The architecture and evolution of continental lithosphere:

Multi-disciplinary mapping & the GLAM Project

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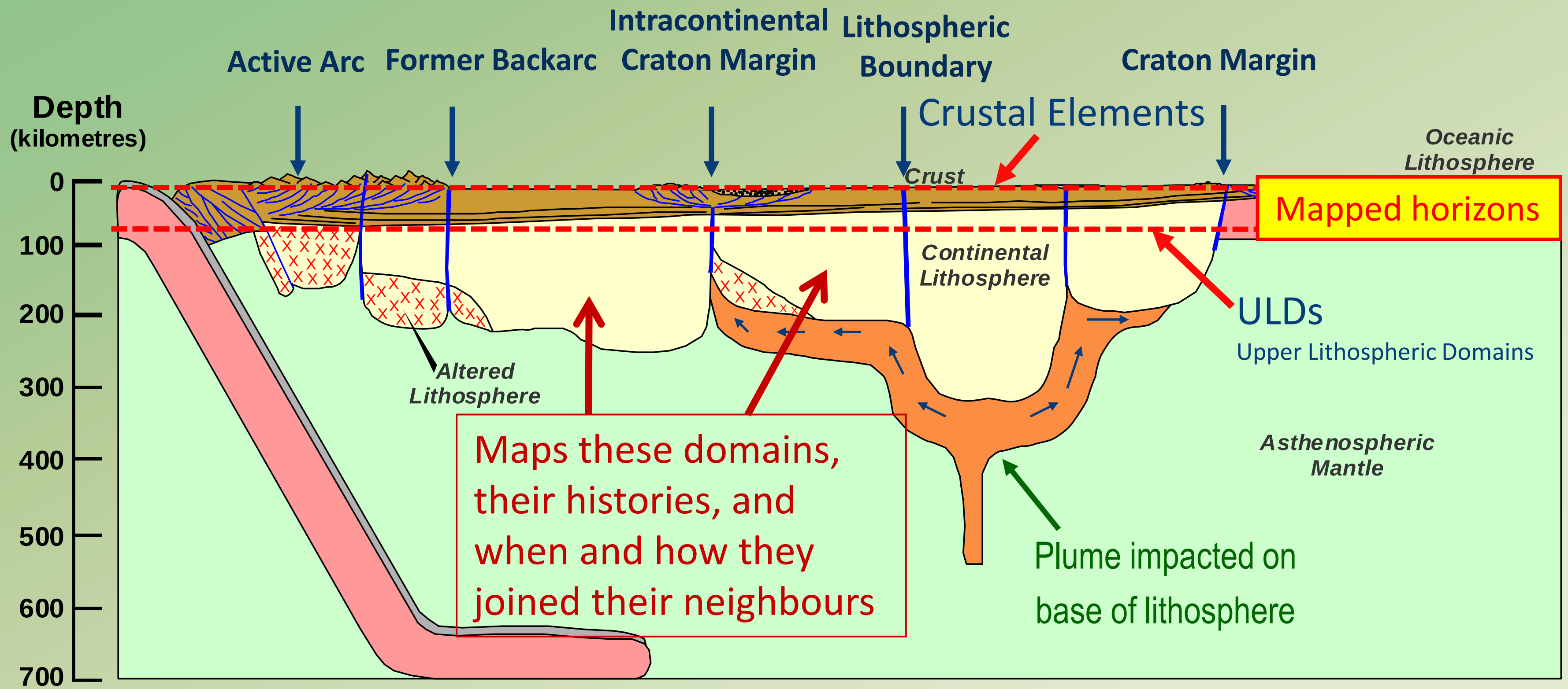
www.mineralstargeting.com

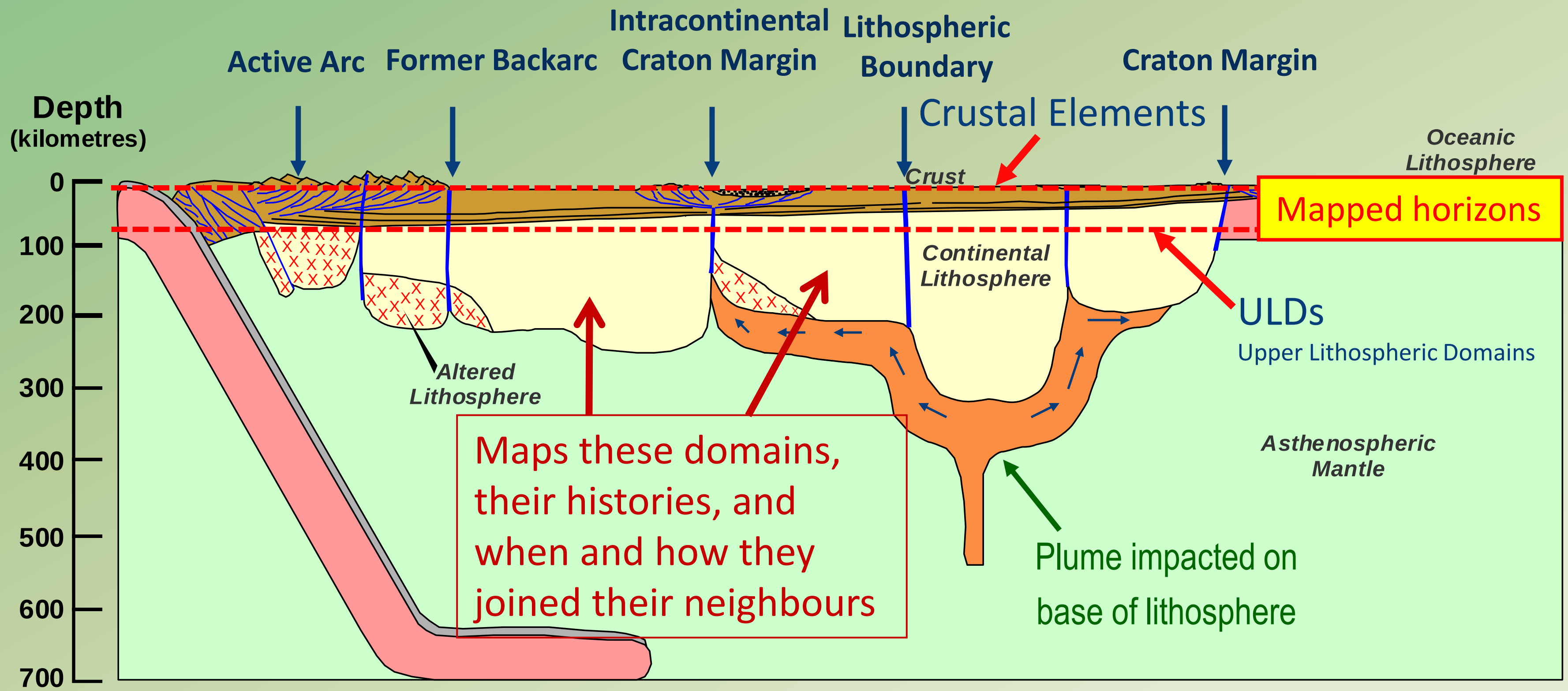
The Global Lithospheric Architecture Mapping Project (GLAM): 2002-2021



Continents = Amalgams of lithospheric blocks

Crust + Continental Mantle (CLM) + Geodynamics

Multi-Disciplinary Mapping



Continents = Amalgams of lithospheric blocks

Composition
Structure
Age
Context

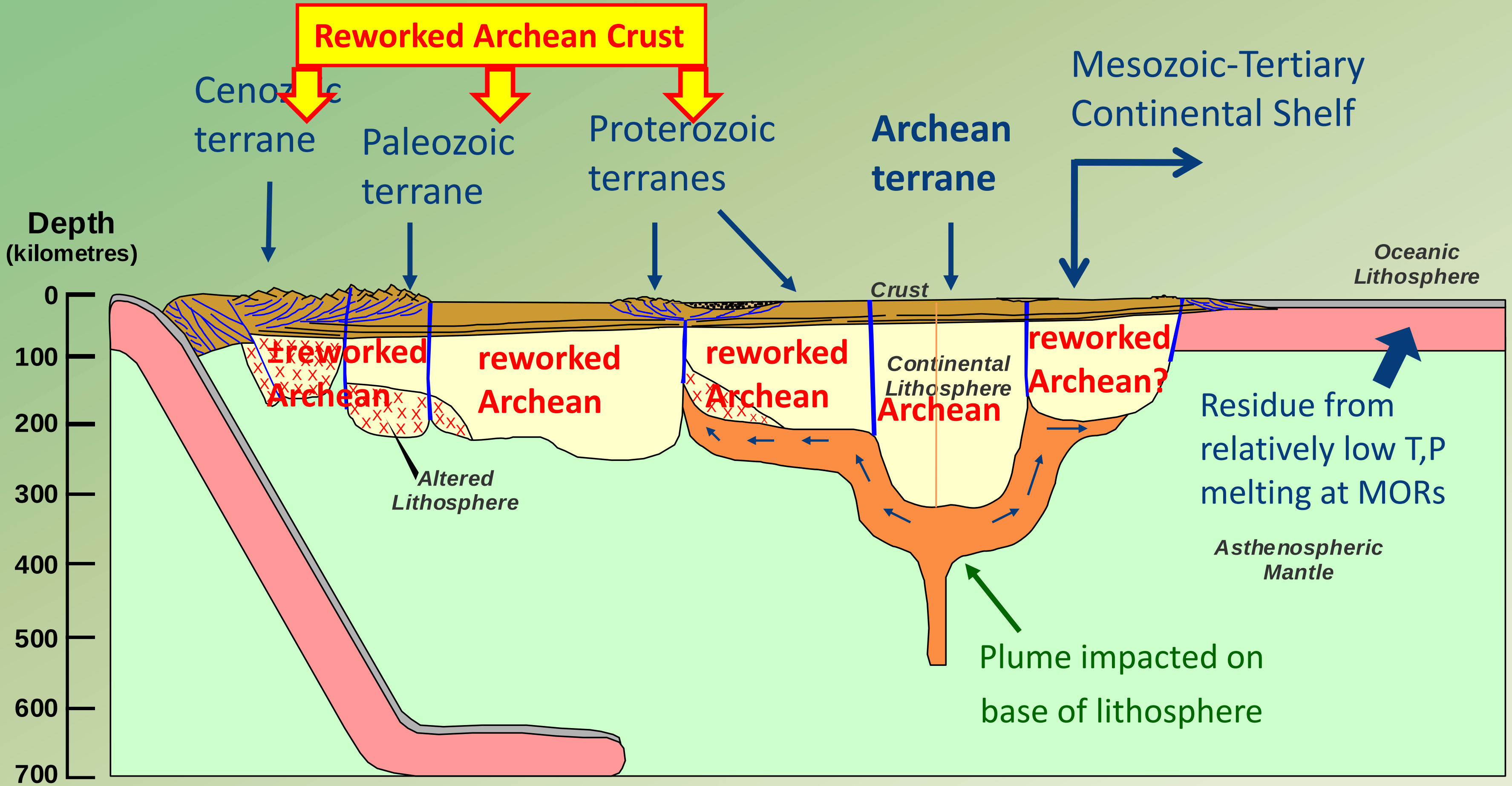
Gravity
Magnetics
Seismic
MT

Major Element
Trace Element
Isotopic (U-Pb, Hf, Nd, Pb, Sr, Re-Os)

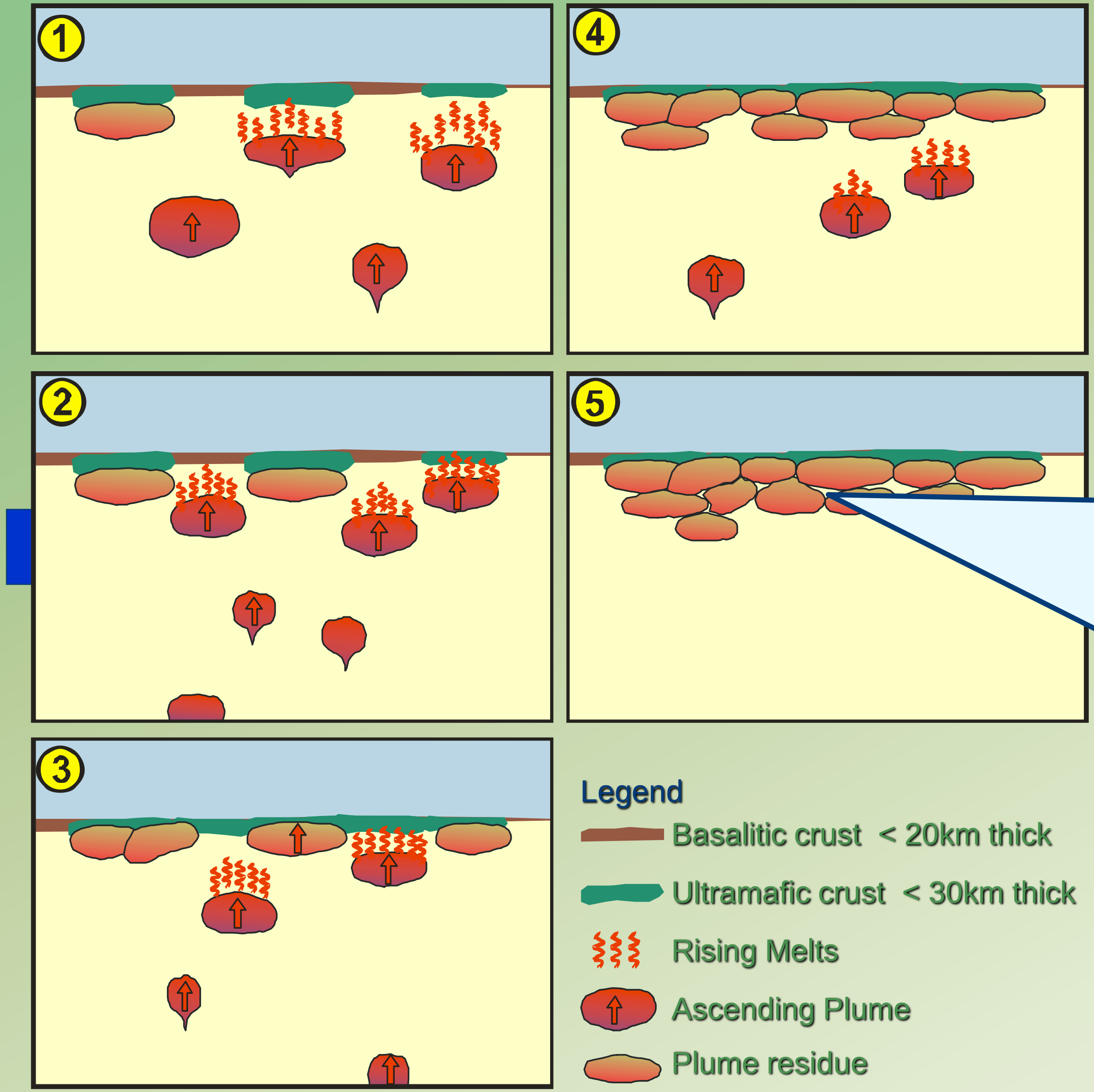
Lessons from 19 years of GLAM

- The CLM is segmented
- Continents are amalgams of cratons and microcontinents
- >60% of CLM and continental crust is Archean

Complex Crust on Archean CLM



HOT Archean Plumes(?) Formed the CLM



CLM IS A (PLUME) MELT RESIDUE

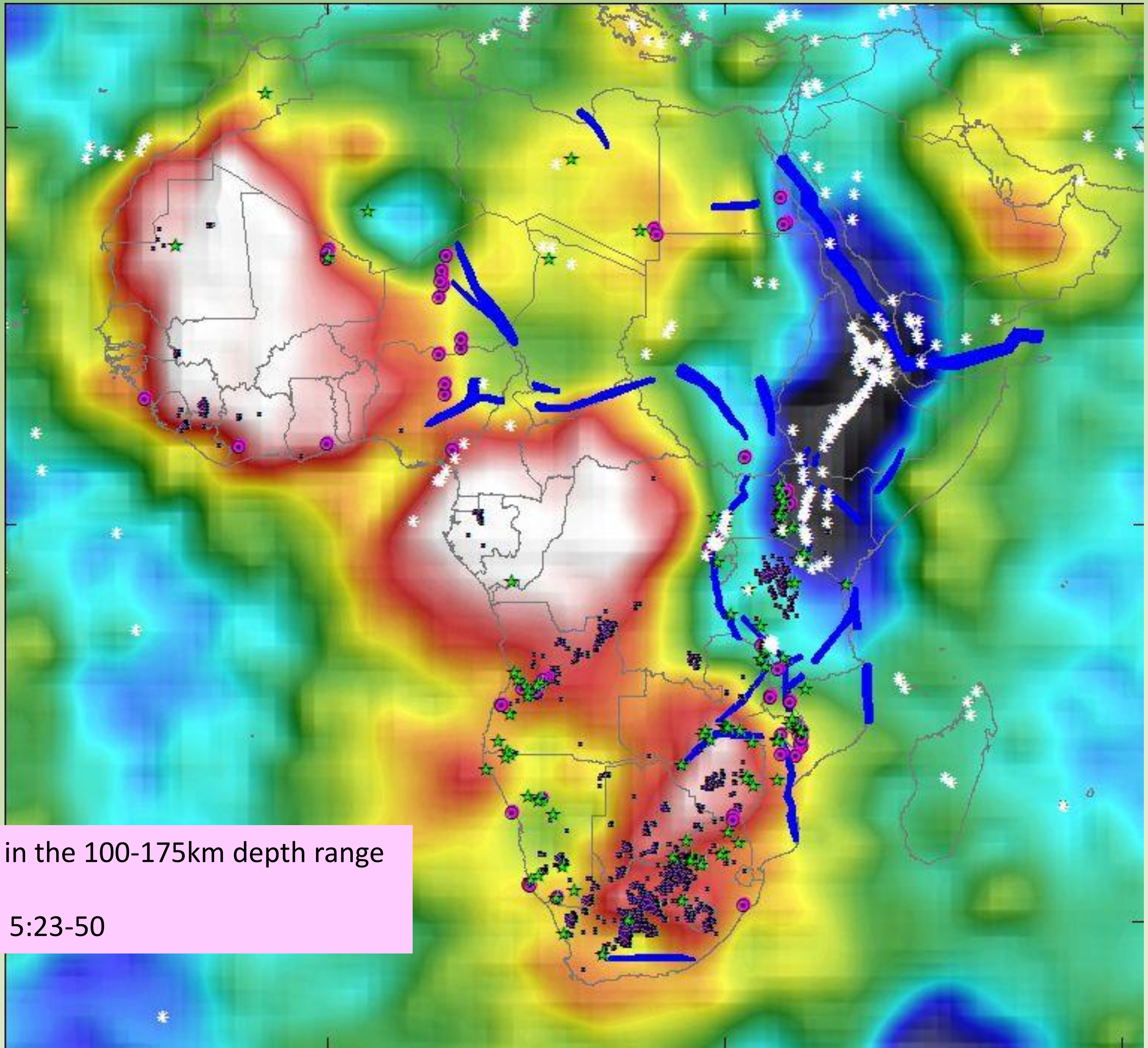
- High **Mg-rich** Olivine content
- Unique to melting of high T Archean plumes
- Distinctive **High Velocity**
- Anhydrous, **High Rheology**

The Sub-Continental Lithospheric Mantle (SCLM):

Exerting gross control on crustal features

CLM Control on Rifts and Alkaline Mantle Melts

Cratonic margins act as focal point for deformation and mantle melts



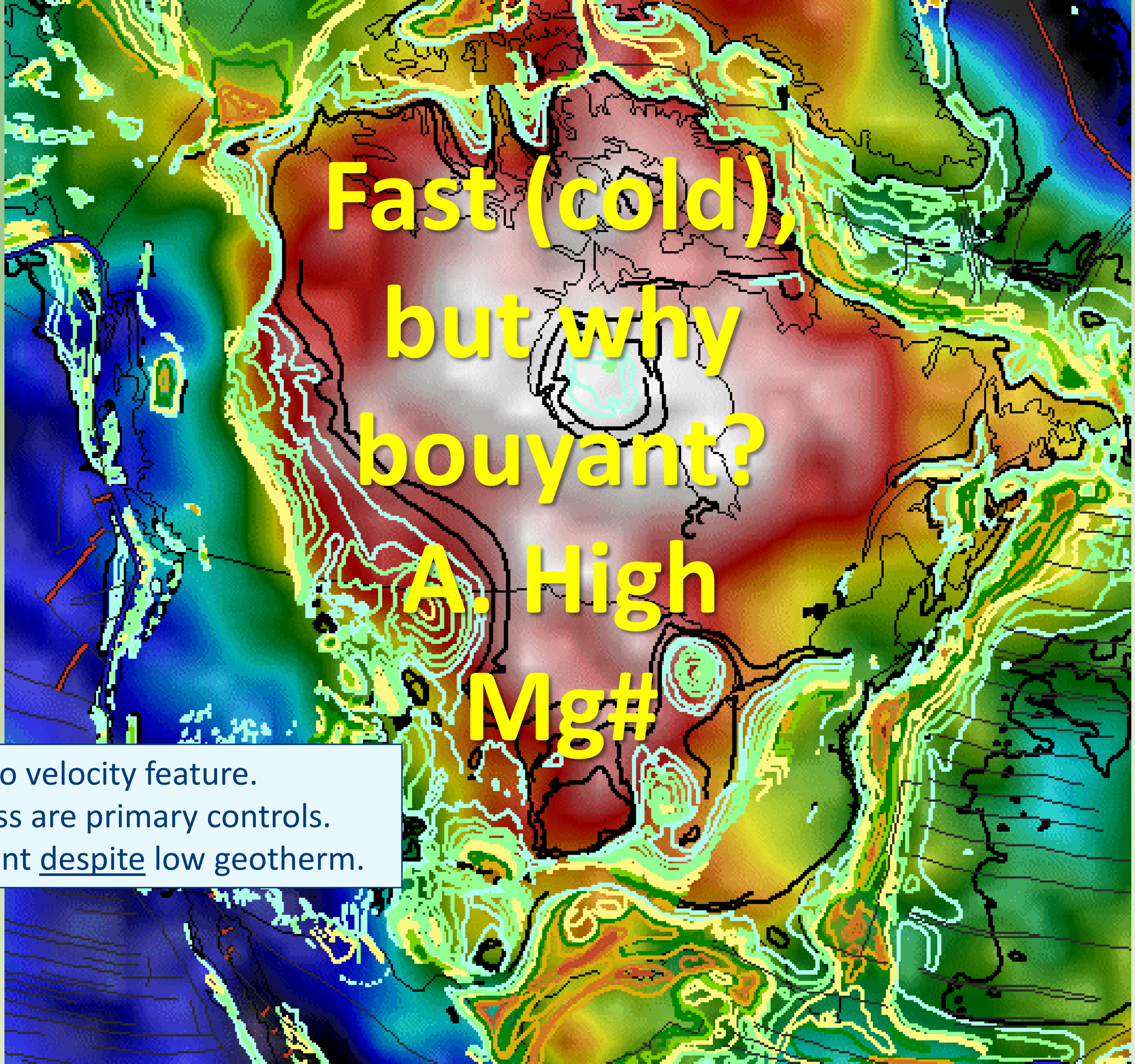
Squares = Kimberlites
Stars = Carbonatites
Circles = Syenites
Polygons = Rifts
Asterisks = Volcanoes

Image is seismic velocity (Grand, 2002) in the 100-175km depth range (**Red**=fast; **Blue**=slow).
From Begg, G.C. et al. Geosphere 2009; 5:23-50

CLM CONTROL ON BASINS at the Continental-scale: North America

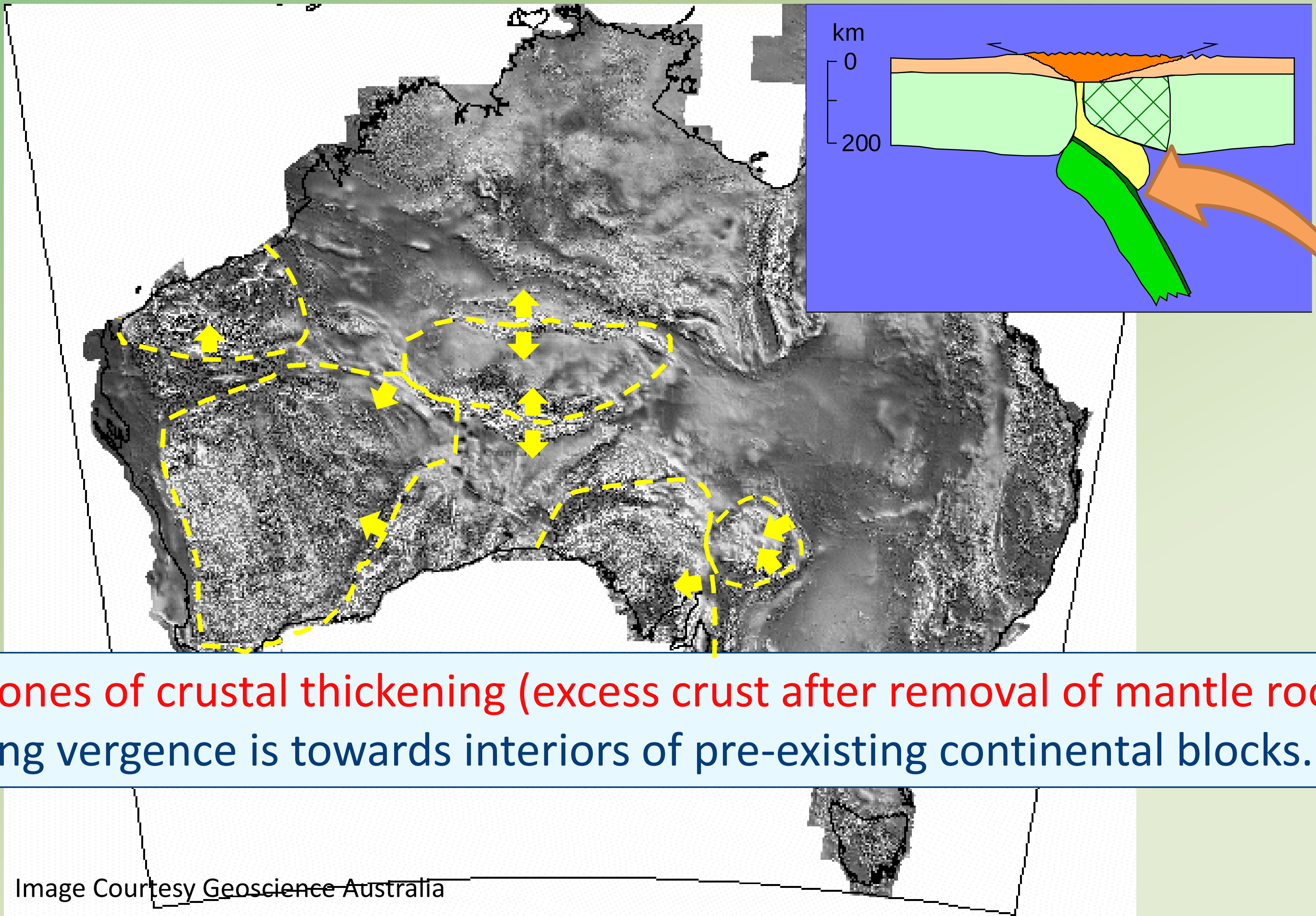
Background image is 100-175km depth seismic tomography:
Red = high Vs
Blue = low Vs

Basin isopachs:- 500m intervals



Note fit of sedimentation pattern to velocity feature.
Bouyancy of CLM & lithosphere thickness are primary controls.
Depleted (Fe-poor, high Vs) SCLM is bouyant despite low geotherm.

