The stability and instability of thick continents

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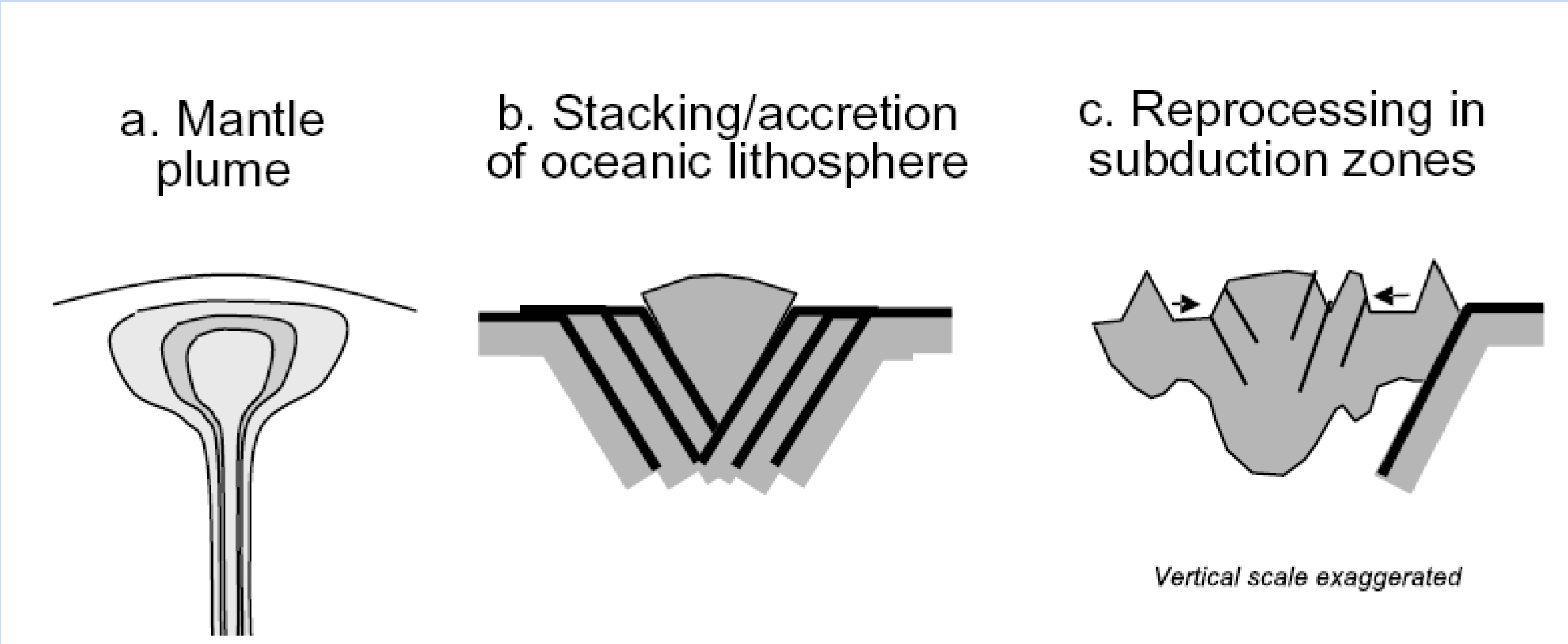
ISSUES

- Lithospheric stability depends on thermal structure and thermal evolution
- Heat production in lithospheric mantle poorly known

Generation of thick continental roots

3 popular models



Open questions:

(1) What determines thickness

(2) Stability

QUESTION 1
What makes thick and cold continents stable ?

Sub-continental lithosphere is made of depleted mantle rocks,

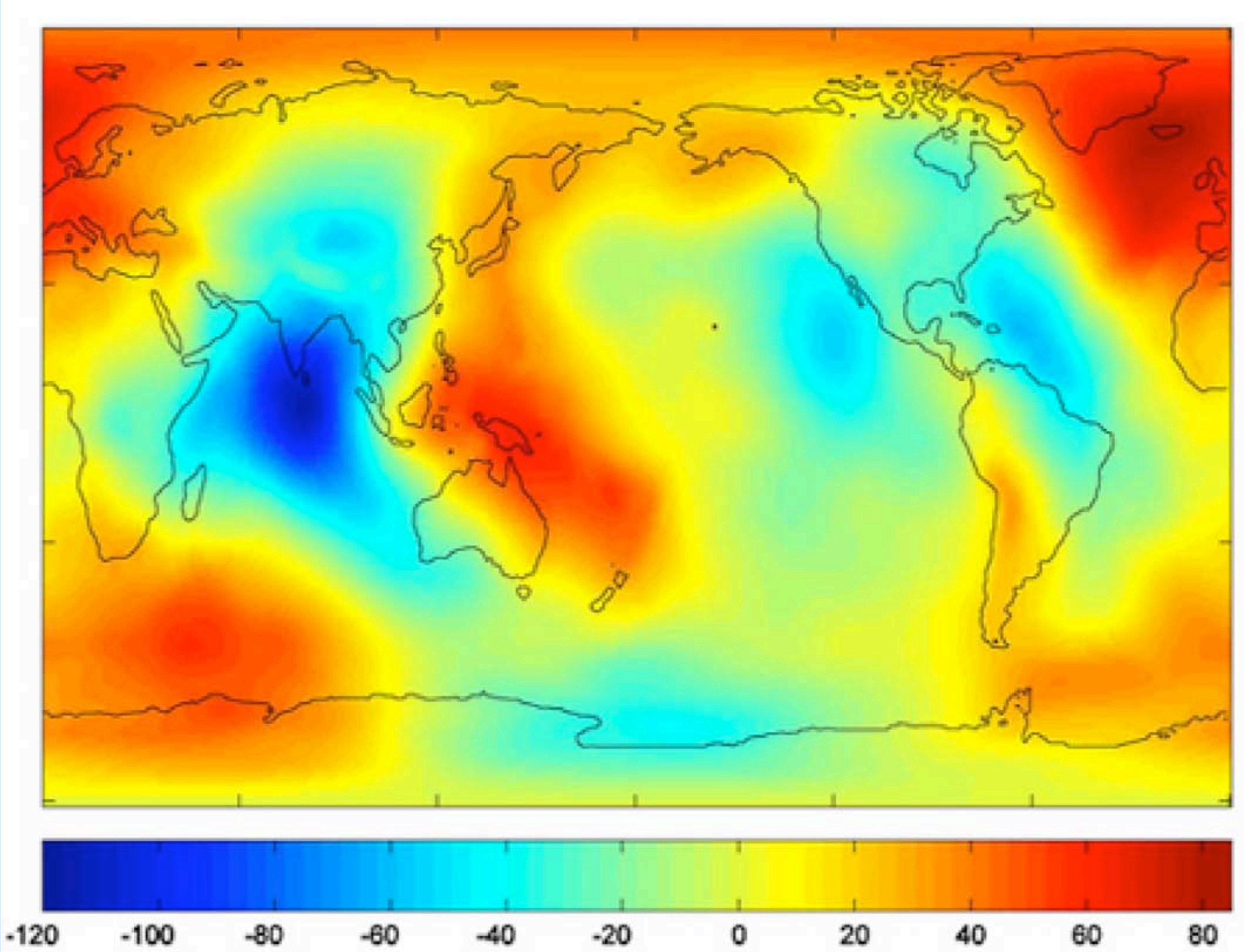
i.e. material that is (1) buoyant
(2) viscous (dehydrated)

QUESTIONS 2

(1) Magnitude of density change due to depletion.

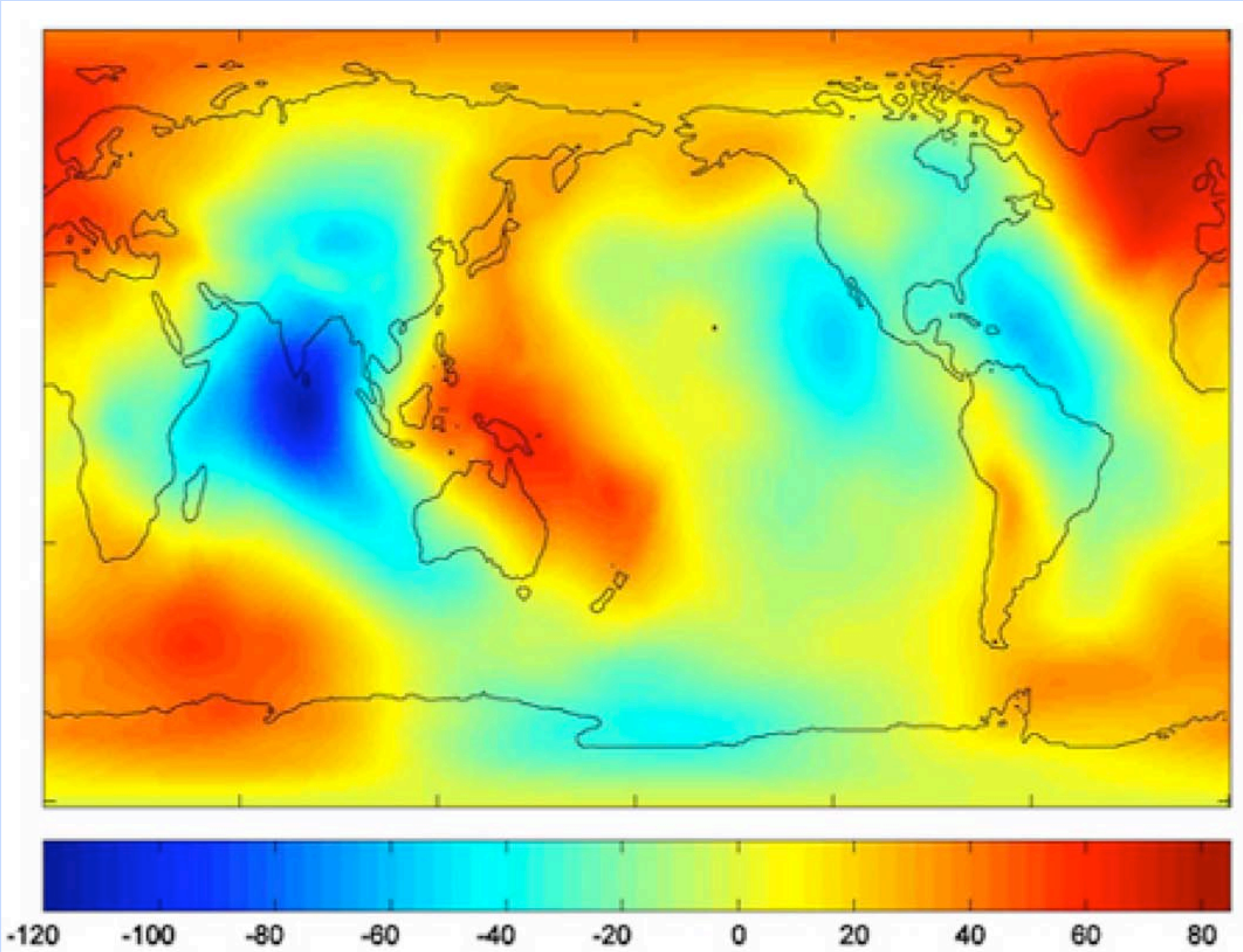
(2) If $\Delta\rho_c \approx \Delta\rho_T$, what accuracy is required for temperature determinations in deep lithosphere ?

Geoid anomalies over cratons are small

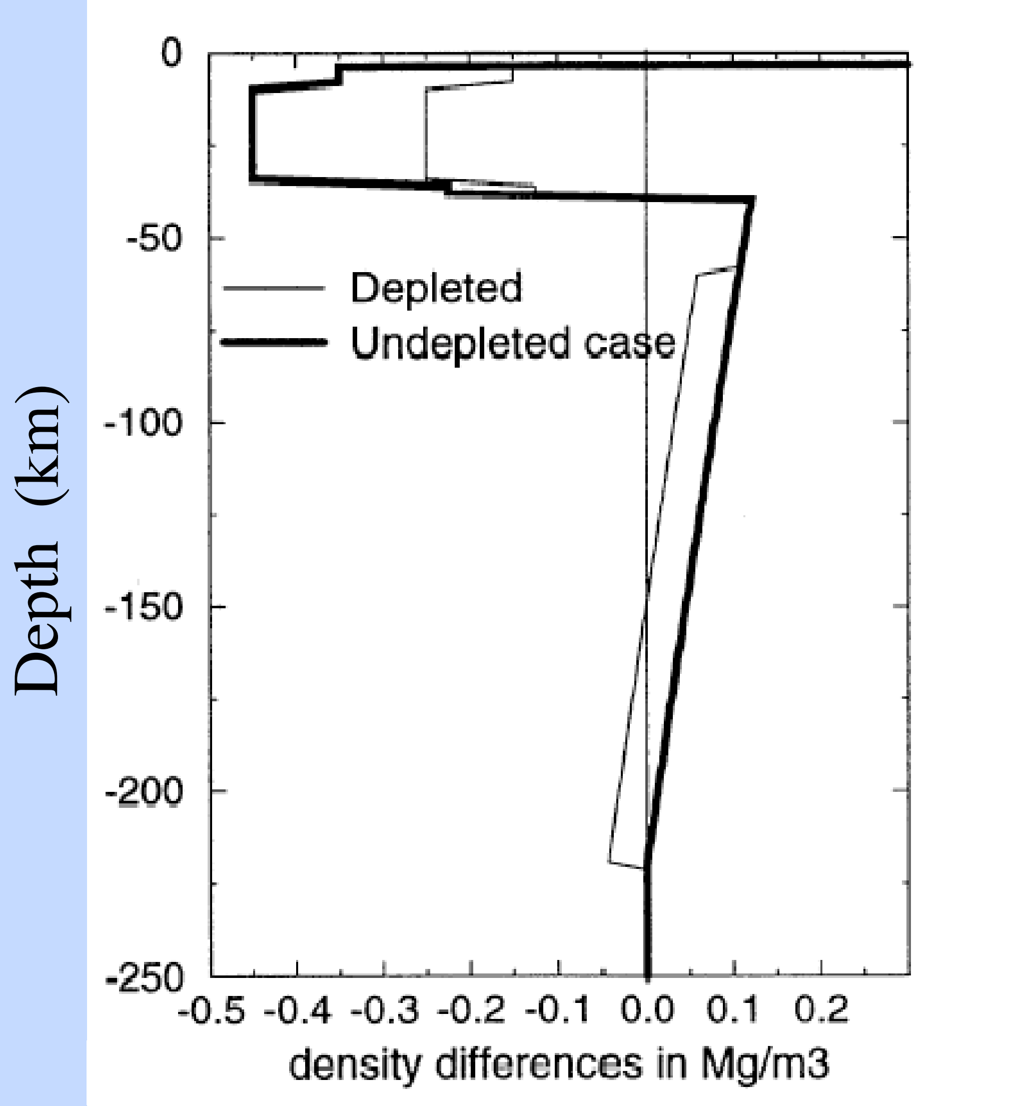


Geoid anomaly from GRACE mission (m)

Geoid anomalies over cratons are small



$\Delta\rho_T$ is partially compensated by $\Delta\rho_c$



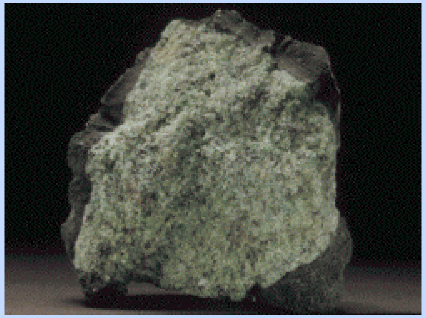
(From Doin, Fleitout & McKenzie, JGR 1996)

