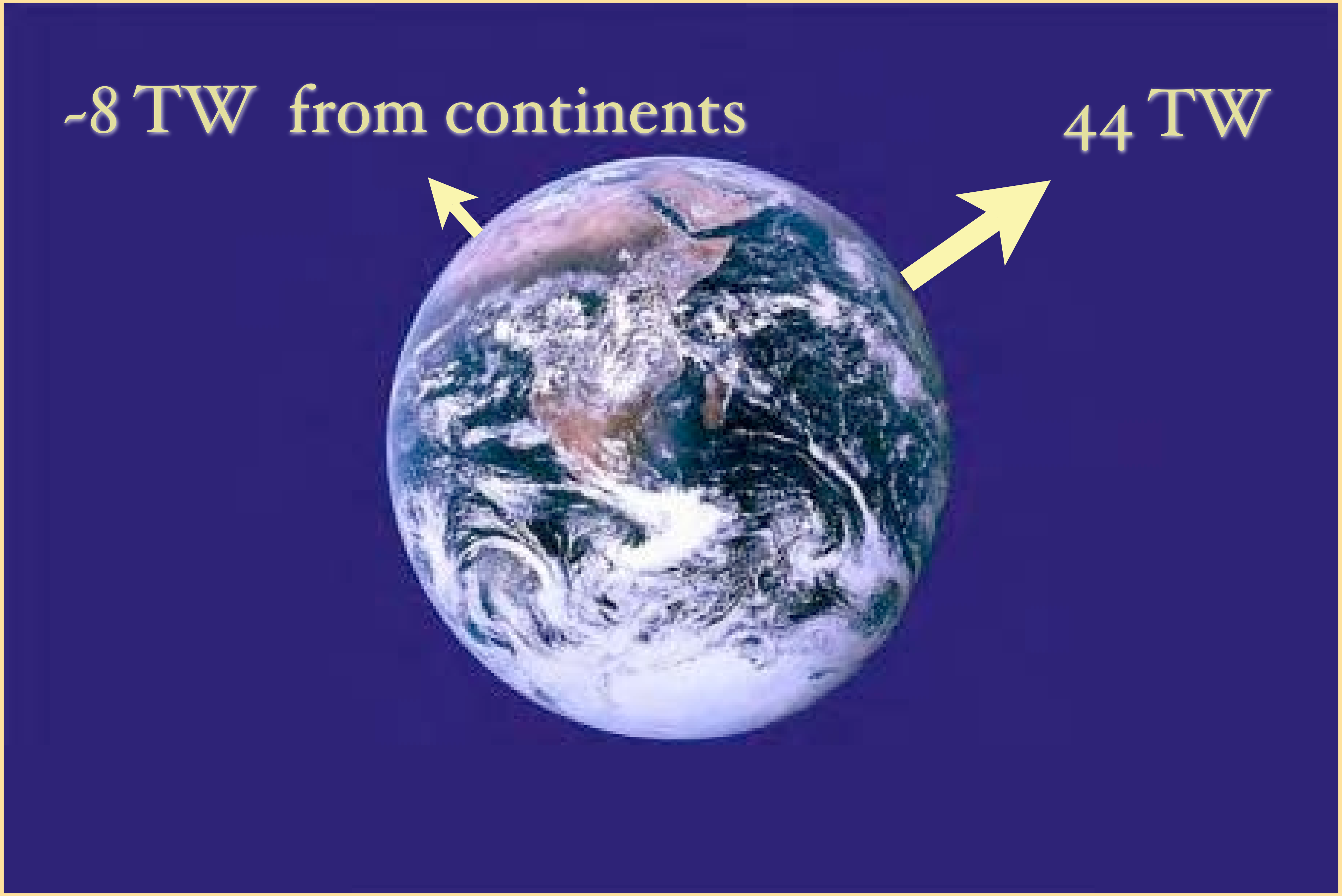
Seismic tomography and the dilemma of the Earth's heat budget.

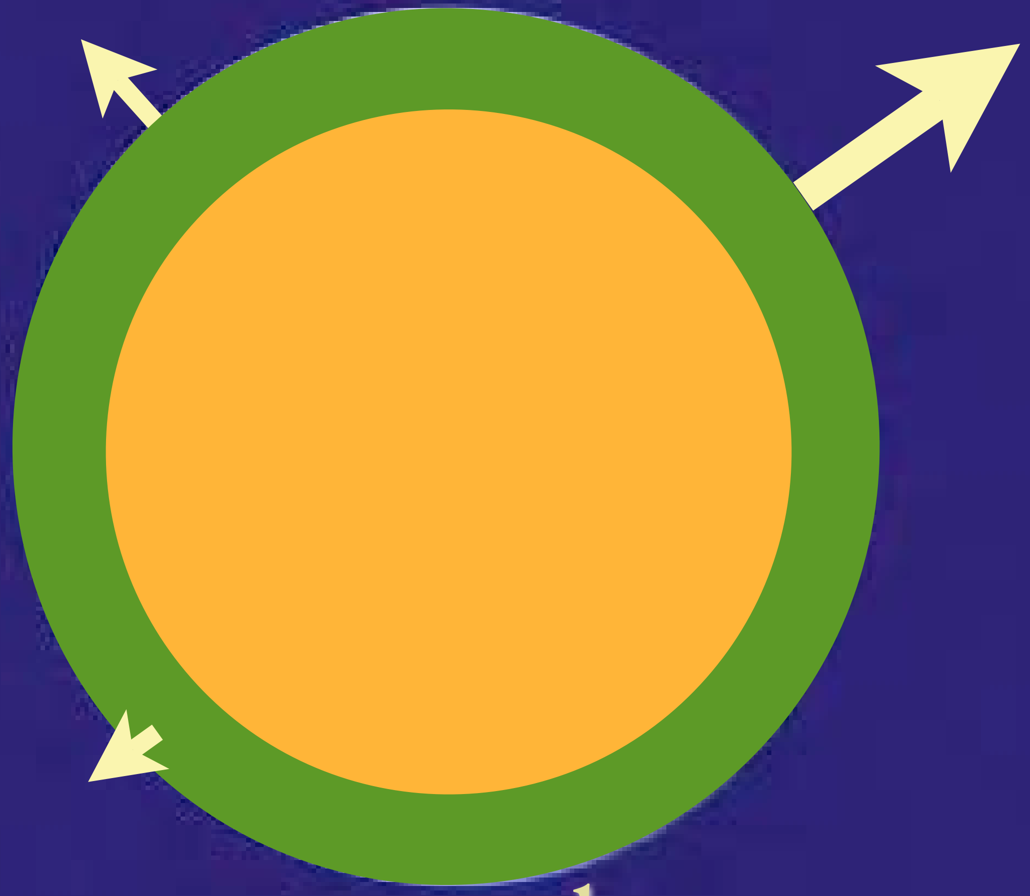
Guust Nolet
Géosciences Azur

The heat flux problem (1)



-8 TW from continents

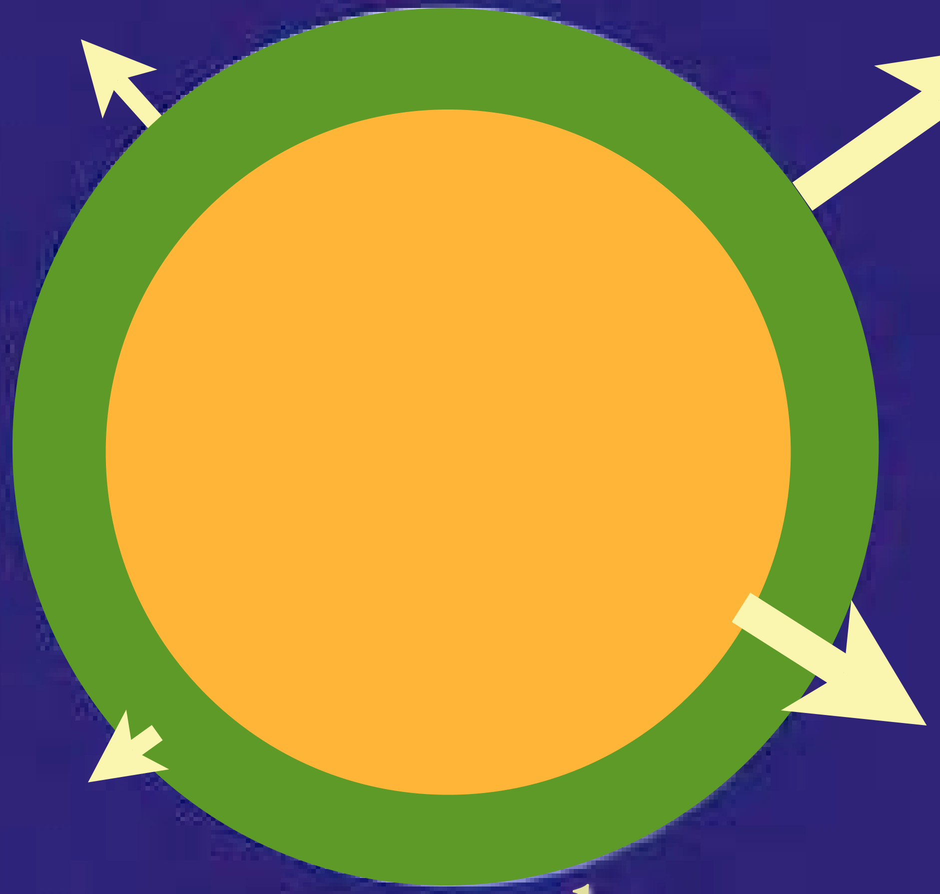
44 TW



-8 TW from continents

44 TW

-5 TW from upper mantle



~8 TW from continents

44 TW

31 TW
across
660

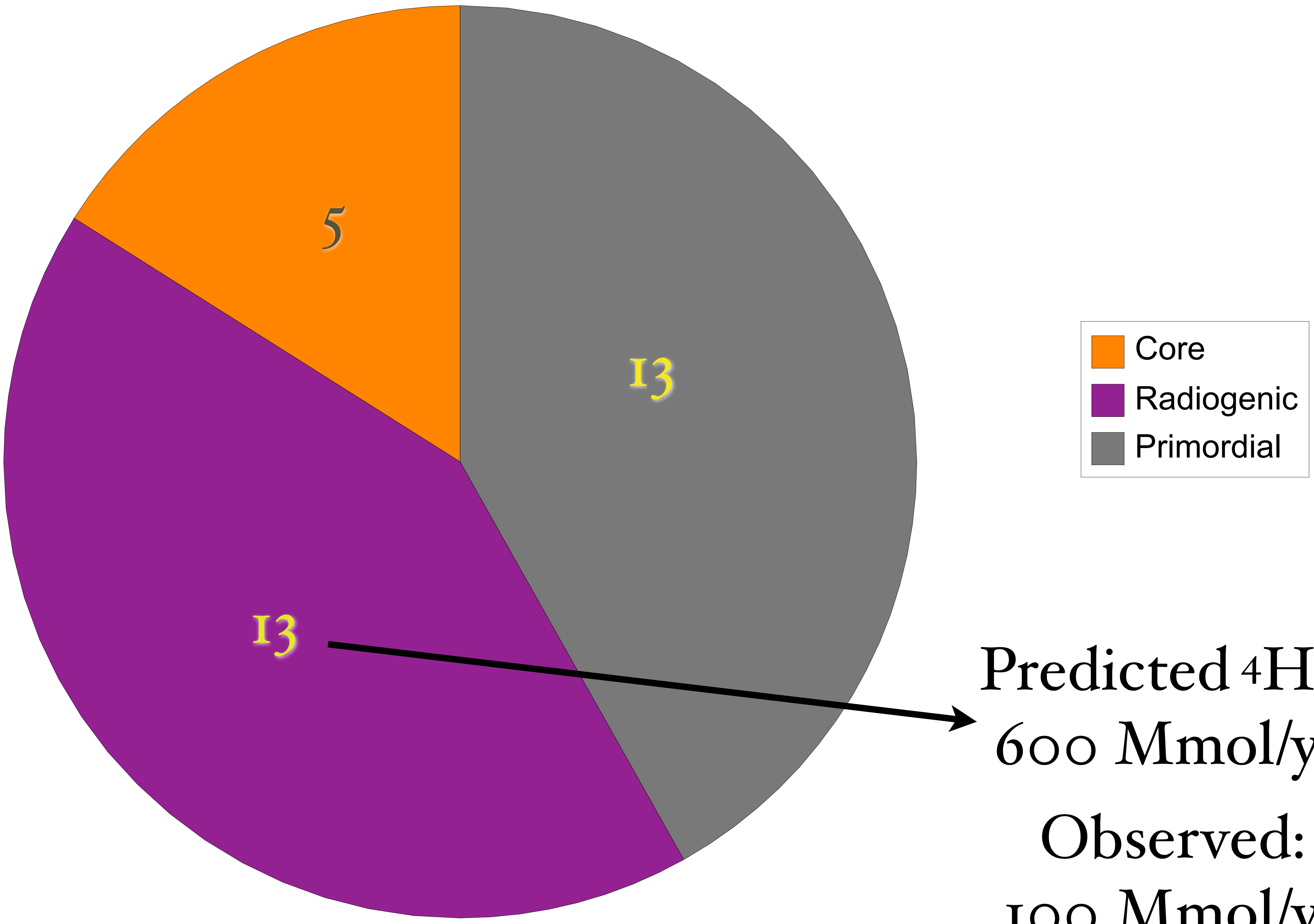
~5 TW from upper mantle

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



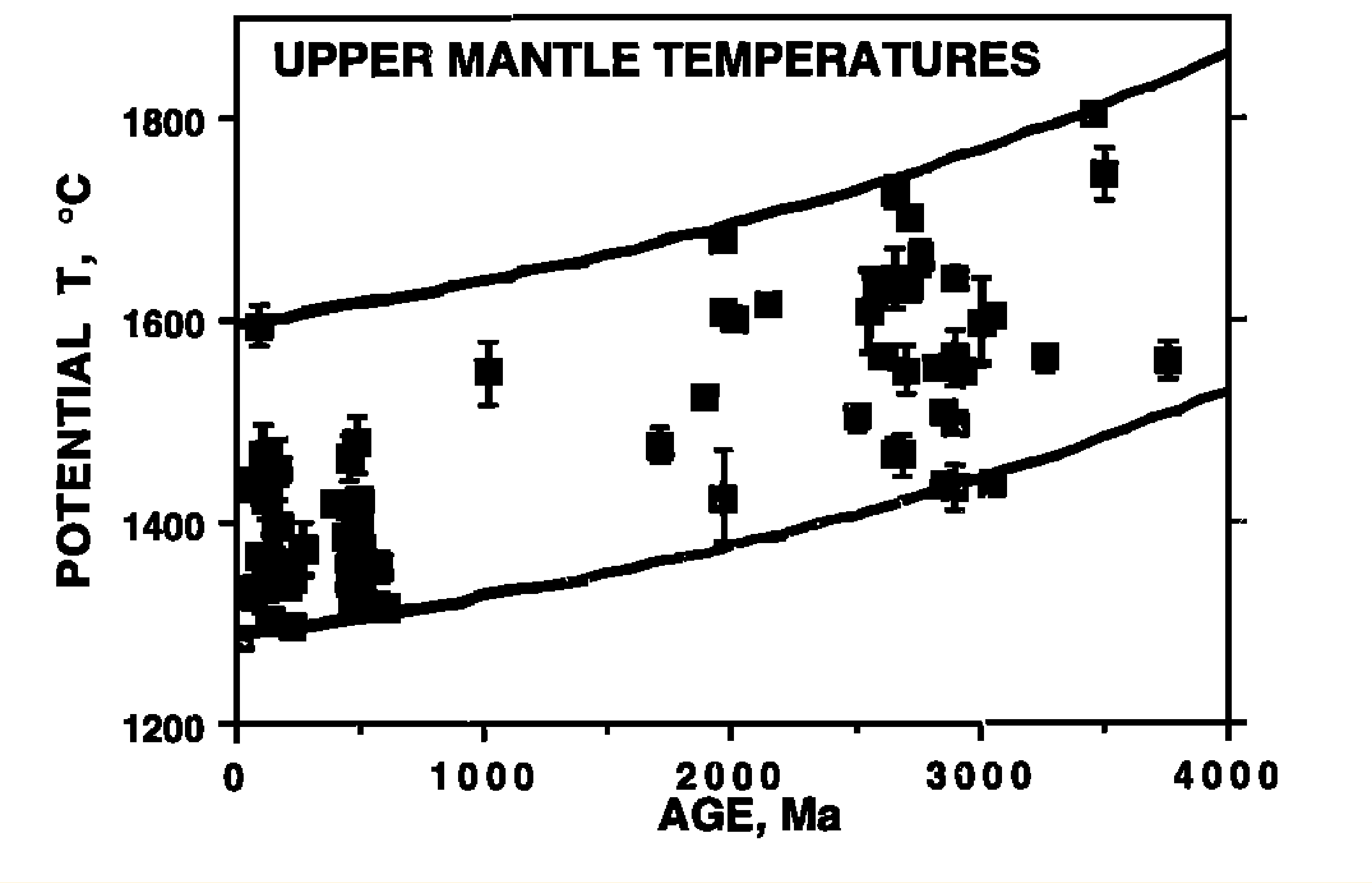
Predicted ^{4}He:
600 Mmol/yr

Observed:
100 Mmol/yr

Argon

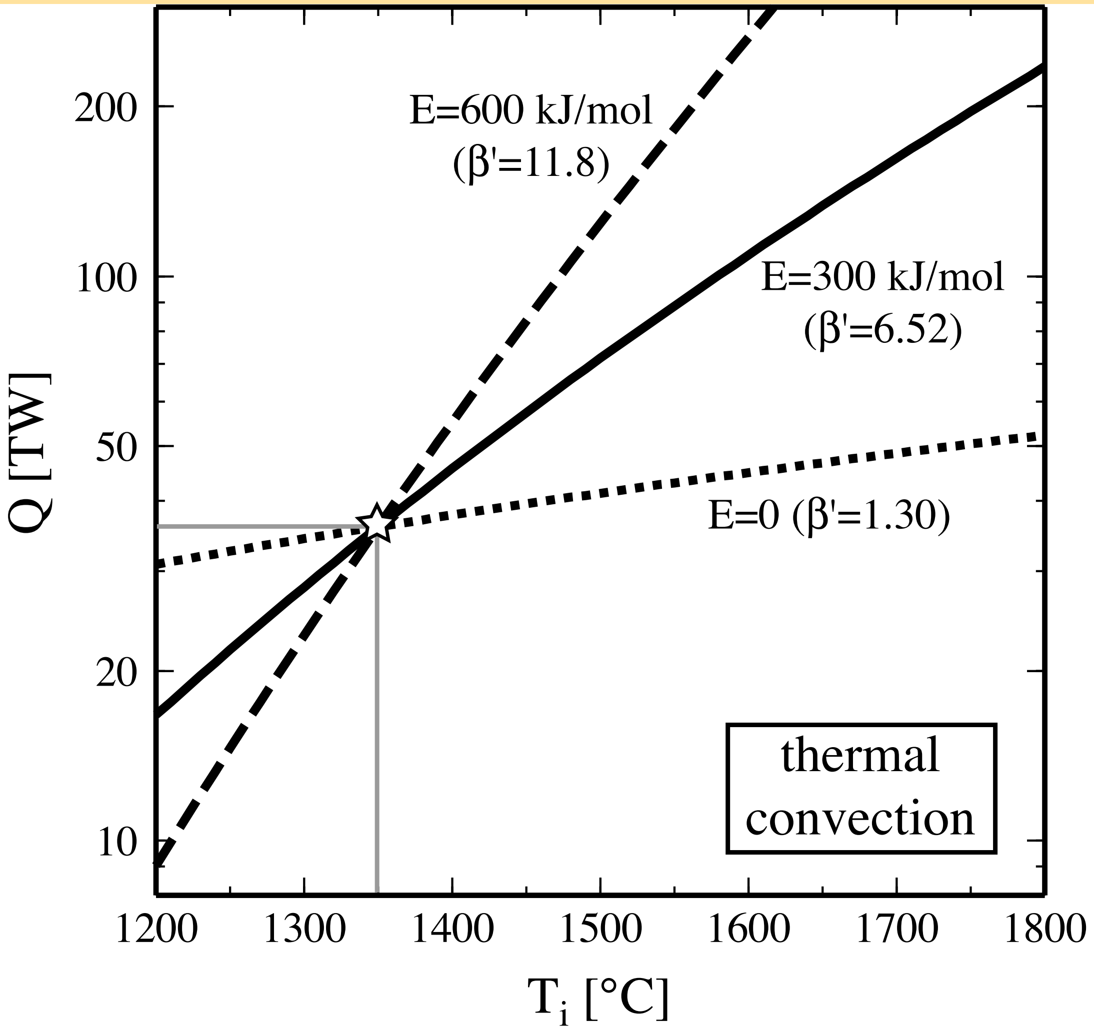
- $^{40}K \rightarrow {}^{40}Ar$
- ^{40}Ar does not escape from the atmosphere
- Only about half the predicted ^{40}Ar is found in the atmosphere
- The rest must be residing *somewhere*

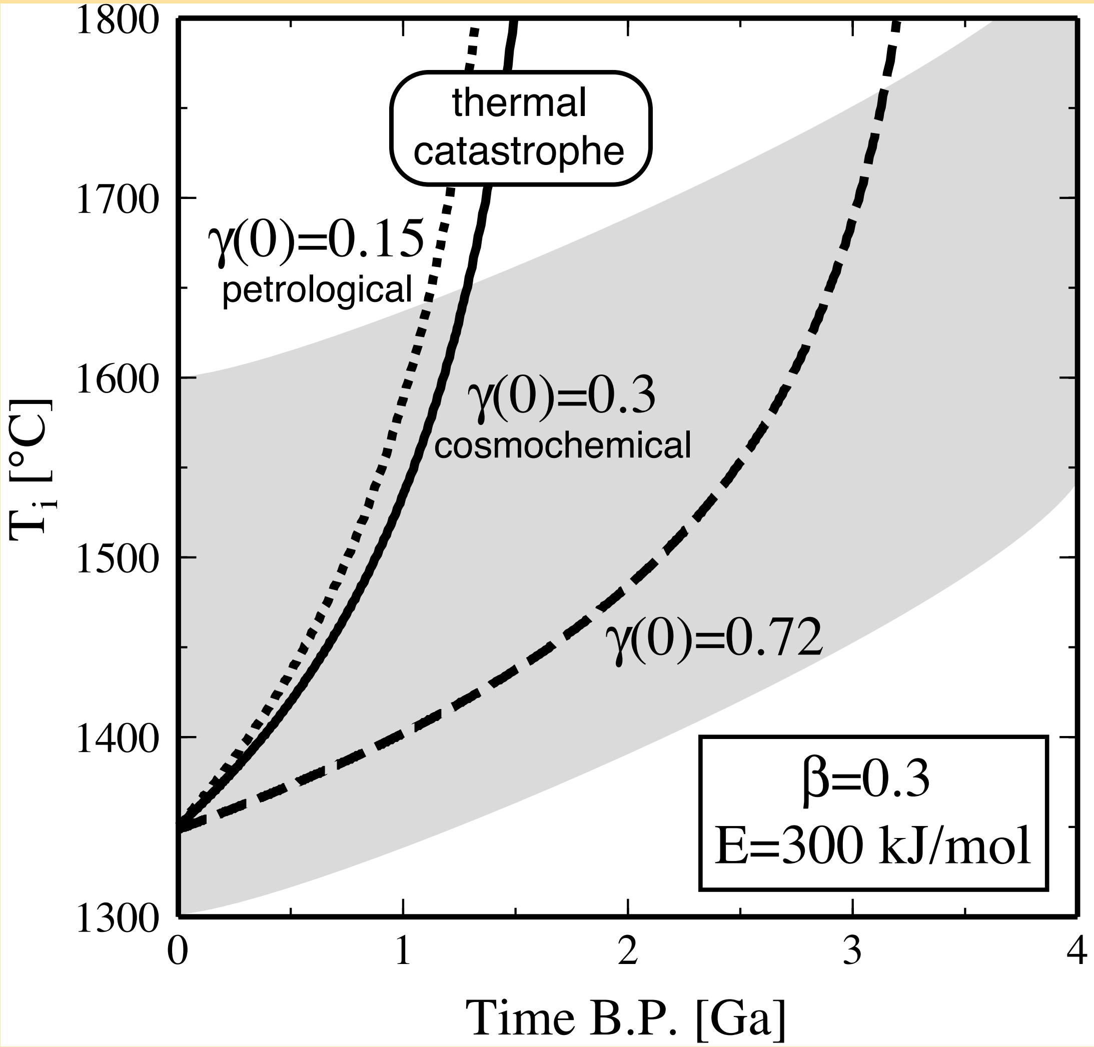
cooling history



Abbott et al., JGR 1994

The heat flux problem (2)





