The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2048-12

From Core to Crust: Towards an Integrated Vision of Earth's Interior

20 - 24 July 2009

Seismic tomography and the dilemma of the Earth's heat budget

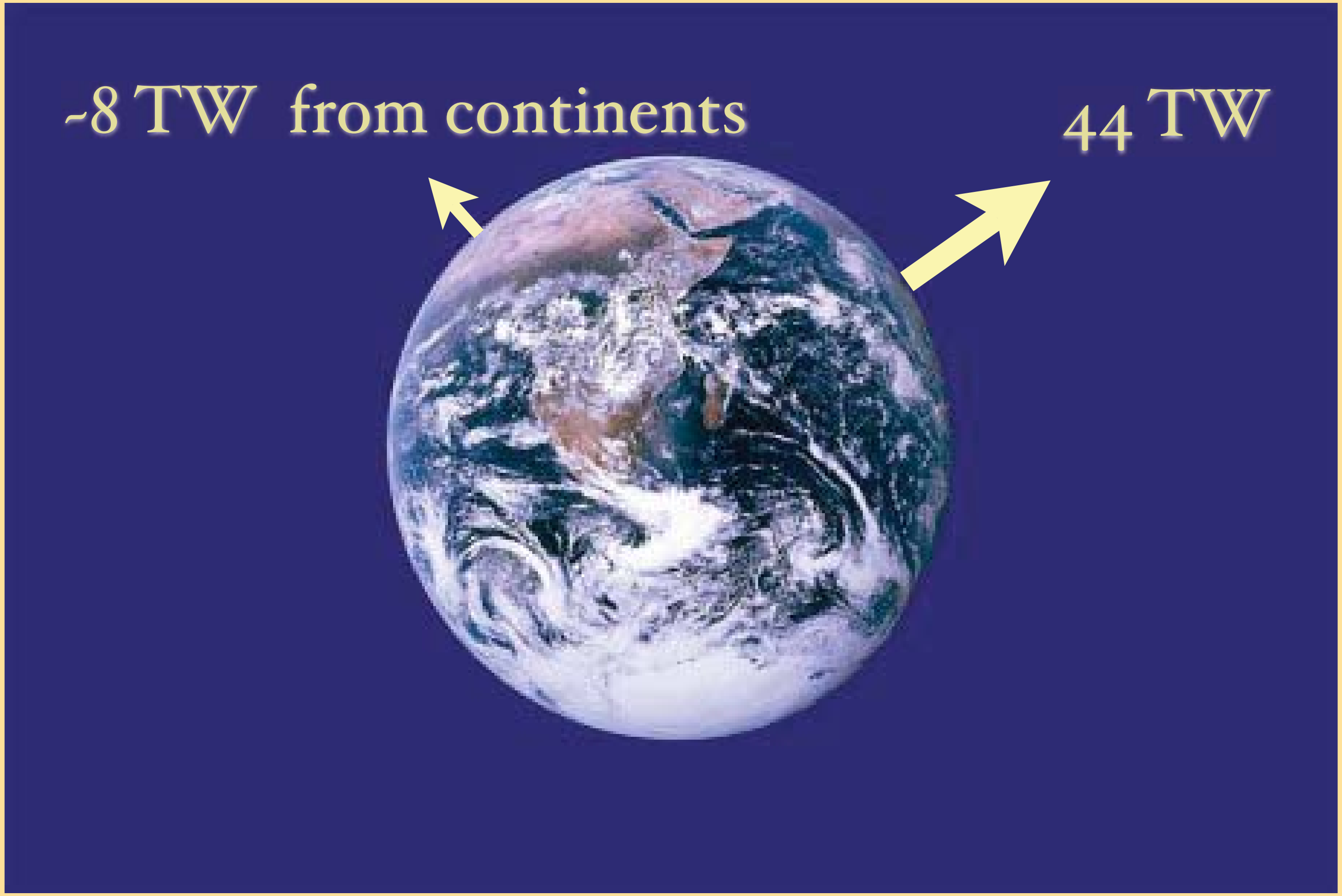
G. Nolet

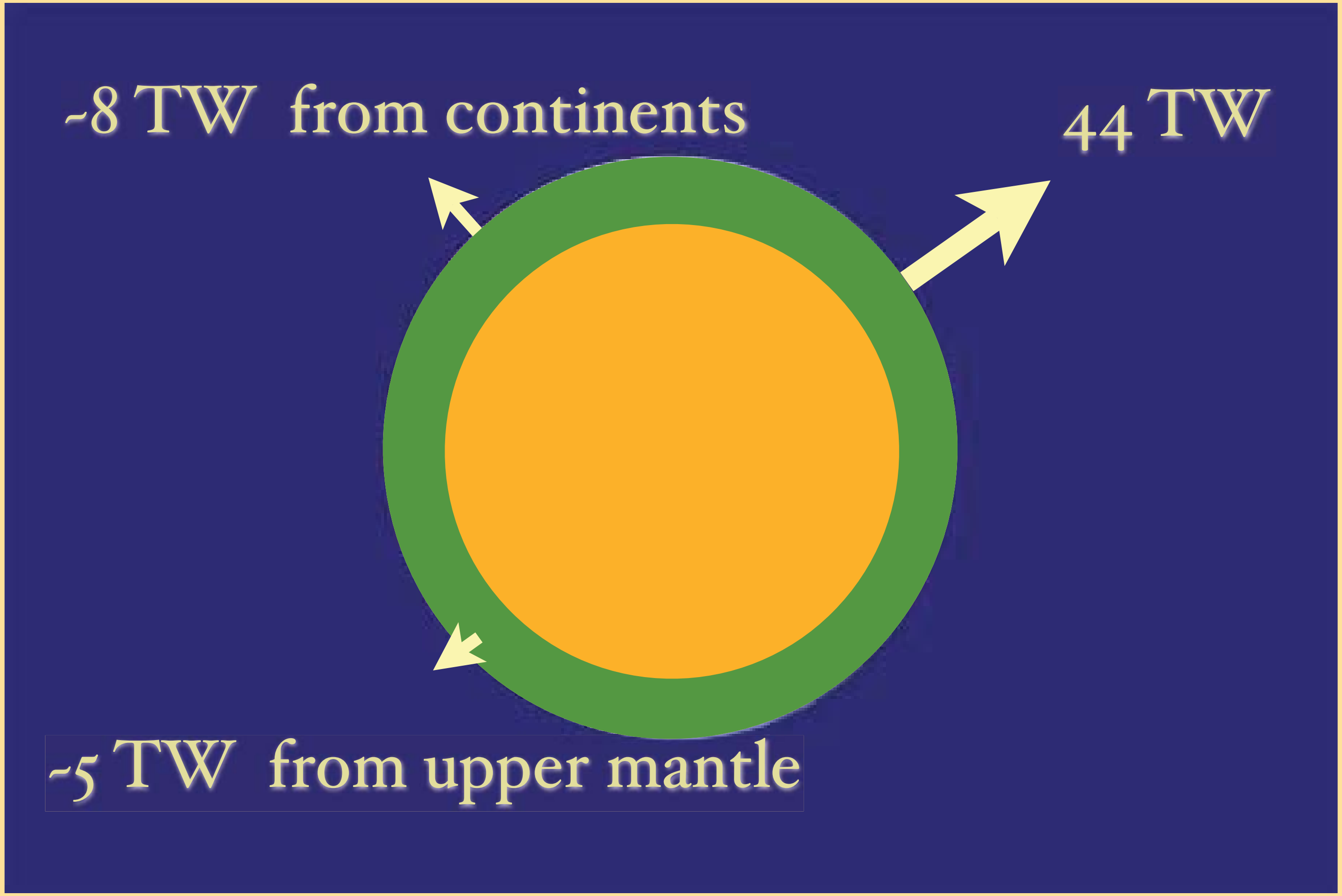
University of Nice, Sophia Antipolis
France

Seismic tomography and the dilemma of the Earth's heat budget.

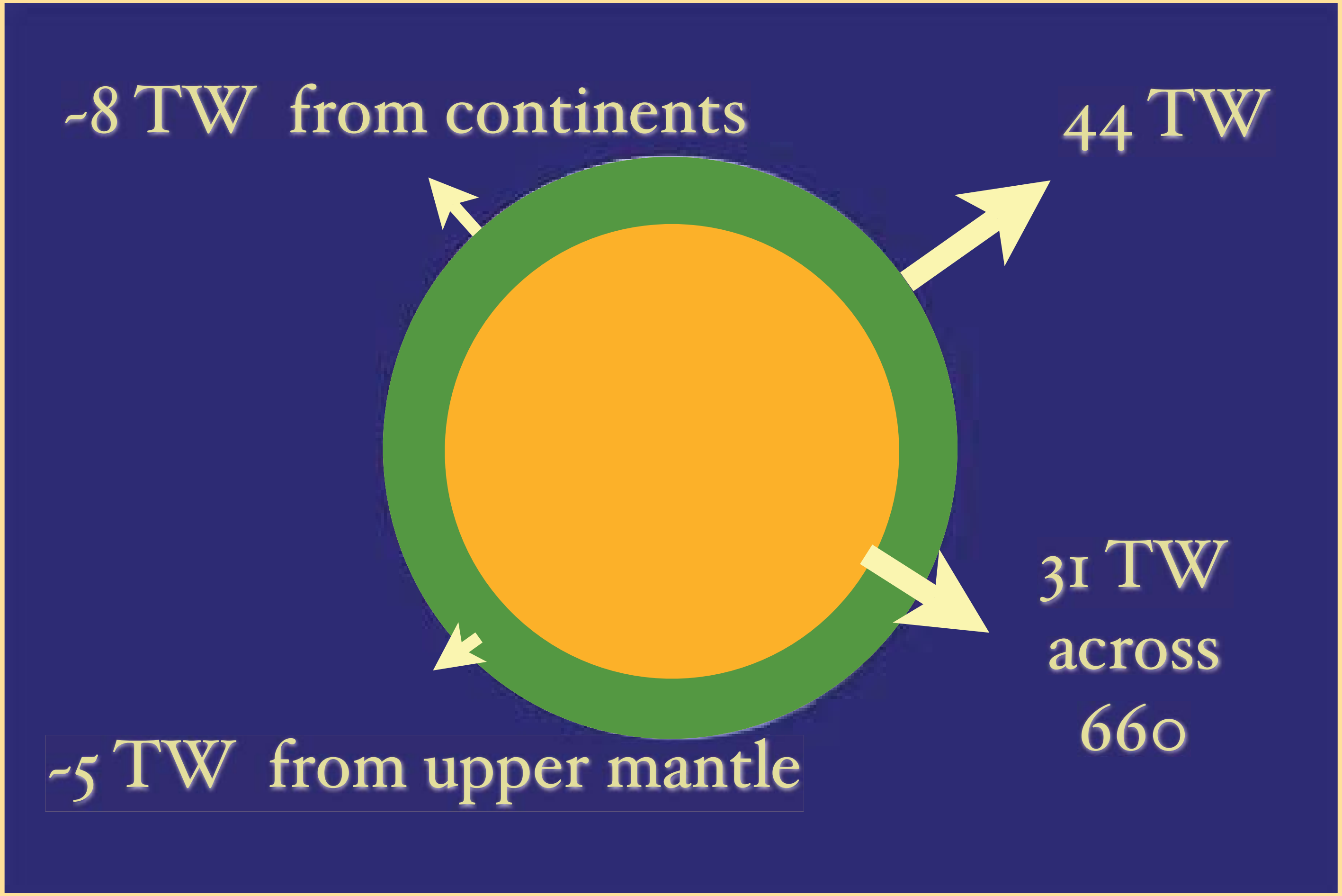
Guust Nolet
Géosciences Azur

The heat flux problem (1)


~8 TW from continents
44 TW



~8 TW from continents
44 TW
~5 TW from upper mantle



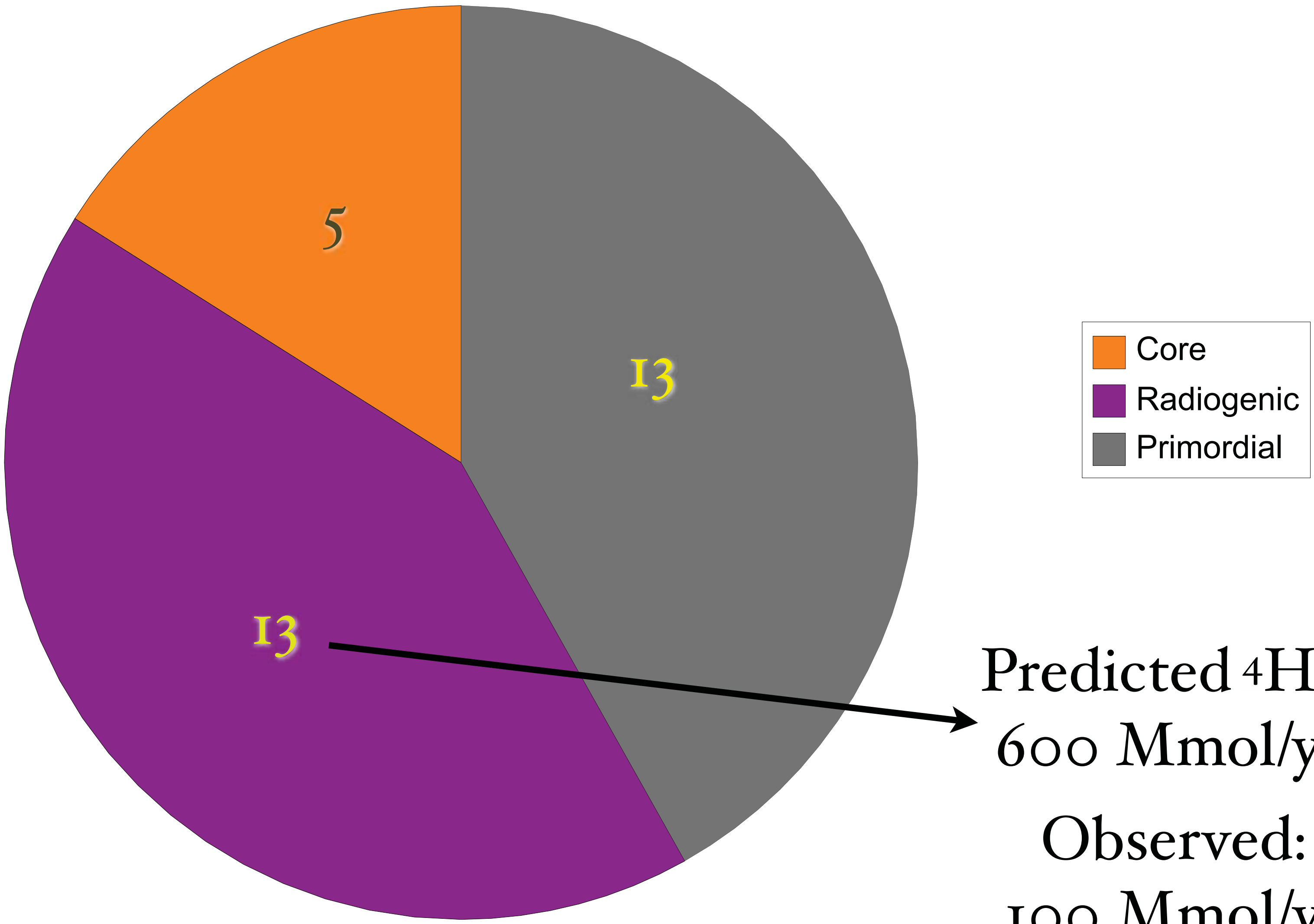
~8 TW from continents
44 TW
31 TW
across
660
~5 TW from upper mantle

Getting 31 TW across 660

- Whole-mantle convection
- Upward advection of hot rock *(plumes)*
- Downward advection of cold rock *(slabs)*
- Conduction (*thermal boundary layer or TBL*)

Question: Does a TBL exclude advection??

Mantle heat flux



Predicted ^4He:
600 Mmol/yr

Observed:
100 Mmol/yr

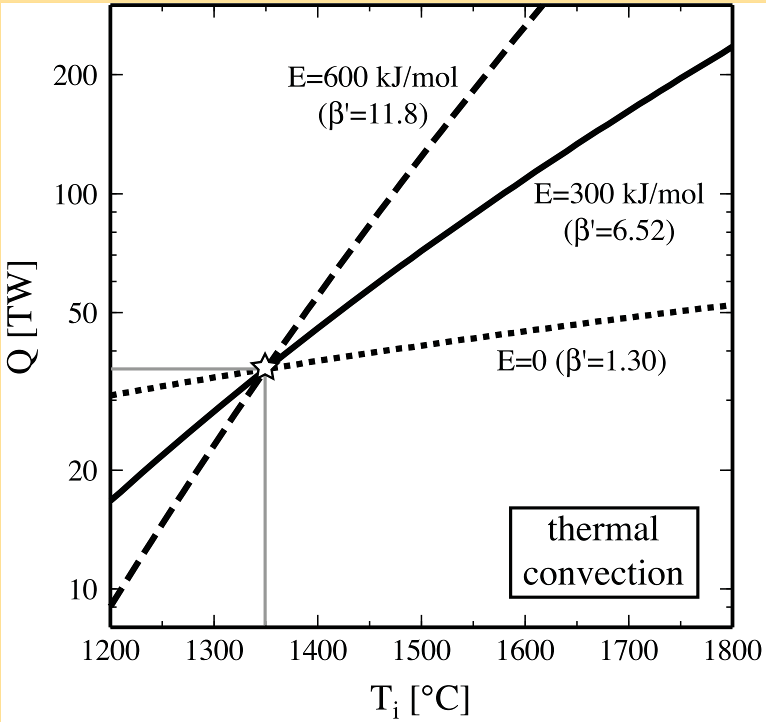
cooling history

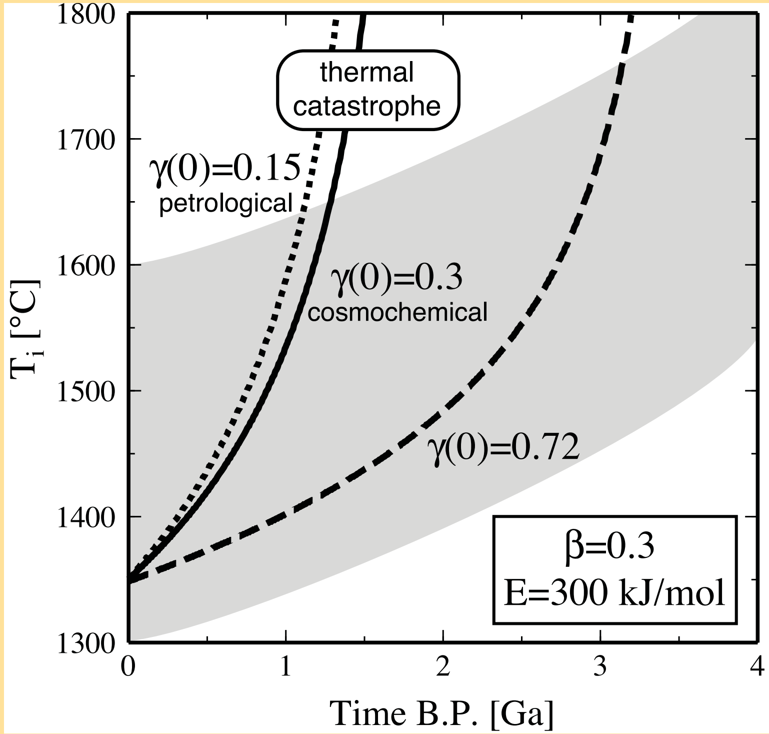
Abbott et al., JGR 1994

Argon

- $^{40}K \rightarrow ^{40}Ar$
- ^{40}Ar does not escape from the atmosphere
- Only about half the predicted ^{40}Ar is found in the atmosphere
- The rest must be residing *somewhere*

The heat flux problem (2)





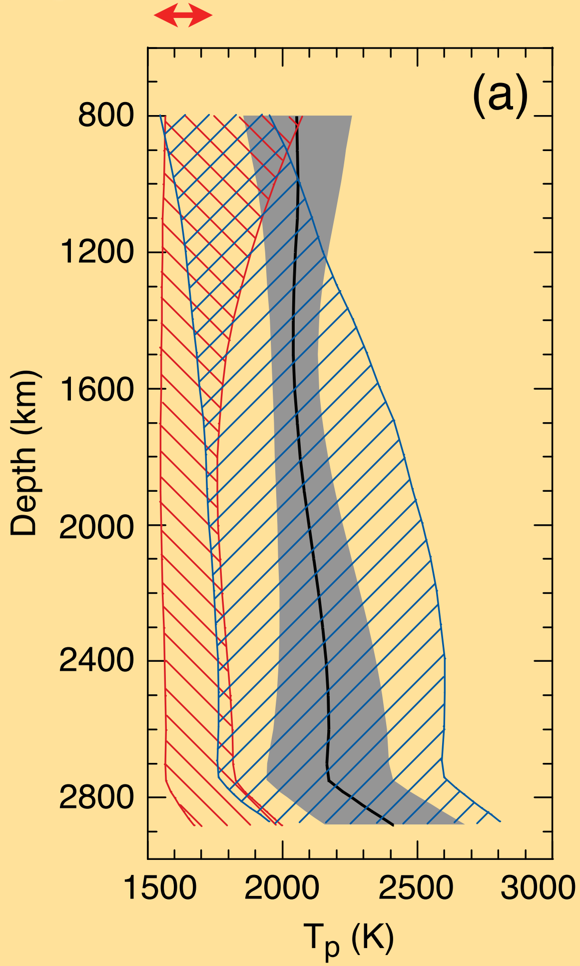
Korenaga, Geophys. Monogr. 2006

Ways to limit the heat flux

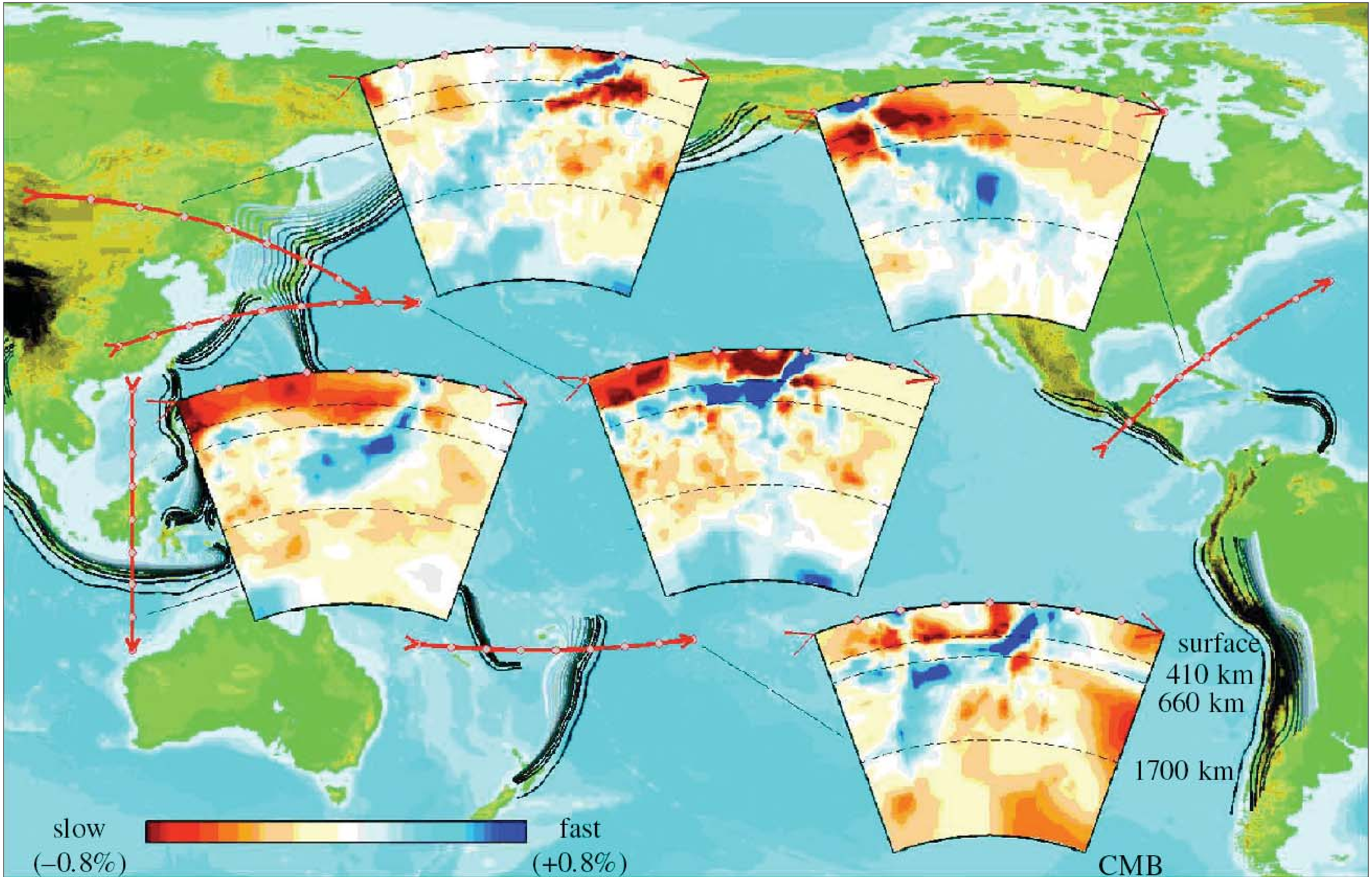
- Plates resist convection (Conrad & Hager, 1999, Korenaga 2006)
- Q is not a simple function of T but depends also on plate configuration (Labrosse & Jaupart, 2007)
- Upper and lower mantle convect separately (McKenzie & Richter, 1981) This would imply a thermal boundary layer (TBL) at 660 km.

TBL: what does PREM tell us?