$\Delta\rho_c \approx - 45 \text{ kg m}^{-3}$

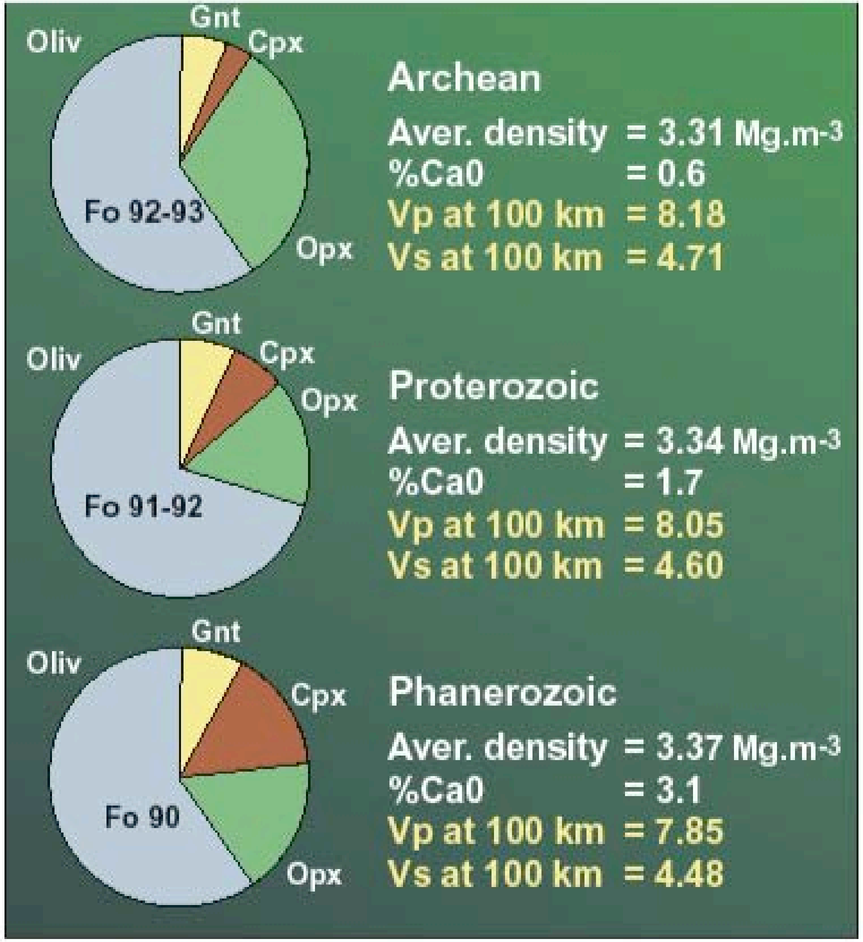
$\Delta\rho_c / \rho \approx - 1.3 \%$

Mantle xenoliths

Finsch kimberlite mine, South Africa



Composition of the subcontinental lithospheric mantle: (1) depleted, (2) varies as a function of age.

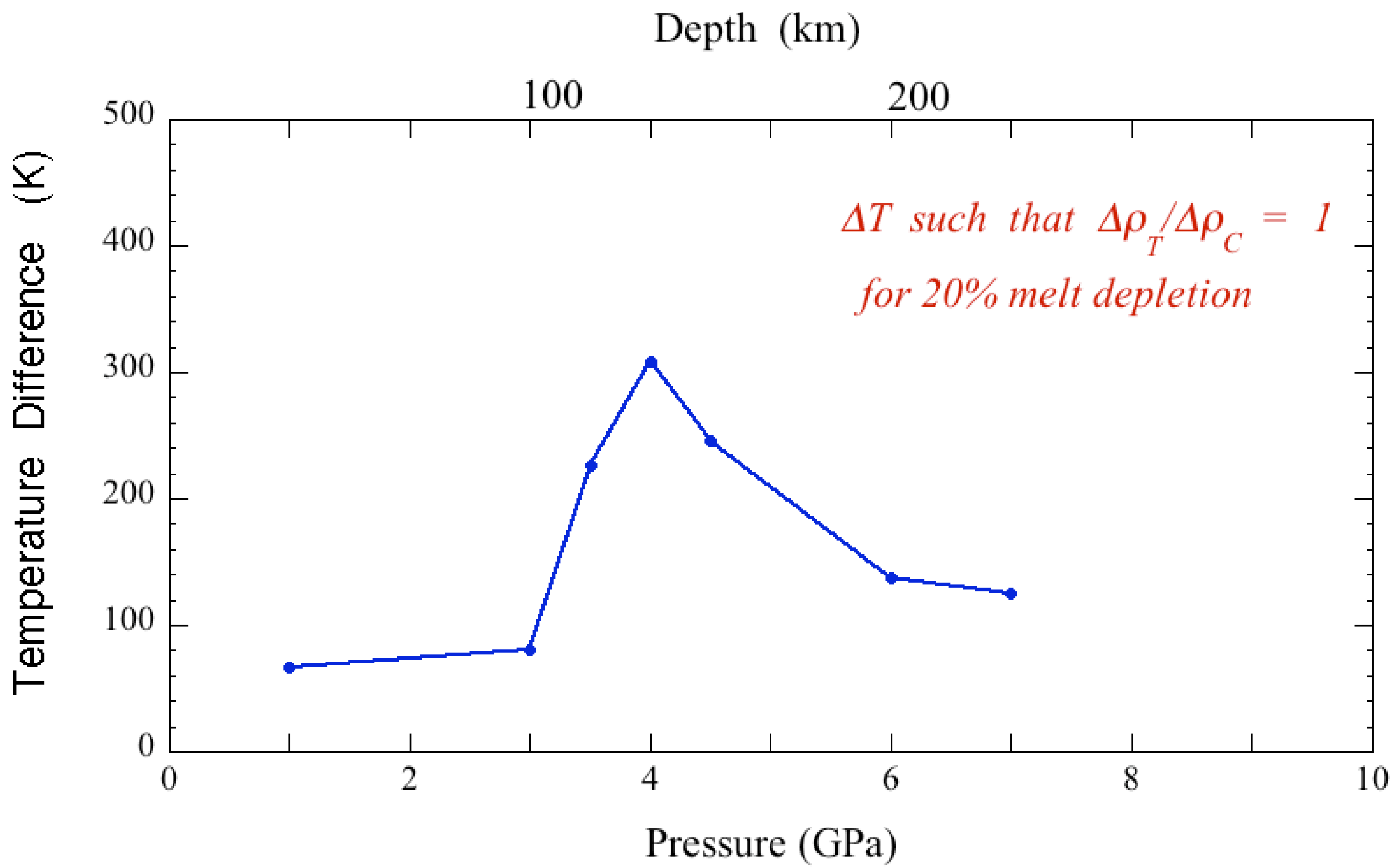


(From Griffin & O'Reilly, 2001)

Very old
(4.0 - 2.5 Ga)

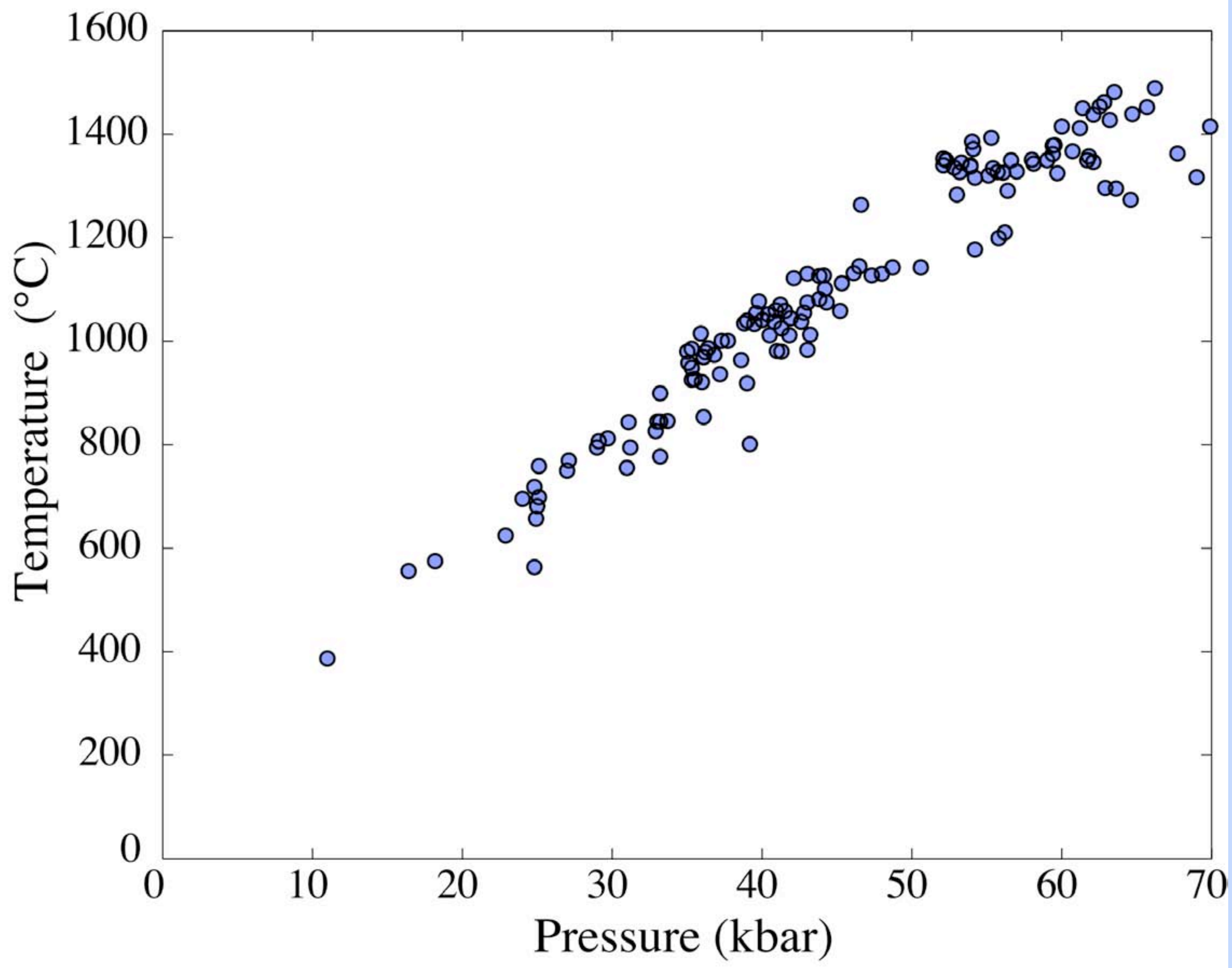
Old
(2.5 - 0.6 Ga)

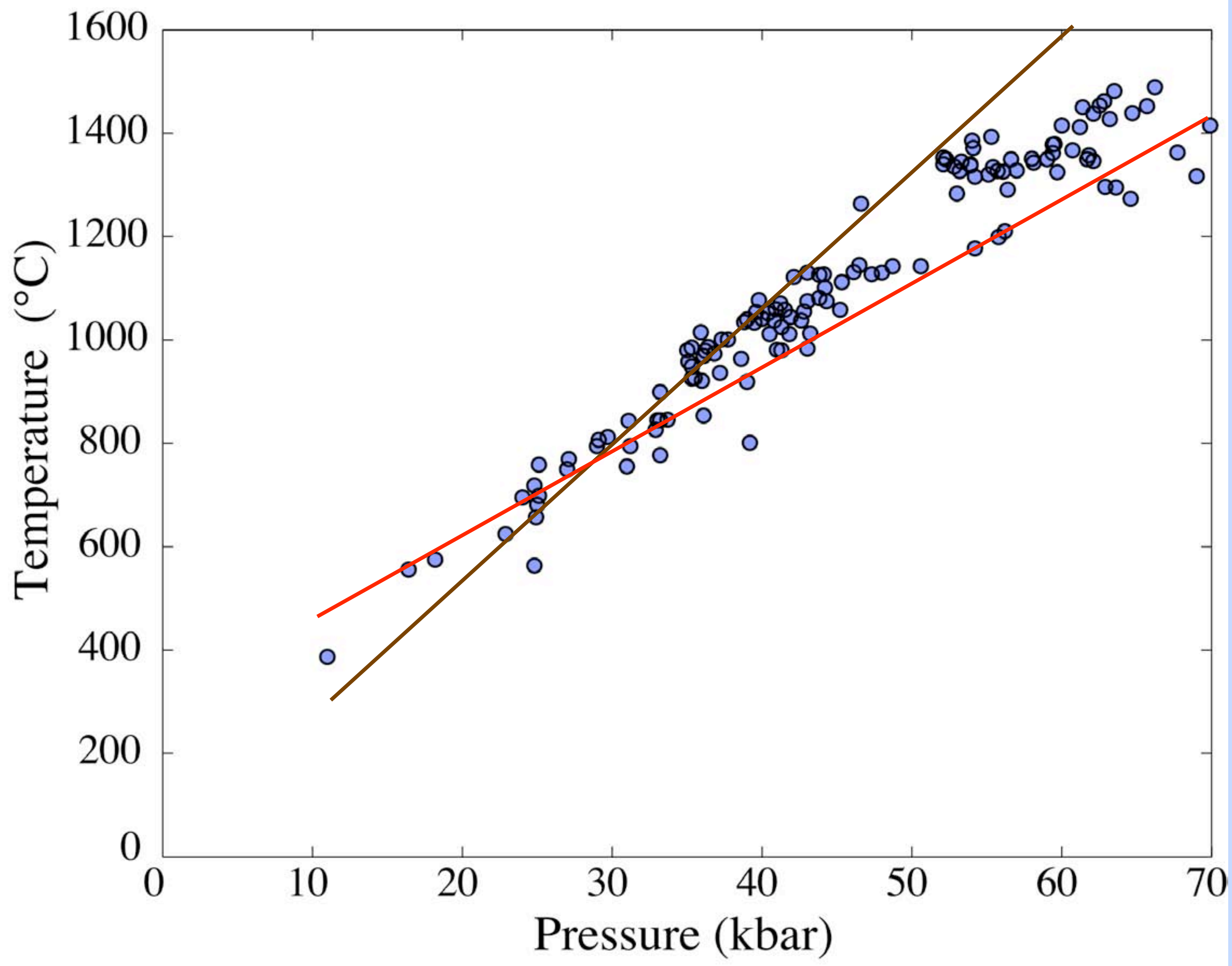
Not so old
(0.6 - 0.0 Ga)



(From Schutt & Lesher, JGR 2006)

(P,T) data from South Africa





Best used together with (1) surface heat flow value, (2) thermal model.

Calculation of continental geotherm
(downward continuation)

(1) Surface heat flow density
(2) 1-D diffusion equation
(3) Steady-state ?
(4) Crustal radioactivity
(5) Mantle radioactivity

Steady state ?