Korenaga, Geophys. Monogr. 2006

Ways to limit the heat flux

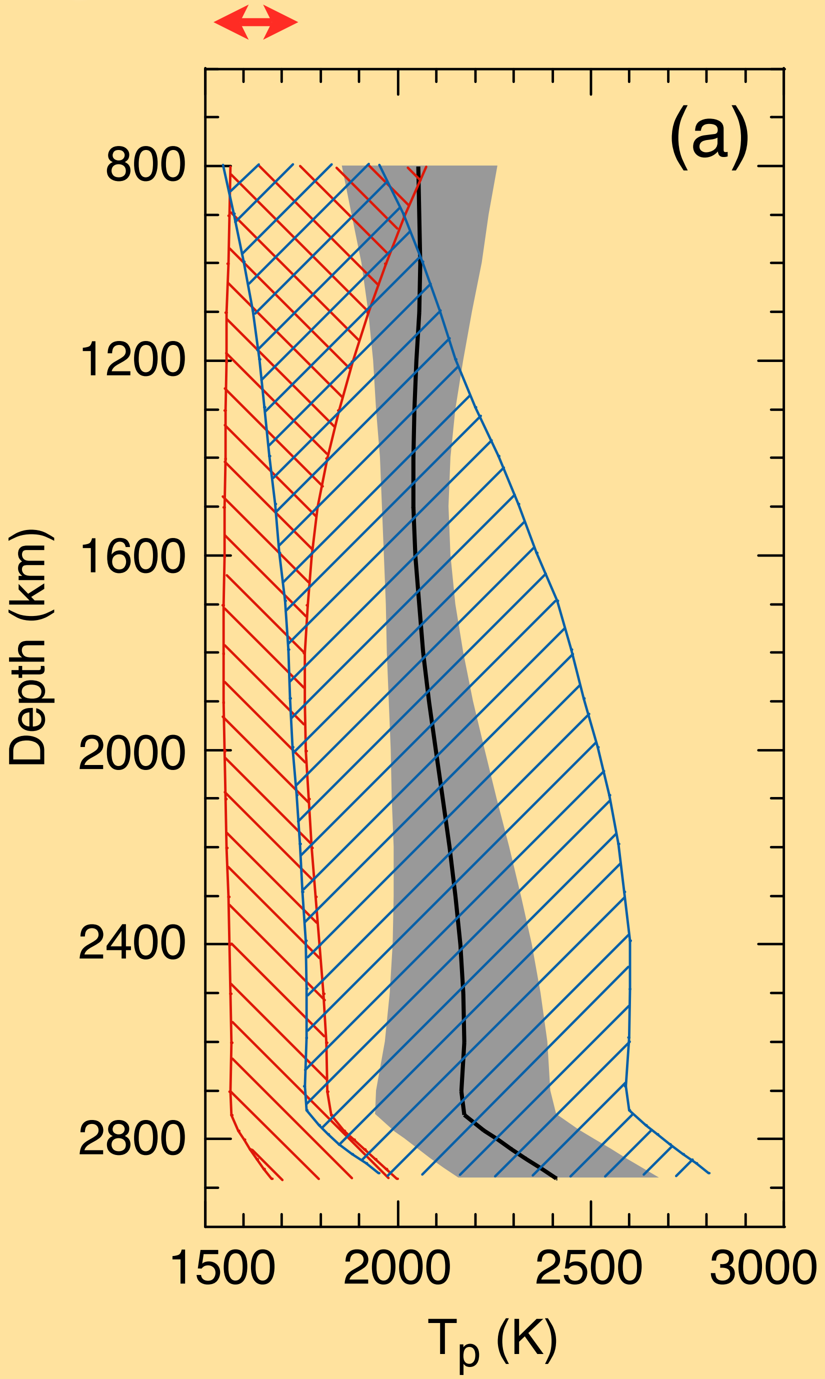
- Plates resist convection (Conrad & Hager, 1999, Korenaga 2006)
- Q is not a simple function of T but depends also on plate configuration (Labrosse & Jaupart, 2007)
- Upper and lower mantle convect separately (McKenzie & Richter, 1981)

Ways to limit the heat flux

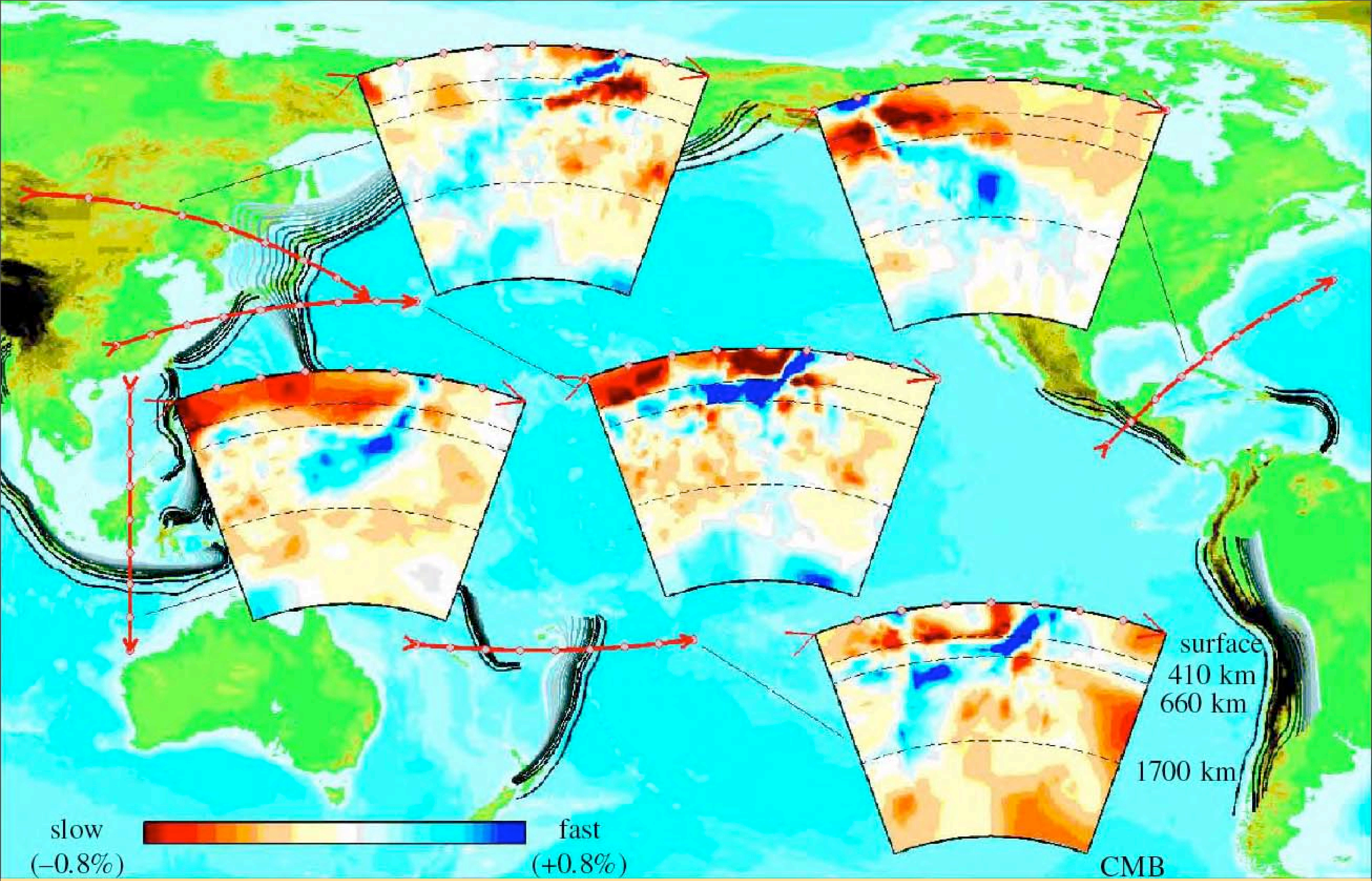
- Plates resist convection (Conrad & Hager, 1999, Korenaga 2006)
- Q is not a simple function of T but depends also on plate configuration (Labrosse & Jaupart, 2007)
- Upper and lower mantle convect separately (McKenzie & Richter, 1981) This would imply a thermal boundary layer (TBL) at 660 km.

TBL: what does PREM tell us?

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

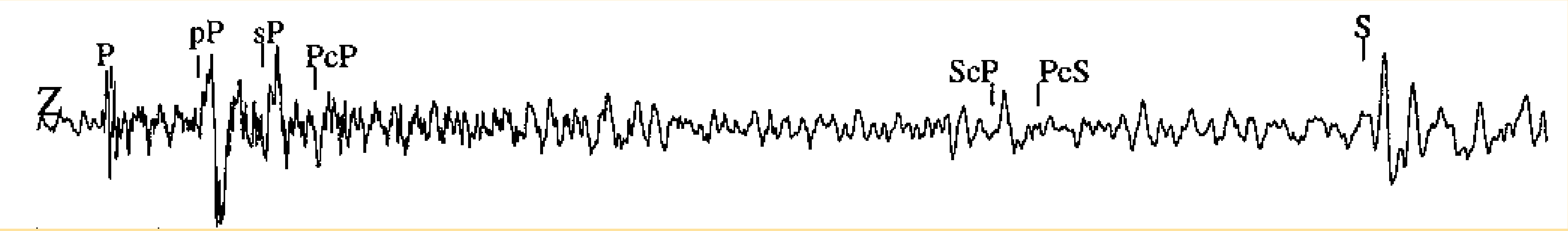


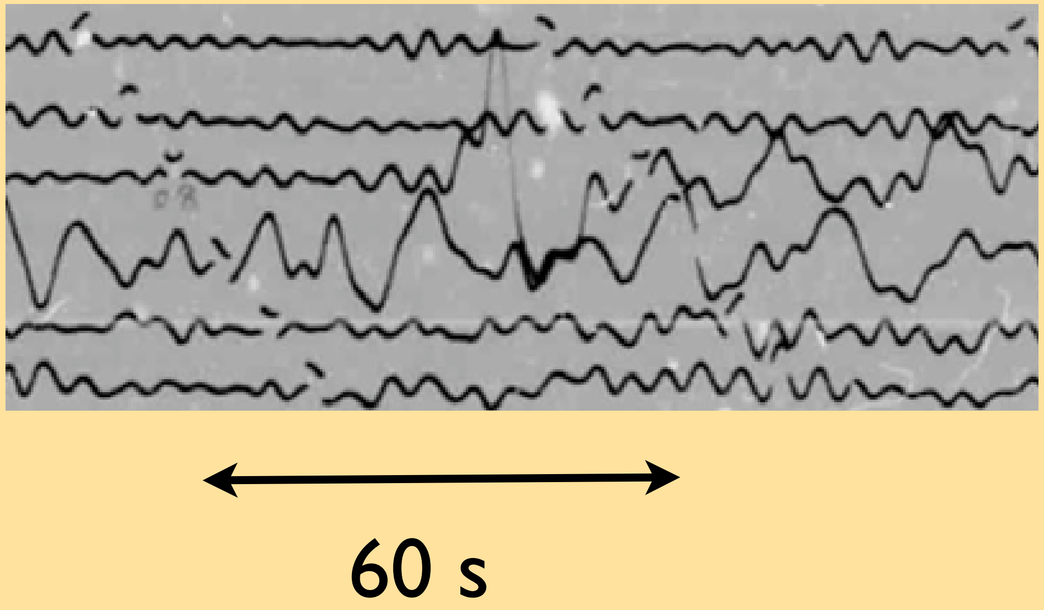
Deschamps & Trampert, EPSL 2004

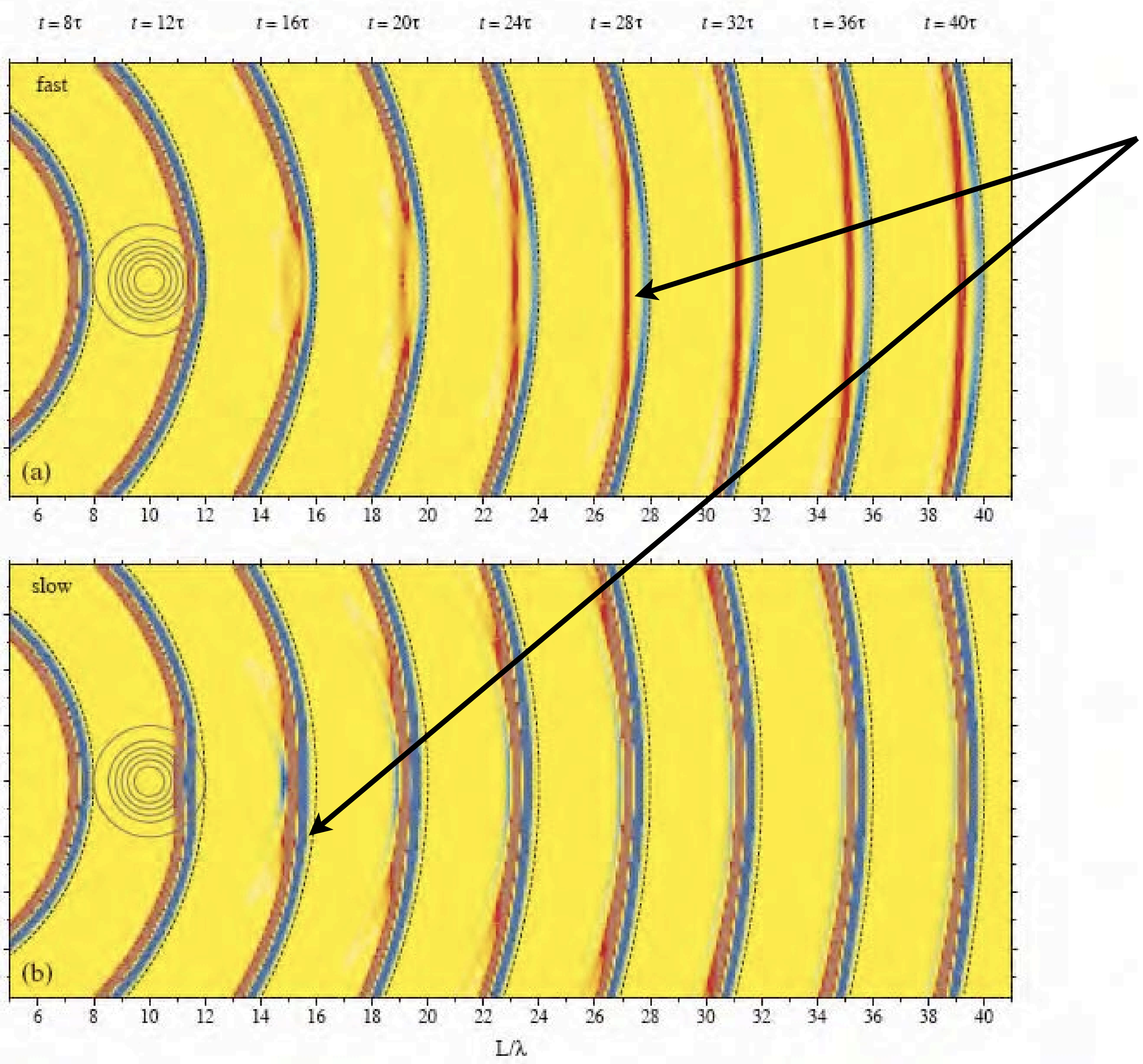


Albarède & Van der Hilst, 2002

Intermezzo: from onset times to cross-correlations



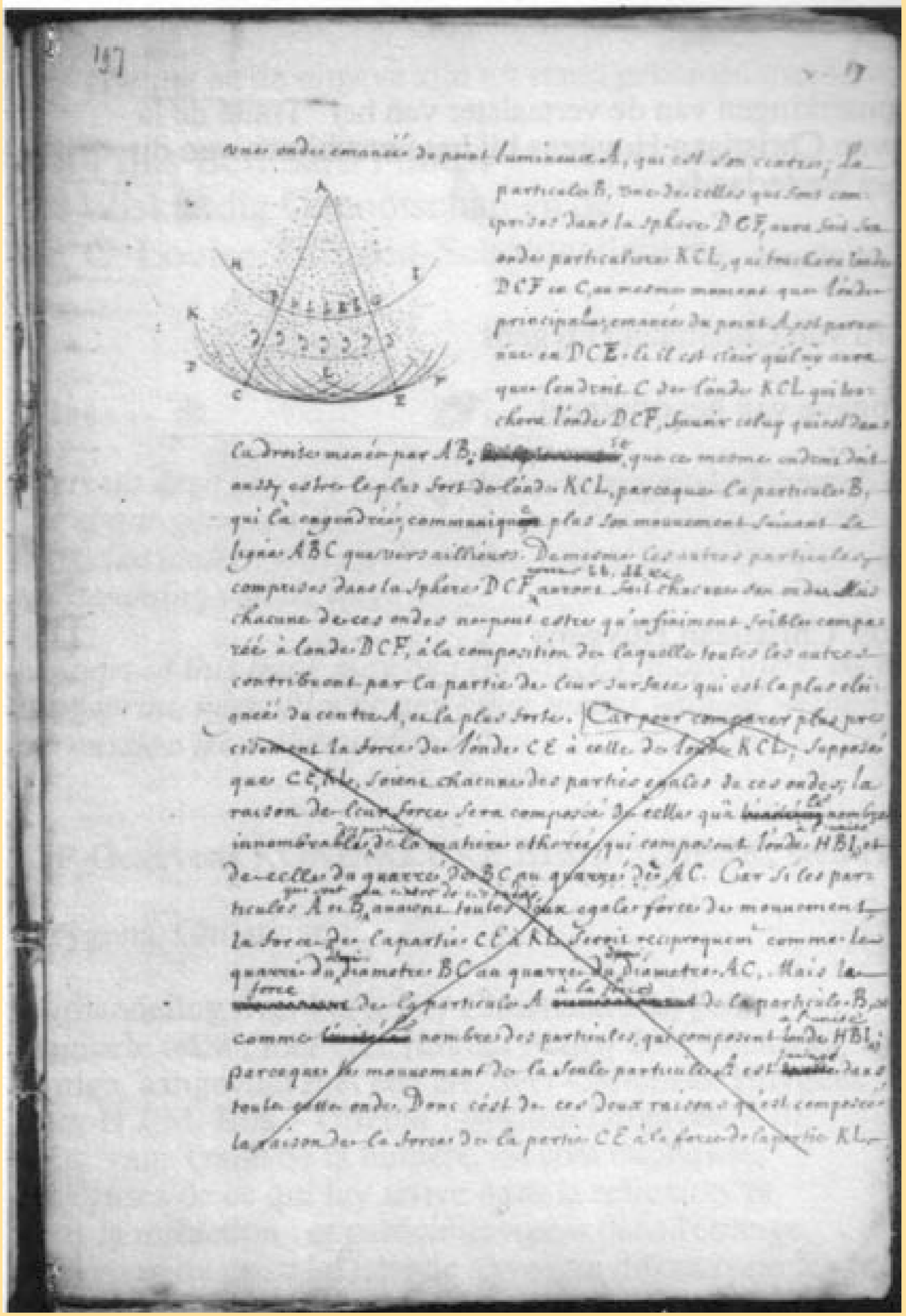




The most dramatic effects are at later times in the waveform!

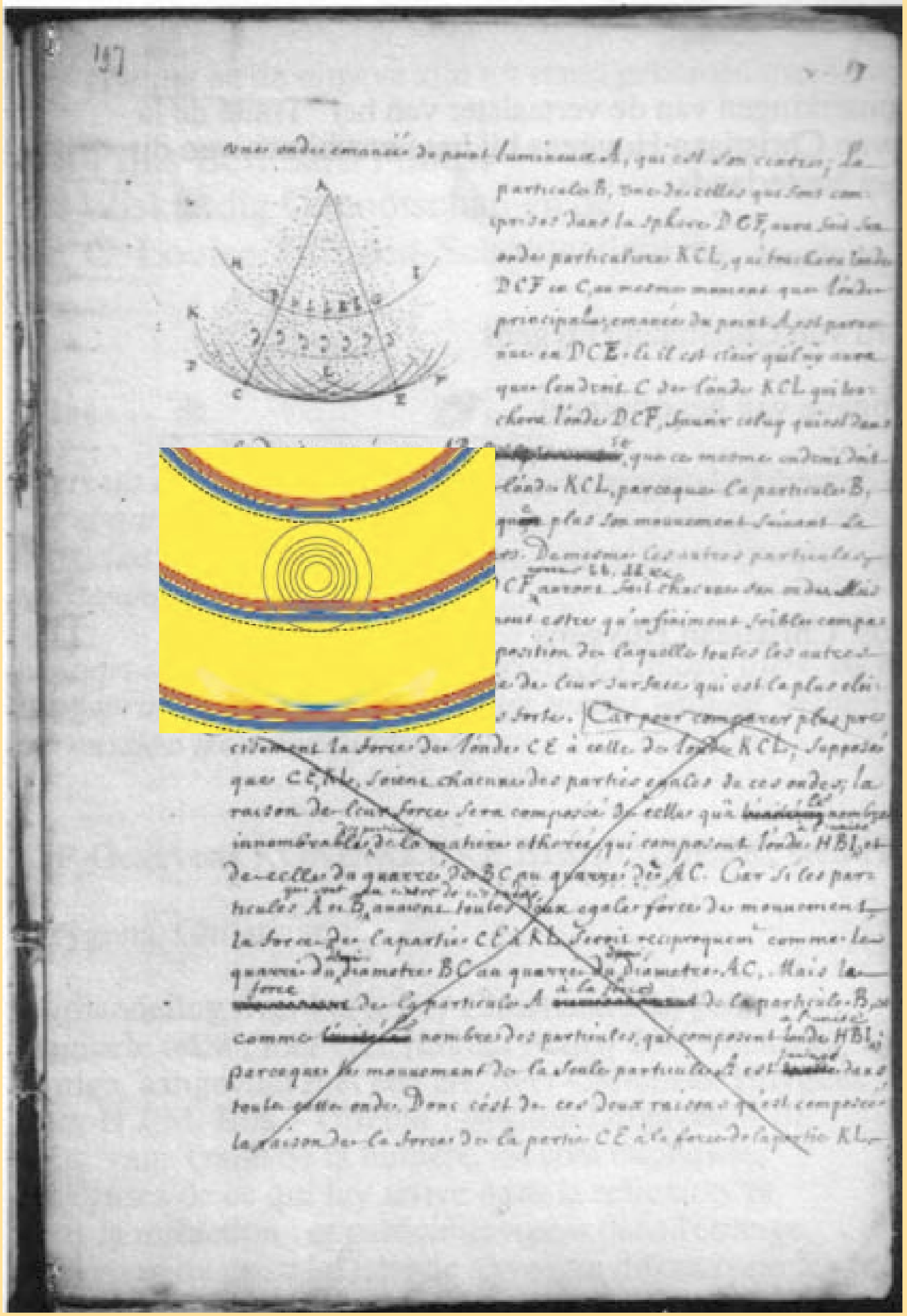
Hung et al., GJI 2001

Wave diffraction



Christaan Huygens (1629-1696)