Upper mantle potential temperature range (Jaupart et al, 2008)

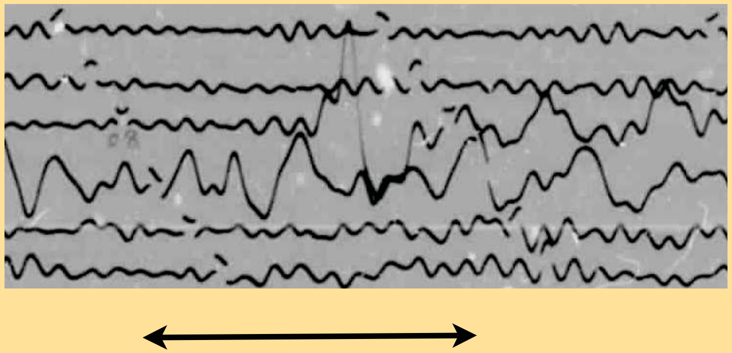


Deschamps & Trampert, EPSL 2004



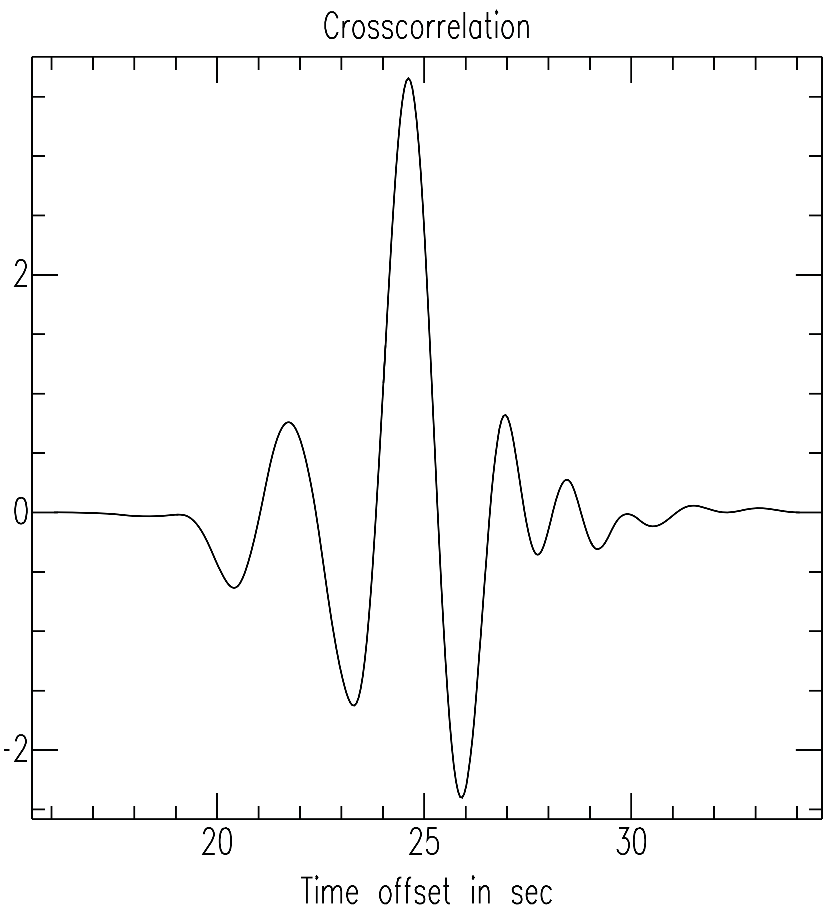
Albarède & Van der Hilst, 2002

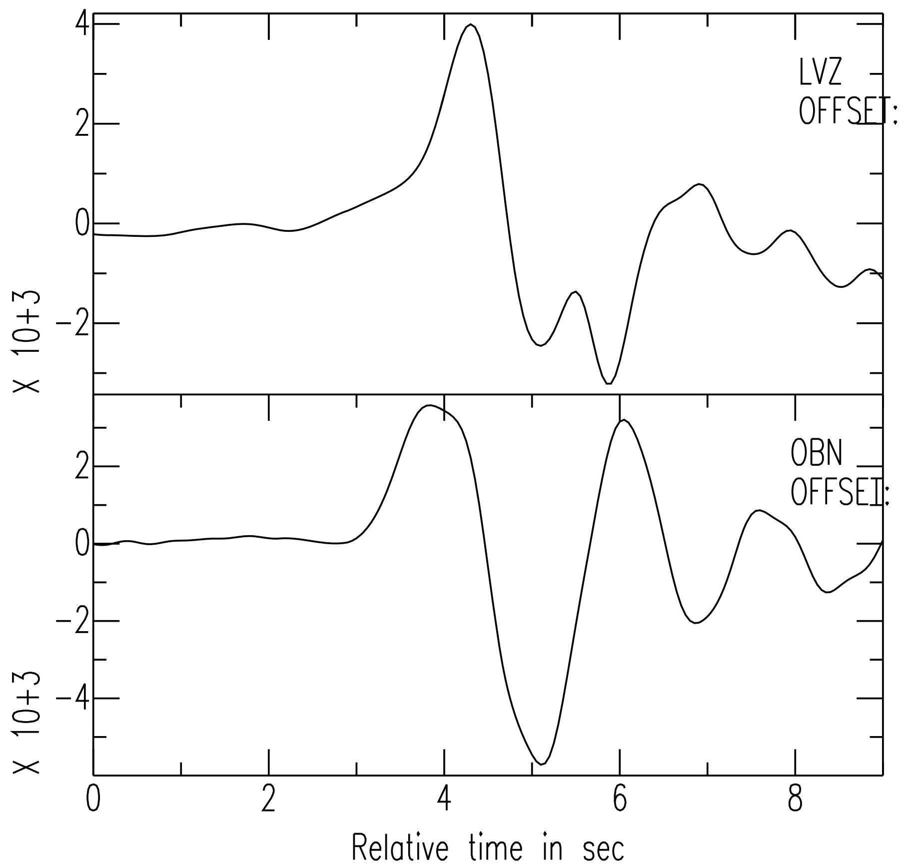
Intermezzo: from onset times to cross-correlations



Cross-correlation

$$\gamma(t) = \int s(t')u(t' - t)\mathrm{d}t'$$



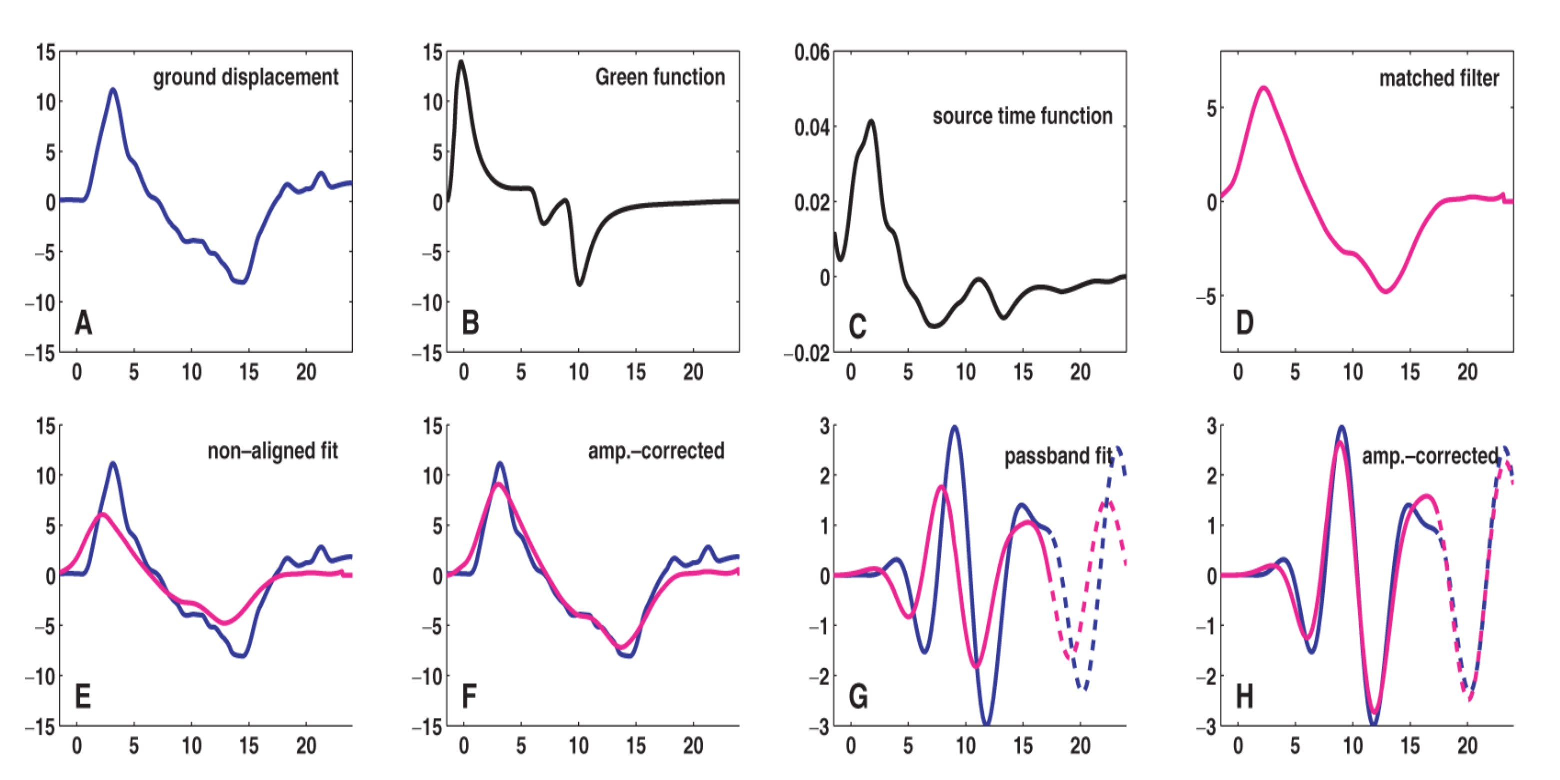


Cross-correlation

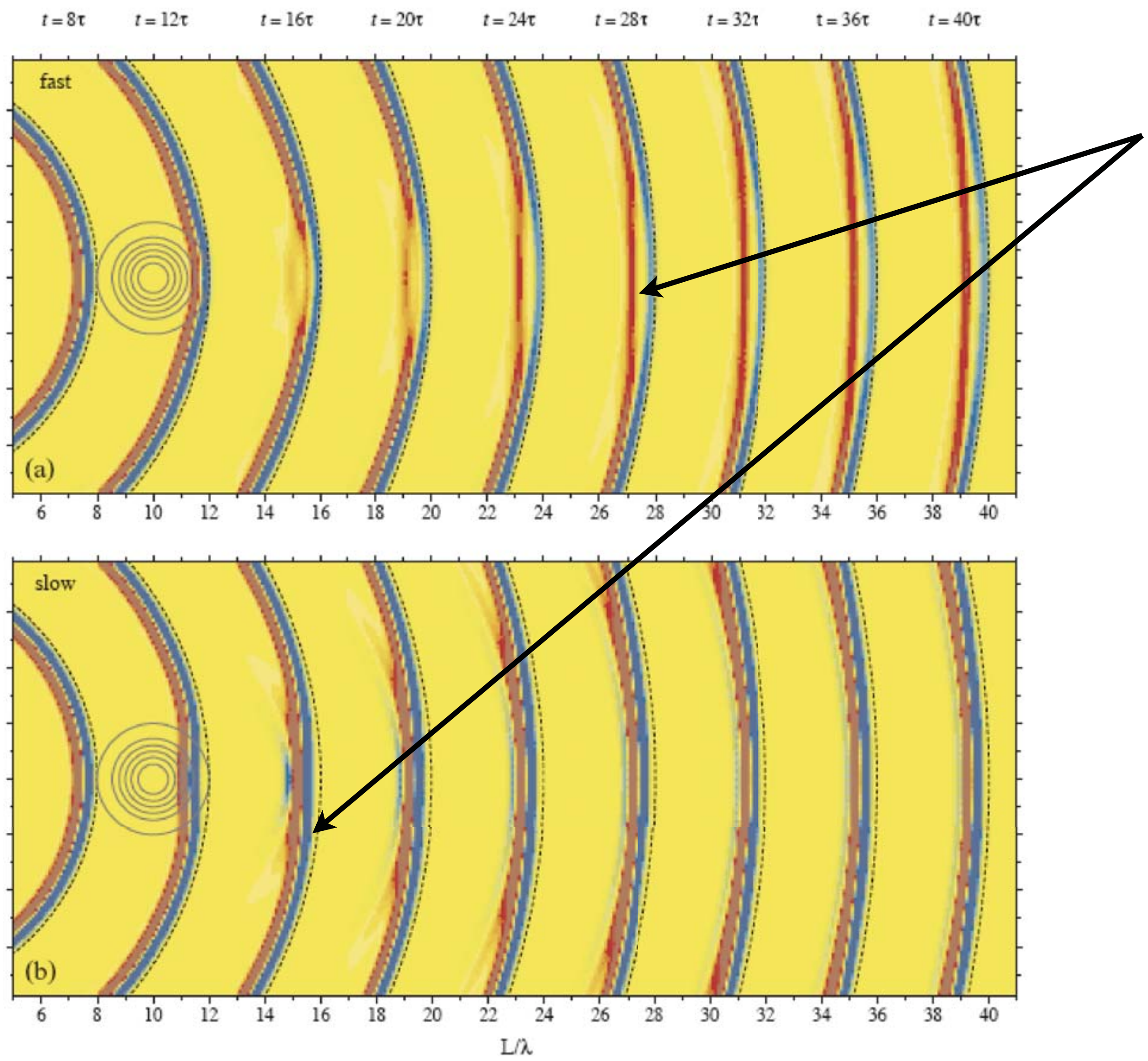
$$\gamma(t) = \int s(t')u(t' - t)\mathrm{d}t'$$

$$\sigma^2_{\mathrm{CRLB}} = \frac{3}{8\pi^2} \frac{1 + 2\mathrm{SNR}}{\mathrm{SNR}^2} \frac{1}{\Delta f^3 T_{\mathrm{w}}}$$

Body wave cross-correlations



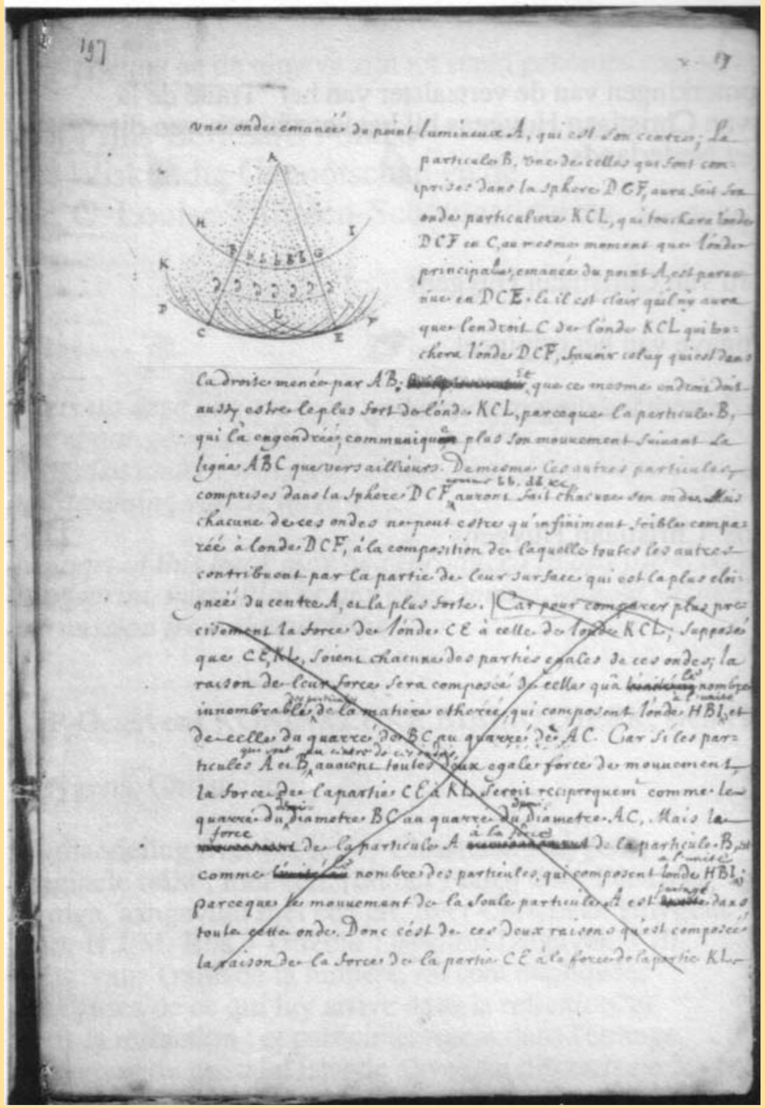
Sigloch & Nolet, GJI 2006



The most dramatic effects are at later times in the waveform!

Hung et al., GJI 2001

Wave diffraction


197

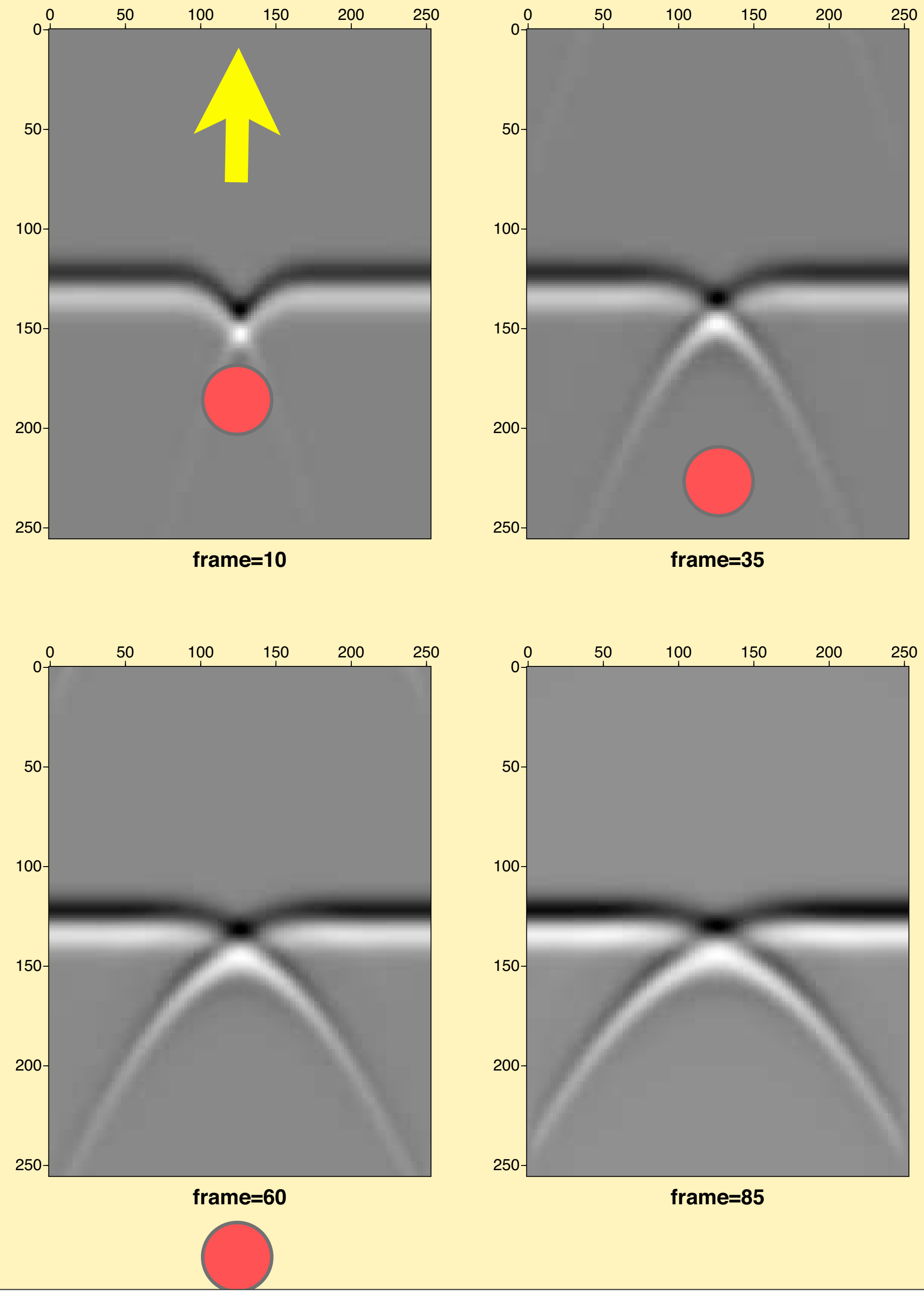
x. 17

une onde emanée du point lumineux A, qui est son centre; la particule B, une de celles qui sont comprises dans la sphere DCF, aura fait son onde particuliere KCL, qui touchera l'onde DCF en C, au mesme moment que l'onde principale, emanée du point A, est parvenue en DCE. et il est clair qu'il n'y aura que l'endroit C de l'onde KCL qui touchera l'onde DCF, sçavoir celuy qui est dans la droite menée par AB; et que ce mesme endroit doit aussy estre le plus fort de l'onde KCL, parceque la particule B, qui l'a engendrée, communique plus son mouvement suivant la ligne ABC que vers ailleurs. De mesme les autres particules, comme bb, dd &c, comprises dans la sphere DCF, auront fait chacune son onde. Mais chacune de ces ondes ne peut estre qu'infiniment foible comparée à l'onde DCF, à la composition de laquelle toutes les autres contribuent par la partie de leur surface qui est la plus eloignée du centre A, et la plus forte. Car pour comparer plus precisement la force de l'onde CE à celle de l'onde KCL, supposé que CE, KL, soient chacune des parties egales de ces ondes; la raison de leur force sera composée de celles qu'a le nombre innombrable des particules de la matiere etherée, qui composent l'onde HBI, à l'unité et de celle du quarré de BC au quarré de AC. Car si les particules A et B, qui sont au centre de ces ondes, avoient toutes deux egale force de mouvement, la force de la partie CE à KL seroit reciproquement comme le quarré du demi diametre BC au quarré du demi diametre AC. Mais la force de la particule A à la force de la particule B, est comme le nombre des particules, qui composent l'onde HBI, à l'unité; parceque le mouvement de la seule particule A est partagé dans toute cette onde. Donc c'est de ces deux raisons qu'est composée la raison de la force de la partie CE à la force de la partie KL.

Christiaan Huygens (1629-1696)

Wave diffraction

Christaan Huygens (1629-1696)

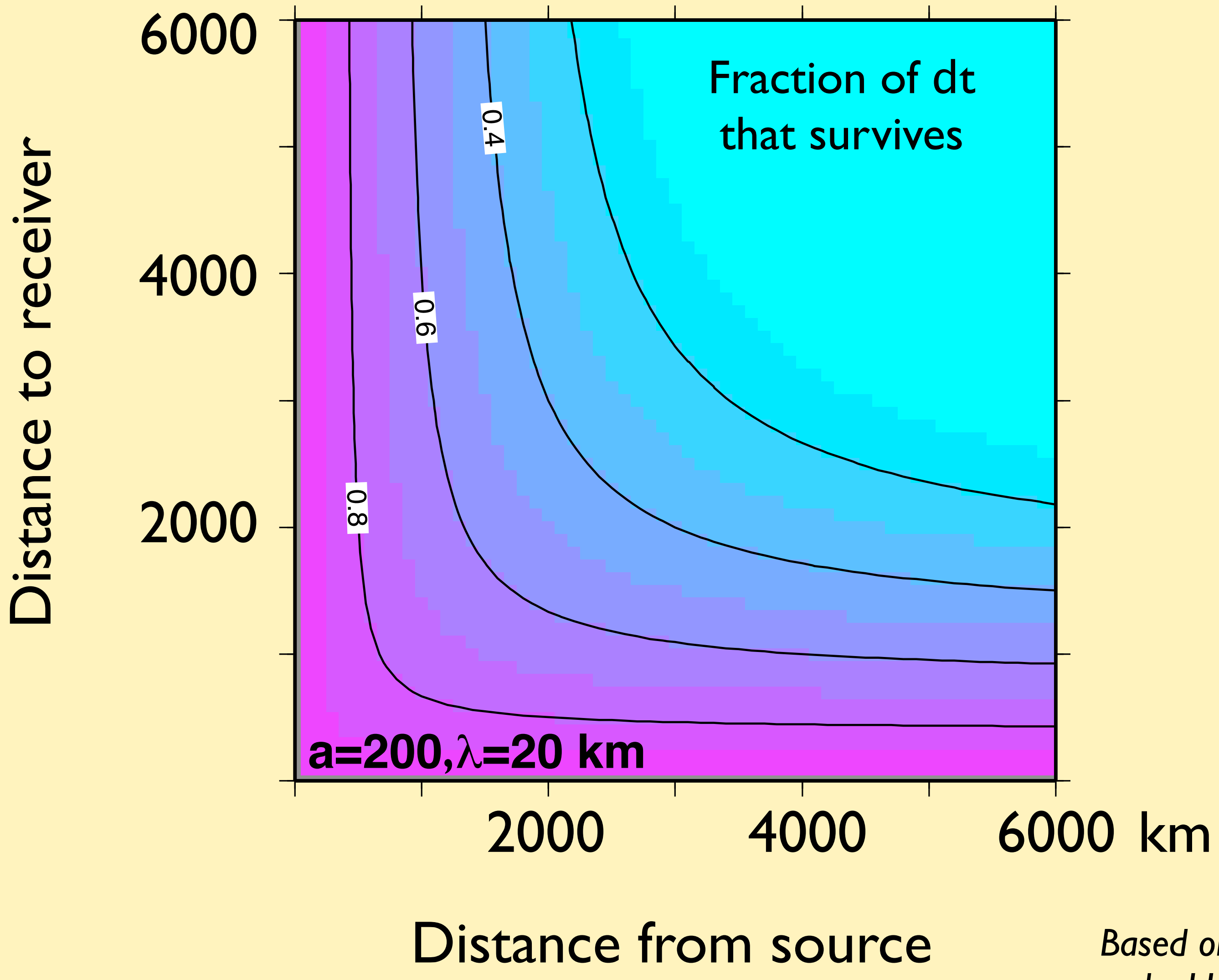


Wavefront healing:

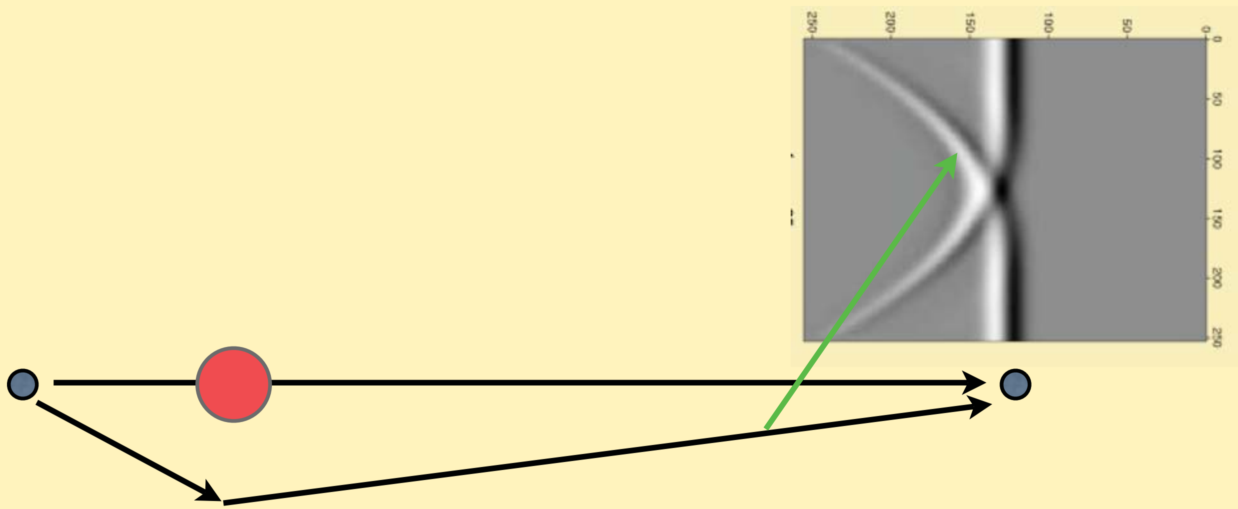
time delays are slowly annealed

Waves may take detours

Healing of cross-correlation delays (Period=2 s)

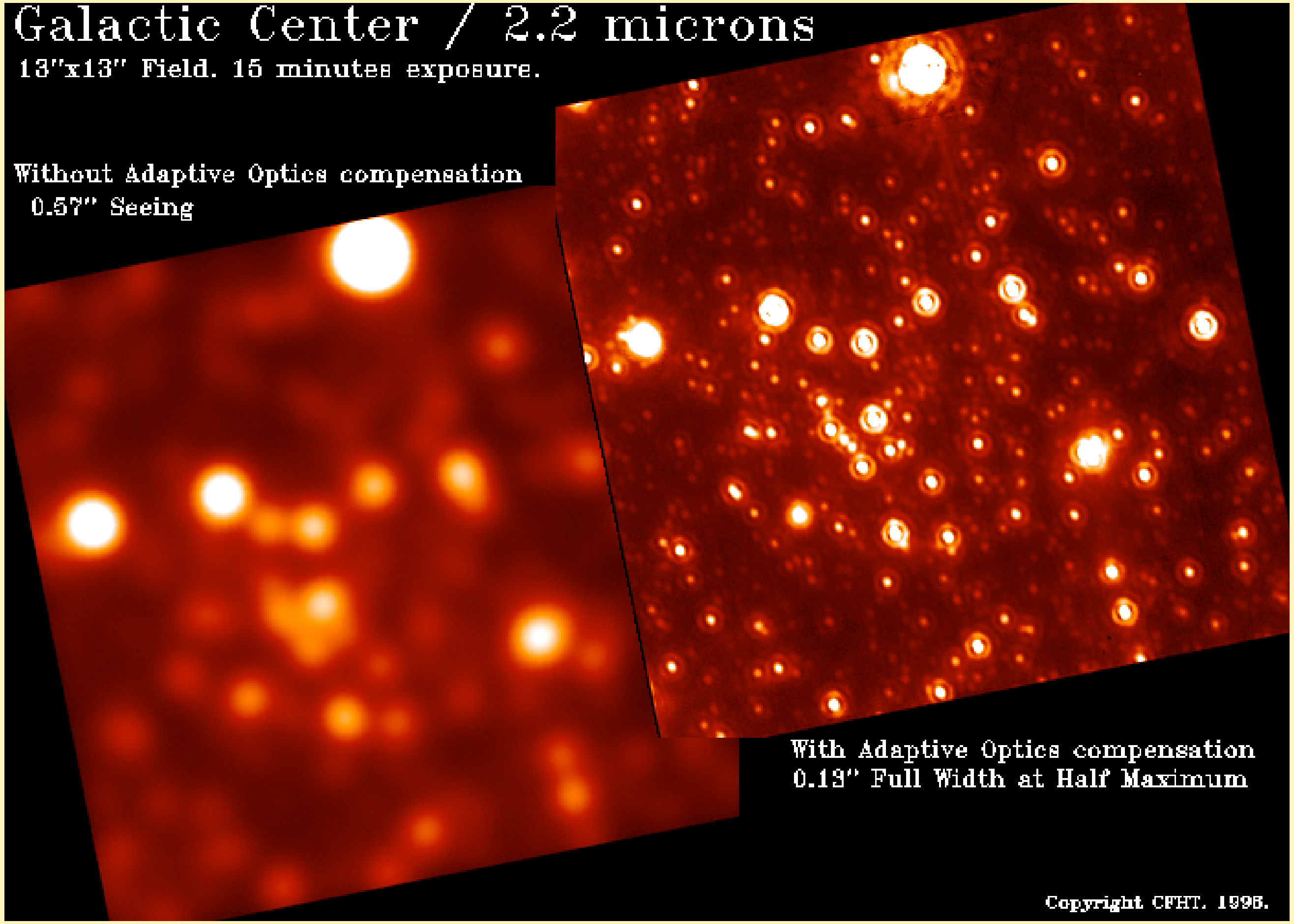


Based on numerical simulations by Hung et al., GJI 2001.

