Transition Zone in the Context
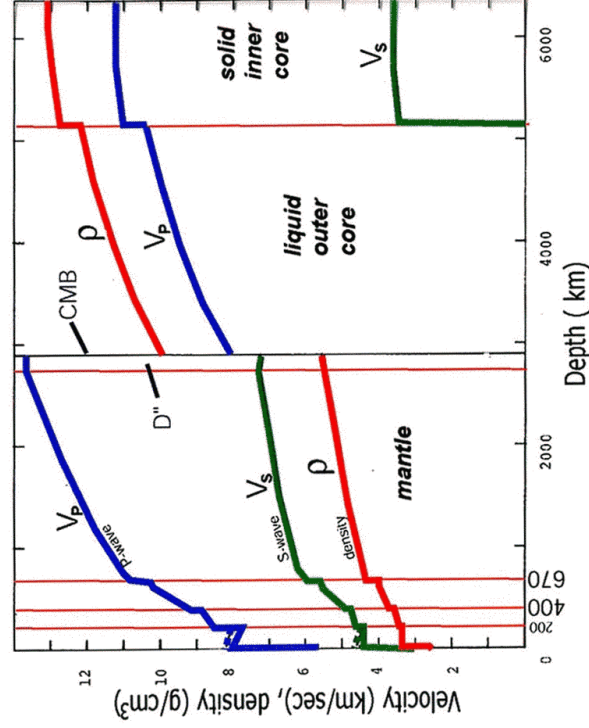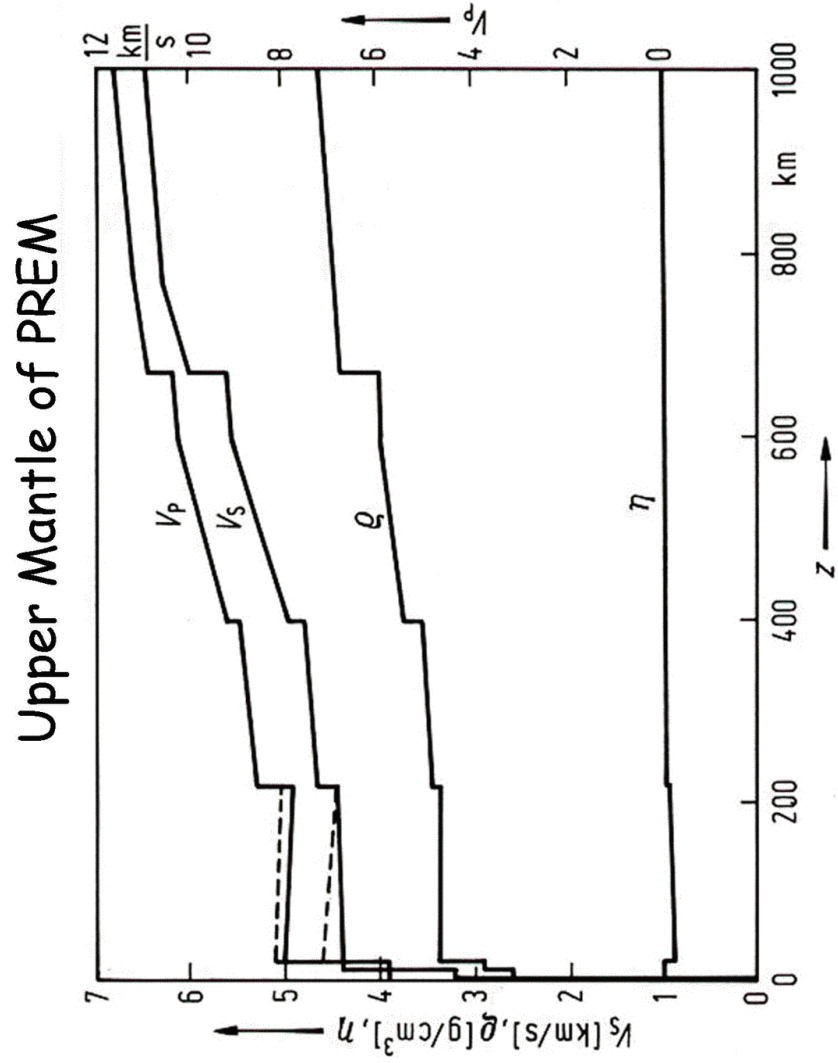
....

Adam M. Dziewonski
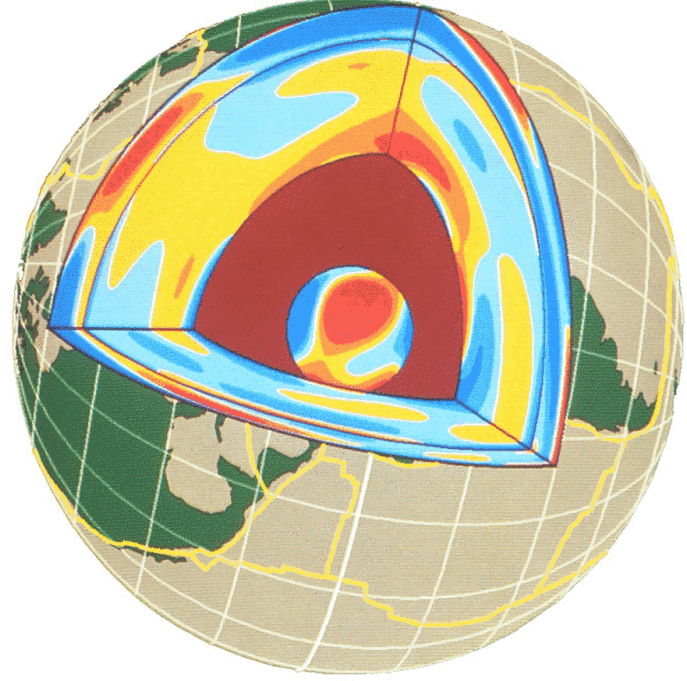
July 29, 2006

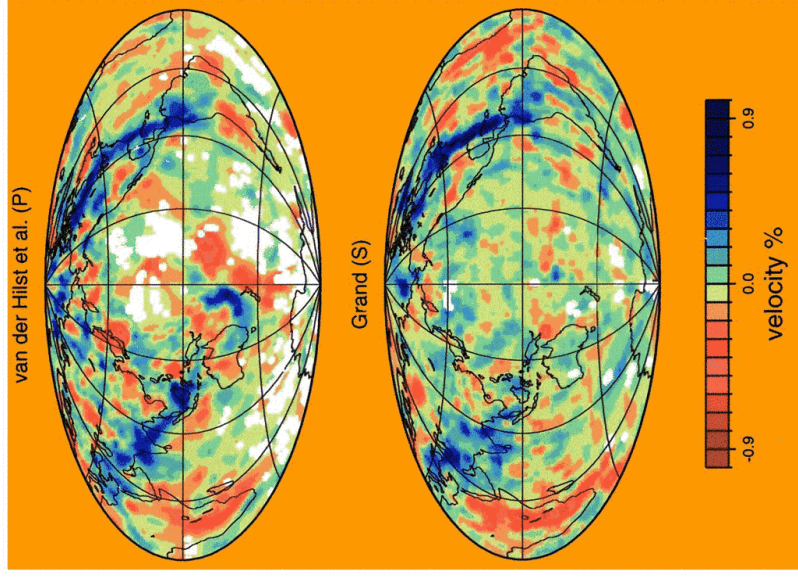*CIDER at KITP*

The PREM Model

PREM was obtained using nearly 1000 normal mode and a wide range of travel time phases. After 22 years, it is still widely used as a reference model.
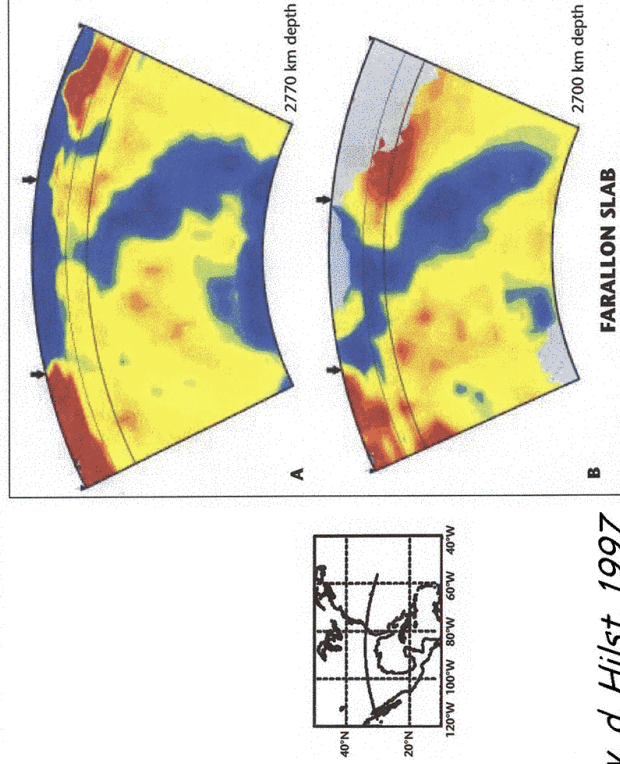
Upper Mantle of PREM

