Secular change in Archean crust formation recorded in Western Australia

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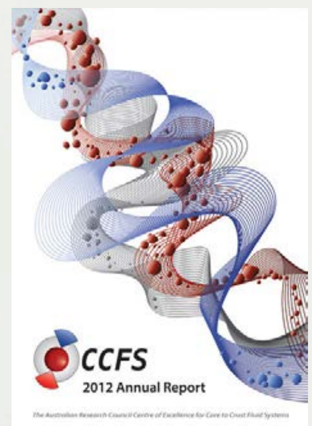
ARC Centre of Excellence for Core to Crust Fluid Systems (CCFS)

Research Themes:

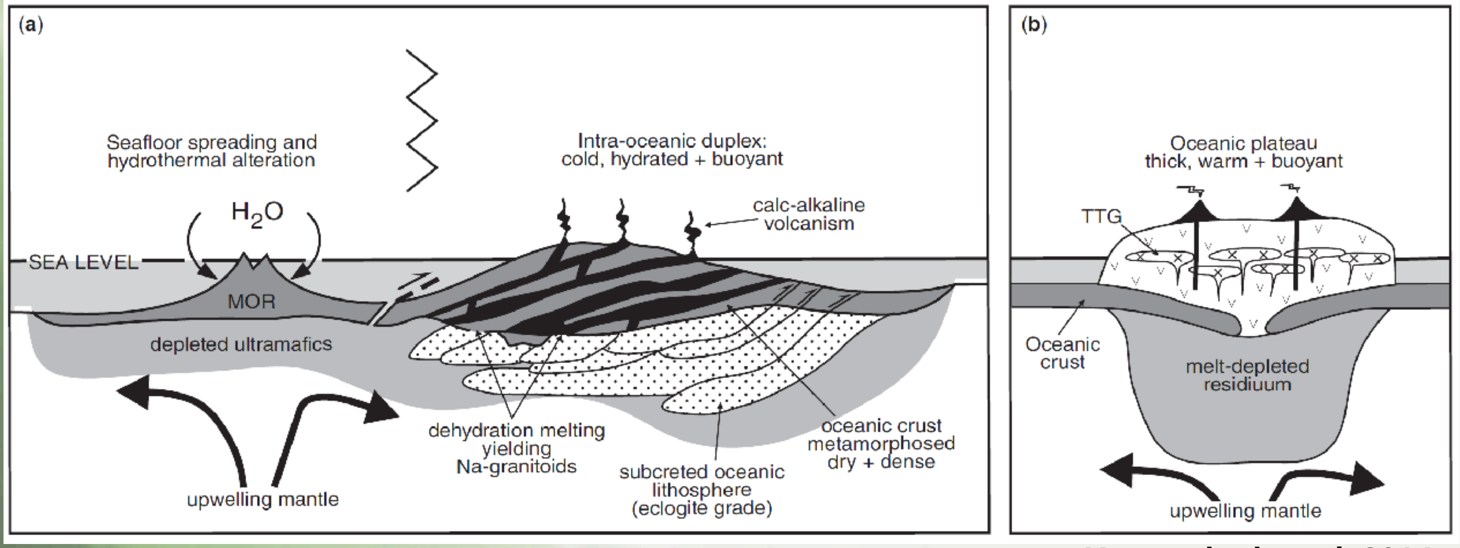
Early Earth, Earth's Evolution, and Earth Today



"Geophysical imagery gives us a **snapshot of the current status** of the deep Earth, but also carries the **imprints of past processes**."

Archean Tectonics - making of the early crust

- Horizontal (**subduction** accretion) tectonics (eg, Blewett, 2002)
- Vertical (**plume** accretion) tectonics (eg, Hickman 1975)



van Kranendonk et al. 2014

Paleoarchean Africa (Barberton), Australia (Pilbara) and West Greenland (Nuuk): explained equivalently **with surface observations (structural geology, geochemistry, …)**

Crustal architecture can add more constraints, e.g. from seismology, magnetotellurics…

Seismic Characteristics of Archean Crust

Global Seismic Compilation shows Archean crust:

- ❑ 99% Archean crust > 2.9Ga
  - o Sharp/Flat Moho (large velocity contrast)
  - o Lack of internal structure
  - o Low crustal velocity
  - o Thin (32-39km) crust

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Review Article

The character of the Moho and lower crust within Archean cratons and the tectonic implications

Dallas H. Abbott [a,*], Walter D. Mooney [b], Jill A. VanTongeren [c]

Seismic Characteristics of Archean Crust

- ~70 % Archean crust formed 2.8 - 2.5Ga
  - Sharp at the Moho (large velocity contrast)

- Post-archean crust (<2.5 Ga)
  - Internal layers
  - Diffusive/dipping Moho
  - high lower-crustal velocity (magmatic underplating)
  - Thick (41-km) crust

- A secular change of Archean crust formation mechanism may occur between 3.0 – 2.5 Ga;

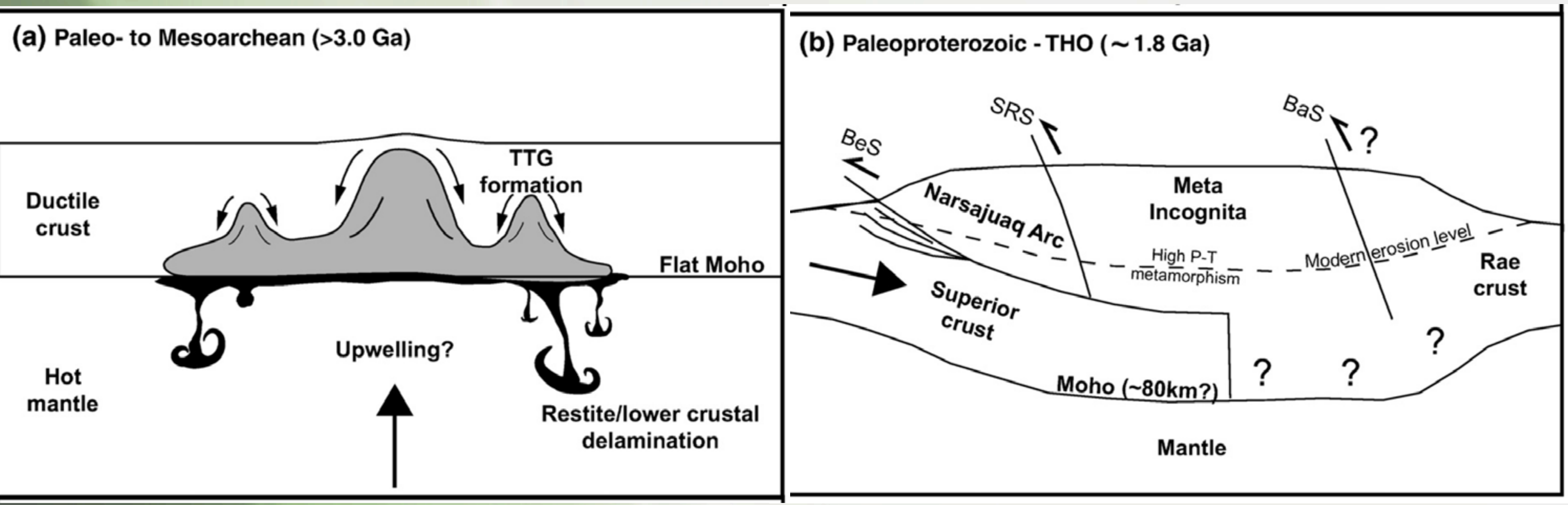
Crust Differences in Archean and Proterozoic

- The Archean-Proterozoic boundary:

  - Transitioning to modern plate tectonics (e.g. Thompson et al 2010; Abbott et al 2013);
  - Consistent with other studies in the past decade.

