Seismic Surface Waves

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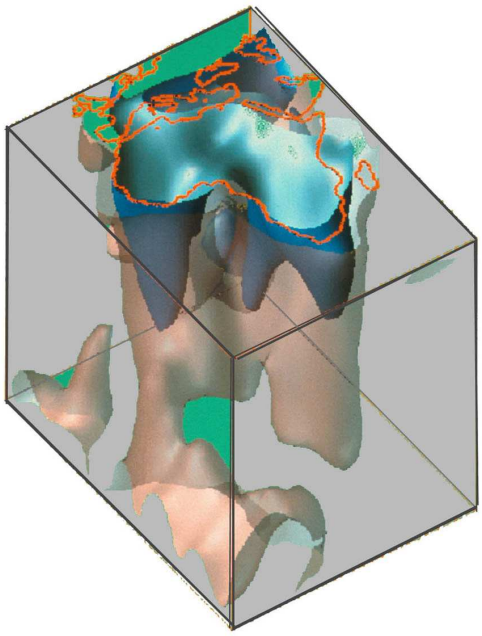

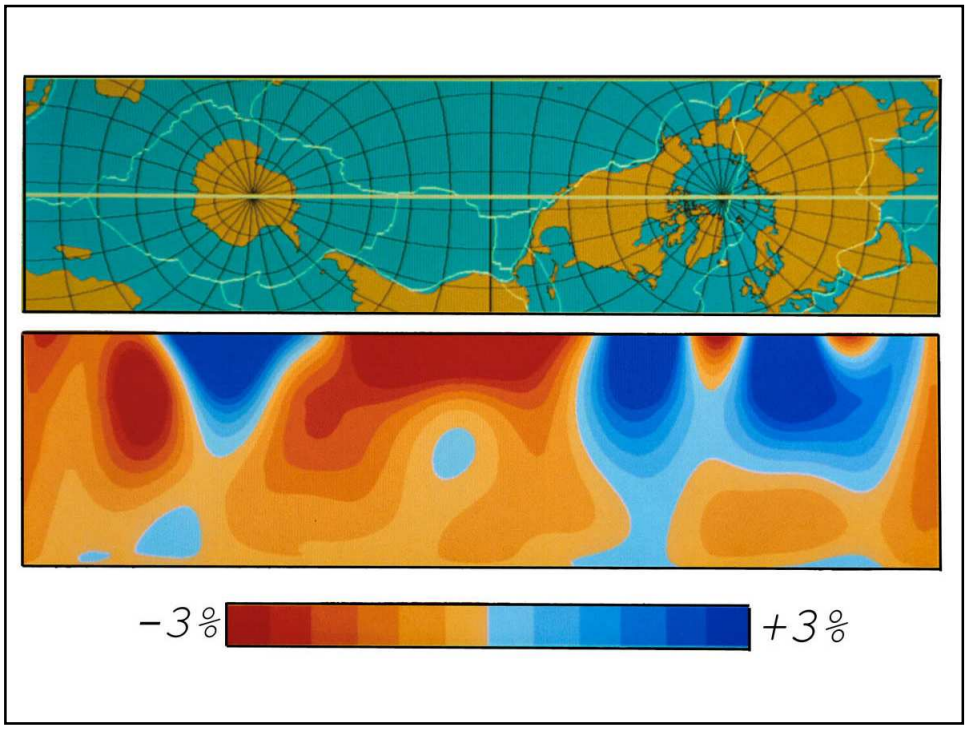
−3%
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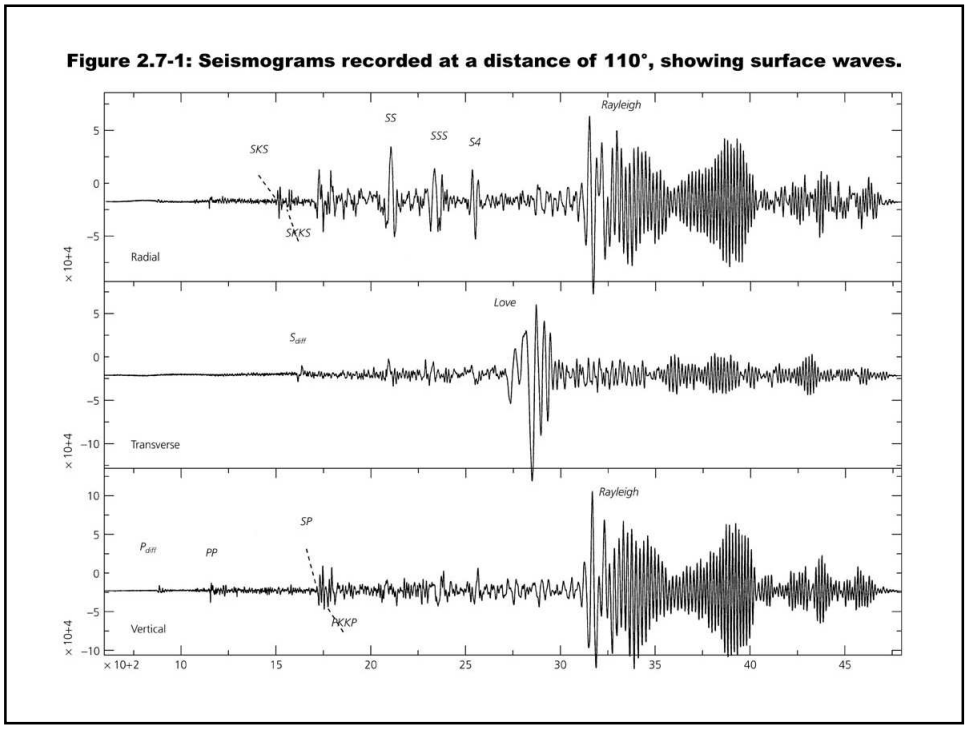


Figure 2.7-1: Seismograms recorded at a distance of 110°, showing surface waves.
Rayleigh
SS
SSS
S4
SKS
SKKS
Radial
Love
S_{diff}
Transverse
Rayleigh
SP
P_{diff}
PP
PKKP
Vertical
× 10+4
× 10+2
10
15
20
25
30
35
40
45

Figure 2.7-2: Geometry for Love and Rayleigh wave motions.

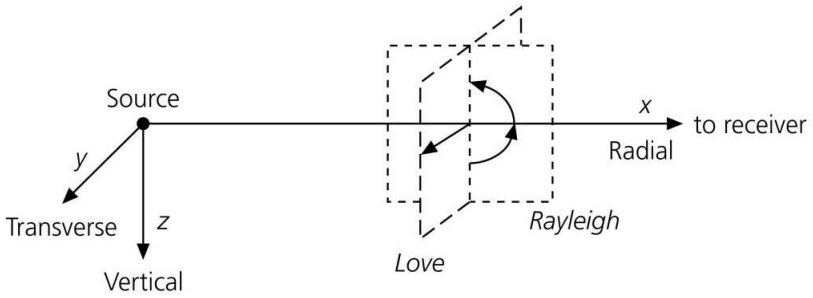
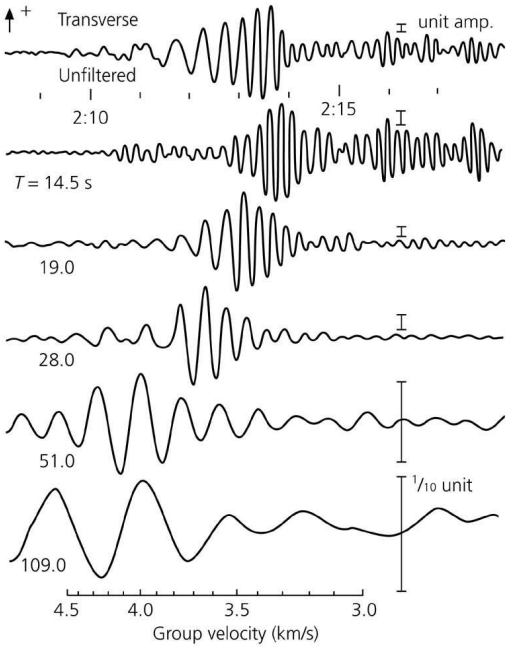
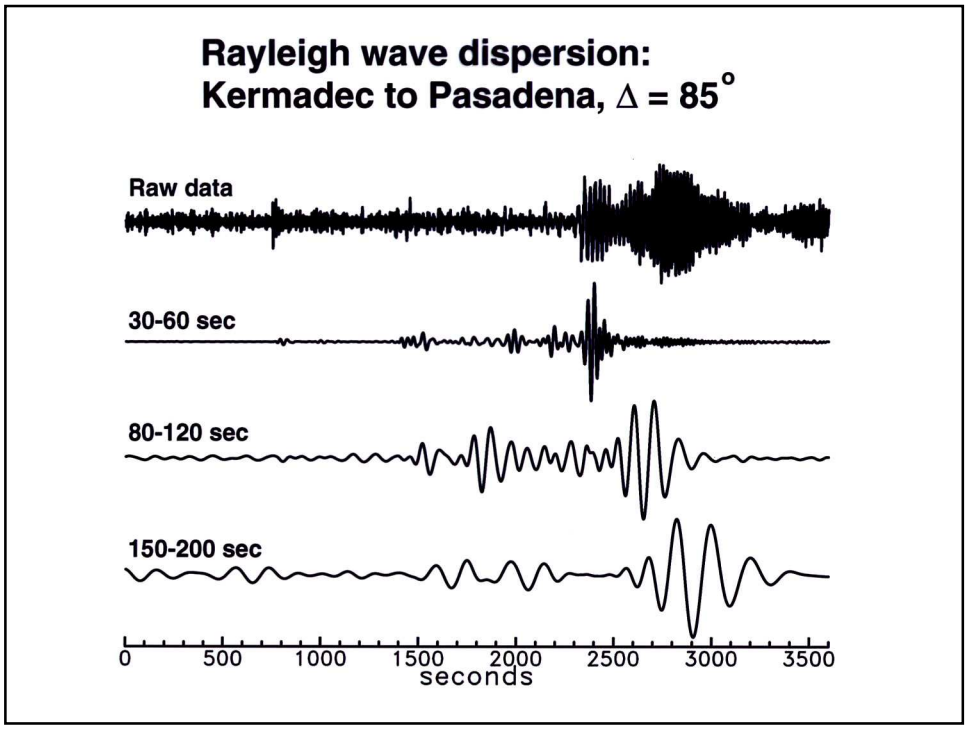


Figure 2.8-4: Example of Love wave group velocity dispersion through bandpass filtering.




Rayleigh wave dispersion:
Kermadec to Pasadena, Δ = 85°
Raw data
30-60 sec
80-120 sec
150-200 sec
0
500
1000
1500
2000
2500
3000
3500
seconds

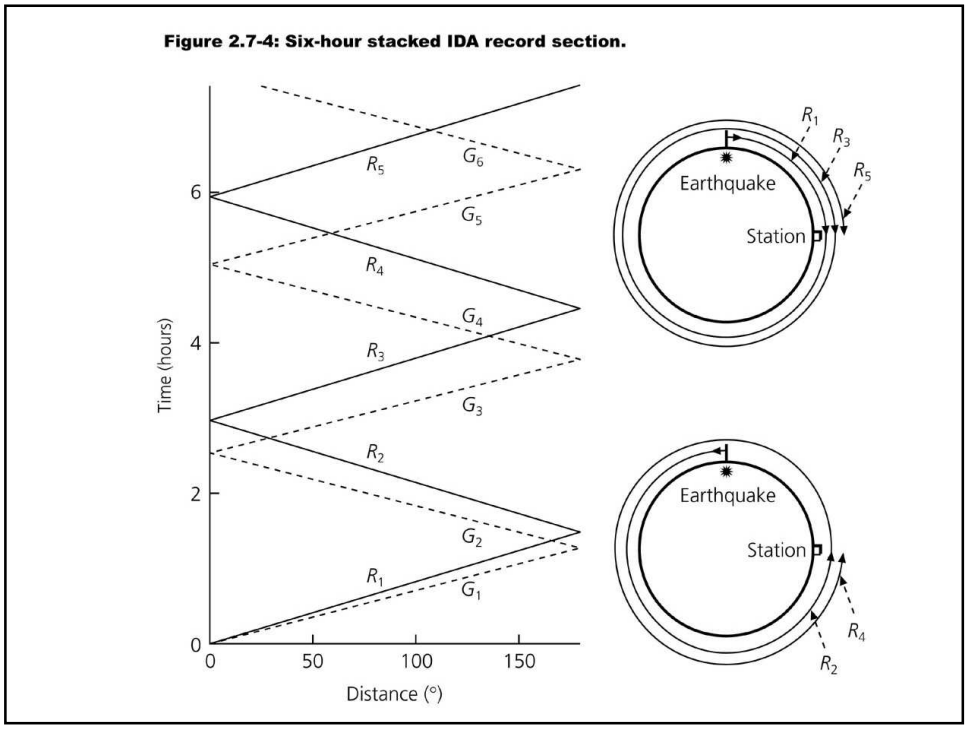


Figure 2.7-4: Six-hour stacked IDA record section.
Time (hours)
Distance (°)
0
2
4
6
0
50
100
150
R1
R2
R3
R4
R5
G1
G2
G3
G4
G5
G6
Earthquake
Station
Earthquake
Station