- Radioactive heat production decays with time:

Nuclide	^{238}U	^{235}U	^{232}Th	^{40}K
$T_{1/2}$ (Ga)	4,46	0,70	14,0	1,26

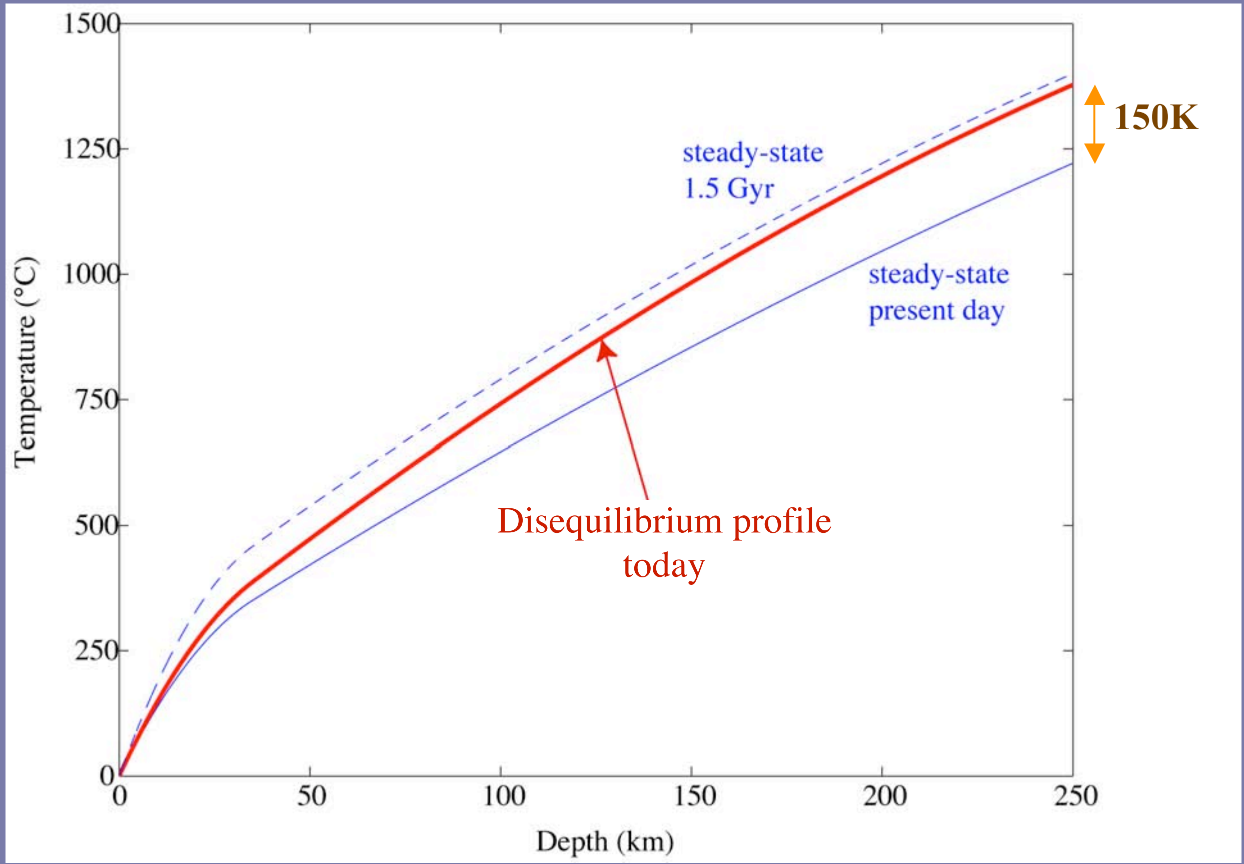
A has decreased by a factor of **2.5** in the last 3 Gyr.

$\Rightarrow$ **$T_r \approx 3$ Gyr**

- Characteristic time for diffusion through continent: $T_d = \frac{H^2}{\kappa}$

H ≈ 250 km $\Rightarrow$ **$T_d \approx 1.9$ Gyr**

Departure from instantaneous thermal equilibrium



H = 250 km

$Q_b = 10\ mW.m^{-2}$

$A_c = 0{,}9\ \mu W.m^{-3}$

$A_m = 0{,}02\ \mu W.m^{-3}$

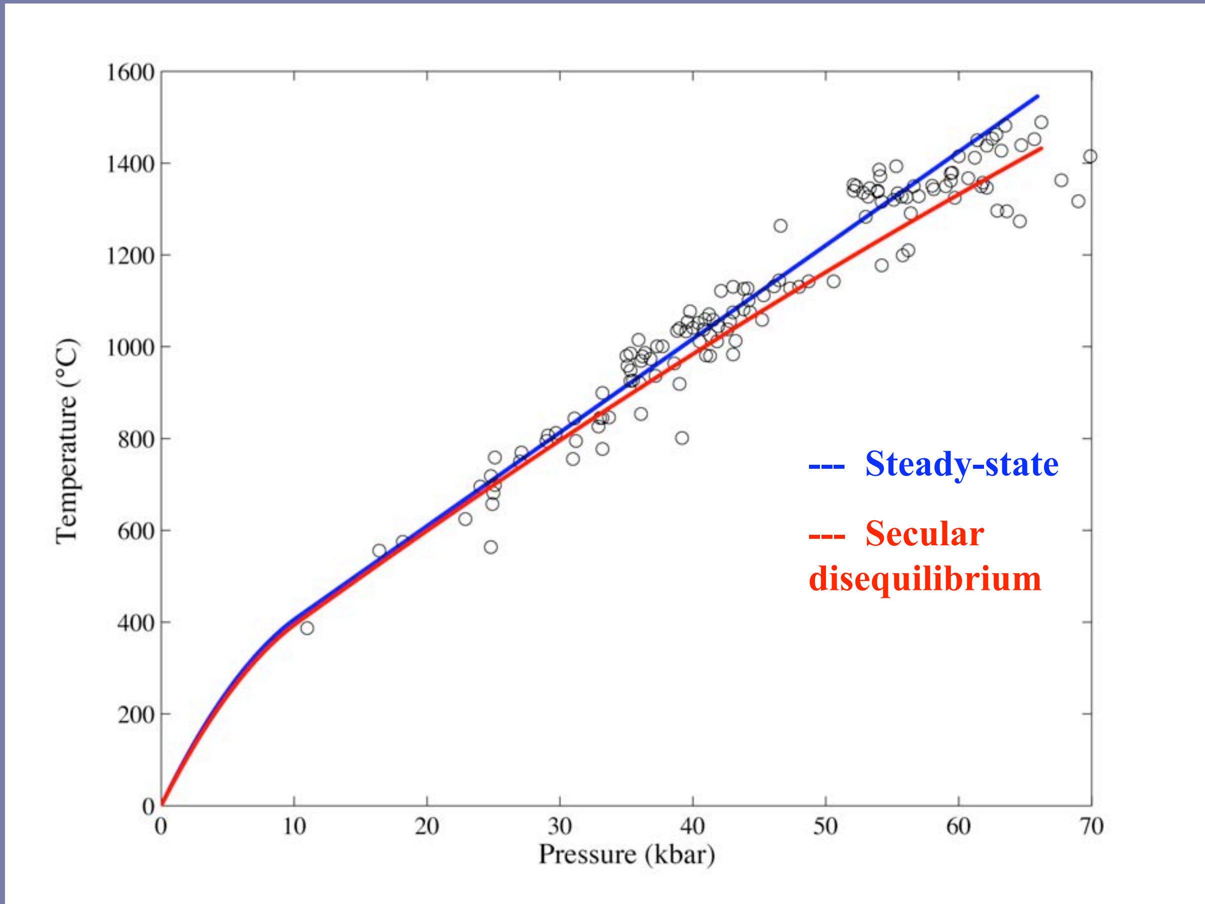
The departure from the steady-state profile increases with depth.

The T-profile has significant curvature.

(work done in collaboration with David Bell and Chloé Michaut)

Fit to xenolith (P,T) data

Temperature difference near base of lithosphere ≈ 150 K

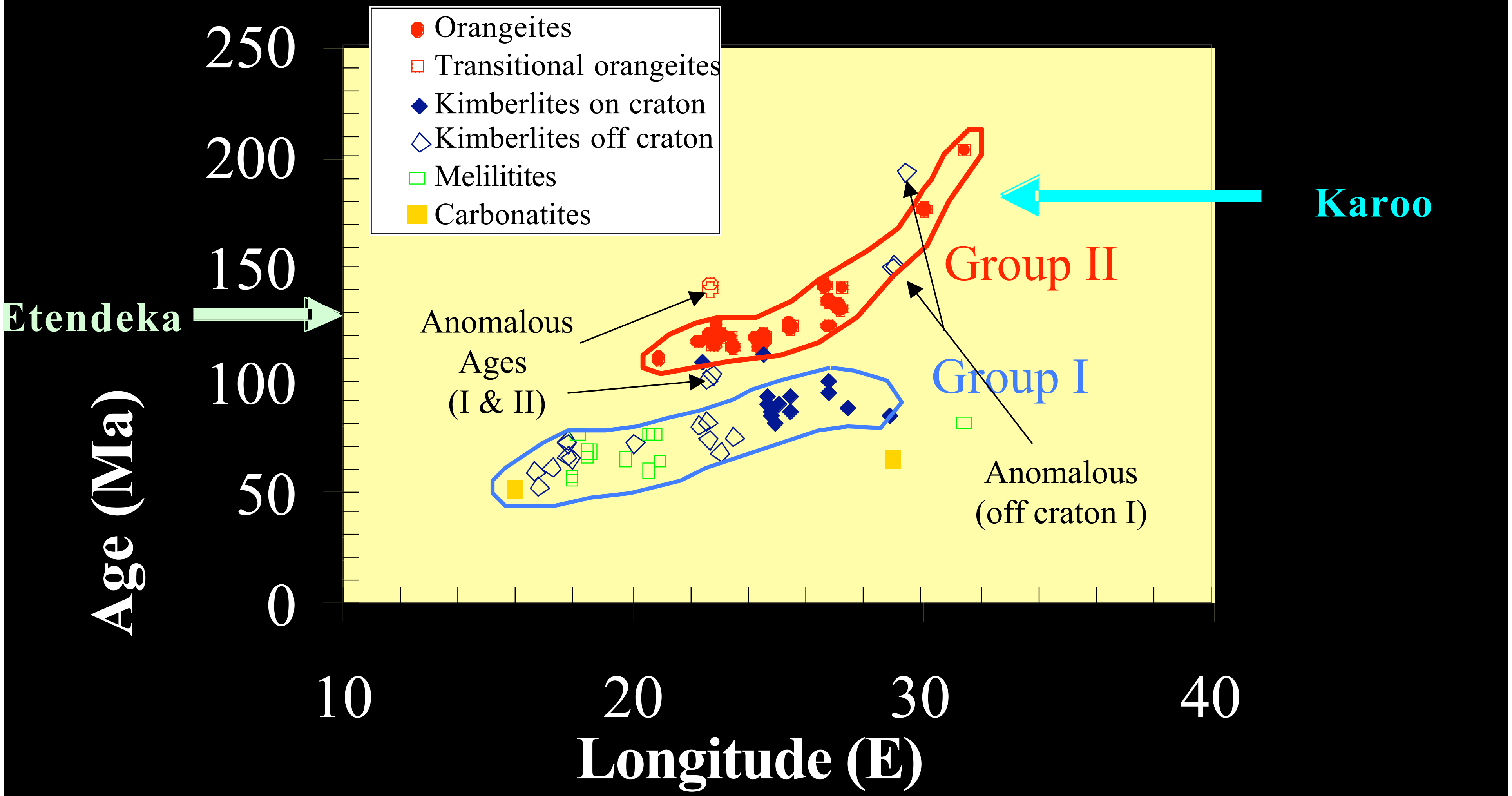


OBSERVATIONS

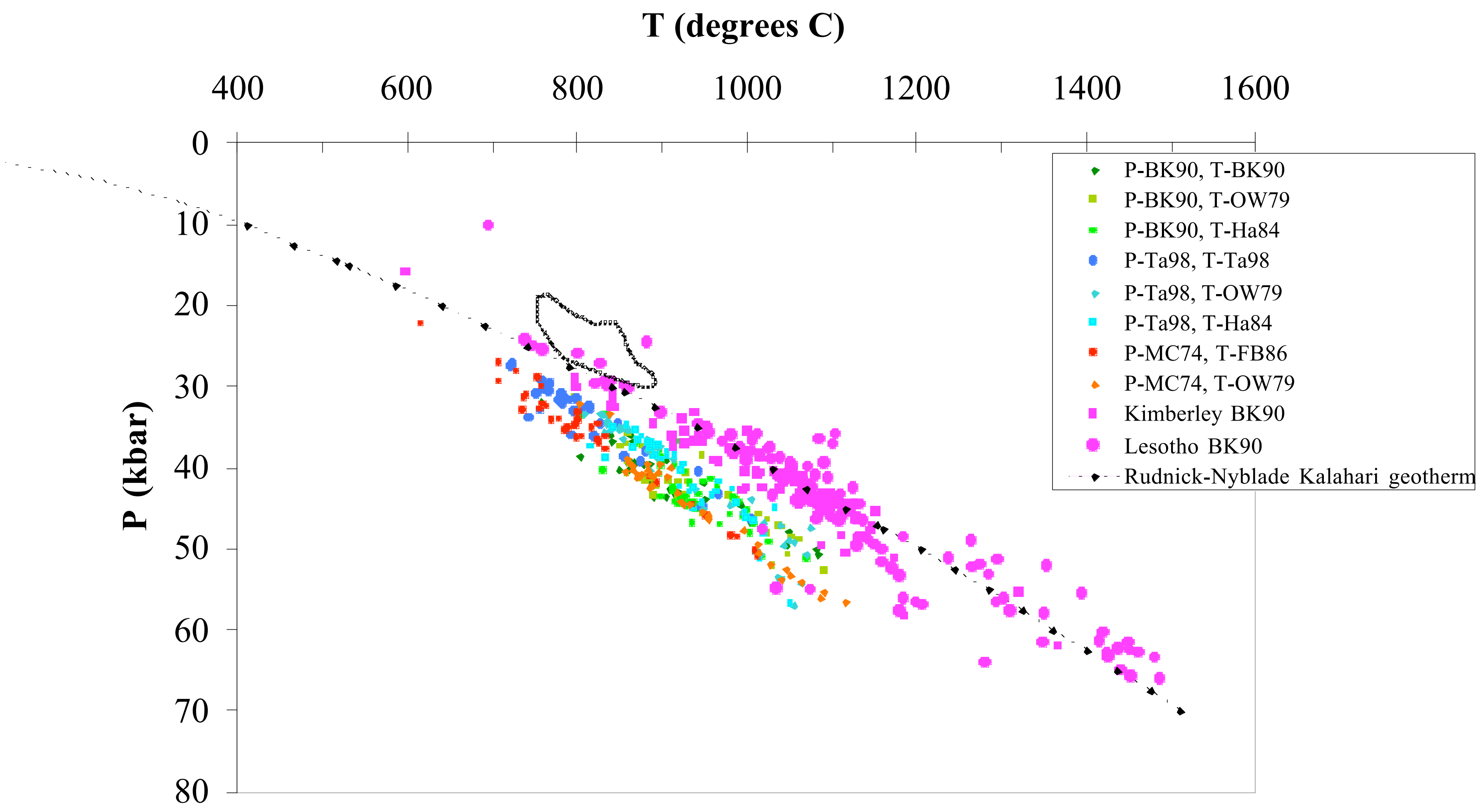
- Two geochemically distinct groups of kimberlites erupted in southern Africa during the Mesozoic
- Group I kimberlites erupted about 30 Ma after Group II kimberlites in the same area
- Archean cratonic xenoliths from Group I and Group II kimberlites define different geotherms

Longitude vs. Age

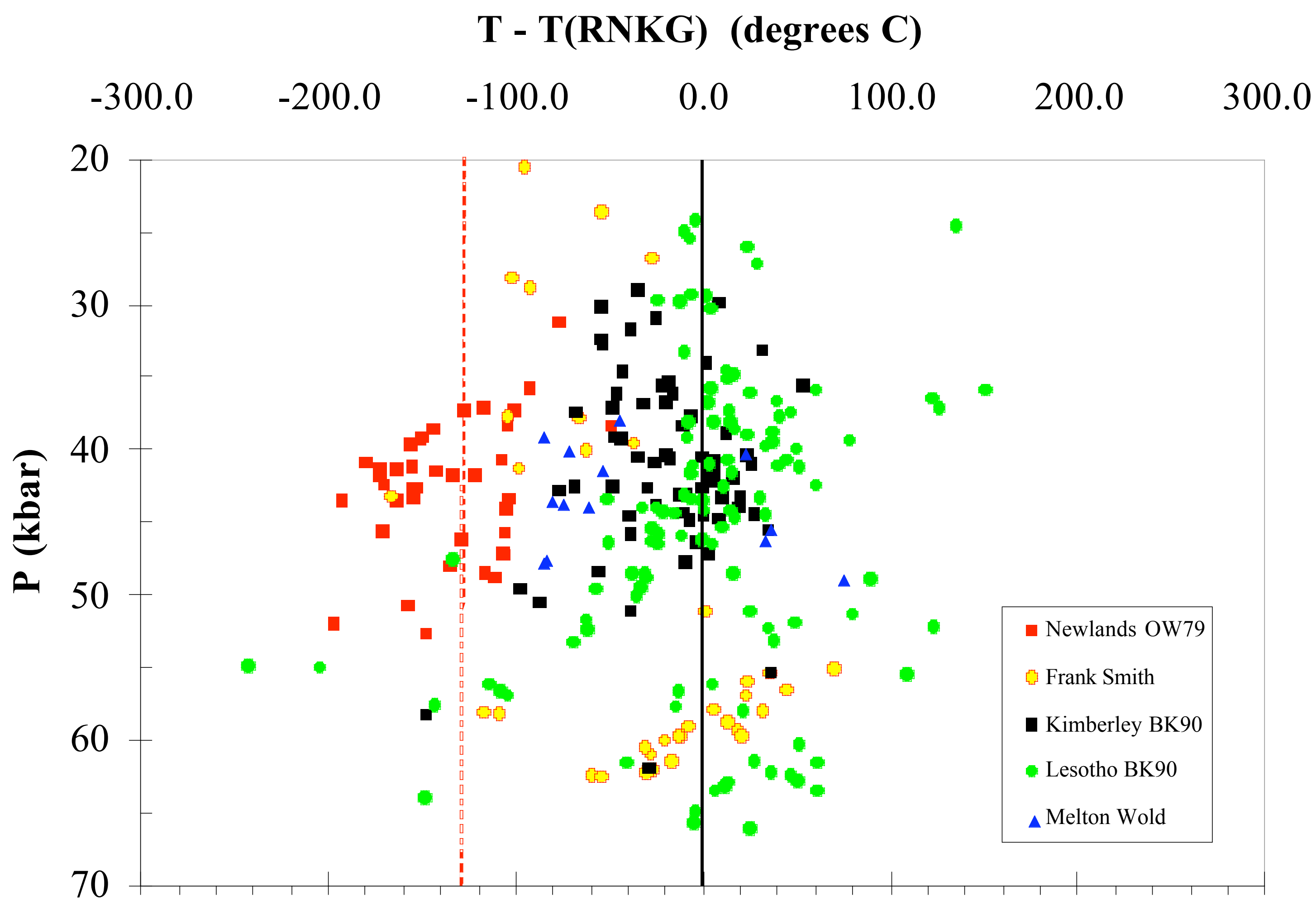
Mesozoic kimberlites and related rocks



Newlands (Group II) PT data compared with Kaapvaal Cretaceous Group I kimberlites



