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CCFS Lithosphere Workshop
4-6 November 2013

Weronika Gorczyk and Juan Carlos Afonso

Postgraduate Awards to:

Kate Robertson (Univ of Adelaide)
Christopher Grose (CCFS Macquarie)
Adam (Monash Univ)
Richard Chopping (ANU)

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Tackling the giant 4-D Sudoku of the lithosphere

***Suzanne Y. O'Reilly, W.L. Griffin, N.J. Pearson,* G. Begg, J. Hronsky, TARDIS and Crust Evolution teams**

Acknowledgments to many collaborators on many projects

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Constraints for Interpretation of Geophysical Datasets

Seismic response:	sensitive to composition and temperature Dominated by olivine composition and content
Gravity:	determined by composition, density, thermal state, lithospheric thickness
Gravity derivatives:	reveal rheological state
Magnetic:	determined by thermal state, mineralogy
Thermal:	heat production, conductivity
Resistivity:	? attributed to graphite, fluids

4-D Lithosphere Mapping

Uses **information from mantle materials to define composition and architecture of the SCLM**

- **Paleogeotherms at time of host magma's eruption**
- **Composition of mantle domains (vertical, lateral)**
- **Age of stabilisation of mantle domains**
- **Timing and nature of metasomatic events**
- **Response of SCLM to crustal events**

Provides **the basis for interpretation of geophysical data, to map the SCLM globally and *back in time***

paleogeophysics→ changing architecture and process

Key Methodologies Developed for 4-D Lithosphere Mapping

- ***Paleogeotherms*** from xenoliths, garnet concentrates: the framework for spatial distribution of chemical data
- ***Single-grain thermometers*** for garnet, cpx (T_{Ni}), chromite (T_{Zn}); P_{Cr} barometer for garnets
- ***X_{Mg} in olivine***, calculated from garnet
- ***%Al_2O_3 in whole rock***, calculated from garnet: gives major-element composition (density) of rock
- ***Chemical tomography***: distribution of rock types and fluid processes from garnet and cpx data

3 Major Advances since 2000: Tools to understand lithosphere evolution

- *In-situ* analysis of Hf isotopes in zircon — *Griffin et al, GCA 2000*
  - Understand *origins* of magmas, not just ages
- *In-situ* analysis of Os isotopes in mantle sulfides
  - Ages of mantle depletion, metasomatism — *Pearson et al., 2002, GCA*
- High-resolution seismic tomography
  - *Geological interpretation* from mantle petrology
  - Mapping extent of Archean lithosphere

Integration of Geology, Geochemistry, Tectonics, Geophysics, Geodynamics and Numerical Modelling

Global geodynamic consequences

Sampling the Deep Earth I

Samples of the lithospheric mantle

- mantle xenoliths
- disaggregated minerals: *garnet*, chromite, cpx, *diamond* with inclusions

lowermost lithosphere in recent rift zones is near primitive mantle (cooled asthenosphere)

UHP xenoliths, UHP diamonds and their inclusions: samples from underplated plumes – seen as lowermost SCLM in some regions (eg Slave, South Australia)

Geophysical datasets

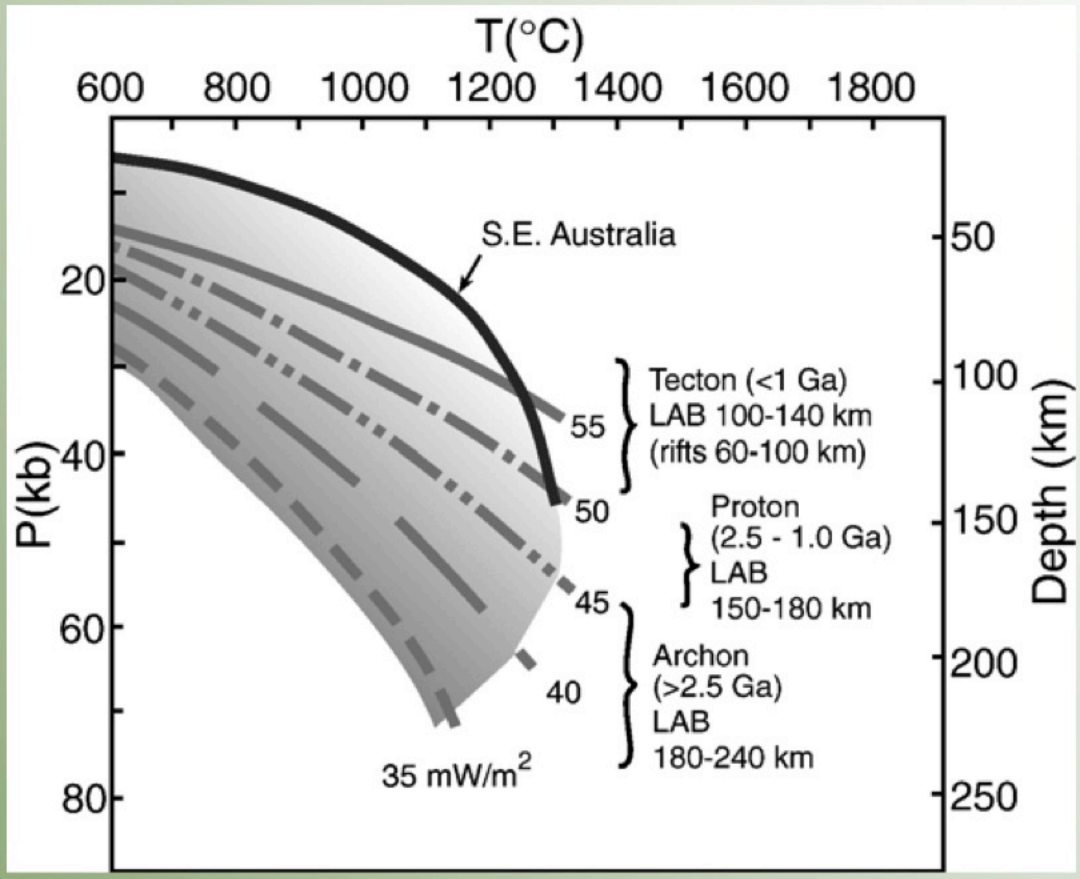
- seismic data → tomographic images
- gravity, thermal, electromagnetic

Xenolith Geotherms

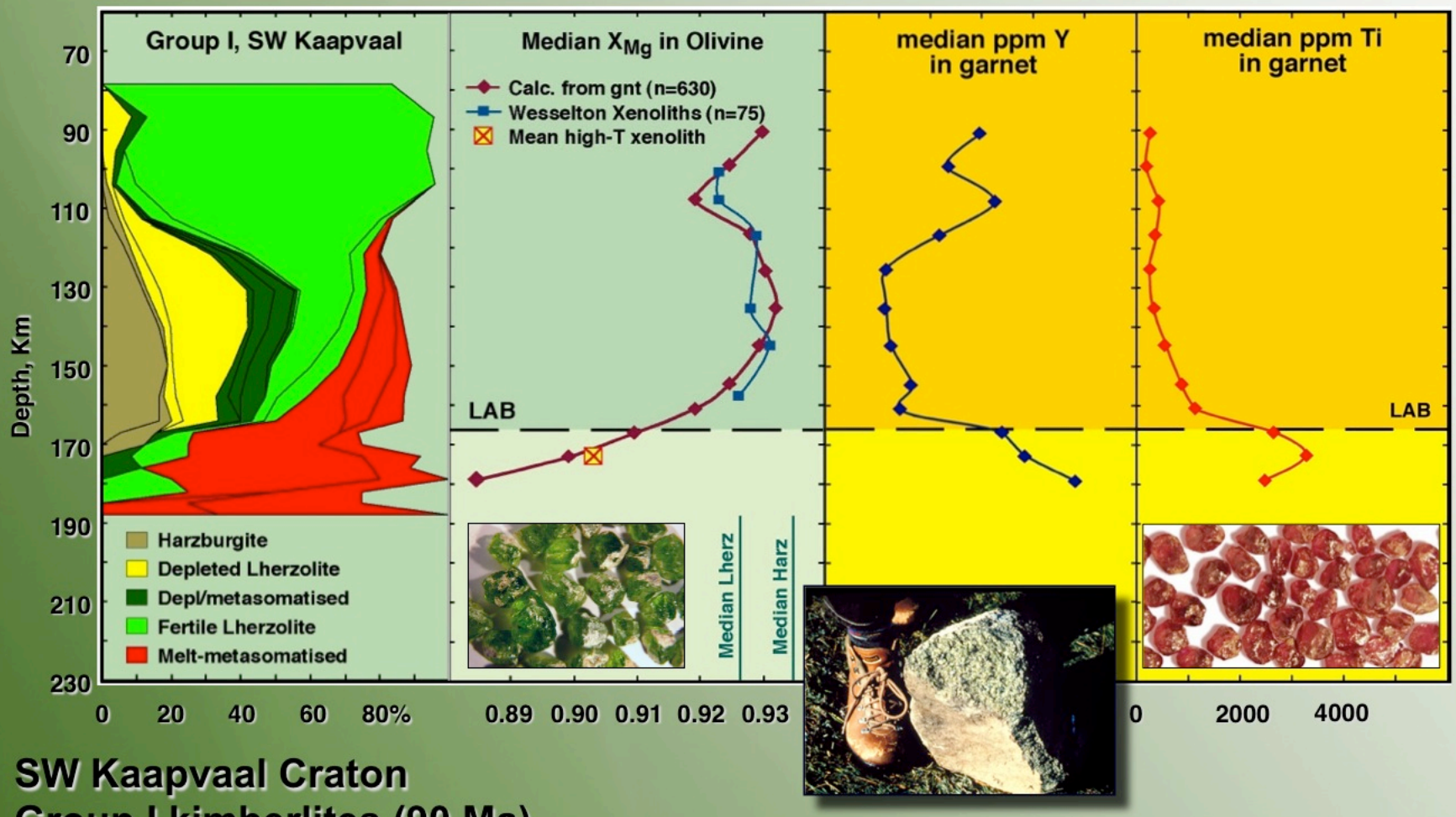
- ***Spatial context to xenoliths and xenocrysts***

- Empirical method of building up PT profiles
- Independent of assumptions for extrapolation of surface heat flow
- Depth of each xenolith and garnet xenocryst can be used to develop a rock-type sequence for each mantle section

- Results in "Chemical Tomography" sections



Constructing mantle composition profiles = Chemical Tomography



SW Kaapvaal Craton
Group I kimberlites (90 Ma)

Orogenic massifs, ophiolites, some ocean-floor peridotites - tectonically exposed mantle

Gusdal quarry and Ugelvik peridotite, Norway

- **A few examples:**
  - * **Finero** (Italy),
  - * **Lherz** (France)
  - * **Ronda, Ajen** (Spain)
  - * **Luobosa, Zedong, Shenglikou** (Tibet)
  - * **Western Gneiss Region** (Norway)
- Exposed mantle outcrops show rock-type relationships and meso-scale structures
- Show veins and dyking

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

- Zones of garnet lherzolite around eclogite dikes

- Western Norway: huge bodies of *dunite and harzburgite* - show rock-type relationships and meso-scale structures
- Represent mantle from > 200 km - from subduction event
- Re-Os dating:
  - * dunites = Archean
  - * lherzolites = Proterozoic
- Refertilisation process - analogue for most Archean SCLM observed?