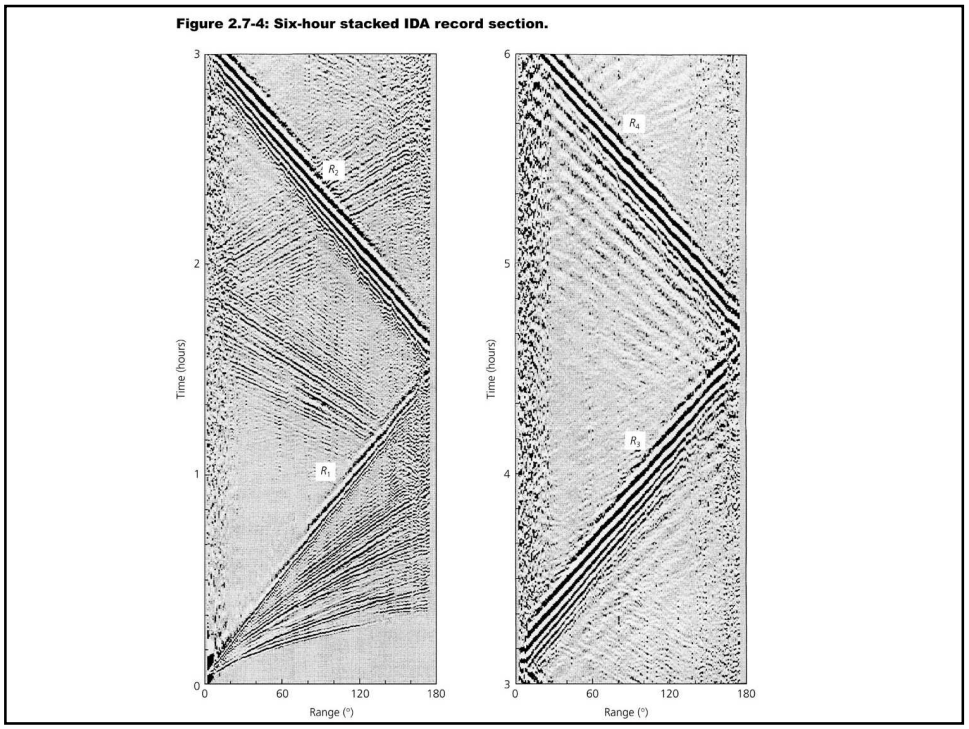
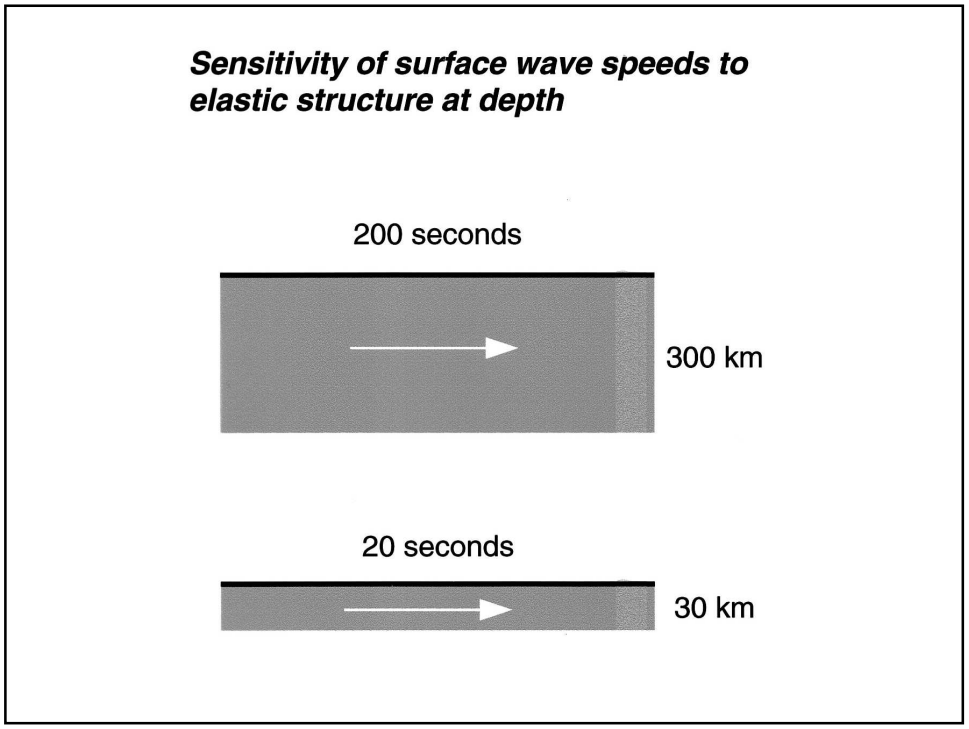


Figure 2.7-4: Six-hour stacked IDA record section.
Time (hours)
Range (°)
R_1
R_2
R_3
R_4


Sensitivity of surface wave speeds to elastic structure at depth
200 seconds
300 km
20 seconds
30 km

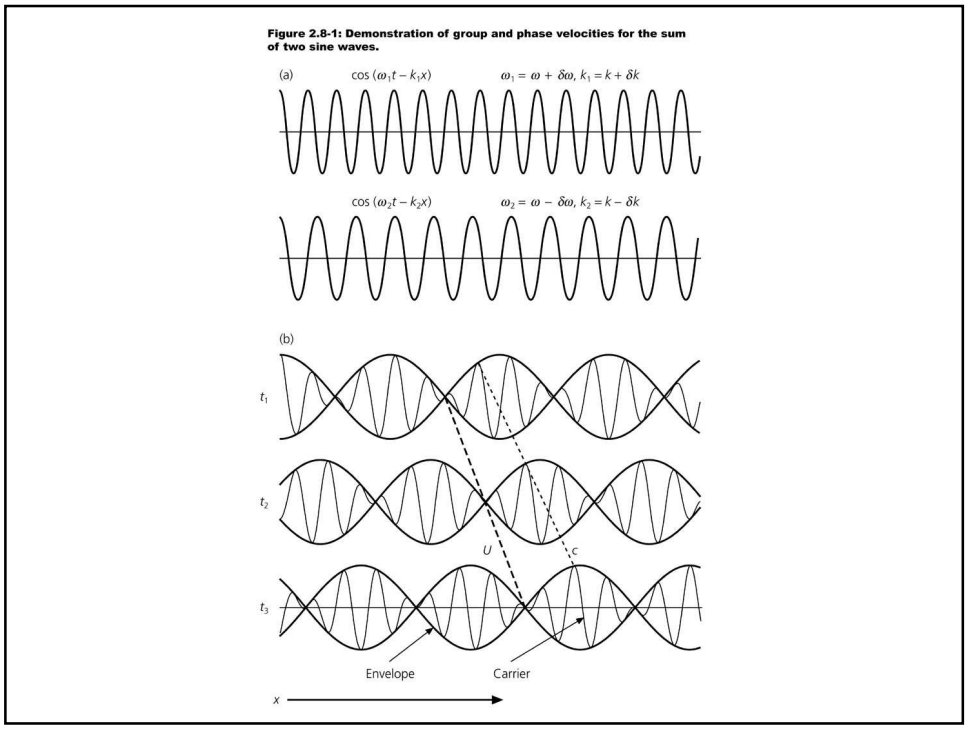


Figure 2.8-1: Demonstration of group and phase velocities for the sum of two sine waves.
(a)
cos (ω1t − k1x)
ω1 = ω + δω, k1 = k + δk
cos (ω2t − k2x)
ω2 = ω − δω, k2 = k − δk
(b)
t1
t2
t3
U
c
Envelope
Carrier
x

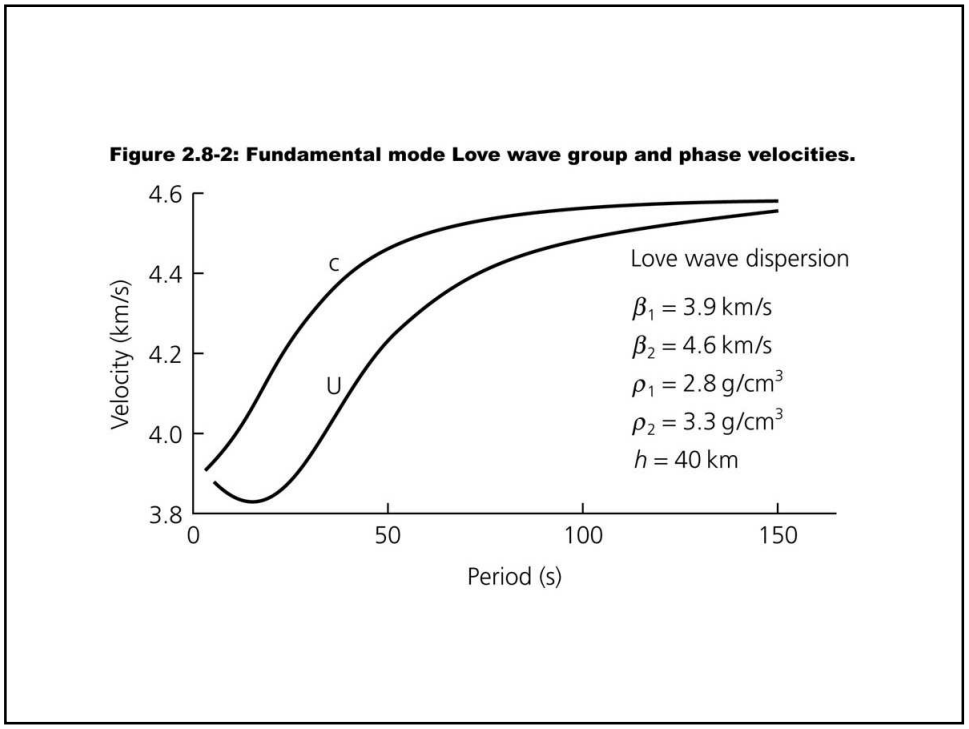


Figure 2.8-2: Fundamental mode Love wave group and phase velocities.
Velocity (km/s)
4.6
4.4
4.2
4.0
3.8
0
50
100
150
Period (s)
C
U
Love wave dispersion
β1 = 3.9 km/s
β2 = 4.6 km/s
ρ1 = 2.8 g/cm3
ρ2 = 3.3 g/cm3
h = 40 km

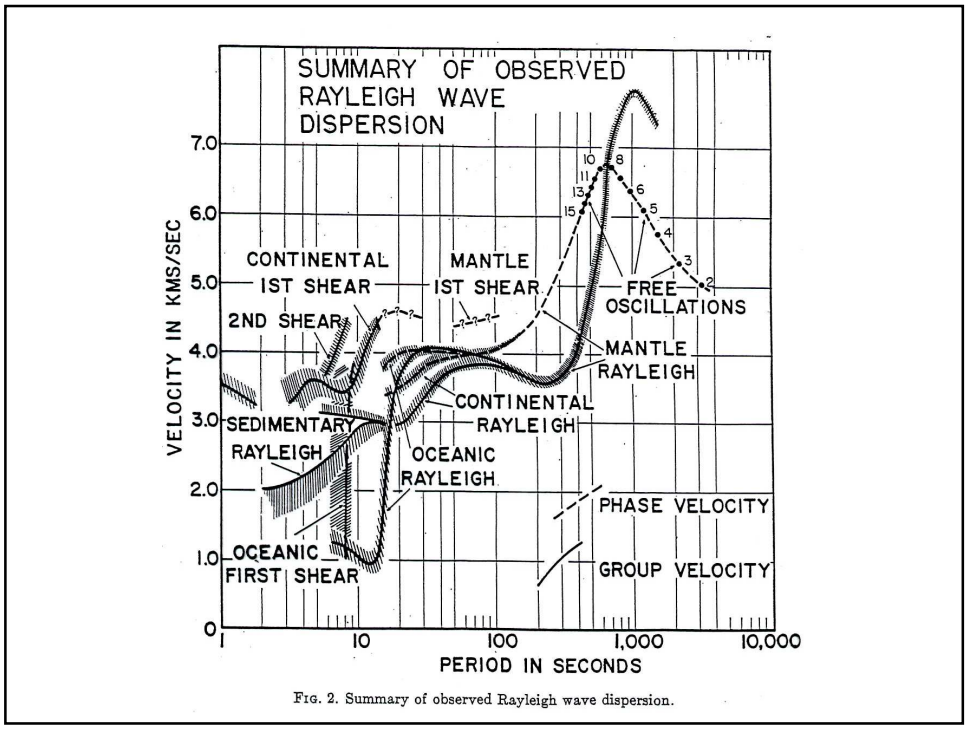


FIG. 2. Summary of observed Rayleigh wave dispersion.

