united nations
educational, scientific
and cultural
organization

international atomic
energy agency

the
abdus salam
international centre for theoretical physics
40th anniversary 1964 2004

H4.SMR/1586-13

"7th Workshop on Three-Dimensional Modelling of Seismic Waves Generation and their Propagation"

25 October - 5 November 2004

GLOBAL SEISMOLOGY

From Normal Modes to Surface and Body Waves Application to Anisotropic Tomography

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Global Seismology

From normal modes to surface waves and body waves

Jean-Paul Montagner

Dept. Sismologie, I.P.G., Paris; France

Overview
Large scale Seismology: an observational field

- Data (Seismic source) + Instrument (Seismometer) -> Observations (seismograms)
- Historical evolution: Ray theory, Normal mode theory, Numerical techniques (SEM, NM-SEM)
- Scientific Issues: earthquakes, structure of the Earth and planets
- Tomographic Technique
- Seismic Experiment: Plume detection
- NM-SEM and time reversal

Seismic Instruments

- Seismoscope

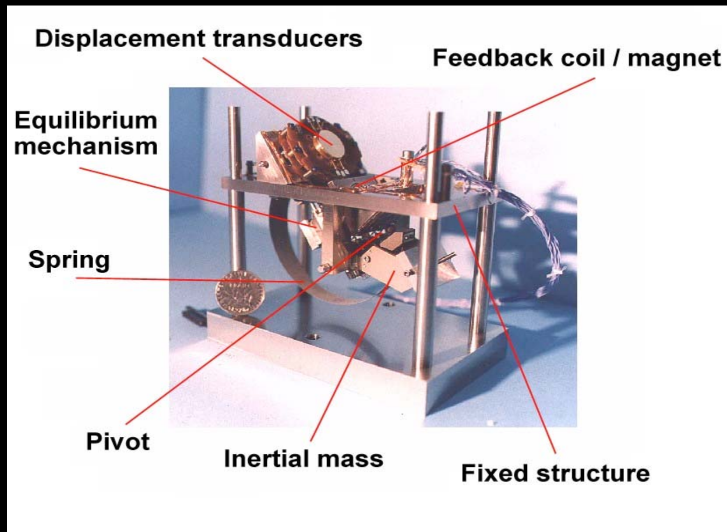
(China -100BC)