Beyer et al. J. Petrology, 2006, 2012; Geology 2004

Are Lithospheres Born Equal?

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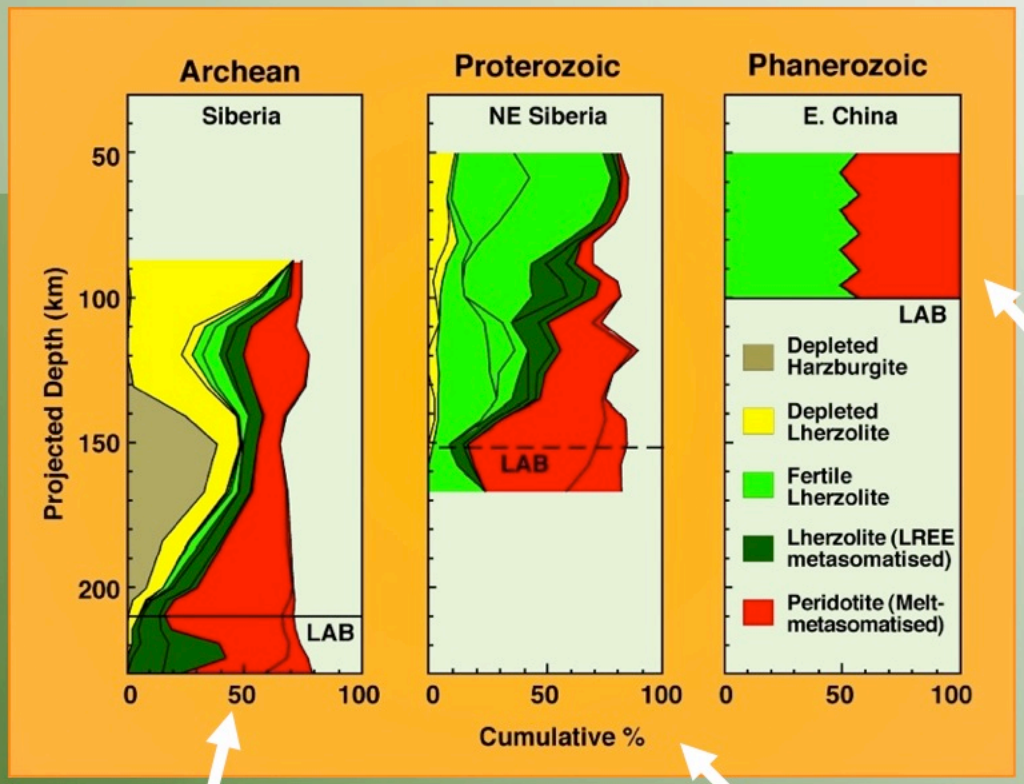


Phanerozoic

Higher density - 3.37 mg/m^{-3}

Low Vp Vp at 100 km = 7.85

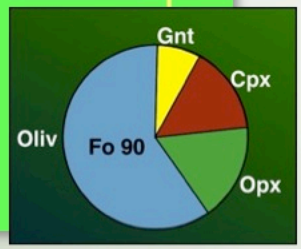
Vs at 100 km = 4.48

Thin (60-120 km)

High Geotherm

High Ca, Al, Fe, Ti

Olivine (Fo 88-90)



Archean

Buoyant - 3.31 mg/m^{-3}

High Vp Vp at 100 km = 8.18

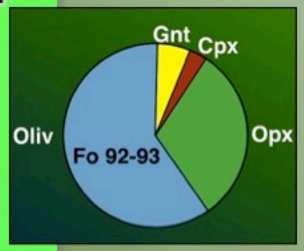
Vs at 100 km = 4.71

Thick (180-240 km)

Low Geotherm (TODAY)

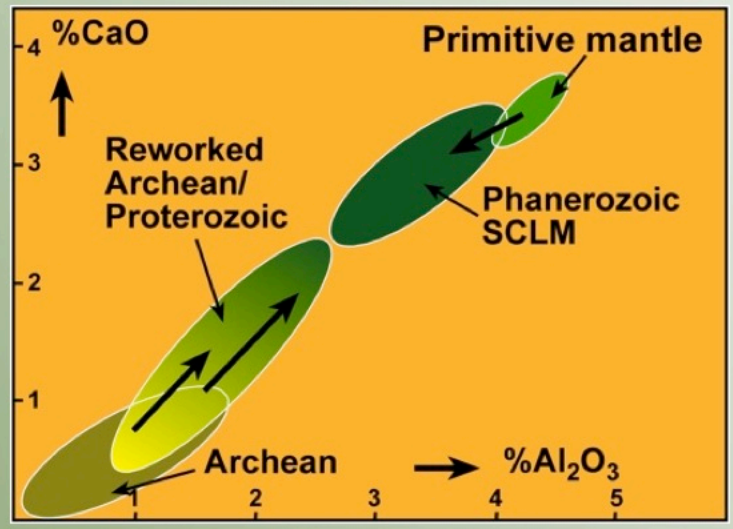
Low Ca, Al, Fe, Ti = Depleted

Olivine (Mg-rich: Fo 91-93)

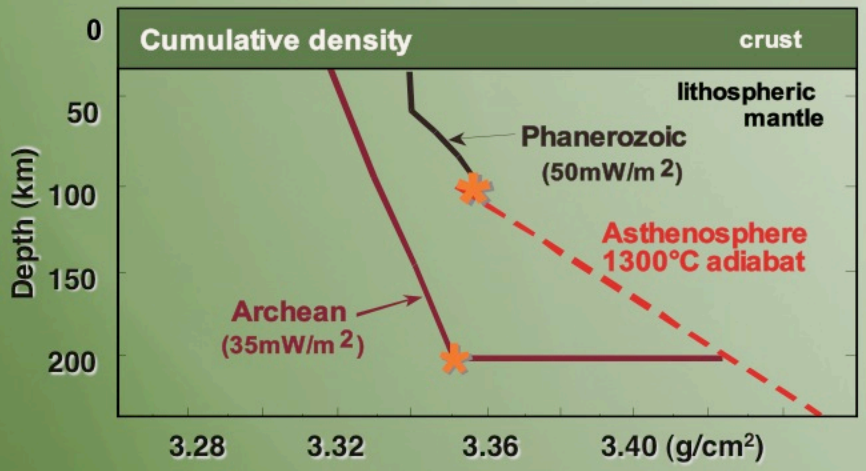


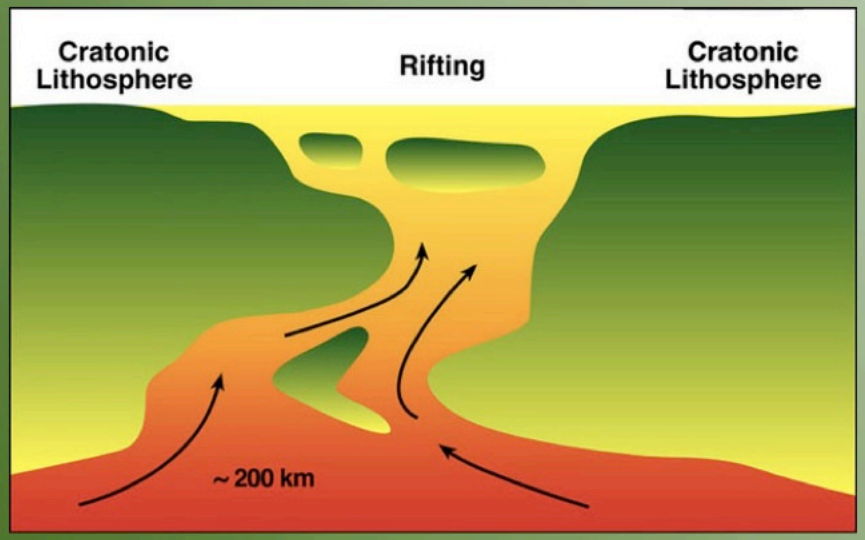
Proterozoic

Intermediate



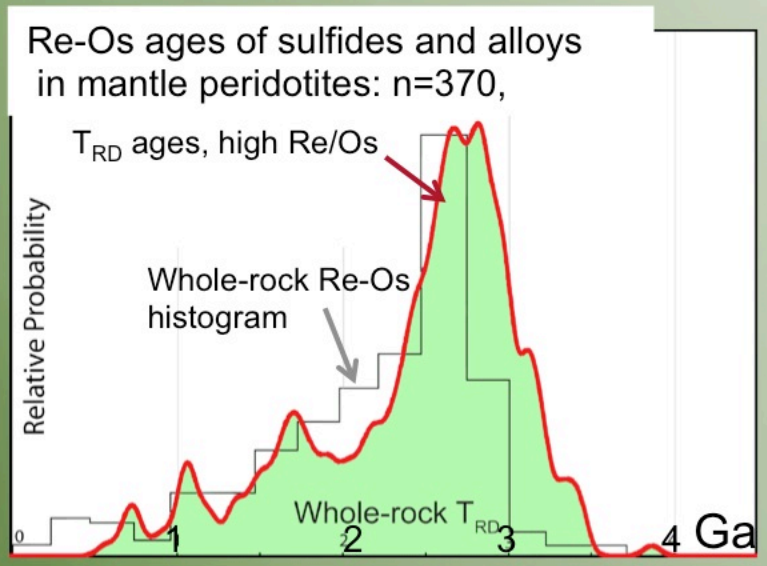
The Buoyant Archean



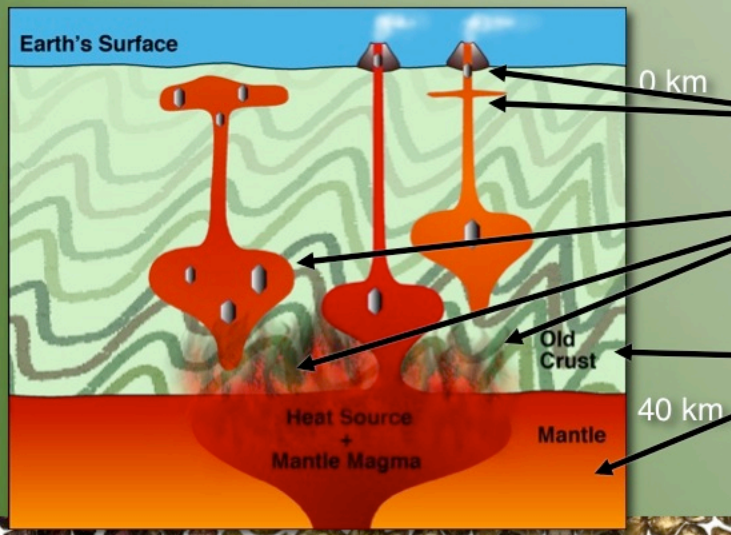


- Archean SCLM too buoyant to be delaminated (gravitationally removed)
- Requires disruption and mechanical disaggregation (eg rift)
- Accompanied by geochemical changes (metasomatism) → > density
- Stranded blobs of Archean lithosphere in oceanic areas

