3D IMAGING OF THE EARTH'S MANTLE: FROM SLABS TO PLUMES

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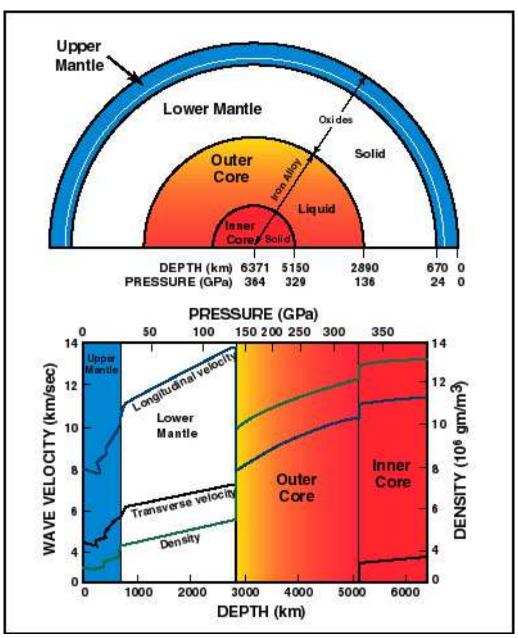
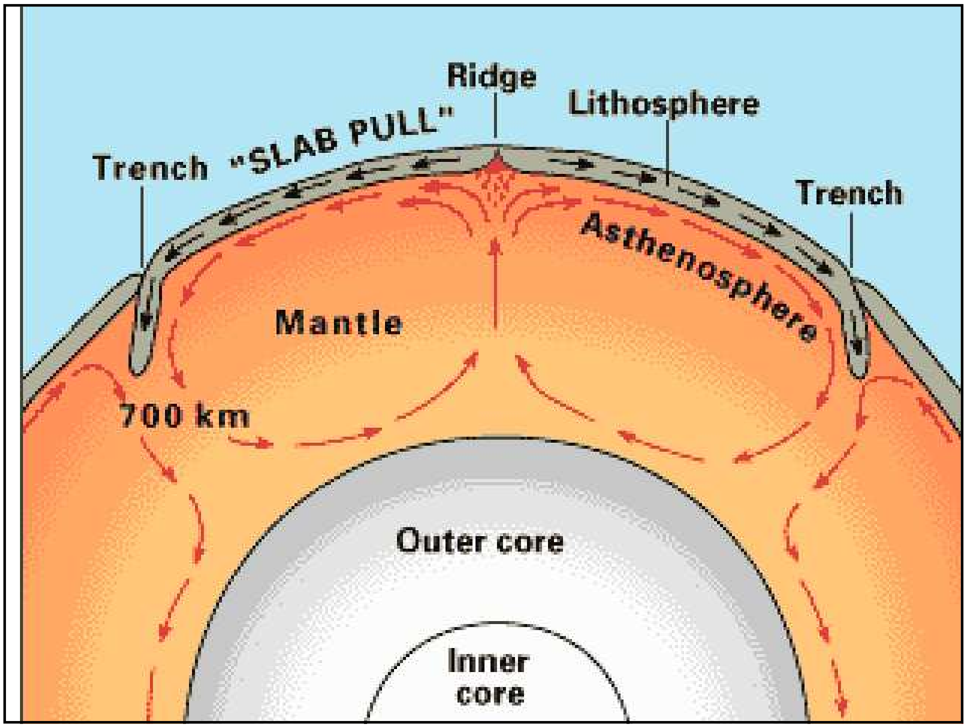
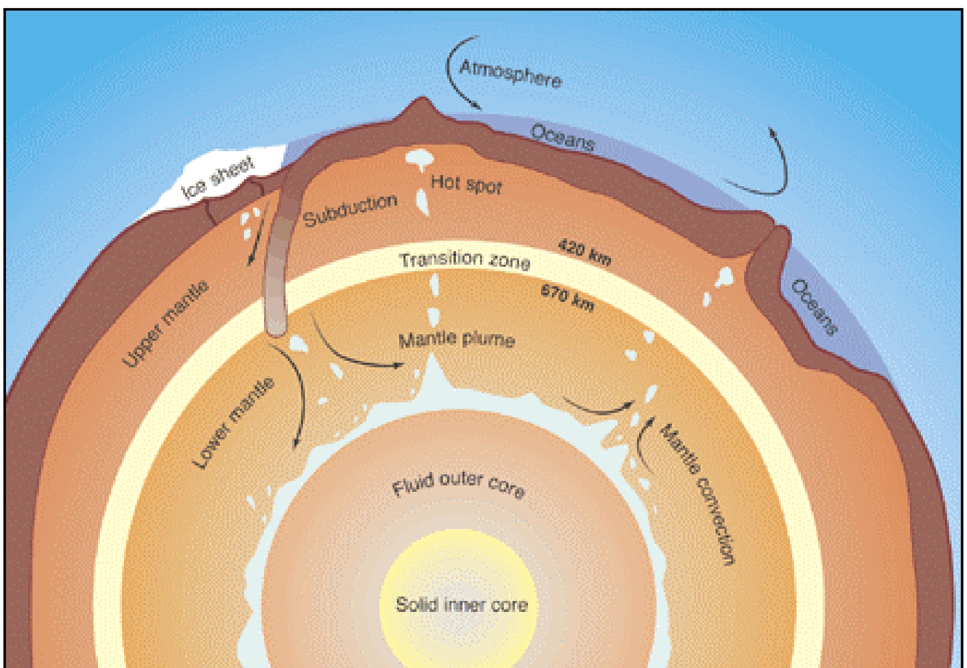
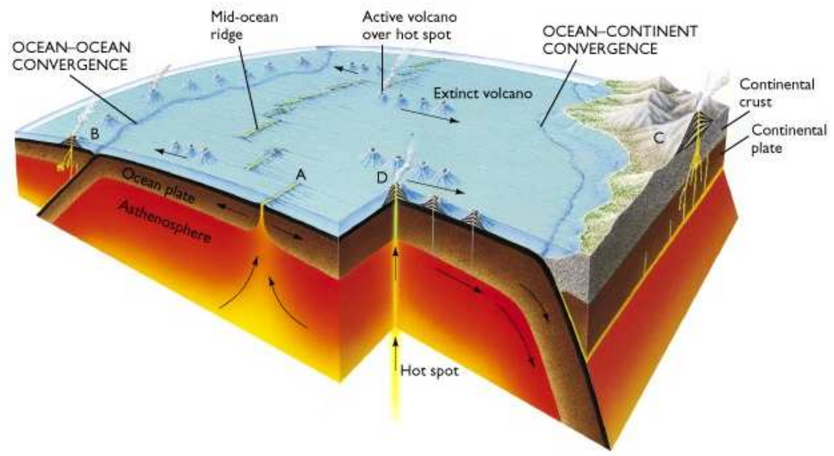
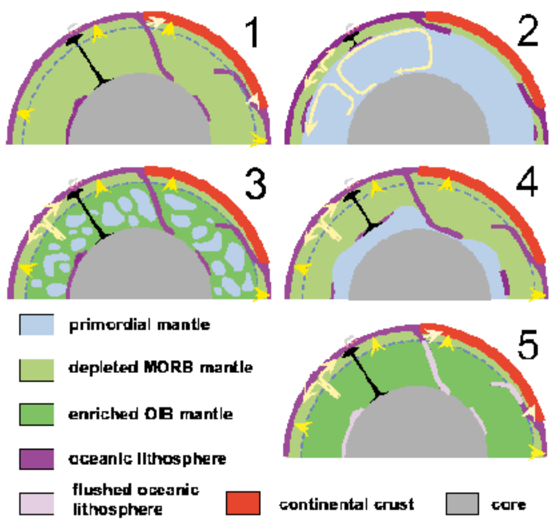