Broadband

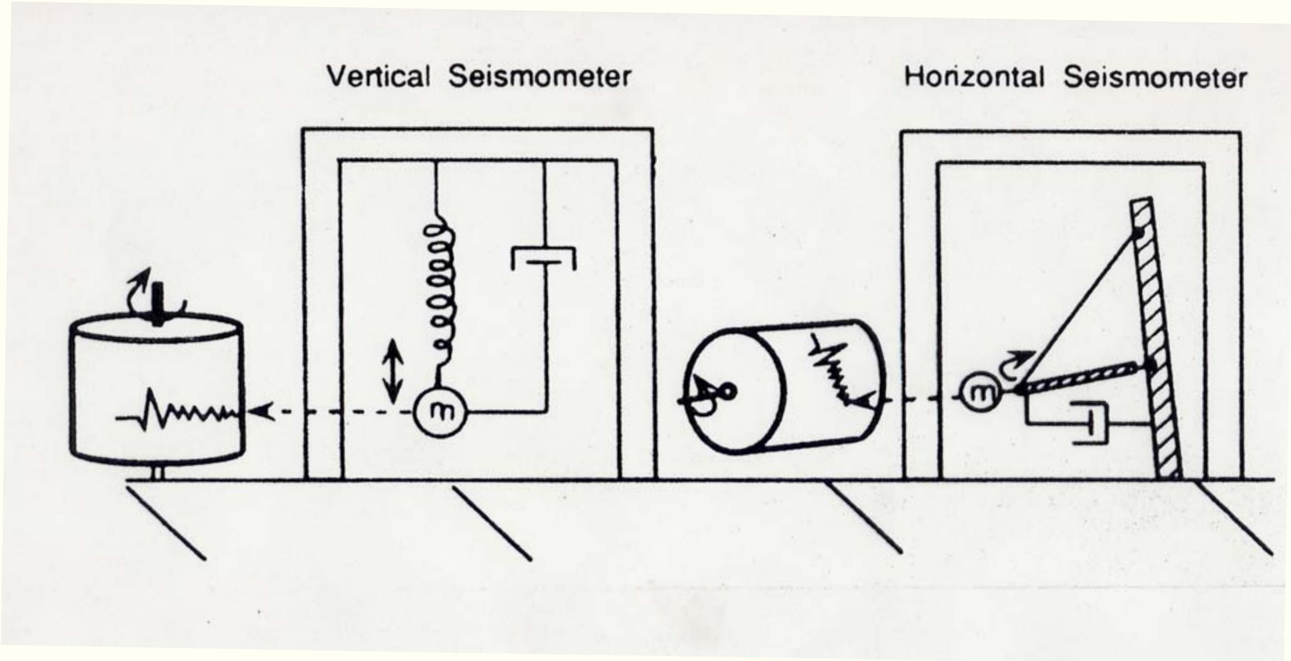
Seismometer

