Western Mining Services

Geo conferences (WA) Inc.

Understanding Major Trans-Lithospheric Structures, their Evolution and Relationship to Ore Deposits

Jon Hronsky

5 November 2013

CCFS Lithosphere Dynamics Workshop

Perth, WA

Tim O'Driscoll
(1919-2004)

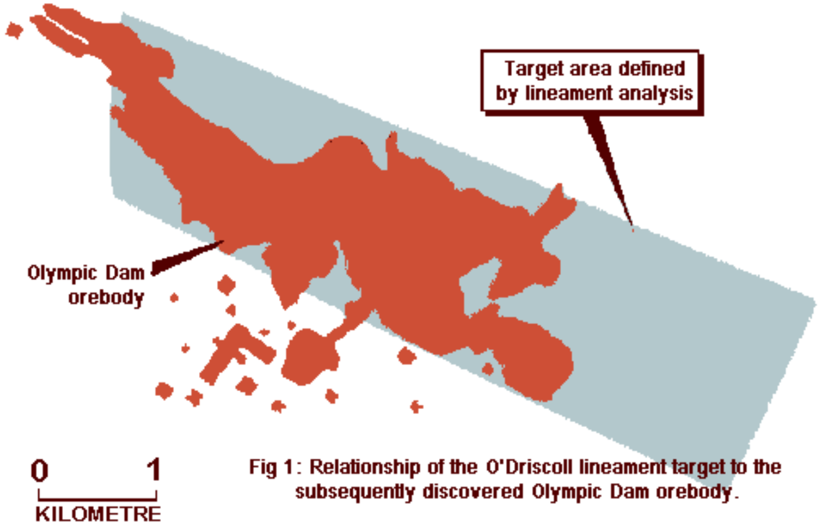


Fig 1: Relationship of the O'Driscoll lineament target to the subsequently discovered Olympic Dam orebody.

Source: Roy Woodall

This talk is dedicated to the memory of E.S.T. (Tim) O'Driscoll


WARNING
FOUR-DIMENSIONAL
THINKING REQUIRED!

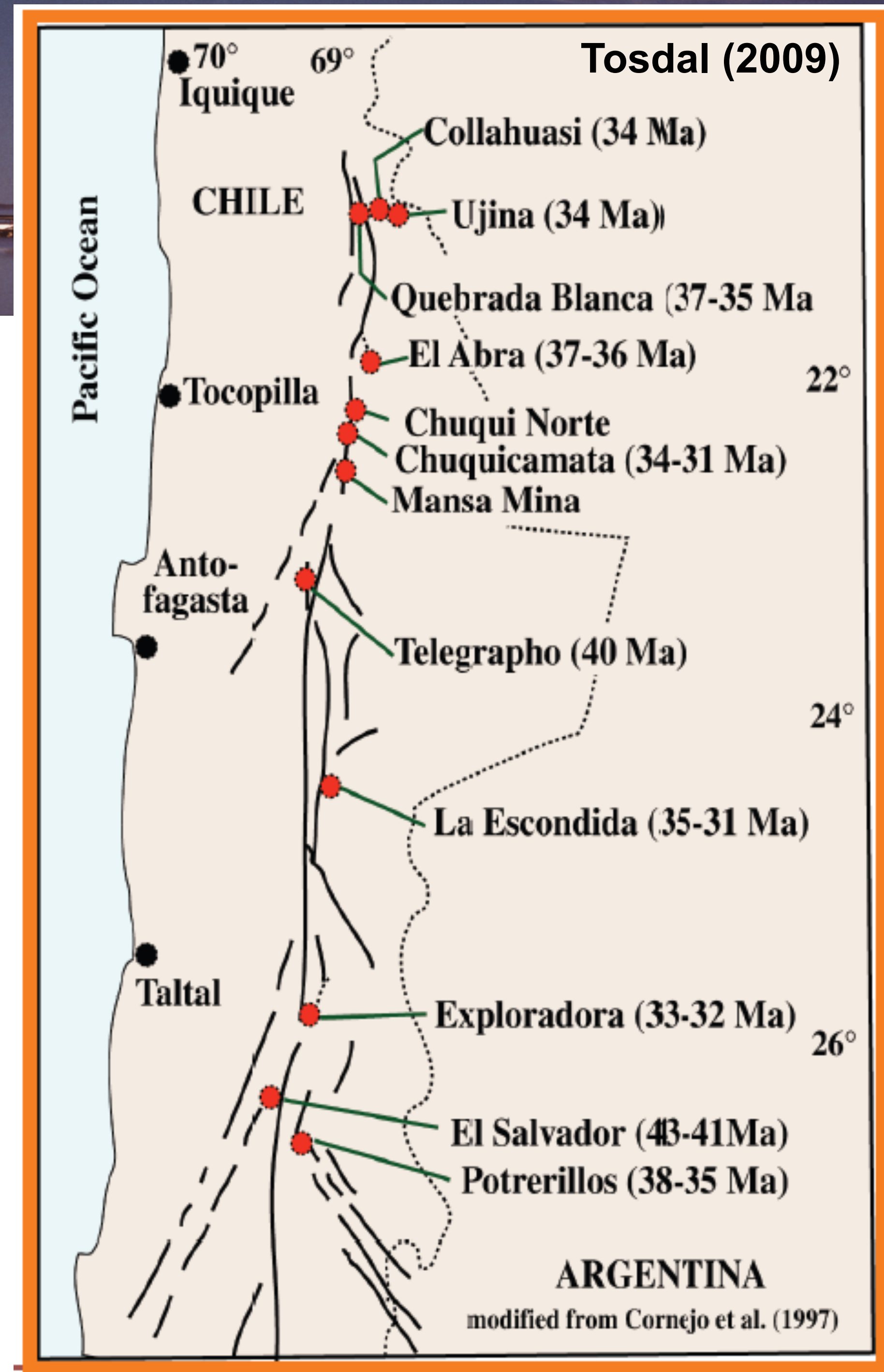
Trans-Lithospheric Structures: Exploration Targeting 101

- **Most important and consistent structural pattern in mineral targeting**
- **Recognized since at least the 1930's**
- **Often cryptic in near-surface mapping so commonly only recognized as "lineaments"**
- **Historically largely ignored by academic community**

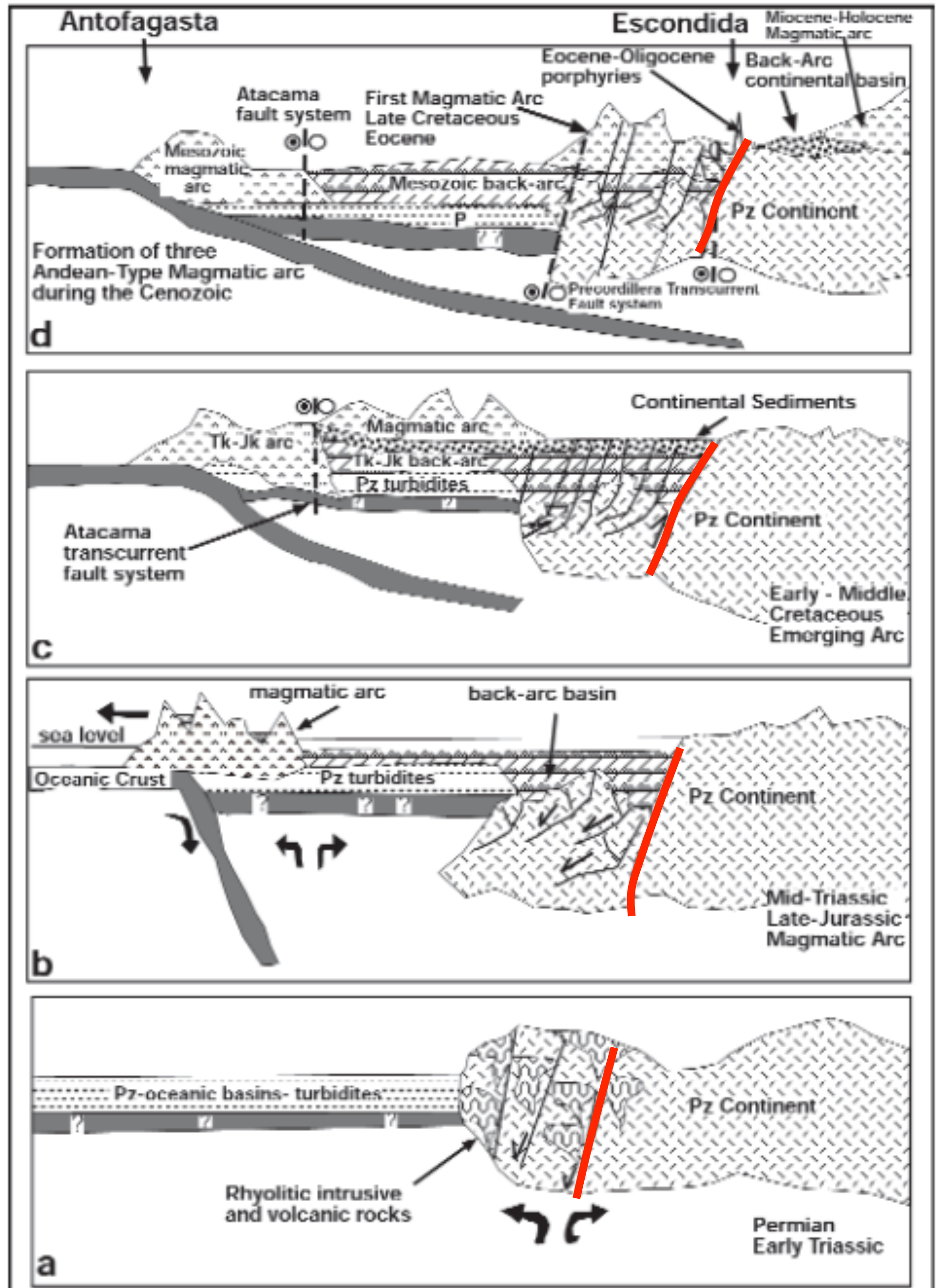
Billingsley, P., and Locke, A., 1935, Tectonic position of ore districts in the Rocky Mountain region: American Institute of Mining and Metallurgical Engineers Transactions, v. 115, p. 59–68.

——1941, Structure of ore districts in the continental framework: American Institute of Mining and Metallurgical Engineers Transactions, v. 144, p. 9–64.

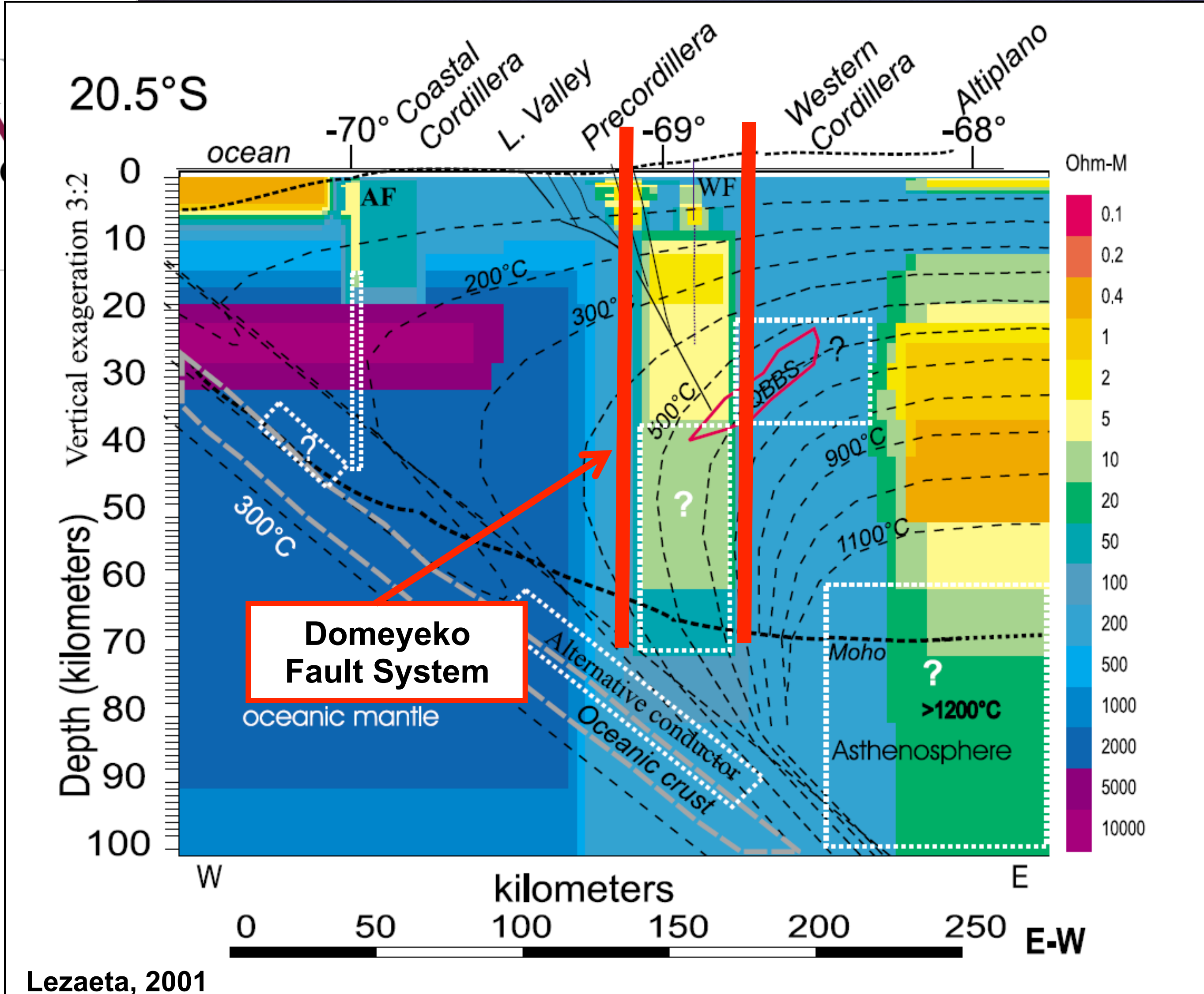
Case Study: Domeyko Fault (West Fissure), Northern Chile



History can be traced back to at least the Paleozoic - Probably much older



Padilla et al (2001)



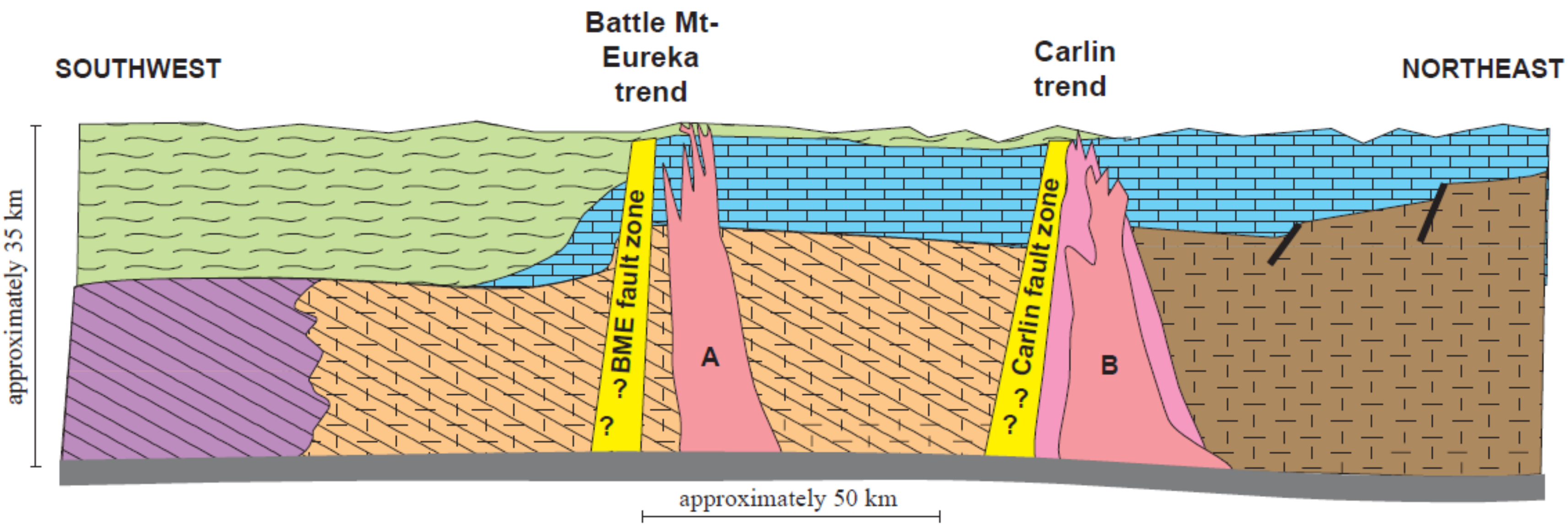
MT Section through Northern Chile (at 20.5°S) indicating that the Domeyko Fault System can be imaged as a *steep*-dipping structure extending to below the Moho

(WF = West Fault; AF = Atacama Fault)

WESTERN MINING SERVICES

Northern Nevada Gold Province Case Study

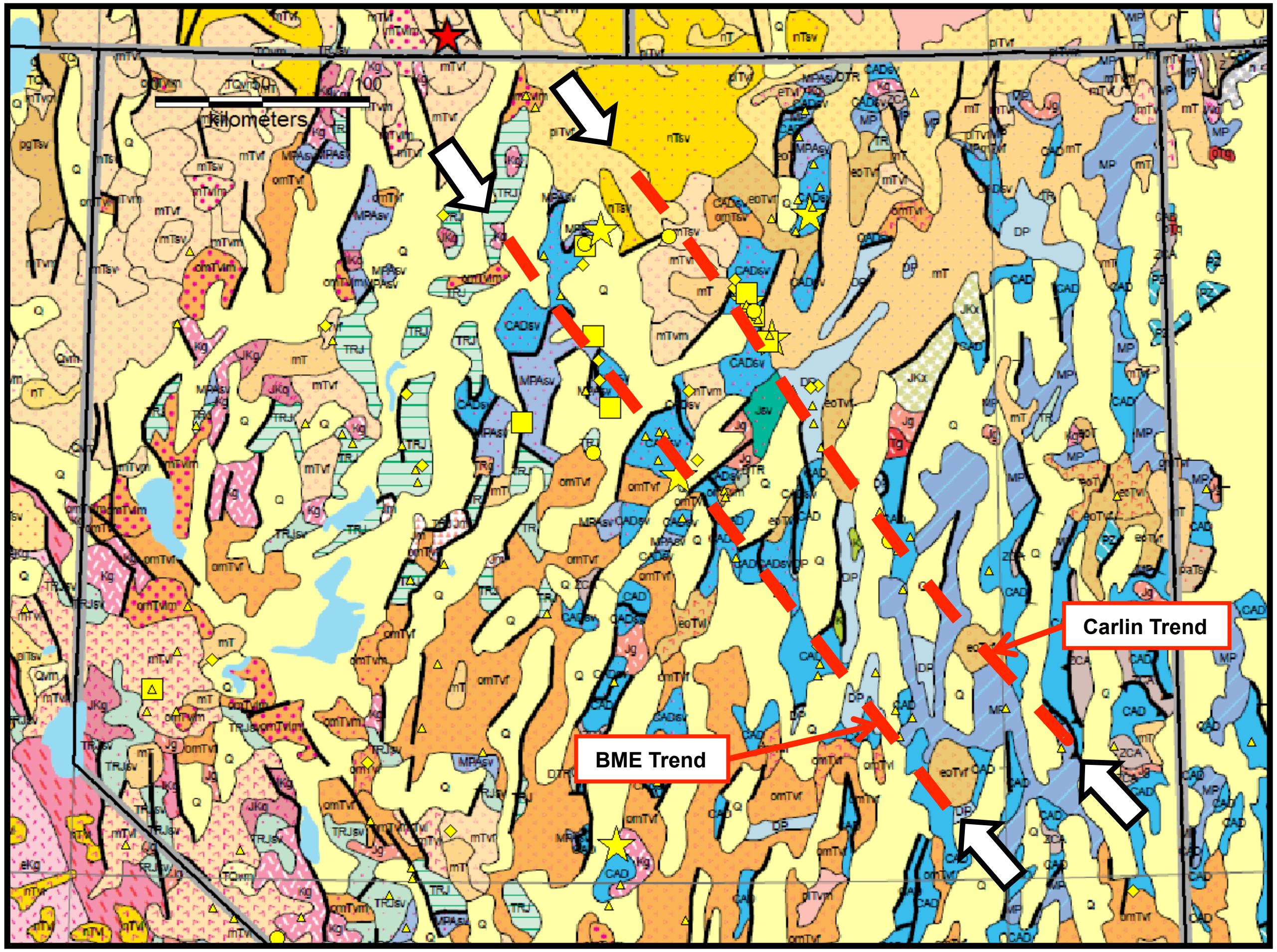
- Gold mineralisation in the highly endowed Eocene Northern Nevada gold province long known to be controlled by major basement structures
- The two most important: Battle Mountain-Eureka Trend and Carlin Trend
- Geological and geophysical studies has definitively established these are fundamental, steep trans-crustal features
- However, despite this they are still difficult to map in our common geoscience data sets