Cartoon from Cazenave, 2002

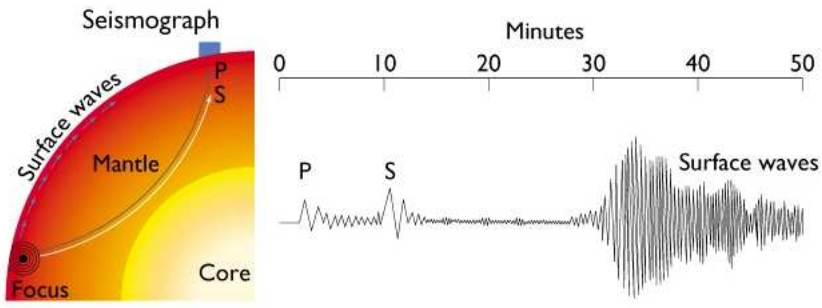


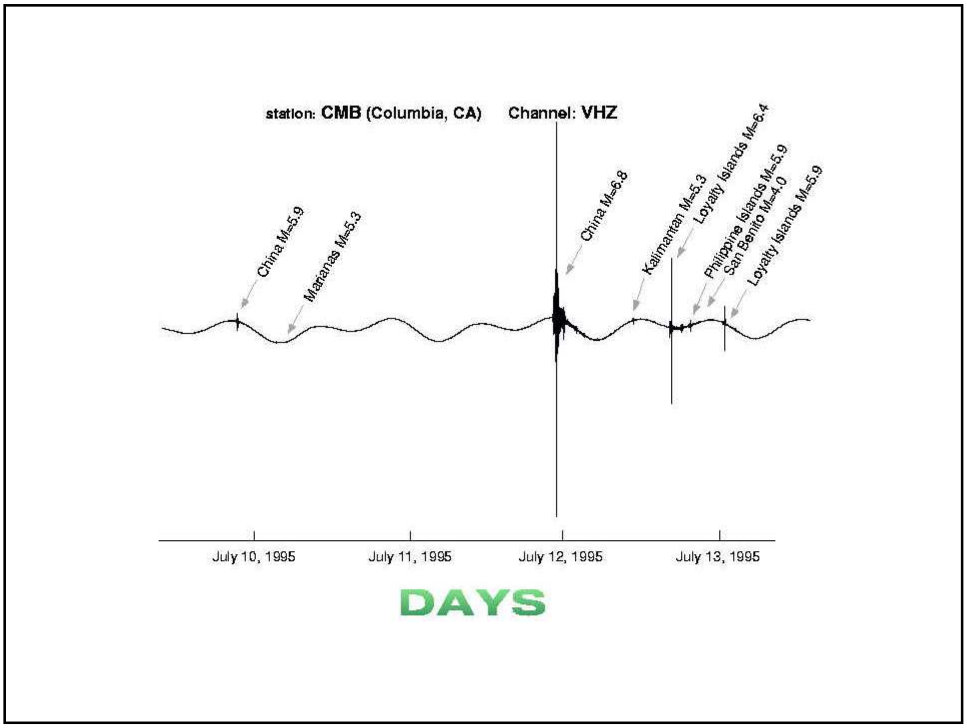


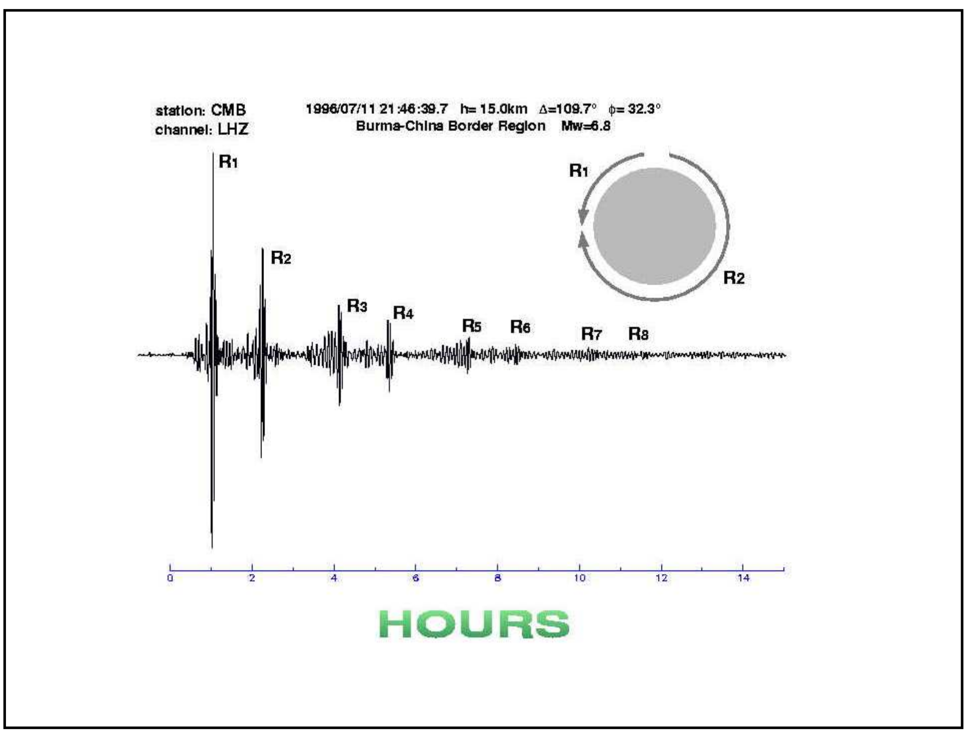
(Albarède and van der Hilst, 1999)

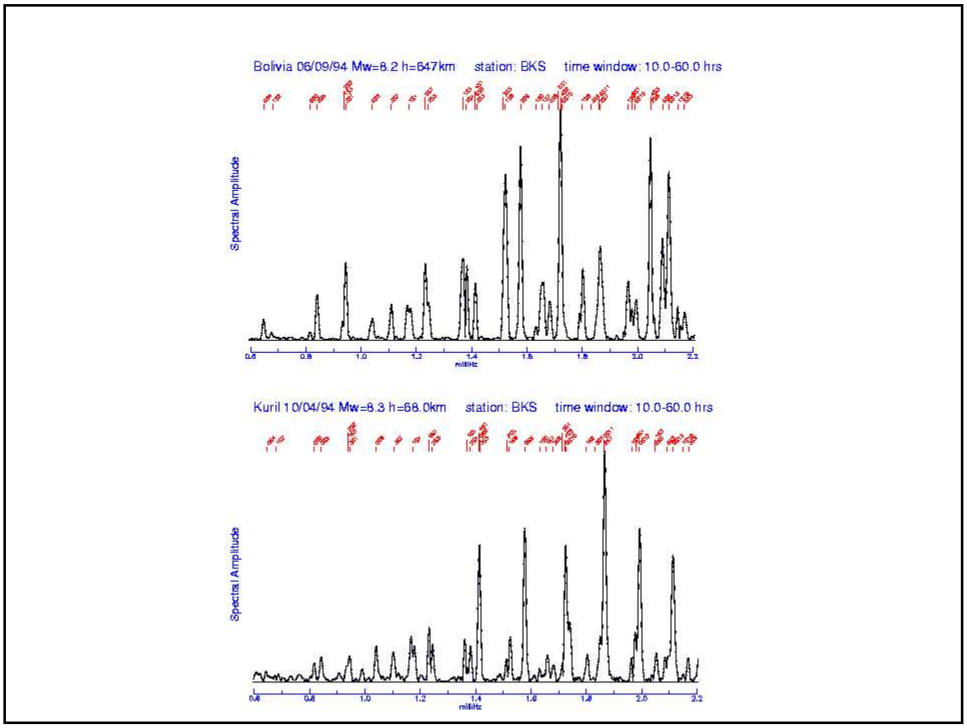
SOME KEY QUESTIONS

- Global mantle circulation: 1, 1.5, 2 layers?
- Fate of subducted slabs in the lower mantle?
- Role of mantle plumes in global circulation?
- Chemical reservoirs in the lower mantle
- Role of the D” layer in global thermal/chemical processes?

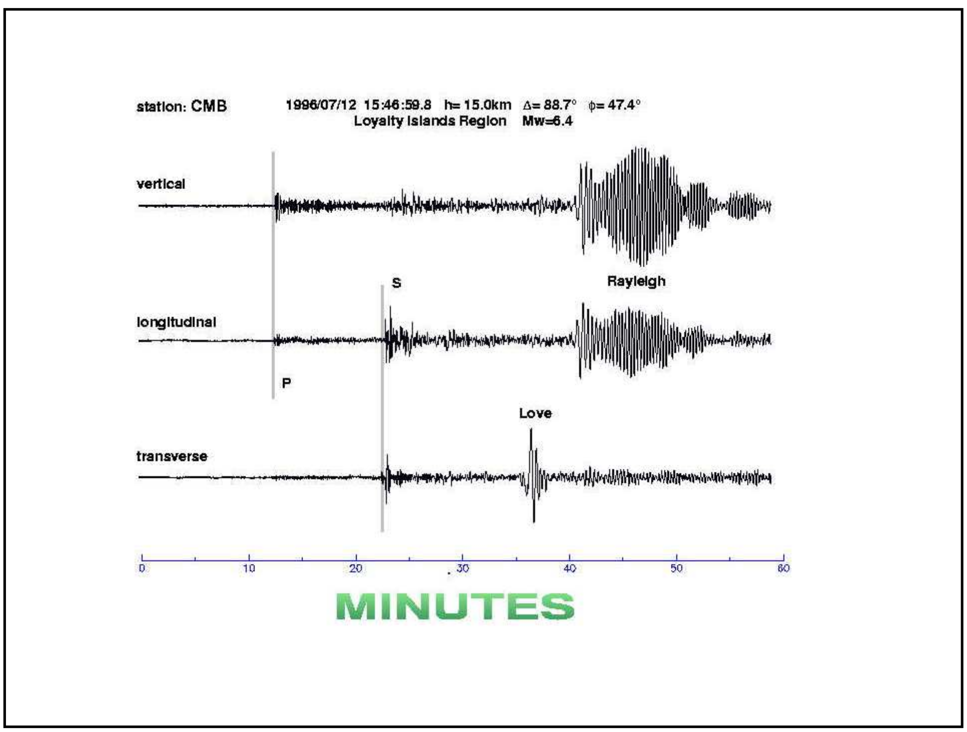



station: CMB (Columbia, CA)
Channel: VHZ
China M=5.9
Marianas M=5.3
China M=6.8
Kalimantan M=5.3
Loyalty Islands M=6.4
Philippine Islands M=5.9
San Benito M=4.0
Loyalty Islands M=5.9
July 10, 1995
July 11, 1995
July 12, 1995
July 13, 1995
DAYS

