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Archean SCLM: What do we (think) we know?

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ARC Centre of Excellence for Core to Crust Fluid Systems (CCFS)

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Geological Survey of Western Australia

What is the Sub-Continental Lithospheric Mantle (SCLM)?

- Non-convecting uppermost mantle formed
  - as partial melting residues
  - by cooling of upwelling asthenosphere
  - by plume accretion to existing lithosphere
- Depleted in basaltic components, then *overprinted by metasomatic processes* -- geochemically complex
- Base of depleted SCLM = Lithosphere-Asthenosphere Boundary (LAB) -- recognisable chemically, ?seismically
- Temperature at LAB ≈ 1200-1300 °C

What do we *need* to know about the Archean SCLM?

- Age – relative to crust, etc. One hit, or a long process?
- Composition – bulk; stratification?
- Origin – subduction, or what?
- Why/how is it different from younger SCLM?
- Tectonic effects – what changed once we had an SCLM, and why?

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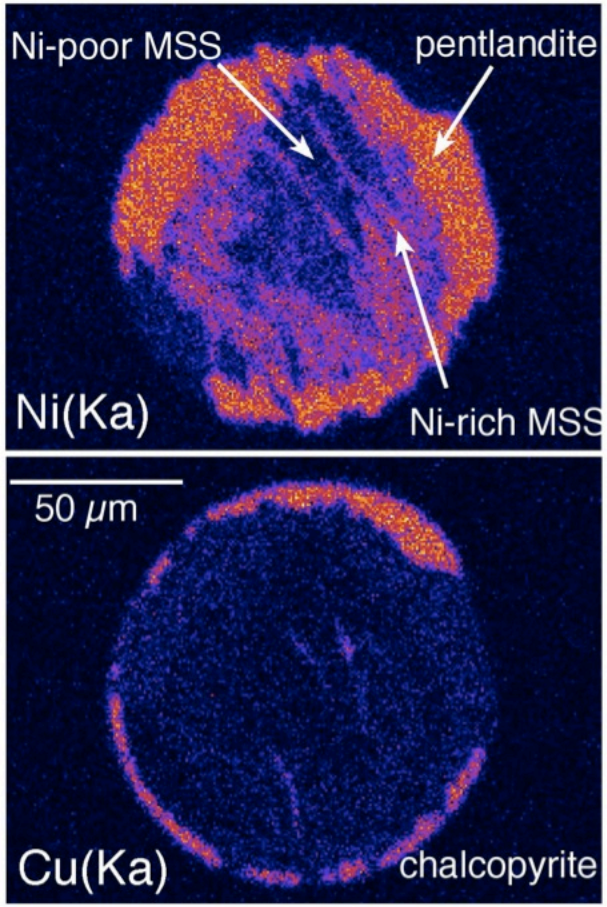
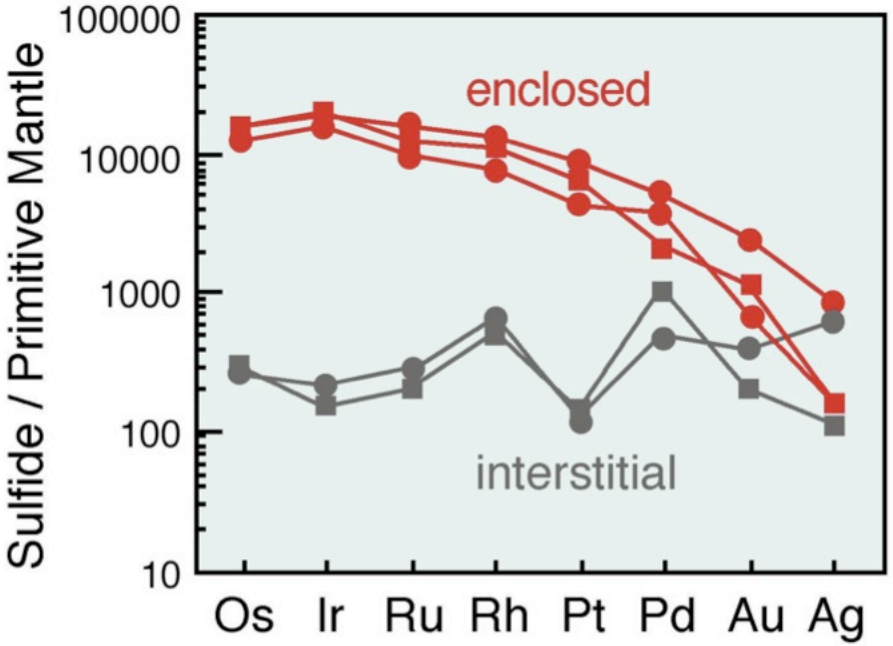
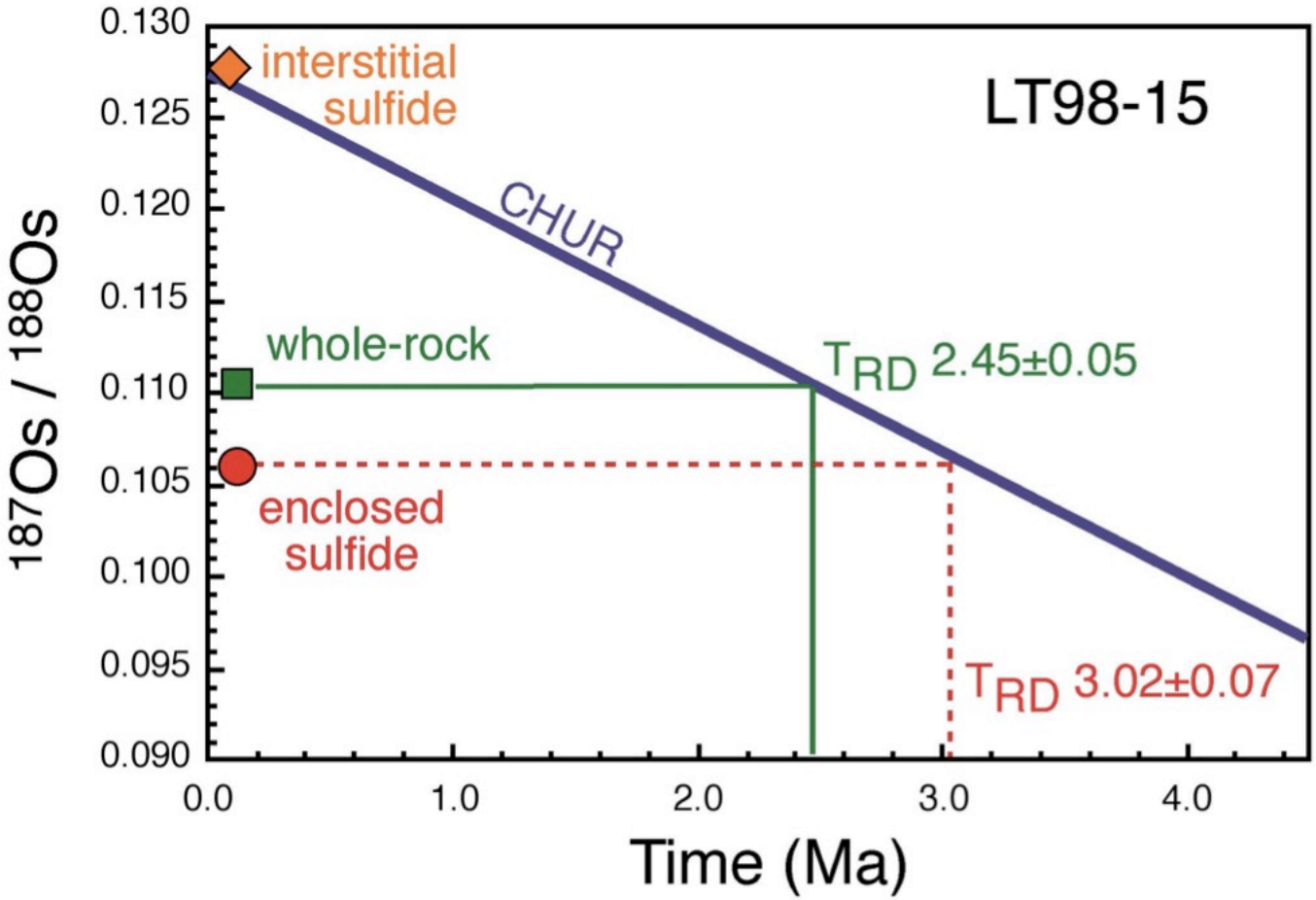
mantle sulfides – enclosed

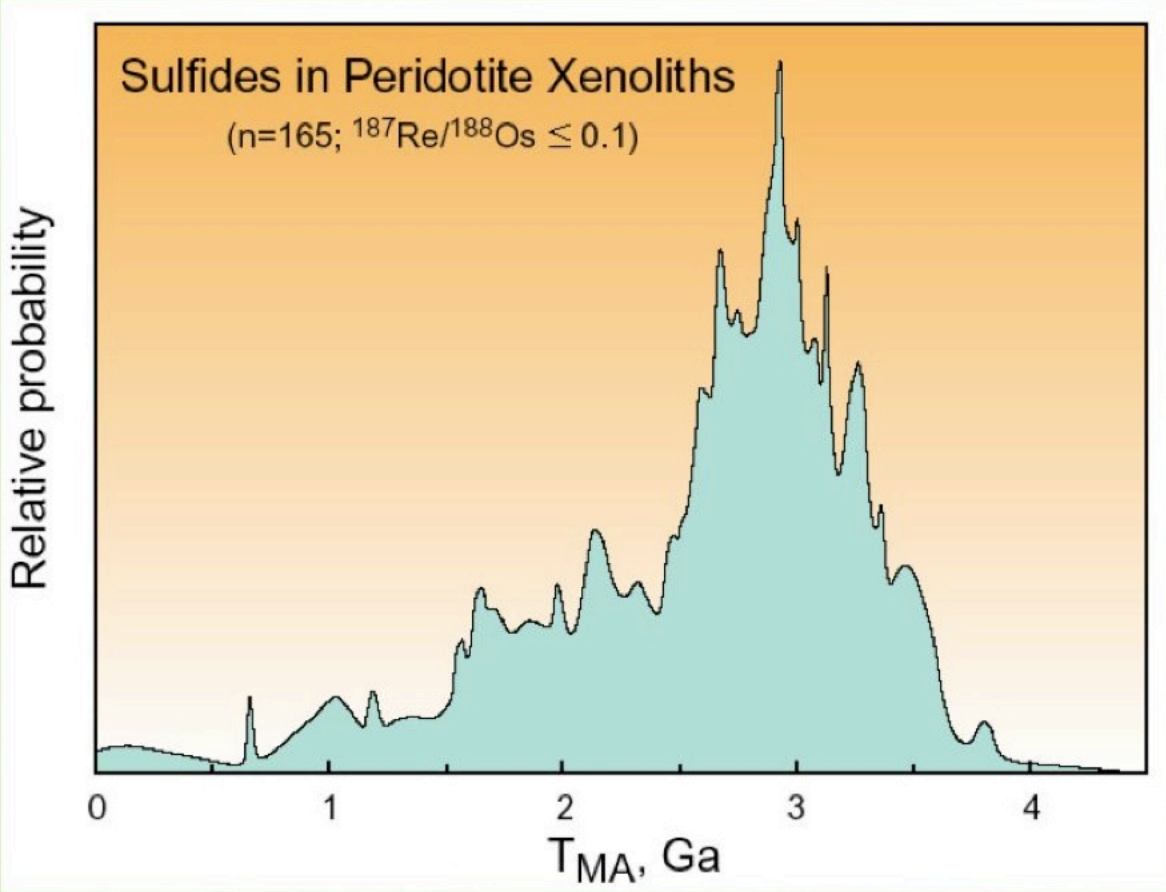




T_{RD} sulfide ages



How old is the SCLM?
Re-Os dating of mantle sulfides



Individual sulfide grains in peridotite xenoliths

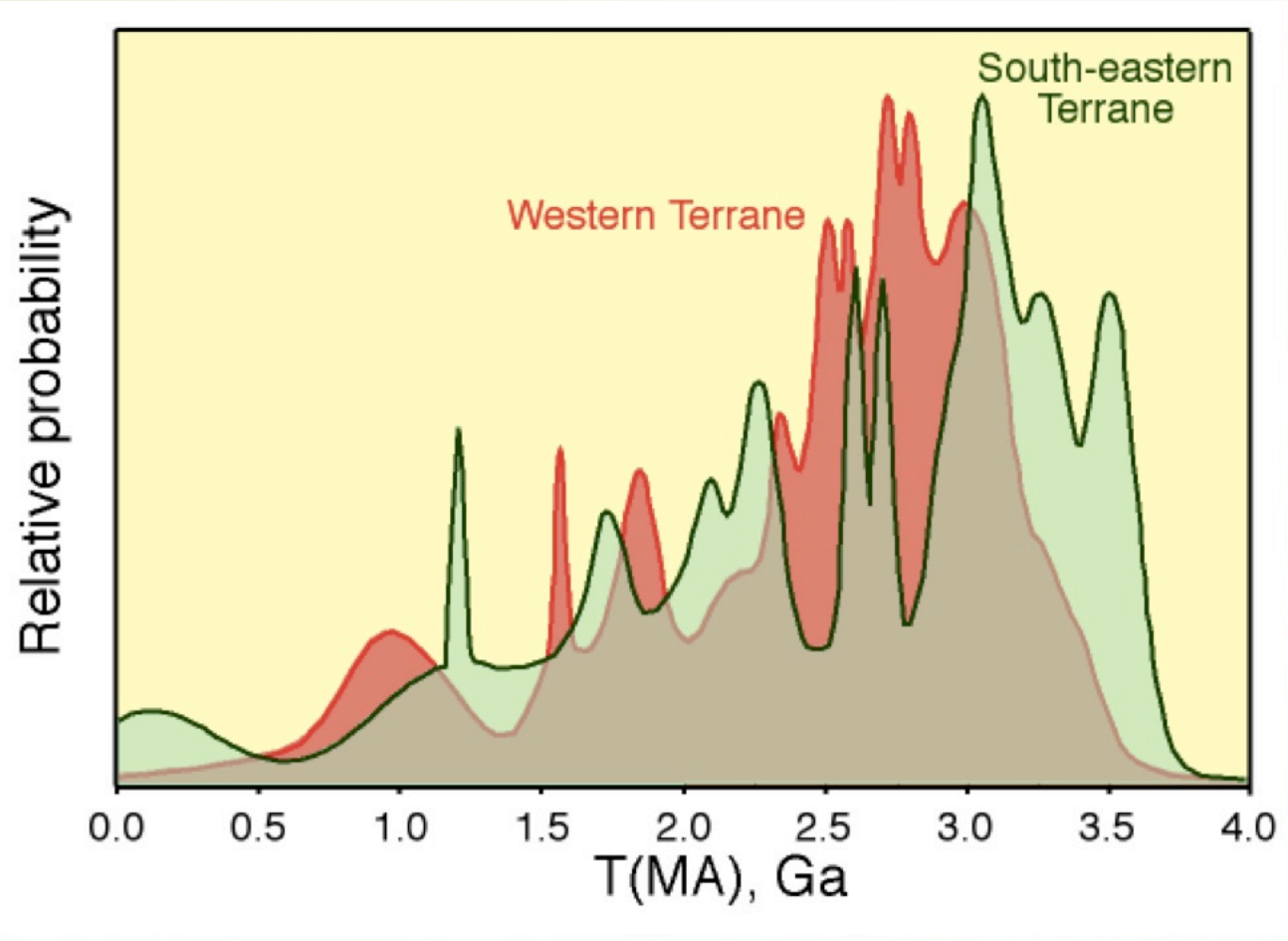
No Hadean model ages - few >3.5 Ga

Major peak ~3.0 Ga -- formation of most Archon SCLM?

Later peaks = metasomatic events?

A unique period in Earth history!