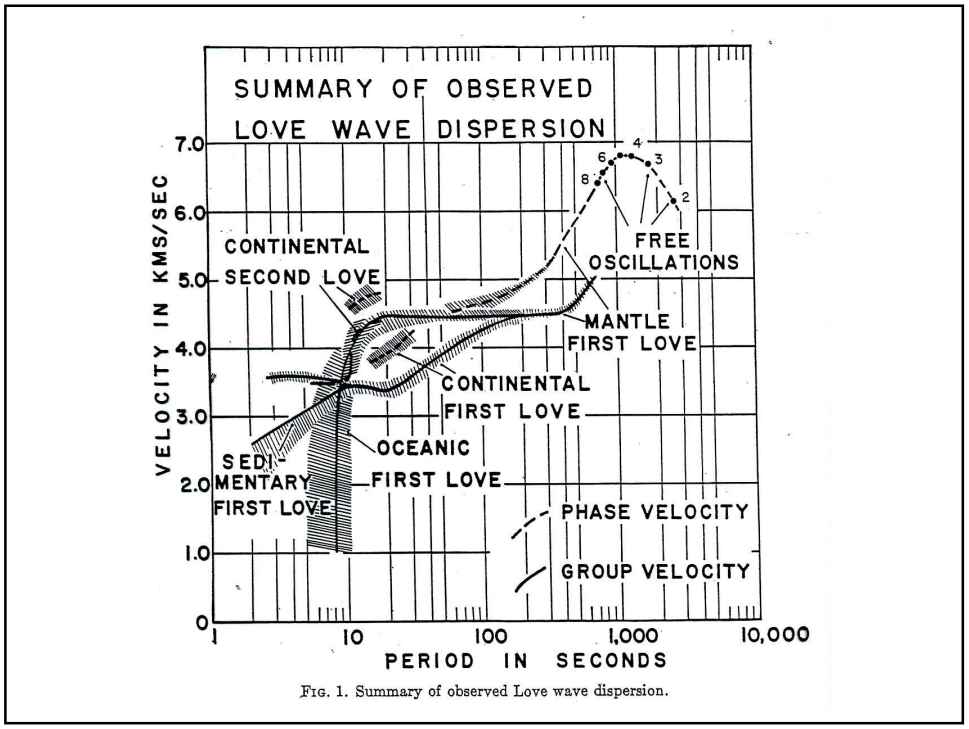


FIG. 1. Summary of observed Love wave dispersion.

Figure 2.5-2: Interface between two media.

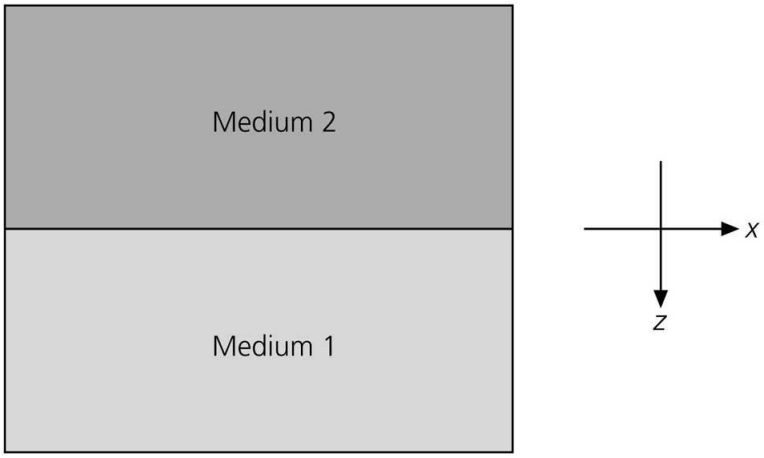
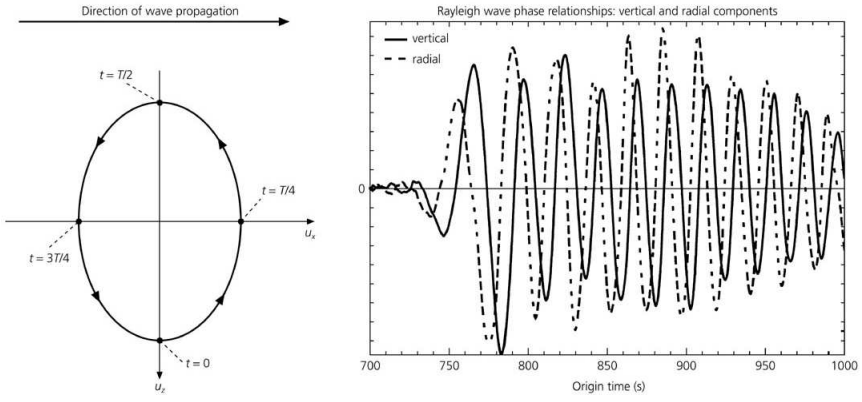


Figure 2.7-6: Horizontal and vertical Rayleigh wave motions.



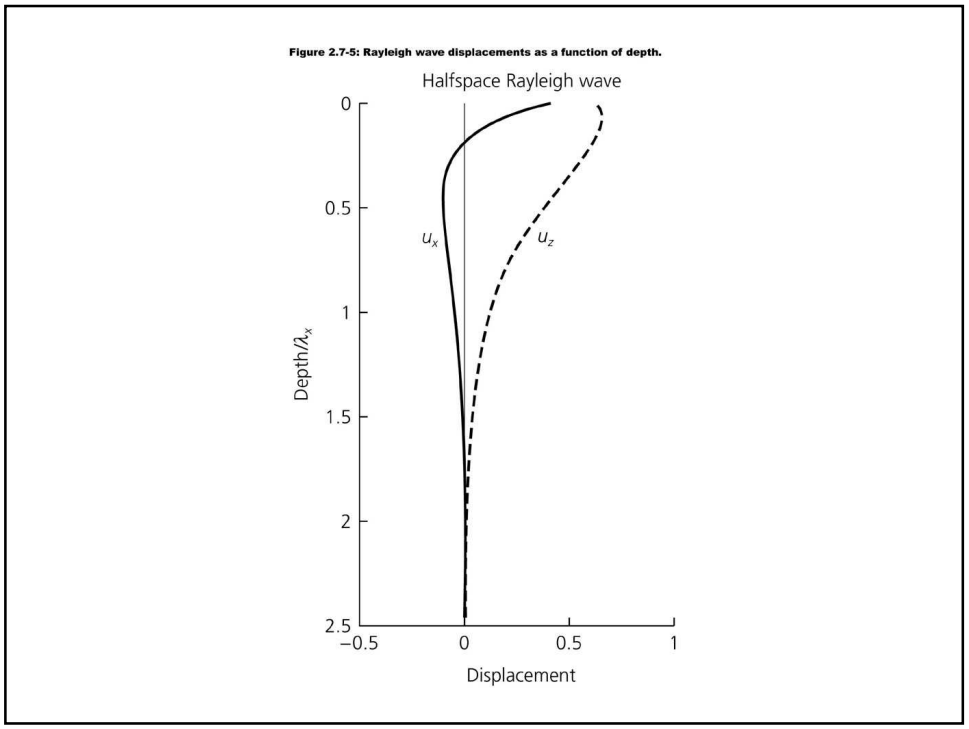


Figure 2.7-5: Rayleigh wave displacements as a function of depth.
Halfspace Rayleigh wave
0
0.5
1
1.5
2
2.5
Depth/λ_x
u_x
u_z
−0.5
0
0.5
1
Displacement

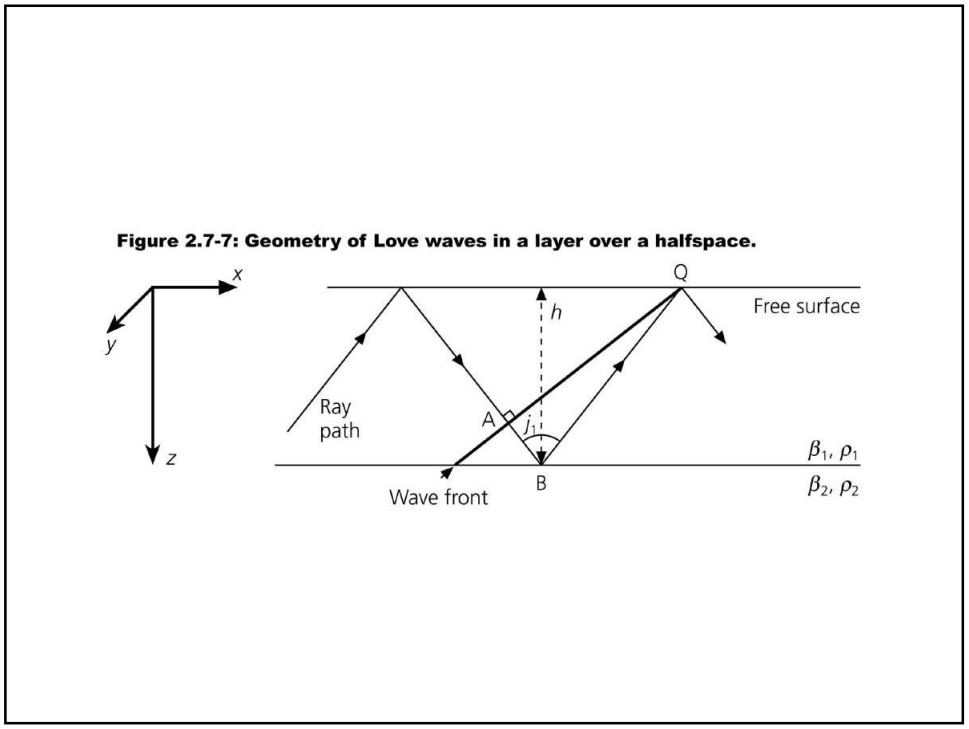
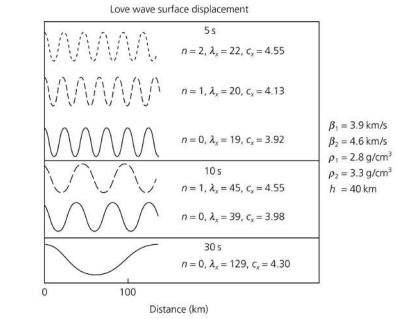
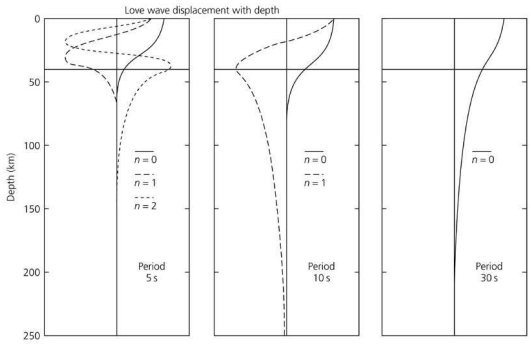
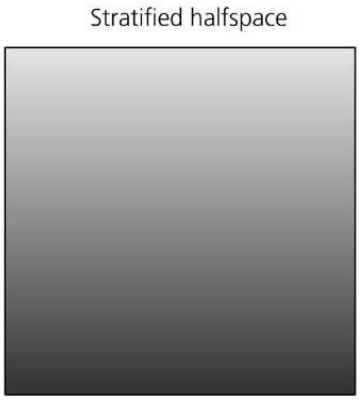


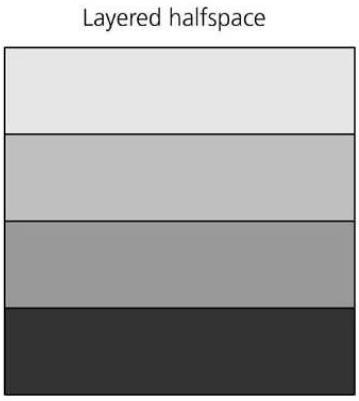
Figure 2.7-7: Geometry of Love waves in a layer over a halfspace.
x
y
z
Q
h
Free surface
Ray
path
A
j_1
β_1, ρ_1
β_2, ρ_2
B
Wave front

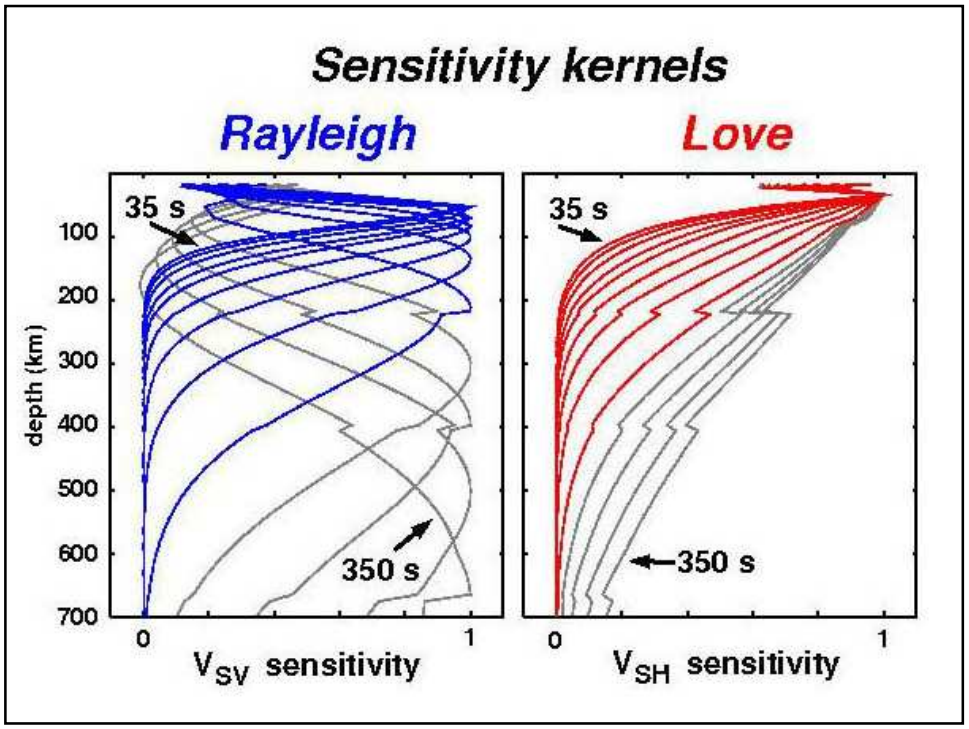
Figure 2.7-10: Displacements of for Love waves in a layer over a halfspace.