3-D Tomography Allows a New Look

P- and S-velocity anomalies at 1300 km depth

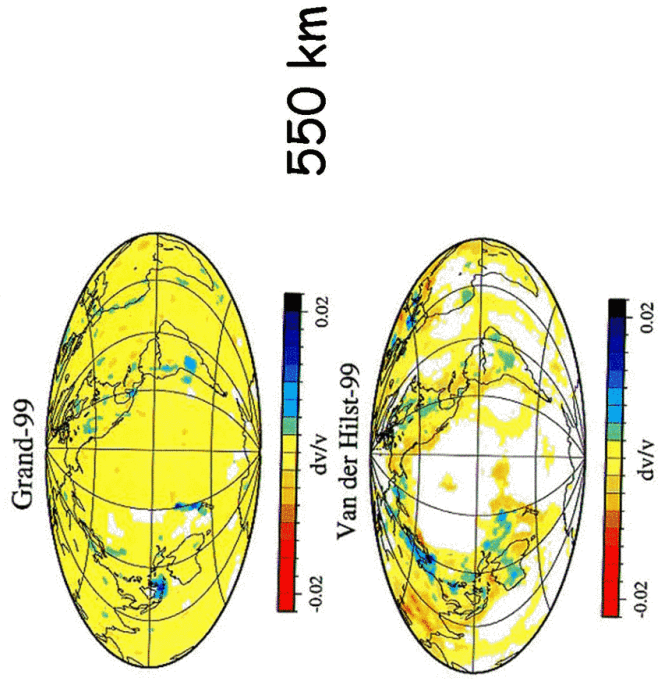Slab Penetration into the Lower Mantle

Grand and v. d. Hilst, 1997

Transition Zone Velocity Anomalies

Grand-99

Van der Hilst-99
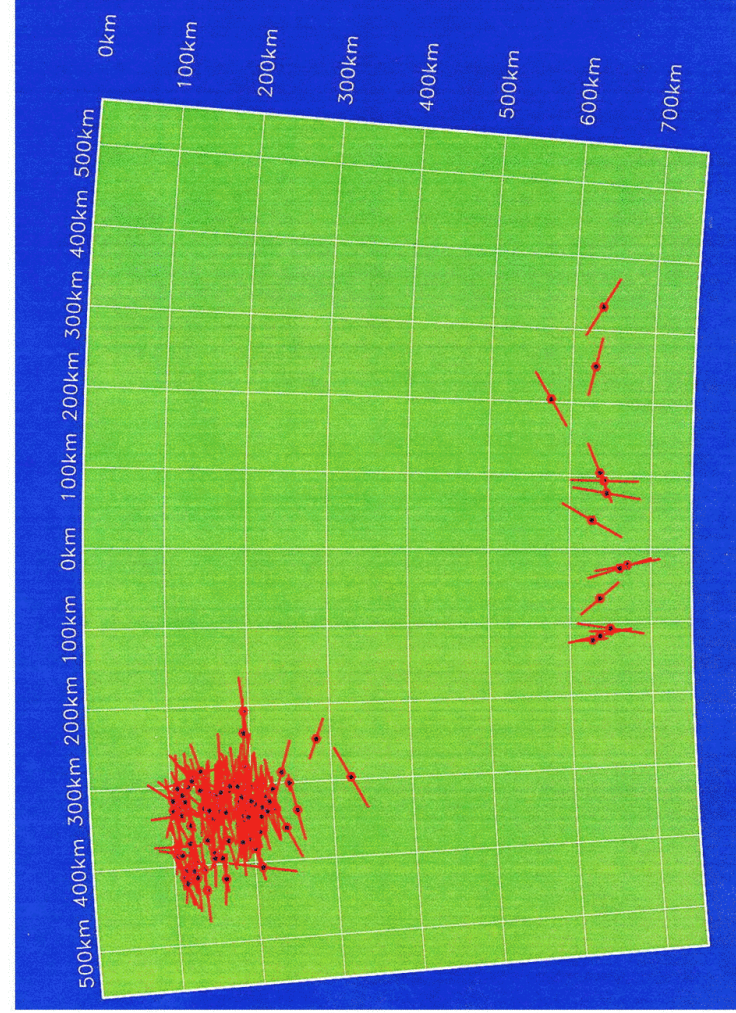
550 km
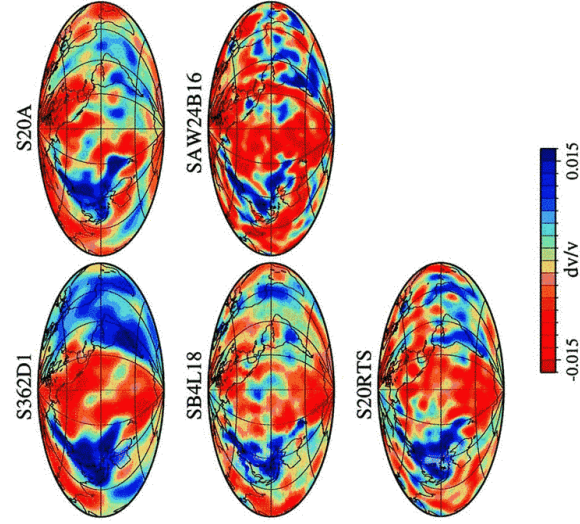
Shear Velocity Anomalies in the Transition Zone Obtained Using Surface Wave and/or Waveform Data

550 km depth

S20A, SAW24B16, S362D1, SB4L18, S20RTS
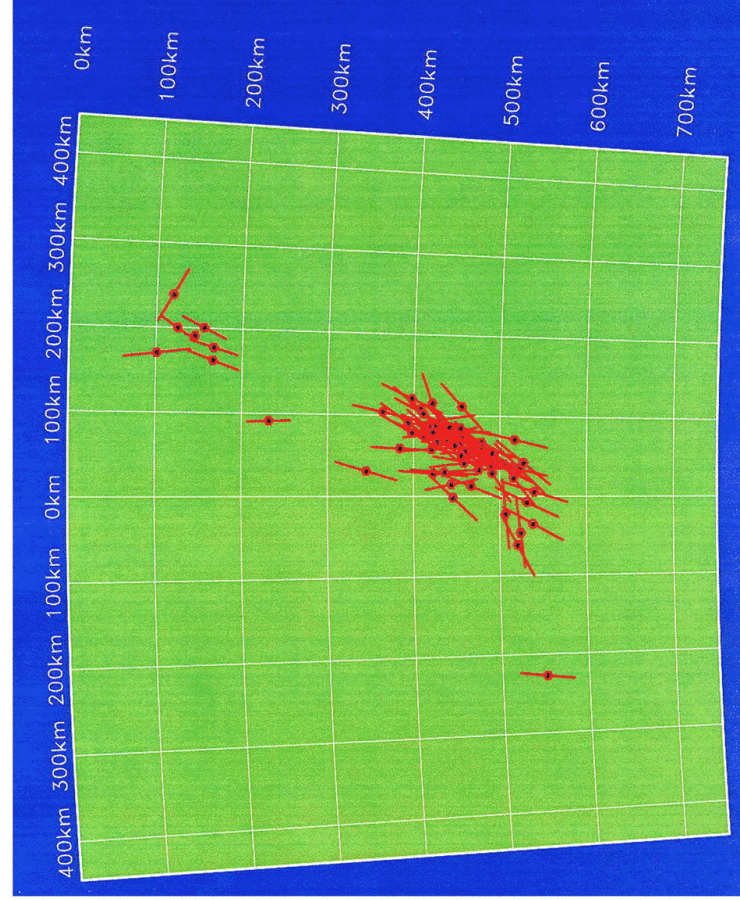
Earthquakes Outside Slabs

Fiji Plateau

Central Tonga-Kermadec
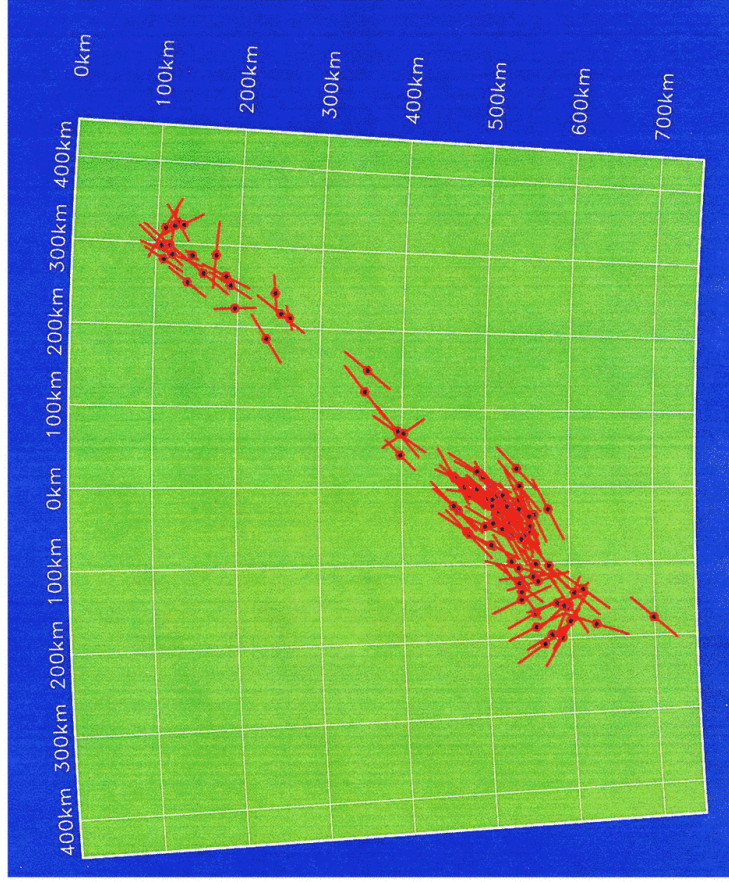
Izu-Bonin

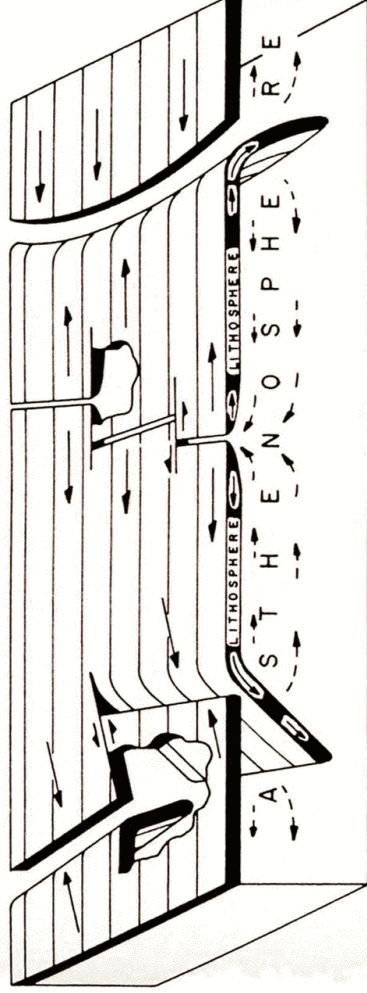## Early Plate Tectonics; Flow Limited to Upper mantle

FIGURE 42   The Isacks-Oliver-Sykes model of plate configurations. Plates are created from the asthenosphere at mid-oceanic ridges, cool, and thicken to 70–150 kilometers to form the lithosphere as they slide over the asthenosphere and move away from the ridges; they reenter the asthenosphere at subduction zones.

Velocity Anomalies in the Transition Zone

Seismic Rays in a Smooth Medium
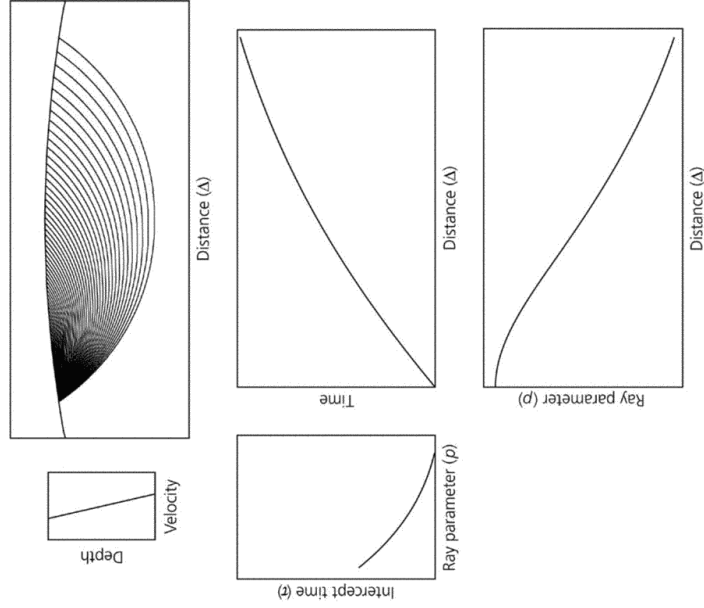
Rays in a Medium with Steep Gradients and a Low Velocity Zone
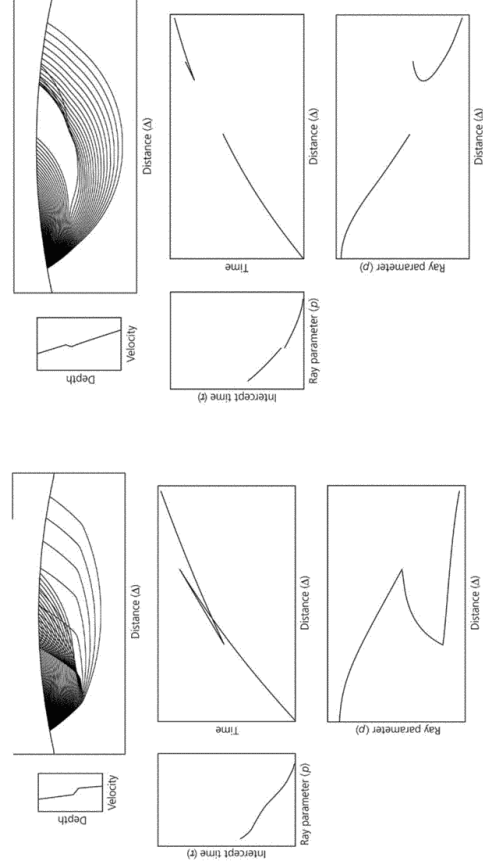
Surface Wave Sensitivity Kernels