Archean Tectonics

3.0 – 2.5 Ga: start of modern style plate tectonics



Canadian shield; Thompson et al., 2013

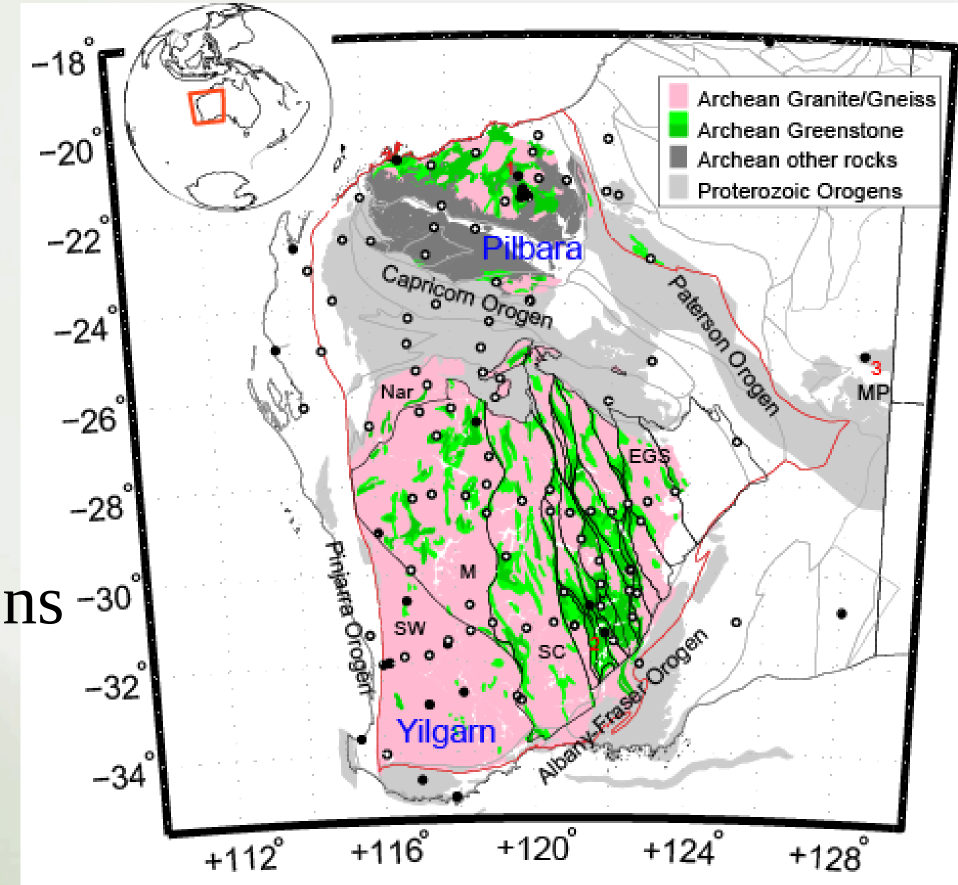
Crust in the Western Australia

- Oldest samples (~4.4 Ga Zircon, Jack Hills, Yilgarn; Wilde et al., 2001)

- Rich crust-forming history: Spanning >1Ga in Archean

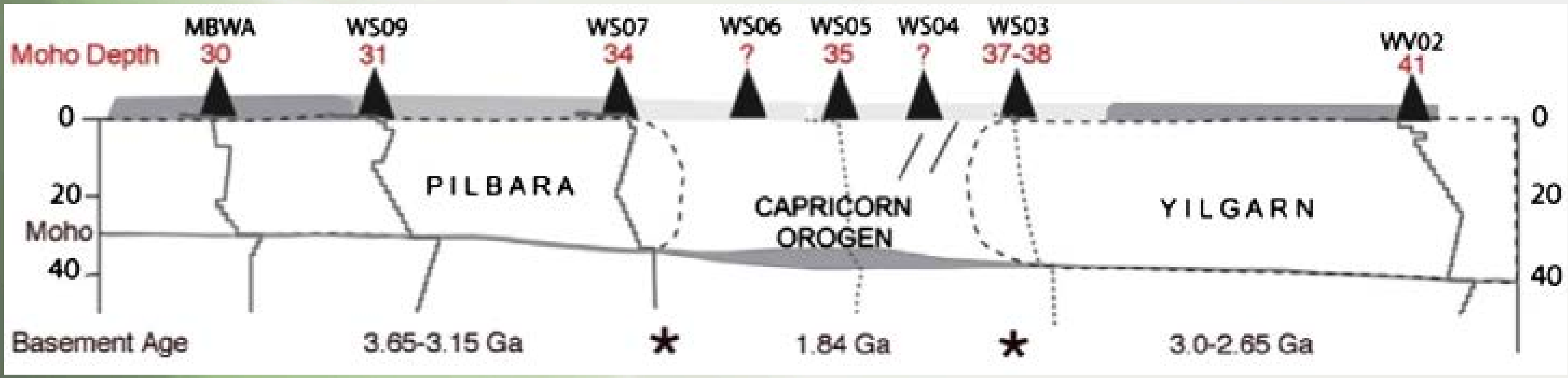
- Good seismic coverage

- Perfect for Receiver Functions



Early studies showing WA crust

- Typical Archean and Proterozoic crust:
  - Thin and sharp Moho in the Archean
  - Thick and "diffused" Moho in the Proterozoic



WA crust; Reading and Kennett 2007

Receiver Functions

- Receiver
  station
- Function
  structural response
  velocity/impedance contrast

LETTERS TO NATURE NATURE · VOL 374 · 9 MARCH 1995

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30. McCave, I. N. & Tucholke, B. E. in *The Western North Atlantic Region* Vol. M (eds Vogt, P. R. & Tucholke, B. E.) 451–468 (Geol. Soc. Am. Boulder, 1986).
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ACKNOWLEDGEMENTS. We thank G. Foreman and M. Hall for technical assistance, B. Haskell for data and N. Shackleton for encouragement. This work was supported by the UK NERC for BOFS.

Continental crust composition constrained by measurements of crustal Poisson's ratio

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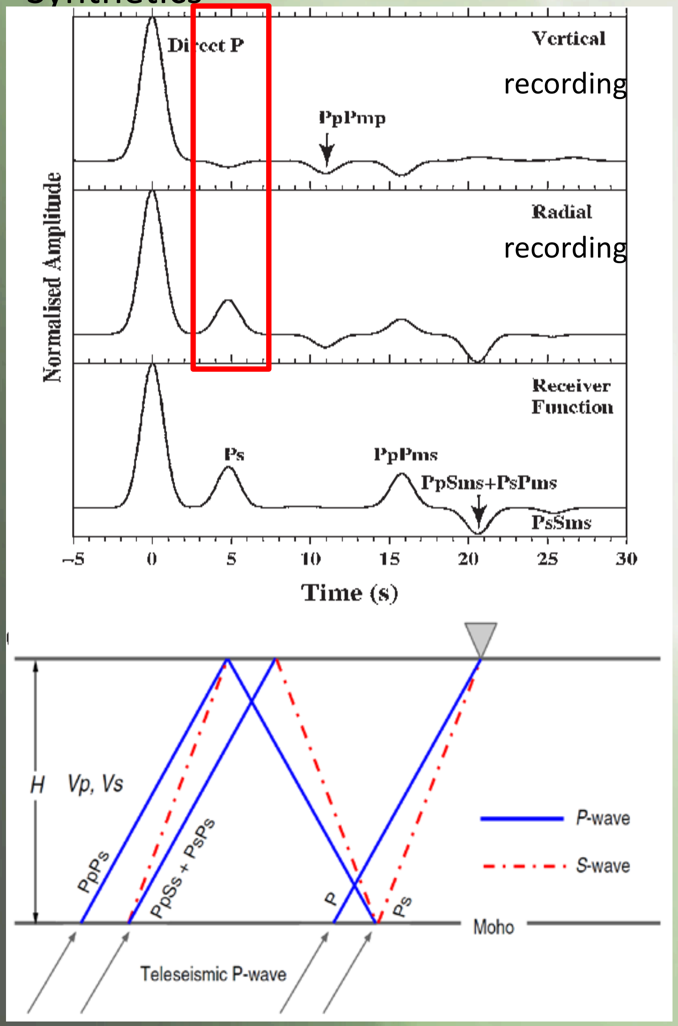
Receiver Functions