A surface wave seismogram $u(\omega)$ can be written

$$u(\omega) = A(\omega)\exp[i\Phi(\omega)]. \quad (1)$$

The phase Φ is the sum of two terms,

$$\Phi = \Phi_S + \Phi_P. \quad (2)$$

Φ_S is the source phase and Φ_P is the propagation phase,

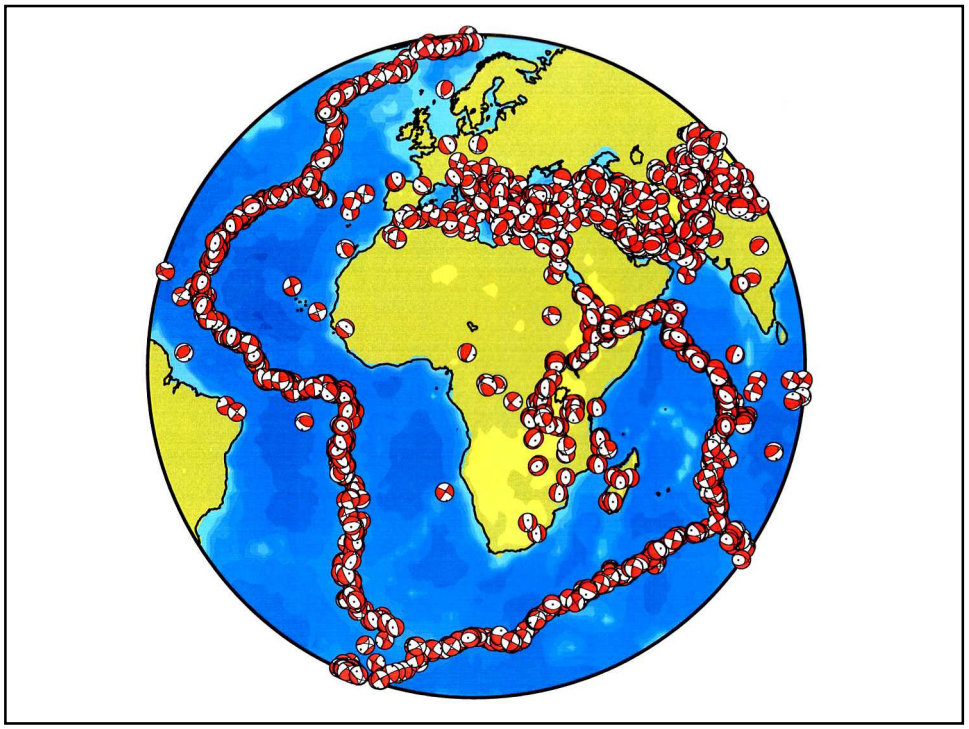
$$\Phi_P(\omega) = \int \frac{\omega}{c(\omega)} ds. \quad (3)$$

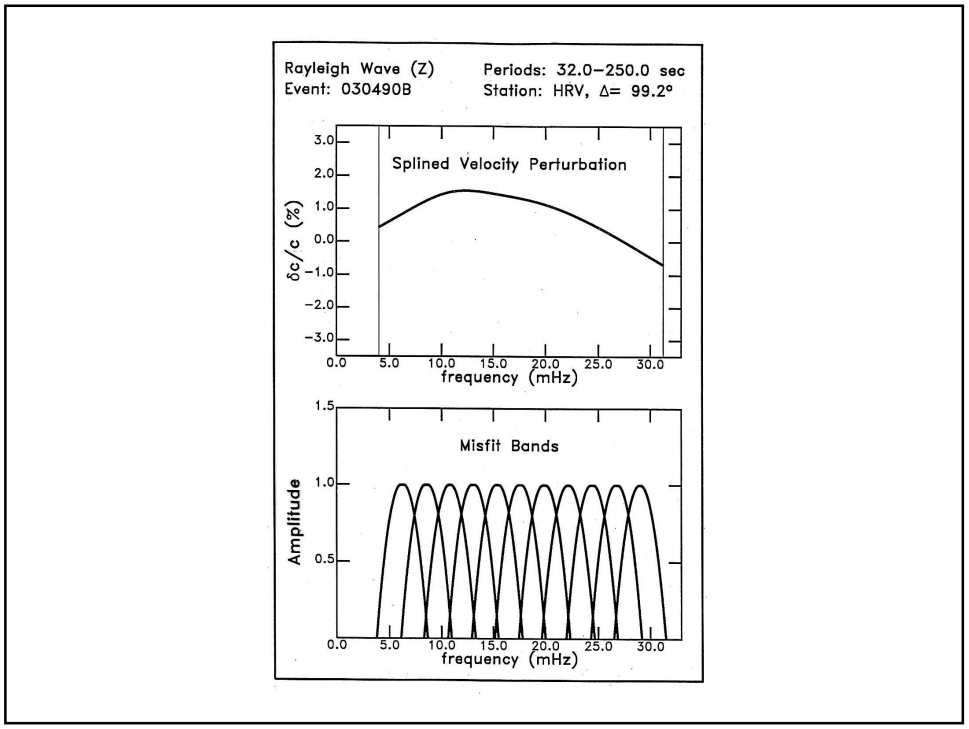
For a spherical reference Earth we write

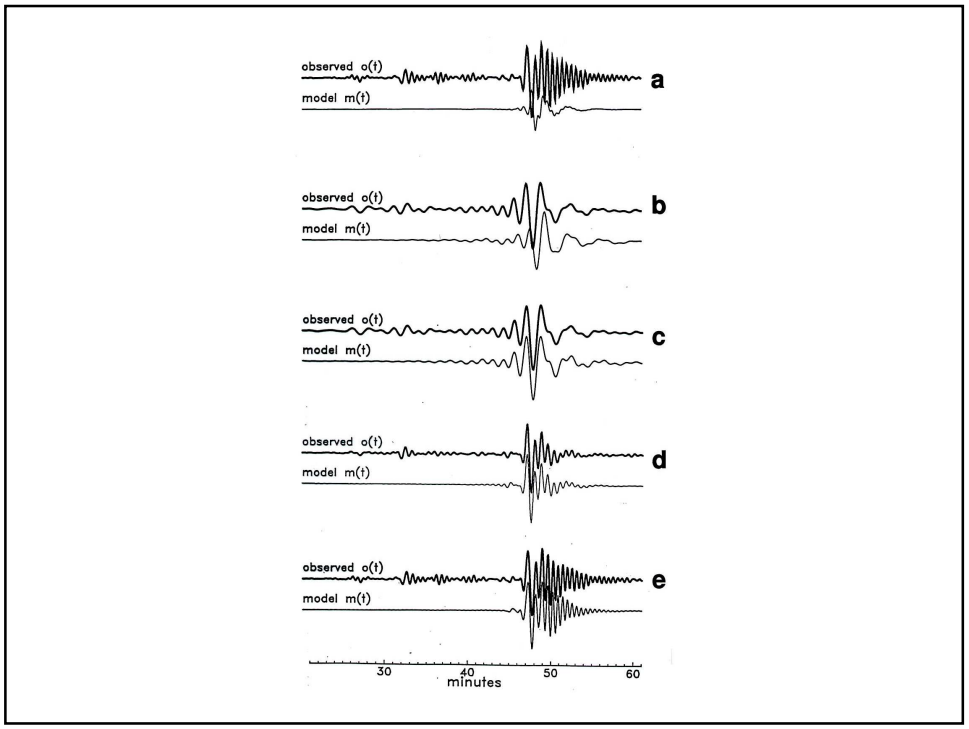
$$\Phi_P^0(\omega) = \frac{\omega R\Delta}{c^0} = \frac{\omega X}{c^0}. \quad (4)$$

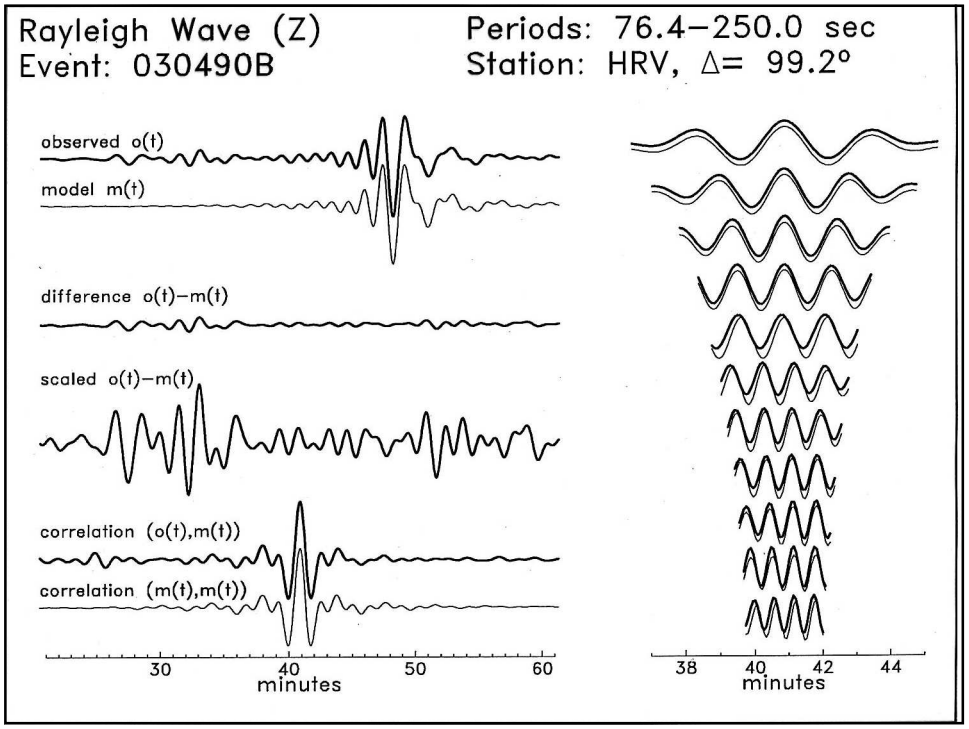
We approximate the observed phase as

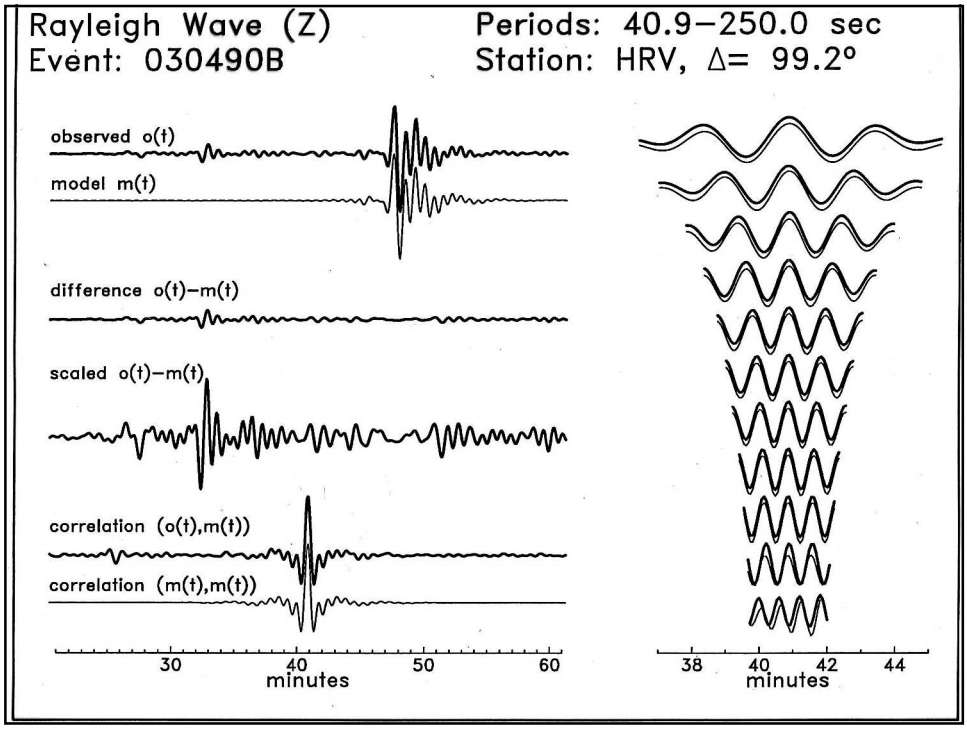
$$\Phi_P = \Phi_P^0 + \delta\Phi = \frac{\omega X}{c^0 + \delta c}. \quad (5)$$