Crust - Mantle Linkages I



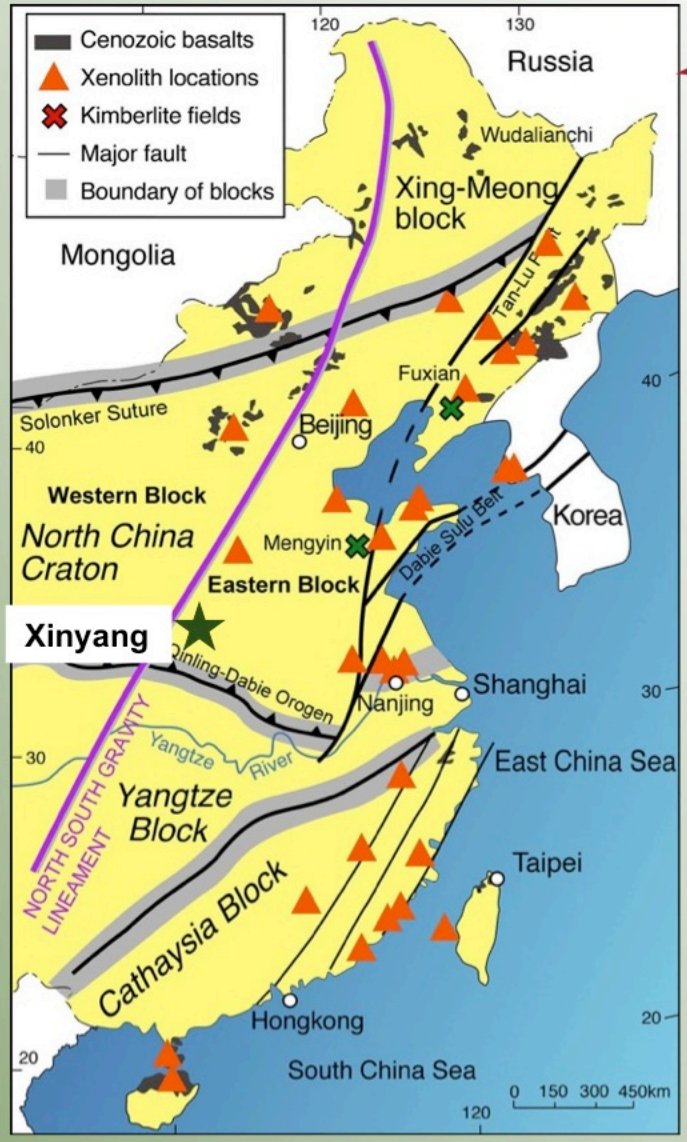
- ***Re-Os dating of mantle sulfides and rocks →***
  - ***Timing of stabilisation of mantle lithosphere domains***
  - ***Timing of (multiple) fluid events in the lithosphere***
  - ***No Hadean ages, few > 3Ga***
  - ***Major peak 3.0 Ga - formation of most Archean SCLM?***



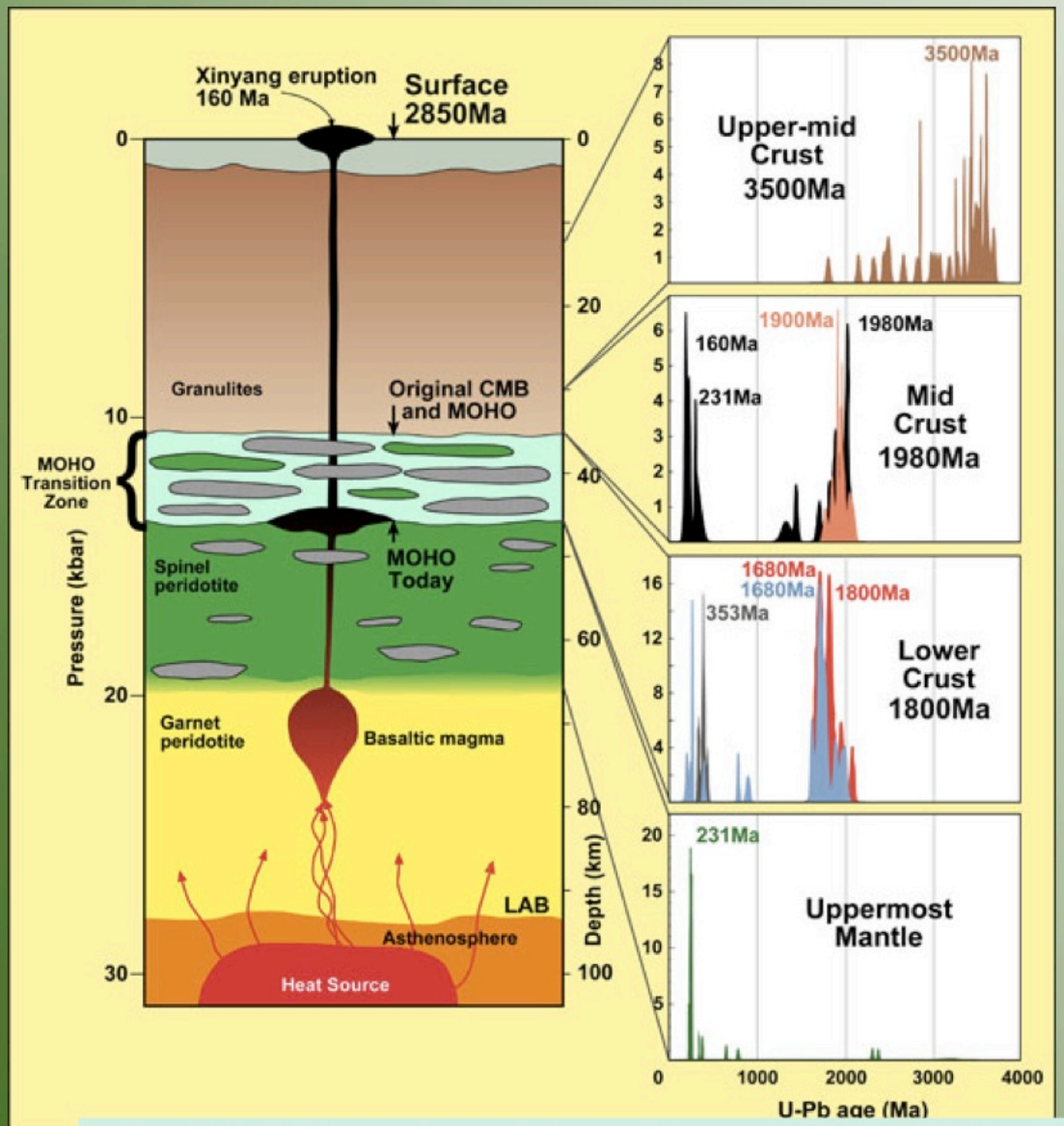
- ***Zircon U-Pb and Hf isotopes:***
  - ***Age and type of magma***
  - ***Age of source region + location (deep crust or mantle or mixing)***
  - ***Identifies fertility of host magma and deep source (eg Au, Cu)***

Eastern China: a complex geodynamic evolution

- **Tectonic framework *today***
  - 4 ***major*** **domains:**
    - Xing-Meong Block
    - North China Craton (NCC)
    - Yangtze Block
    - Cathaysia Block
  - **Subduction boundaries on 3 sides of North China Craton**
- **Ideal natural laboratory to unravel lithosphere evolution**
  - **Mantle xenoliths in volcanics 500Ma to now**
  - **Timeslices of lithosphere**
  - **Excellent geophysical data**



60 km of time travel through lithosphere evolution in the North China craton (NCC)



- ***Zircons in 160 Ma diatremes (Xinyang) sample lithosphere column:***
  - **Original crust Archean (now mid crust)**
  - **Resurfaced at 2850 Ma**
  - **Underplated at 1980 Ma**
  - **Underplated again 1800 Ma**
  - **Upper mantle events at 160, 231, 400, ~700-800, + older**

Records collisions of:

- **E and W NCC /Pangea assembly at ~2 Ga**
- **Yangtze and NCC at 440 (Qinling) / 240 (Dabie-Sulu) Ma**

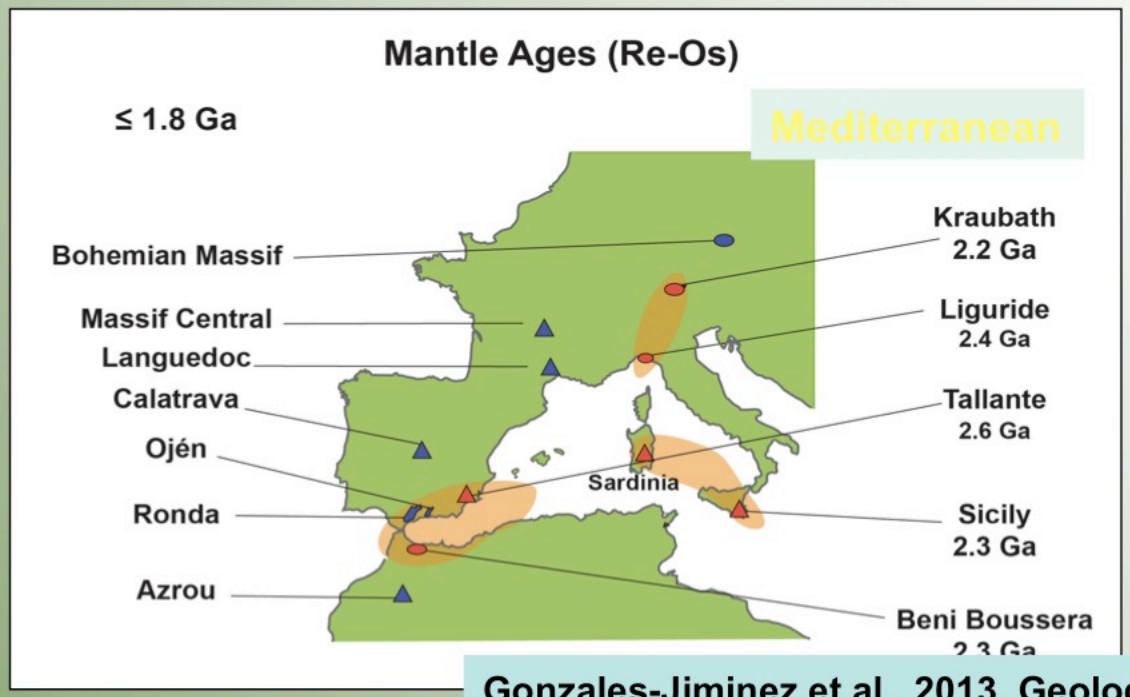
Zheng et al EPSL 2006
Chen et al. Lithos 2001