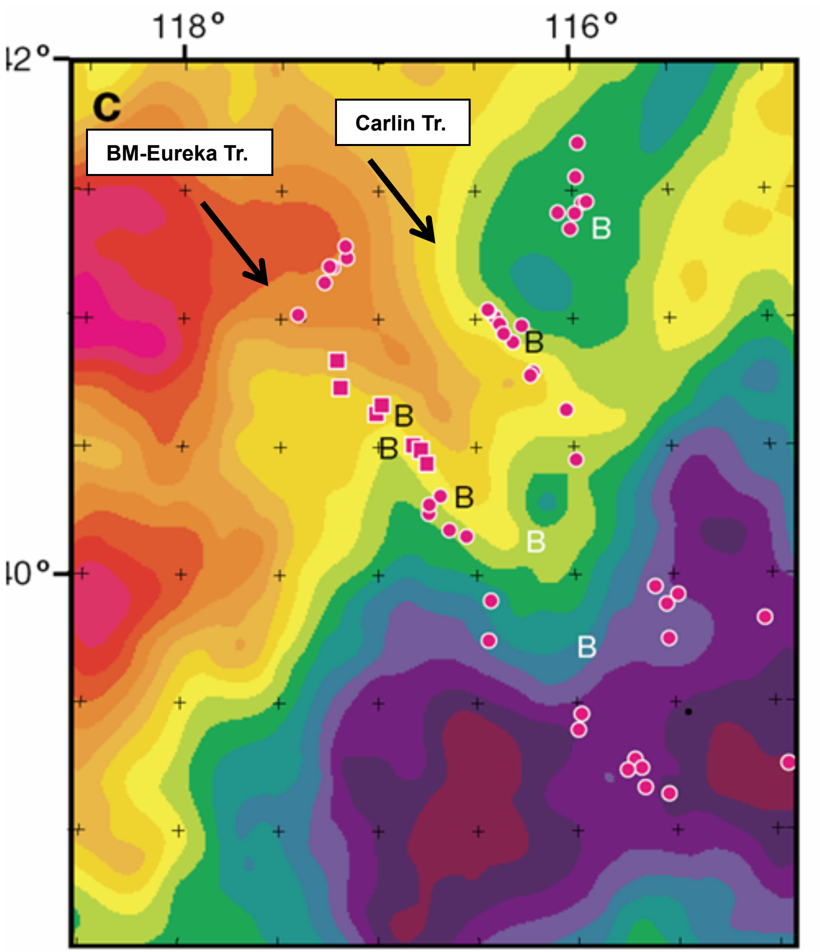
KEY	INTERPRETED ELEMENT	EVIDENCED IN WHICH DATA SET(S)
Yellow	Fault zone that probably served as a conduit for mineralizing fluids. First formed during development of a passive margin in Late Precambrian and reactivated during subsequent tectonic events.	BME fault zone: MT, basement gravity Carlin fault zone: MT, isotopic data
Pink	Intrusions. A: Extensive, linear, rift and magmatic system formed after Carlin-type mineralization. B: Multiple intrusions localized near southern end of Carlin trend, emplaced before and during Carlin-type mineralization.	MT, magnetic data, geology
Blue	Dominantly carbonate rocks, thrusted and extended.	Basement gravity, MT, geology
Green	Dominantly clastic and volcanic rocks, thrusted and extended.	Basement gravity, MT, geology
Brown	Continental crust.	Isotopic data
Purple	Dominantly oceanic crust.	Isotopic data
Orange	Transitional crust.	Isotopic data
Gray	Moho (base of the crust)	Seismic-reflection data

Grauch (2005)

Carlin and Battle Mountain-Eureka Trends *not* obvious in surface geology map



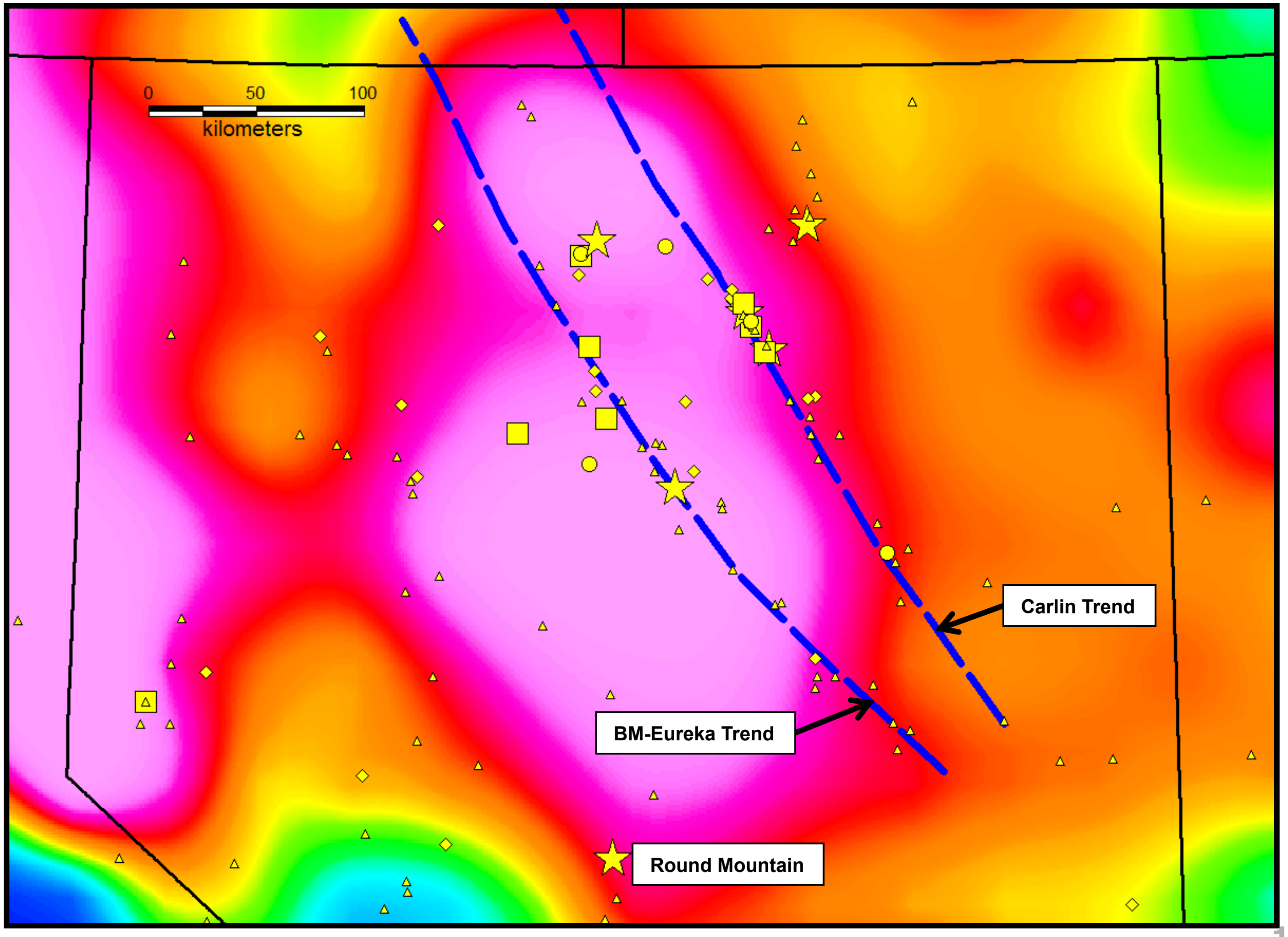
But if we process the Bouguer data to strip off "near-surface" geology Gold trends become much clearer!



Bouguer gravity minus basin effects, up 5 km

Grauch et al., 2003

Surprisingly, also quite obvious in 350km depth slice of Seismic Tomographic data



(US array tomography)

Characteristics of Large-Scale Ore Controlling Structures

- **Strike-extensive (100's of km)**
- **Depth-extensive with relatively steep dips**
- **Low ratio of (recent) displacement to strike length**
- **Juxtapose distinctly different basement domains**
- **Multiply-reactivated (commonly with variable senses of movement) with a *very long* history**
- **Vertically-accretive growth histories**
- **Relatively complex, anastomosing map patterns (at least at the structural level of ore-formation)**
- **Commonly (but not always) cryptic in surface geological mapping**

Key Concept: Vertical Accretion and Cryptic Nature

- **Major, long-lived shear-zones can be overlain by younger volumes of sedimentary or volcanic rock**
- **These structures grow *upward* over time ("vertical accretion"); reactivation of the underlying shear-zone initially produces complex anastomosing fractures in the overlying rock volume**
- **Association of ore-deposits with the upper, relatively cryptic and anastomosing sections of these structural zones consistent with ore deposition being favoured in upper 10km of crust (steeper P,T,X gradients)**

Anastomosing Near-Surface Pattern overlying Fundamental Structure at depth

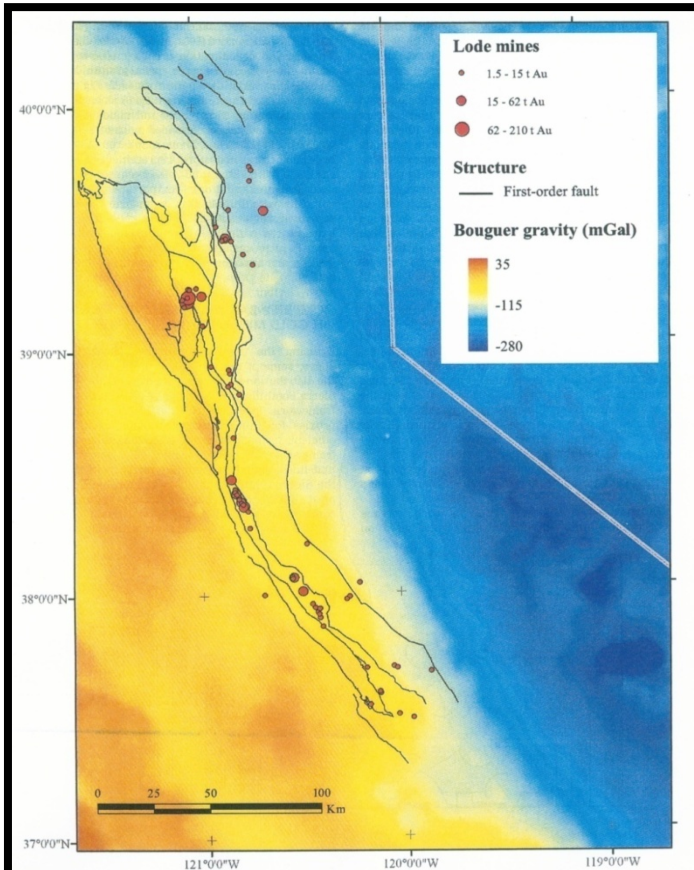
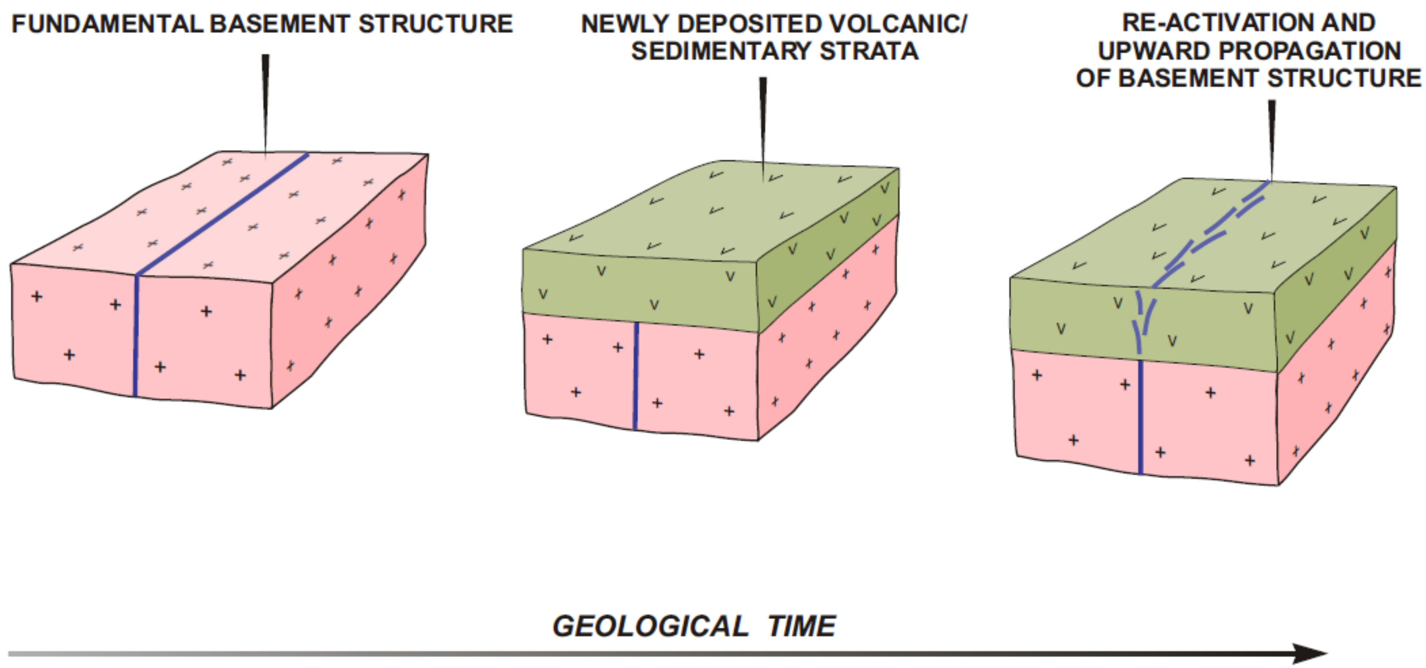


Figure 8 Pseudocolour representation of the constructed Bouguer gravity layer for the Sierra Nevada Foothills Metamorphic Belt, with significant lode-gold deposits and first- and second-order faults in the northern and central portion of the belt superimposed (data from Ferguson & Gannett 1932; Clark & Lydon 1962; Clark 1992; Long *et al.* 1998; Frank 1999; Saucedo *et al.* 2000; Bankey *et al.* 2002; USGS 2002, 2006).

Sierra Foothills Gold Province, California; from Bierlein et al (2008)

Vertical Accretive Growth History

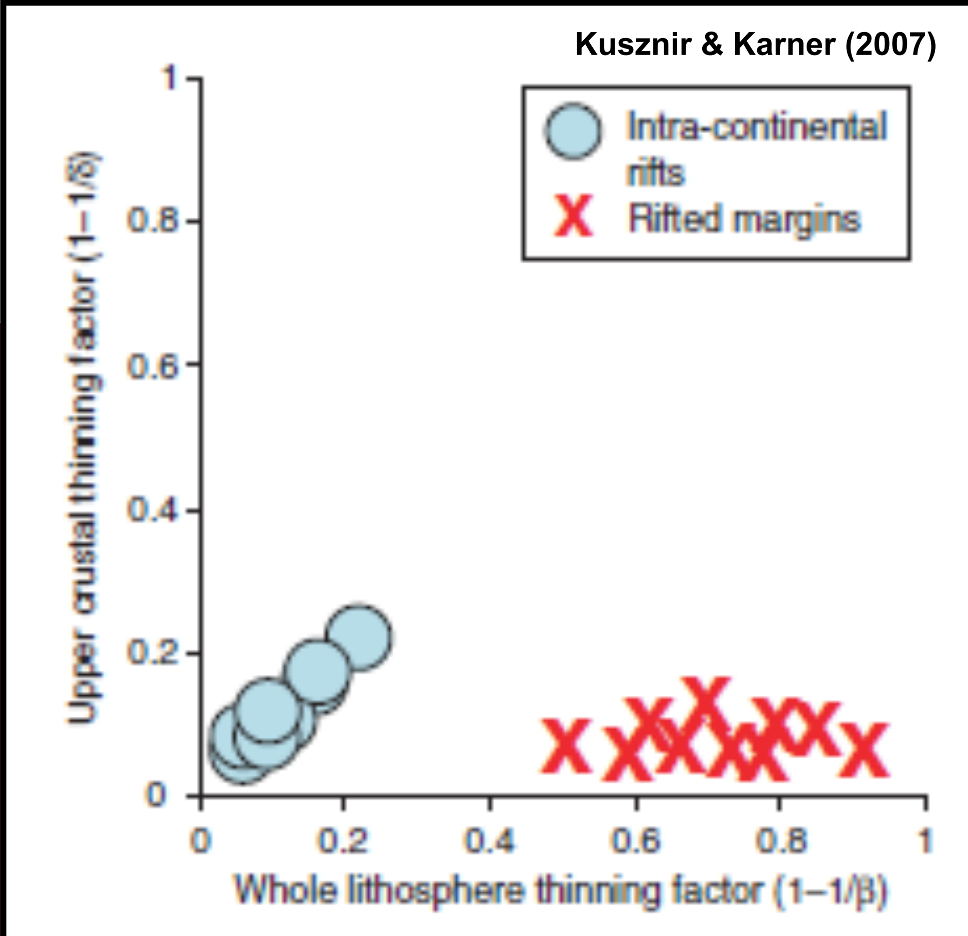


How to Recognise a Metallogenically-Important Translithospheric Structure

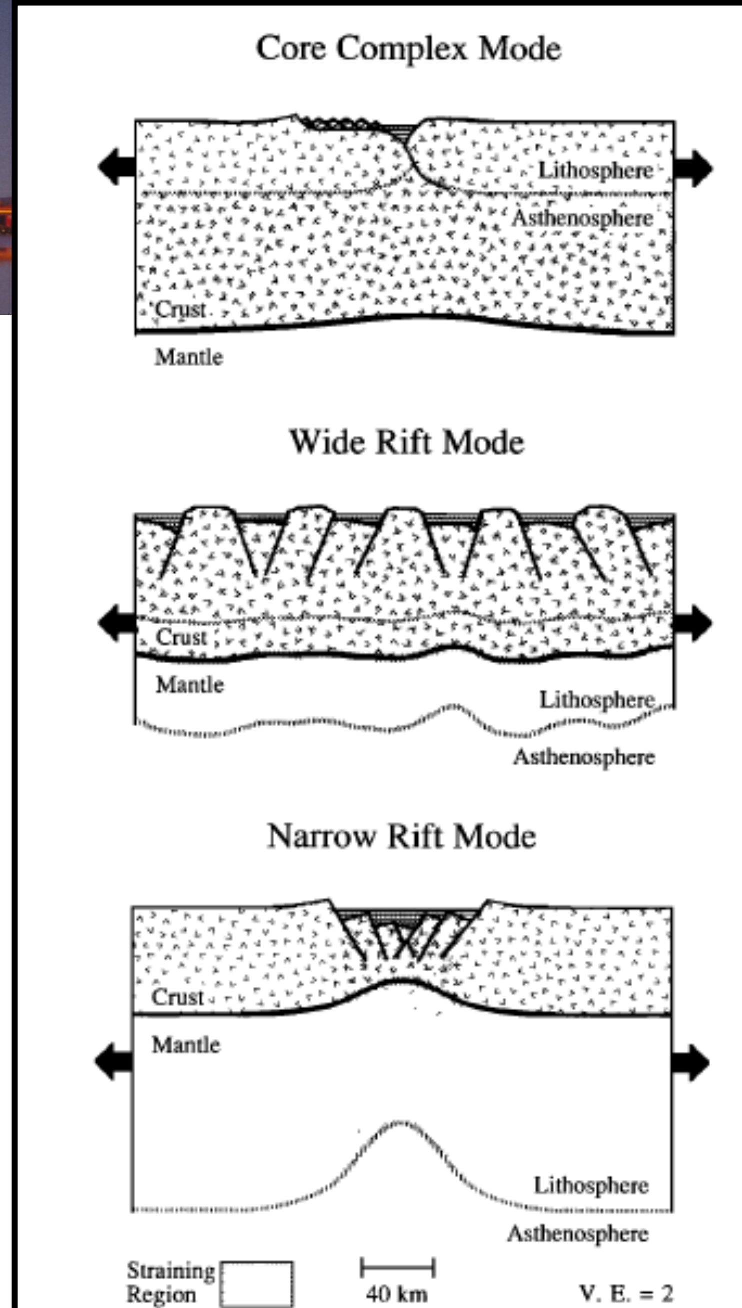
1. Strike-extensive linear structural trend
2. Major discontinuity in basement geology
   - Steep gradients in "deeper-looking" geophysical data (eg MT, seismic tomography and gravity)
   - Major facies changes (e.g. shelf-rift transitions)
   - Discontinuities in patterns of near-surface structures
   - Isotopic boundaries
3. Evidence of long-lived loci of mantle-derived magmatism (ie mafic and/or alkalic)
4. Evidence for multi-stage geometric control of rifting and uplift episodes

Why are Translithospheric structures important for ore-formation?