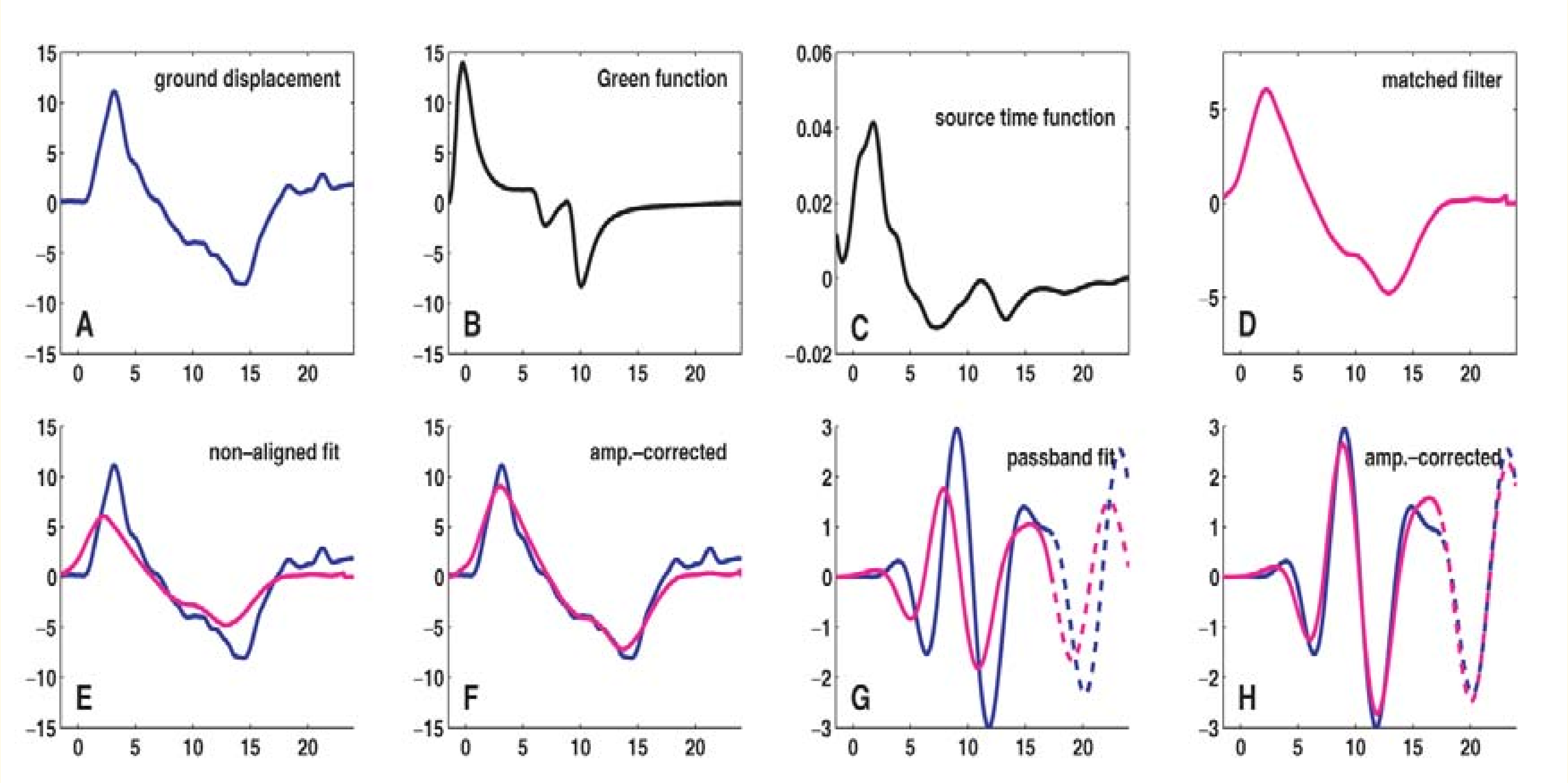
Wave diffraction



Christaan Huygens (1629-1696)

Waves may take detours

Body wave cross-correlations



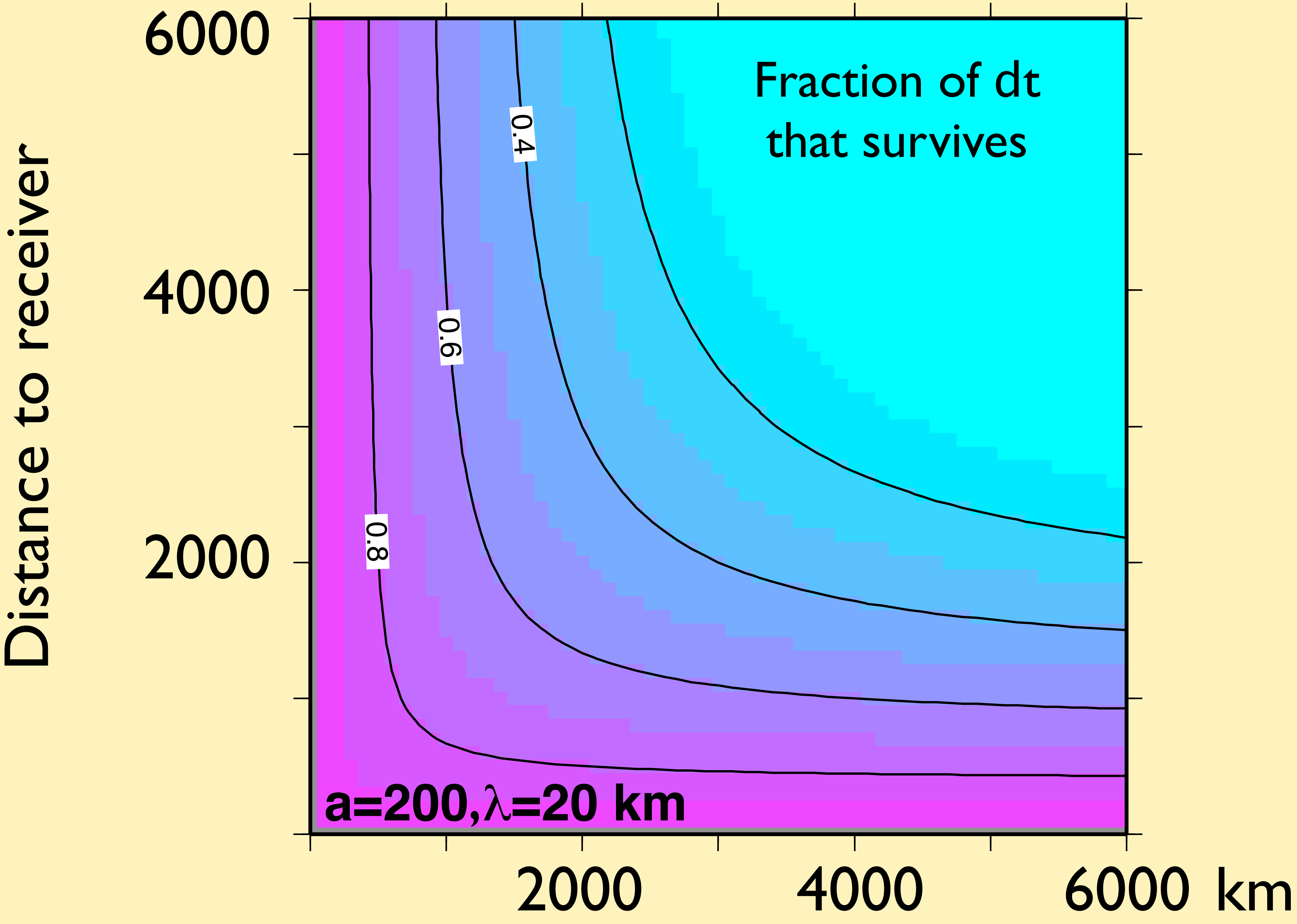
Sigloch & Nolet, GJI 2006

Cross-correlation

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

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

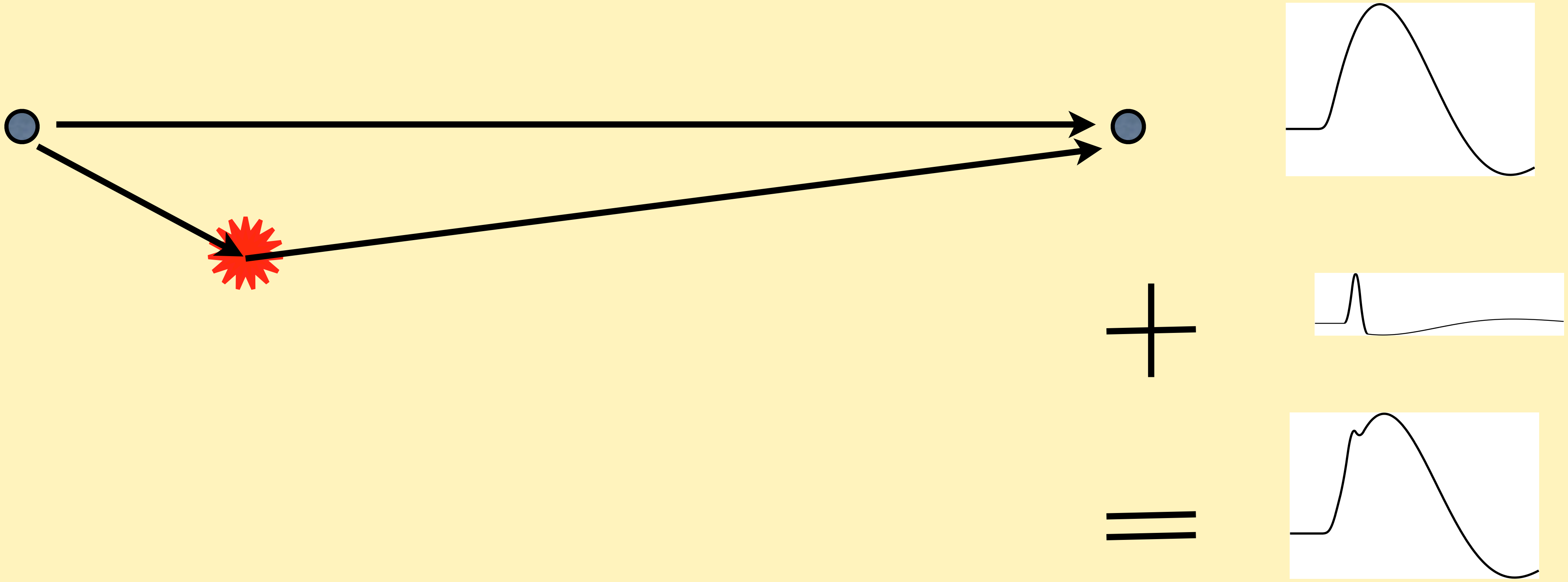
Healing of cross-correlation delays (Period=2 s)



Distance from source

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

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

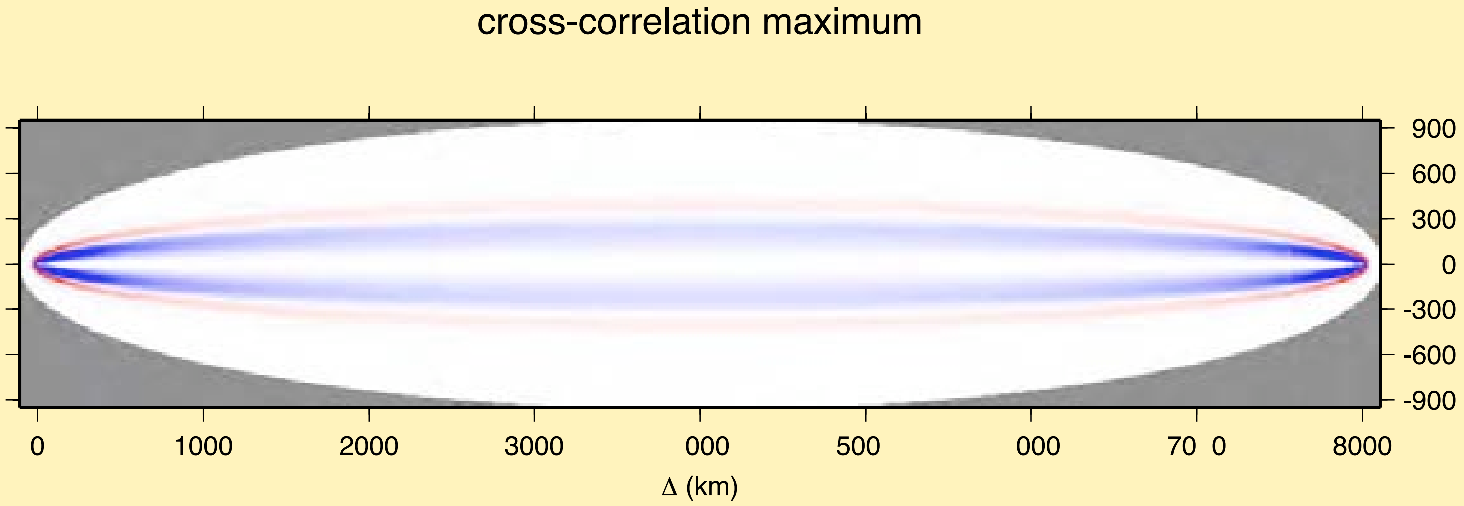


Scattered wave perturbs crosscorrelation

Born

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

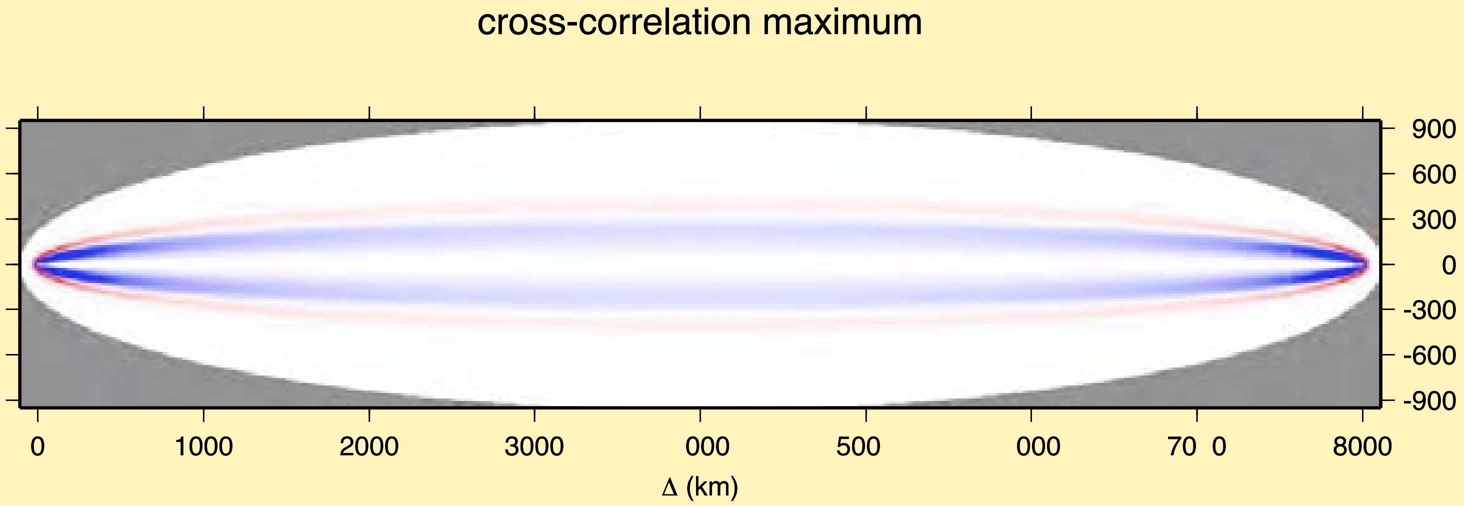
Scattered waves + delay from cross-correlation → “banana-doughnut” kernels


cross-correlation maximum

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

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

Scattered waves + delay from cross-correlation ➡ "banana-doughnut" kernels



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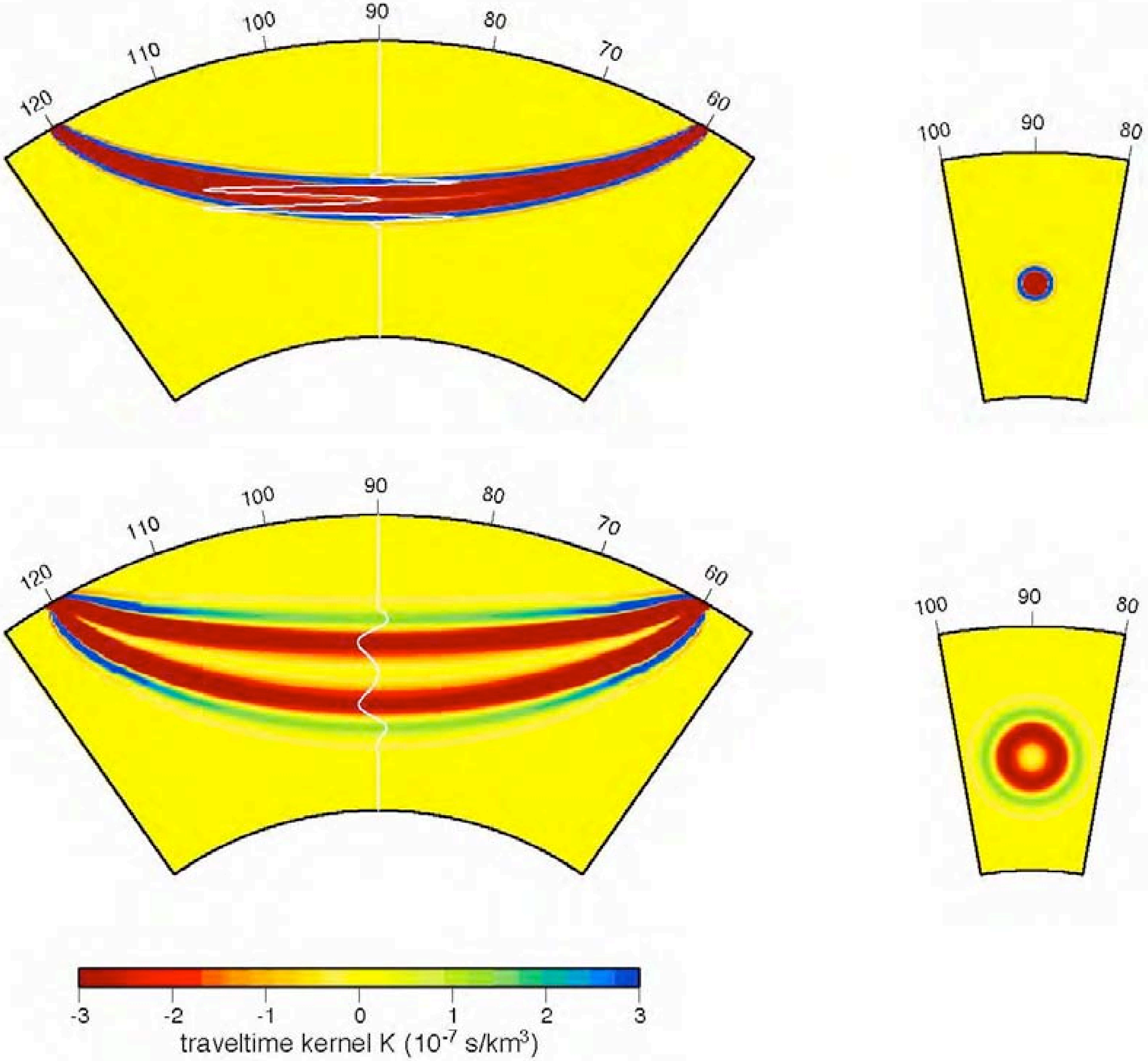
$$-\frac{\int_{-\infty}^{\infty} \dot{u}(t') \delta u(t') \mathrm{d}t'}{\int_{-\infty}^{\infty} \ddot{u}(t') u(t') \mathrm{d}t'} \, .$$