After NCC lithosphere thinned from ~ 200 to 80 km between 450 – 250 Ma

Widespread Archean lower crust

- *Archean lower crust now identified in many "new" regions with younger upper crust eg:*
  - Southeastern China
  - Yangtse Craton
  - Spitsbergen
  - North China Craton
  - NE Australia

  New ancient mantle finds
  - Tibet (ophiolites)
  - Mediterranean



Gonzales-Jiminez et al., 2013, Geology

- *Implications:*
  - Significant crustal "resurfacing"
  - Archean lower crust and lithospheric mantle formed and commonly (but not always) persisted together
  - *Need to rethink the more traditional models of crustal growth rates*

Global Lithosphere Architecture Mapping (GLAM): Africa Vs Tomography 100-175 km

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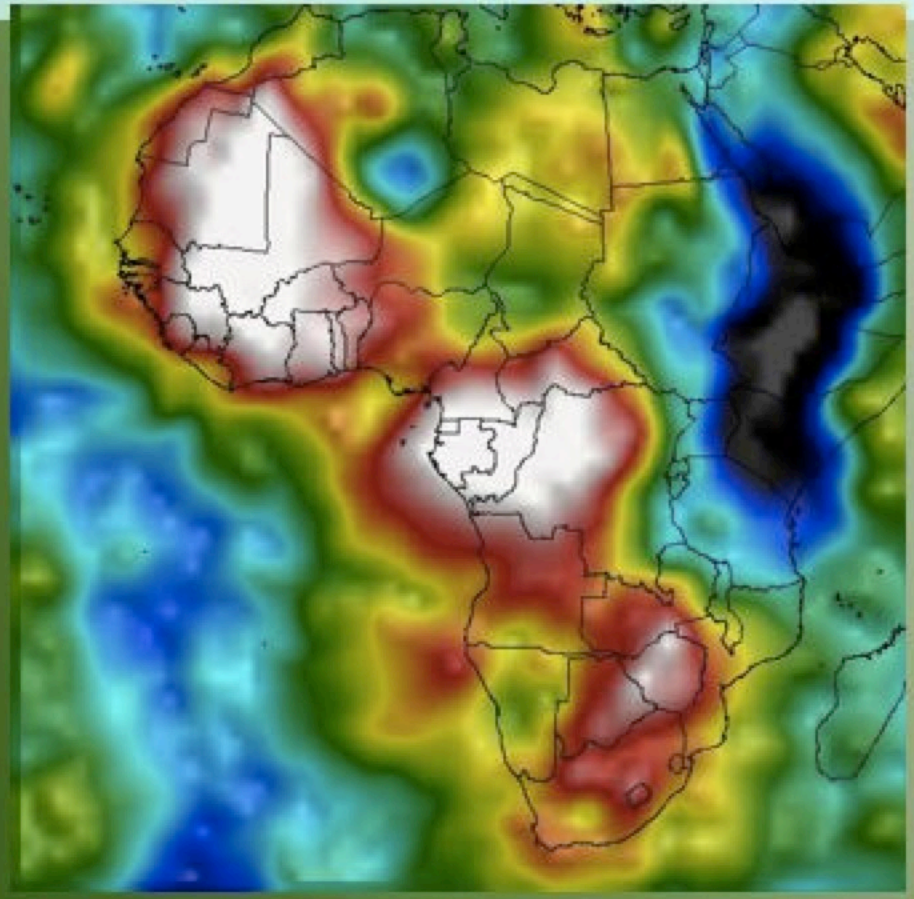
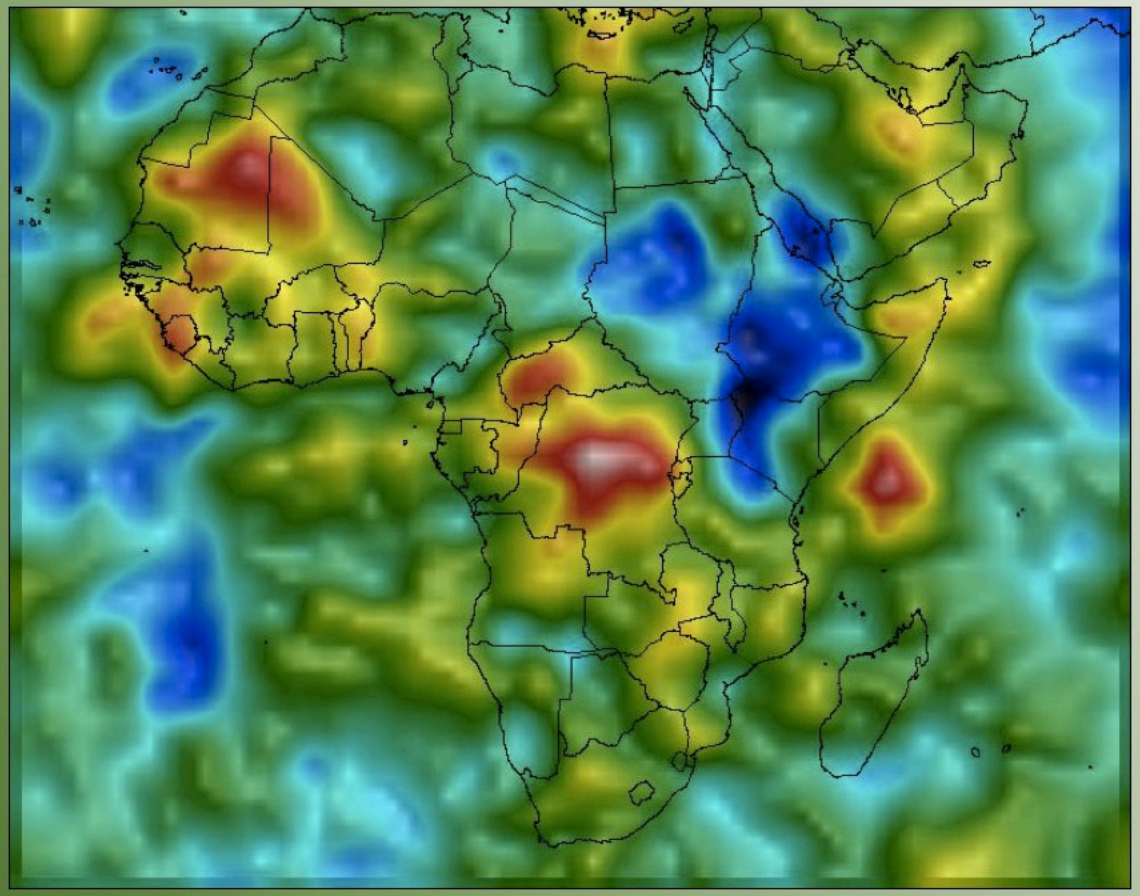
(Model from Steve Grand, refined by WMC, BHP Billiton - under continual refinement)



- Integrates global seismic tomography with deep xenolith petrology, geochemistry, geochronology, tectonic history and regional geophysical datasets
- Window to subcontinental lithospheric mantle (SCLM) and lower crust domain distribution
- → *identification of tomographic signature for Archean SCLM compositions*

- Note colour reversal :
- red = fast (high Vs) blue = slow (low Vs)