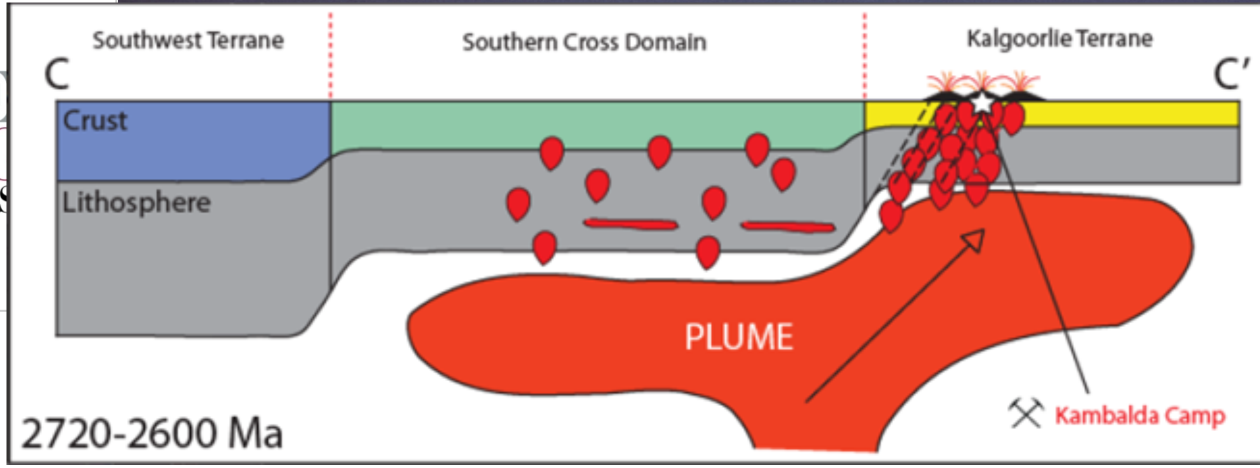
- **Optimal permeable pathways through lithosphere (fluids and magmas)**
  - **conduits with the steepest pressure-gradient**
- **Susceptible to reactivation and therefore fracturing and permeability generation**
- **Control narrow rift zones and related focused heat transfer into the upper crust**
- **Commonly located at lithospheric domain boundaries so well positioned to:**
  - **access zones of enhanced (subduction-related) refertilisation at domain margins**
  - **access zones of channellised plume and related melt upflow at domain margins**



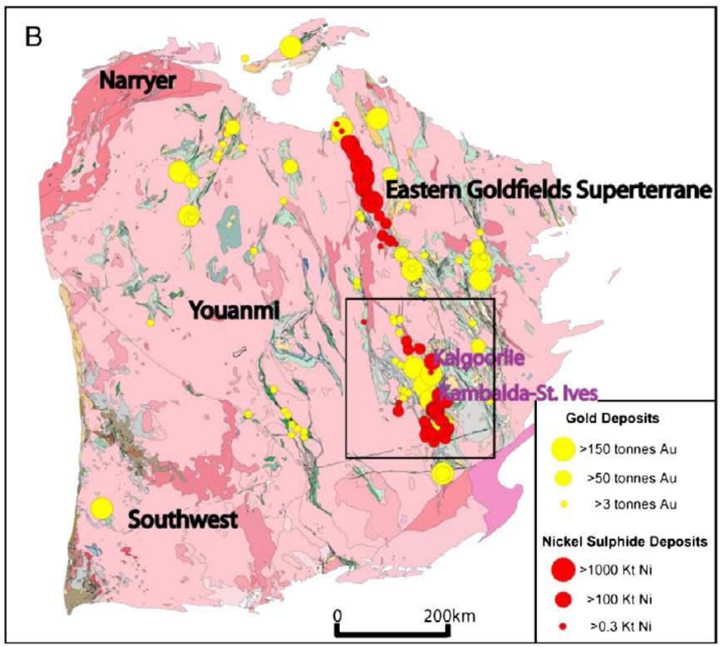
Key Concept: <u>**Narrow Rifts**</u> ***always*** **represent reactivation of underlying translithospheric structural zones**

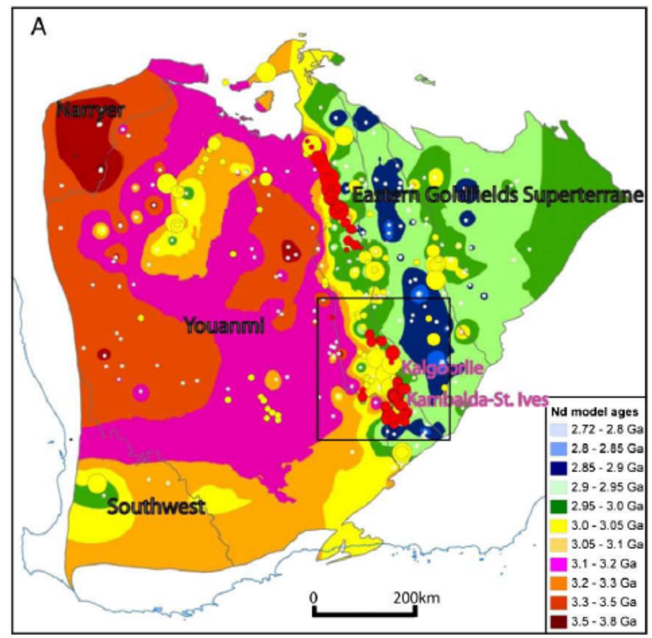


Buck (1991)



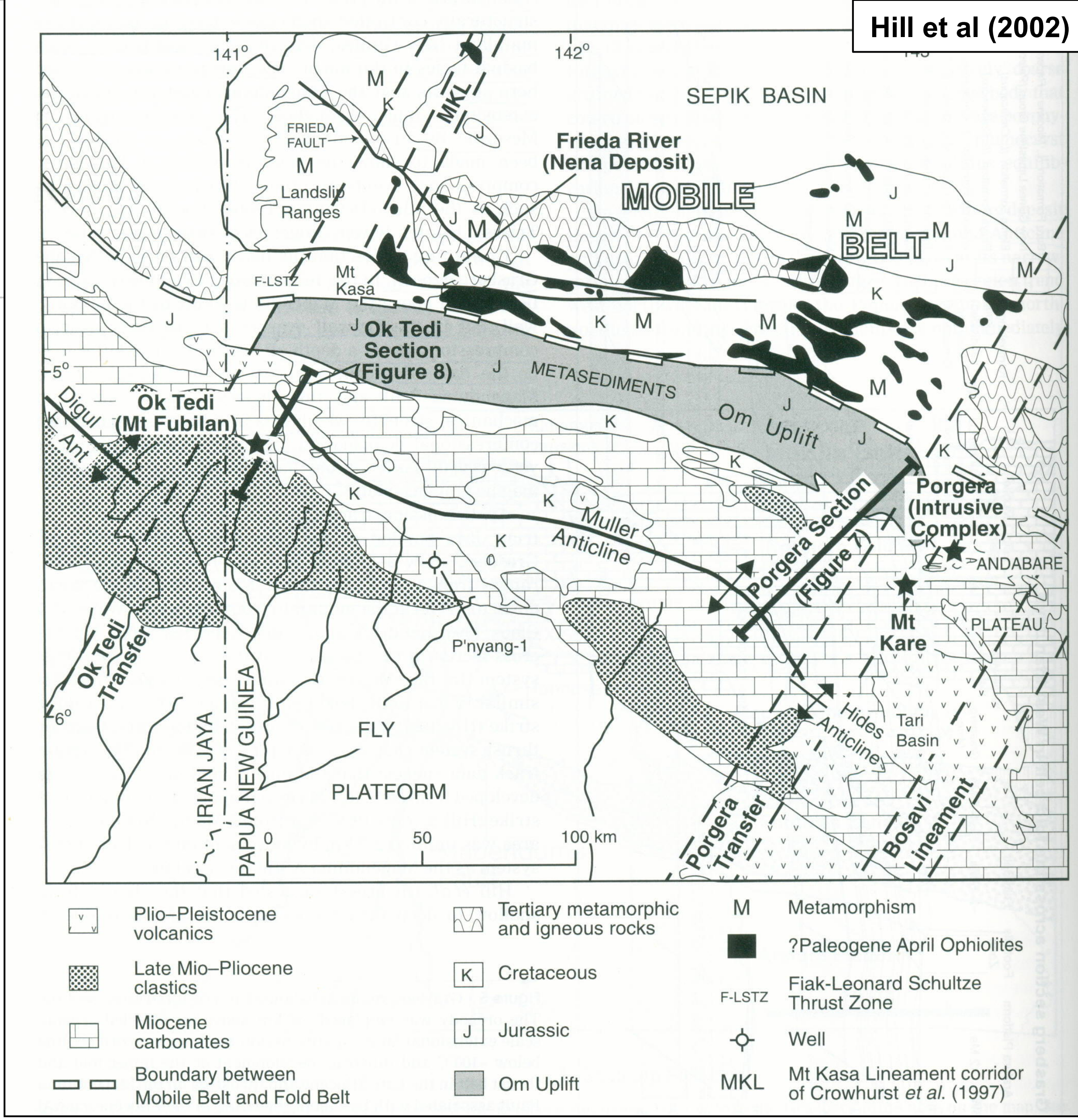
Mole et al (2012)



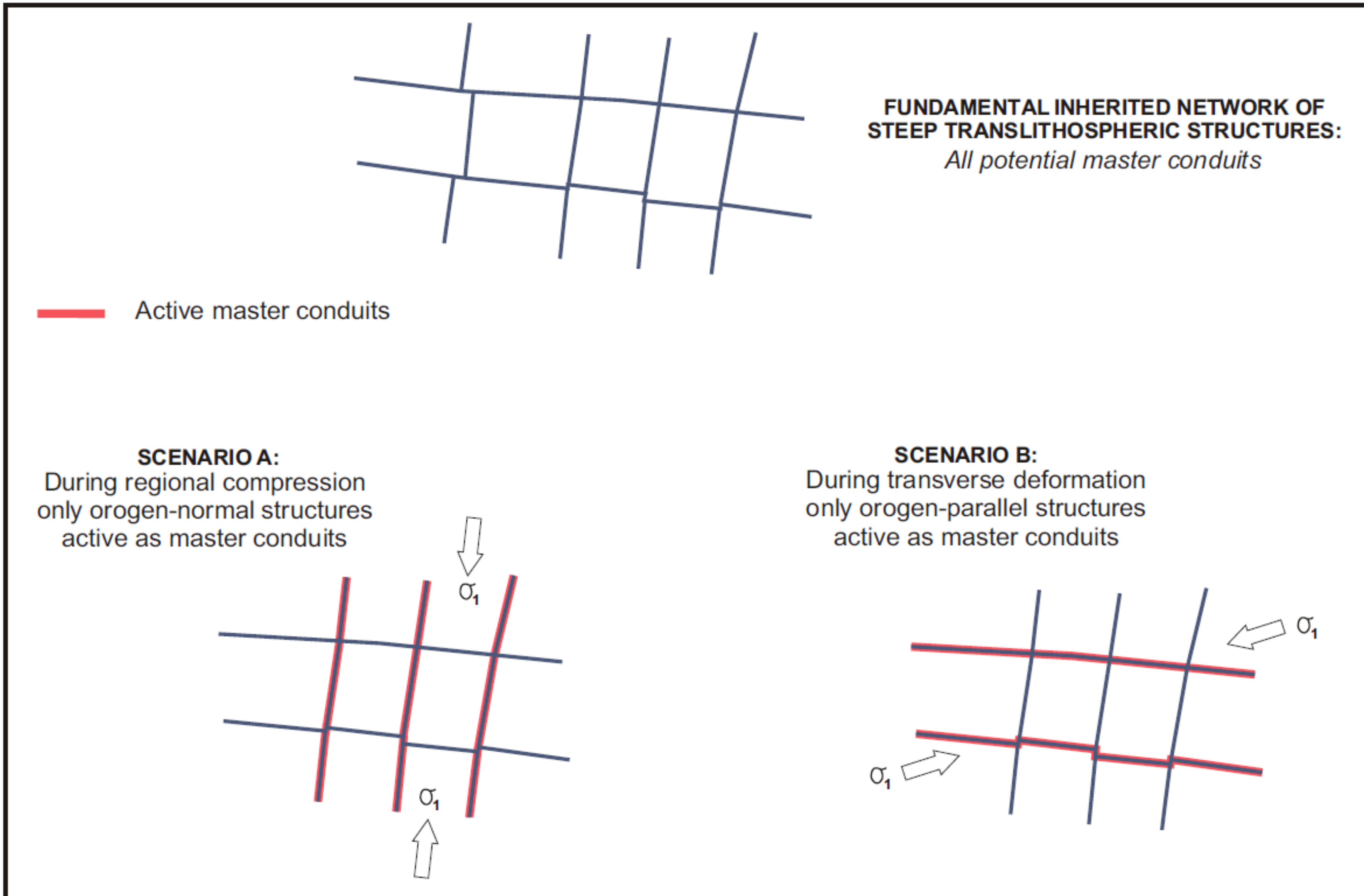


McCuaig et al. (2010); Sm-Nd map from Cassidy & Champion (2004)

Major Translithospheric structures as edges of SCLM keels which focus mantle upwellings and related melts



Orogen-Normal Structures are commonly the most metallogenically important in an Orogen



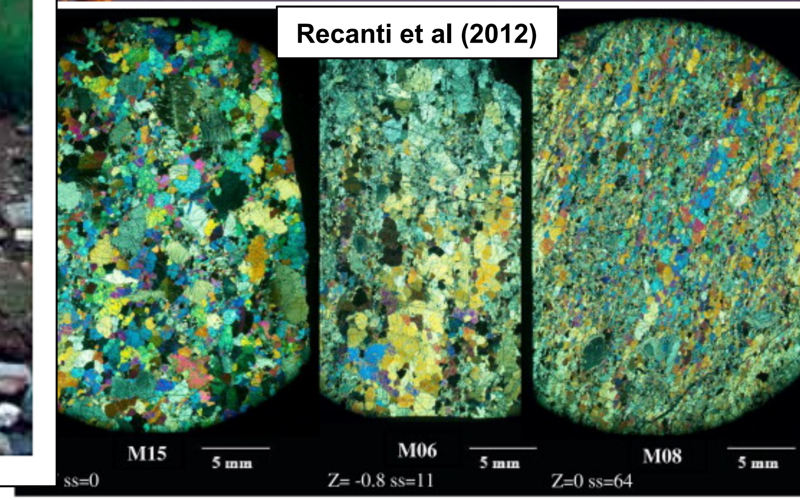
Key Concept: Regional Stress Field Controls Metallogenic Activity on Translithospheric Structures

Sheared Mantle outcrop

Source- GEMOC

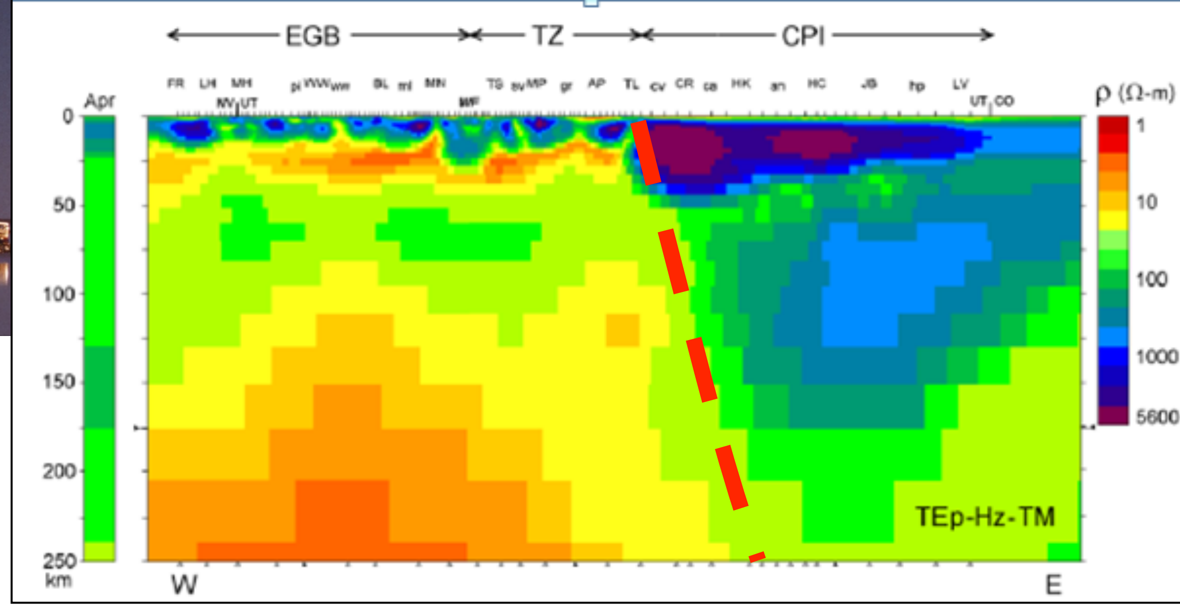
Sheared Mantle – Thin section

Recanti et al (2012)



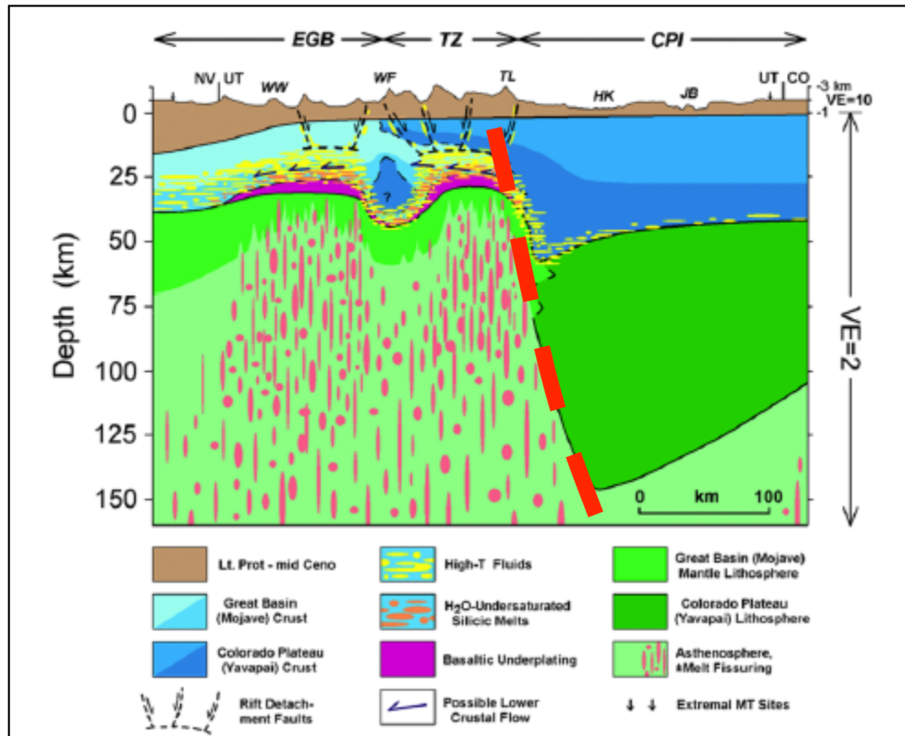
Increasing strain

What is the nature of these structures in the mantle?