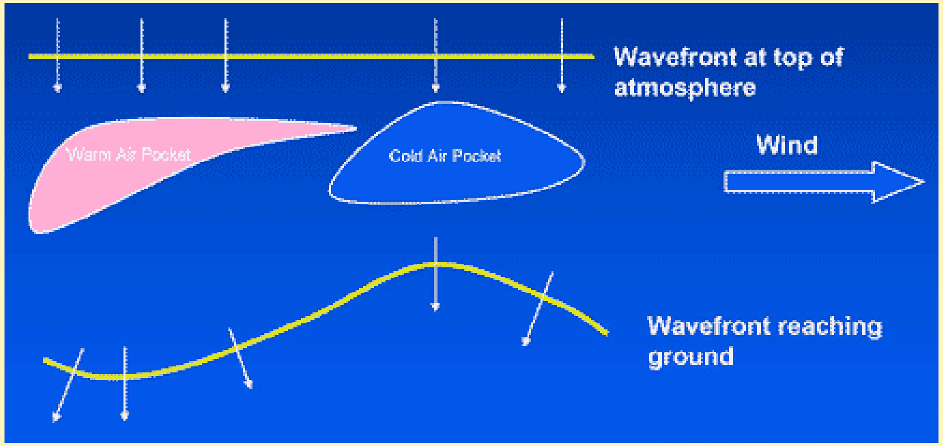


A wavefront heals because energy diffracts *around* the anomaly. Can we correct for it?

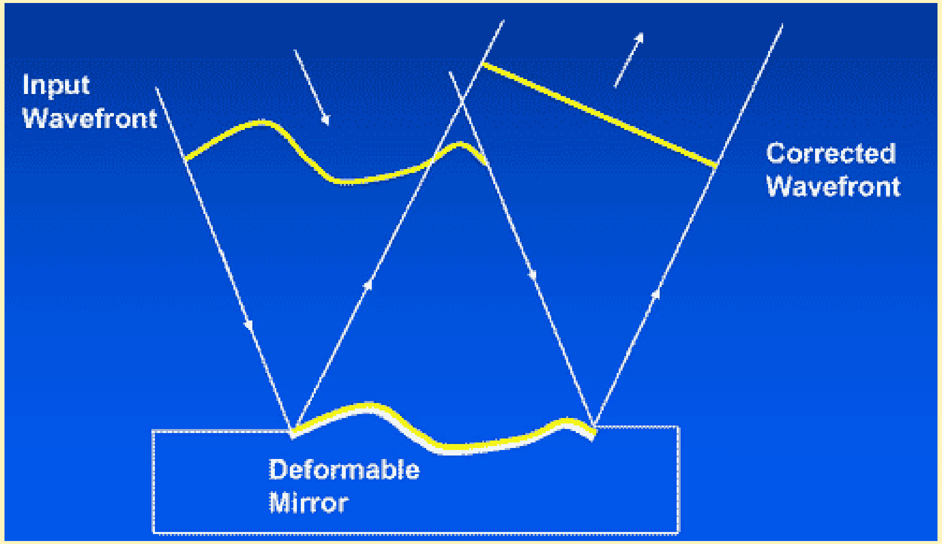
It is like adaptive optics



adaptive optics

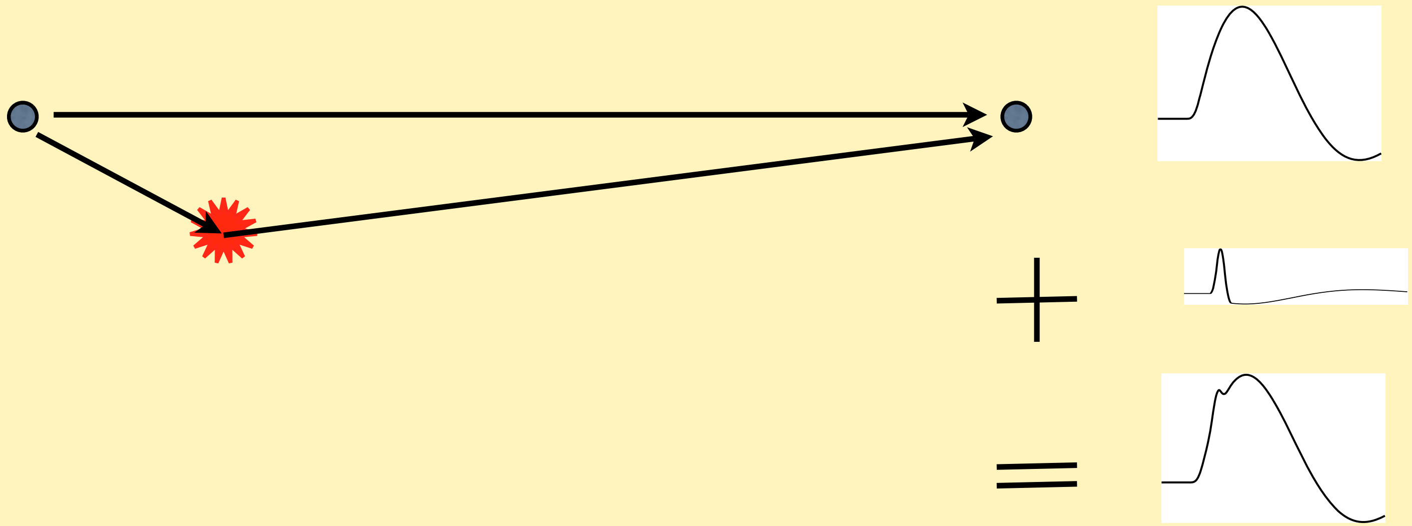


Glen Herriot (NRC-CNRC)



Glen Herriot (NRC-CNRC)

Born theory = first order perturbation *of an early arrival*

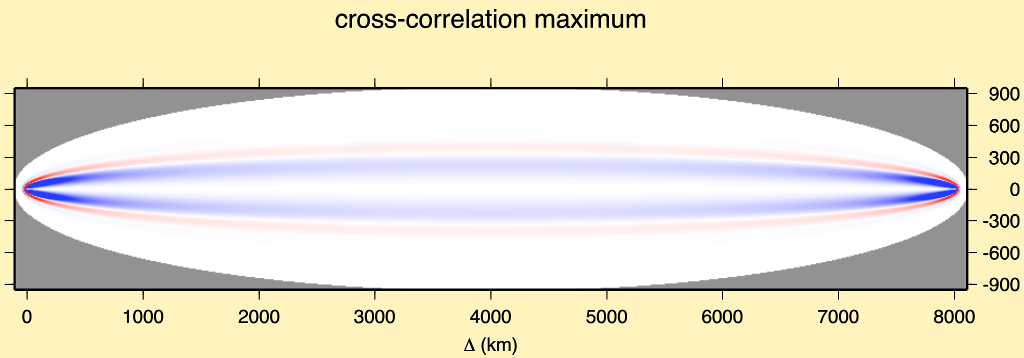


Scattered wave perturbs crosscorrelation

Born

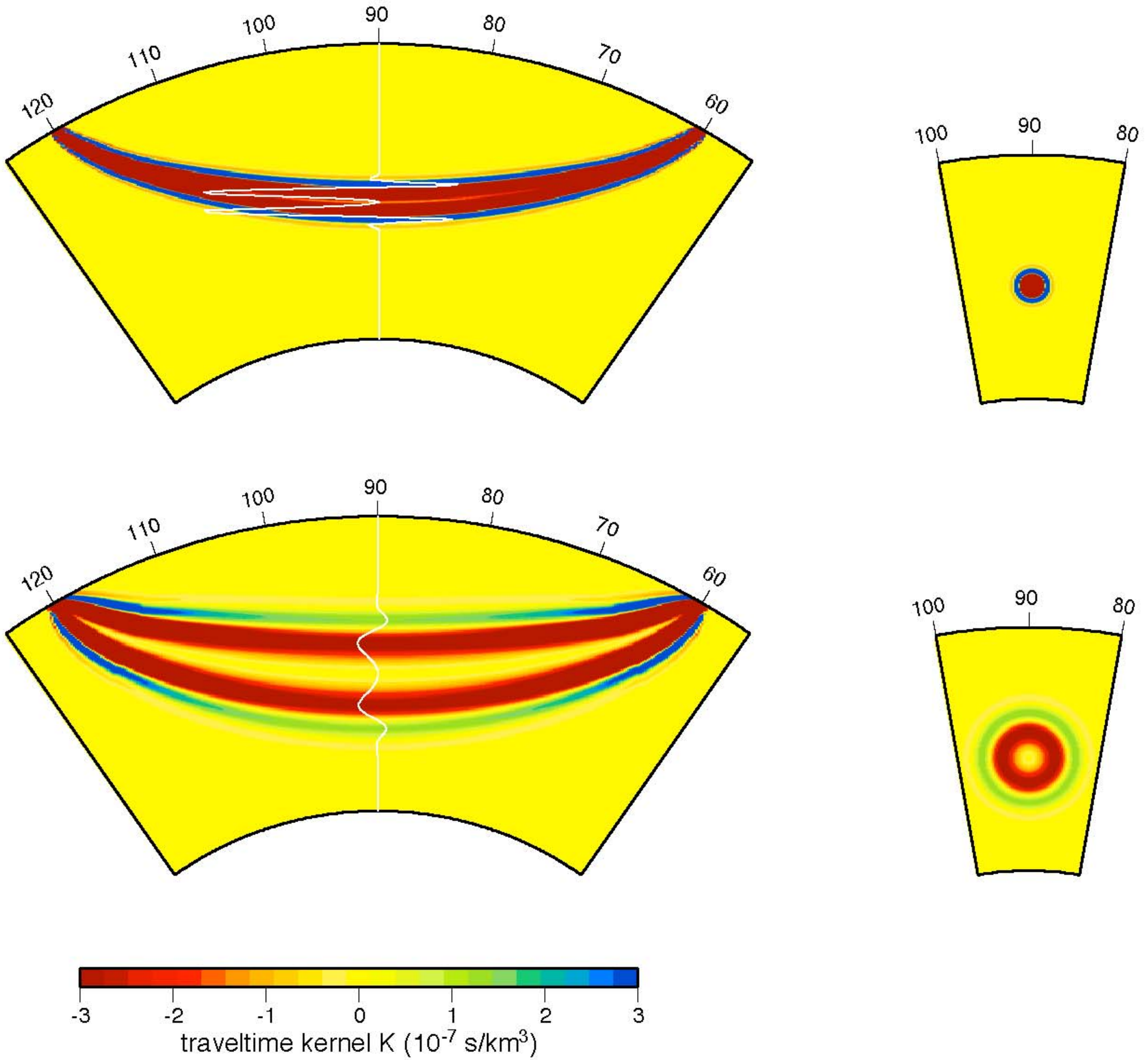
$$\delta T = -\frac{\delta\dot{\gamma}(0)}{\ddot{\gamma}(0)} = -\frac{\int_{-\infty}^{\infty} \dot{u}(t')\boxed{\delta u(t')}\mathrm{d}t'}{\int_{-\infty}^{\infty} \ddot{u}(t')u(t')\mathrm{d}t'} \,.$$

Scattered waves + delay from cross-correlation ⇒ “banana-doughnut” kernels



$$\delta T = \int \underbrace{K_{\mathrm{P}} \left(\frac{\delta V_{\mathrm{P}}}{V_{\mathrm{P}}} \right)} \, \mathrm{d}^3 \boldsymbol{r}_{\mathrm{x}}$$

$$-\frac{\int_{-\infty}^{\infty} \dot{u}(t')\delta u(t')\mathrm{d}t'}{\int_{-\infty}^{\infty} \ddot{u}(t')u(t')\mathrm{d}t'} .$$

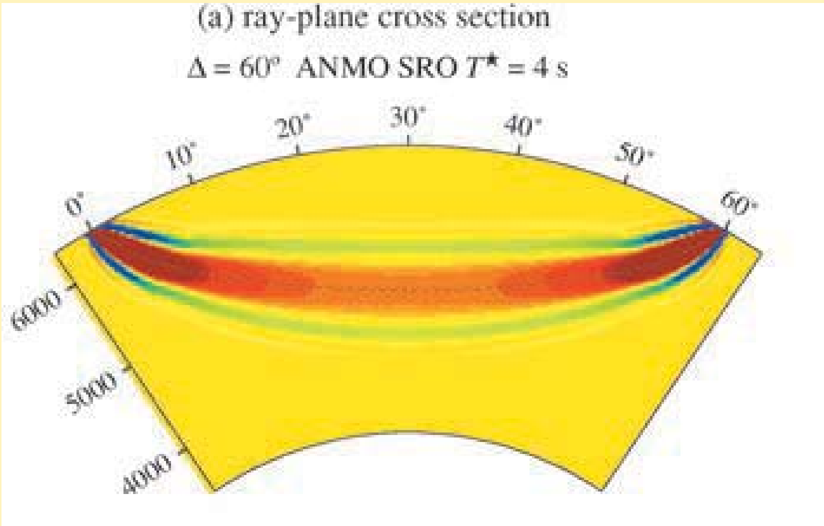


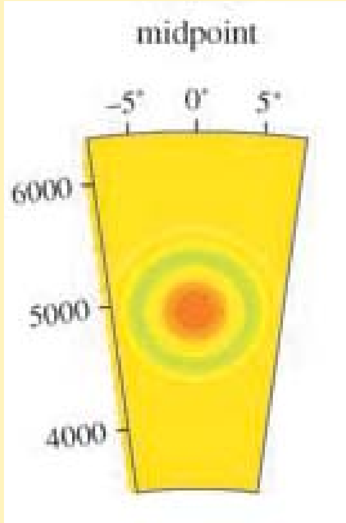
T=2s

T=20s

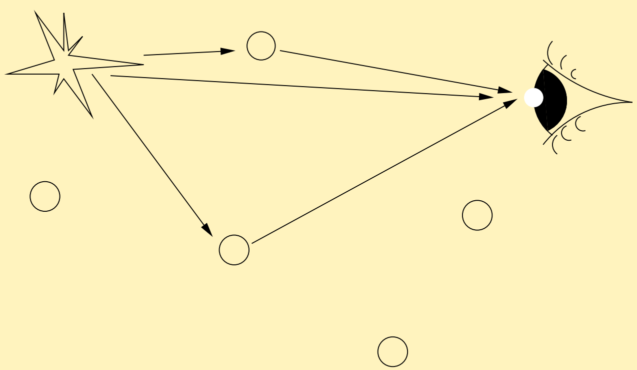
The period T determines the width of the kernel

Amplitude kernels

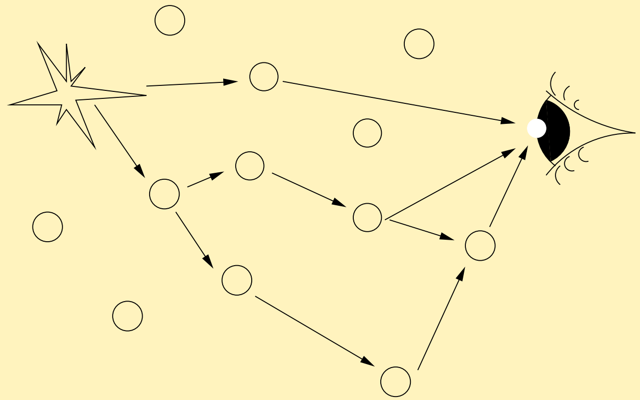




modeling waveforms:
Single or multiple scattering?



(a) Diffusion simple



(b) Diffusion multiple

Single=early

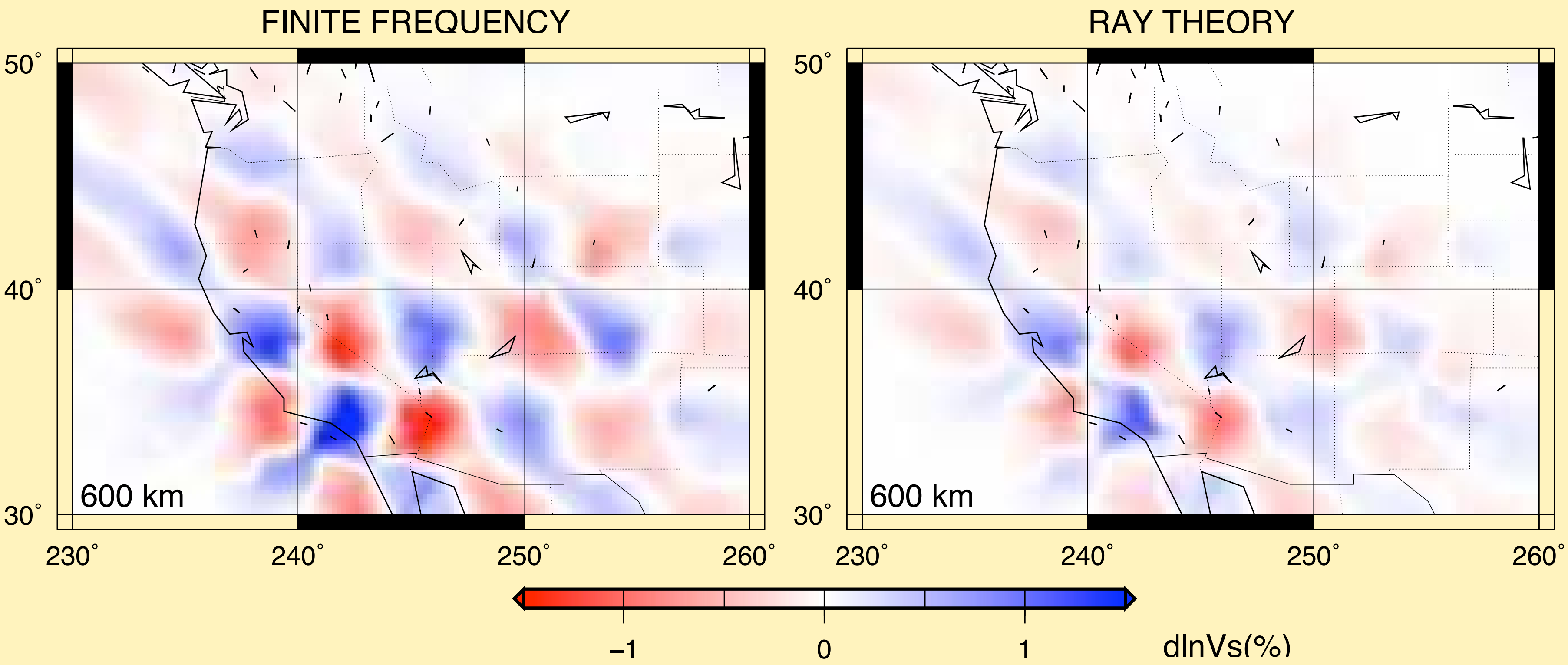
Multiple =late

Domitille Anache, 2008

Forward scattering retains information

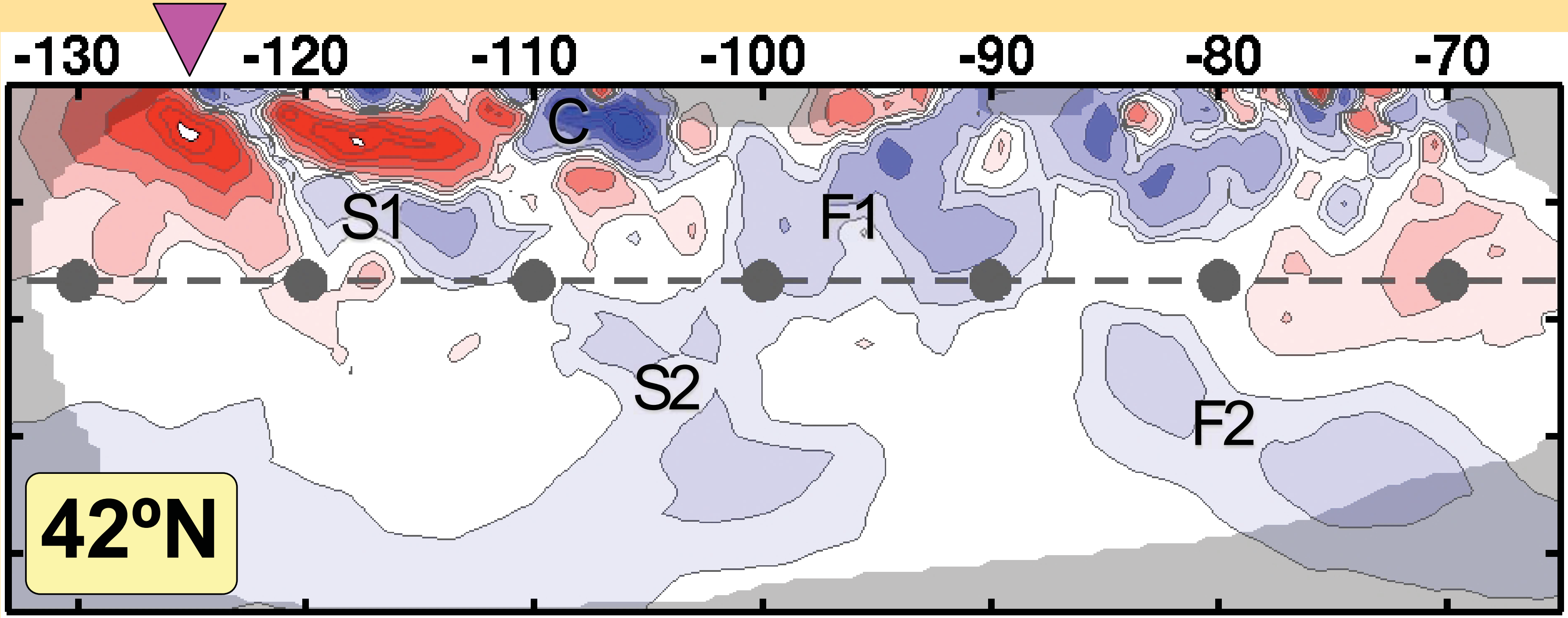
Multiple scattering: ill posed inverse problem

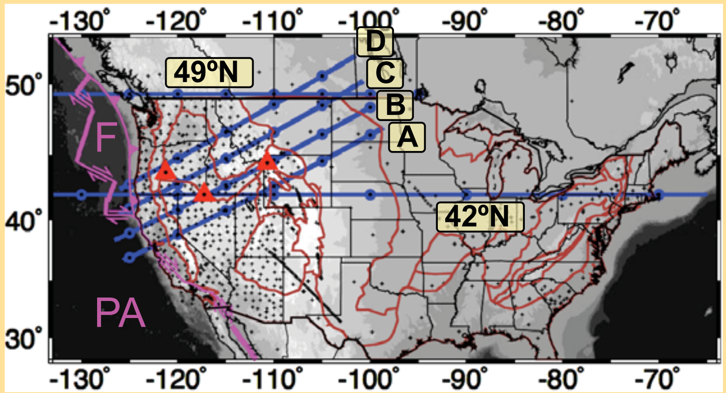
Resolution gain (multiple frequency, delays & amplitudes)