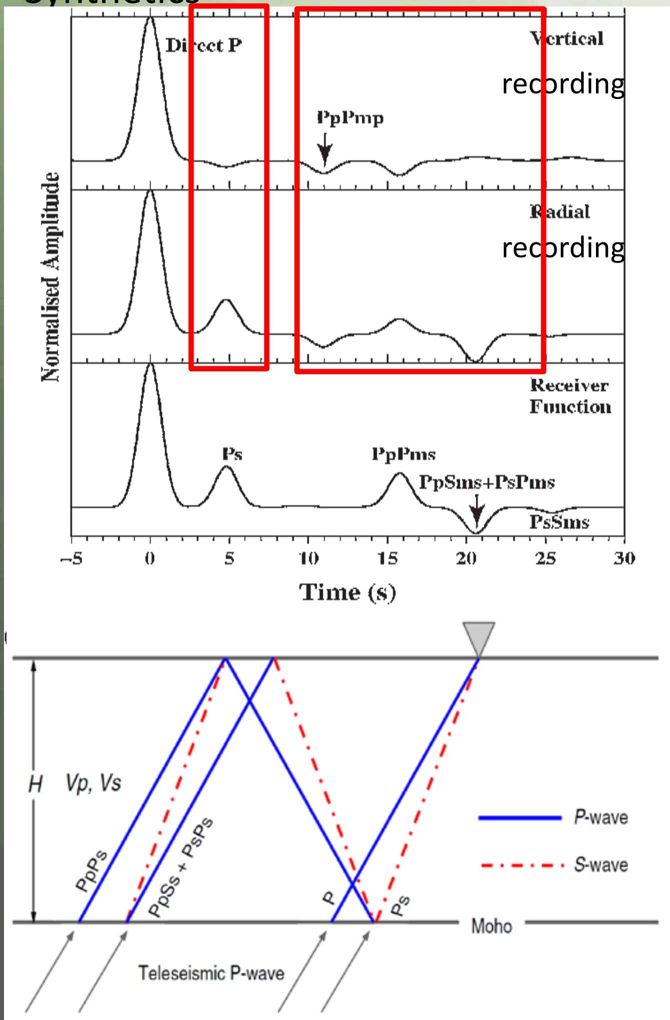
Synthetics



- P-to-s wave converted phase (S-wave)
- Free-surface reverberations (multiples; mixed S- and P-wave paths)

Receiver Functions

Synthetics



- P-to-s wave converted phase (S-wave)
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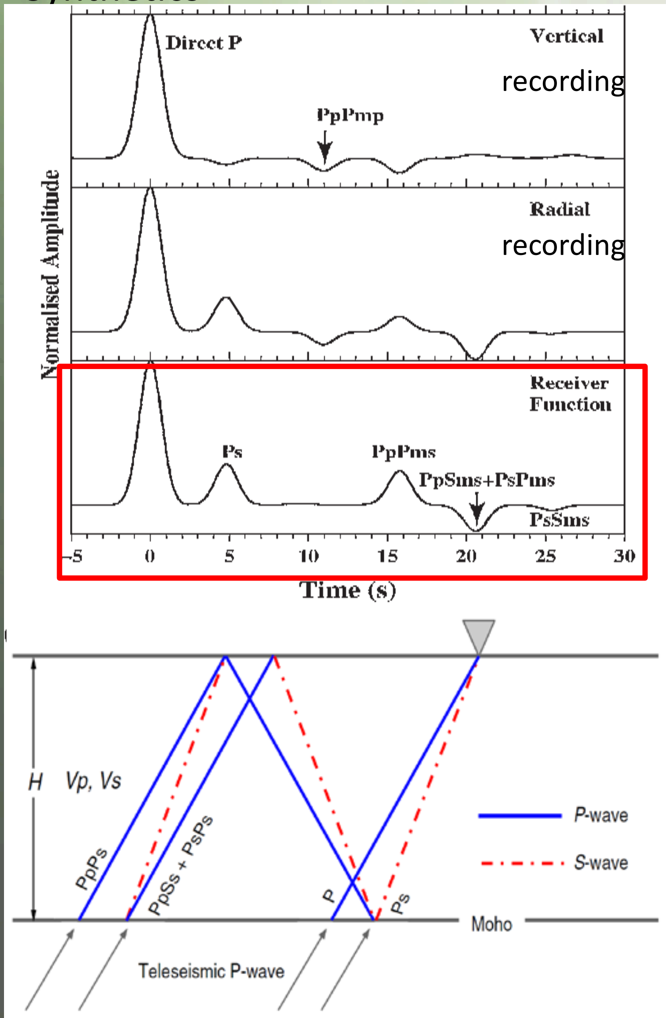
Receiver Functions

Synthetics



- P-to-s wave converted phase (S-wave)
- Free-surface reverberations (multiples; mixed S- and P-wave paths)

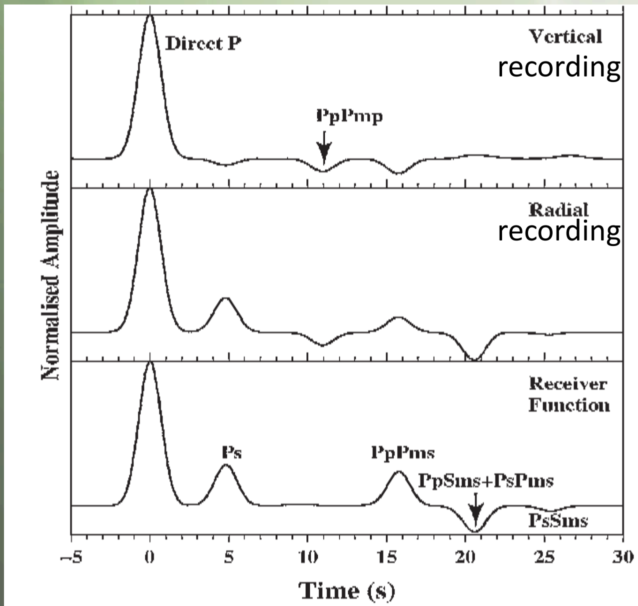
Receiver function

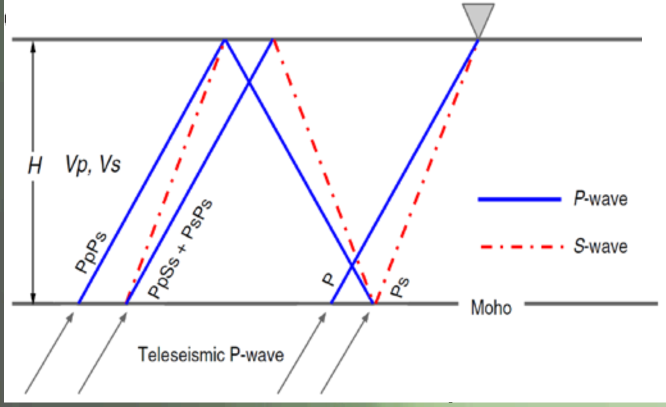
- Arrival times → depth of the Moho
- P- and S-wave path → Vp/Vs ratio

  (Poisson's ratio, rock composition)