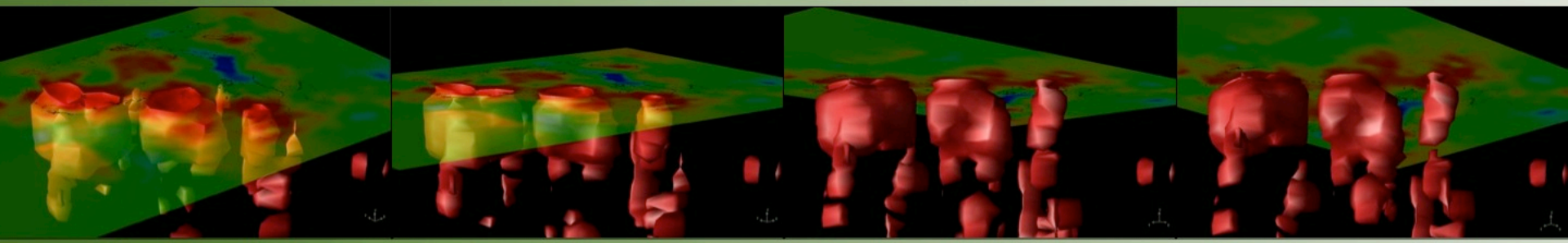
Africa Vs Tomography 325-400 km



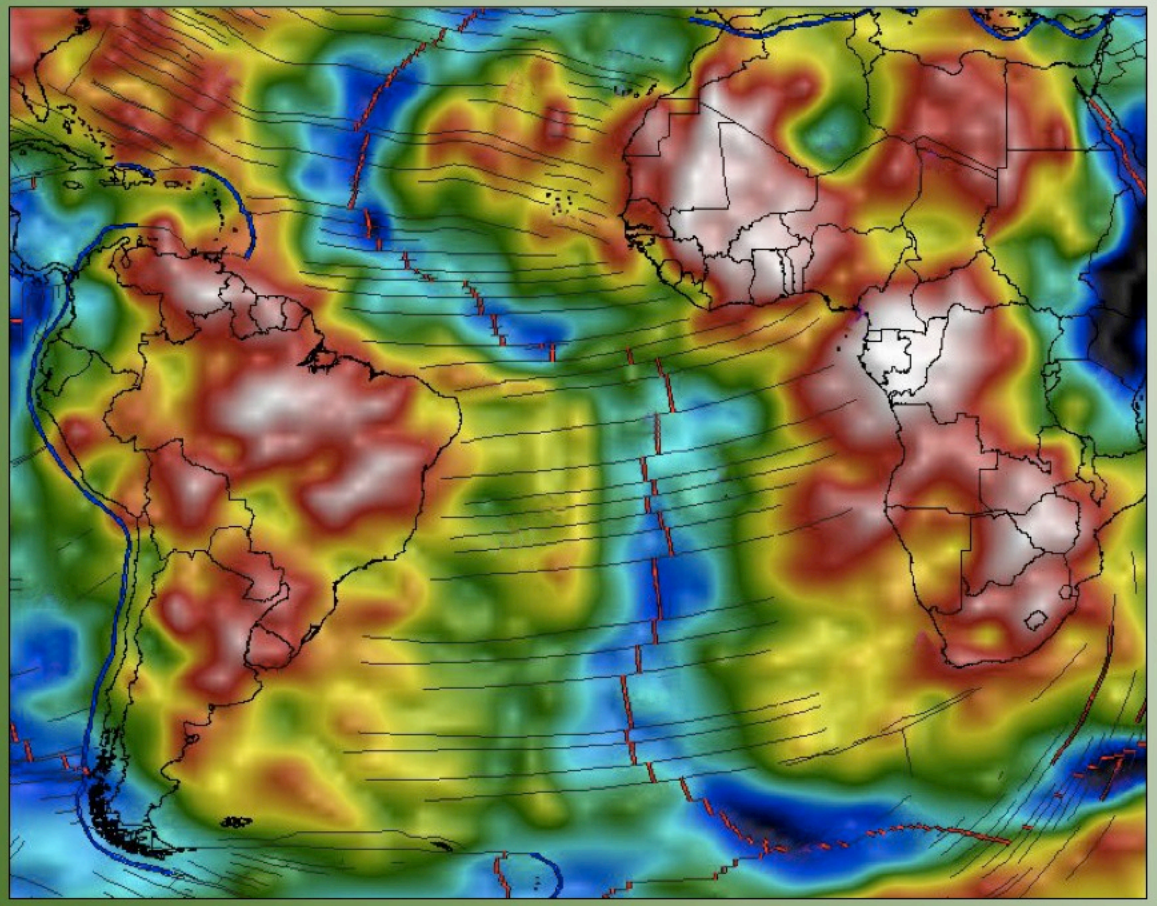
Cratons still visible as regions with contrasting Vs

- **Craton Vs higher than Earth model**
- **Upwellings (rift, Hoggar) follow old pathways - reveal deep fluid pathways**

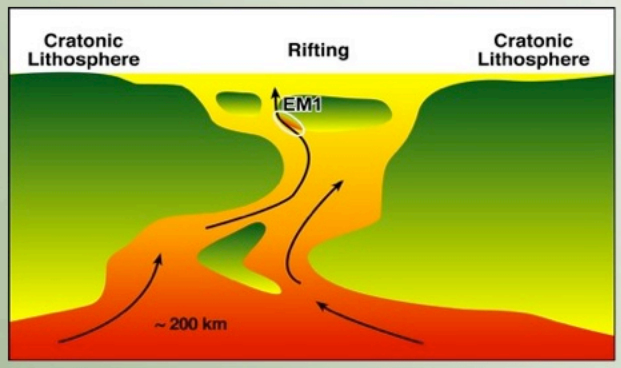
Imaging the architecture of deep fluid conduits



Sth Atlantic Vs Tomography 0-100 km



- Low density domains in oceanic regions = buoyant ancient SCLM remnants?
- Re-Os dating shows ancient mantle lithosphere domains in oceanic regions = old rifted, mechanically disrupted SCLM?



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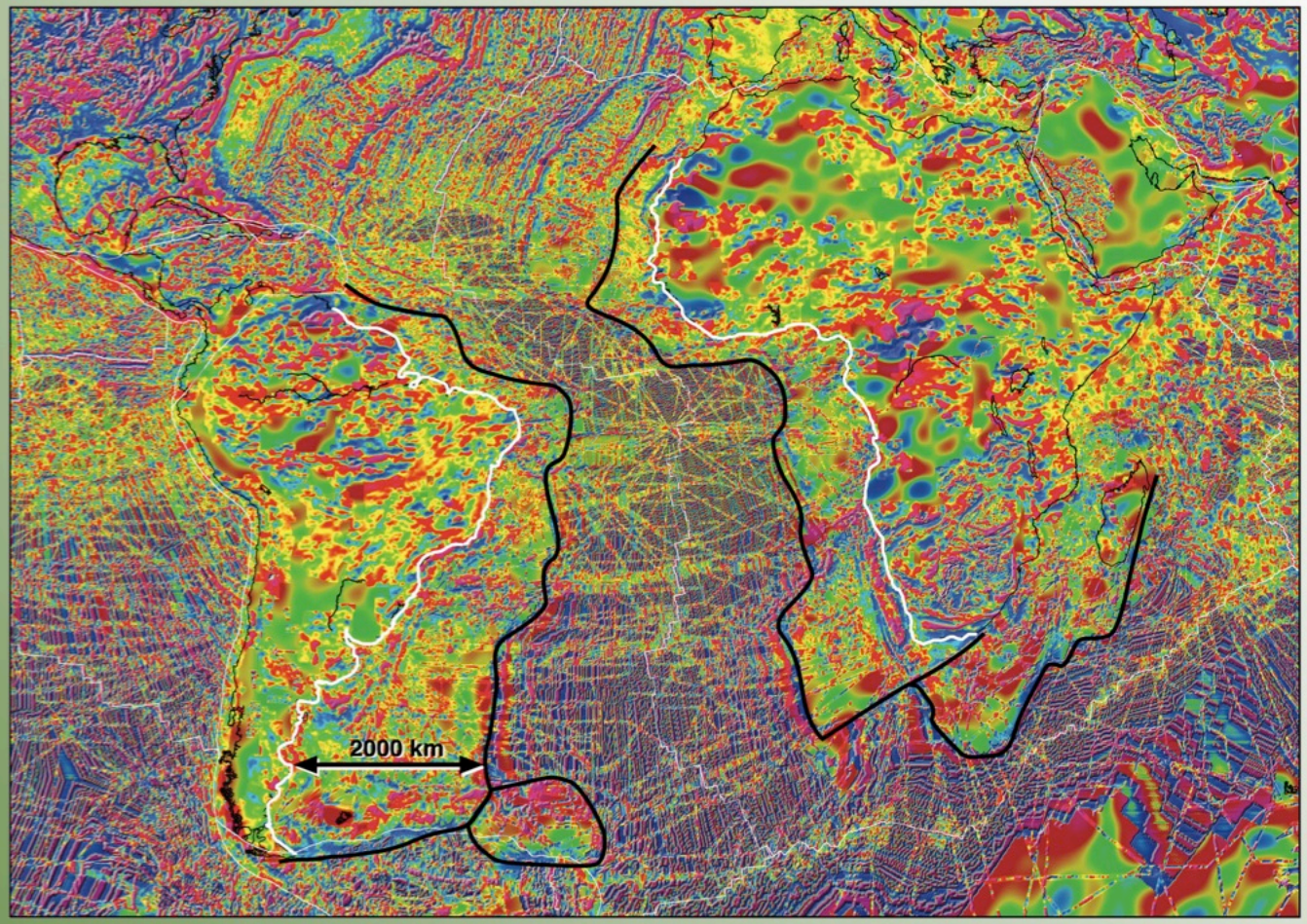
World Magnetic Anomaly Map 2007

- Cratonic extensions into Atlantic Oceanic Basin
- Complex crustal magnetic signature, not magnetic stripes of oceanic mantle
- Rifted continents best fit with hidden parts
- Reveals mechanisms of rifting - listric faulting along rift



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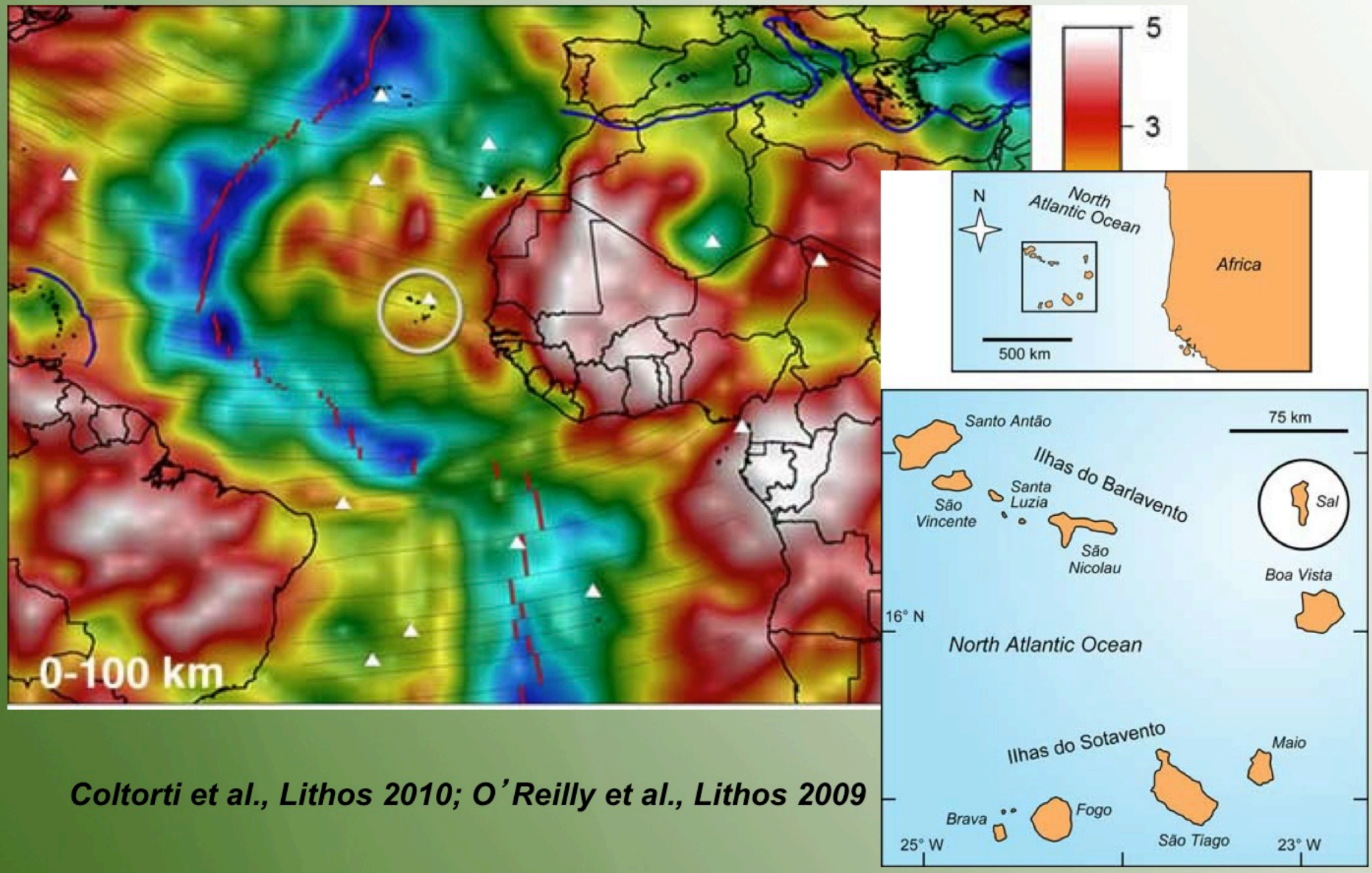
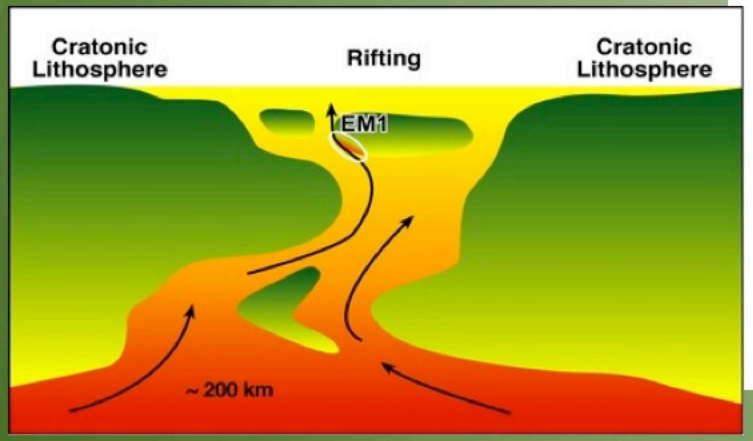
Cape Verde Islands