Yue Tian, AGU 2007

Finite frequency P wave images and USArray

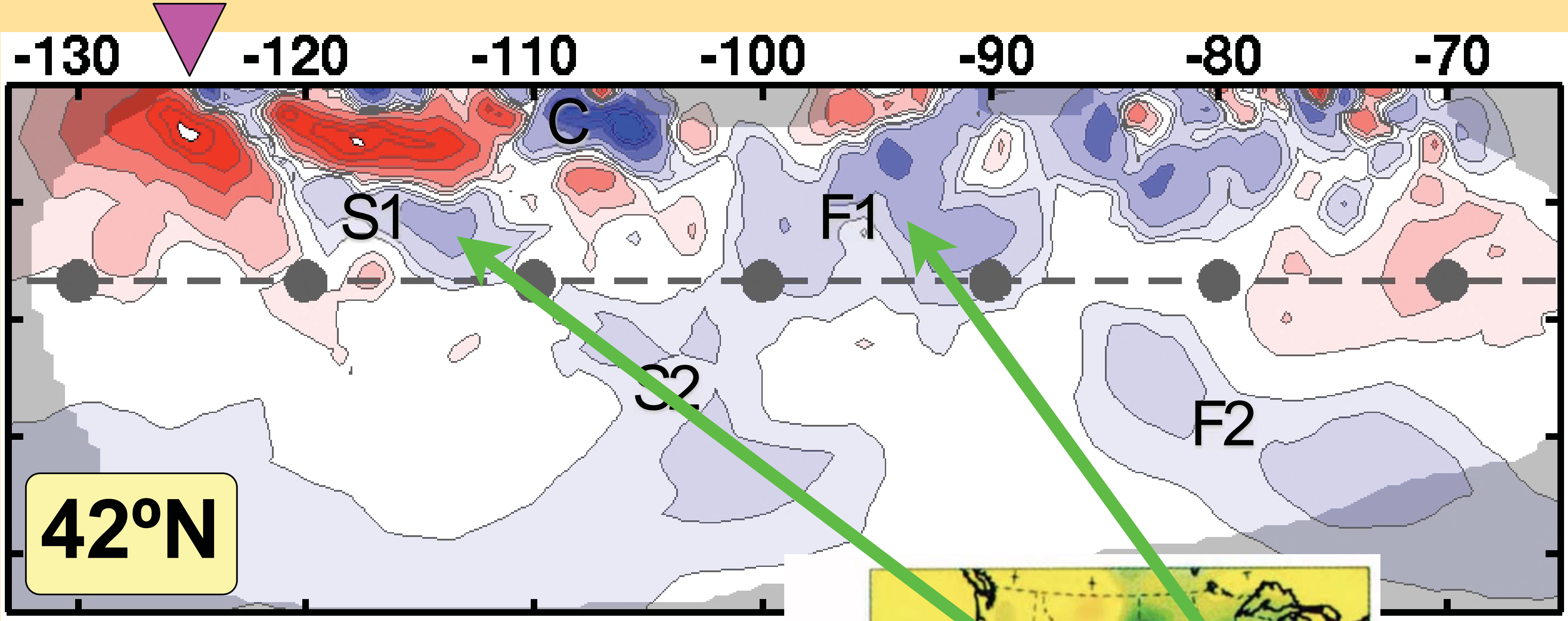


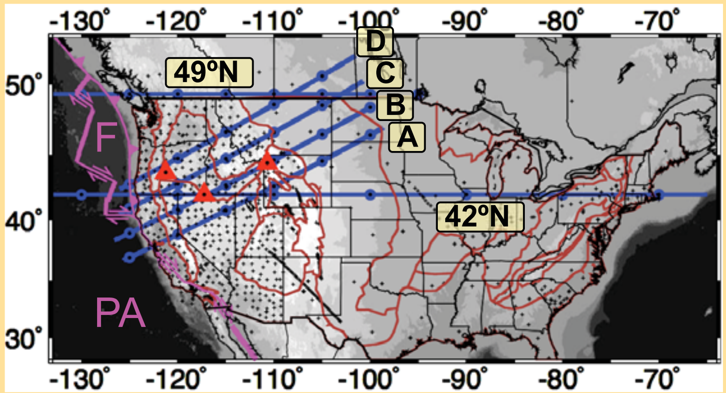


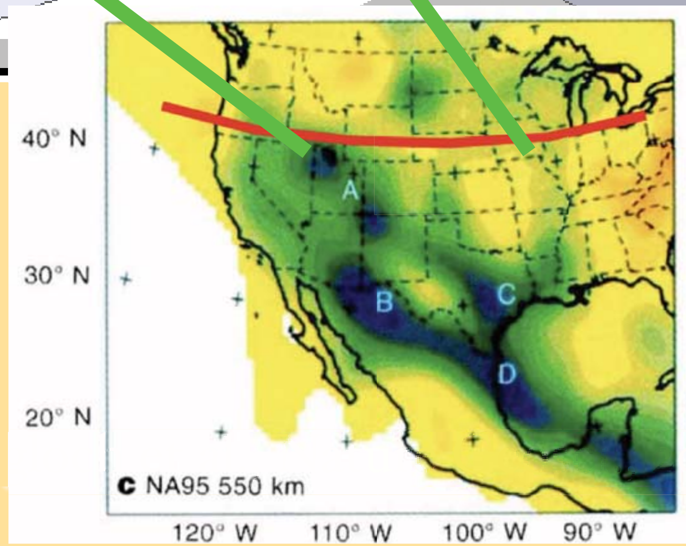
dlnVp

Sigloch et al., Nature Geosci., 2008

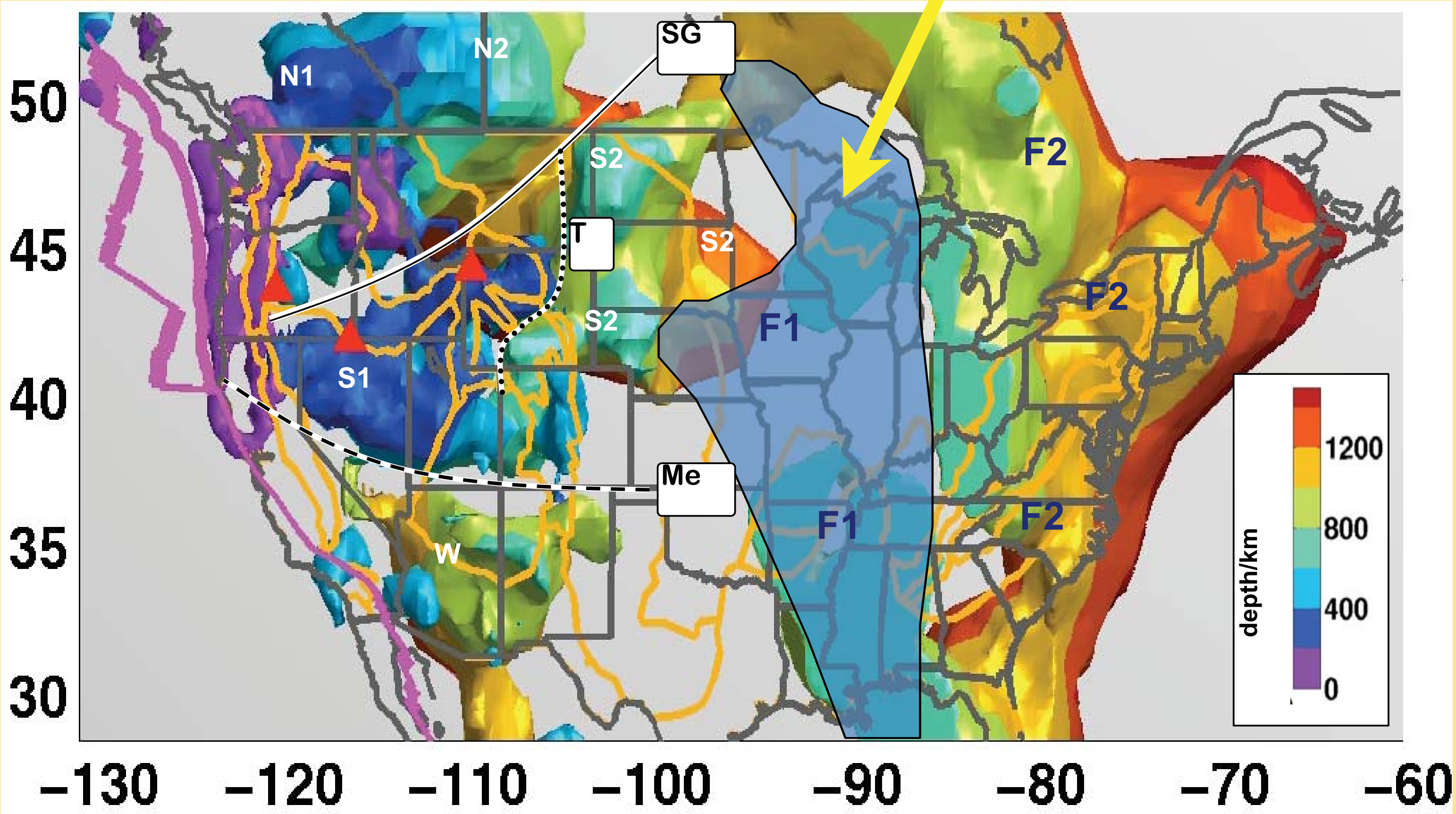
Finite frequency P wave images and USArray





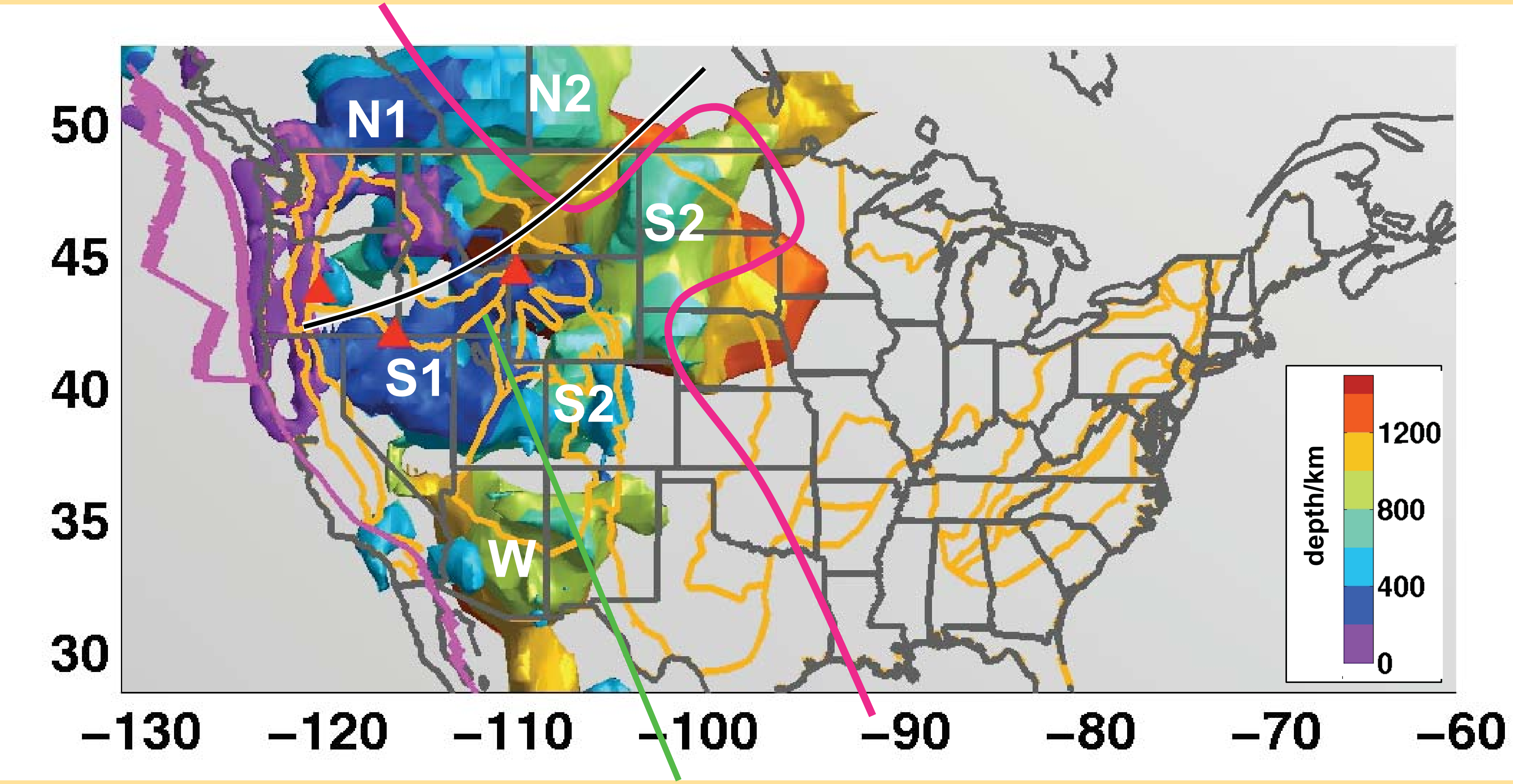


Farallon stuck in TZ



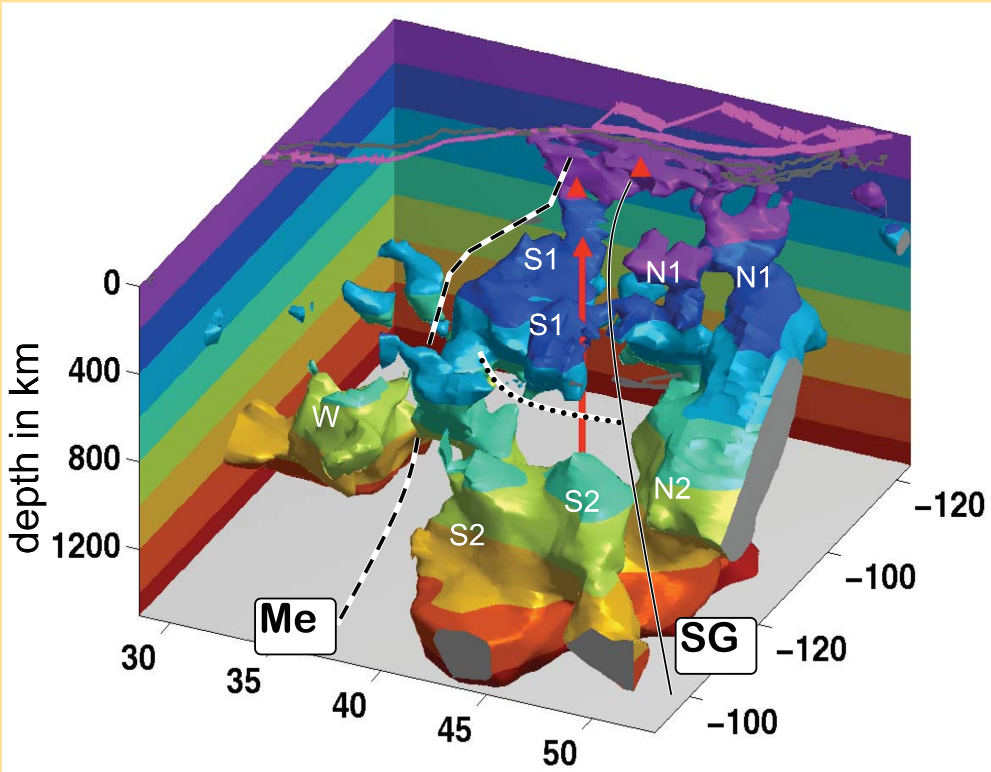
Sigloch et al., Nature Geosci., 2008

Slabs do not go gently into that good night

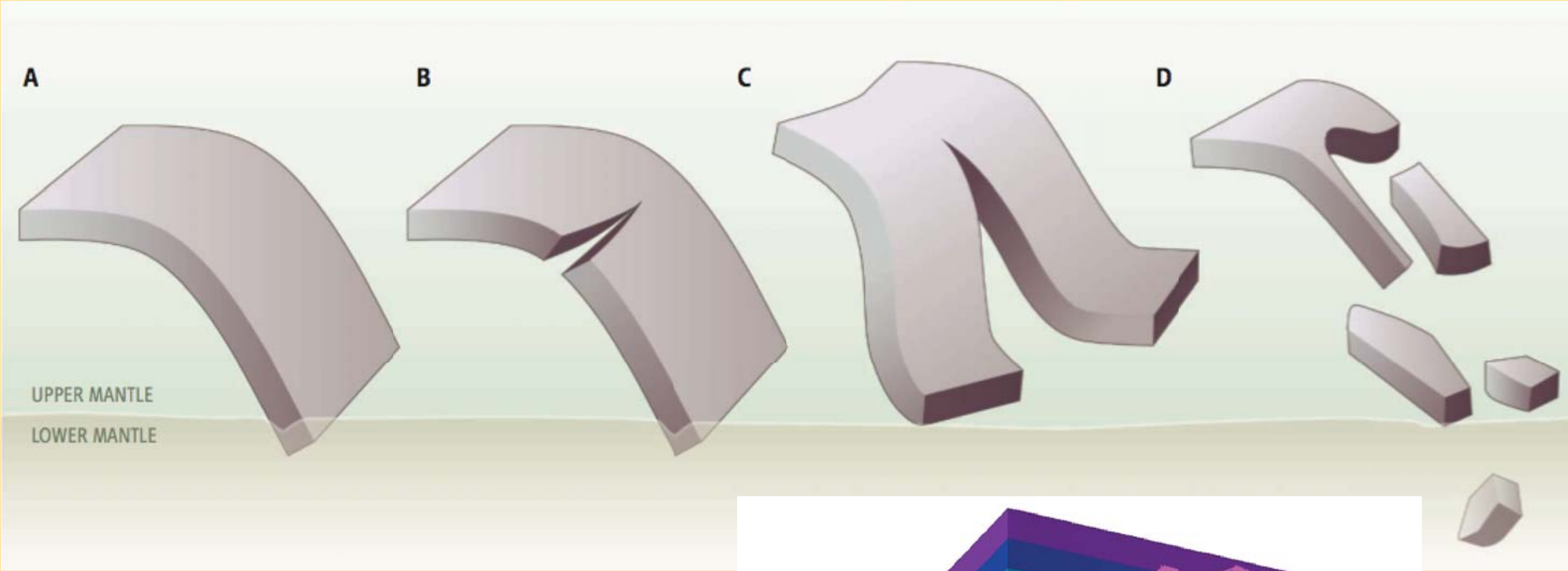


Sigloch et al., Nature Geosci., 2008

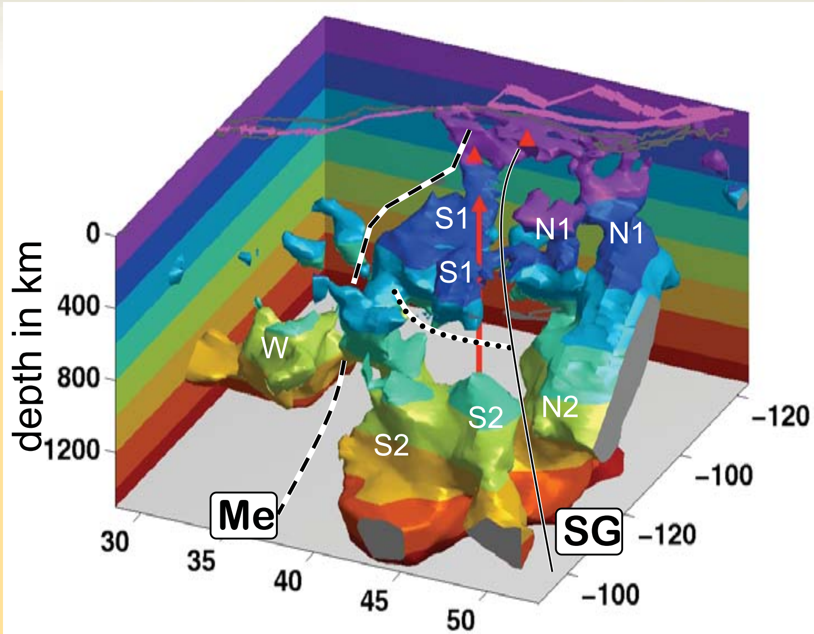
Slabs do not go gently into that good night



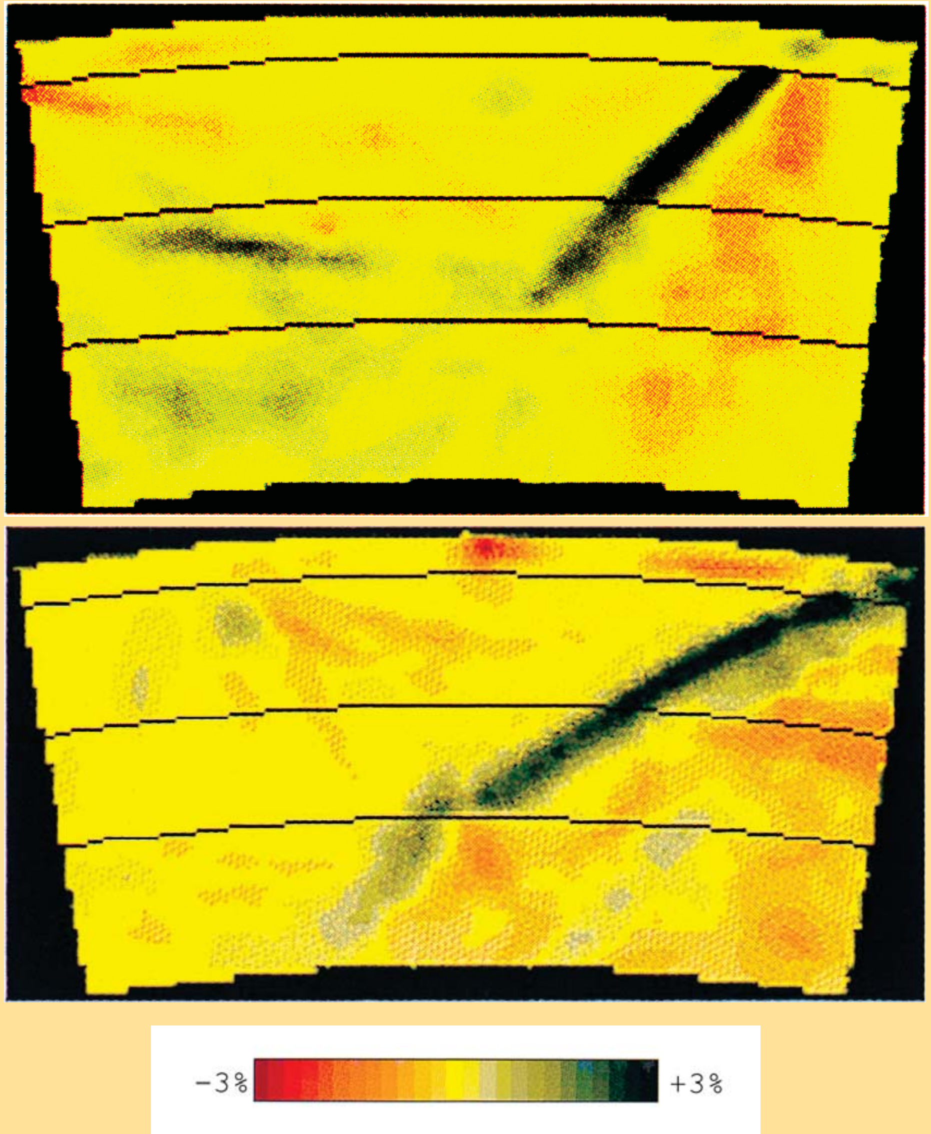
Slab tears



Nolet, Science 2009

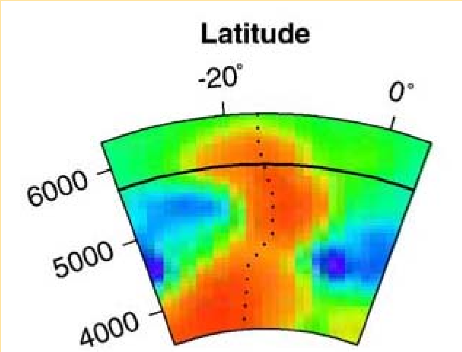


return flow across a TBL?

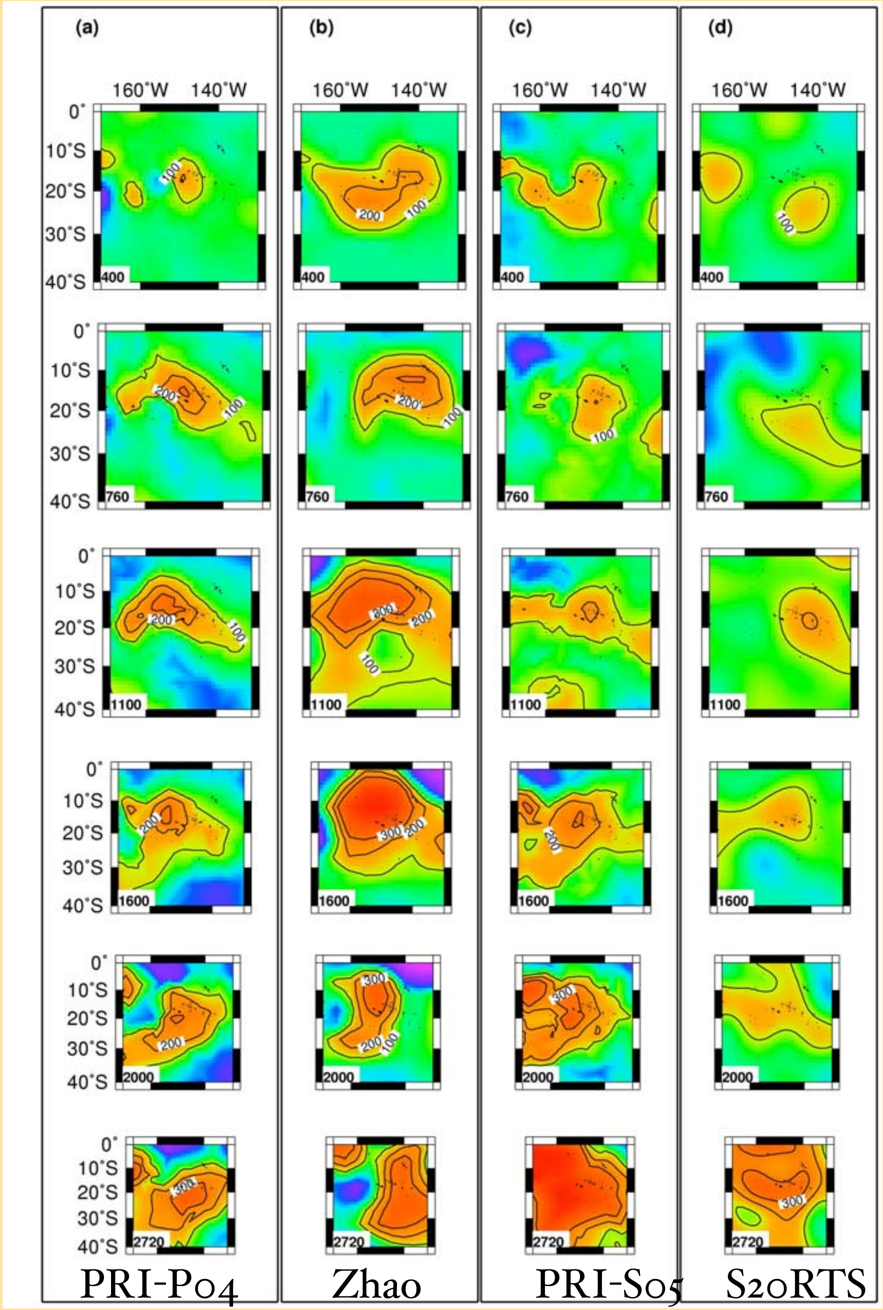


Tonga-Kermadec
(Deal et al., 1999)

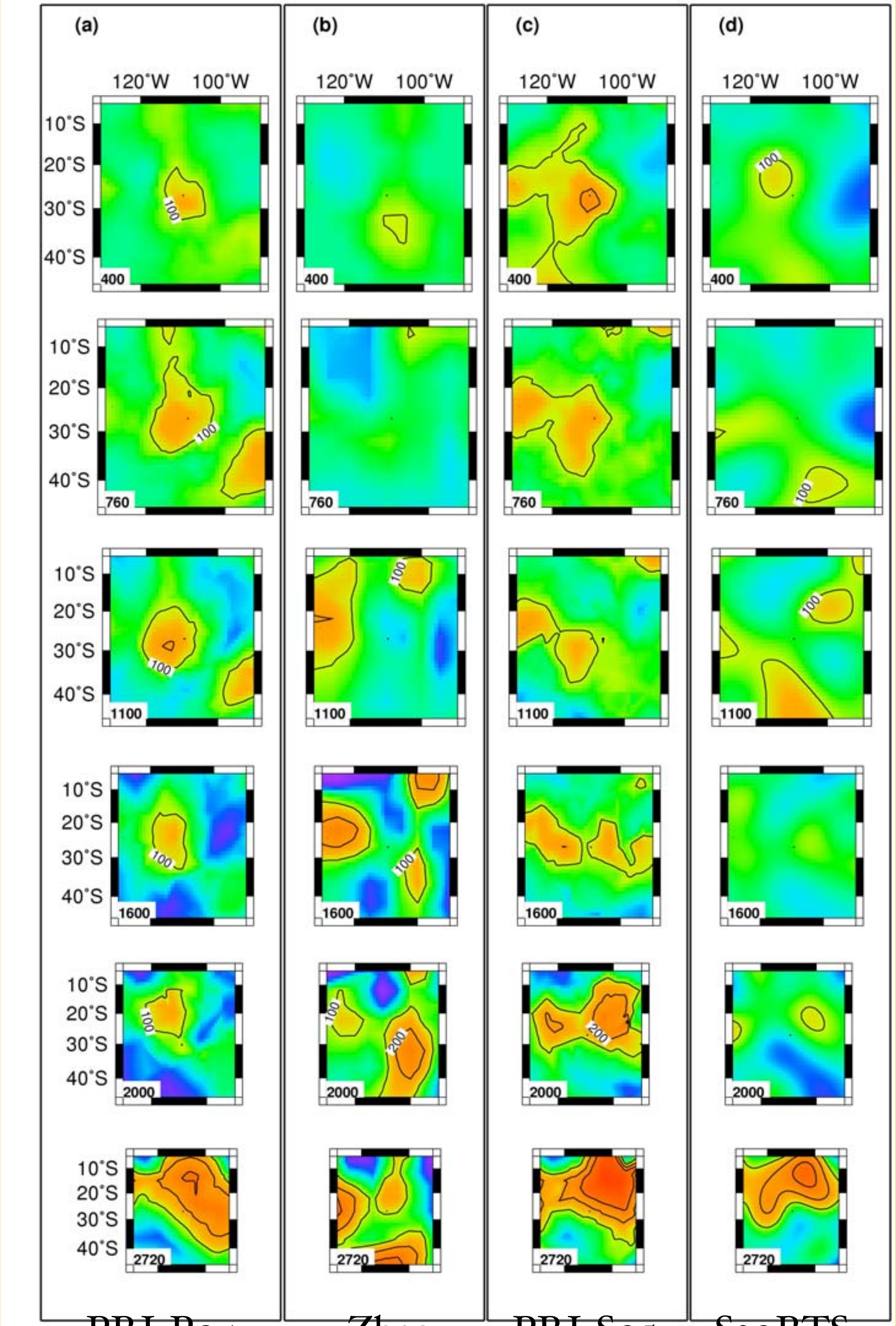
Japan 42° N
(Deal & Nolet, 1999)