CLM blocks and crustal deformation patterns



Orogens:- Zones of crustal thickening (excess crust after removal of mantle root)
Shortening vergence is towards interiors of pre-existing continental blocks.

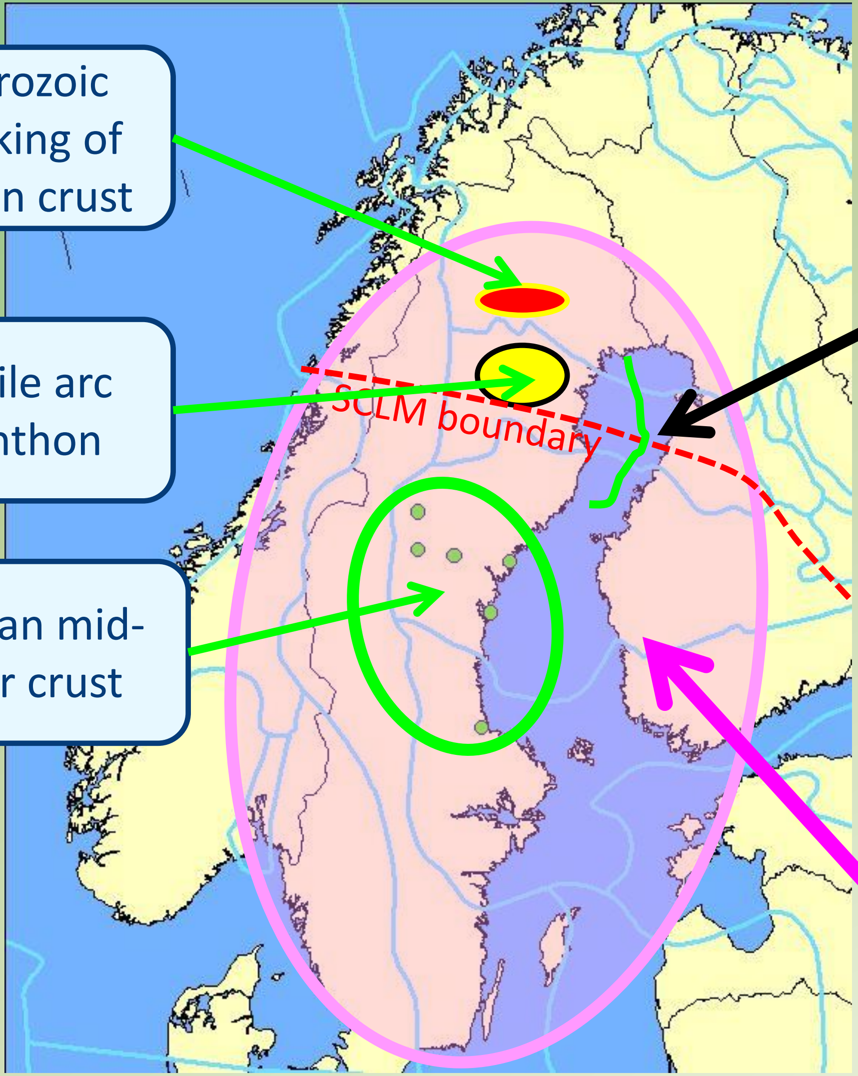
Image Courtesy Geoscience Australia

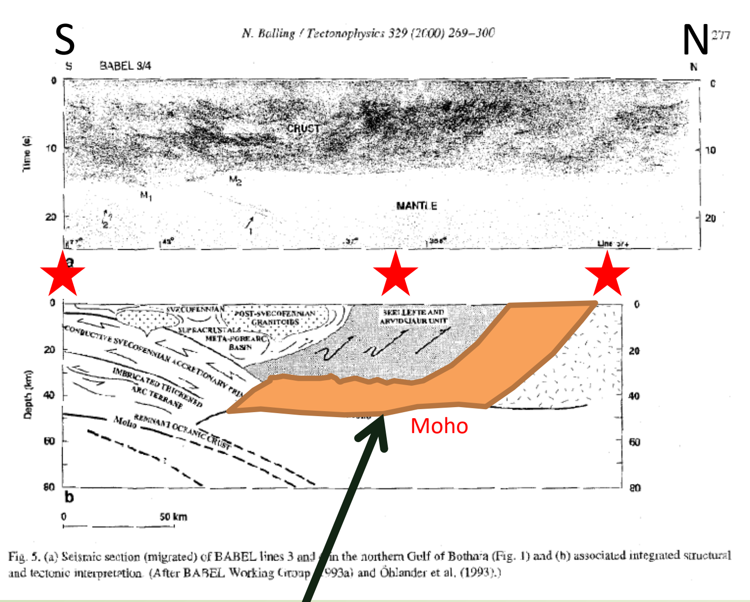
Isotopes reveal abundant Archean Crust

Proterozoic reworking of Archean crust

Juvenile arc allochthon

Archean mid-lower crust





Reworked Archean crust underlies juvenile Proterozoic arc

Palaeoproterozoic ages dominate UPPER crust

Summary

The crust is a passenger

Continents are amalgams of Lithospheric (Mantle) Blocks

i.e. It is legitimate to regard the CLM as large rigid blocks

Mapping the SCLM

Continental lithospheric mantle domain (ULD) boundaries can be mapped ***directly*** as well as by ***inference*** from crustal information

Patterns and responses in seismic tomography, magnetotellurics (MT), gravity, elastic thickness (Te) and epicentre locations are capable of ***directly*** mapping mantle structure

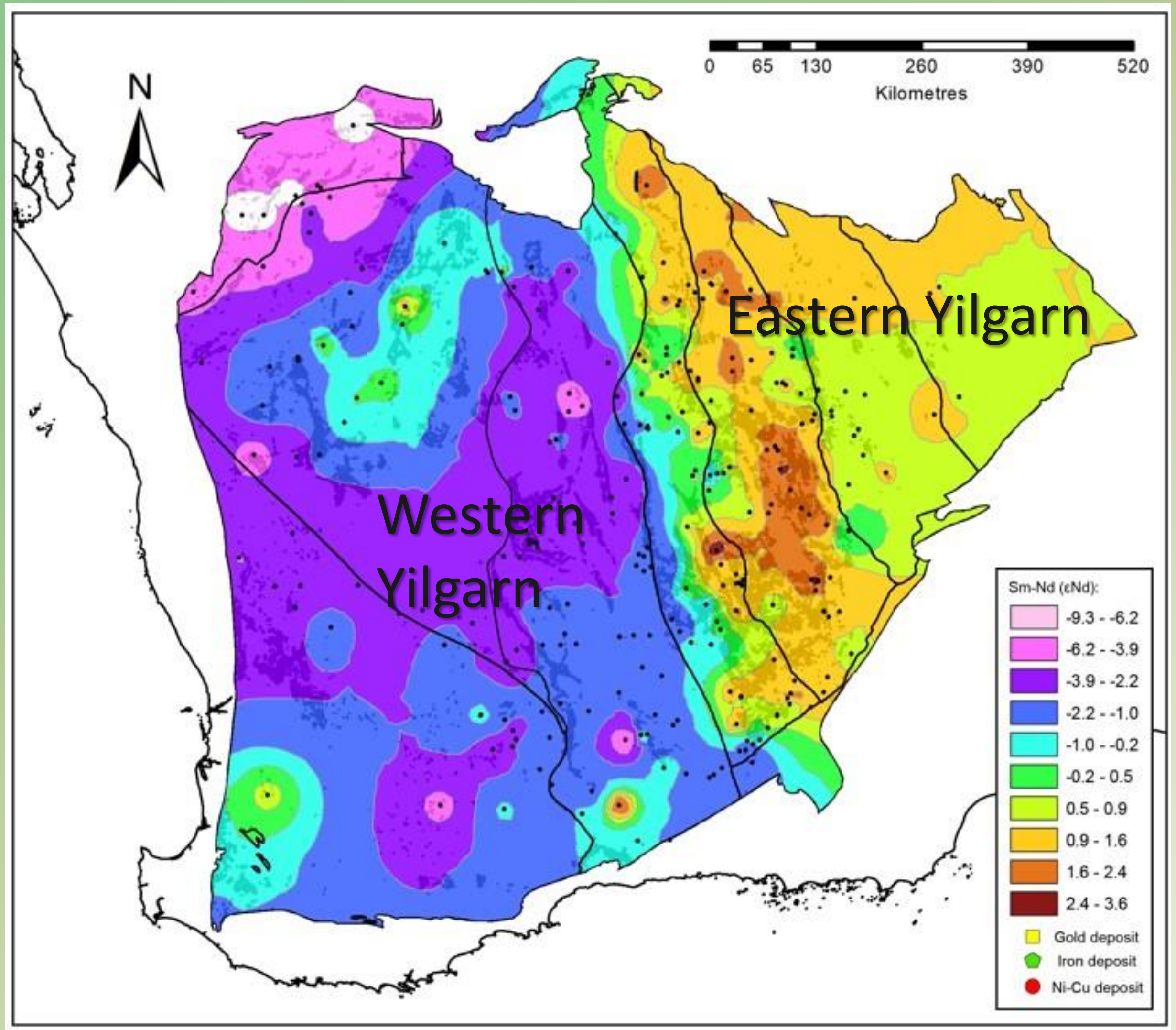
Crustal patterns and responses in gravity data, magnetics, topography, epicentre locations and seismic reflection profiles can be coupled with geology (type, setting, history, geometry) and isotopic maps (Hf, Nd, Pb, Sr) to ***infer*** the position of SCLM boundaries

CLM boundaries: Direct and Indirect Indicators

- Long strike-slip faults & linear high strain corridors
- Mapped, or geologically-inferred, sutures
- Subvertical trans-lithospheric conductive corridors
- Discrete low-velocity corridors at CLM depths
- Sharply-defined crustal Hf- or Nd- isotope domains
- Features in gravity and magnetics data
- Linear belts of mantle-derived rocks
- Narrow, linear sedimentary basins
- Features in seismic reflection profiles (e.g. Moho offsets, vergence patterns)

Higher confidence if geologically supported and/or present in multiple data

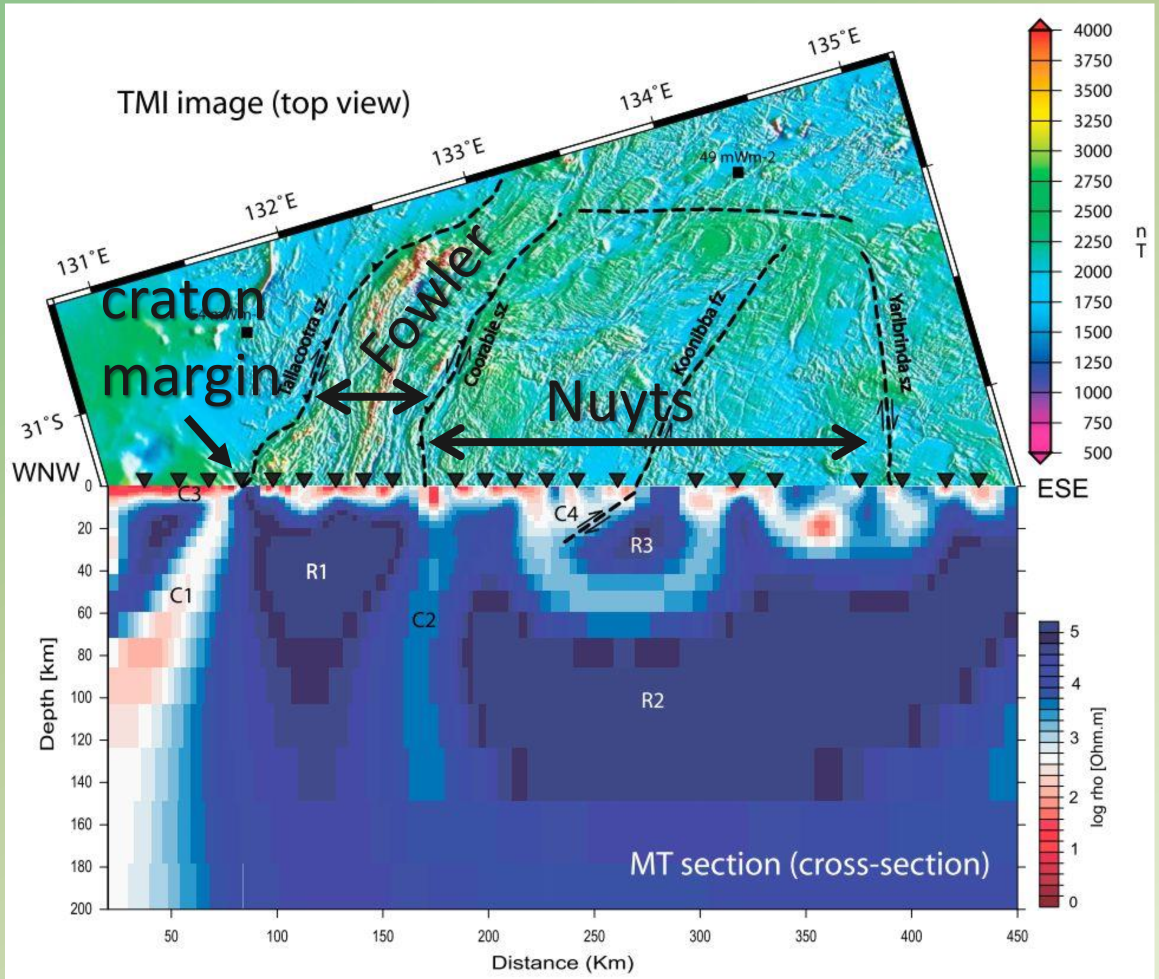
Yilgarn Craton Nd isotope map



Mole et al., 2019, Earth Science Reviews

Sharp break between east and west

The Geoscience Revolution



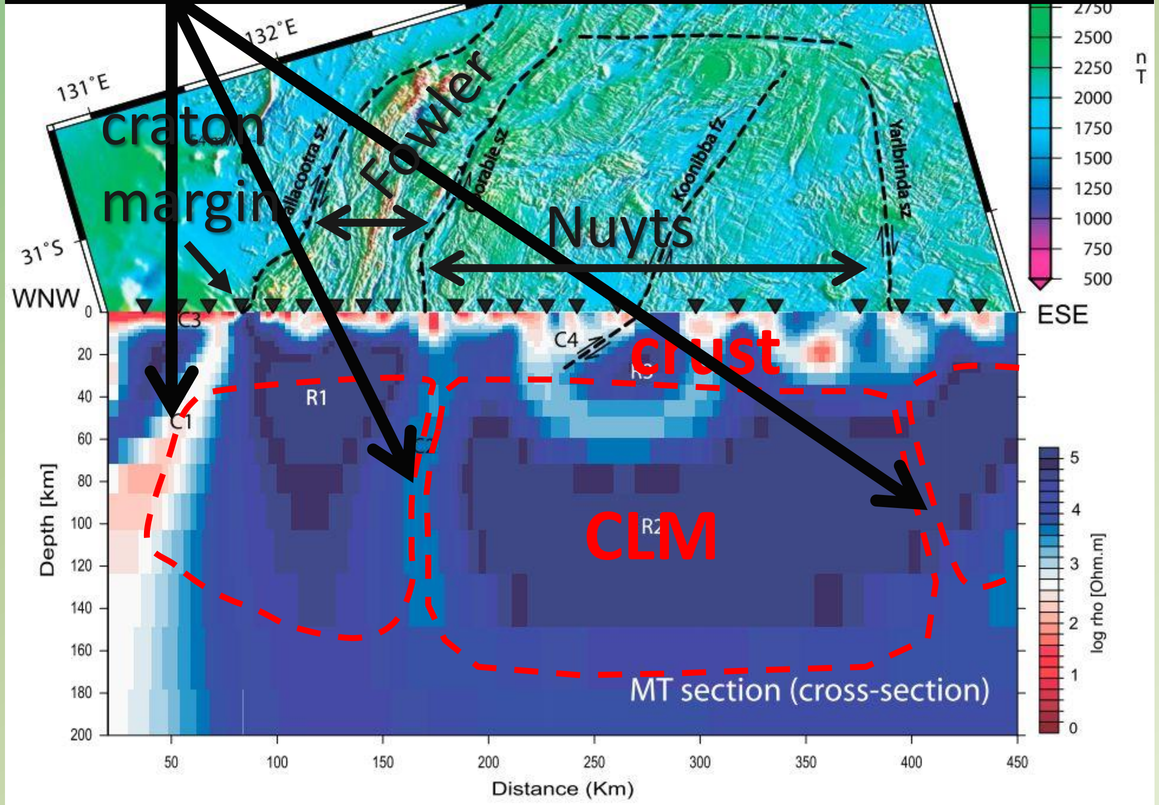
We can now map the architecture of the entire lithosphere

Block diagram of western Gawler Craton shows magnetics and key mapped faults in plan-view, and magnetotelluric (MT) data in sectional-view

Thiel, S. and Heinson, G., 2010, Crustal imaging of a mobile belt using magnetotellurics: An example of the Fowler Domain in South Australia. J. Geophys. Res. 115, B06102, doi:10.1029/2009JB006698

Whole-lithospheric Architecture in 3D

The fundamental structure of continents.
Strong association with big ore deposits

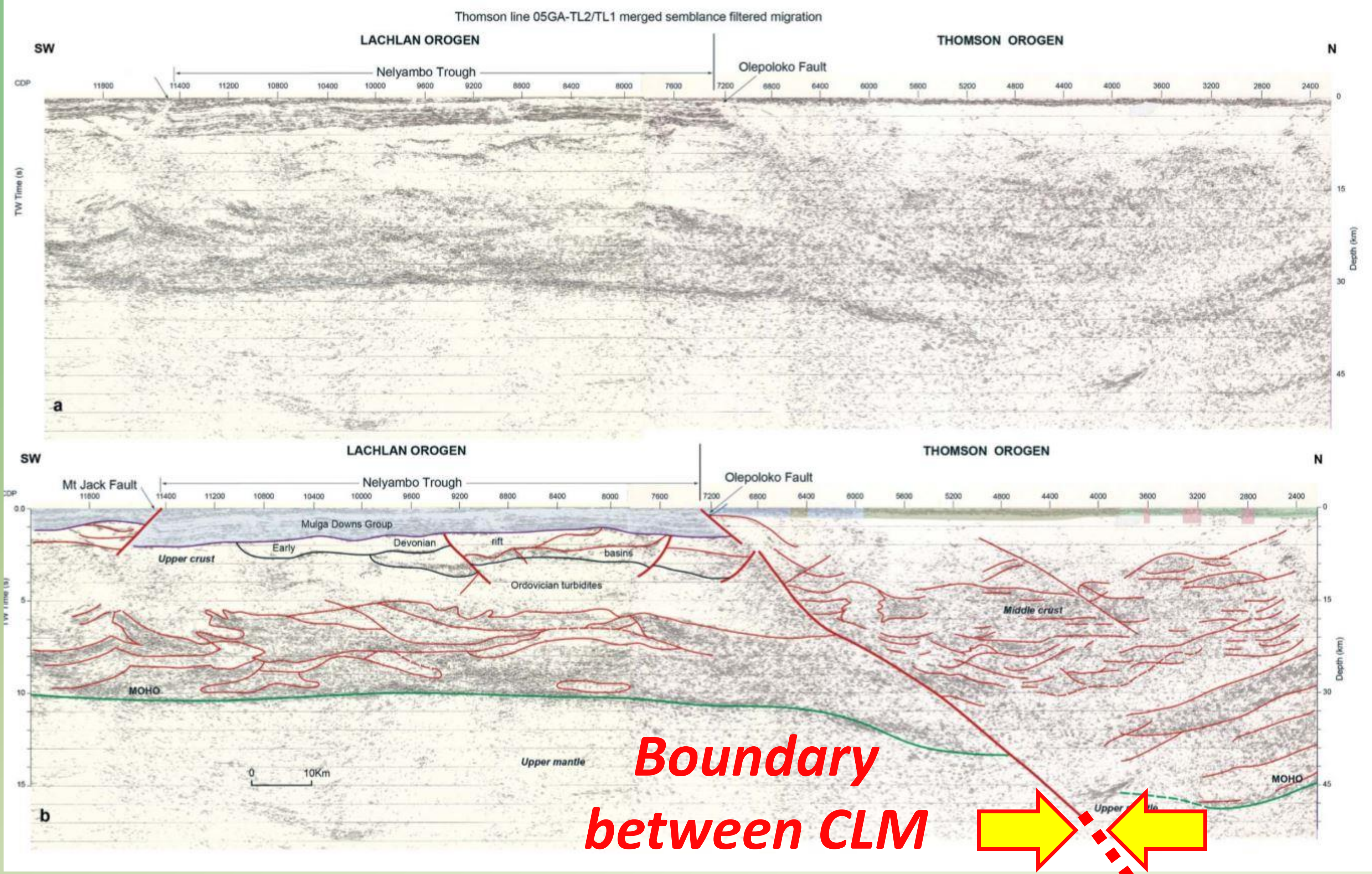


- CLM is segmented
- Major boundaries often conductive

CLM polygons outlined in red

Thiel, S. and Heinson, G., 2010, Crustal imaging of a mobile belt using magnetotellurics: An example of the Fowler Domain in South Australia. J. Geophys. Res. 115, B06102, doi:10.1029/2009JB006698

CLM Boundaries & Crustal Architecture



Boundary between CLM domains

Glen et al., 2013, AJES 60, 371-412

MT Finds the Steep Faults

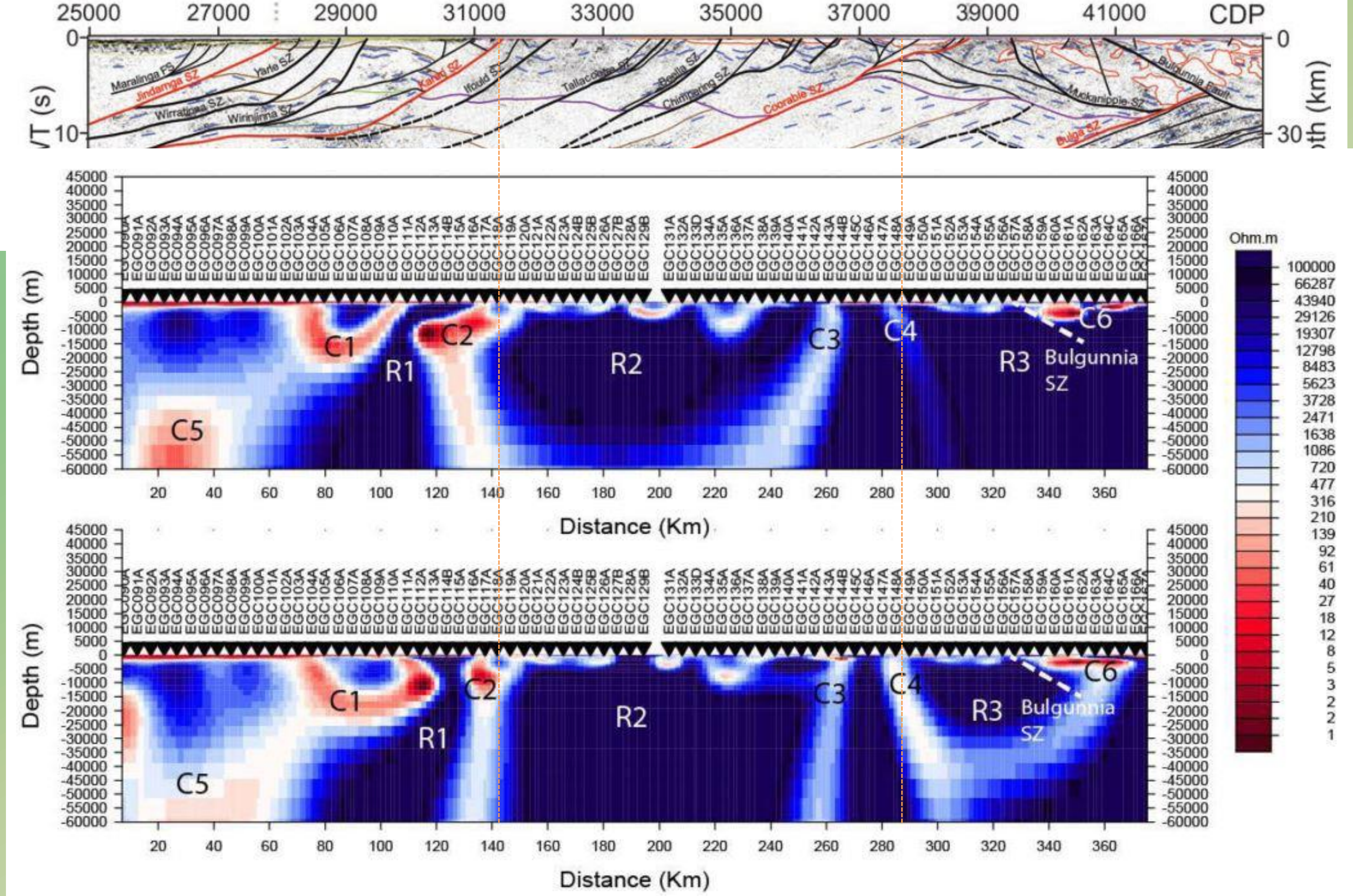


Figure 10 *Final resistivity models for the crust and upper mantle (top 60 km) from MT site EGC090 in the west (Eucla Basin) to EGC167 (Gawler Craton) in the east. Top model represents starting TE-mode inversion followed by inclusion of TM-mode responses. Bottom model is the TM-mode followed by TE-mode addition. Final total rms are 2.39 and 2.42, respectively.*