Differential Travel Times

A single seismogram contains information on the Earth's structure along many paths

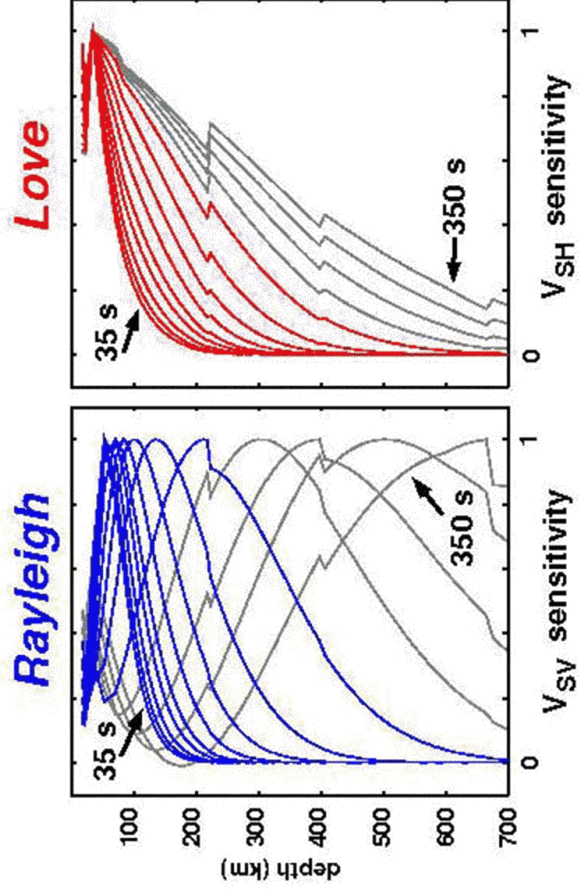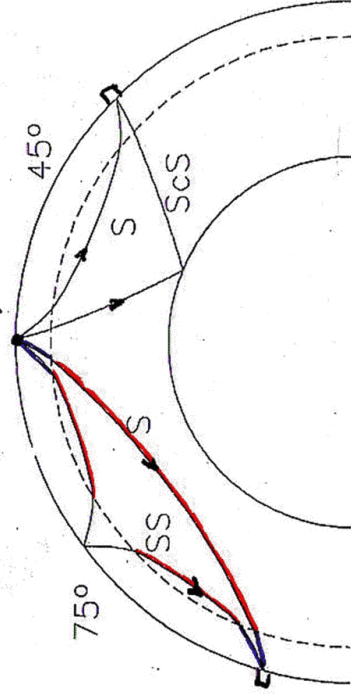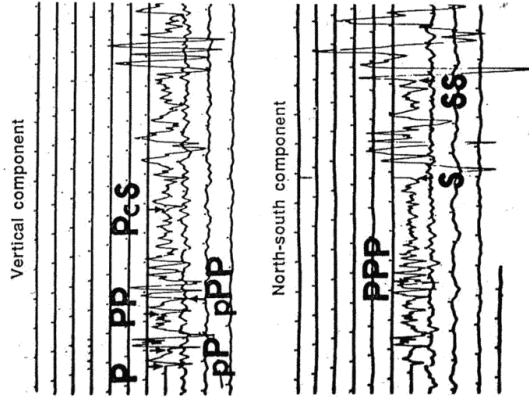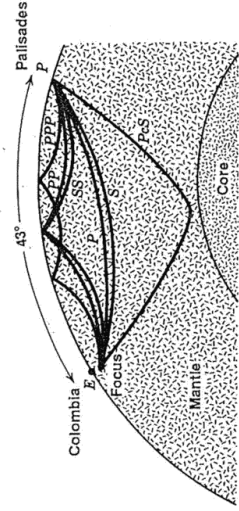**Fig. 1.** Ray paths of seismic waves through the earth (left). The letter P corresponds to compressional waves and S to shear waves. Seismograms in which these phases were recorded are shown on the right. The use of information contained in such recordings ranges from reading of arrival times of various seismic phases to inversion of a complete, but usually low-pass filtered, wave train. Adapted from Donn (22).

Waveform Inversion

Entire seismograms can be inverted directly into structural perturbations. Mantle wave (top) and body wave (bottom) are significantly better fit by a 3-D model S362D1 (Gu et al., 2001)
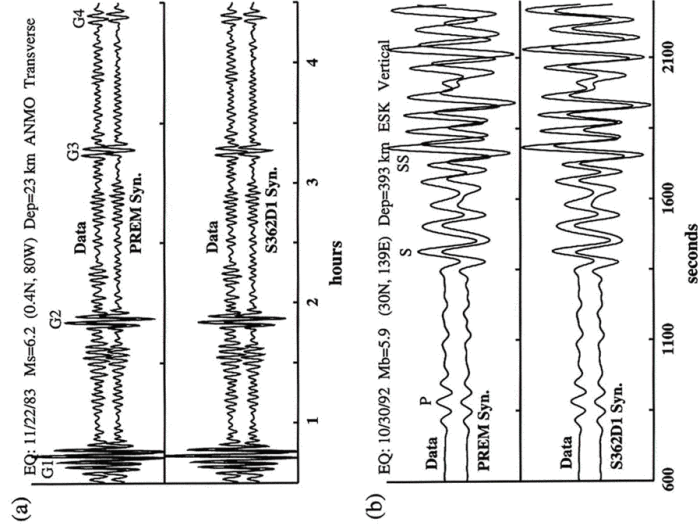
Maximum Resolution of Different Data Types
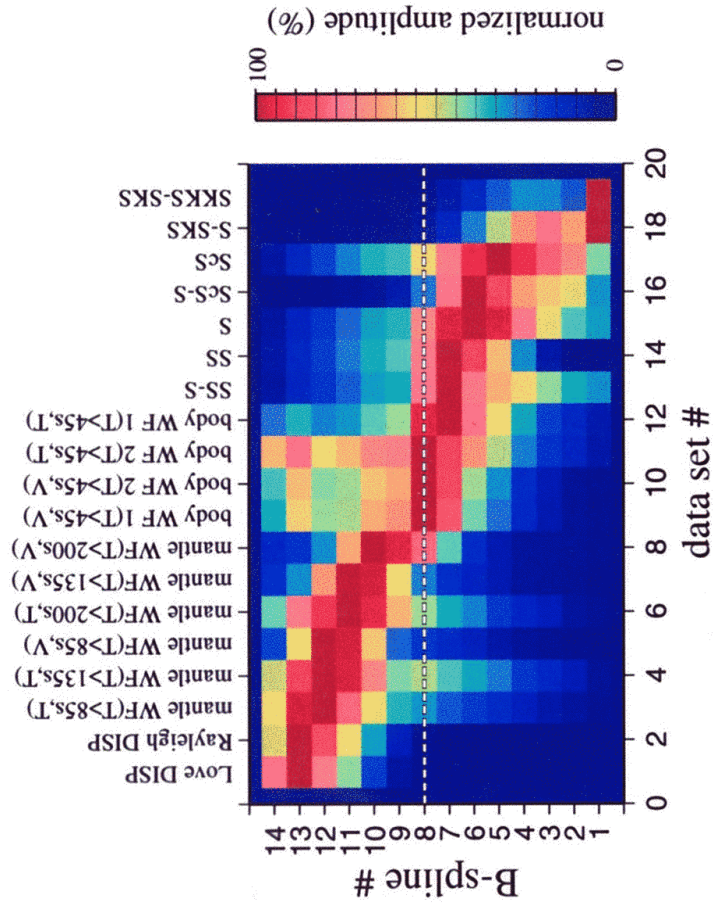
Power Spectra of Model S362CO
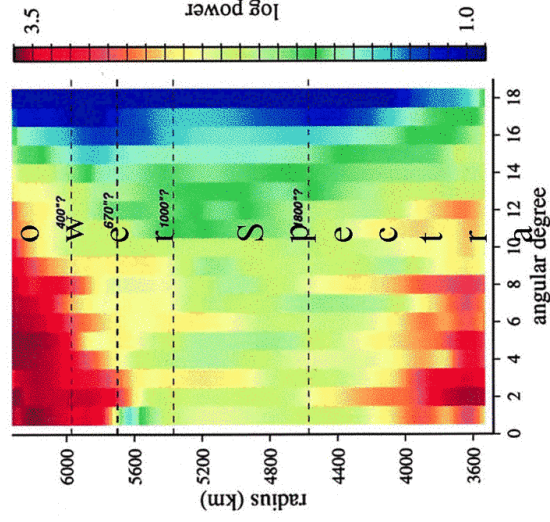
1. Upper mantle: strong and red -- thermal boundary (deg. 5) and transition zone (deg. 2).
2. Middle mantle: weak and white.
3. Lowermost mantle: strong and red (degree 2)