In-situ Re-Os Dating
Mantle sulfides, Kaapvaal Craton

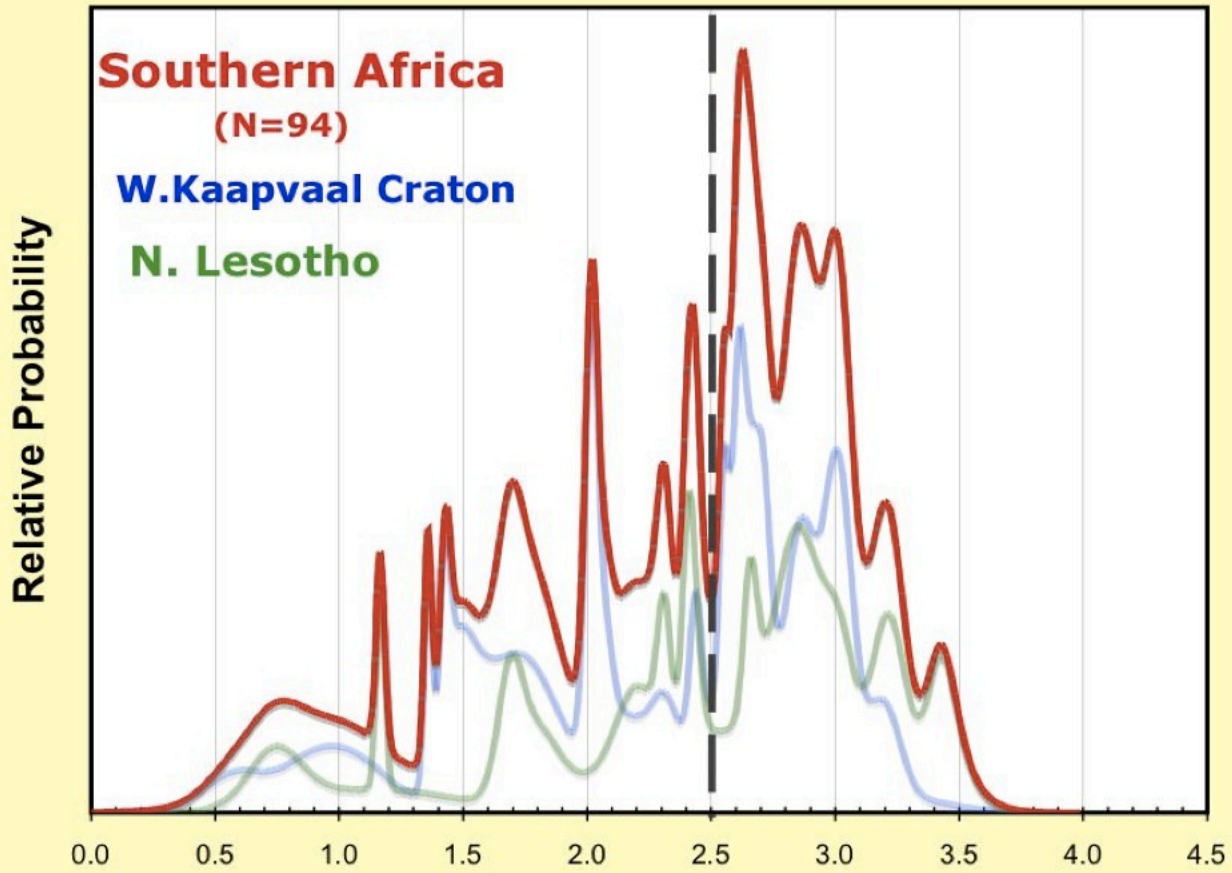


Each terrane carried its own "root" into craton assembly

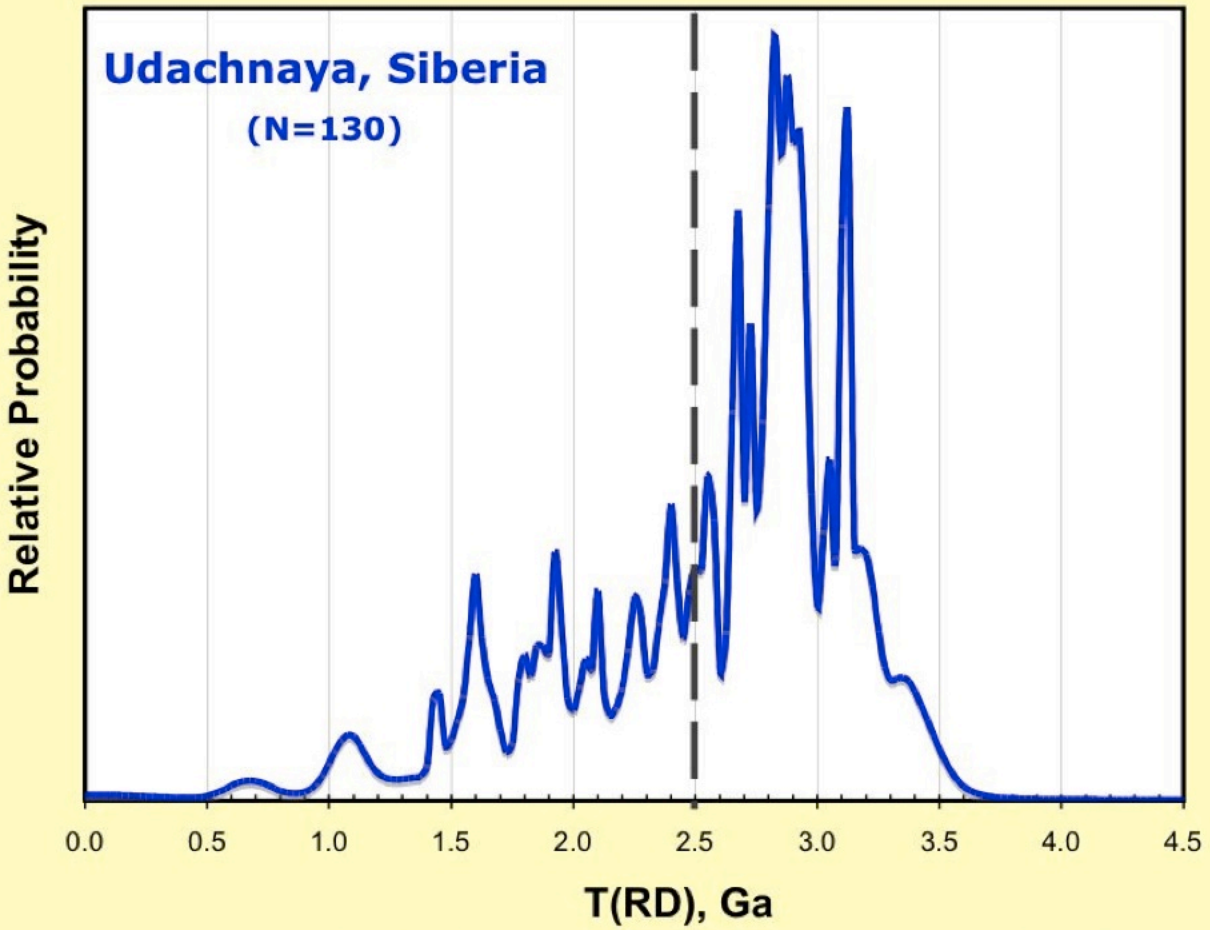
Oldest ages in each terrane = oldest crustal ages

Other peaks = ages of known events (including suturing)

Sulfides in Xenoliths: S. Africa



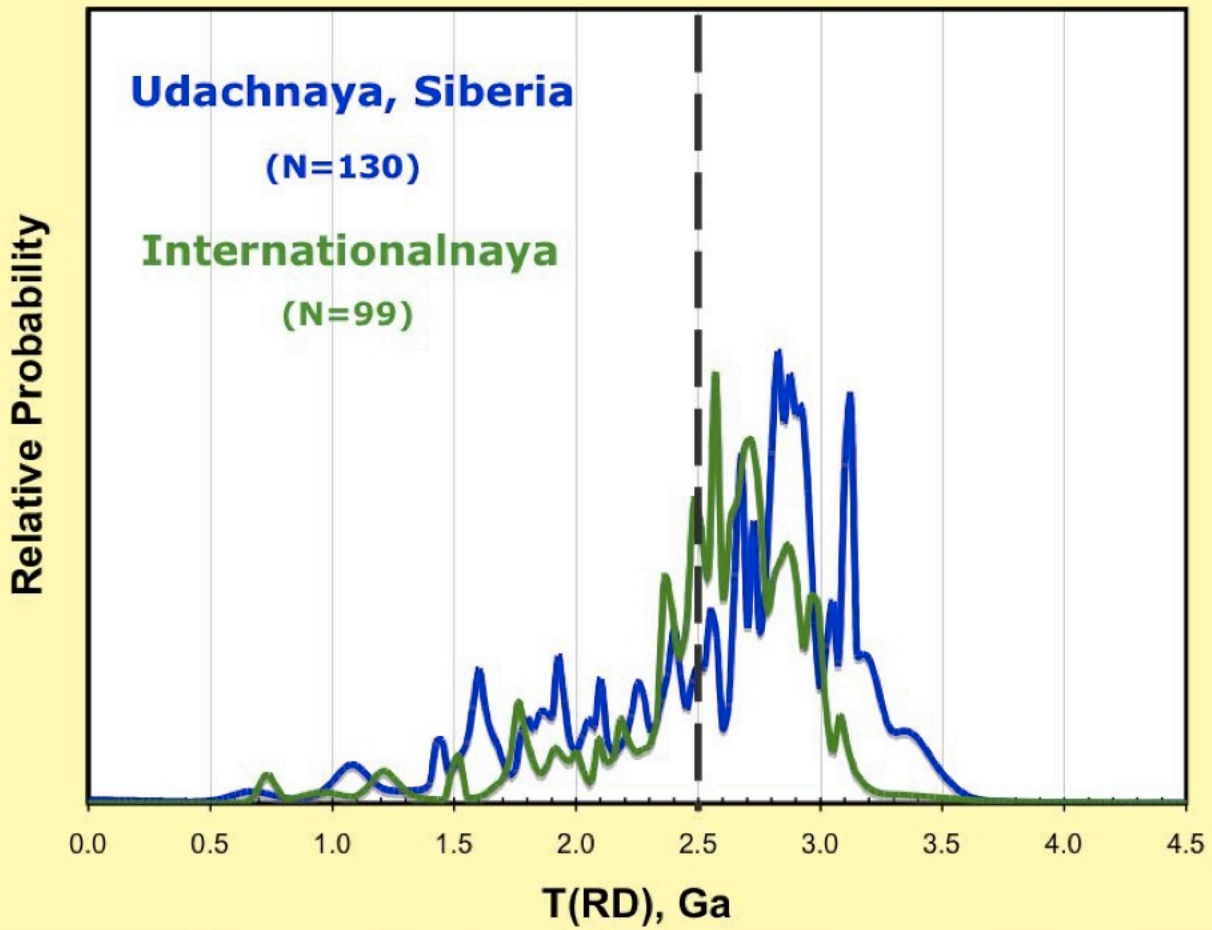
Sulfides in Xenoliths: Siberia



All sulfides enclosed in olivine -- fewer young ages

Main peak 2.7-3.2 Ga

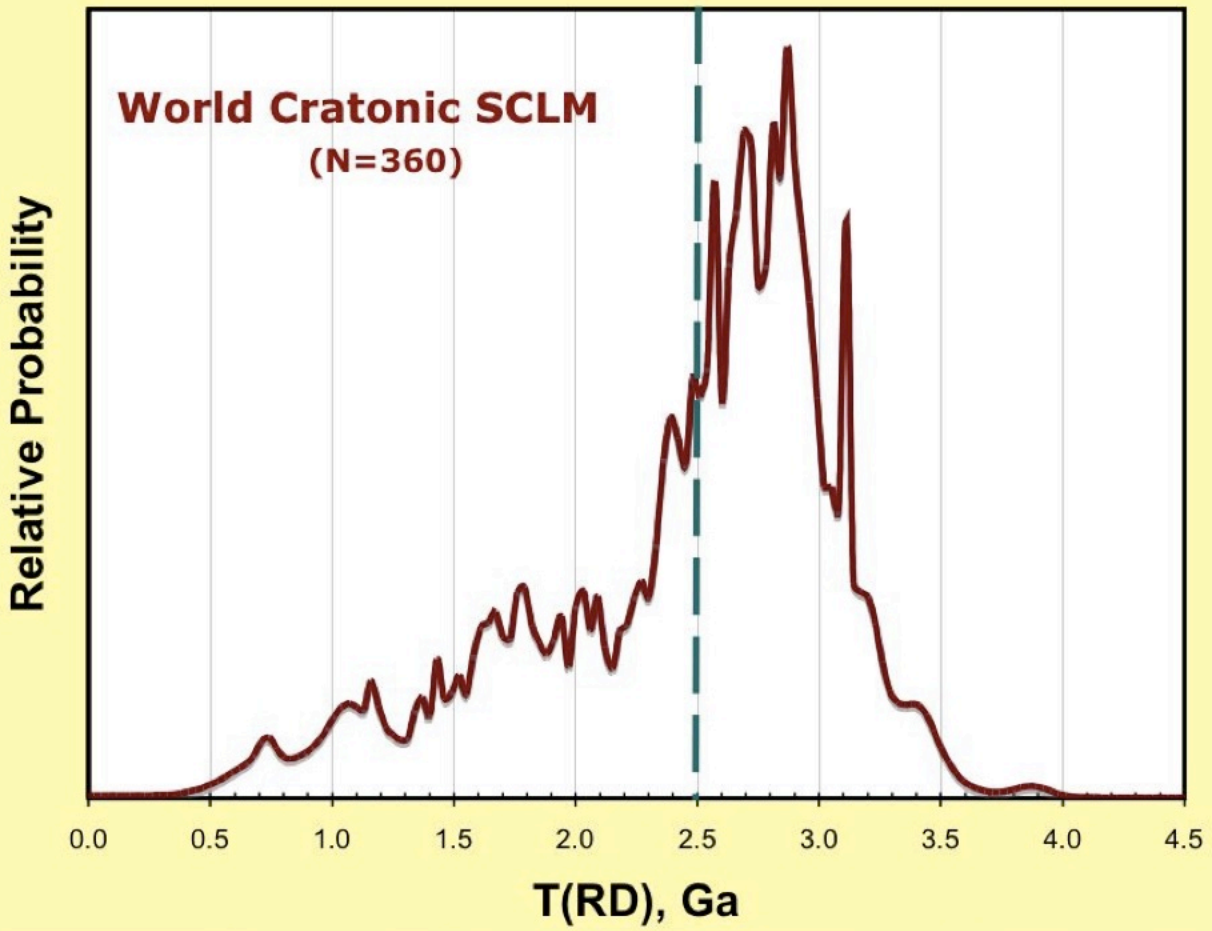
Sulfides in Xenoliths: Siberia



Internationalnaya -- All sulfides enclosed in Gnt -- Cause of age shift?

Main peak 2.4-3.0 Ga

Sulfides in Xenoliths: World



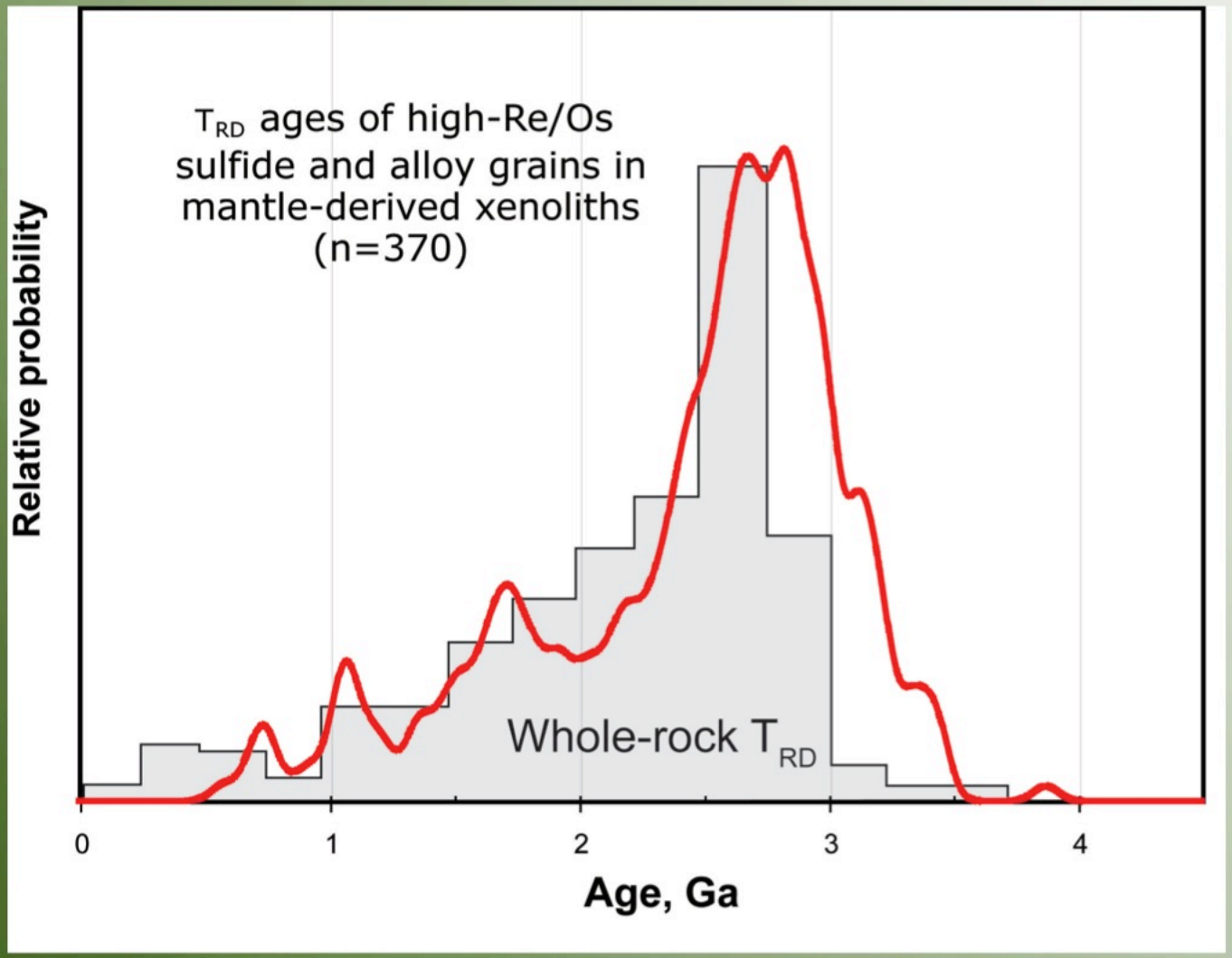
No Hadean model ages - few >3.3 Ga

Major peak 2.7~3.0 Ga -- formation of most Archon SCLM?

Started at ≈ 3.5 Ga!

Later peaks = metasomatic events?

A unique period in Earth history!



