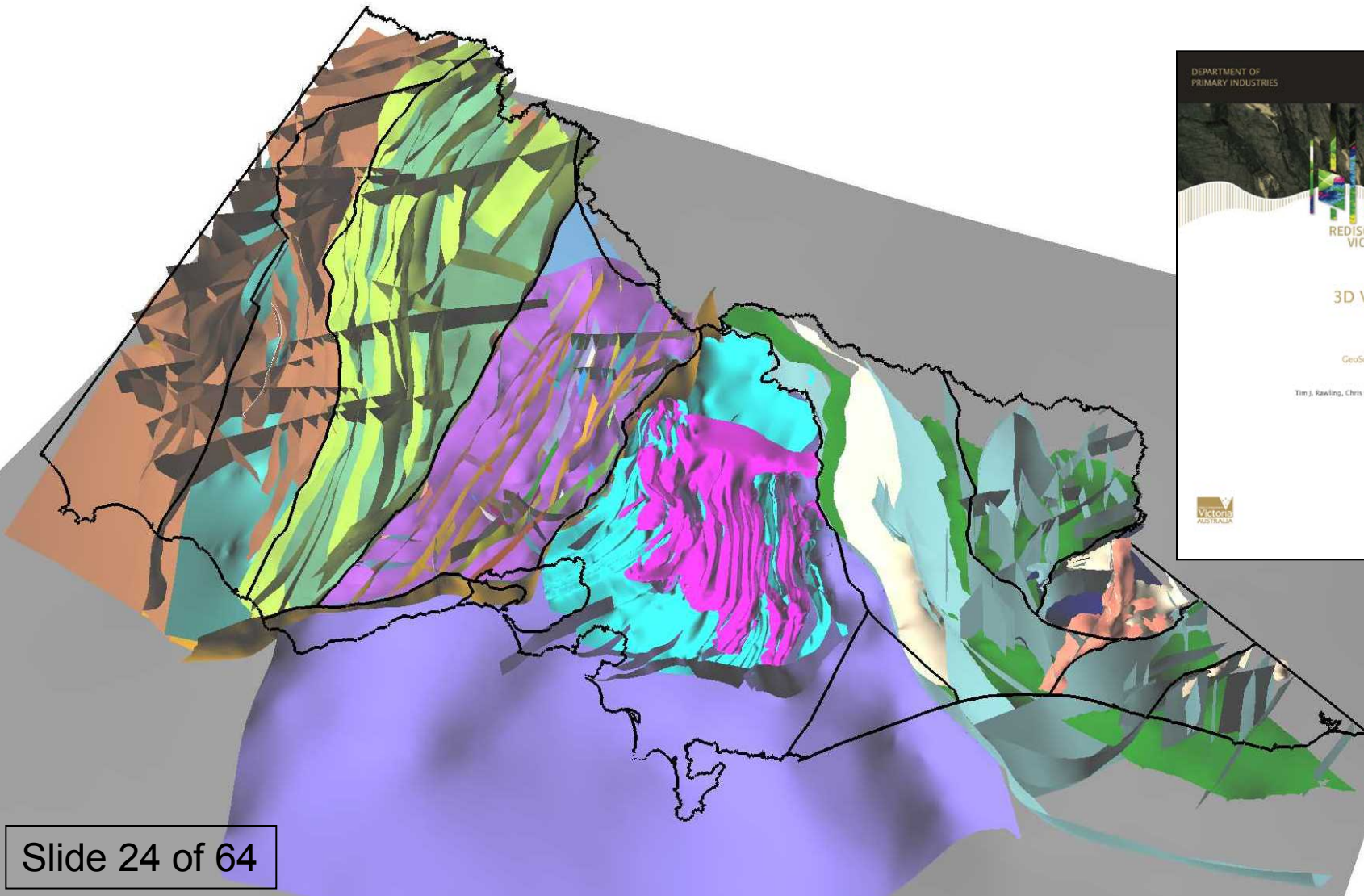
Seismic data and interpretation matches the geometry of the previously drawn cross-section.

- Proves that geological mapping and aeromagnetic data interp. can produce meaningful results.
- Proves that deep seismic reflection profiling can meaningfully image map-scale structures.
- Time to test areas with less existing geological control.....

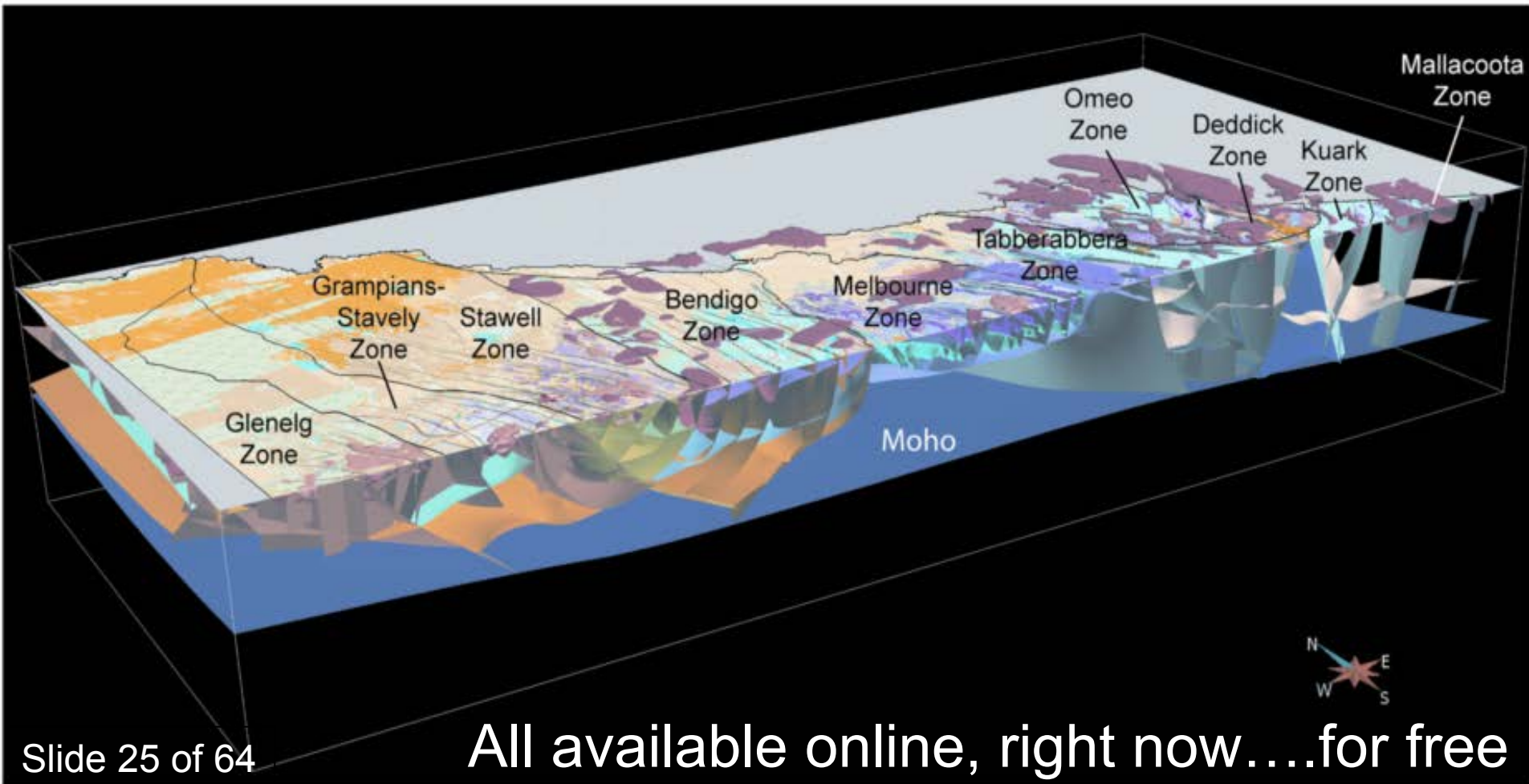


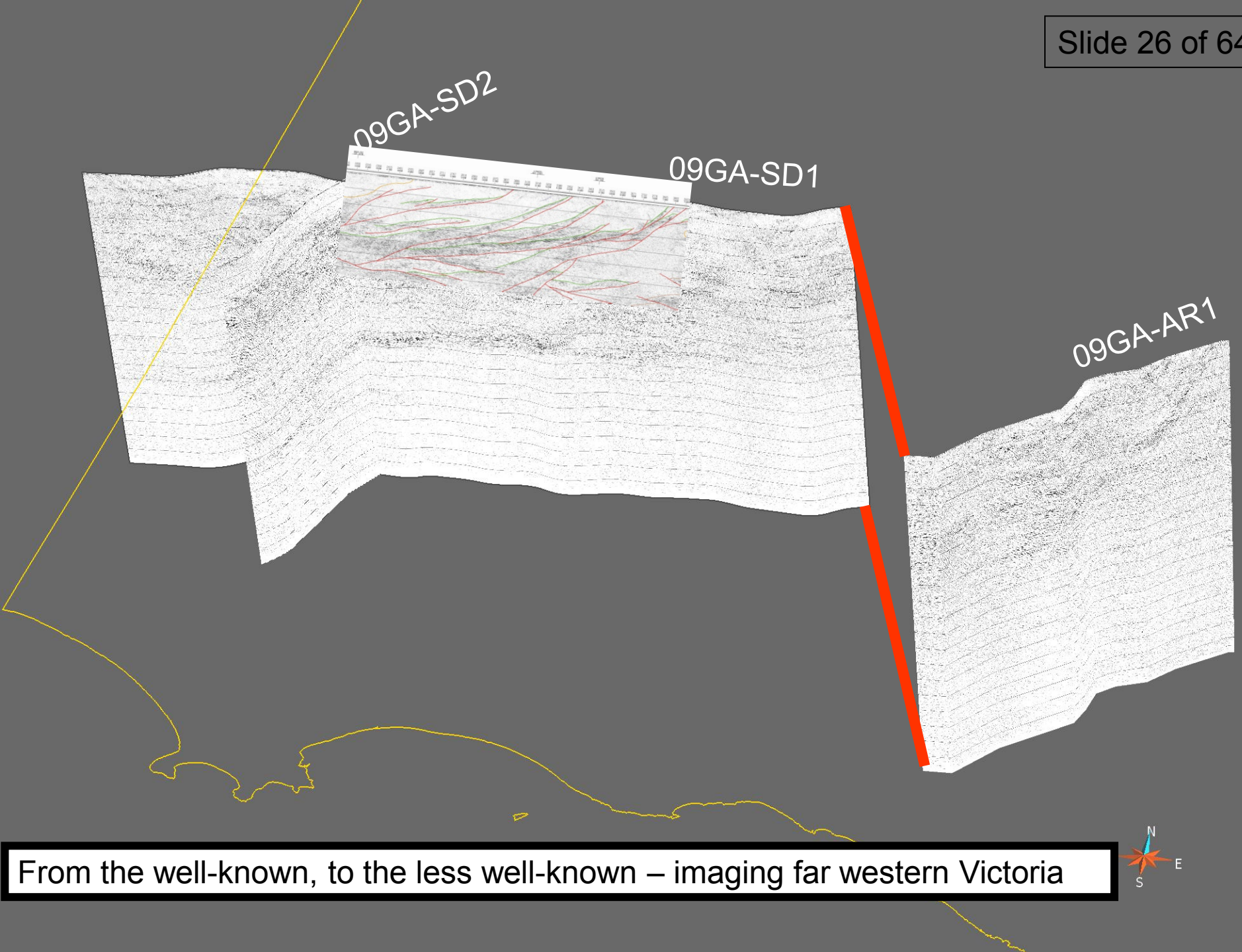
A comprehensive understanding means we can build meaningful 3-D geological models..... (<http://dpistore.efirst.com.au/product.asp?plD=1098&clD=53>)

Full-crustal-thickness (40km!) geological model
at 1:250 000 scale



**Combined: A powerful new paradigm
for geological and tectonic interpretations...**



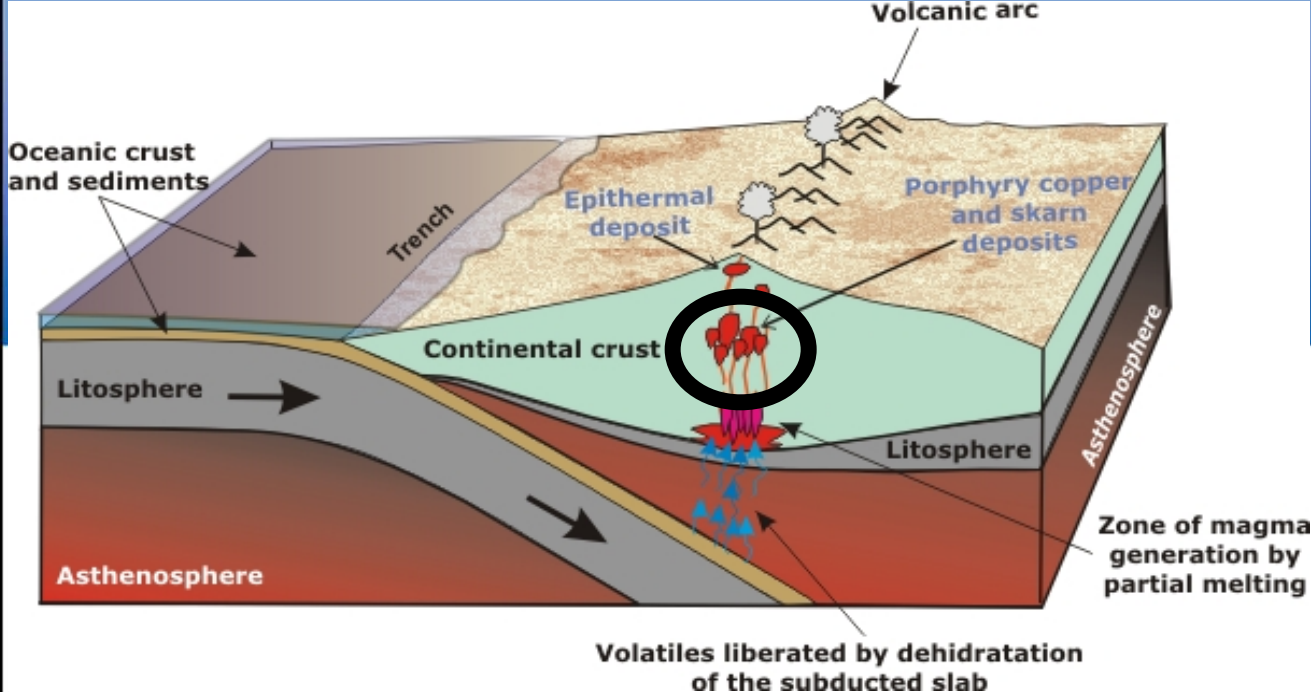


From the well-known, to the less well-known – imaging far western Victoria



Talk outline

- Challenges for the State
- Multi-disciplinary, cross-agency collaboration – the firepower needed to grapple with some tricky problems
- **Arcs – What are they? Why are they important? How can you tell when you've found one?**
- Oroclines – Giant folds of whole mountain ranges. So what?
- A paradigm shift for Victorian gold and base-metals prospectivity – rhetoric or reality?



- Magmatic arcs form in the crust above subduction zones at plate boundaries. At a continent margin (eg. the Andes)...

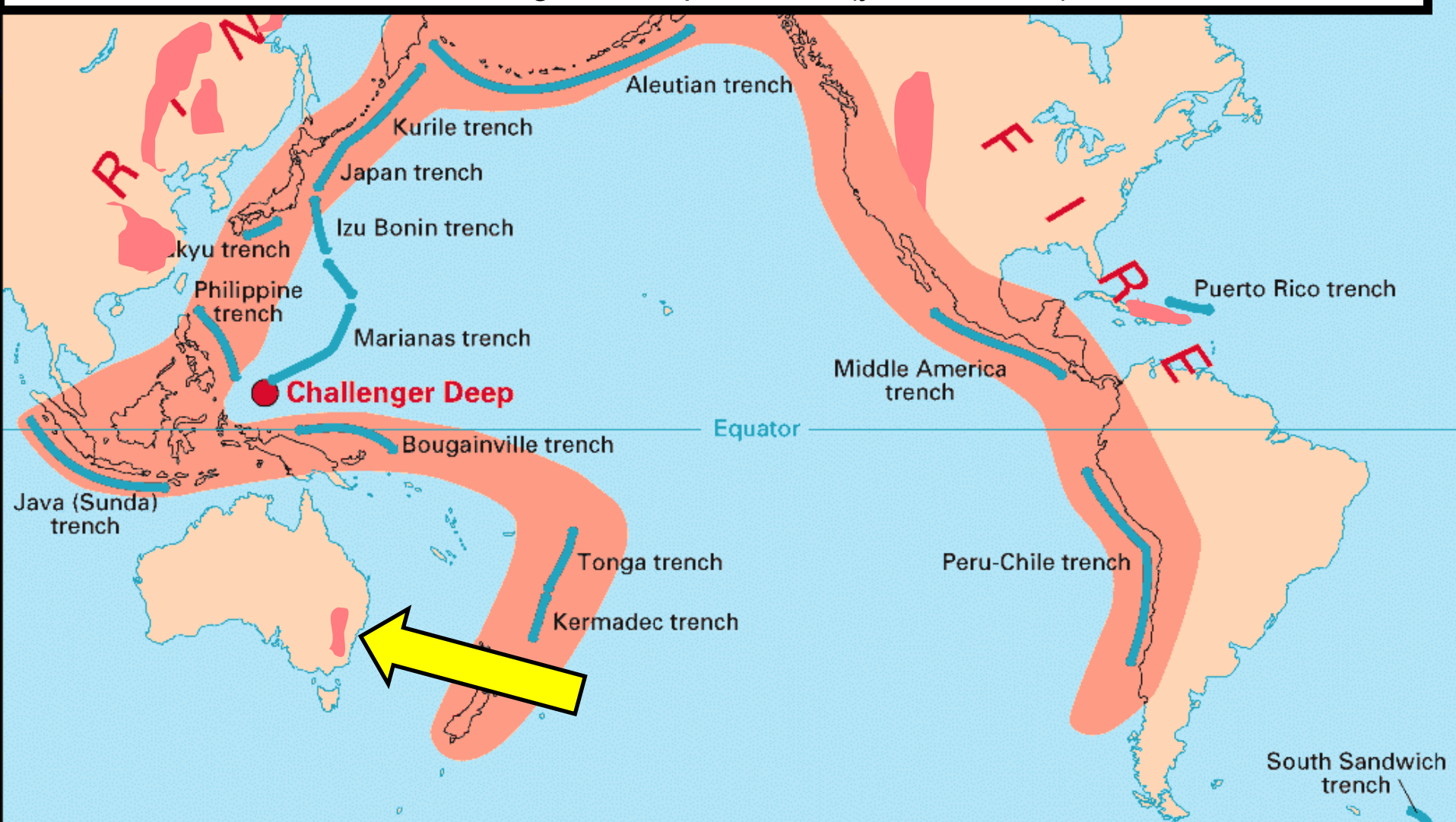
- or in the ocean... an island arc



Why are they important?