Mismatch:-

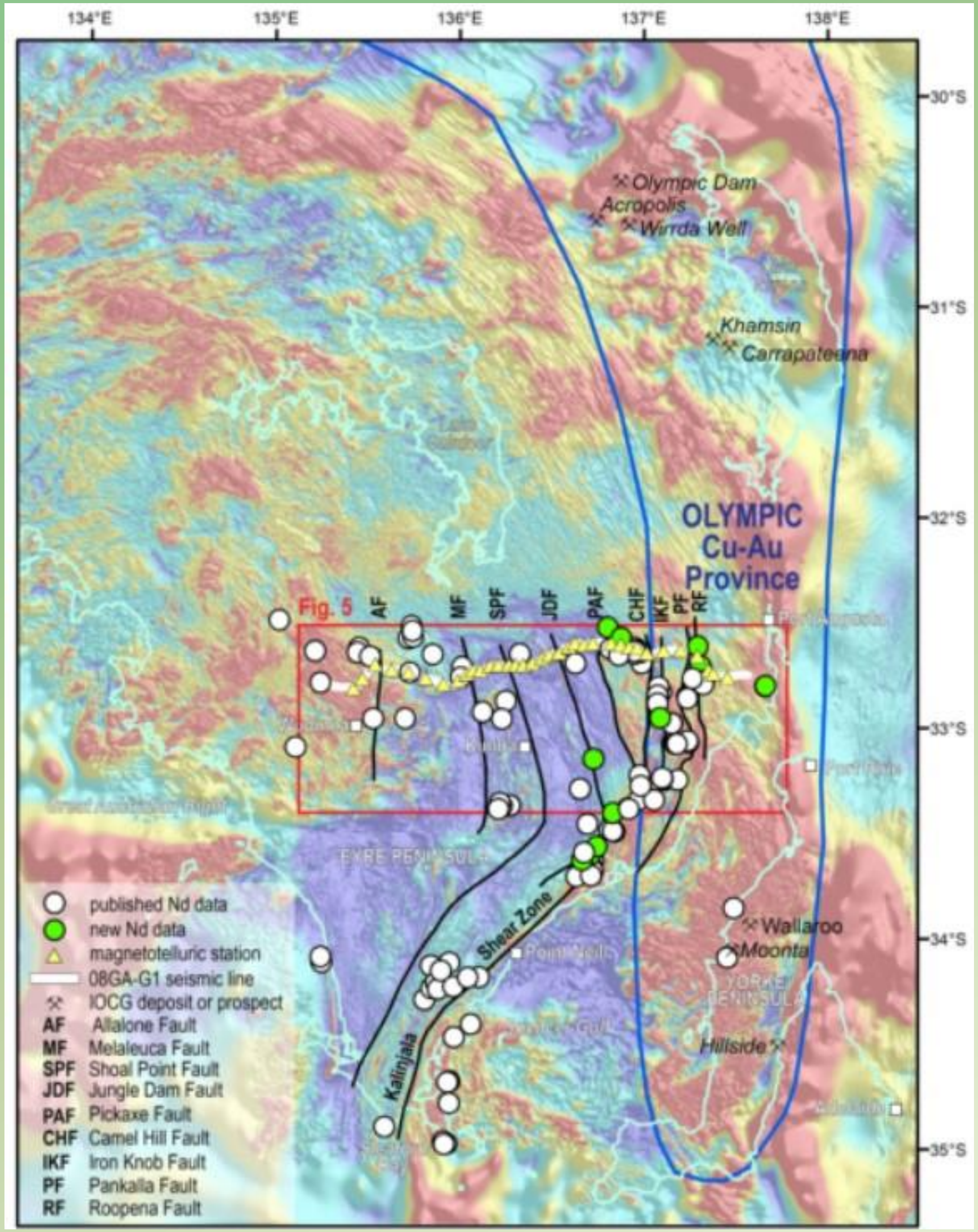
seismic interpretations

Versus

Steep MT features + requirement for major strike-slip faults to displace the whole lithosphere

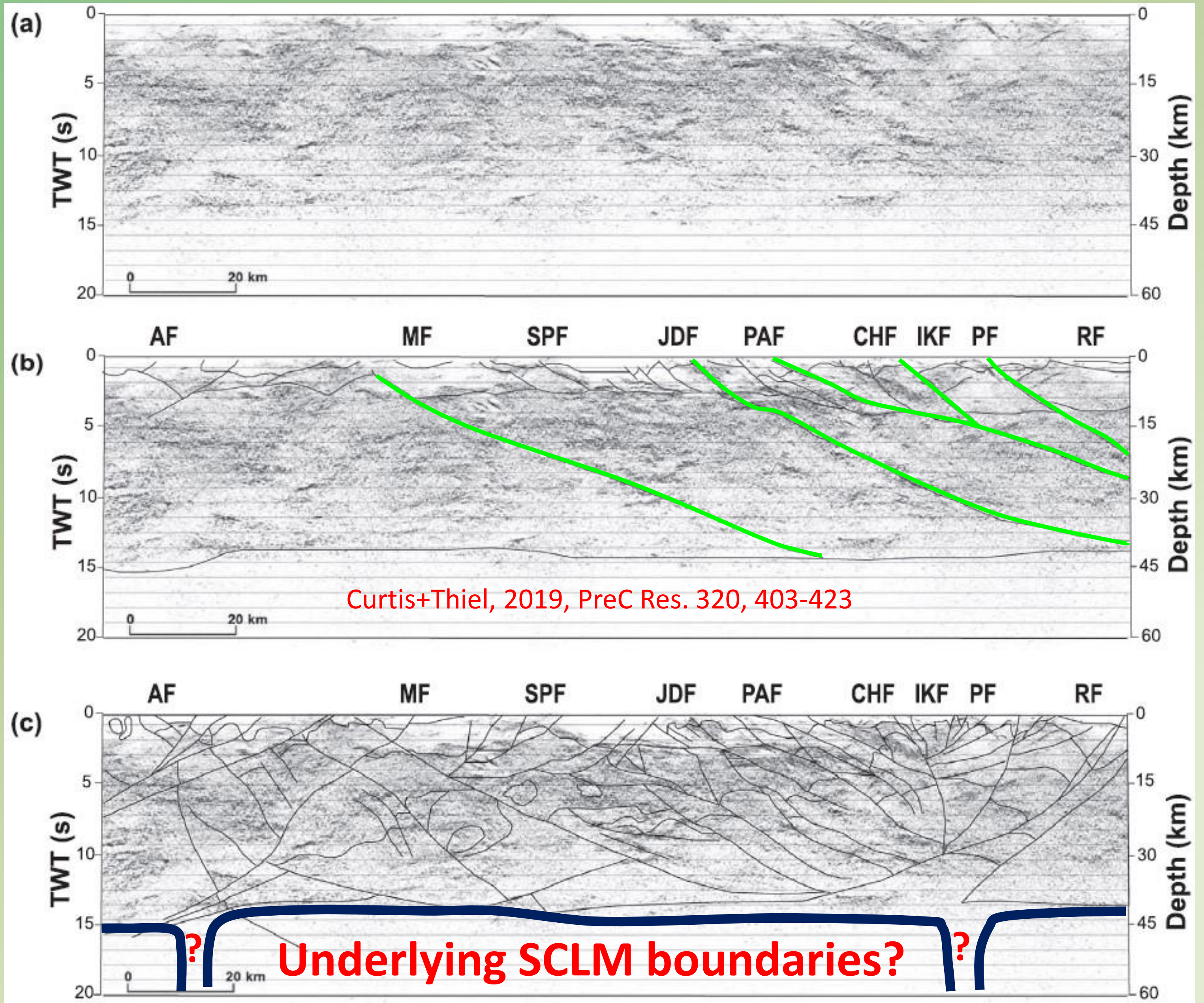
Top: Doublier et al., 2015
Bottom: Thiel et al., 2015

Gawler line 08GA-G1



Curtis+Thiel, 2019, PreC Res. 320, 403-423

Gawler line 08GA-G1



Eastern Gawler

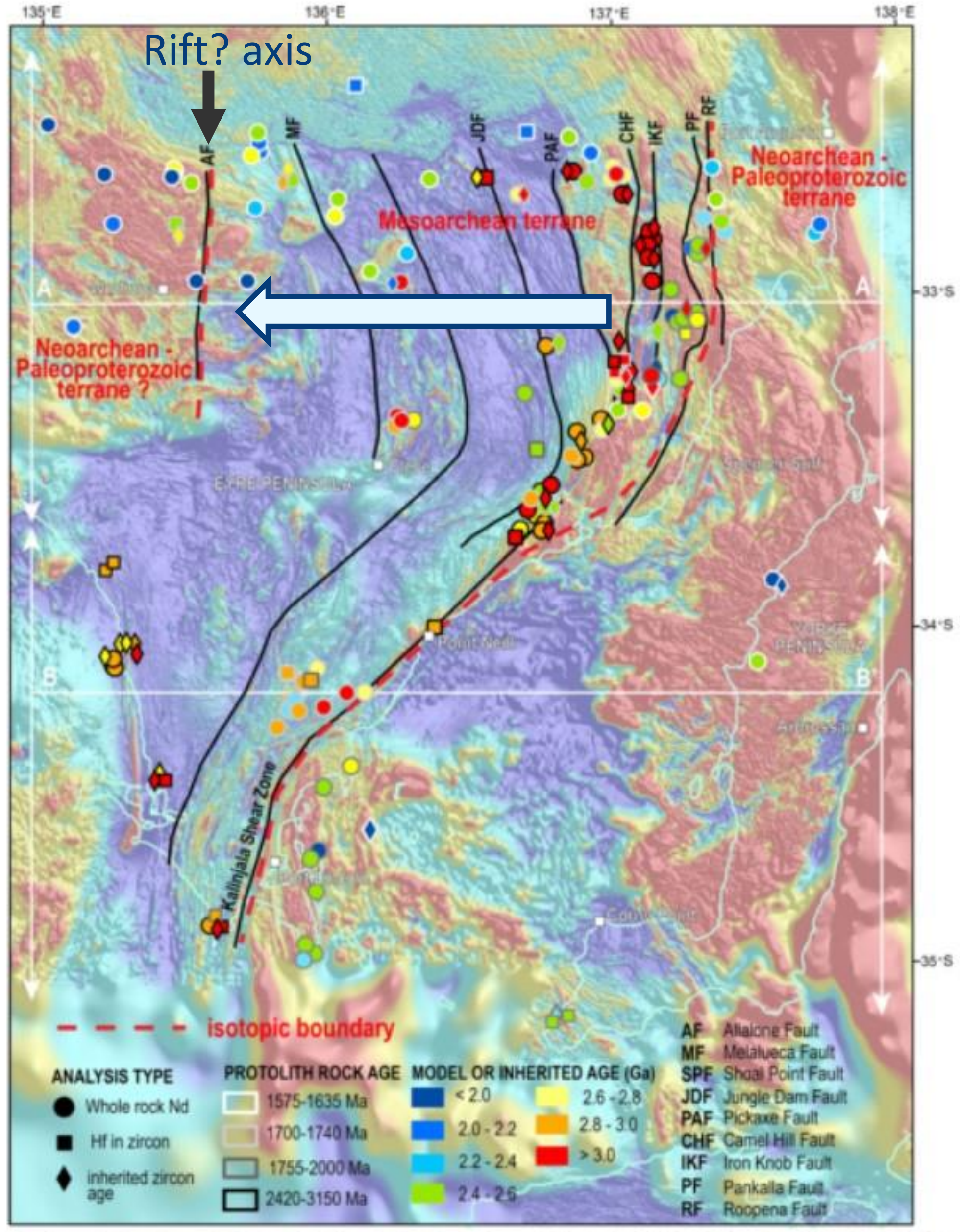


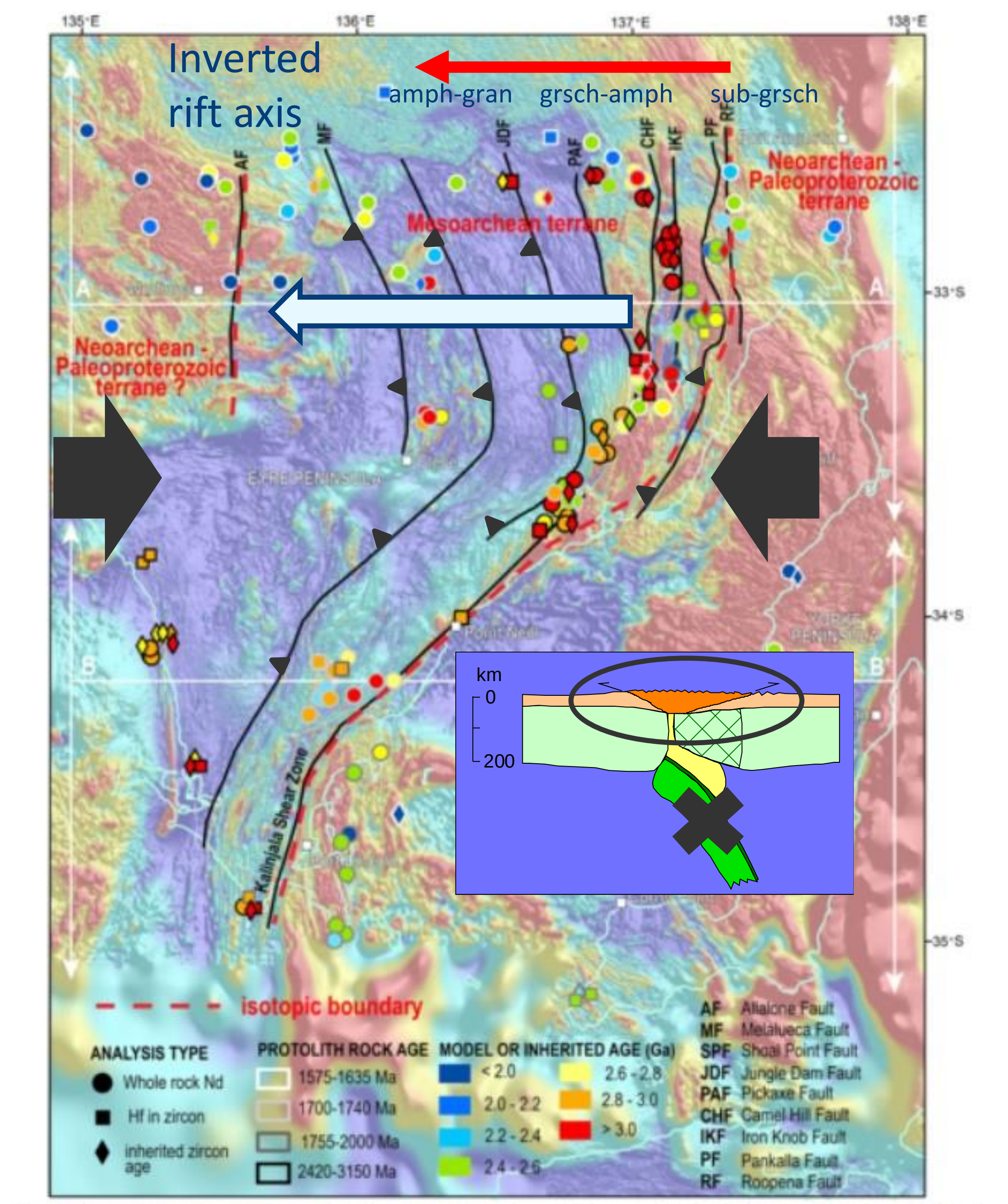
Fig. 7. Total magnetic intensity map of the Eyre and Yorke peninsulas, showing the spatial distribution of Nd depleted mantle model ages (circles), Hf in zircon depleted mantle model ages (squares) and inherited zircon ages (diamonds) for Mesoarchean to Mesoproterozoic felsic (SiO_2 > 60 wt%) igneous rocks. The magmatic age of the rocks is represented by the outline colour, and the model or inherited age by the fill colour. Profile lines A–A' and B–B' relate to the histograms in Fig. 8. The location of the interpreted lithospheric boundary represented by the isotopic data is shown. Nd points include data from this study as well as existing data with sources cited in the Methods section. Hf in zircon data is from Reid and Payne (2017). The sources of inherited zircon age data are cited in the Methods section.

Isotopic and inherited ages show increasing juvenile addition towards the West

This suggests a possible former intracratonic rift

Curtis+Thiel, 2019, PreC Res. 320, 403-423

Eastern Gawler



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Isotopic and inherited ages show increasing ***juvenile addition*** towards West

Metamorphic grade also *increases westwards* to peak between JDF & MF. This suggests W over E thrust imbrication during the 1.73-1.71 Ga Kimban Orogeny

This geometry infers a pre-Kimban rift centred beneath the N-S trending Allalone Fault

Curtis+Thiel, 2019, PreC Res. 320, 403-423

MT on Gawler line 08GA-G1

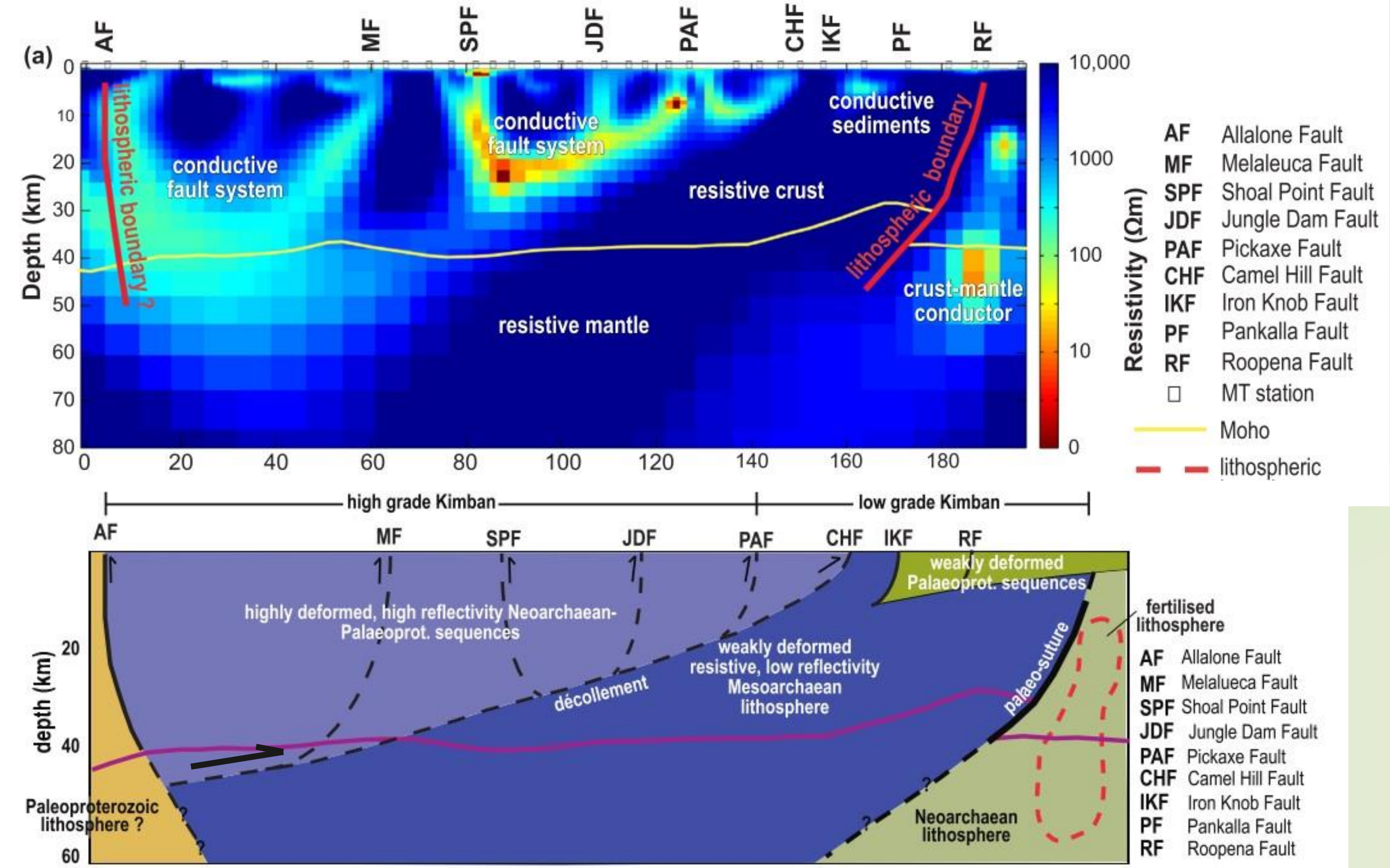
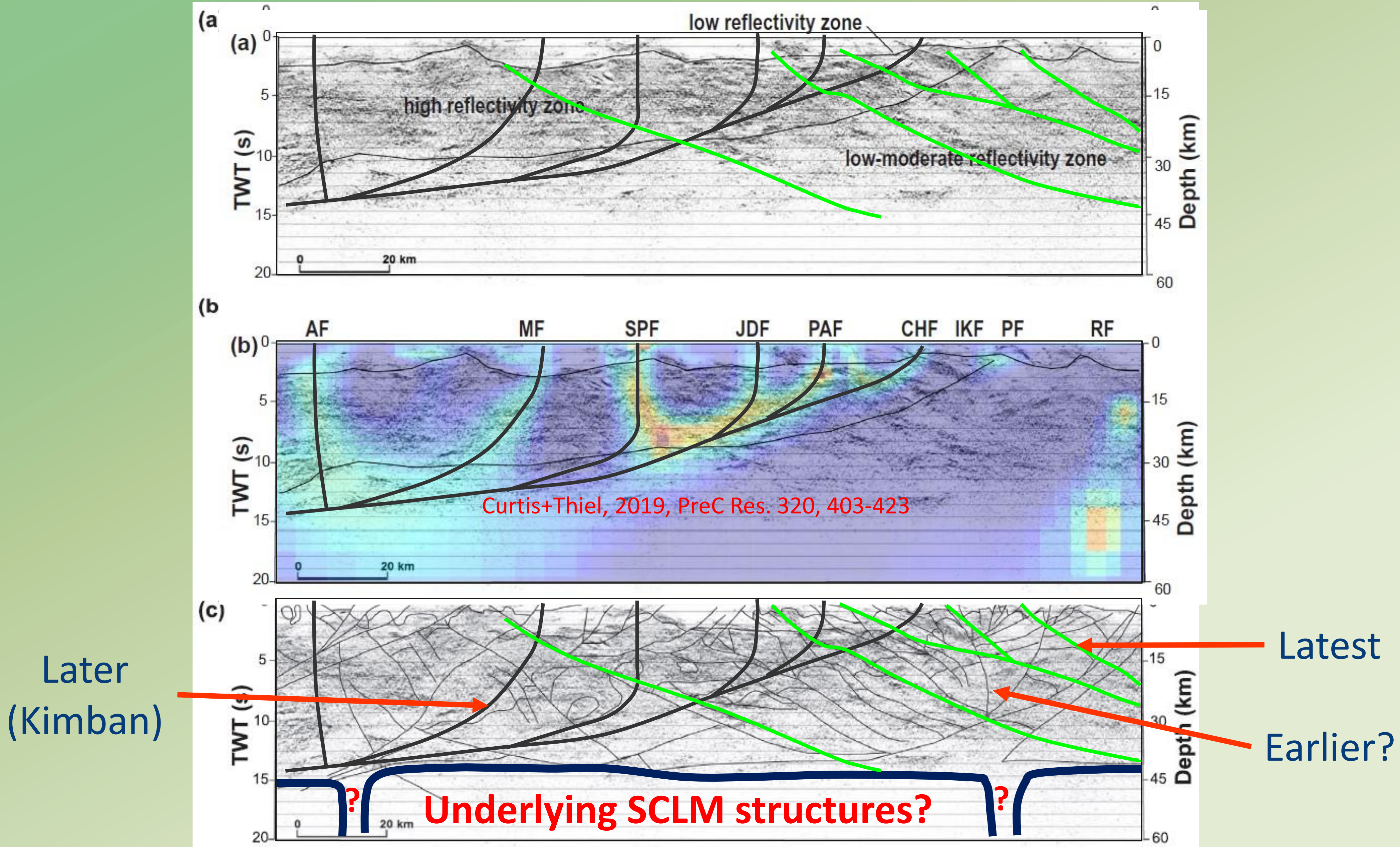


Fig. 10. Interpretative diagram of the major lithospheric elements of northern Eyre Peninsula, based on the integration of magnetotelluric, reflection seismic and isotopic and inherited zircon age data.