Abrupt spectrum change at 660 km

When a discontinuity at 660 km is allowed, we obtain very different images above and below it. From *Gu et al.,* 2001.
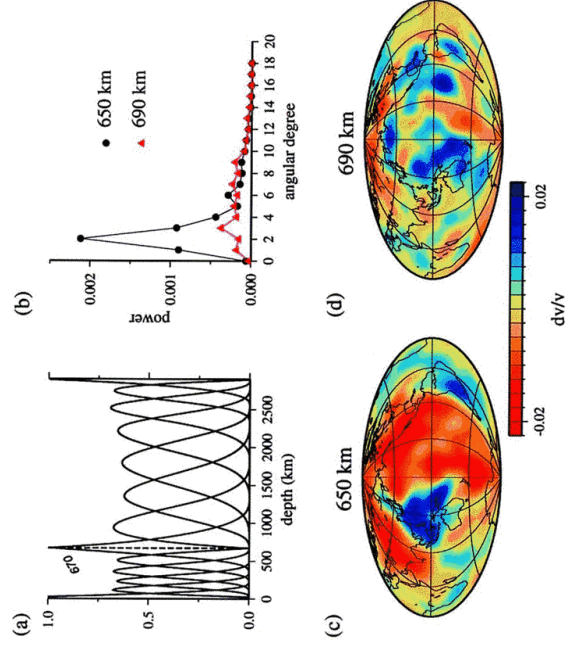
Discontinuity Resolution Test
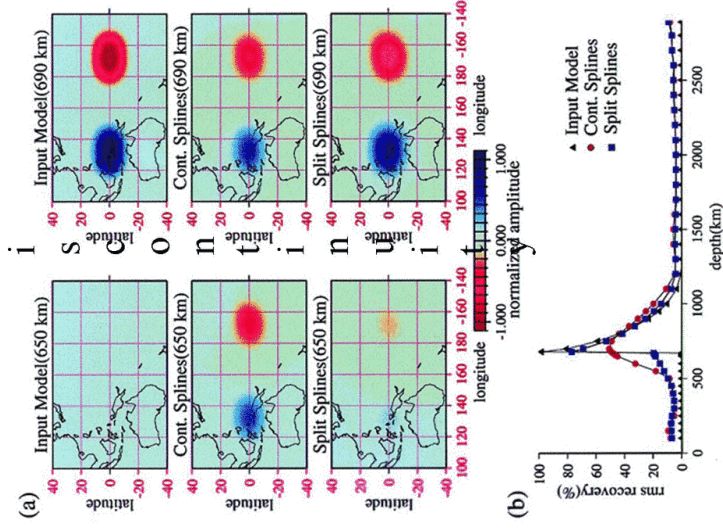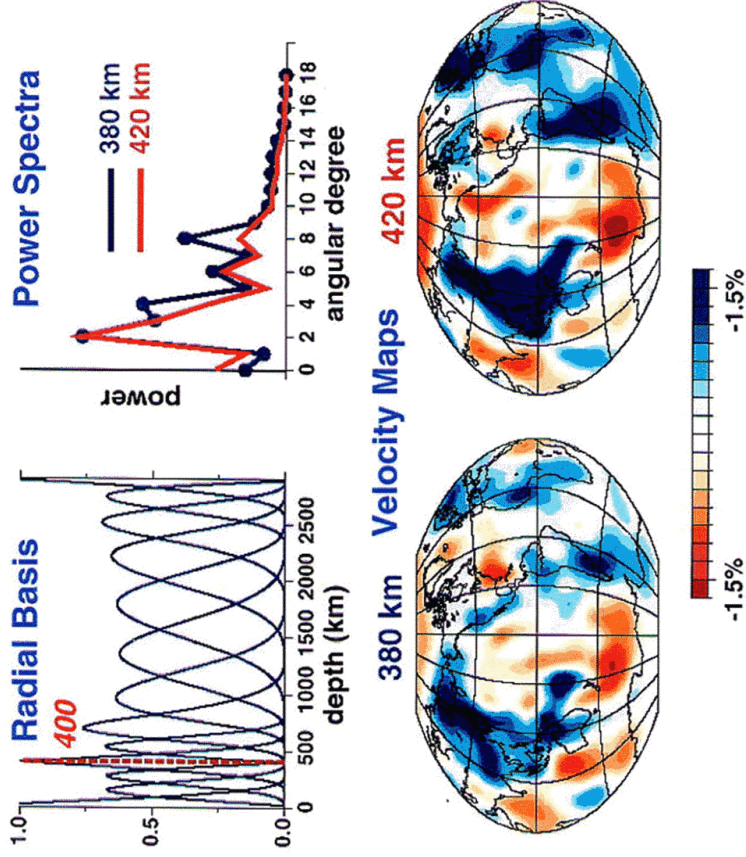
Experiments with introducing the discontinuity at
other depths did not produce similar results
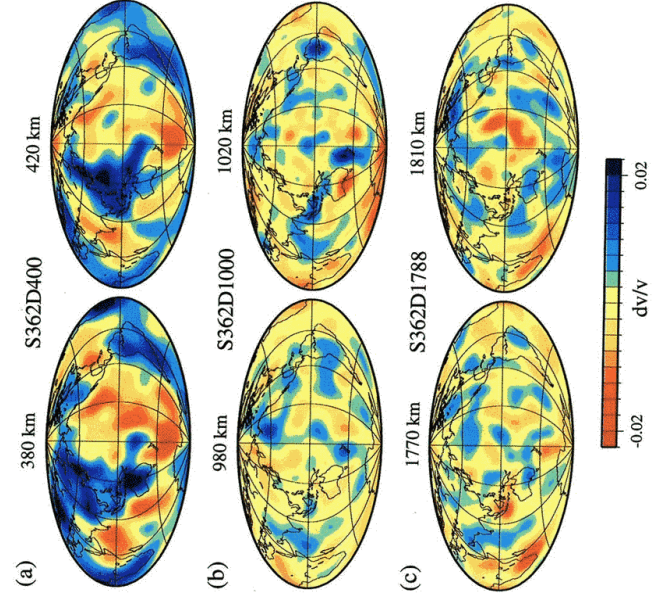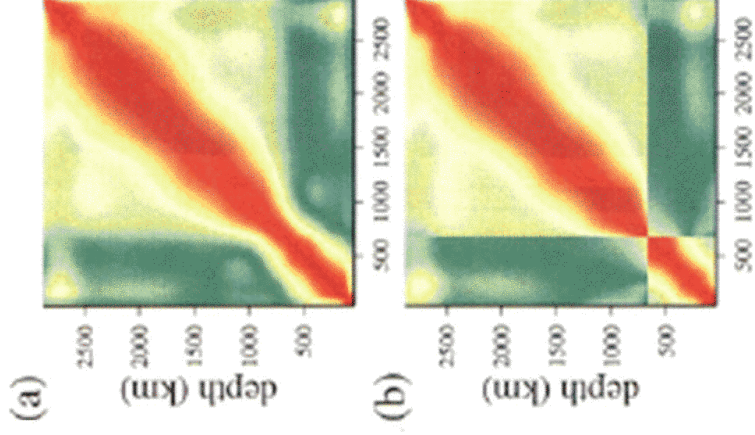
Radial correlation functions
of models S361C and S361D

Radial correlation function

Radial correlation
function (Jordan et al.,
1994) is used to measure
average depth interval
over which the structure
changes. The transition
zone structure changes
rapidly in all models on
the right except for
SB4L18.
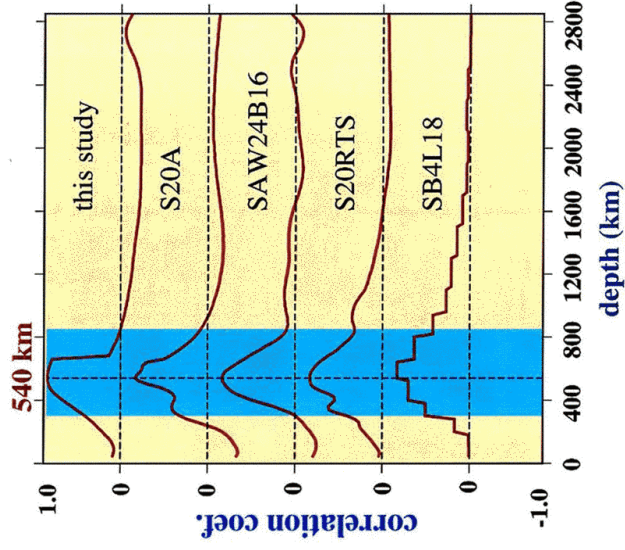
Regional Velocity RMS
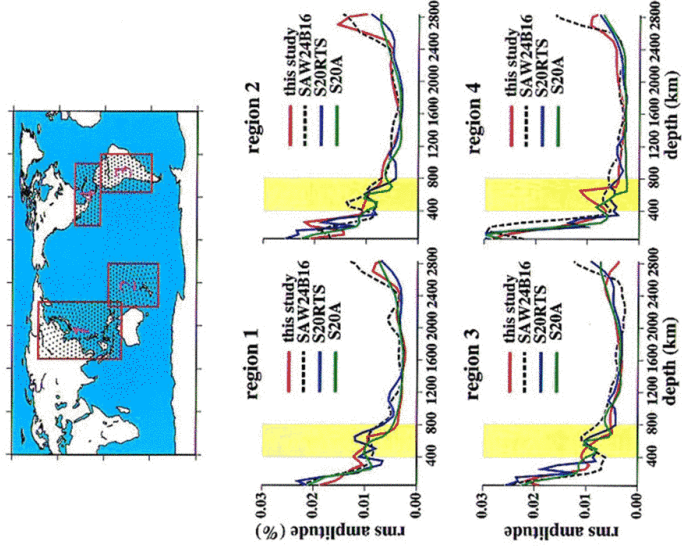
Topography of UM Discontinuities

Differential TT: SS - SdS
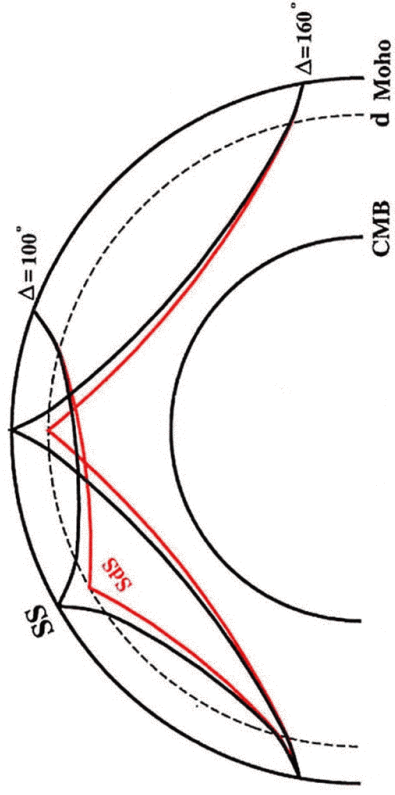
Ray paths of *SS* and precursors of *SS* for distances of 100° and 160°, calculated using PREM [*Dziewonski and Anderson*, 1981]. The trajectories are very similar away from the reflection point. The discontinuity labeled by "d" in this demonstration is the 660-km discontinuity.

Observed and Predicted Arrival Times of the Precursors
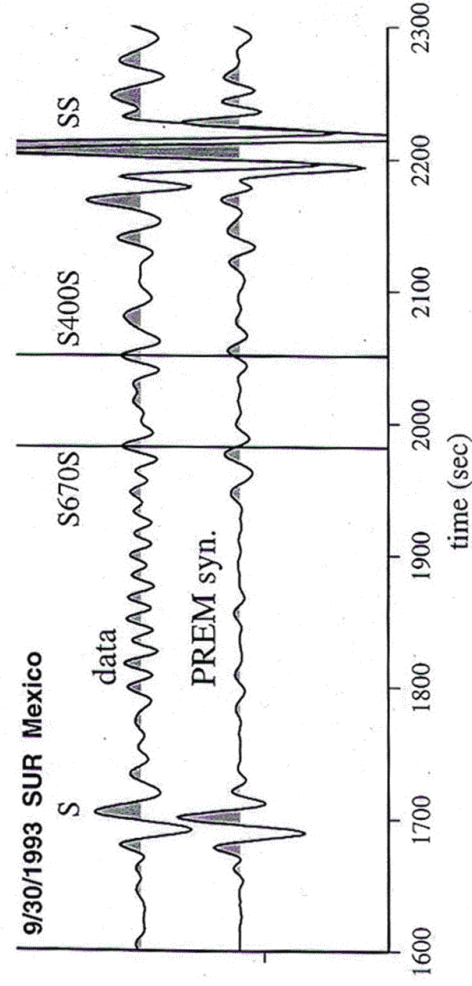
First global study of
the 660 km
Discontinuity;
Shearer and
Masters (1992)
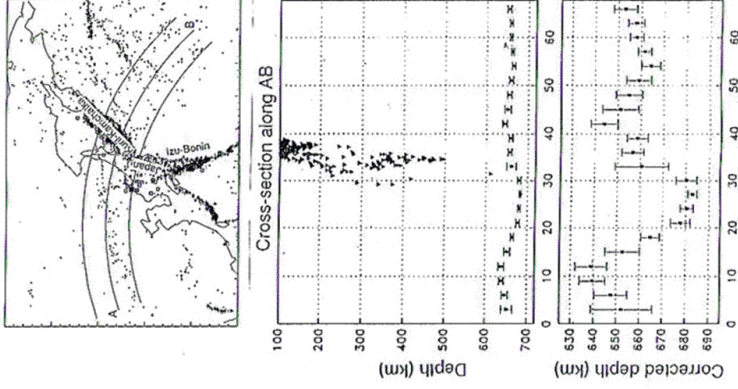
Travel Time Fresnel Zone