Porphyry and VMS systems!!!! (Au, Cu, Mo, etc)

Modern magmatic arcs occur around the Circum-Pacific, above active continent-dipping subduction zones....but these evolve through time, so earlier arc generations also occur, like the Ordovician-aged Macquarie Arc (yellow arrow)



Also: Porphyry Belts of the Circum-Pacific
Oxidised magmatic belts: Porphyry Cu Mo $\pm$ Au

Cadia Hill Porphyry Cu-Au Mine, central NSW



Macquarie Arc

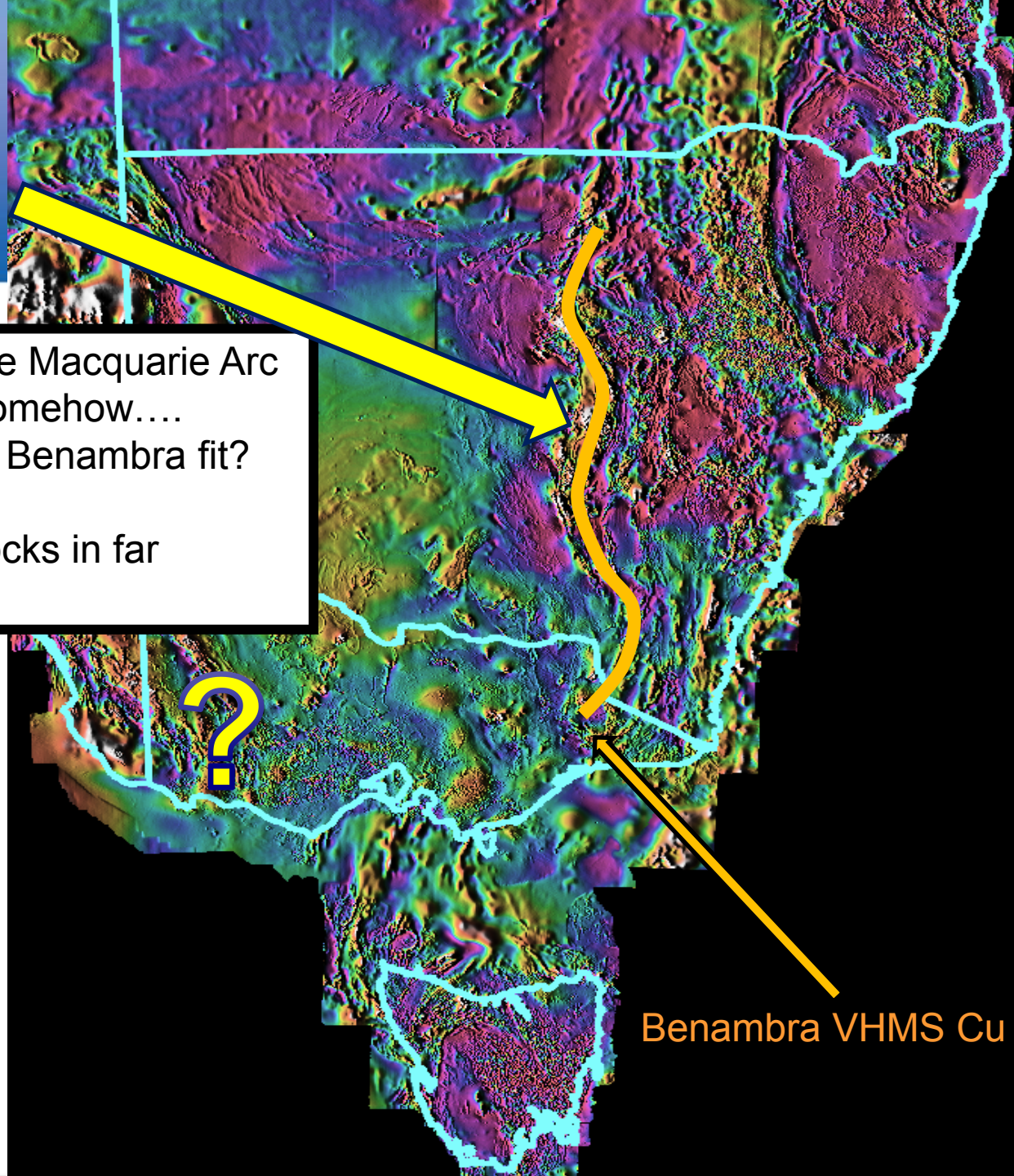
(Cadia)

Magnetic data suggests that the Macquarie Arc extends into eastern Victoria somehow....
but how to test? And how does Benambra fit?

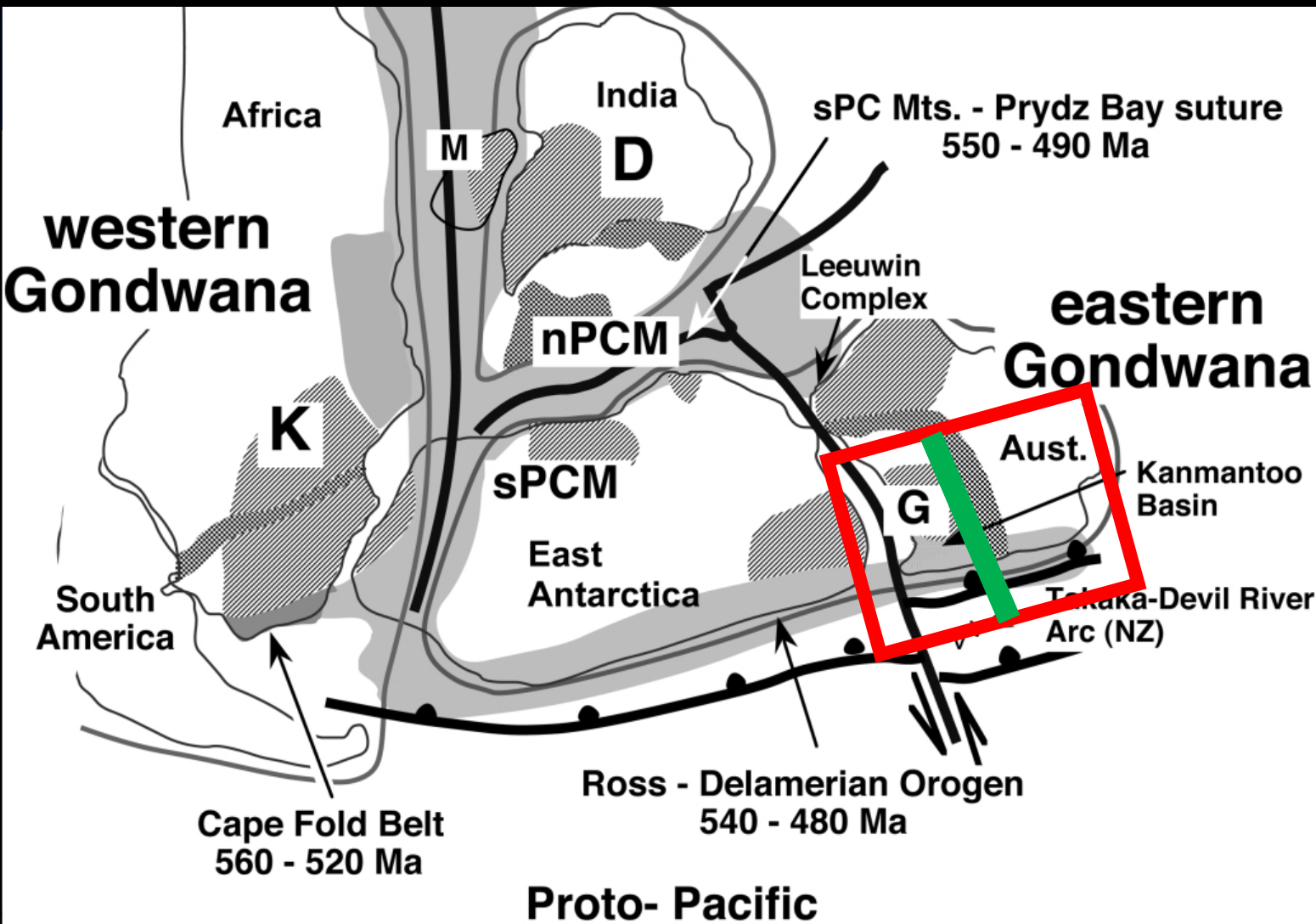
..and, what are the magnetic rocks in far western Victoria?

Regional

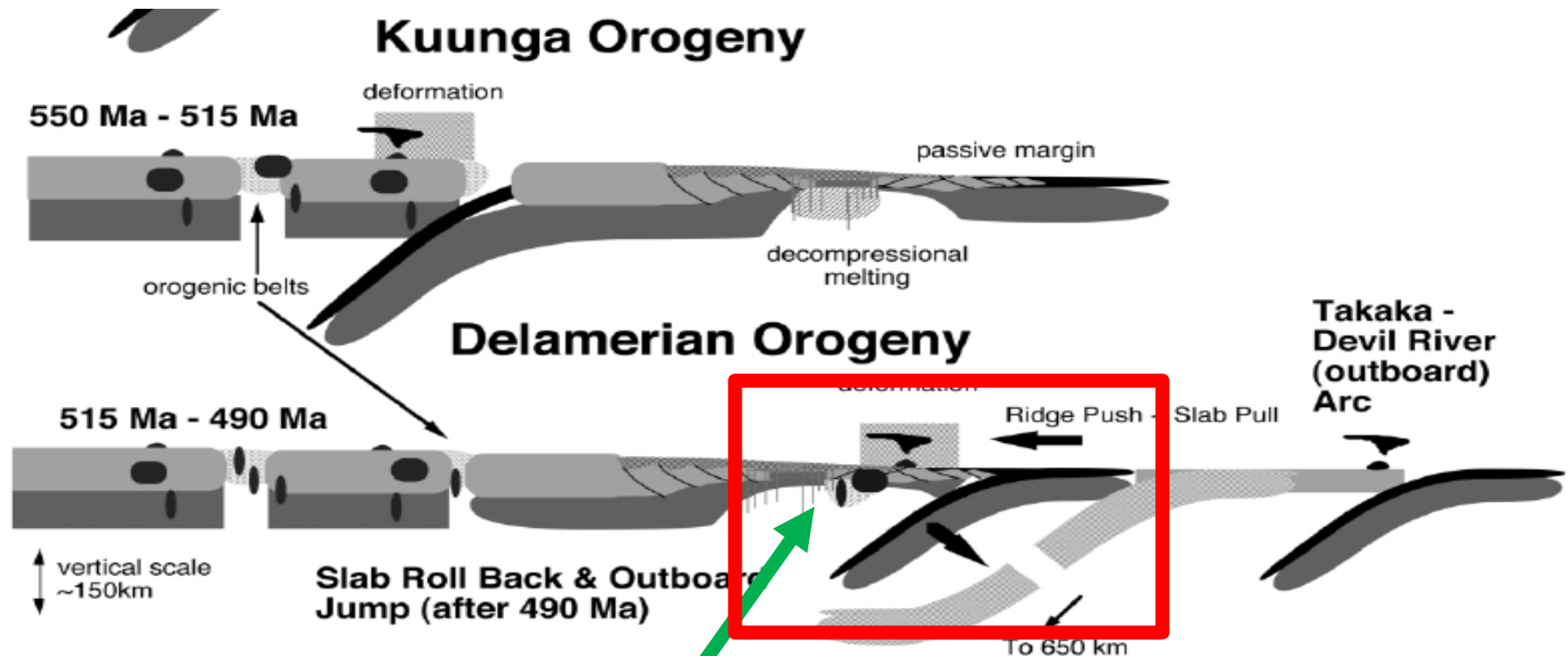
Total Magnetic Intensity



Previous academic work gives the critical clues – a convergent continental margin, active around 500 My ago, passed through western Victoria (green line shows cross-section location)



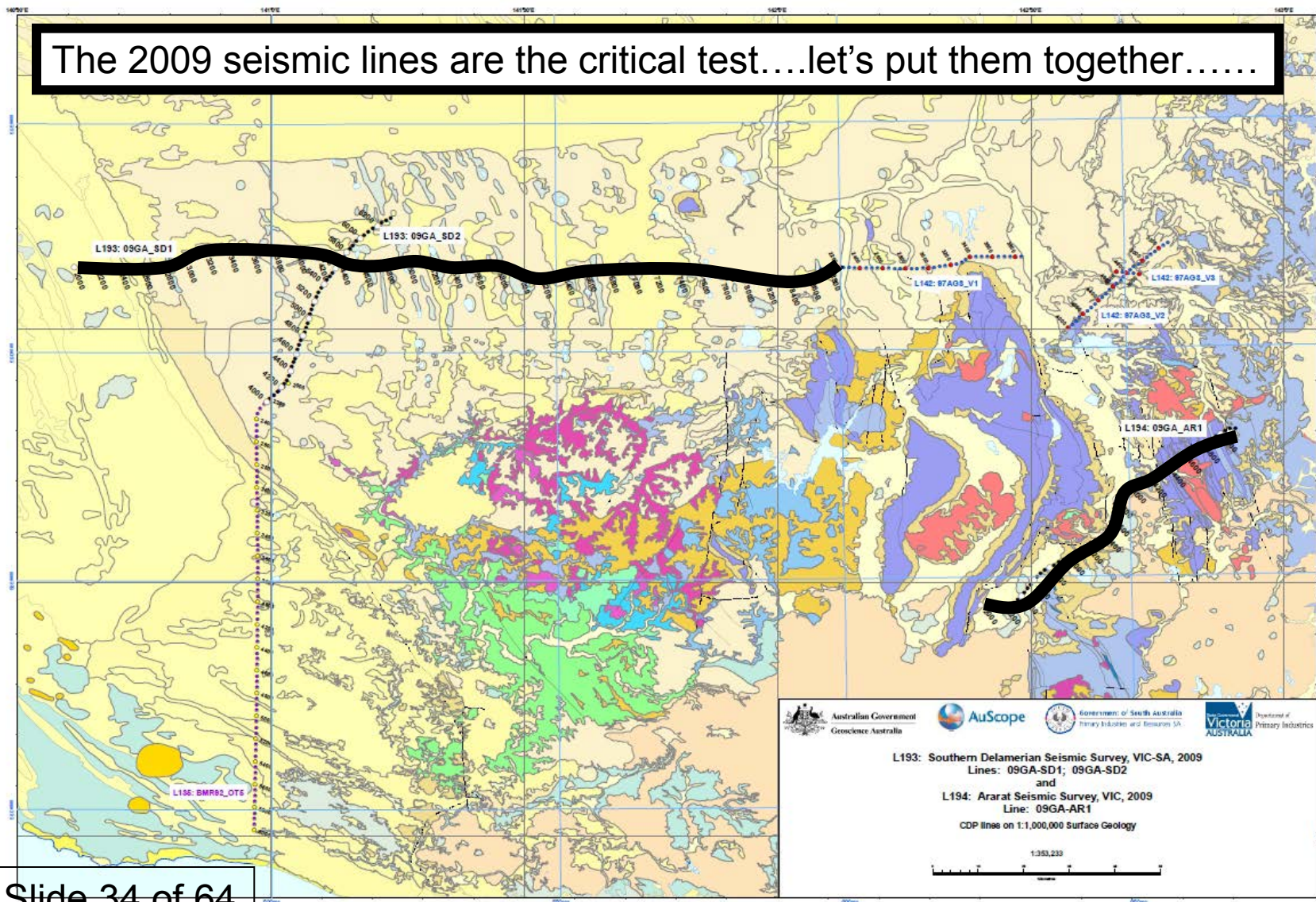
A continent-dipping subduction zone gives regional context for a continental magmatic arc beneath parts of western Victoria around 515-500 My – can we map it?



Boninites at ~514Ma: Kemp, 2003

MIGA ARC IN WESTERN VICTORIA

The 2009 seismic lines are the critical test....let's put them together.....