Curtis+Thiel, 2019, PreC Res. 320, 403-423

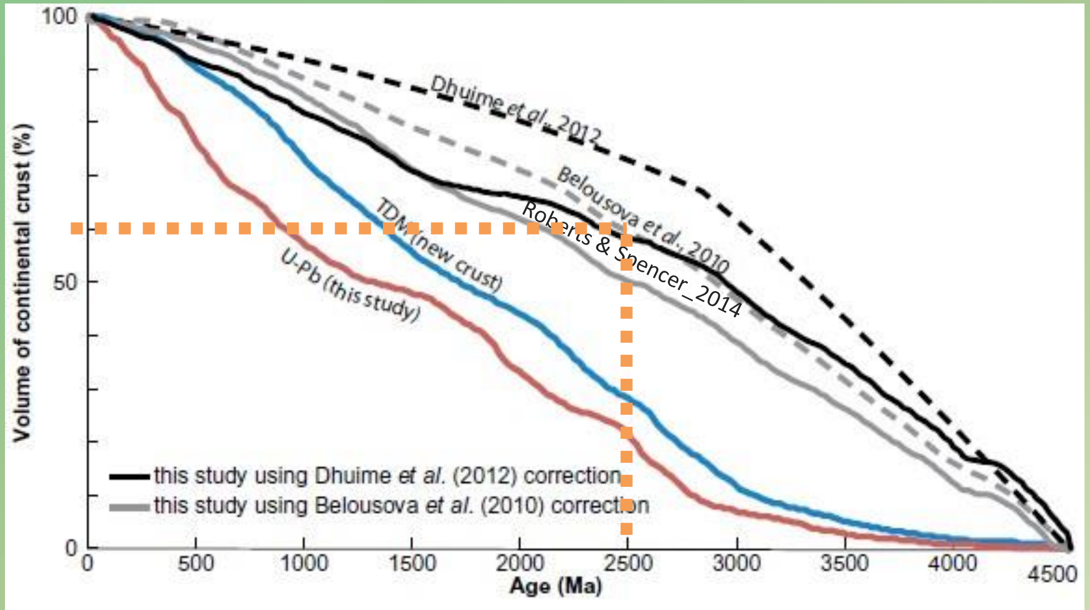
At least 3 Proterozoic Orogenic Events

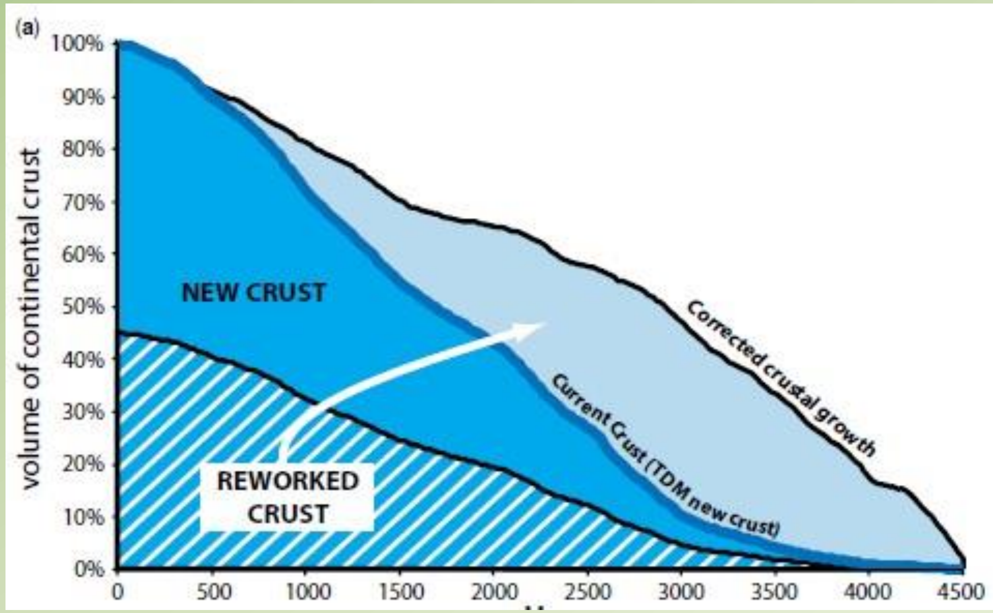


Identifying the Age of the Lithosphere

Have we missed the obvious?

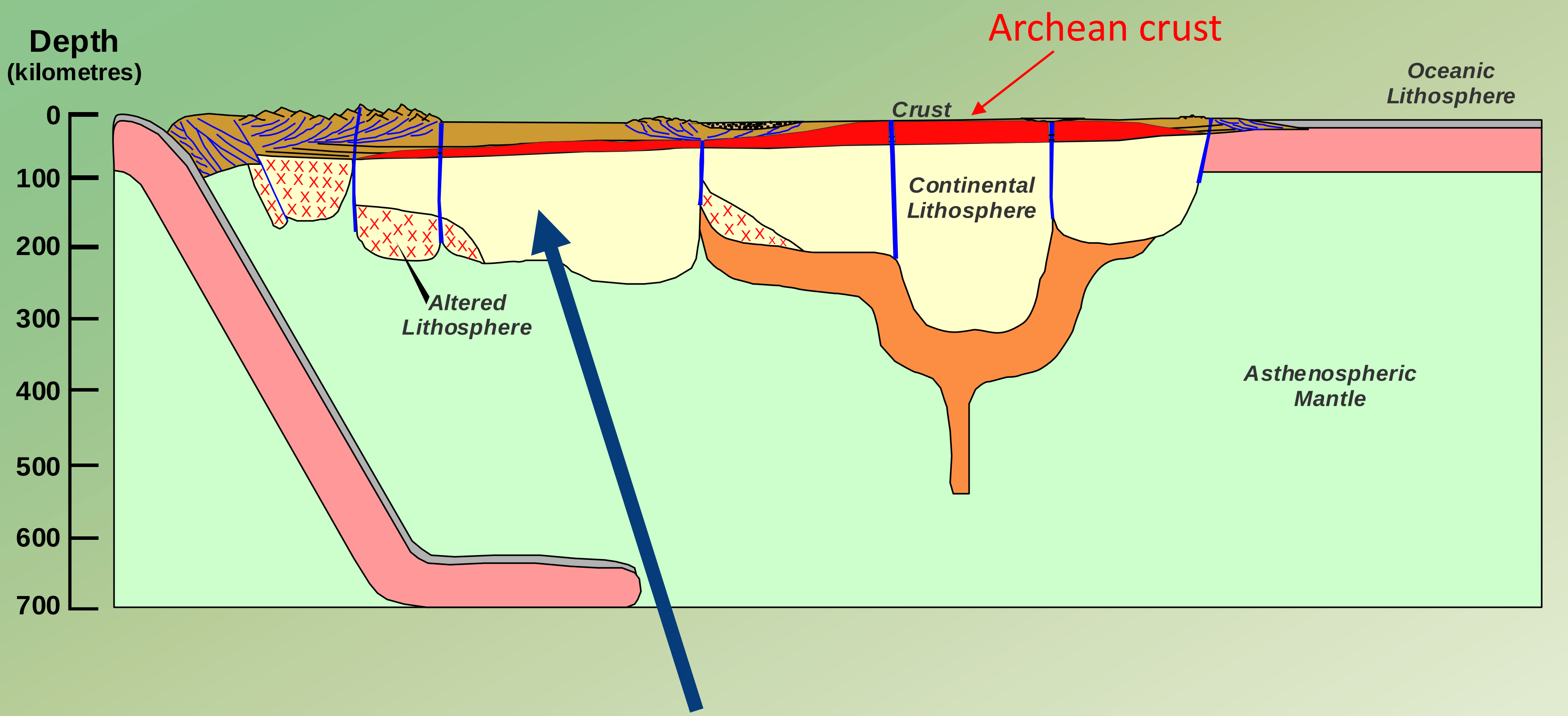
Continental crust is older than we thought





Roberts & Spencer, 2014, Geol. Soc Lond. Spec. Pub. 389

- Isotopically, >60% of today's Continental Crust was extracted from the mantle in the Archean
- ***But this old material cannot survive without protection***



Therefore, MORE THAN 60% of today's Continental Lithospheric Mantle *MUST* be originally Archean

How do we recognise archons?

We either:-

A. Use the **crustal history** as a proxy for the minimum age of underlying CLM

B. Determine the SCLM age directly from **mantle xenoliths** (Re-Os, U-Pb)

C. *Infer the CLM age based on the presence/absence of **high seismic velocities** below 100km.

*verified by experimental and numerical modelling results
(e.g. Deen et al., 2006)

mti

Determining Archean CLM age

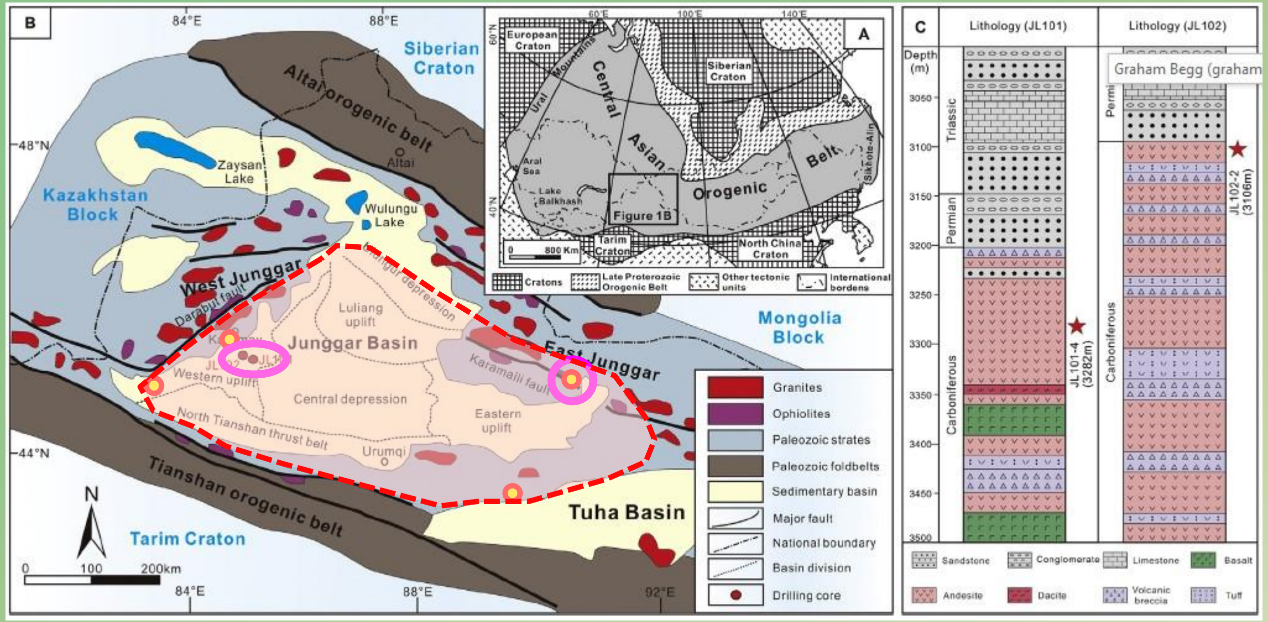
HIGH CONFIDENCE

- Presence of Archean crustal rocks
- Archean Re-Os isotope model ages on CLM xenolith materials
- Archean model ages from Lu-Hf isotopic data on zircons from non-peraluminous, dominantly I-type granitoids
- Archean model ages from Sm-Nd isotopic data on crustal igneous rocks
- Euhedral Archean inherited zircons
- Exclusively Archean unimodal inherited zircon populations

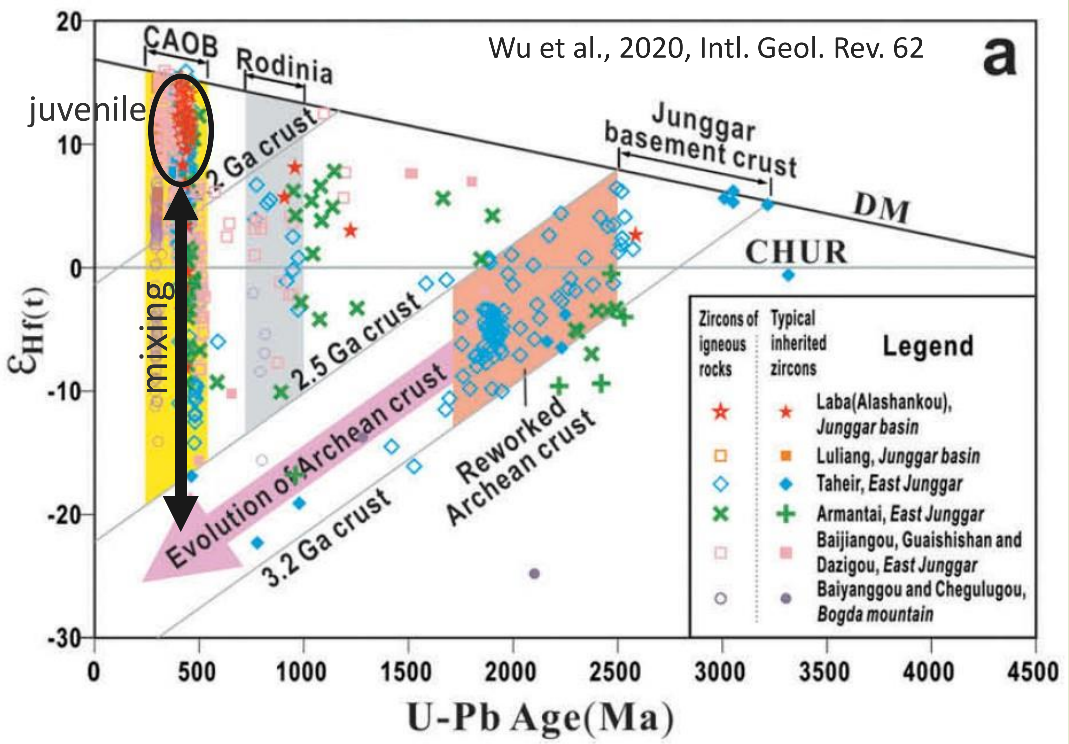
MEDIUM CONFIDENCE

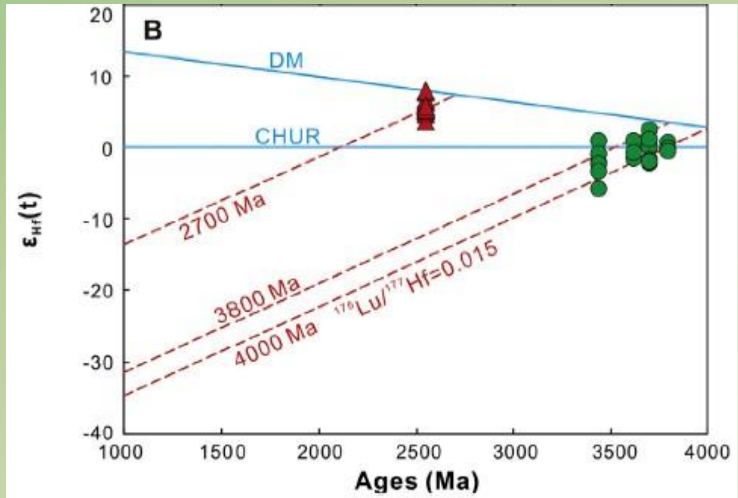
- Presence of anomalously high velocities in Vs body-wave data in the 100-175km layer of Steve Grand's global model → modelling indicates cold *AND* highly depleted (Fe-poor) CLM → xenoliths *ALWAYS* Archean
- Exclusively Archean inherited zircons (multiple populations)
- Near-Archean (e.g. 2.3-2.5Ga) model ages from Lu-Hf (zircons) or Sm-Nd isotopic data from I-type granitoids if no crustal event in that age range exists. i.e. the observed result is a mixing effect

Junggar Archean Microcontinent



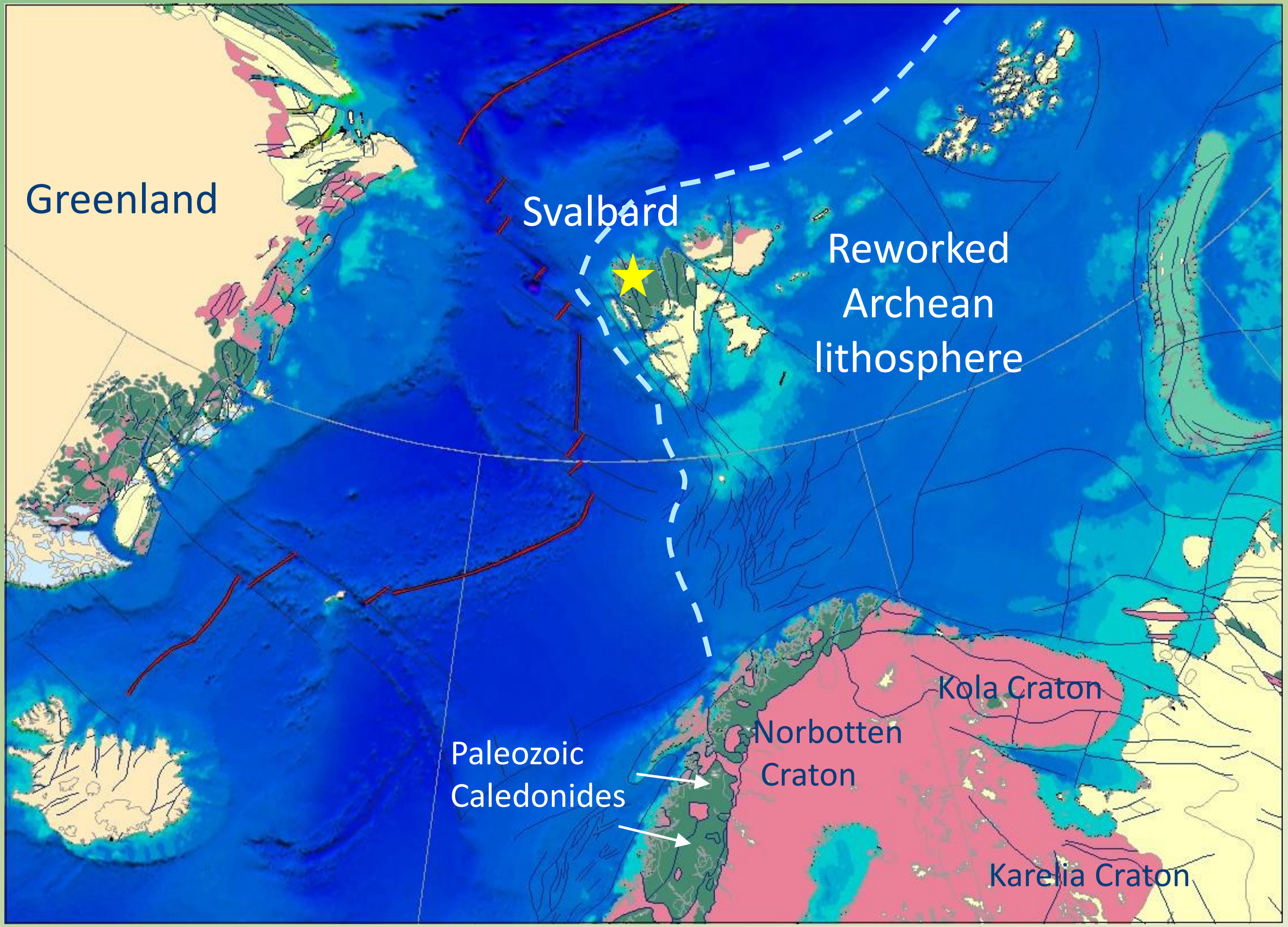
Wang et al., 2020, Lithos 360-361





- Junggar Basin Mesozoic cover on Paleozoic arc basement
- Precambrian detrital & inherited zircons common
- Archean inherited zircons in Paleozoic magmatic rocks
- Enclave of 2.52Ga diorite gneiss (Xu et al., 2015, Gond. Res., 28)
- Carboniferous andesites with abundant ***euhedral-subhedral that are all Archean*** (Wang et al., 2020)

Hidden Archean Basement in Svalbard

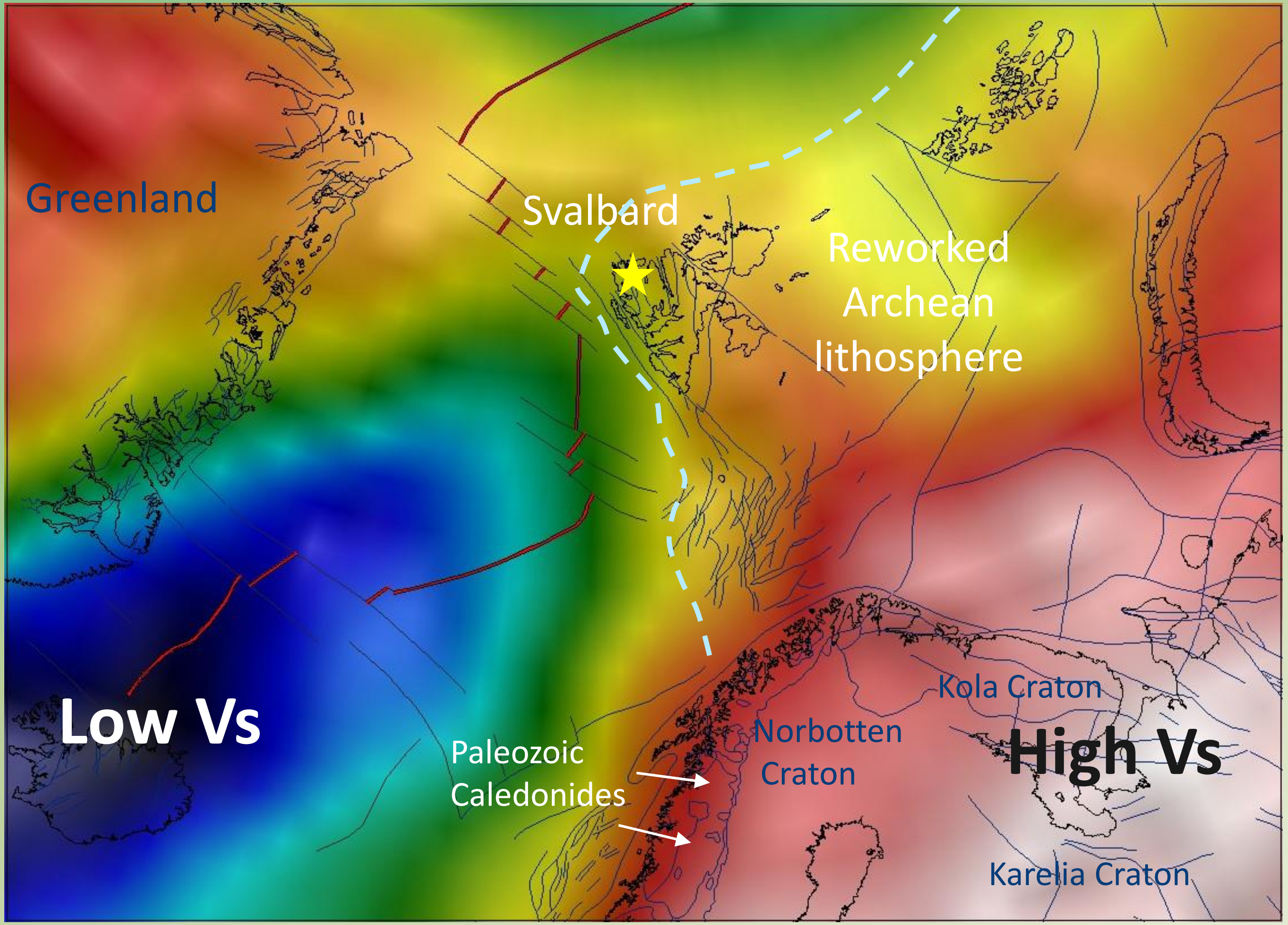


crustal xenolith zircons, plus
in-situ Re-Os isotopes on **mantle xenoliths**:

- **Paleozoic and Proterozoic upper crust** (mostly under cover)
- **3.3-3.2 Ga lower crust** with overprints at ca 2.6-2.5 Ga, 1.9 Ga, 1.6 Ga, 1.2 Ga, 800 Ma, 600 Ma, 439-390 Ma
- **3.3 Ga CLM** with multiple refertilisation/metasomatic overprints at 2.6-2.4 Ga, 1.8-1.6 Ga, 1.3-1.2 Ga, 1.1-0.9 Ga, 0.5-0.4 Ga

Griffin et al., 2012, Lithos 149, 115-135

Hidden Archean Basement in Svalbard



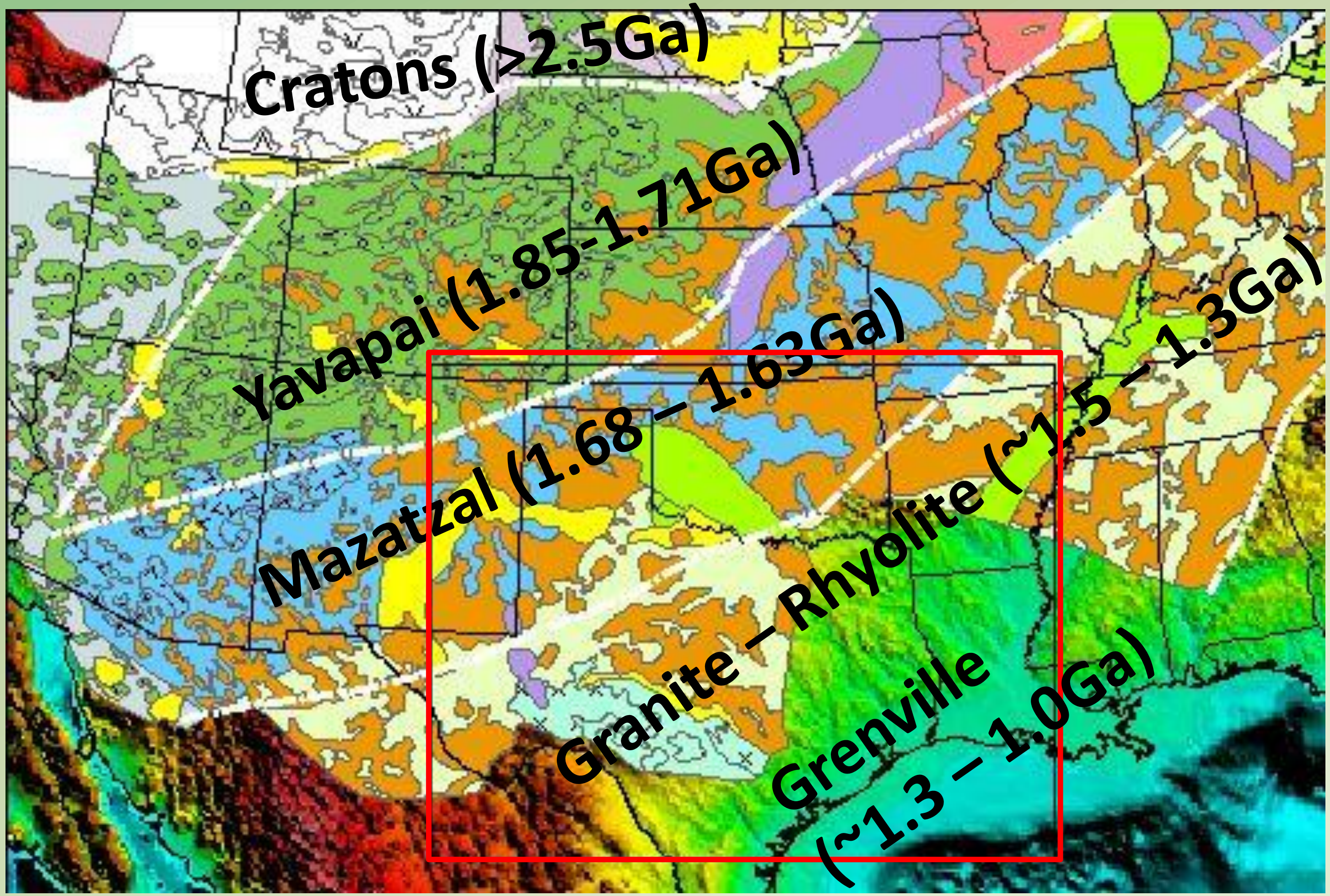
Highly reworked lithosphere has lower velocity CLM

