

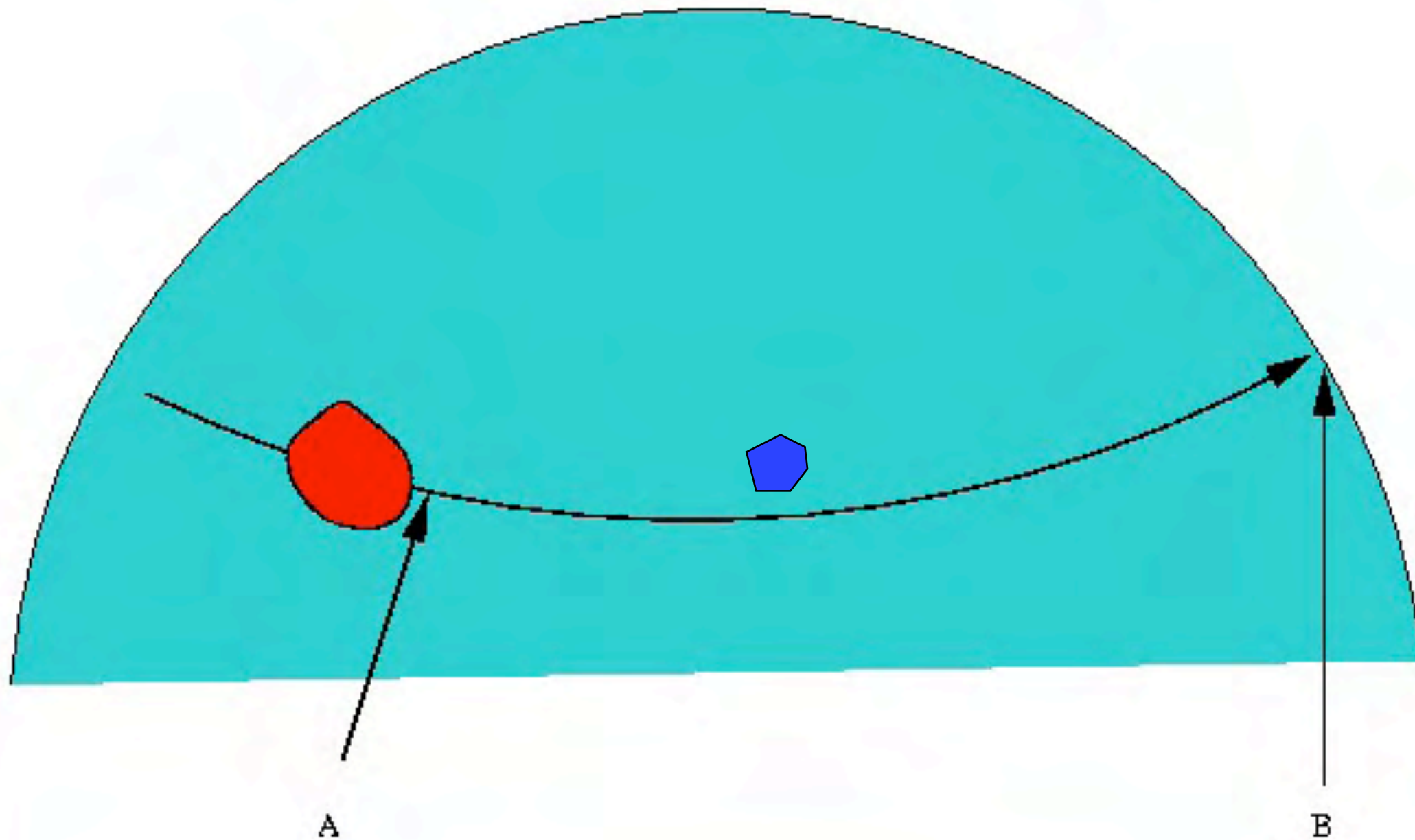
seismic tomography in transition

Guust Nolet, Geoazur (France)

new developments

- Move away from ray theory
- Super-arrays on continents
- Robots in the oceans

What is the width of a ray?



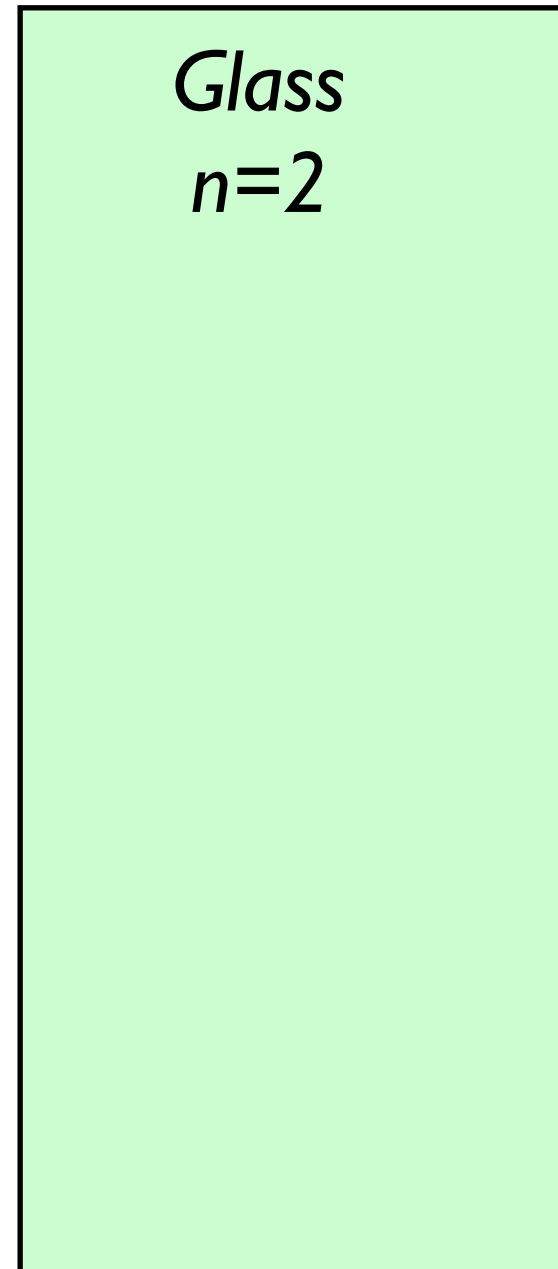
onset time



From Jeffreys, "The Earth"