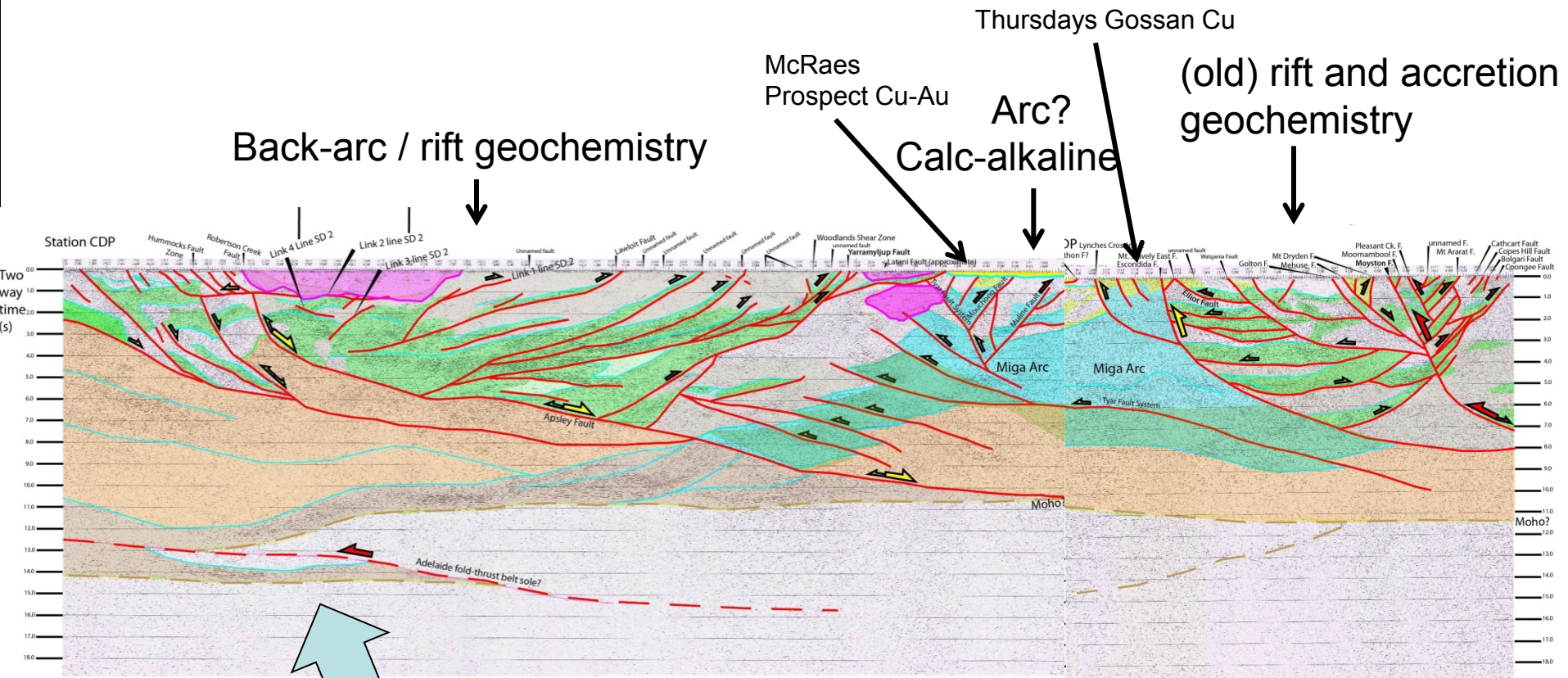


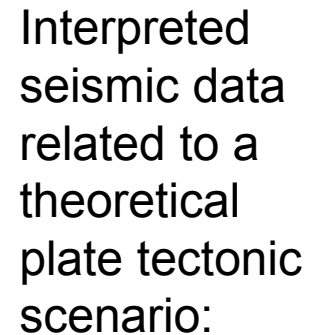
SEISMIC LINES

09GA - AR1

09GA - SD1

.....and the result is an overthrust Cambrian arc succession, superimposed on a former Proterozoic rifted passive margin to Gondwanaland. And it has porphyries!



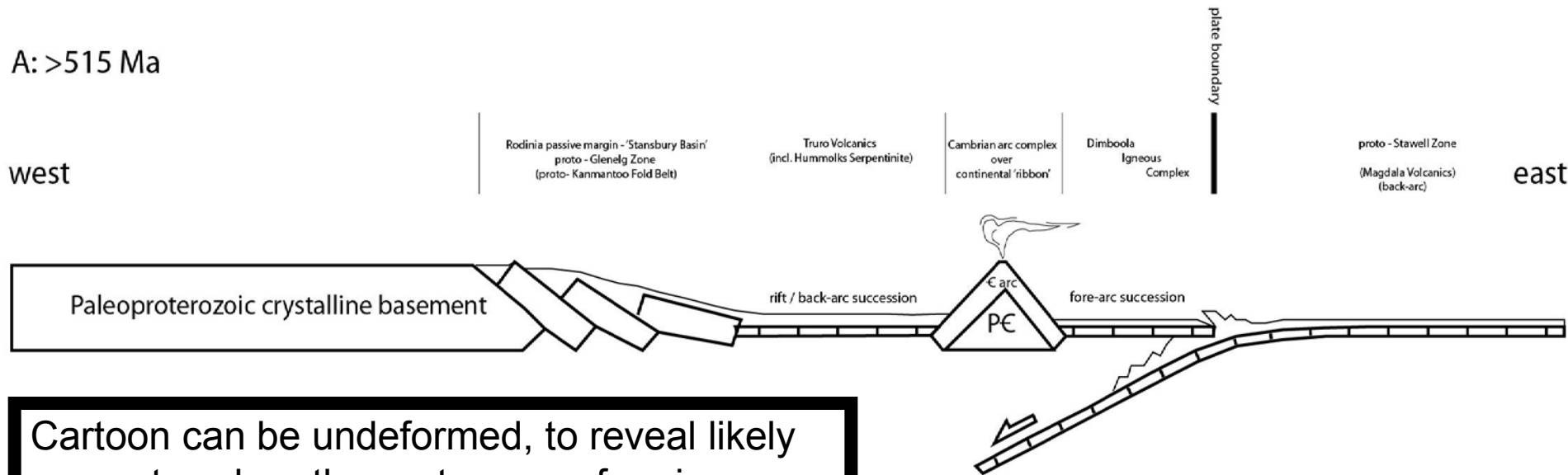


A Cambrian
back arc –
arc –
accretion
complex
succession.

MIGA ARC – ideas about evolution

A: >515 Ma

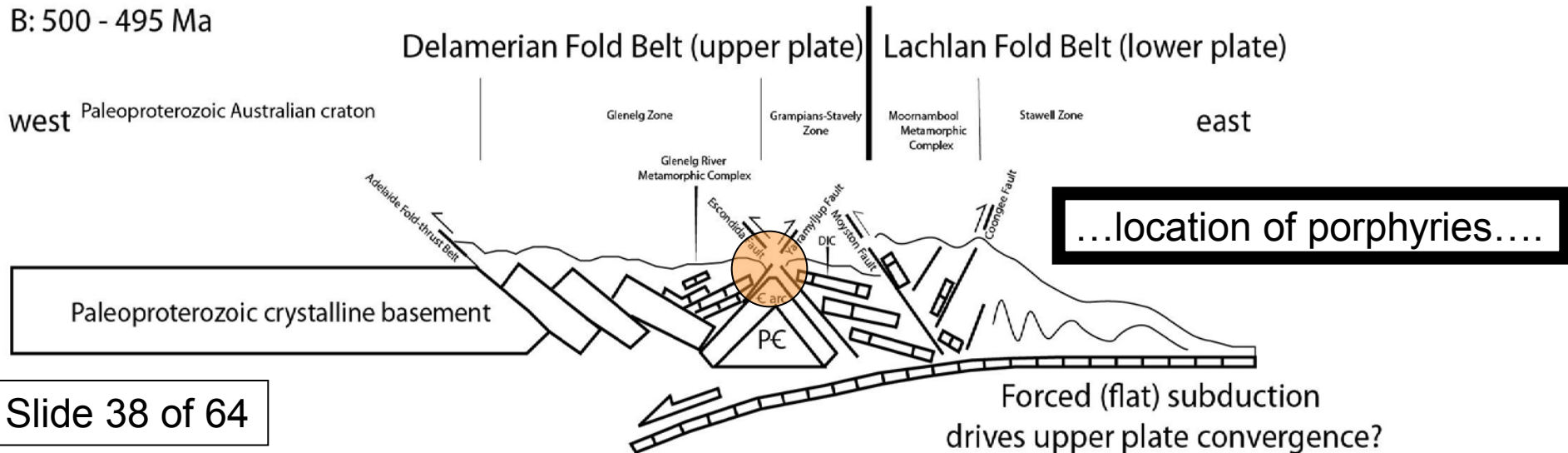
west



Cartoon can be undeformed, to reveal likely geometry when the system was forming.....

B: 500 - 495 Ma

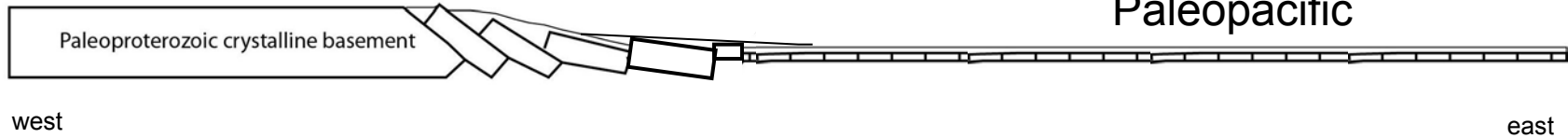
west



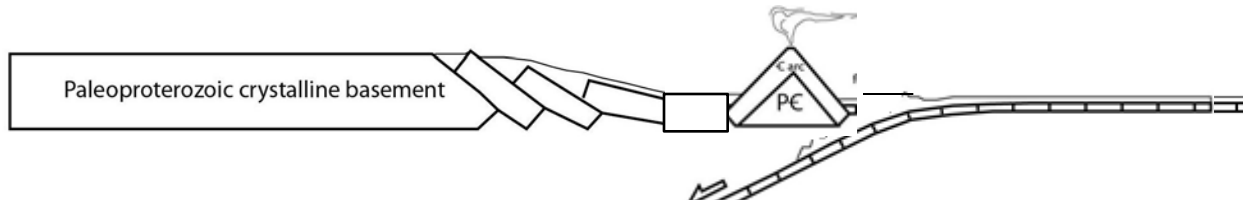
A: Neoproterozoic: passive margin, a relic of Rodinia breakup (Hummocks Serpentinite)

Gondwanaland

Paleopacific

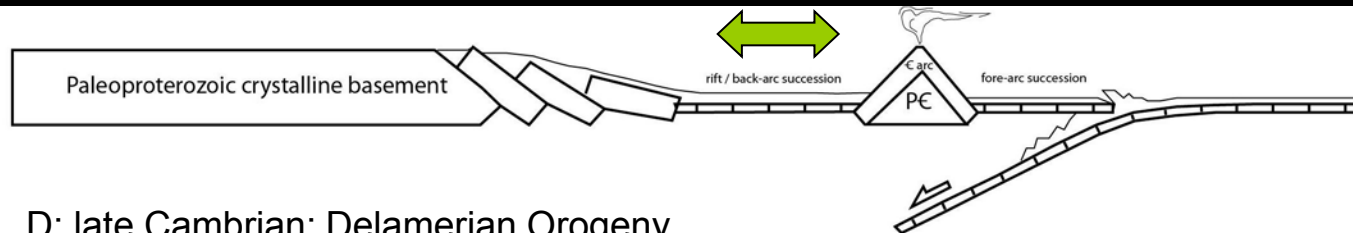


B: early Cambrian: evolution to convergent margin, with continent-fringing Miga Arc

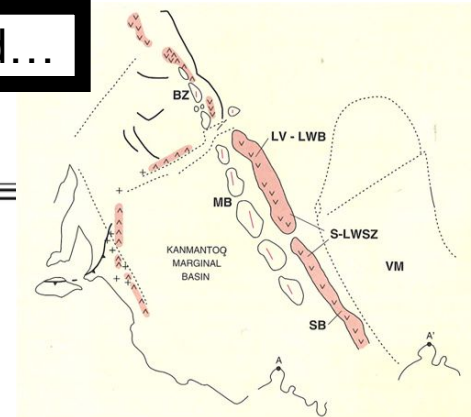
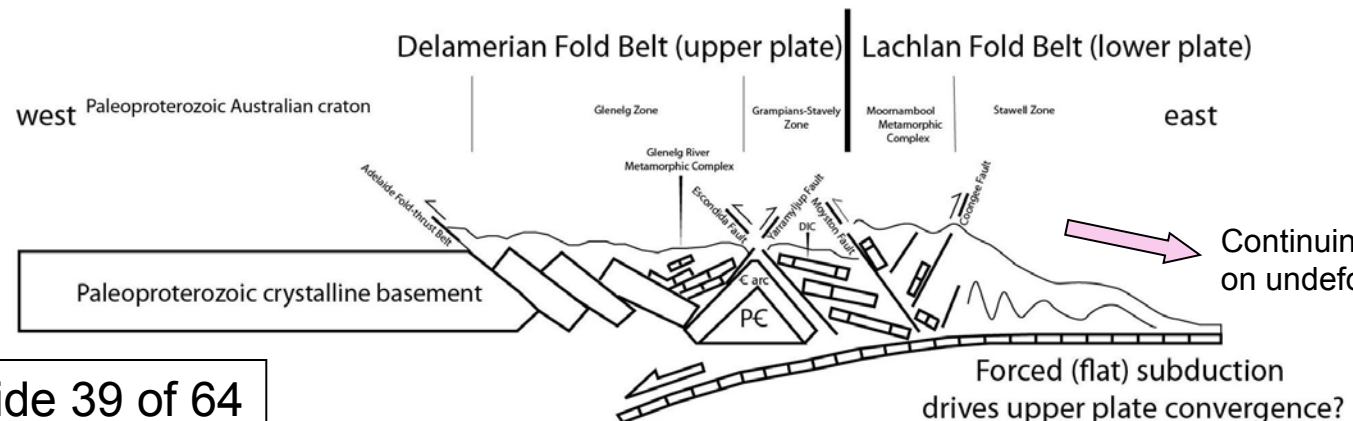


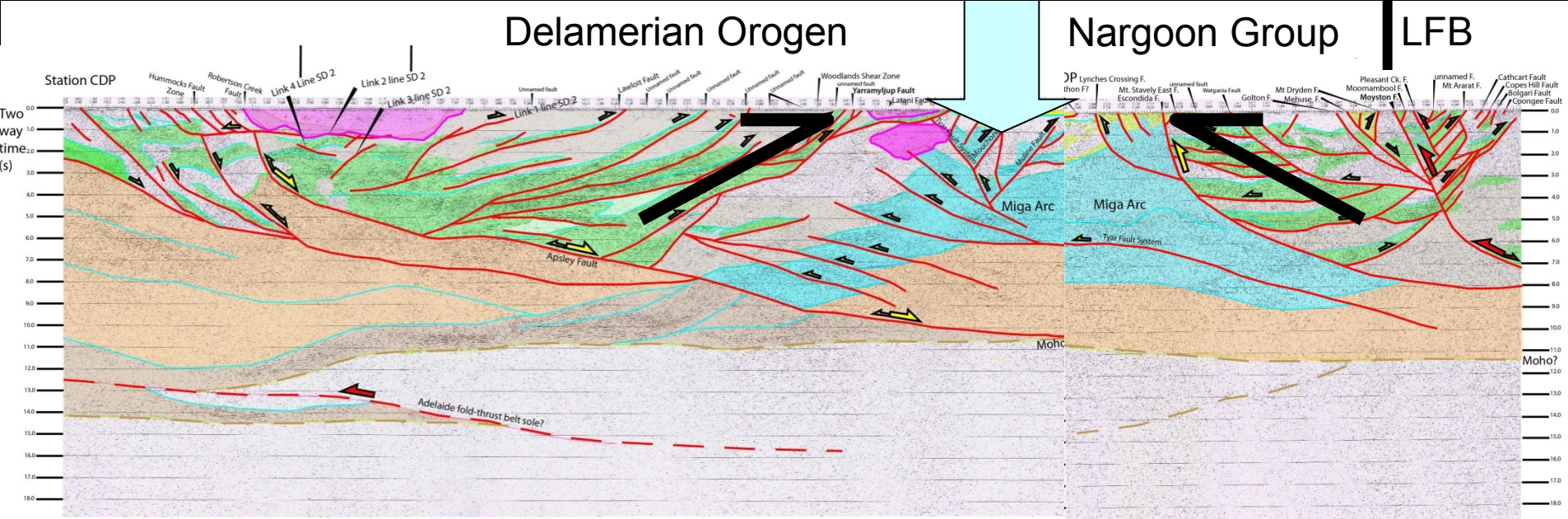
C: early – middle Cambrian: slab rollback pulls arc east, opening backarc basin (Truro Volcanics)

...and a comprehensive geodynamic scenario can be developed...