Lower Vs due to refertilisation by asthenosphere-derived melts

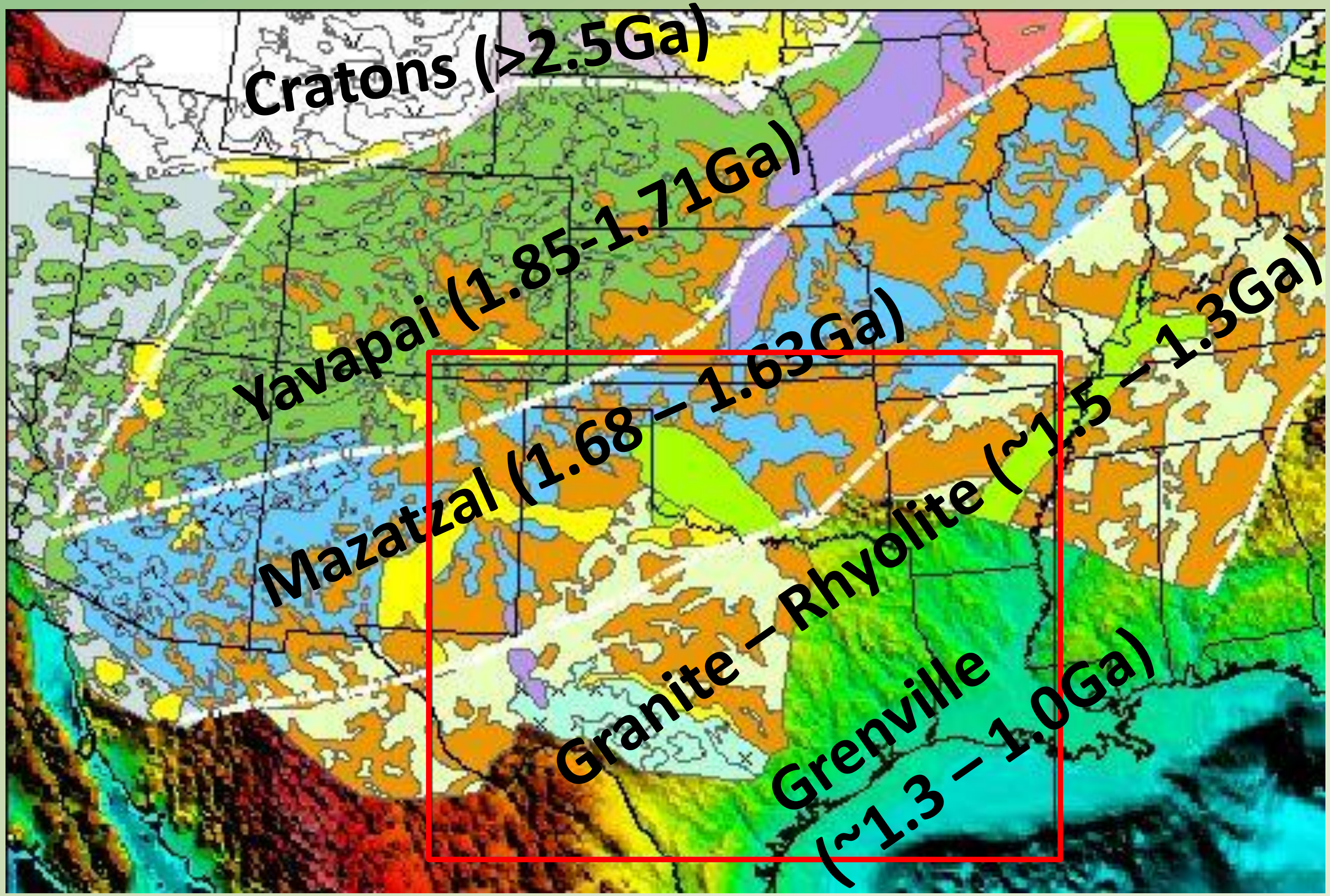
Subduction-related magmatism is the main source of these melts

Shearwave Velocity at **100-175km depth** (modified after Grand, 2011, unpublished)

SE Laurentia (USA) Basement Provinces

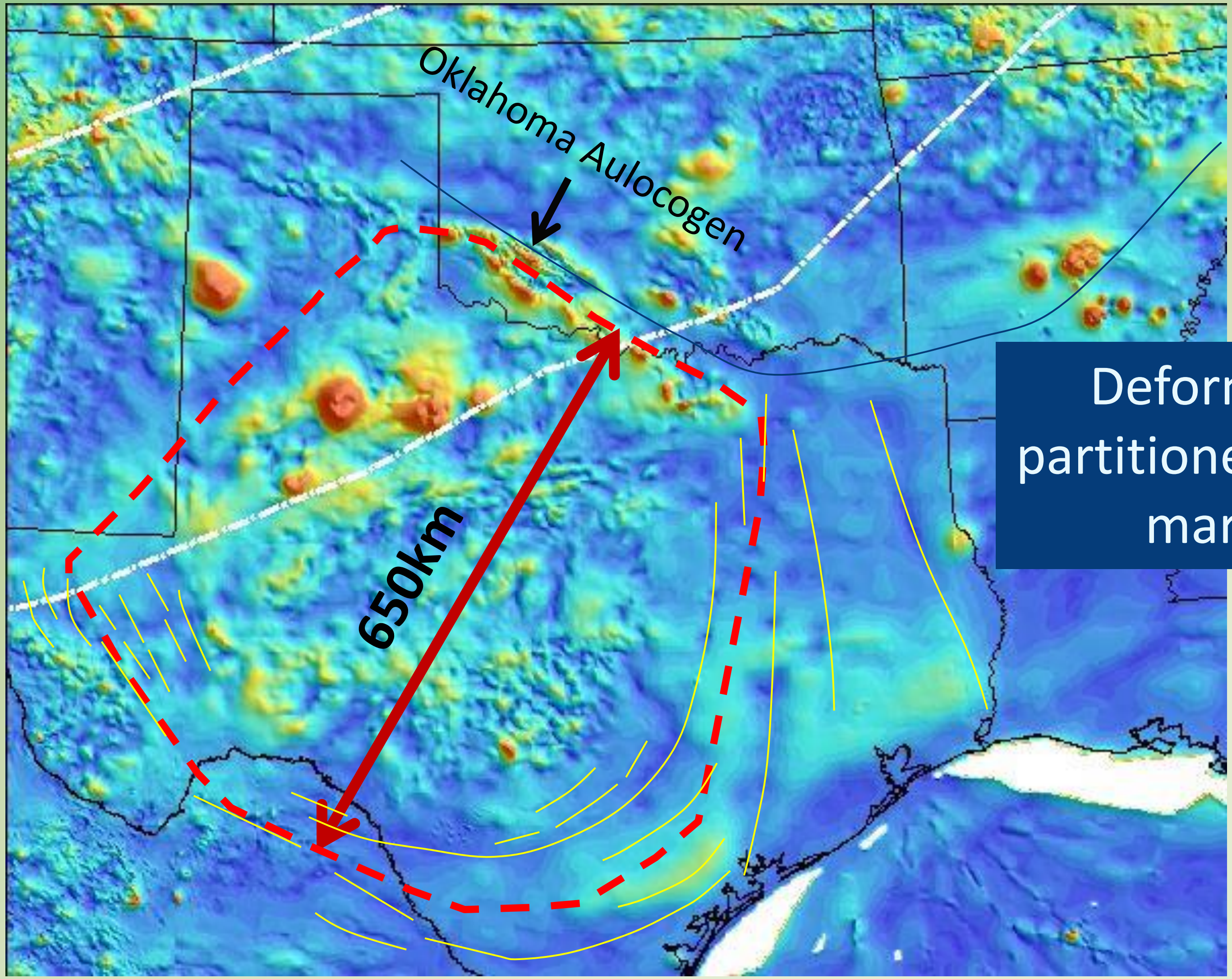


Growth by addition of "juvenile" arcs?



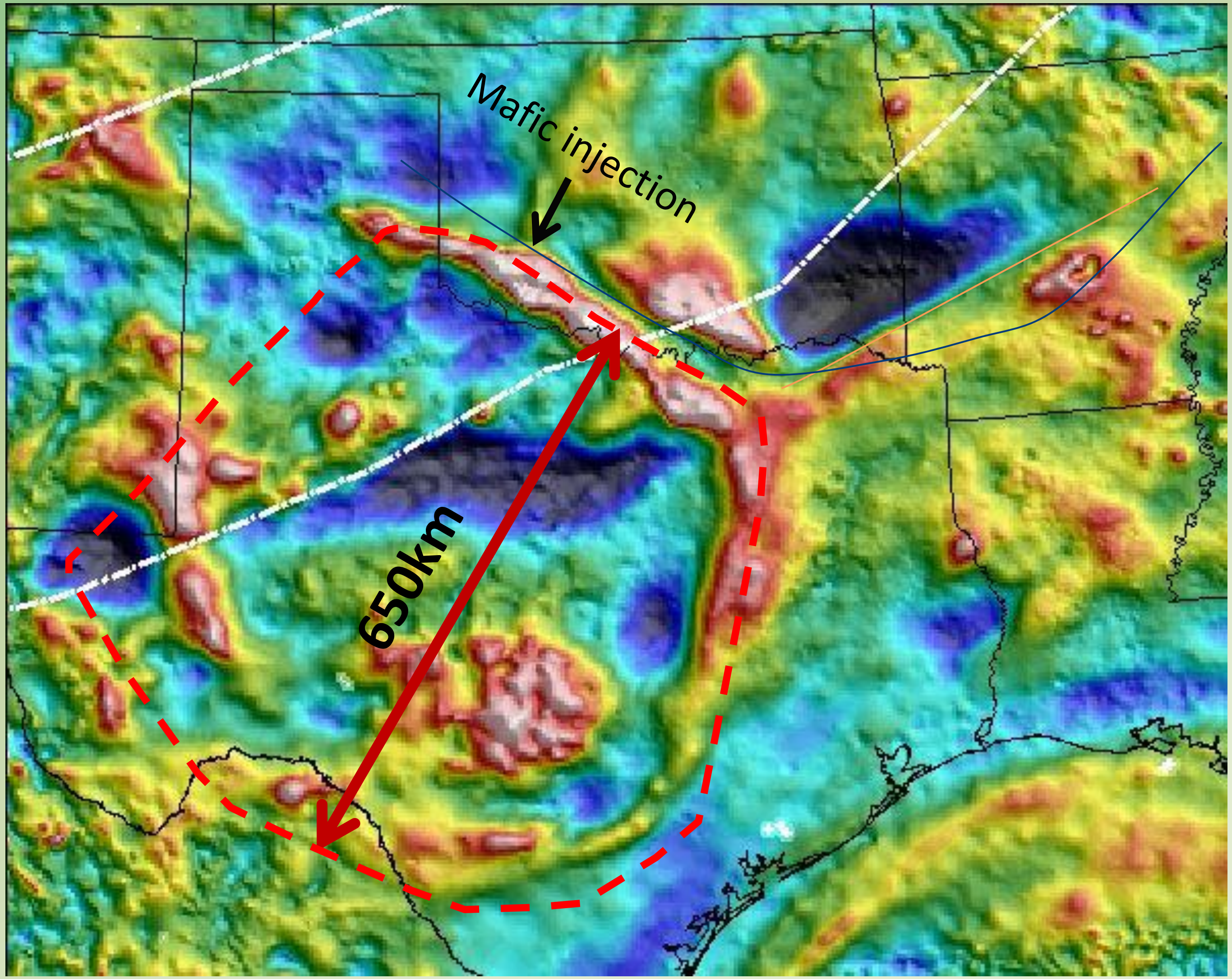
Magnetics outline a microcontinental block

(within 1.5-1.3 Ga Granite-Rhyolite Province)

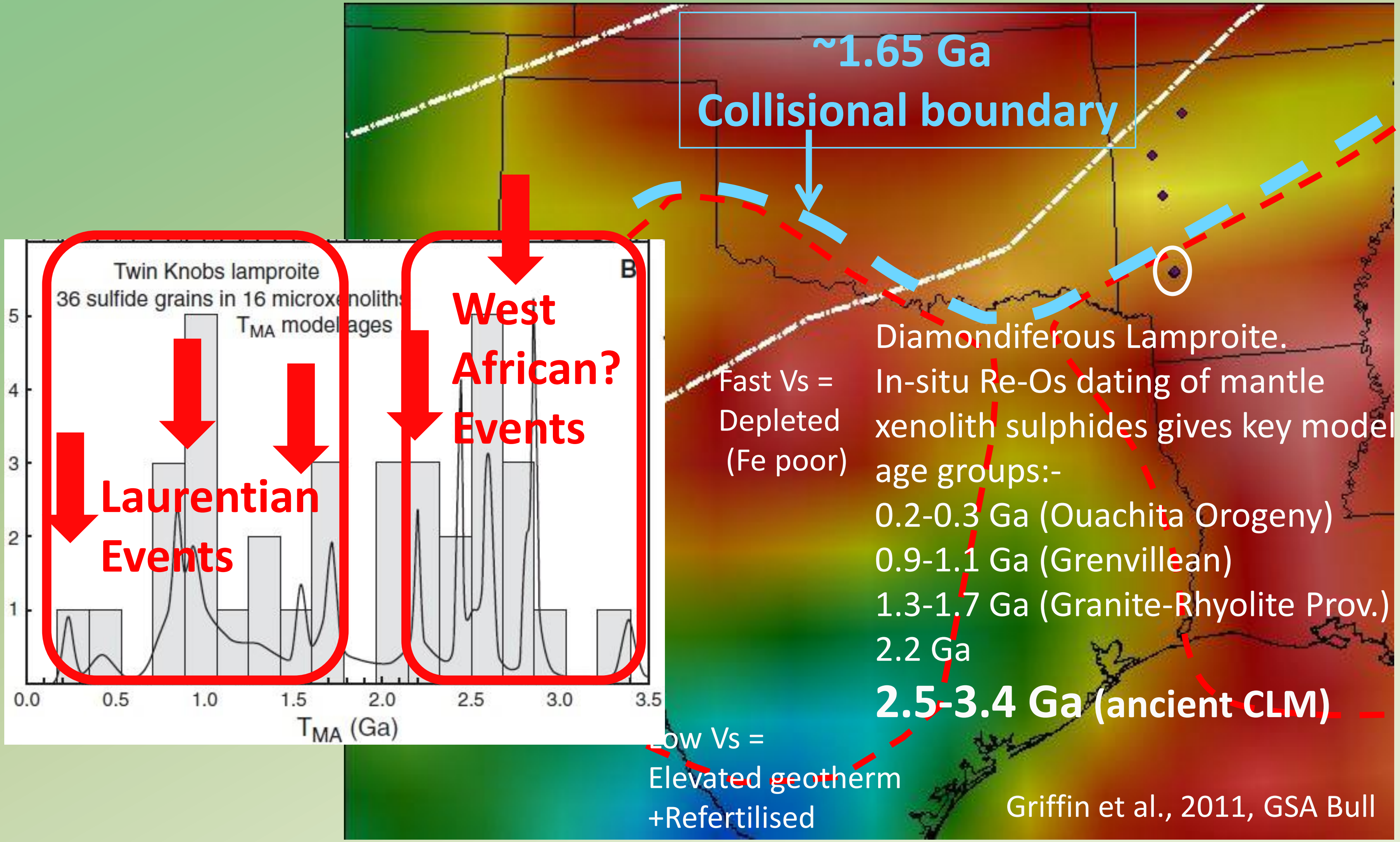


Deformation partitioned around margins

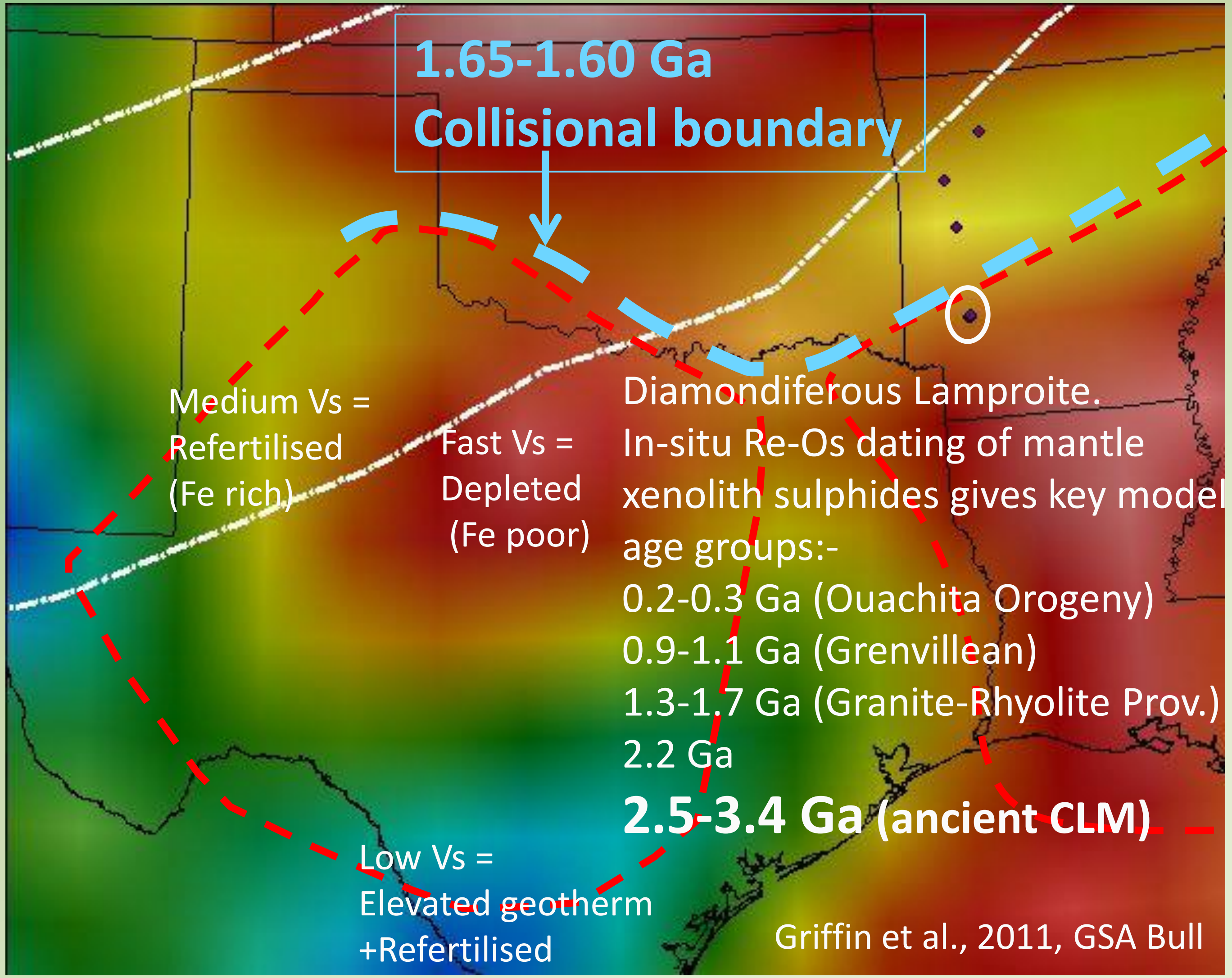
Isostatic Residual Gravity



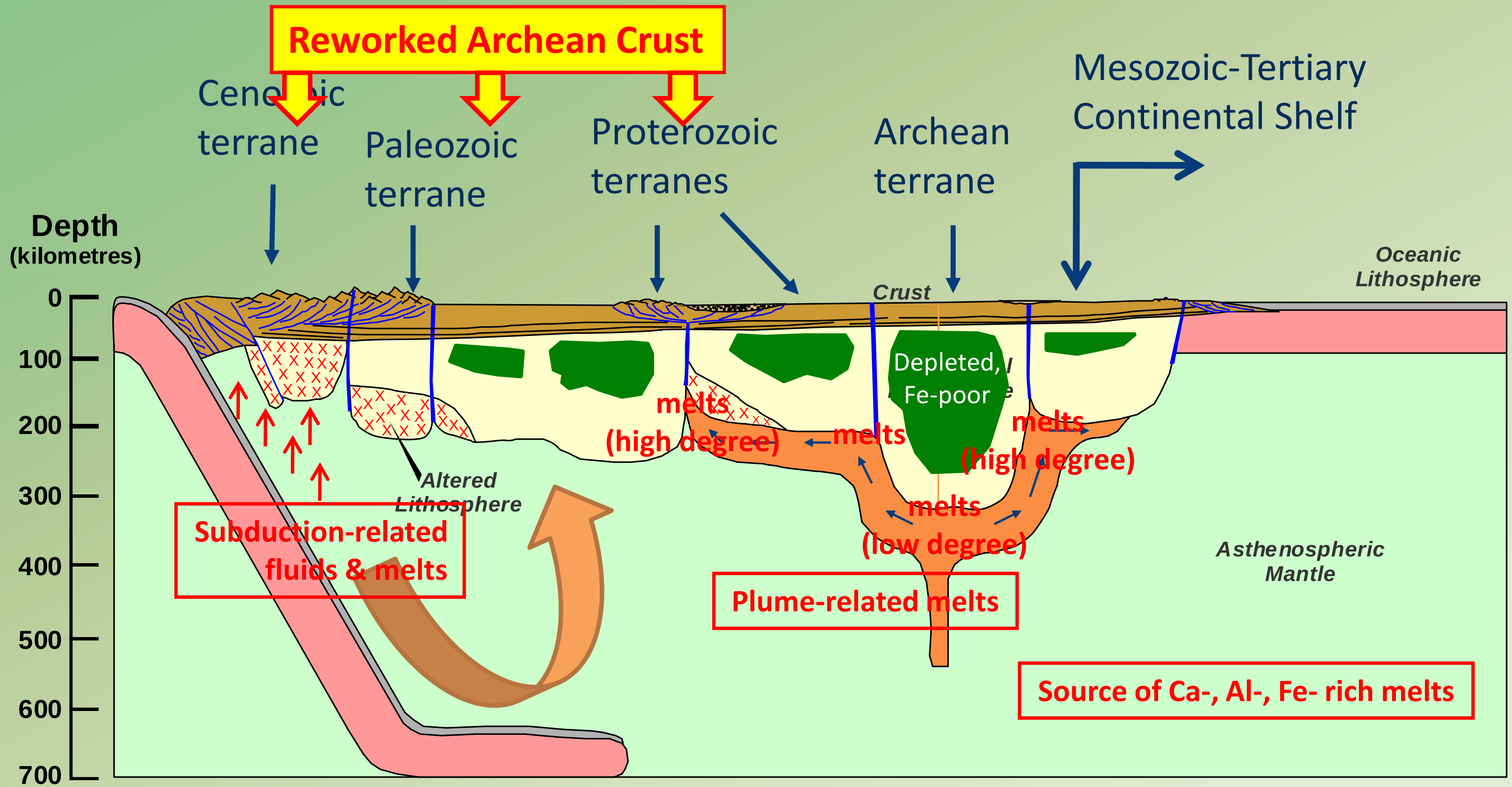
CLM is reworked Archean!