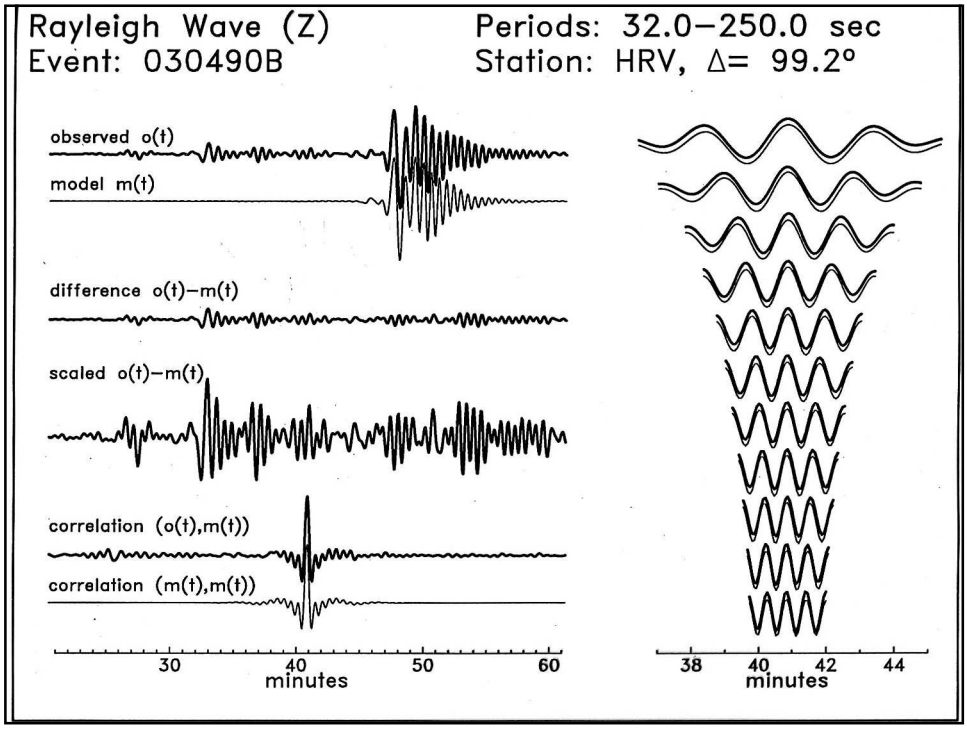


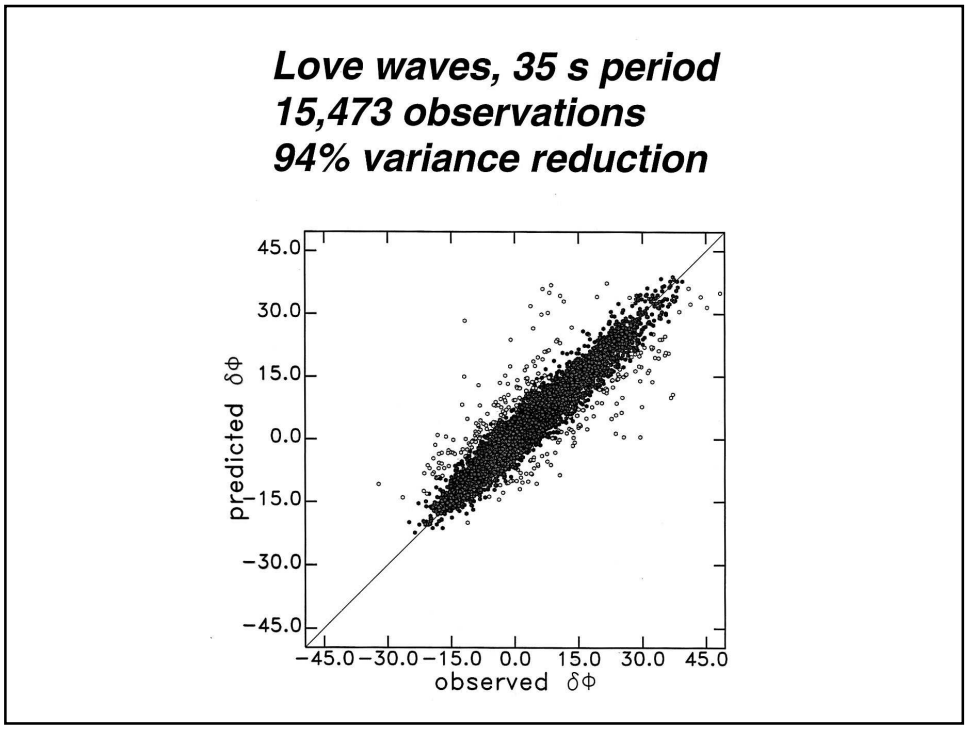

Rayleigh Wave (Z)
Event: 030490B
Periods: 32.0–250.0 sec
Station: HRV, Δ= 99.2°
Splined Velocity Perturbation
δc/c (%)
3.0
2.0
1.0
0.0
−1.0
−2.0
−3.0
0.0
5.0
10.0
15.0
20.0
25.0
30.0
frequency (mHz)
Misfit Bands
Amplitude
1.5
1.0
0.5
0.0
5.0
10.0
15.0
20.0
25.0
30.0
frequency (mHz)

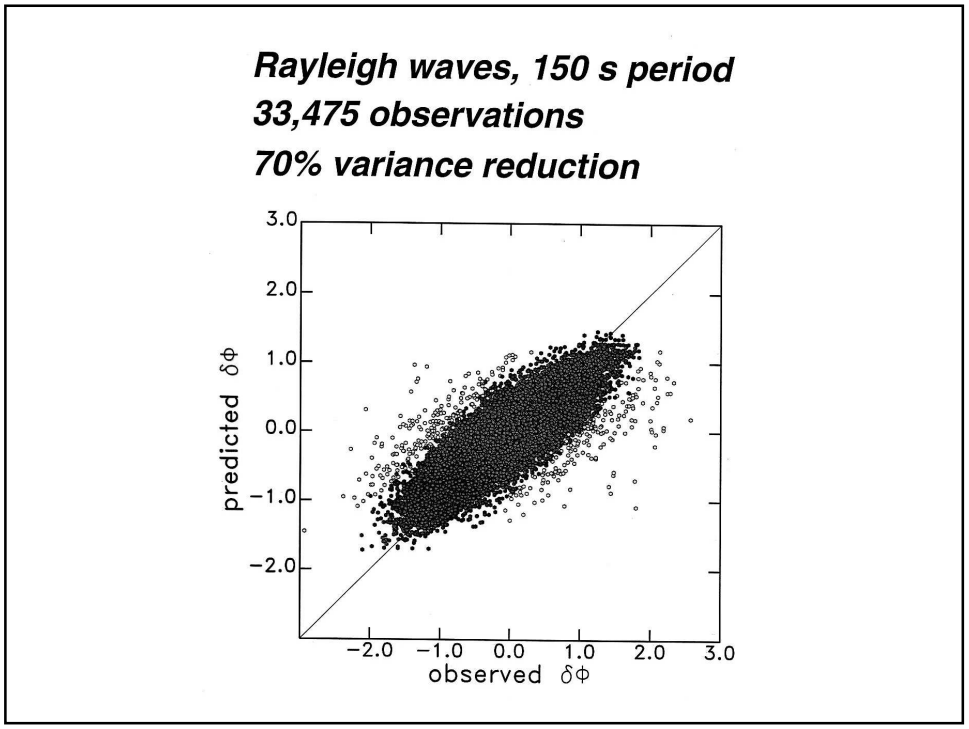

observed o(t)
model m(t)
a
b
c
d
e
30
40
50
60
minutes


Rayleigh Wave (Z)
Event: 030490B
Periods: 76.4–250.0 sec
Station: HRV, Δ= 99.2°
observed o(t)
model m(t)
difference o(t)–m(t)
scaled o(t)–m(t)
correlation (o(t),m(t))
correlation (m(t),m(t))
30
40
50
60
minutes
38
40
42
44
minutes


Rayleigh Wave (Z)
Event: 030490B
Periods: 40.9–250.0 sec
Station: HRV, Δ= 99.2°
observed o(t)
model m(t)
difference o(t)–m(t)
scaled o(t)–m(t)
correlation (o(t),m(t))
correlation (m(t),m(t))
30
40
50
60
minutes
38
40
42
44
minutes


Rayleigh Wave (Z)
Event: 030490B
Periods: 32.0–250.0 sec
Station: HRV, Δ= 99.2°
observed o(t)
model m(t)
difference o(t)–m(t)
scaled o(t)–m(t)
correlation (o(t),m(t))
correlation (m(t),m(t))
30
40
50
60
minutes
38
40
42
44
minutes


Love waves, 35 s period
15,473 observations
94% variance reduction
45.0
30.0
15.0
0.0
−15.0
−30.0
−45.0
predicted δΦ
−45.0 −30.0 −15.0 0.0 15.0 30.0 45.0
observed δΦ


Rayleigh waves, 150 s period
33,475 observations
70% variance reduction
3.0
2.0
1.0
0.0
−1.0
−2.0
predicted δΦ
−2.0 −1.0 0.0 1.0 2.0 3.0
observed δΦ

The phase anomaly is written

$$\delta\Phi = -\frac{\omega}{c^0}\int_{(\theta_S,\phi_S)}^{(\theta_R,\phi_R)} \frac{\delta c(\theta,\phi)}{c^0} ds, \qquad (1)$$

and the phase velocity perturbation is expressed in complex spherical harmonics

$$\frac{\delta c(\theta,\phi)}{c^0} = \sum_{l=0}^{L}\sum_{m=-l}^{m=l} C_{lm} Y_{lm}(\theta,\phi). \qquad (2)$$

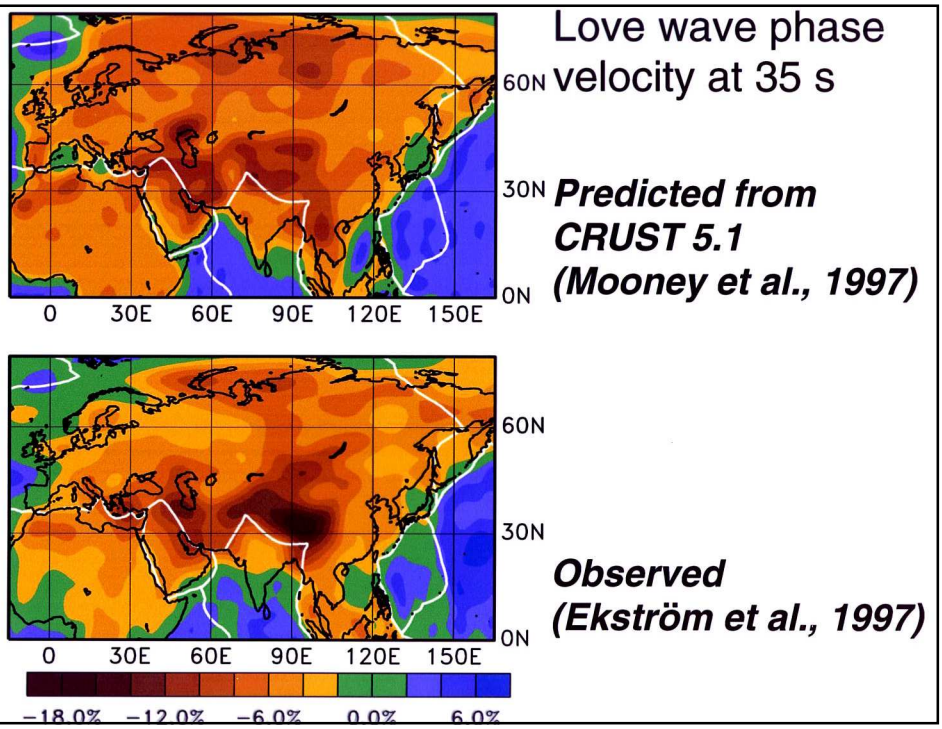
The rms gradient is

$$\mathcal{R} \propto \left[\int_S (\nabla\frac{\delta c}{c^0})\cdot(\nabla\frac{\delta c}{c^0}) d\Omega\right]^{1/2}. \qquad (3)$$

We determine the model coefficients which solve the minimization problem

$$\min\left(\frac{\chi^2}{N} + \gamma\mathcal{R}^2\right), \qquad (4)$$

where γ is a damping parameter.



Interpreting the observed phase anomalies in terms of velocity variations in the six tectonic regions of GTR1 (Jordan, 1981).