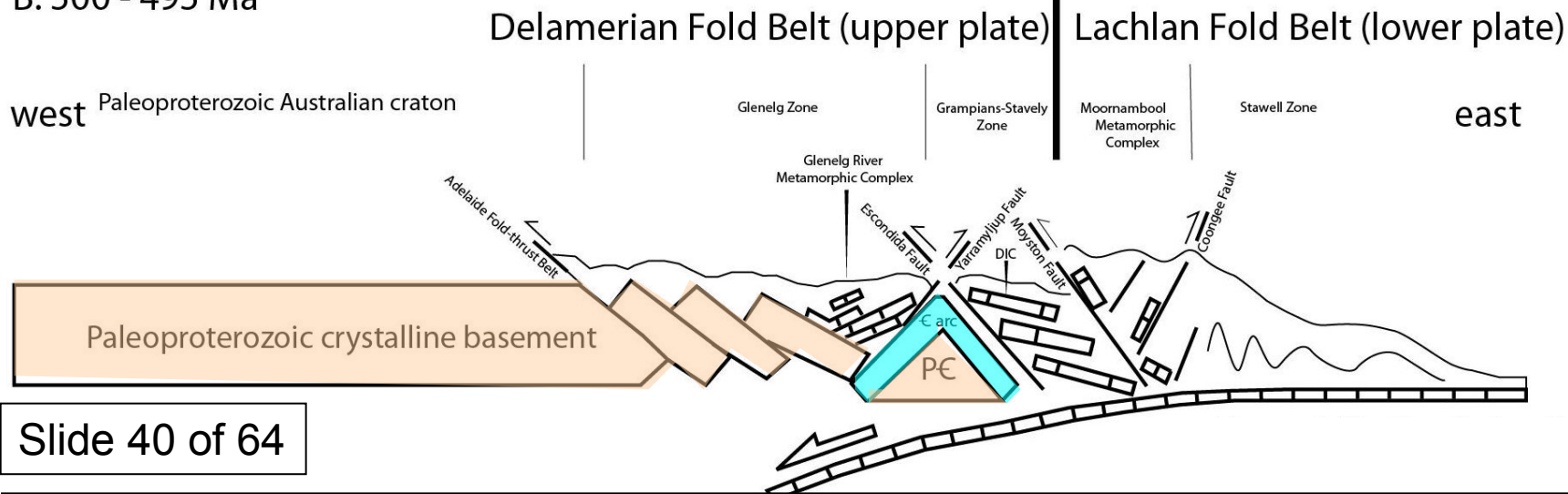


D: late Cambrian: Delamerian Orogeny





B: 500 - 495 Ma



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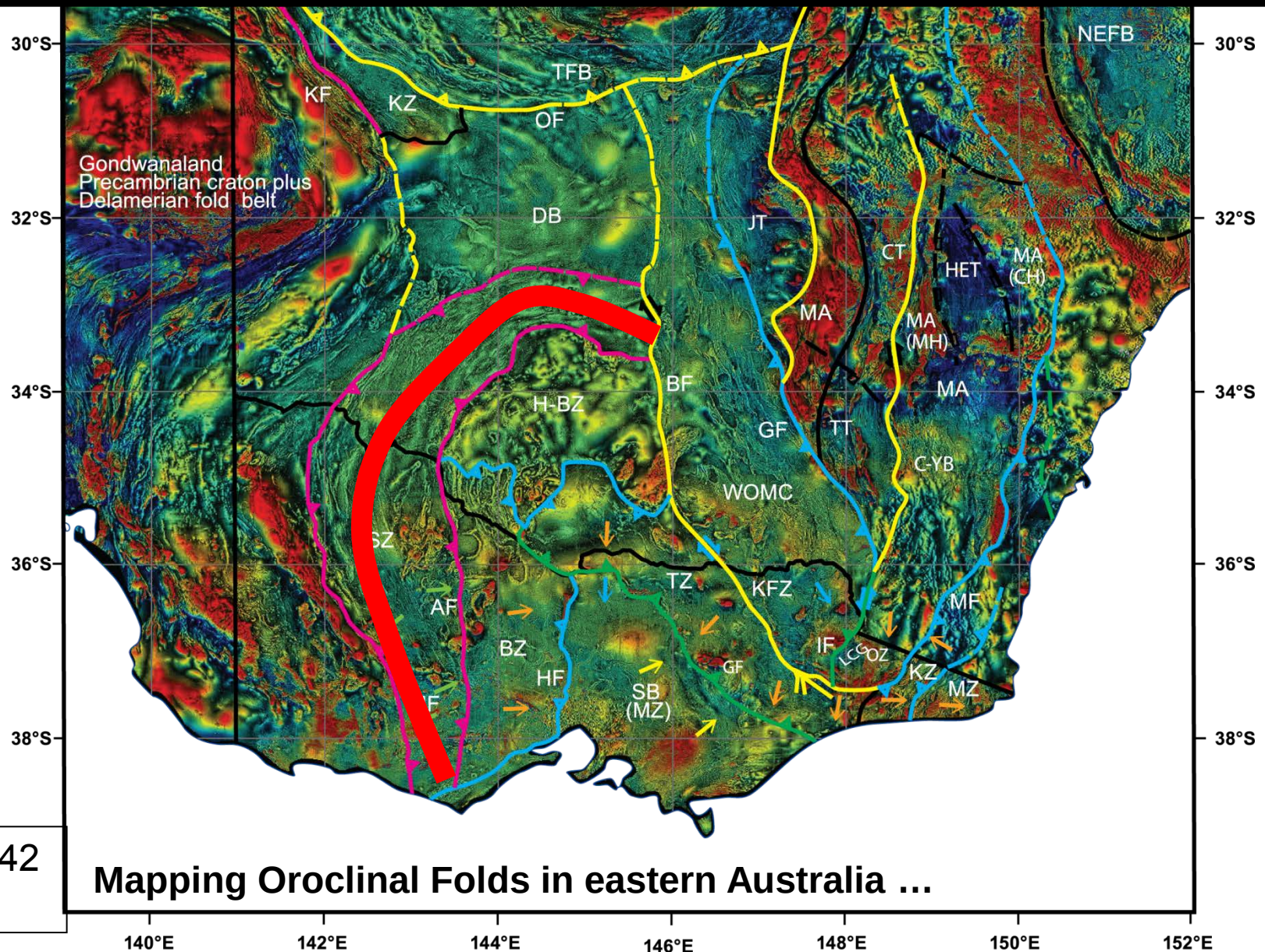
...Miga Arc porphyries may be old, but are still preserved, because arc-accretion involved overthrusting of both arc-flanks, burying the arc, preserving it until today...

Talk outline

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Modern magnetic data shows buried extensions to the Stawell Zone in western Victoria extend north under Murray Basin cover as a giant curved orogen, marked by red line....

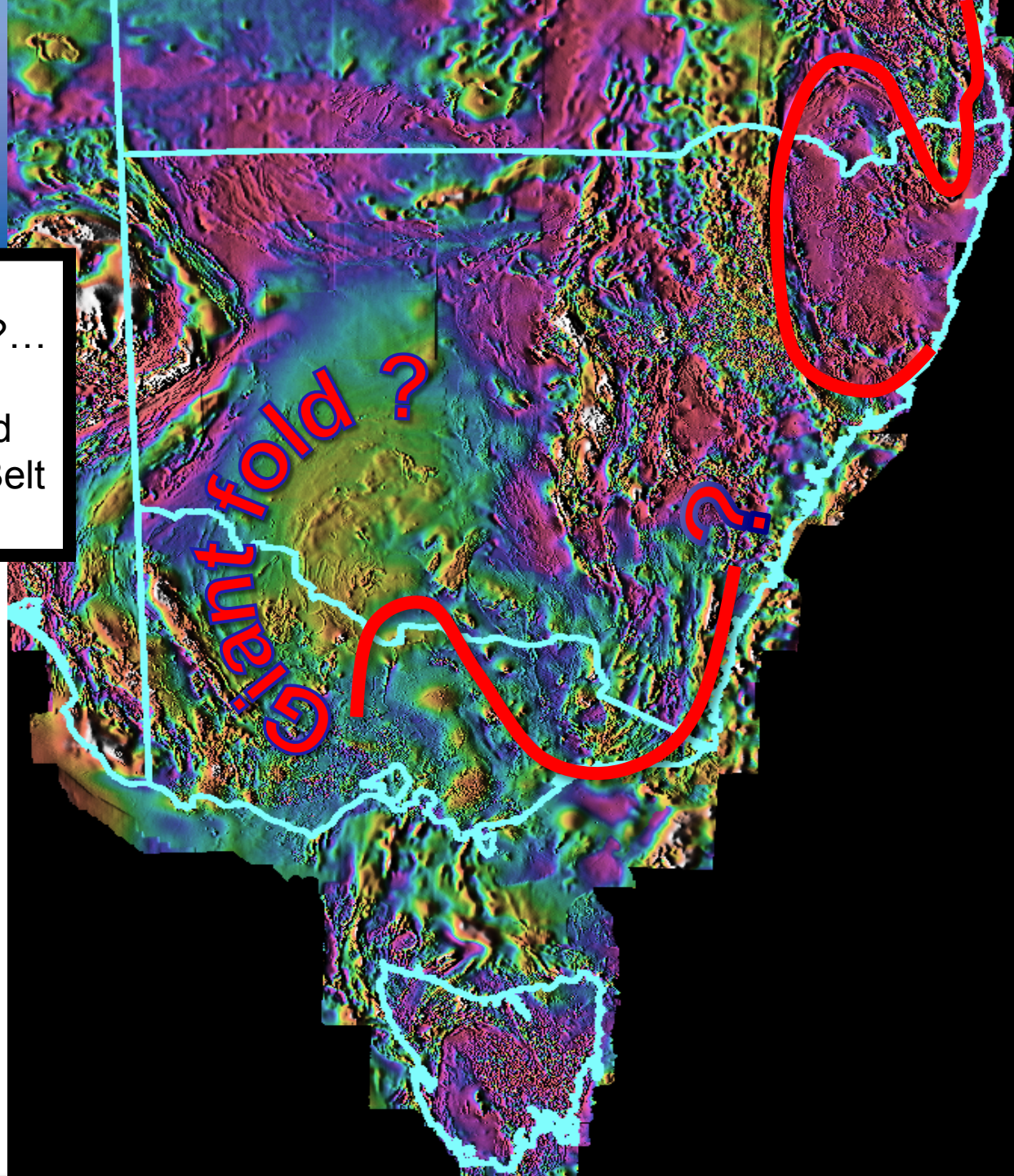


Regional

Total Magnetic Intensity

...what if it was a giant fold,
like the New England Orocline?...

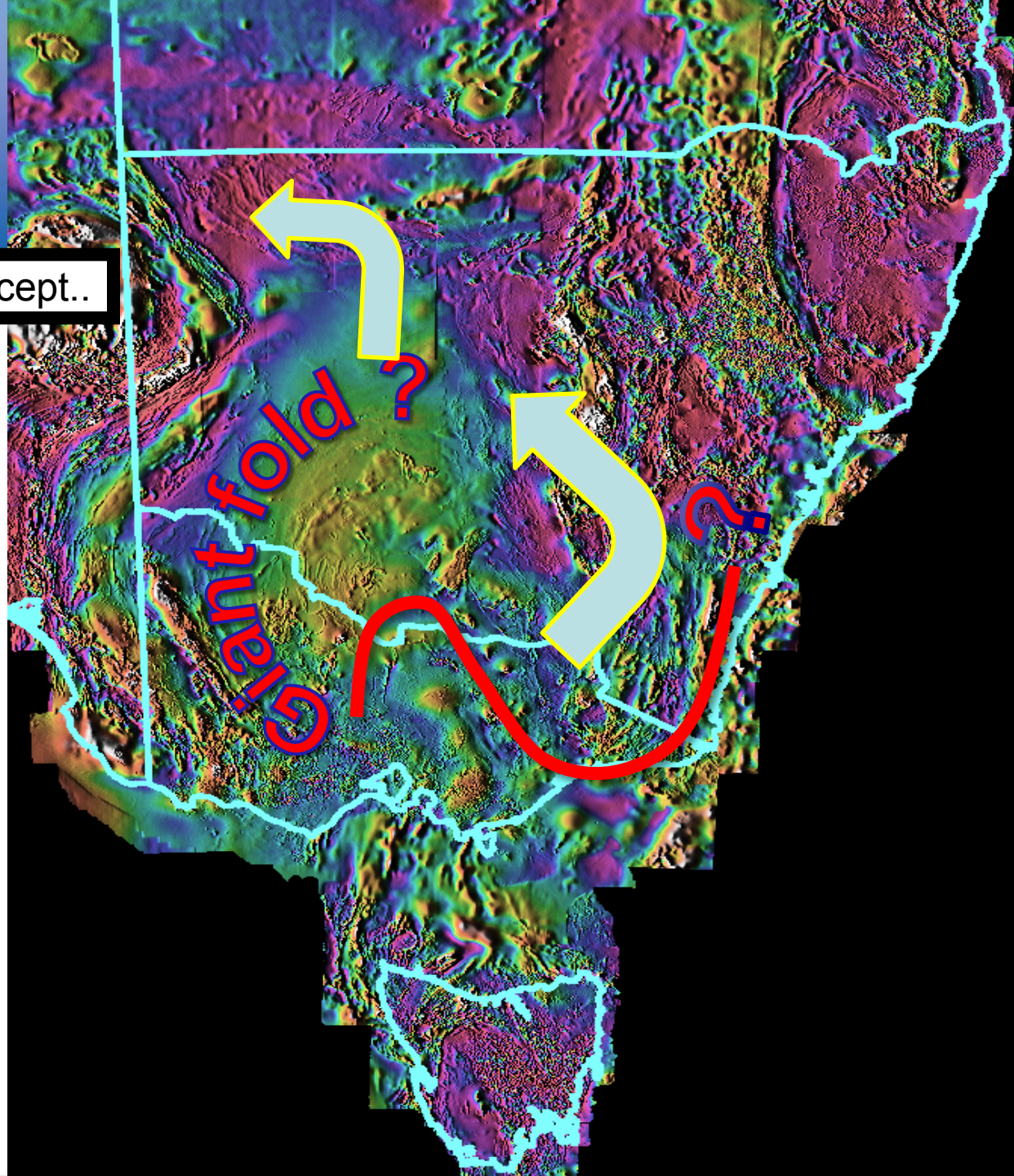
...and what if that fold extended
into the eastern Lachlan Fold Belt
as a giant Z-shaped structure?



Regional

Total Magnetic Intensity

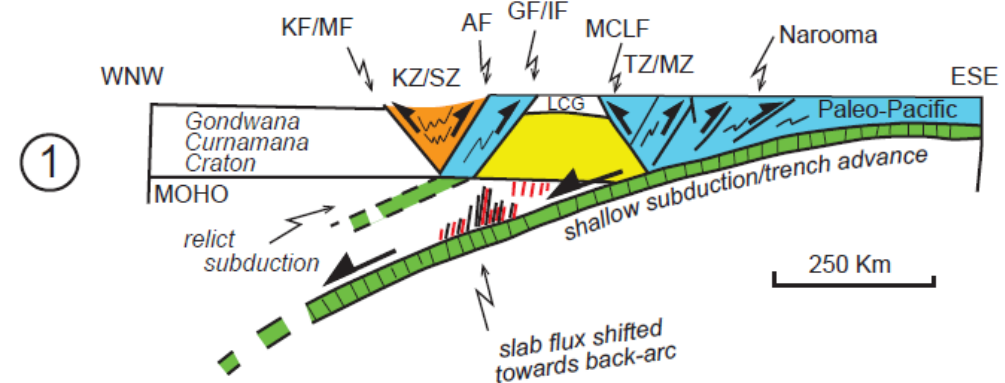
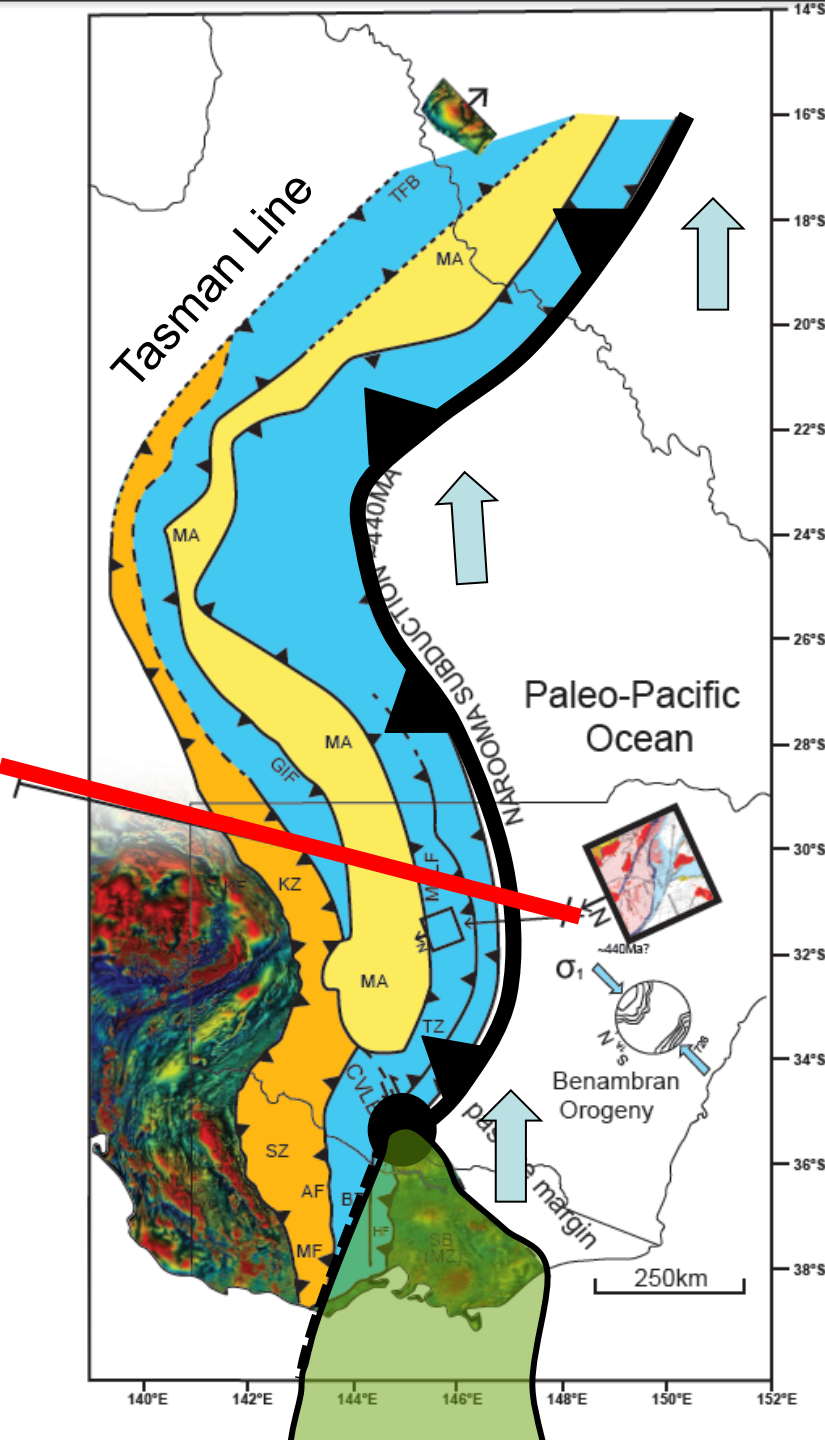
...unfolding is a test of this concept..