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SCLM age=

3 ± 0.5 Ga

Whole-rock model ages = minimum values, because of mixing >1 sulfide generation – but overall agreement on the oldest T_{RD}

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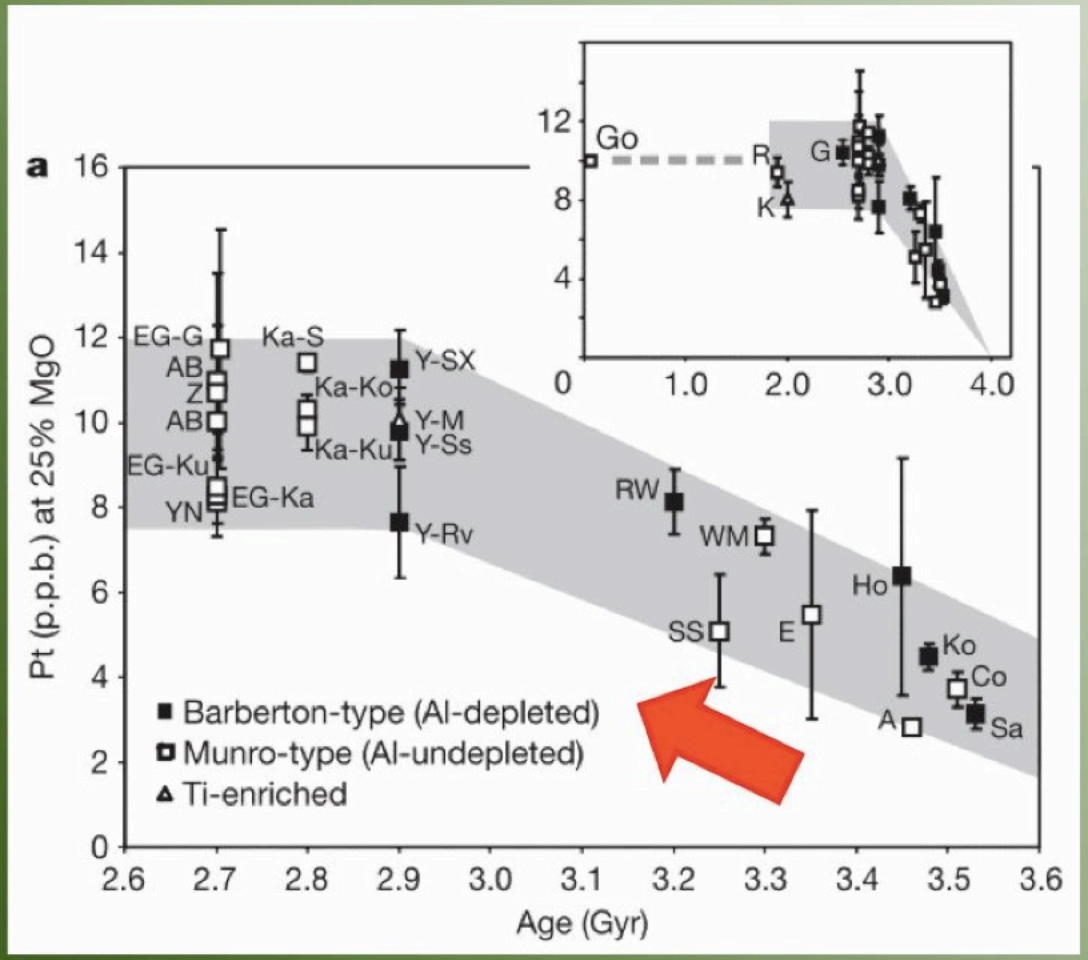
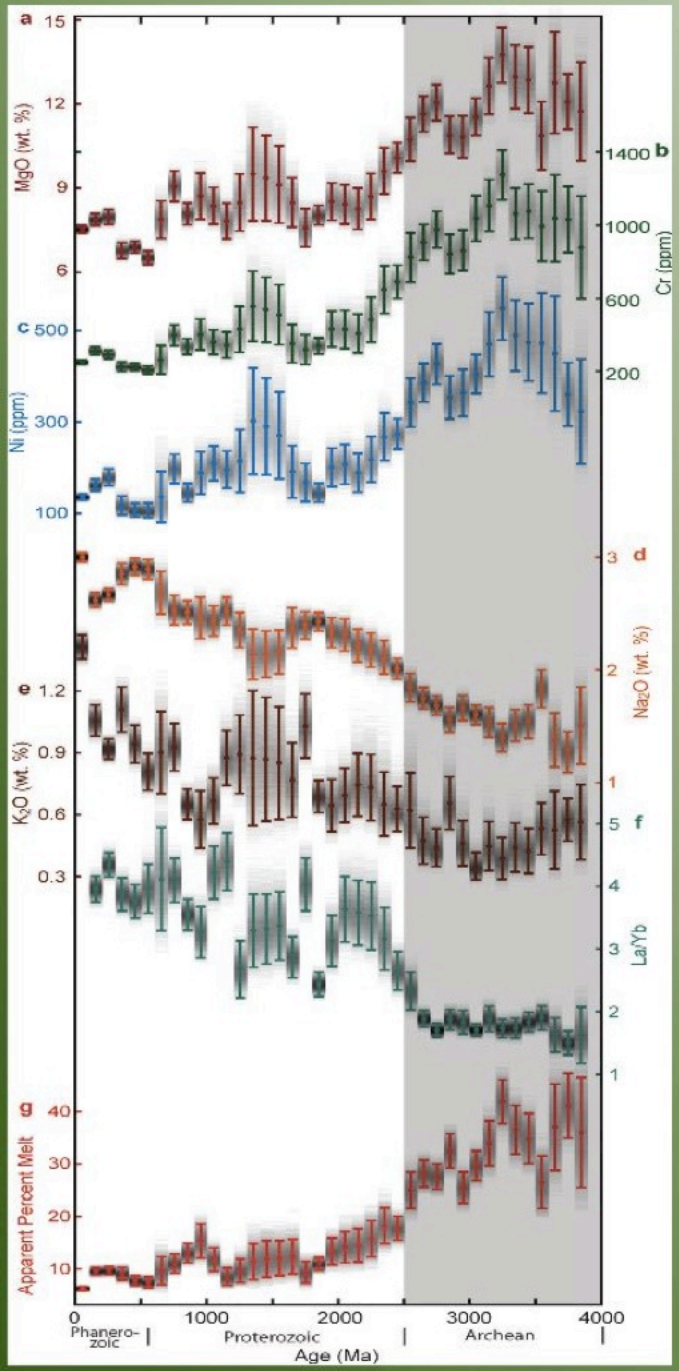
How old is the SCLM?
PGE contents of komatiitic magmas

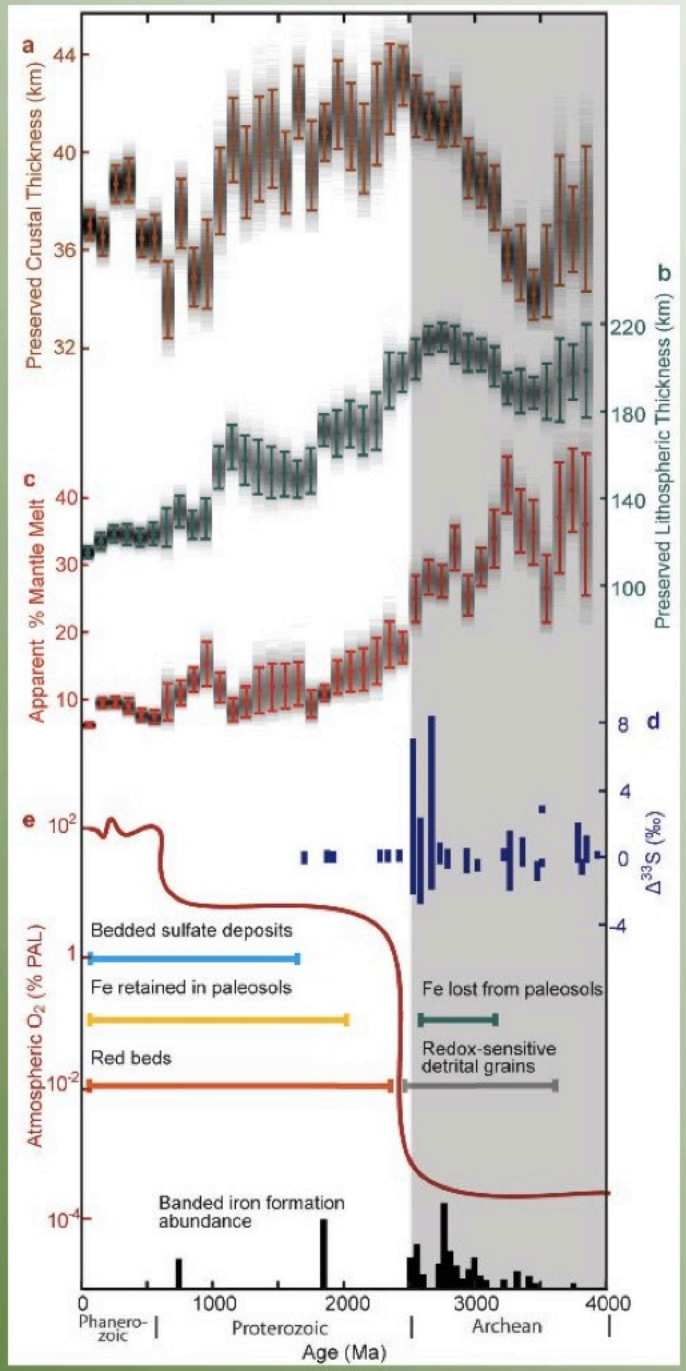


Variations in the PGE content of komatiites through time indicate that the mantle was homogenised between 3.5 and 3.0 Ga.

Consistent with stirring of the mantle by a burst of deep-sourced plumes between 3.5-3.0 Ga (Major Mantle Overturn)

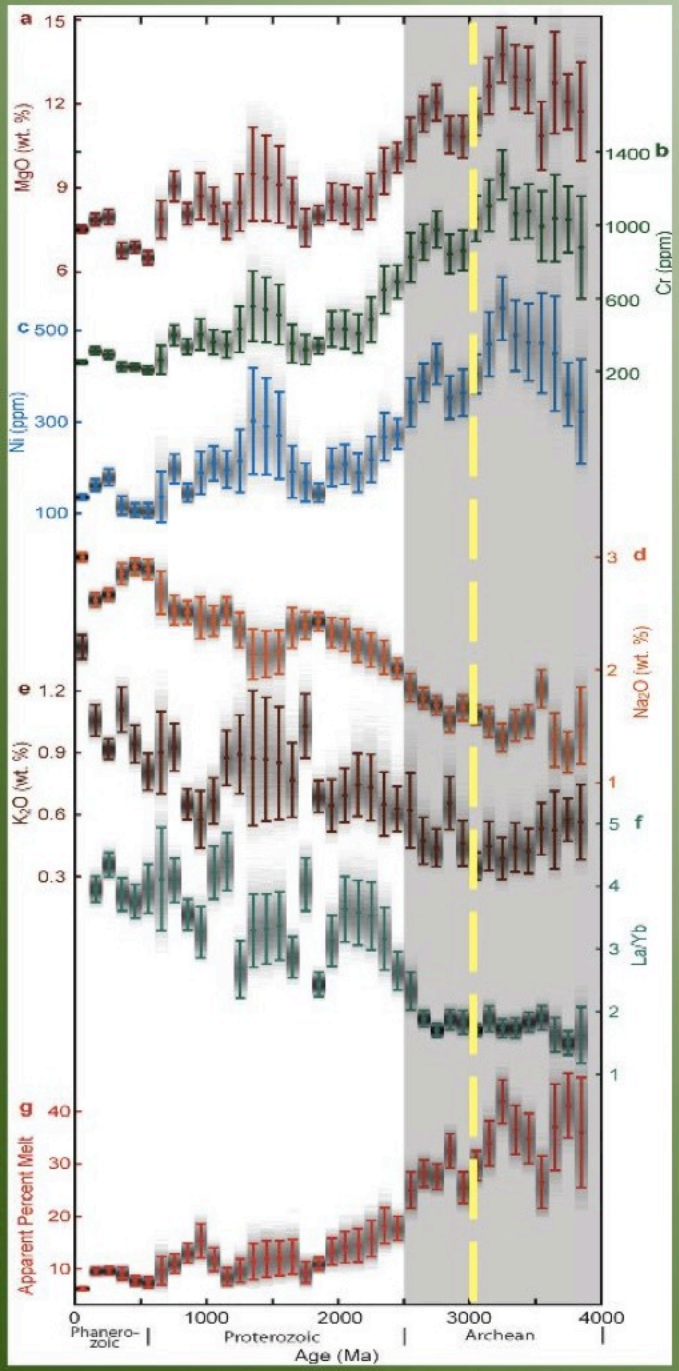
(Maier et al., 2009)

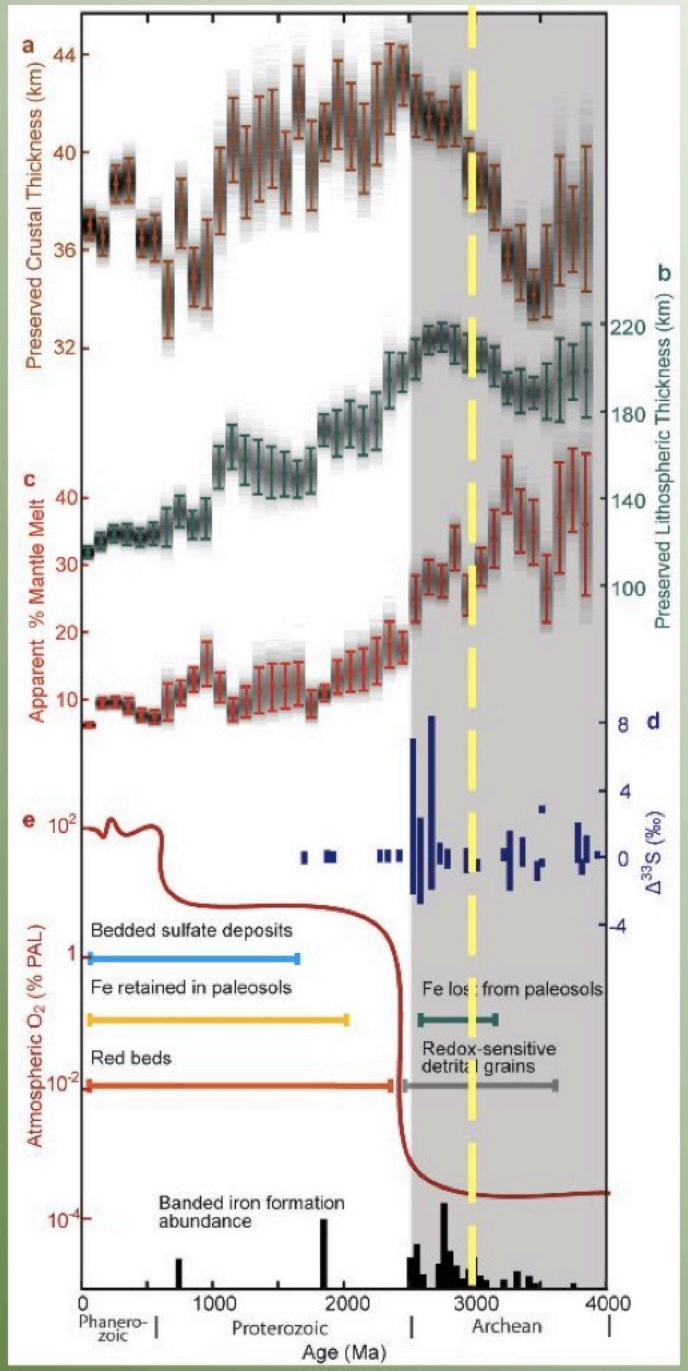




Keller & Schoene
Nature 5/2012

Major changes in chemistry/origin of mafic rocks, and crustal dynamics, at 2.5 Ga ----





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Keller & Schoene
Nature 5/2012

Major changes in chemistry/origin of mafic rocks, and crustal dynamics, at 2.5 Ga ----

Or by 3 Ga?

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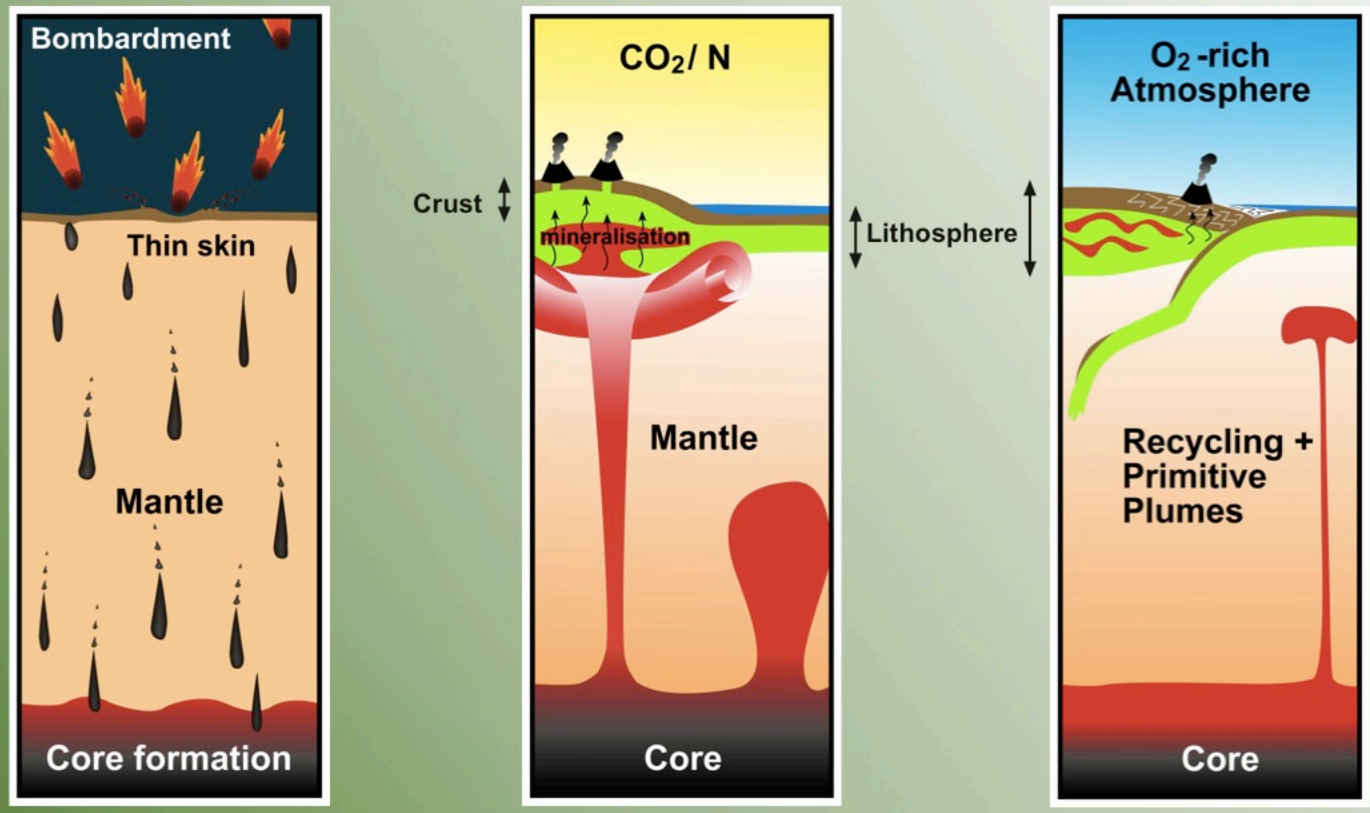
SCLM -- An Archean Genesis