The speed of a photon in glass

Vacuum
 $n=1$



The speed of a photon in glass

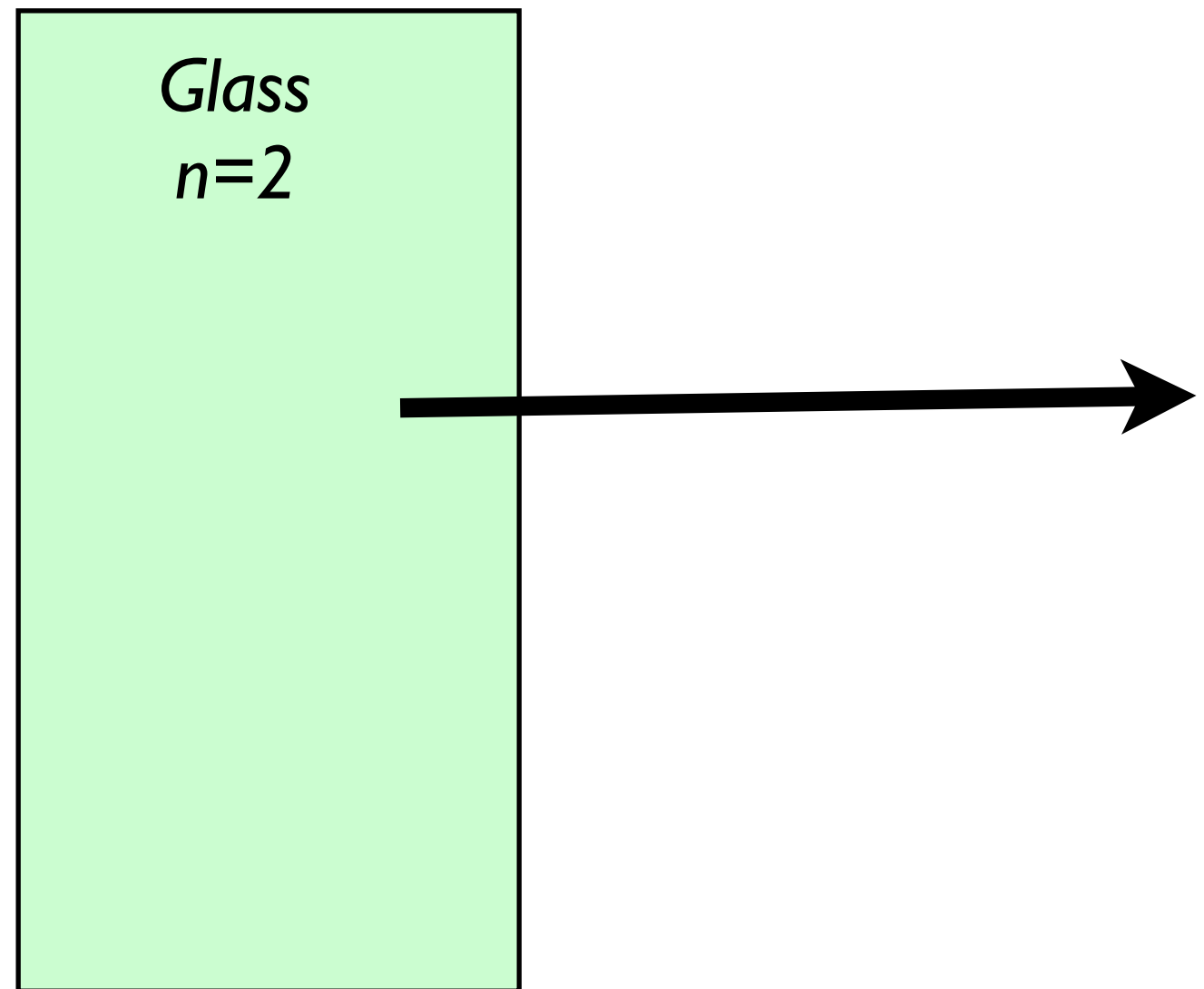
Vacuum
 $n=1$

Glass
 $n=2$



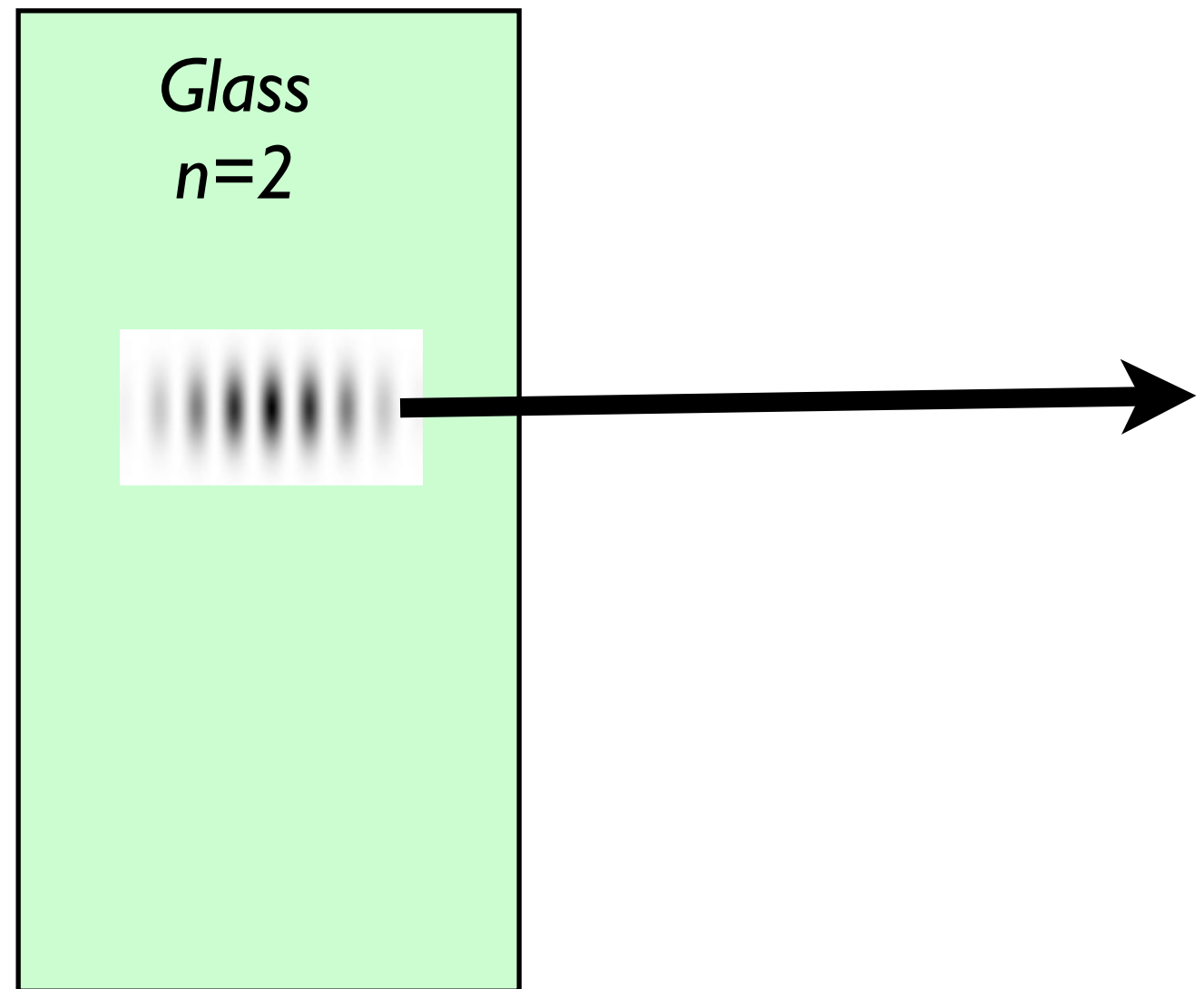
The photon speed

- (a) $v=c$
- (b) $v=c/2$
- (c) don't know

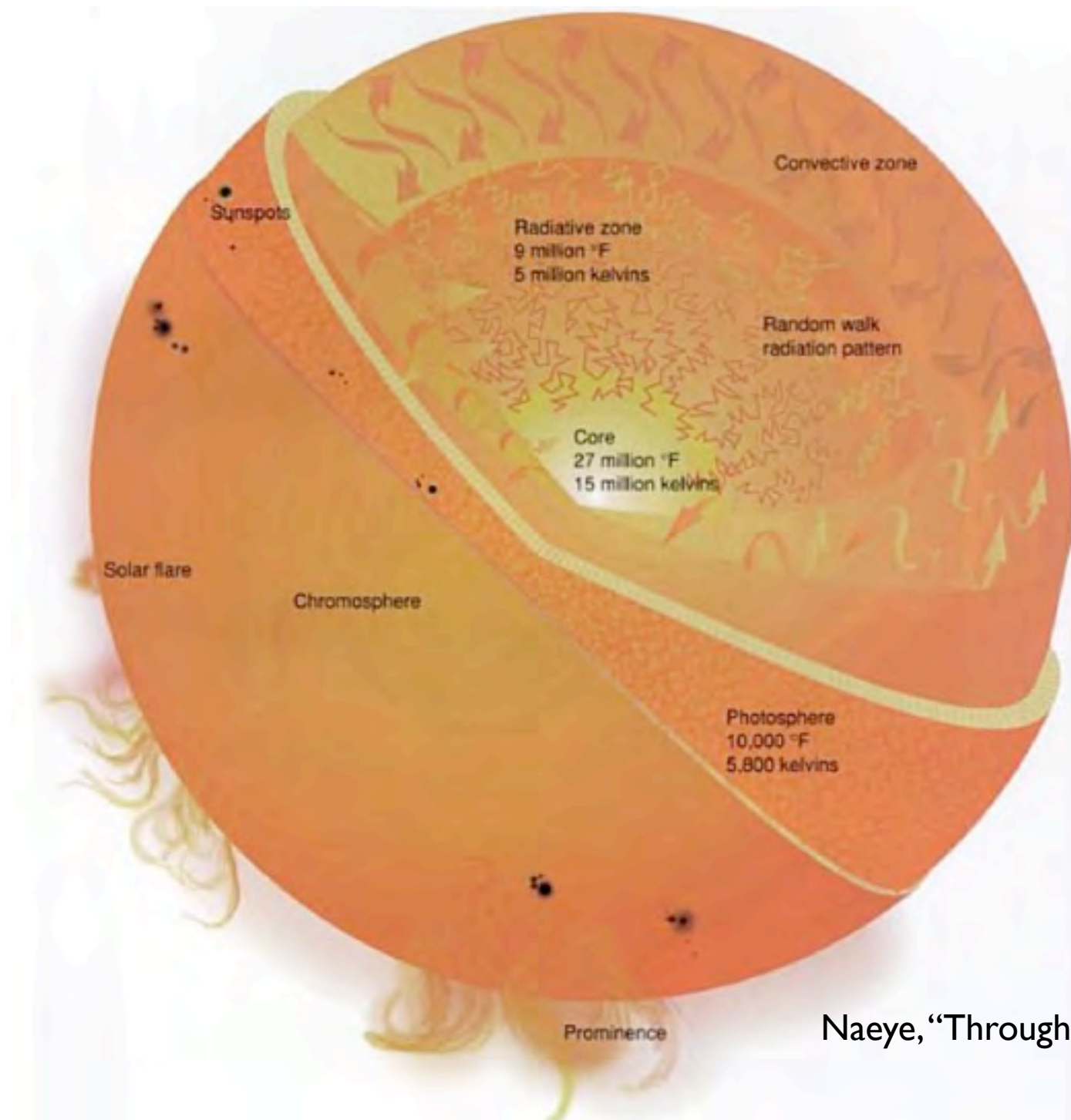


The photon speed

- (a) $v=c$
- (b) $v=c/2$
- (c) don't know

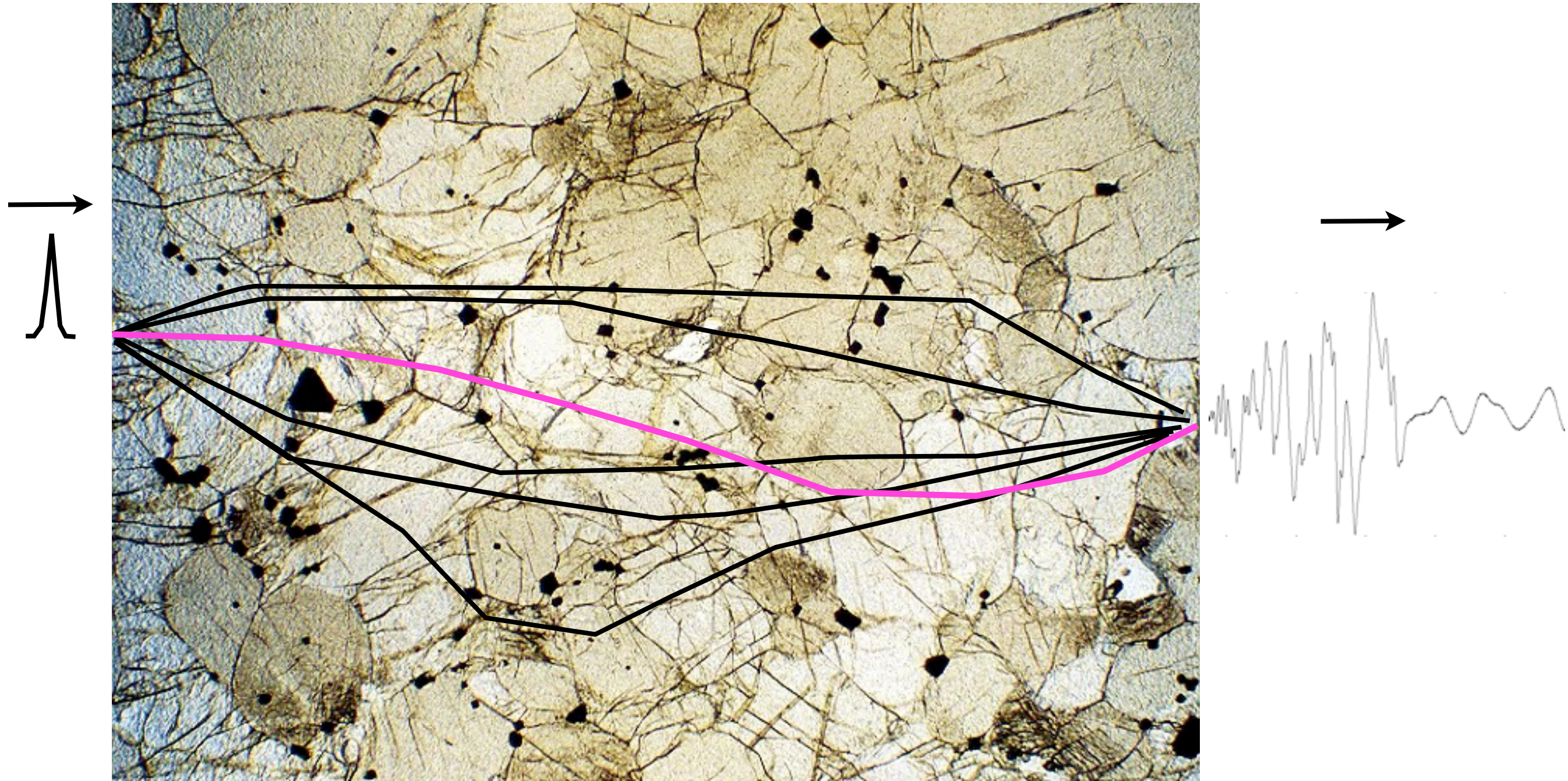


A photon in the Sun

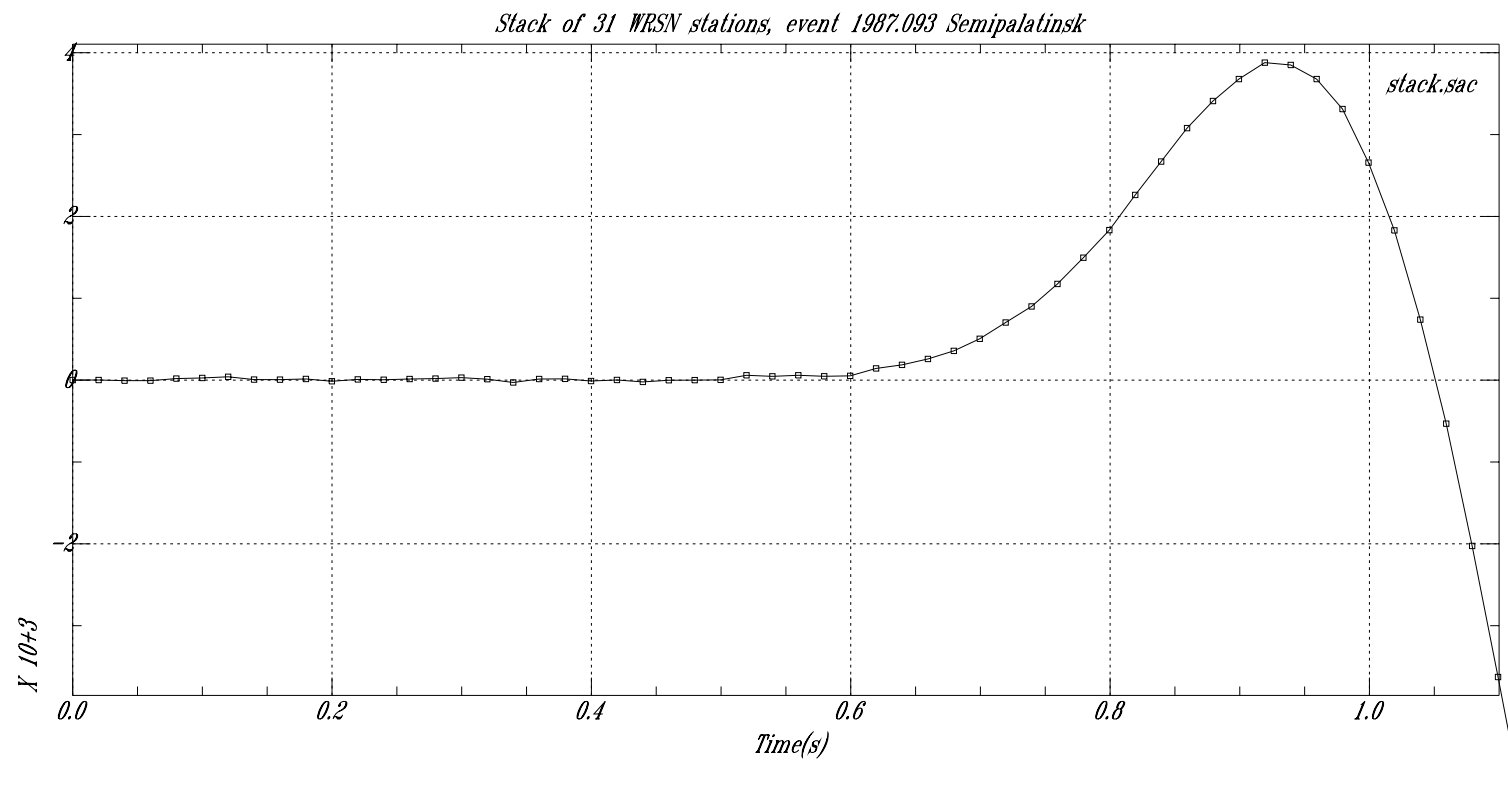


Naeye, "Through the eyes of Hubble" (CRC Press, 1998).

Back to rocks

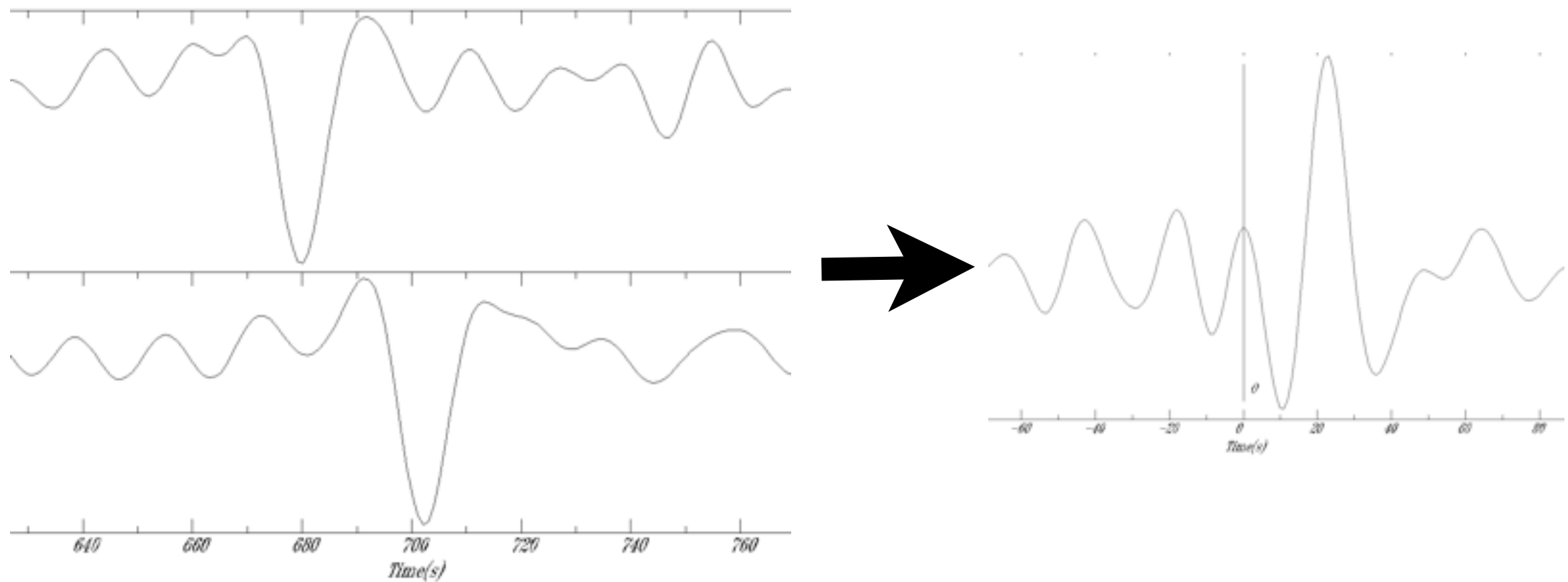


Picking the onset is **at best ambiguous**
or inaccurate, sometimes impossible.



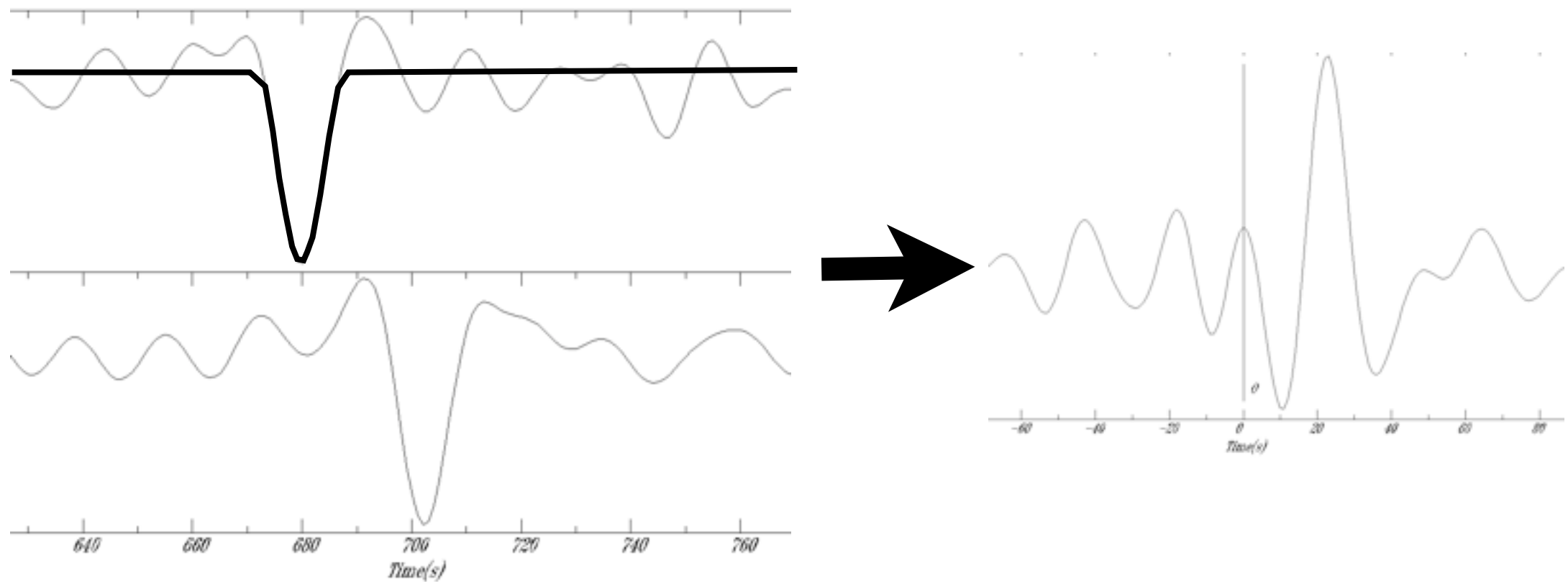
Because onsets require absence of dispersion

cross-correlation



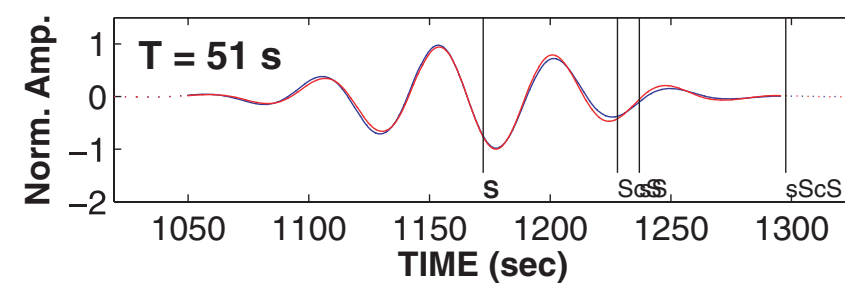
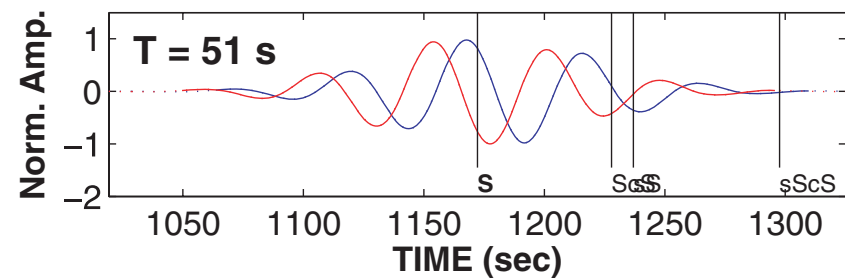
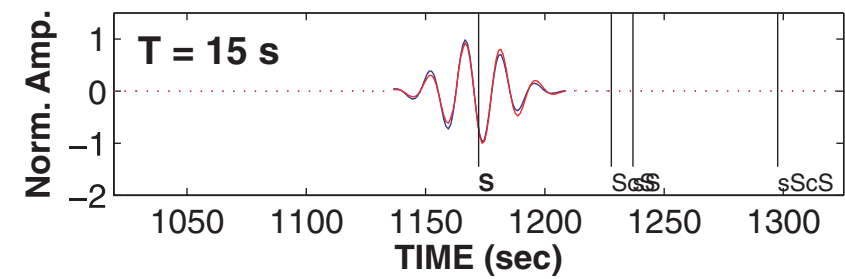
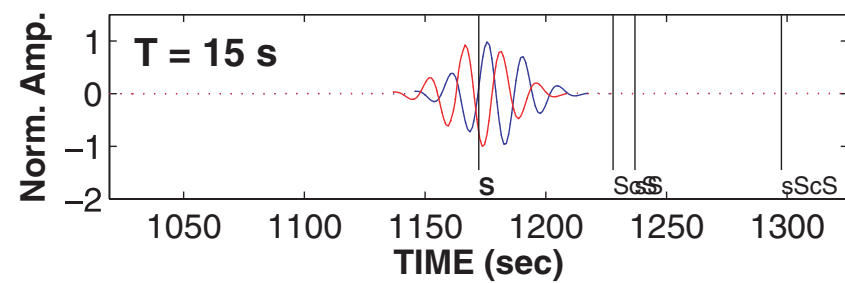
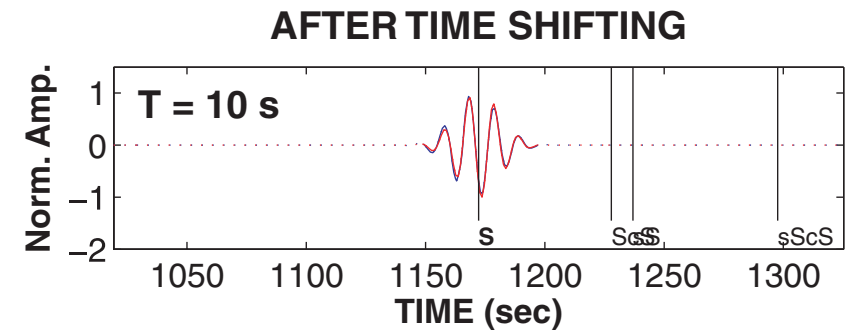
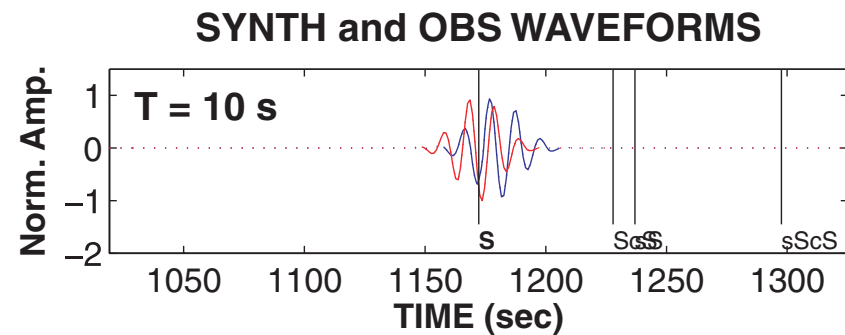
$$C_{uv}(t) = \int u(\tau)v(\tau - t) \, d\tau$$