...the unfolded Lachlan fold Belt appears thin and simple, with a single, shallow continent-dipping subduction zone active along the east- Gondwanaland margin...

(Blue= Ordovician metasedimentary strata. Yellow = Macquarie Arc
red line shows cross-section location)

Plate convergence was sinistral-oblique, eventually drawing a microcontinent into the subduction zone: Vandieland (Tasmania and the Selwyn Block, green).....



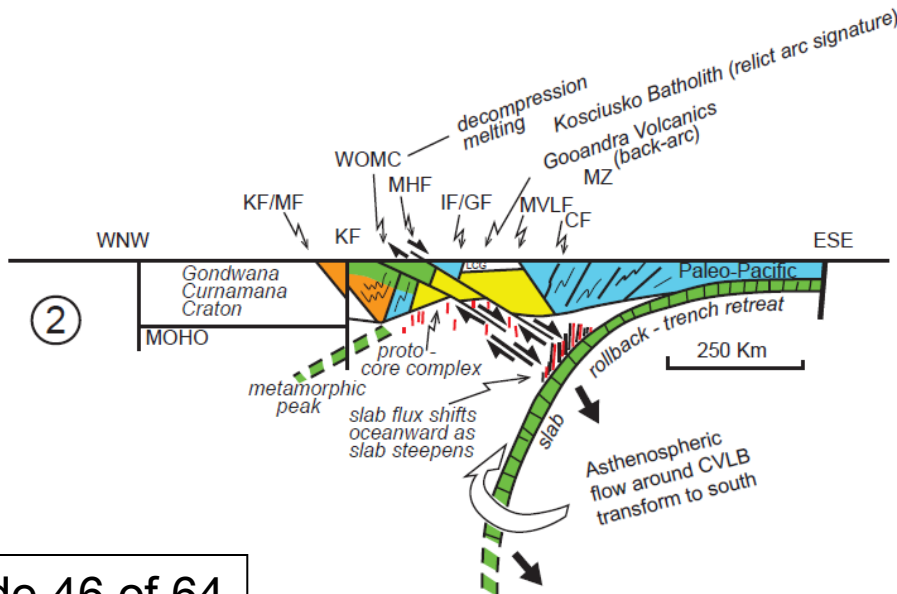
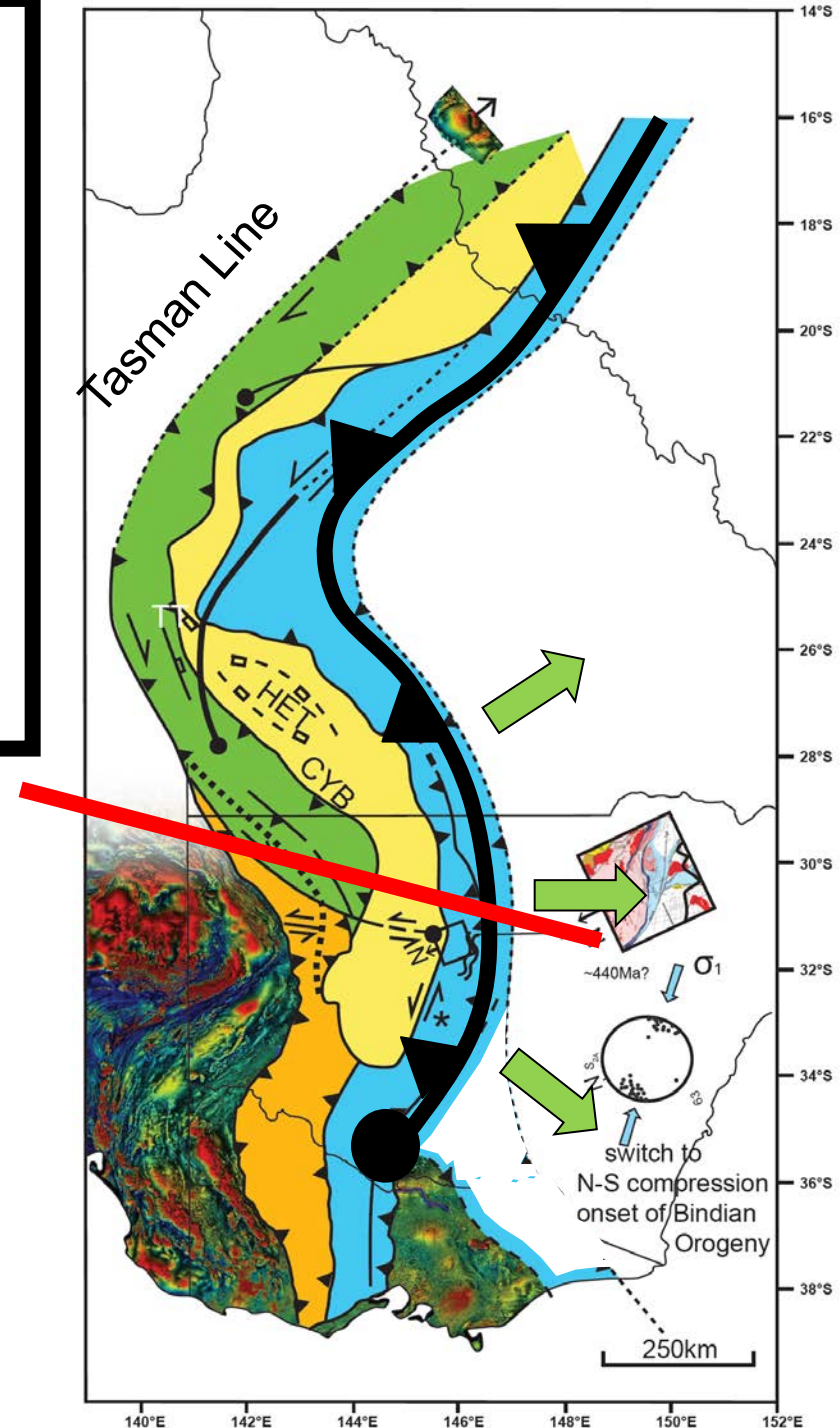
...collision of the Vandieland microcontinent stalled subduction...

With plate-convergence stalled, the sinking slab switched the system into roll-back – a tectonic 'mode switch' (green arrows; red line shows cross-section location)

LFB rollback – see: Collins, 2000 (Geology)

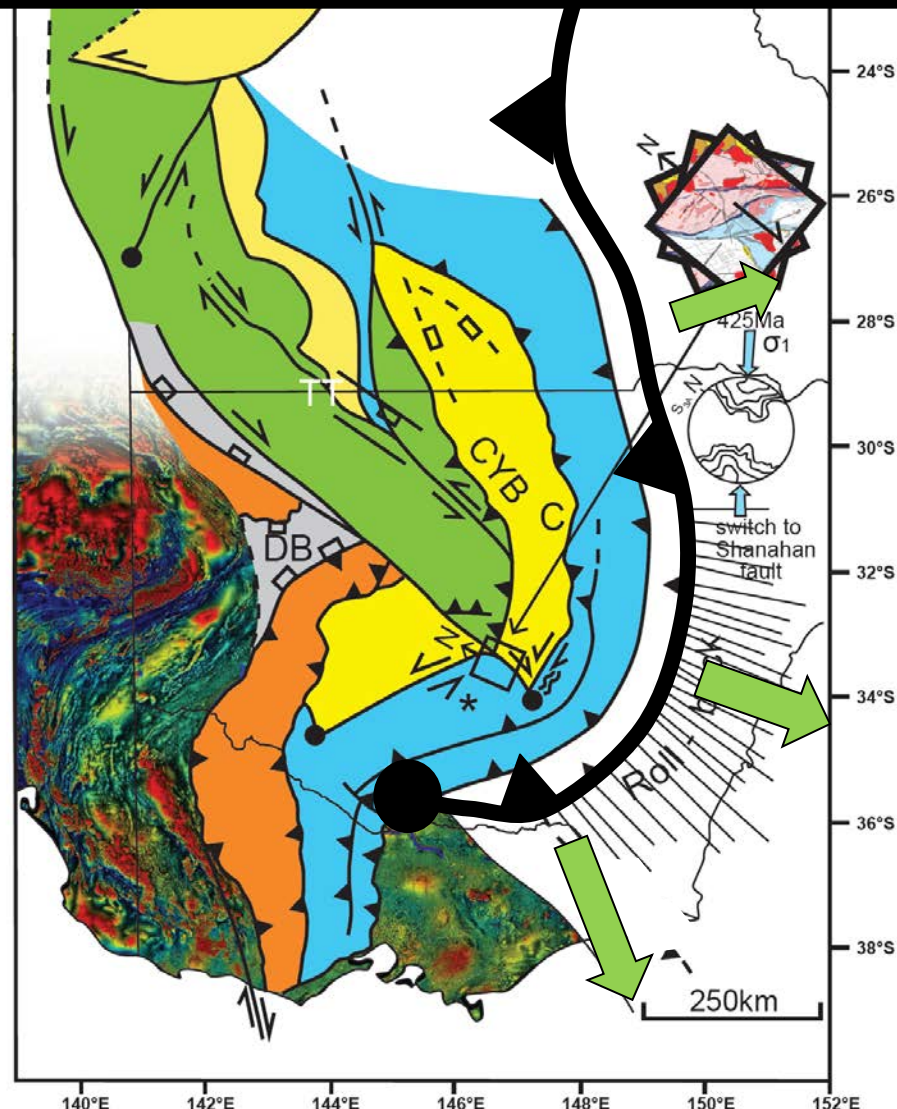
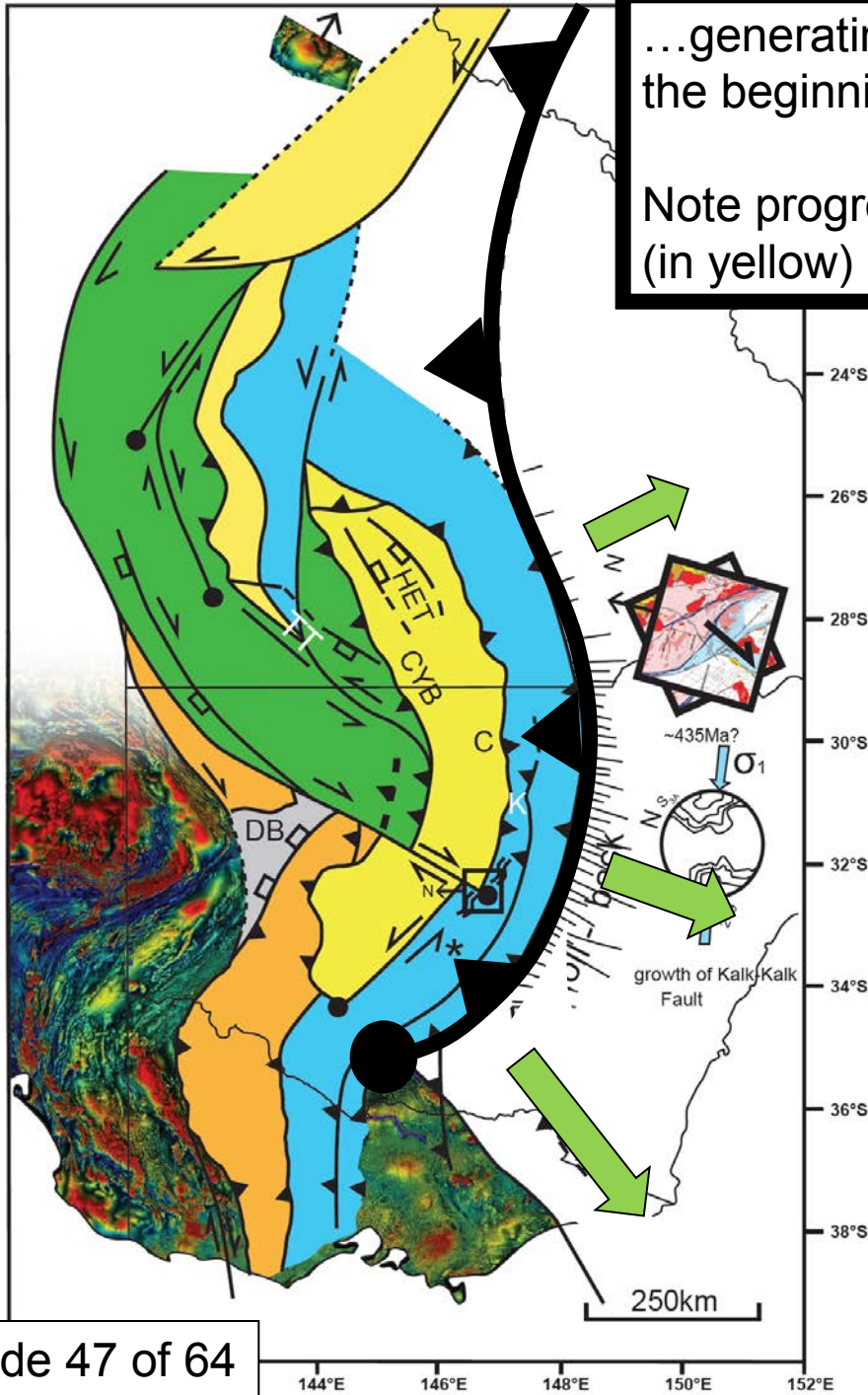
Roll-back caused fragmentation of the Macquarie Arc, and rapid upper-plate extension

Roll-back proceeded oceanward, but remained pinned at its southern margin by Vandieland.....