Period = 20 sec, Δ = 120°

−5sec   +5sec
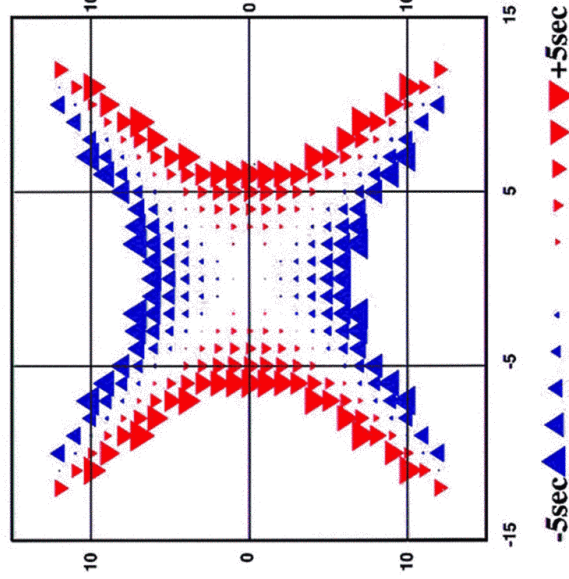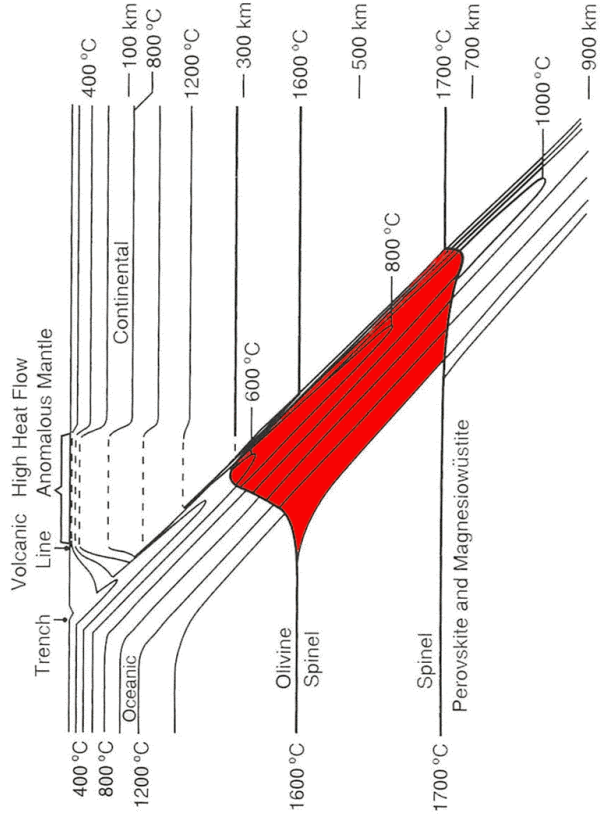
Local variations, such as within the slab, could not be resolved with this technique because of the averaging (smoothing) scheme and the size of the Fresnel zone.

SS – SdS precursors:
a tool to study upper mantle discontinuities
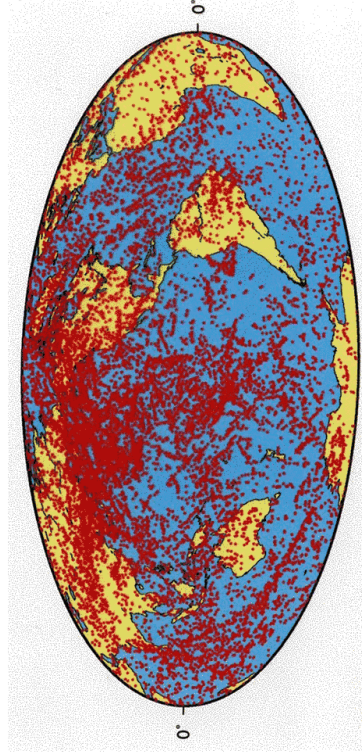
SS-SdS precursors are used to study the presence and topography of upper mantle discontinuities such as 220 km (Lehmann), 410, 520 (?) and 650 km. In contrast with the "receiver functions", they can be used in places where there are no receivers. The dots show mid-point reflections of 21,000 seismograms used in analysis.

Three different studies of the 660 km topography
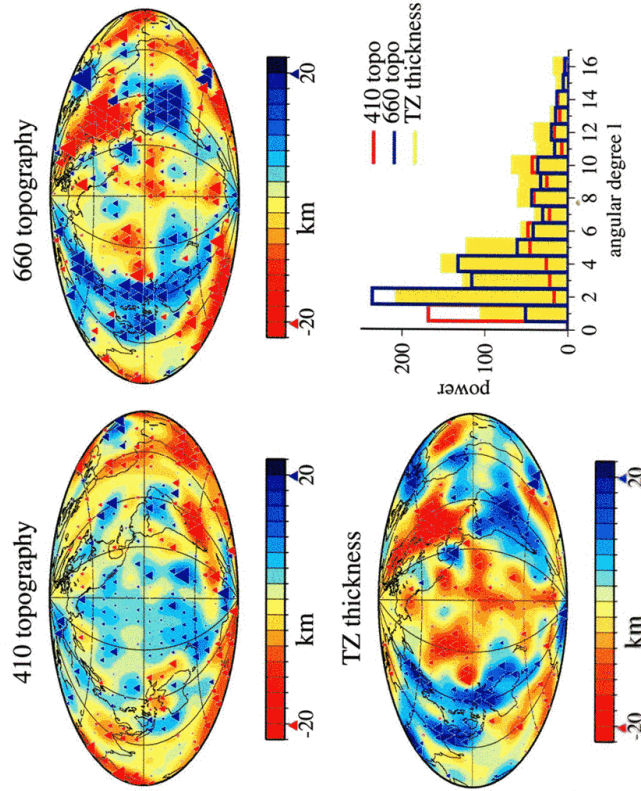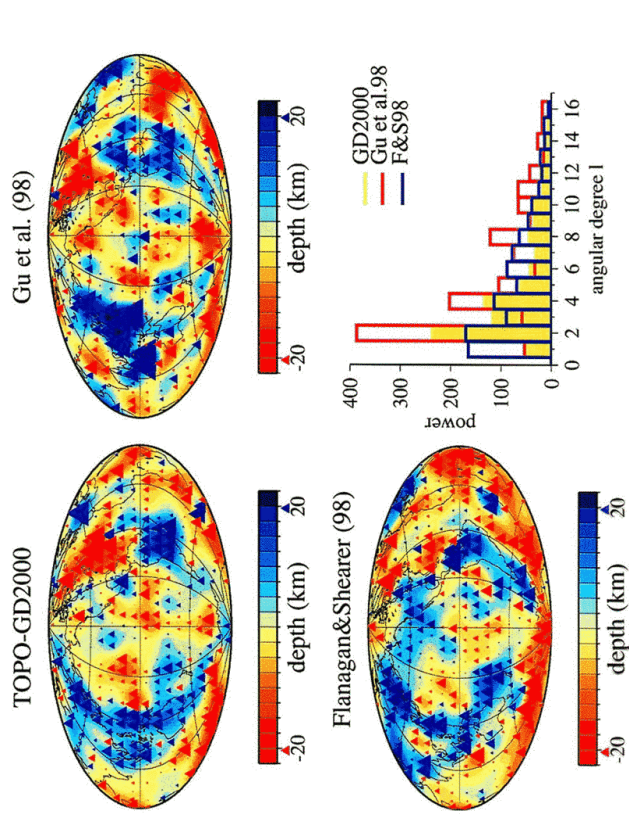
Inversion of SS – SdS data for the topography of 410 and 660 km discontinuities and an independent estimate of TZ thickness from direct cross-correlation of S400S with S670S waveforms.

Correlation of TZ velocity anomalies and 660 topography

Velocity Perturbation
(SH12WM13)
(-1%, 1%)

550 km

660 Topography
(this study)

Avg = 657 km

−20km   +20km
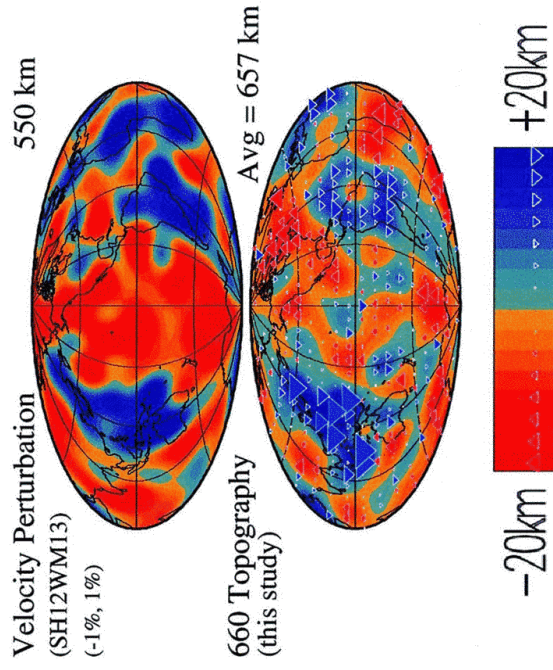
High correlation of the 660km discontinuity topography with velocity perturbations in the transition zone indicates ponding of heavier (cooler) material. There is no correlation with the anomalies below 660km.