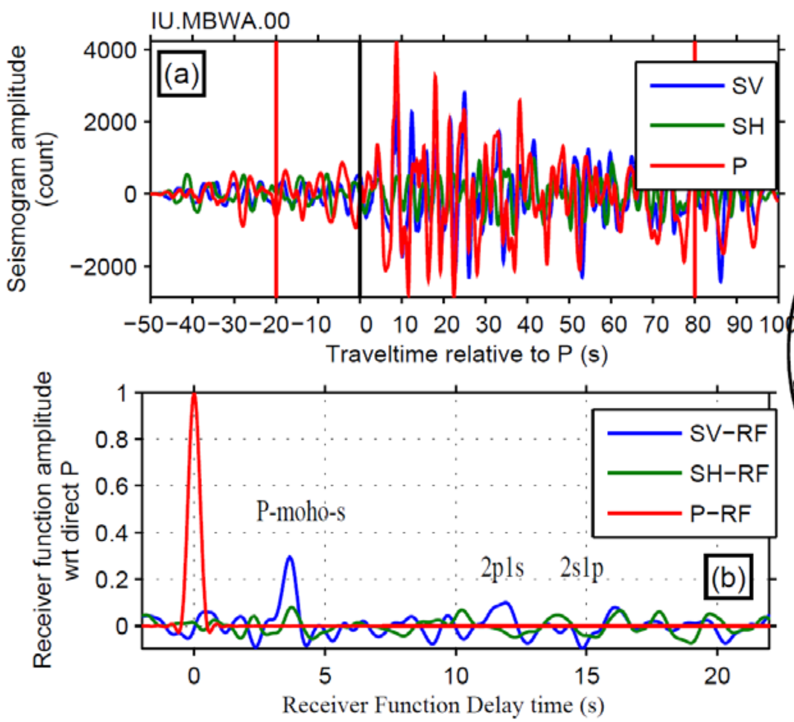
Receiver Functions

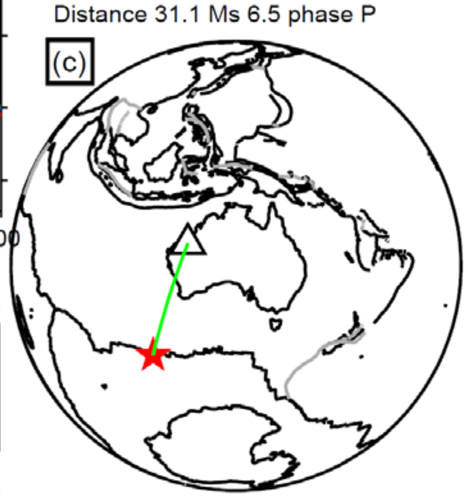
Synthetics





Real Data



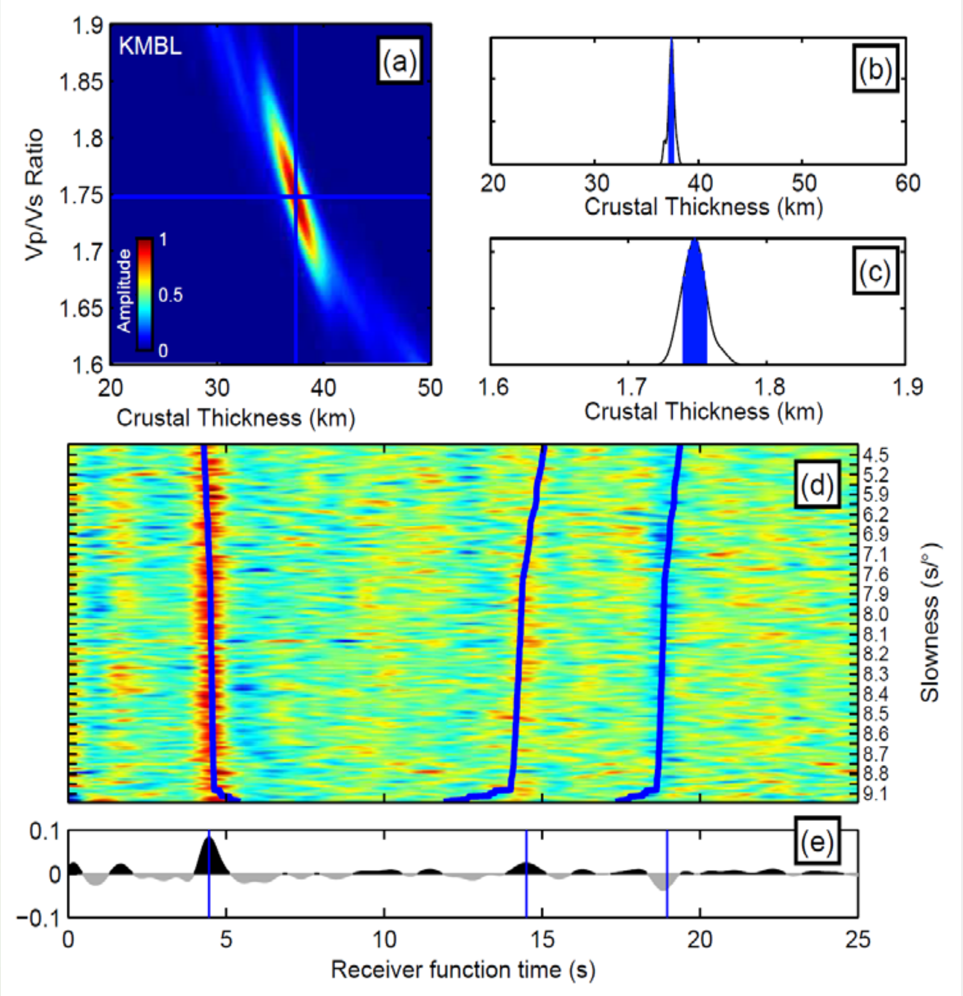


- Constrains Vp/Vs ratio given a starting velocity model
- Good estimate of average crustal composition

  1.71 felsic; 1.76-78 intermediate; >1.84 mafic

Receiver Function H-*k* analysis

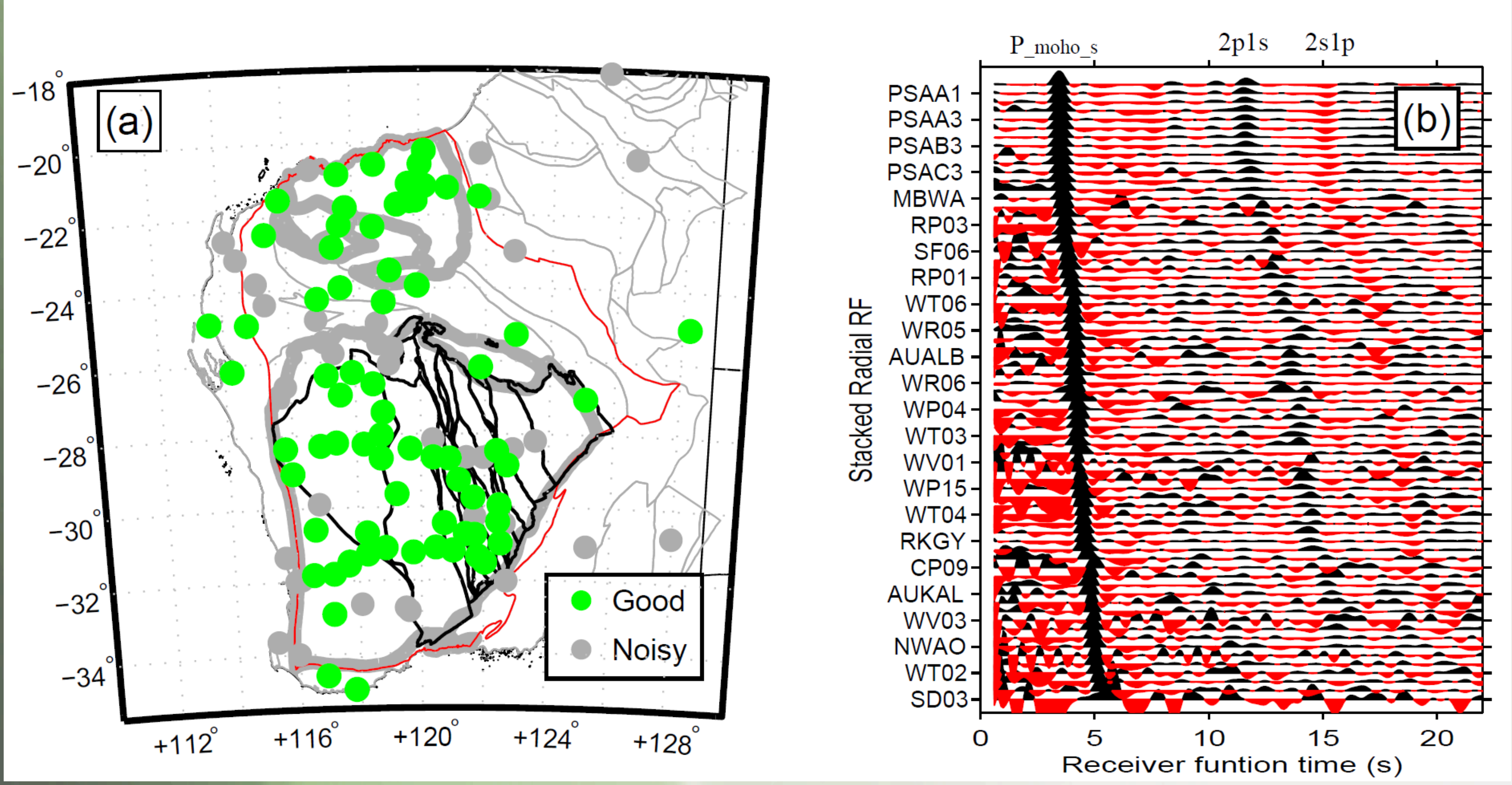
- H: thickness
- *k*: *Vp/Vs* ratio
- 2D search in the H-*k* space
- Max amplitude = most coherent H & k for both direct converted phase and multiples