cross-correlation



$$C_{uv}(t) = \int u(\tau)v(\tau - t) \, d\tau$$

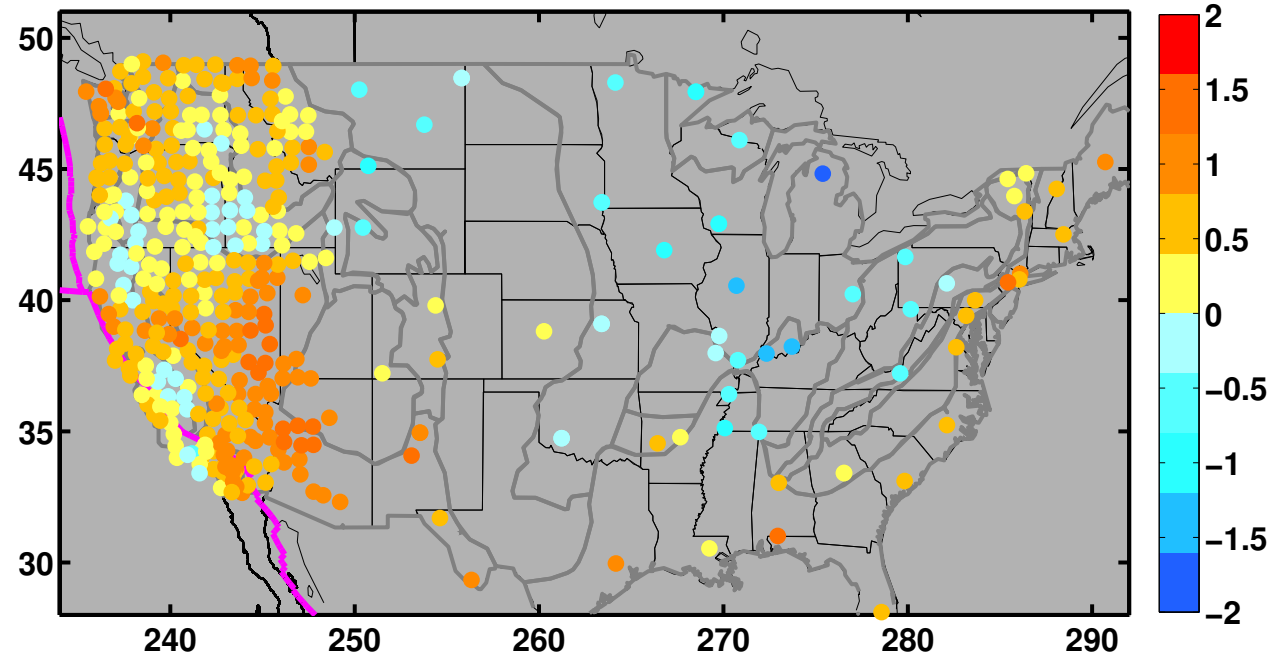
Wavegroup delays



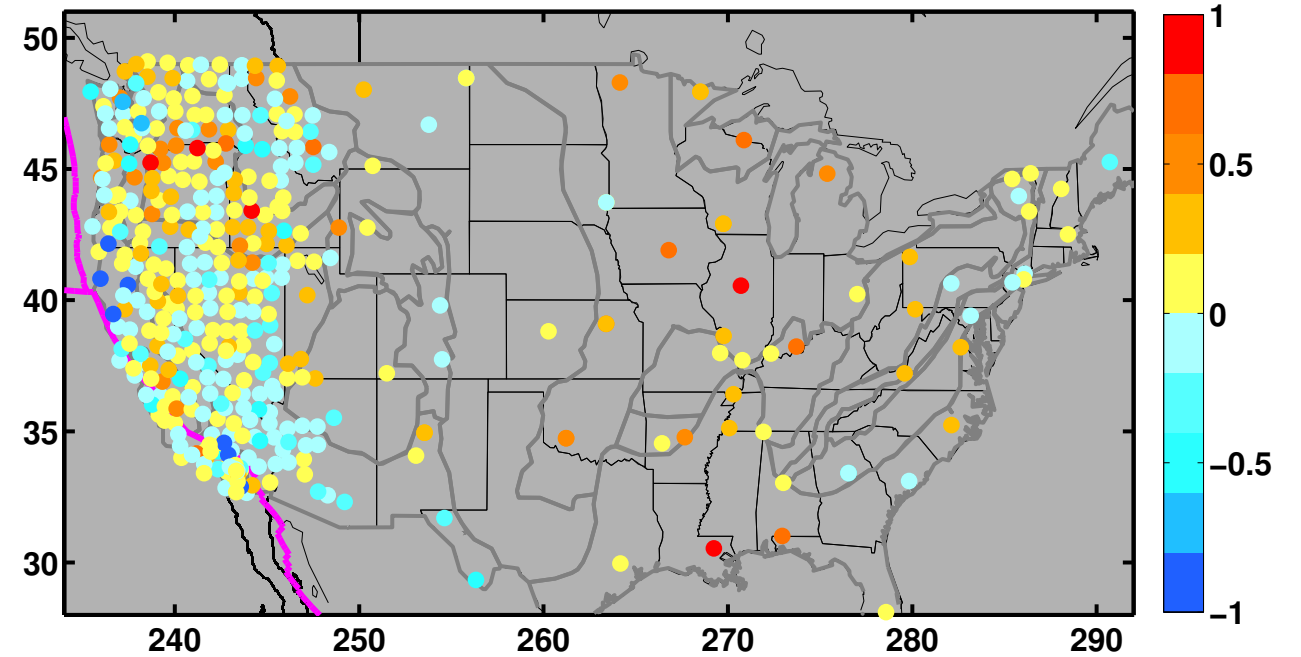
Zaroli et al., GJI 2010

Travel time dispersion

Observed dT (low freq. $T=21$ s)
for event #1531 at (-6.90 , -80.32)



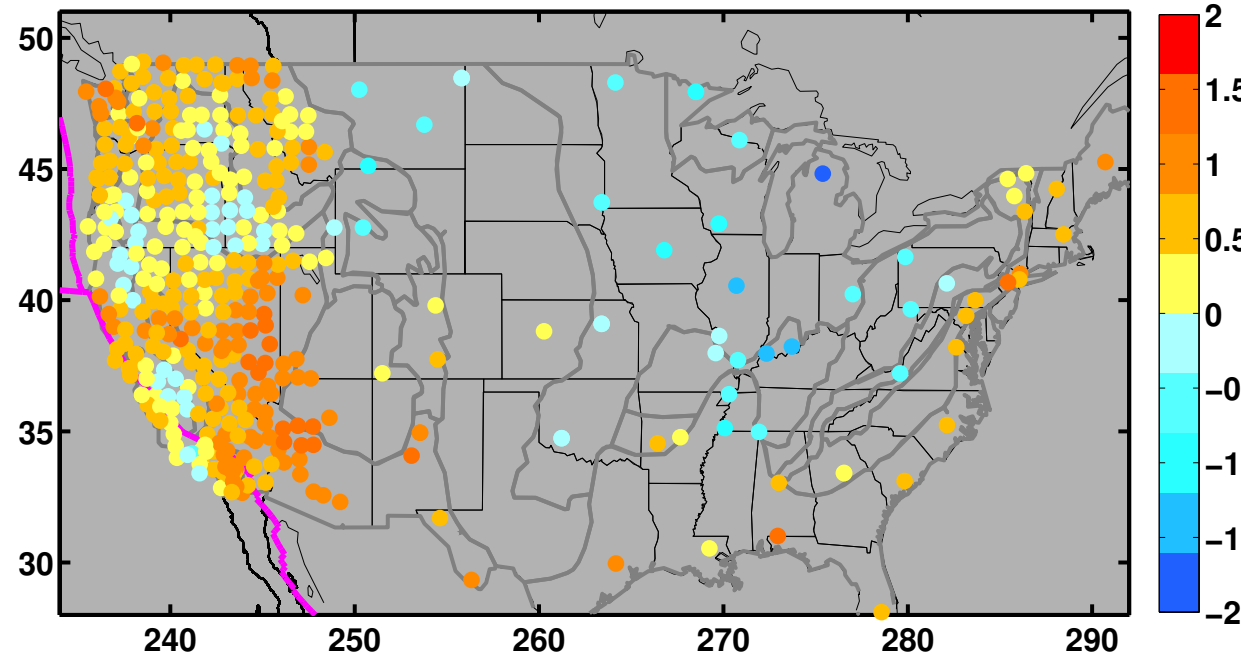
Observed dispersion of dT (high minus low freq.)
for event #1531 at (-6.90 , -80.32)



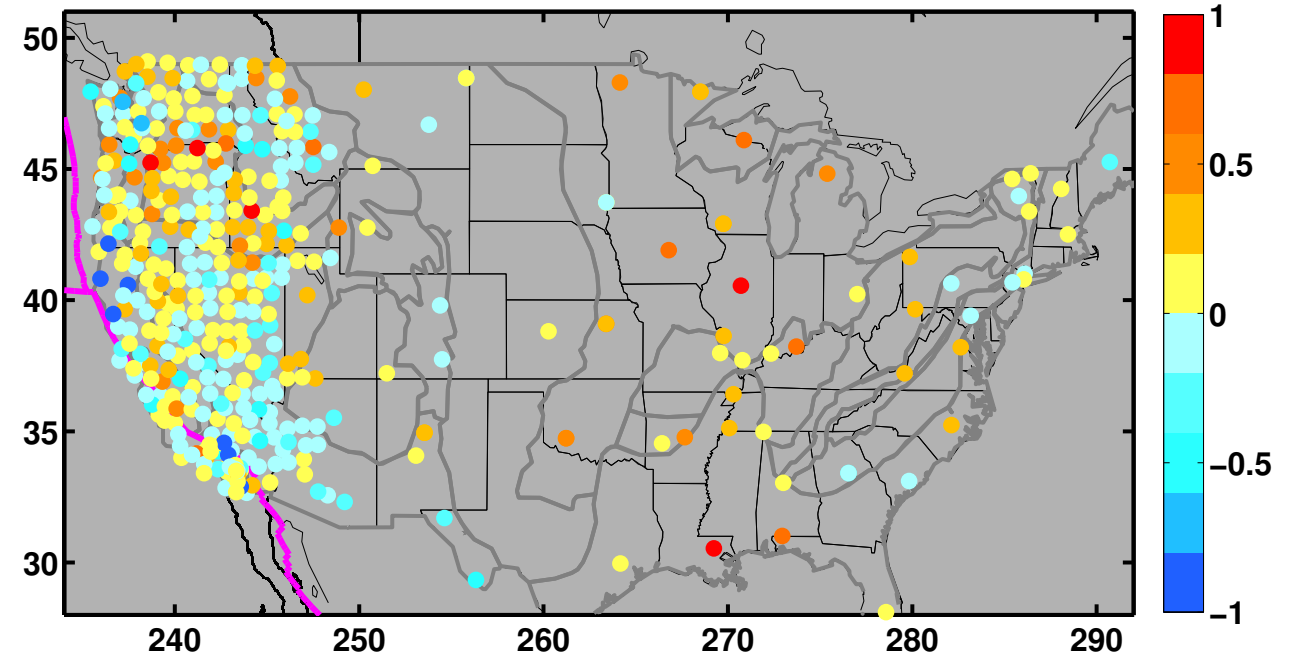
Courtesy Karin Sigloch

Travel time dispersion

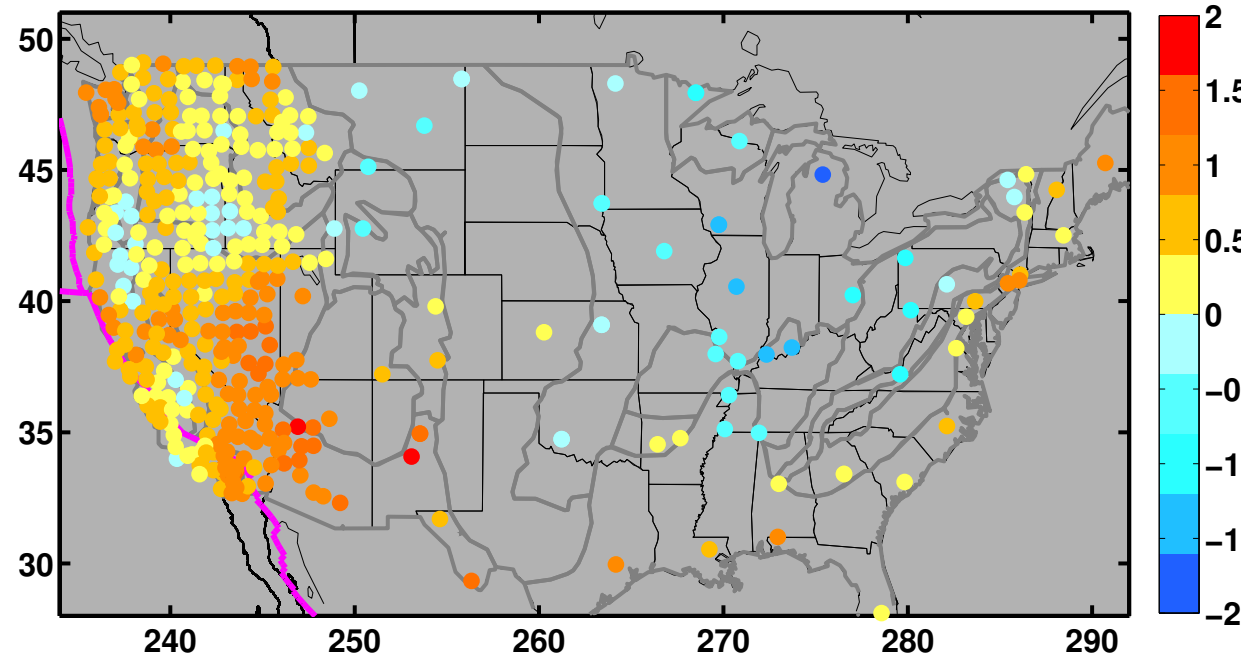
Observed dT (low freq. $T=21$ s)
for event #1531 at (-6.90 , -80.32)



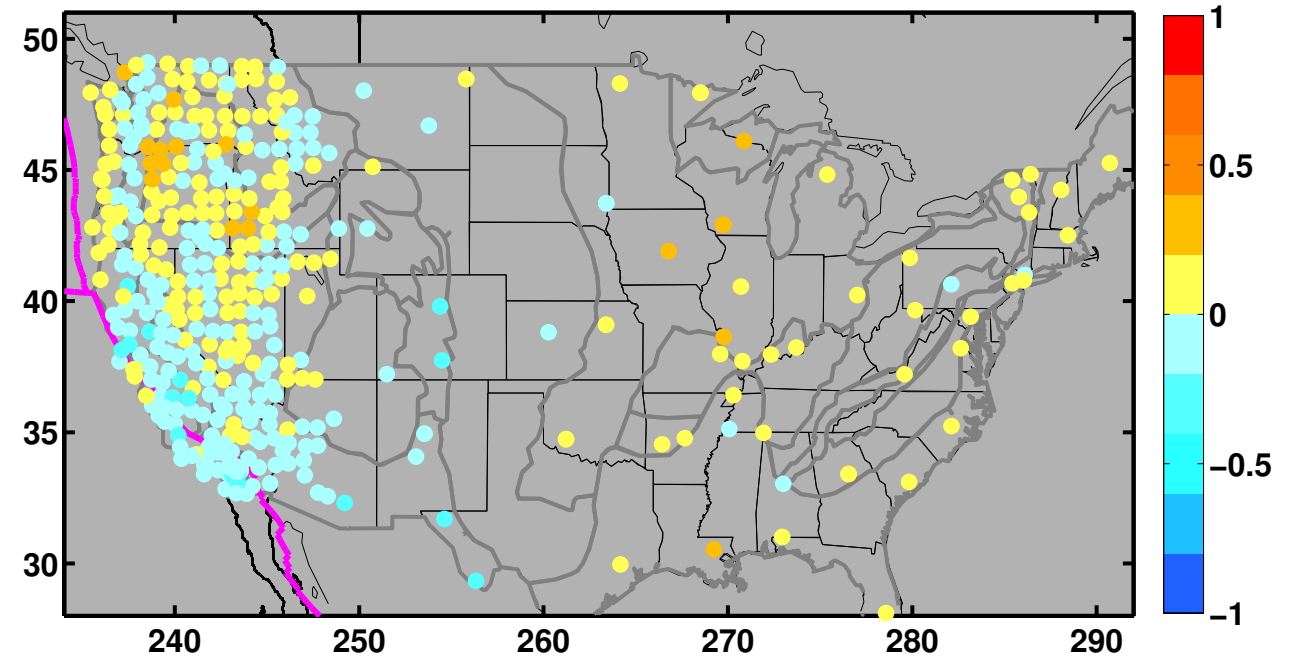
Observed dispersion of dT (high minus low freq.)
for event #1531 at (-6.90 , -80.32)



Predicted dT (low freq. $T=21$ s)
for event #1531 at (-6.90 , -80.32)

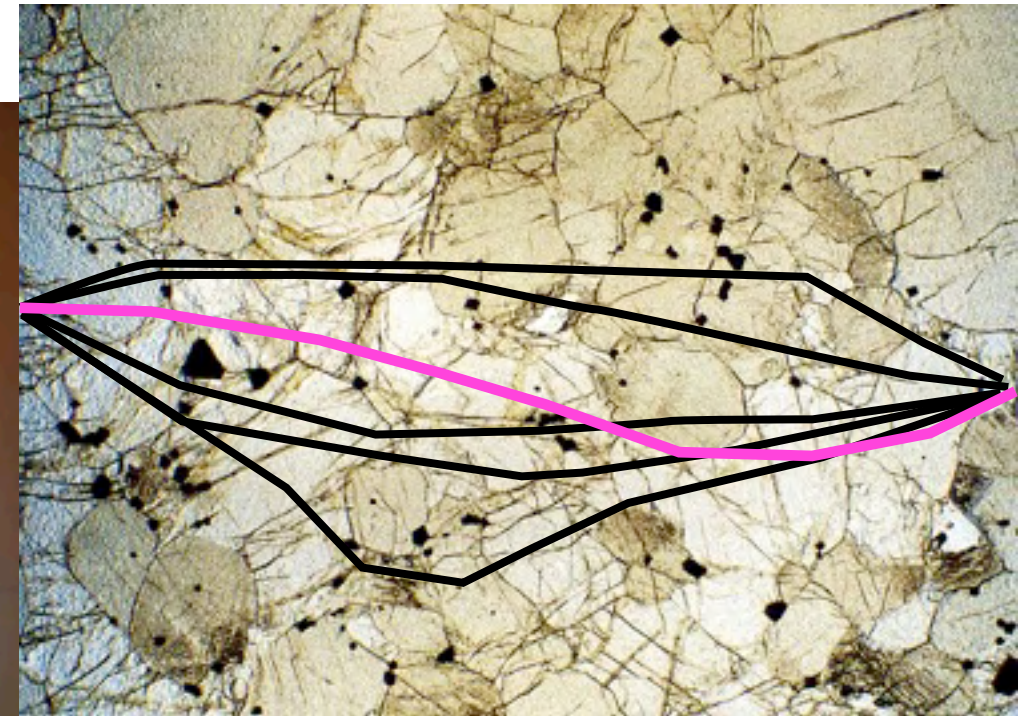


Predicted dispersion of dT (high minus low freq.)
for event #1531 at (-6.90 , -80.32)