The observed phase anomaly is approximated as

$$\delta\Phi = \frac{\omega X}{c^0 + \delta c} - \frac{\omega X}{c^0} \approx -\frac{\omega X \delta c}{(c^0)^2}. \qquad (1)$$

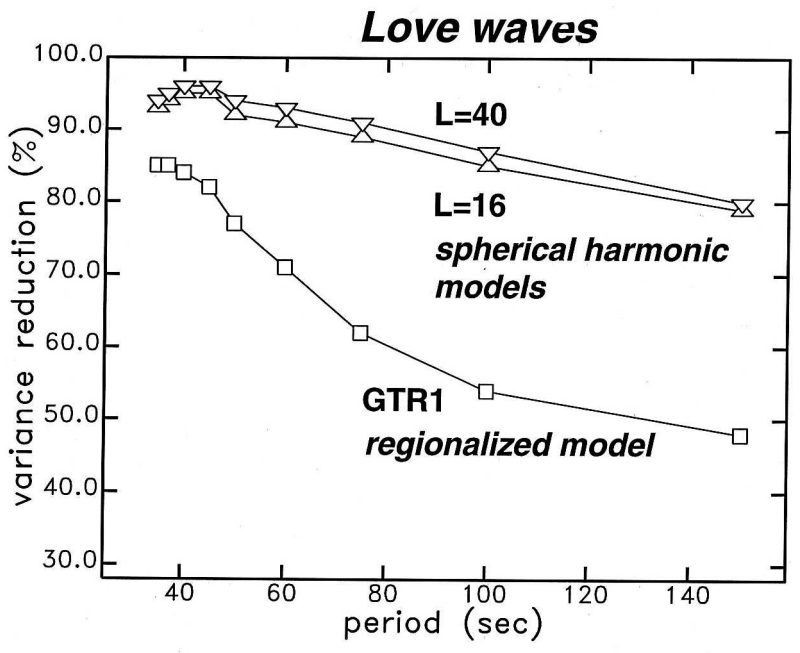
The phase anomaly $\delta\Phi$ is modeled as

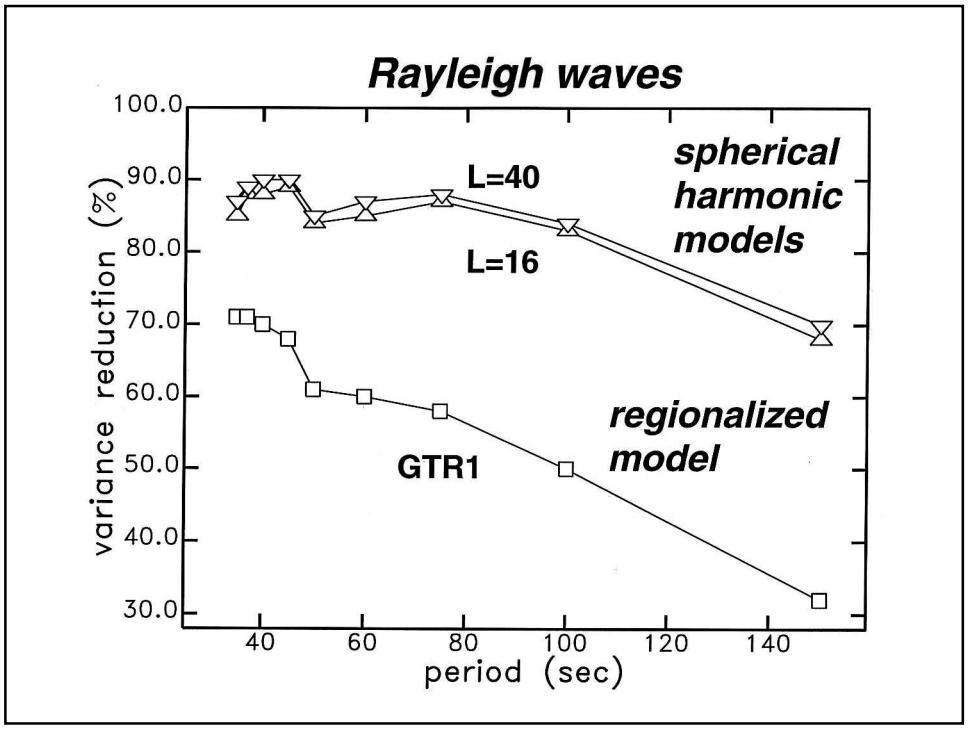
$$\delta\Phi = -\frac{\omega}{c^0} \sum_{i=1}^{6} X^i \frac{\delta c^i}{c^0}. \qquad (2)$$

The misfit function χ^2 is formed as

$$\chi^2 = \sum_{j=1}^{N} \frac{1}{\sigma_j^2} \left(\delta\Phi_j - \frac{\omega}{c^0} \sum_{i=1}^{6} X_j^i \frac{\delta c^i}{c^0} \right)^2, \qquad (3)$$

where j is the index of the observation, N is the total number of observations, and σ_j is the associated observational uncertainty.




Rayleigh waves
variance reduction (%)
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
40
60
80
100
120
140
period (sec)
L=40
L=16
spherical harmonic models
GTR1
regionalized model

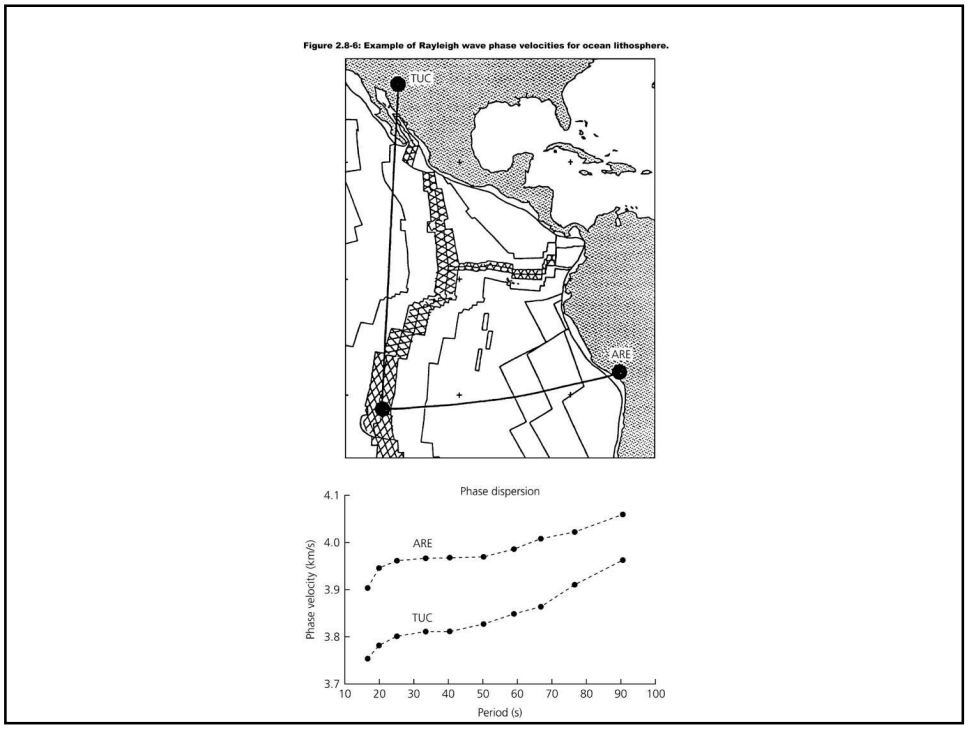
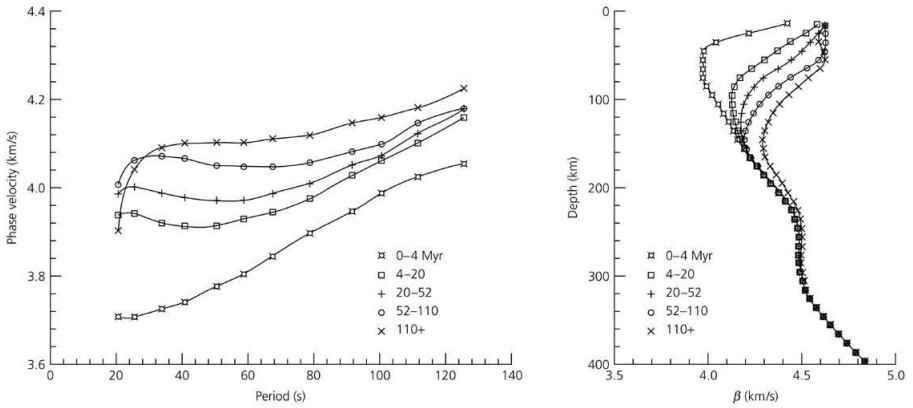


Figure 2.8-6: Example of Rayleigh wave phase velocities for ocean lithosphere.
TUC
ARE
Phase dispersion
Phase velocity (km/s)
4.1
4.0
3.9
3.8
3.7
ARE
TUC
10
20
30
40
50
60
70
80
90
100
Period (s)

Figure 2.8-7: Rayleigh wave phase velocity dispersion as a function of oceanic plate age.



Radial Anisotropy =
Transverse Isotropy
with a Vertical Symmetry Axis

$c_{ij} \rightarrow$ A, C, L, N, F

or

$\rightarrow V_{SH}, V_{SV}, V_{PH}, V_{PV}, \eta$

Common expectation:

$\delta V_{PH} \sim \delta V_{SH}$
$\delta V_{PV} \sim \delta V_{SV}$
$\eta \sim 1$