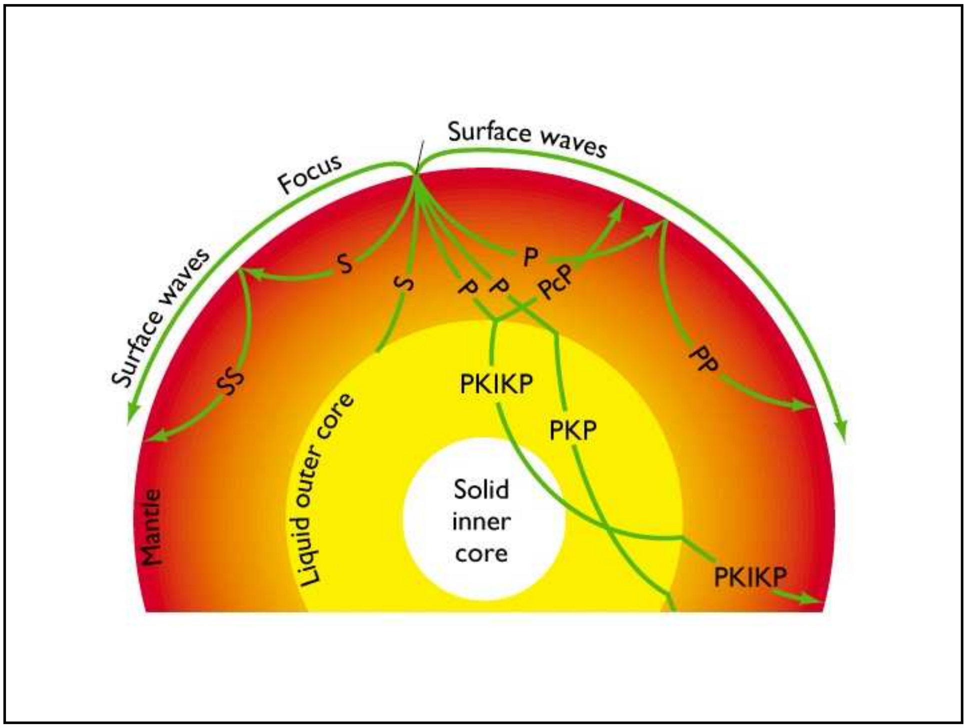

station: CMB
channel: LHZ
1996/07/11 21:46:39.7 h= 15.0km Δ=109.7° φ= 32.3°
Burma-China Border Region Mw=6.8
R1
R2
R3
R4
R5
R6
R7
R8
0
2
4
6
8
10
12
14
HOURS

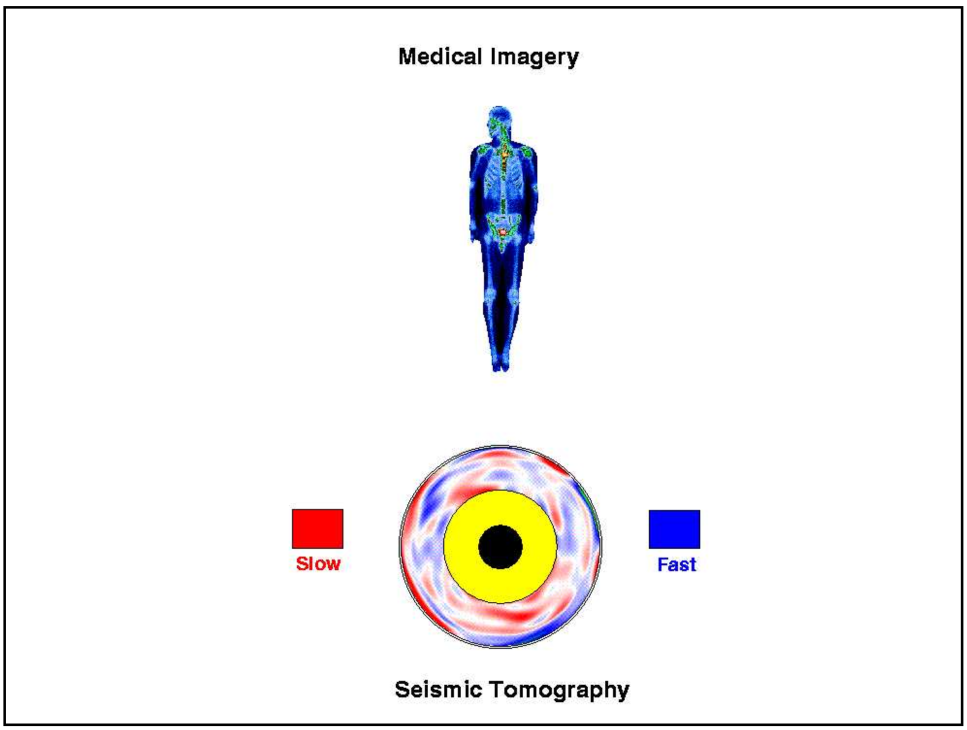


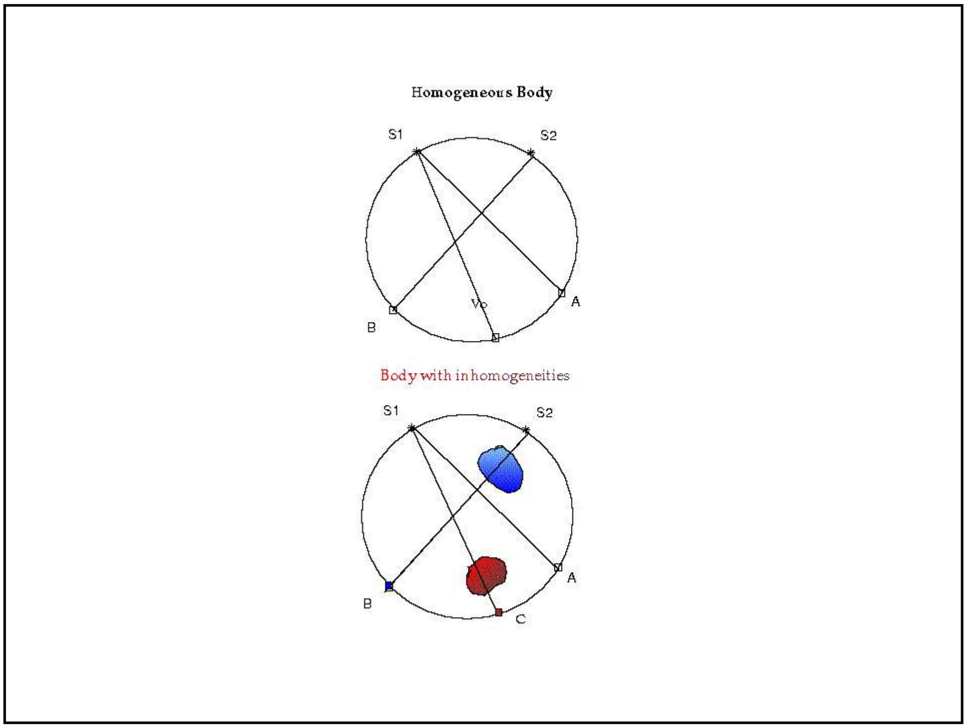
Bolivia 06/09/94 Mw=8.2 h=647km station: BKS time window: 10.0-60.0 hrs
Spectral Amplitude
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
milliHz
Kuril 10/04/94 Mw=8.3 h=68.0km station: BKS time window: 10.0-60.0 hrs
Spectral Amplitude
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
milliHz