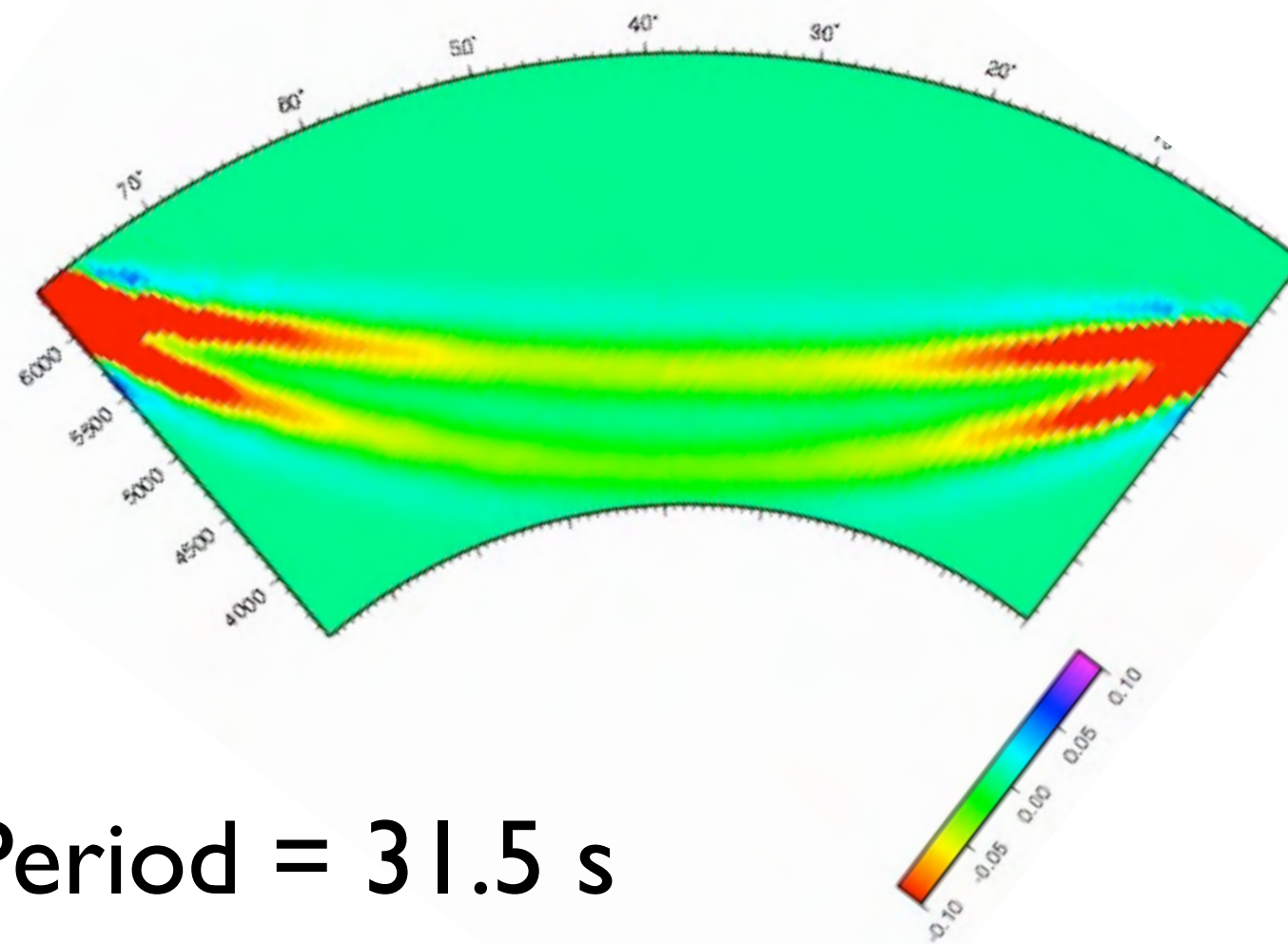


Courtesy Karin Sigloch

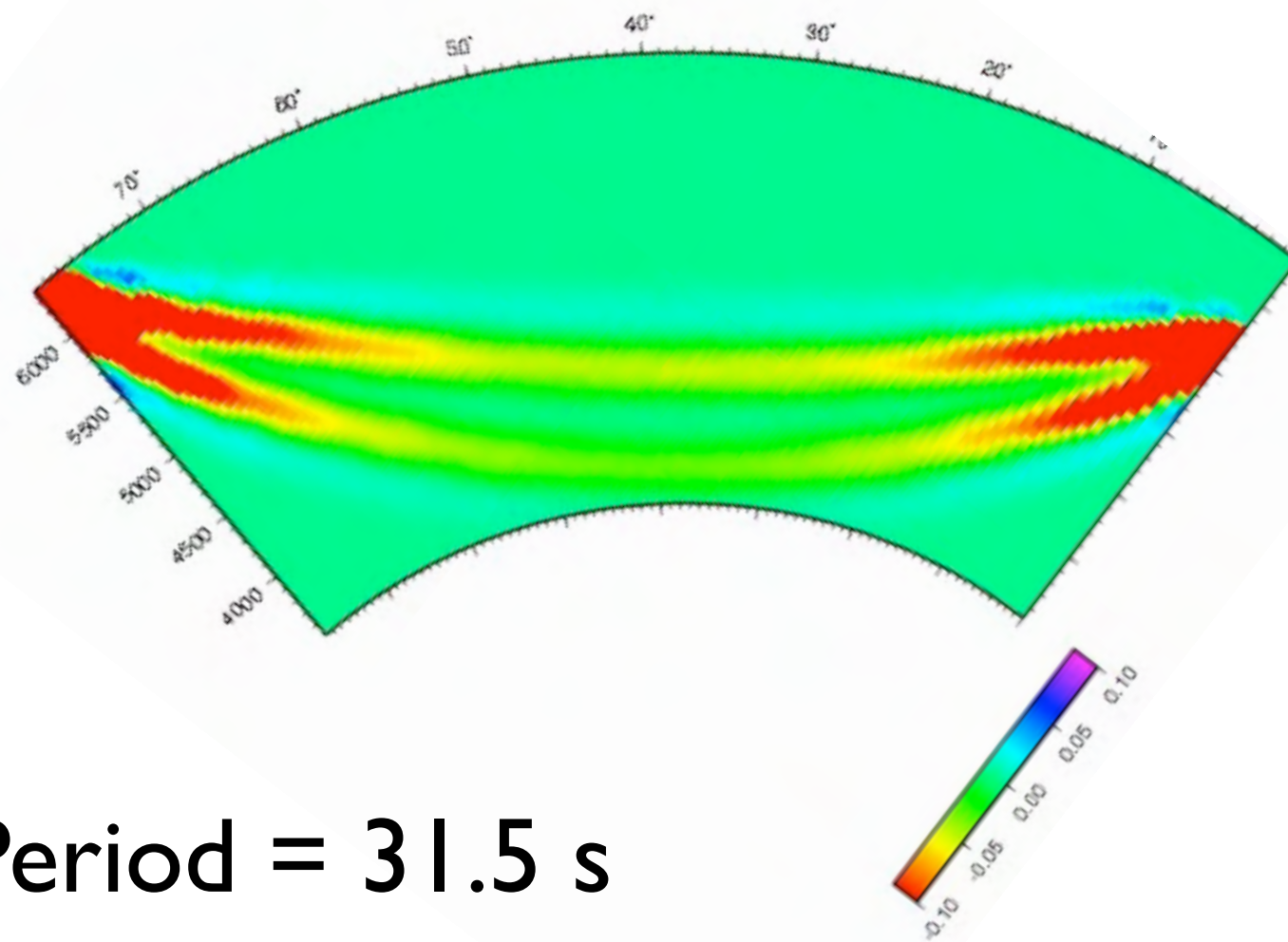
Waves take detours



‘Banana-doughnut’ kernels



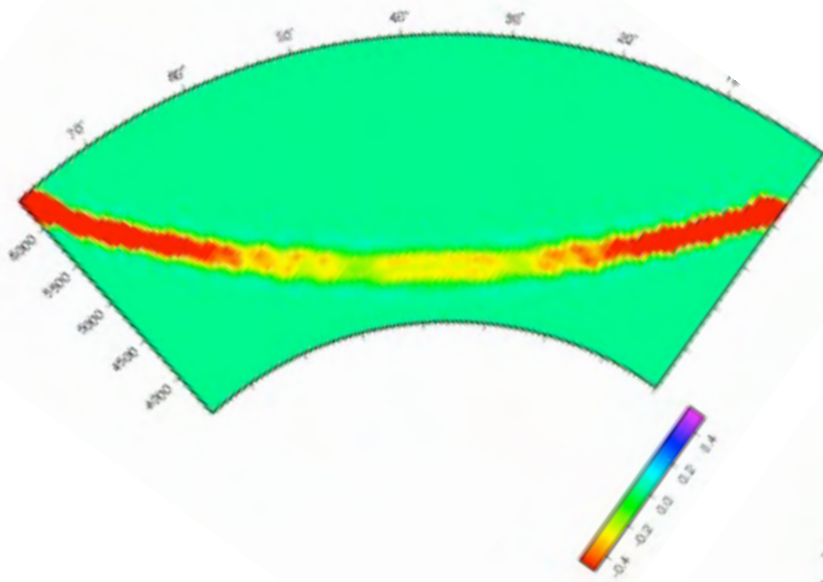
‘Banana-doughnut’ kernels



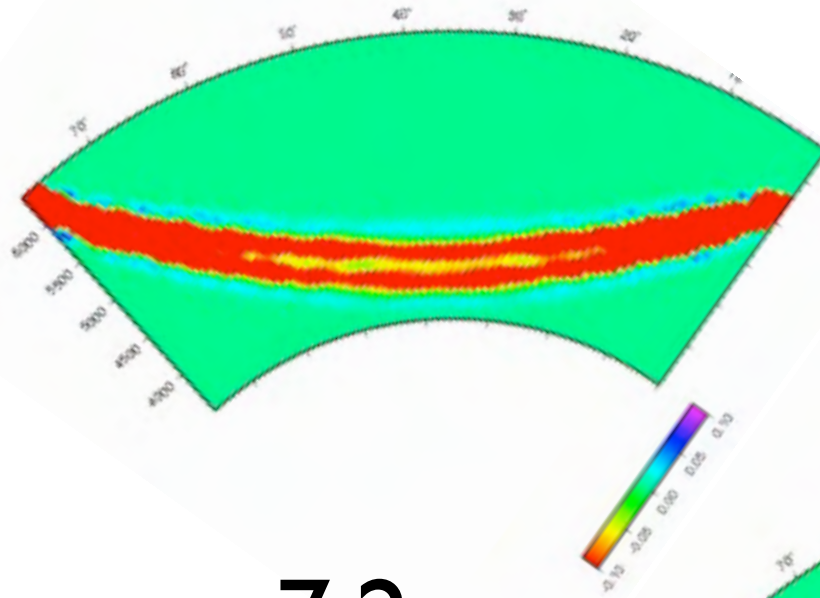
Period = 31.5 s



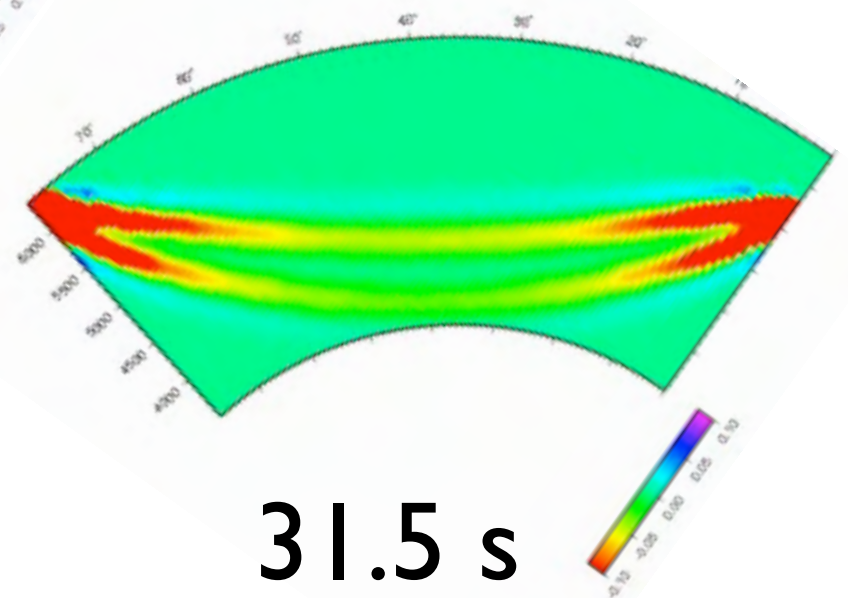
frequency dependence of the sensitivity



2.8 s

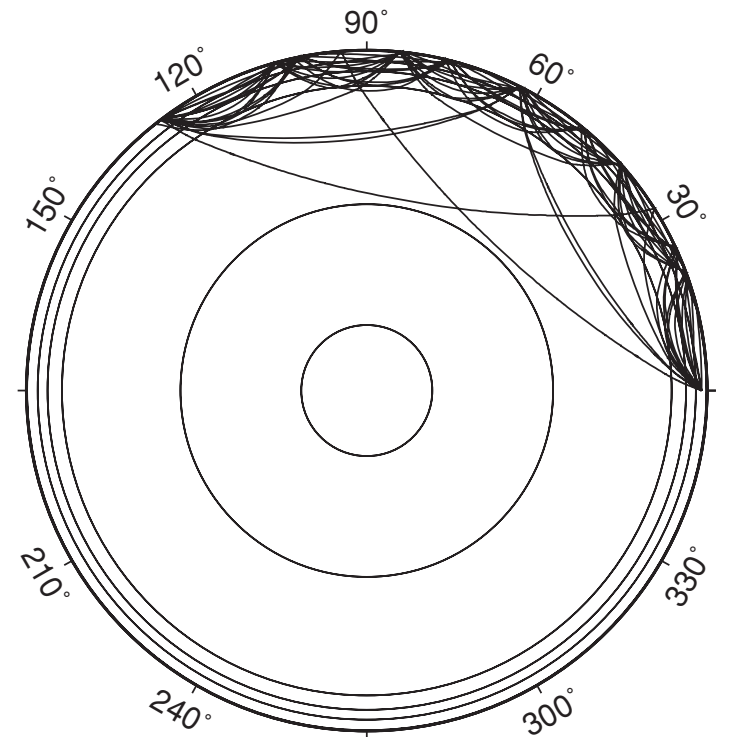
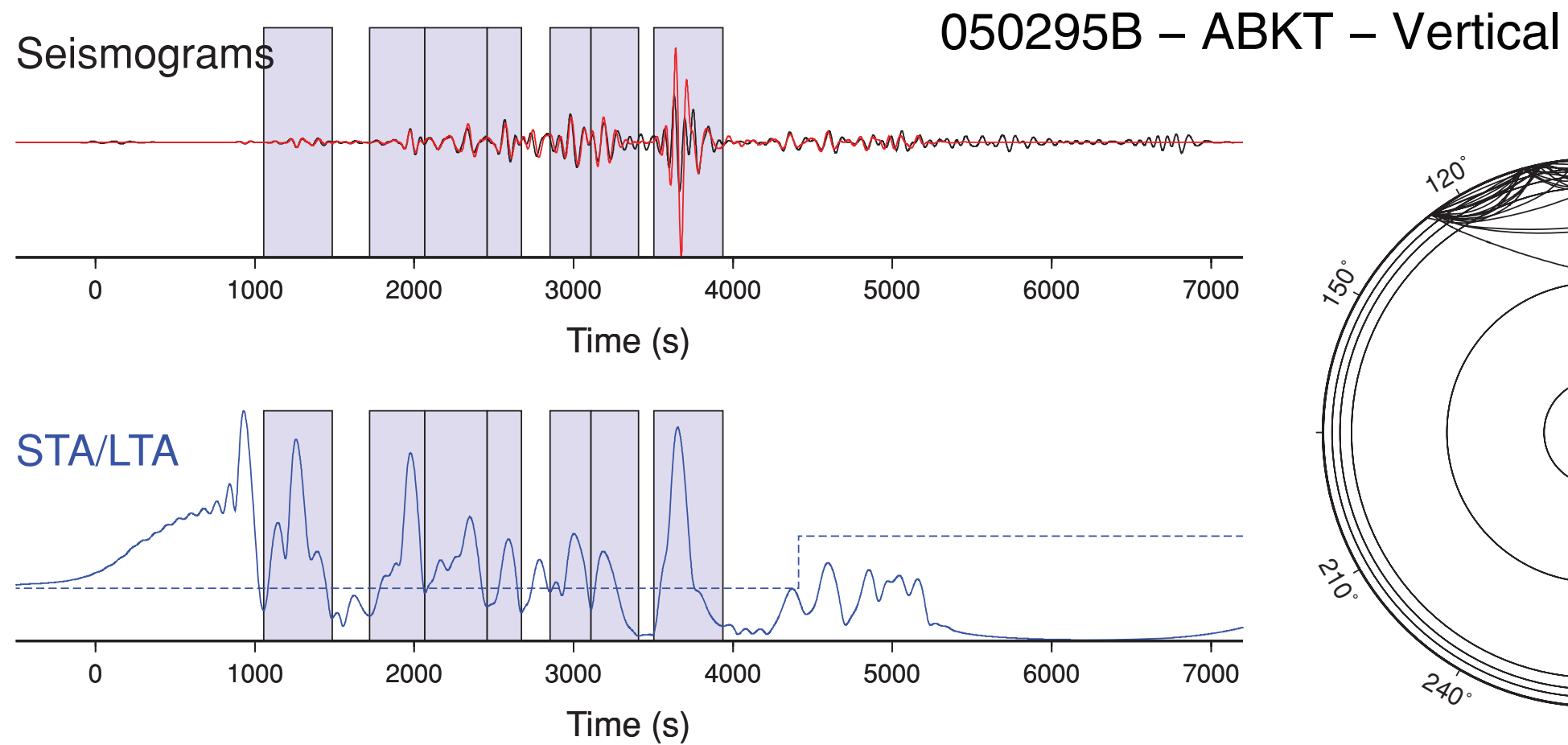