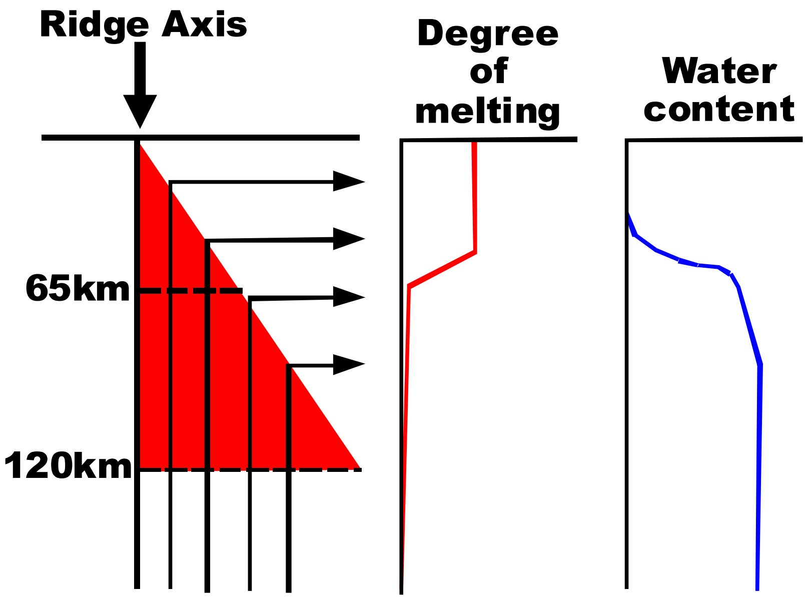


Major translithospheric structures as major lithospheric domain boundaries: Colorado Plateau margin example

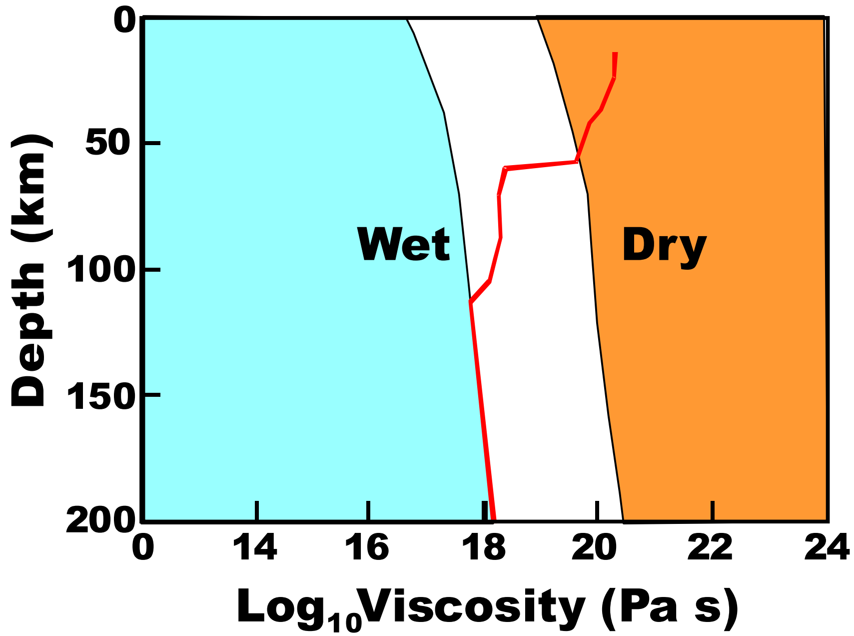
Wannamaker et al (2008)



Great Basin-Colorado Plateau Transition
Interpretive Physical State, from MT



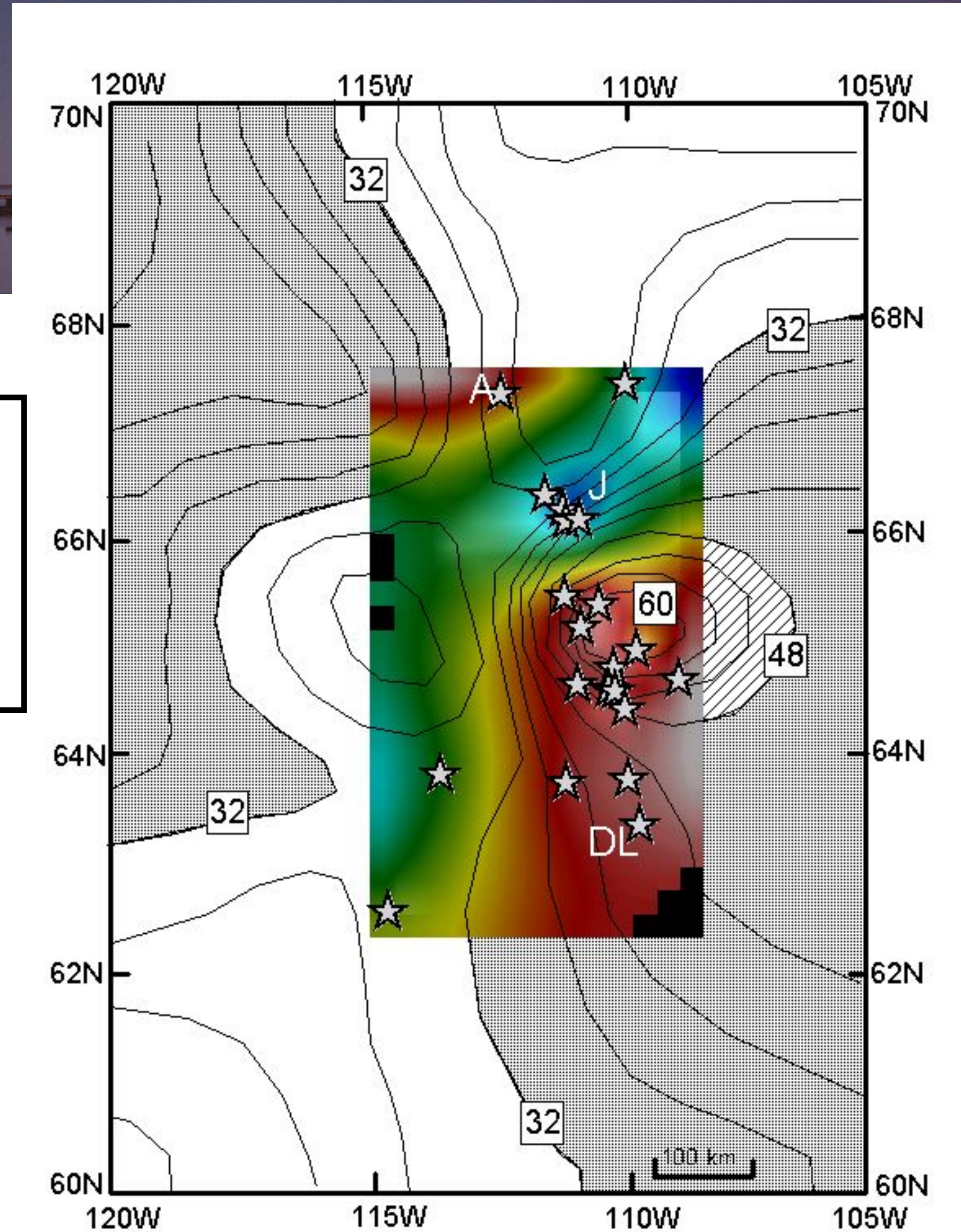
Melting at mid-ocean ridges and the redistribution of water.
(Karato and Jung 1998)



The viscosity profile of the oceanic mantle.
(after Hirth and Kohlstedt 1996)

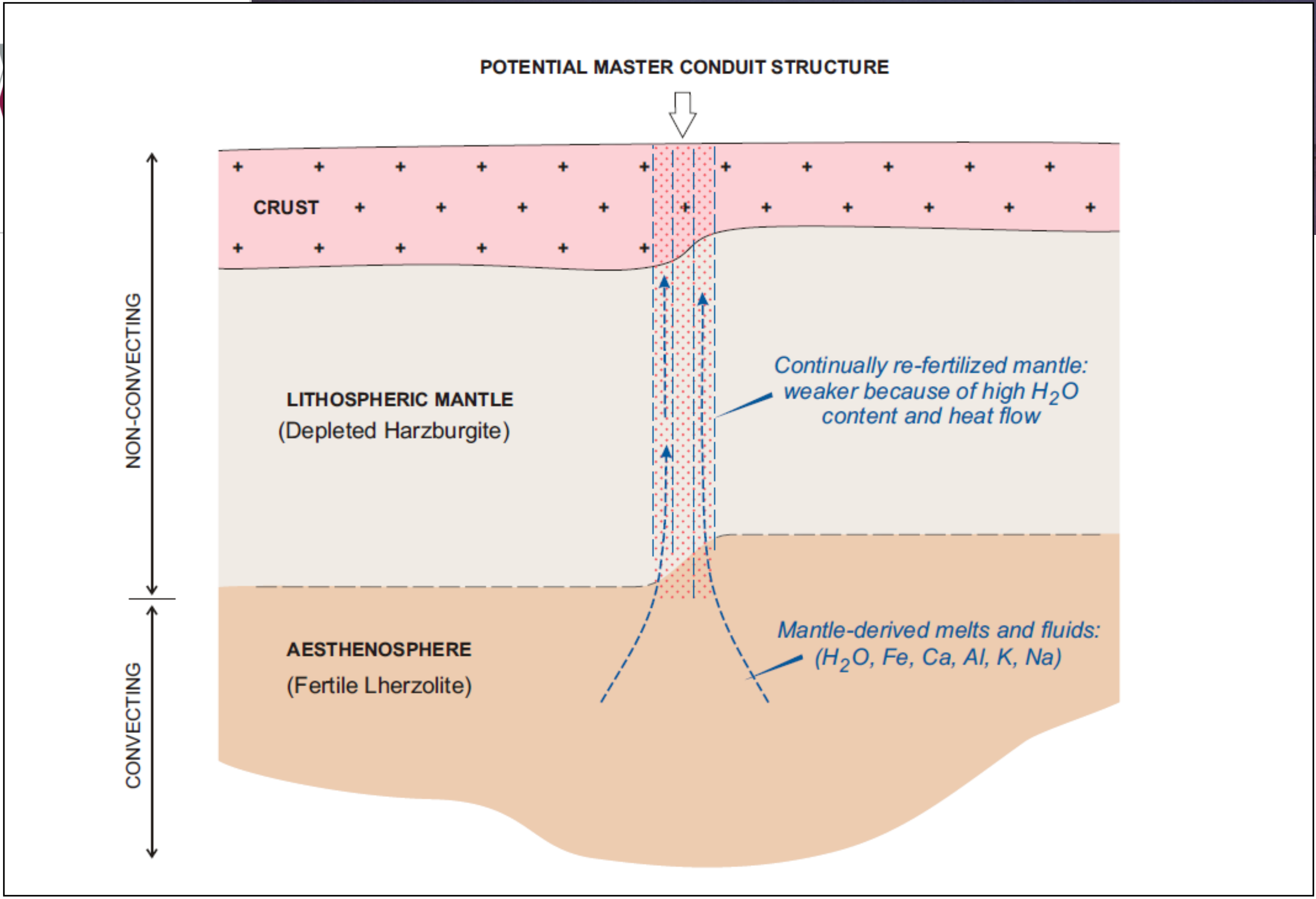
Key Concept : Water is the fundamental control on mantle rheology and is removed by melt extraction. Therefore Depleted Mantle is strong and Refertilised Mantle is weak

More Fertile Mantle Lithosphere is Weak Mantle Lithosphere: Slave Province, Canada



Te contours in black and white; pseudo-colour grid depicts proportion of xenocrystic garnets of depleted harzburgitic composition

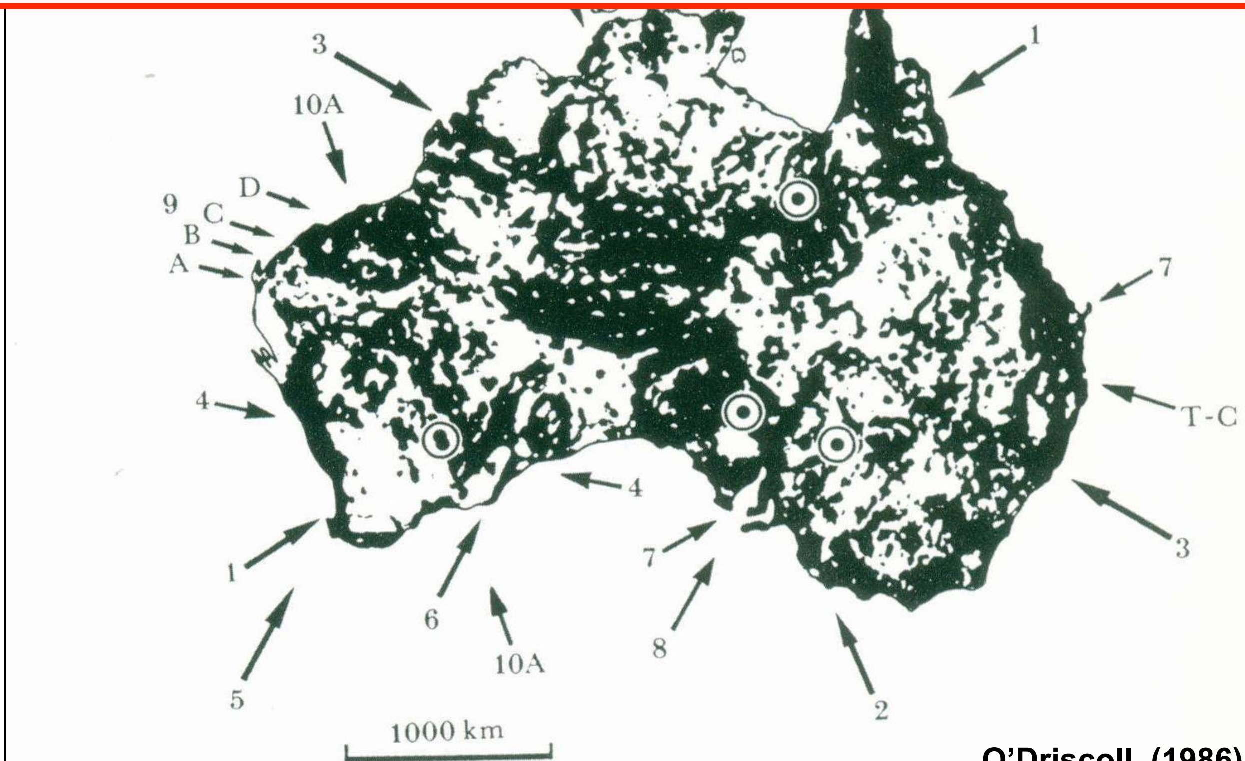
(Poudjom-Djomani et al – GEMOC)



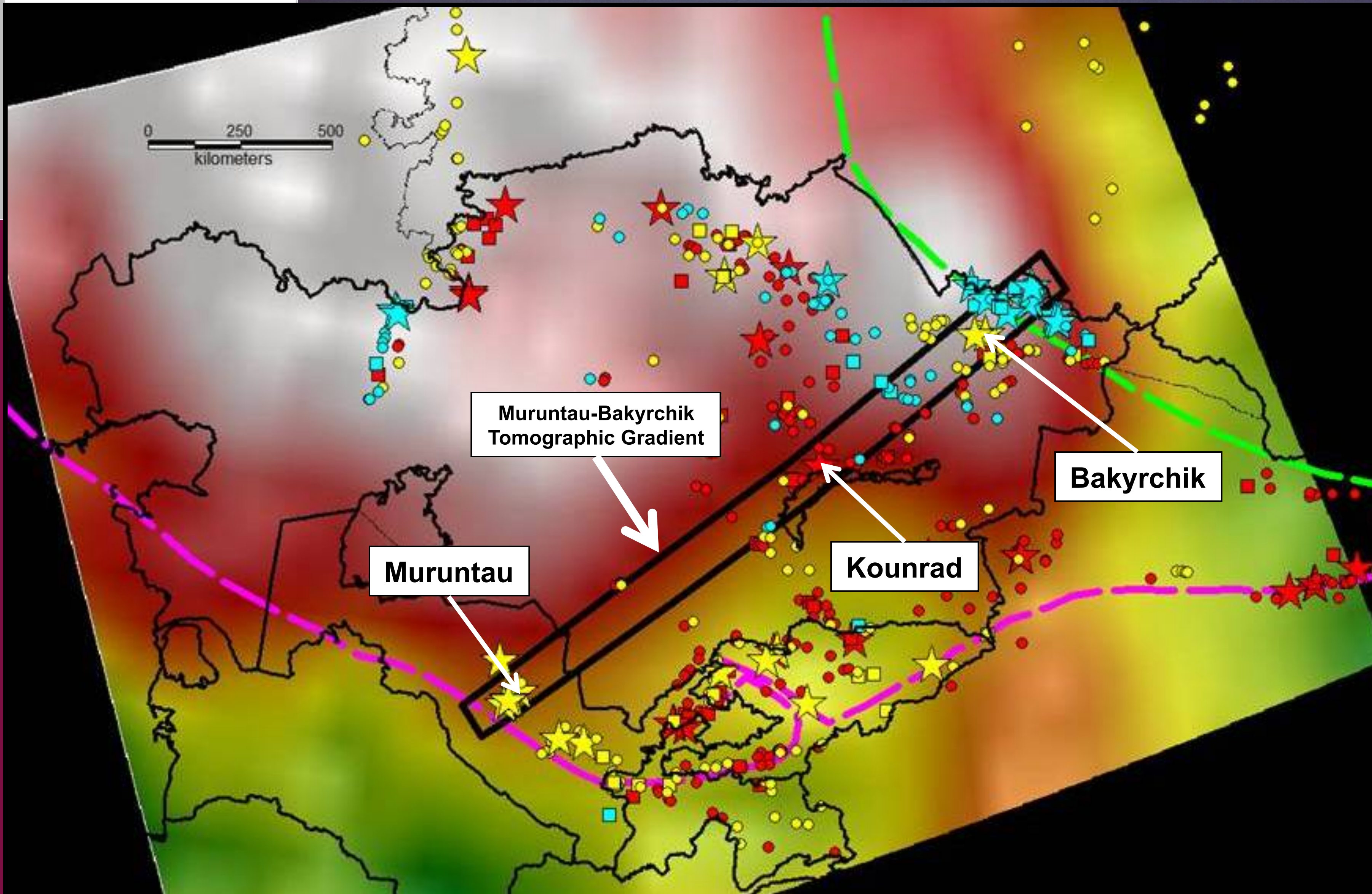
Generic conceptual model for a metallogenically-important Translithospheric Structure

What about Continental-Scale Lineaments?

These are *aggregate* patterns of organisation of translithospheric structures!

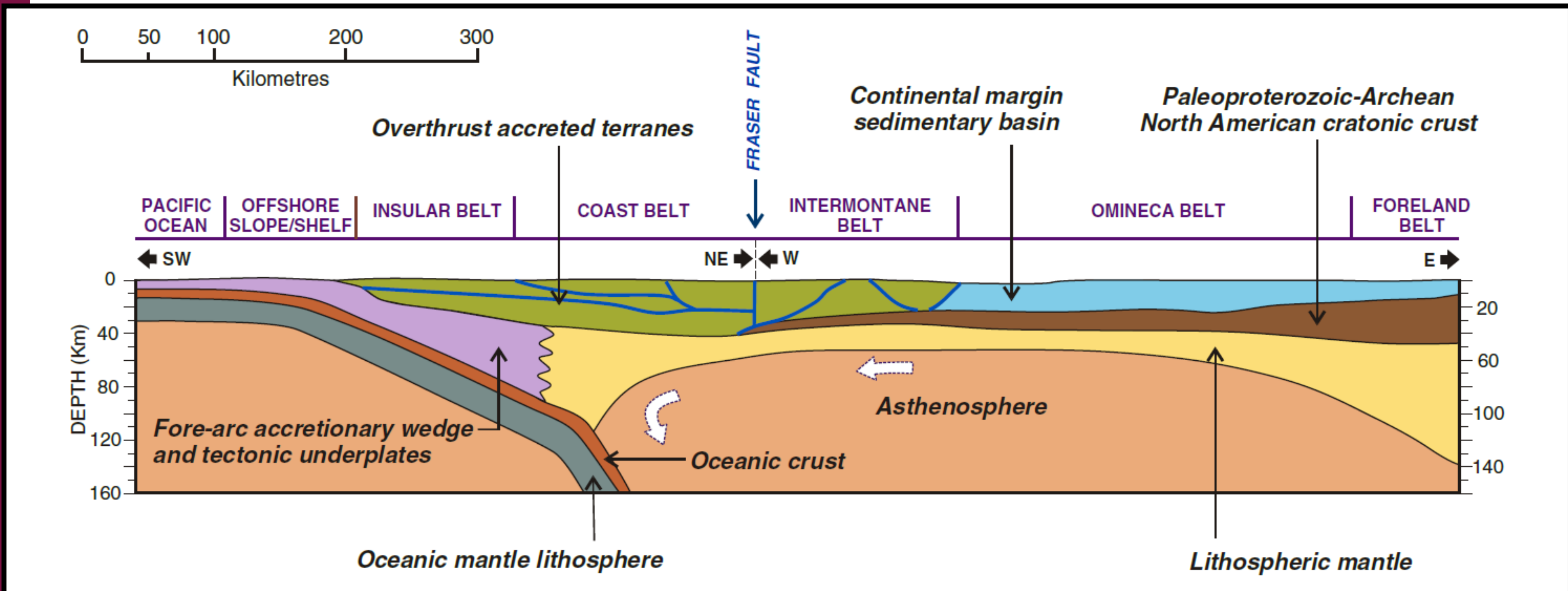


O'Driscoll, (1986)



Muruntau-Bakyrchik Tomographic Gradient Corridor on Grand 2006 smoothed model (100-175km layer)

Goldfields and MTI are thanked for permission to use this image

Modified from Clowes et al (1995)

Key Concept: Accretionary Orogens are dominantly underlain by old, variably-attenuated continental lithosphere

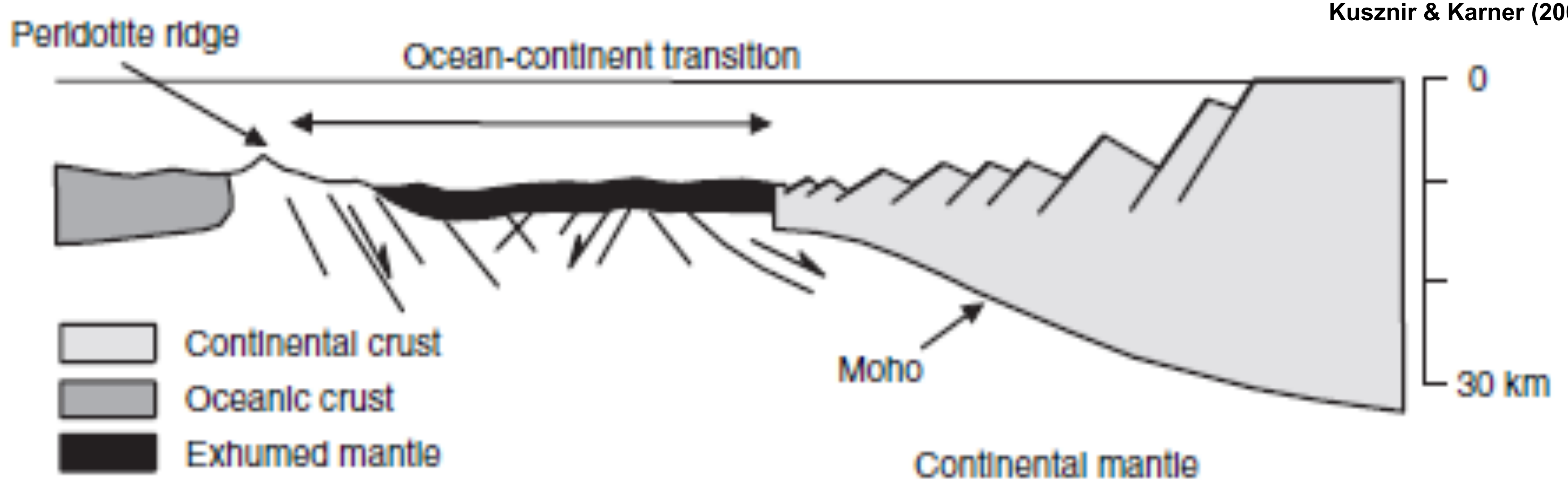


Fig. 9. Non-volcanic margins show an ocean–continent transition (OCT) consisting of a broad region of exhumed mantle up to 150 km wide separating thinned continental crust and oceanic crust (modified from Pickup *et al.* 1996).