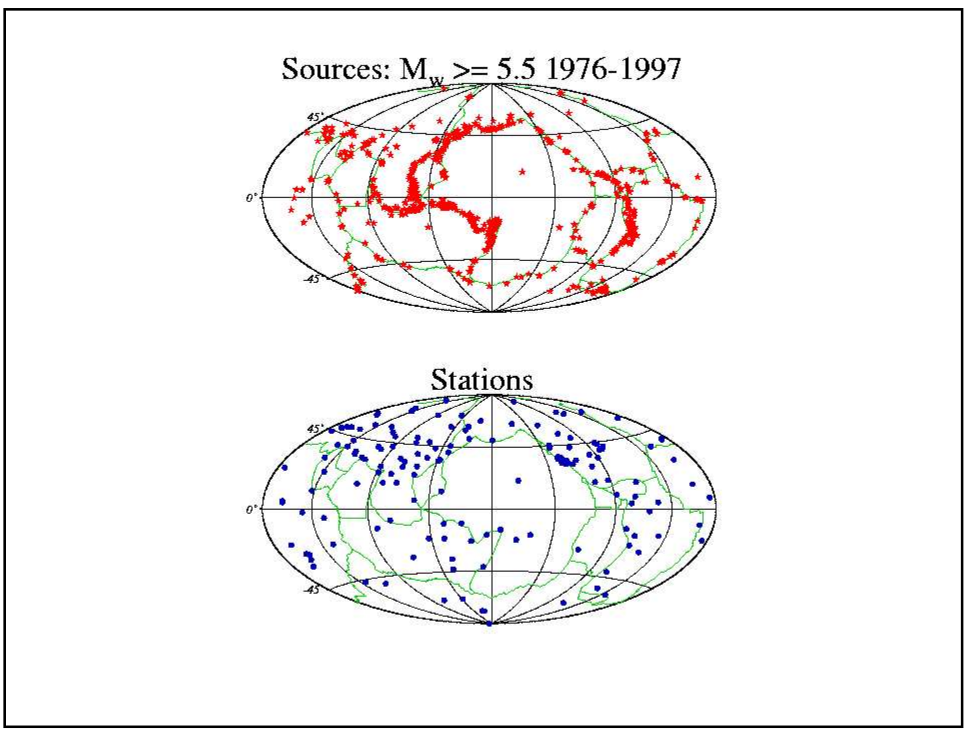


station: CMB
1996/07/12 15:46:59.8 h= 15.0km Δ= 88.7° ϕ= 47.4°
Loyalty Islands Region Mw=6.4
vertical
S
Rayleigh
longitudinal
P
Love
transverse
0
10
20
30
40
50
60
MINUTES


Focus
Surface waves
Surface waves
S
S
SS
P
P
P
PcP
PP
PKIKP
PKP
PKIKP
Mantle
Liquid outer core
Solid
inner
core


Medical Imagery
Slow
Fast
Seismic Tomography


Homogeneous Body
S1
S2
A
B
Vo
Body with inhomogeneities
S1
S2
A
B
C


Sources: M_w >= 5.5 1976-1997
45°
0°
-45
Stations
45°
0°
-45

Datasets for seismic tomography:

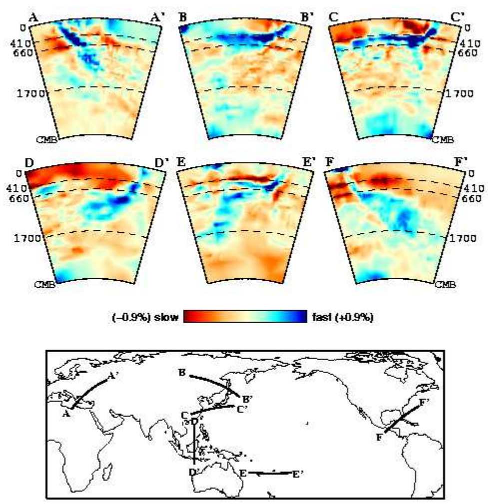
- International Seismological Centre bulletins:
  - Over 30 years collection of arrival time data from several hundred stations around the world
  - No quality control -> statistical averaging to ensure quality
  - "First arrivals" (P phases) are most reliable
- Last 15 years: "broadband", digital waveform data available on line from several data centers (e.g. IRIS)

GLOBAL TOMOGRAPHIC MODELS

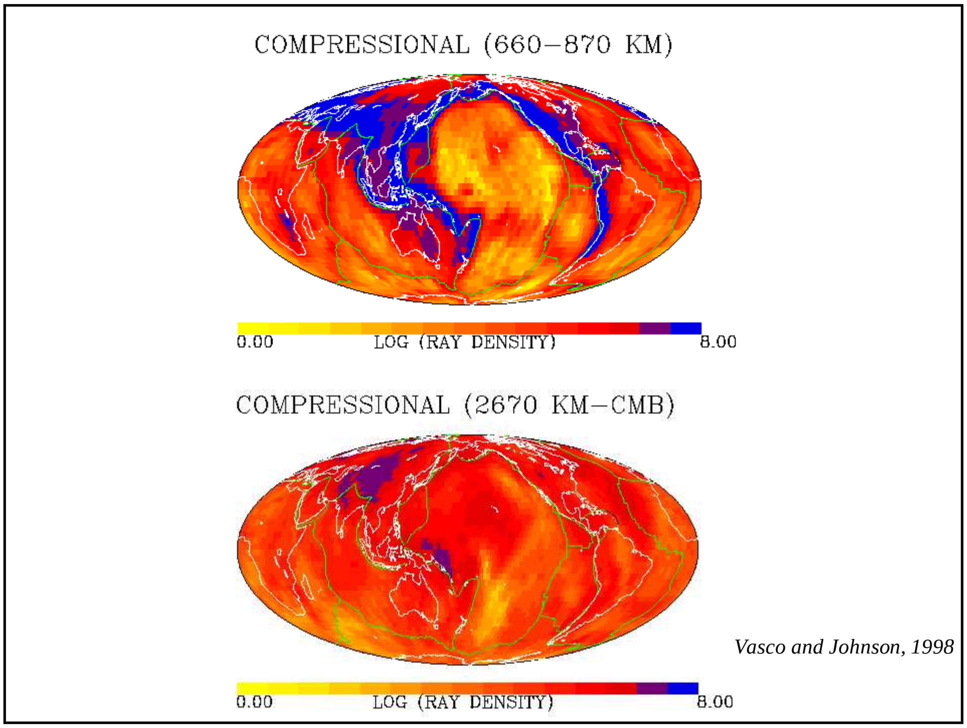
- "*High-resolution models*"
  - Derived using mostly ISC bulletin data (P wave first arrivals)
  - Local parametrization (blocks)
  - ray theory (infinite frequency approximation)

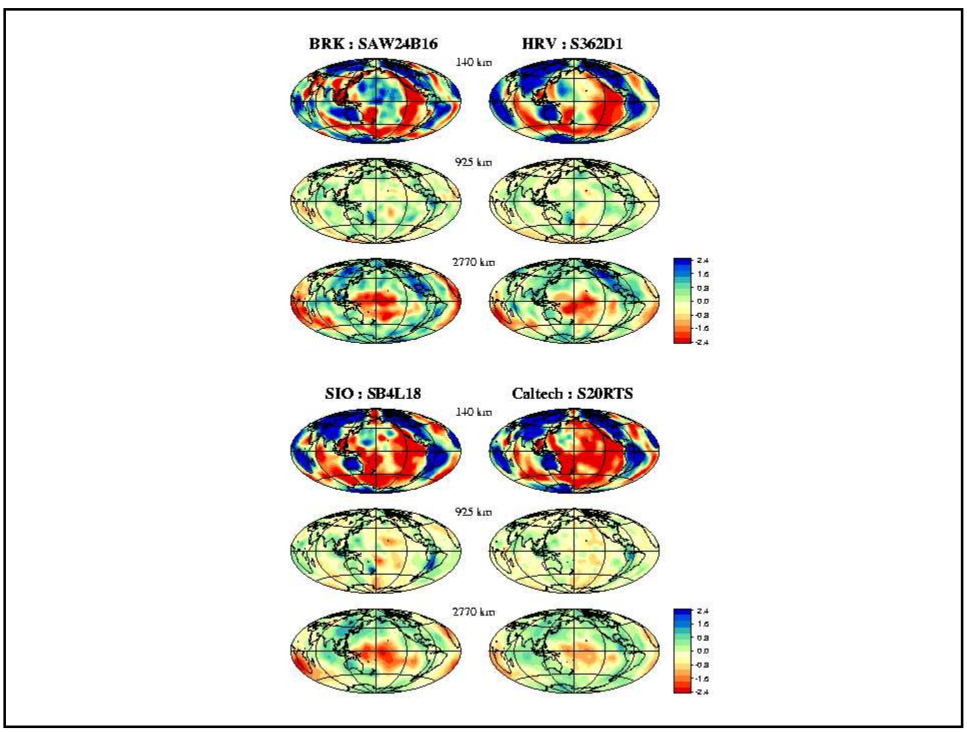
GLOBAL TOMOGRAPHIC MODELS

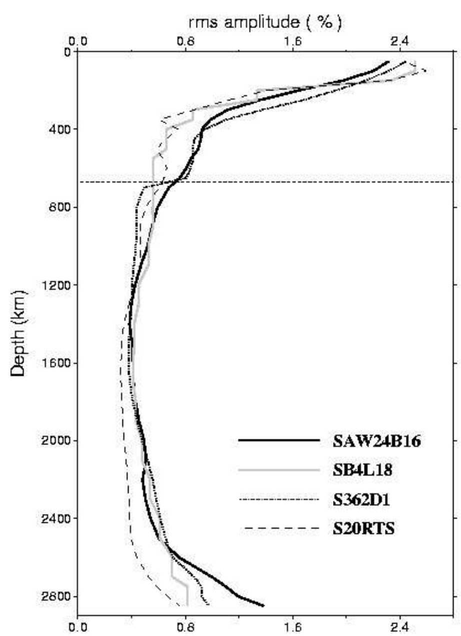
- "*Long-wavelength models*"
  - Mostly S velocity models
    - Surface wave dispersion
    - Normal mode splitting coefficients
    - S, SS, ScS travel times ("Hand Picked")
  - Global parametrization (spherical harmonics)