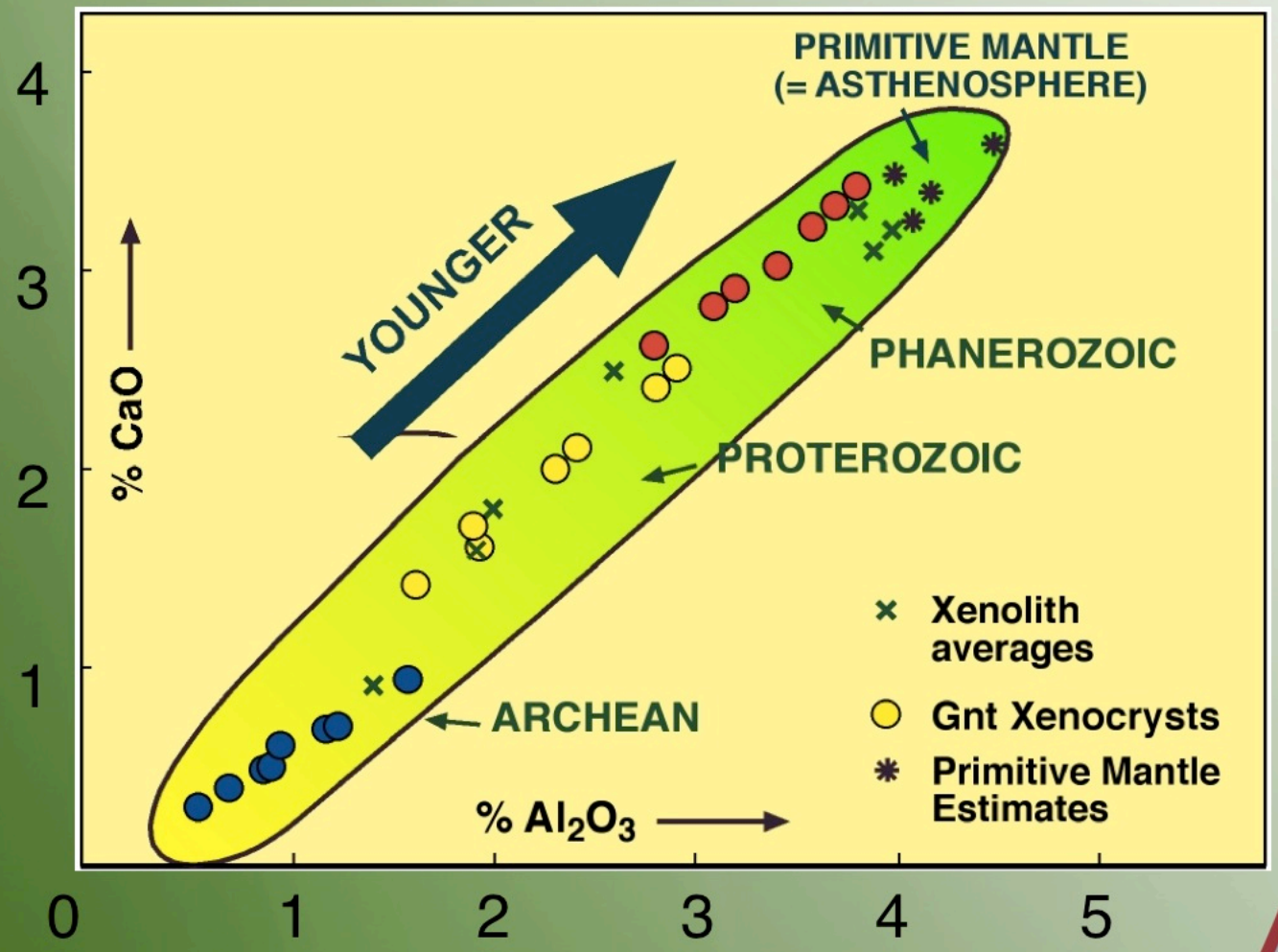


Early Earth
- no stable SCLM
- little preserved crust

Archean (3.6-3.0 Ga)?
- mantle overturns form stable SCLM
- some subduction?

Present Day
- subduction
- steady-state recycling
- no stable SCLM formed

Secular change in SCLM composition



Samples

Xenoliths and Gnt xenocrysts in

-Kimberlites

- Lamproites

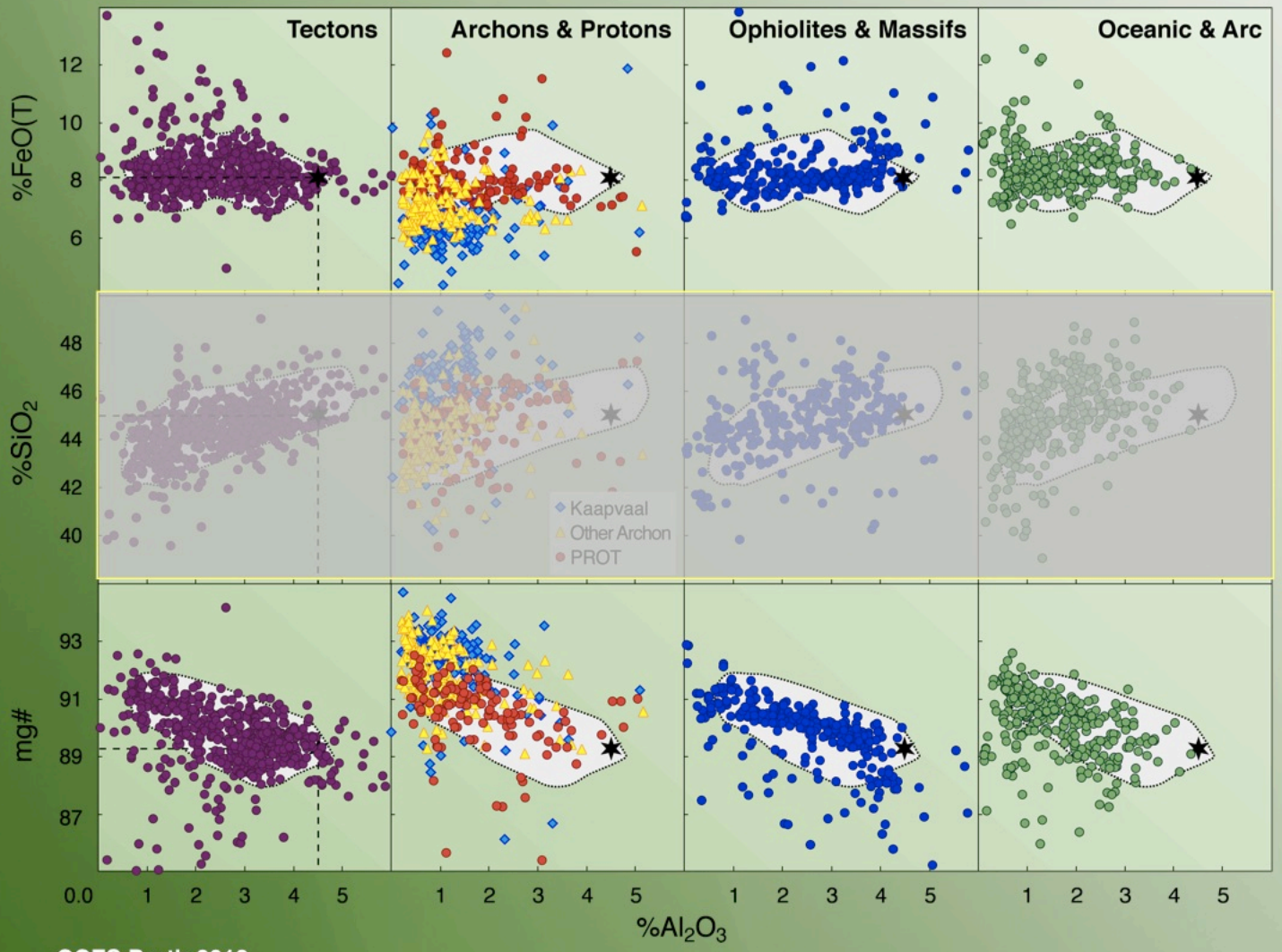
- Basalts

Progressively less depletion through time?

Sampling the Archean SCLM

- Xenolith Suites in Kimberlites
  - 85% of analyses from Kimberley mines (huge dumps)
  - Completely dominated by garnet lherzolites
    - Pretty, can do P-T, etc etc
    - High Si/Mg (opx-rich)
    - Now obvious these are metasomatically refertilised!
- Xenolith suites in alkali basalts
  - Rare -- E. Greenland, Cape Verde Islands, W. USA
- Exposed massifs with Archean ages
  - Rare -- mainly Western Gneiss Region (Norway)

Archean SCLM's unique Fe depletion -- a signature of high-P melting?



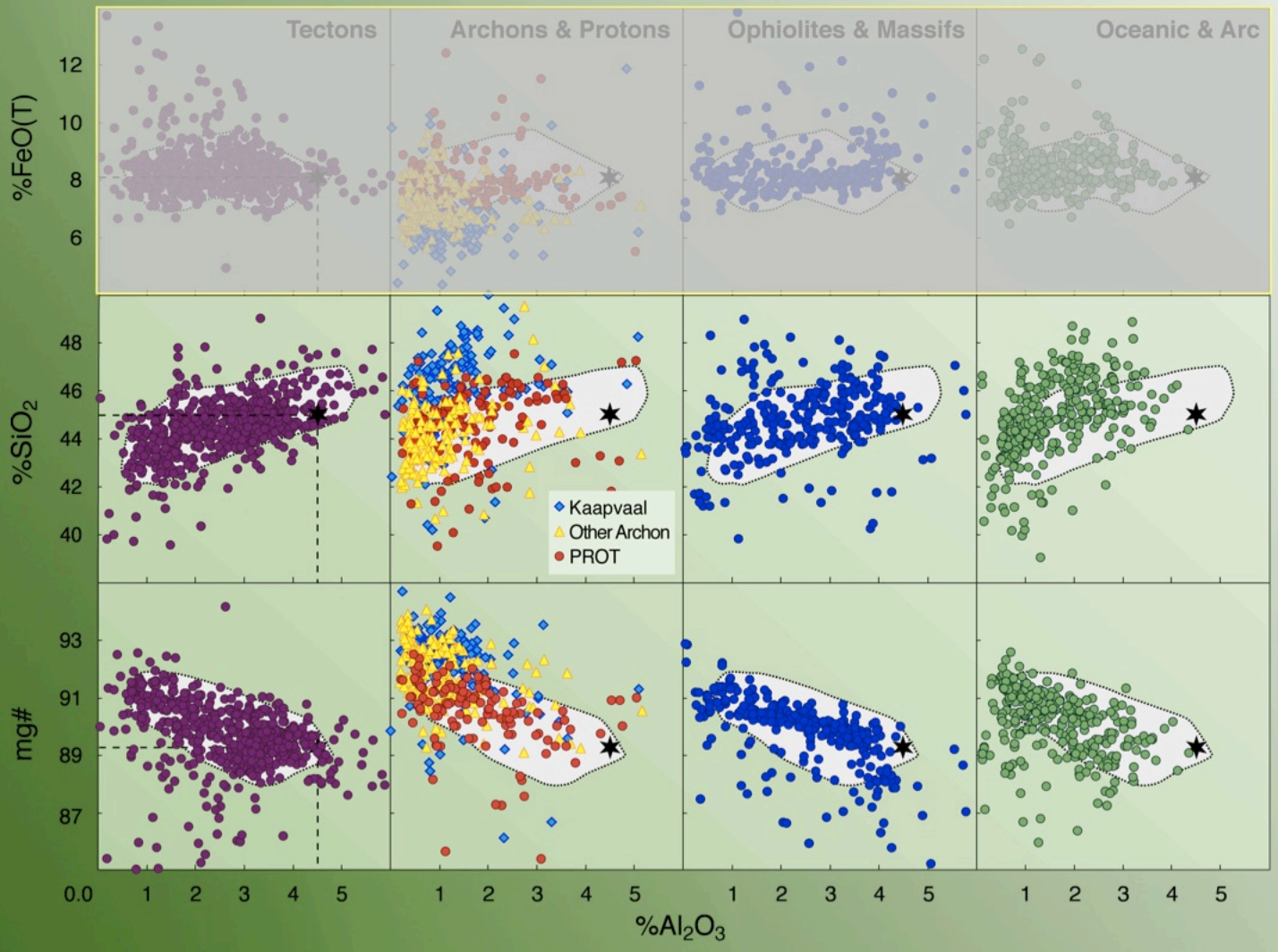
Young peridotites have FeO = 8±1% at any degree of depletion

Shallow melting processes…..

Most Archon SCLM lower-Fe

High-P melting !

Archean SCLM: Si enrichment (?)



Most Archon SCLM high-Mg#

High Si/Mg rare outside Kaapvaal Craton

Biased sample!

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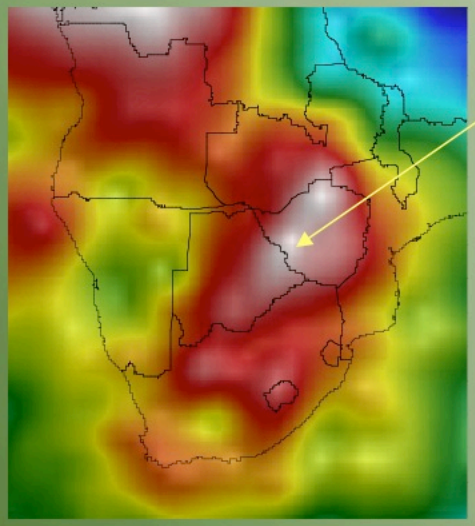
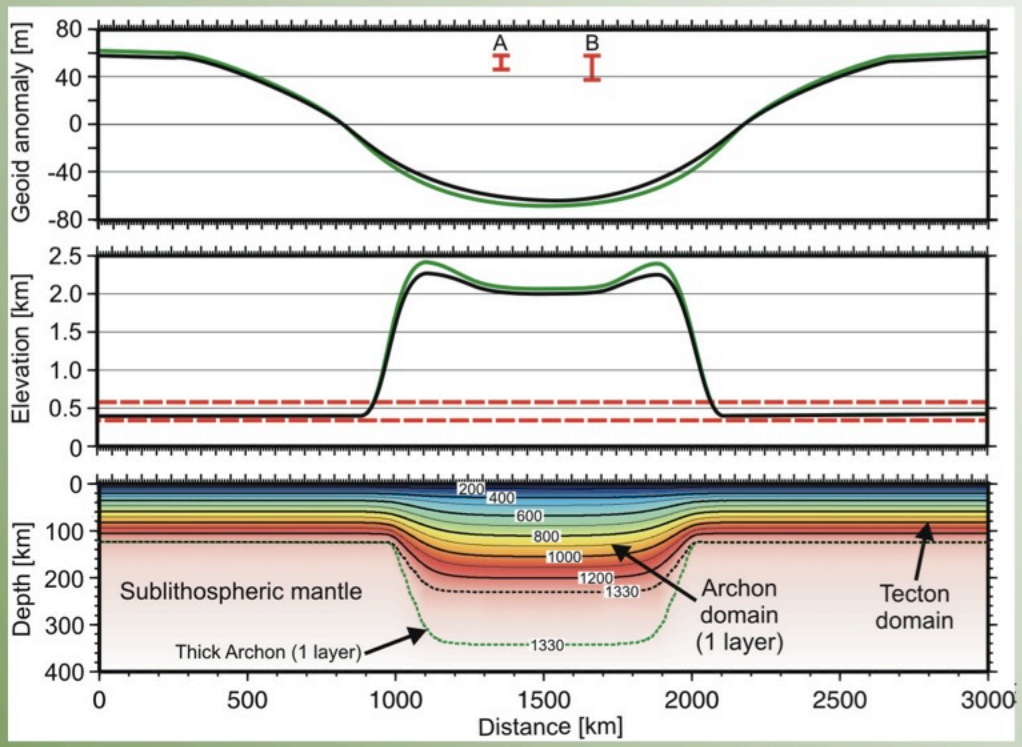
Seismic Tomography -- A problem with the models



Archon cores: thick, depleted, cool; high Vs

Can't model with "typical Archean SCLM"