Key Concept: Continental extension typically ***unroofs*** old SCLM

Explains why Accretionary Orogens are underlain by old lithosphere and why old trans-lithospheric structures propagate through them

Key Concept: Discontinuity Zones within active accretionary orogens will localise anomalous magmatism and mineralisation through processes such as slab tear

Note Lihir location associated with subduction zone bend and slab tear

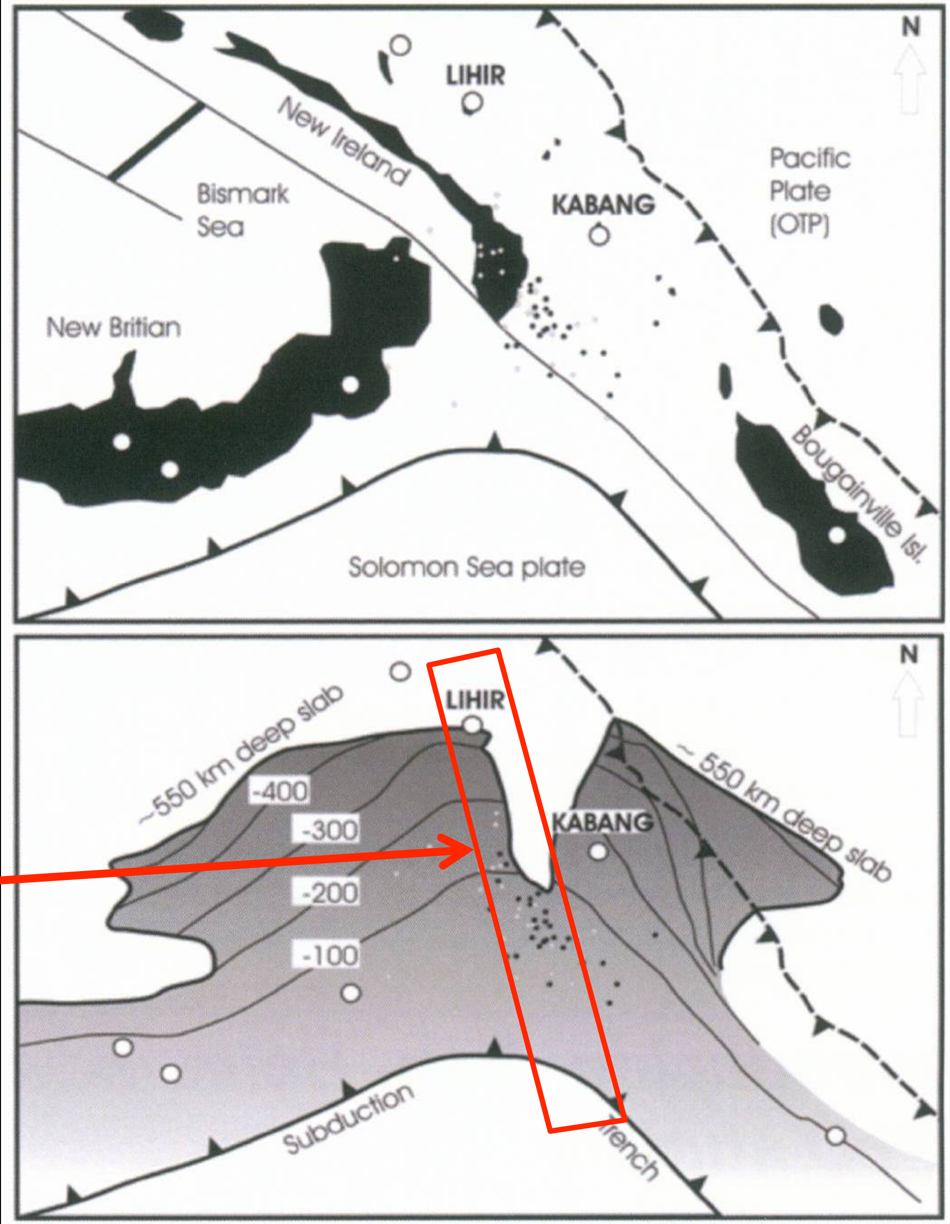
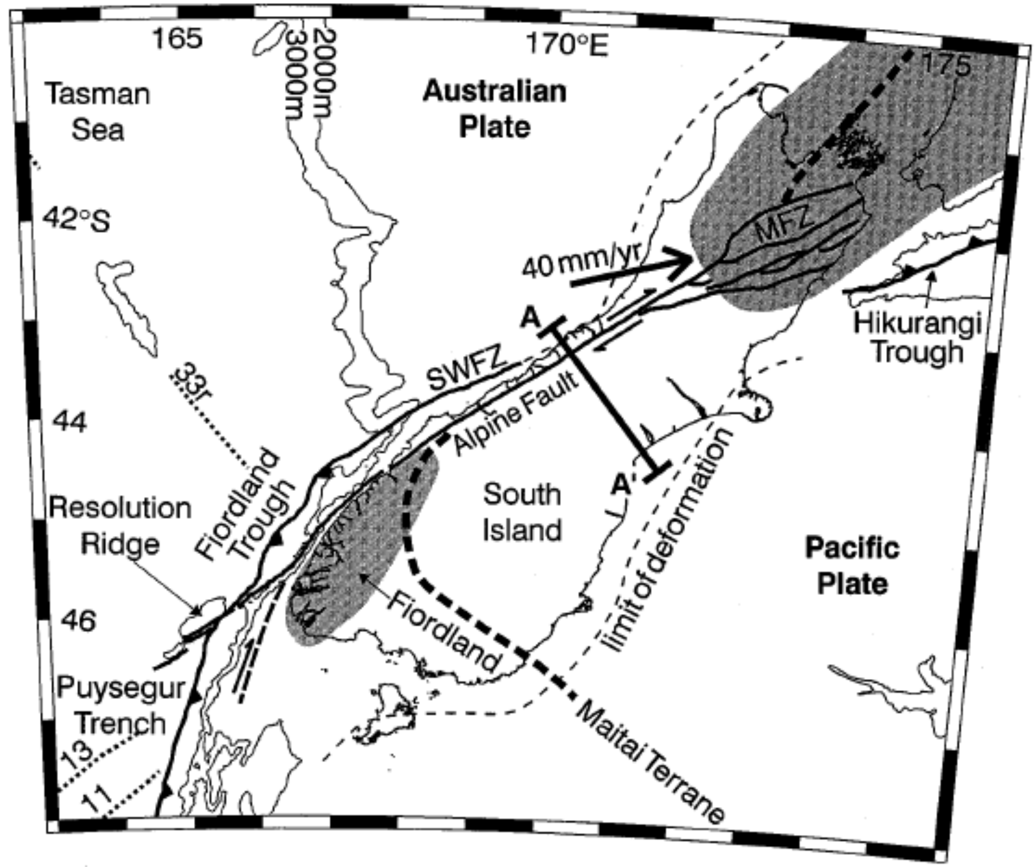


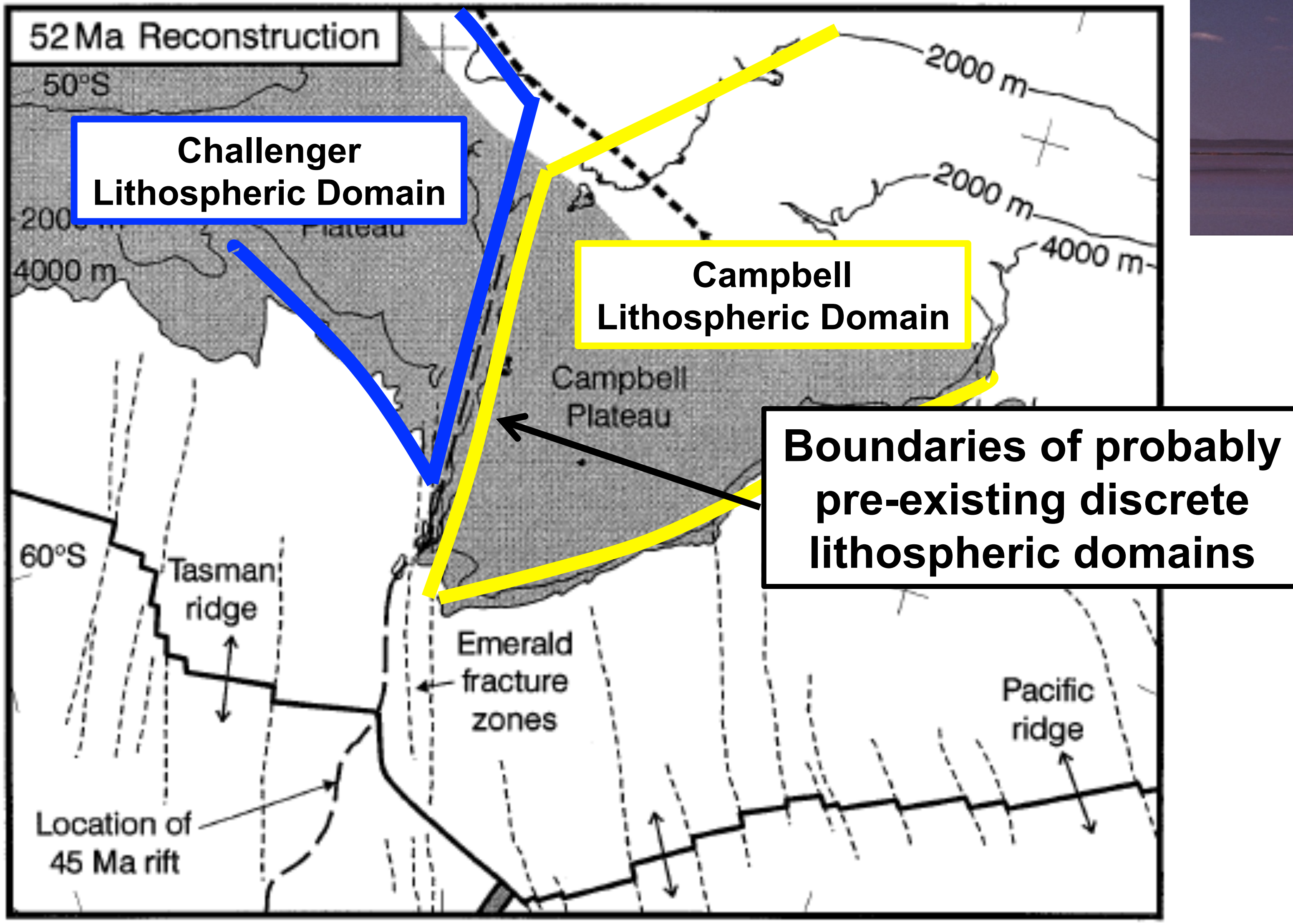
Figure 2. Location map showing the tectonic elements of the eastern Papua New Guinea and Western Solomon Islands (Above).

Holm (2010) – EGRU Newsletter

Sutherland et al (2000)



Key Concept:
Lithospheric-domain bounding structures are *older and more fundamental* that the (relatively) ephemeral major faults they may sometimes comprise parts of - Alpine Fault example

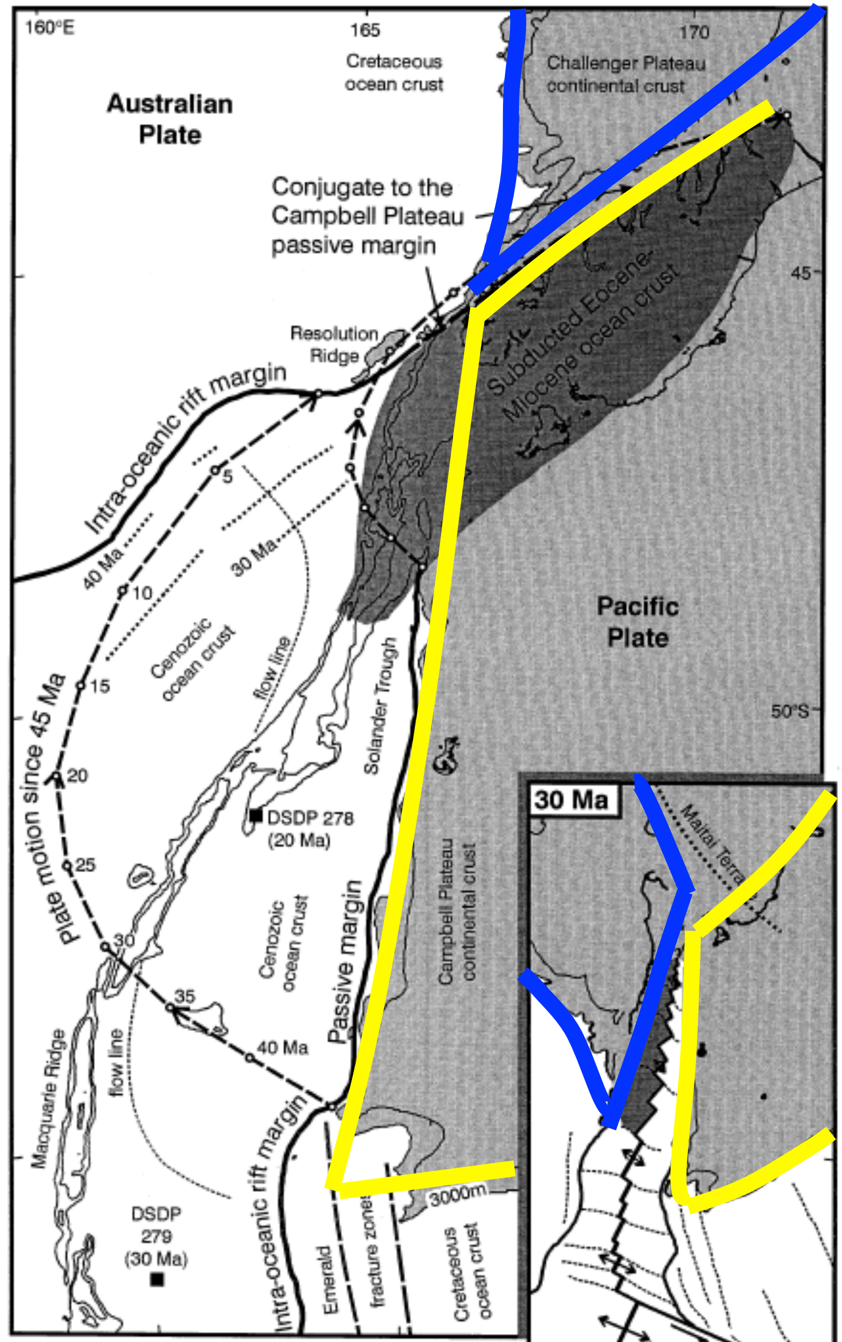


Pre-Rifting Configuration – New Zealand Microcontinent

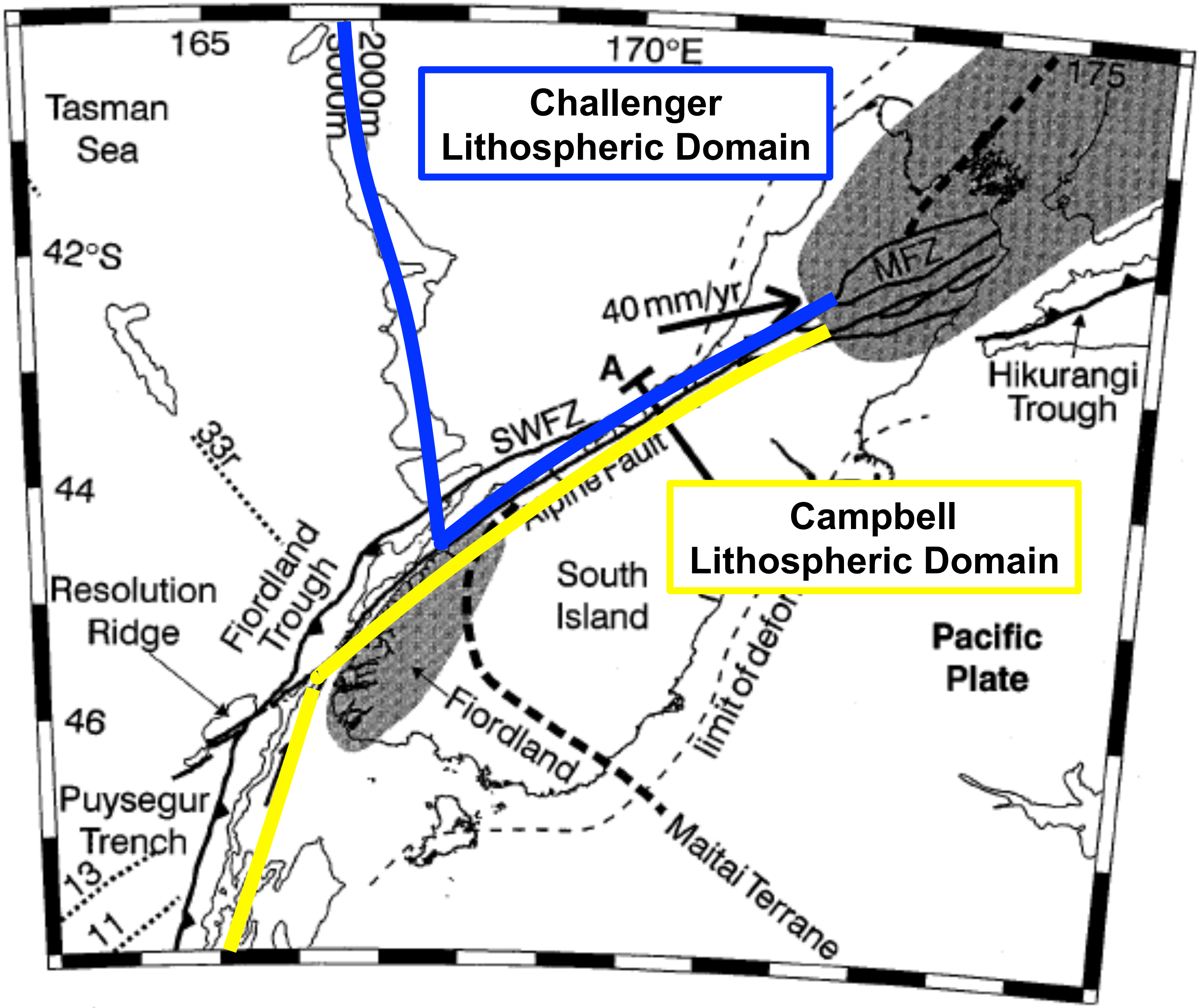
(Note that rifting probably reactivates an older boundary)

Sutherland et al (2000)

45-5 Ma:
Reorganisation of old lithospheric domain boundaries by a combination of rifting, sea-floor spreading and subduction to form Modern Alpine Fault