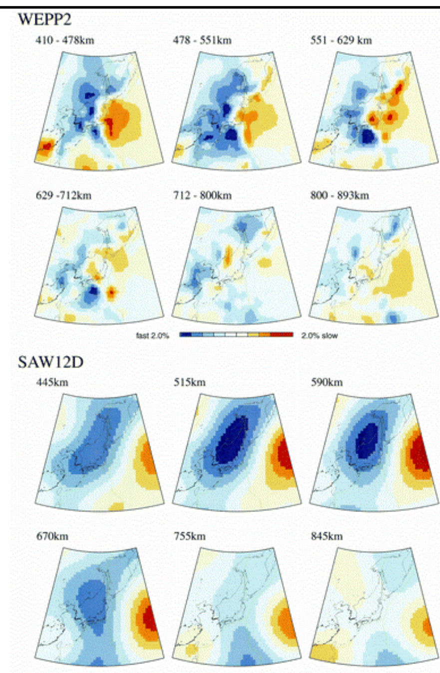


Van der Hilst et al., 1998

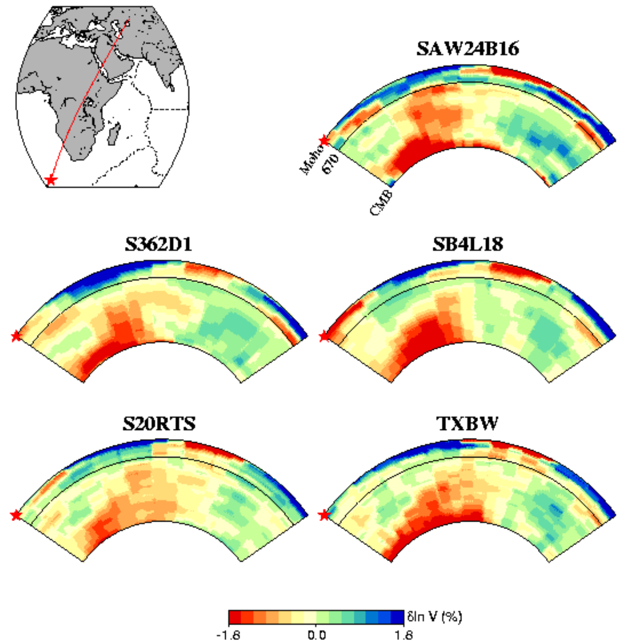

COMPRESSIONAL (660−870 KM)
0.00
LOG (RAY DENSITY)
8.00
COMPRESSIONAL (2670 KM−CMB)
Vasco and Johnson, 1998
0.00
LOG (RAY DENSITY)
8.00


BRK : SAW24B16
HRV : S362D1
140 km
925 km
2770 km
SIO : SB4L18
Caltech : S20RTS
140 km
925 km
2770 km





Fukao et al., 2001

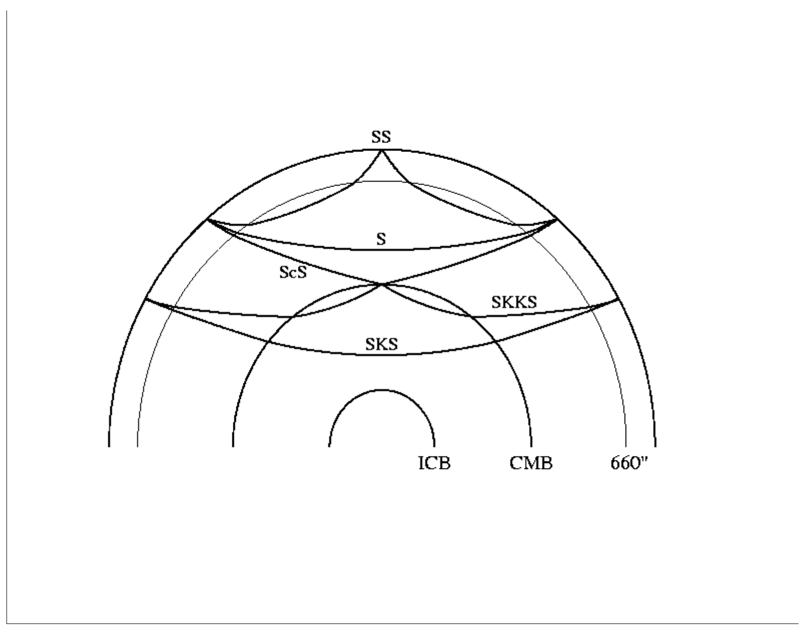


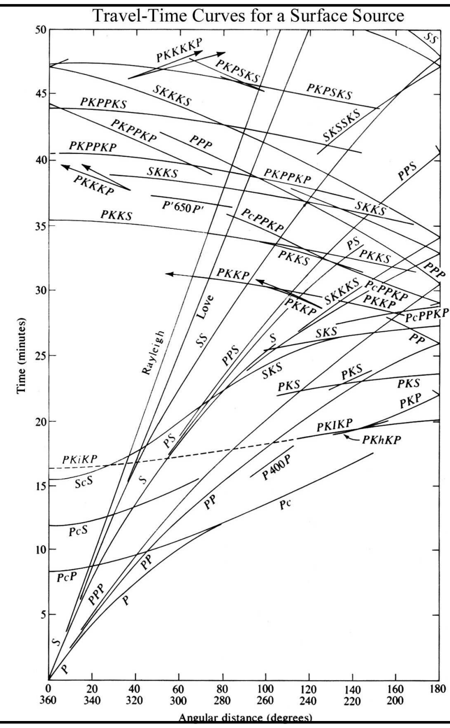
Long wavelength S models

- Not as “sharp” in subduction zones
- Better resolution in upper mantle and under oceans
- Better coverage in lower mantle
- Resolution of low degree heterogeneity
- Anisotropy
- *Provide insights into slow regions*

Most long wavelength S models

- *Limitations*:
  - Well separated body wave phases only
  - No diffracted waves
  - Inaccurate sensitivity kernels for body waves



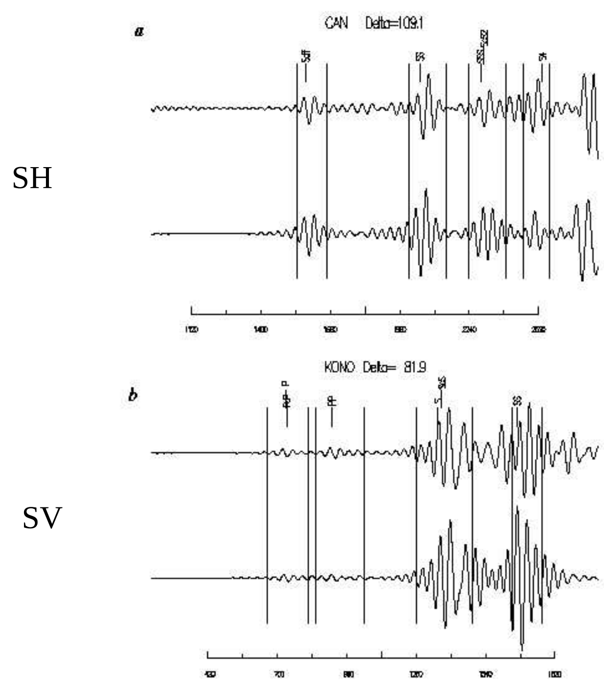


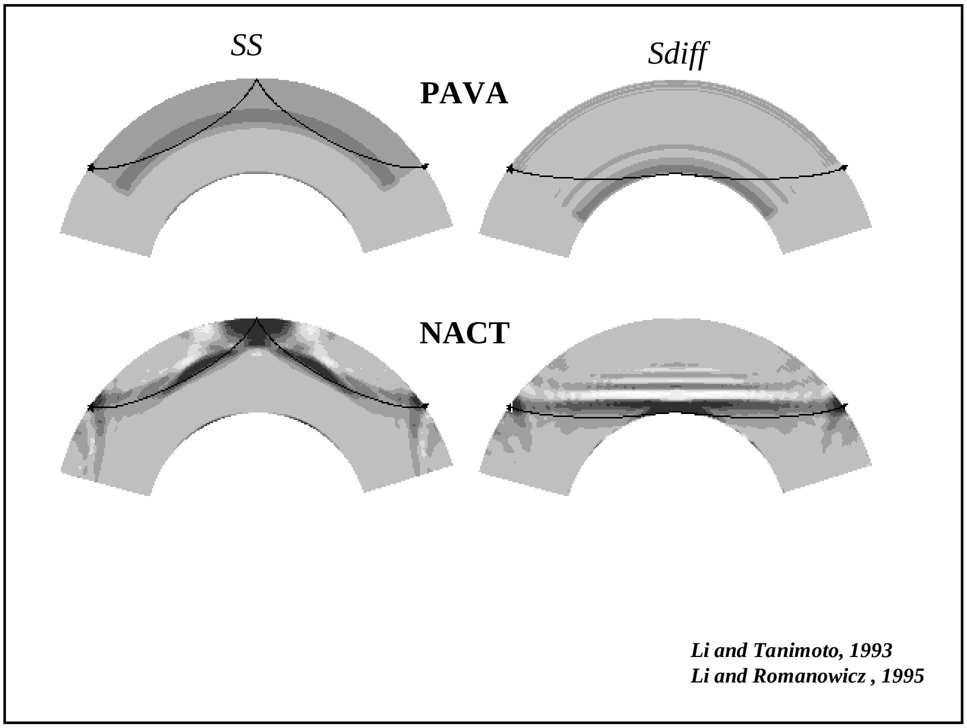
Towards the future: whole mantle waveform tomography -the UCB approach