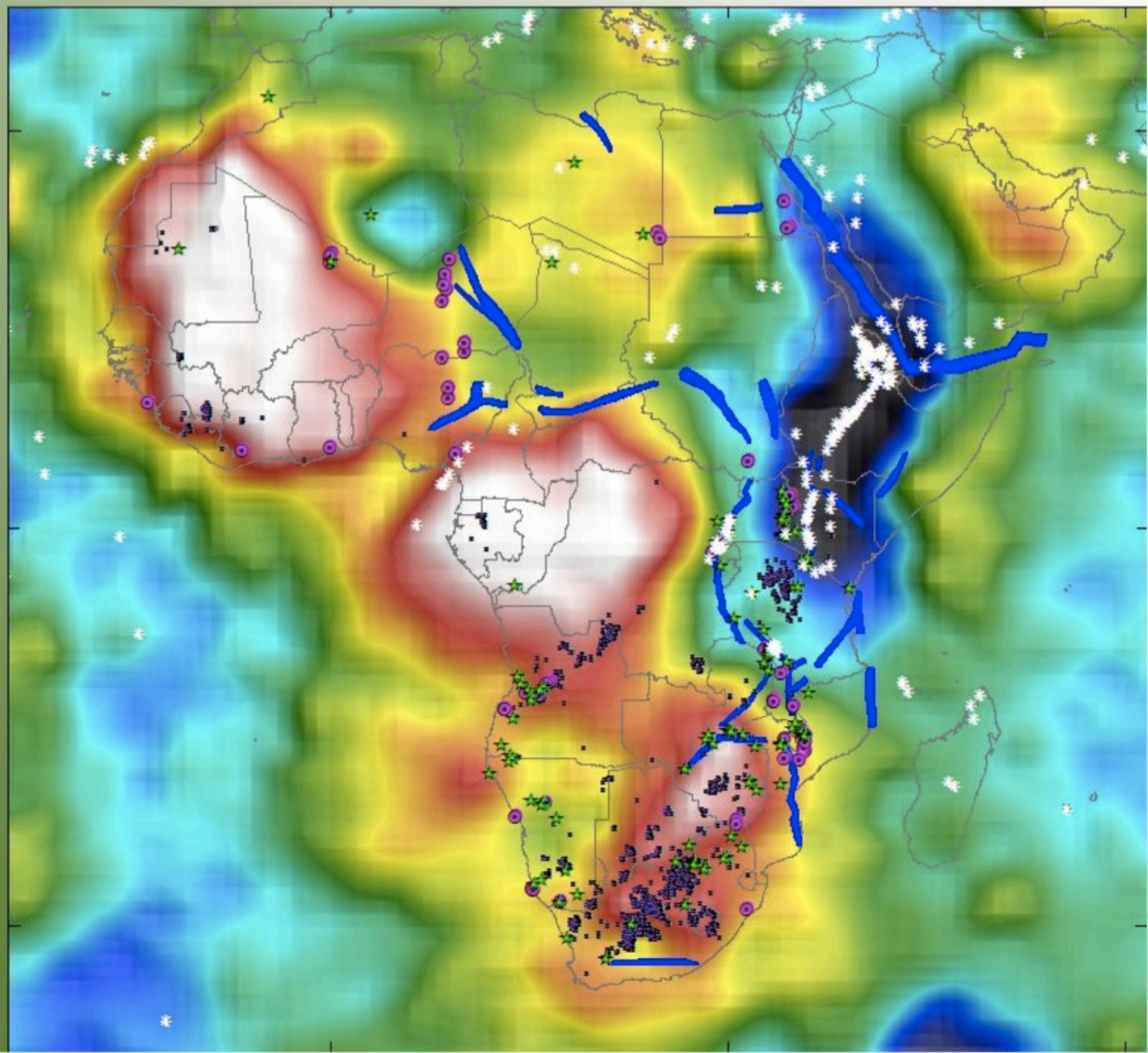
AND -- thick "typical" SCLM is *too* buoyant -- gives too low geoid and too high elevation

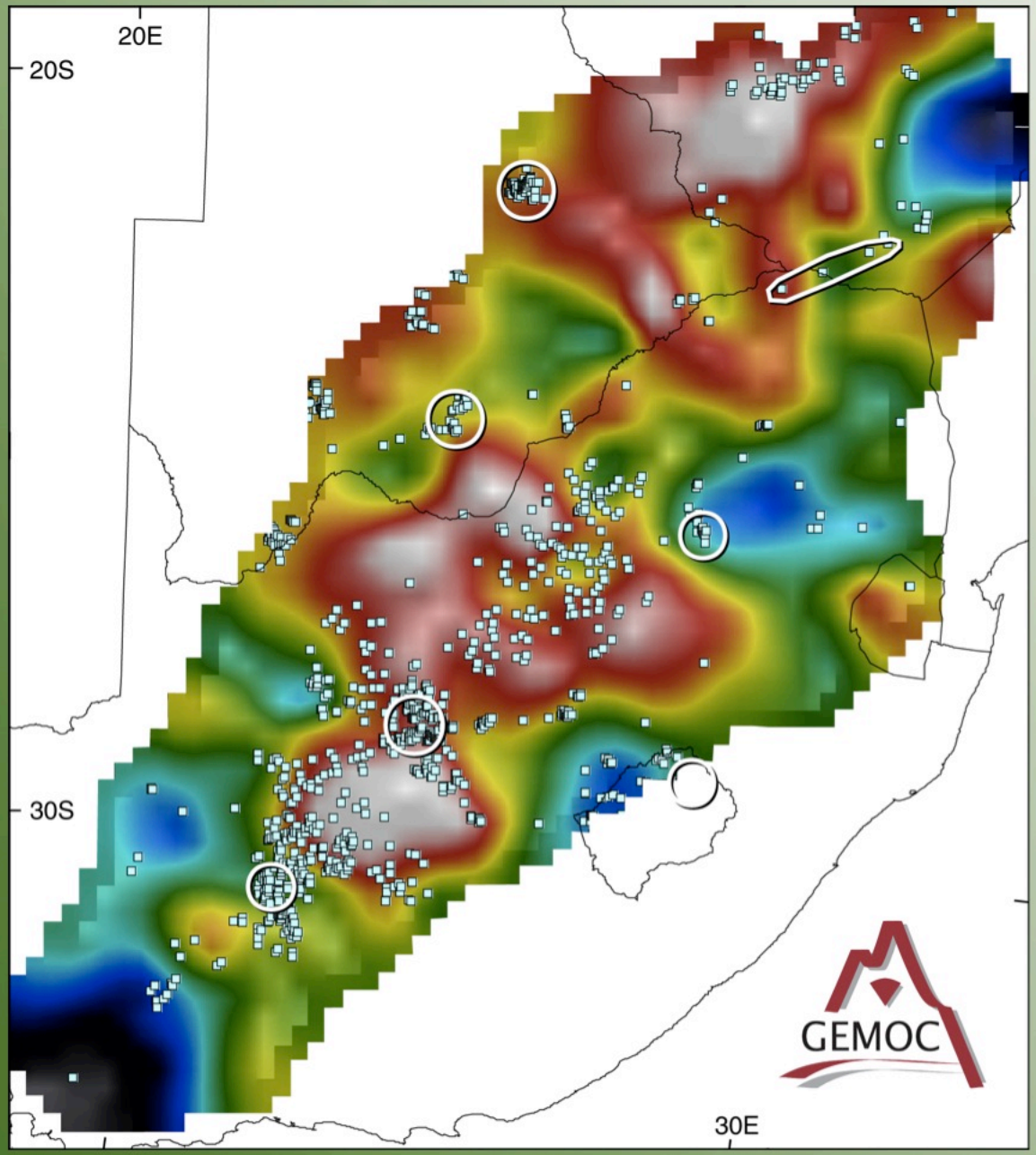


SCLM Control on Rifts and Alkaline Magmas

Cratonic margins act as focal point

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





Detailed Vs model 200±50 km

Fouche et al. 2004

+ kimberlites

Kimberlites cluster *around* high-Vs domains -- no samples of these depleted cores

Circles -- best xenolith - xenocryst suites: sampling refertilised low-Vs SCLM

A biased sample!

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Lherz(olite) -- Case study in mantle refertilisation

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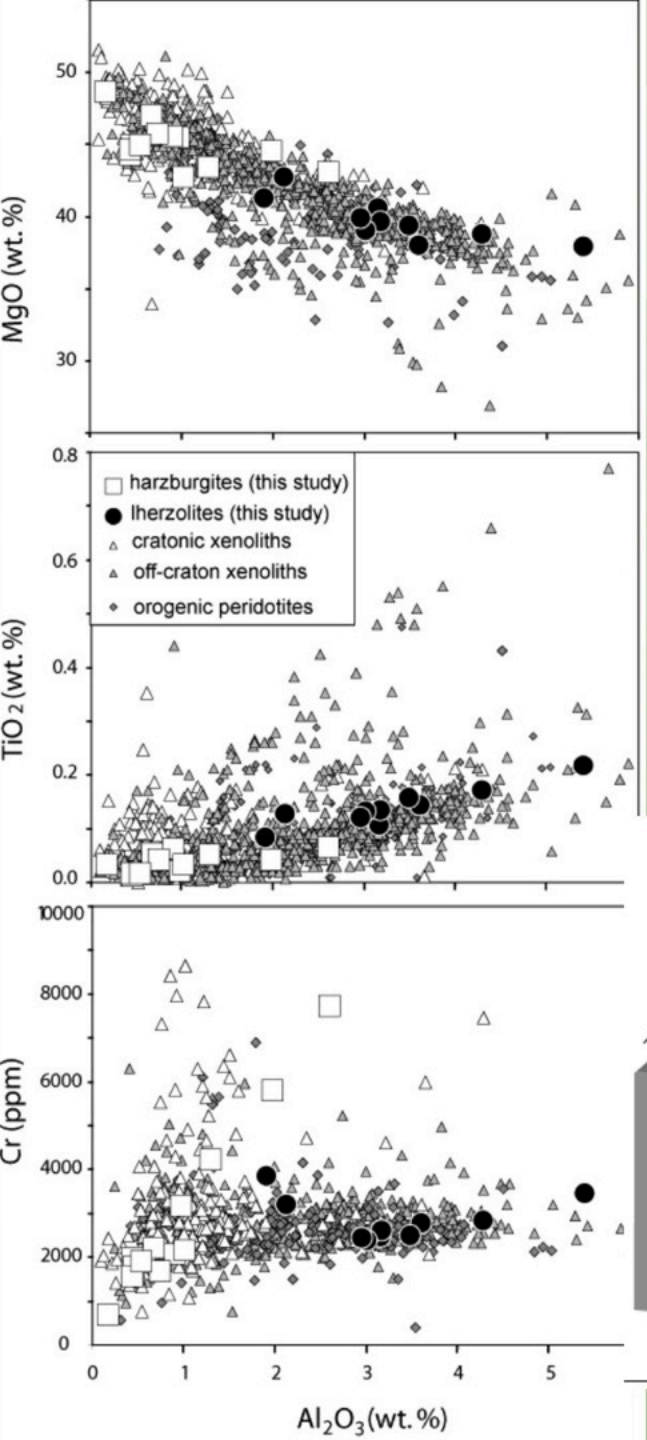
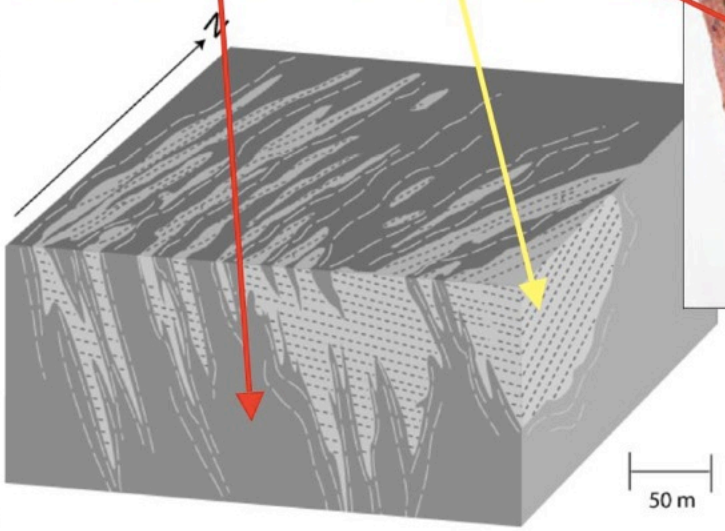
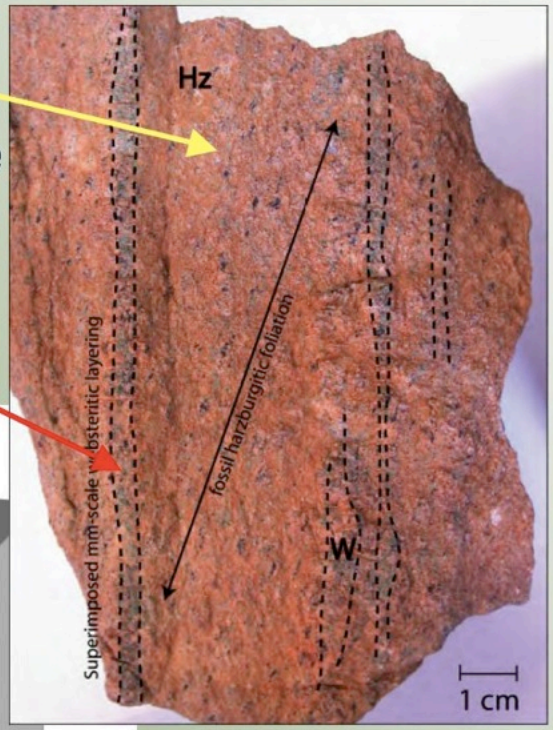
Harzburgite

Lherzolite/websterite







Le Roux et al., 2006

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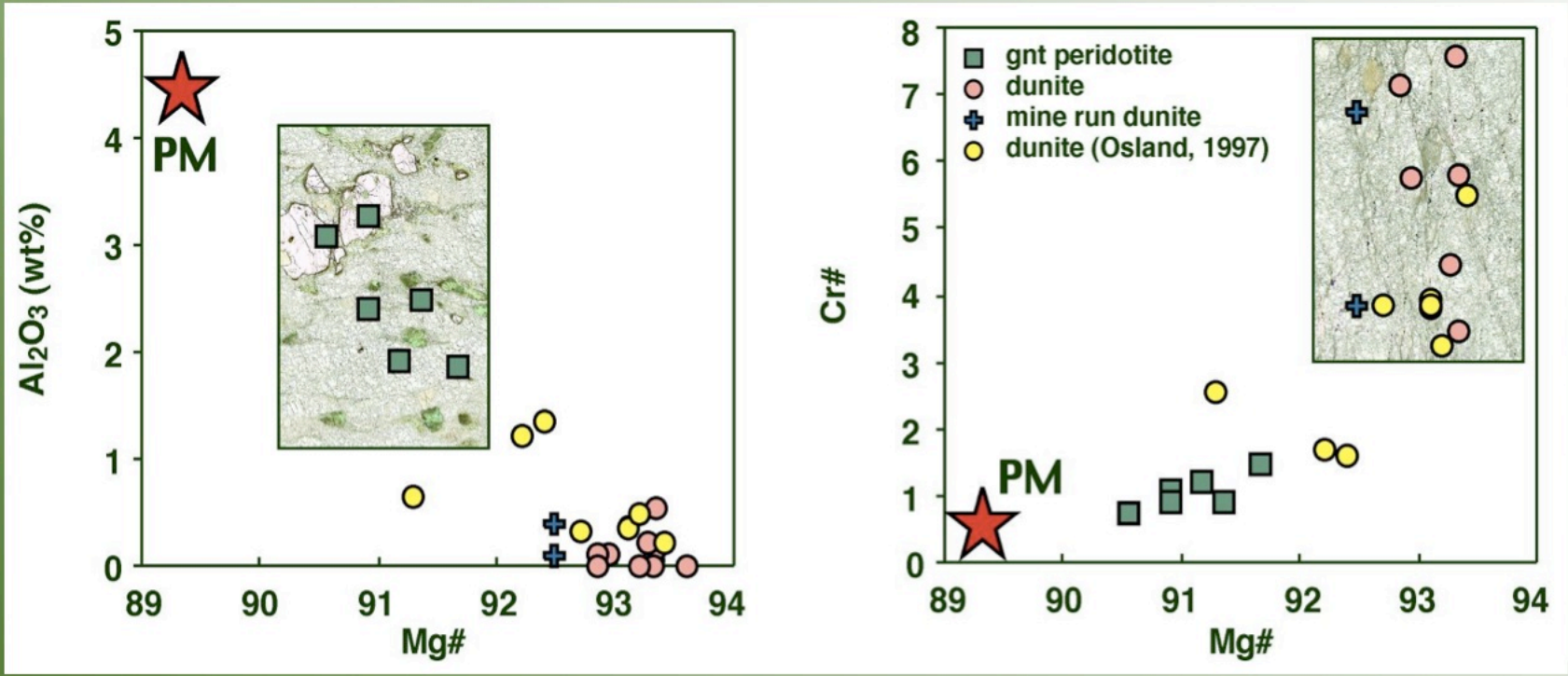
"Pristine" Archean SCLM: More depleted than we think?

Gusdal quarry and Ugelvik gnt peridotite, Norway

- Western Norway: huge bodies of dunite/harzburgite
- Zones of garnet lherzolite ± eclogite
- Re-Os: dunites are *Archean*, lherzolites are *Proterozoic*
- *Refertilisation process* -- an analogue for most Archean SCLM?

Western Gneiss Region (Norway) Dunites: Refertilisation to Lherzolite



Proterozoic refertilisation of Archean dunite/harzburgite:

add gnt + cpx; increase Al, Fe, Ca, Na; lower Mg#, Cr#

~ *All* trace elements (REE, Sr, Zr etc) also increased!