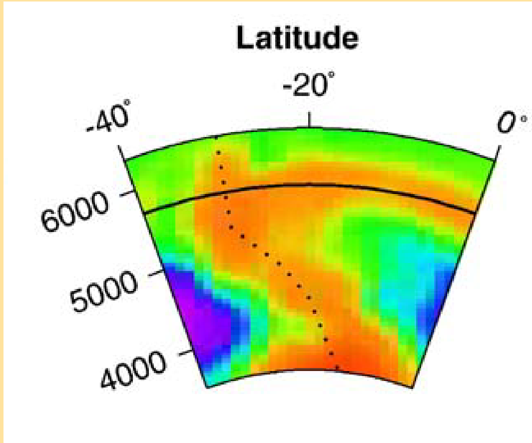
Tahiti
(Society Isl)



ΔV_P and ΔV_S converted to ΔT (K)



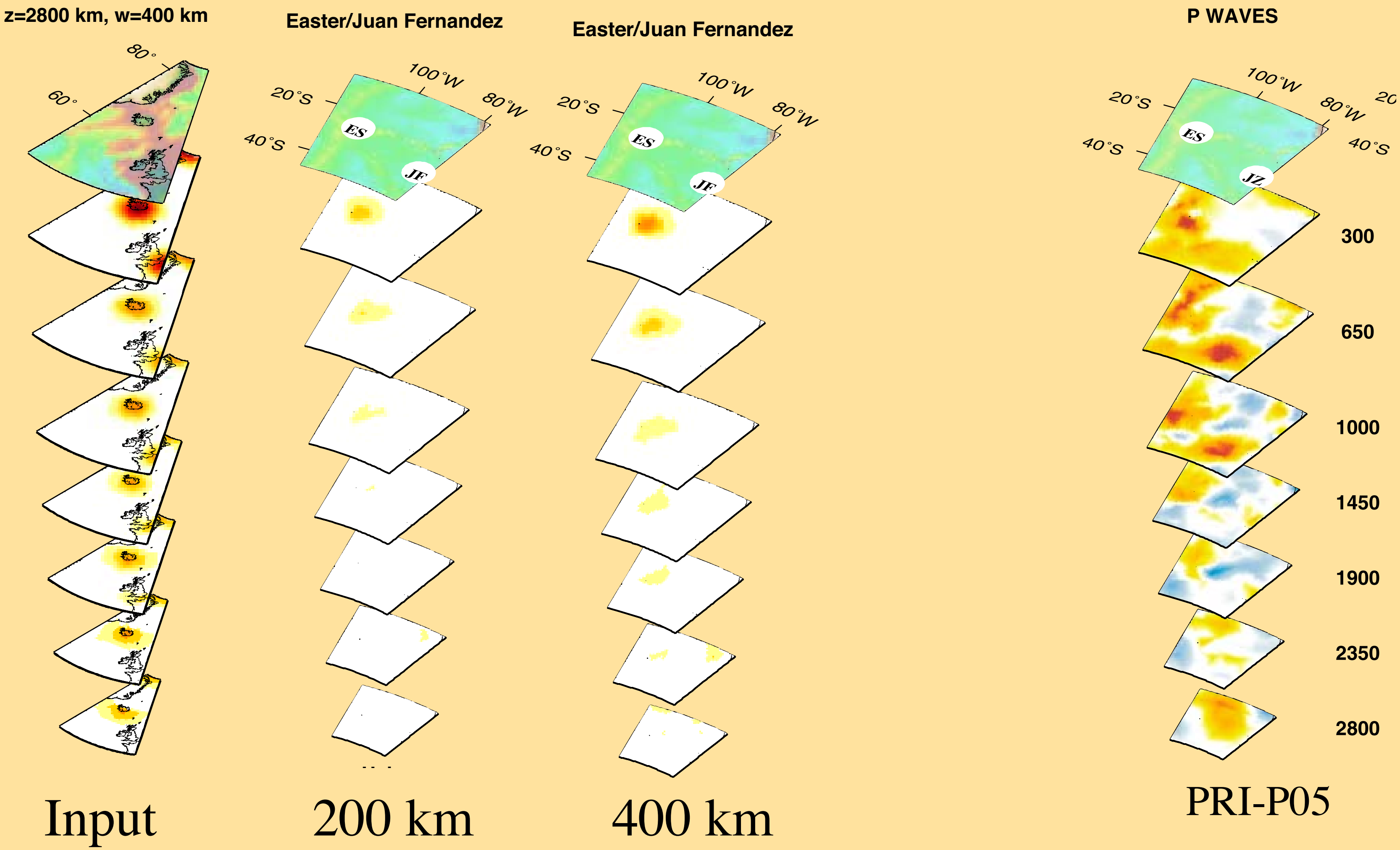
PRI-P04 Zhao PRI-S05 S20RTS



Easter island

ΔV_P and ΔV_S converted to ΔT (K)

Thin plumes are not resolved

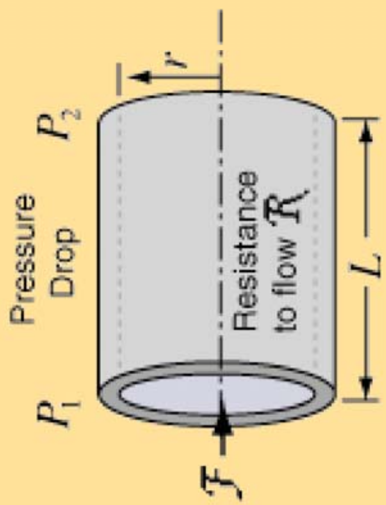


Plumes are larger than we thought

- Buoyancy flux indicates weak plume flux
- Early estimates limit plume flux to ~ 3 TW
- Theory predicts narrow (<100 km) plumes
- But such plumes would *not* show up
- Plume width must be *several hundred km*

Can we estimate plume flux from tomography?

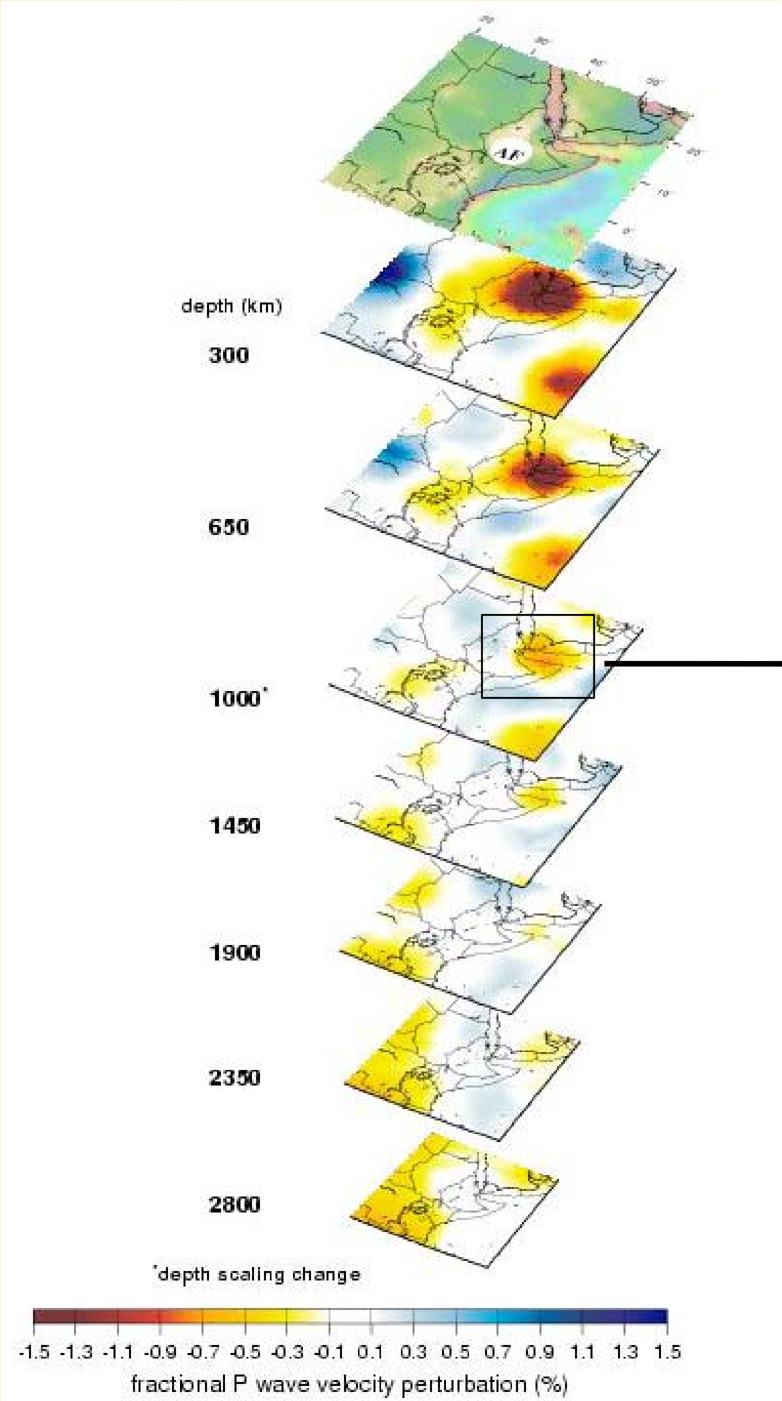
- The honest answer is: *barely*
- But even a simplified treatment leads to surprising lower limits in plume flux



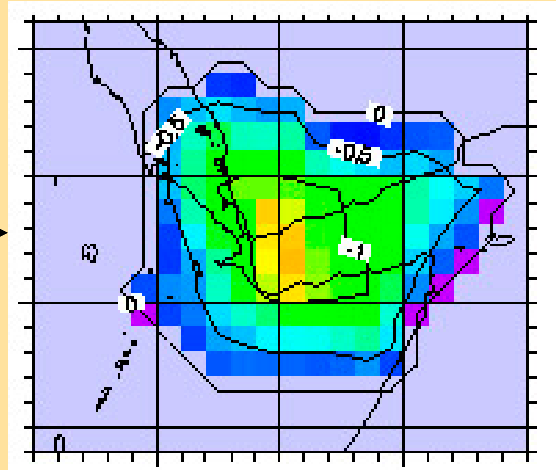
face of rotation whose meridian section is a parabola. In this case we speak of a *parabolic velocity profile*. The total volume W issuing per second is obtained by taking the integral $\int \mathbf{v}\, d\mathbf{S}$ over a cross-section. In this case we have

$$W = \int_0^a \frac{p_1 - p_0}{4\eta l}(a^2 - r^2)\, 2\pi r\, dr = \frac{\pi(p_1 - p_0)a^4}{8\eta l}. \qquad (74)$$

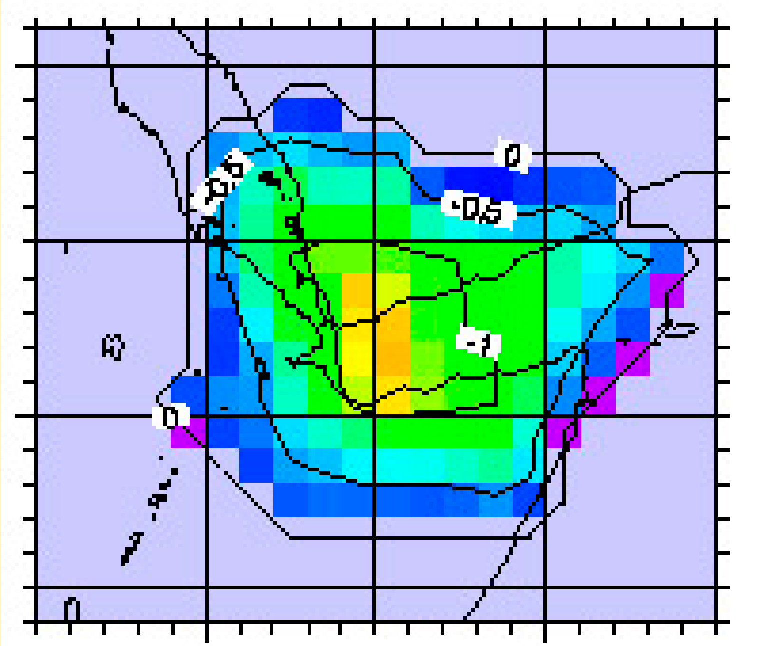
This is **Poiseuille's Formula**, which states that the quantity of fluid issuing each second is directly proportional to the pressure difference and to the fourth power of the radius of the tube, and inversely pro-

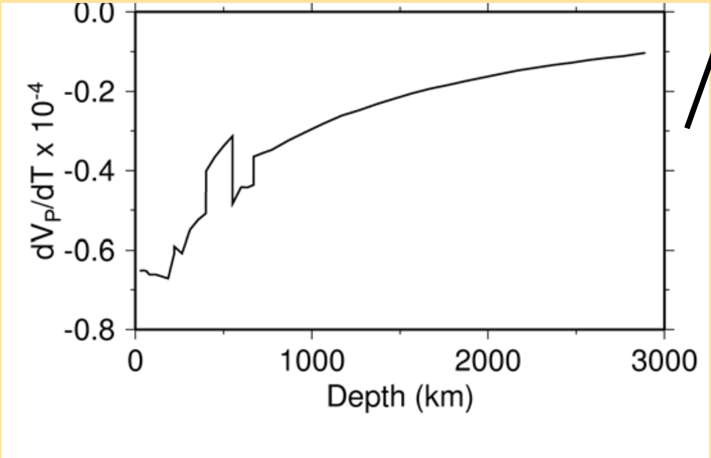


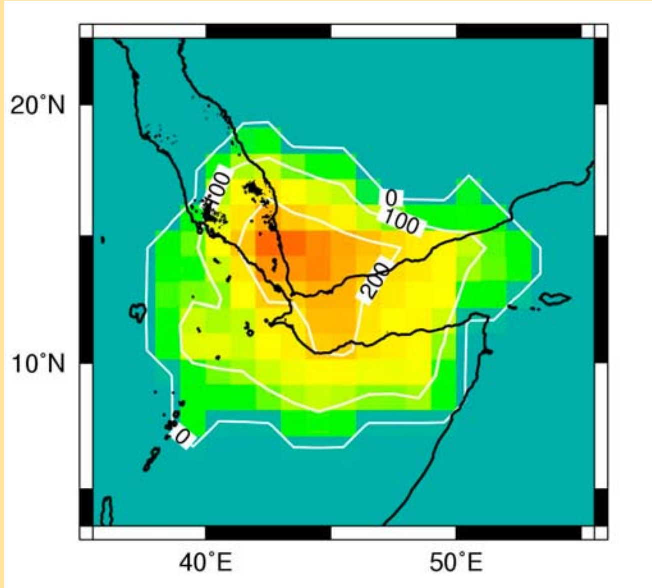
The method, step 1:
isolate a depth section from the 3D model of ΔVp/Vp



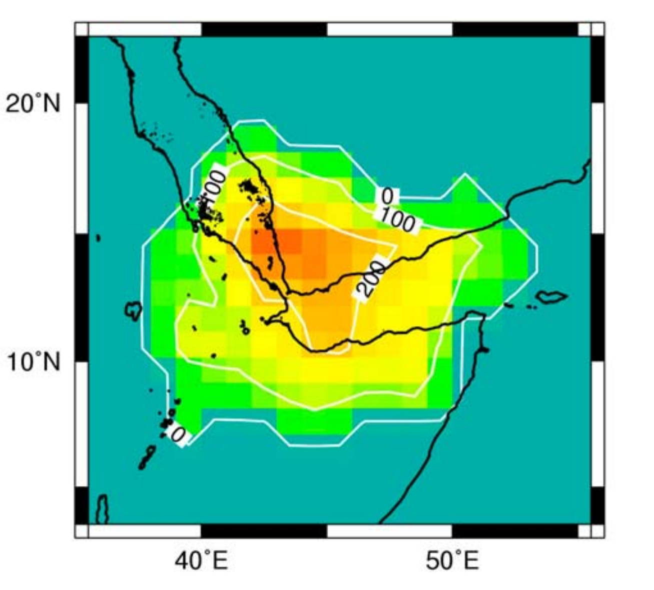
step 2: from V_P anomaly to Temperature anomaly

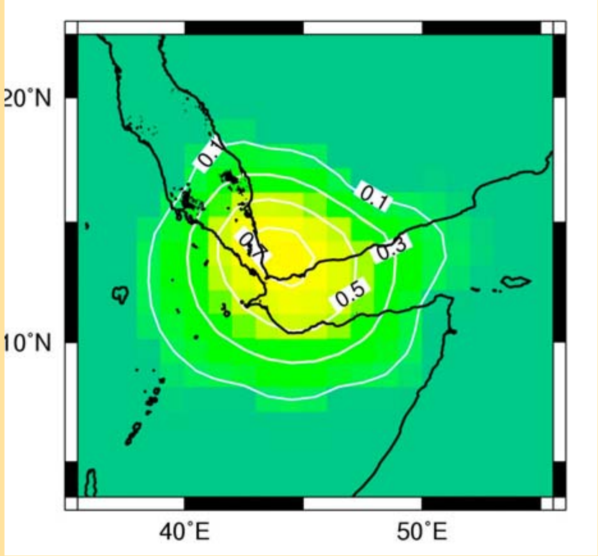






3: from Temperature anomaly to Rise velocity

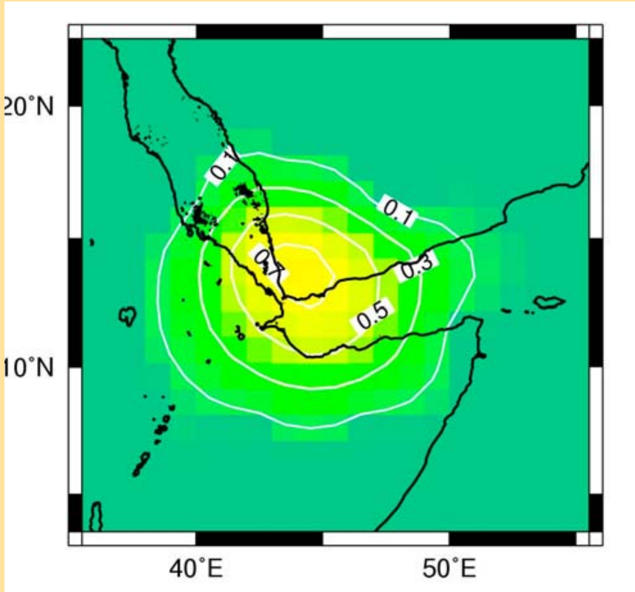


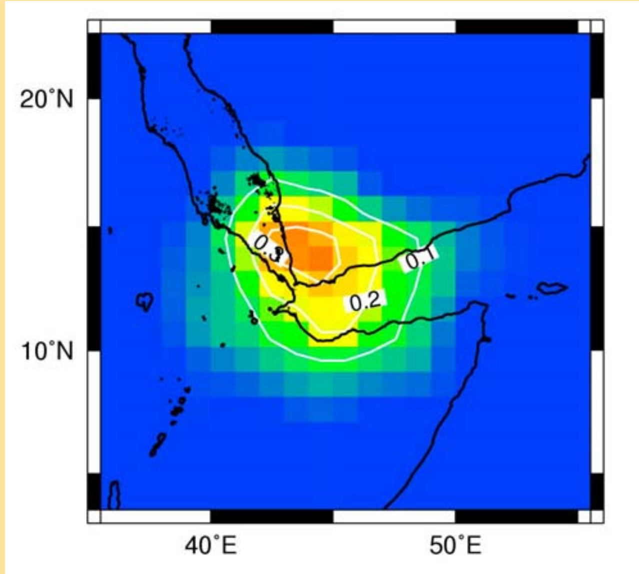


$$\eta \nabla^2 v_z = -\alpha \rho g \Delta T + g \Delta \rho_{Fe}$$

$$\eta = \eta_R \exp\left(\frac{\beta T_m}{T}\right)$$

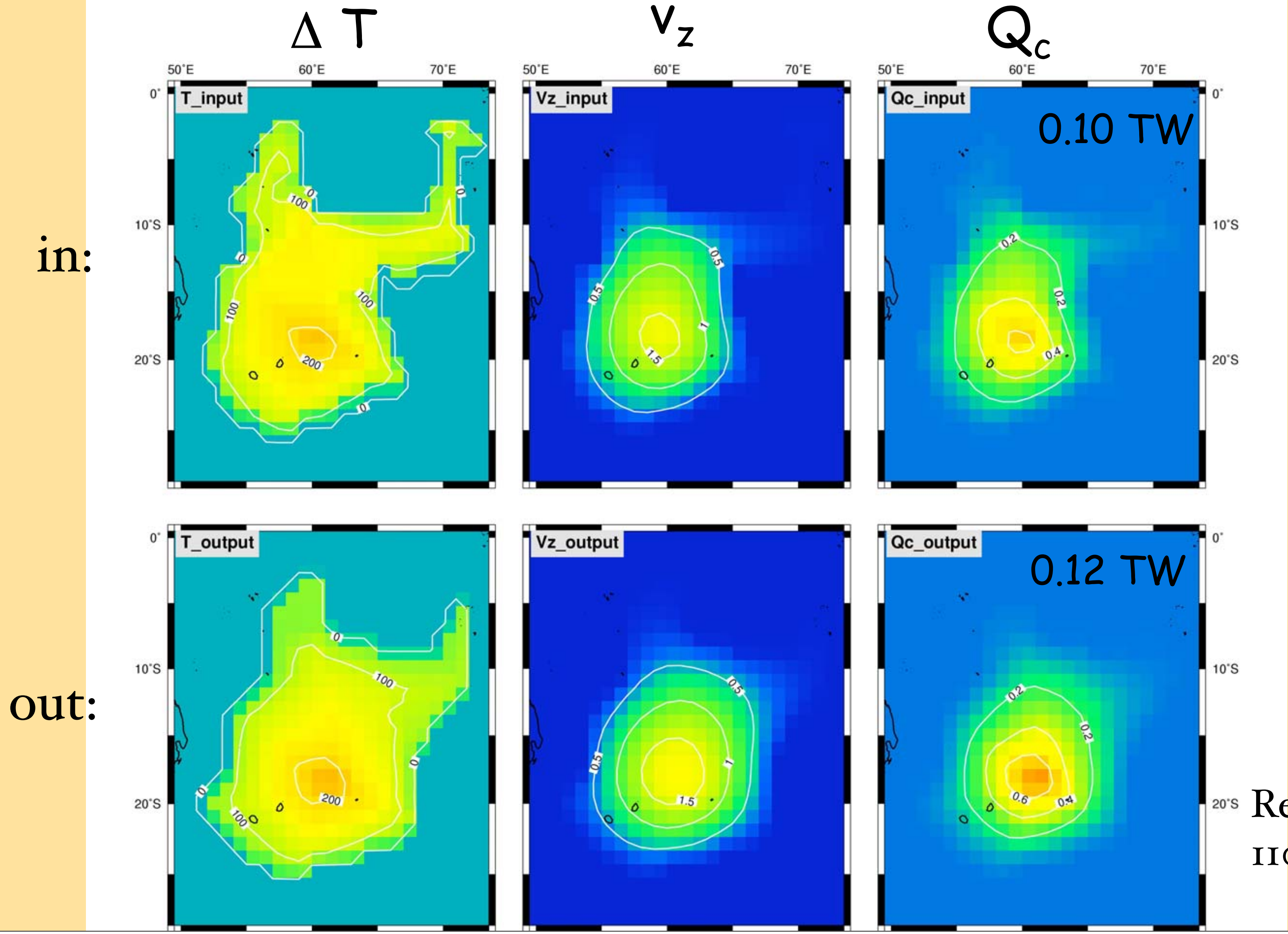
4: from rise velocity to Heat flux





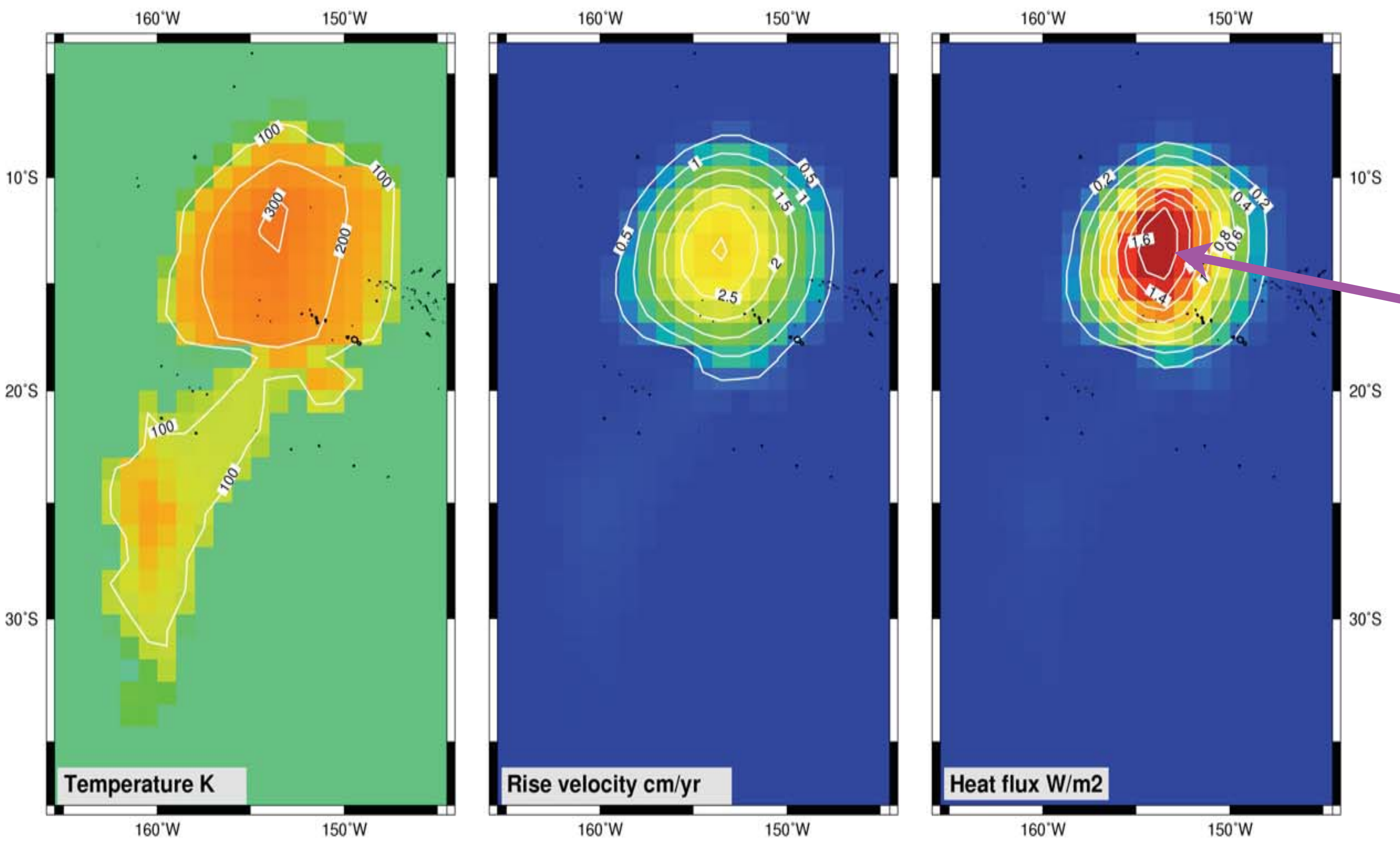
$$Q_c = c_P \ \rho \Delta T \ v_z$$

Sensitivity test: how good is the estimate?