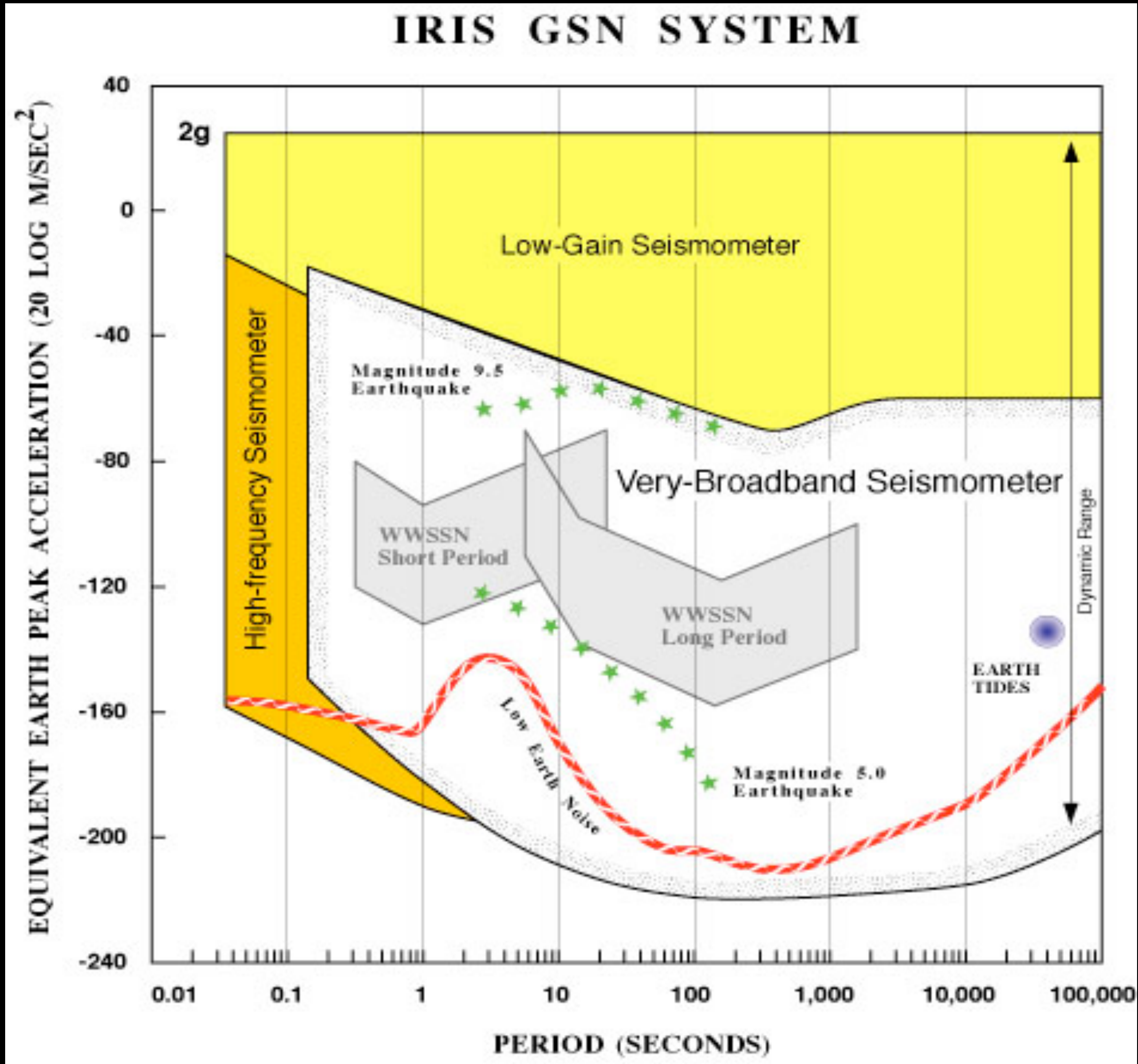
(1mHz-20Hz)