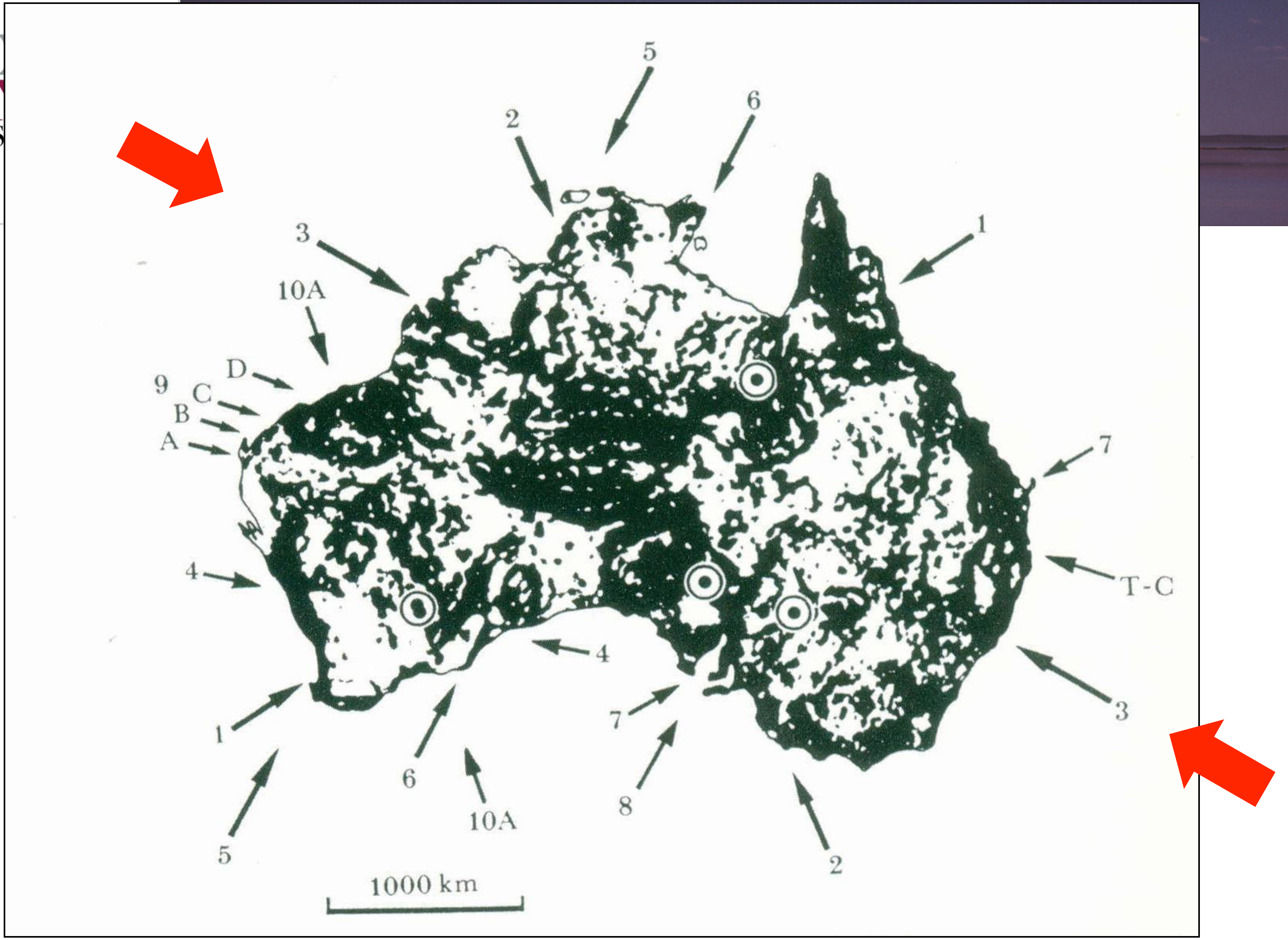


Sutherland et al (2000)



Modern Alpine Fault Configuration

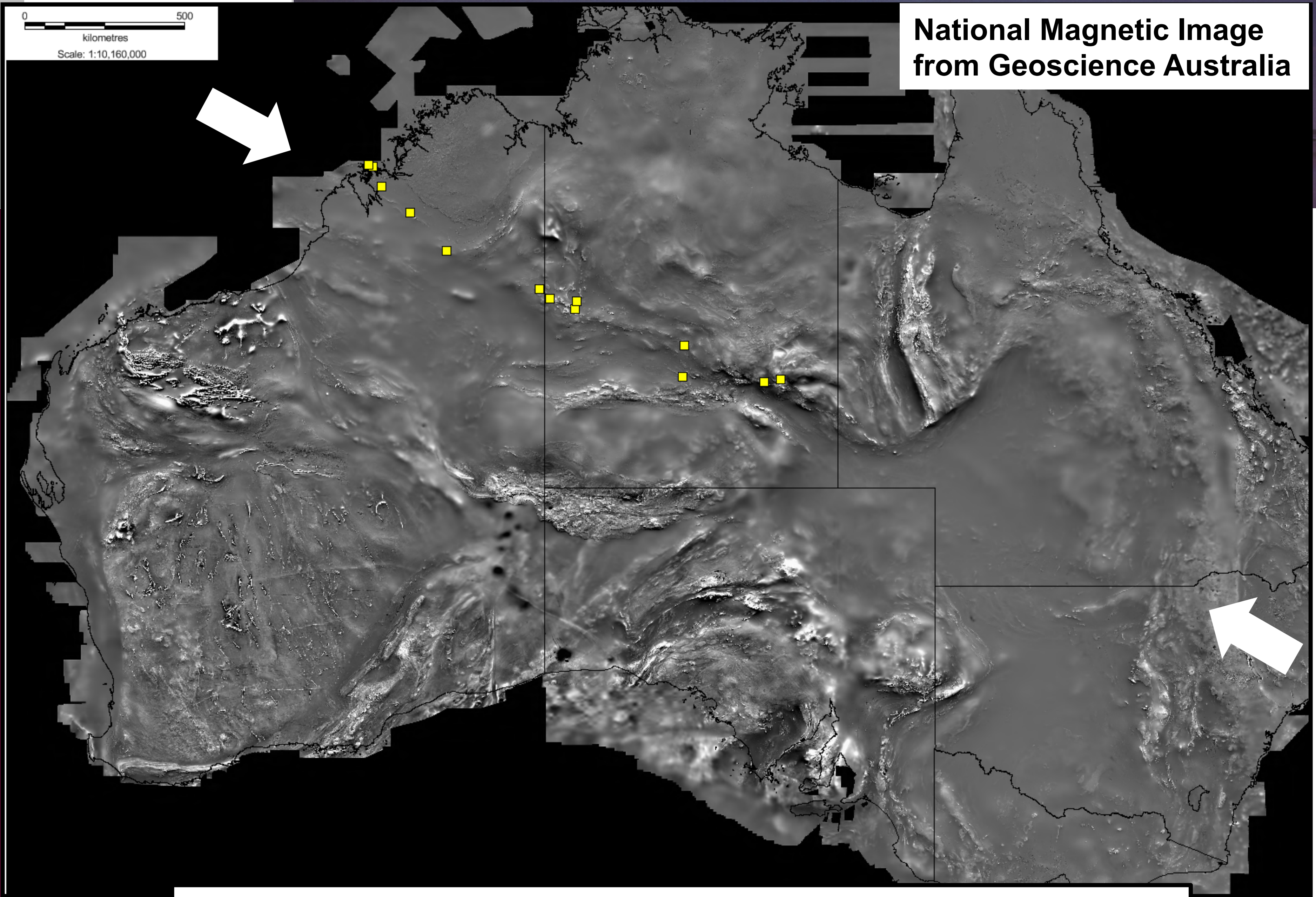
Sutherland et al (2000)

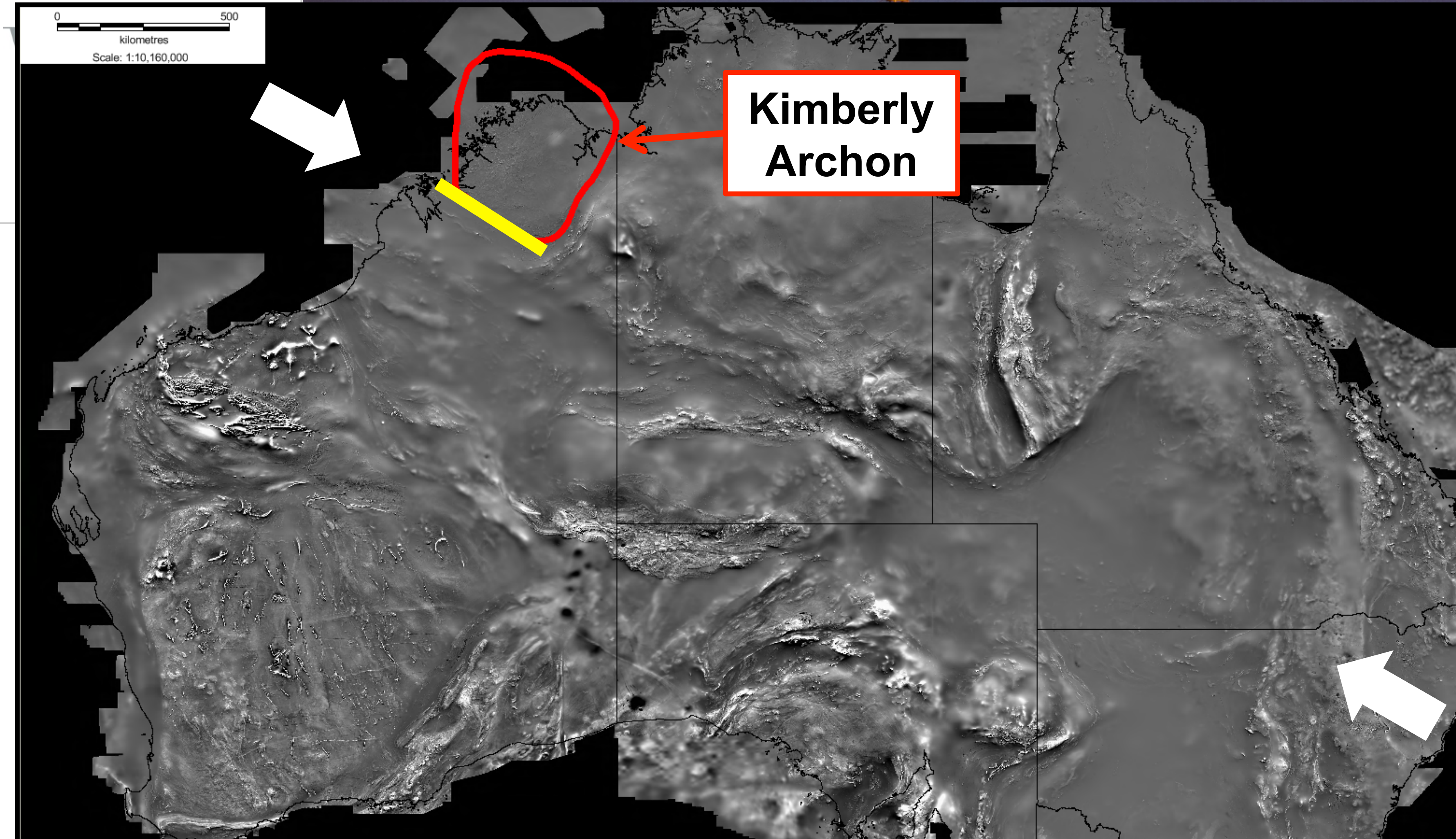


G3 Case Study

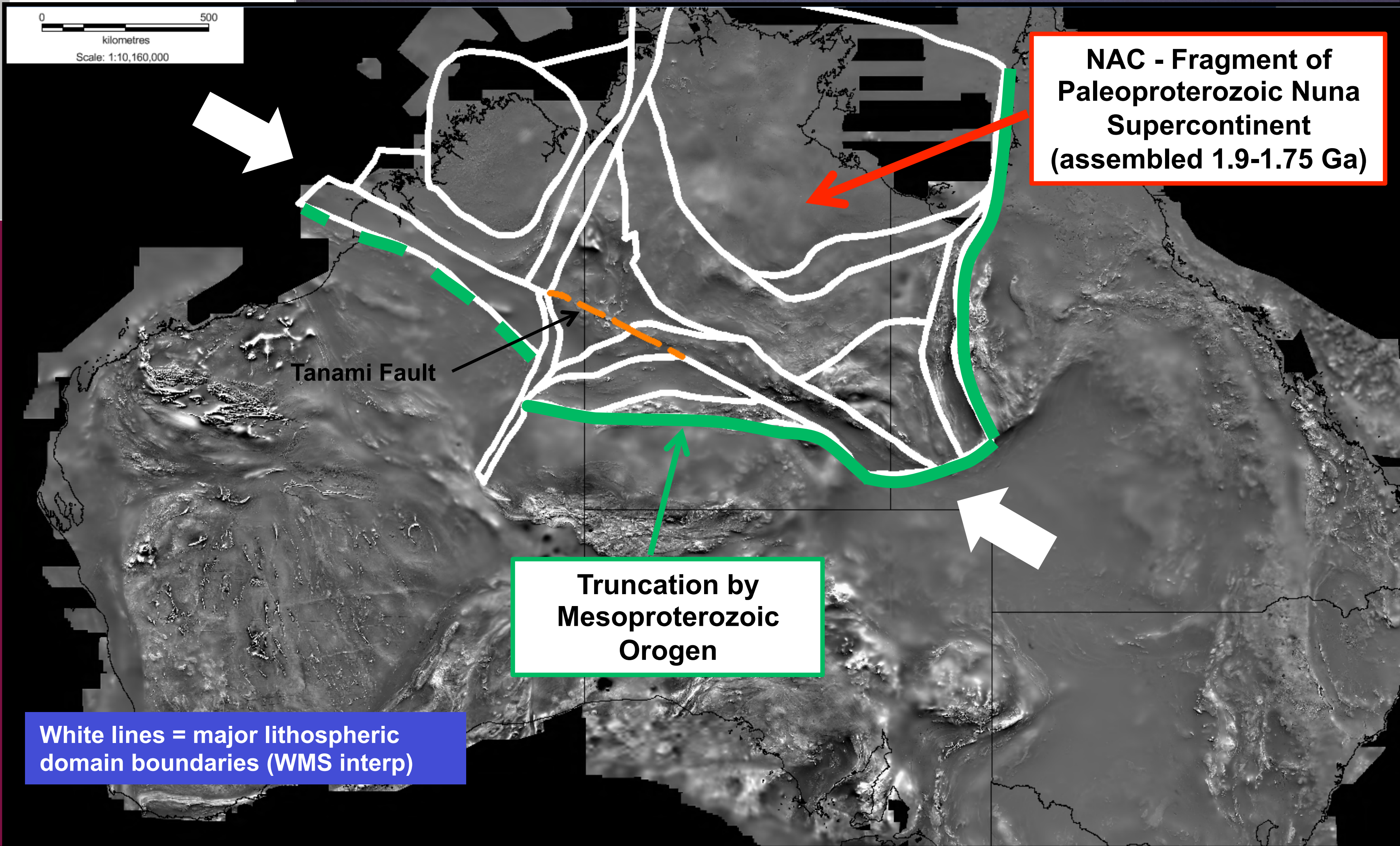
Map of image-diffused Bouguer gravity contours (O'Driscoll, 1986)

Alignment of Major Mineral Deposits along G3





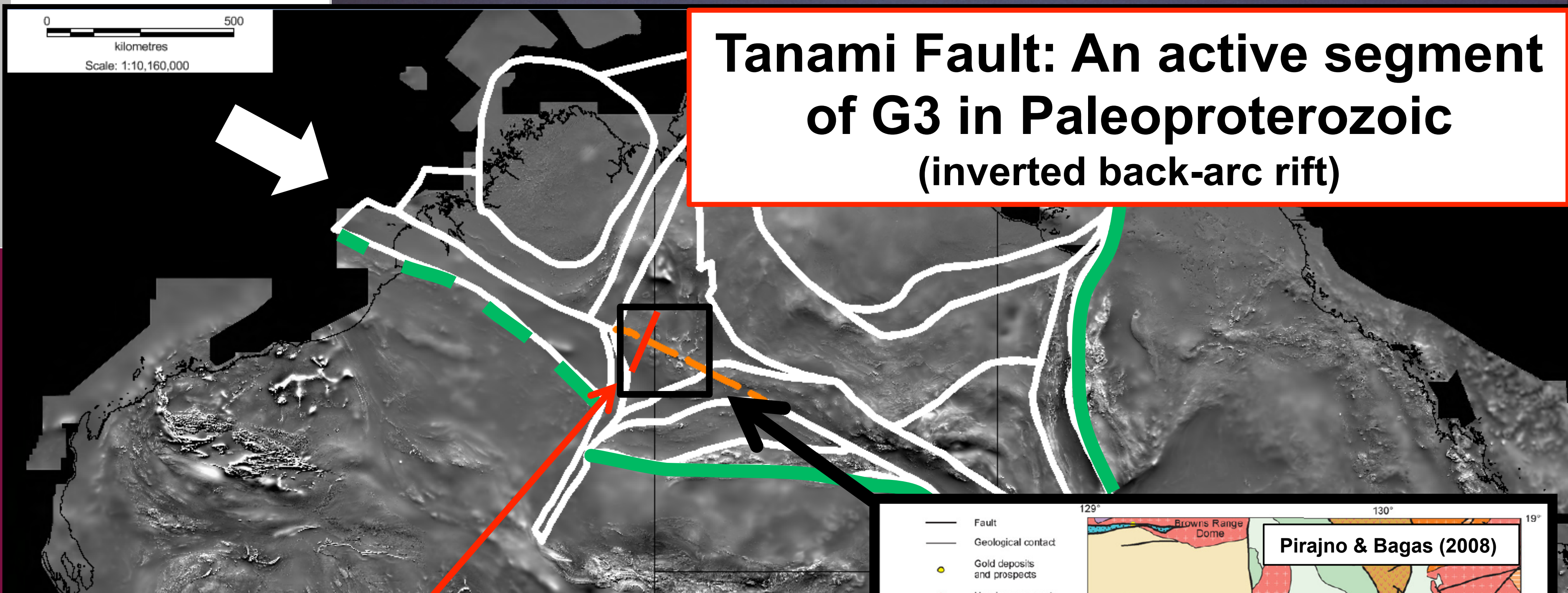
Oldest discernible element of G3 is southern margin of Kimberly Archon:
Must be at least as old as Kenorland break-up (c. 2.4 Ga) but probably older pre-existing Archean suture

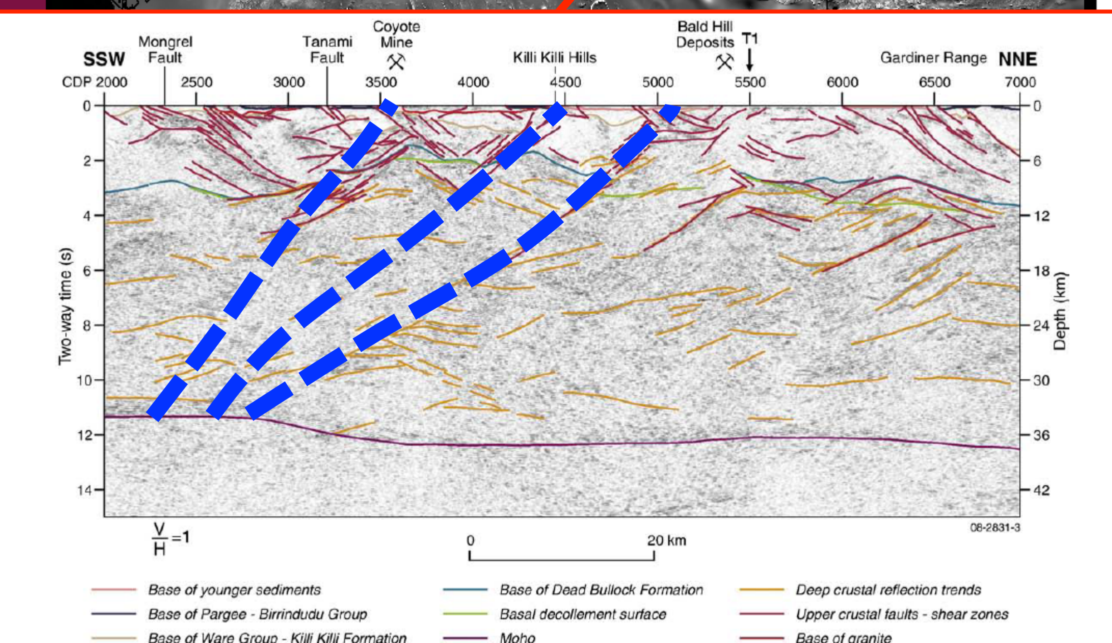


G3 is established by an alignment of translithospheric structures (mostly pre-existing lithospheric domain boundaries) during the Paleoproterozoic assembly of Nuna

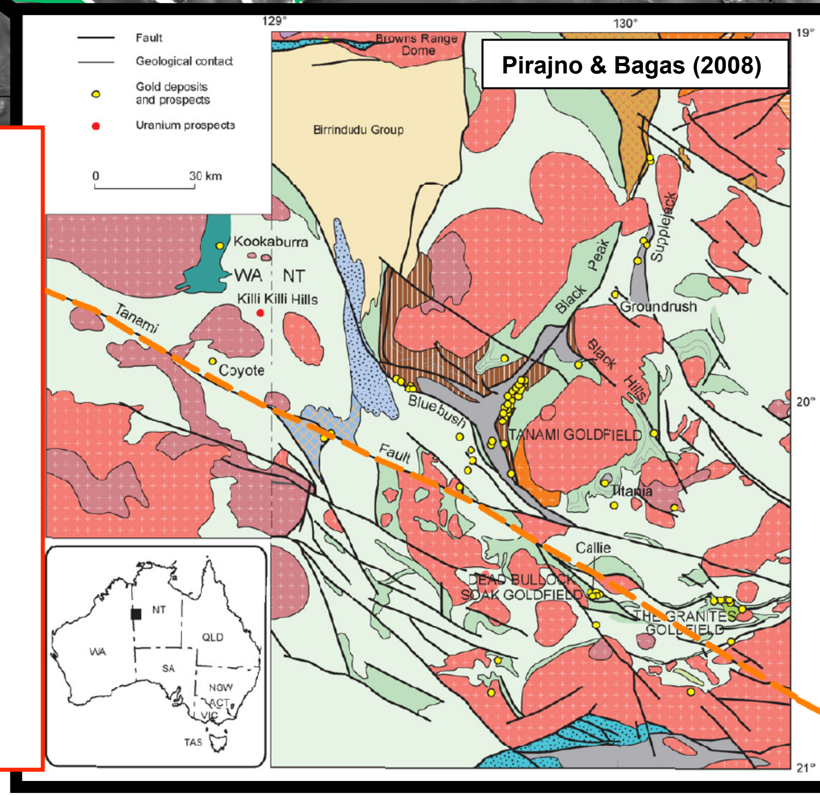
Tanami Fault: An active segment of G3 in Paleoproterozoic