7.2 s



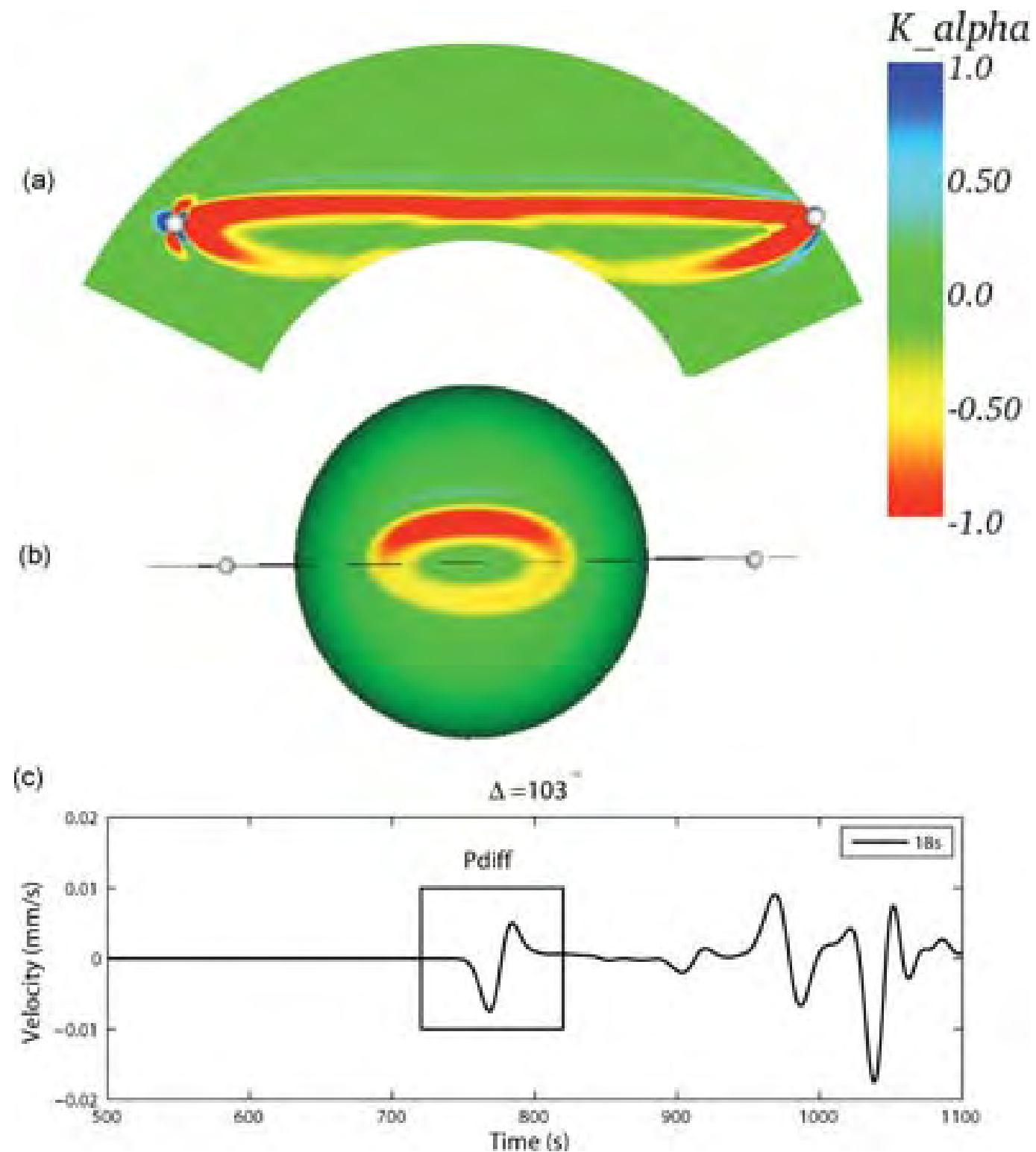
31.5 s

FlexWin



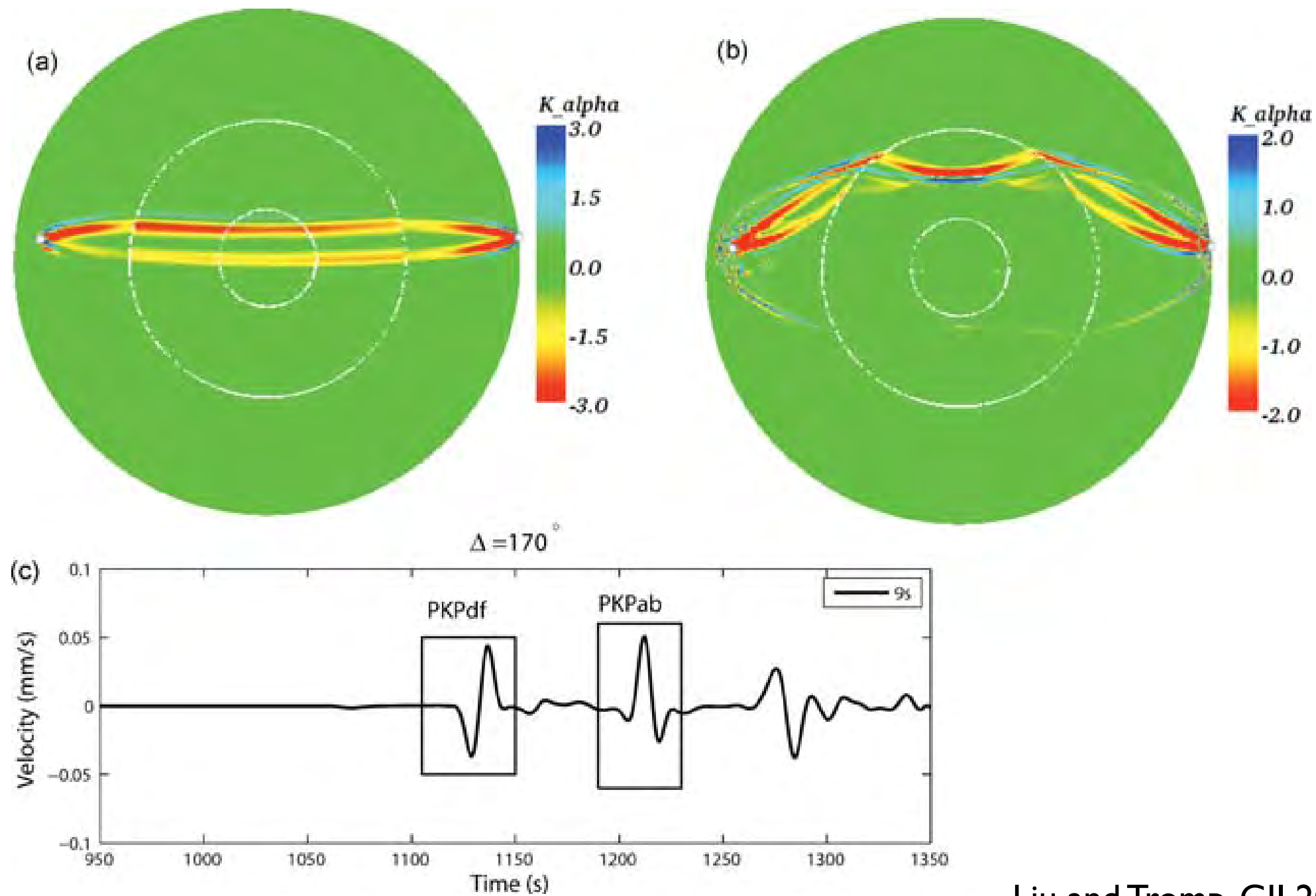
Maggi et al., GJI 2009

diffracted P wave



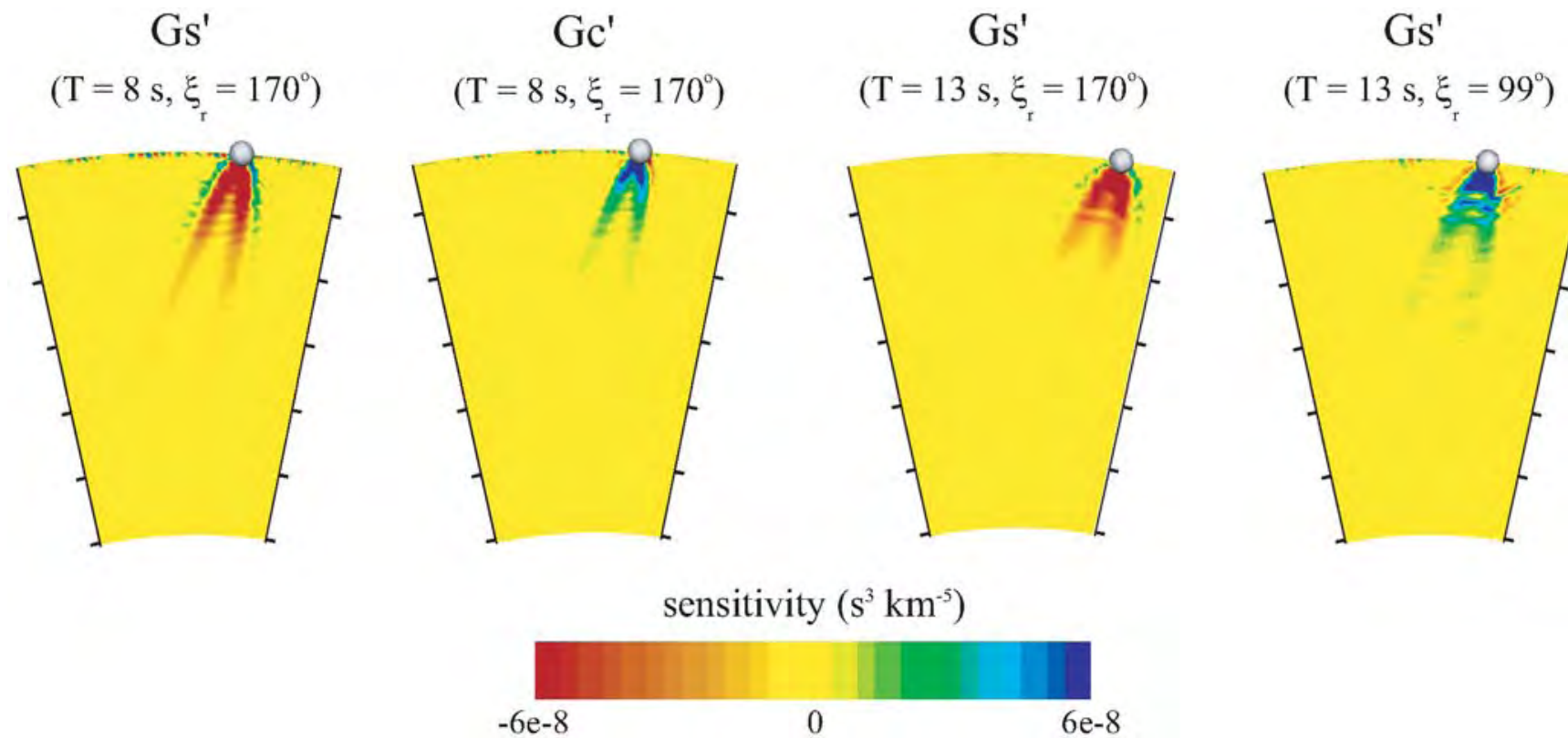
Liu and Tromp, GJI 2008

PKP waves



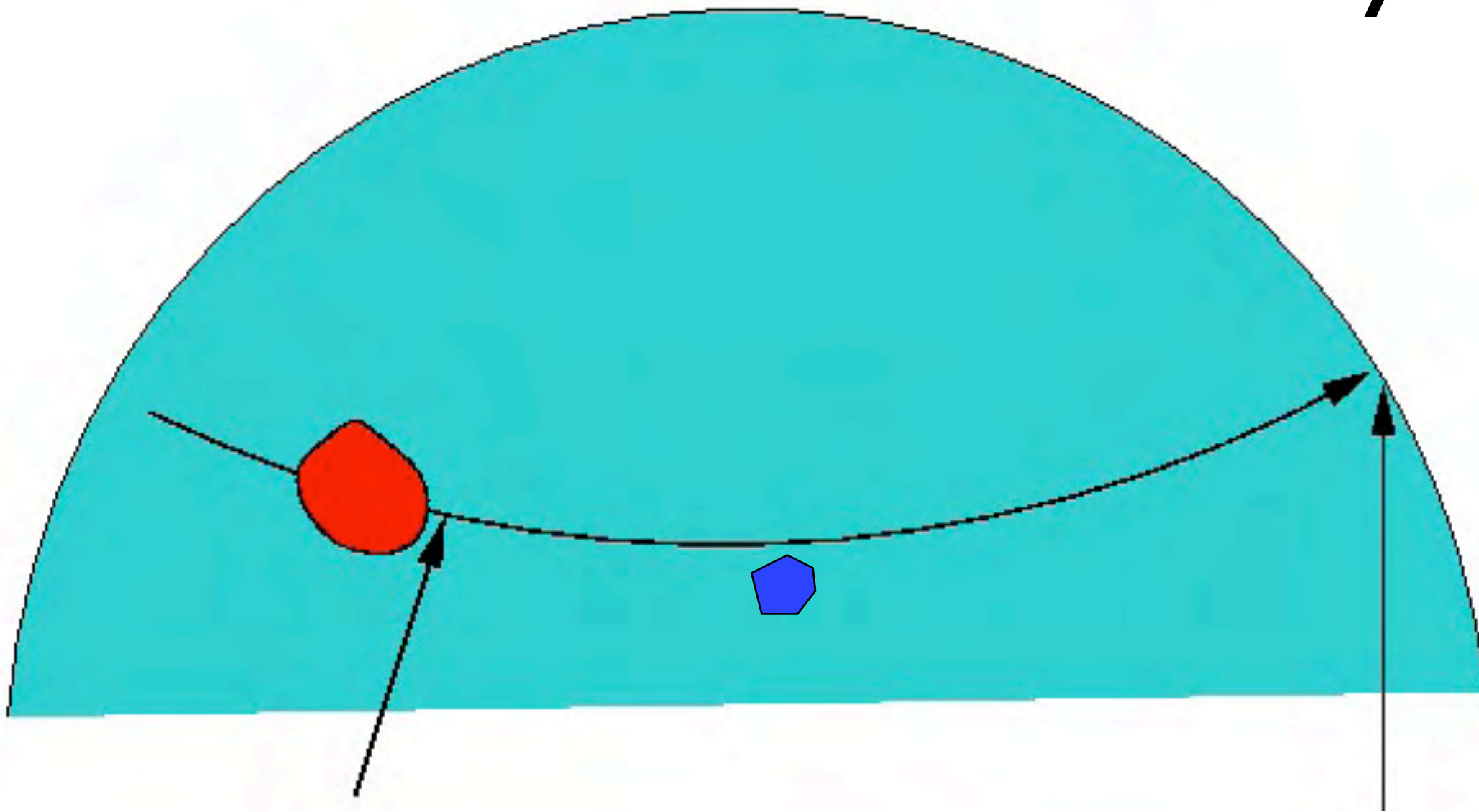
Liu and Tromp, GJI 2008

SKS splitting sensitivity



Sieminski et al. , BSSA 2008

What is the width of a ray?



Answer: it all depends on what you measure

Software

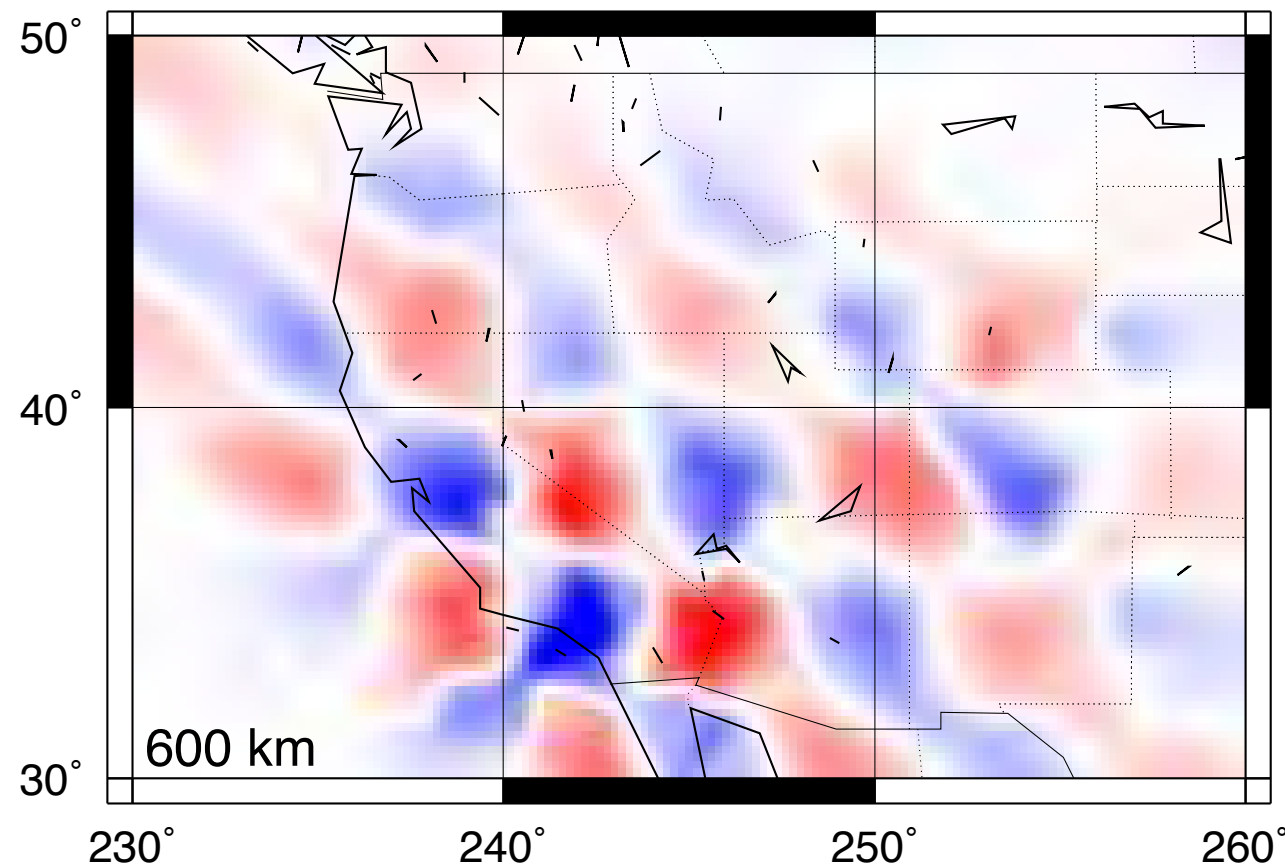
<https://www.geoazur.net/GLOBALSEIS/Soft.html>

two ways to solve:

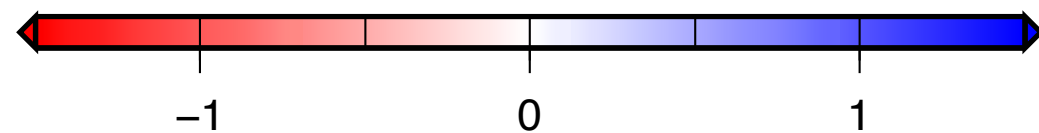
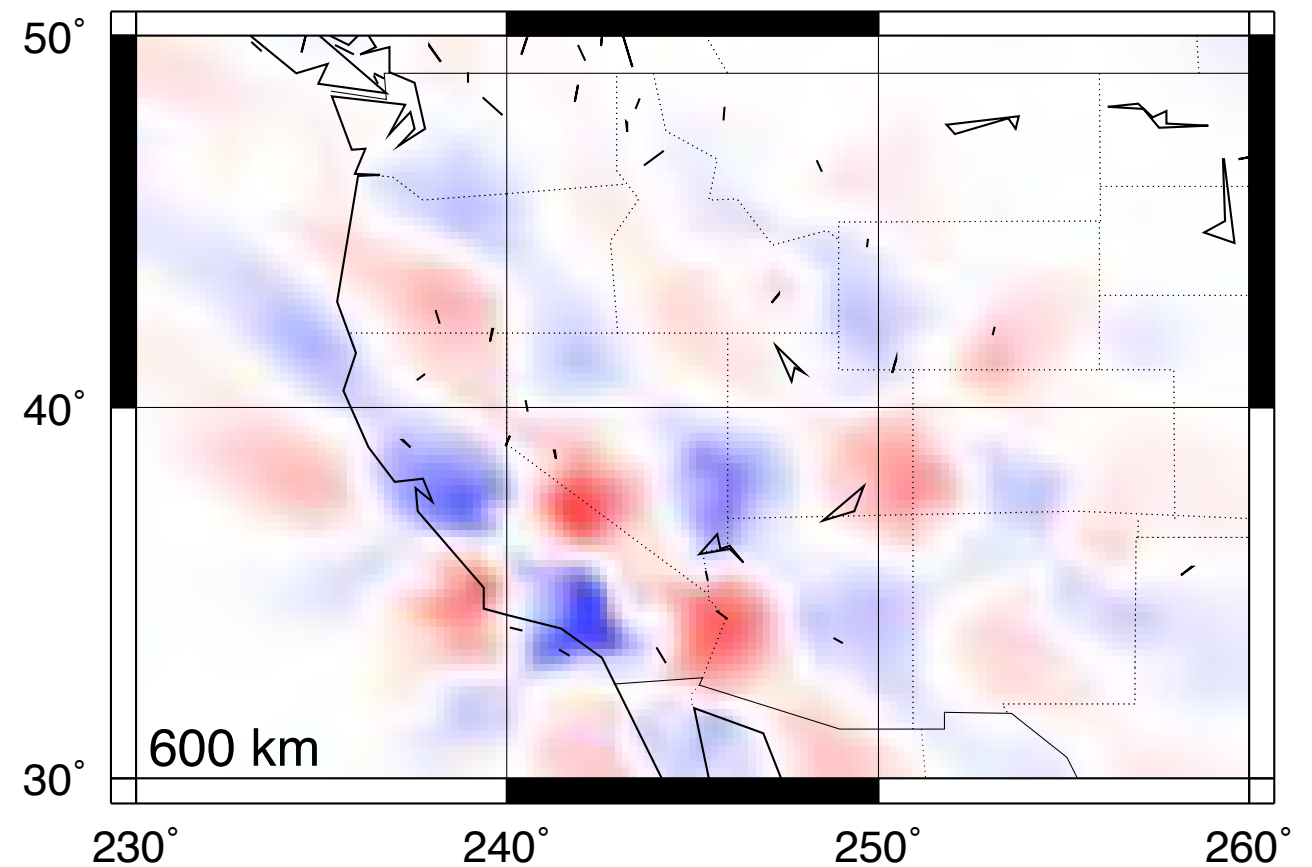
- Direct inversion of the system $Am = d$
expensive on memory, fast for 1D starting models
- Search in the direction of the gradient of
 $X^2 = |Am - d|^2$
expensive on CPU, flexible for 3D

gain in resolution

FINITE FREQUENCY



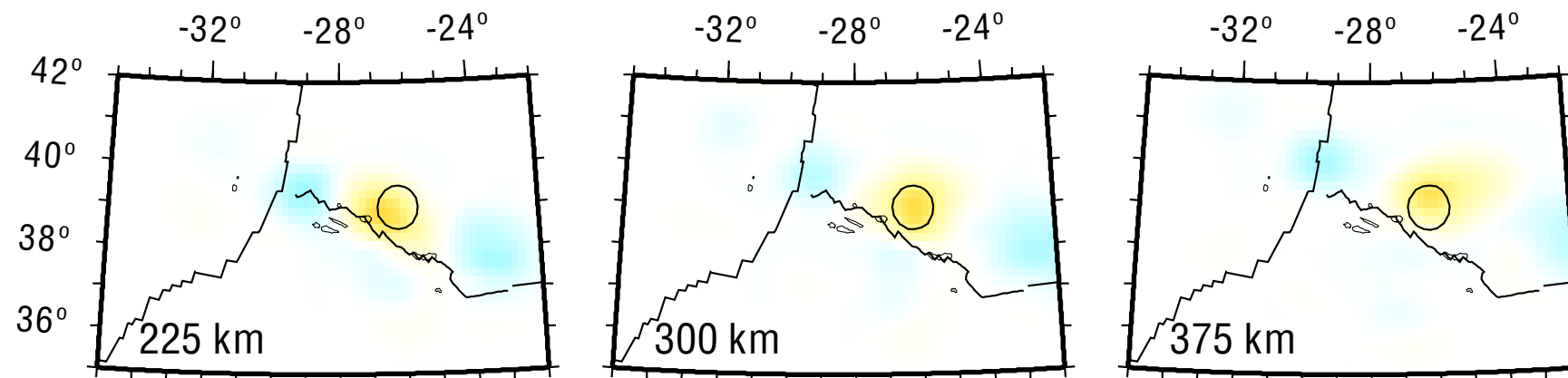
RAY THEORY



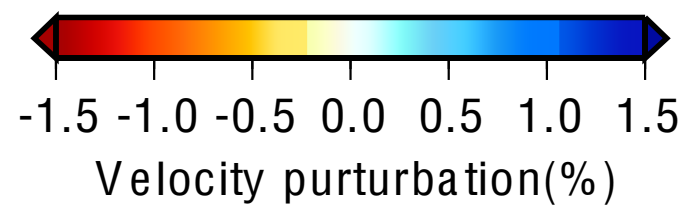
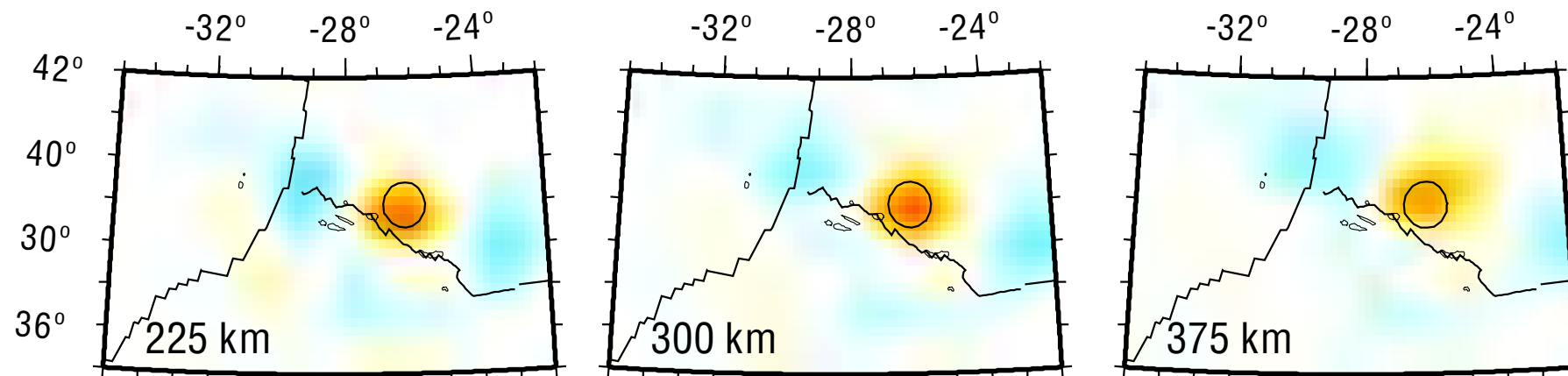
$d\ln V_s(\%)$

Yue Tian, AGU 2007

Azores: resolution for $f > 0.1$ Hz:



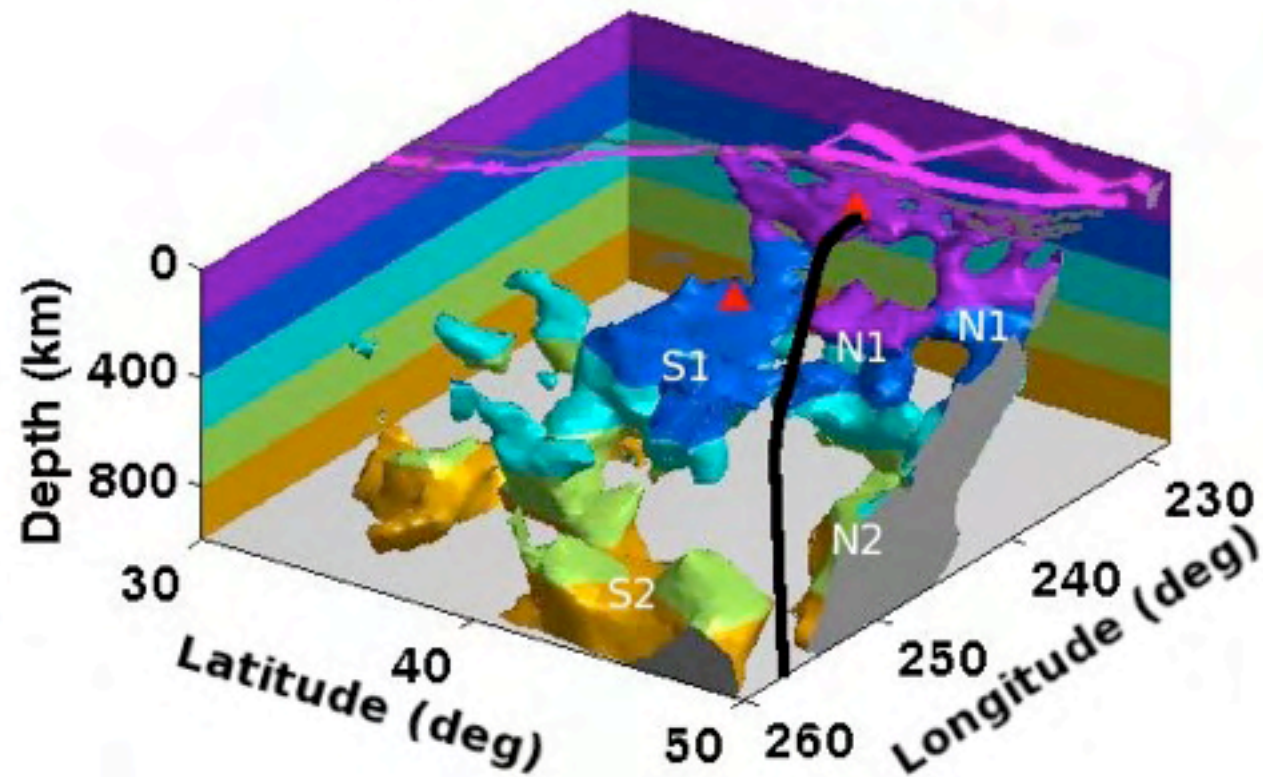
and including also 0.03-0.1 Hz:



Yang et al., EPSL 2006

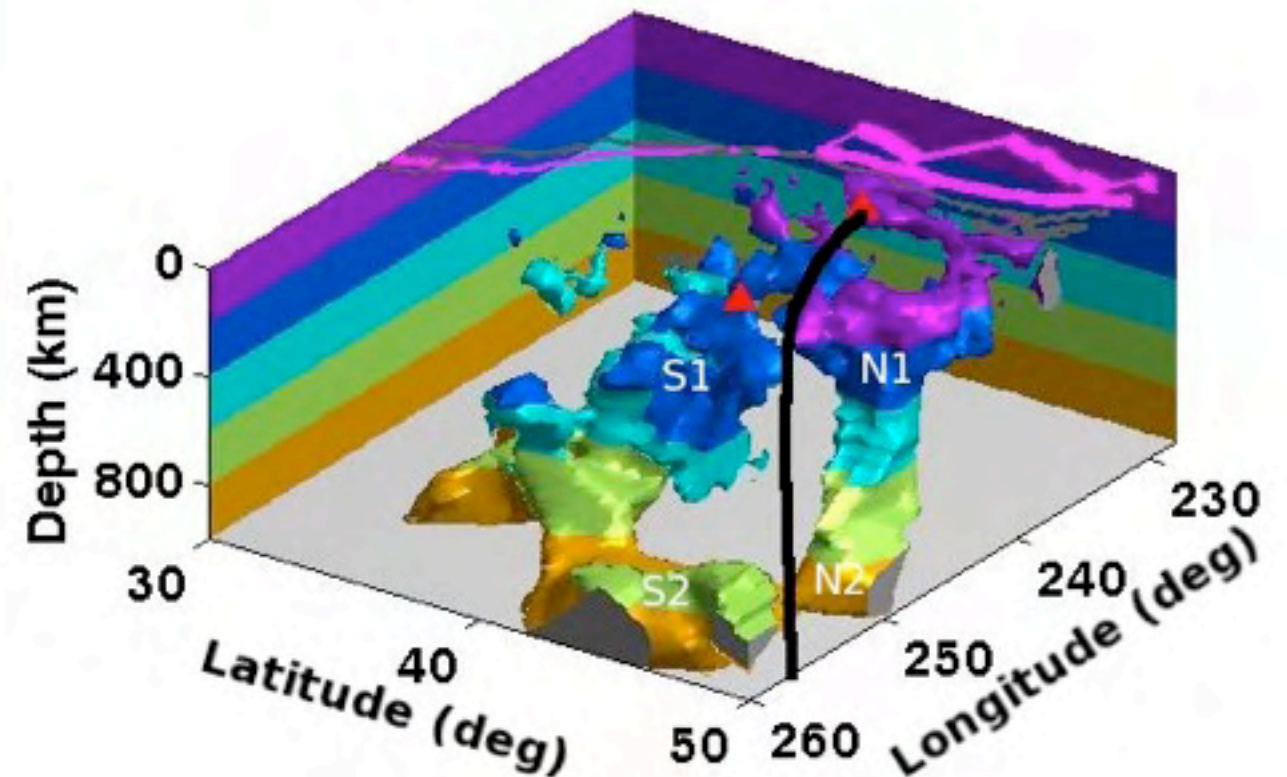
It works!

(a) $\delta \ln V_p$ 0.4% isosurface

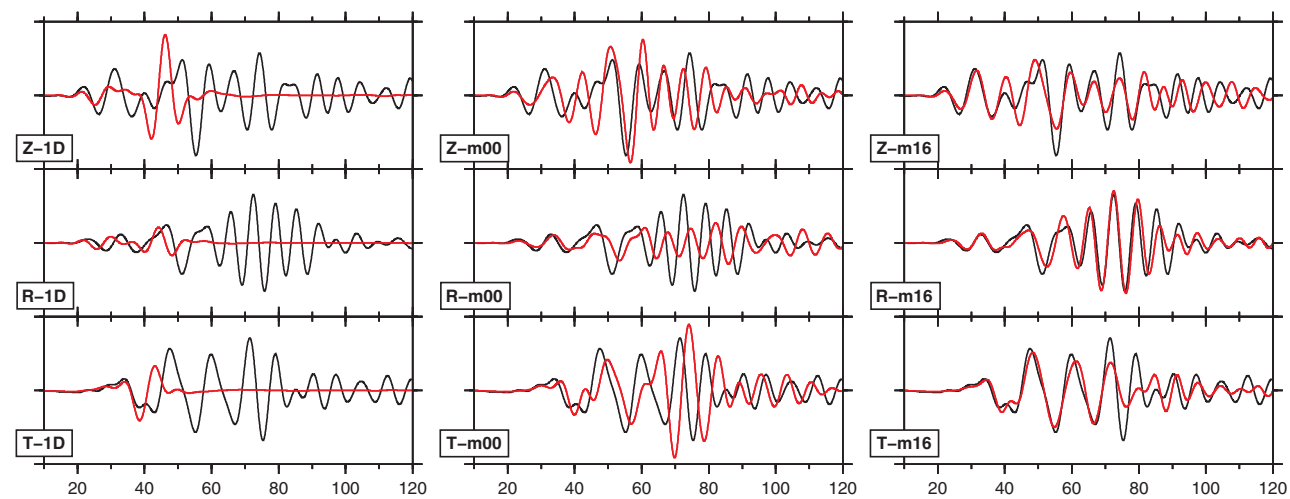
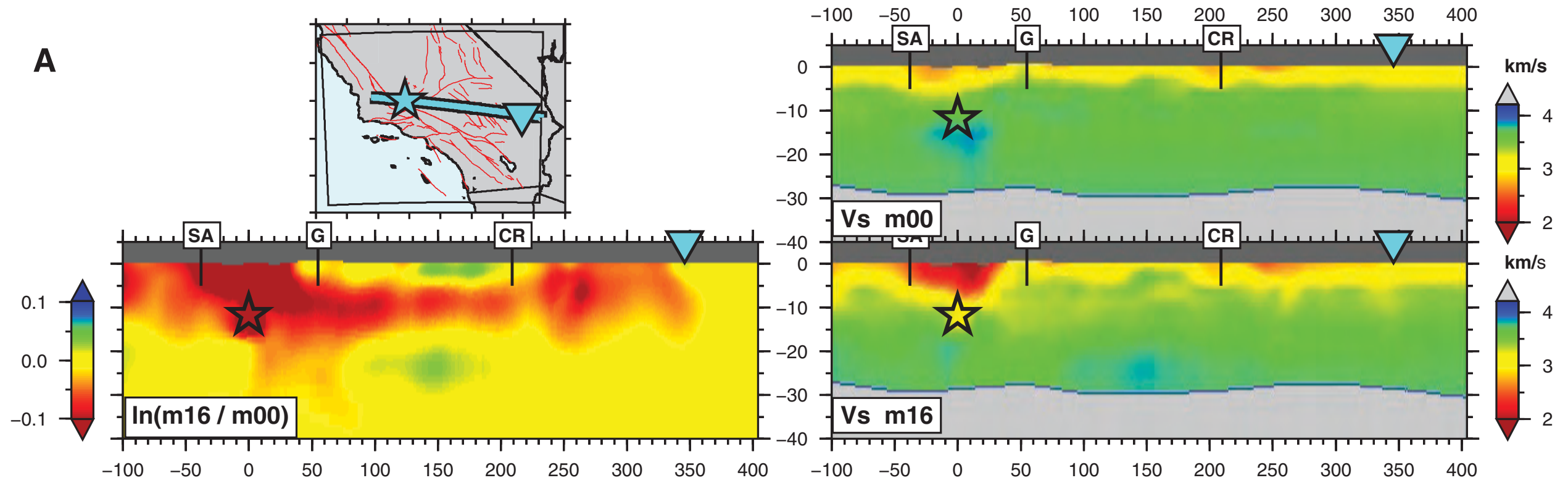