(Cacho, 1998)



Principle of a Seismometer





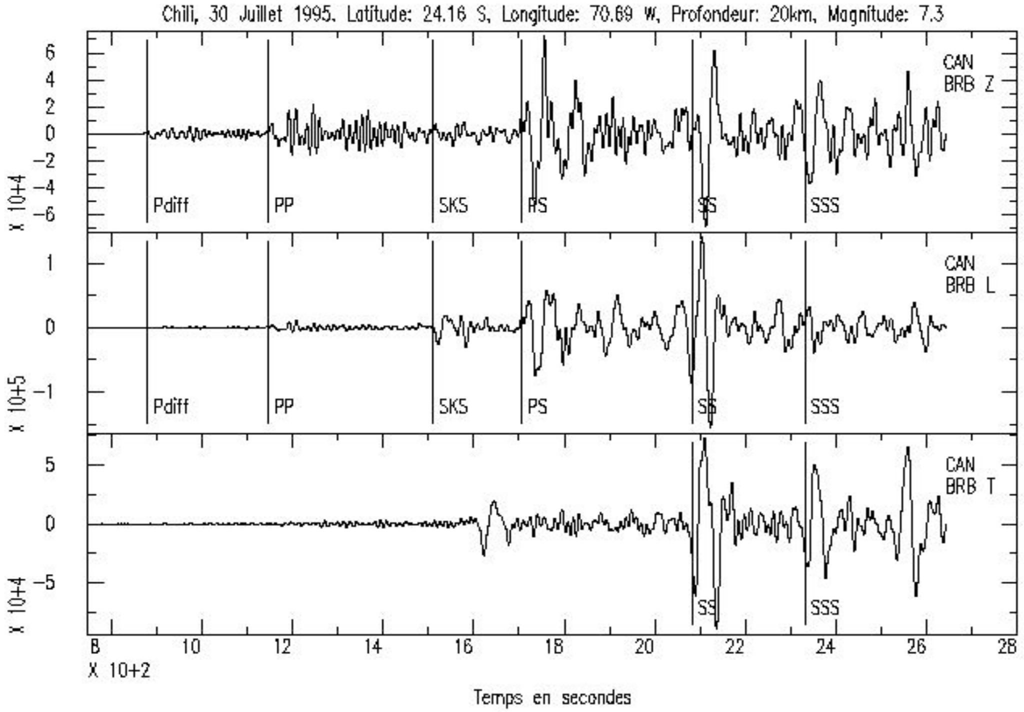
Butler et al., 2004

3 components

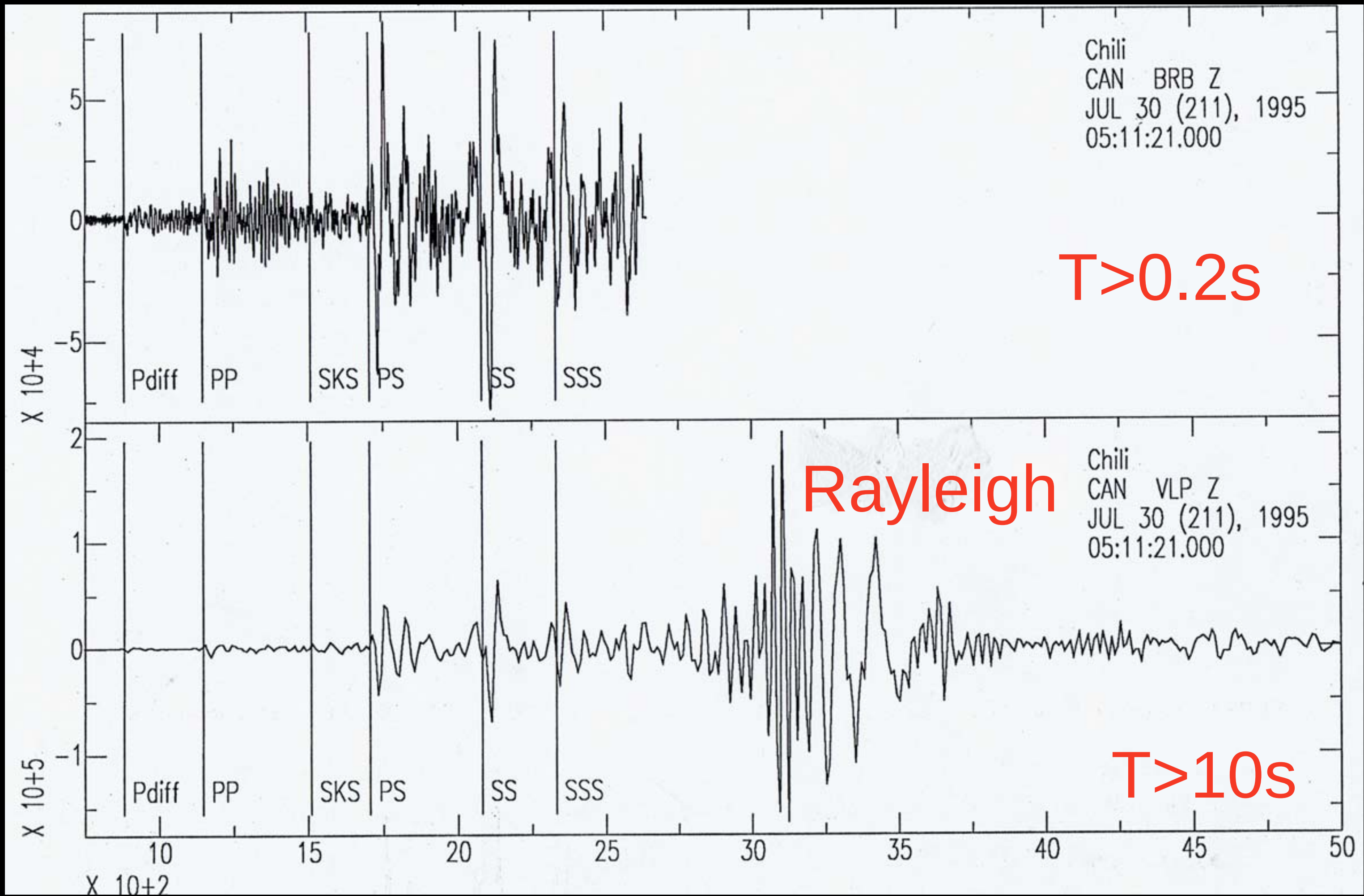
frequency range: 1mHz-20Hz