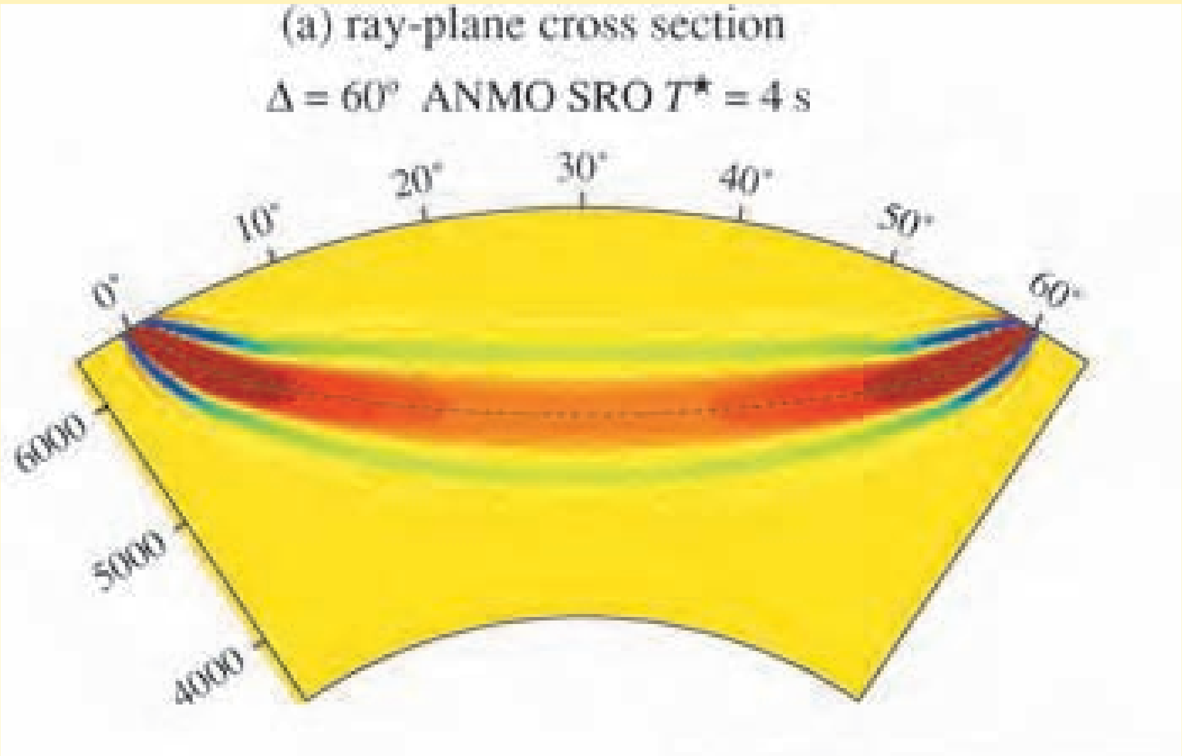


T=2s

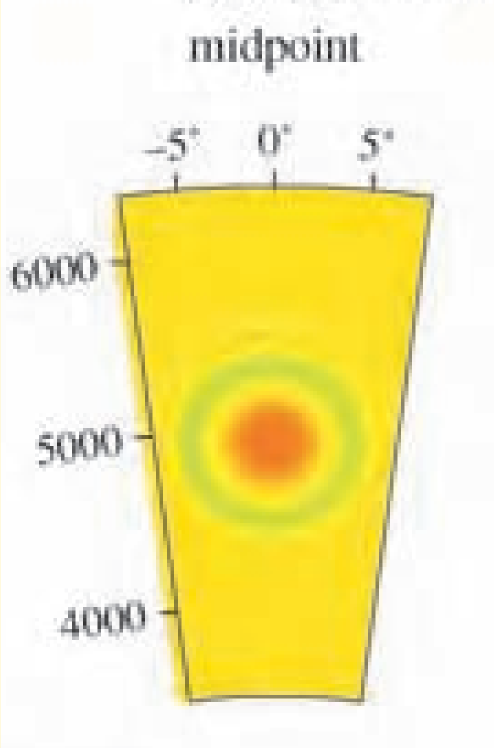
T=20s

The period T determines the width of the kernel

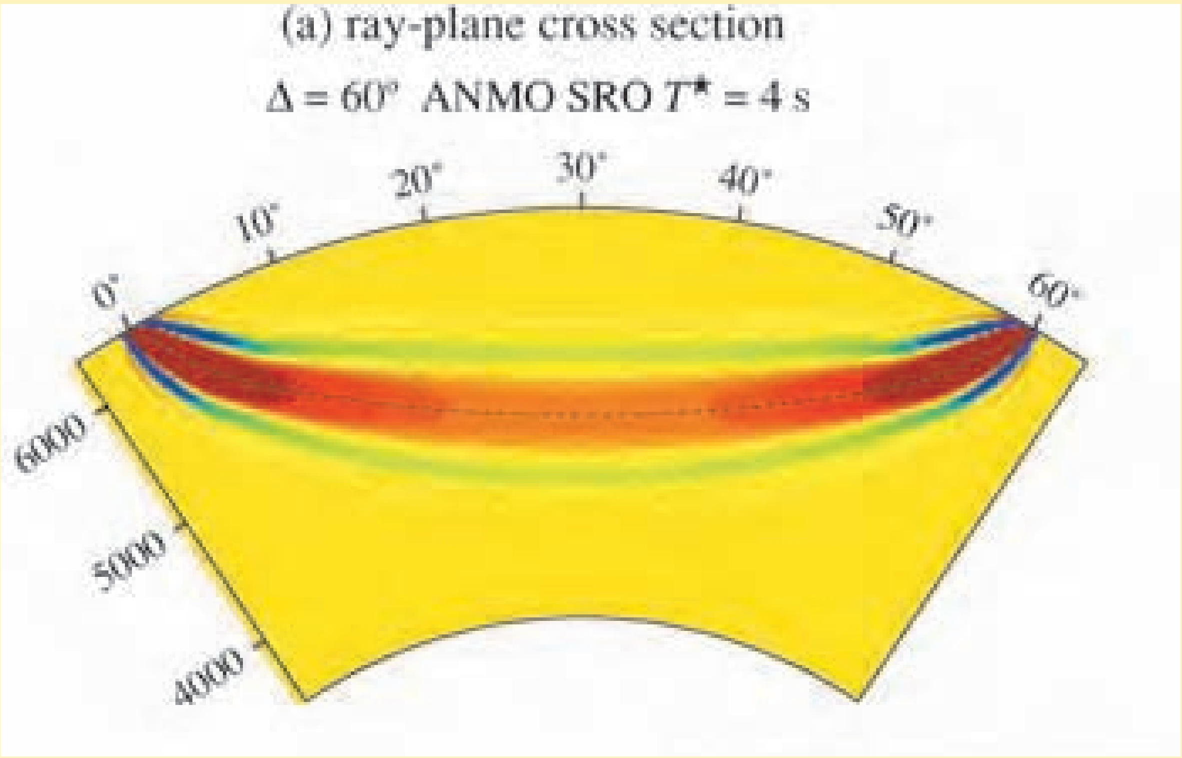
Amplitude kernels

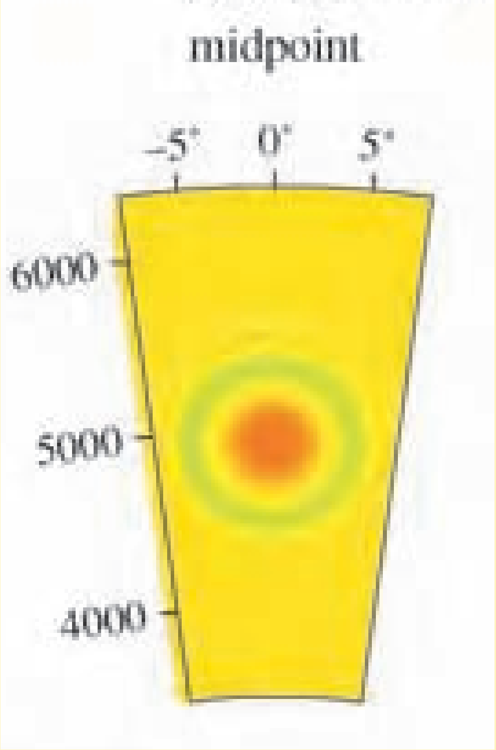

(a) ray-plane cross section

$\Delta = 60°$ ANMO SRO $T^* = 4$ s

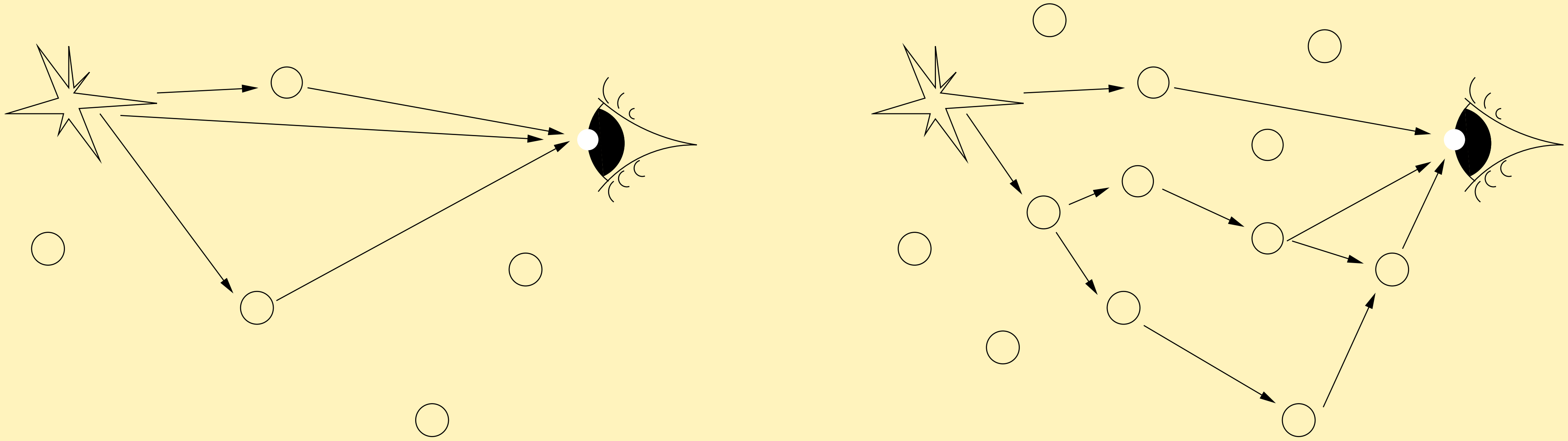

midpoint

Amplitude kernels





modeling waveforms:
Single or multiple scattering?



(a) Diffusion simple

(b) Diffusion multiple

Single=early

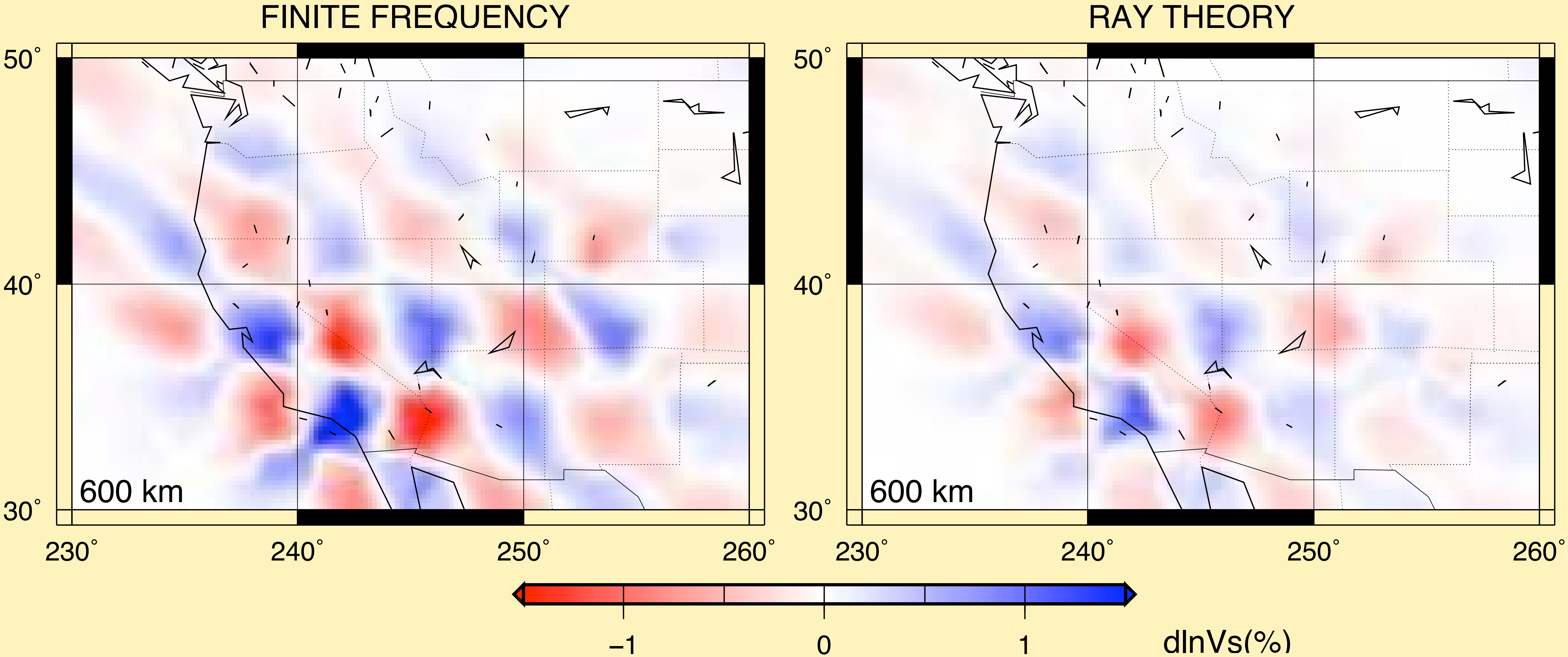
Multiple =late

Domitille Anache, 2008

Forward scattering retains information

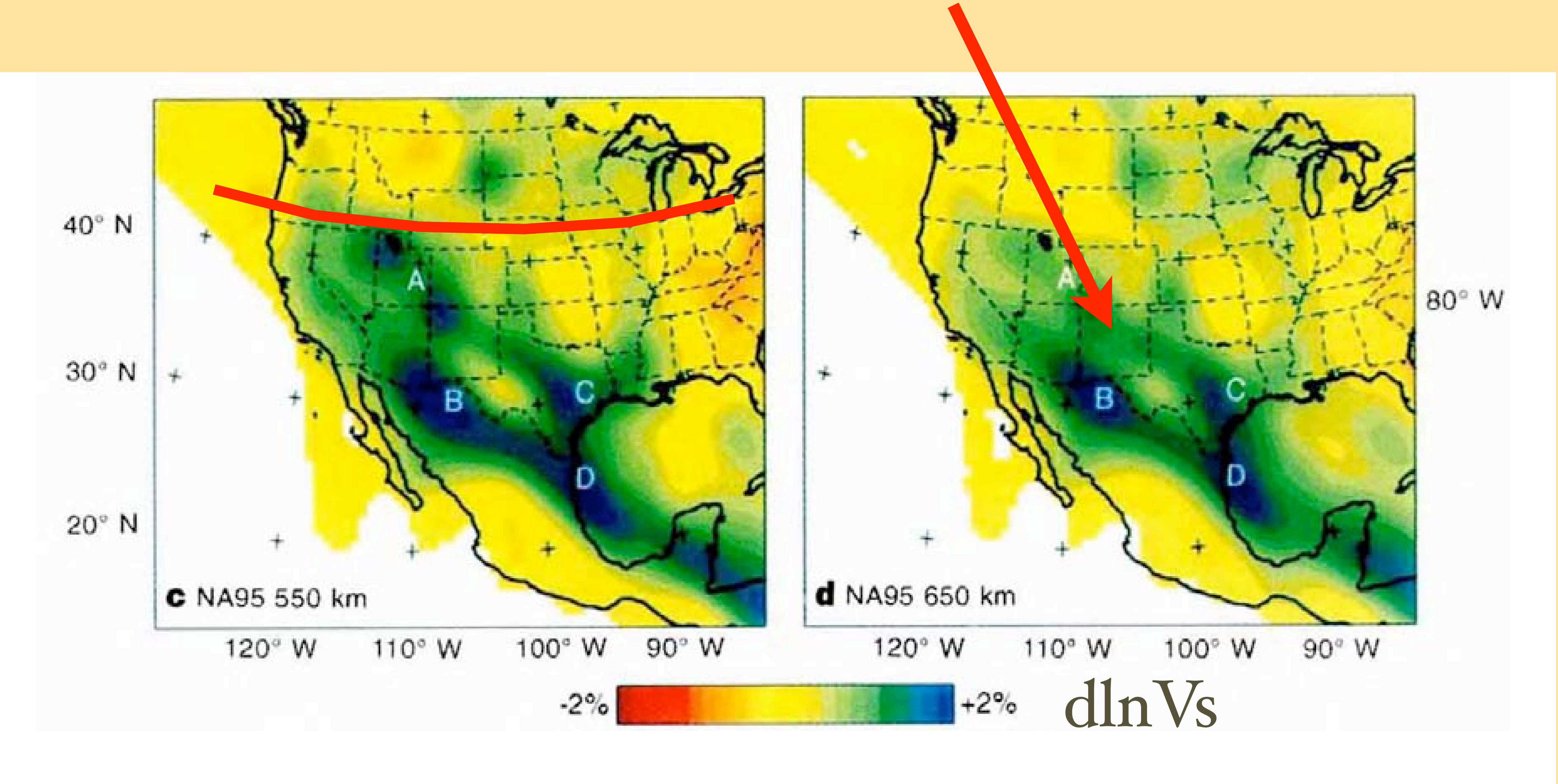
Multiple scattering: ill posed inverse problem

Resolution gain (multiple frequency, delays & amplitudes)