H-k analysis, Zhu and Kanamori 2000

Good Signal in WA Craton

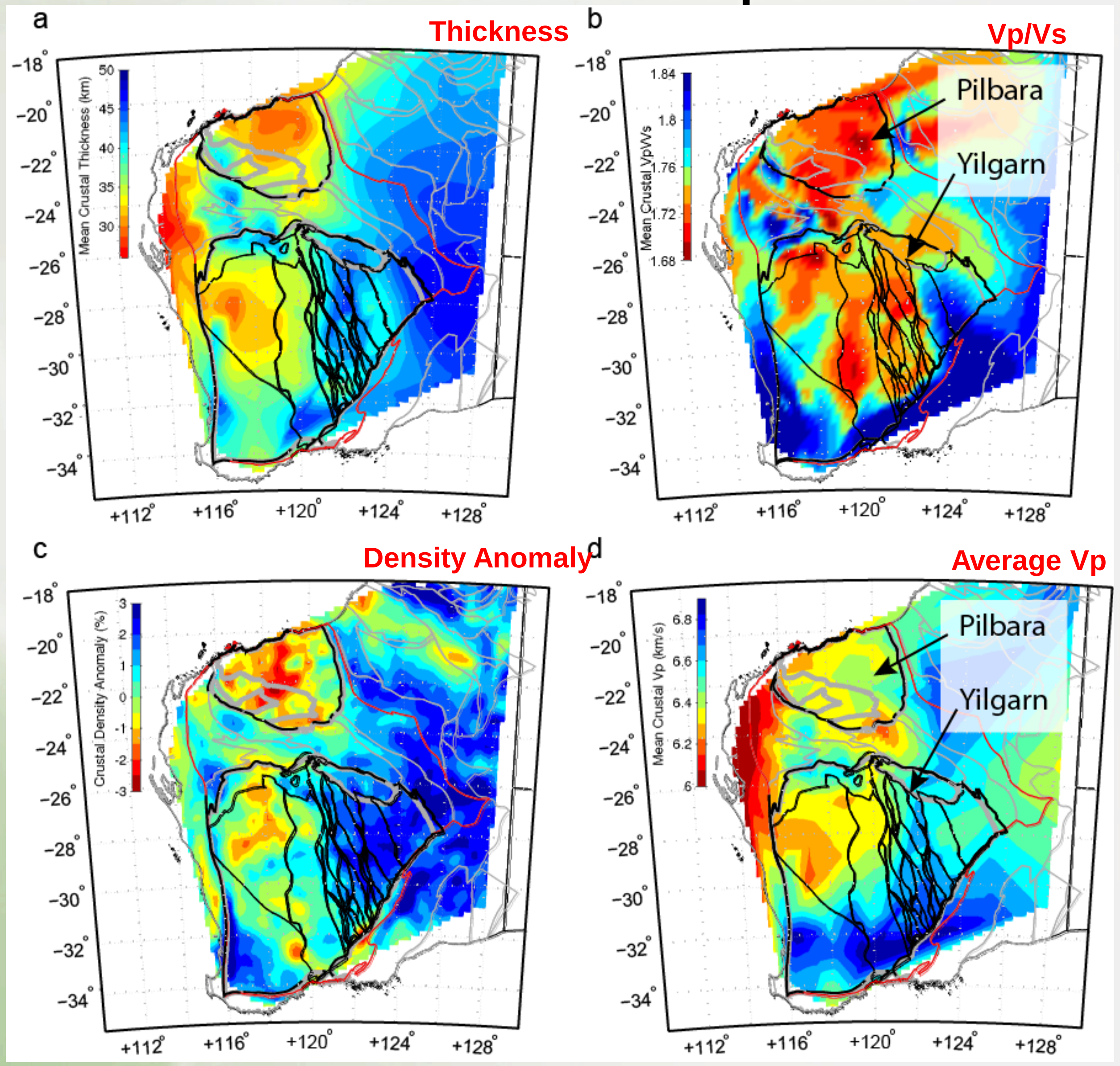
- Archean Moho is flat: good for crustal multiples!



Spatial Distribution of Crustal Properties

- Bulk crustal thickness a
- *Vp/Vs* ratio b
- Crustal density anomaly c
- Crustal P-velocity d

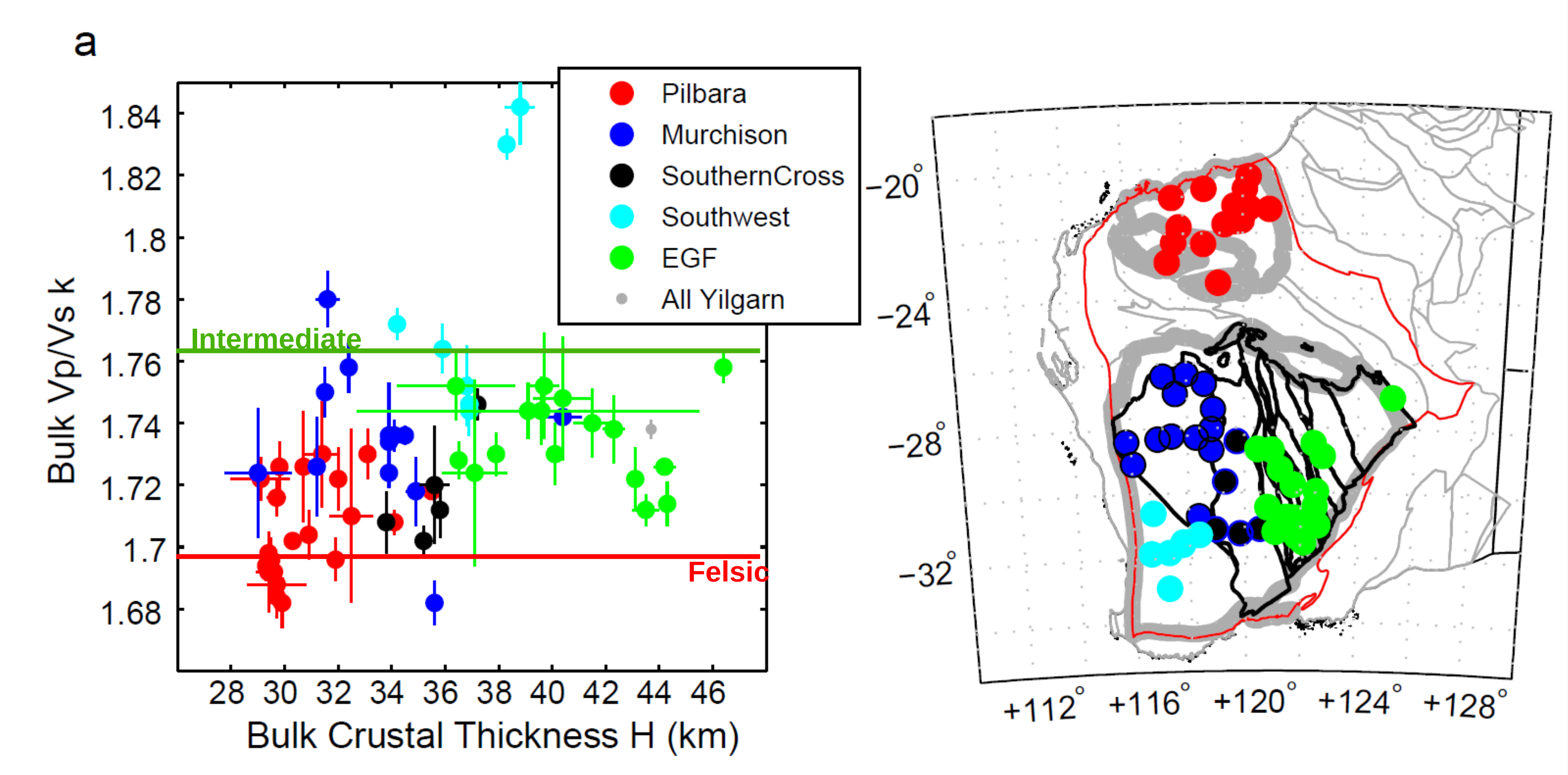
Crustal properties clustered to tectonic sub-units