(inverted back-arc rift)

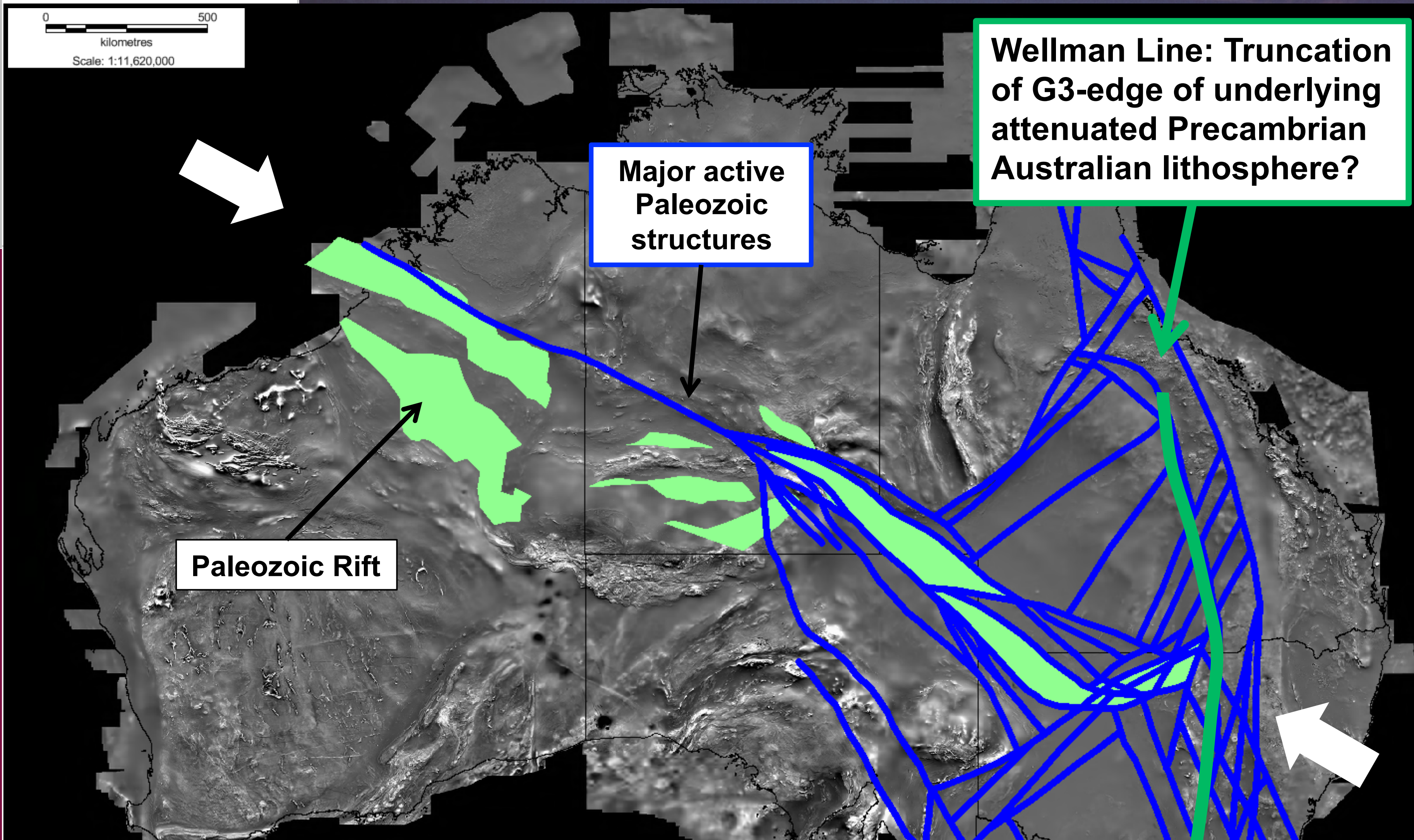




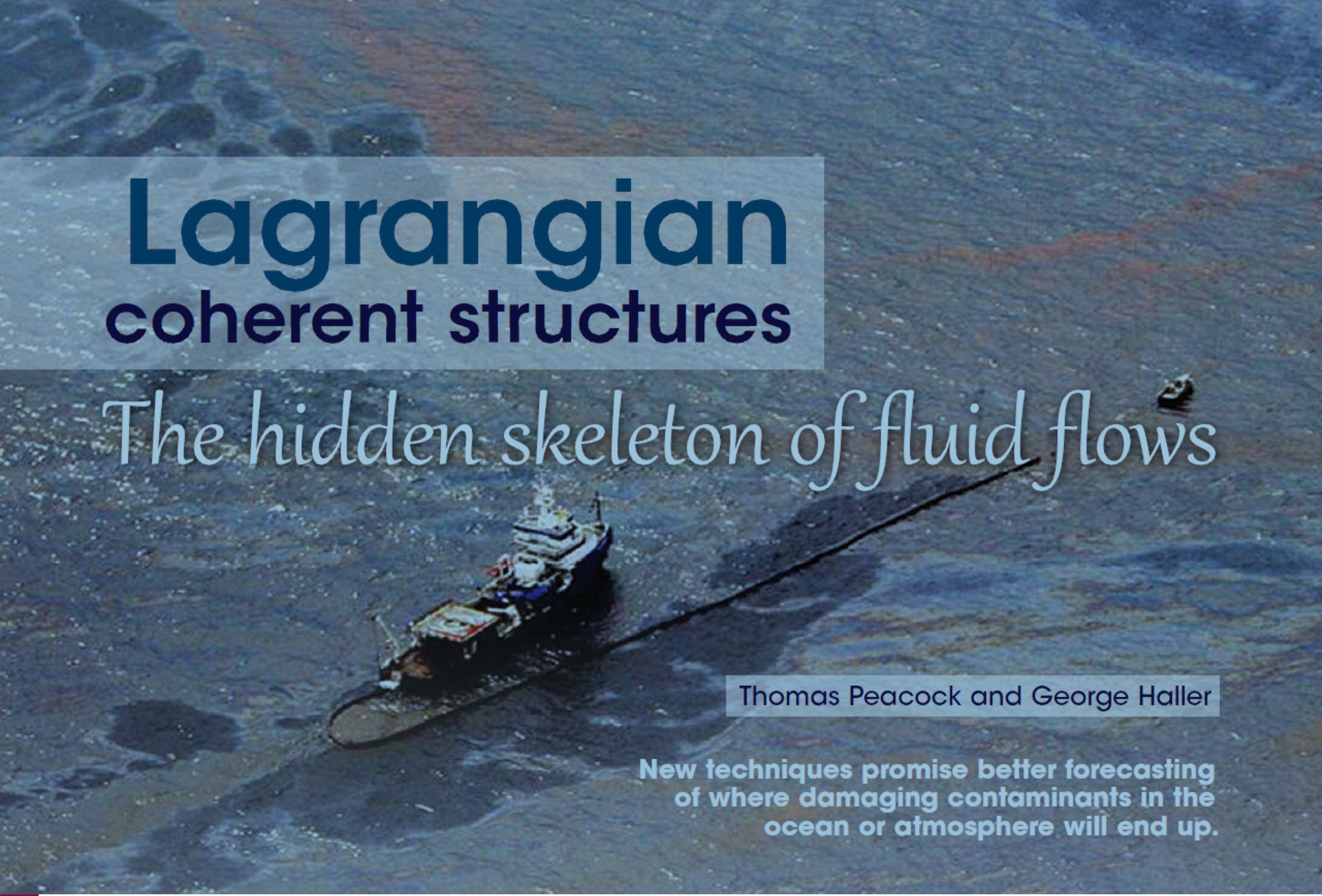
Goleby et al (2009)



Pirajno & Bagas (2008)



Precambrian Australia as we see it today assembled as part of Rodinia – Paleozoic extension (Larrapinta Event) and inversion (Alice Springs Orogeny) reactivates G3 and propagates it east into the Tasmanides



Lagrangian coherent structures

The hidden skeleton of fluid flows

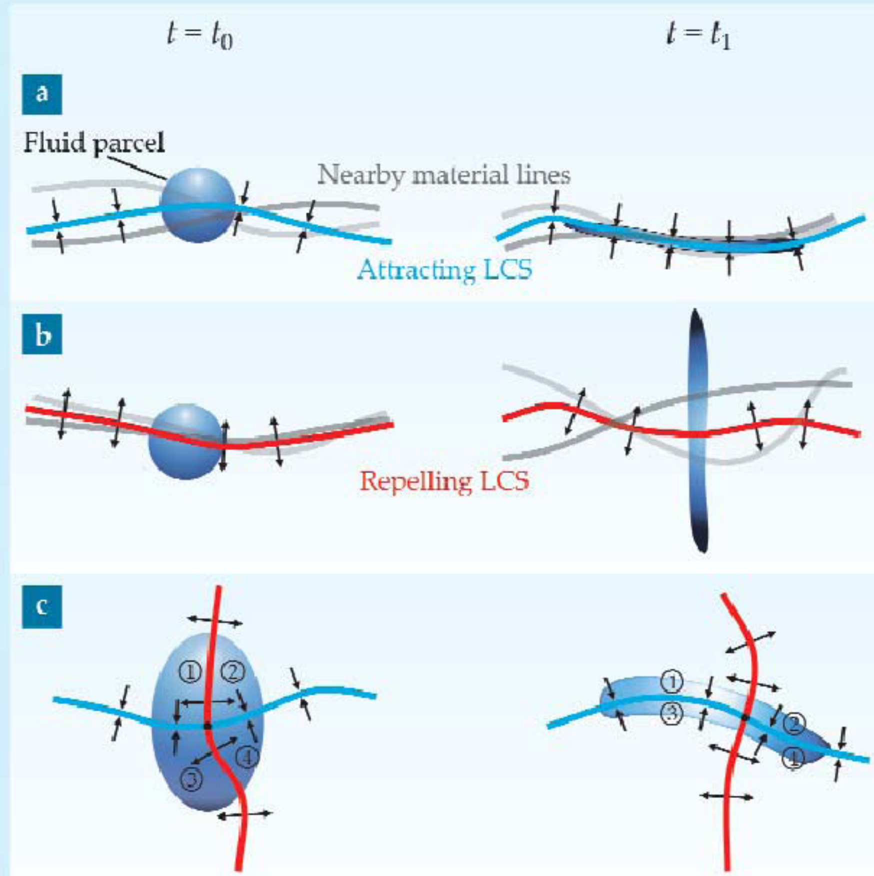
Thomas Peacock and George Haller

New techniques promise better forecasting of where damaging contaminants in the ocean or atmosphere will end up.

February 2013 Physics Today

Lagrangian Coherent Structures are structures which separate dynamically distinct regions in time-varying systems such as turbulent flows. They can reveal geometry in flows which is otherwise often hidden
(modified from Wikipedia)

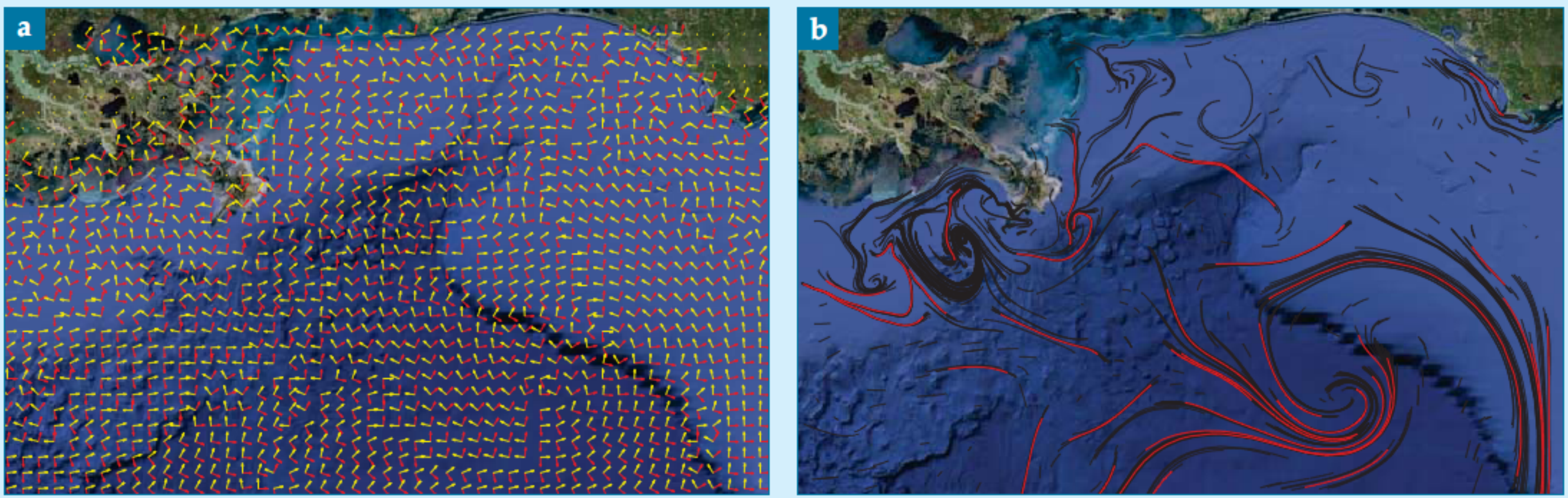
Figure 3. Lagrangian coherent structures in the time interval $[t_0, t_1]$. **(a)** An attracting LCS is a material line (blue) that attracts fluid onto itself more strongly than does any nearby material line (gray). **(b)** Similarly, a repelling LCS is a material line (red) that repels fluid more strongly than any other nearby line. **(c)** A repelling LCS acts as the boundary between domains of attraction for an attracting LCS. Because LCSs cannot be crossed by material, they bound and shape the regions labeled 1–4. The intersection between the repelling and attracting LCSs is a generalized saddle point.



Peacock & Haller (2013)

Peacock & Haller (2013)

Figure 5. The developing tiger tail in the Deepwater Horizon oil spill (see figure 1b). **(a)** The eigenvector fields ξ_1 and ξ_2 for the backwards time window 17 May to 14 May 2010 are shown, respectively, by the yellow and red arrows. **(b)** Several attracting strainlines (trajectories of the ξ_1 field) are plotted in black. The dominant strainlines, highlighted in red, are the attracting Lagrangian coherent structures responsible for shaping the tiger tail in figure 1b.



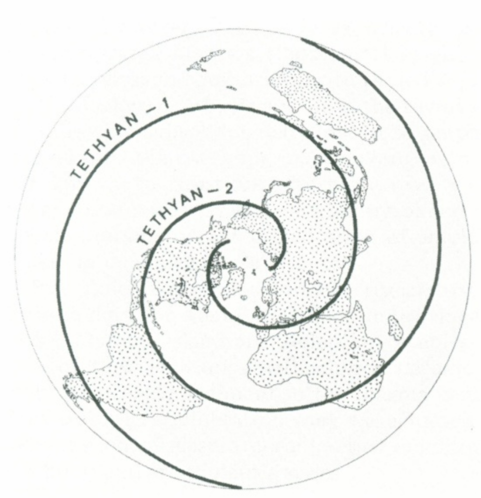


Fig. 10. The spirals T-1 and T-2 of the Tethyan double helix plotted on a north-polar azimuthal projection extended to include the southern hemisphere to latitude 60°S.

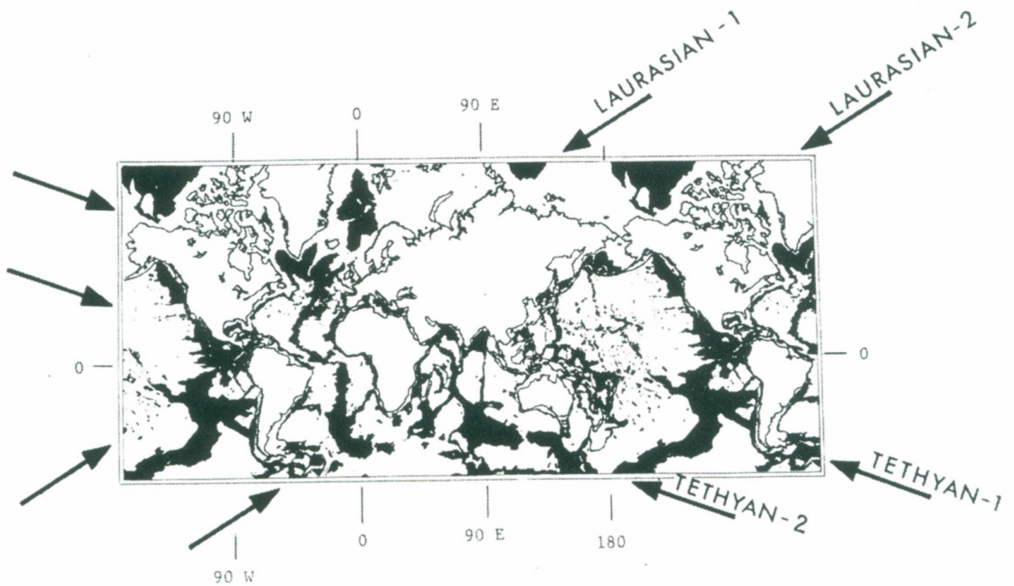


Fig. 2. Mercator map of continents with ocean bathymetry represented by contour slice (black) at 2000—4000 m depth. The Tethyan and Laurasian belts are shown as T-1, T-2, L-1 and L-2, respectively. (Data from John Bartholomew.)

Do we see global-scale LCSs?

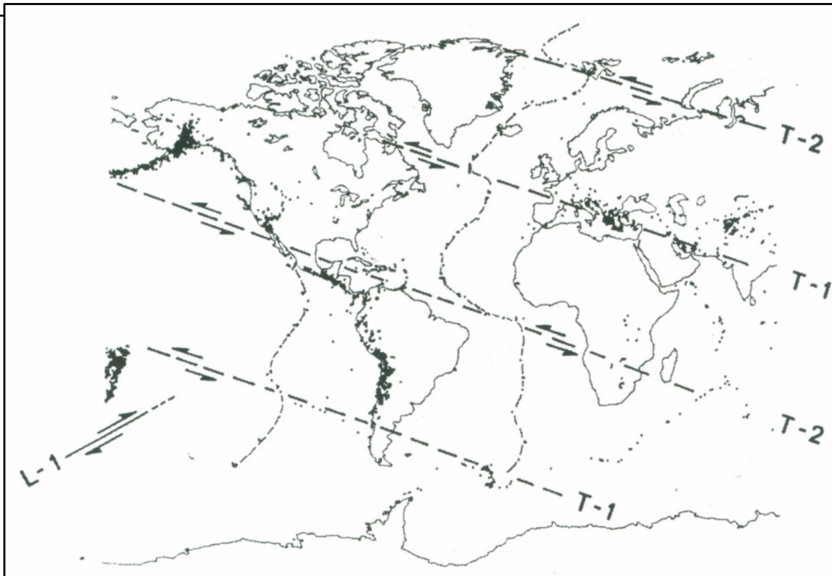
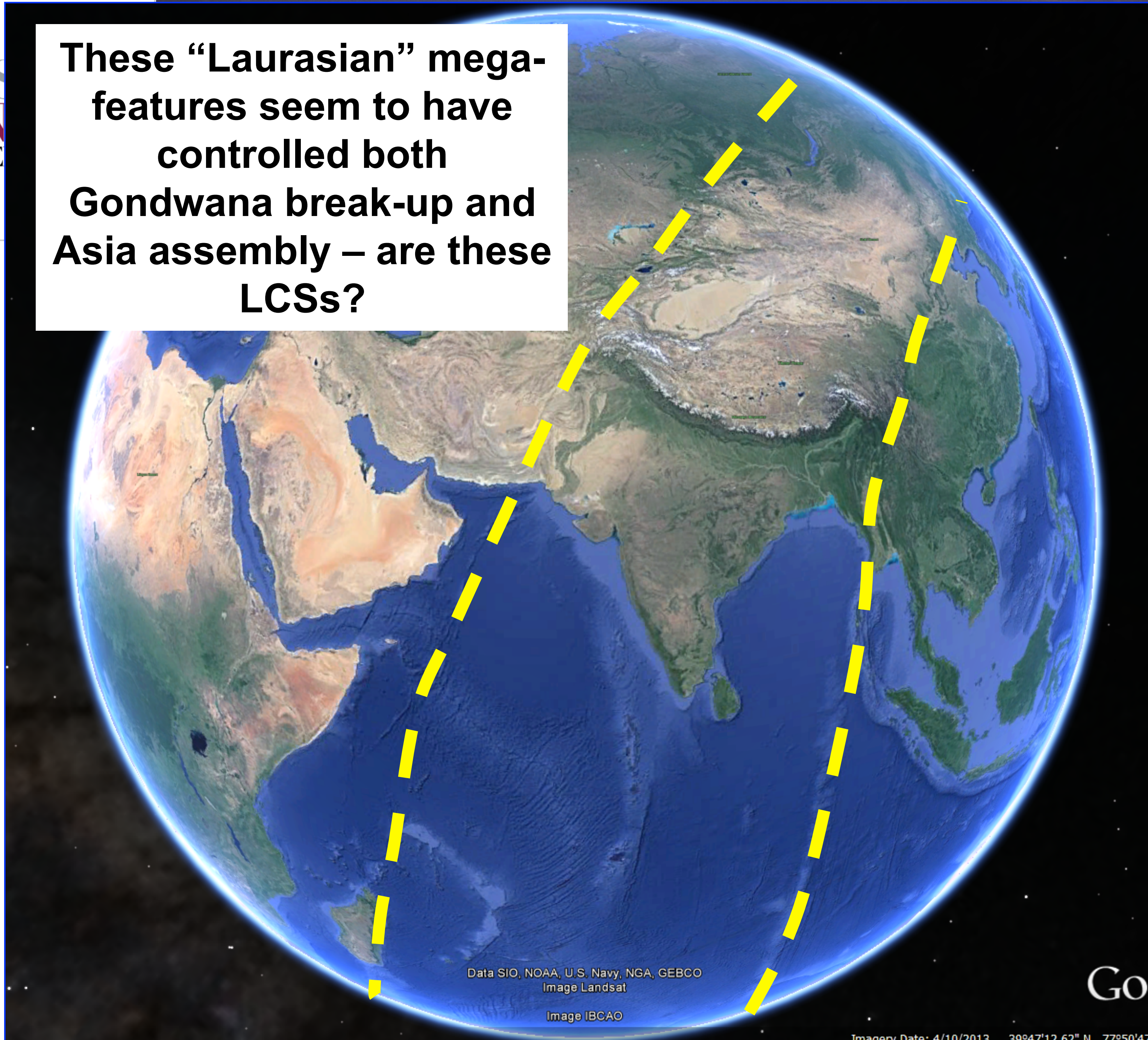