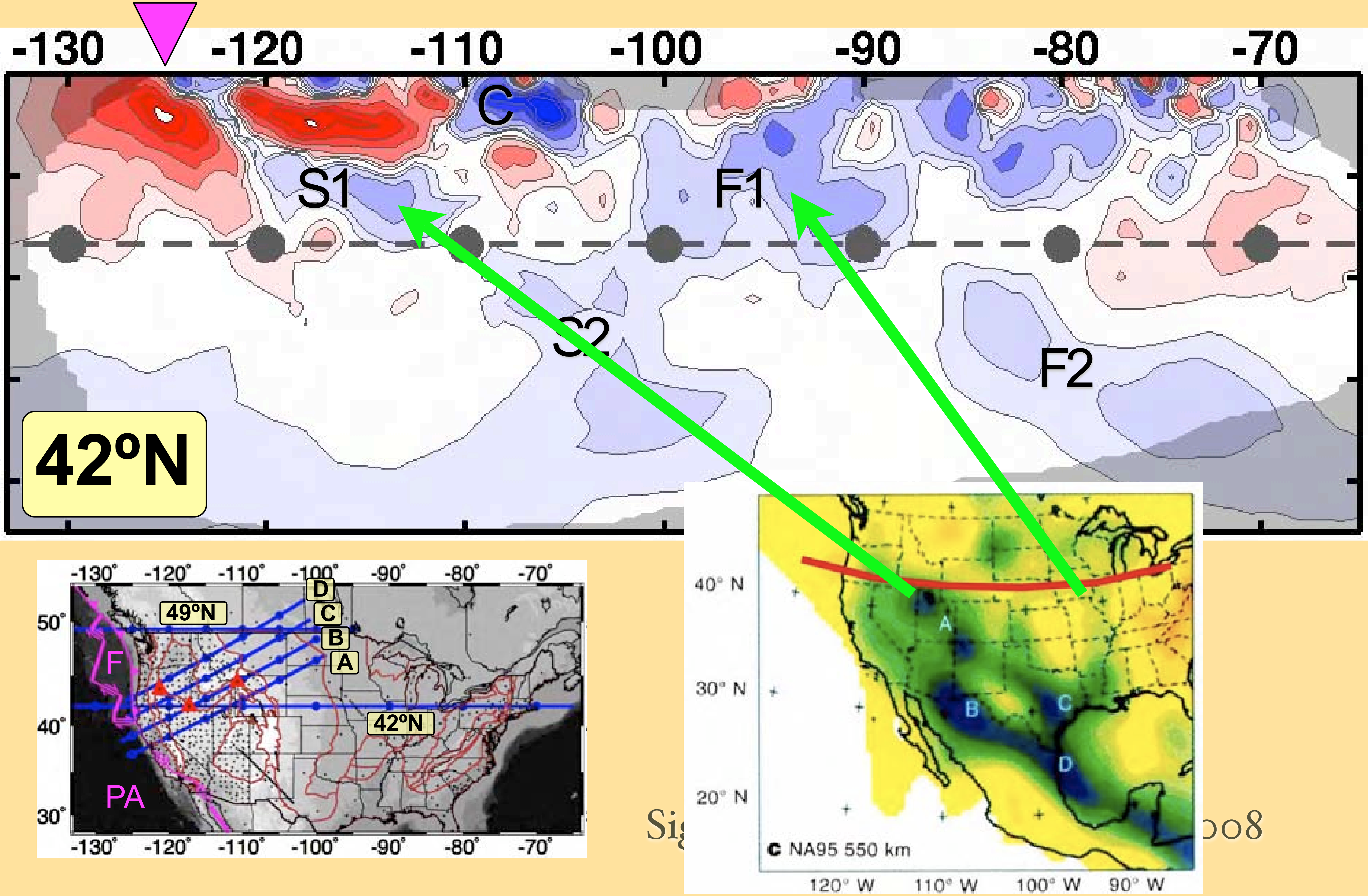
Yue Tian, AGU 2007

Early surface wave images: Farallon stuck in the TZ



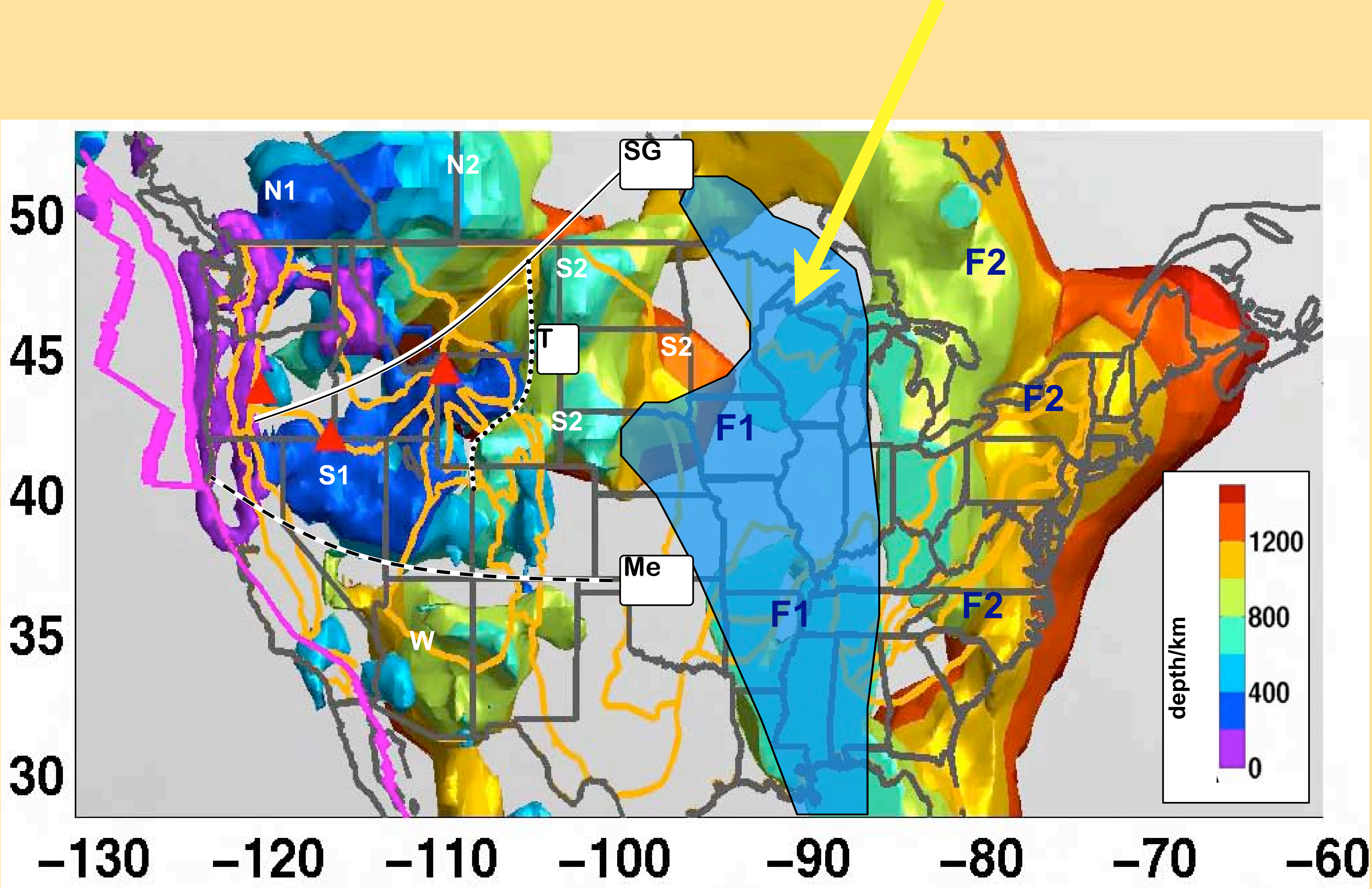
Van der Lee & Nolet, Nature 1997

Finite frequency P wave images and USArray



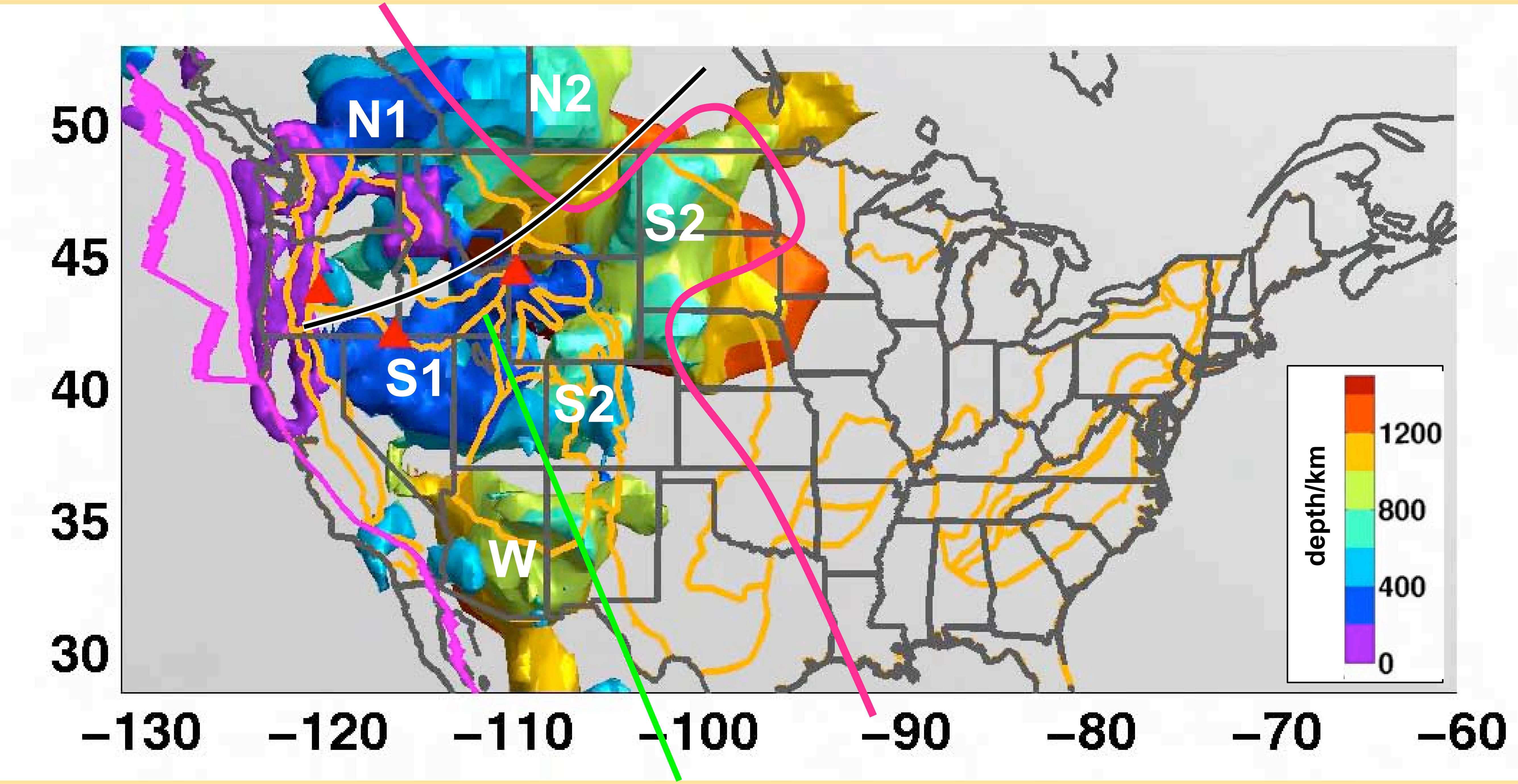
Sig 008

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

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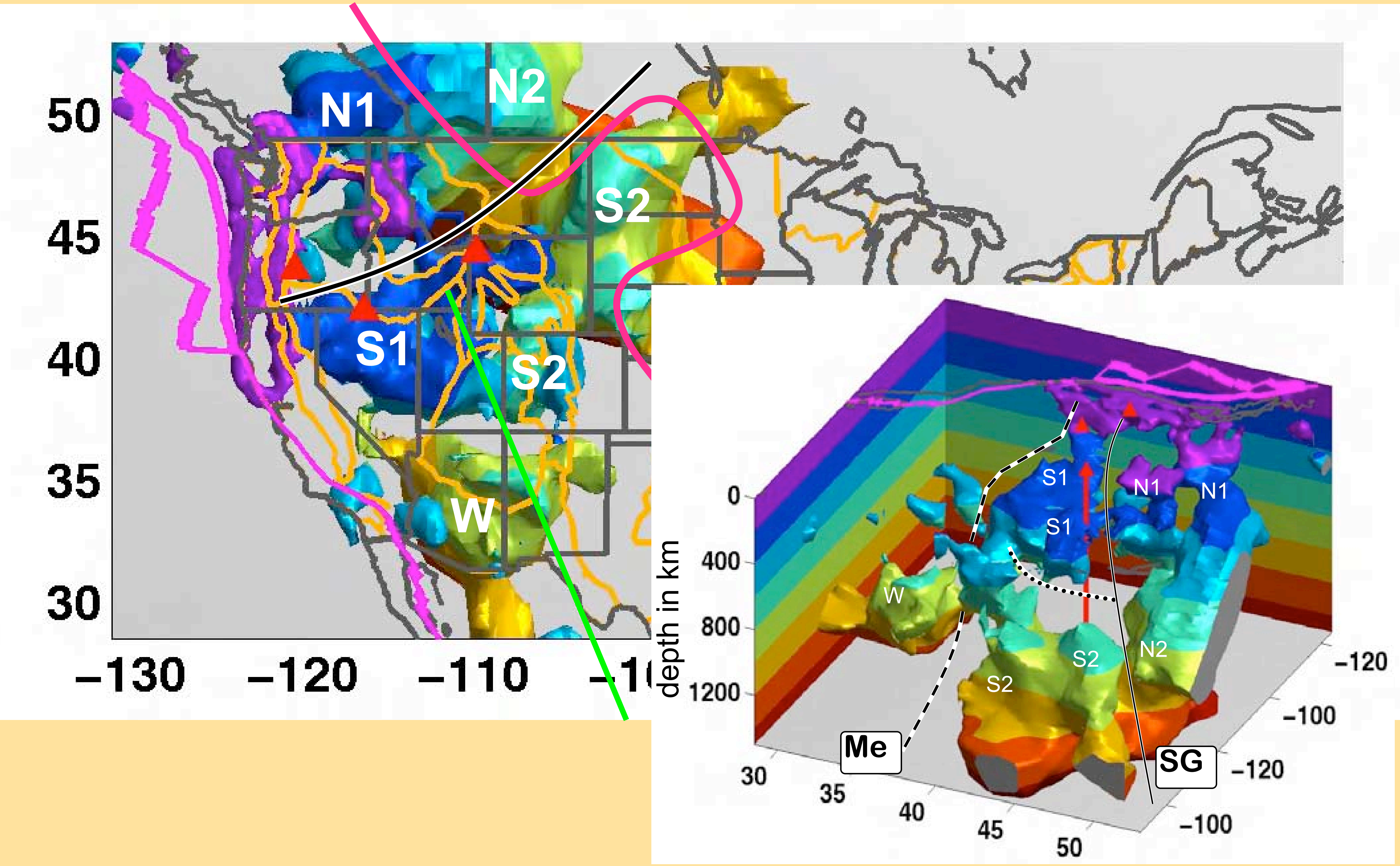
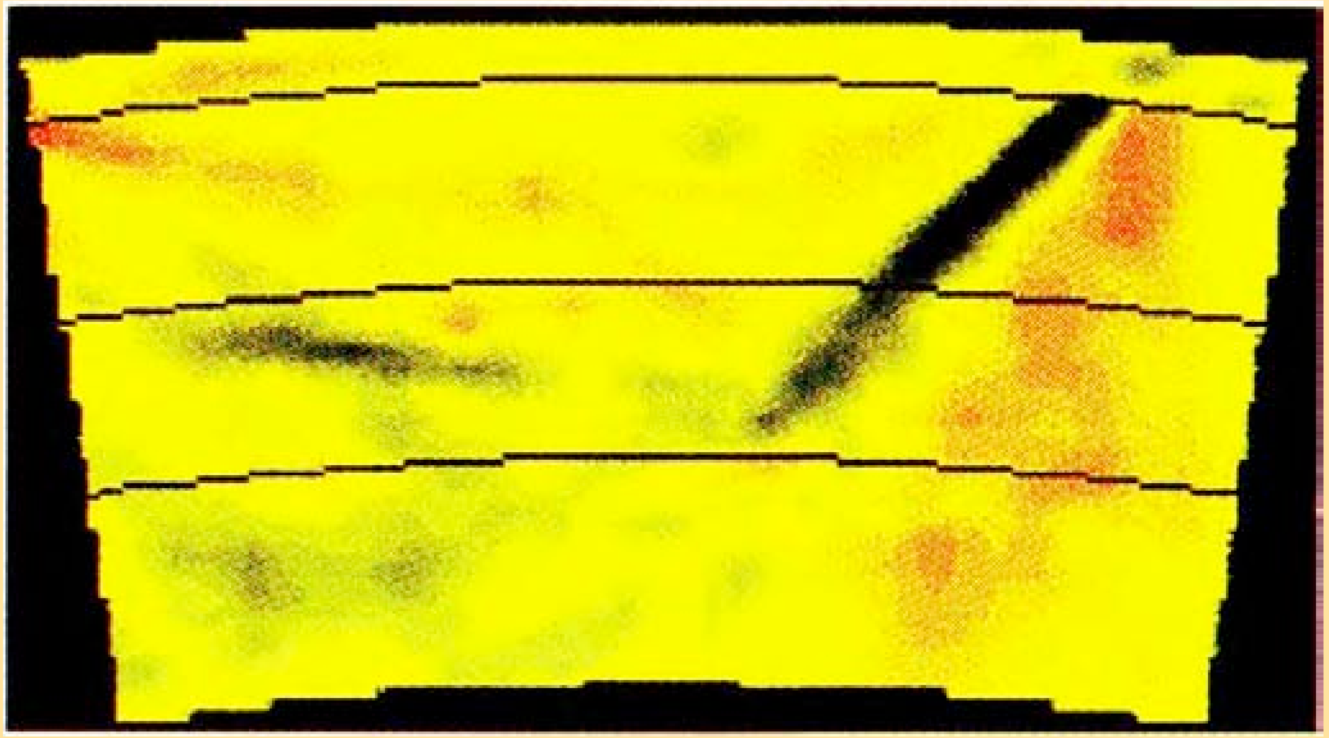
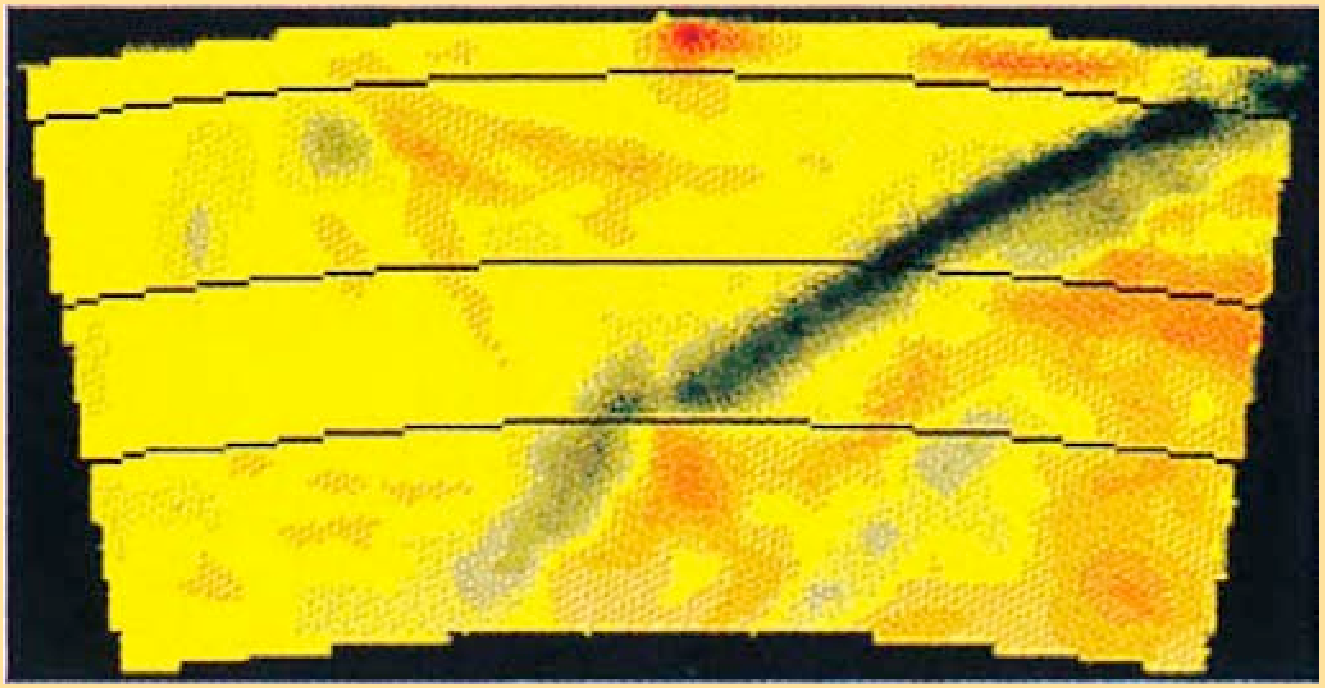


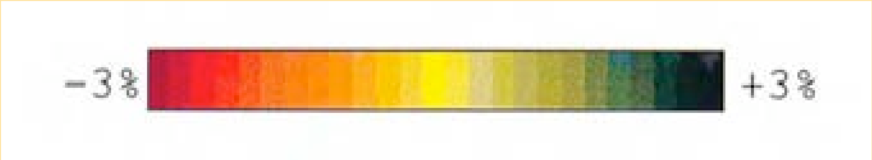
return flow across a TBL?

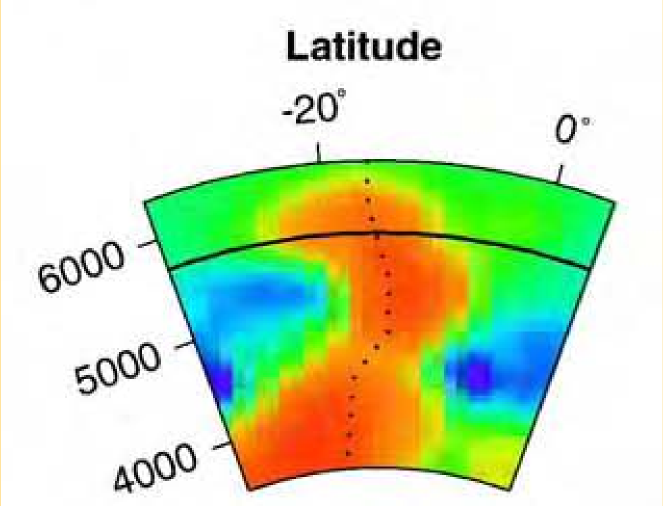


Tonga-Kermadec
(Deal et al., 1999)

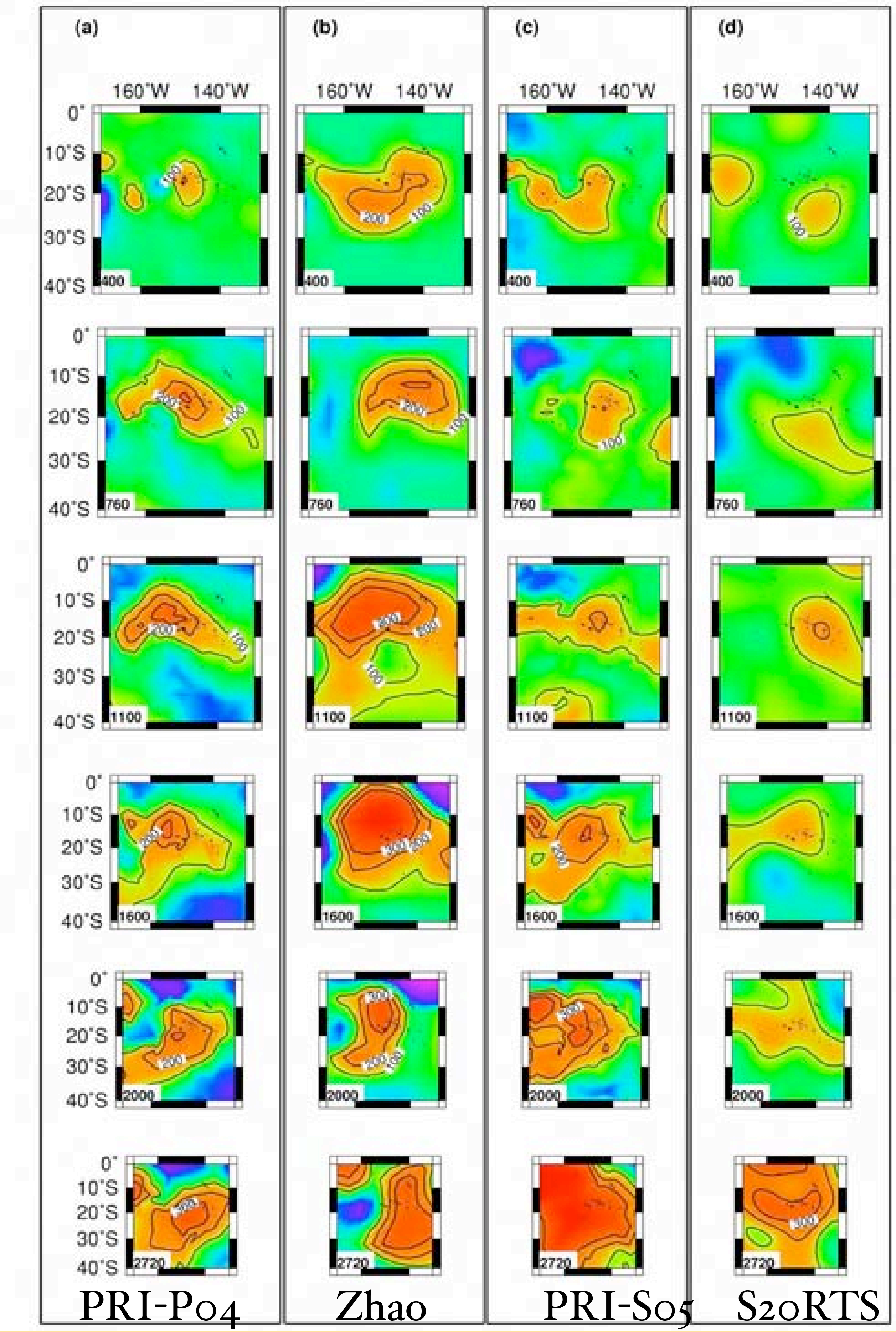


Japan 42° N
(Deal & Nolet, 1999)

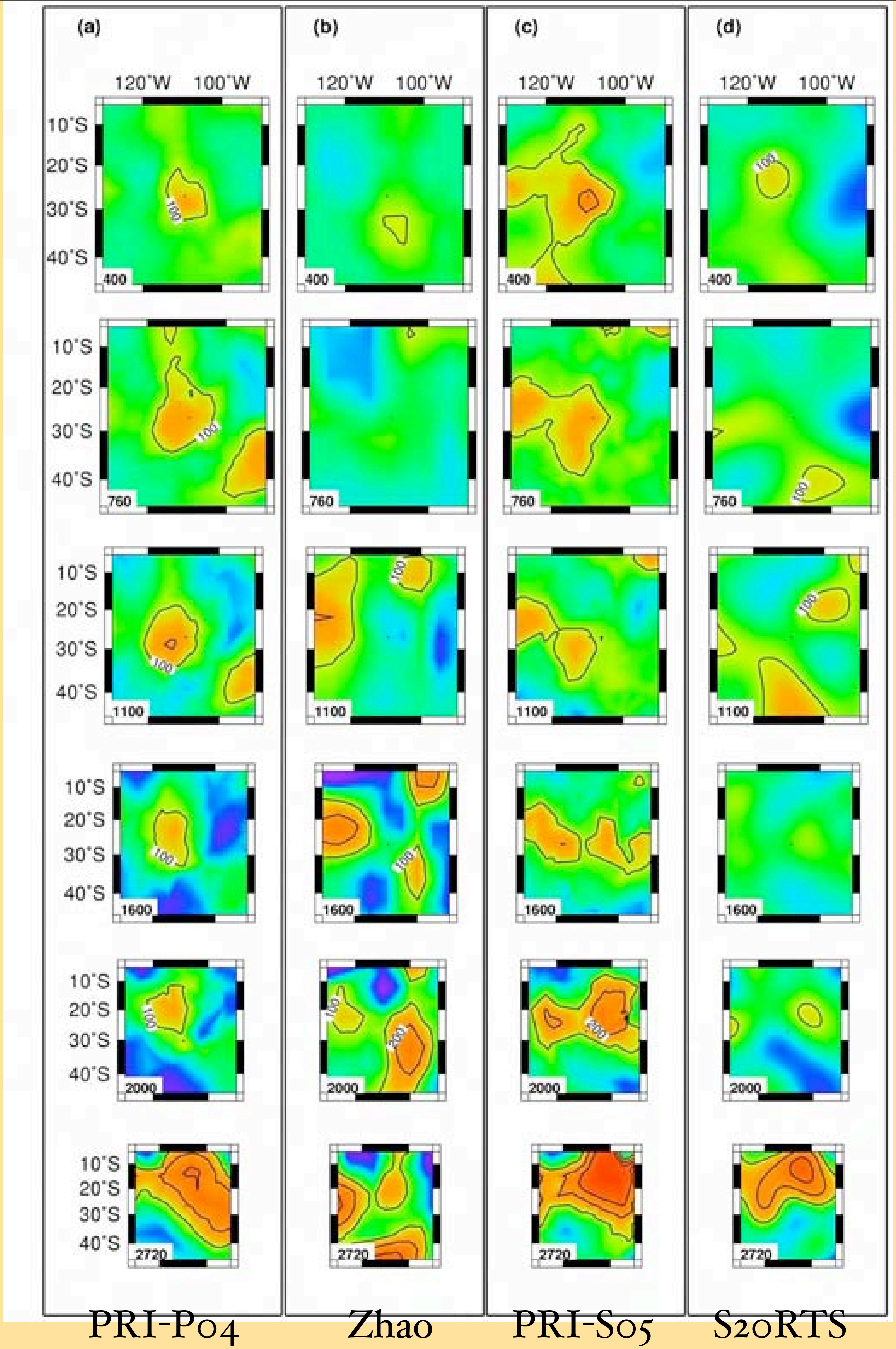




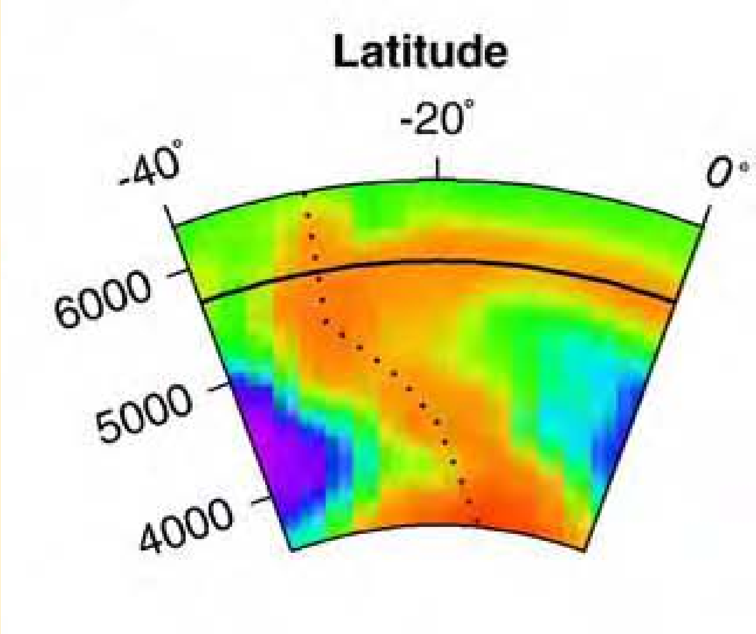
Tahiti
(Society Isl)



ΔV_P and ΔV_S converted to ΔT (K)



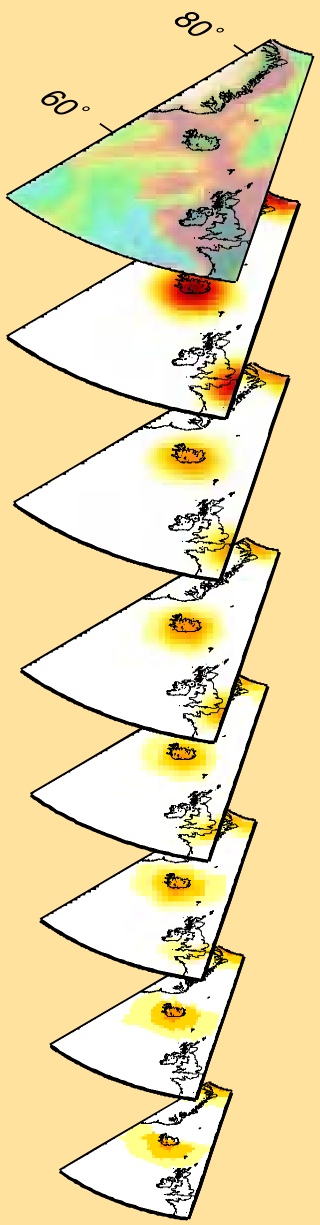
PRI-P04 Zhao PRI-S05 S20RTS



Easter island

ΔV_P and ΔV_S converted to ΔT (K)