Sigloch et al.,
Nature Geosc., 2008

(b) $\delta \ln V_s$ 0.4% isosurface

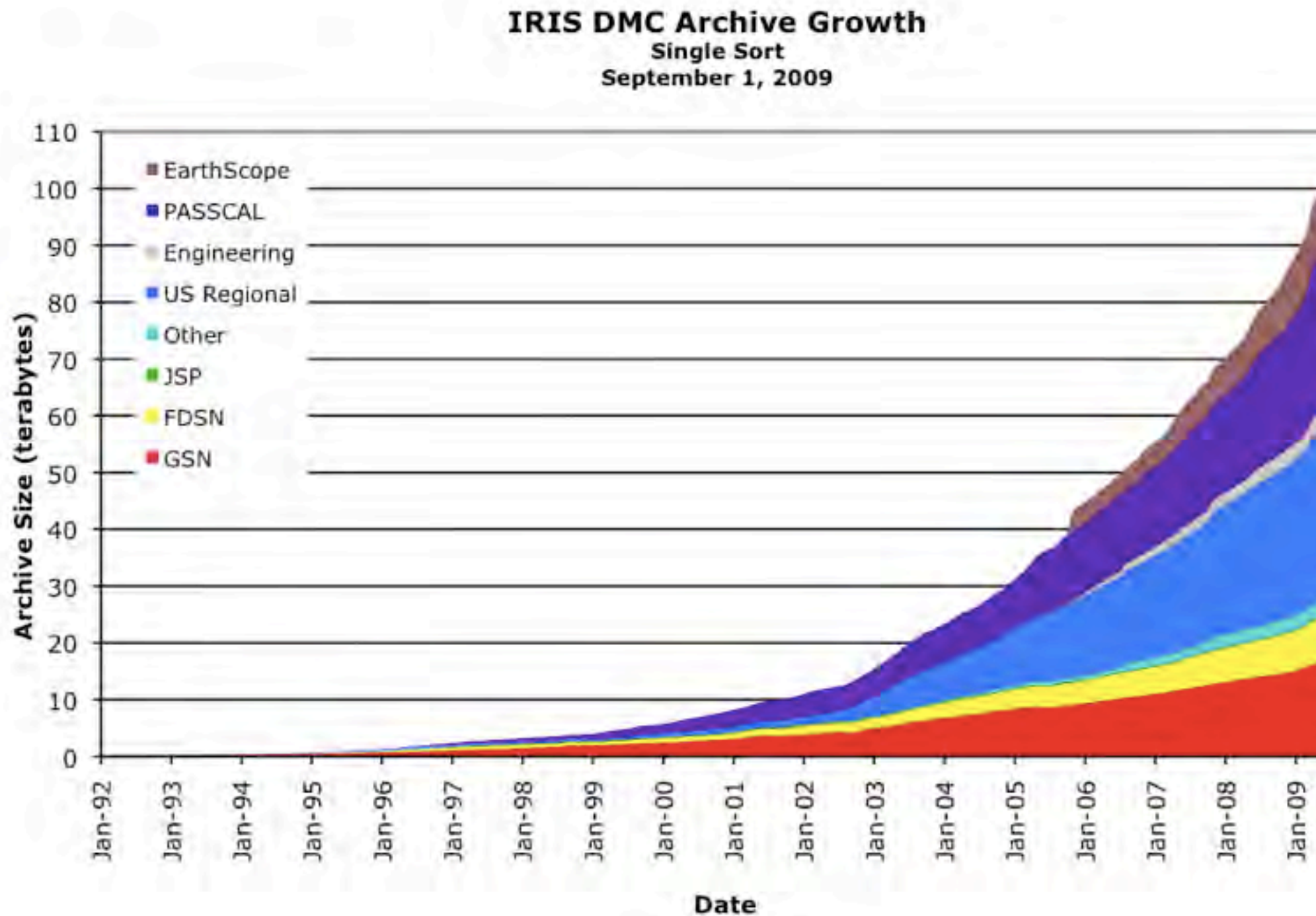


Tian et al.,
GJI., 2009

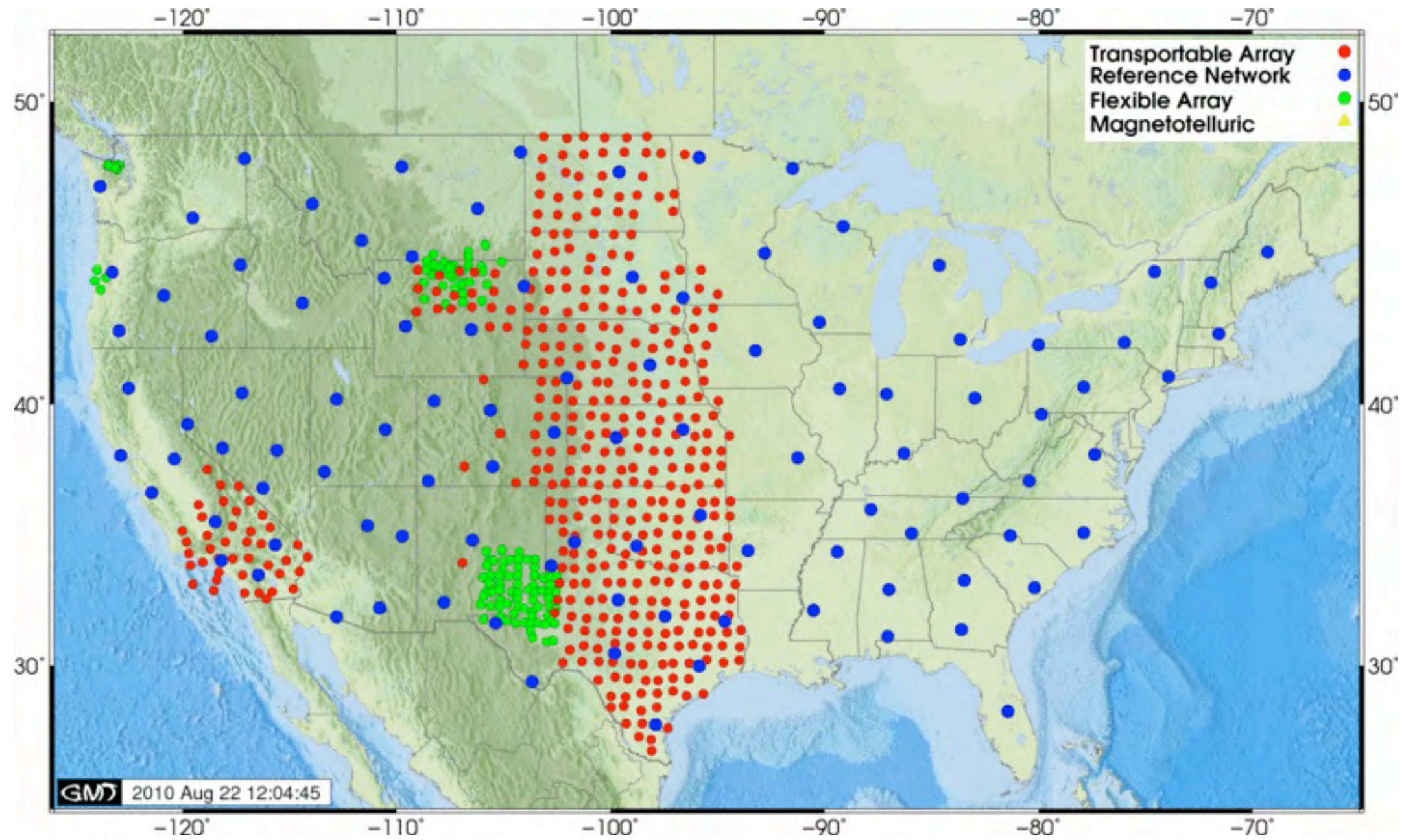


Tape et al., Science 2009

The data explosion



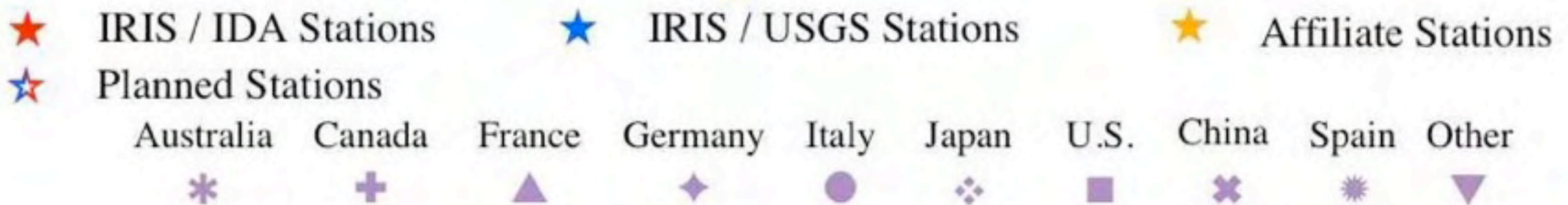
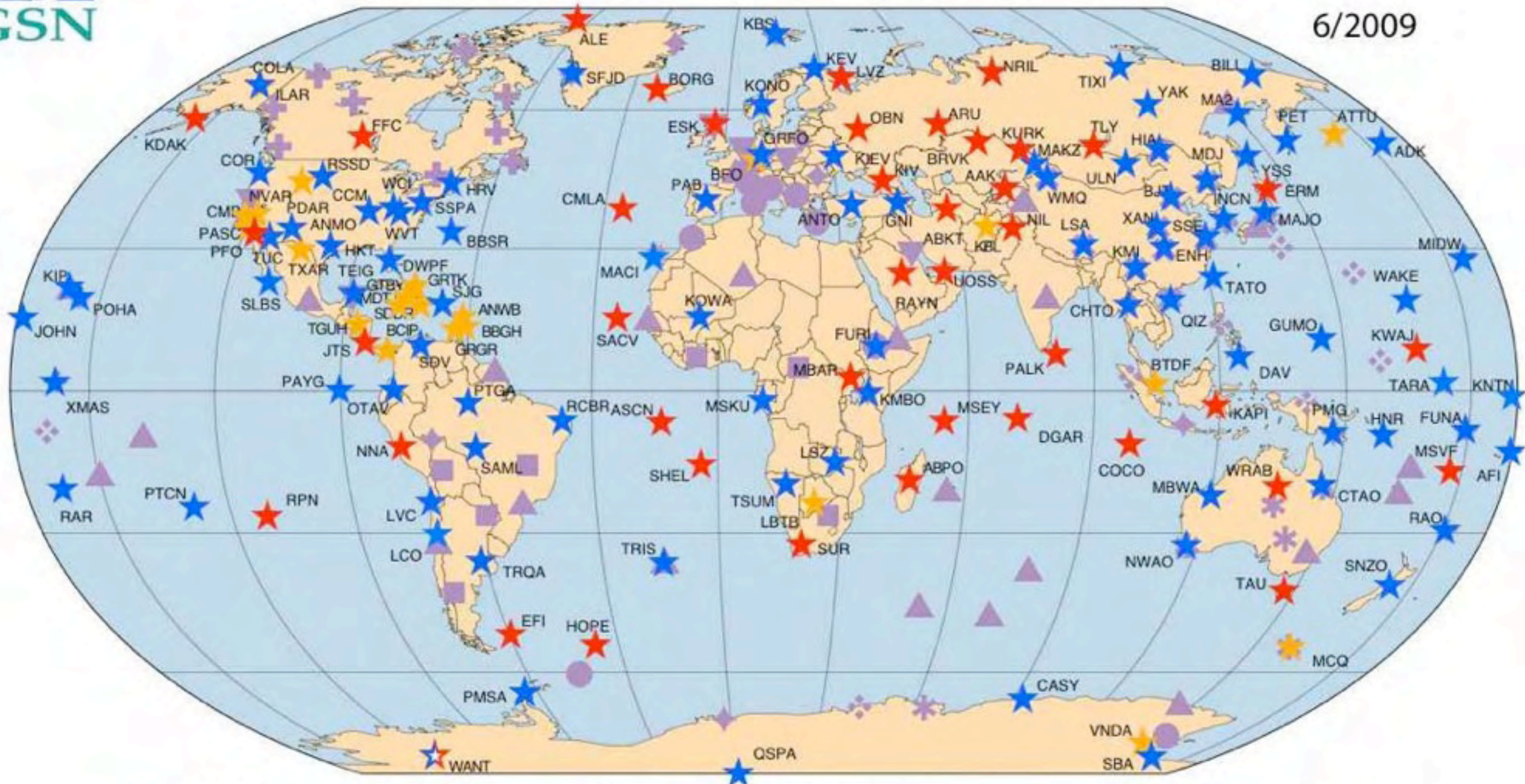
US array



GLOBAL SEISMOGRAPHIC NETWORK

FEDERATION OF BROADBAND DIGITAL SEISMIC NETWORKS (FDSN)

6/2009

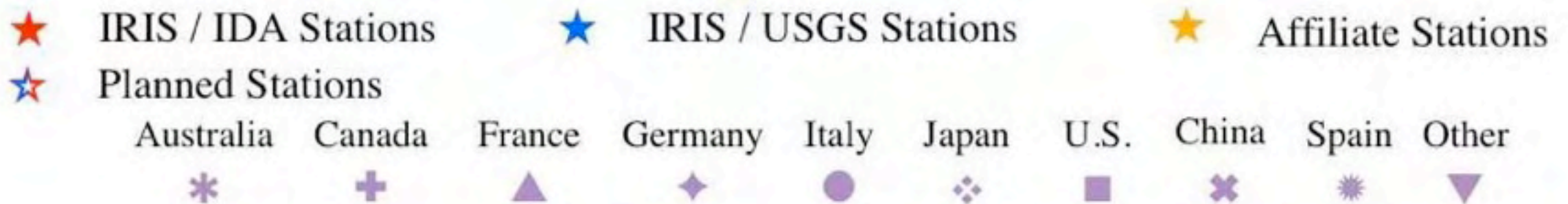
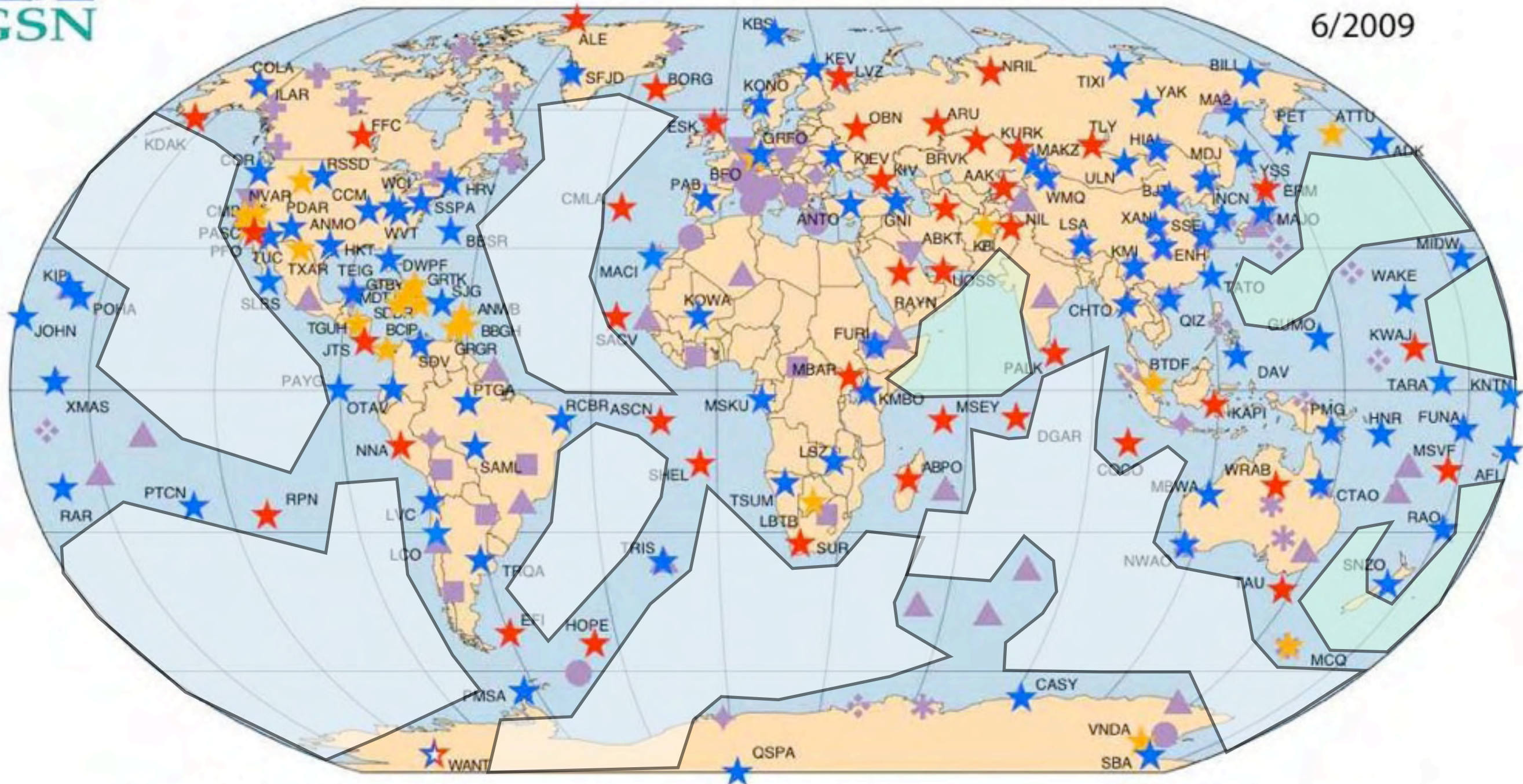




GLOBAL SEISMOGRAPHIC NETWORK

FEDERATION OF BROADBAND DIGITAL SEISMIC NETWORKS (FDSN)