Difference from RN Kalahari Geotherm



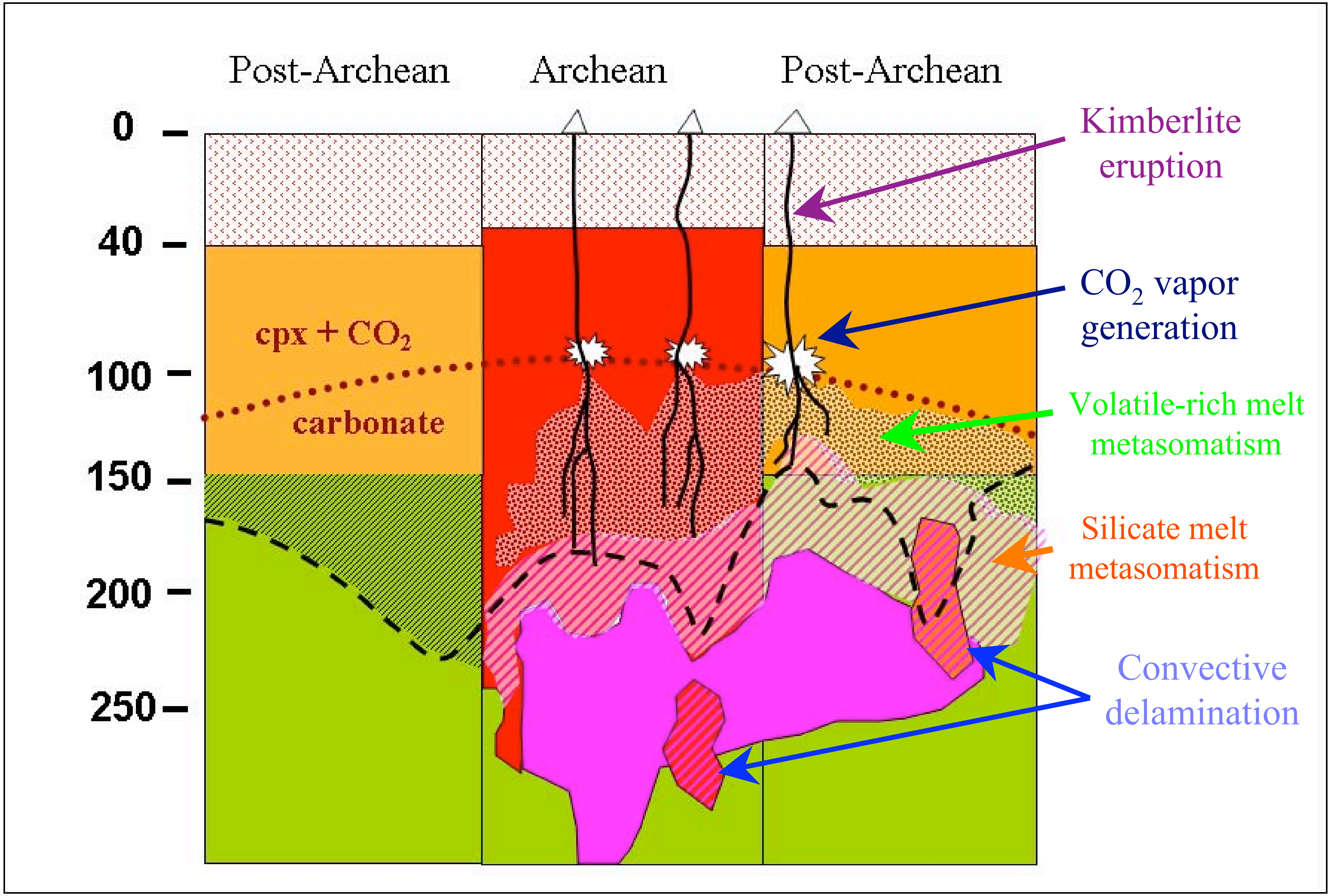
-135°C ± 32

QUESTIONS

- Does the hotter geotherm represent conductive adjustment of the lithosphere to heating +/- thinning at the base?
- How much of the temperature difference is due to influx of radioactive HPE during Mesozoic metasomatism?
- How much of the temperature difference is due to longstanding (~1-3 Ga) heterogeneities in HPE distribution

"Plume" – lithosphere interaction:

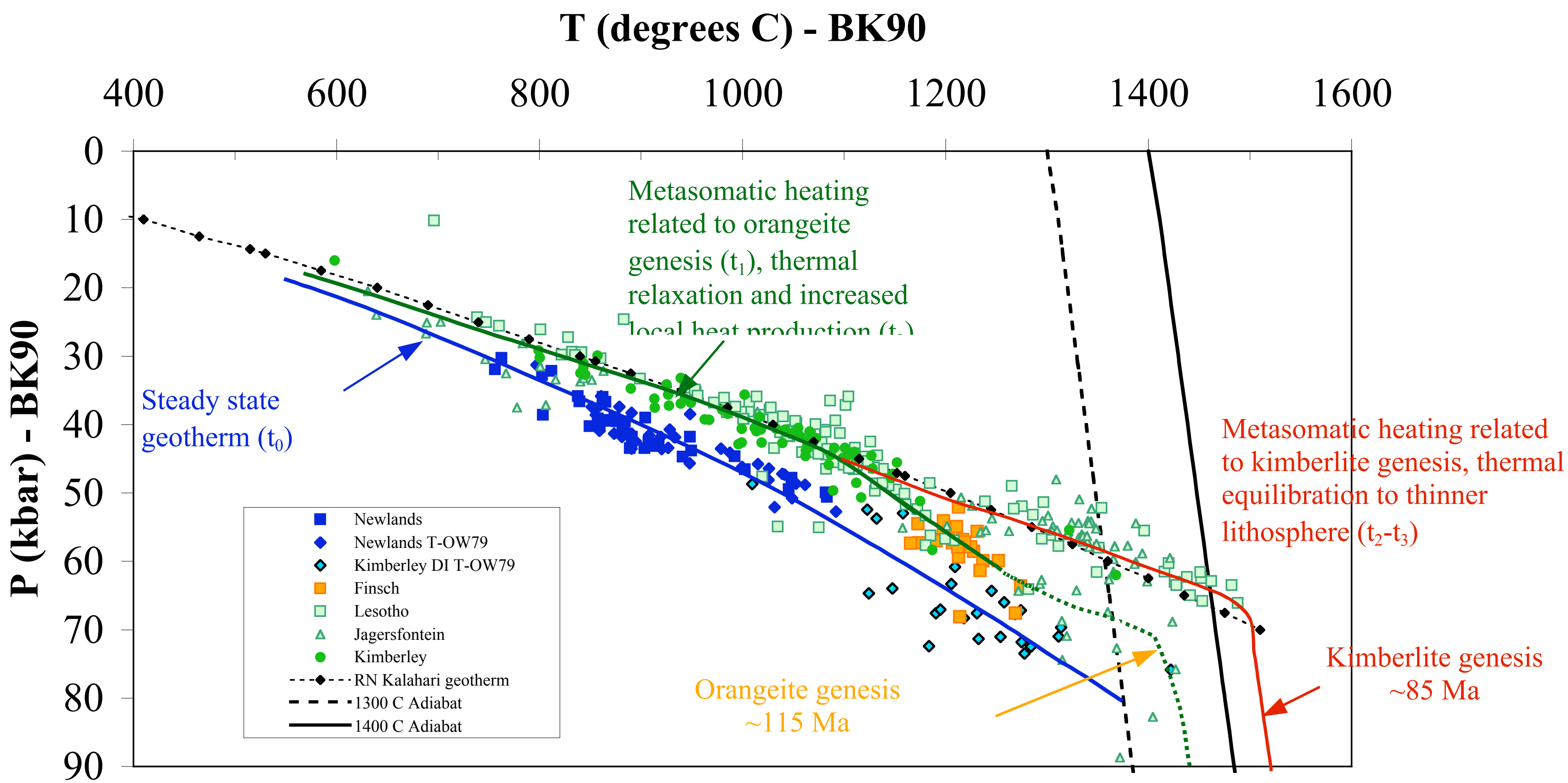
metasomatism, lithospheric thinning, heating, kimberlite eruption



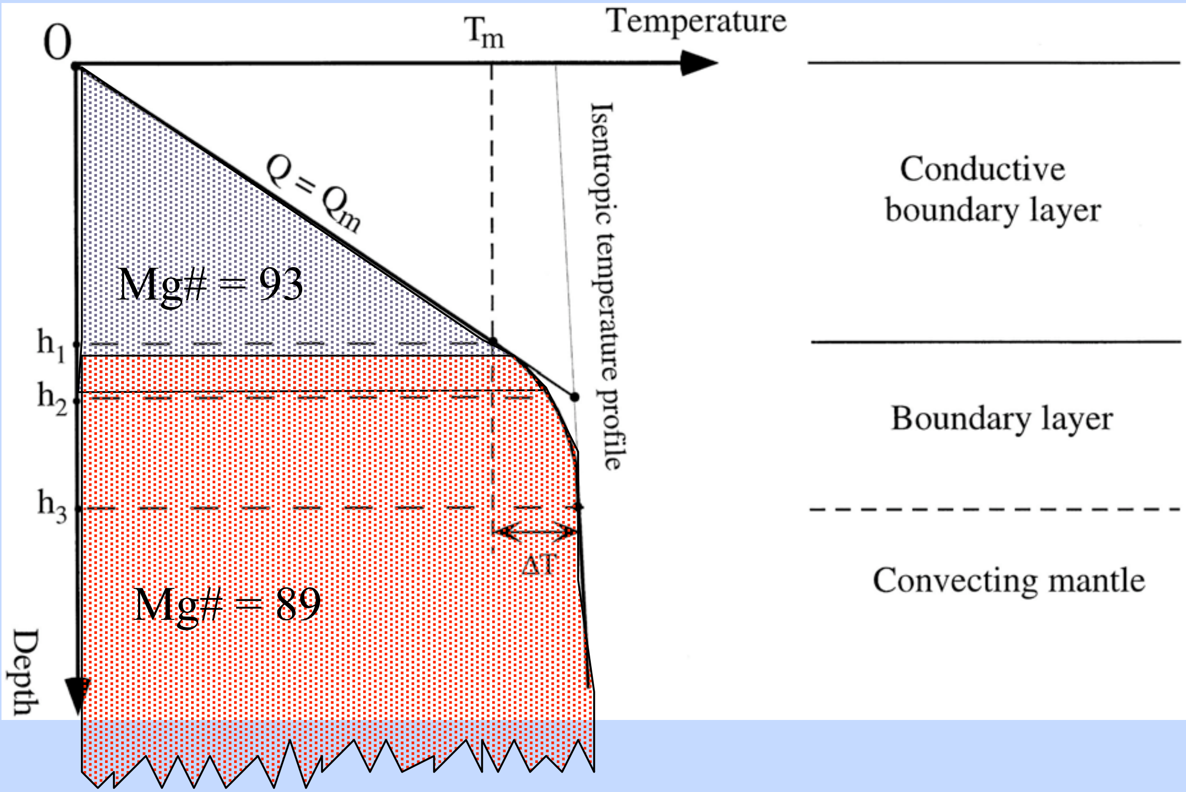
Metasomatic heating hypothesis

- Conductive heating by Karoo plume "sweated out" minimum melts from lithosphere (orangeite/MARID)
- Also plume melts arrested at base of lithosphere percolated into lithosphere and differentiated to carbonatitic melts
- Both could transport heat to higher levels in lithosphere
- Abundant petrologic evidence for metasomatism in Kimberley xenoliths, but not at Newlands.

Dynamic – lithosphere erosion and metasomatic heating



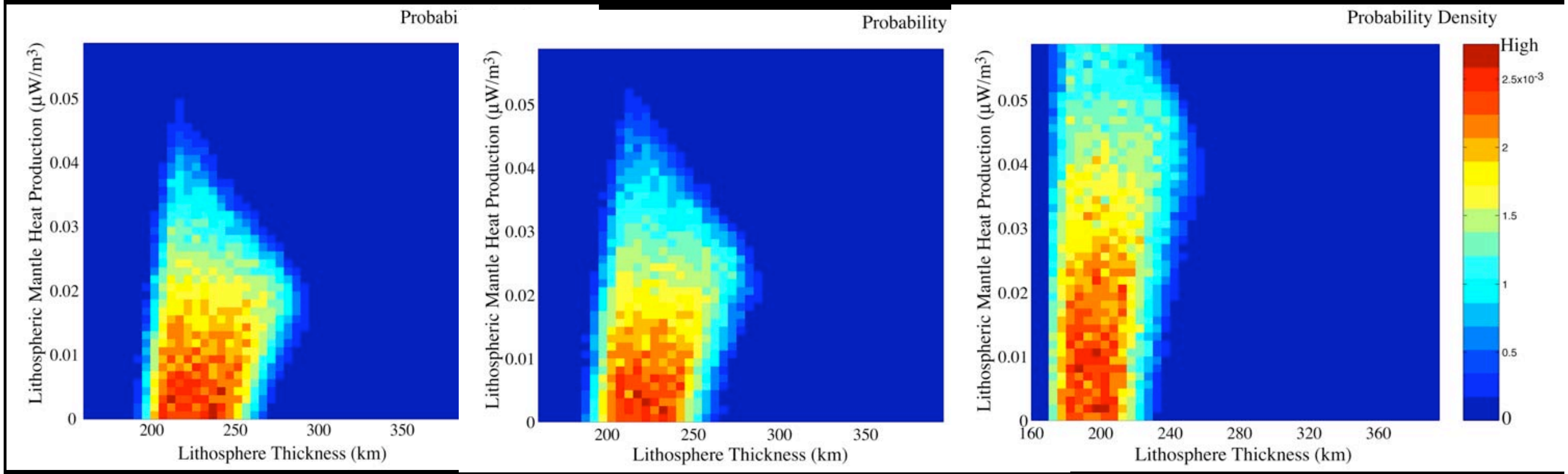
Thermal structure and lithosphere thickness



Jaupart & Mareschal 1999

Thickness of craton roots

Thermal modeling (Michaut et al. 2007)