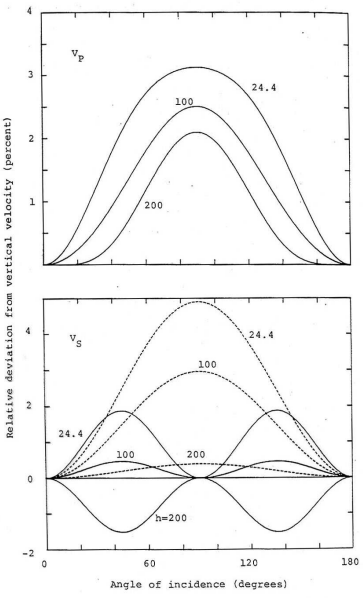
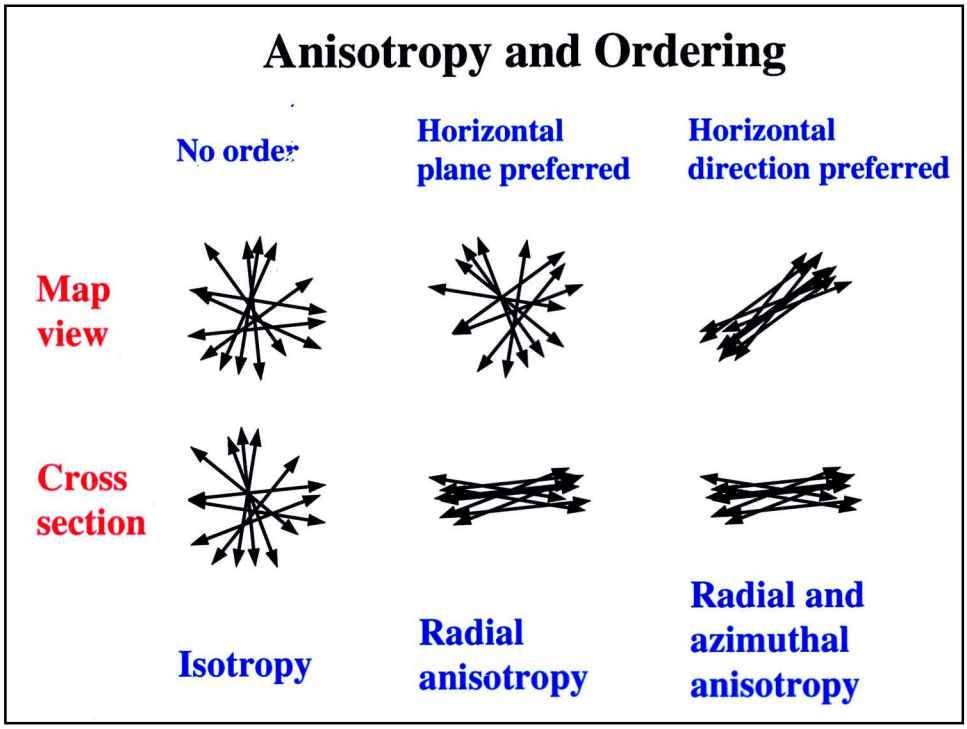
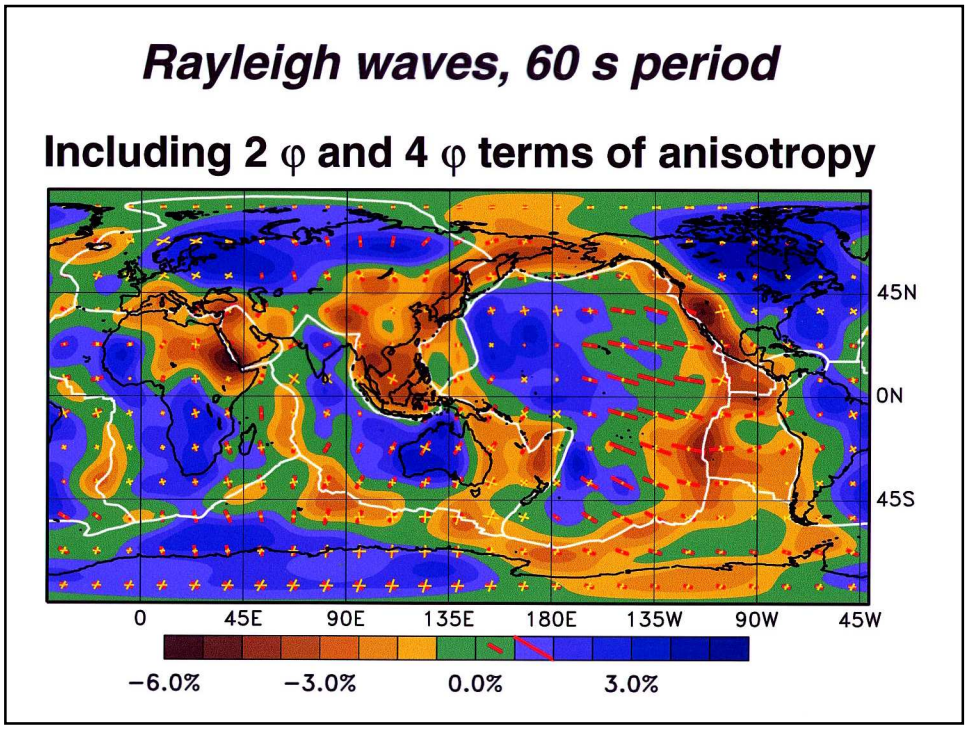
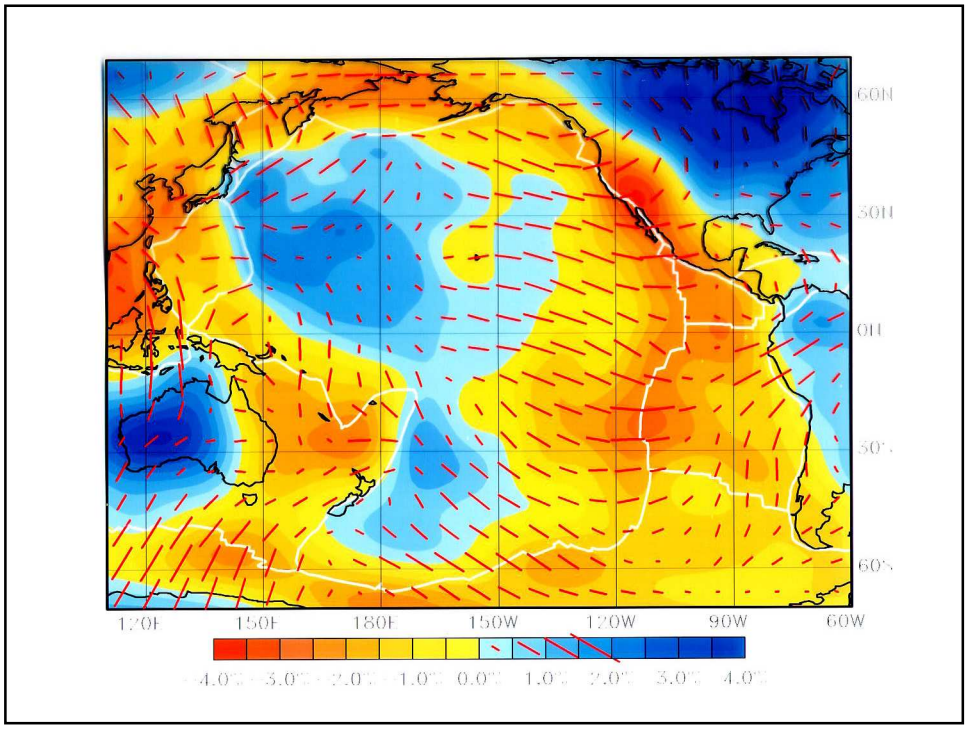
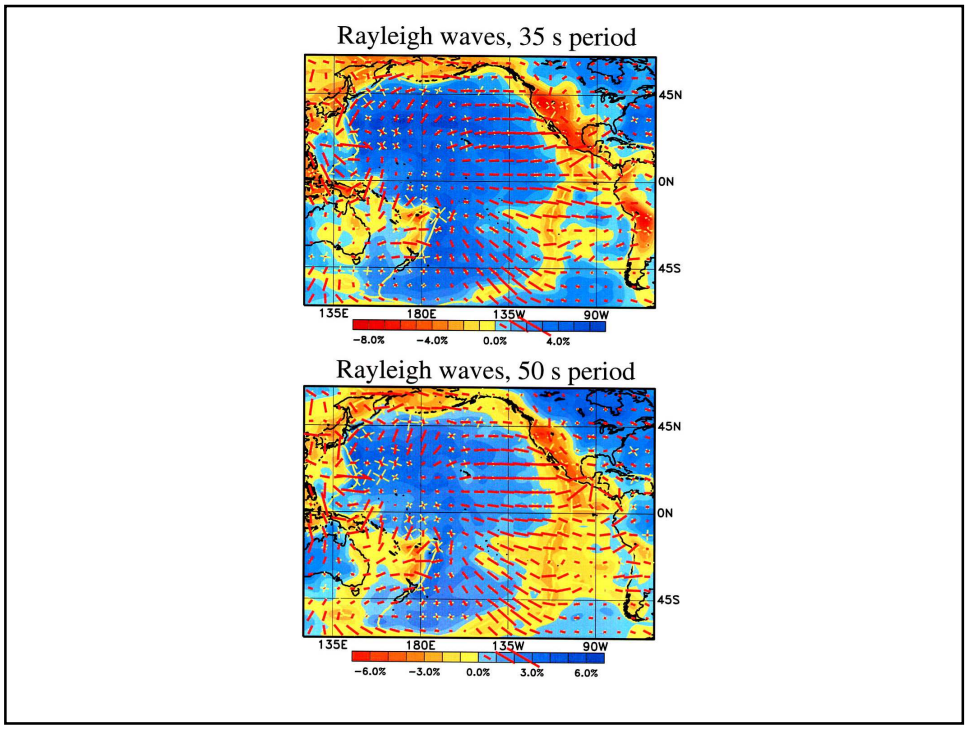


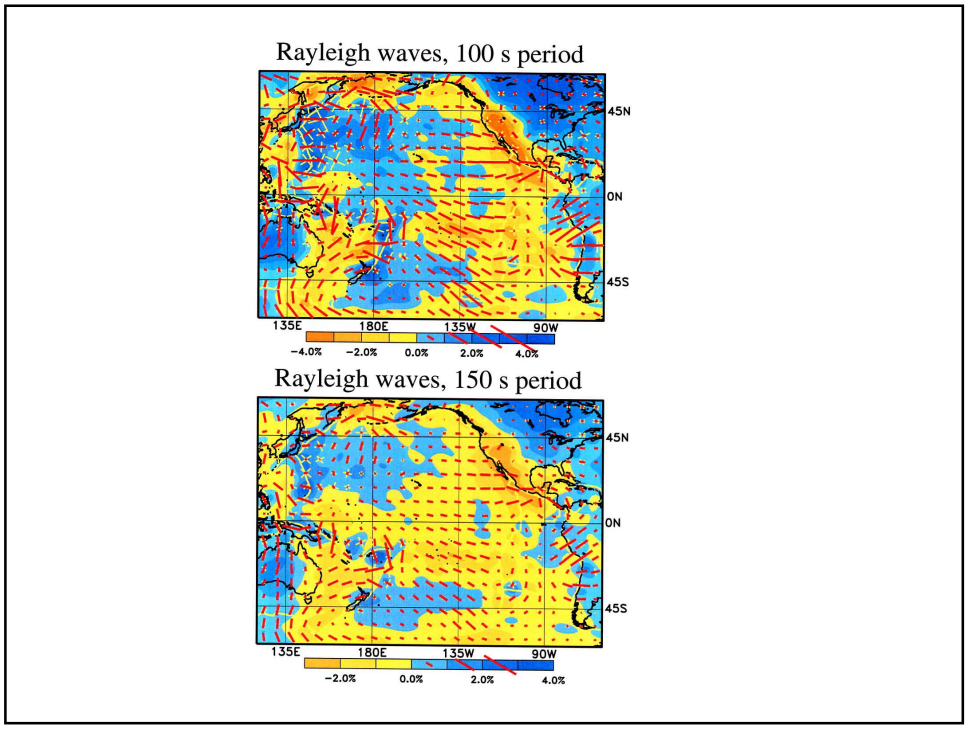
Fig. 9. Velocity as a function of direction of angle of incidence for three depths in the anisotropic region of the PREM model. Upper curves are compressional velocities; lower panel gives V_{SV} (solid) and V_{SH} (dashed).

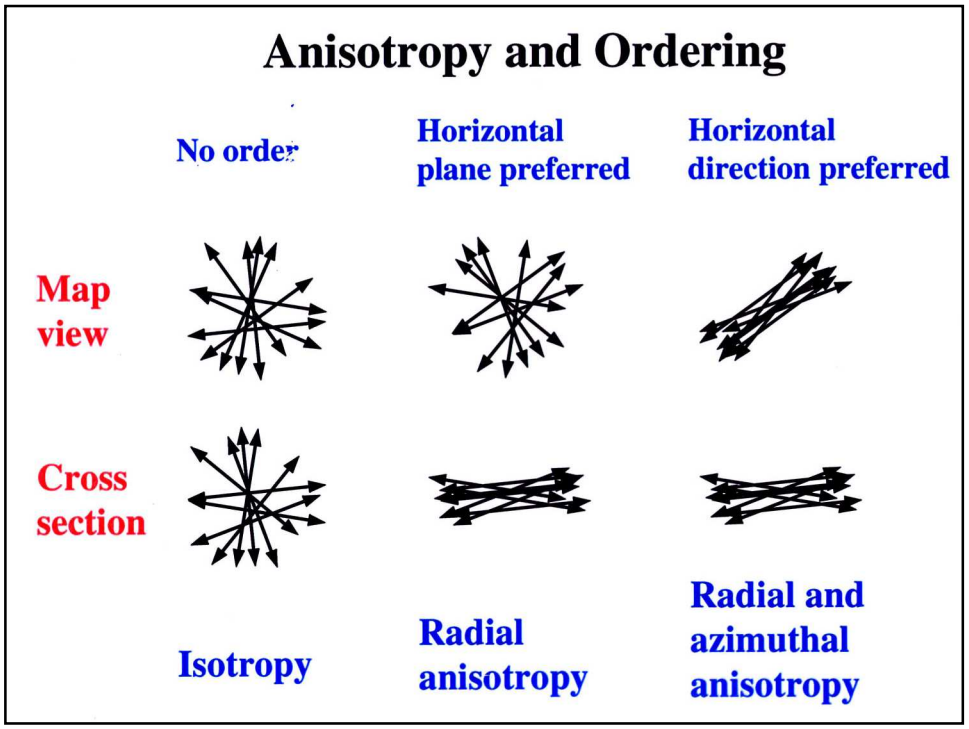


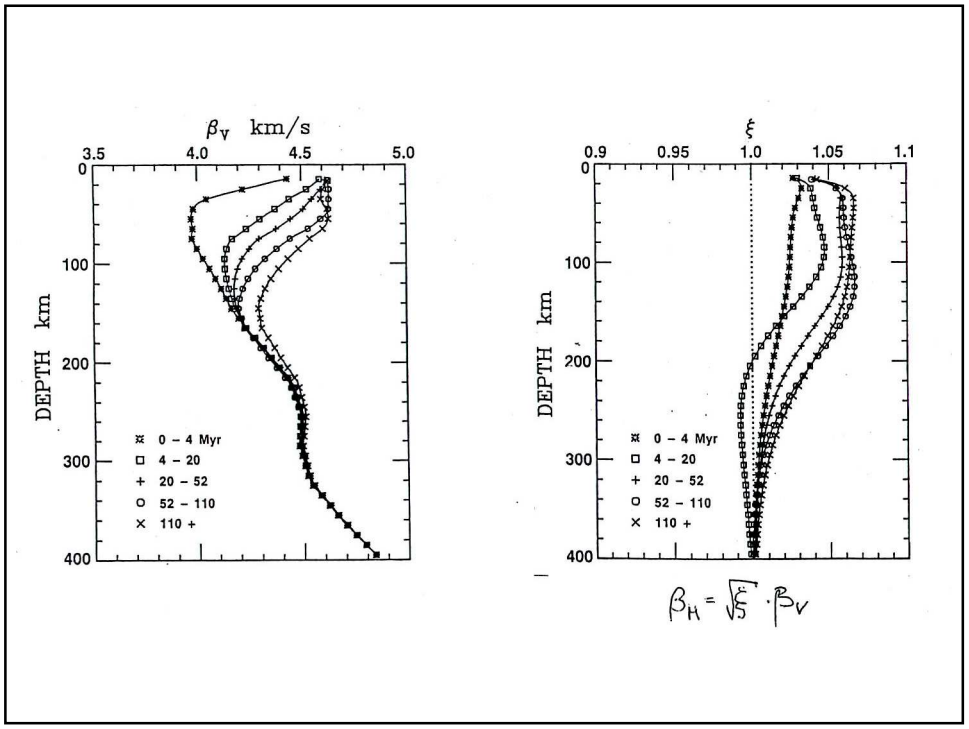

Rayleigh waves, 60 s period
Including 2 φ and 4 φ terms of anisotropy
45N
0N
45S
0
45E
90E
135E
180E
135W
90W
45W
−6.0%
−3.0%
0.0%
3.0%