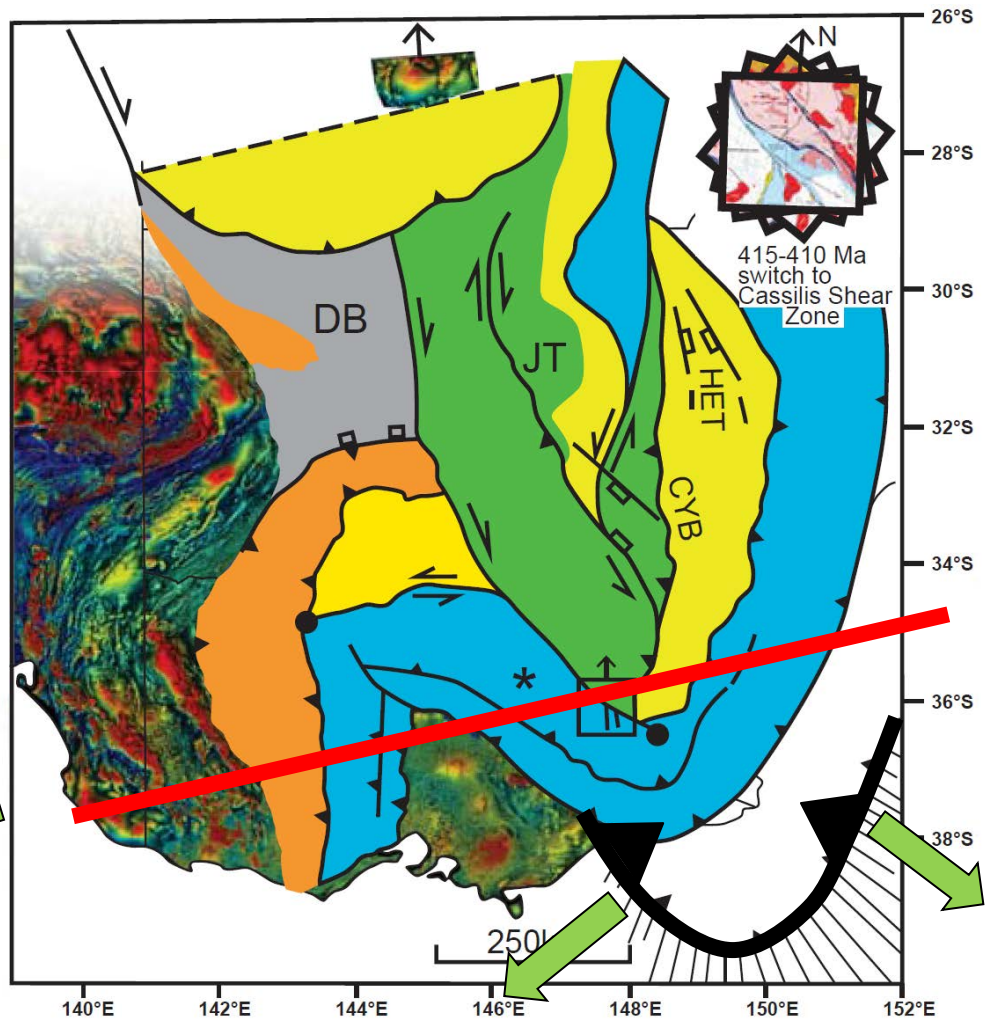
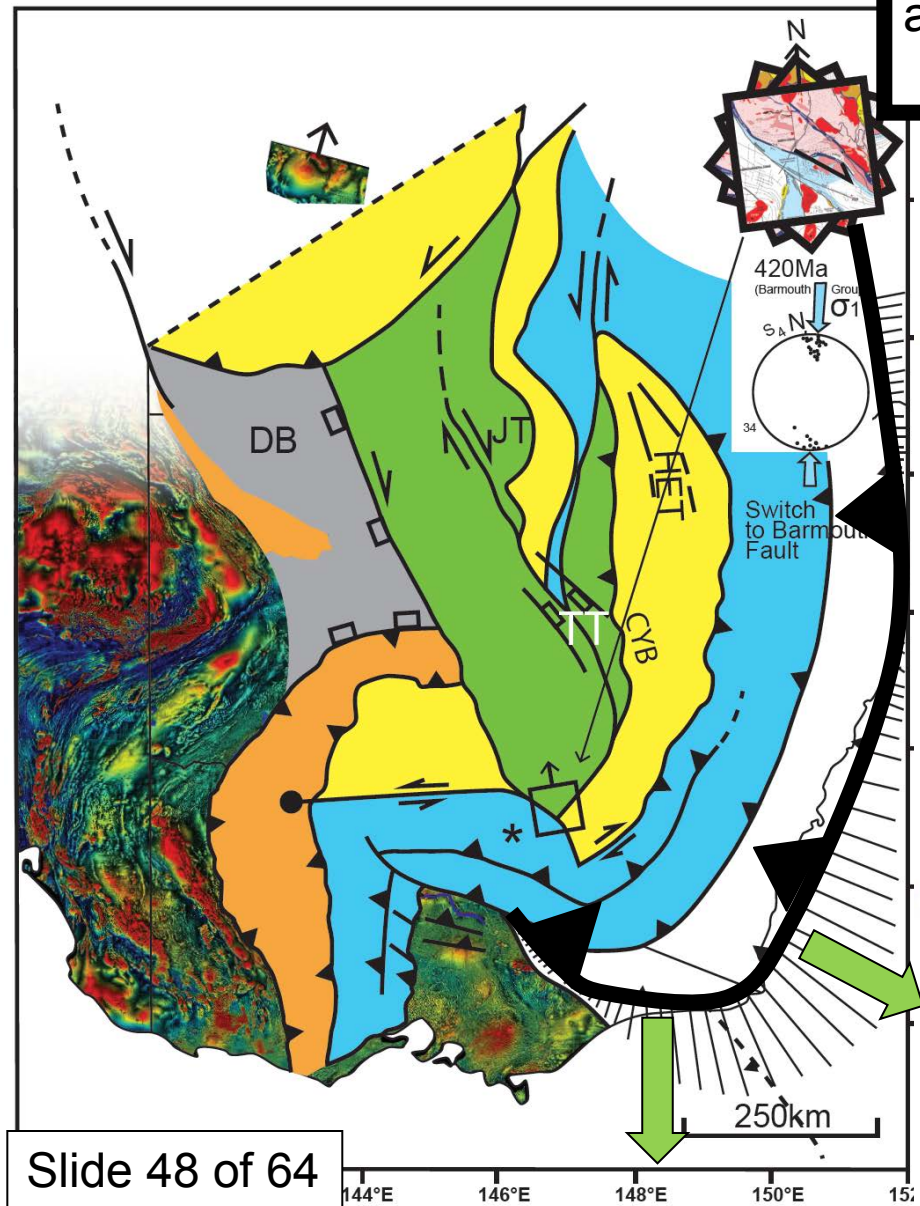


...generating a curved system.....
the beginning of the Lachlan Orocline....

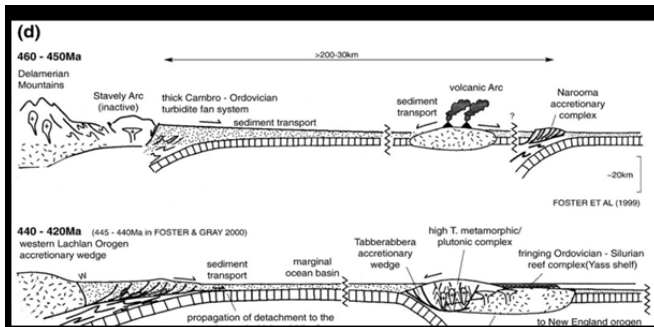
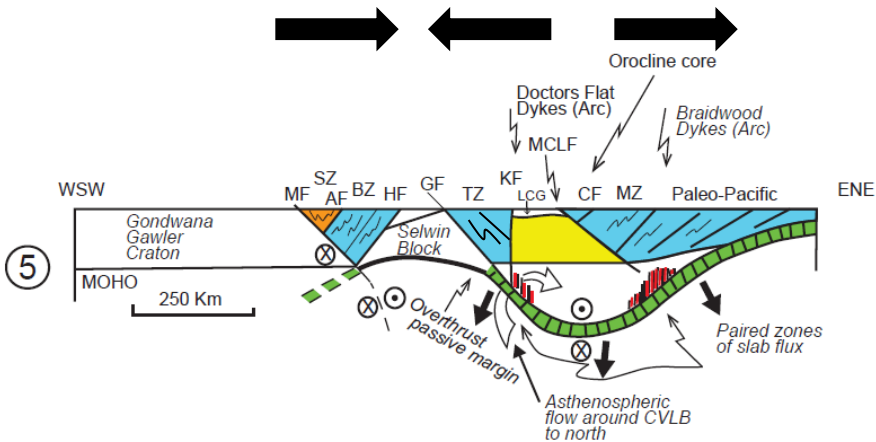
Note progressive fragmentation of the Macquarie Arc
(in yellow)



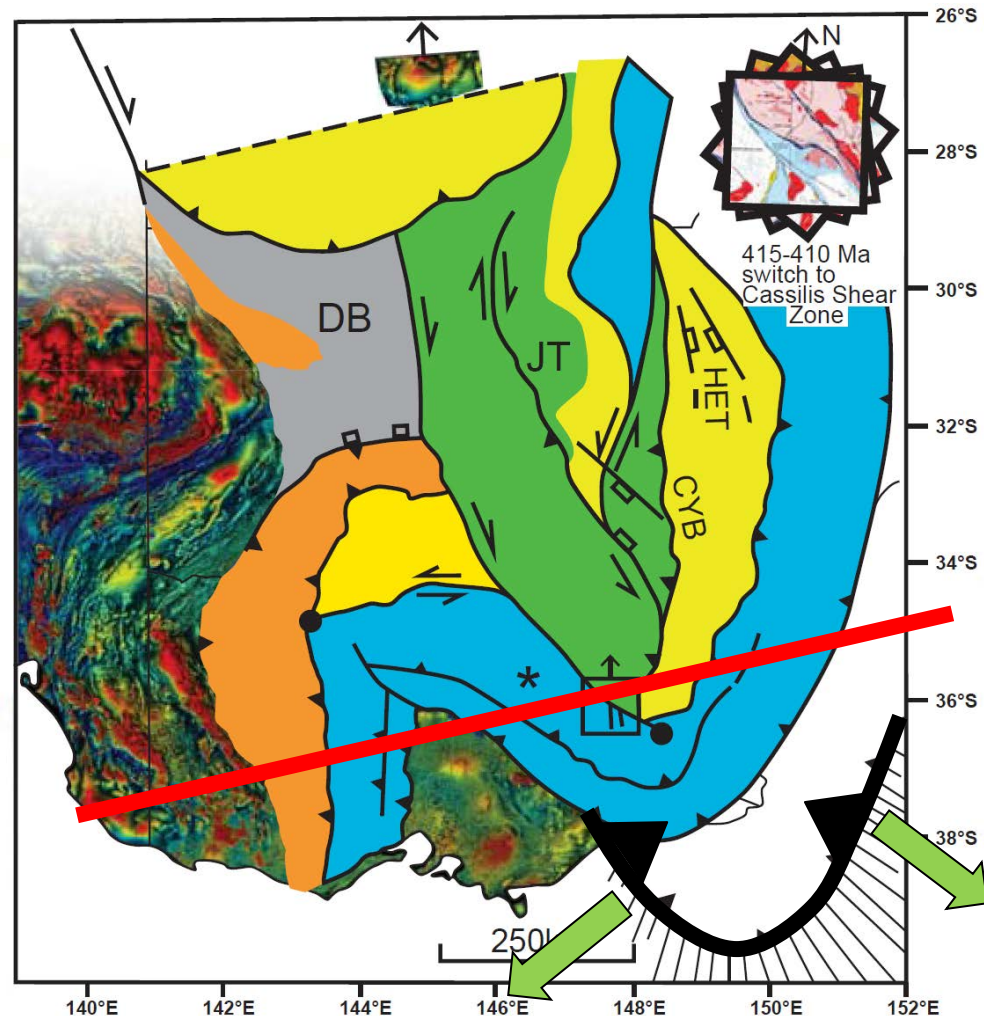
...eventually the orocline grew to the point where the geometry of parts of the Macquarie Arc accretionary complex (in blue) appeared effectively 'reversed' in geometry....



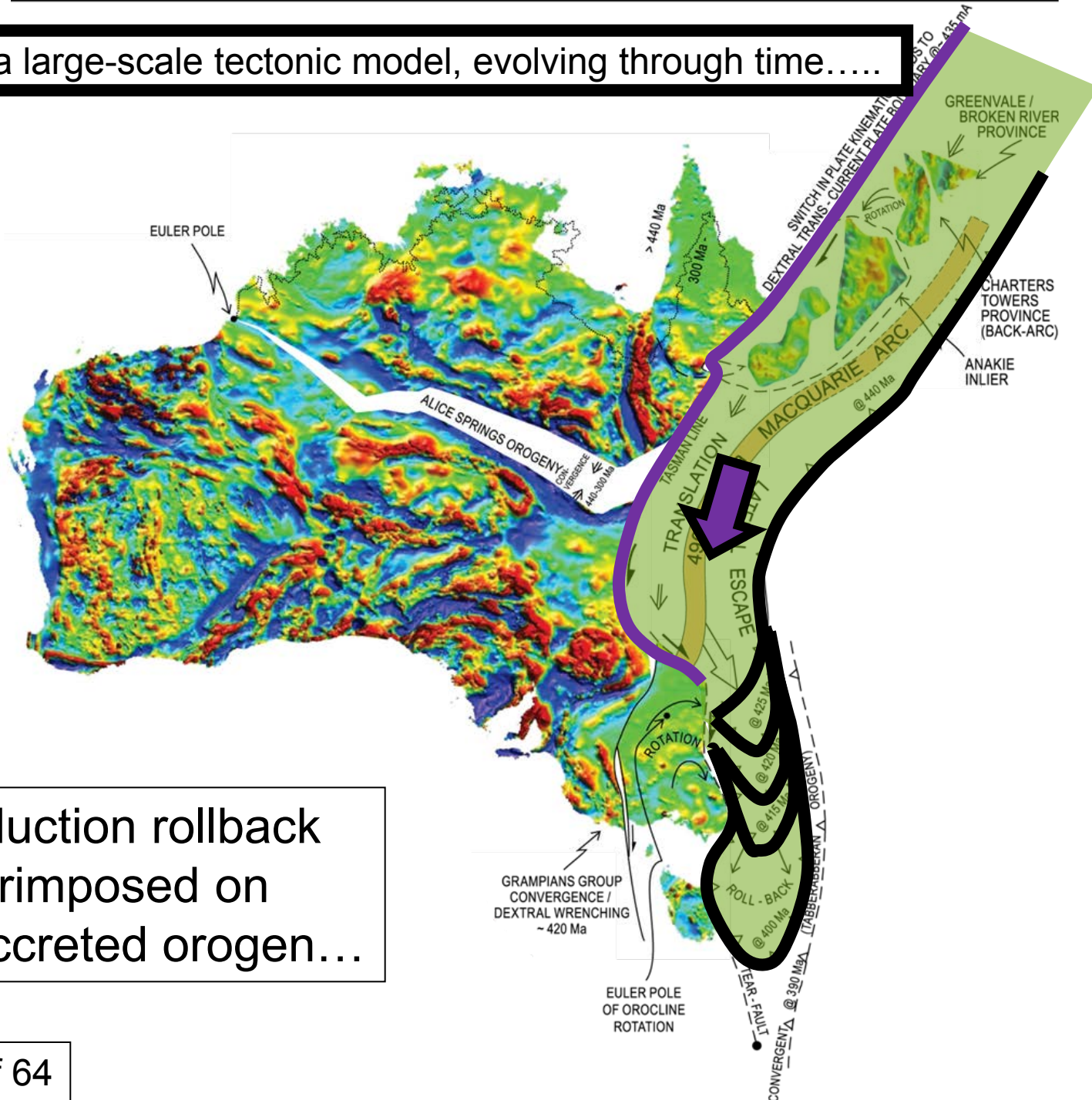
...one 'reversed portion' is the Tabberabbera Zone....
 Oroclinal folding is a simple alternative to the previous
 double-divergent subduction models proposed to explain
 apparently complex Lachlan Fold Belt geometries.....



(eg. Gray & Foster, 2000)

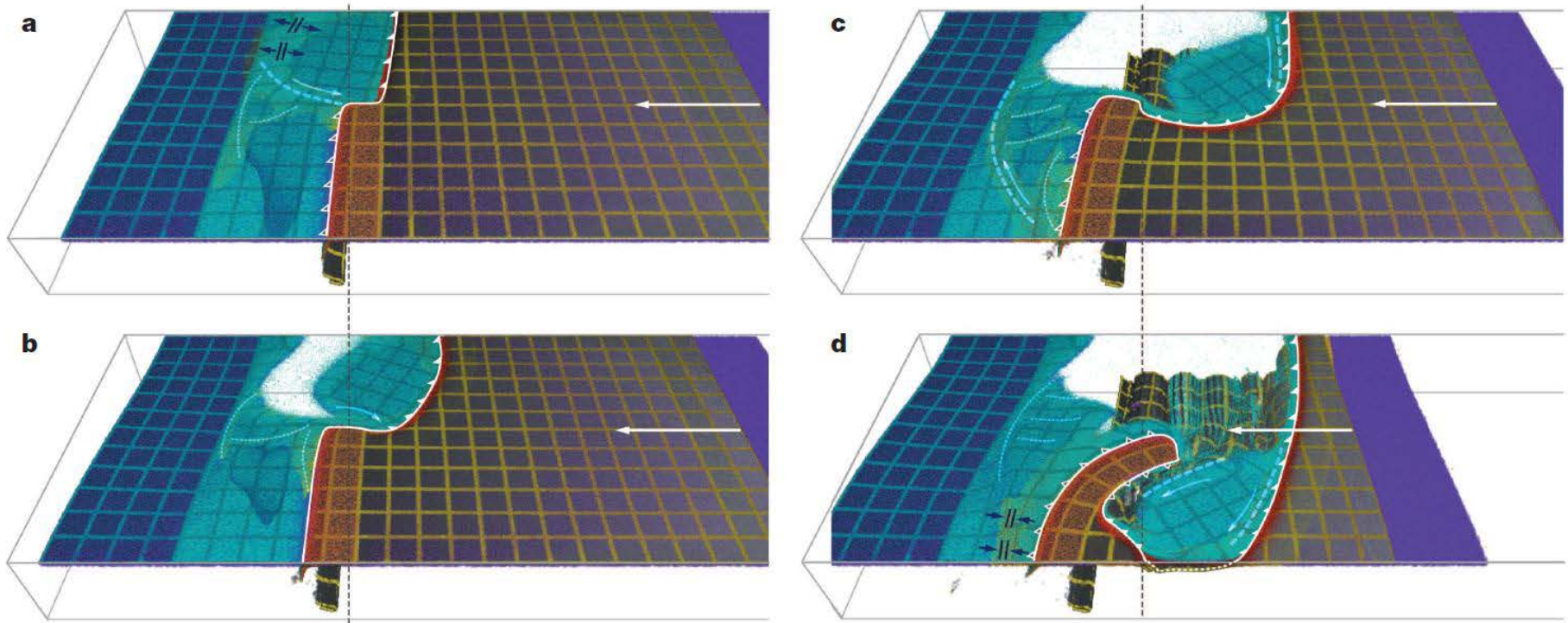


...this is a large-scale tectonic model, evolving through time.....



Subduction rollback
superimposed on
an accreted orogen...