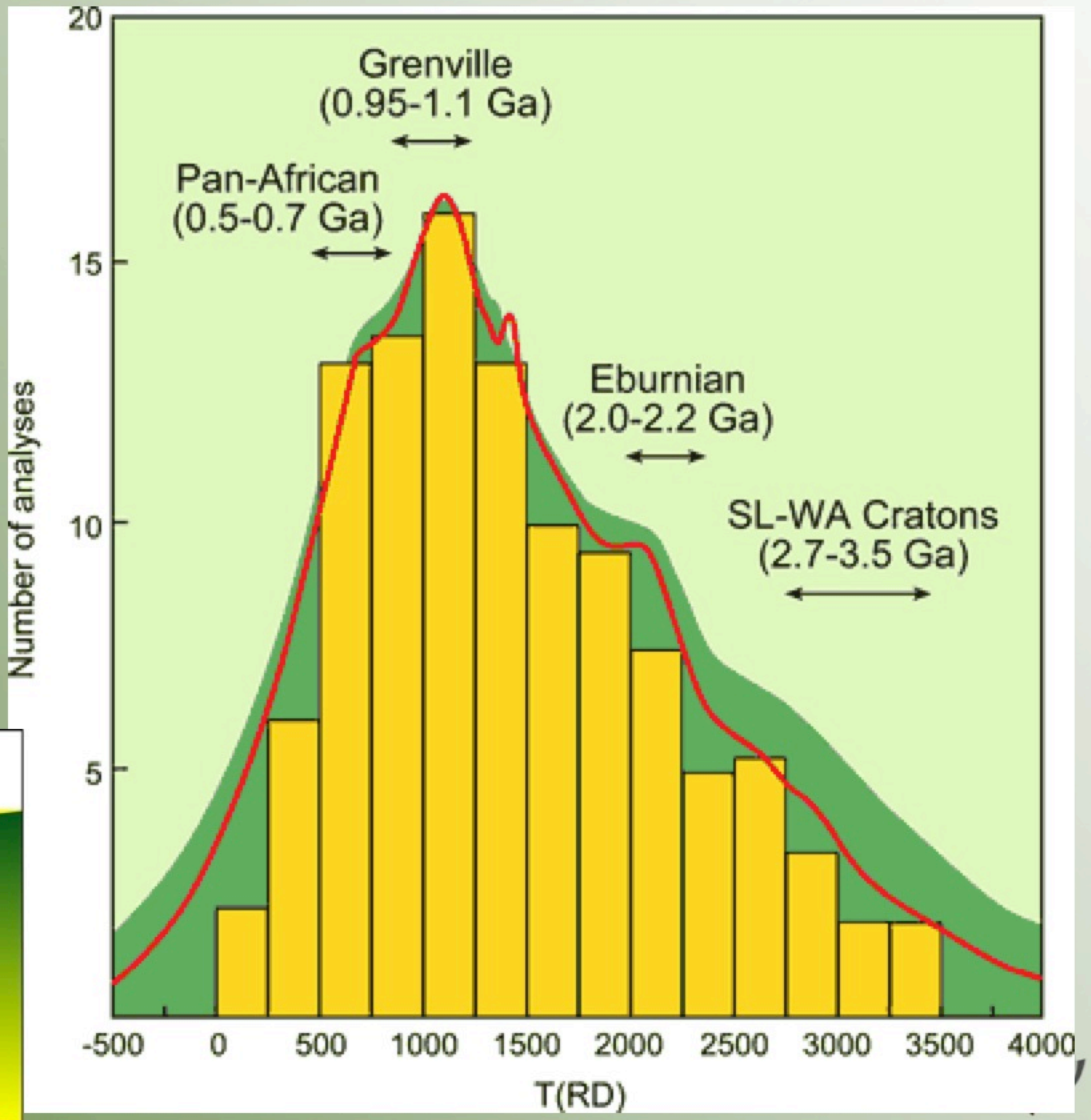


Coltorti et al., Lithos 2010; O'Reilly et al., Lithos 2009

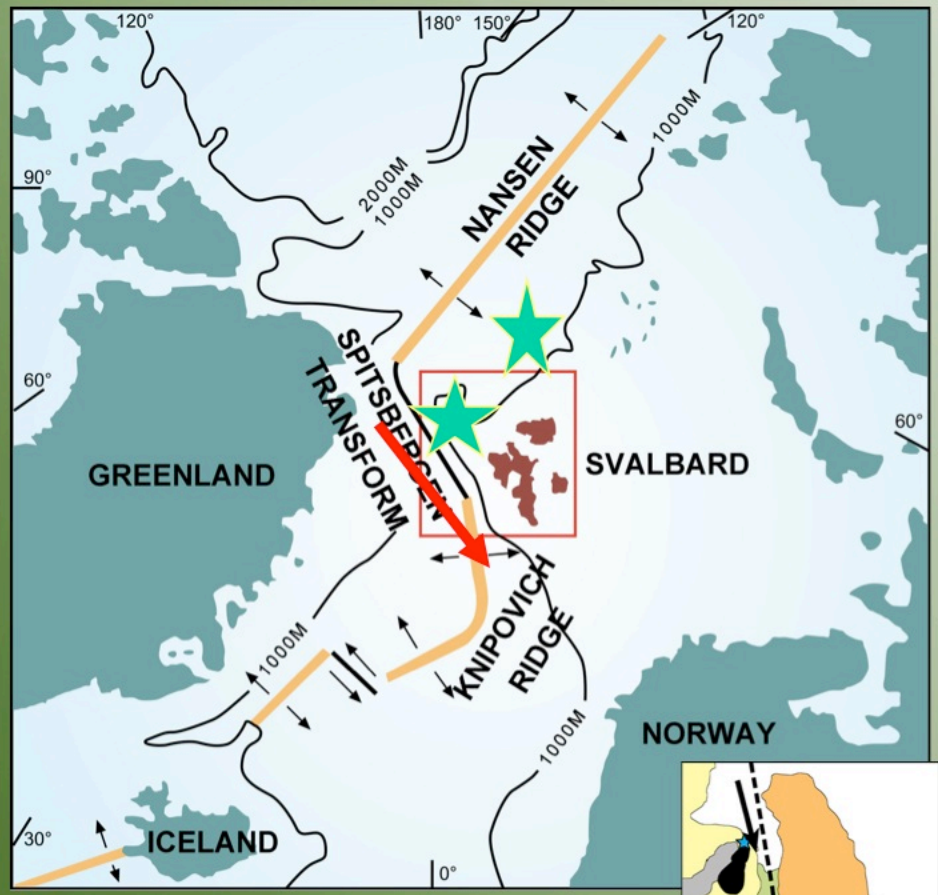
Re-Os Age distribution Cape Verde Lithospheric Mantle

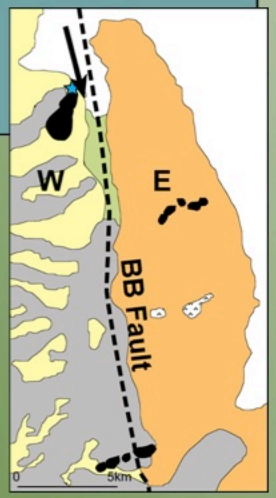
- Reflect ages of tectonic events of the West Africa Craton
- Represents relict ancient lithospheric blob stranded as ocean floor opened and South America and South Africa rifted apart





Svalbard - a case of detached SCLM?





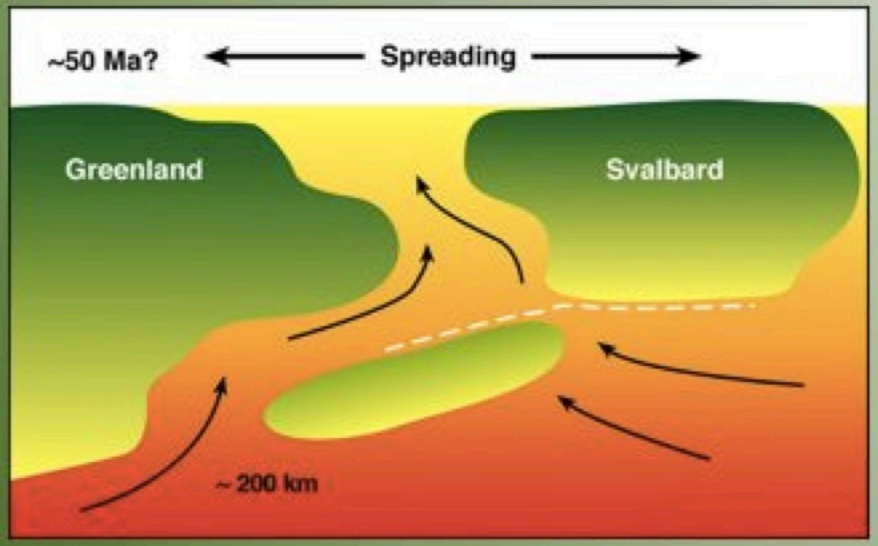
Gakkel (Nansen) Ridge = stranded SCLM along the track of Svalbard's journey. (*Low magmatism, peridotites exposed on ocean floor)*

Goldstein et al. 2008 -> Dupal anomaly in basalts = SCLM "contamination"