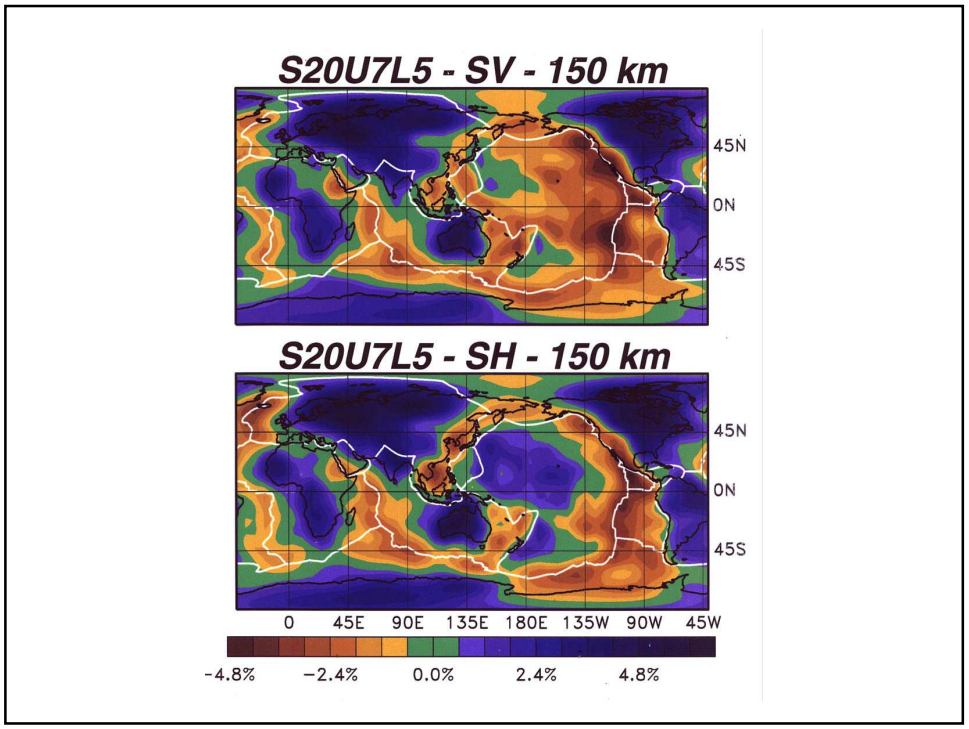

60N
30N
0N
30S
60S
120E
150E
180E
150W
120W
90W
60W

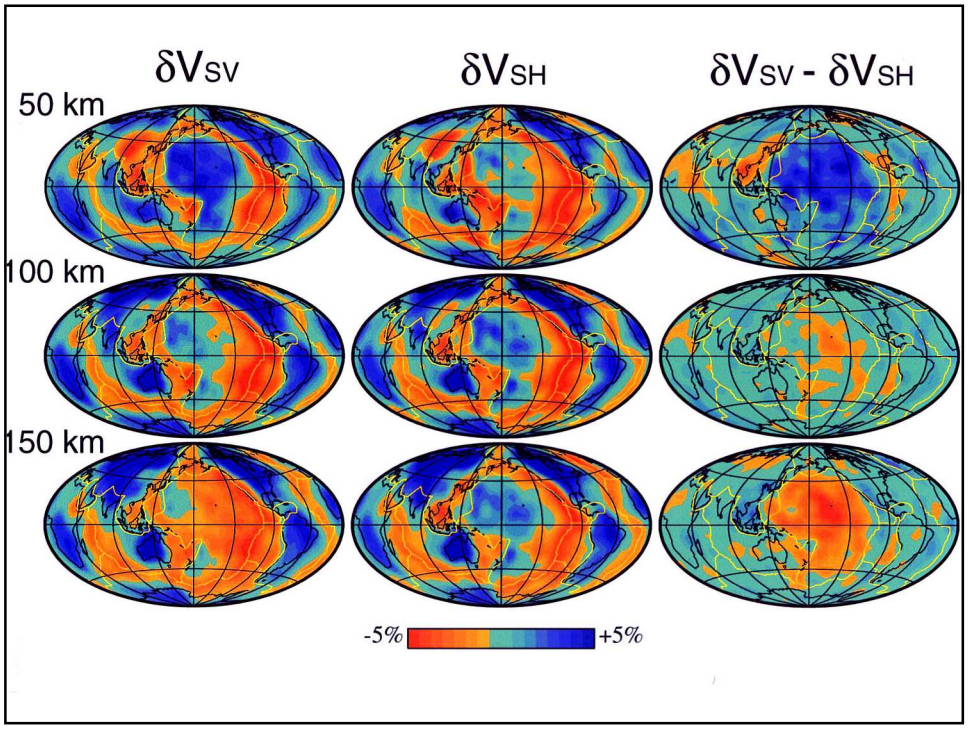

Rayleigh waves, 35 s period
45N
0N
45S
135E
180E
135W
90W
−8.0%
−4.0%
0.0%
4.0%
Rayleigh waves, 50 s period
45N
0N
45S
135E
180E
135W
90W
−6.0%
−3.0%
0.0%
3.0%
6.0%

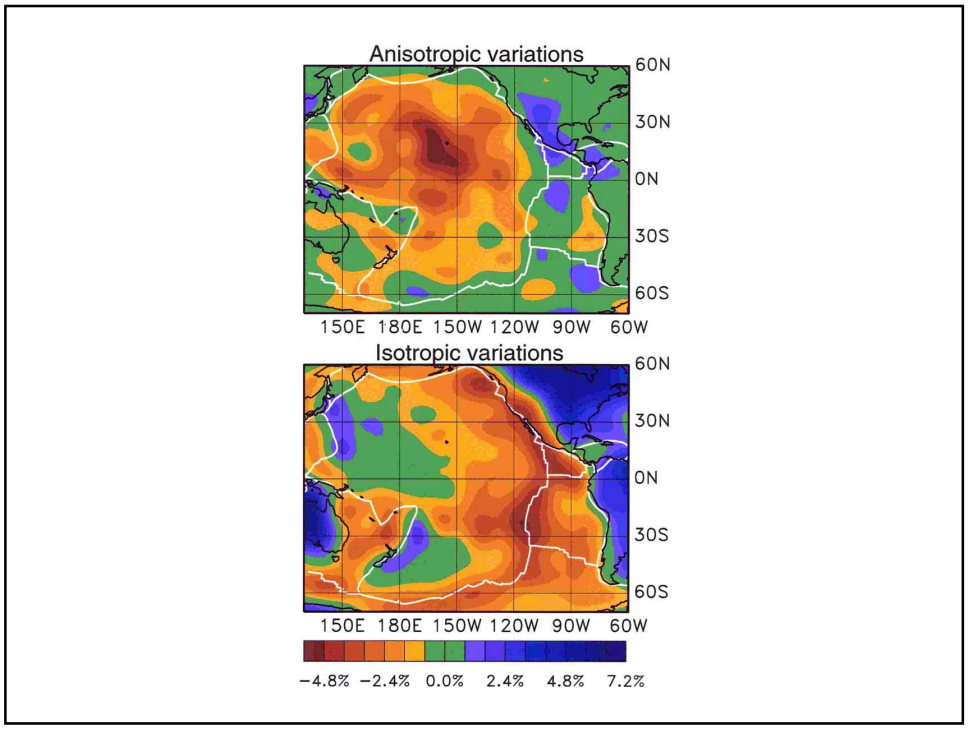

Rayleigh waves, 100 s period
45N
0N
45S
135E
180E
135W
90W
−4.0%
−2.0%
0.0%
2.0%
4.0%
Rayleigh waves, 150 s period
45N
0N
45S
135E
180E
135W
90W
−2.0%
0.0%
2.0%
4.0%

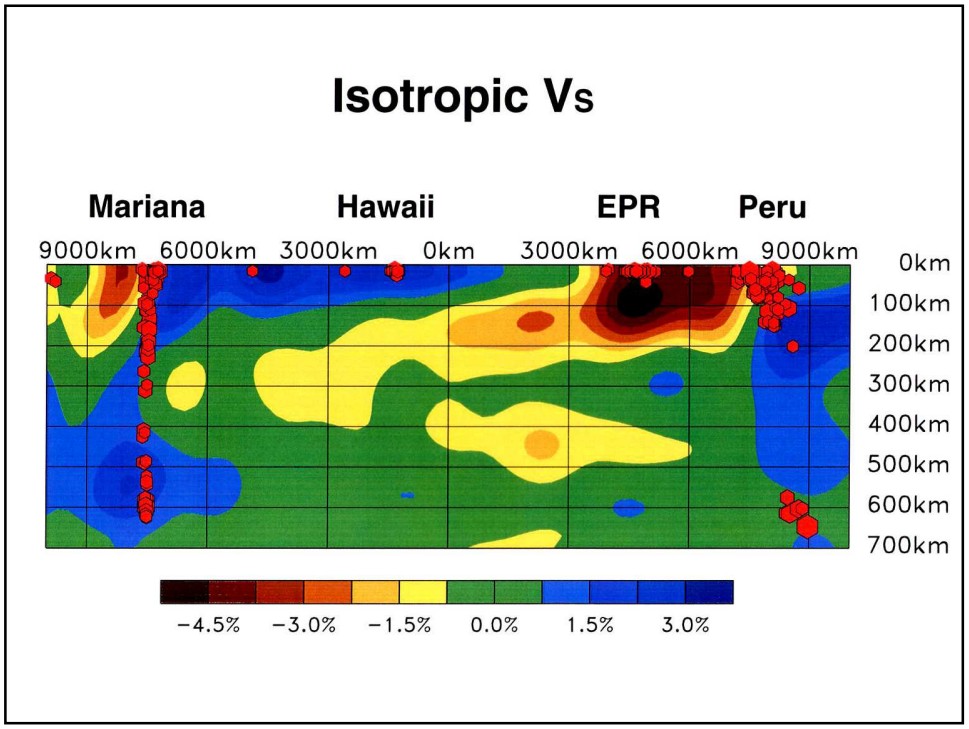

Anisotropy and Ordering
No order
Horizontal plane preferred
Horizontal direction preferred
Map view
Cross section
Isotropy
Radial anisotropy
Radial and azimuthal anisotropy

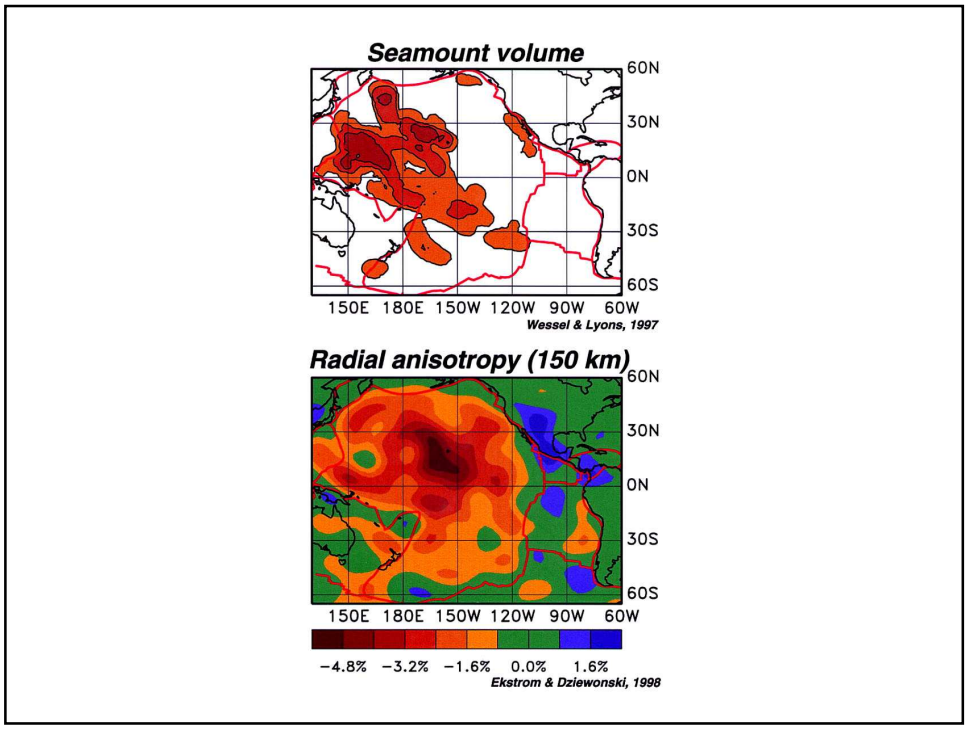

β_V km/s
3.5
4.0
4.5
5.0
DEPTH km
0
100
200
300
400
0 – 4 Myr
4 – 20
20 – 52
52 – 110
110 +
ξ
0.9
0.95
1.0
1.05
1.1
$\beta_H = \sqrt{\xi} \cdot \beta_V$


S20U7L5 - SV - 150 km
45N
0N
45S
S20U7L5 - SH - 150 km
45N
0N
45S
0 45E 90E 135E 180E 135W 90W 45W
-4.8% -2.4% 0.0% 2.4% 4.8%


δVSV
δVSH
δVSV - δVSH
50 km
100 km
150 km
-5% +5%


Anisotropic variations
60N
30N
0N
30S
60S
150E 180E 150W 120W 90W 60W
Isotropic variations
60N
30N
0N
30S
60S
150E 180E 150W 120W 90W 60W
−4.8% −2.4% 0.0% 2.4% 4.8% 7.2%


Isotropic Vs
Mariana
Hawaii
EPR
Peru
9000km 6000km 3000km 0km 3000km 6000km 9000km
0km
100km
200km
300km
400km
500km
600km
700km
−4.5% −3.0% −1.5% 0.0% 1.5% 3.0%


Seamount volume
60N
30N
0N
30S
60S
150E 180E 150W 120W 90W 60W
Wessel & Lyons, 1997
Radial anisotropy (150 km)
60N
30N
0N
30S
60S
150E 180E 150W 120W 90W 60W
−4.8% −3.2% −1.6% 0.0% 1.6%
Ekstrom & Dziewonski, 1998