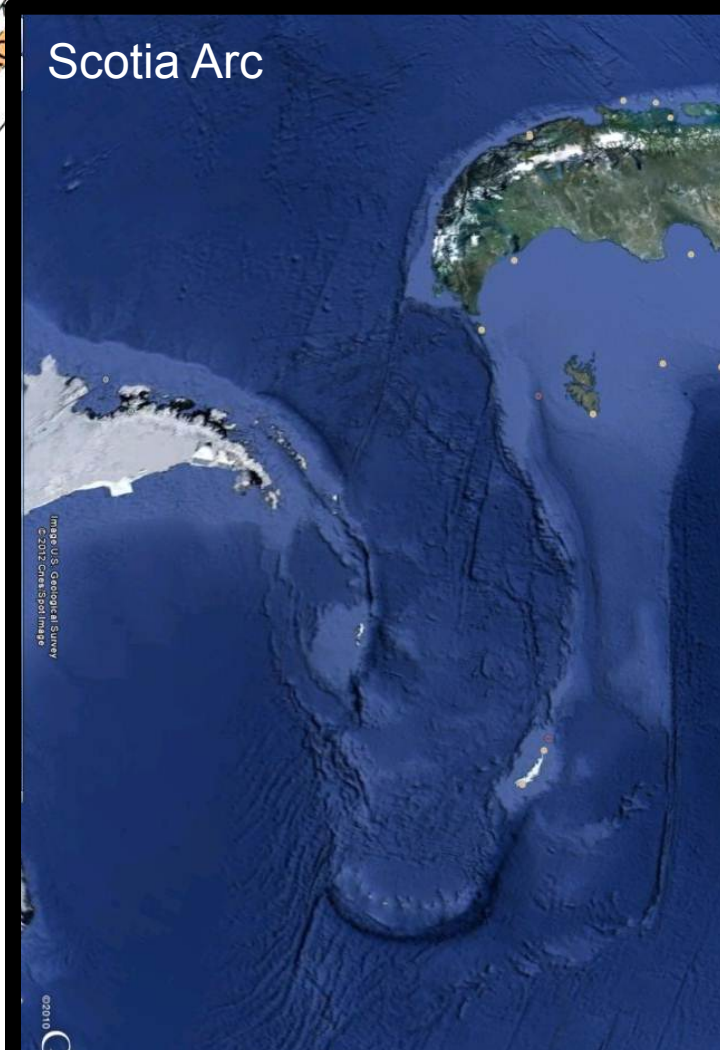
...and now supported by independent crustal-scale geodynamic numerical modelling.....



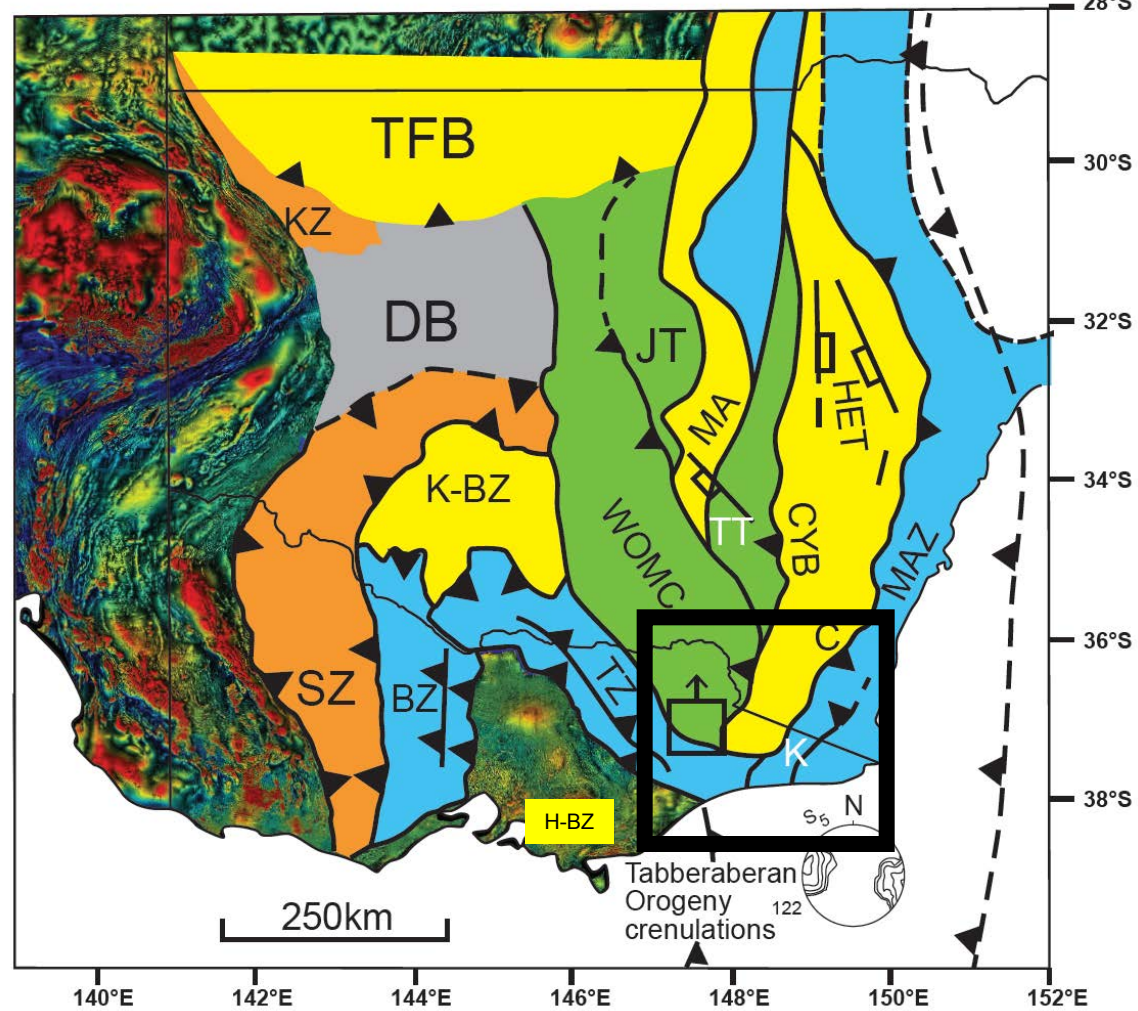
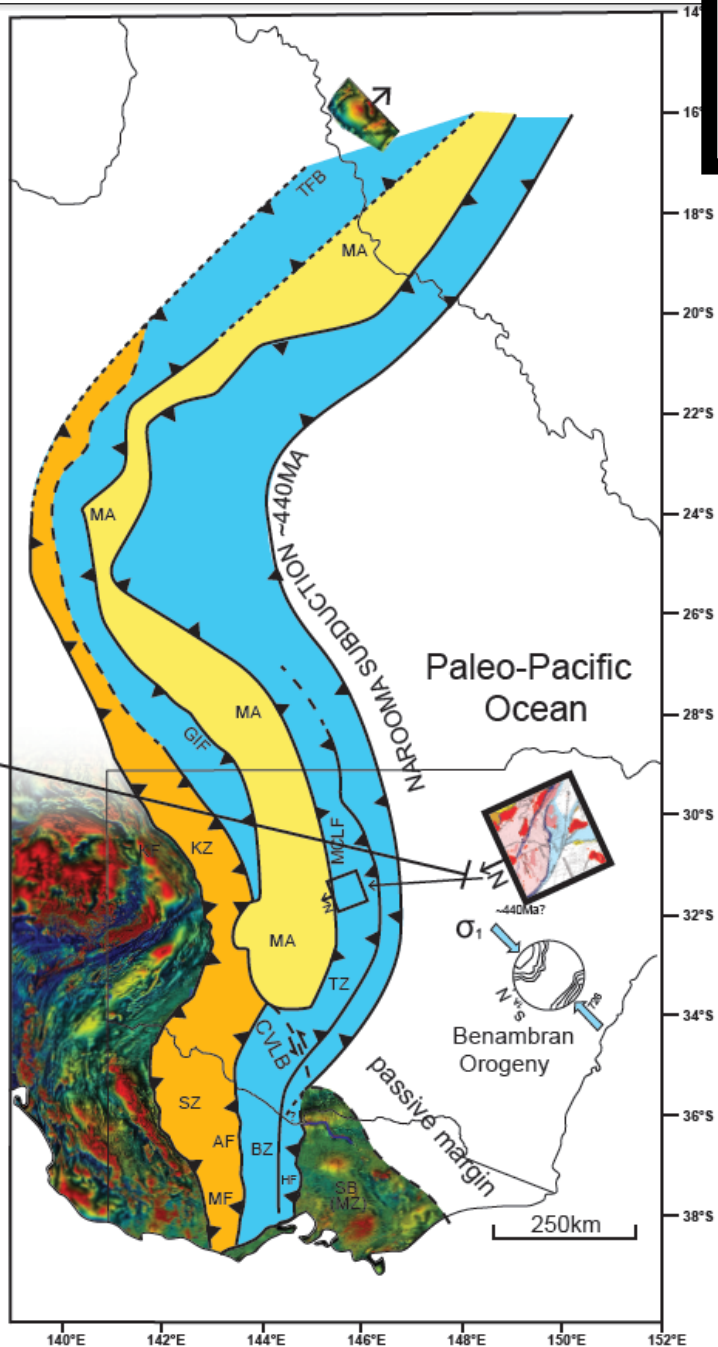
Moresi, Betts, Miller, Cayley, 2014: NATURE

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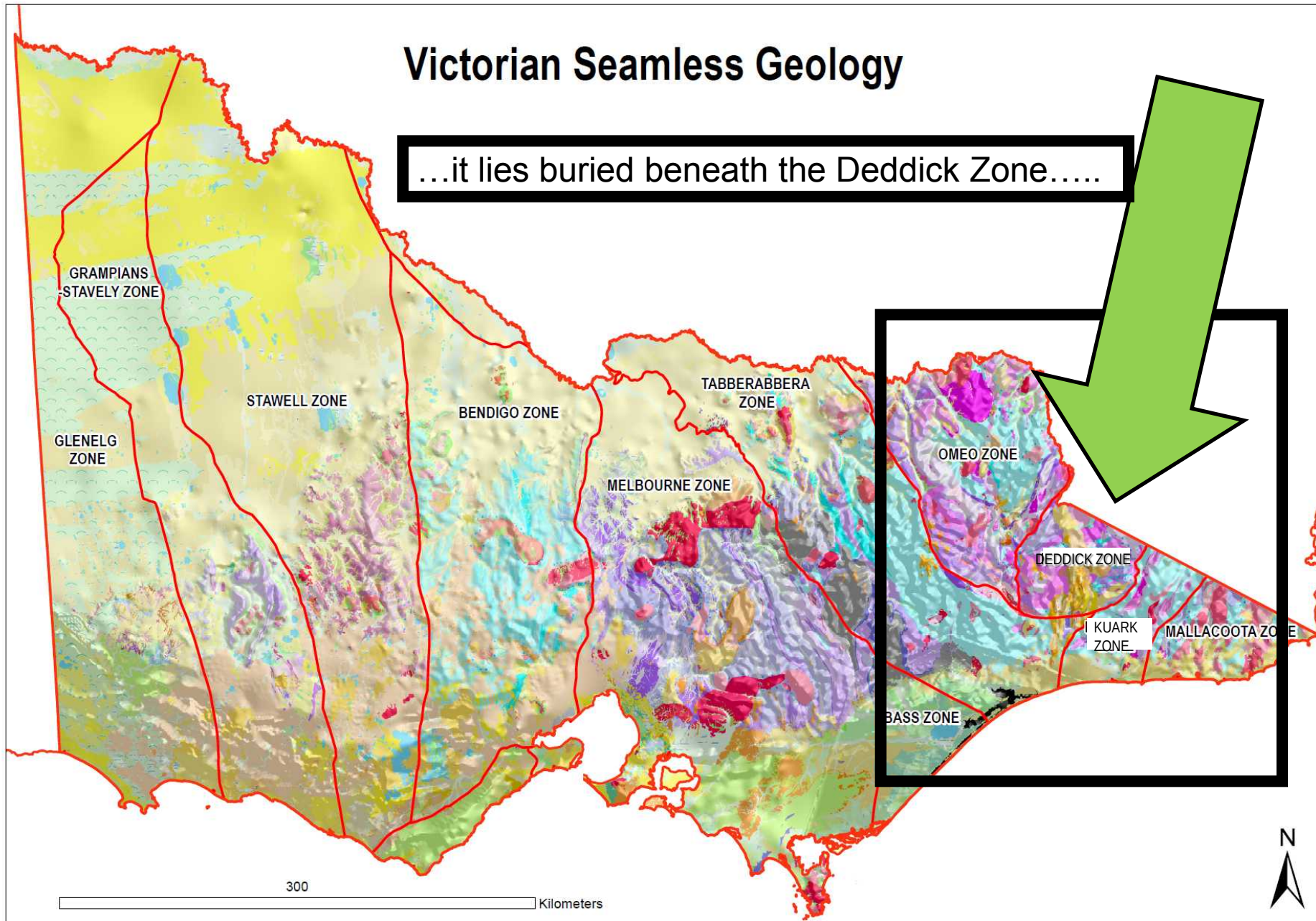


Implications for mineral exploration.....the model demonstrates how and where the Macquarie Arc extends into Victoria.....and elsewhere.....

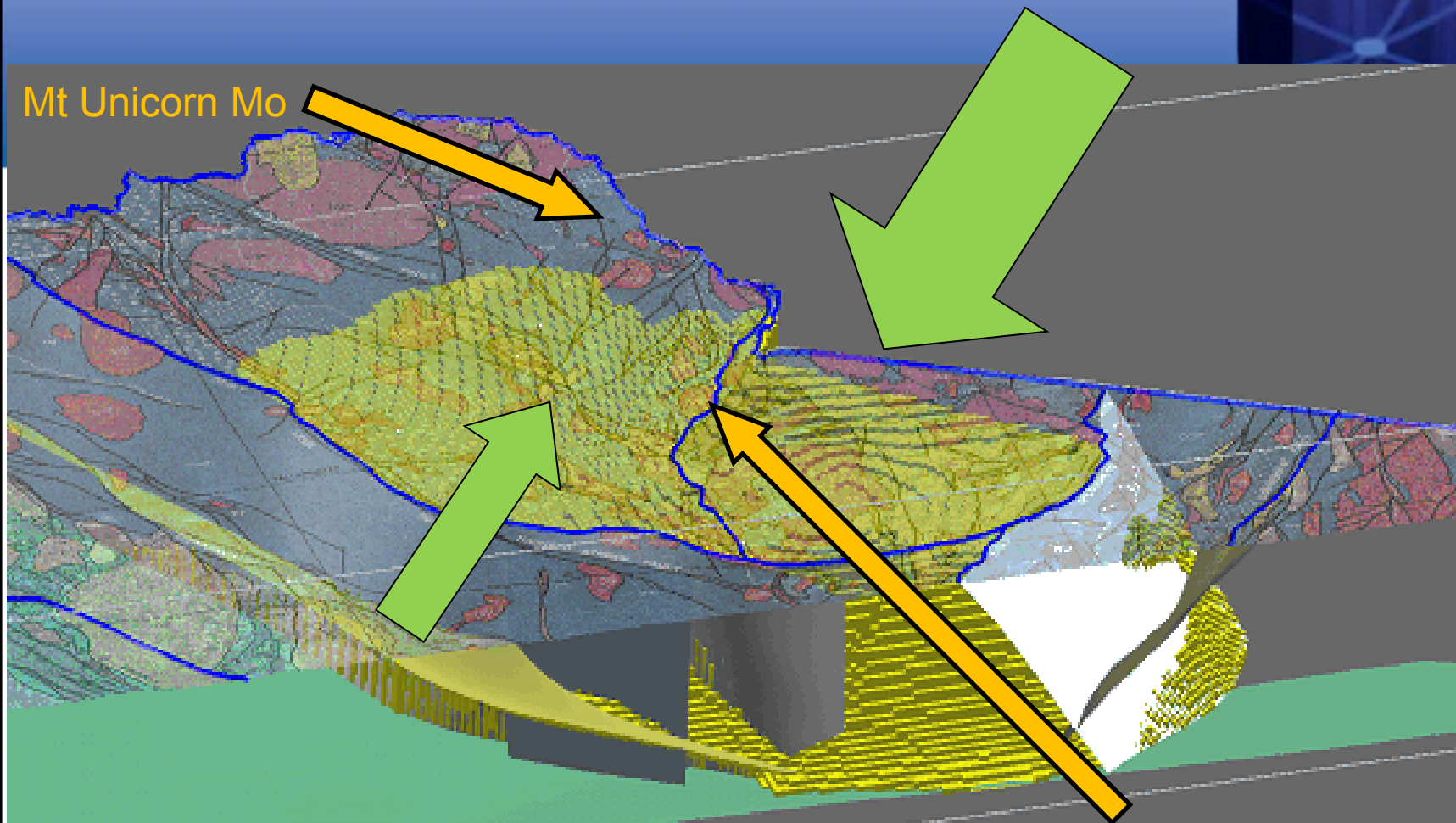


Victorian Seamless Geology

...it lies buried beneath the Deddick Zone....



MACQUARIE ARC IN EAST VICTORIA



.....and we can model where it may extend at greater depths (Macquarie Arc in yellow).

It may underlie a region rich in base metal deposits

Benambra VHMS

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Talk outline

- Challenges for the State
- Multi-disciplinary, cross-agency collaboration – the firepower needed to grapple with some tricky problems
- Arcs – What are they? Why are they important? How can you tell when you've found one?
- Oroclines – Giant folds of whole mountain ranges. So what?
- **A paradigm shift for Victorian gold and base-metals prospectivity – rhetoric or reality?**

...the Oroclinal fold model shows how the gold-rich terrane of the Bendigo Zone may extend east around a fold hinge into the Tabberabbera Zone.....