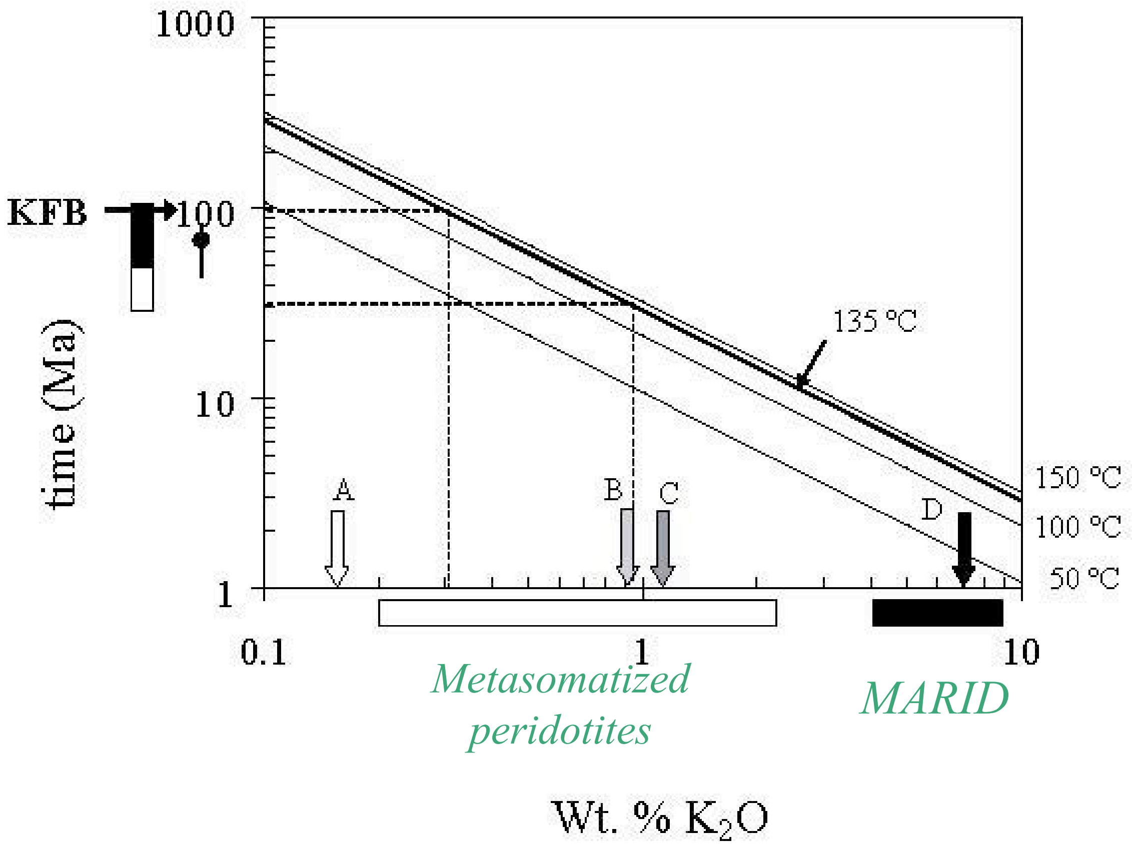
Slave	Kaapvaal Group II	Kaapvaal Group I
200-245 km	200-240 km	175-210 km

QUESTION

- Is there enough time (< 30 Ma) to propagate temperature changes at the base of the lithosphere into the shallow lithospheric mantle by conduction?

Possible solution to heat supply problem:

Metasomatic heating followed by increased heat production in metasomatized zones

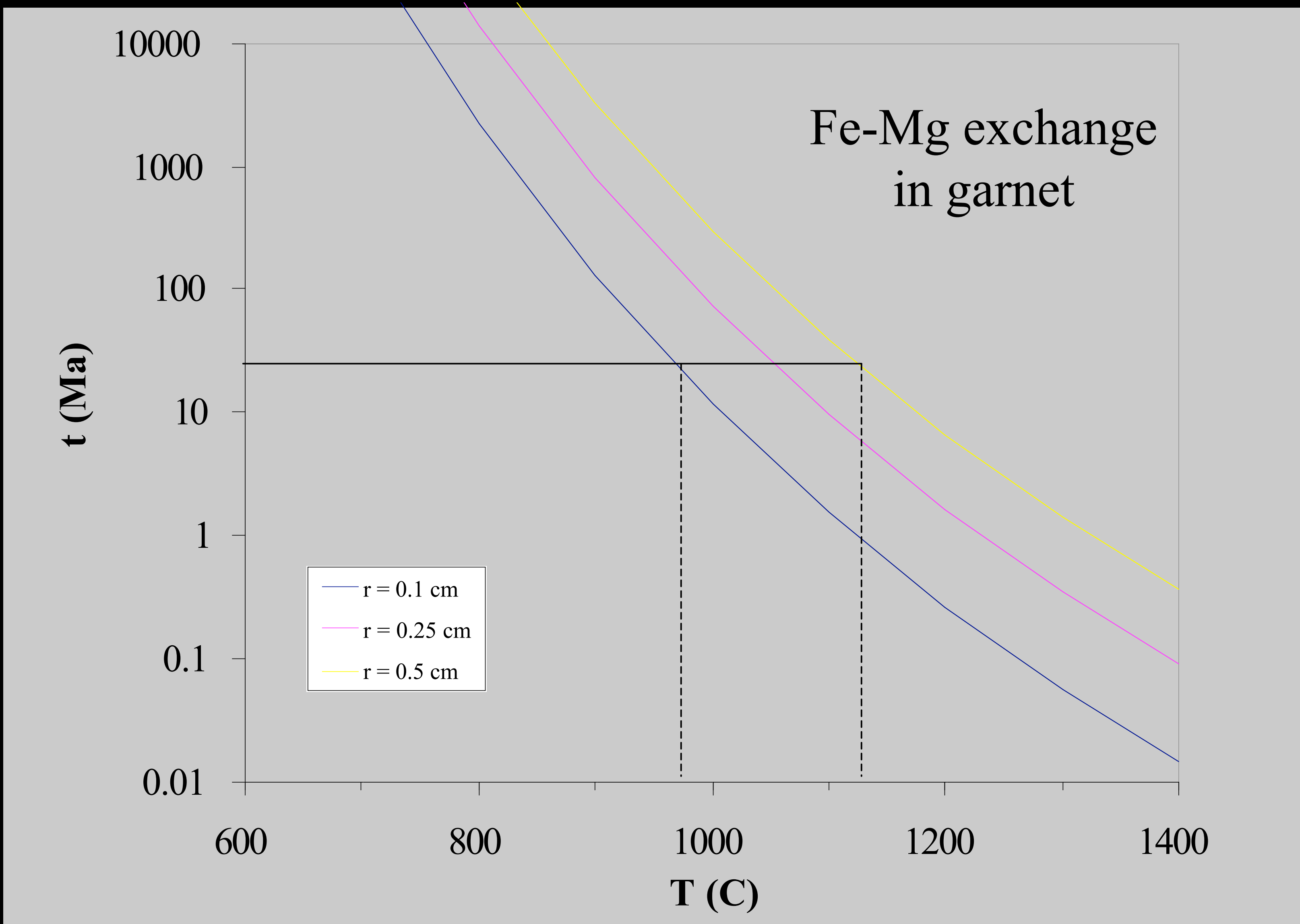


High heat production by K-rich metasomatic minerals (phlogopite, K-richterite) can generate heating in required time.

PROBLEM

- At T < ~1000 C, there does not seem to be enough time (< 30 Ma) for chemical diffusion to permit minerals to fully adjust compositionally to increased lithospheric temperature
- This adjustment must have occurred or we would not record different geotherms

Timescales for mineral equilibration



Summary

- Temperature differences exist within the South African mantle lithosphere.
- In Proterozoic mantle domains there is a time-dependent westward-migrating Mesozoic heating event (Bell et al. 2003).
- In Archean mantle, a combination of lithospheric erosion, metasomatic heating and increased heat production from metasomatism can be the cause of a Mesozoic increase in lithospheric temperature; however, this explanation appears to incur problems with mineral re-equilibration rates.
- In Kaapvaal, variation in HPE established early in craton history may result in long-lived, short-wavelength lateral variations in temperature, which can potentially influence lithospheric tectonics. *Work in progress to test this hypothesis*

HYPOTHESIS

- There are pre-existing lateral (and vertical) variations in HPE concentration and consequently, temperature, in the lithospheric mantle
- High HPE regions developed by hydrous metasomatism during ancient subduction events
- These warmer, wetter, and weaker zones become foci for deformation, magmatic intrusion and repeated re-activation of continental lithosphere.

Could there be long-term lateral T gradients due to HP variations?

- Difficult to measure K, U, Th due to kimberlite contamination (>90% of WR incompatible elements on grain boundaries)
- Curvature of geotherm could be obscured by later heating of deep xenoliths.
- Evidence for low temperatures in Kimberley diamond inclusions supports curvature in geotherm
- Shallow lithosphere may be variable in HPE (high at Kimberley, low at Newlands) but deep lithosphere appears uniformly low in HPE. These observations can be explained by phlogopite distribution

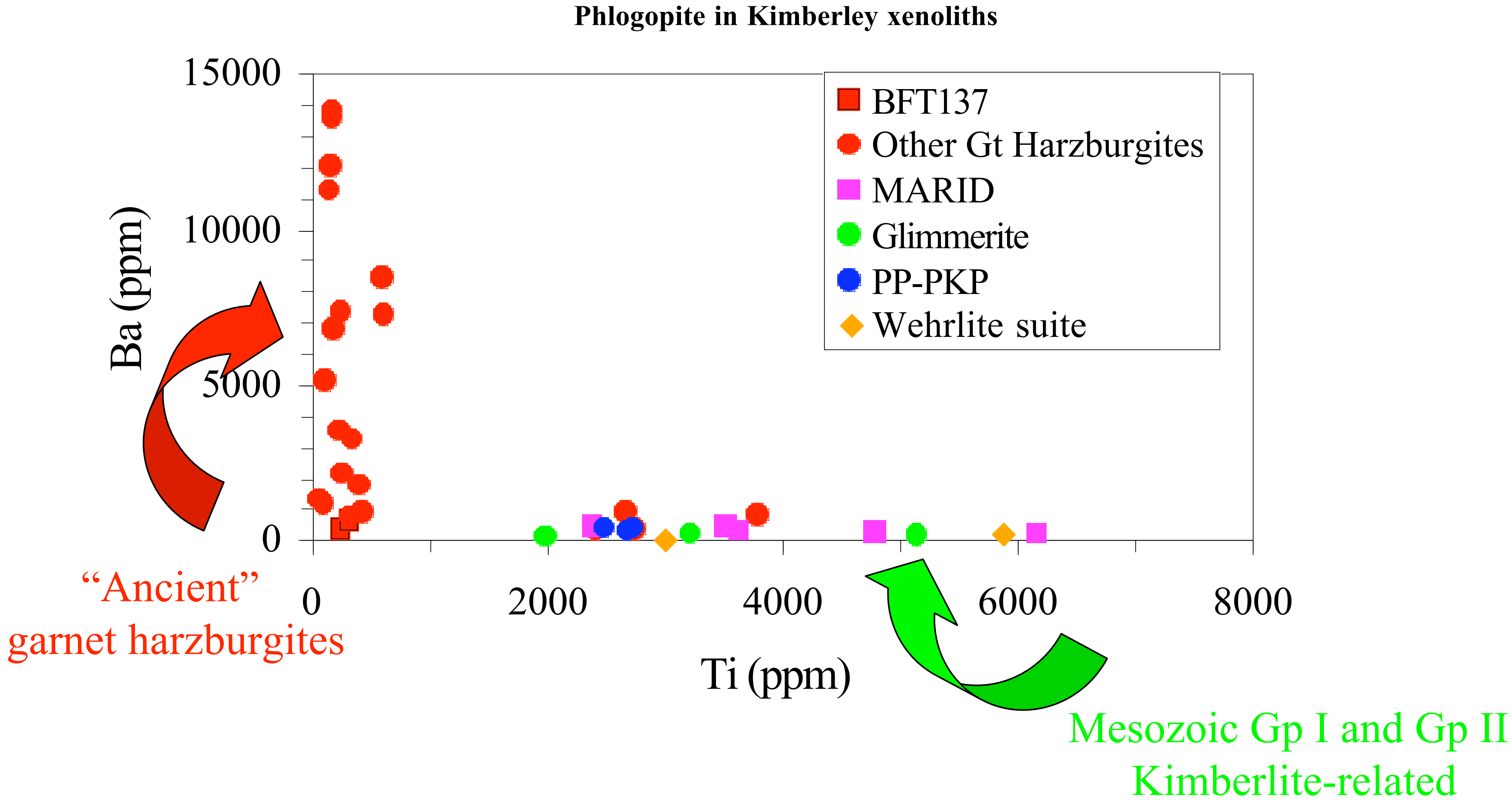
PROJECT

- Measure HPE content of lithospheric mantle rocks from the Kaapvaal Craton
- Compare HPE in regions with different geotherms

Project details

- Bulk determinations of HPE in xenoliths are generally meaningless due to contamination by kimberlite – hence mineral and modal analysis
- Both young (Mesozoic) and ancient (? 2.9 Ga) metasomatism have affected the Kimberley mantle (and possibly other events too)
- A long term project (Grégoire, Bell, Le Roex) is dedicated to unraveling the characteristics of these events using LA-ICP-MS and MC-ICP-MS trace element and isotope studies
- HPE (K, U, Th) are being determined in minerals at CNRS, Toulouse
- Focus on HPE in depleted garnet harzburgites containing dispersed phlogopite with characteristic high Ba/Ti

Two generations of metasomatic phlogopite in Kimberley xenoliths



Is this a map of lithospheric HPE content?