i.e. Laurentia grew by microcontinent accretion



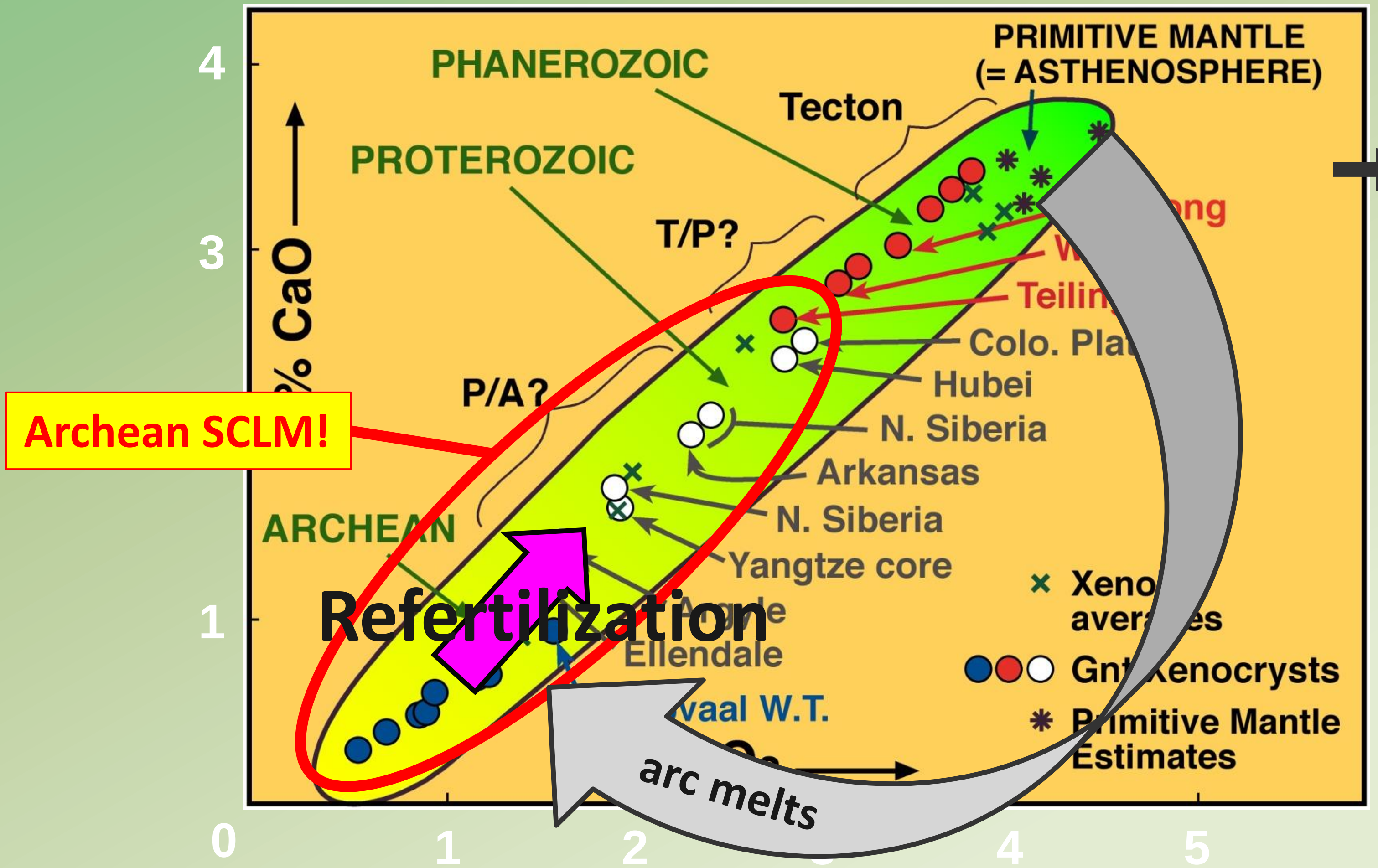
Refertilising the Archean roots



Mantle melts attack the Archean CLM from below and along structures

CLM Xenoliths

Duration of magmatism ≈ degree of **Refertilisation**

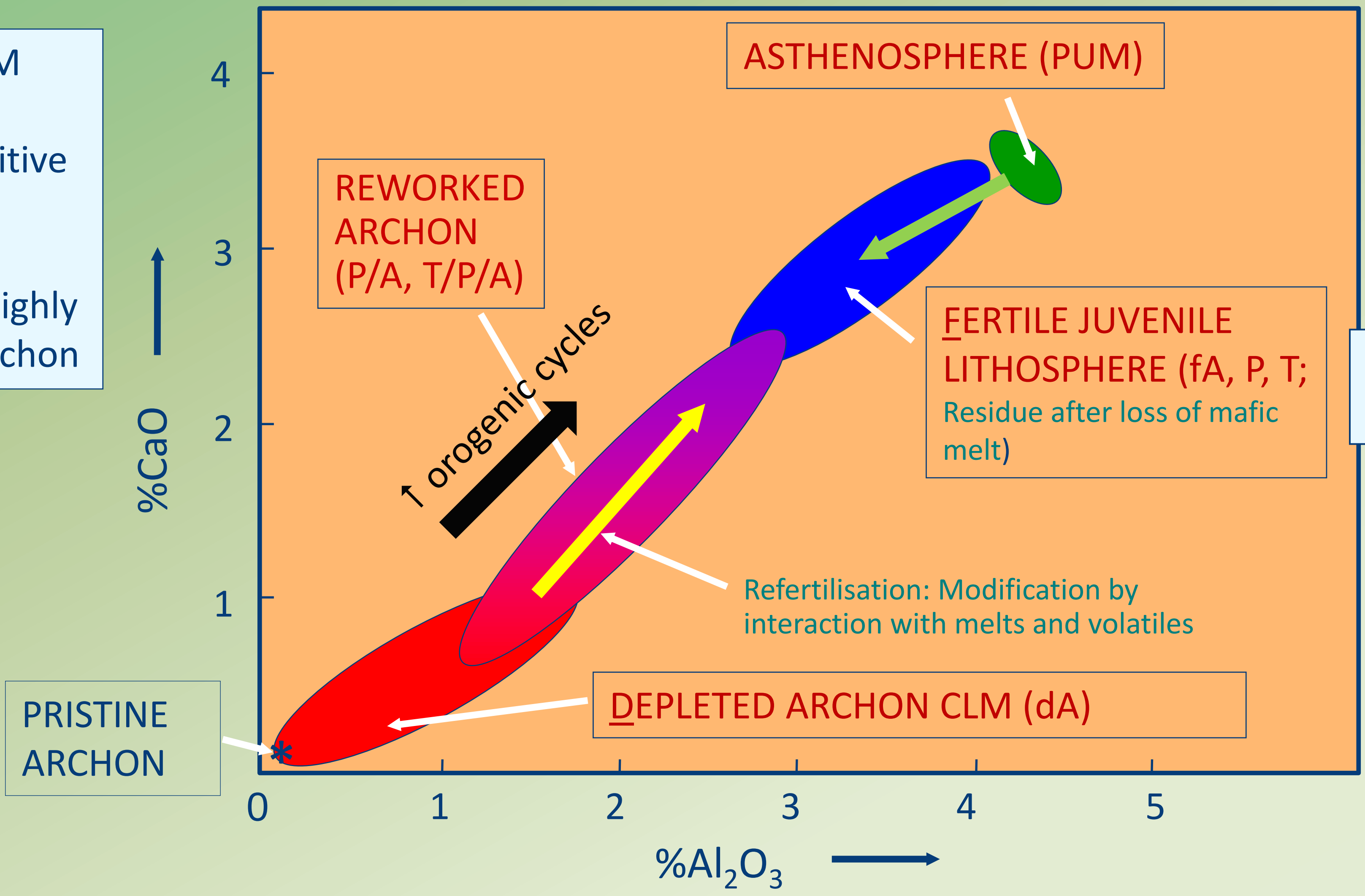


→ ↓Velocity, ↑Density

CLM Compositions and 2 Processes

1) Juvenile fertile CLM following mafic melt extraction from primitive upper mantle

2) Refertilisation of highly depleted (unique) Archon



e.g. Island arc mantle, oceanic lithosphere

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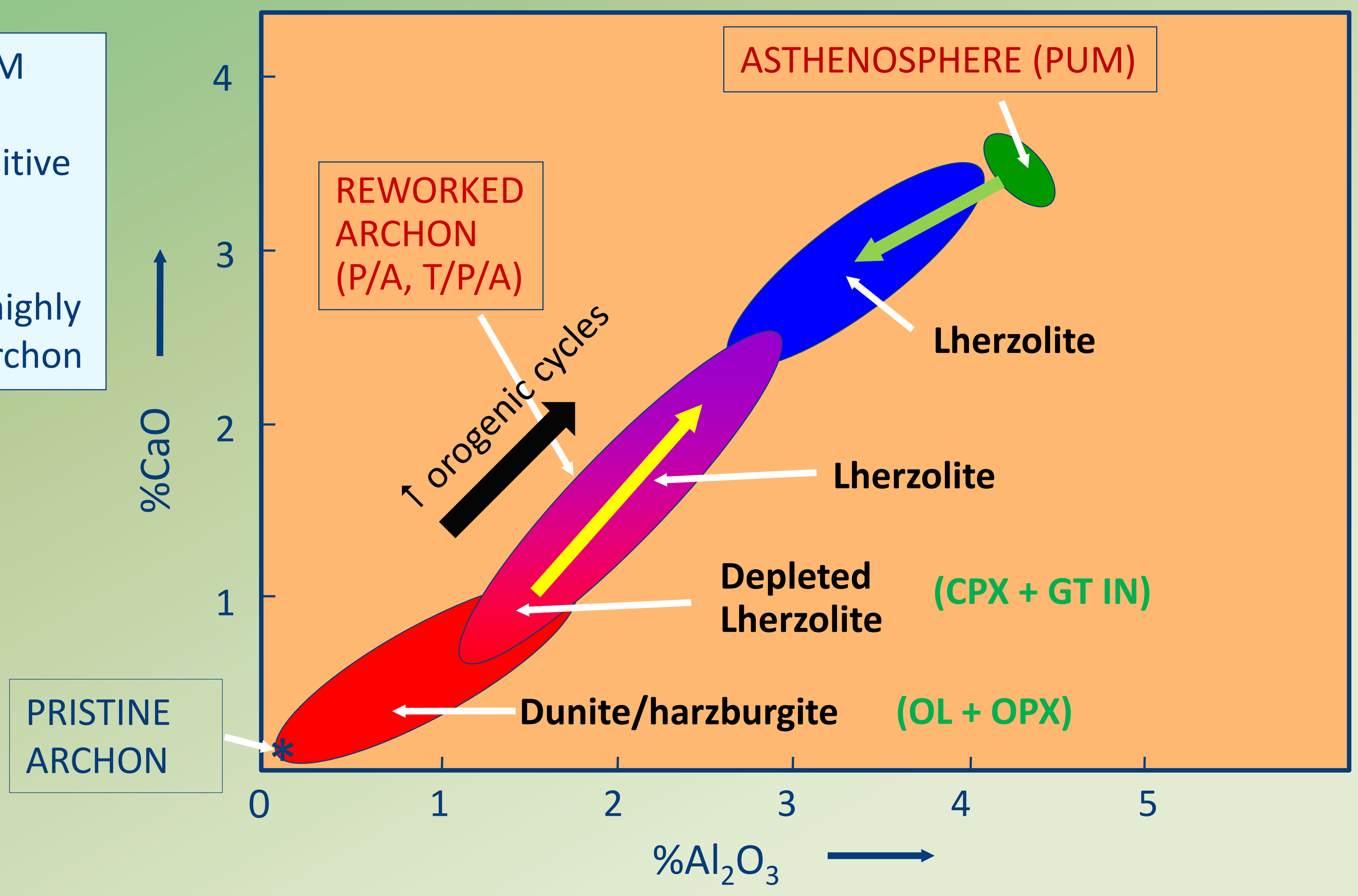

CLM Compositions and 2 Processes

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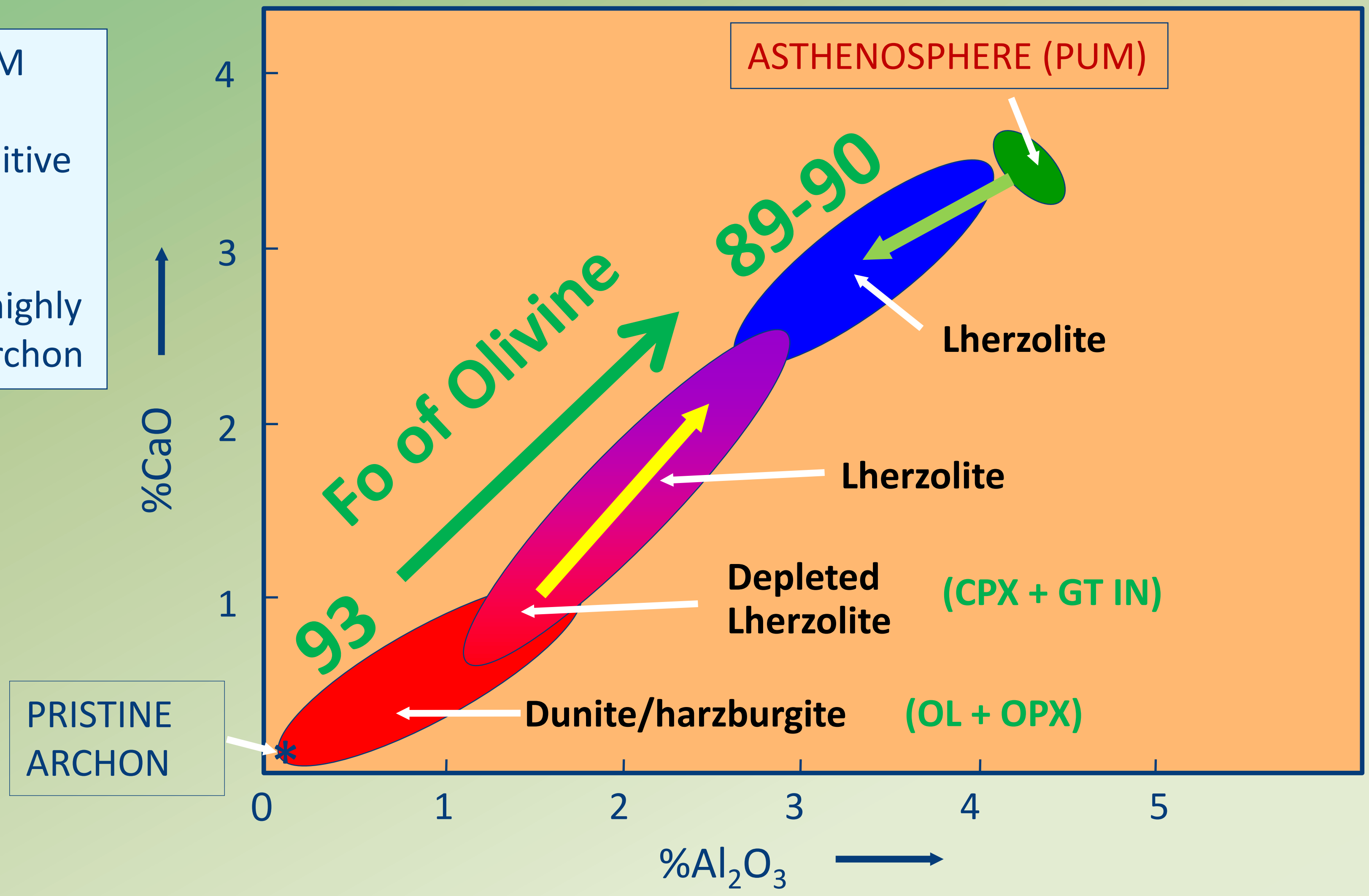
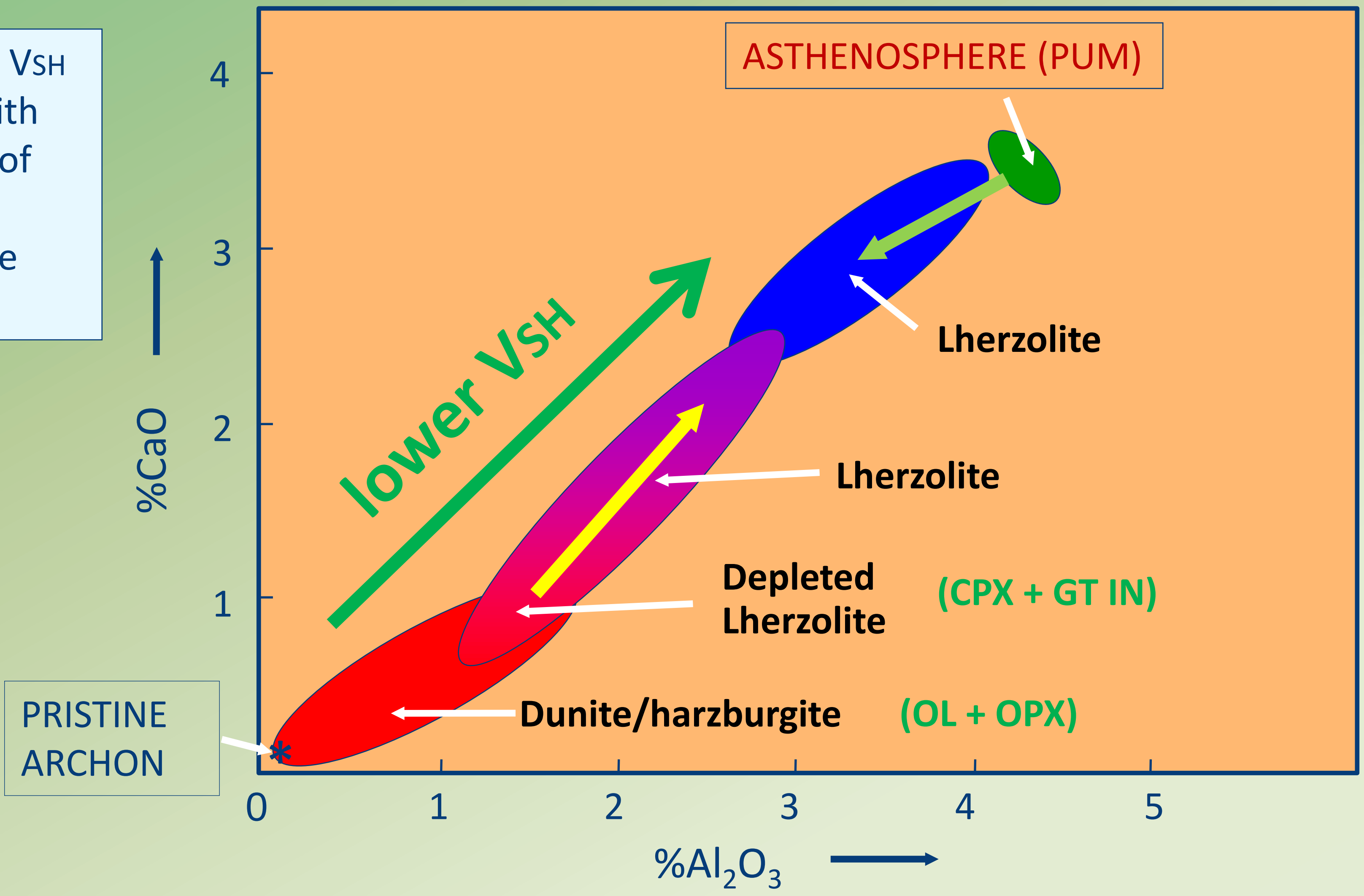


CLM Compositions and Seismic Velocity

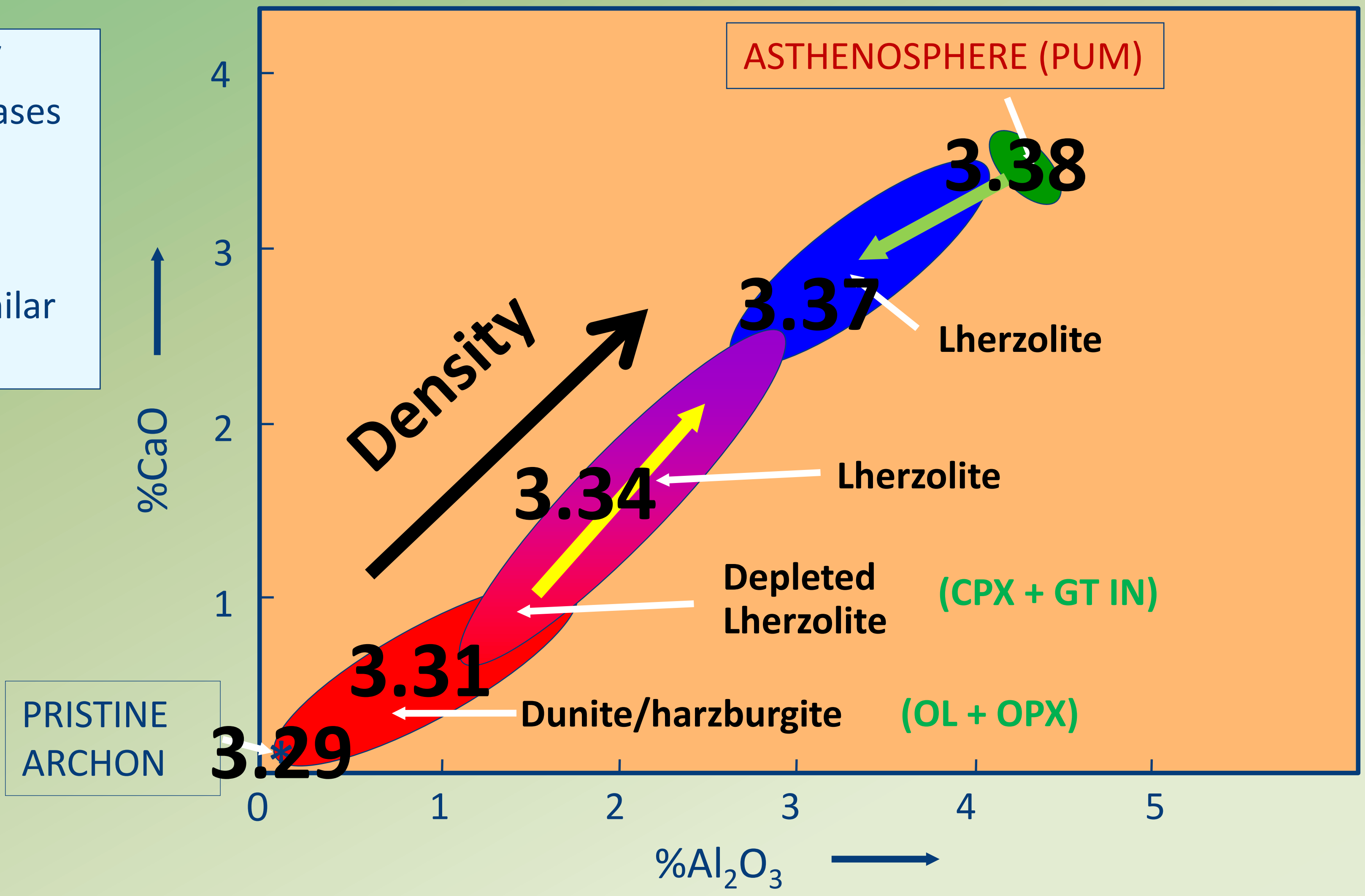
Shear wave velocity VSH drops markedly with lower Fo content of olivine
(i.e. increasing Fe content)



Refertilisation Increases Density

Metasomatism/ refertilisation increases density

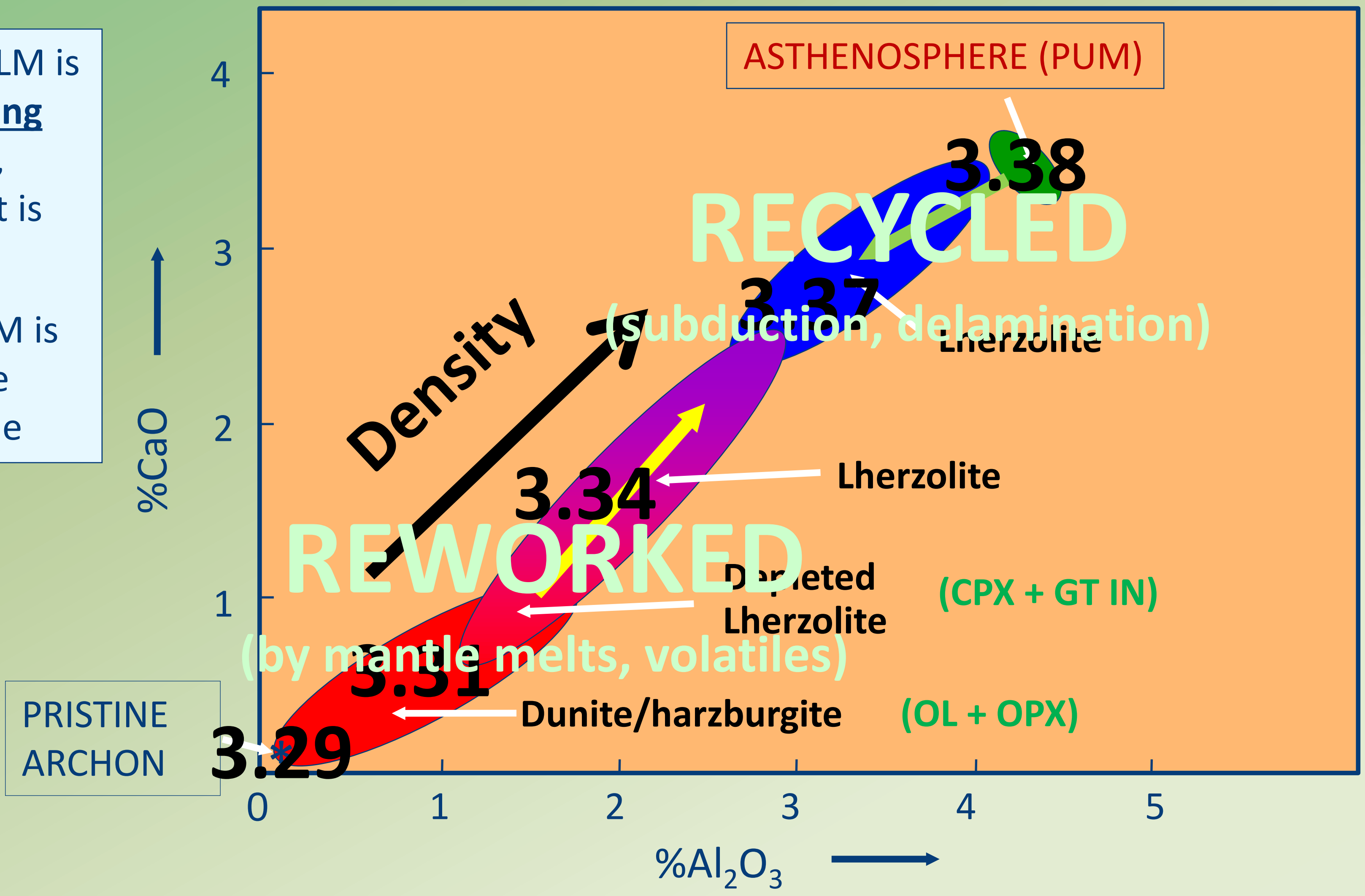
Juvenile mantle lithosphere has similar density to PUM