Gu et al., 1998

Lawrence & Shearer, 2006

Flannagan & Shearer, 1998

221   241   261
MTZ Thickness (km)
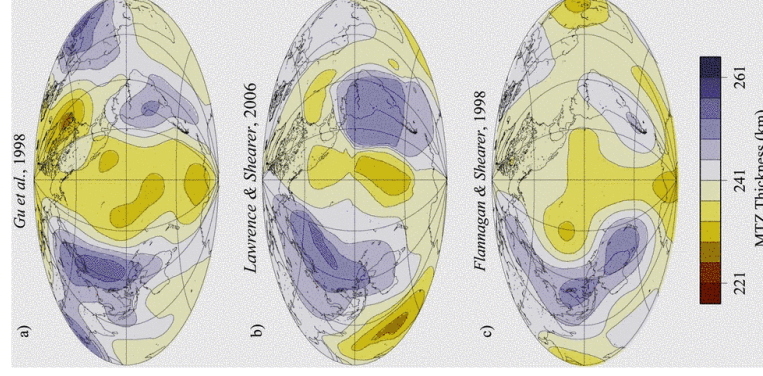
Additional comparisons of TZ thickness; the middle figure is obtained using converted waves

Problem:

Velocity ⇅ Boundary Topography

Trade-offs

Solution:

Residual = 3D + 400 Topo + 670 Topo

Main phases

Surface

400
670

SS

S, SS, ScS, SKS

SS precursors

Surface

400
670

S670S
S400S

Model Vector

3D Velocity   400 Topo   670 Topo

(5068   362   362)
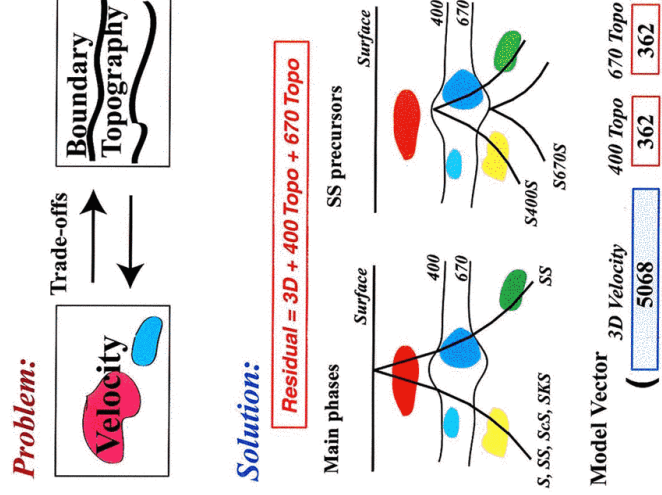
To avoid possible tradeoffs between the velocity anomalies and topography of the discontinuities we perform a joint inversion for a 3D velocity model and the boundary topographies
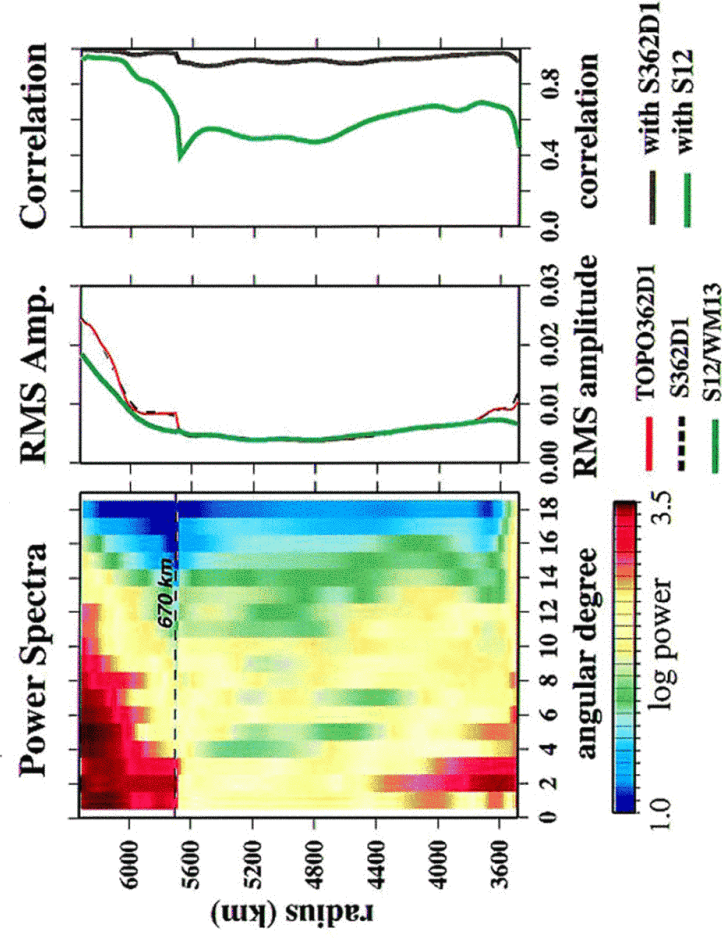
Power Spectra   **RMS Amp.**   **Correlation**

radius (km): 6000 5600 5200 4800 4400 4000 3600

670 km

angular degree: 0 2 4 6 8 10 12 14 16 18

log power: 1.0 — 3.5

RMS amplitude: 0.00 0.01 0.02 0.03

correlation: 0.0 0.4 0.8

— TOPO362D1
---- S362D1
— S12/WM13

— with S362D1
— with S12

Joint inversion diminishes the topography of the 410 km discontinuity and enhances that of 660 km discontinuity

410 km

660 km

separate
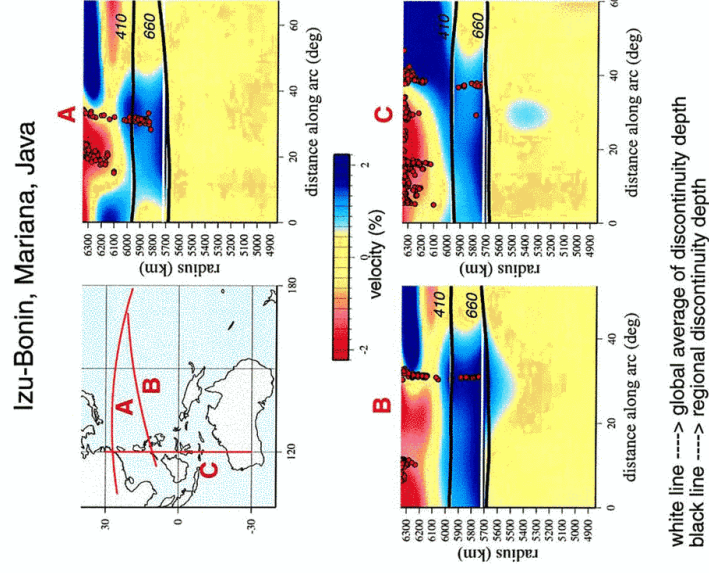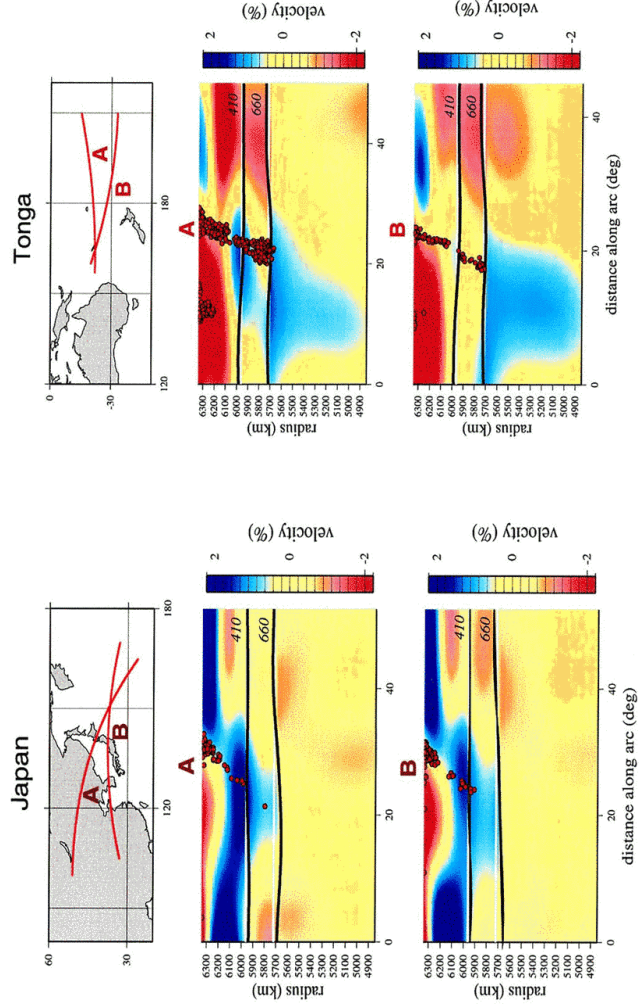
joint

km   km
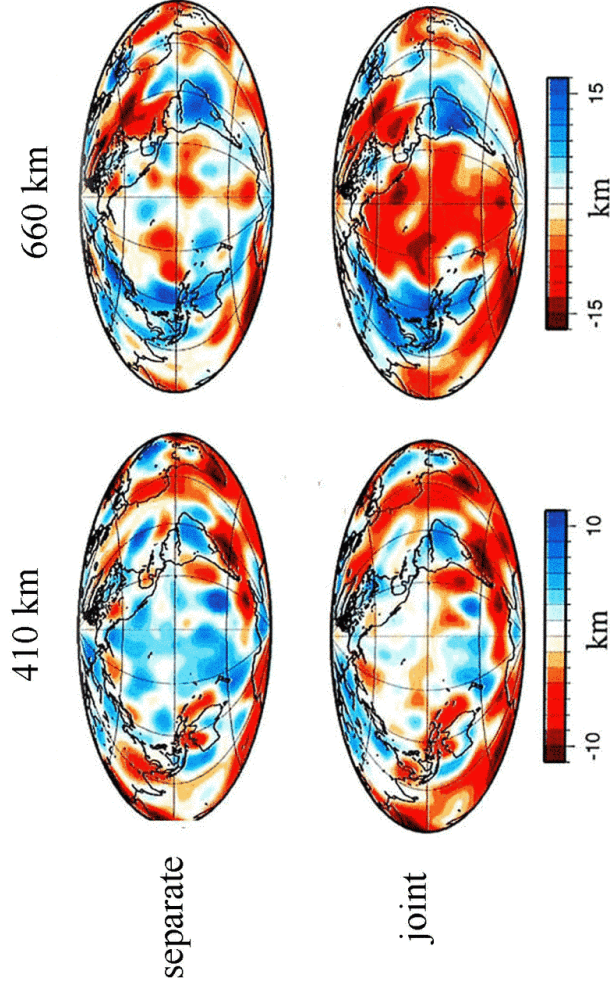
Notice the difference in scales of the maps

Izu-Bonin, Mariana, Java

A   B   C

Cross-sections in the Western Pacific show extended high velocity anomalies in the transition zone, with little or no continuation into the lower mantle

velocity (%)

distance along arc (deg)

radius (km)

410   660

white line ----> global average of discontinuity depth
black line ----> regional discontinuity depth

Cross-sections through other subduction zones show different signatures. Notice the depth of anomalies under the Tonga.
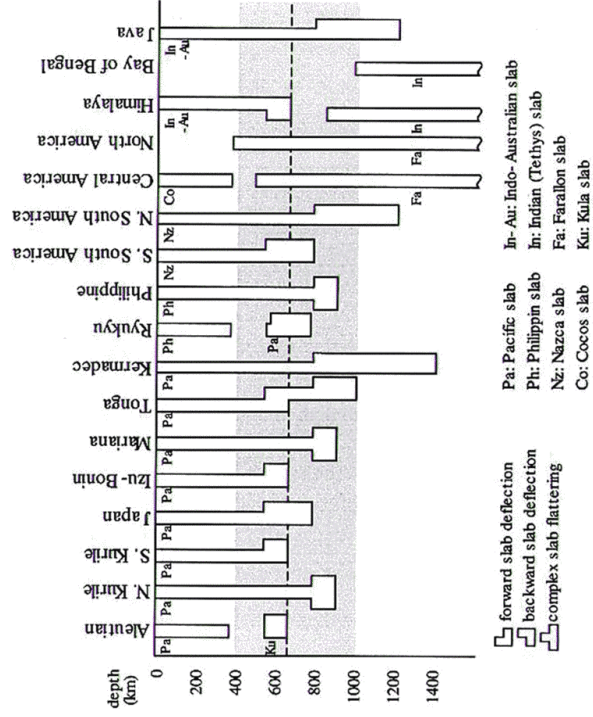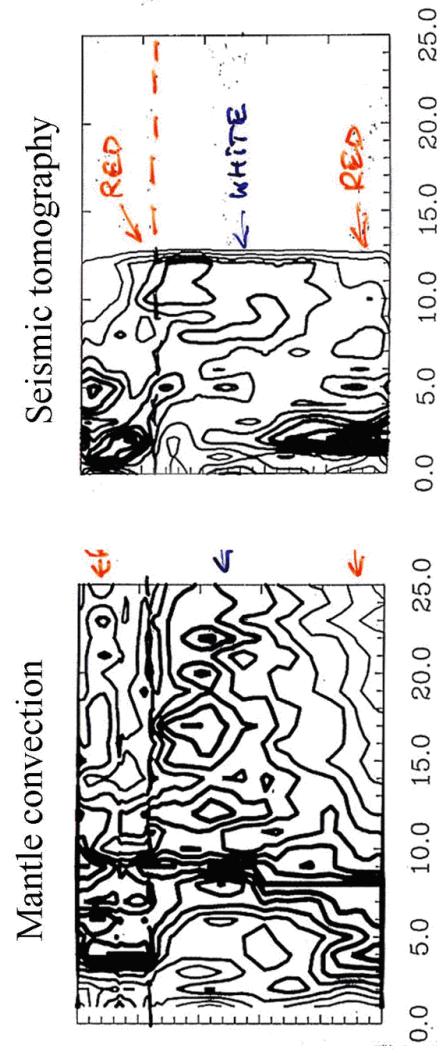