Crustal density anomaly: Aitken et al., 2013
AuSREM Crust: Salmon et al., 2013

Spatial Distribution of WA crust

- Distinct tectonic units <==> distinct crustal properties

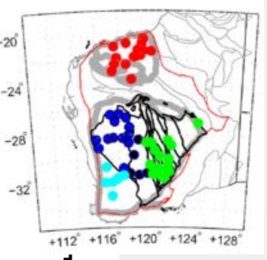


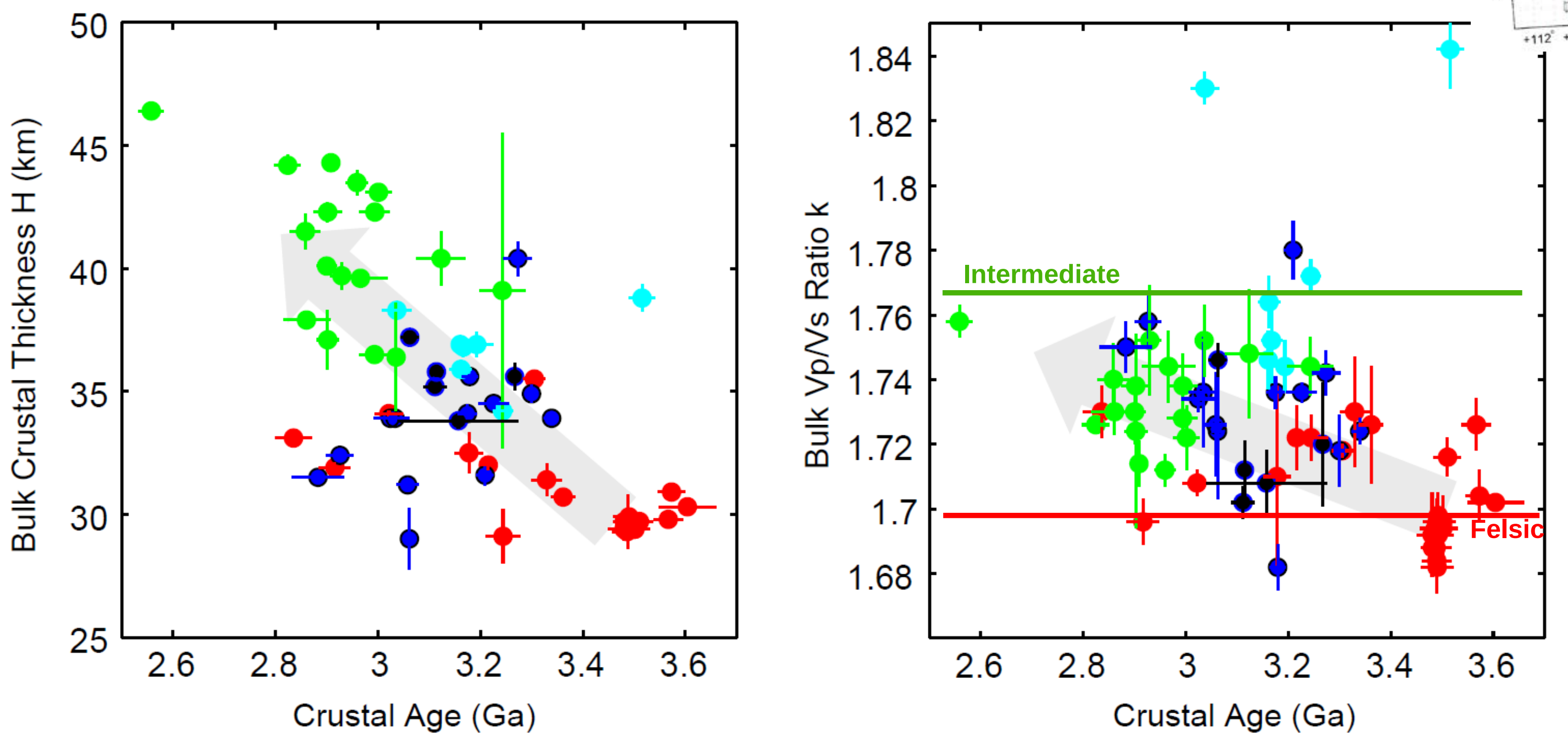
- Different crust growth models!

Temporal Variation in WA Crust

❑ **Thickness and composition correlate with time**

- Systematic **thickening** of Archean crust from 3.6 to 2.6 Ga
- **Evolving** composition from felsic to intermediate





Two-stage Nd depleted mantle model age, Champion 2013

Archean: Last Billion Years

- **Cooling of Earth**
  - Dissipating of initial internal heat
  - Decaying of radiogenic elements
  - Dropping of mantle temperature

- **Recycling of Archean lower Crust**
  - Melt differentiation leaves a dense and mafic lower crust
  - Lower crust will delaminate (drop) into the mantle
  - Lower crustal component may be brought back

Temporal Variation in WA Crust

- Systematic **thickening** of Archean crust

- Early Archean: hotter Tp → fast lower crustal removal → thin crust (Pilbara)

- Late Archean: colder mantle → slow delamination → thicker crust (Yilgarn)

nature geoscience
LETTERS
PUBLISHED ONLINE: 1 DECEMBER 2013 | DOI: 10.1038/NGEO2019

Delamination and recycling of Archaean crust caused by gravitational instabilities

Tim E. Johnson[1]*, Michael Brown[2], Boris J. P. Kaus[1,3] and Jill A. VanTongeren[4]

Temporal Variation in WA Crust

- **Evolving** composition from felsic to intermediate

- Early Archean: efficient delamination removes mafic lower crust + episodes of plumes or vertical tectonics (inferred from surface geology) →further crustal melt differentiation →more felsic crust (Pilbara)

- Late Archean: less efficient delamination → more lower curst preserved

- Lower crust is mafic → increased “average” composition

Transitioning of crust-making paradigm

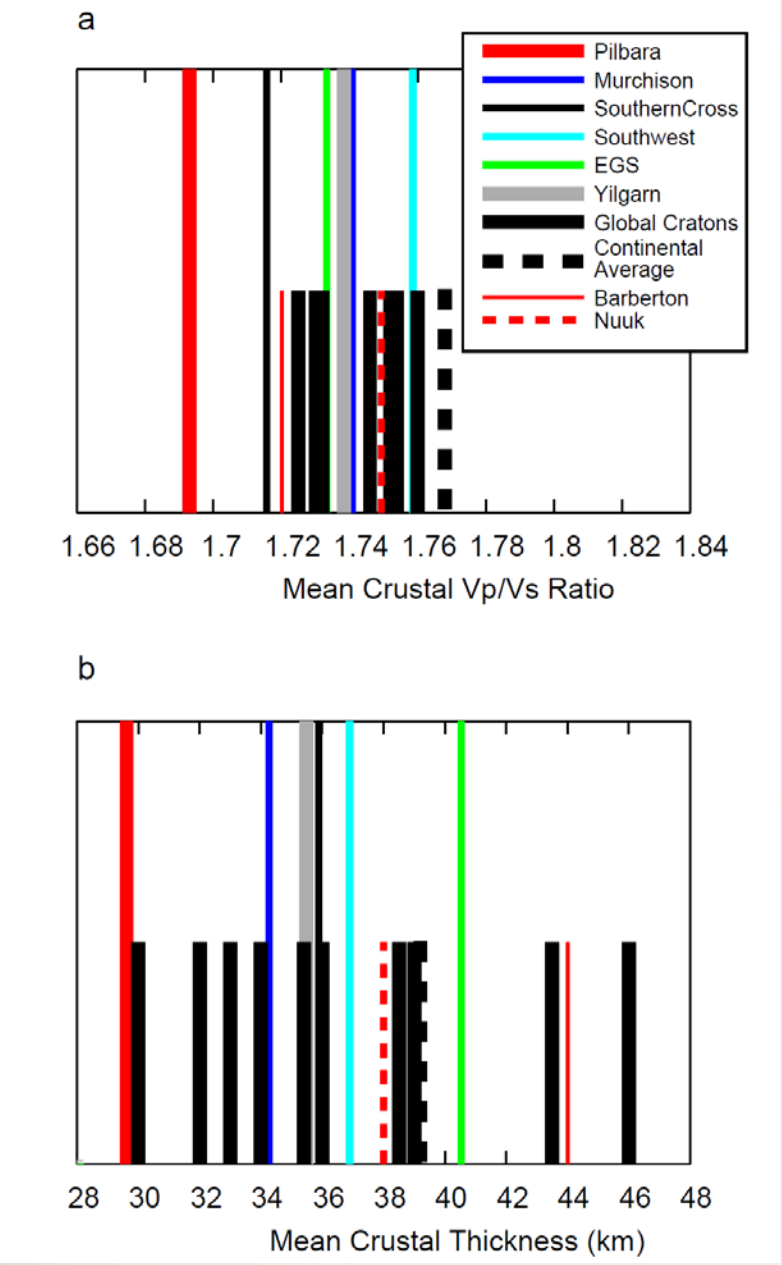
- Geodynamic modeling: decreasing Tp leads to subduction initiation in late Archean (Sizova et al 2010; O'Neill & Debaille 2014)