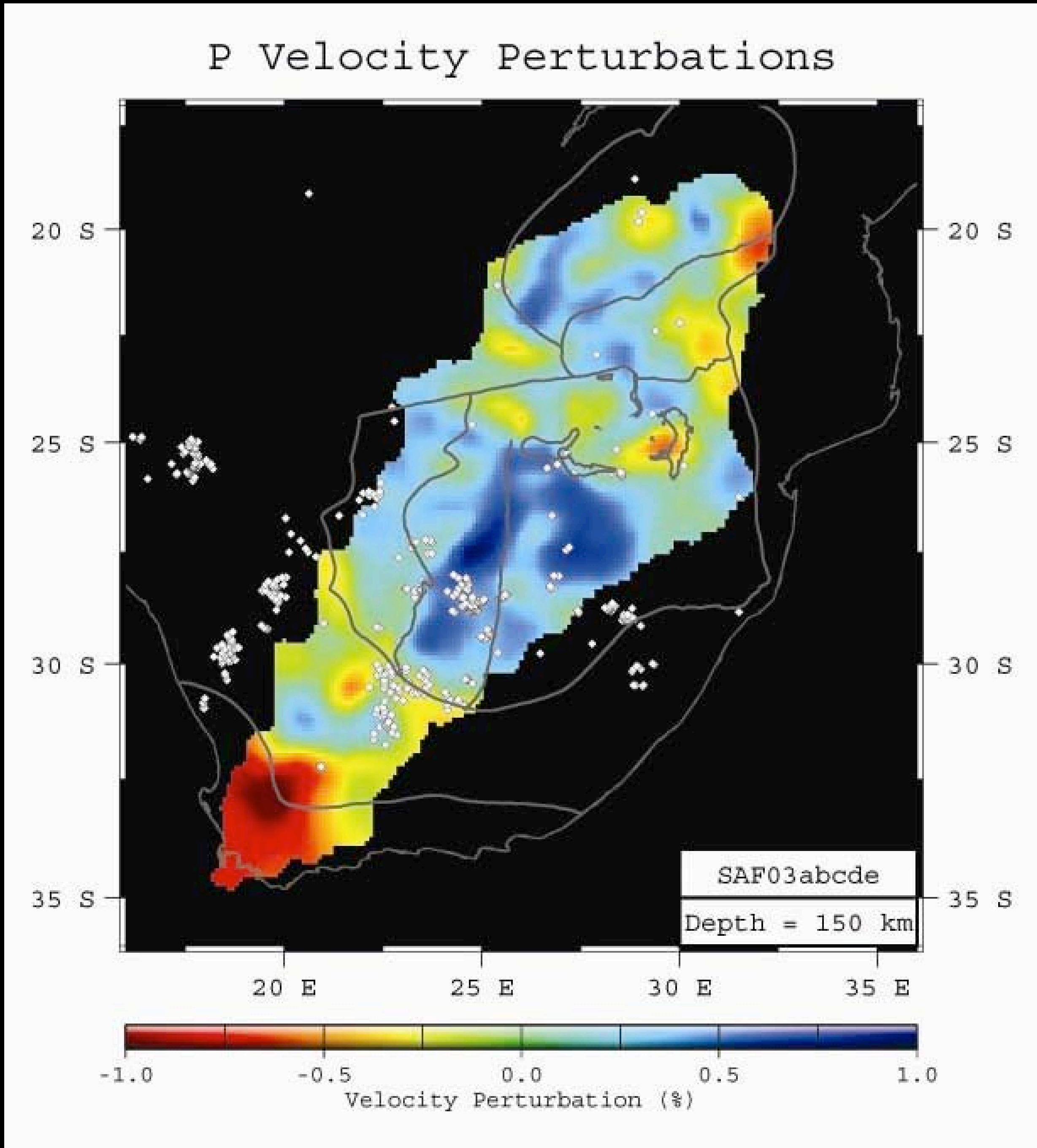
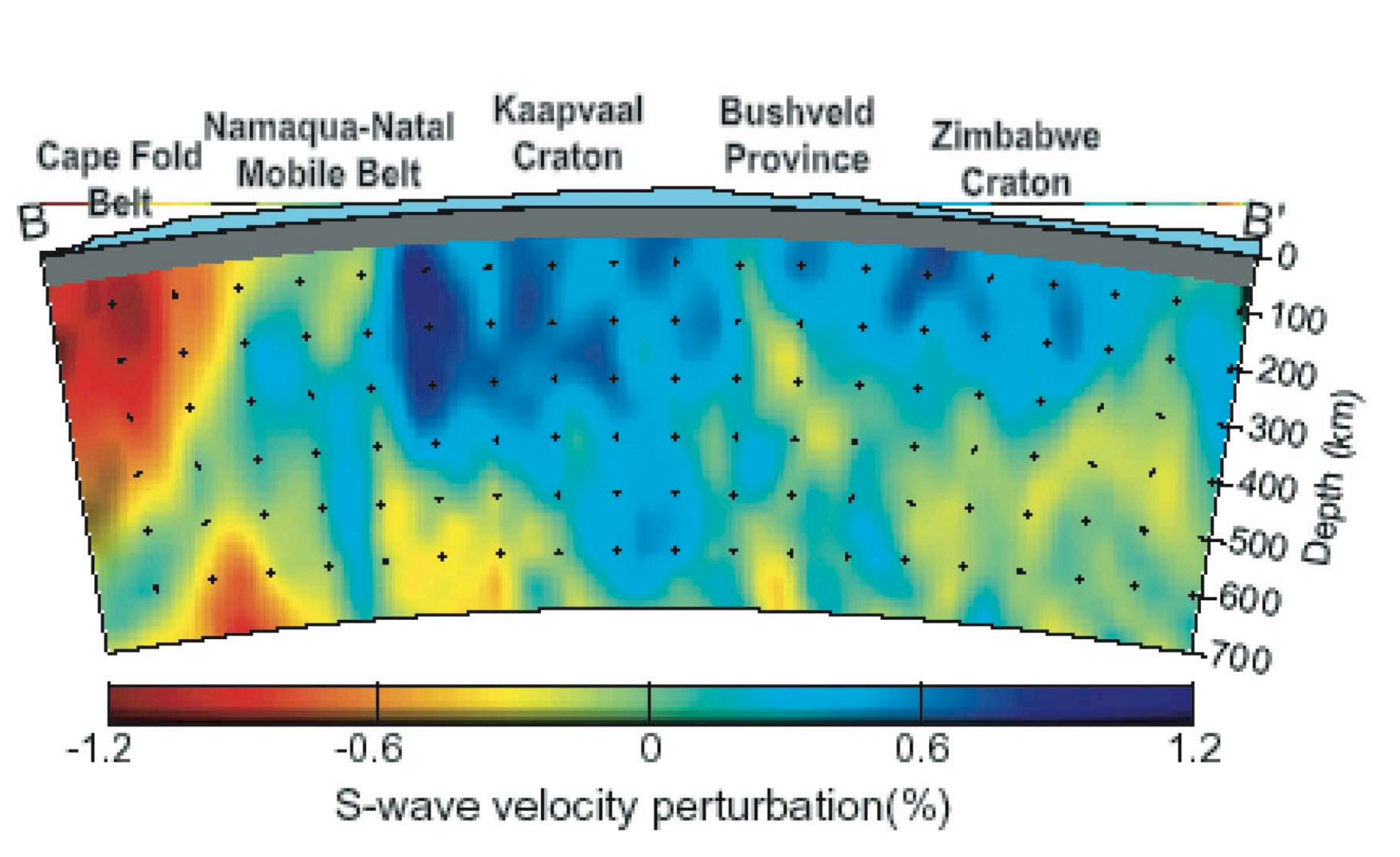
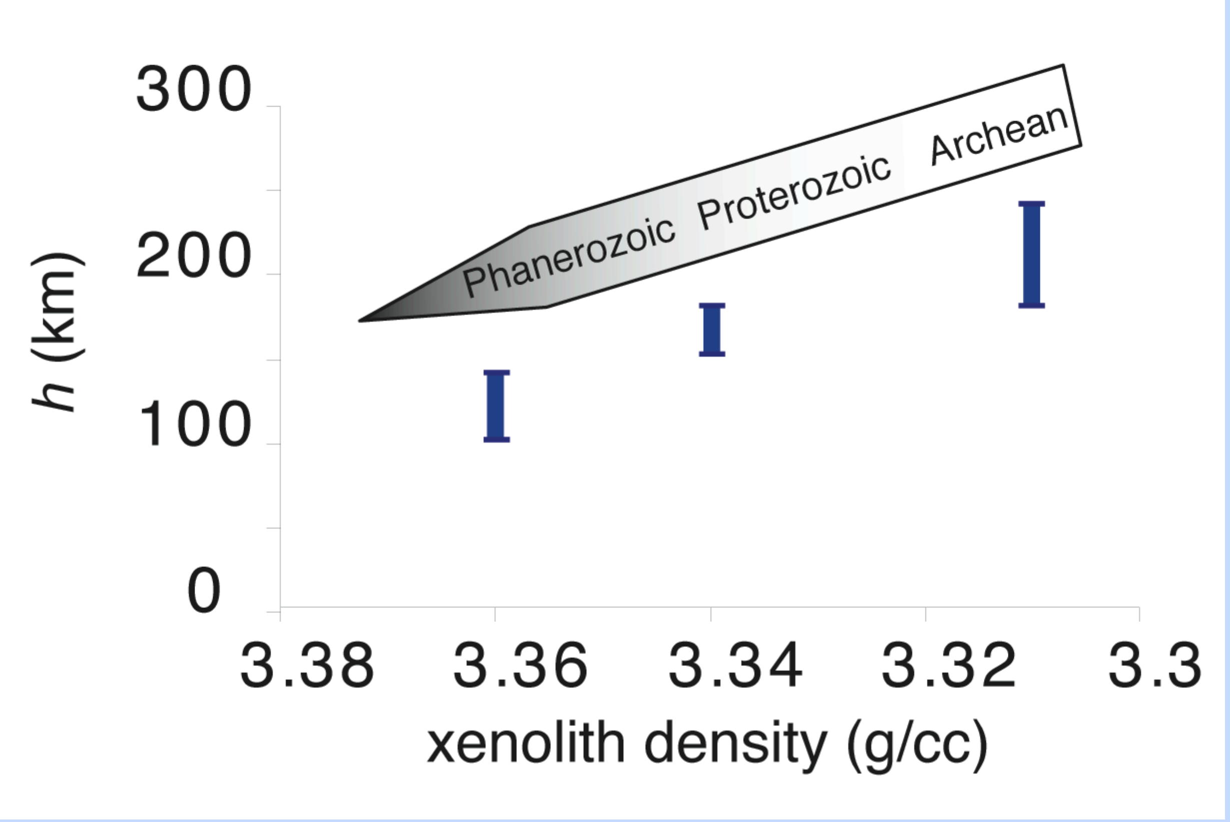


Image courtesy of M. Fouch

South Africa



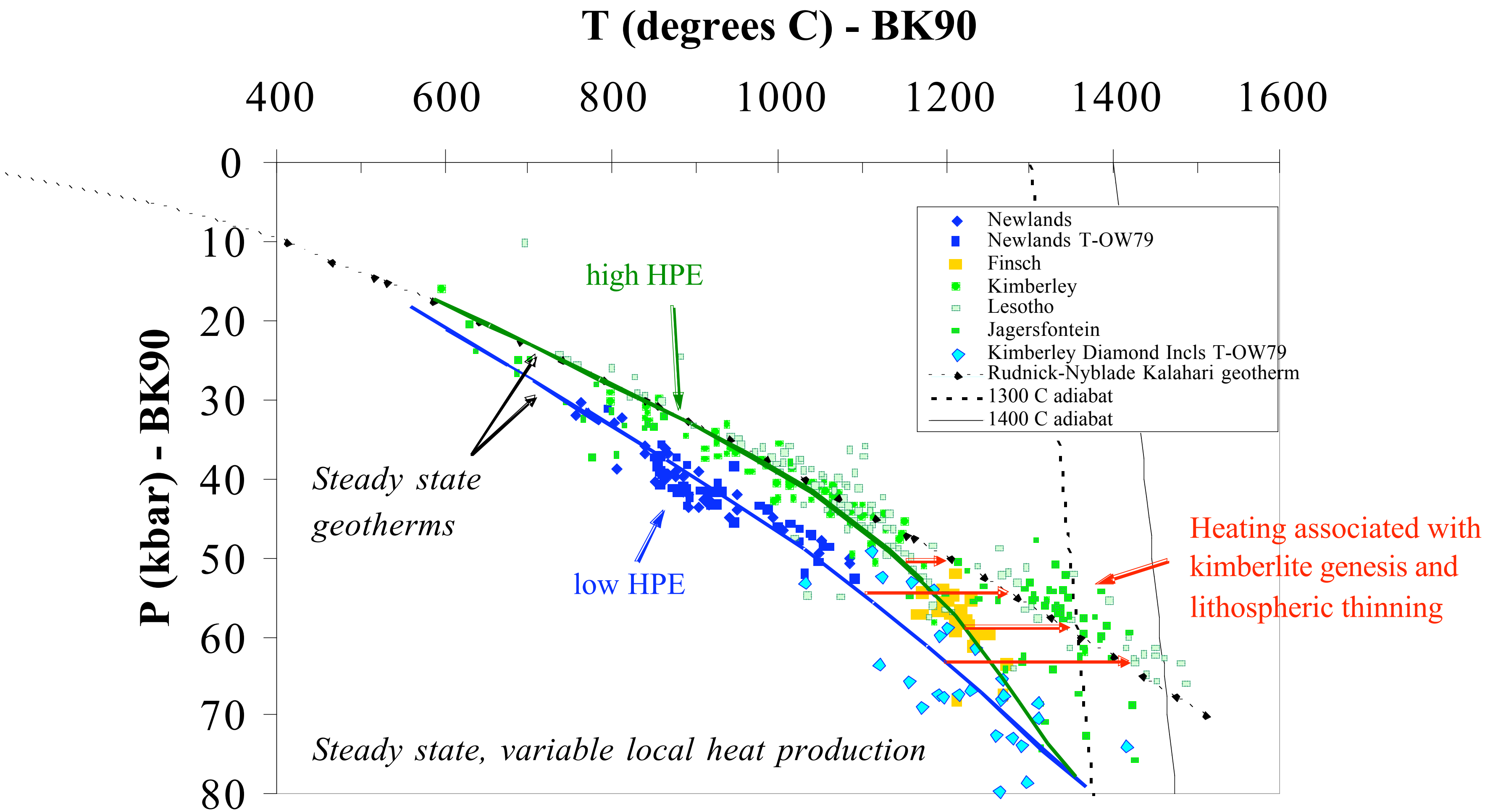
Thickness of continental lithosphere



(from Poudjom-Djomani, O'Reilly & Griffin)

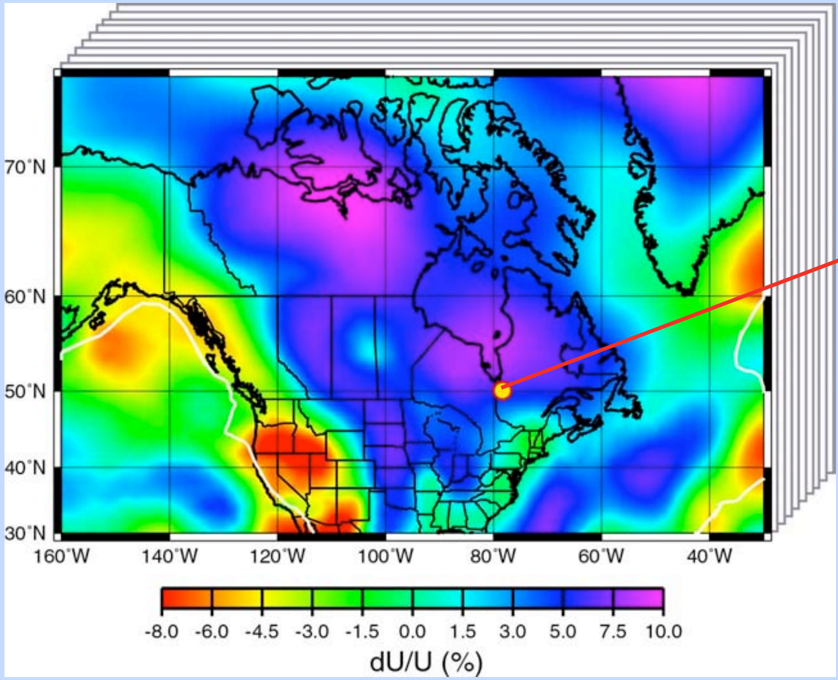
There are several stable states in (thickness, density) space.