*Depth of penetration of subducted slabs. From Fukao et al., 2001*

Mantle convection

Tackley et al., 1993

Behavior of the power spectra as a function of depth for a simulated mantle convection with a phase change boundary and a tomographic model (Su et al., 1994) is very similar.
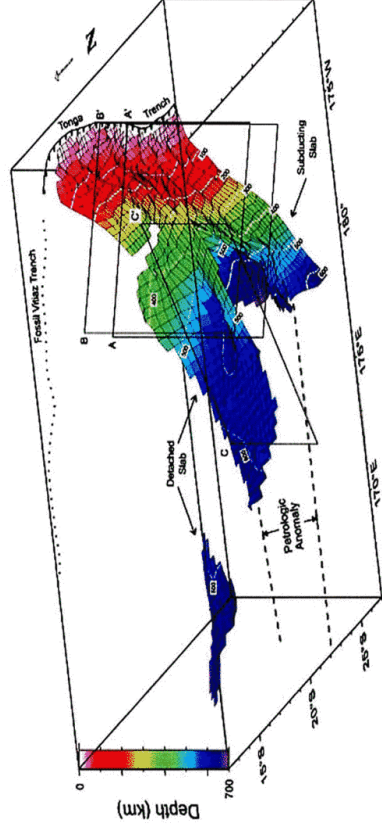
Seismic tomography

Mantle convection

From Tackley et al., 1994

Lower Mantle

Vanuatu-Fiji-Tonga anomaly
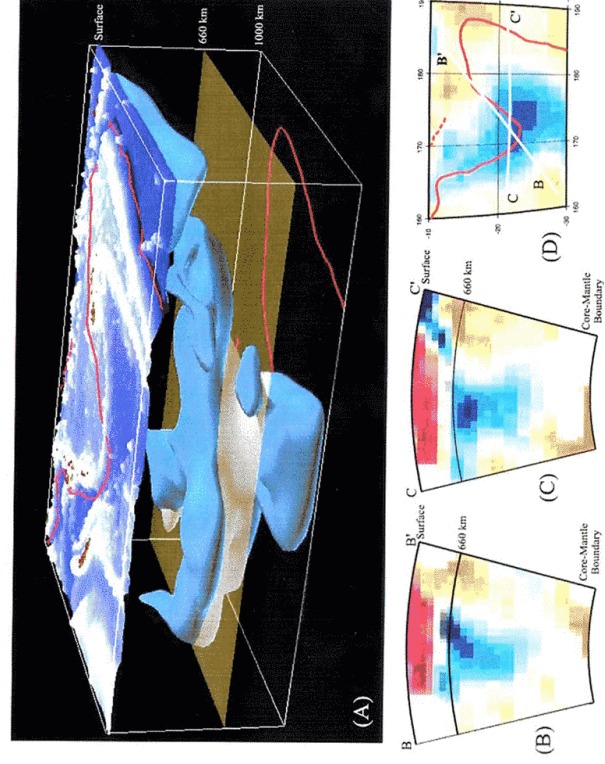
Tonga, 3-D seismicity


Chen & Brudzinski (2001)

Seismicity in the Tonga-Fiji-Vanuatu region shows great complexity, including earthquakes outside the Wadati-Benioff zones.
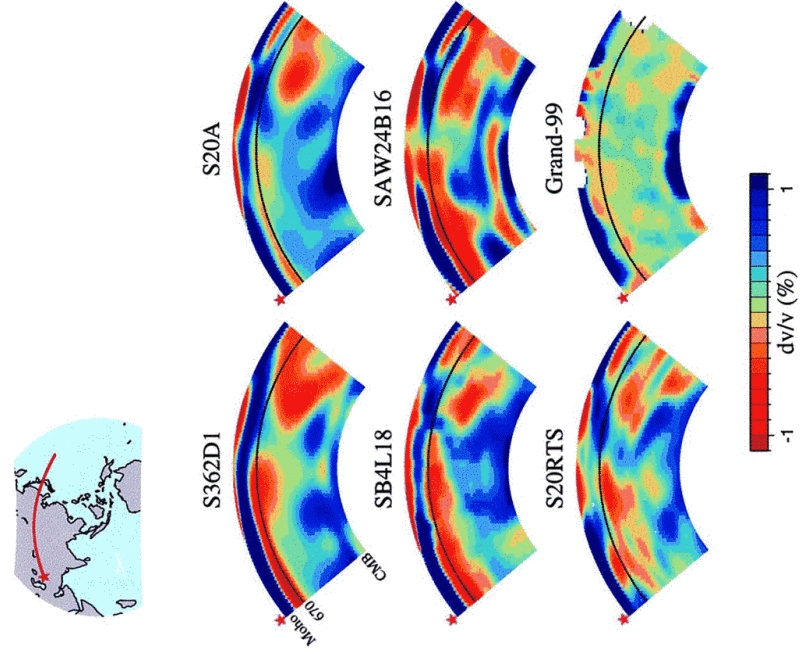
Fiji avalanche simulation

Pysklywec et al. (2003) have proposed that the tectonics of the Fiji Basin for the lat 10 My can be explained by the occurrence of an avalanche caused by the breakthrough of a stagnant slab
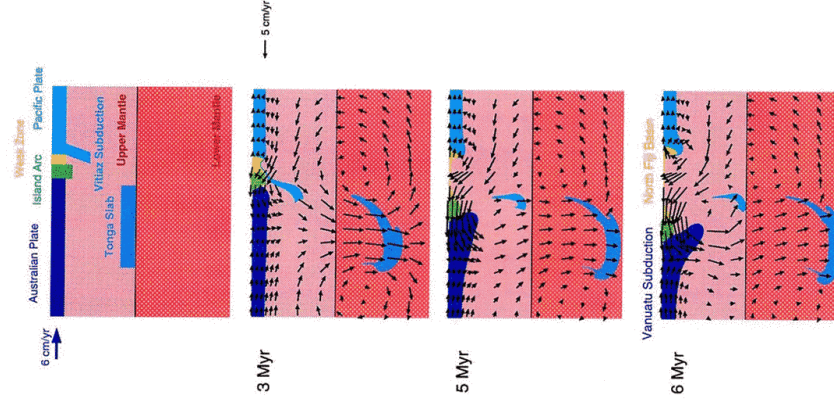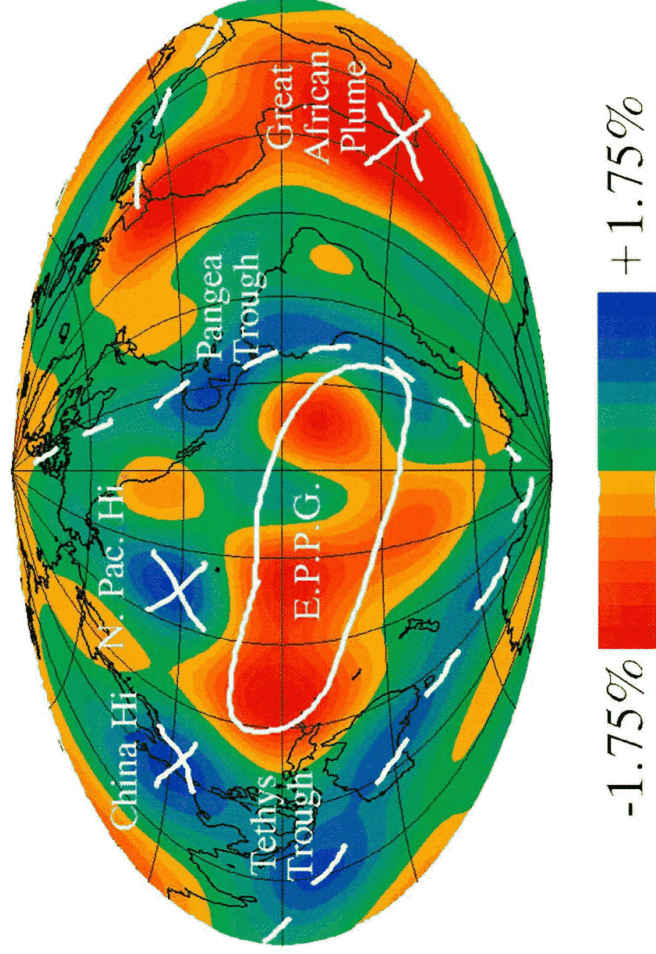
Velocity models
show fast structures in
the lower mantle that
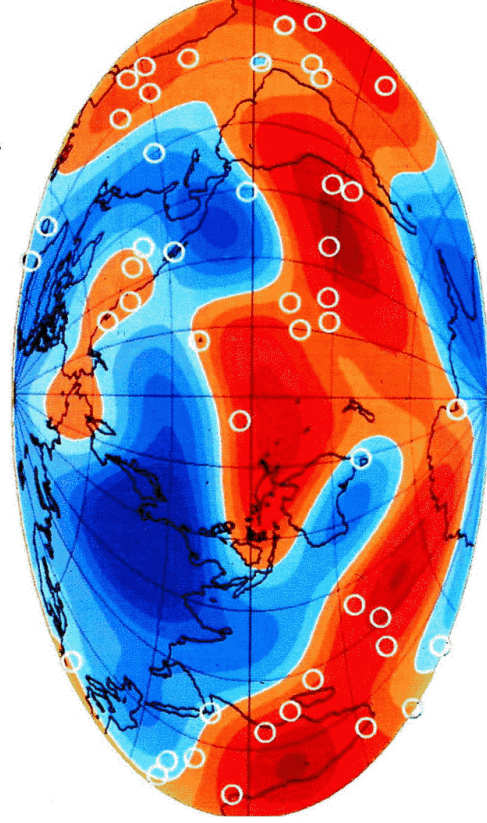are not consistent
with the recent
subduction.
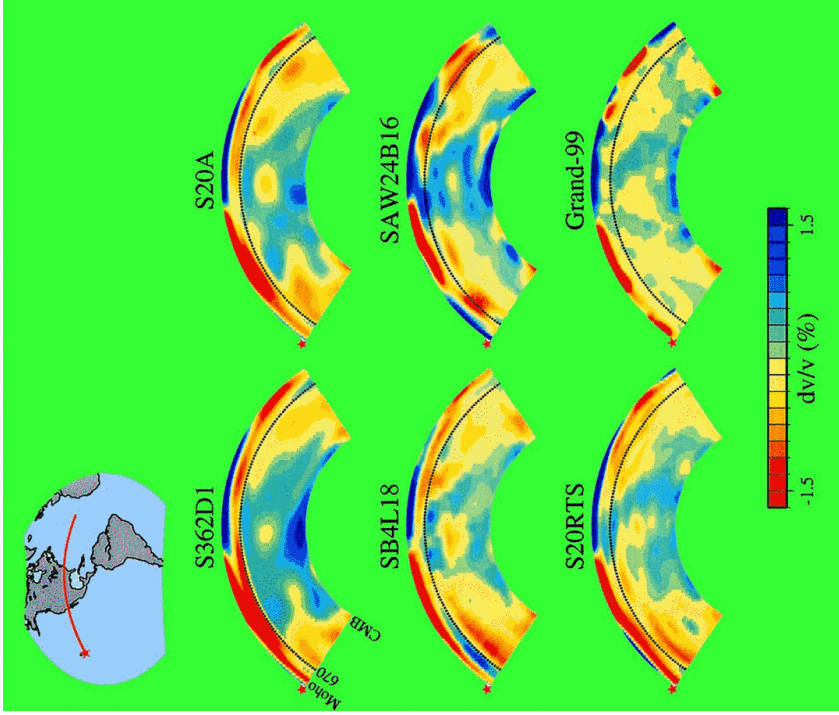
The same is true of
a region in eastern
Asia, where van der Voo
proposed existence
of a jurassic subduction
zone