6/2009

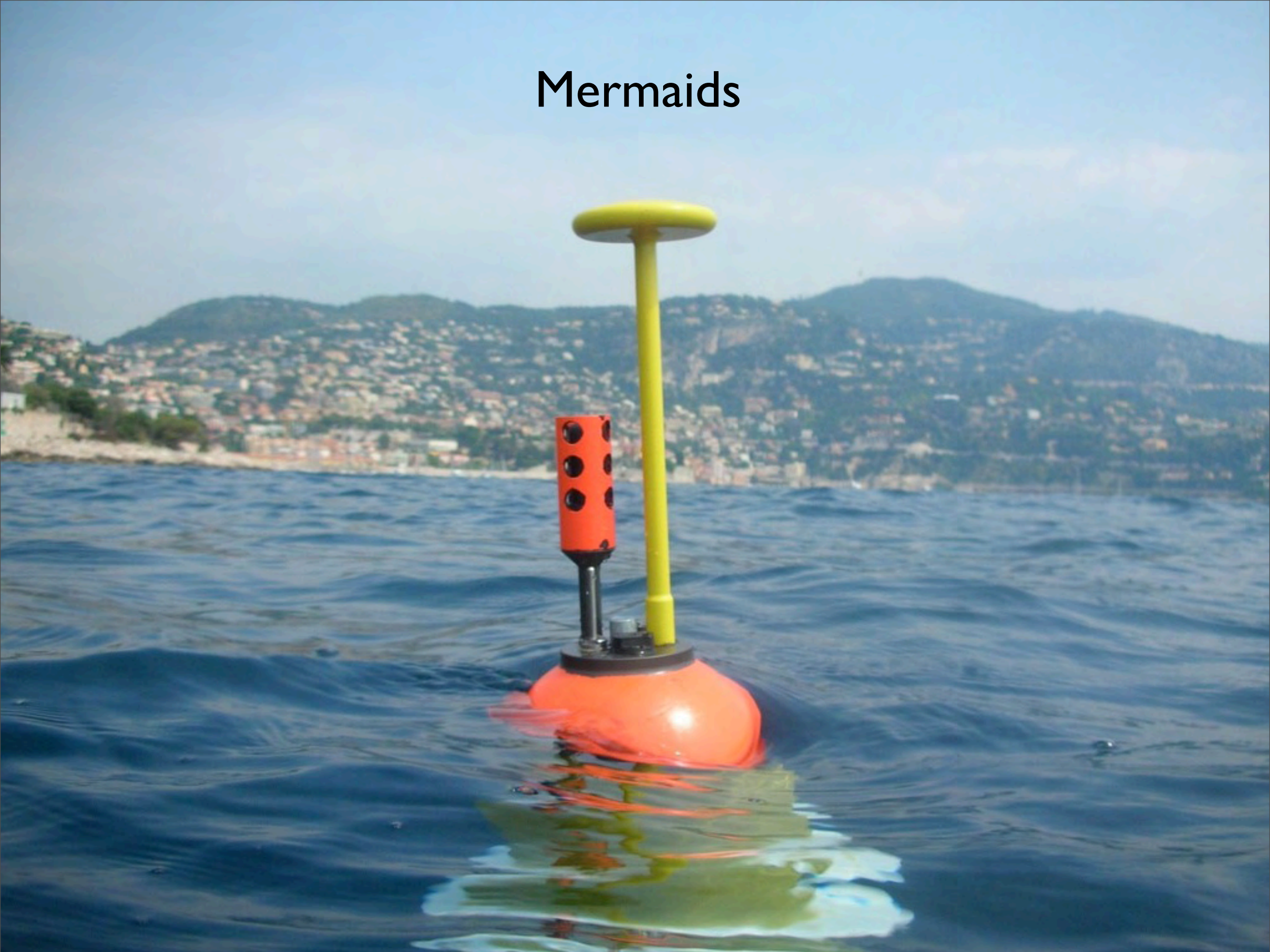




6/2009

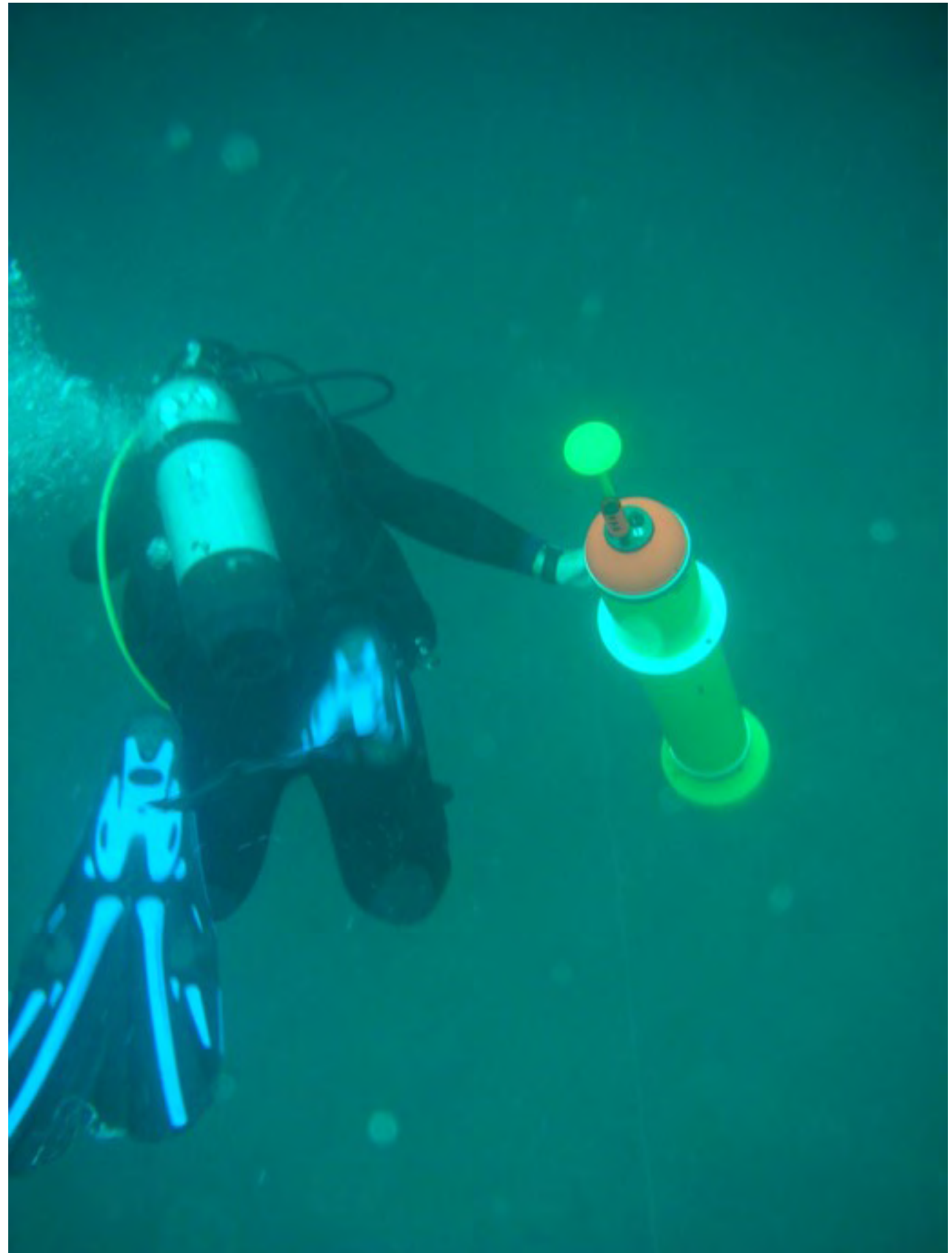
Australia Canada France Germany Italy Japan U.S. China Spain Other

Mermaids

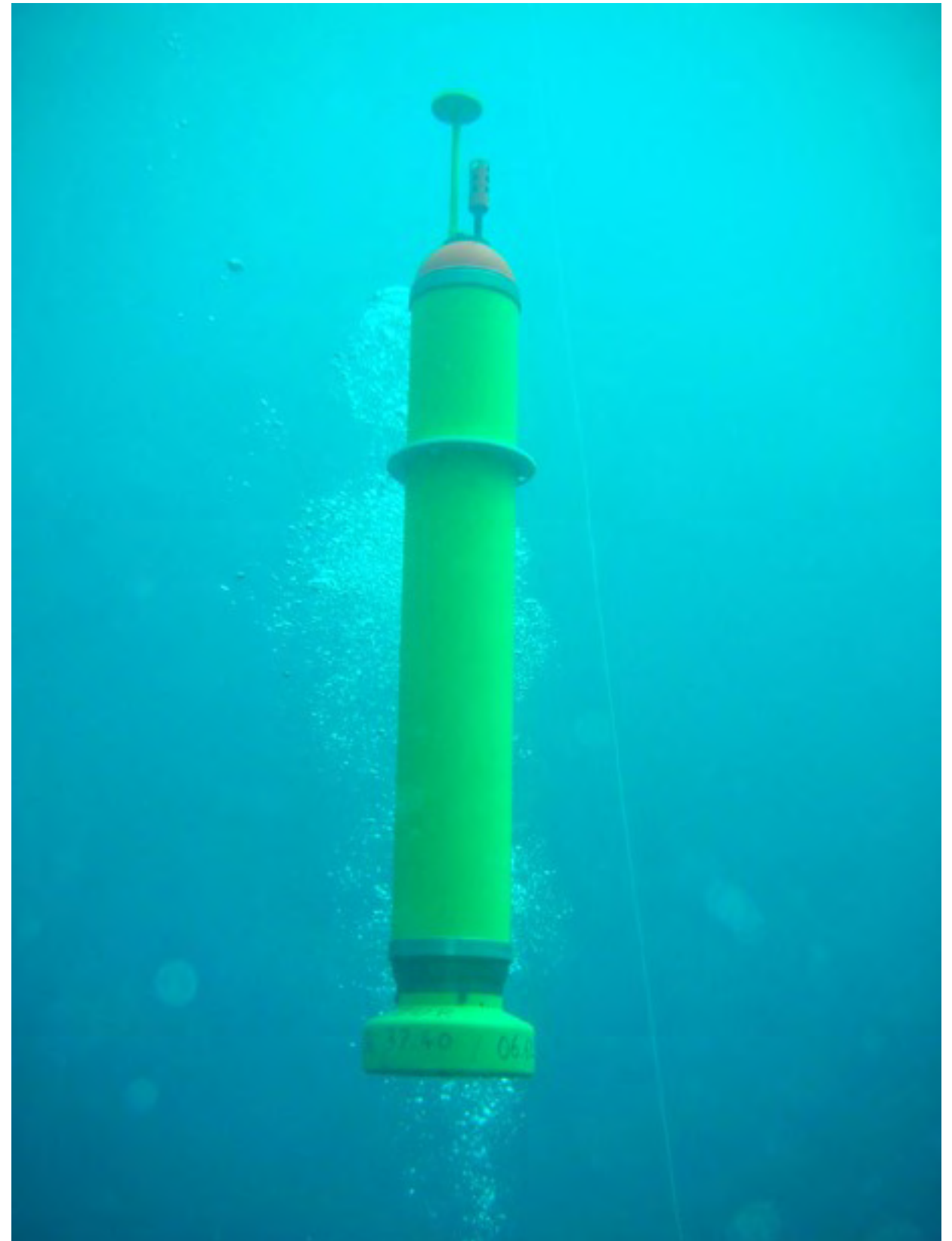


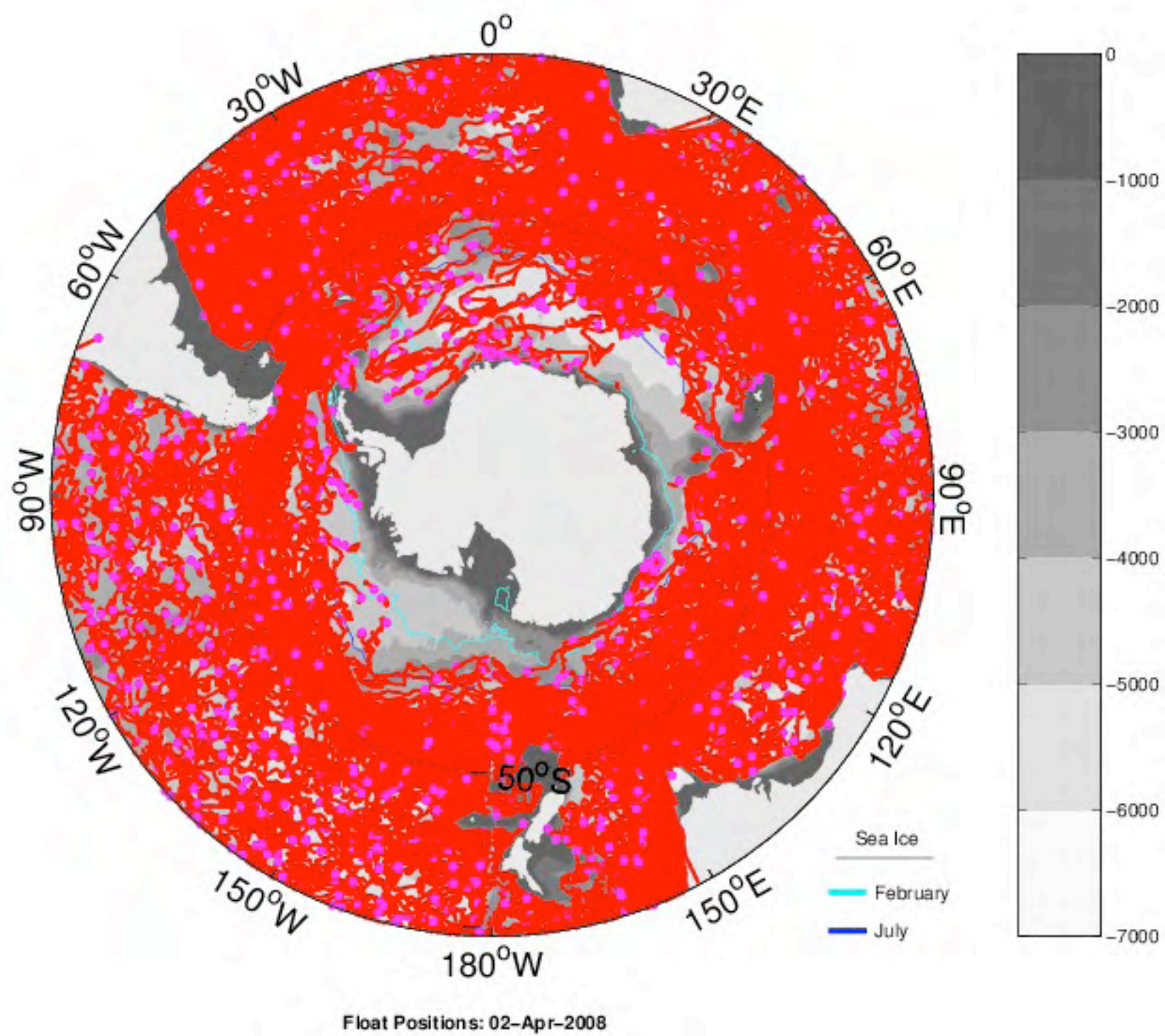
Cruising depth
to 2000 m

Lifetime about 3
years

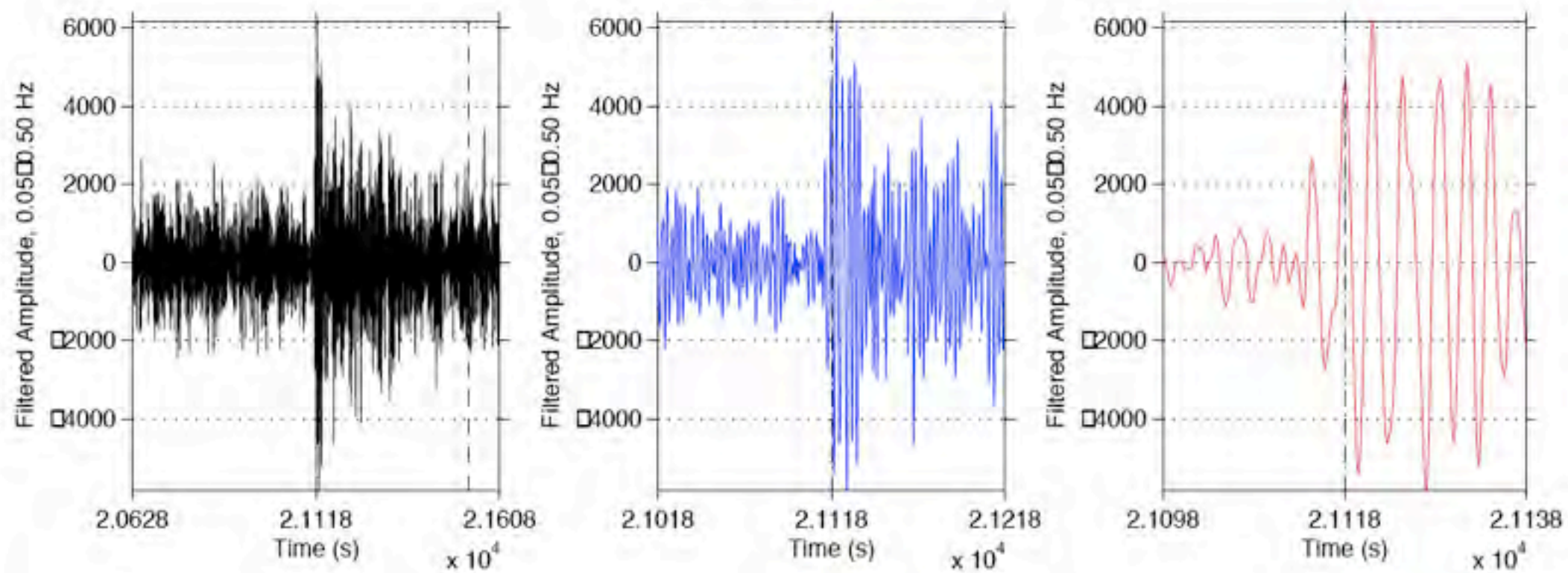


Expected to get good
signal for magnitudes 6 and
higher (100/yr)





Zooming in on the onset



1000 s



200 s



40 s

Courtesy Frederik Simons

To learn more....

- Nolet, *A Breviary of Seismic Tomography*, 344p, Cambridge Univ. Press, 2008
- Tromp et al., *Seismic tomography, adjoint methods, time reversal and banana-doughnut kernels*, GJI **160**:195-216, 2005
- Sigloch and Nolet, *Measuring finite-frequency body wave amplitudes and travel times*, GJI **167**:271-287, 2006
- Simons et al., *On the potential of recording earthquakes for global seismic tomography by low-cost autonomous instruments in the oceans*, JGR **114**:B053071, 2009
- Maggi et al., *An automated time-window selection algorithm for seismic tomography*, GJI **178**:257-281, 2009