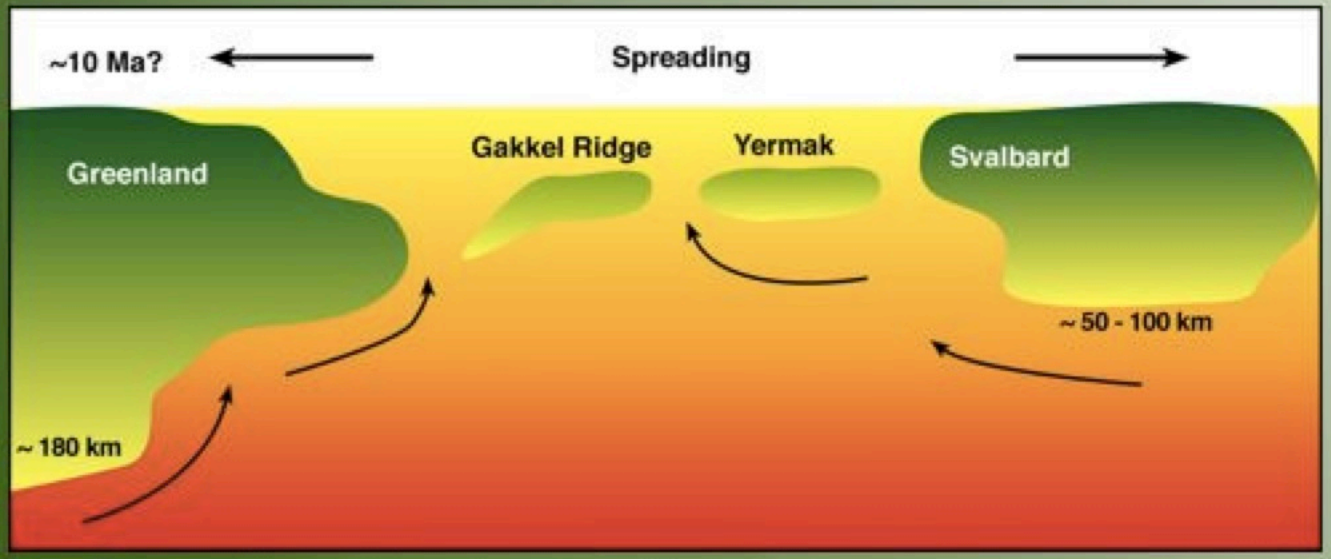
Liu et al. 2008 -->
WR Re-Os ages on peridotites - back to 2.2 Ga (min. age)

The missing root…..?

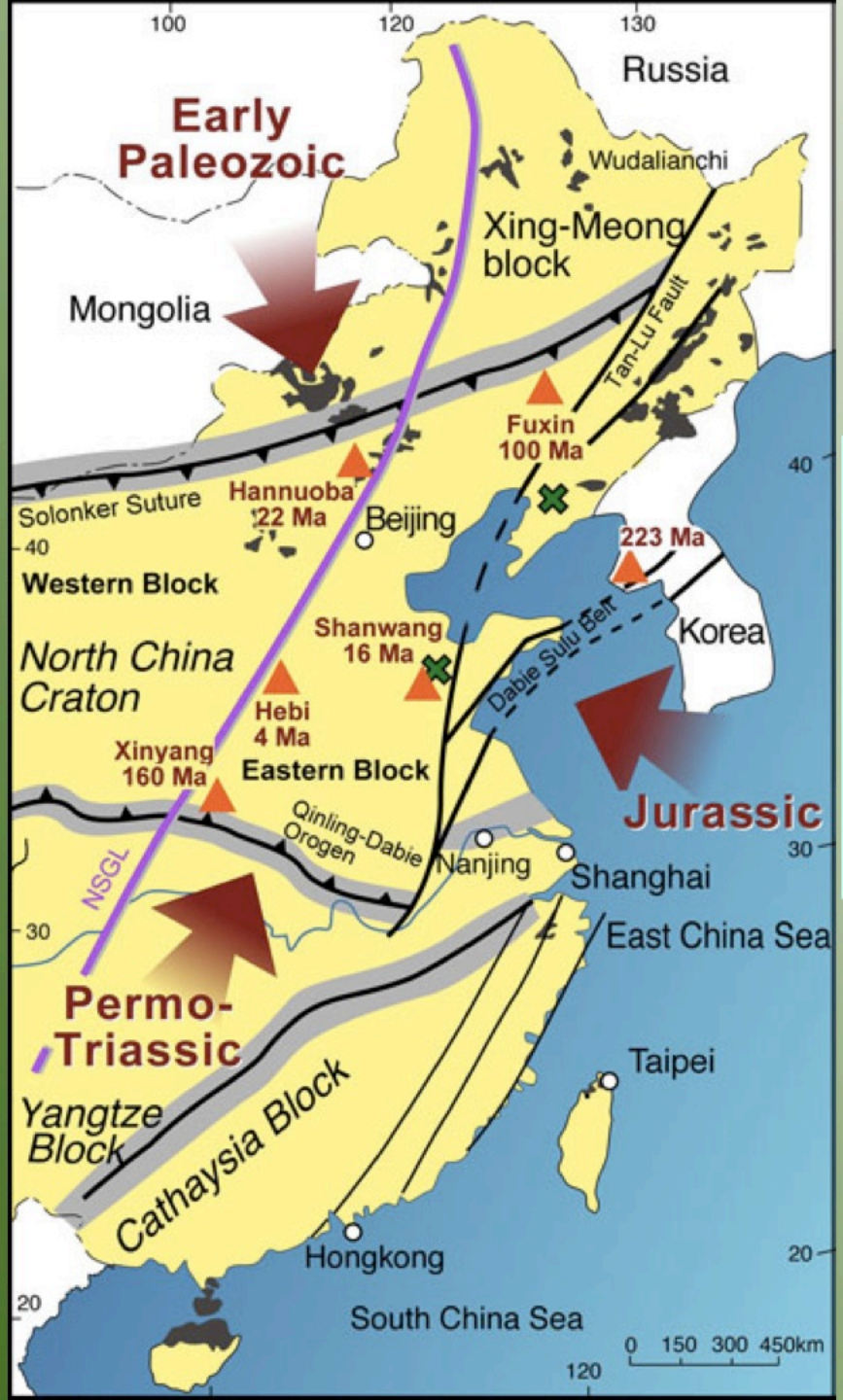
Tectonic evolution from ~50 Ma to present



- Rifting of eastern margin of Greenland ~ 50 Ma
- Detachment of lower lithosphere of rifted margin



- Stretching of stranded lithospheric mantle relics →
  * *Gakkel Ridge*
  * *Yermak plateau*
  * *Thinned Svalbard lithosphere*



3 directions of subduction:

"The whole Upper Mantle under NE Asia is a Big Mantle Wedge"

Zhao et al, 2009 PEPI

- **Multiple** subduction (from **East, North *and* South** delivers *Yangtzes* of water into the mantle -
- Greatest global volume known - *1150 Ma equivalents of subduction since early Paleozoic* *(Windley et al., 2010)*

Are NCC (and Tethyan) belts templates for the future fate of the Pacific

Oceanic region ringed by subduction?

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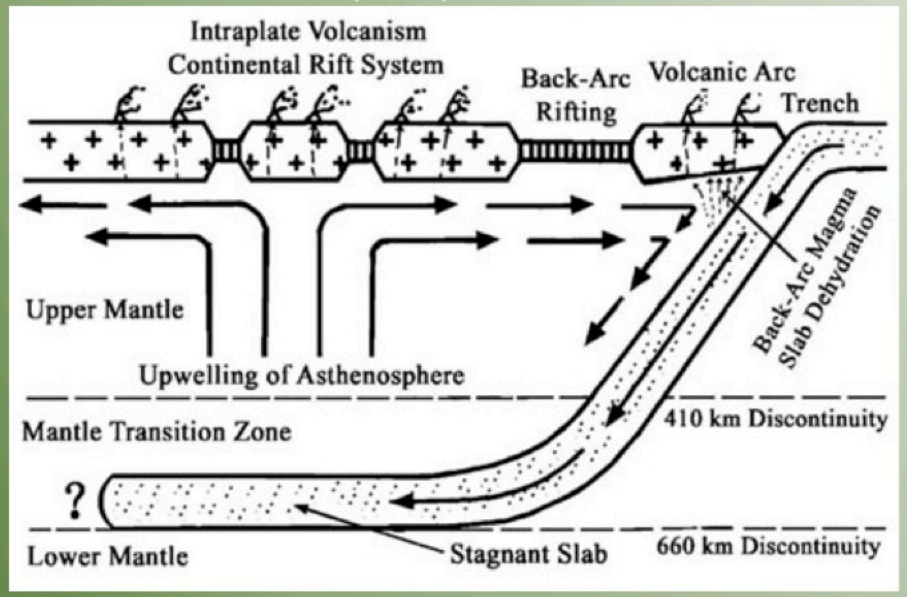
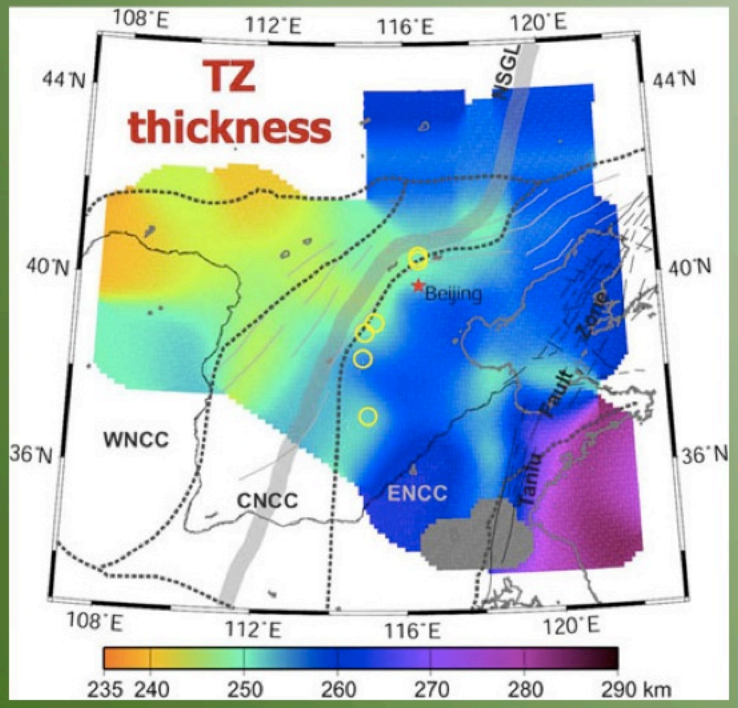
Zhao D. et al., GR, 2007