Megastructures of the Earth's Interior

Great African Plume

Pangea Trough

N. Pac. Hi.

China Hi.

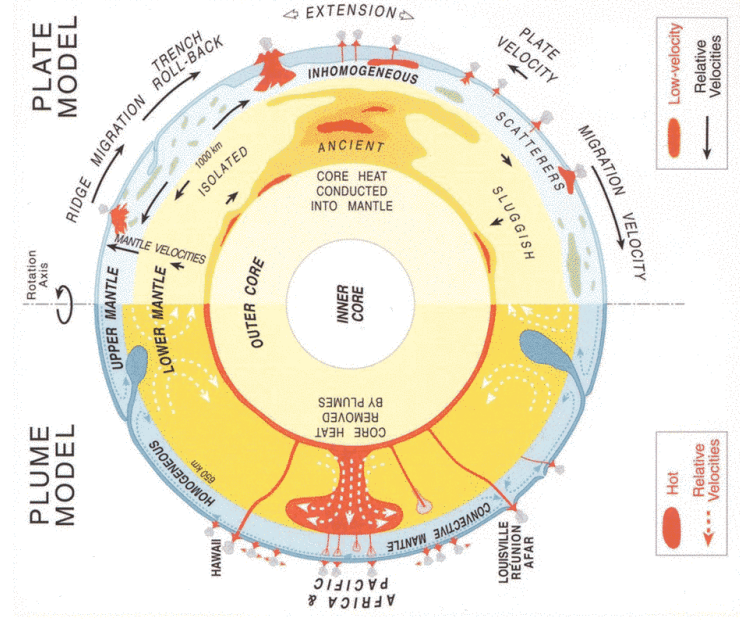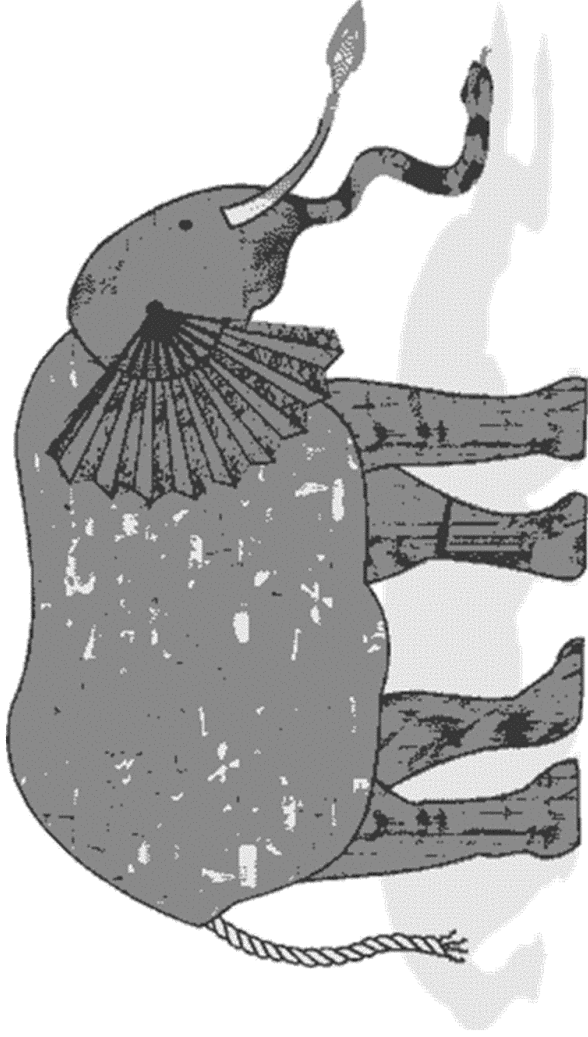E.P.P.G.

Tethys Trough

-1.75%   +1.75%

Lowermost mantle velocity anomalies and distribution of hotspots

Surface locations of hotspots correspond closely to the distribution of slow velocity anomalies near core-mantle boundary (2750 km depth)
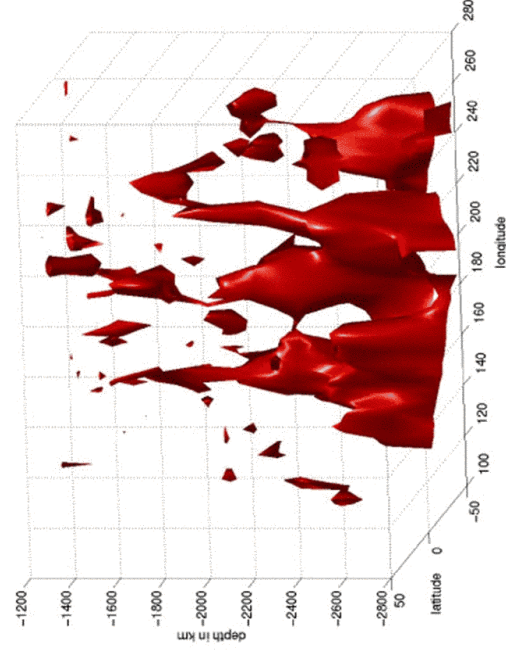
Six blind men and the Elephant

Cover of the GSA
Special Paper: Plumes,
Plates and Paradimes;
Foulger et al., ed., 2005

Ocean function (l=1-32)

+15

km
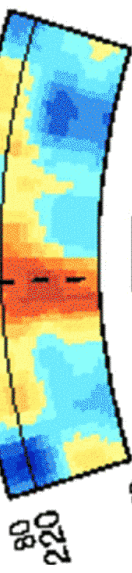
-15

Ocean function (l=1-8)

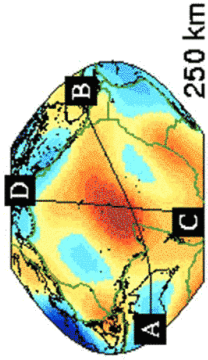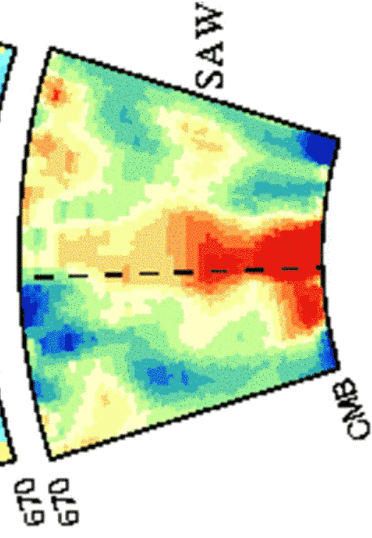+15

km

-15
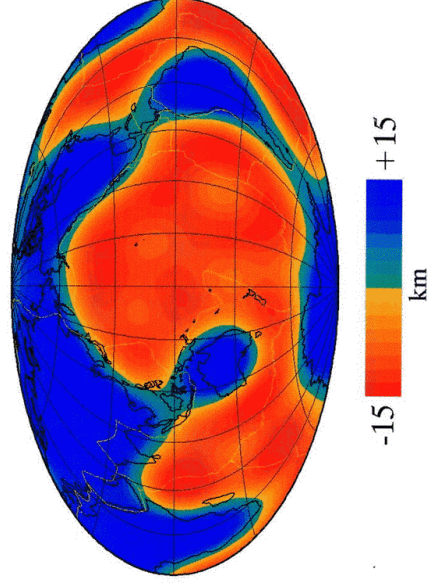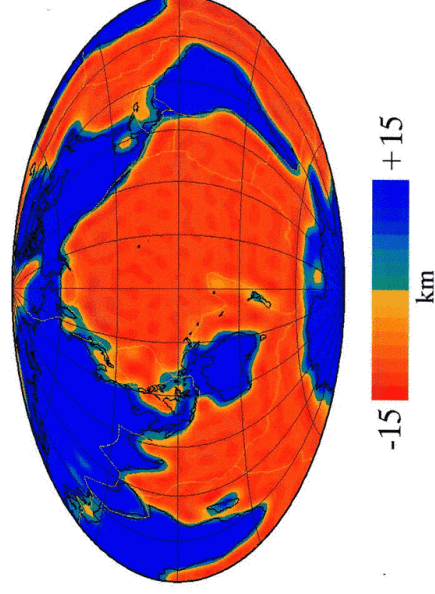
Equatorial Pacific Plume Group

The Pacific super-plume shows structure in this 3-D expansion of the –1% iso-surface of a recent Scripps model of shear velocity anomalies.

Pacific "superplume"

QRLf12
(Q⁻¹)

SAW24B16
(Vs)

QRl

A – B

SAW

80
220

670
670

CMB

250 km

A B C D

A connection between the slow velocities of a superplume with high attenuation in the transition zone

Romanowicz and Gung, 2002

The Blind Men and the Elephant
by John Godfrey Saxe

*It was six men of Indostan
    to learning much inclined,
Who went to see the Elephant
    (though all of them were blind),
That each by observation
    might satisfy his mind.*

. . . .

And so these men of Indostan
disputed loud and long,
Each in his own opinion
exceeding stiff and strong,
Though each was partly in the right,
and all were in the wrong!

Moral:

So oft in theologic wars,
the disputants, I ween,
Rail on in utter ignorance
of what each other mean,
And prate about an Elephant
not one of them has seen!

Regional Avg. of TZ Thickness

(N.Atl, -2.7 km)
(S.Atl, 5.2 km)
(N.Atl, +9.6 km)
(S.Am., +4.3 km)
(N.Am., +9.6 km)
(Pacific, -5.6 km)
(Antarctica, -3.7 km)
(Eurasia, +7.6 km)
(Indian, -5.5 km)
(Africa, +1.0 km)