- Yilgarn crust - late Archean subductions: calc-alkaline andesites, intermediate composition (Barley et al, 2008; Morris & Kirkland 2014)

- Systematic transition to plate tectonics:
  - Pilbara dominated by "plumes"
  - Yilgarn plate-tectonics

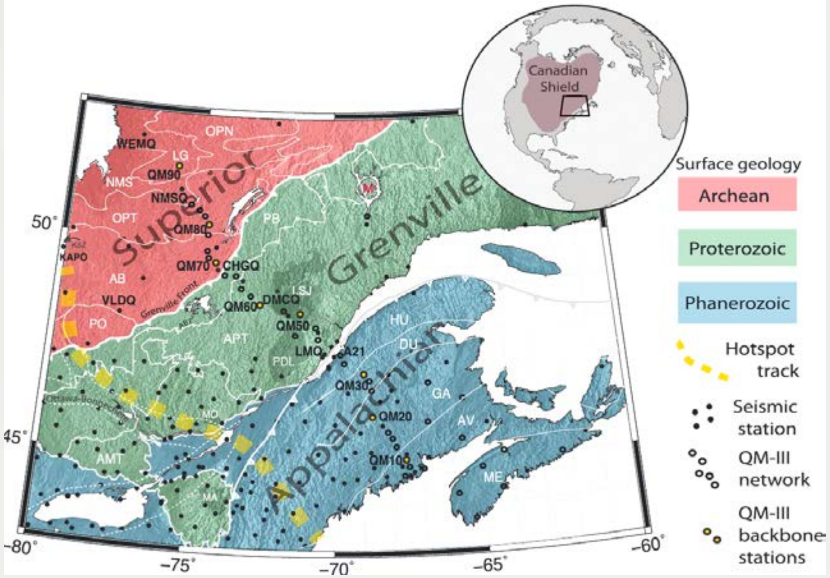
Comparison with world cratons

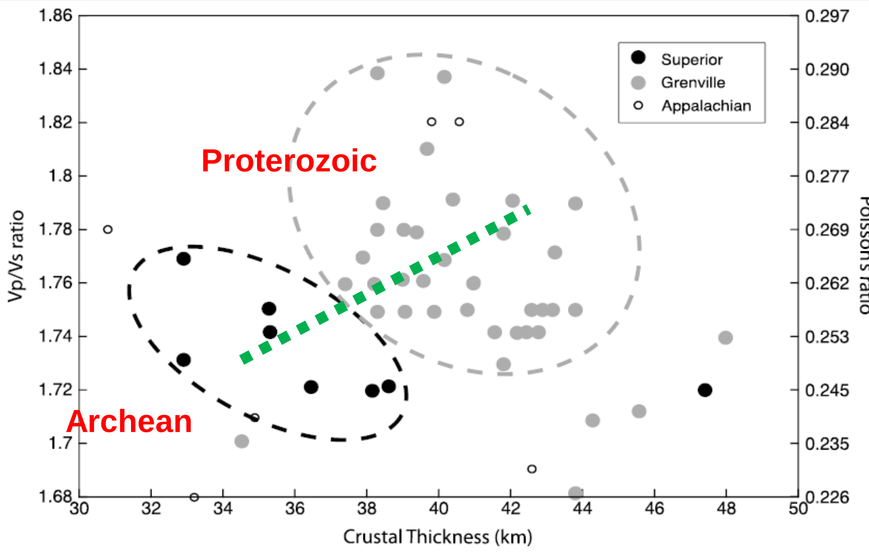
- ❑ World cratons
  - o Felsic-to-intermediate composition
  - o Thinner than continental average
- ❑ Yilgarn falls in global average
- ❑ Pilbara unique; unlike other old cratonic regions (Barberton & Nuuk; less sampled)



Comparison with world cratons

- ❑ North American cratons:
  - o Similar secular variation
  - o Elevated thickness and Vp/Vs ratio





AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Solid Earth

RESEARCH ARTICLE

10.1002/2015JB012348

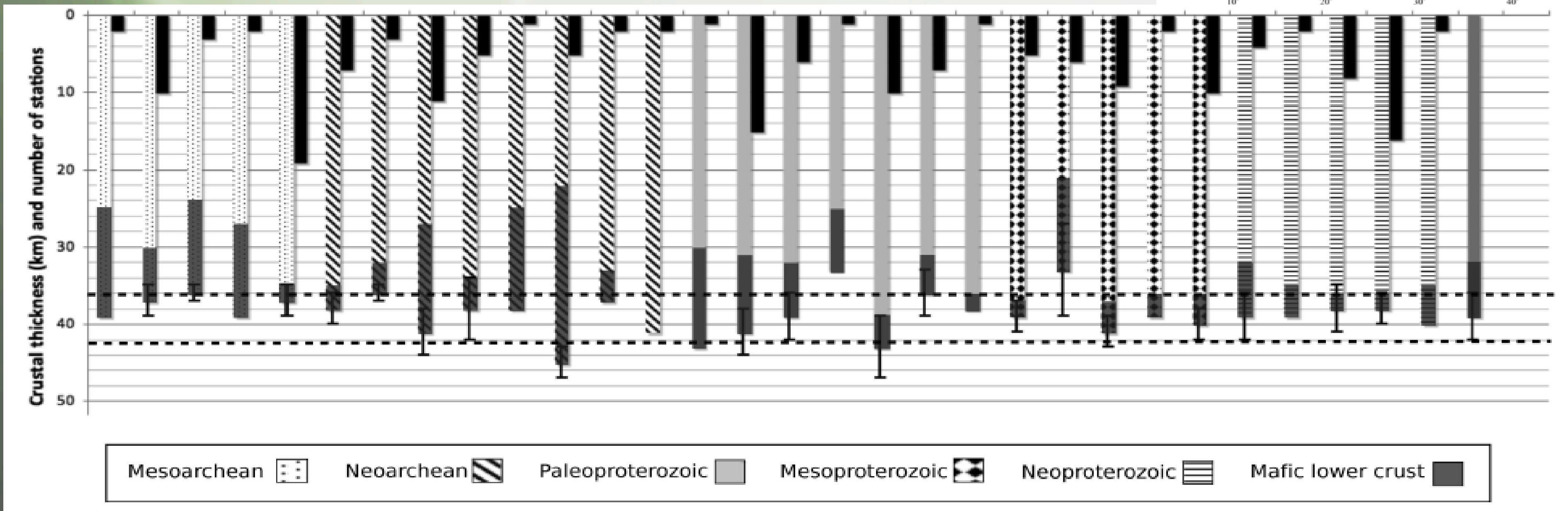
Three billion years of crustal evolution in eastern Canada: Constraints from receiver functions

L. Petrescu[1], I. D. Bastow[1], F. A. Darbyshire[2], A. Gilligan[1], T. Bodin[3], W. Menke[4], and V. Levin[5]

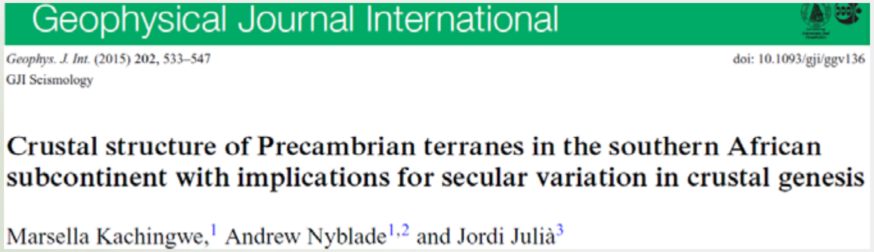
Key Points:
- We constrain the seismic crustal