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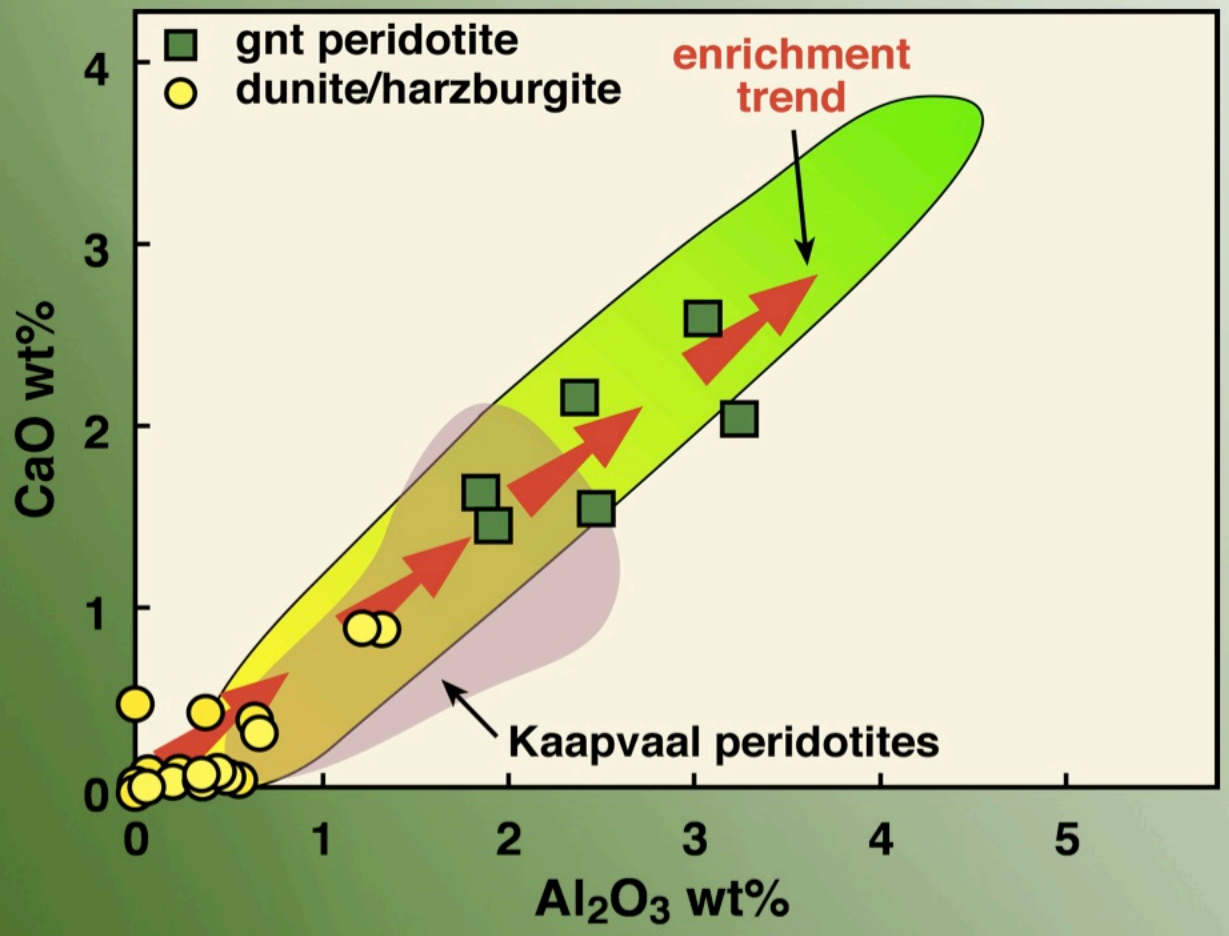
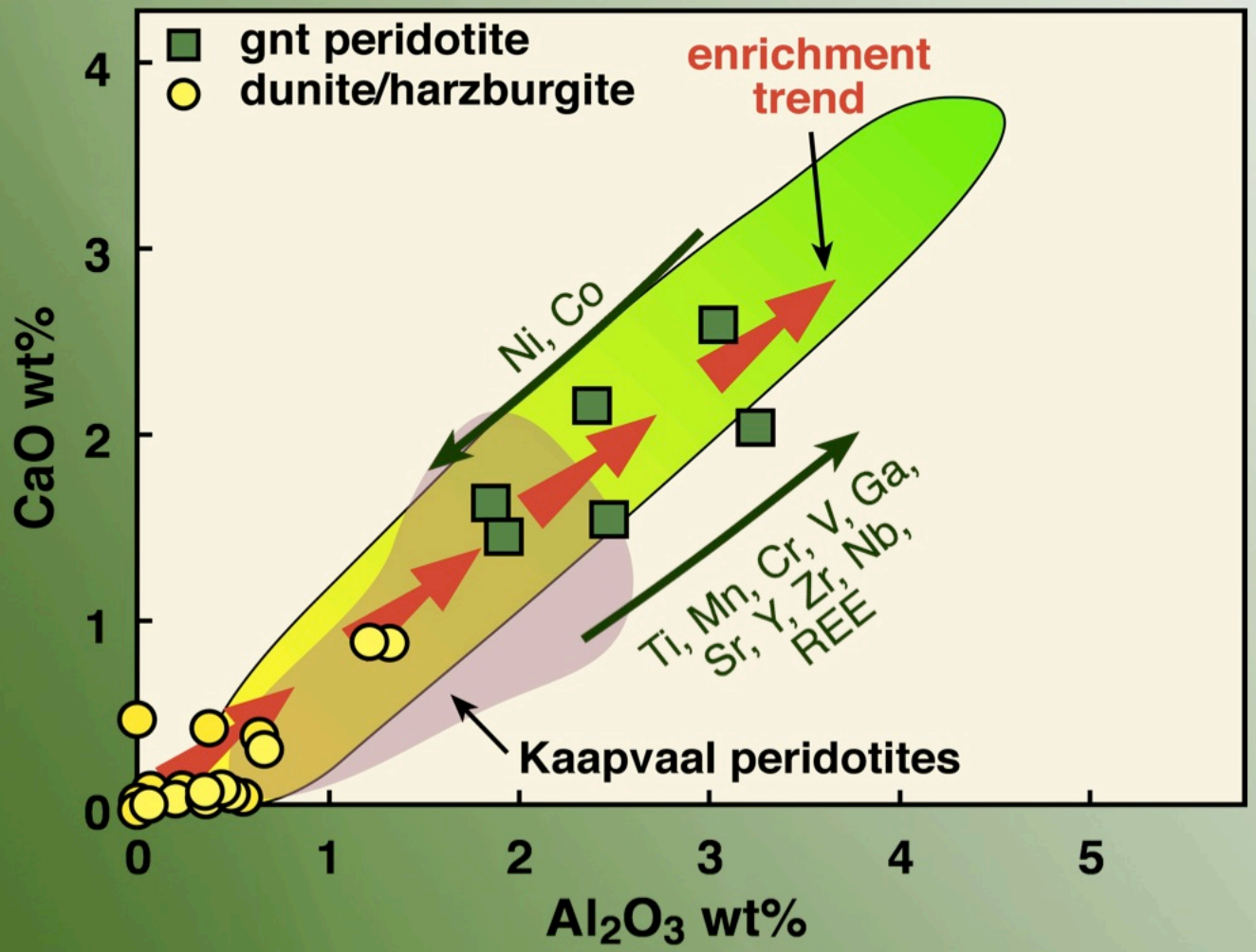
Ockham's
Razor
See Weak
Hypotheses
fall like FLIES!

WGR Dunites -- Refertilisation to Lherzolites



- Dunites/harzburgites extremely depleted
- Lherzolite refertilisation trend mimics xenolith "depletion trend" *--in reverse*
- Kaapvaal peridotite xenoliths = same trend
- Original Archean SCLM ≈ WGR dunite/harz ?

WGR Refertilisation -- Trace elements

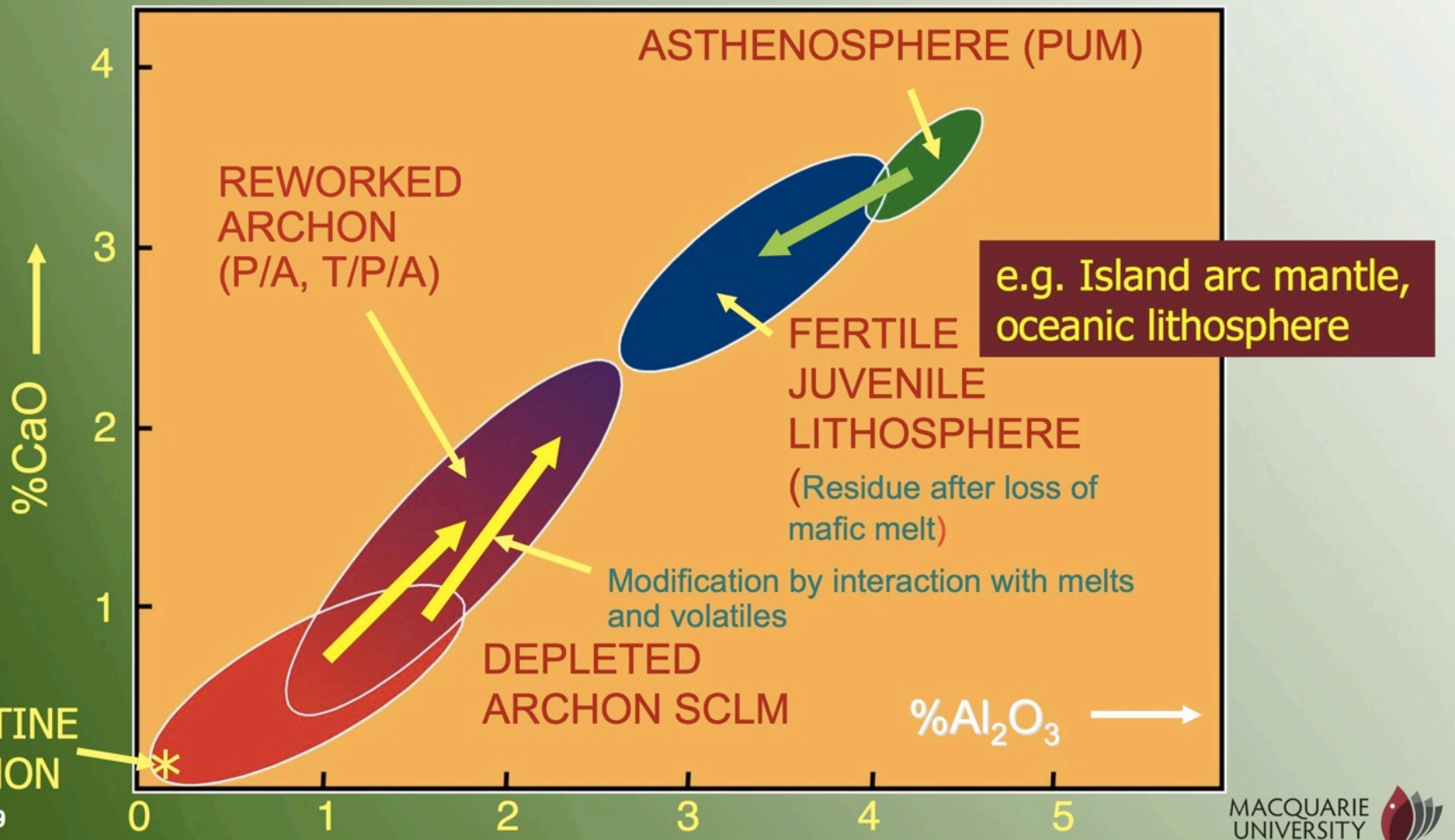


Refertilisation affects all of the "diagnostic" or "robust" trace elements -

None can be used to argue for shallow melting processes

SCLM Compositions and Processes

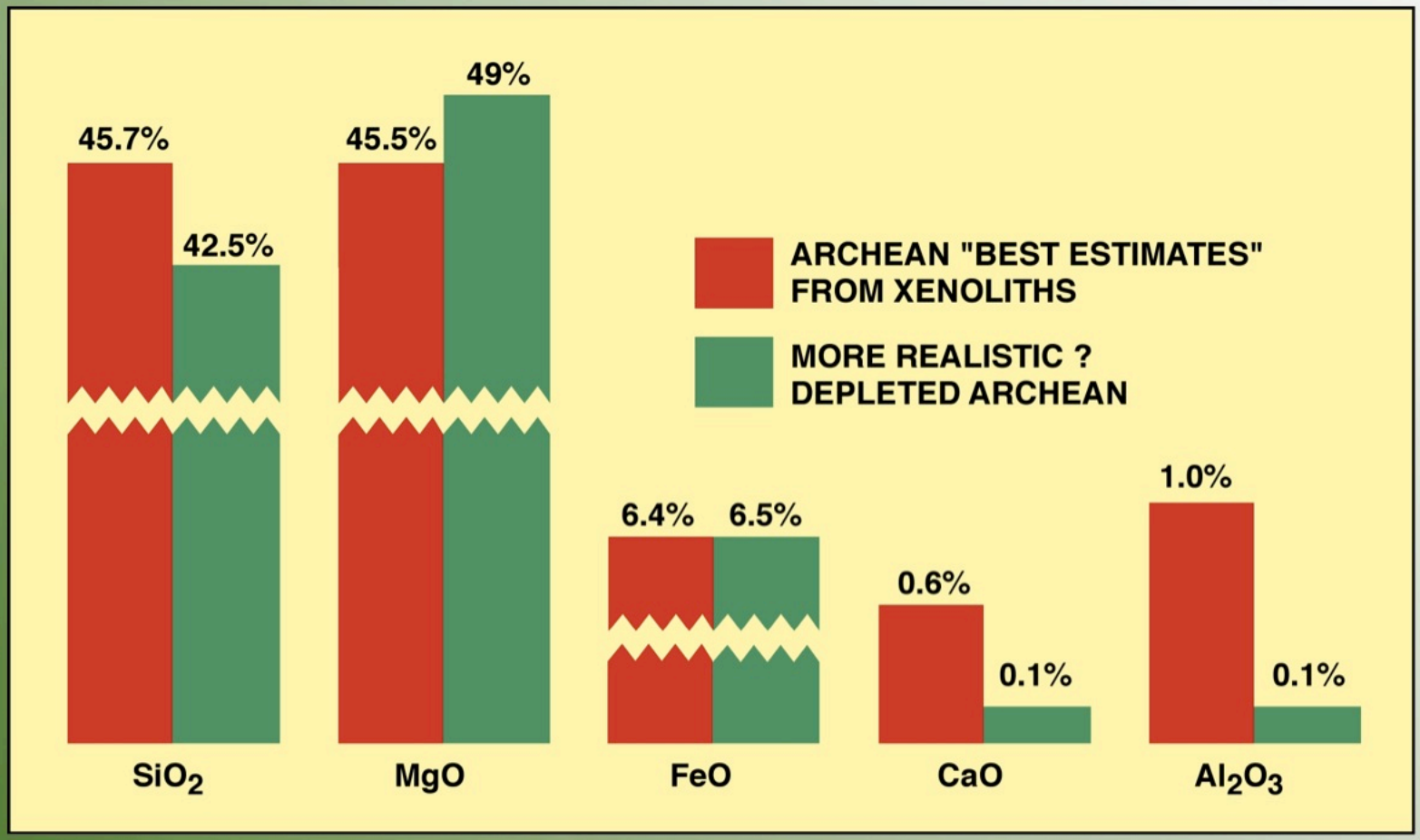
2 processes:- 1) Juvenile fertile SCLM = mafic melt extraction from PUM;
2) Enrichment of depleted Archon



Xian 2009

A More Depleted Archon SCLM

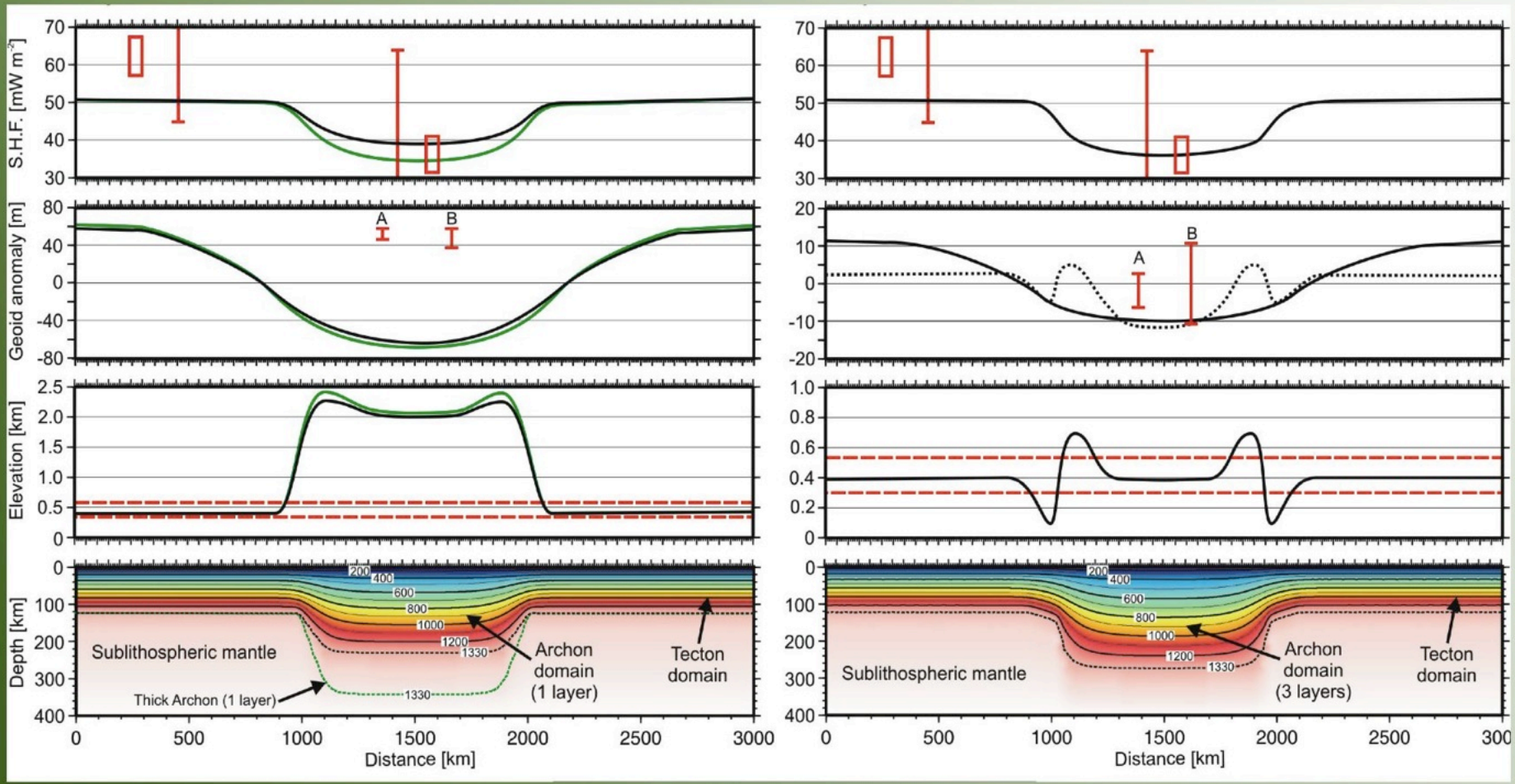
Tough, Buoyant and Still With Us



Griffin et al. 2009, *J. Petrology* 50

A More Realistic Archon SCLM

Solves the Geoid/Elevation problem



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Conclusions: Archean SCLM

- "Typical" Archean gnt lherzolite is a metasomatic product -- cannot be used to model SCLM formation
- Primitive Archean SCLM is much more depleted than estimates from xenoliths -- inconsistent with shallow origin
- Most (all?) formed >3 Ga ago, by deep high-degree melting
- Archean lithosphere (lower crust and SCLM) is much more widespread laterally and vertically than previously thought
- original volume of lithosphere formed in the Archean (>2.7 Ga) far greater than currently assumed -- ≥ 70%
- *What about the Yilgarn?* Only two small kimberlites – sampling fertile mantle – very poor and biased sample – over to geophysics!