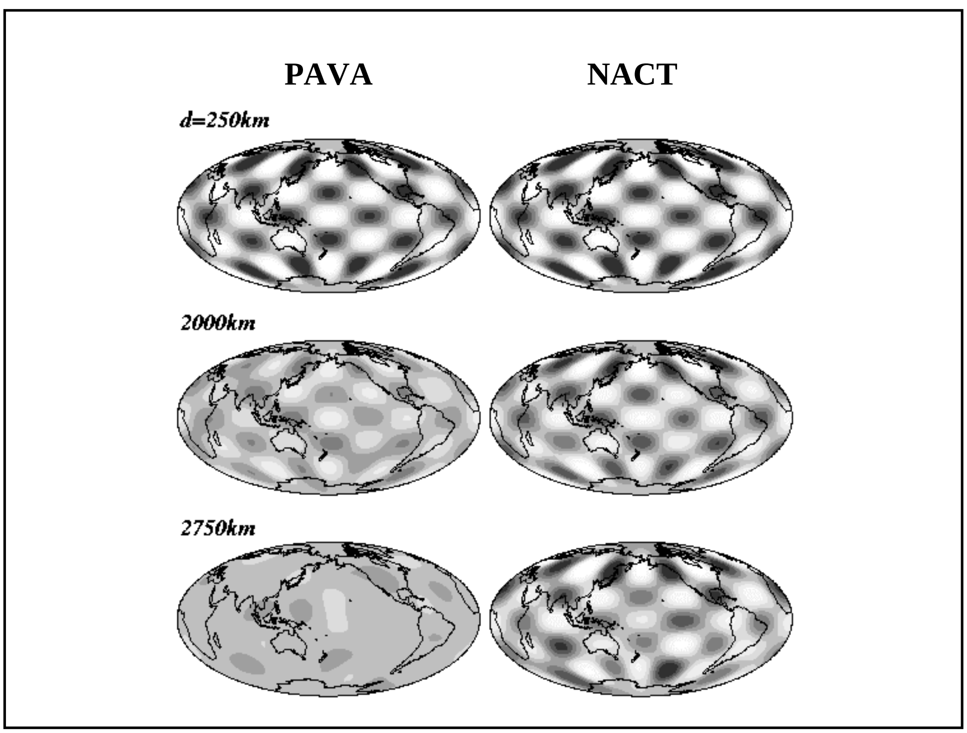
- compare observed waveforms with synthetics computed using summation of normal modes
- perturbation theory: include mode coupling due to 3D heterogeneity

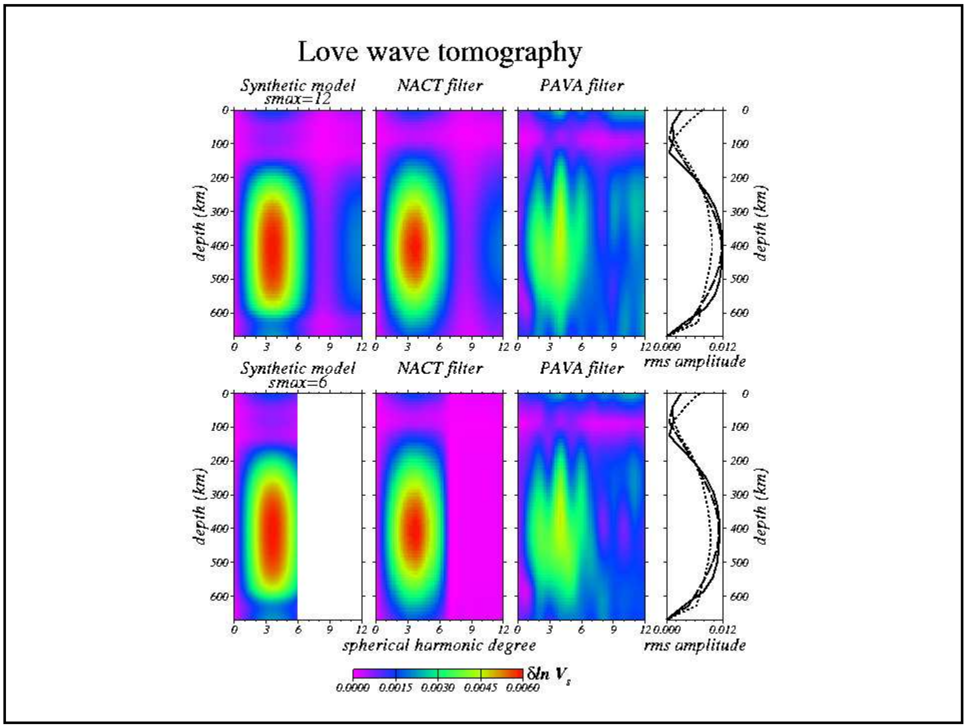
Asymptotic formalism

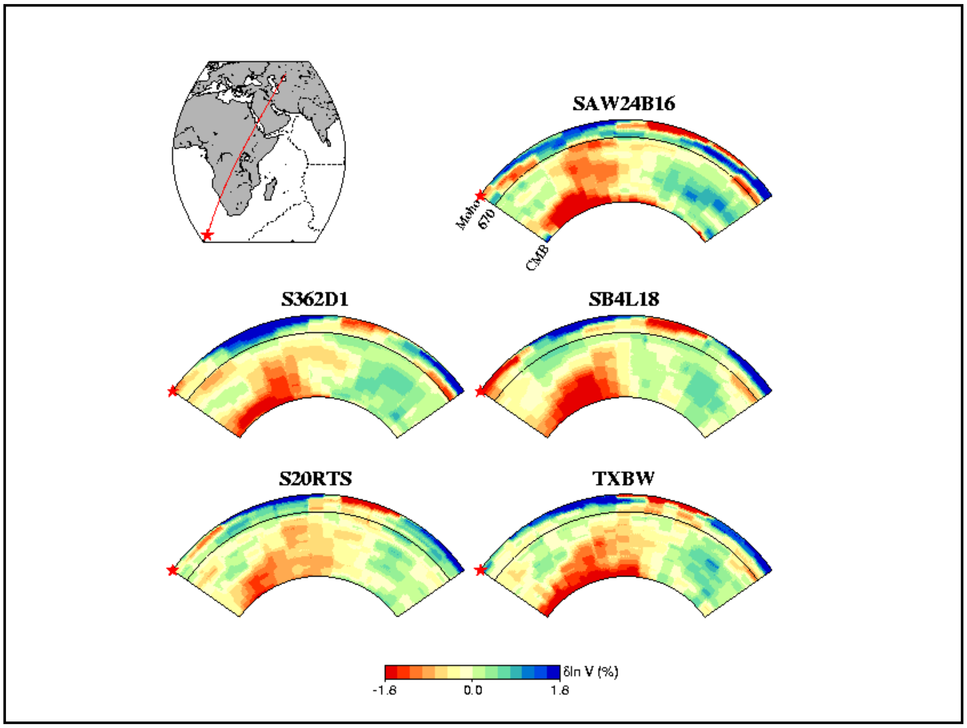
- along branch coupling : PAVA (standard)
- across branch coupling : NACT-> 2D kernels
- off-path propagation effects (“focusing”)




SS
Sdiff
PAVA
NACT
Li and Tanimoto, 1993
Li and Romanowicz , 1995


PAVA
NACT
d=250km
2000km
2750km


Love wave tomography
Synthetic model smax=12
NACT filter
PAVA filter
depth (km)
rms amplitude
Synthetic model smax=6
spherical harmonic degree
δln V_s
0.0000 0.0015 0.0030 0.0045 0.0060