Thin plumes are not resolved

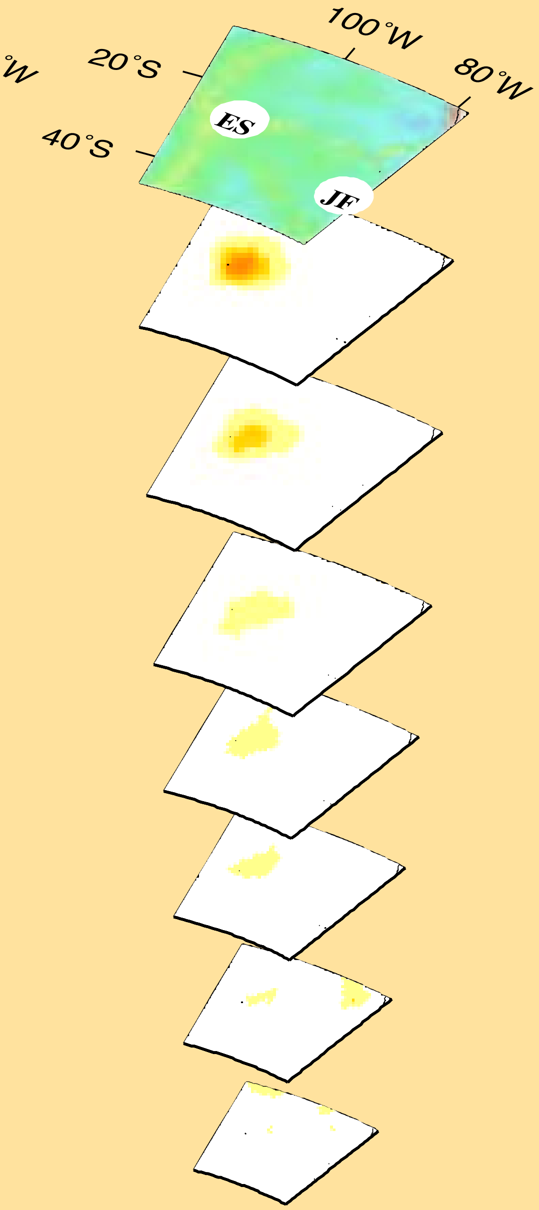


z=2800 km, w=400 km

Input

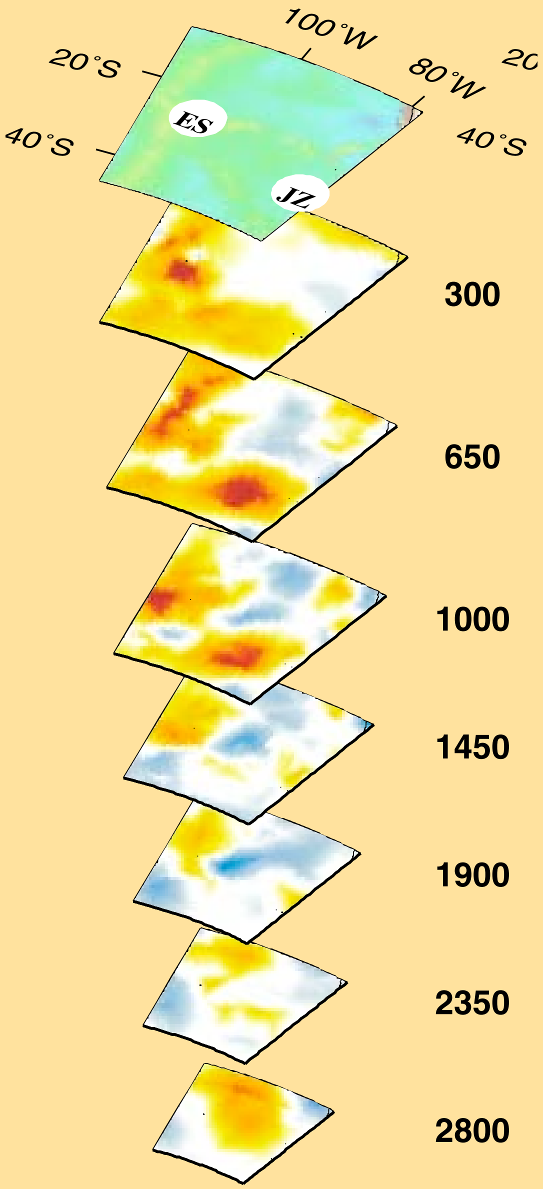
Easter/Juan Fernandez

200 km



Easter/Juan Fernandez

400 km



P WAVES

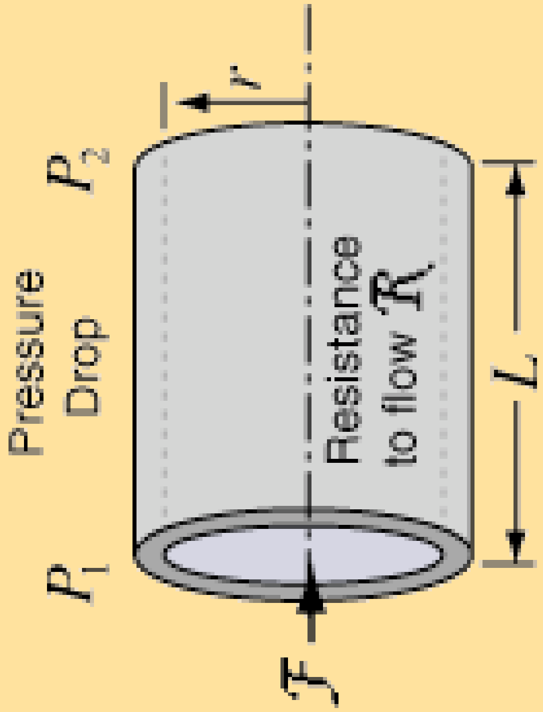
PRI-P05

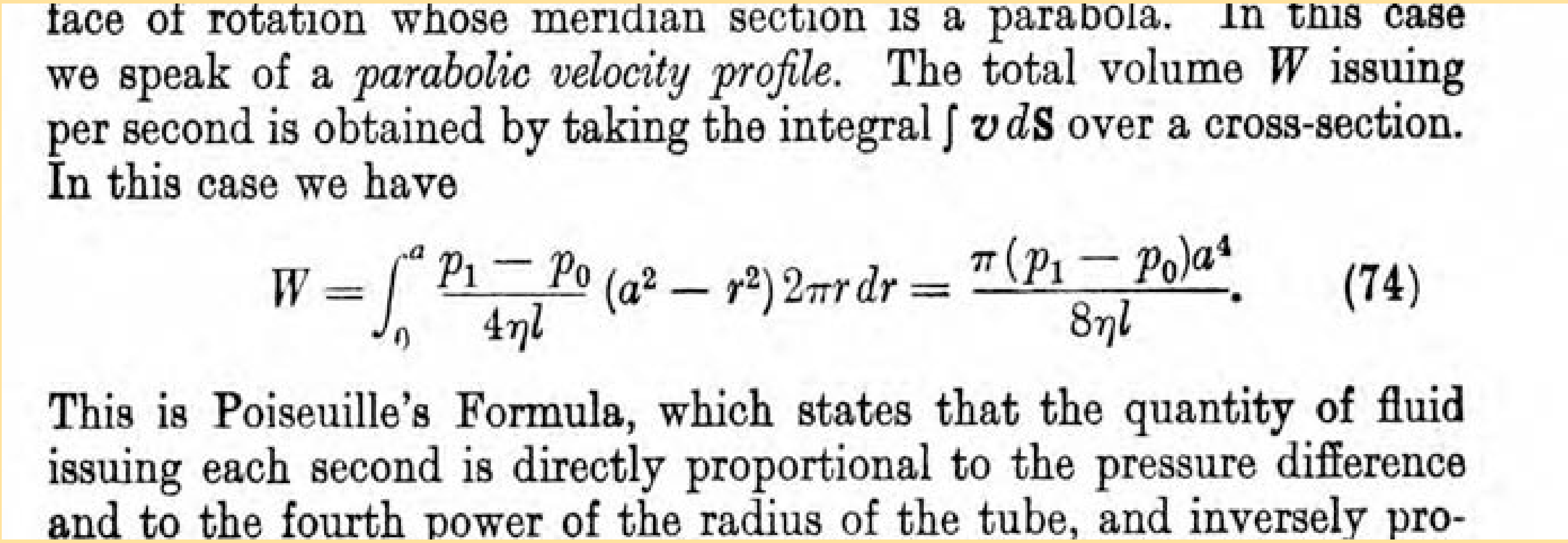
Plumes are larger than we thought

- 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

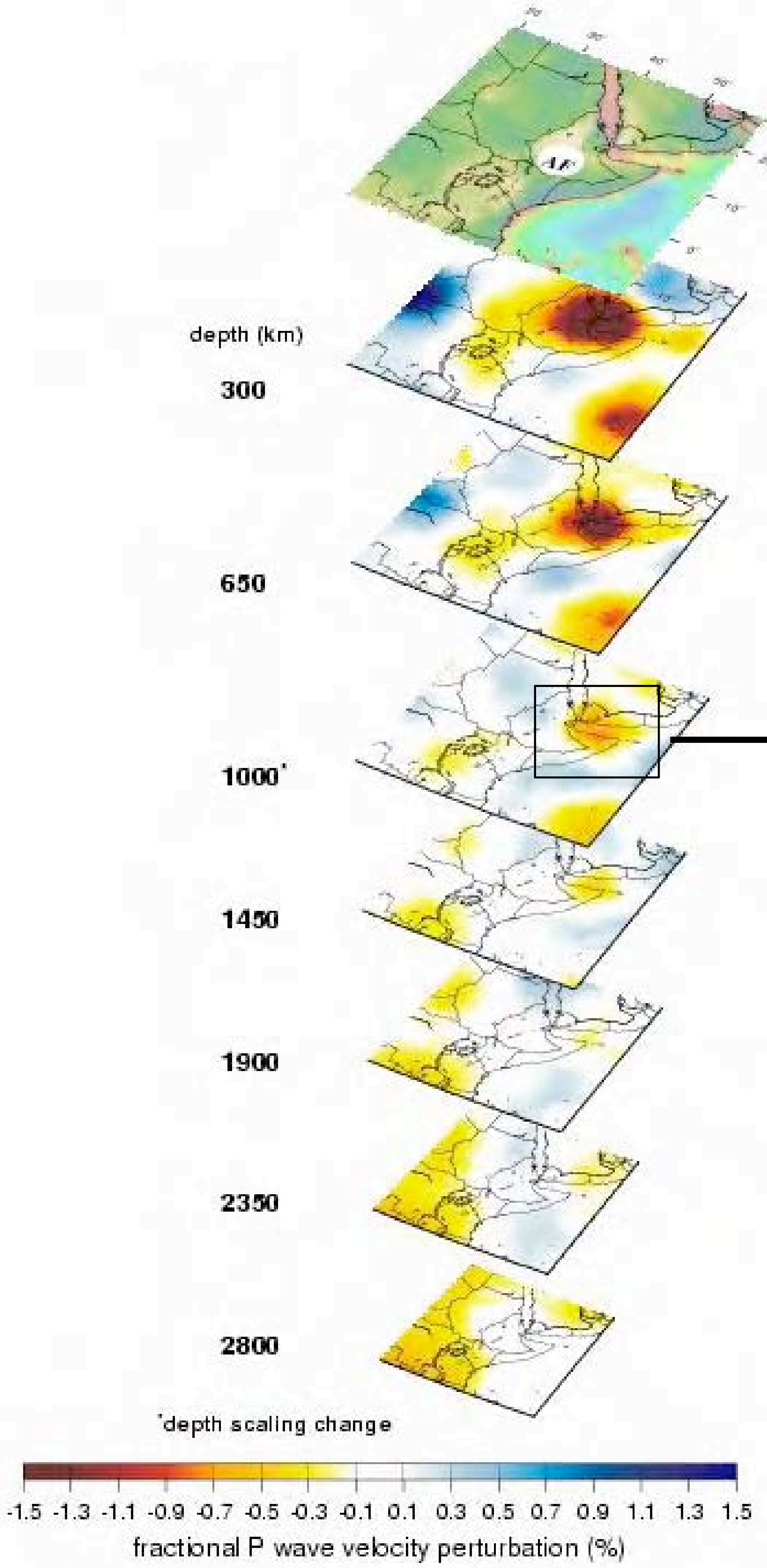


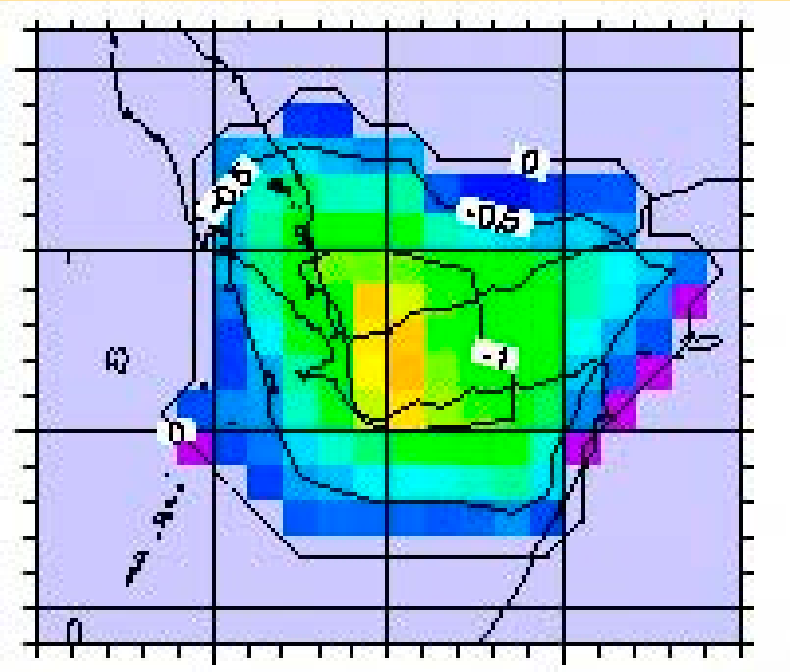

face of rotation whose meridian section is a parabola. In this case we speak of a *parabolic velocity profile*. The total volume W issuing per second is obtained by taking the integral $\int \boldsymbol{v}\, d\mathbf{S}$ over a cross-section. In this case we have

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

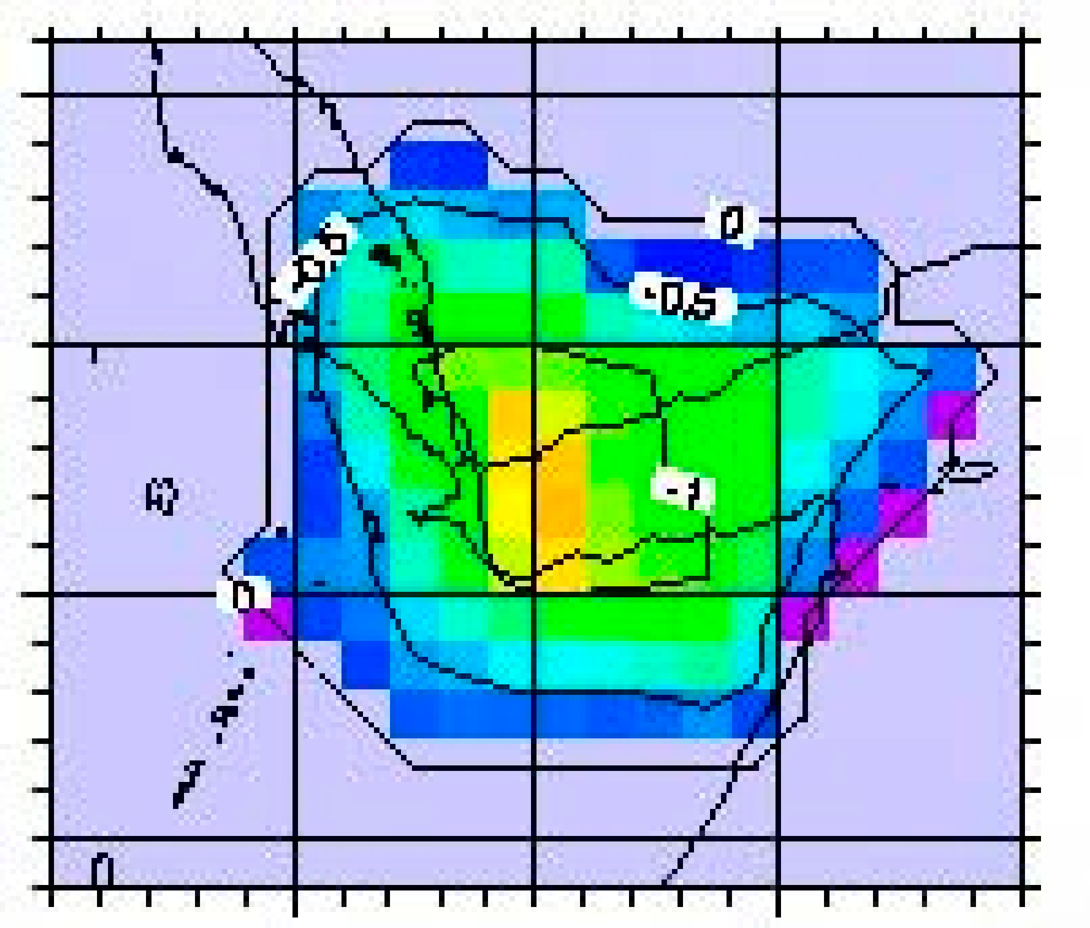
This is Poiseuille's Formula, which states that the quantity of fluid issuing each second is directly proportional to the pressure difference and to the fourth power of the radius of the tube, and inversely pro-

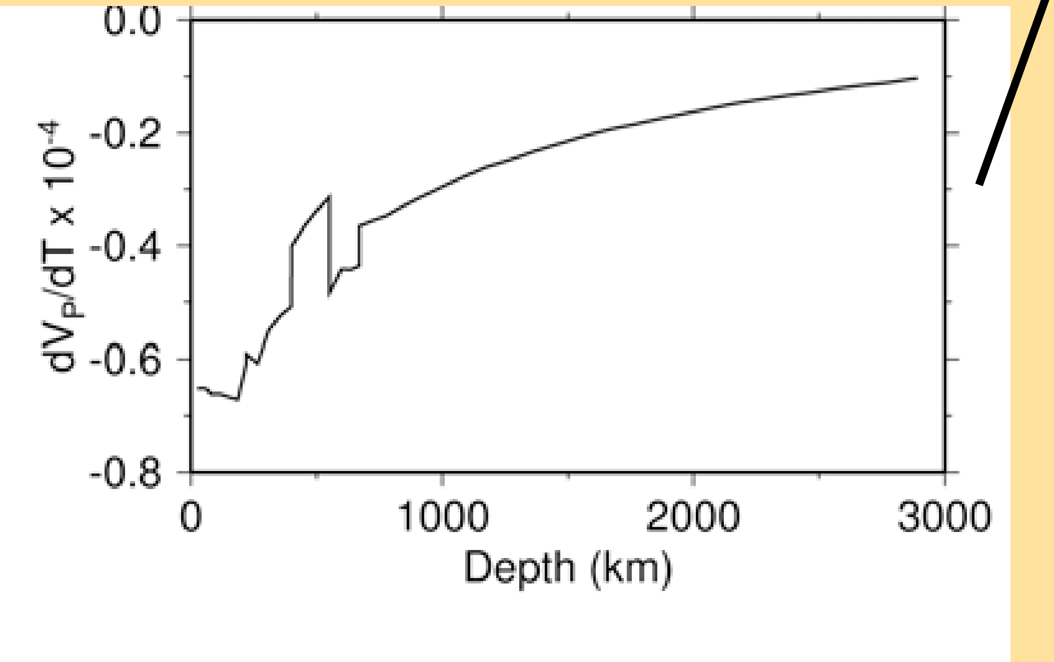
The method, step 1: isolate a depth section from the 3D model of ΔVp/Vp

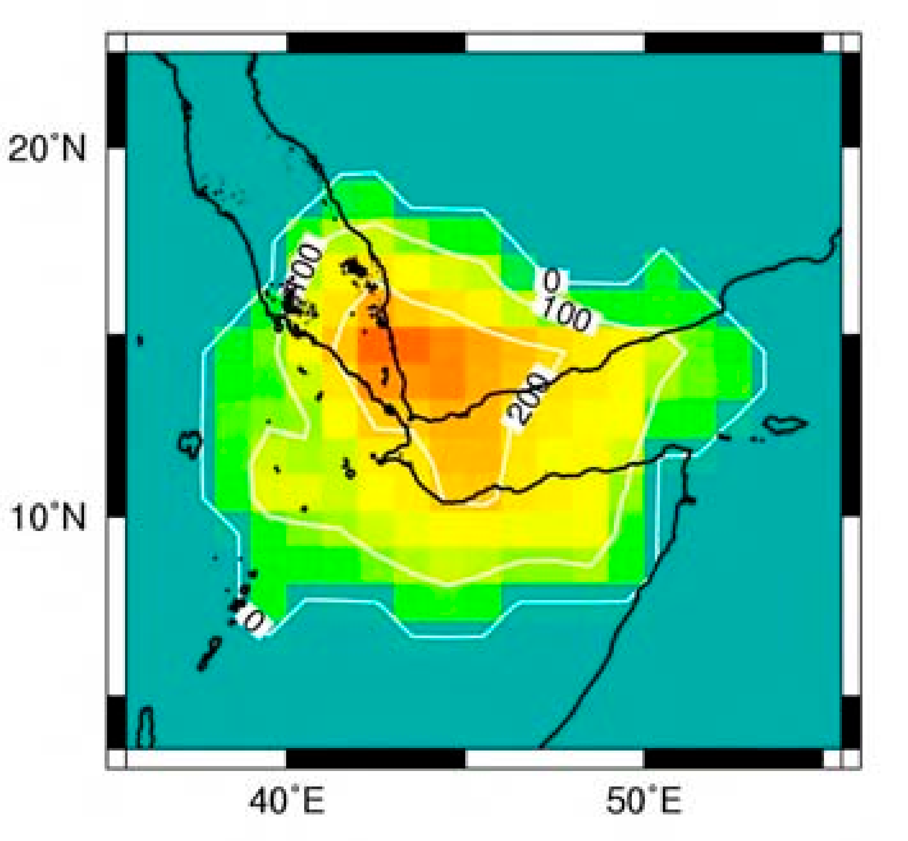




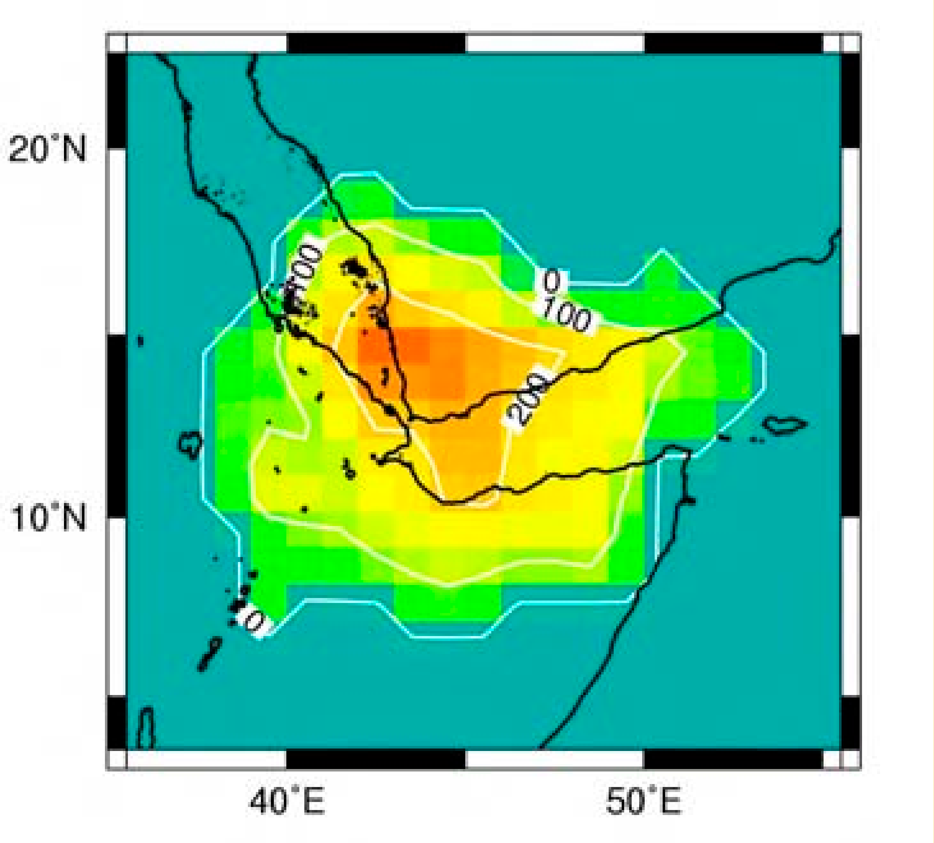
step 2: from V_P anomaly to Temperature anomaly