Continental drift without subduction on a stagnant-lid planet
Comparisons between the Archaean Earth and Venus

Jean Bédard (Geological Survey of Canada)
Lyal Harris (Institut National de la Recherche Scientifique)

Bédard, Harris & Thurston, The hunting of the snArc (2013) Precambrian Research 229:20-48
Harris & Bédard, Crustal evolution and deformation in a non-plate-tectonic Archaean Earth: Comparisons with Venus (2013) Archean Earth and Early life, Springer (in press)

Natural Resources Canada
Geological Survey of Canada
GSC-Québec

INRS
Université d'avant-garde

Why do people believe in Archaean Plate Tectonics ?

1) Generation of compressional fabrics and assembly of Terranes requires horizontal tectonics… But does this REQUIRE Plate Tectonics ?

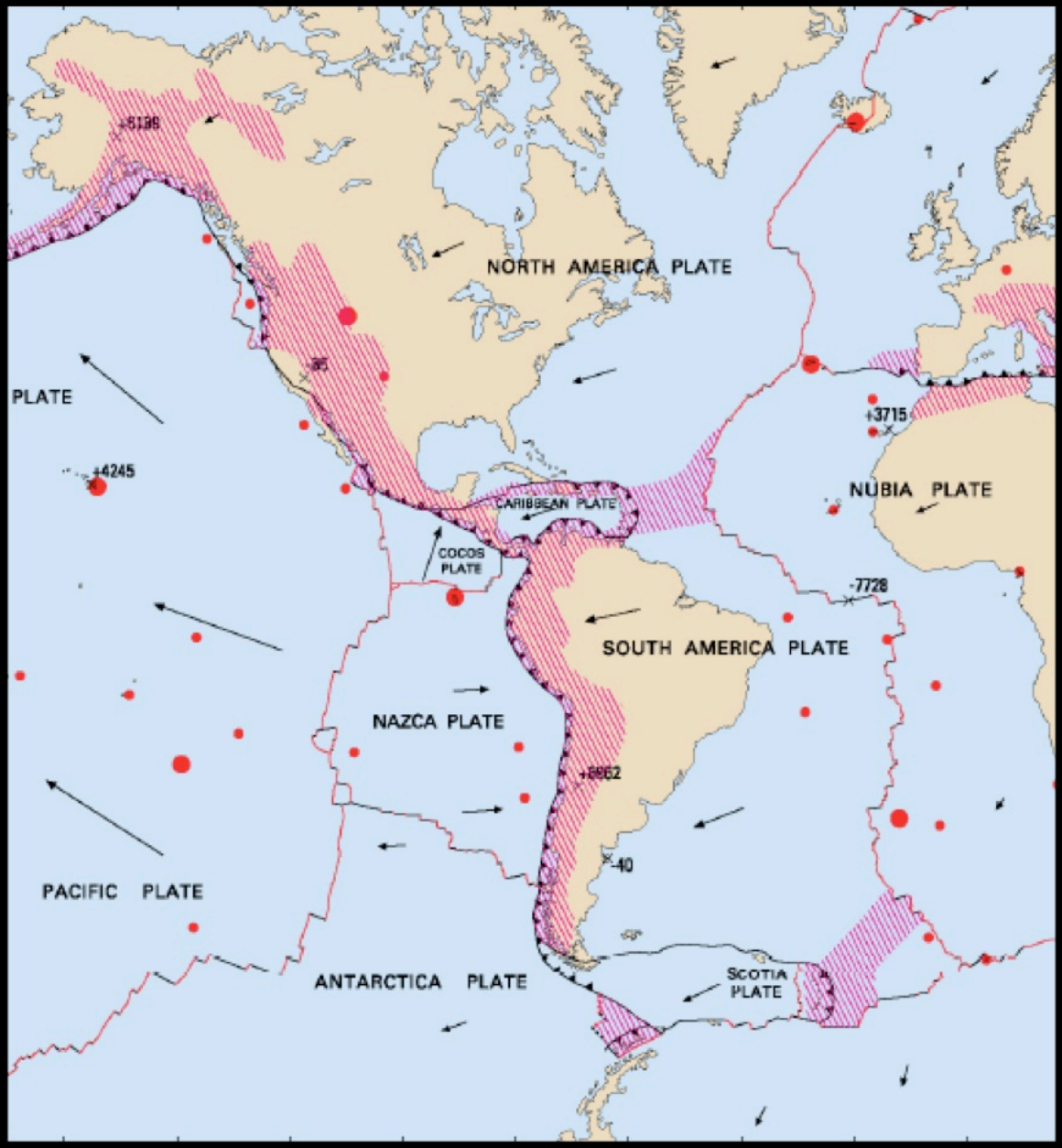
2) Calc-Alkaline magmas with –Nb-Ta-Ti & +LILE anomalies. Do these REQUIRE ARCs ?

What Defines Plate Tectonics?

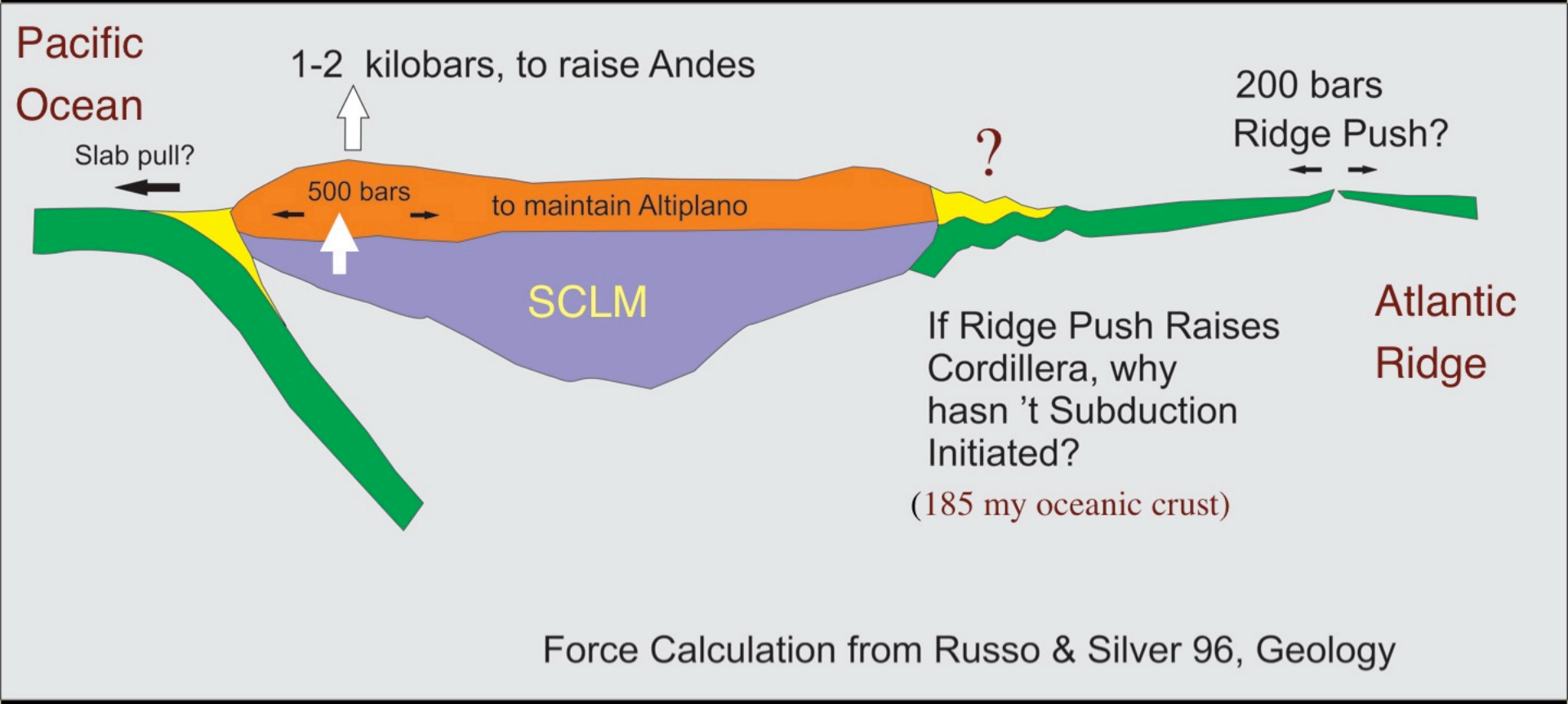
Seafloor Spreading

Subduction

Continental drift ?

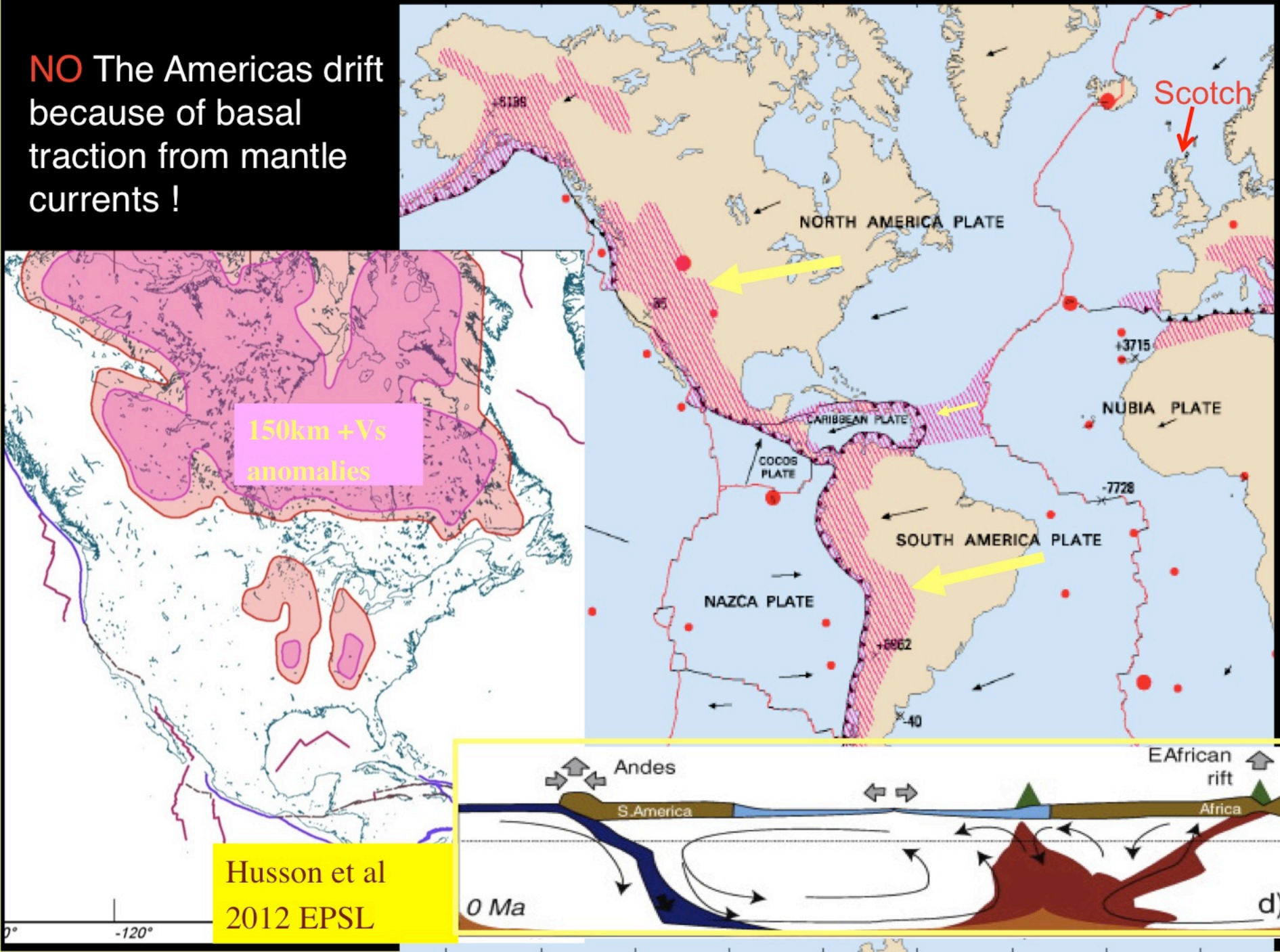


Do the Americas drift westward because of Plate Boundary Forces?



Force Calculation from Russo & Silver 96, Geology

NO The Americas drift because of basal traction from mantle currents !



Husson et al 2012 EPSL

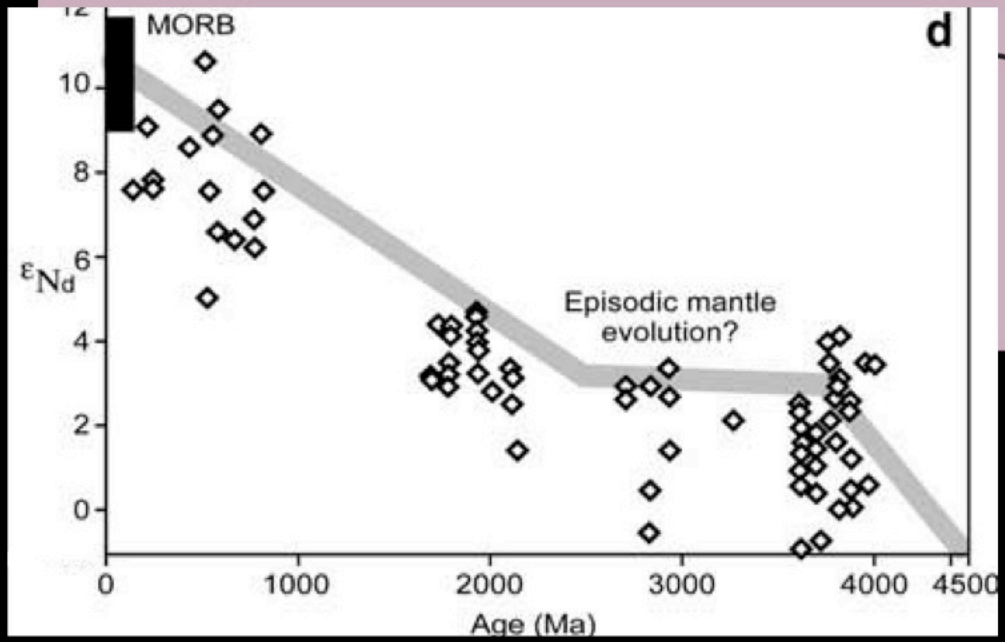
Unstable Stagnant Lid Planet

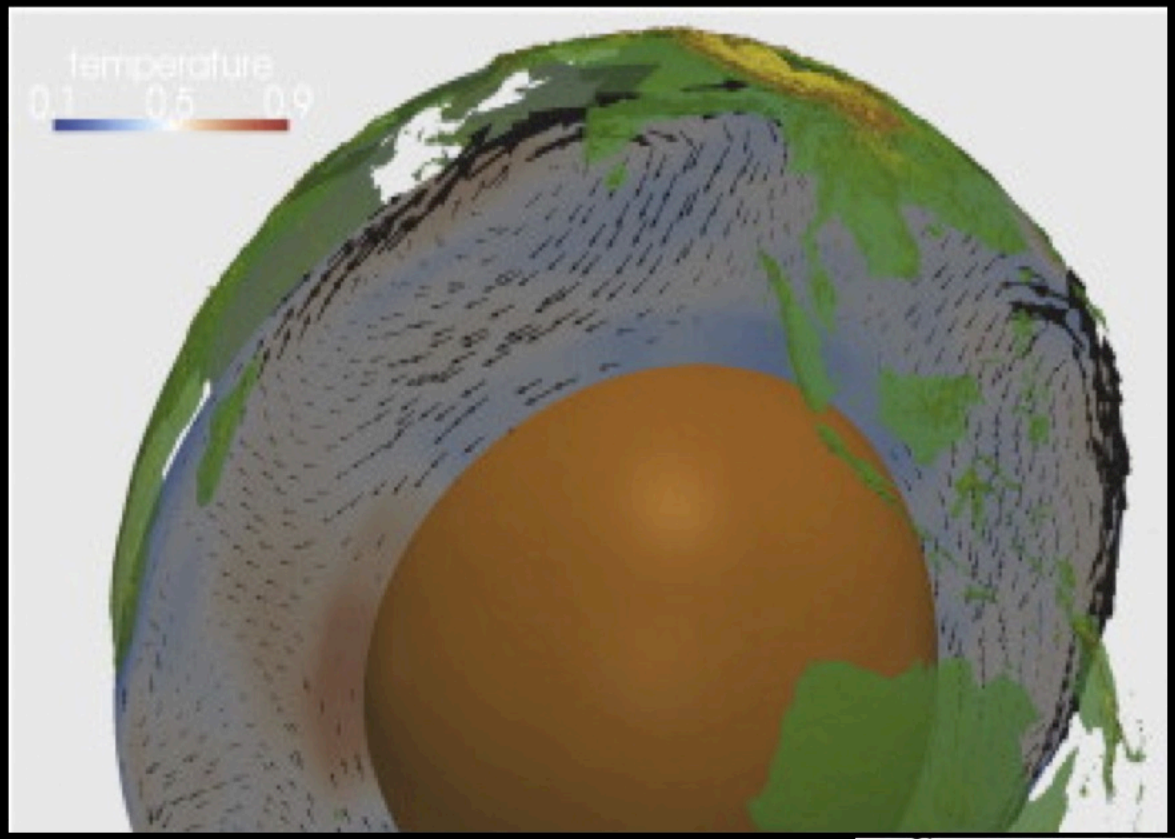
Komatiites Above
Plume-Like Instabilities
Craton + SCLM
Start to Form

Stagnant Lid Convection Prevents
Formation of Oceanic Lithospheric Mantle

s.l.