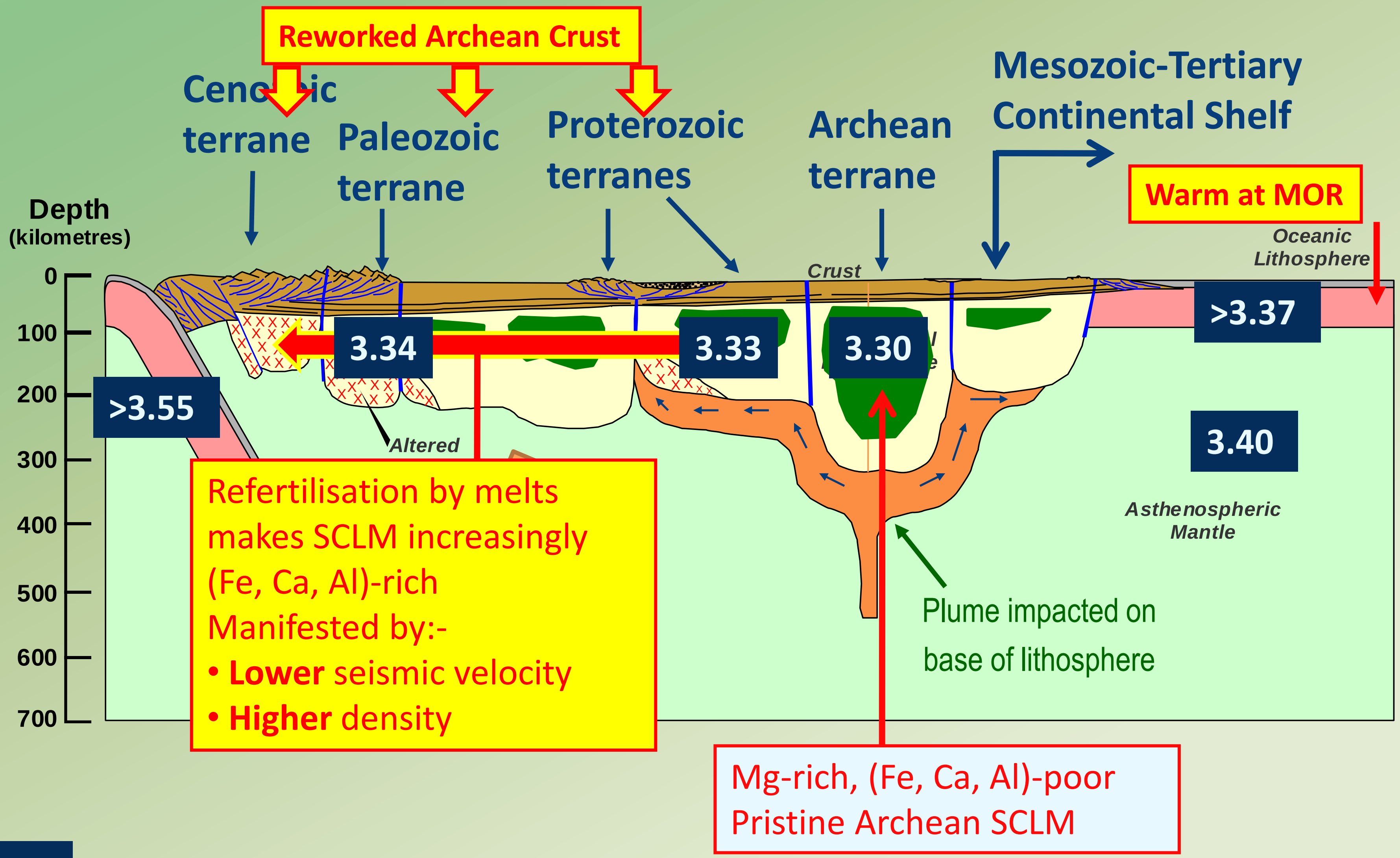
Density and Rheology Determines Fate

Ancient depleted SCLM is subject to **reworking** (metasomatism, refertilisation), but is durable

Juvenile fertile SCLM is **recycled** into the convecting mantle

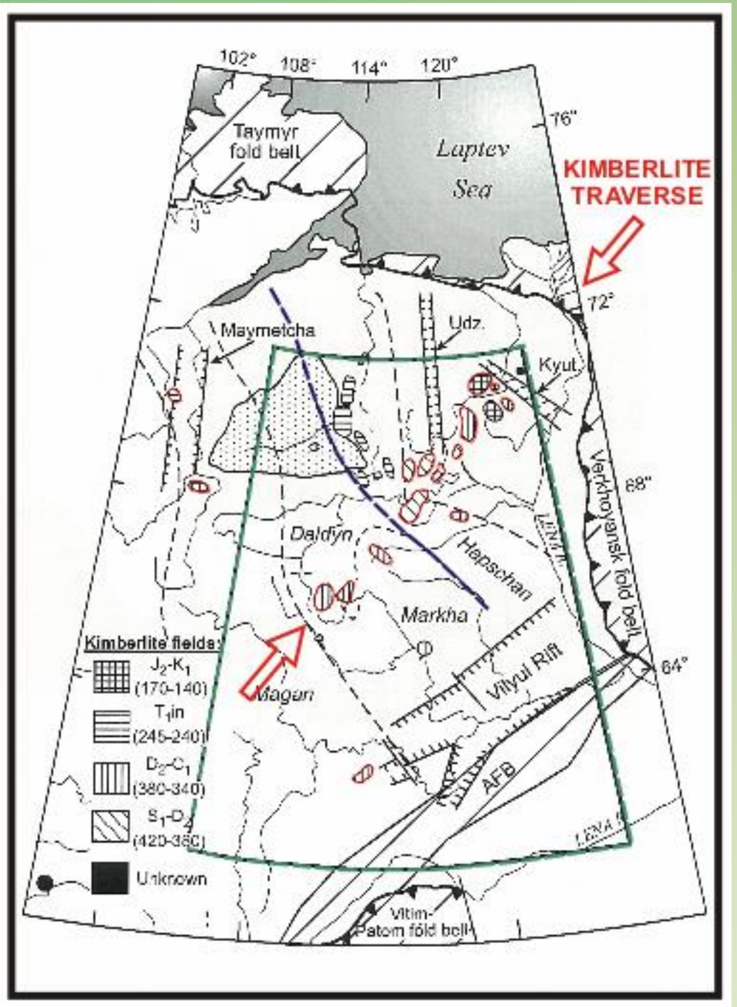


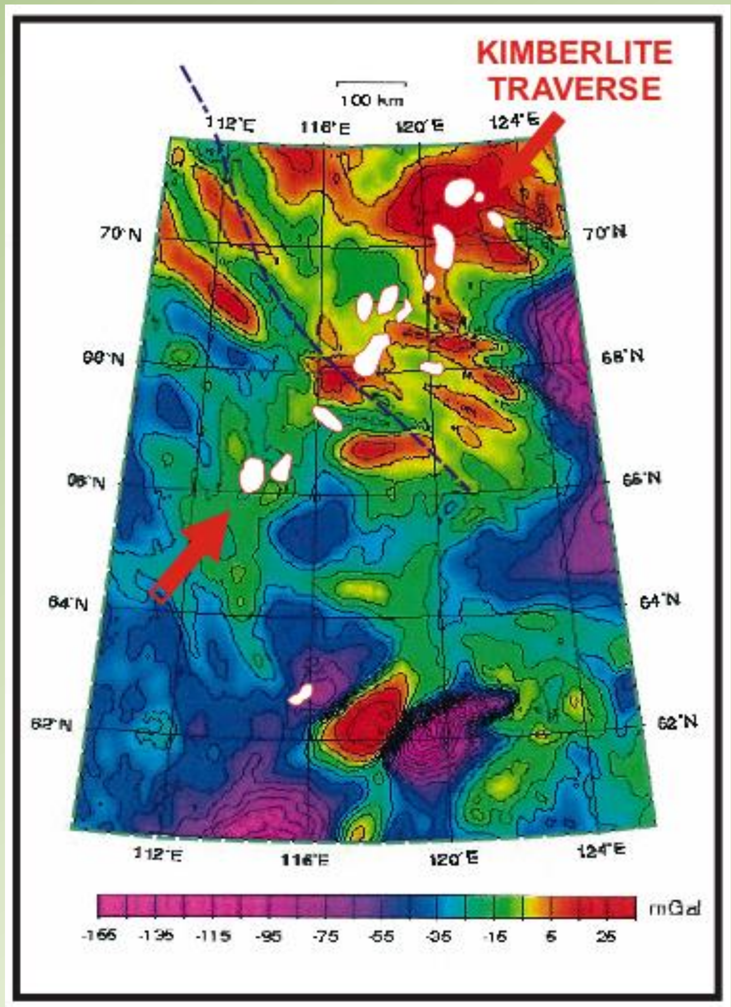
Refertilising CLM changes density & velocity



3.38 **Density** (e.g. Fernandez et al., 2009, Tectonophys)

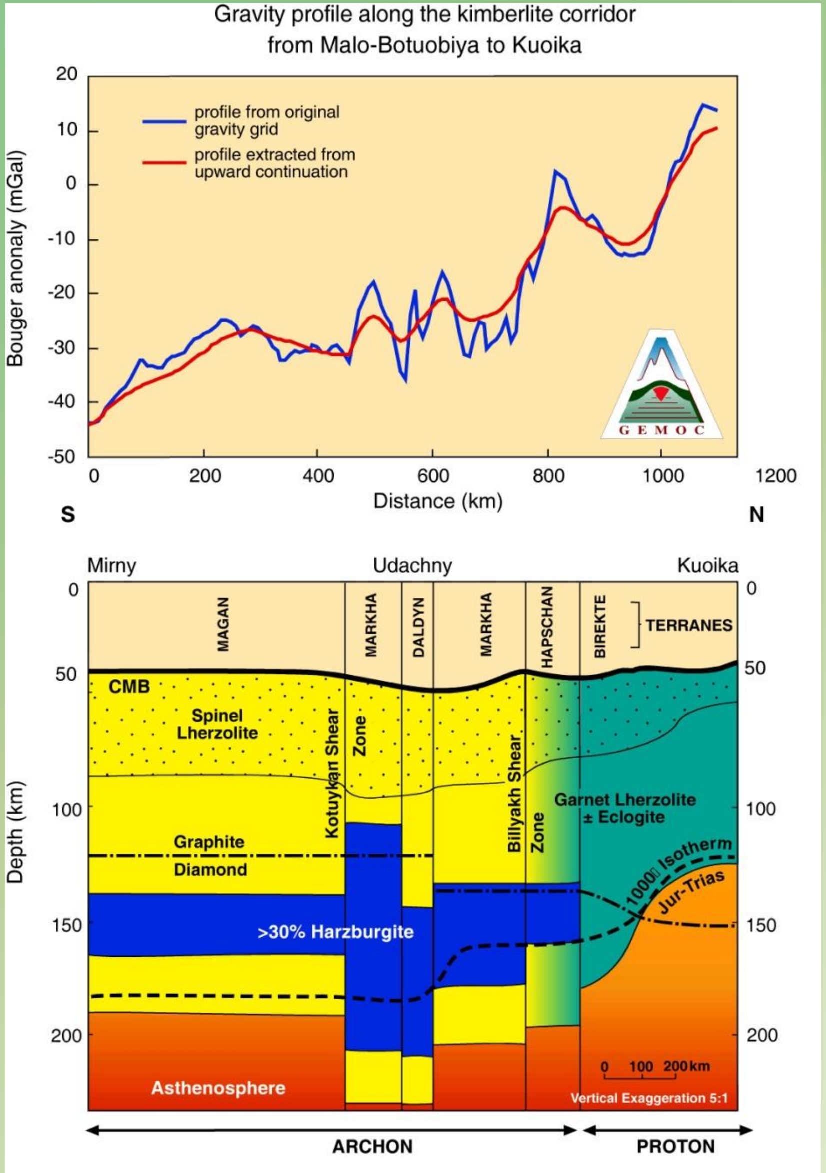
Siberian Kimberlite “Traverse” samples CLM





Poudjom Djomani, Y.H., O’Reilly, S.Y., Griffin, W.L., Natapov, L.M., Erinchek, Y., Hronsky, J., 2003. Upper mantle structure beneath eastern Siberia: evidence from gravity modeling and mantle petrology. Geochemistry, Geophysics, Geosystems 4 (7), 1066, doi:10.1029/2002GC000429.

CLM Composition vs Bouguer Response



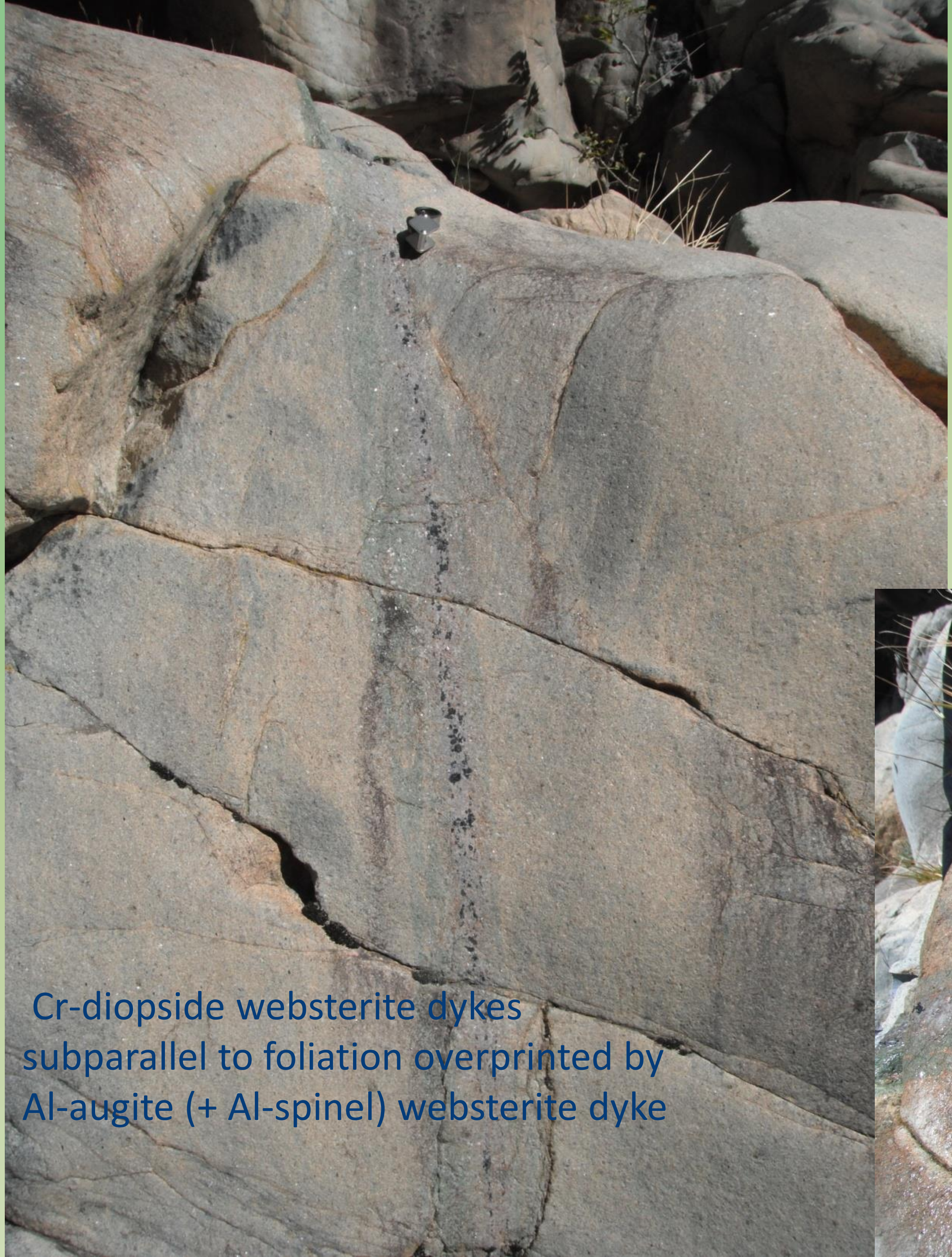
Long wavelength (100s km) –ve Bouguer Response correlates with thickest section of Depleted SCLM (Archon; least refertilised)

i.e.

- Overprinting results in SCLM refertilisation (Fe enrichment)
- Fe enrichment increases density

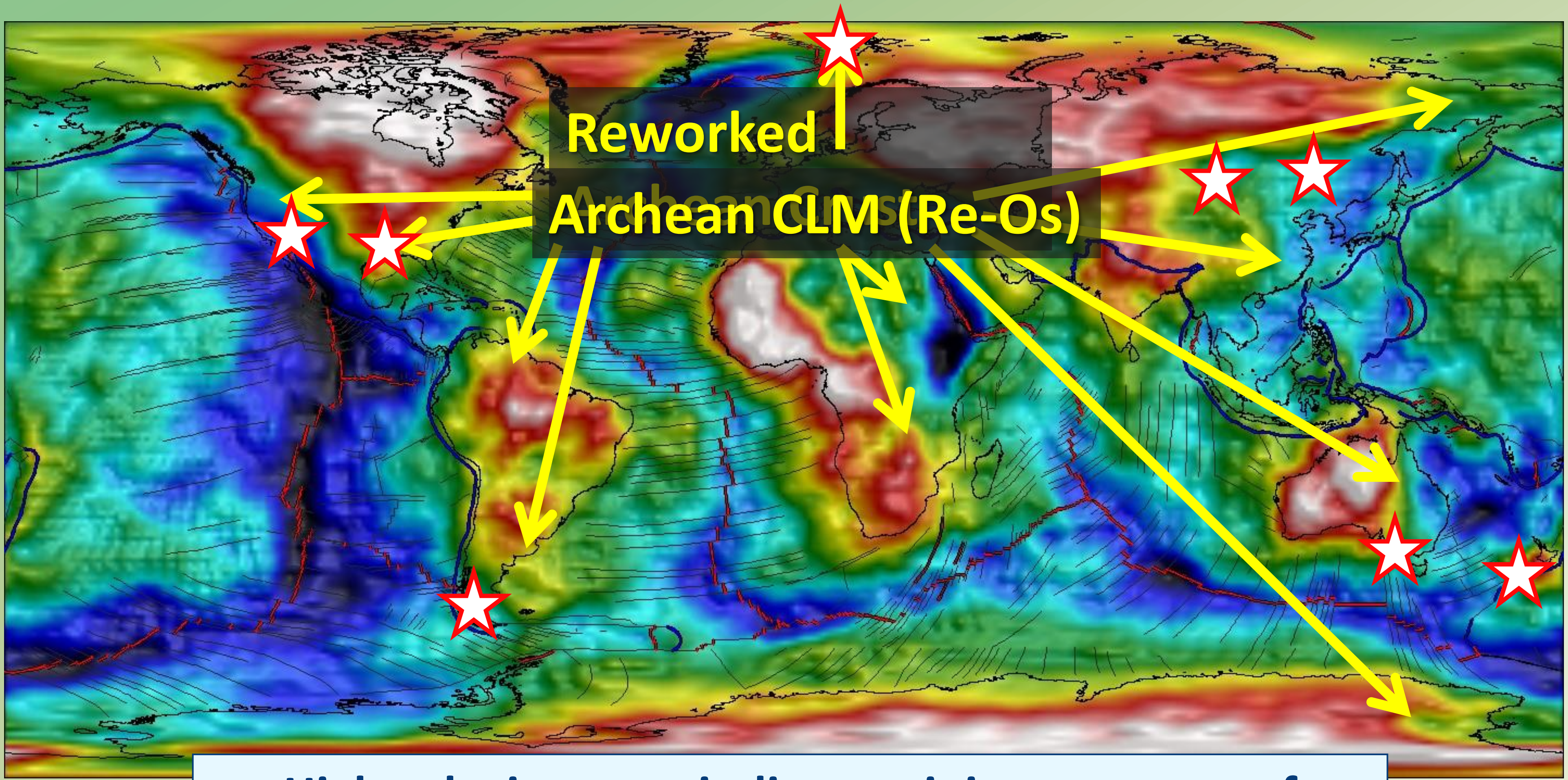
Poudjom Djomani, Y.H., O'Reilly, S.Y., Griffin, W.L., Natapov, L.M., Erinchek, Y., Hronsky, J., 2003. Upper mantle structure beneath eastern Siberia: evidence from gravity modeling and mantle petrology. Geochemistry, Geophysics, Geosystems 4 (7), 1066, doi:10.1029/2002GC000429.

Balmuccia Peridotite: multiple episodes of fracture-controlled melt-related metasomatism



Cr-diopside websterite dykes subparallel to foliation overprinted by Al-augite (+ Al-spinel) websterite dyke

CLM seismic velocity: reflecting tectonothermal history



High velocity roots indicate minimum extent of highly depleted (Mg-rich; generally >3Ga) lithosphere

(Deen et al., 2005; Afonso & Schutt, 2012)

Image is seismic velocity (Grand, 2002) in the 100-175km depth range (**Red**=fast; **Blue**=slow)

Archean CLM (black) – 19 years of mapping

GEMOC

i.e. under younger crust is a lot of old continental mantle, containing ancient structure and a variable metal inventory

As at August 2021

CLM:

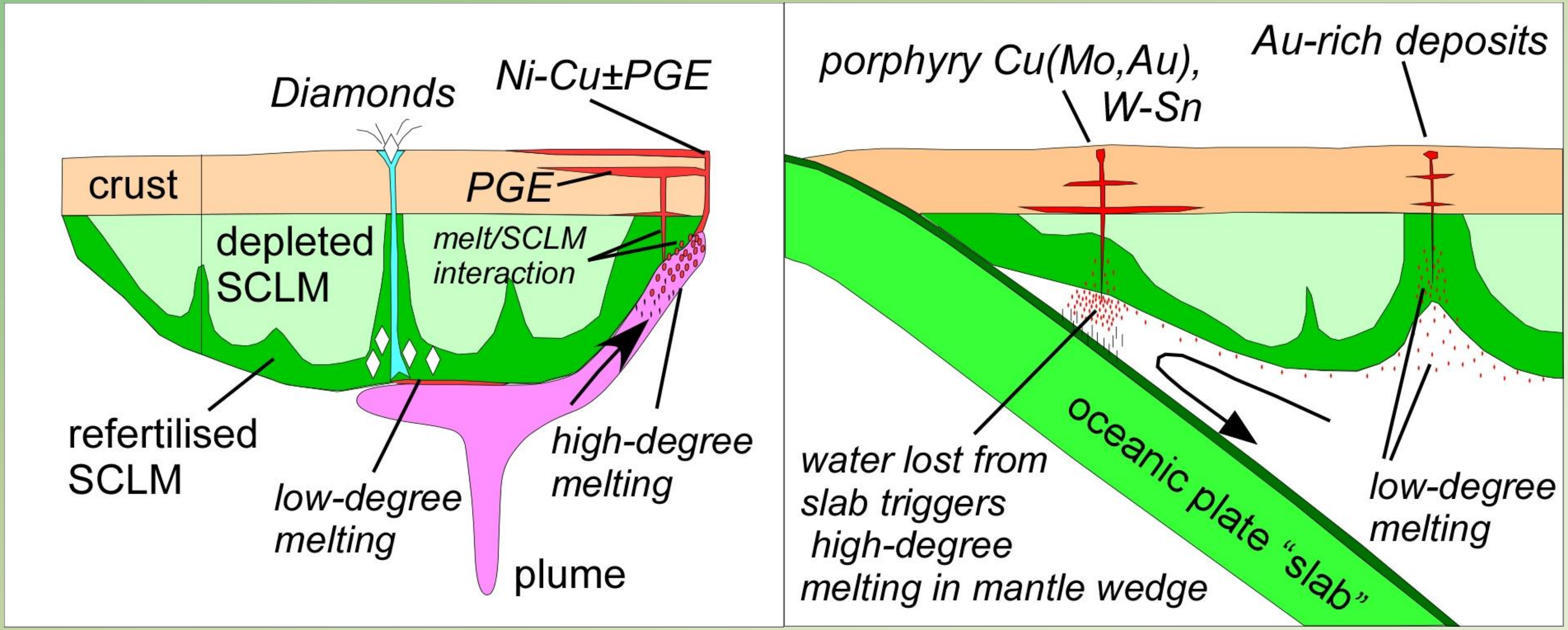
>70% seems to be (originally) Archean

e.g. Begg et al., 2009, Geosphere 5, 23-50

CLM influence on Ore Deposits

Mineral Systems at the lithosphere-scale

The CLM influences the location and style of Mineral Systems

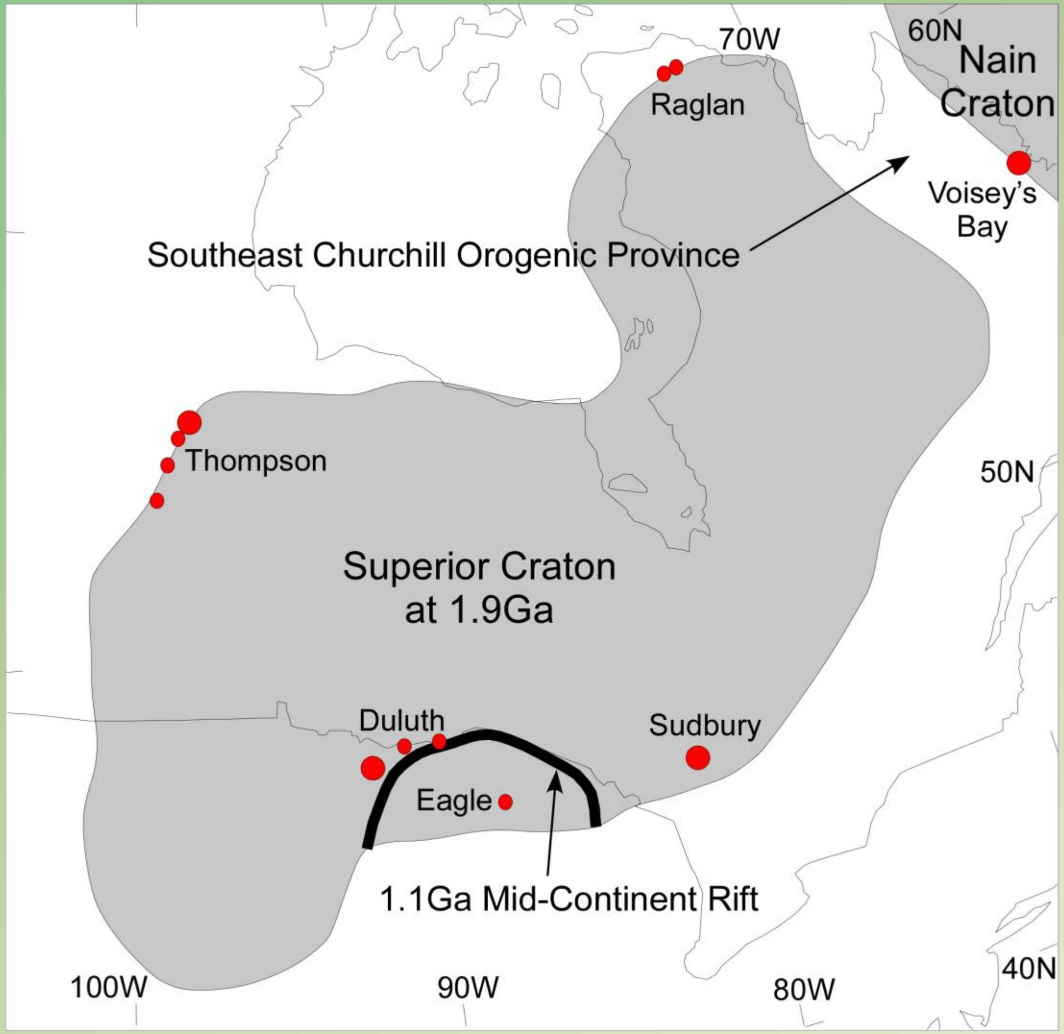


Deposits involve Mantle & Crust:

linked by faults (architecture)