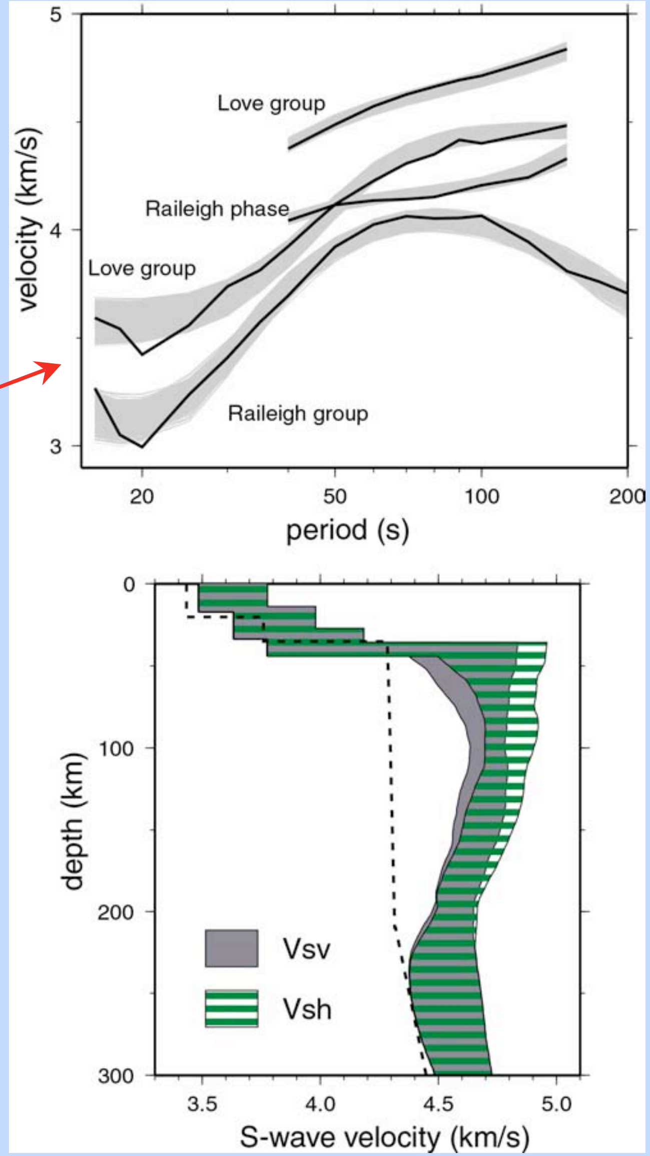
Variations in long-term HPE content exploited by plume reactivation



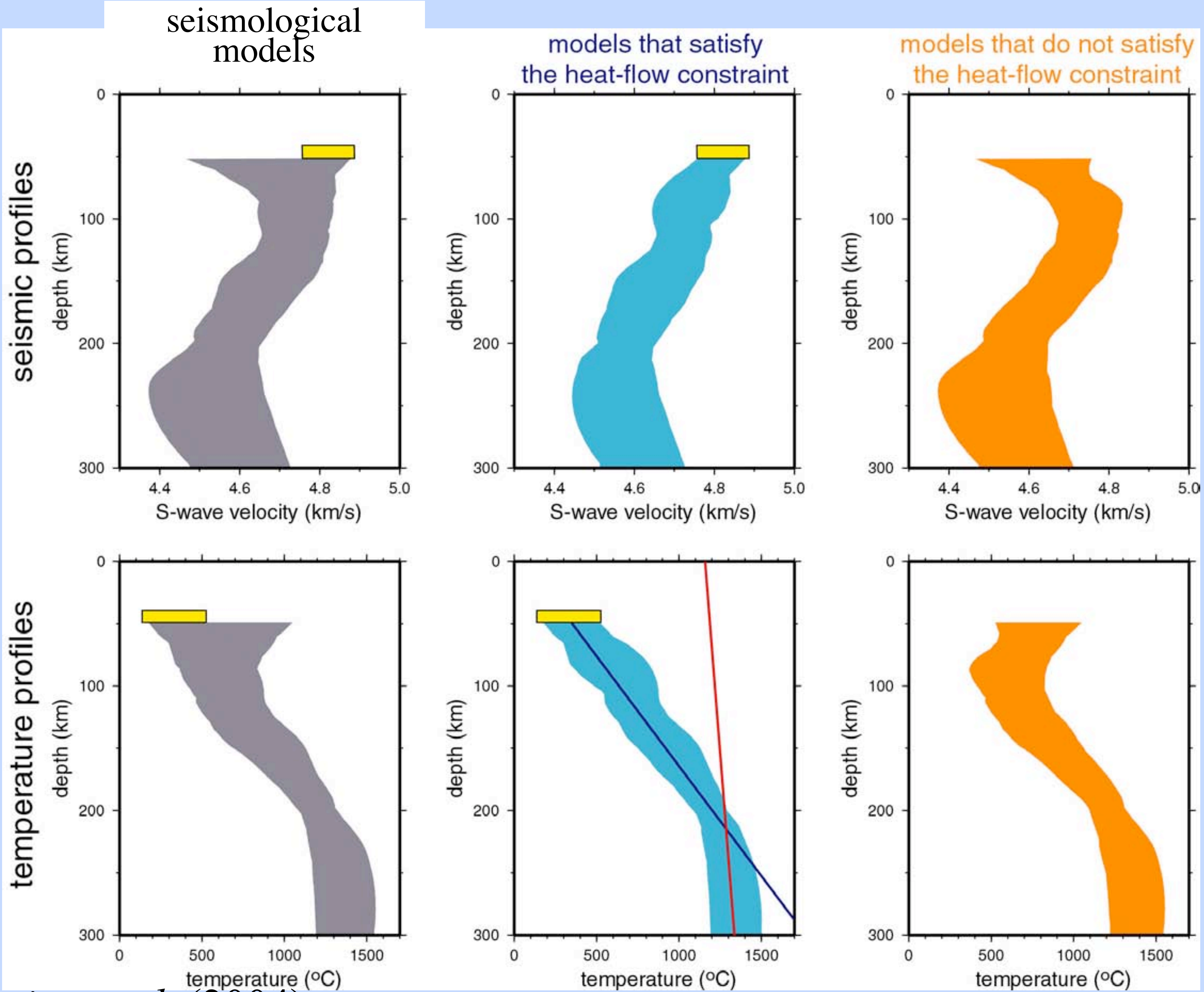
Inversion of dispersion curves

All dispersion maps: Rayleigh and Love wave group and phase velocities at all periods



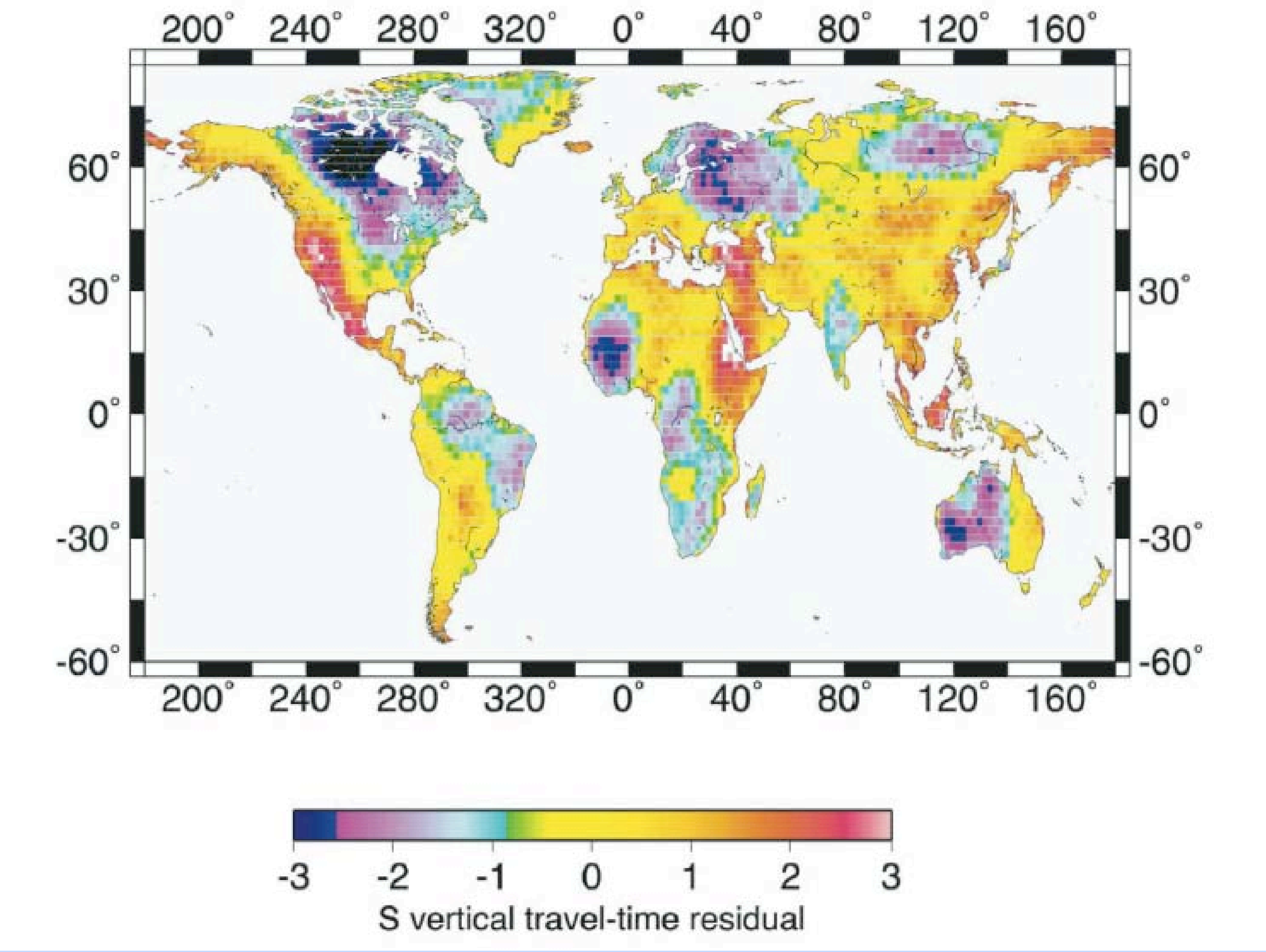


Inversion of dispersion curve with heat flow constraint



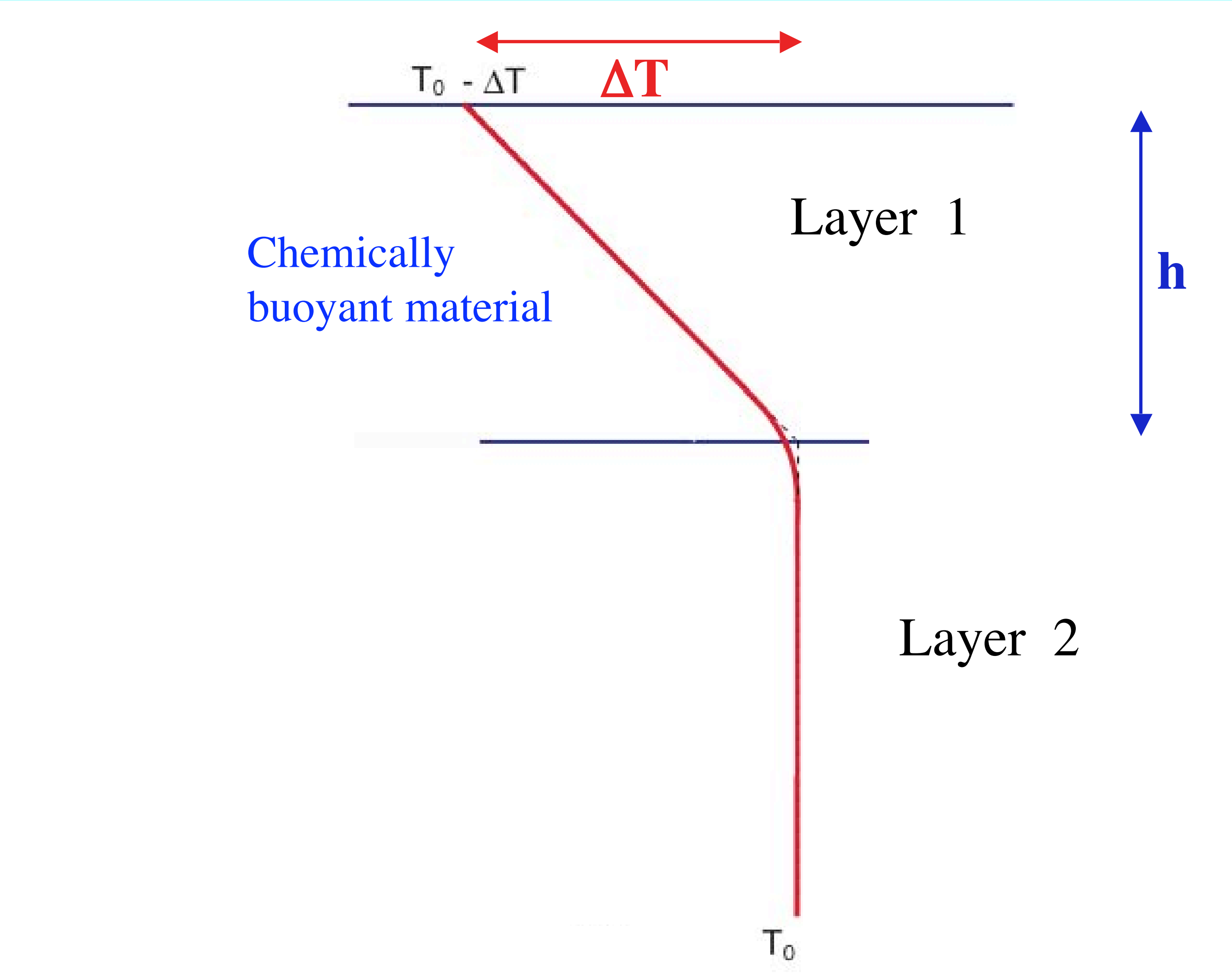
From *Shapiro et al.* (2004)

Is Archean lithosphere stable ?

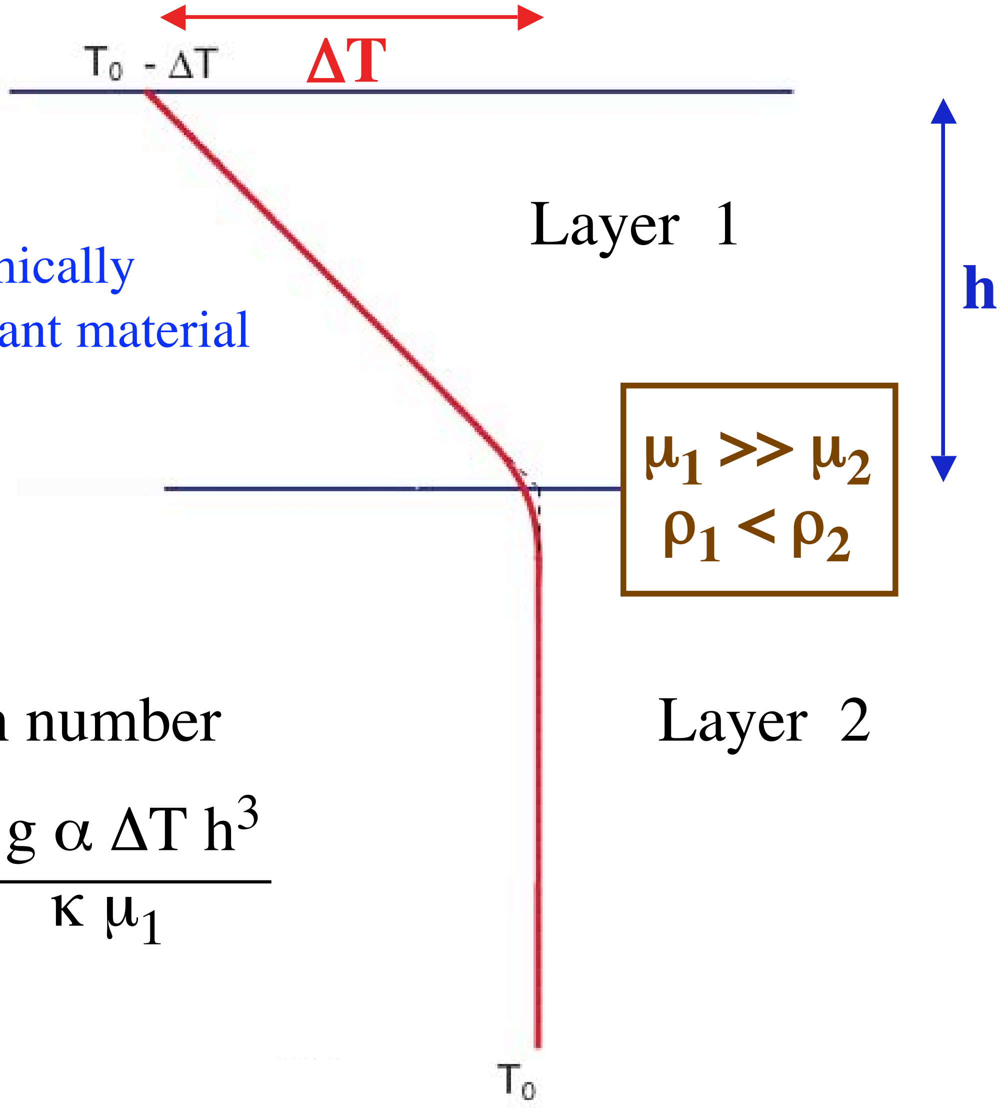


(From Poupinet et al., EPSL)