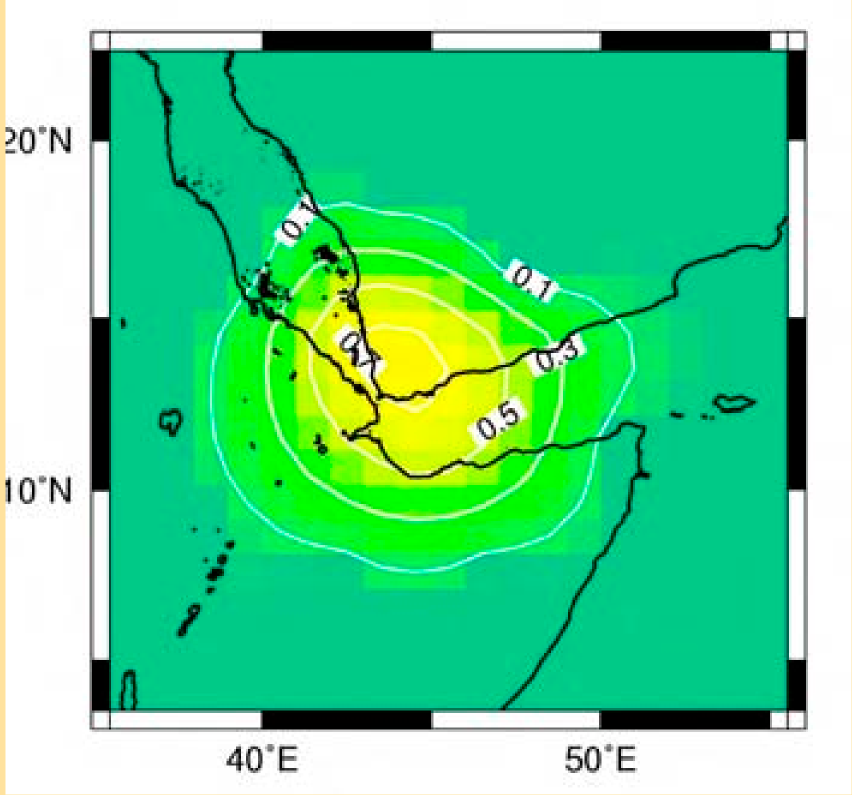






3: from Temperature anomaly to Rise velocity

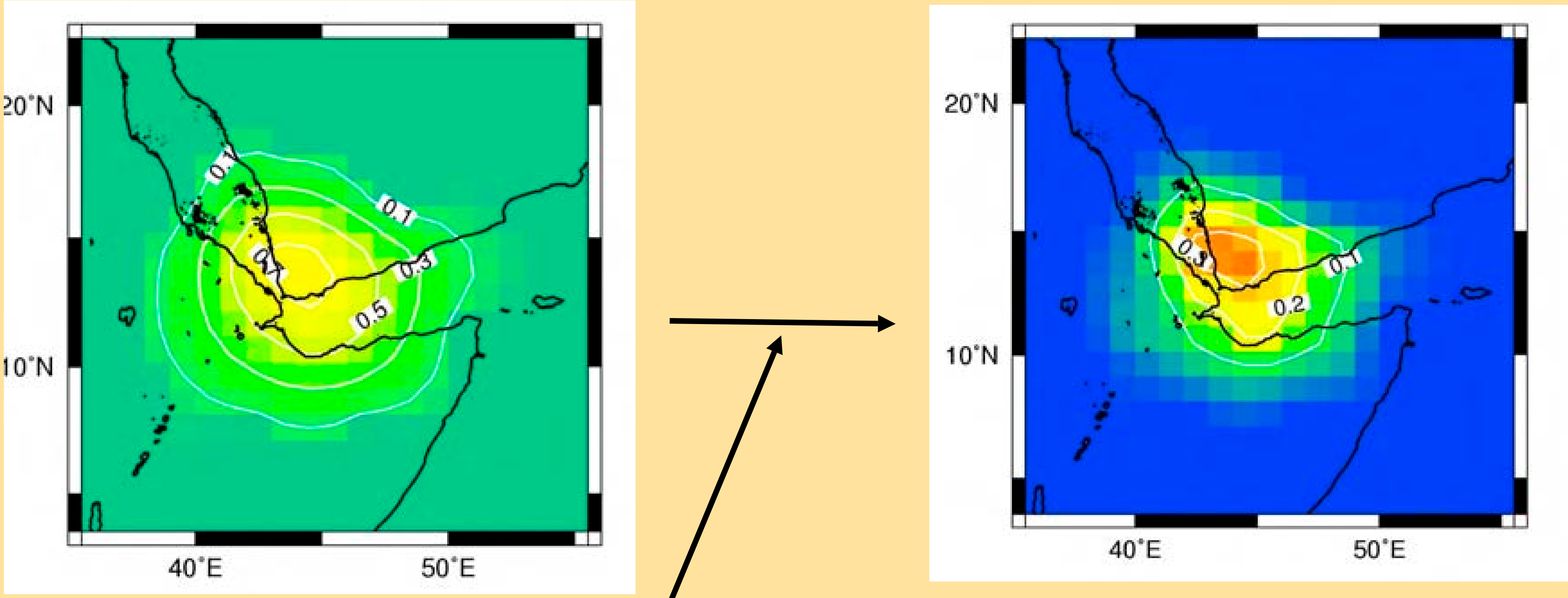




$$\eta \nabla^2 v_z = -\alpha \rho g \Delta T + g \Delta \rho_{Fe}$$

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

4: from rise velocity to Heat flux

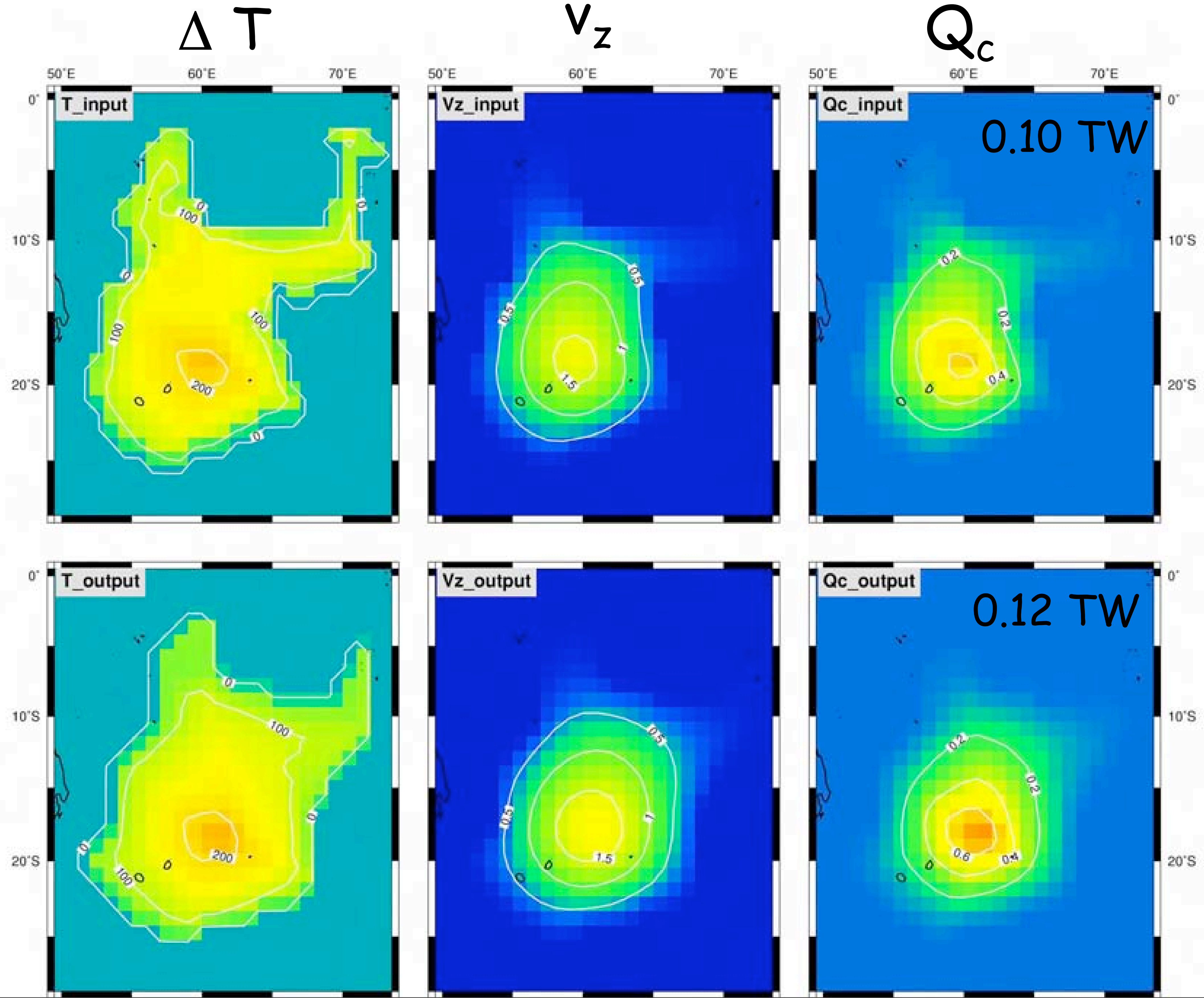


$$\boxed{Q_C = c_P \ \rho \Delta T \ v_z}$$

Sensitivity test: how good is the estimate?

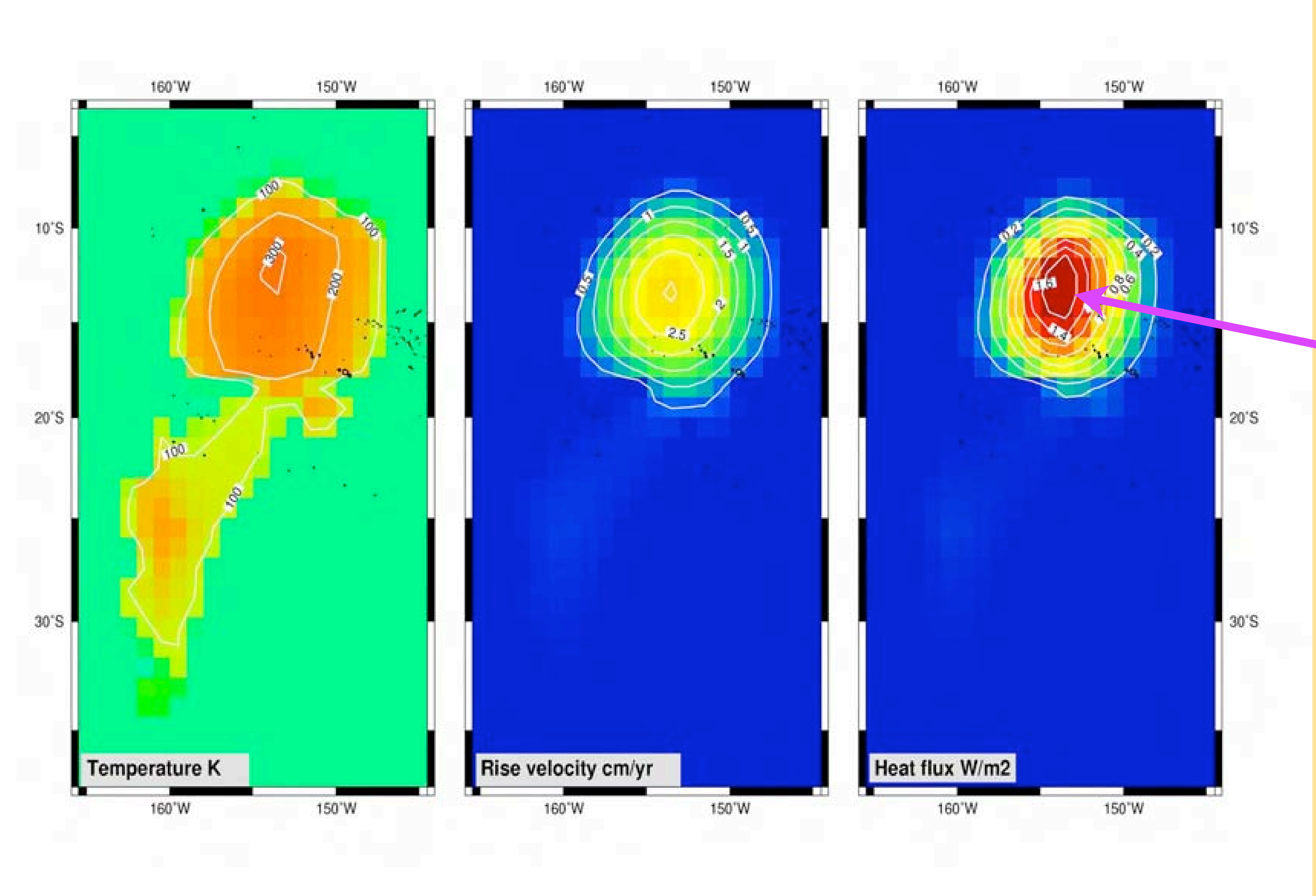
in:

out:



Reunion
1100 km

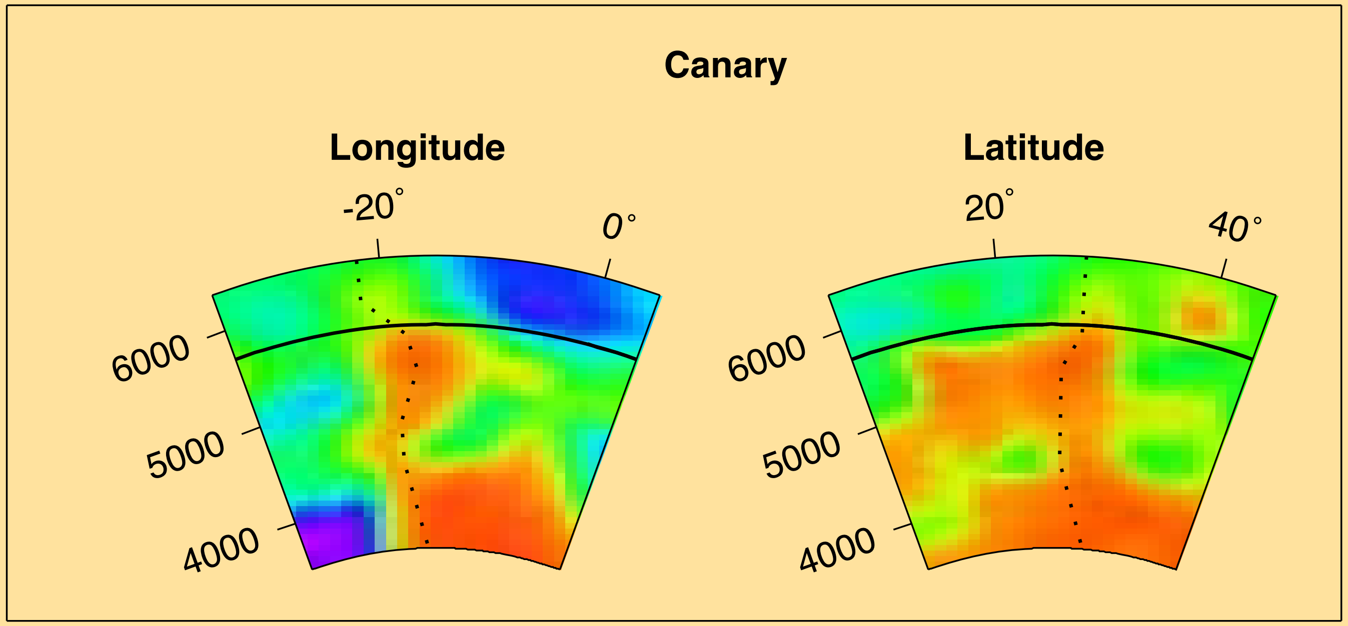
Plumes are larger than we thought

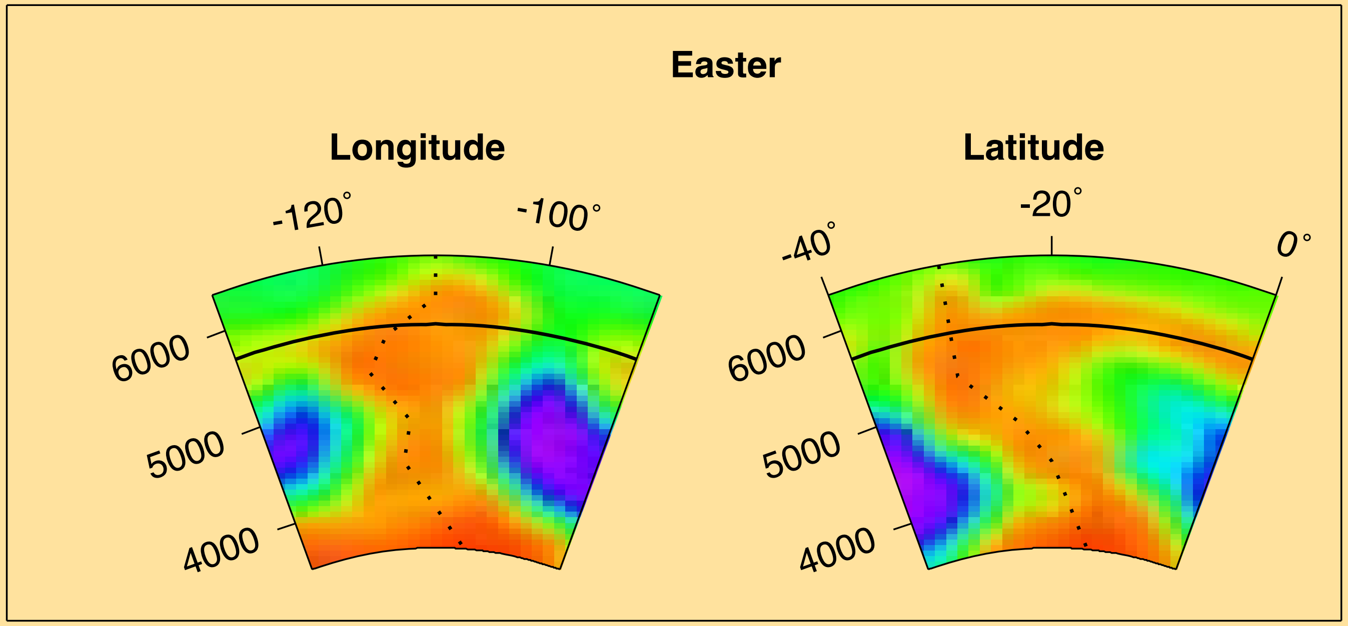


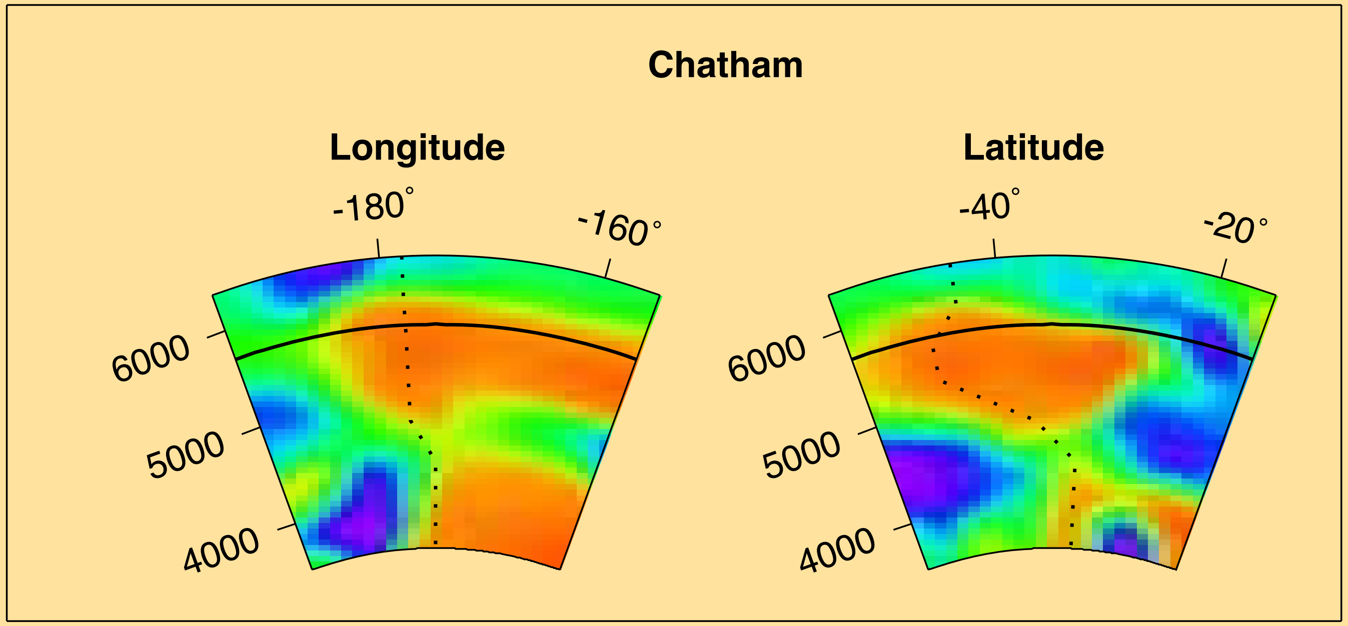
Total
flux
0.5 TW

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

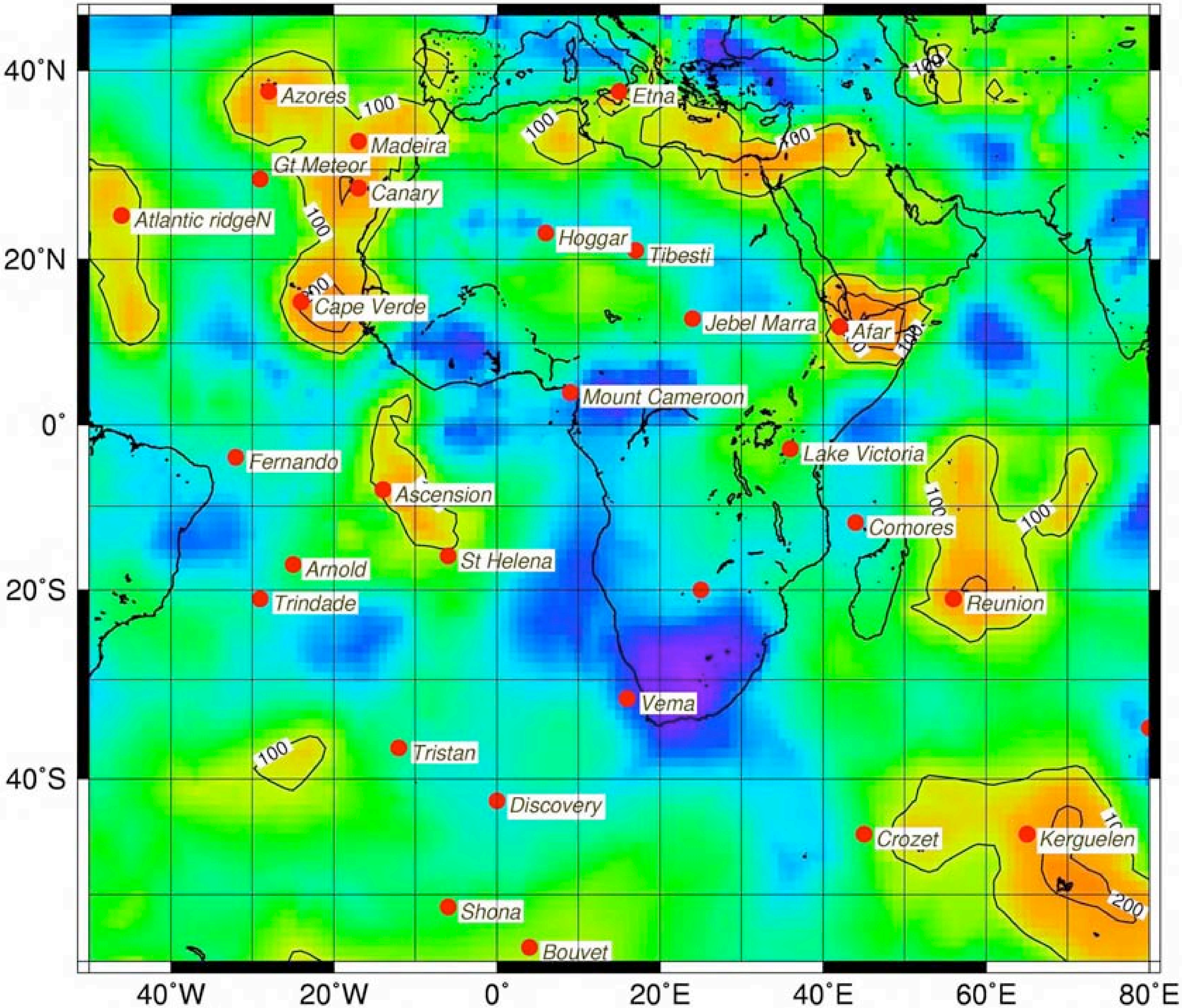
(Some) plumes broaden below 660 km depth