Griffin, Begg & O'Reilly, 2013, Nature Geoscience

Craton Margin Ni-Cu(-PGE): Superior and Nain summary



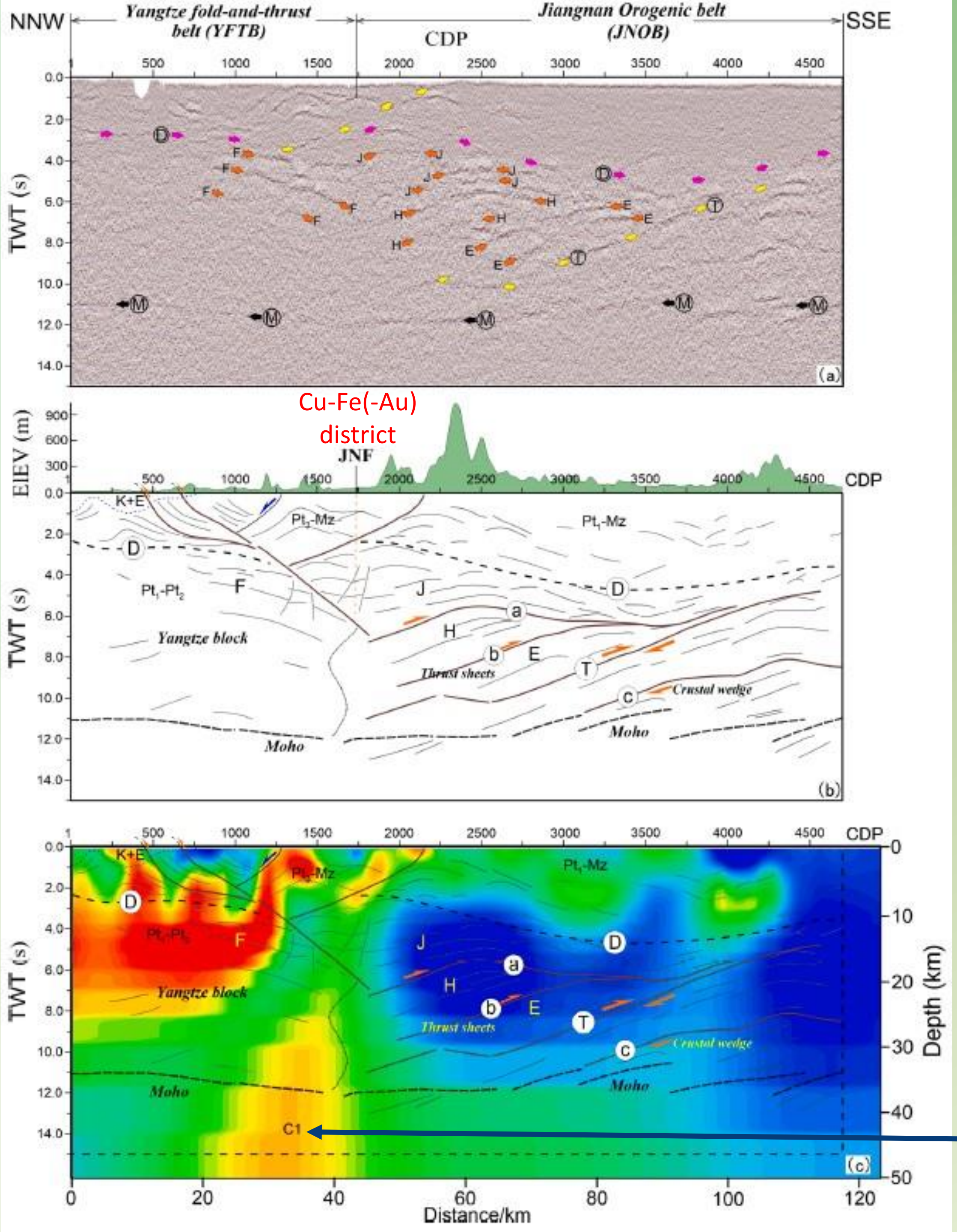
Tectonically activated craton margins focus deposits

1.88-1.85Ga (***Nuna peak***)
Thompson, Raglan and Sudbury

1.33 Ga
Voisey's Bay

1.1Ga (***Rodinia peak***)
Duluth Camp and Eagle

Begg et al., 2010,
Econ. Geol., 105, 1057-1070



Lithospheric-scale Mineral Systems:

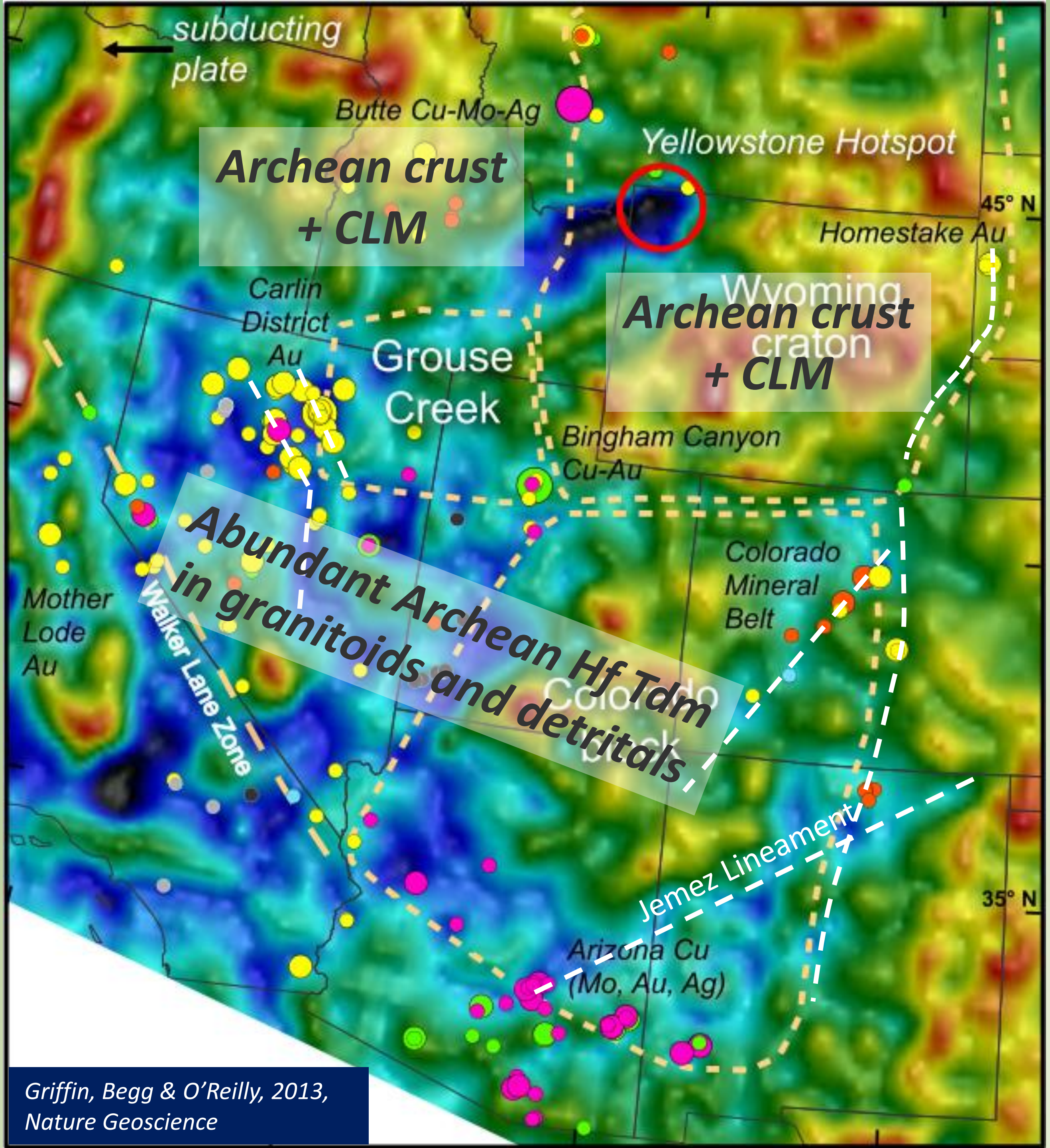
Lower Yangtze Metallogenic Belt

Ca 140Ma Porphyry skarn Cu-Fe(-Au) deposits along trend of the JiangNan Fault (JNF)

Seismic and MT data demonstrate linkage between mantle and upper crust

Mantle conductor at craton boundary

Lu et al 2021, Ore Geology Reviews 132, 103989



W USA
90km depth Velocity

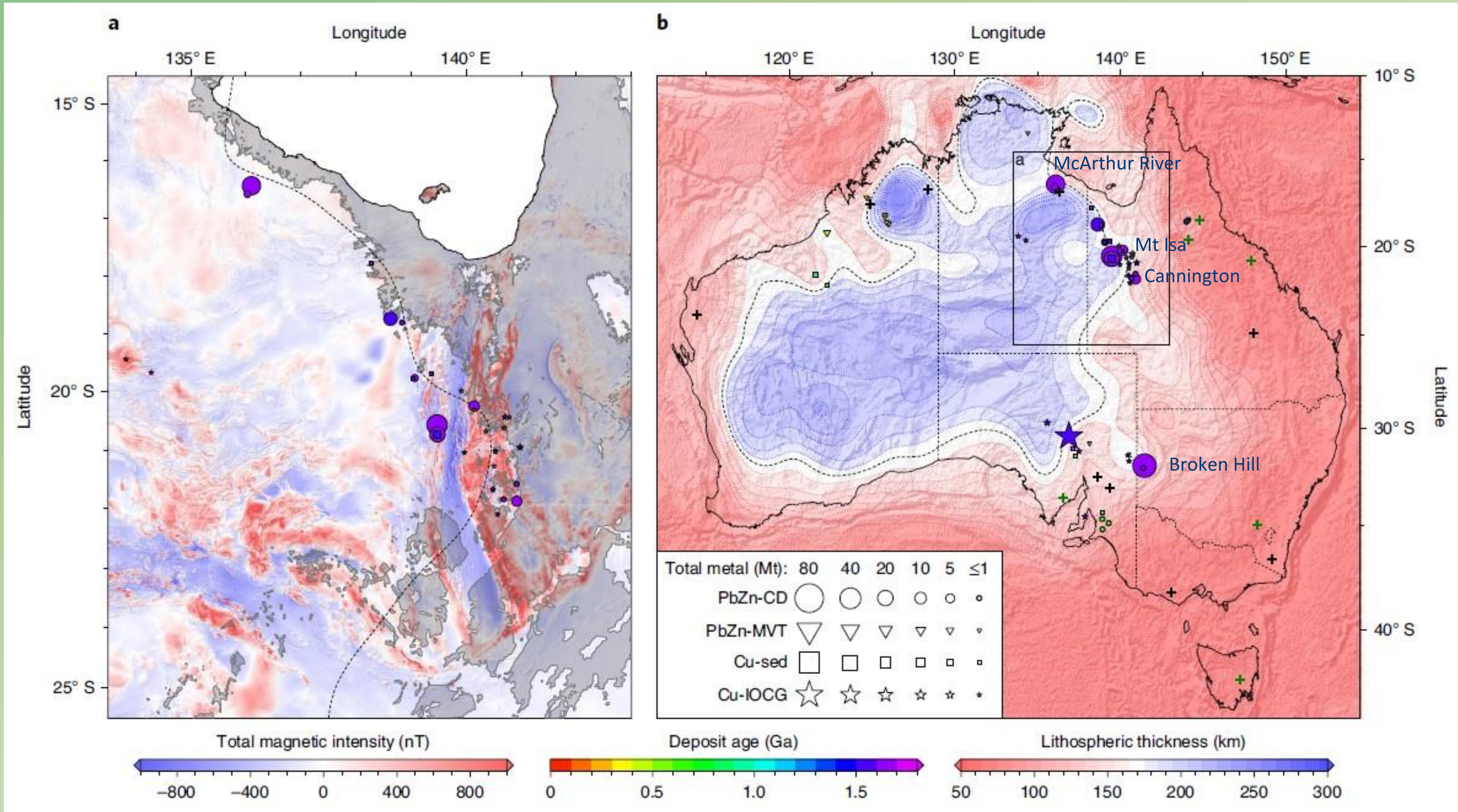
Deposit size (supergiant, giant, major) & dominant metals:

yellow, Au
green, Cu-Au-Mo
pink, Cu-Mo-Ag-Au
orange, Mo
light blue, REE
light grey, W(-Sn)
dark grey, Fe

Big deposits concentrate along prominent trans-lithospheric structures, particularly in lower-velocity regions (blue) or on the flanks of highs

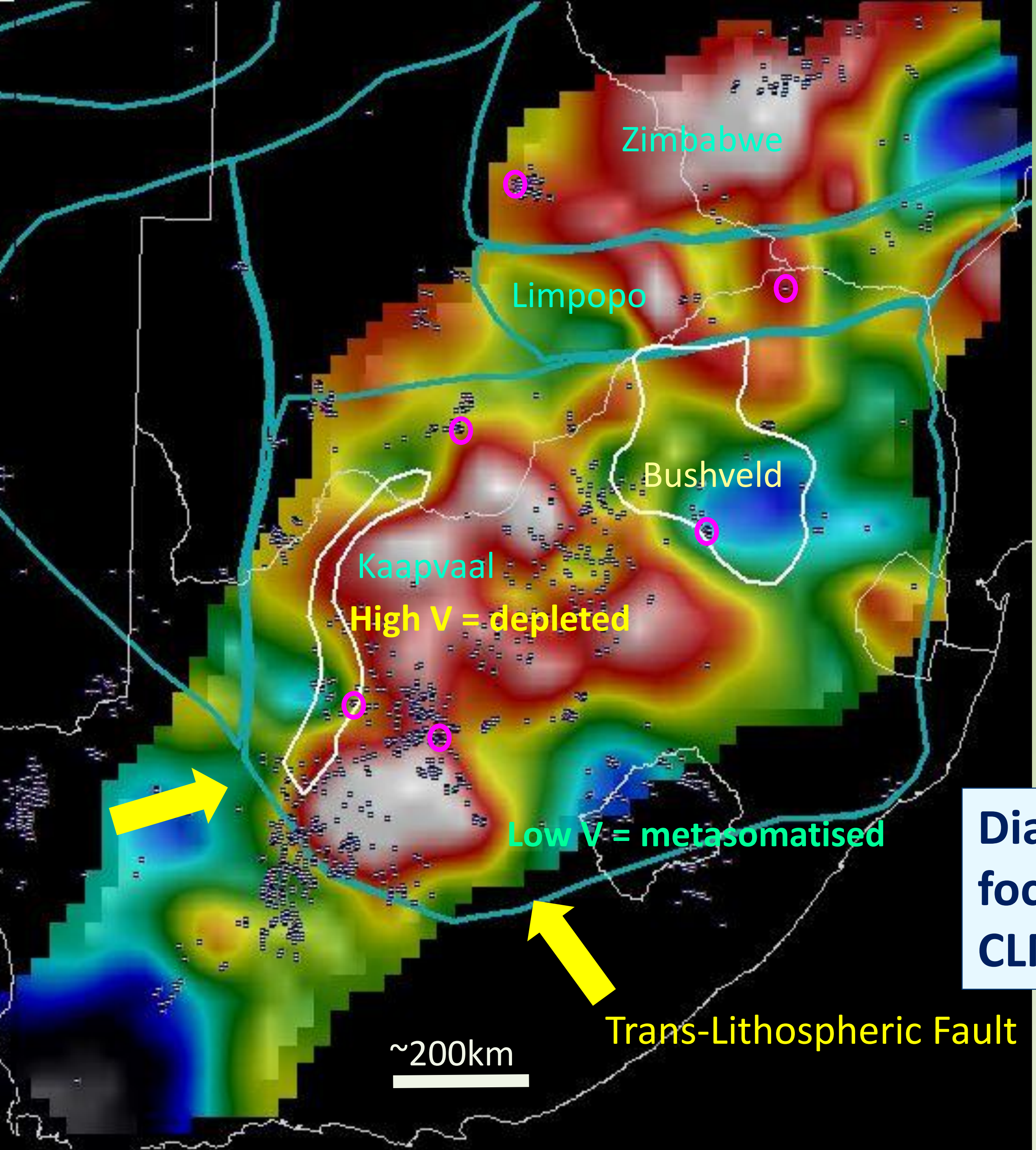
There is abundant evidence of widespread Archean lithosphere

Sed-Hosted Base Metals - Edge of thick Lithosphere



Hoggard et al., 2020, Nature Geoscience 13, 504-510

Kimberlites and Diamonds in Vs at 200km



Resolution ~50km

(Carnegie Kaapvaal Experiment; Fouch et al., 2004)

Red = fast

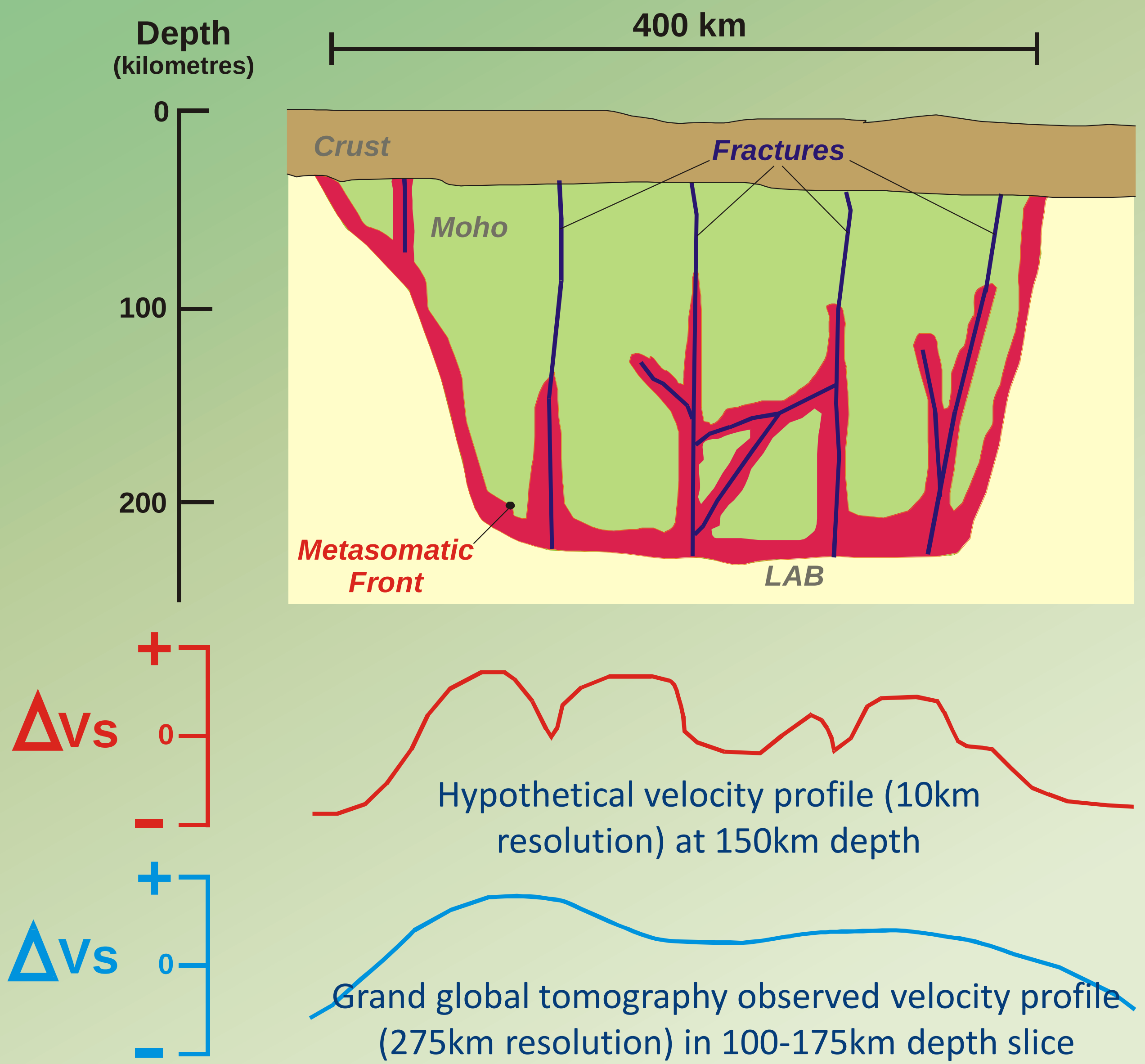
Blue = slow

O Giant Diamond Deposit

Kimberlites from Faure (2006)

Diamondiferous kimberlites focus around edges of depleted CLM (high velocity) regions

SCLM Heterogeneiity vs Seismic Velocity



- Depleted SCLM has a distinctive **high** velocity
- Metasomatic effects **lower** the seismic velocity
- **Kimberlites and mafic magmas preferentially sample metasomatised SCLM flanking old fractures**

Olympic Dam - MT reveals whole IOCG mineral system

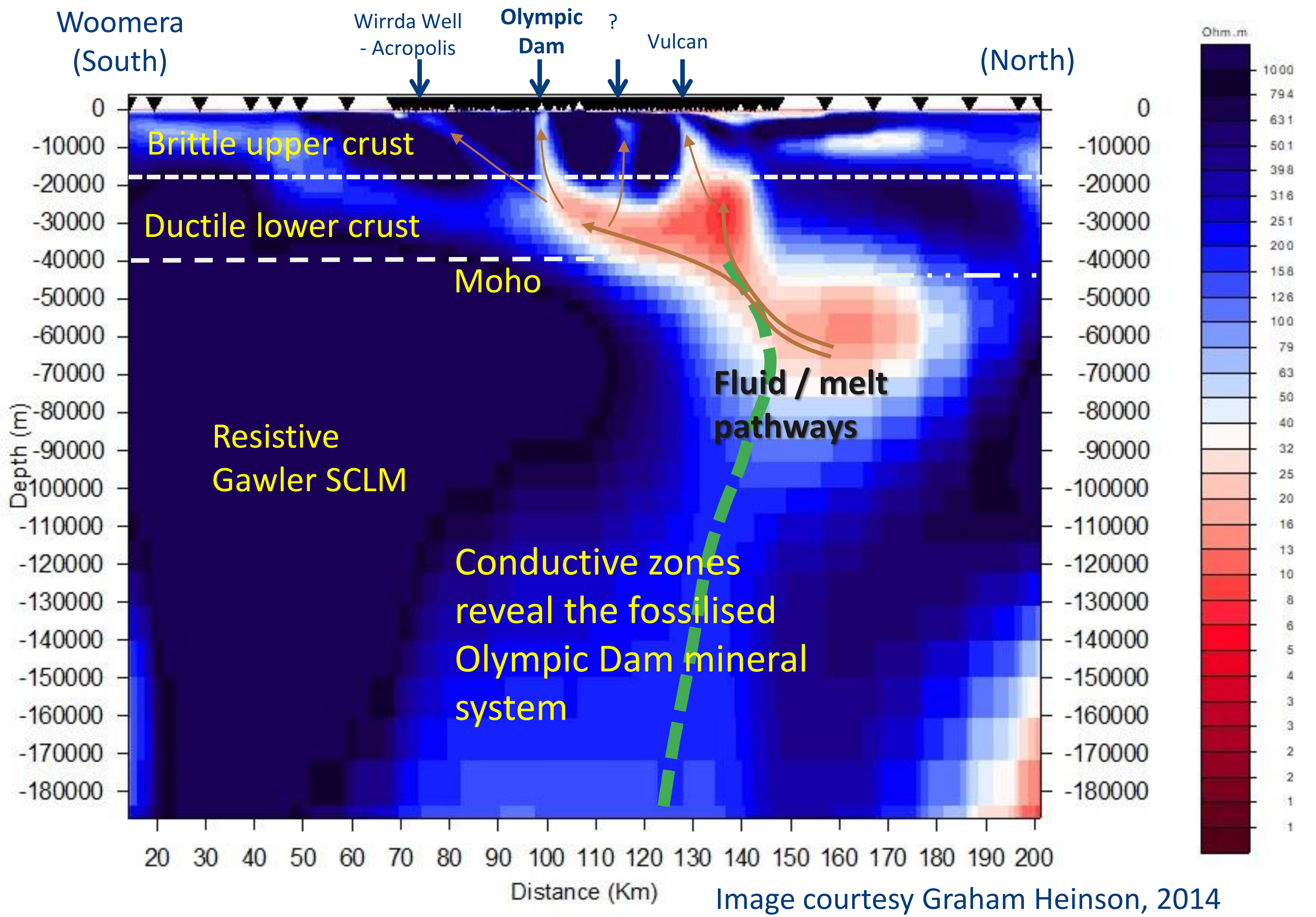


Image courtesy Graham Heinson, 2014

Lessons from 19 years of GLAM mapping

- **>60% of CLM *and* continental crust is Archean**
- Continents are amalgams of cratons and microcontinents
- **Tectonothermal reworking** is the dominant process affecting CLM and crust
- Crustal **recycling** has dominated over crustal growth since ~3Ga
- CLM structure imposes a fundamental control on many types of ore-forming systems

mti

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