STABILITY AGAINST CONVECTIVE OVERTURN



STABILITY AGAINST CONVECTIVE OVERTURN



Rayleigh number

$$Ra = \frac{\rho\, g\, \alpha\, \Delta T\, h^3}{\kappa\, \mu_1}$$

5 dimensionless numbers

Rayleigh number $Ra = \dfrac{g\,\alpha\,\Delta T\,h^3}{\kappa\,\mu_1}$ (calculated for layer 1)

Buoyancy number $B = \Delta\rho_c / \Delta\rho_T$

Viscosity ratio $\gamma = \mu_1/\mu_2 \gg 1$

Thickness ratio $h_1/h_2 \ll 1$

Prandtl number $Pr = \nu/\kappa \gg 1$

1. Theory : stability analysis.

Time-dependence

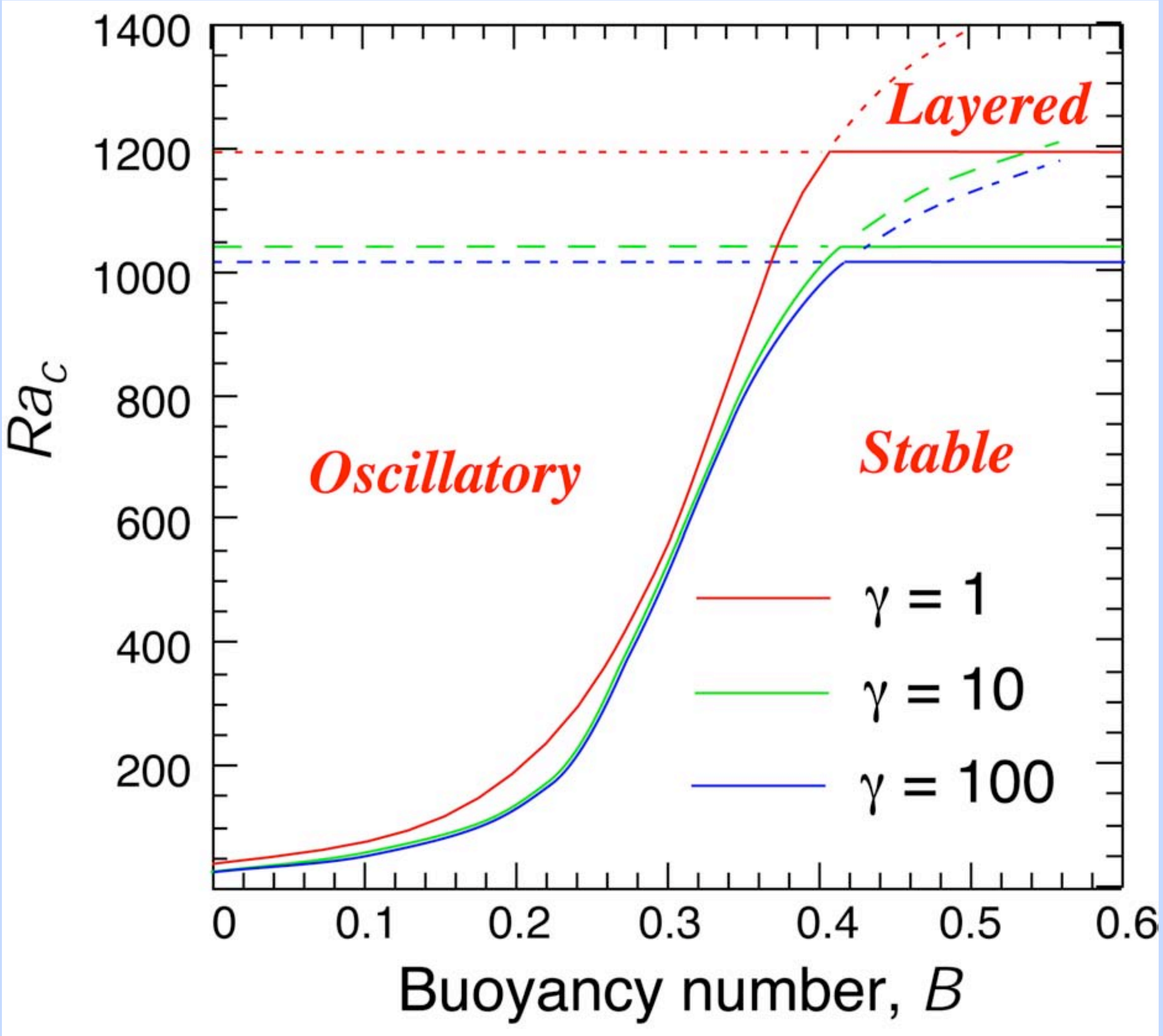
$\sim \exp\{(\sigma_r + i\sigma_i)t\}$

Marginal stability

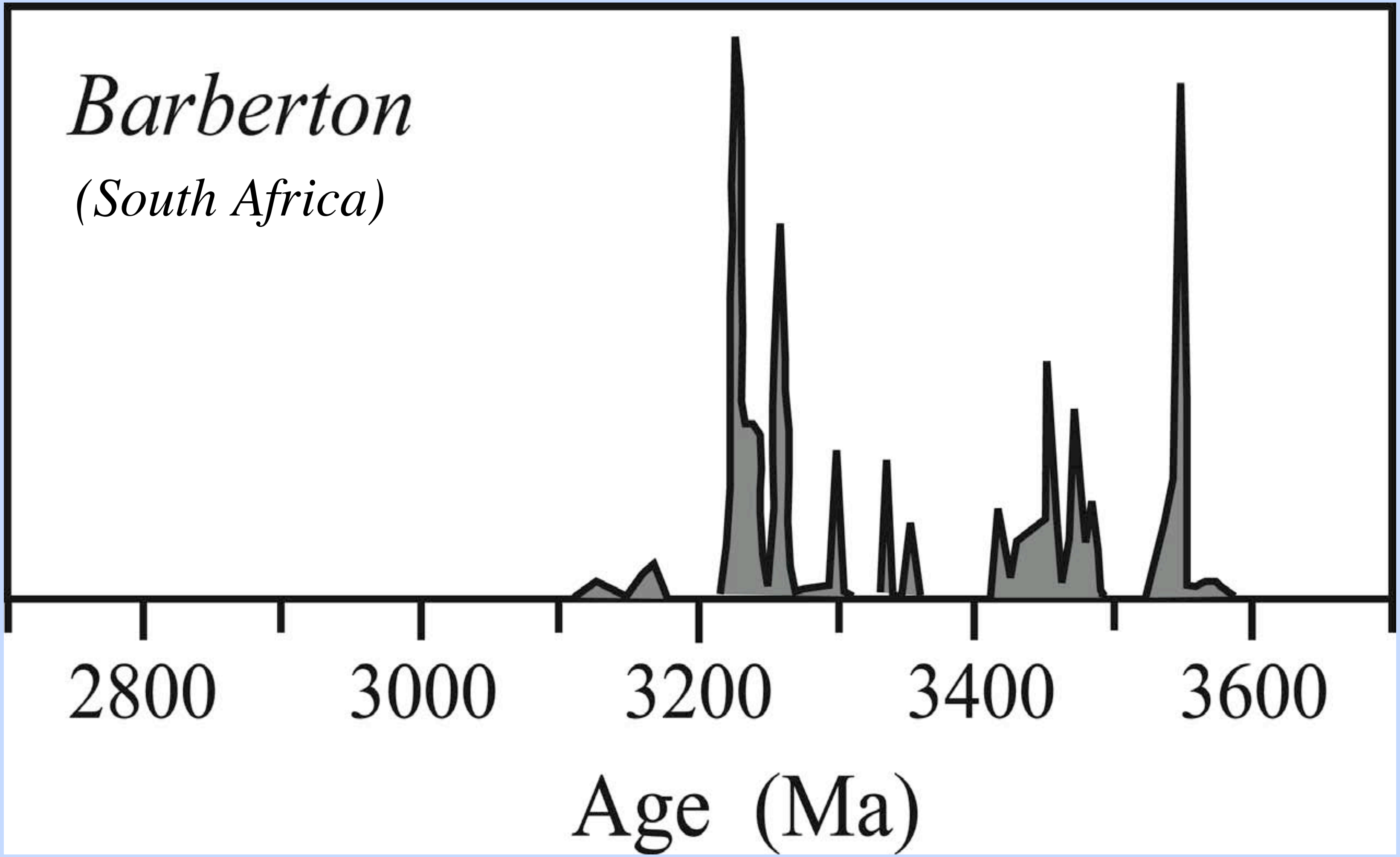
$\sigma_r = 0$

$\sigma_i = 0$ layered mode
(interface stable)

$\sigma_i \neq 0$ oscillatory mode

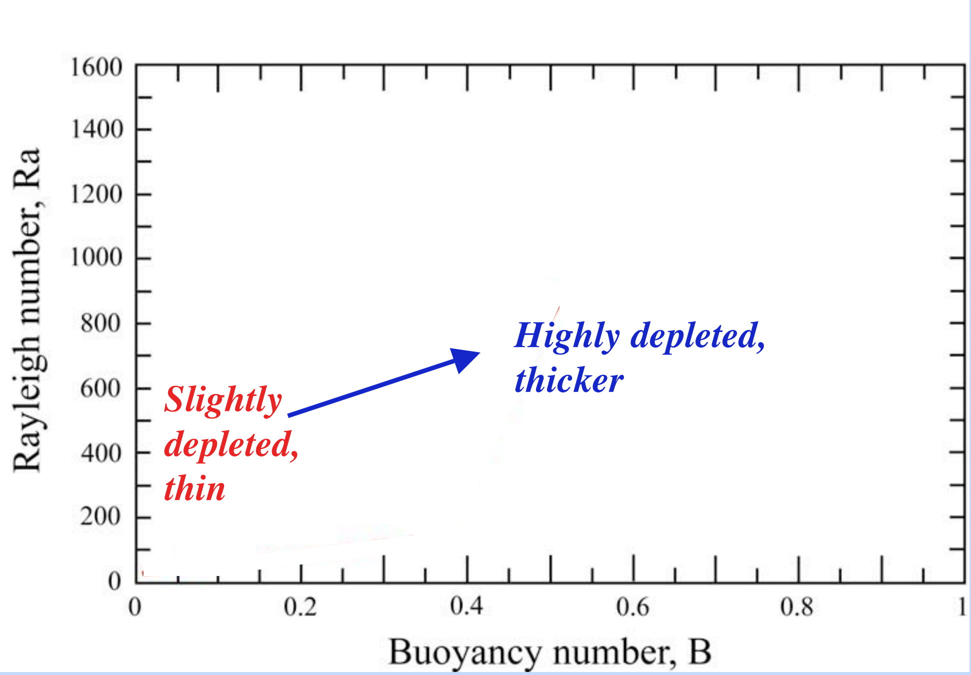


Early melting events are episodic

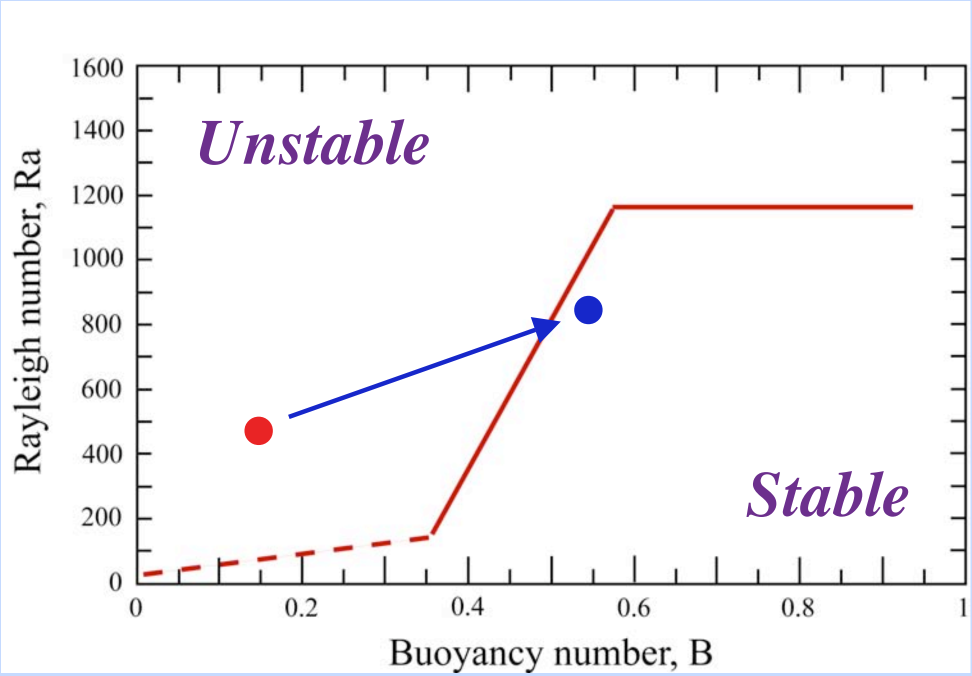


(From Eglington & Armstrong, S. African J. Geol. 2004)

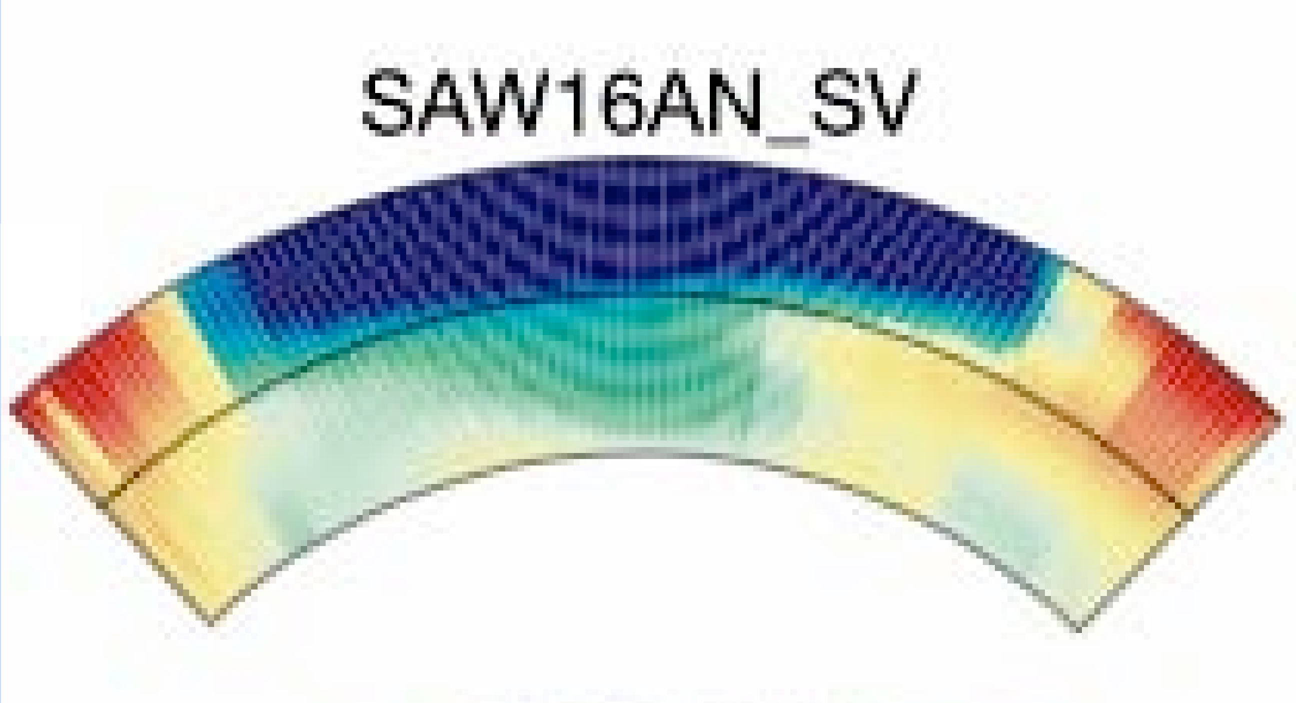
Path to stability



Path to stability



Across North America



Thermal structure
with decaying heat sources is intrinsically transient :

secular disequilibrium

$$T_i(z,t) = Z_i(z)e^{-\lambda_i t}$$

$\Rightarrow$ ***SECULAR COOLING***

Temperatures and heat flux are not
in instantaneous equilibrium with heat production.