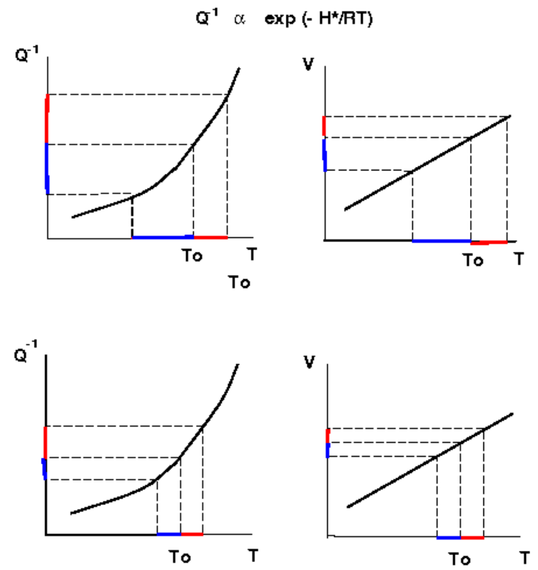

SAW24B16
Moho
670
CMB
S362D1
SB4L18
S20RTS
TXBW
δln V (%)
-1.8 0.0 1.8

Conclusions I: elastic tomography

- High resolution P models allow detailed mapping of subducted slabs
- L. w. S models "see" the same fast structures as P models in mid-mantle
- L. w. S models bring additional information on slow regions
- Two major "plumes" with a broad base in D" extending from the CMB high into the lower mantle
- The key to better resolution: *waveform tomography*

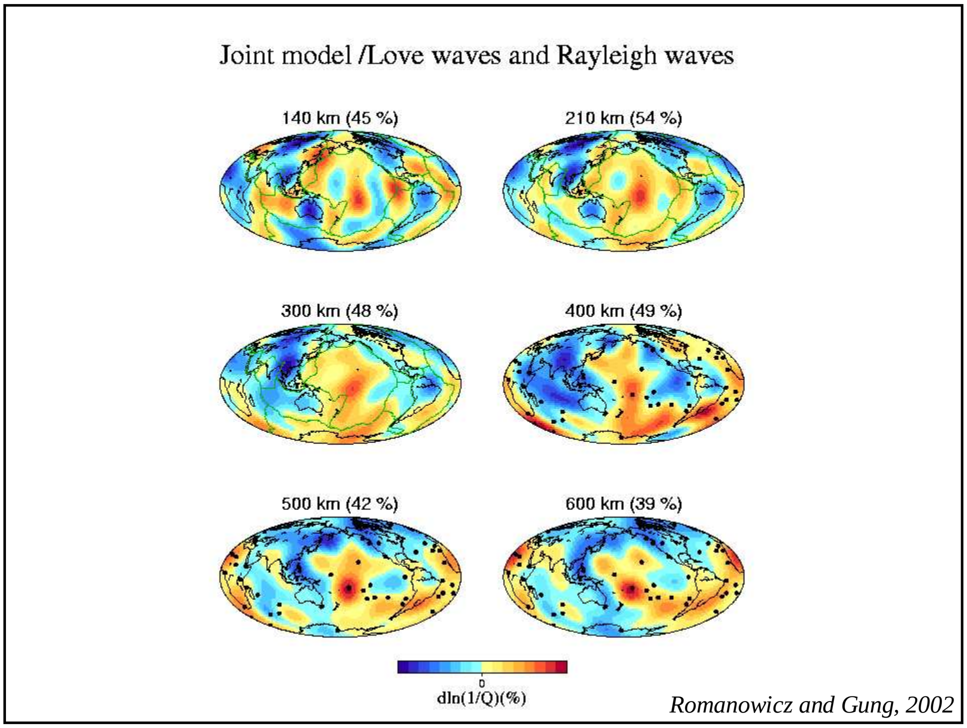
INVERSION FOR ANELASTIC STRUCTURE

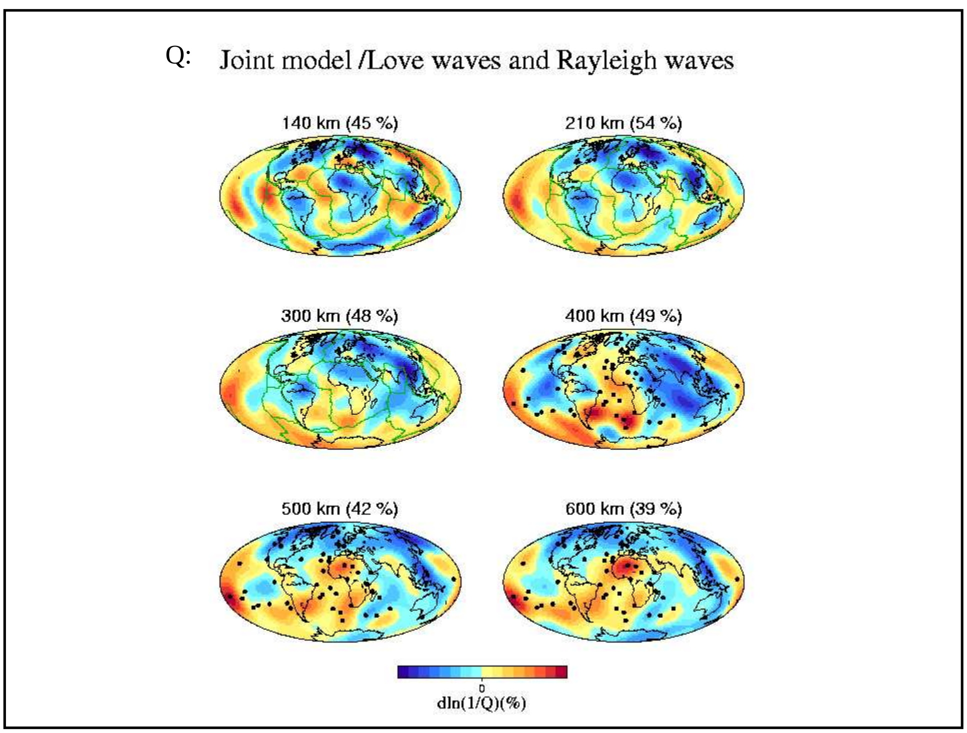
- A waveform approach gives us access to amplitude information
- Attenuation strongly dependent on temperature => additional constraints
- Address issues of dispersion due to attenuation

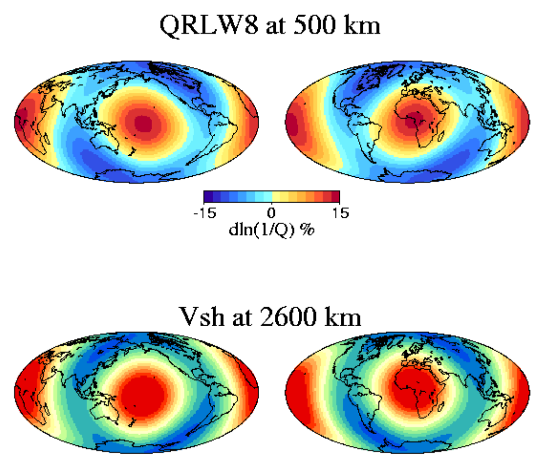


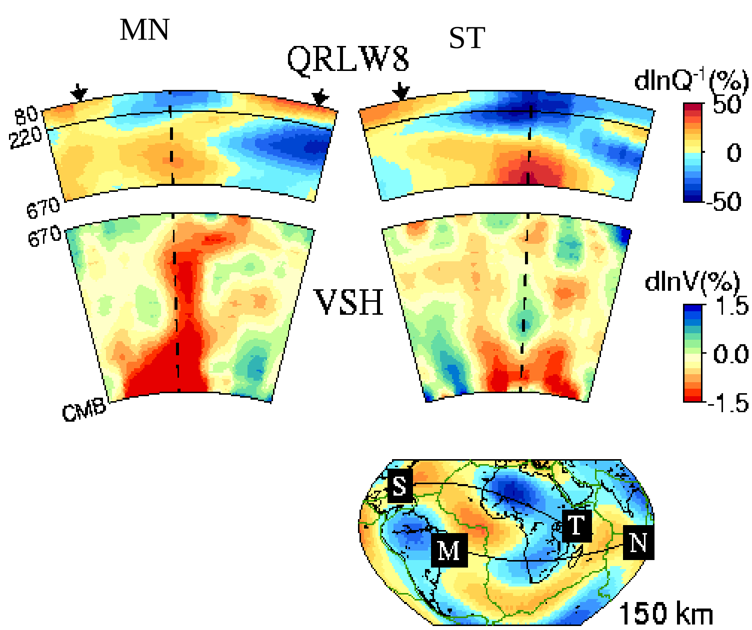
INVERSION FOR Q STRUCTURE

- Iterative inversion for:
  - 1) Elastic structure (align waveform phase)
  - 2) Attenuation structure (match amplitude)
    - using 3D elastic model and 1D Q model as starting models
- So far: upper mantle only