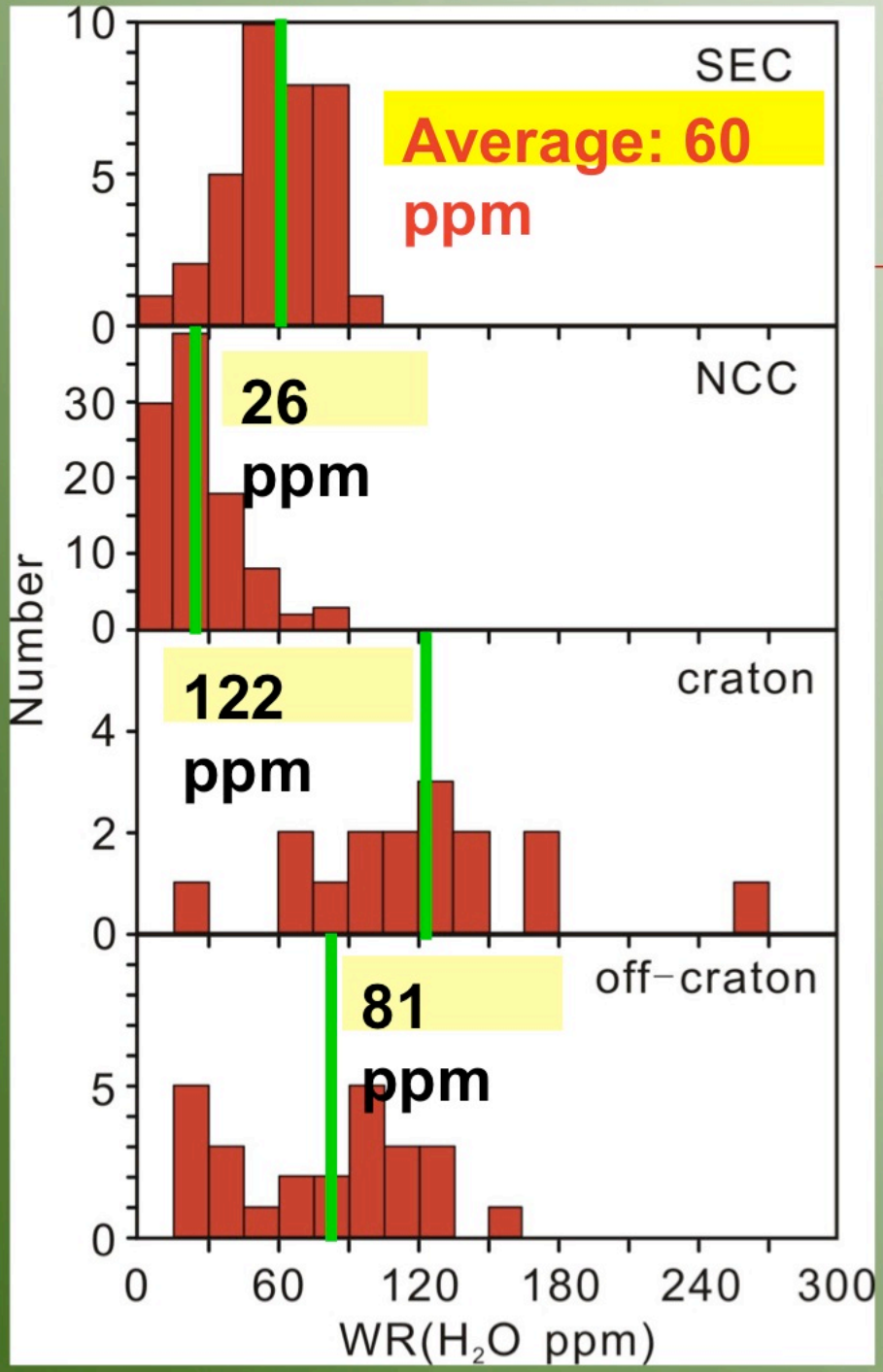
Stagnant slab underlies NCC (mainly from Pacific subduction)

- **Multiple** subduction (from **East, North *and* South** delivers *Yangtzes* of water into the mantle -
- **Greatest global *volume and rate*** of subduction recognised - *1150 Ma equivalents of subduction since early Paleozoic*
  (Windley et al., 2010)



Is NCC a template for the future fate of the Pacific Oceanic region ringed by subduction?

Ling Chen Lithos 2010



Whole-rock H_2O contents

- South China craton SCLM wetter than NCC
- Drier than other cratonic and off-craton SCLM

(*Bell & Rossman, 1992a; Peslier et al., 2002; Peslier & Luhr, 2006; Demouchy et al., 2006; Grant et al., 2007; Aubaud et al., 2007; Li et al., 2008; Bonadiman et al., 2009; Xia et al., 2010*)

Conclusions #1 at November 2013

- *Lateral and v*ertical heterogenities in the crust and lithosphere can be tracked ***in space and time*** by integrating geochemical, tectonic and geophysical datasets

- Lithosphere domains in crust and mantle slices have now been mapped at scales of ~75-150kms (talks on Tuesday am)

- *Most continental lower crust and SCLM were originally formed in the Archean, then geodynamic processes changed…..*

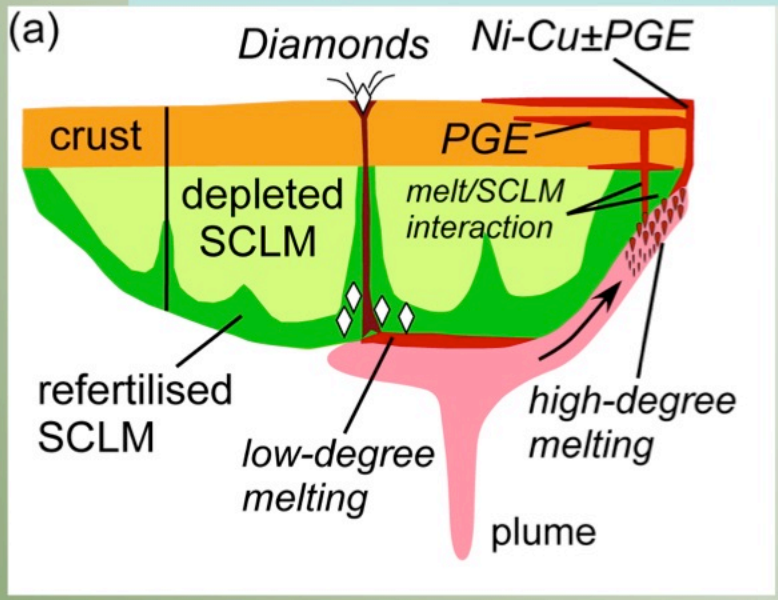
- *Archean lithosphere was more depleted than conventional estimates - **refertilised variously** through time*

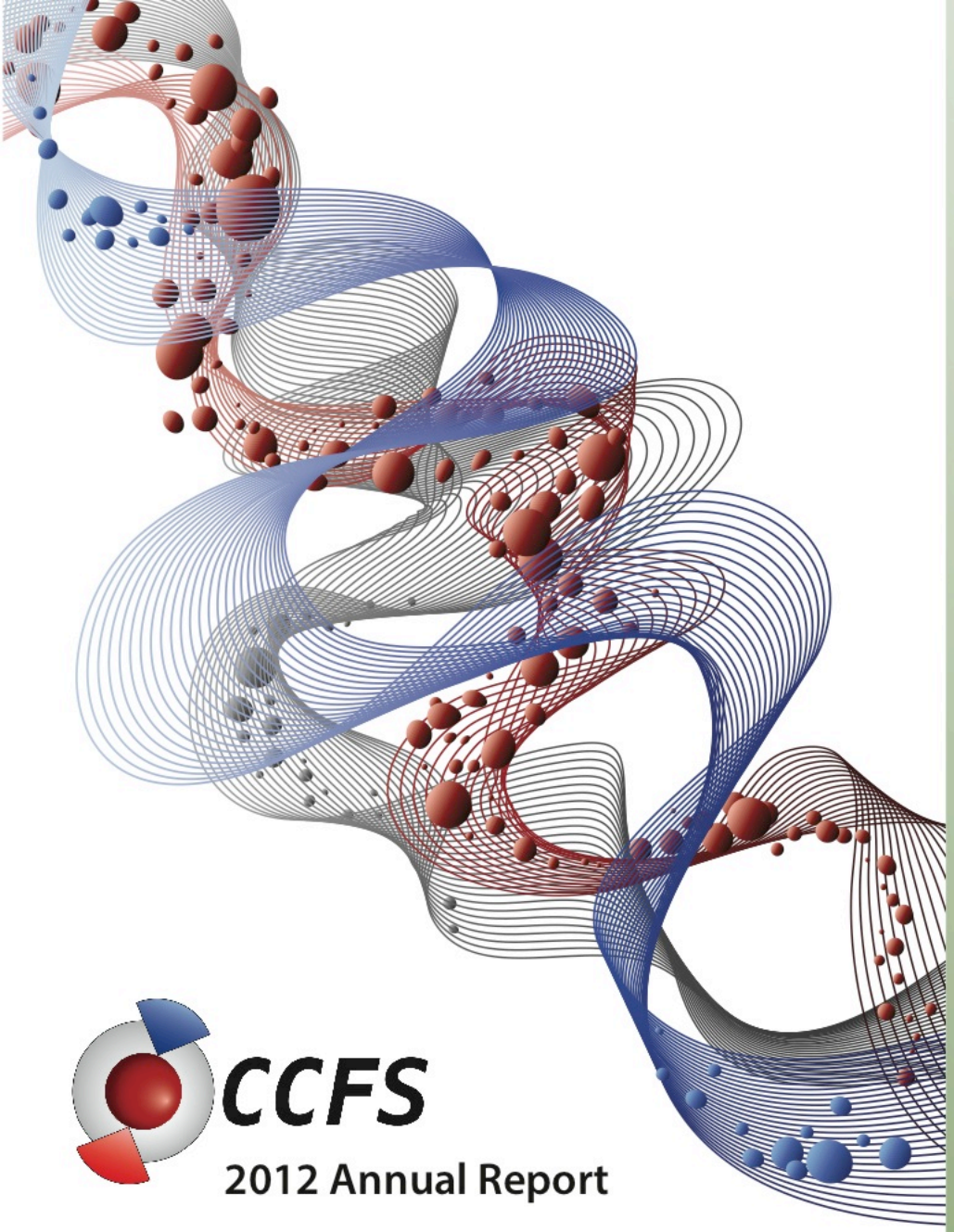
Conclusions #2 at November 2013

- Discontinuities in the lithosphere are critical for fluid-flow pathways, geochemical exchange and metallogenic fertility of mantle and crustal fluids.
- *Lithosphere structure is a first-order determinant for localisation of a variety of ore deposits:*
  - *Ni, PGEs, Au, Cu, diamonds*

This Workshop program promises to present state-of-the-art ideas on the lithosphere across a broad spectrum of cogent topics

Griffin et al, Nature Geoscience, in press





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