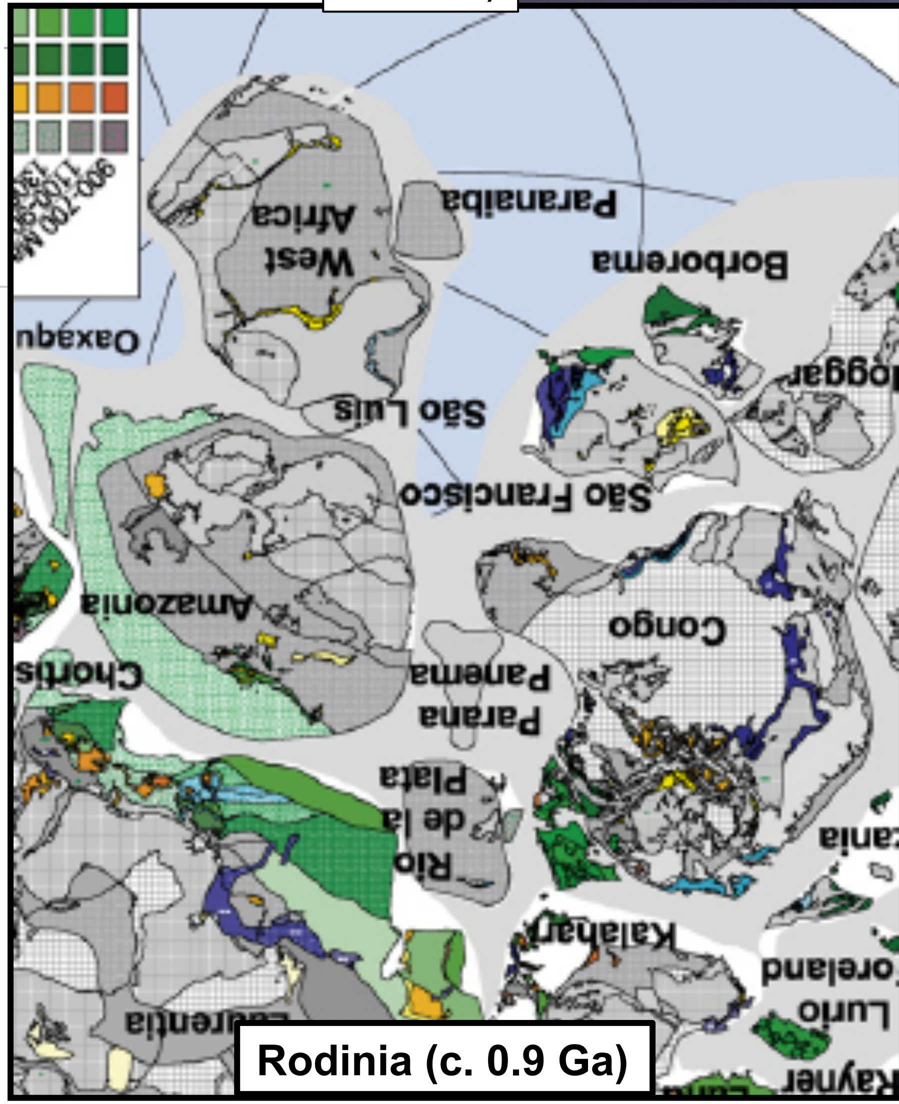
Fig. 9. Left-lateral displacements of mid-ocean ridges by the two Tethyan belts T-1 and T-2. A corresponding right-lateral displacement is indicated for the Laurasian belt, L-1. (Data from U.S.G.S.)

(O'Driscoll, 1980)

These "Laurasian" mega-features seem to have controlled both Gondwana break-up and Asia assembly – are these LCSs?

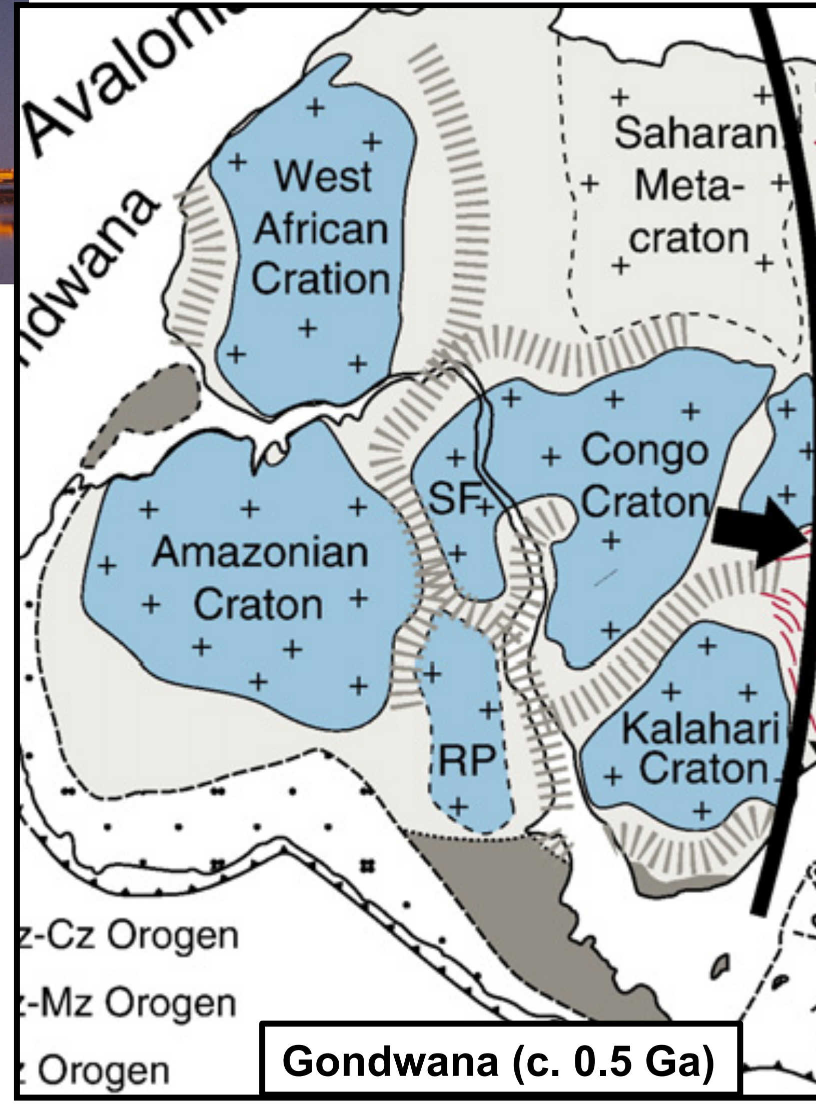


Li et al (2008)



Rodinia (c. 0.9 Ga)

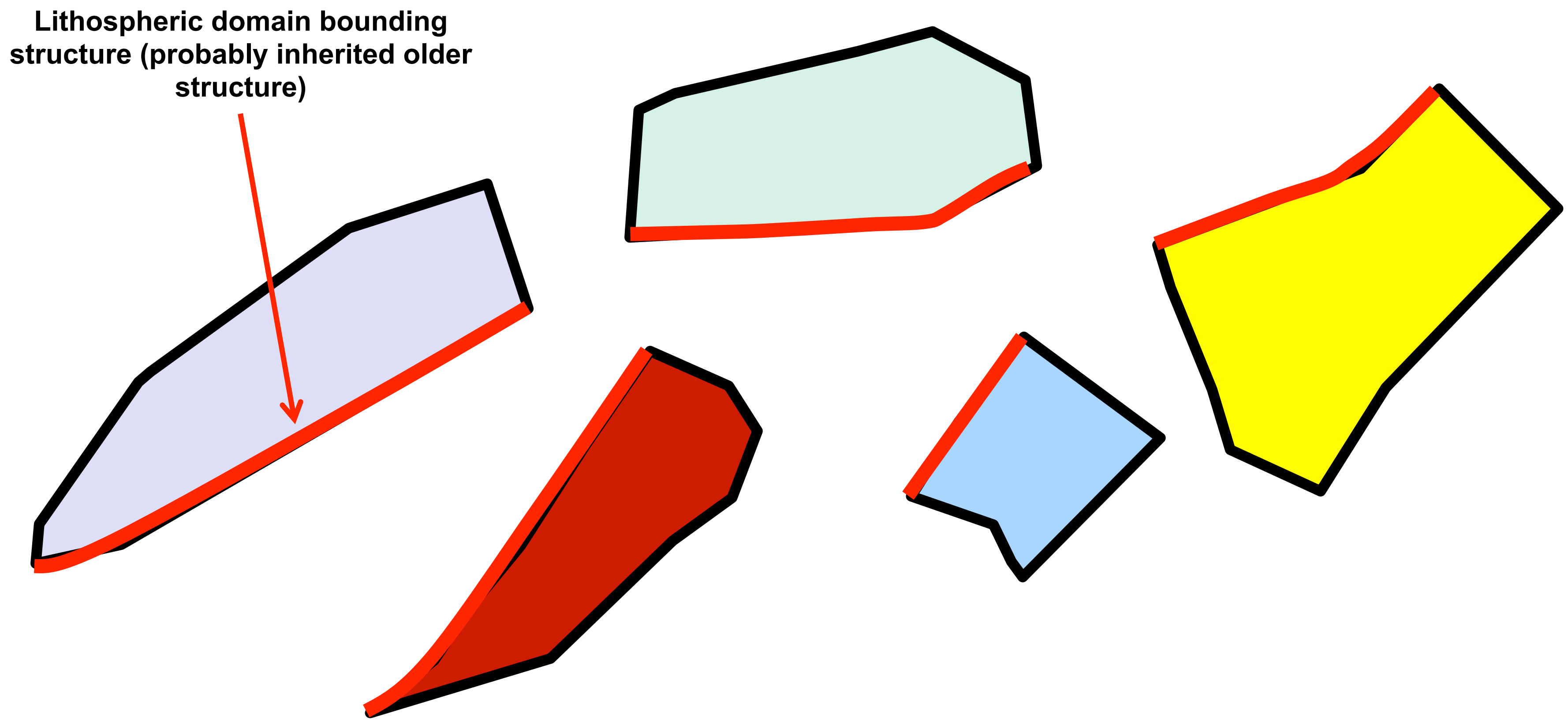
(Stern & Johnson , 2010; modified after Meert & Lieberman, 2008)



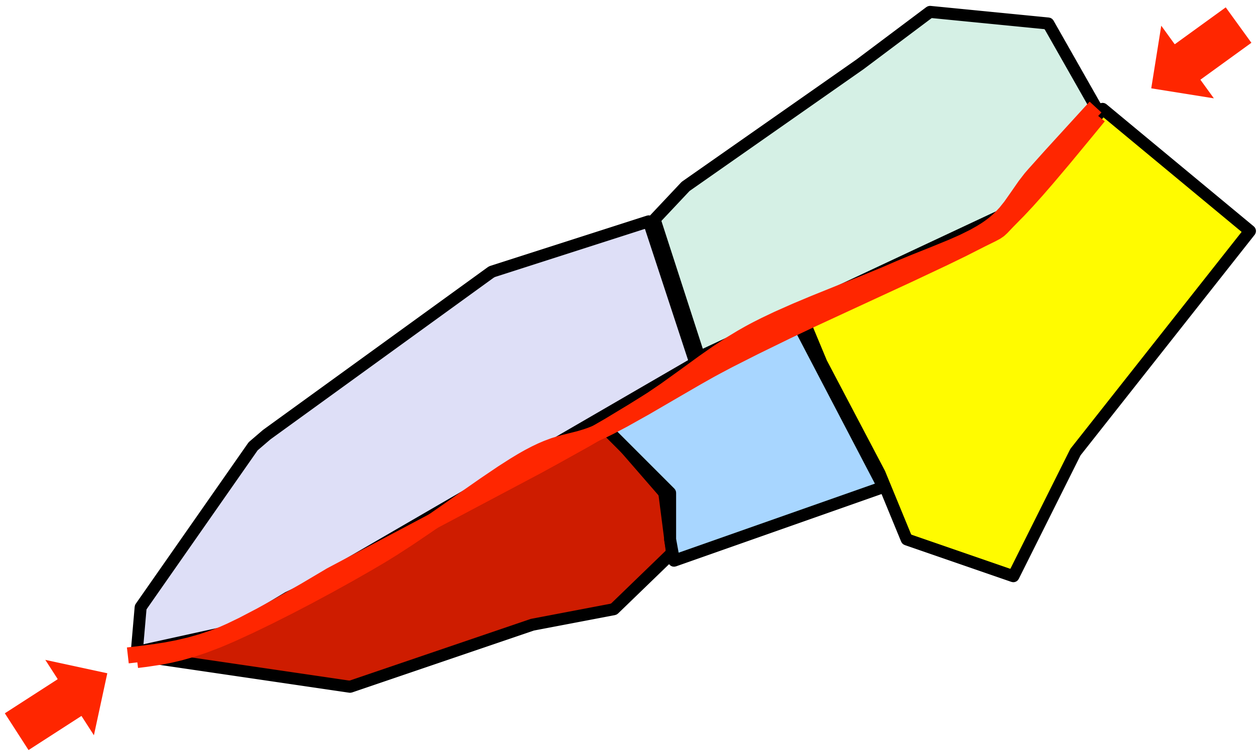
Gondwana (c. 0.5 Ga)

Comparison between Rodinia and Gondwana : Dispersal and reassembly in more or less the same configuration – effect of a LCS?

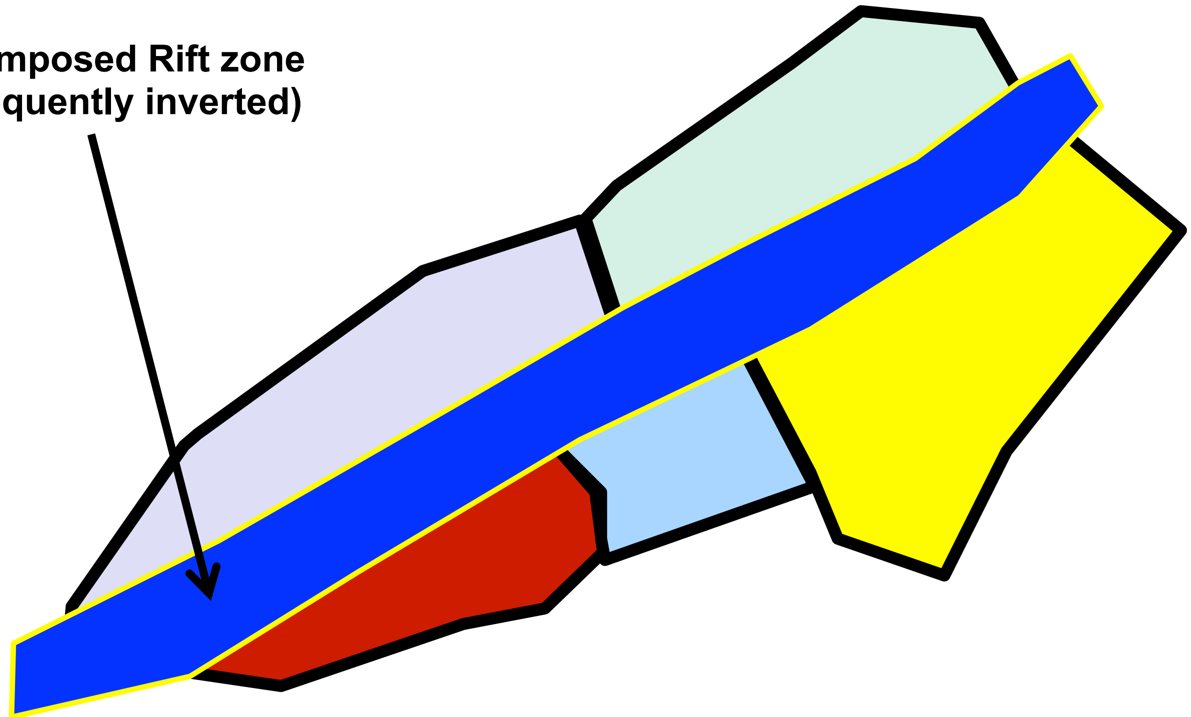
Simple Model for the Formation of a Continental-Scale Lineament



Stage 1: Multiple lithospheric domains, bounded by translithospheric structures, within an evolving accretionary orogen



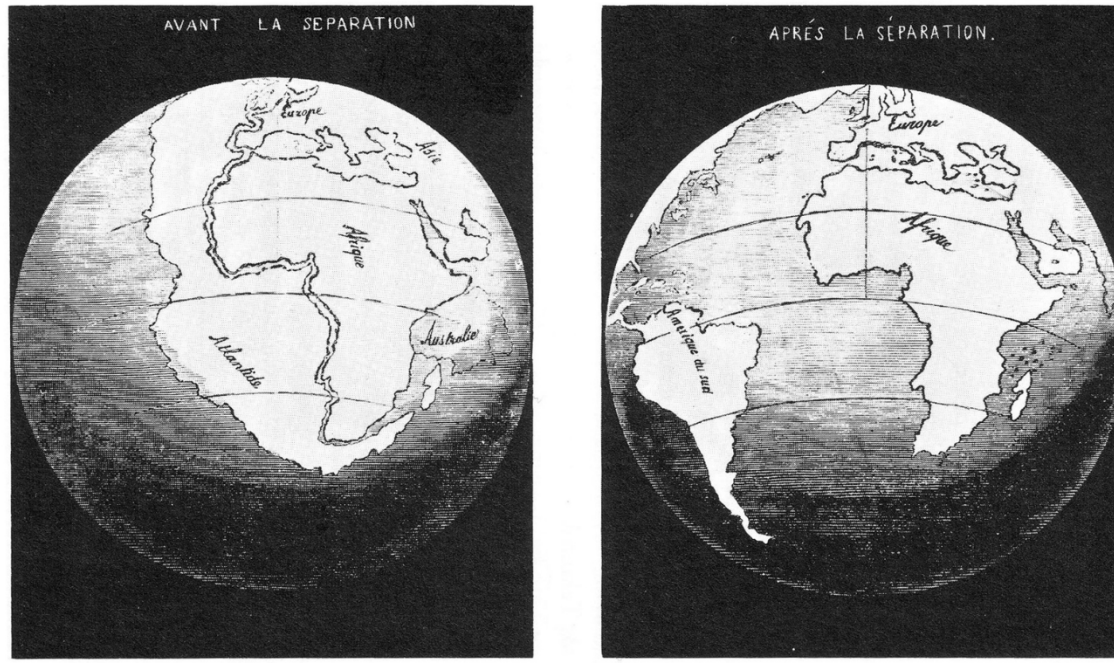
Stage 2: Alignment and organisation of lithospheric domain boundaries during termination of accretionary orogen and continent assembly (controlled by LCS?)



Stage 3: Reactivation of Lineament by rifting and subsequent inversion – in some cases rifting may produce an ocean that closes in the same position

The Big Lesson from the History of Tectonics: We see patterns long before we understand mechanisms

First person to suggest South America and Africa were joined:
Abraham Ortelius, 1596



First known illustration of the Opening of the Atlantic Ocean:
by Antonio Snider-Pellegrini, 1858

END