Reunion
1100 km

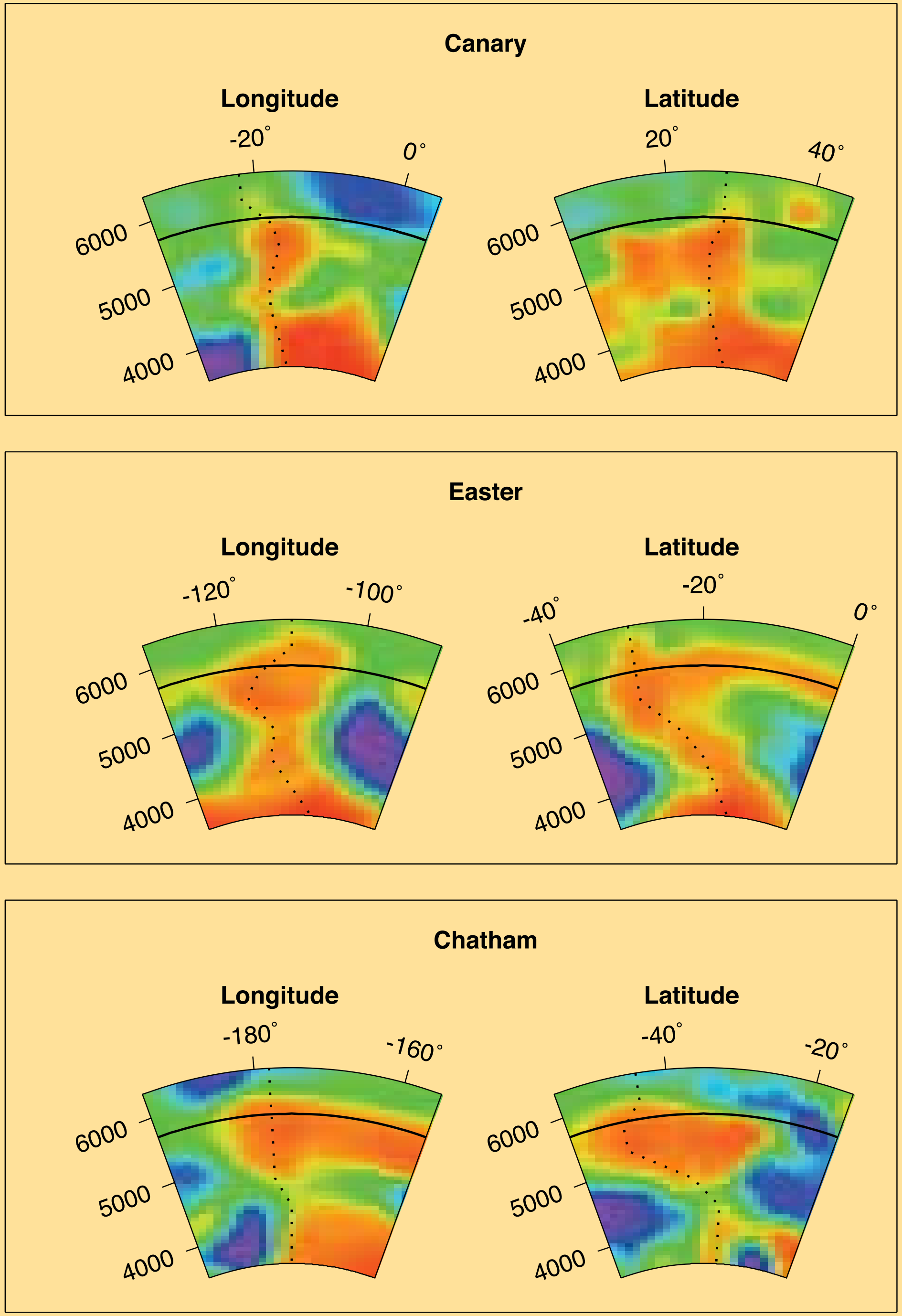
Plumes are larger than we thought



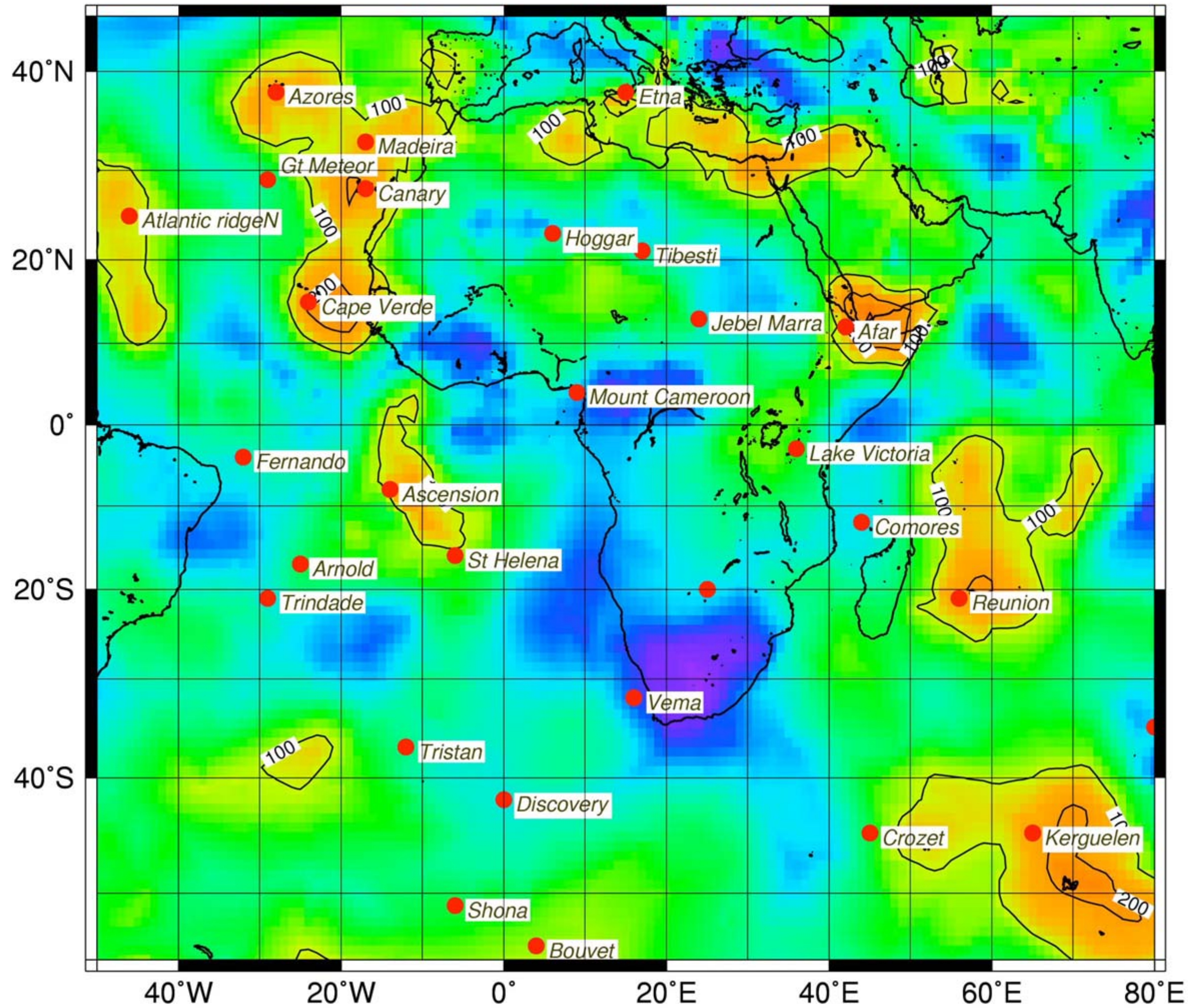
Total flux 0.5 TW

Tahiti plume at 1600 km depth (Nolet, EPSL 2006)

(Some) plumes broaden below 660 km depth

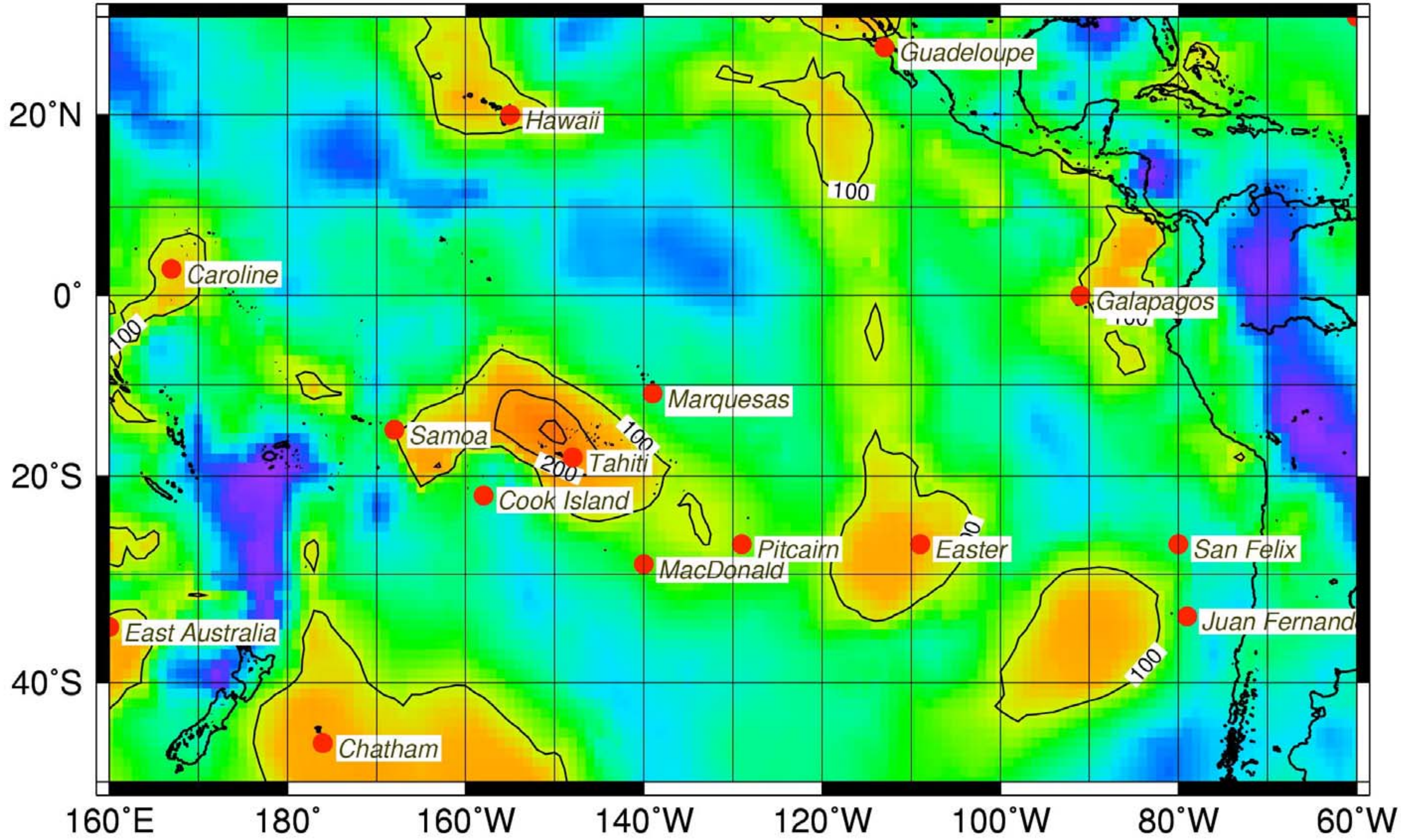


Nolet et al., 2006



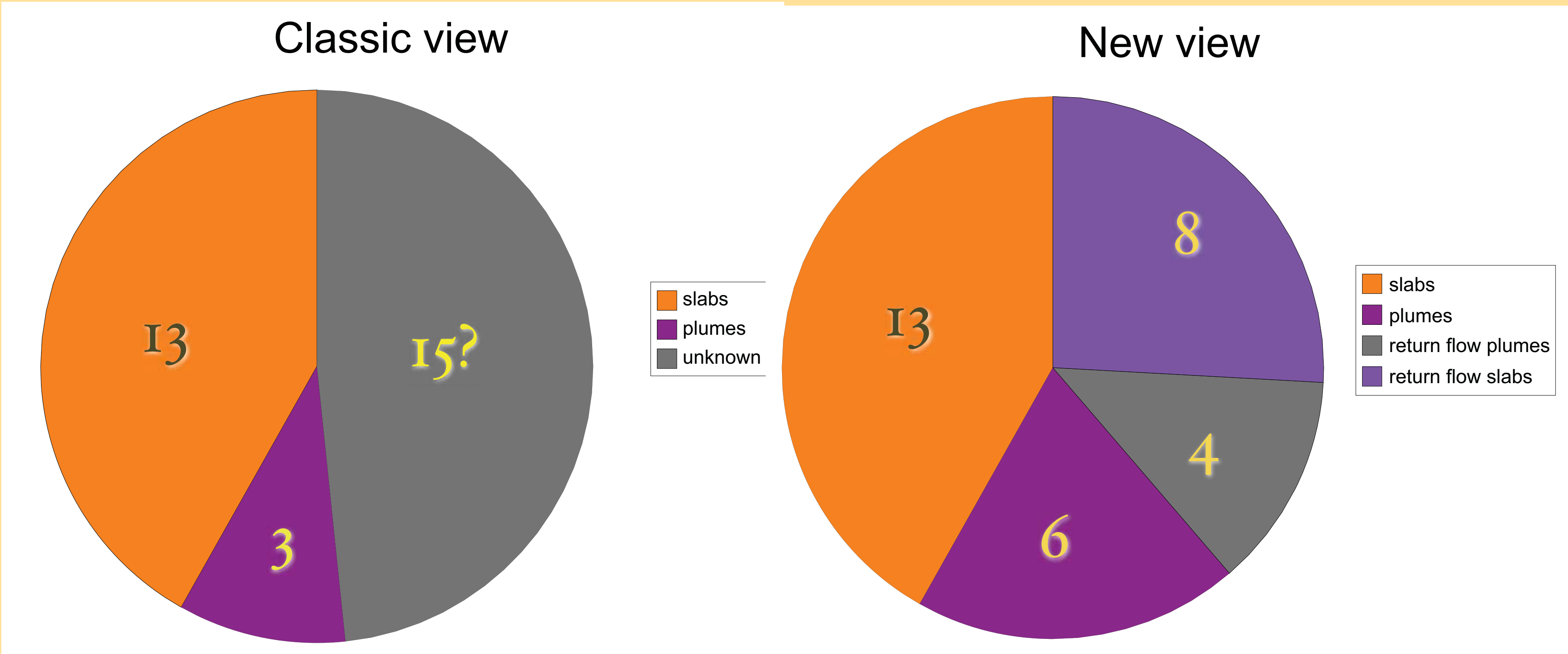
40°N
20°N
0°
20°S
40°S
40°W
20°W
0°
20°E
40°E
60°E
80°E
Azores
Madeira
Gt Meteor
Canary
Atlantic ridgeN
Cape Verde
Etna
Hoggar
Tibesti
Jebel Marra
Afar
Mount Cameroon
Lake Victoria
Fernando
Ascension
Comores
Arnold
St Helena
Trindade
Reunion
Vema
Tristan
Discovery
Crozet
Kerguelen
Shona
Bouvet
100
200

ΔT (K)
at 800 km

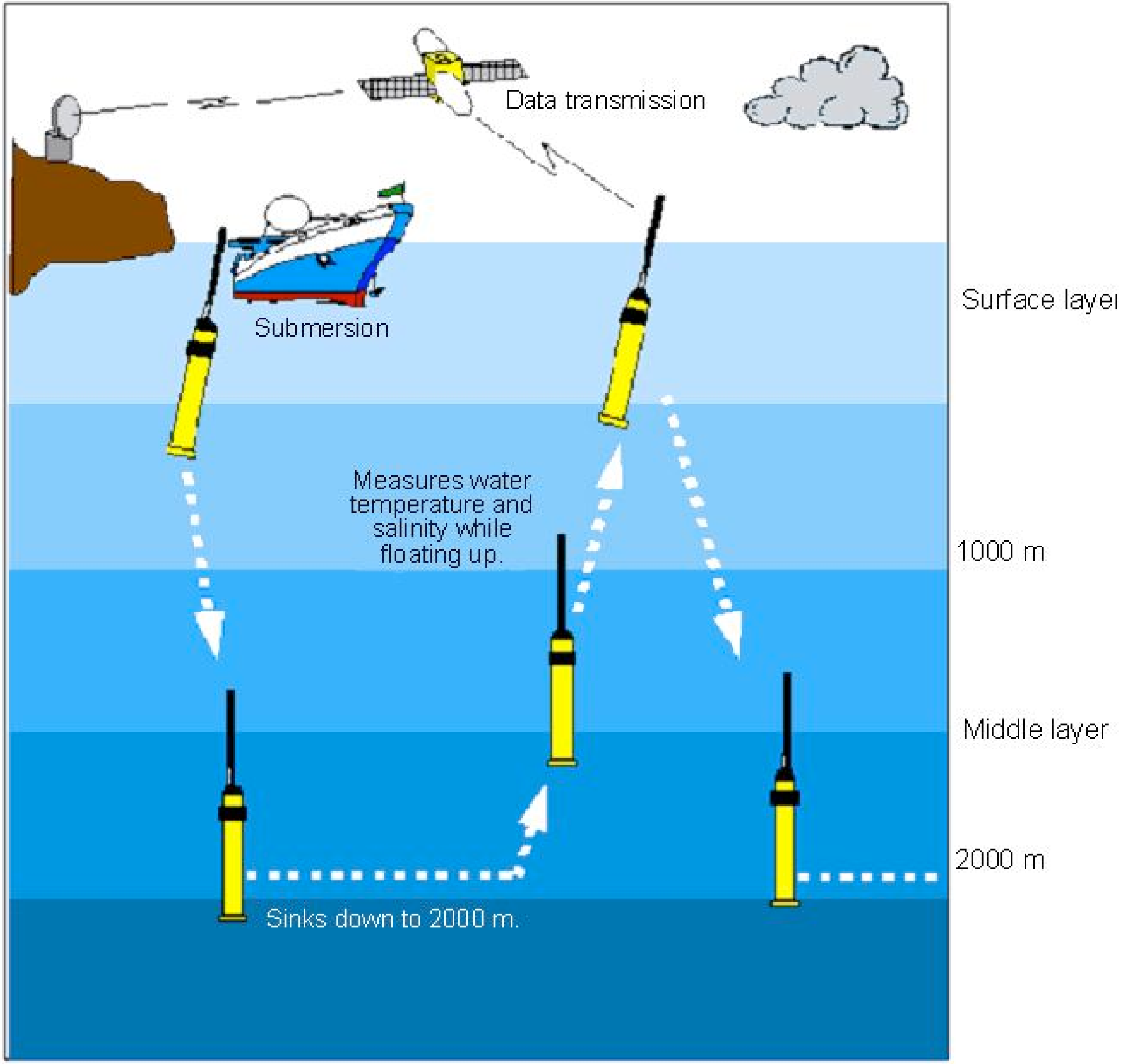


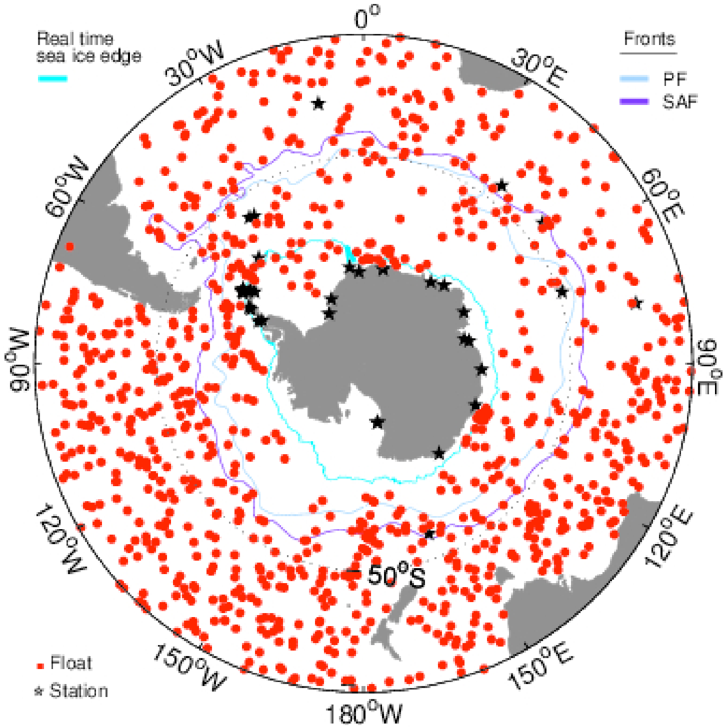
Inferred ΔT (K) from ΔV_P at 800 km depth

31 TW across 660 ?



ARGO floats

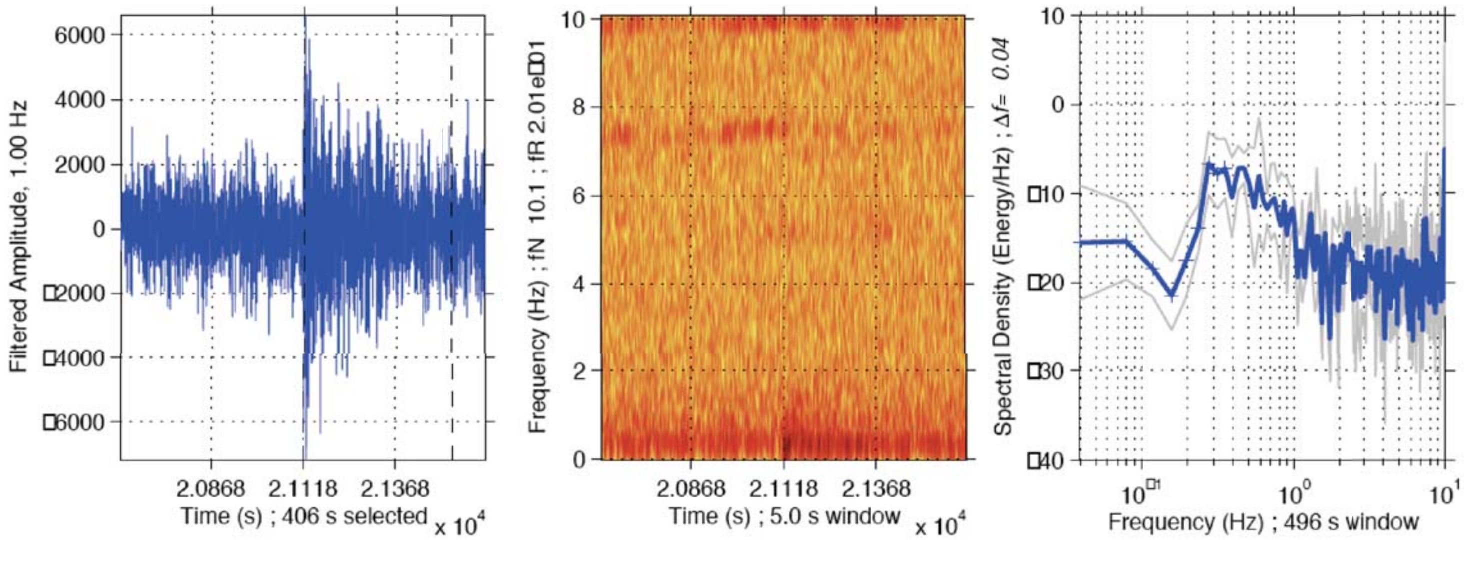

Data transmission
Submersion
Surface layer
Measures water temperature and salinity while floating up.
1000 m
Middle layer
2000 m
Sinks down to 2000 m.



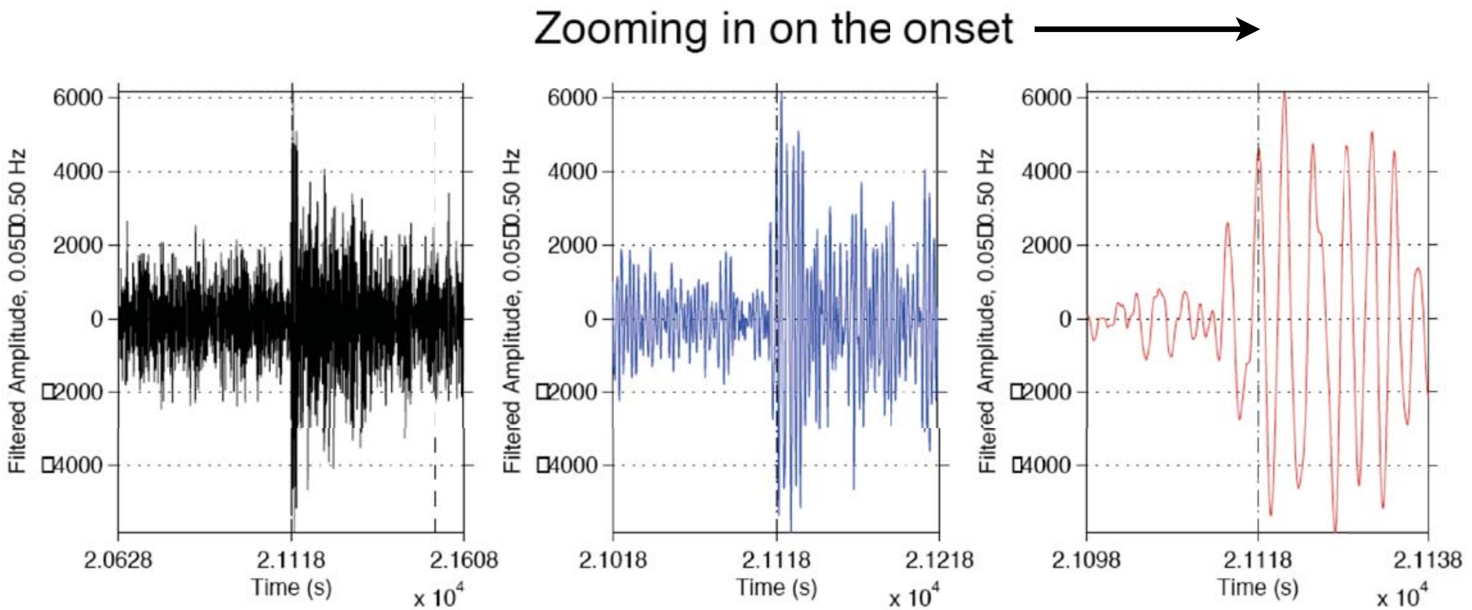
Float Positions: 02–Apr–2008

Frederik Simons (pers. comm.)

Near West Coast of Colombia Mw 5.95 at 46.5°



Frederik Simons (pers. comm.)



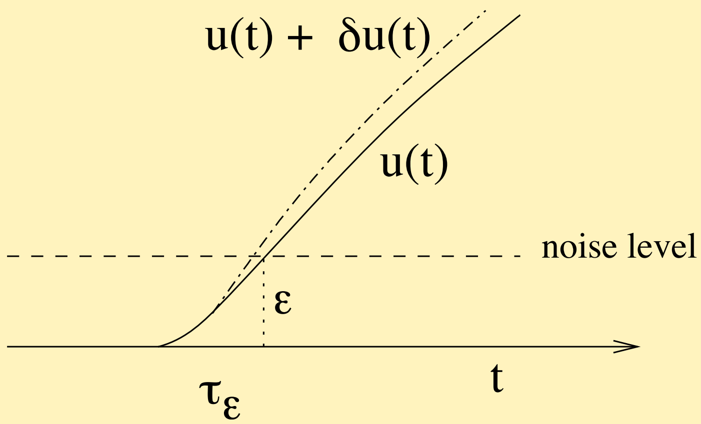
Frederik Simons (pers. comm.)

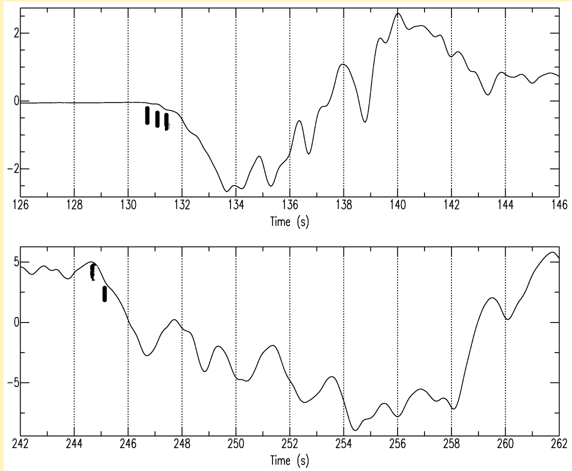
Conclusion

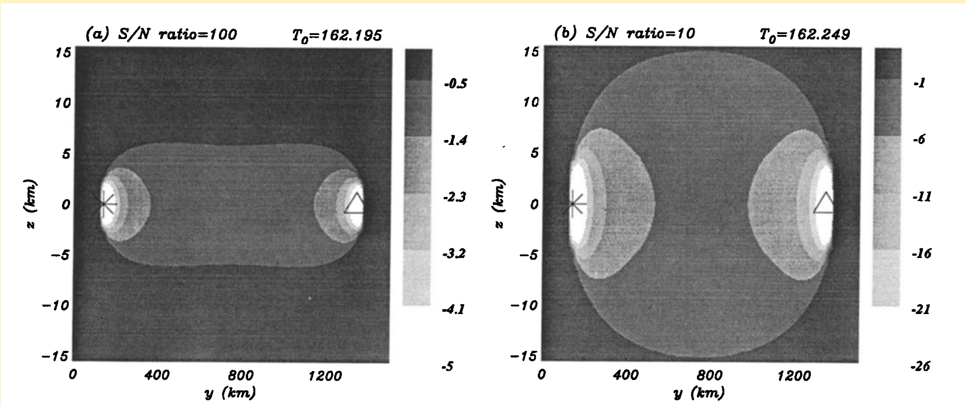
- Slabs stalling at 660,
- Plumes widening below 660,
- Plume flux too large in lower mantle,
- Low velocities below the slabs,

- TOMOGRAPHIC EVIDENCE POINTS TO THE 660 BEING A THERMAL BOUNDARY LAYER
- MASS EXCHANGE: ONLY SLABS AND PLUMES

What is the sensitivity of a first break?