Comparison with world cratons

- South African cratons:



- Lack of secular variation
- Mafic lower crust in the Mesoarchean


Geophysical Journal International

Geophys. J. Int. (2015) 202, 533–547 doi: 10.1093/gji/ggv136

GJI Seismology

Crustal structure of Precambrian terranes in the southern African subcontinent with implications for secular variation in crustal genesis

Marsella Kachingwe,[1] Andrew Nyblade[1,2] and Jordi Julià[3]

Conclusions

- Spatially and temporally clustered WA Archean crust
- Paleoarchean Pilbara: thin and felsic composition;

  Late Archean Yilgarn terranes: thicker and more intermediate
- Transition between plume- to subduction-tectonics
- Secular cooling of Earth's mantle

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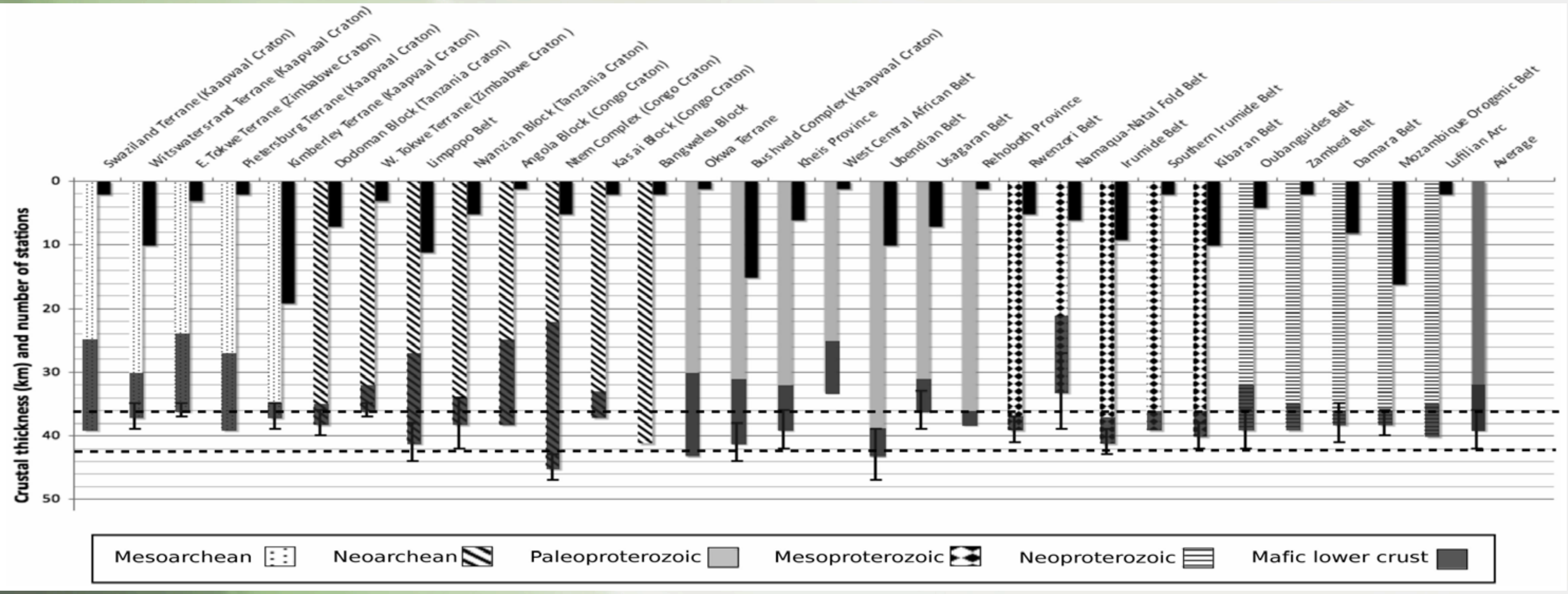
Southern Africa



- No secular variation found in S African crustal structure
- Crust made same way since Meso-Archean?
- Plate tectonic processes reworked the crust?

Reworking of cratons

- **Narryer:**

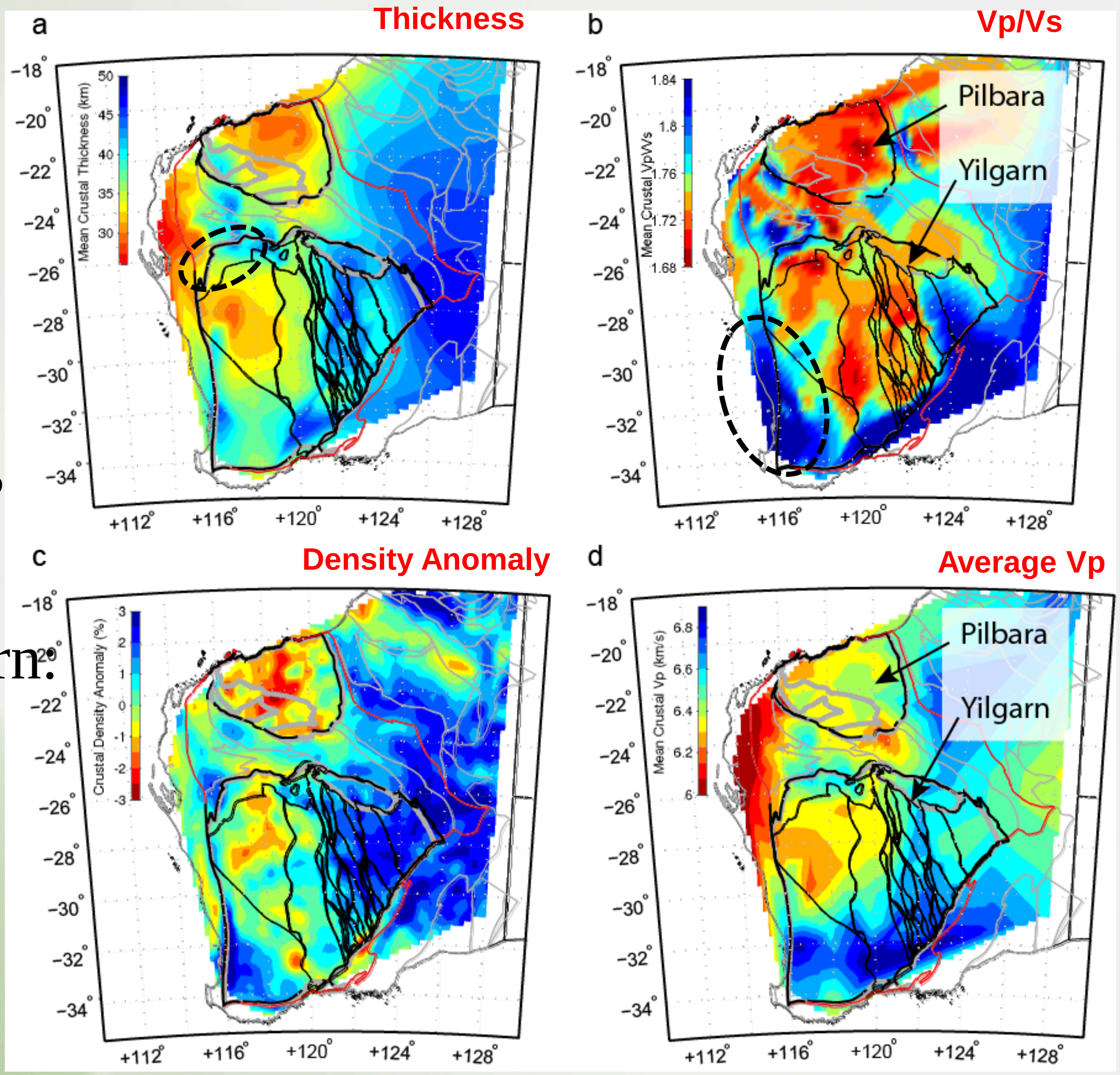
Capricorn orogenic deformation?

- **Southwest:**

Rifting – opening of Indian ocean?

- **Western vs. eastern Yilgarn:**

Plume activities?



Crustal density anomaly: Aitken et al., 2013
AuSREM Crust: Salmon et al., 2013

Southern Africa