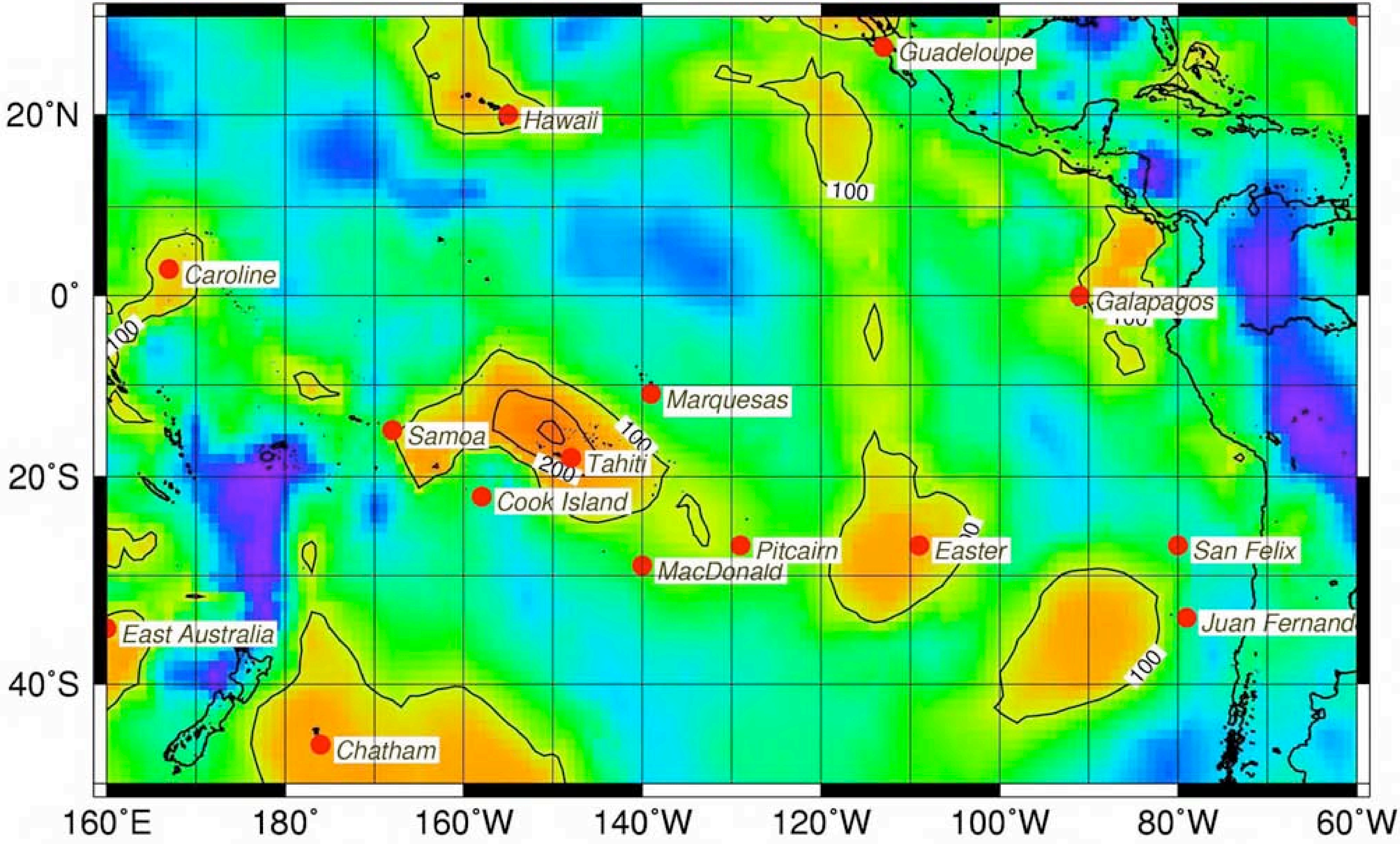




Nolet et al., 2006

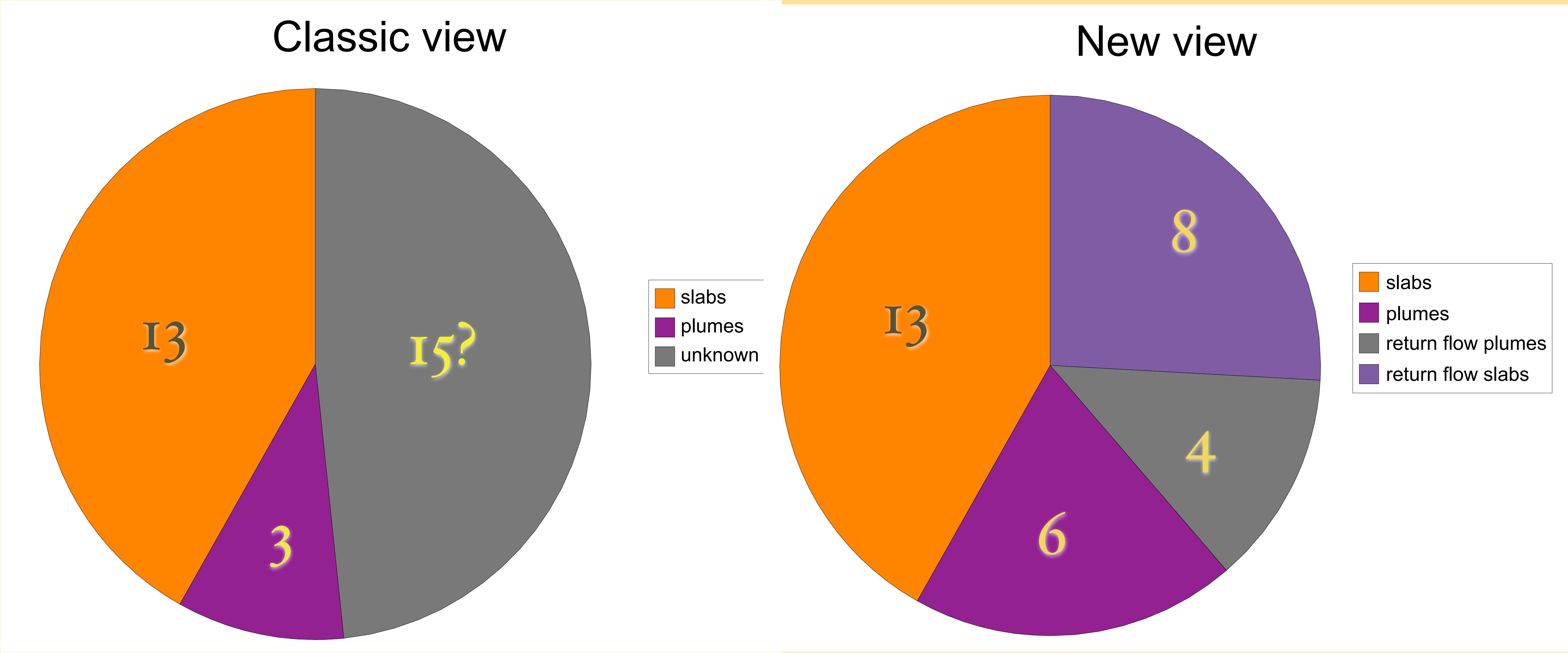

40°N
20°N
0°
20°S
40°S
40°W
20°W
0°
20°E
40°E
60°E
80°E
Azores
Etna
Madeira
Gt Meteor
Canary
Atlantic ridgeN
Hoggar
Tibesti
Cape Verde
Jebel Marra
Afar
Mount Cameroon
Lake Victoria
Fernando
Ascension
Comores
Arnold
St Helena
Trindade
Reunion
Vema
Tristan
Discovery
Crozet
Kerguelen
Shona
Bouvet
100
200

ΔT (K)
at 800 km

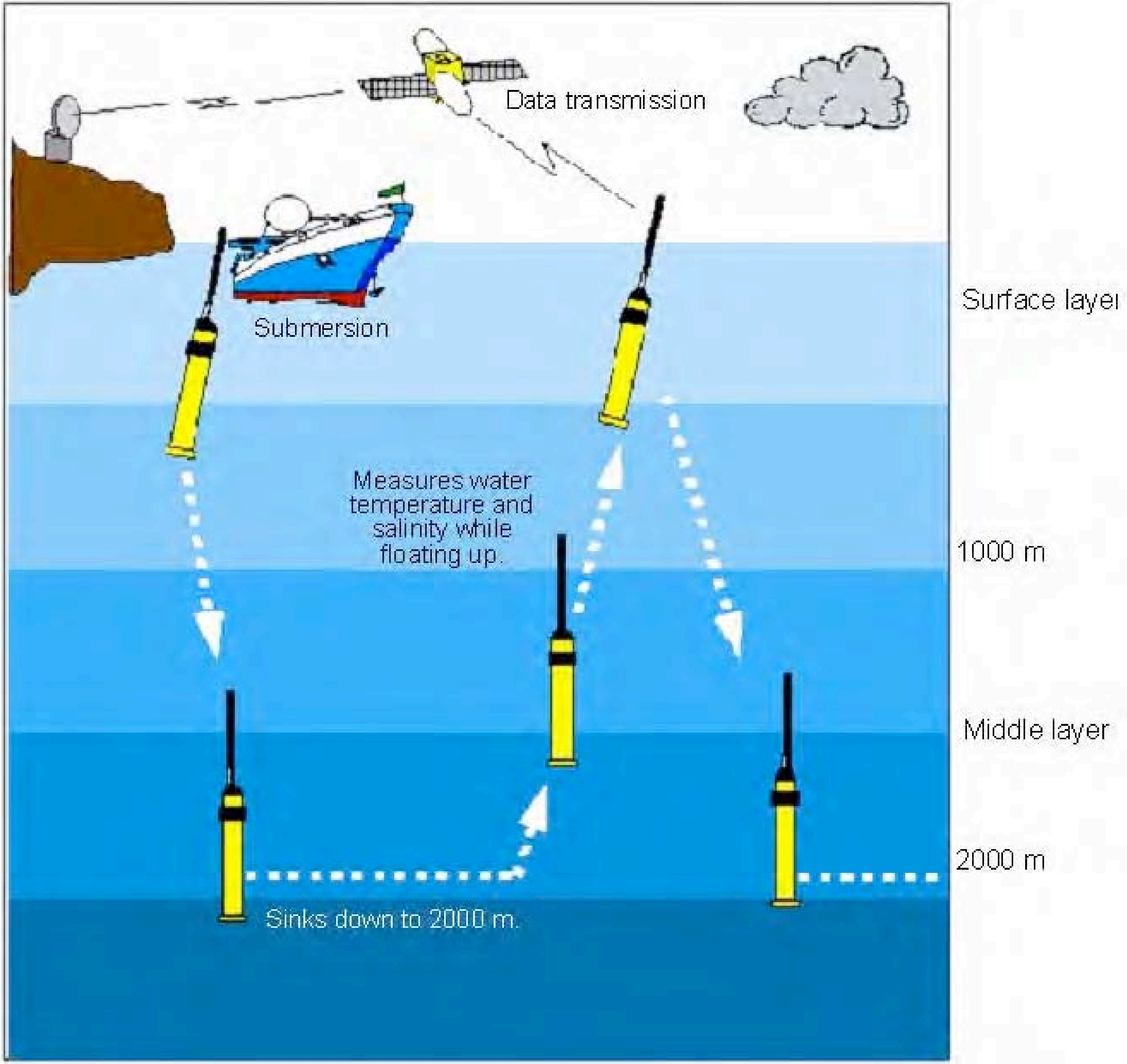


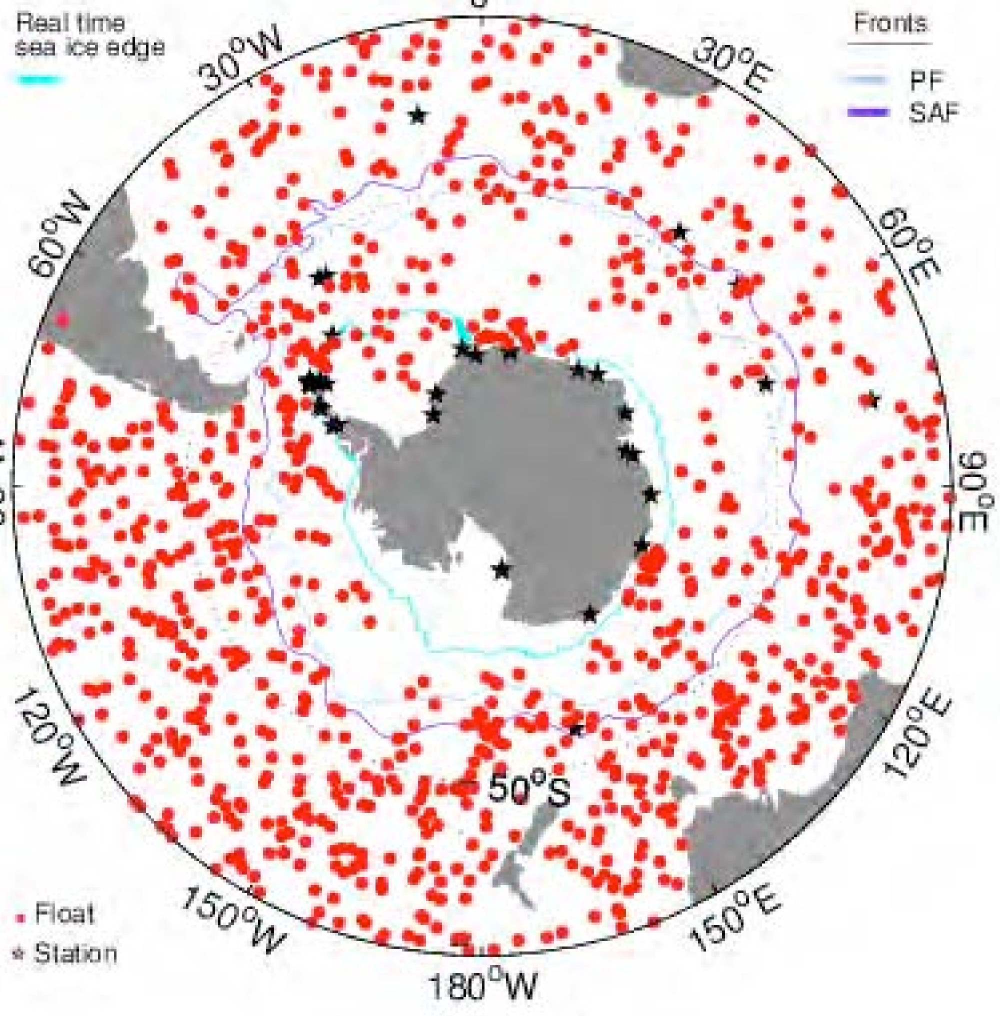
Inferred ΔT (K) from ΔV_P at 800 km depth

31 TW across 660 ?



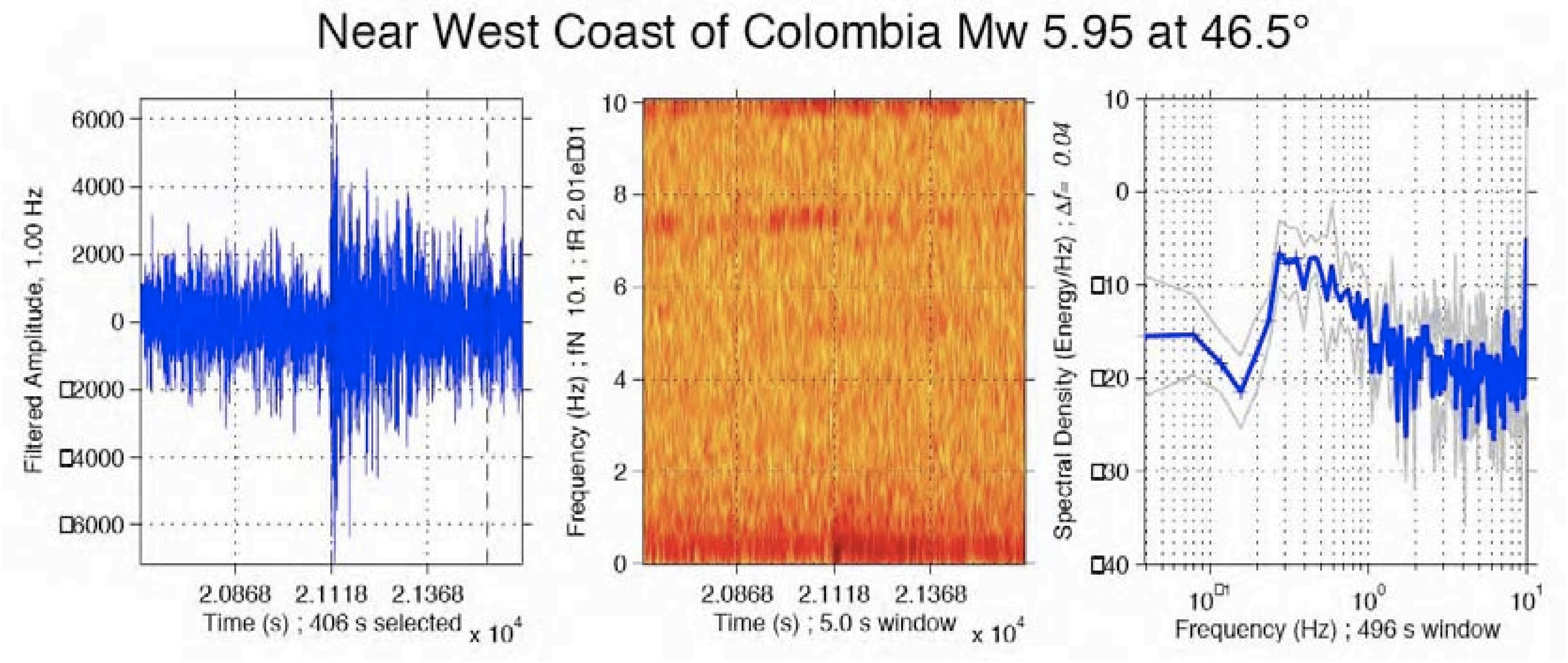
ARGO floats


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



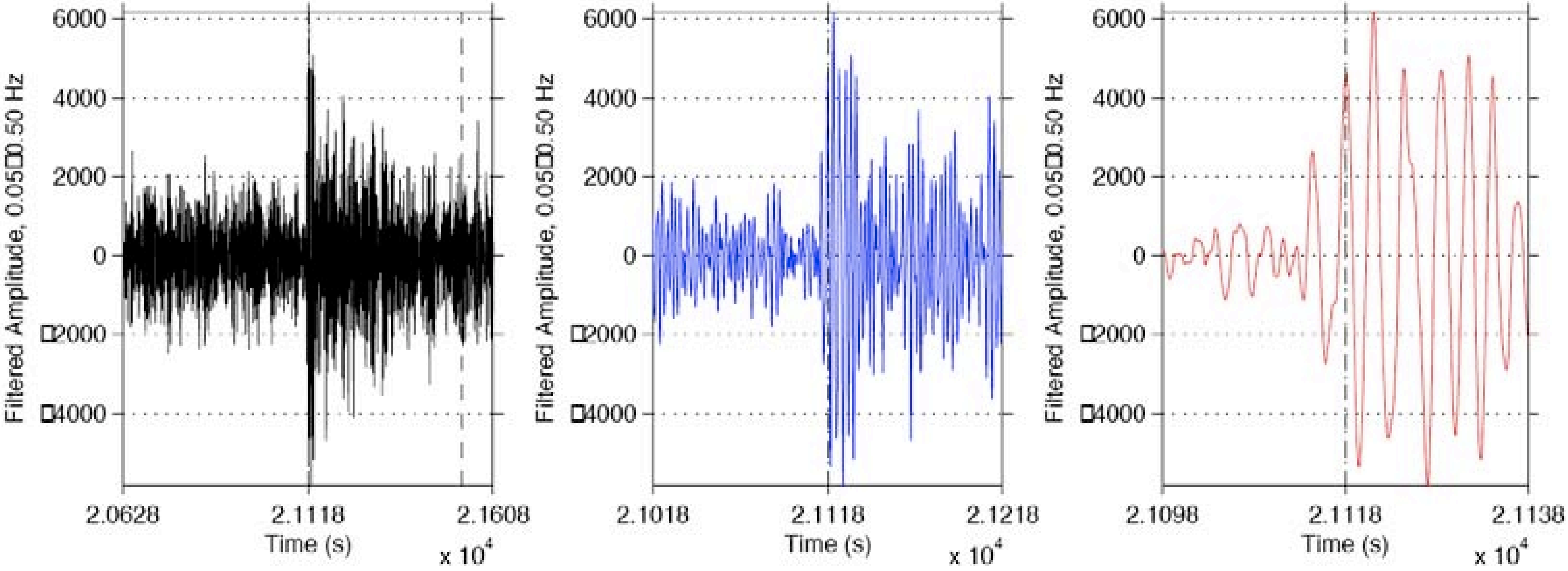
Float Positions: 02–Apr–2008

Frederik Simons (pers. comm.)


Near West Coast of Colombia Mw 5.95 at 46.5°

Frederik Simons (pers. comm.)

Zooming in on the onset →



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