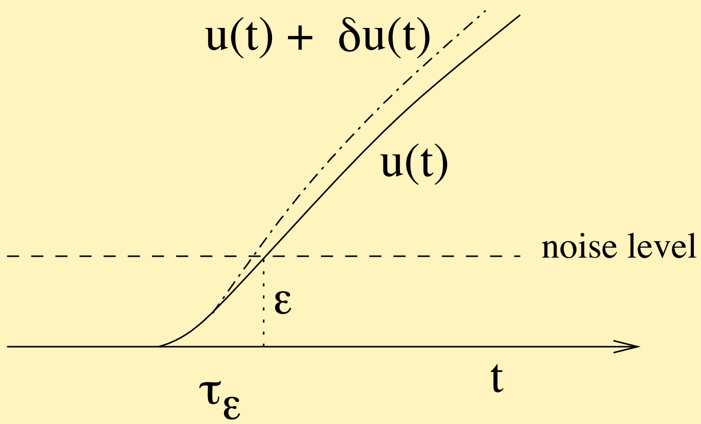


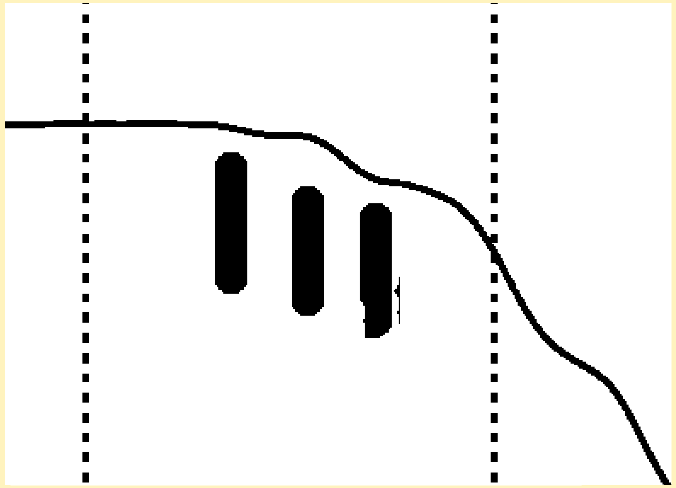


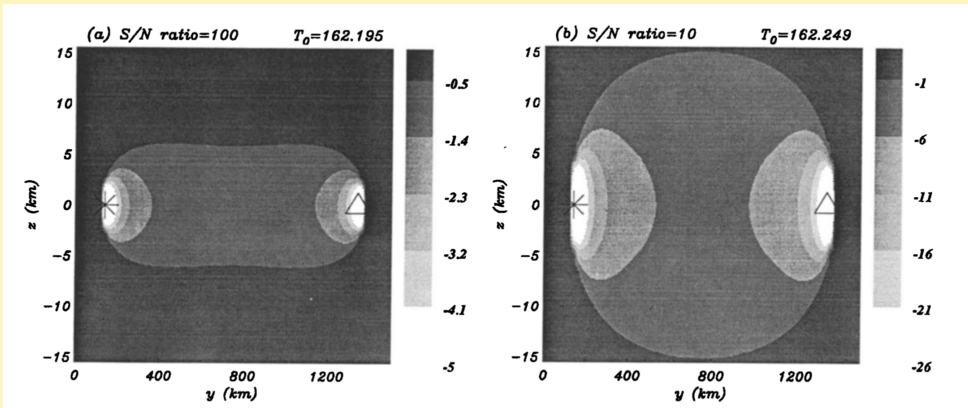


Stark & Nikolayev, JGR 1993

What is the sensitivity of a first break?

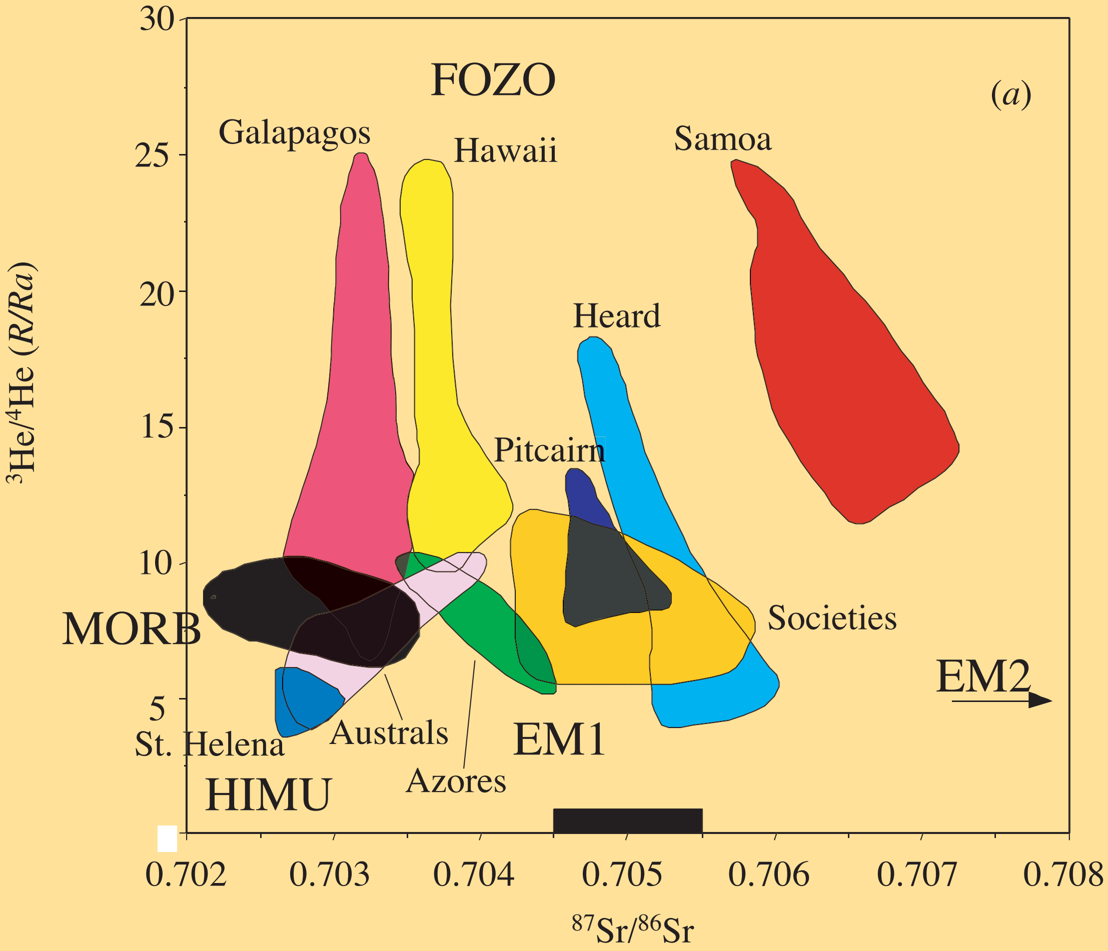




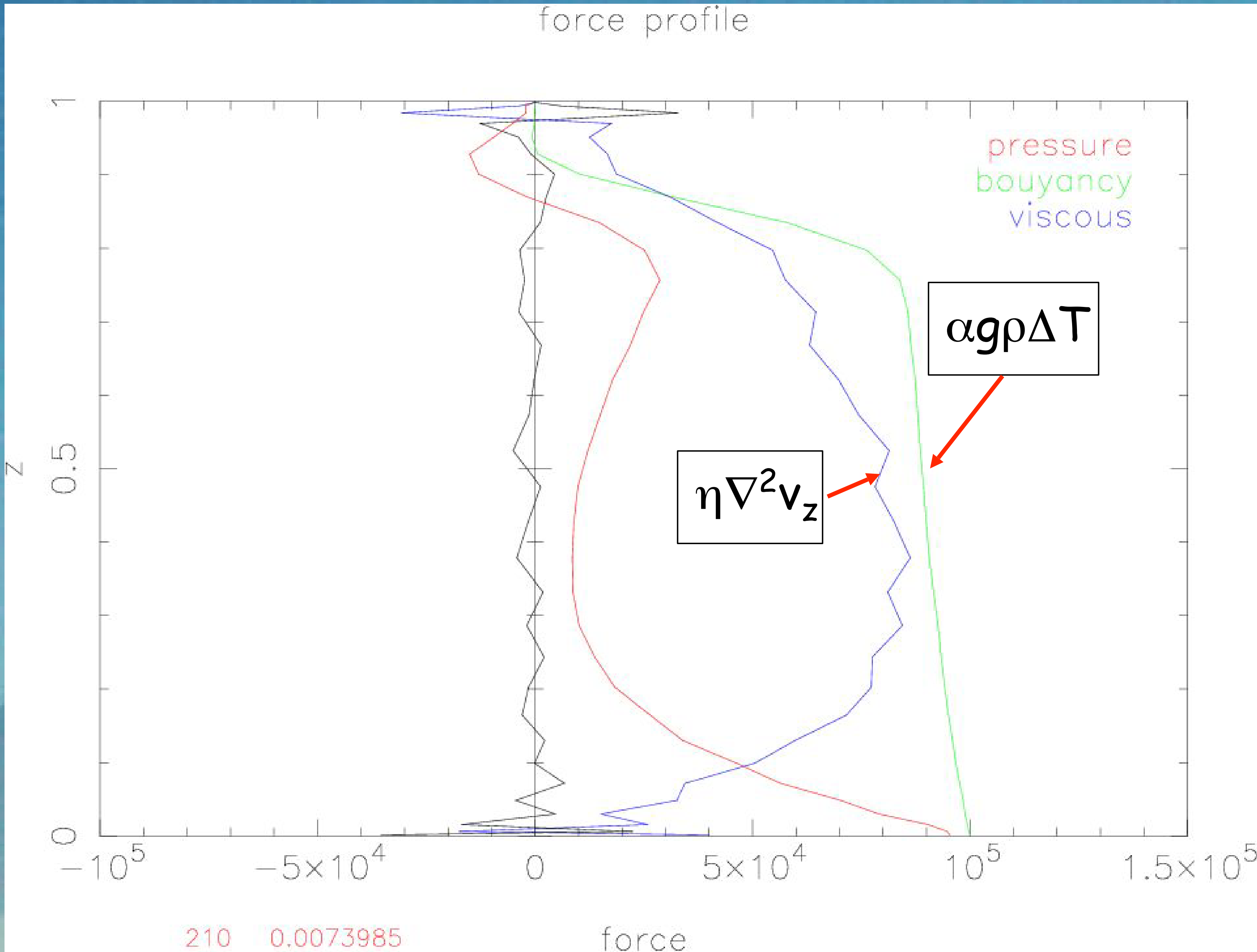


Stark & Nikolayev, JGR 1993

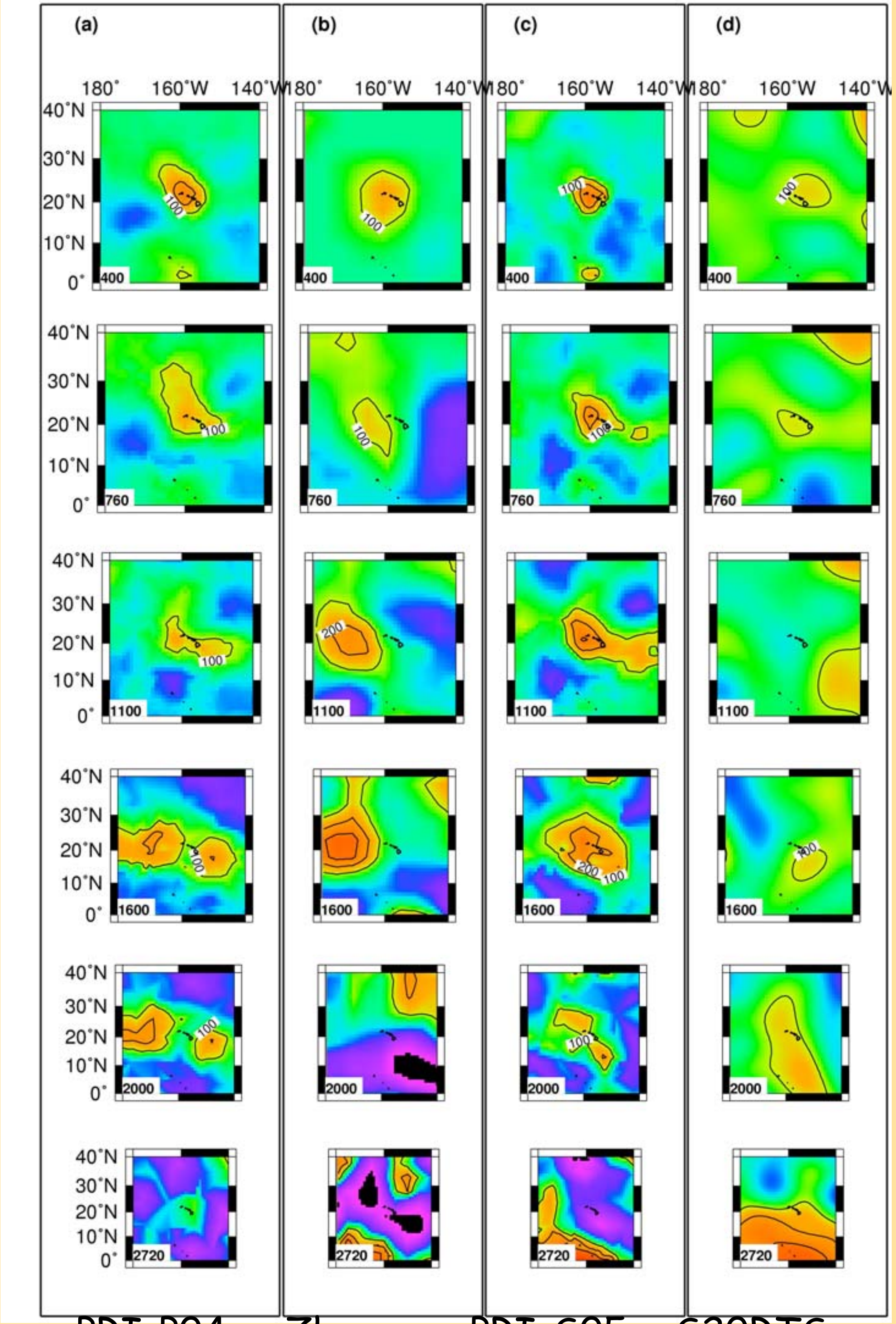
Helium and hotspots



Ballentine et al., 2002



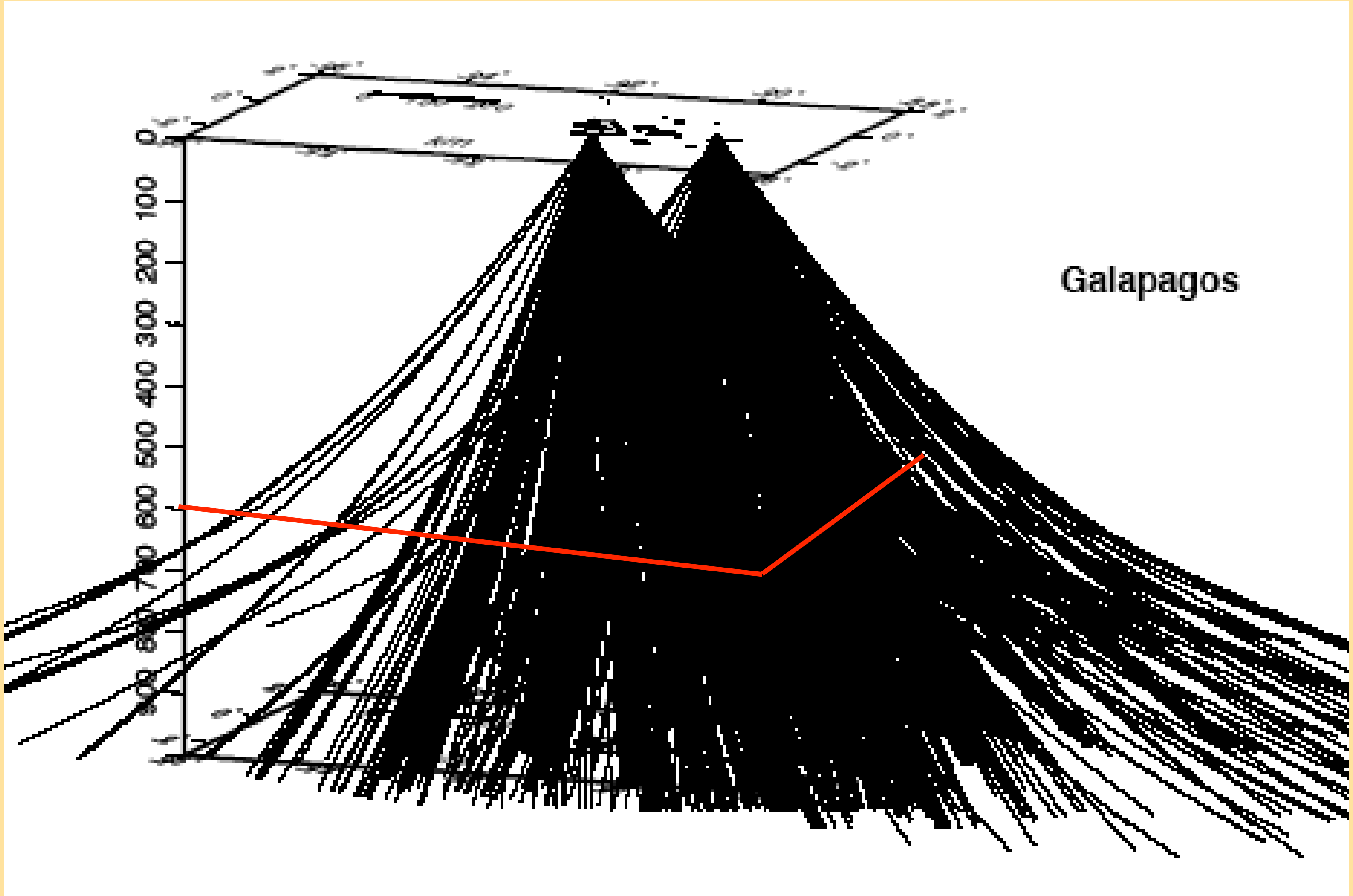
Uli Hansen (pers. comm. 2004)



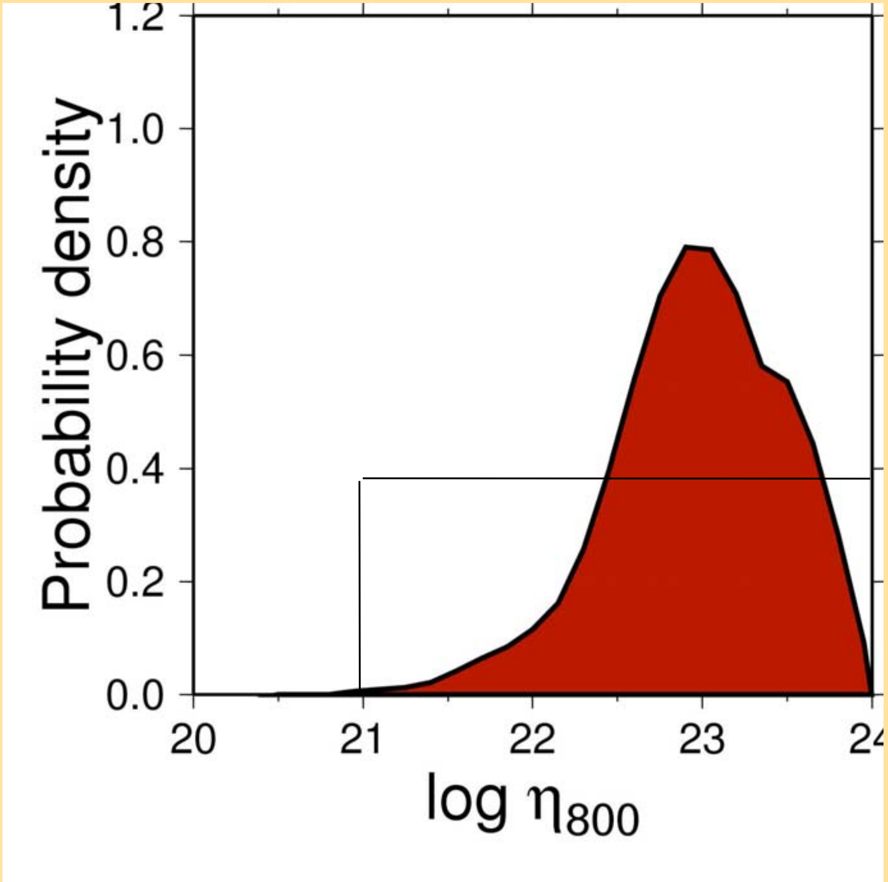
PRI-P04 Zhao PRI-S05 S20RTS

Hawaii

ΔT (K)