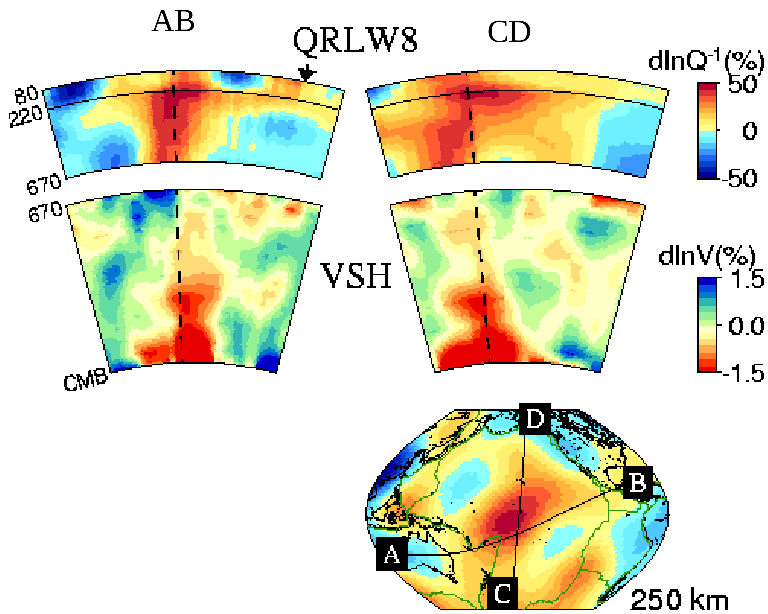

Joint model /Love waves and Rayleigh waves
140 km (45 %)
210 km (54 %)
300 km (48 %)
400 km (49 %)
500 km (42 %)
600 km (39 %)
0
dln(1/Q)(%)
Romanowicz and Gung, 2002


Q:
Joint model /Love waves and Rayleigh waves
140 km (45 %)
210 km (54 %)
300 km (48 %)
400 km (49 %)
500 km (42 %)
600 km (39 %)
0
dln(1/Q)(%)

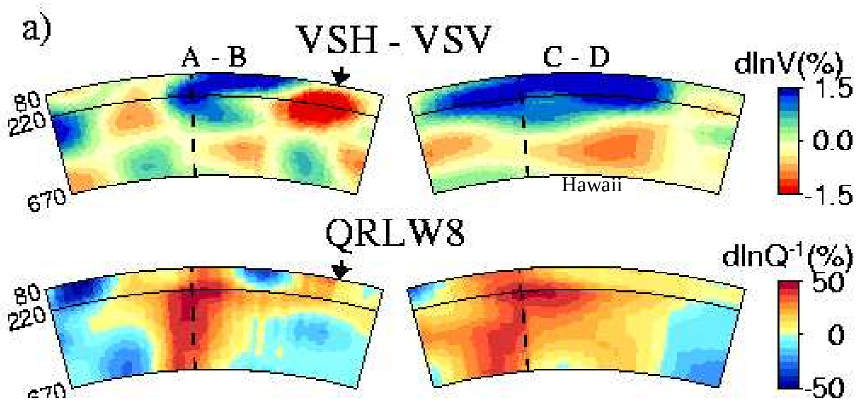




Romanowicz and Gung, 2002



Under Pacific: transverse isotropy versus Q



Conclusions 2: Q tomography

- The combination of:
  - Q tomography in the upper mantle
  - Velocity tomography in the whole mantle
  - Anisotropy (Vsh-Vsv and azimuthal)
- Brings important insights on the dynamics of the upwelling part of the global mantle circulation

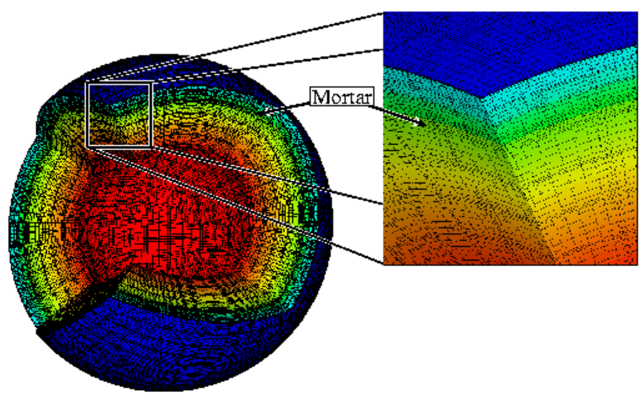
Conclusions 2: Q tomography

- Two "superplumes" (south Pacific, Africa)
  - -> rise from the CMB high into the upper mantle
  - -> merge into the low-viscosity asthenospheric channel
  - -> mix with the slab-pull ridge perpendicular shear flow to create complex horizontal flow pattern in the central Pacific

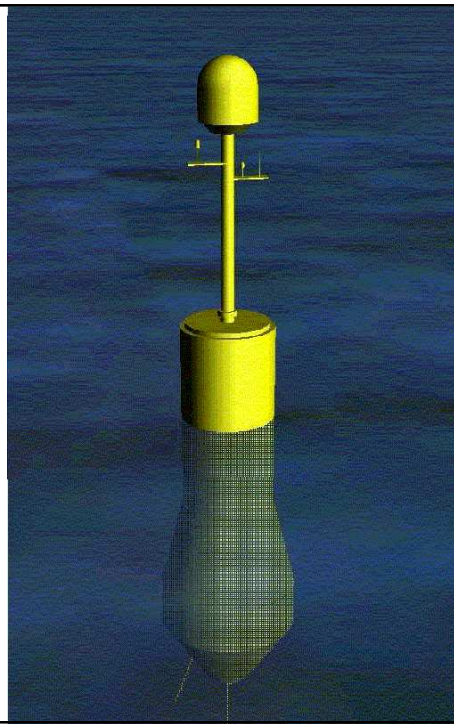
Challenges for the future

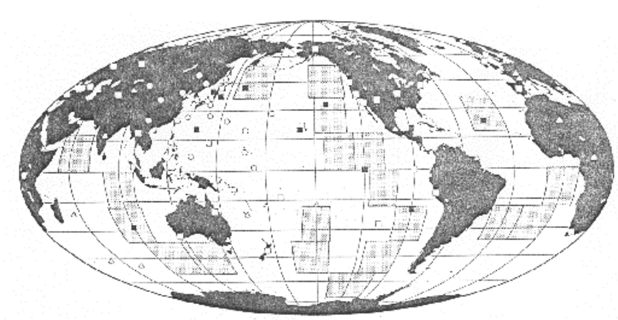
- Waveform tomography to shorter periods
  - 2D, 3D kernels, converted phases
- Improve coverage
  - Ocean bottom, southern hemisphere
- Complement inversion with accurate forward modelling in 3D

Spectral element method

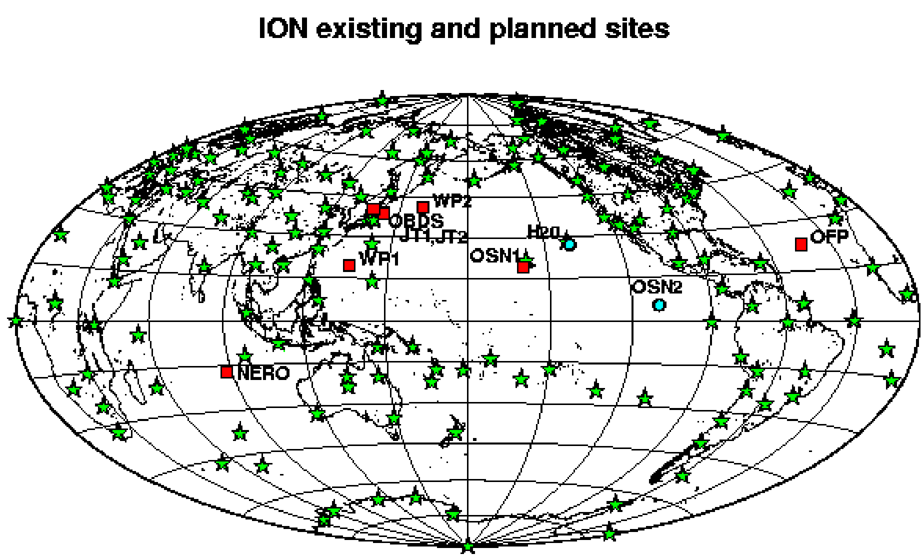


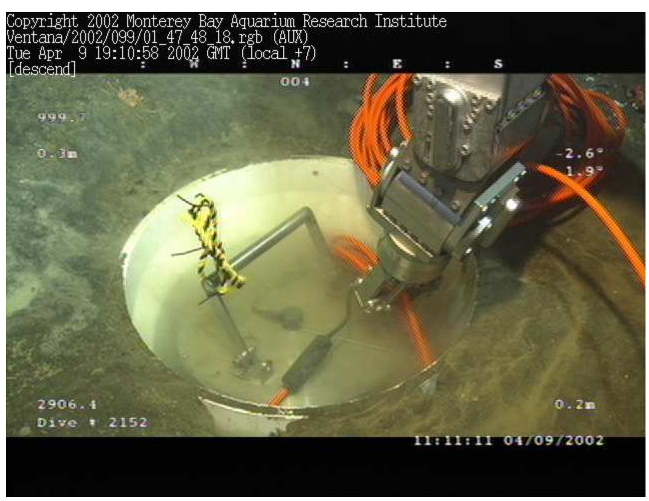
Capdeville, 2000





Target regions on the ocean floor endorsed by ION
(International Ocean Network), 1993


ION existing and planned sites
WP2
OBDS
JT1,JT2
H2O
OFP
WP1
OSN1
OSN2
NERO


Copyright 2002 Monterey Bay Aquarium Research Institute
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