GRAMPIANS
STAVELY ZONE

Bendigo Zone...

GLENELG
ZONE

WELL ZONE

BENDIGO ZONE

TABBERABBERA
ZONE

MELBOURNE ZONE

= Tabberabbera
Zone

OMEO ZONE

KUARK ZONE

DEDDICK
ZONE

MALLACOOTA ZONE

BASS ZONE

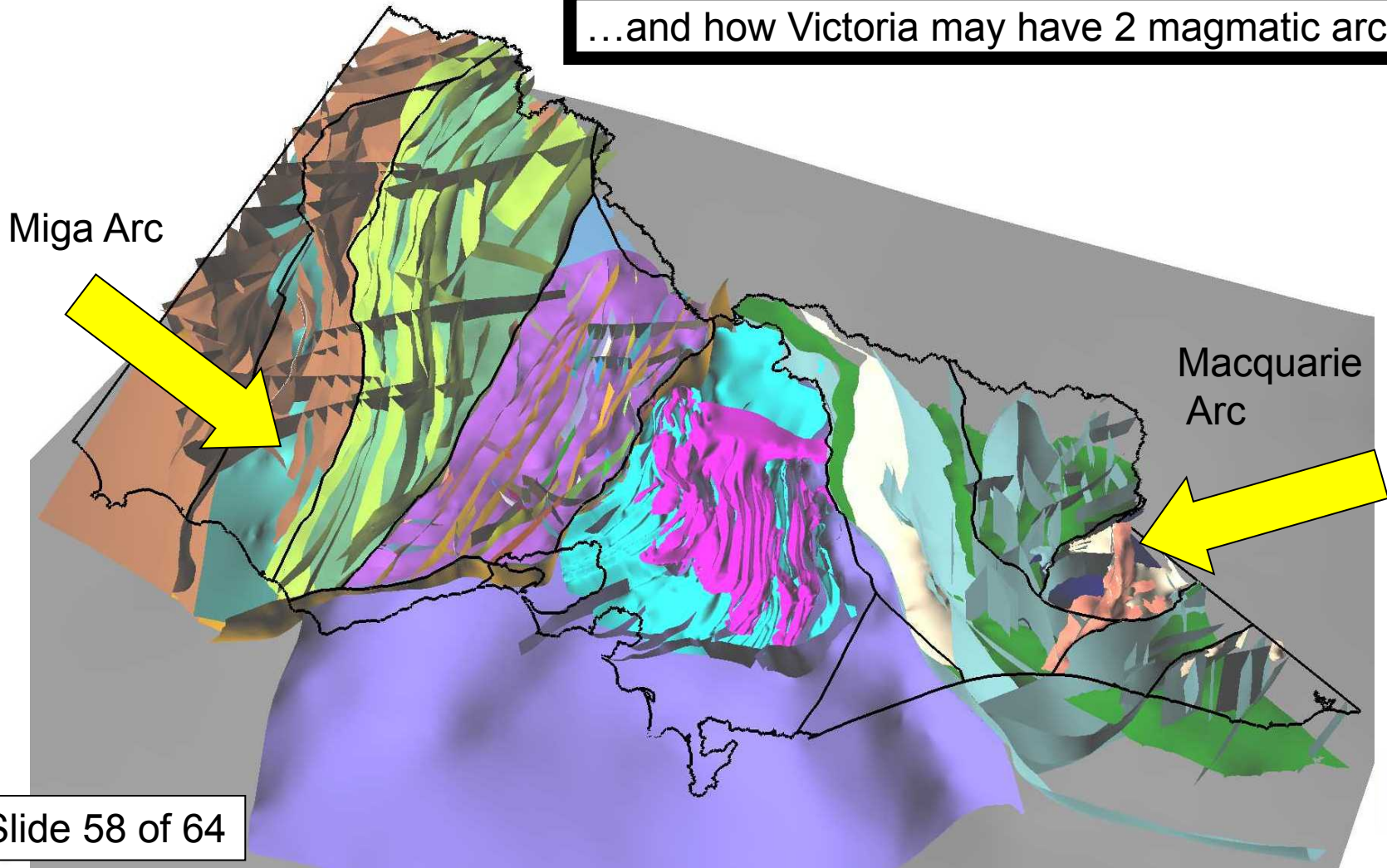
300

Kilometers



Cambrian and Ordovician arc-systems, of the type known to host giant porphyry-type Cu –Au ore deposits

...and how Victoria may have 2 magmatic arcs.....

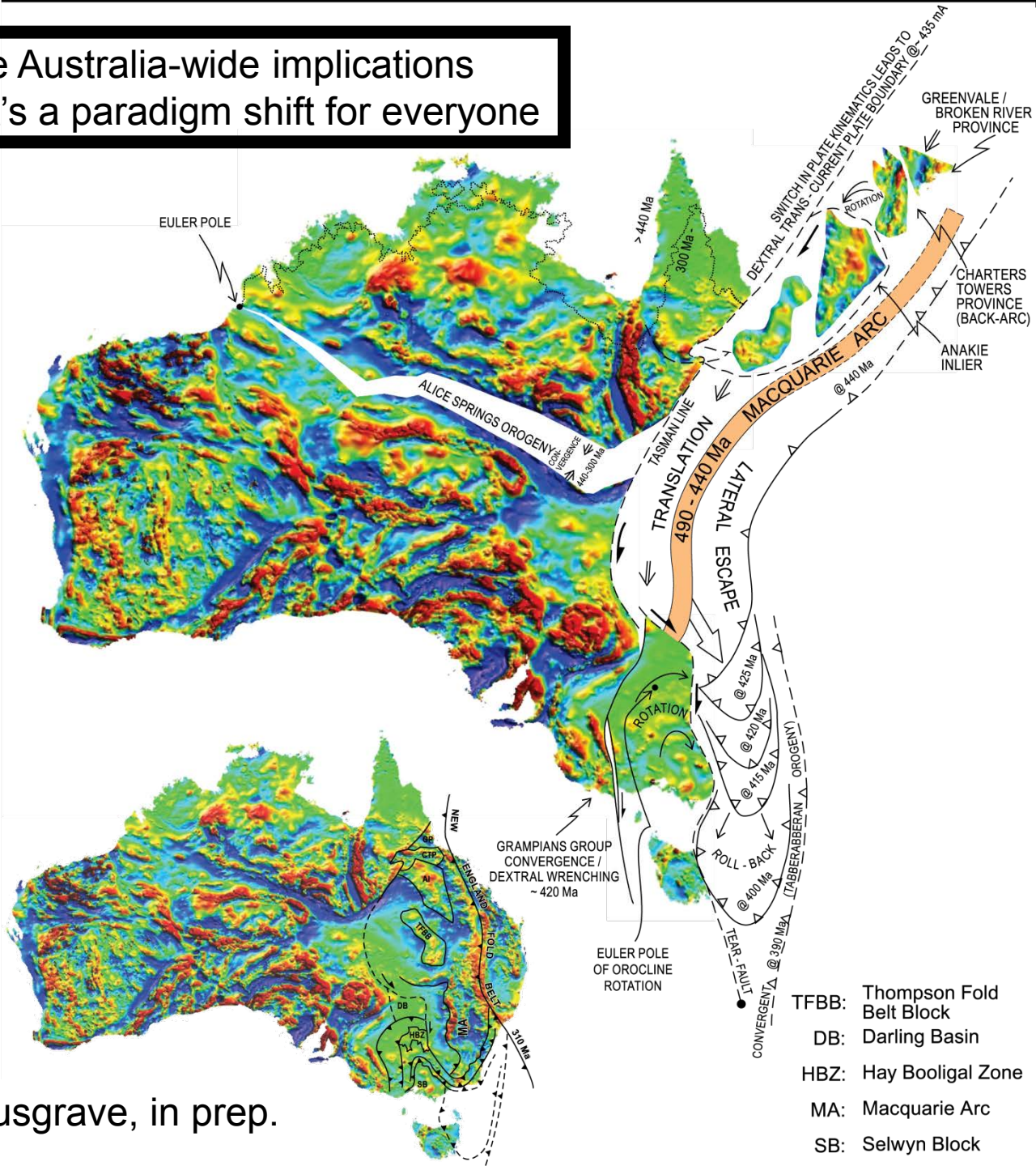


...It provides understanding that allows, for the first time,
a systematic characterisation of Victoria's
mineral exploration fairways



1. **Kanmantoo-Strathalbyn SEDEX Base-Metals Fairway:** newly recognised opportunity extending from southeast South Australia; Cambrian age mineralisation.
2. **Delamerian Ultramafics Nickel Fairway:** NeoProterozoic–Early Cambrian age mineralisation.
3. **Miga Arc Base-Metals/Gold Fairway:** newly-recognised continental margin volcanic arc setting for Cambrian magmatic succession; Cambrian age mineralisation. Porphyry and VMS plays.
4. **Stawell Zone Orogenic Gold Fairway:** greenstone (+/- VMS) – gold association. Ordovician age mineralisation (hosted by Cambrian rocks +/- VMS); Multi-million oz plays.
5. **Bendigo Orogenic Gold (+/- Antimony) Fairway:** slate belt gold association. Ordovician-Devonian age mineralisation. Multiple multi-million oz nuggetty gold and disseminated gold-antimony plays.
6. **Selwyn Block Base-Metals (Gold) Fairway:** recently recognised opportunity extending from western Tasmania into Central Victoria – Mt Read Volcanics and Avebury-Ni play types; Cambrian age mineralisation.
7. **Wagga-Omeo Zone Tin Fairway:** Plays in Koetong Supersuite igneous rocks. Silurian age mineralisation.
8. **Macquarie Arc Base Metals (Gold) Fairway:** newly recognised opportunity extending south from New South Wales into the Deddick Zone – Ordovician age mineralisation. Potential for porphyry and VMS plays.
9. **Macquarie Arc Derivatives Base Metals (Gold) Fairway:** Newly recognised context for several play types in overlying rocks: Silurian back-arc/rift VMS (eg. Benambra Zn/Cu (Ag), Devonian porphyry (eg. Mt Unicorn Mo/Cu). Full areal extent of potential now recognised.

There are Australia-wide implications
– it's a paradigm shift for everyone



Cayley & Musgrave, in prep.

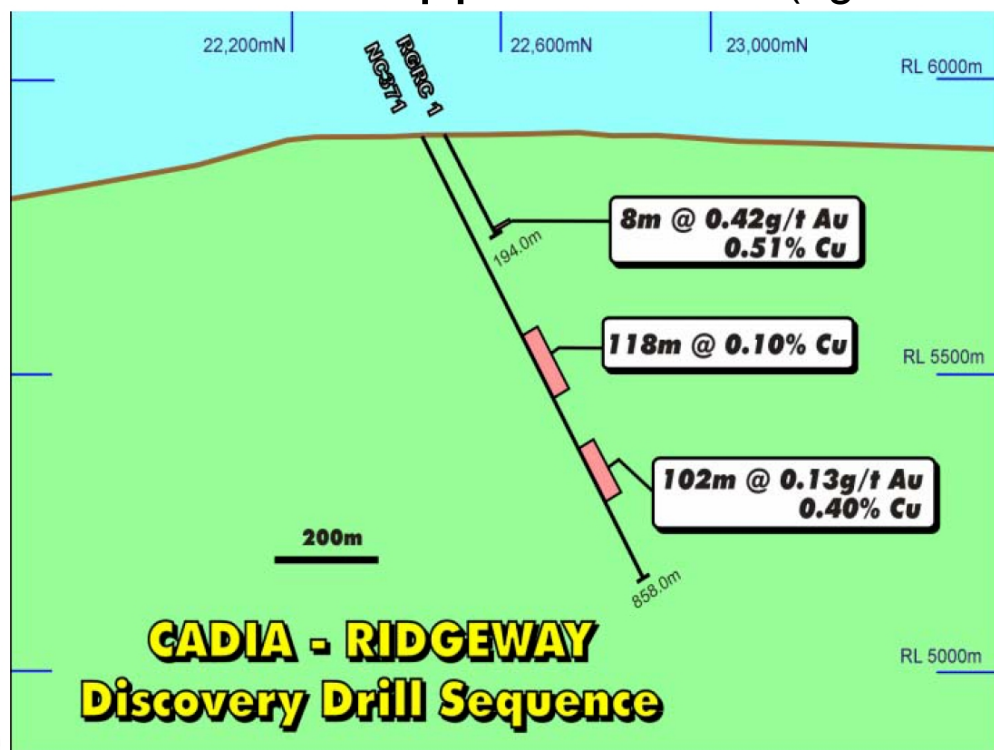
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Still a work in progress...

- Regional geology still too uncertain for most
- But, hard work and modern geoscience are finally closing the gap.
- Exciting opportunities available for early-adopters
- Victorian Government keen to foster collaboration with industry to maximise value from existing mines and new exploration opportunities

What might success look like?

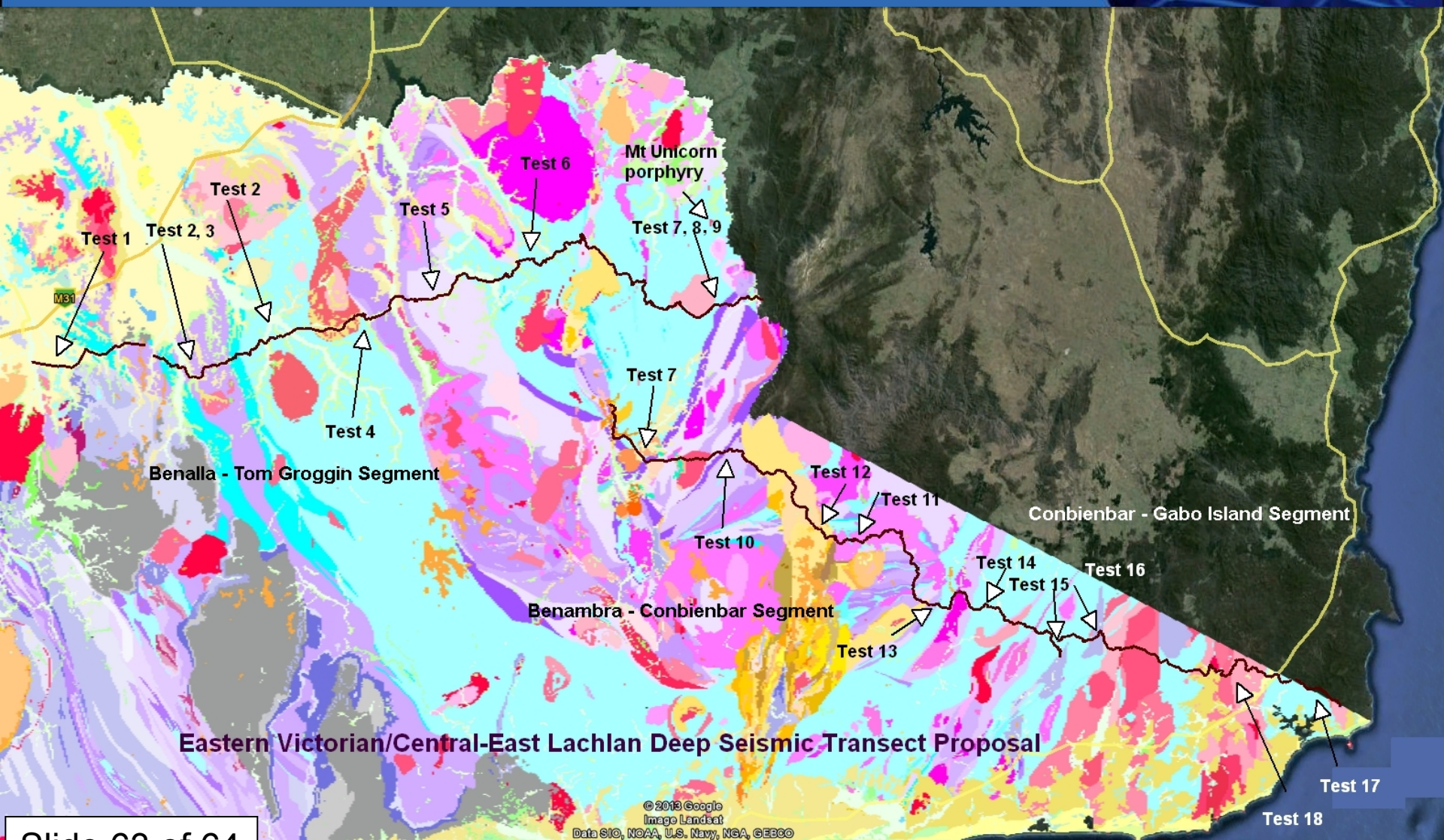
- New Stawell-type or Bendigo/Fosterville-type deposits located under cover (Tandara.....)
- New porphyry system discoveries....
- Bonus opportunities (eg. extension of Kanmantoo-Strathalbyn SEDEX into western Victoria)



Note for comparison:
Beaconsfield Gold intersected
35m @ 3.7% Cu at Junction 1, Mt Stavely
and 7.7m @ 4.2% Cu at Thursdays Gossan

What next for the GSV?

Testing our new models against reality.....



Queries?

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Regional Geology:

structure, tectonics, geodynamics, metallogeny

DEPARTMENT OF
STATE DEVELOPMENT
BUSINESS AND
INNOVATION