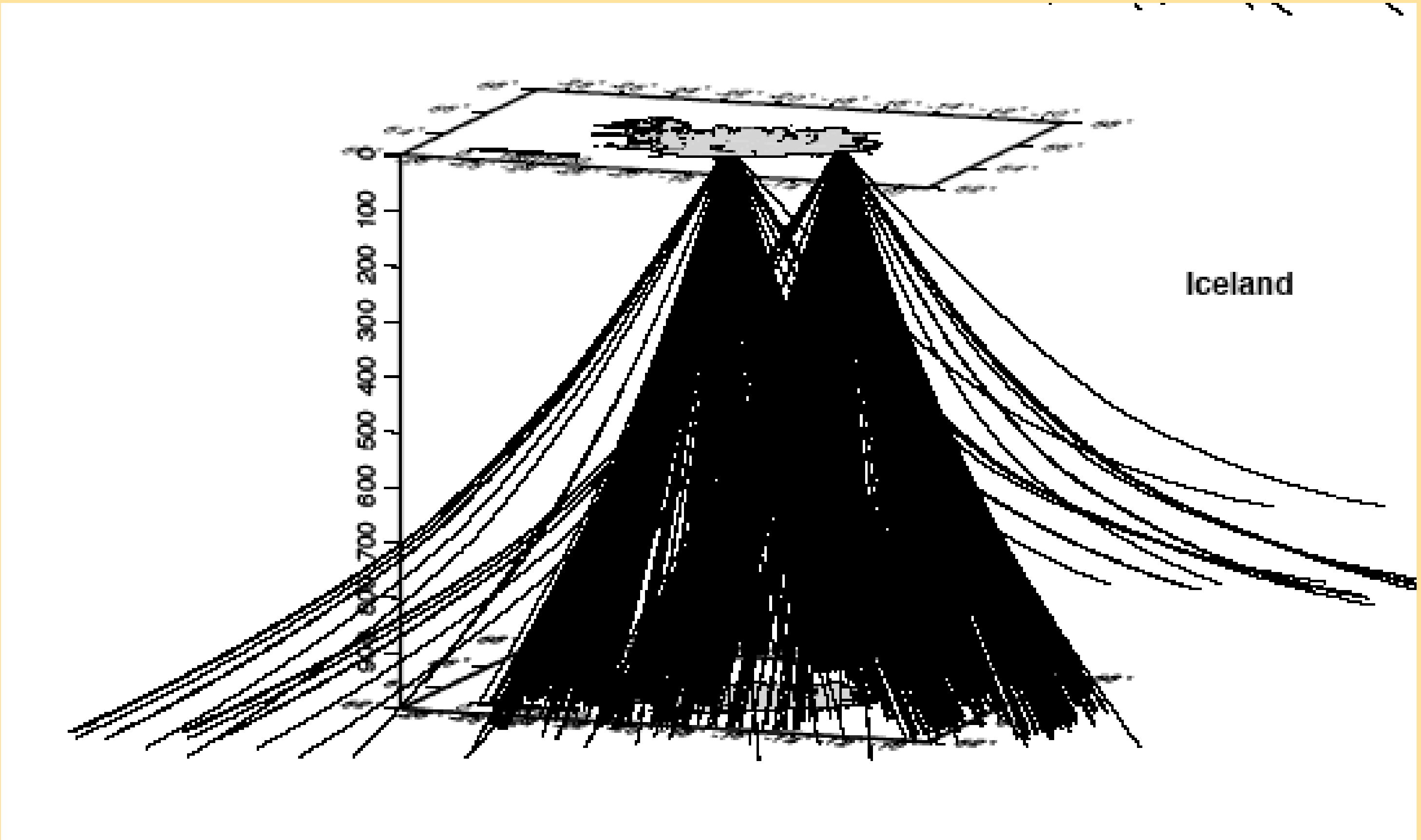


R. Allen

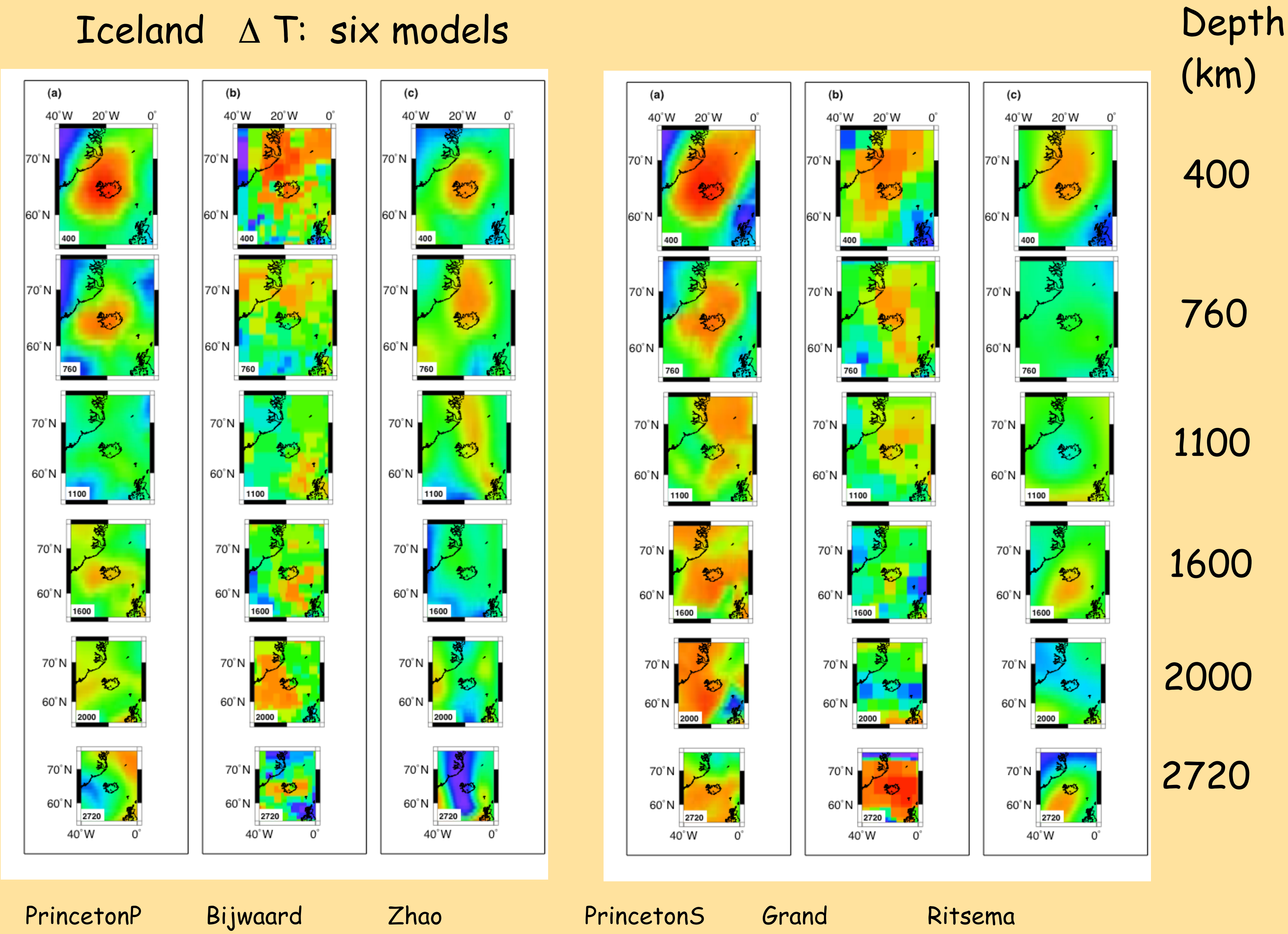


The earth likes η to be high

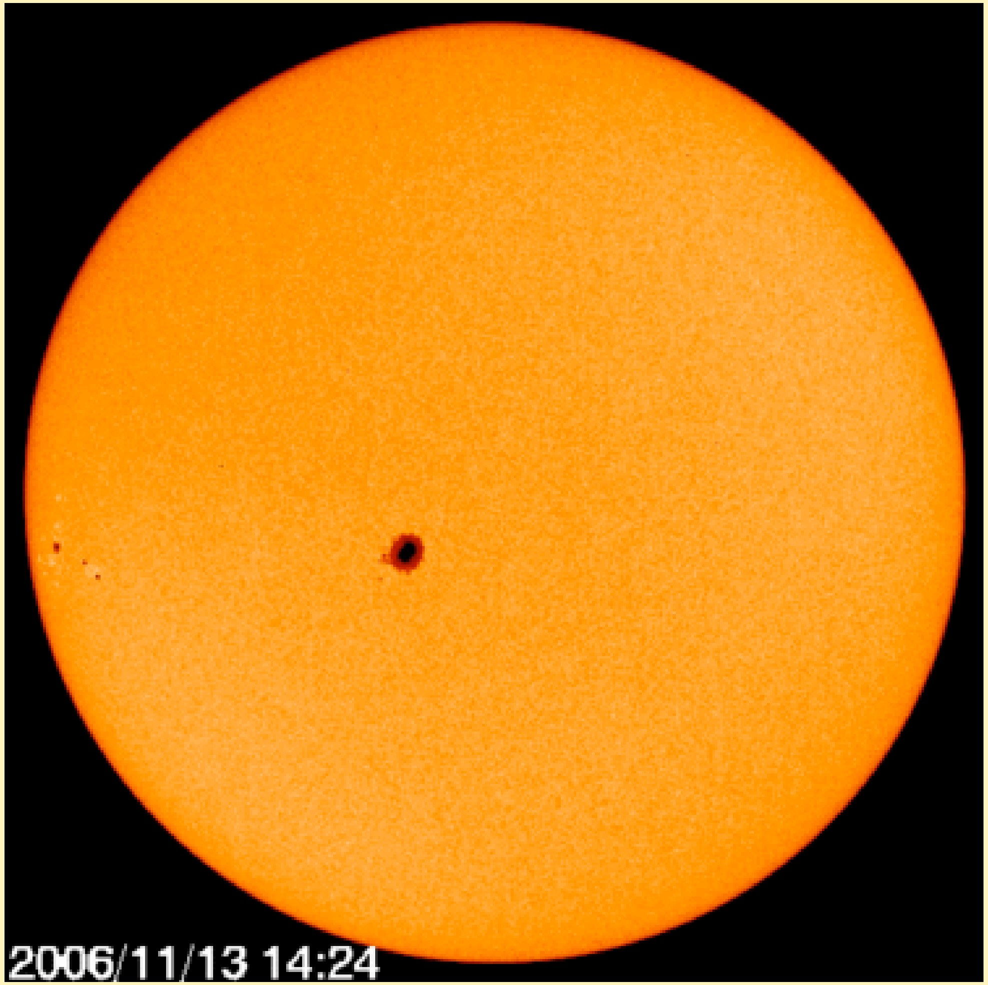
R. Allen



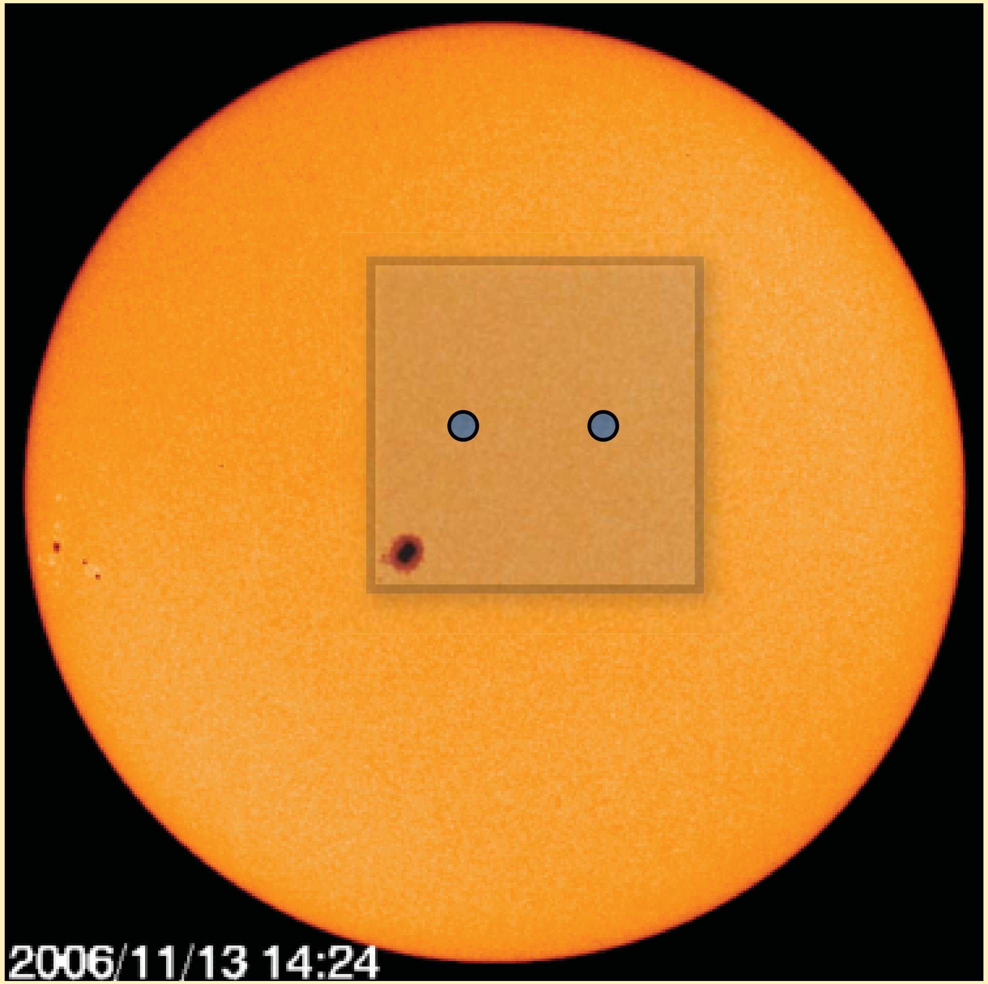
Iceland ΔT: six models



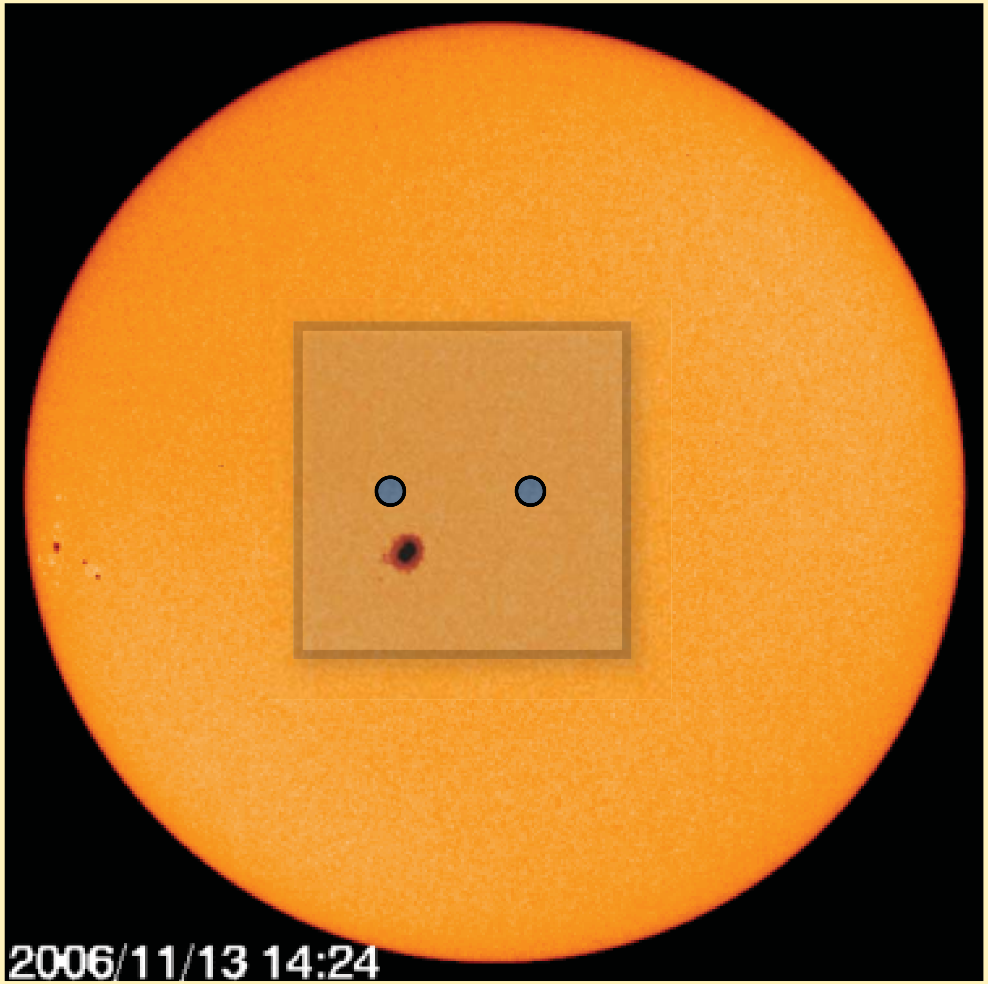
Born theory: an experimental confirmation



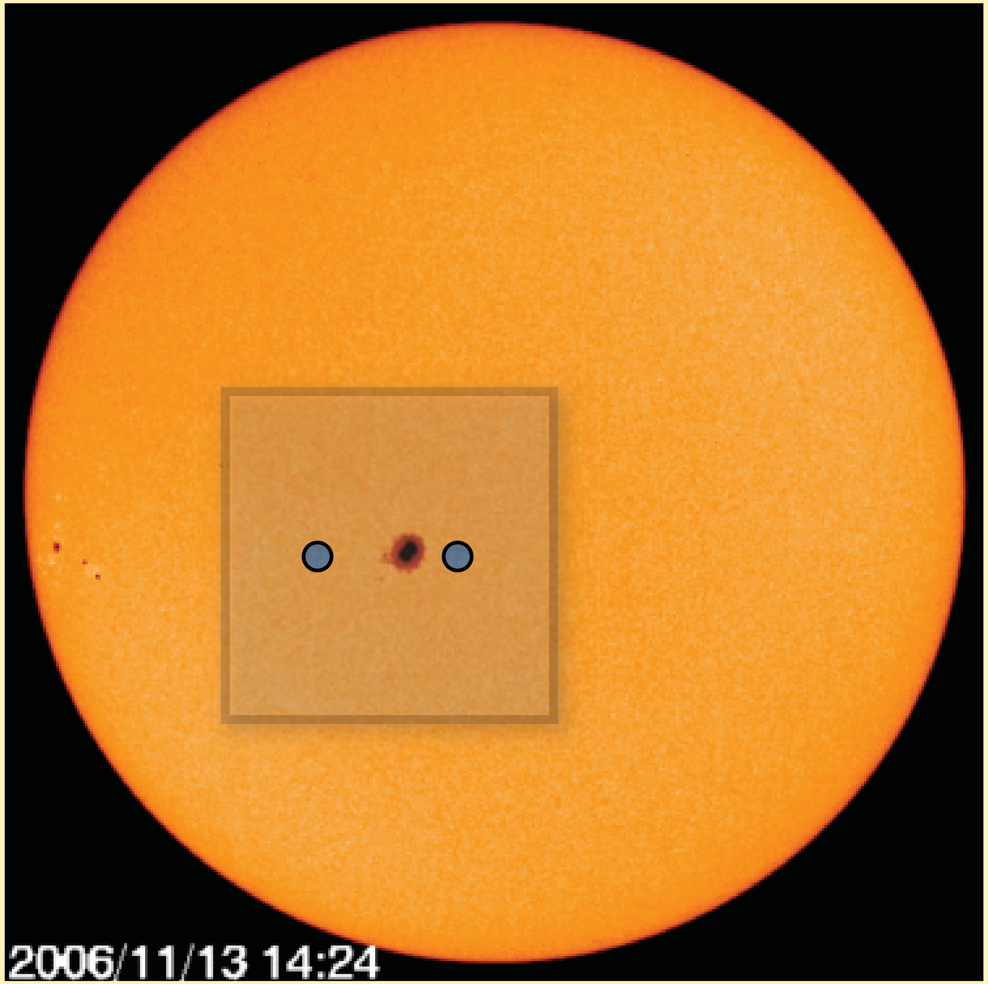
Born theory: an experimental confirmation

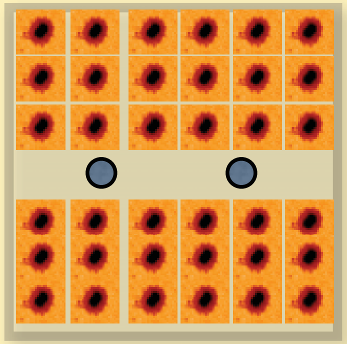


Born theory: an experimental confirmation

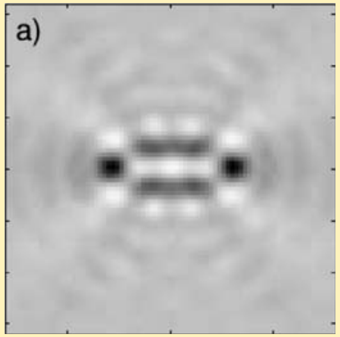


Born theory: an experimental confirmation



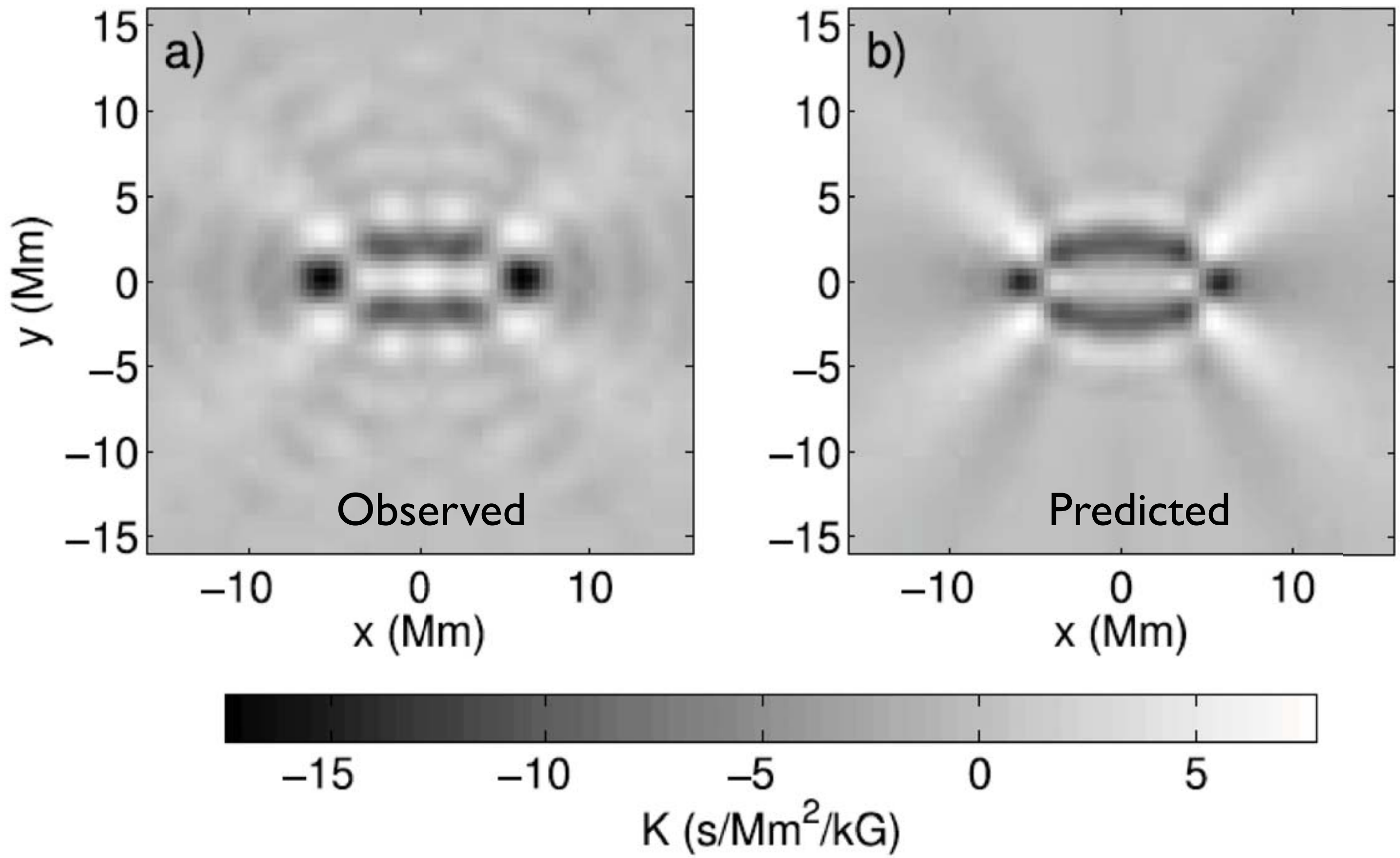


Travel time
observations

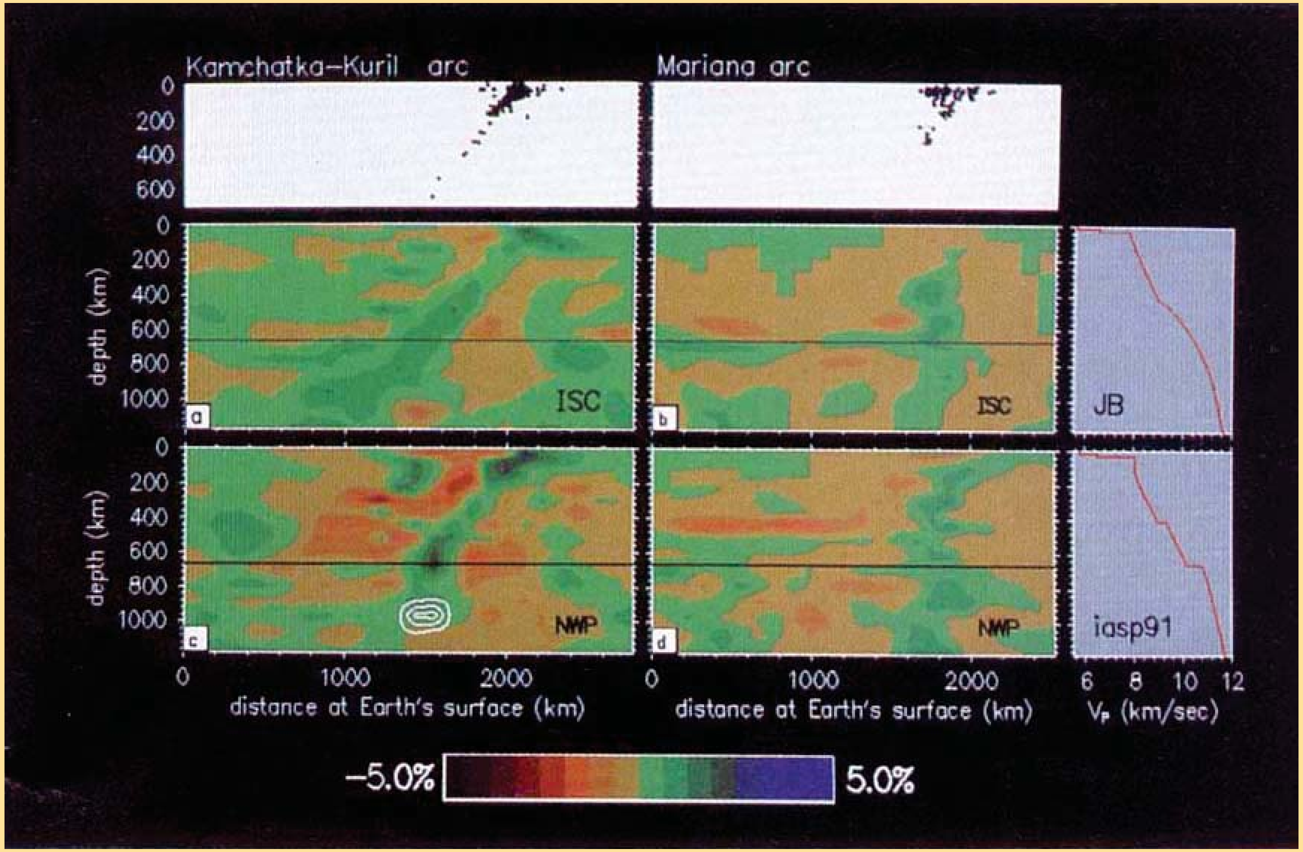


An experimental confirmation

DUVALL, BIRCH, & GIZON Astrophys. J., 2006



Whole mantle convection?

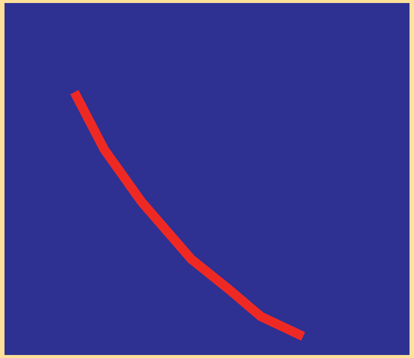


Van der Hilst et al., Nature 1991

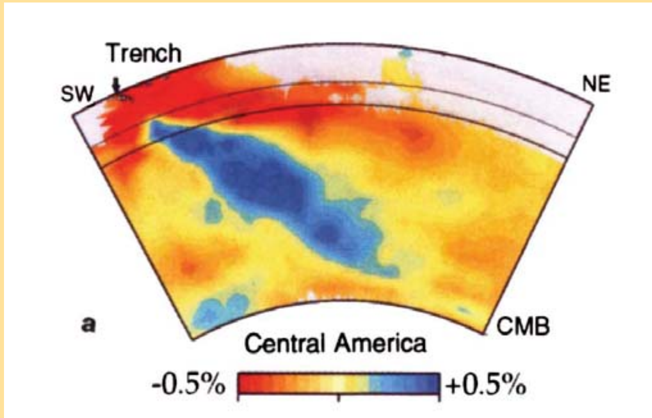
Or thermal coupling?

Our images are consistent with a convection model that allows local mass transport across the boundary between upper and lower mantle. One should be cautious of such interpretations, however: tomographic images depict variations in seismic velocity, and from the images alone one can not unambiguously discriminate between actual mass transport across the upper–lower mantle boundary or velocity perturbations in the lower mantle resulting from thermal coupling in layered convection[50], possibly combined with a locally depressed 670 km discontinuity.

The Farallon: deep slabs are real

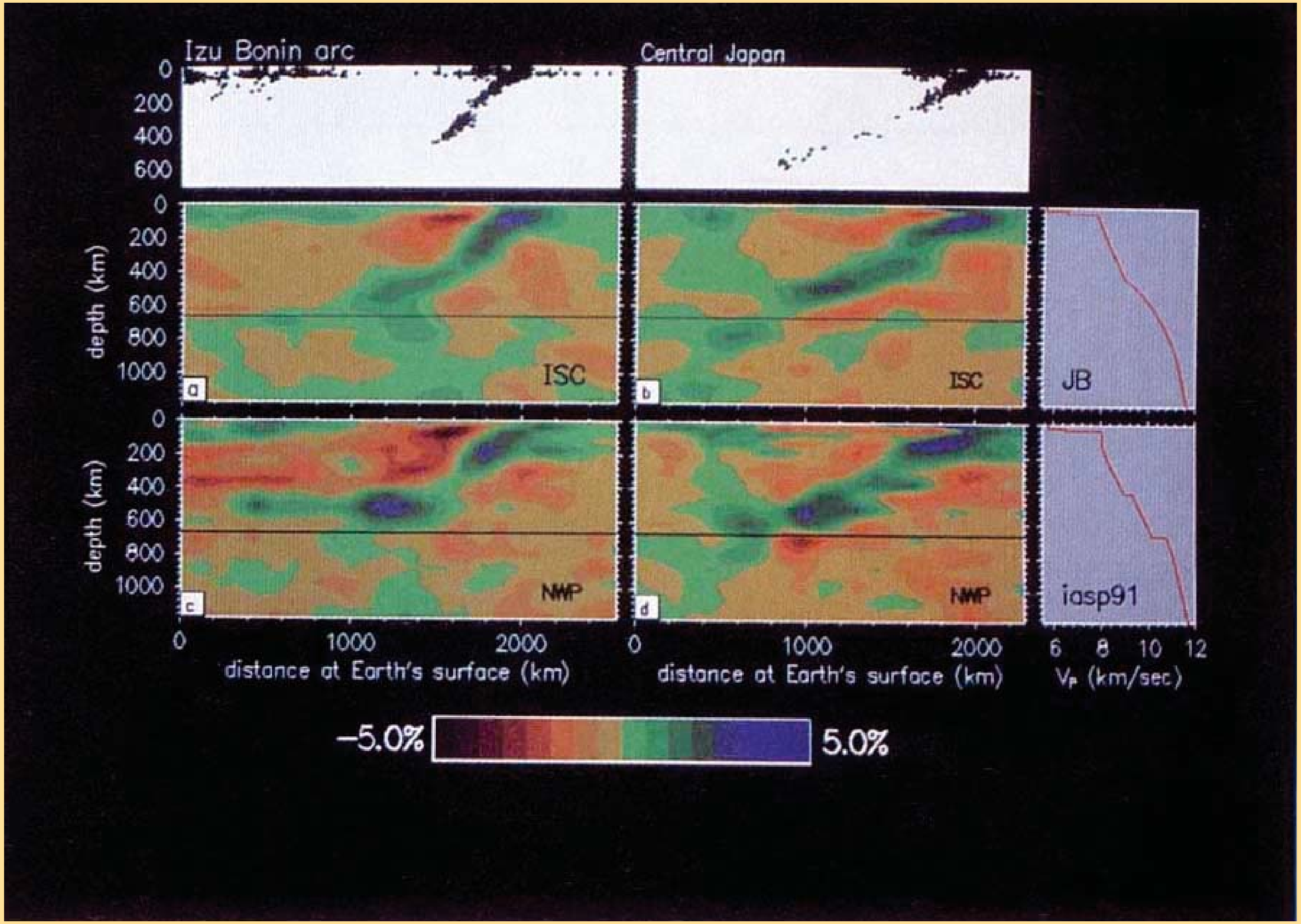


Grand, JGR 1994



Van der Hilst et al., Nature 1997

But do they imply ‘whole mantle’ convection?



Van der Hilst et al., 1991