Shallow Mantle (Tholeiites), No Systematic Chemical Evolution

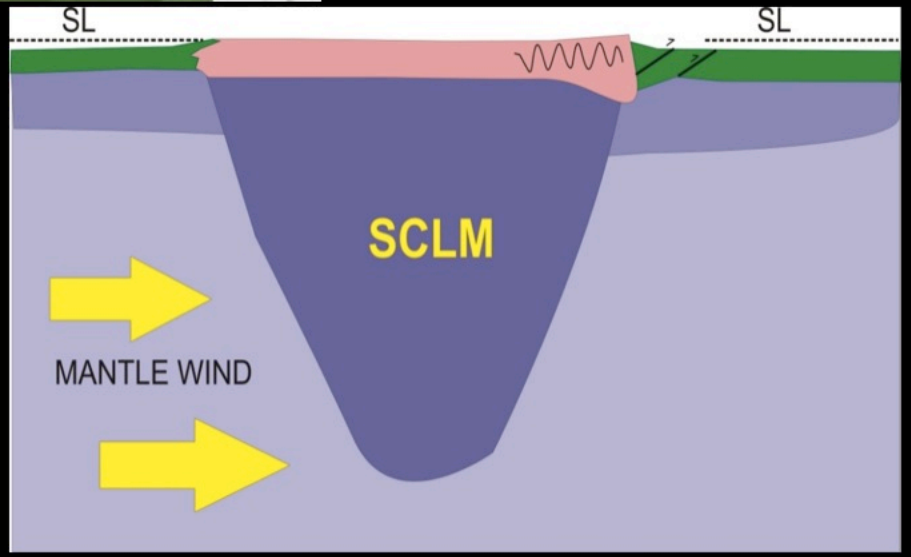




If continents with deep lithospheric roots migrate due to mantle traction, subduction is not needed to explain terrane accretion & orogenesis !

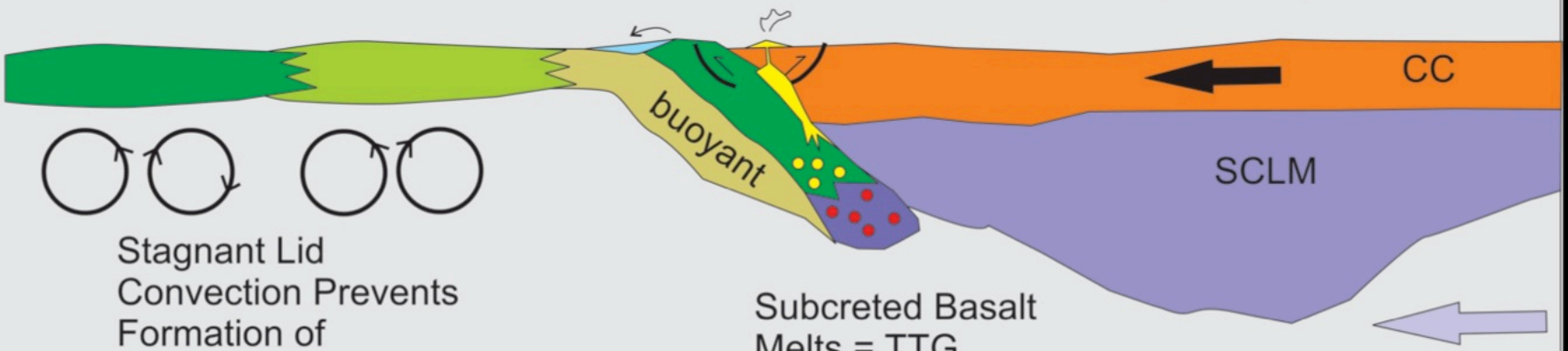
Becker & Facenna, 2011, EPSL
Alvarez 2010, EPSL

So if the SCLM is of Archaean age, then Cratons would have started drifting in the Archaean !



Archaean Continental Drift
Causes Accretion of Buoyant Oceanic
Plateau Type Crust. Transient
Tectonic Relief Feeds Sedimentary Belts

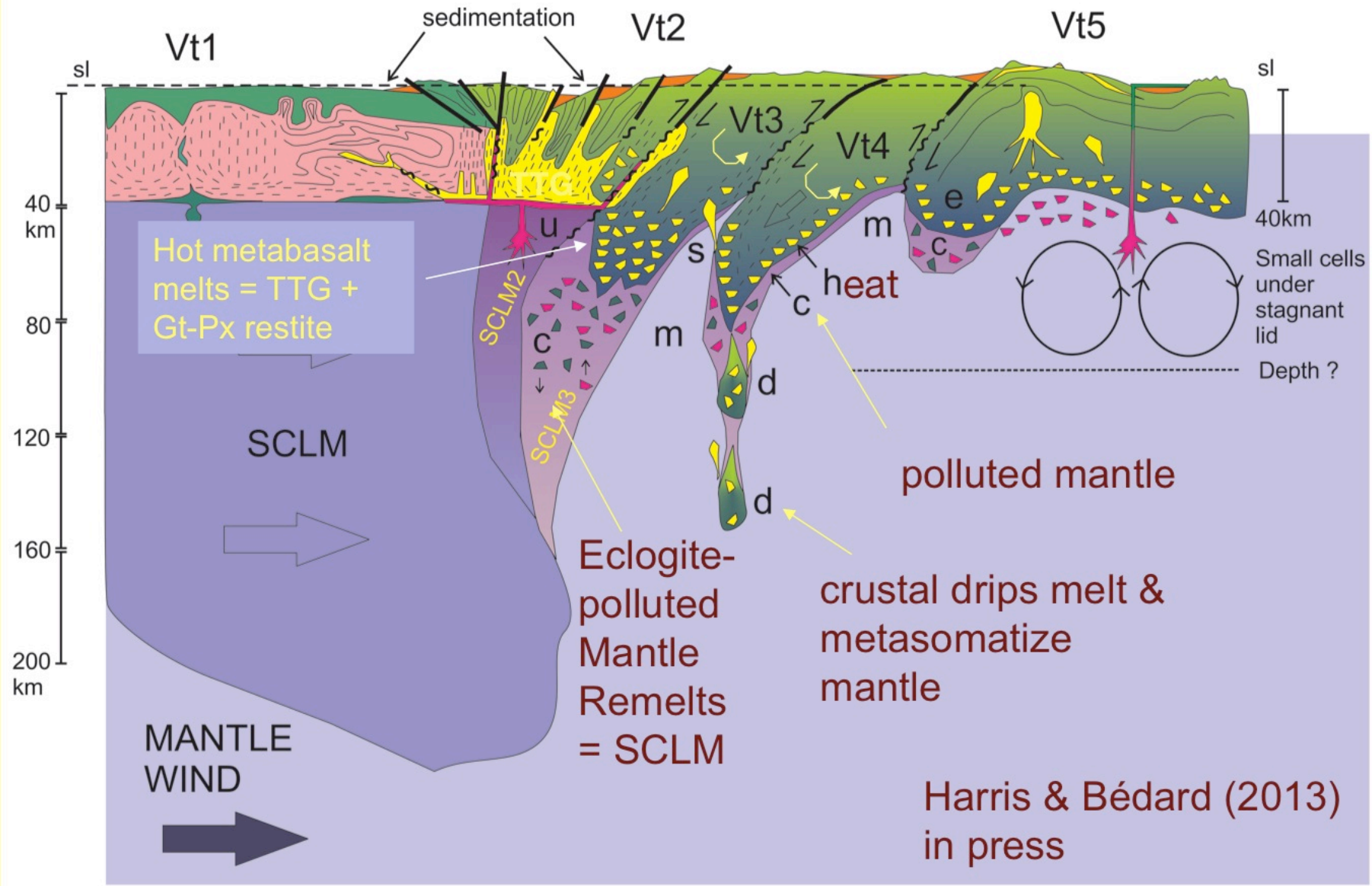
Archaean Continental
Crust Has No
Relief (Too Soft)

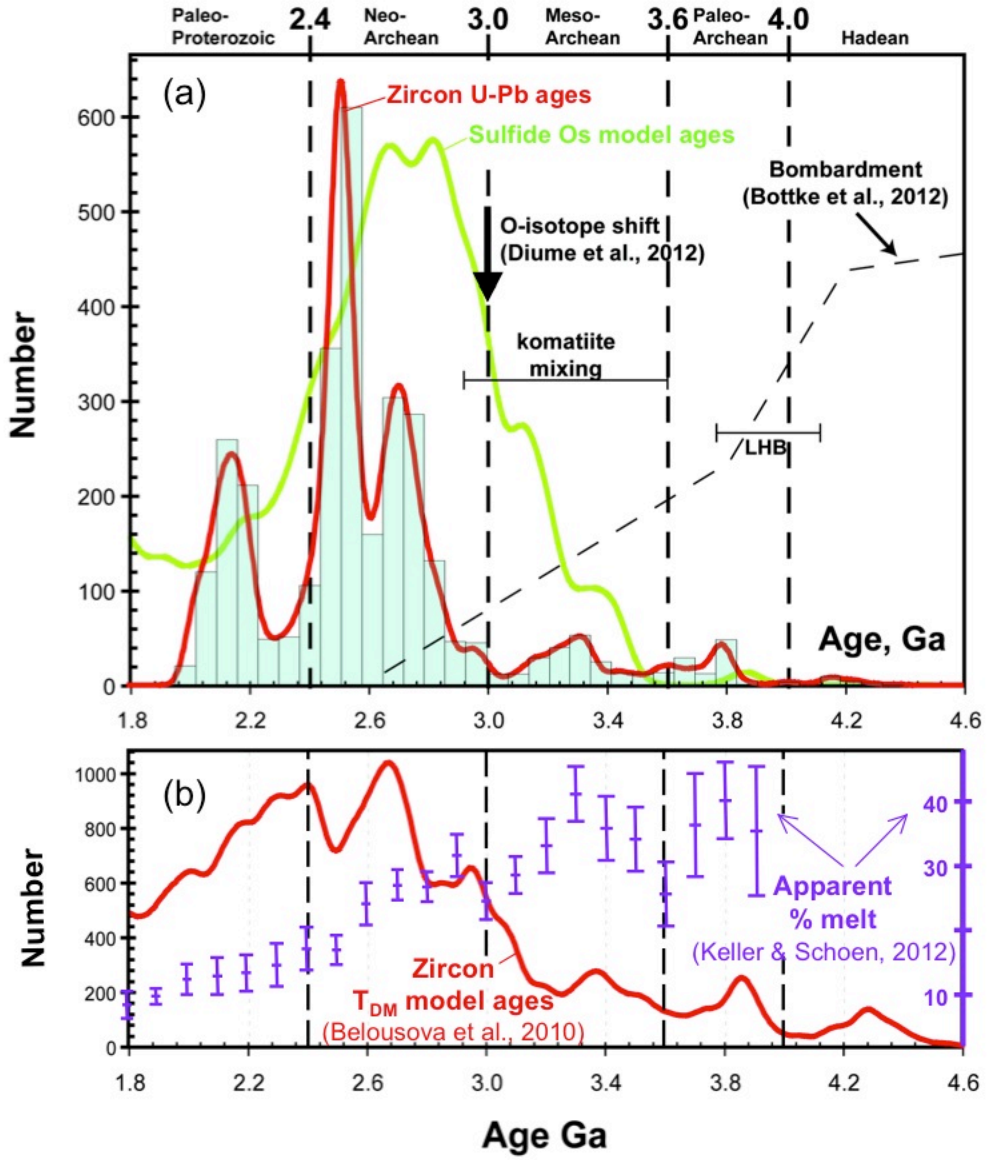


Stagnant Lid
Convection Prevents
Formation of
Oceanic Lithospheric
Mantle = Buoyant
Simatic Lithosphere

Subcreted Basalt
Melts = TTG
Restite+Mantle
Remelt = SCLM

Mantle
Traction


Vt1
sedimentation
Vt2
Vt5
sl
sl
Vt3
Vt4
TTG
40
km
80
120
160
200
km
u
s
m
e
c
heat
c
Hot metabasalt
melts = TTG +
Gt-Px restite
SCLM2
c
m
d
SCLM3
d
SCLM
40km
Small cells
under
stagnant
lid
Depth ?
polluted mantle
Eclogite-
polluted
Mantle
Remelts
= SCLM
crustal drips melt &
metasomatize
mantle
MANTLE
WIND
Harris & Bédard (2013)
in press



Summary: Linked Evolution of SCLM and continental crust

-- SCLM formed mainly 3.5-3.0 Ga – massive overturns, mixing – buoyant because of Fe removal

Provided basis for continents, “modern” plate tectonics (and Archean psuedo-plate tect.)

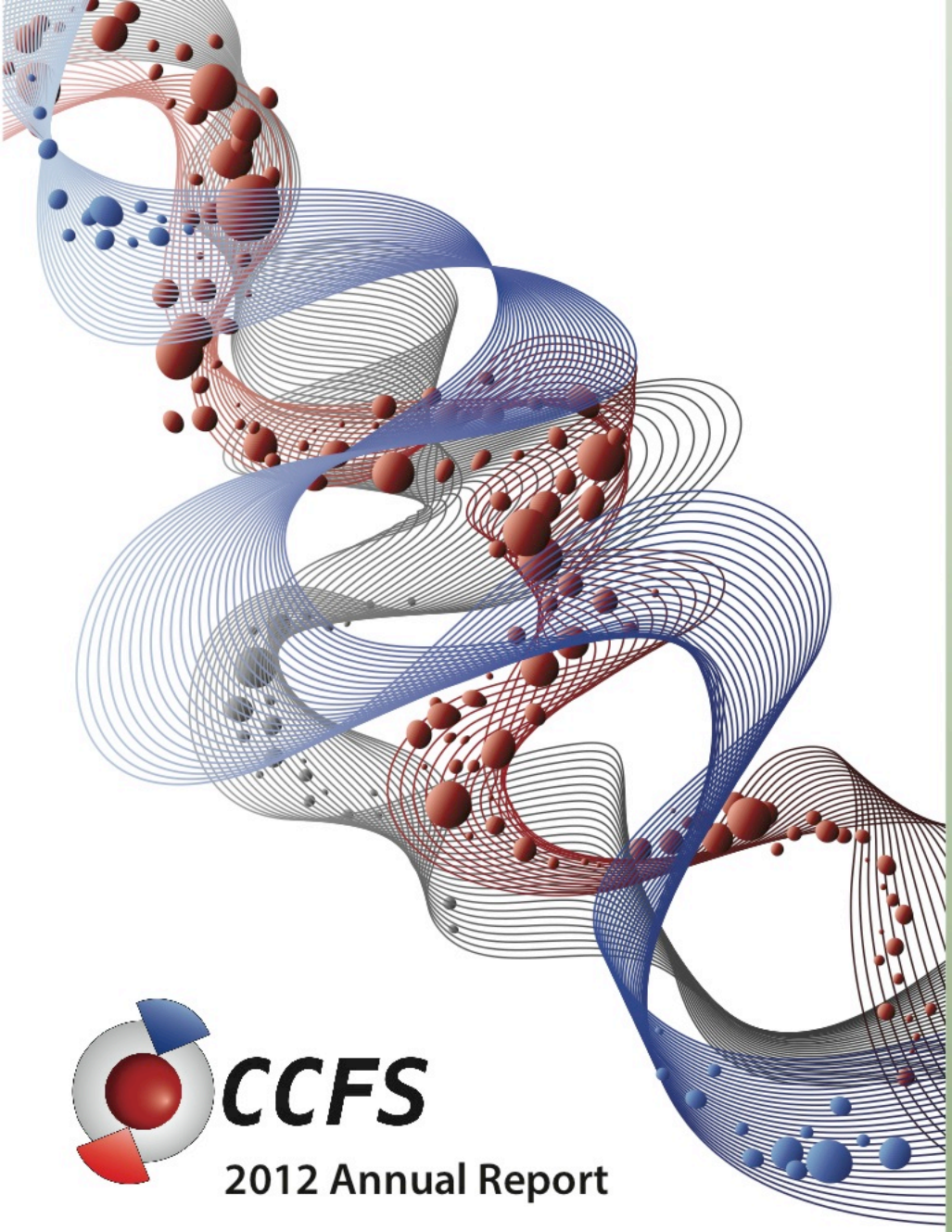
4-fold division of Archean (4.0-2.4 Ga)/Hadean?

and what *Don't* we know?

- Real composition of high-Vs cratonic cores – fundamental to estimates of SCLM composition, origin(s)
- Sources/origins of metasomatic fluids – in any detail
- Sources of non-cratonic lithospheric mantle – relict vs new, residual vs refertilised,…….accreted plates?
- Nature/properties of mid-lithospheric discontinuity – is this how Archean SCLM gets thinned?
- Fate of Hadean lithosphere – stored at depth?

Thank You
and
Goodbye

MACQUARIE UNIVERSITY



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