Period range: 0.05-1000s

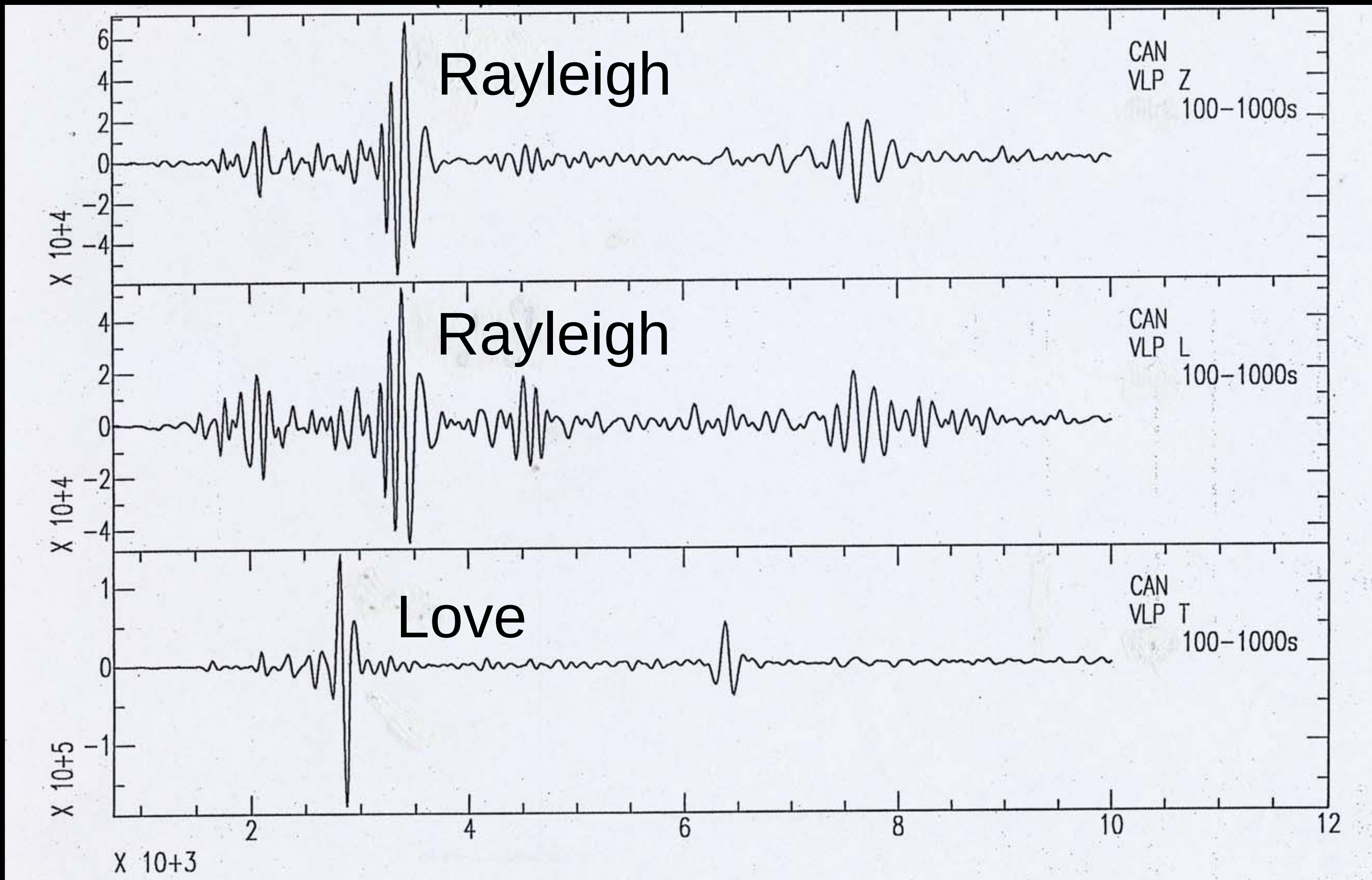
Chile July 30, 1995, Ms=8.3



Chile earthquake   magnitude= 7.3
Epicentral distance = 12,300km-depth 20km



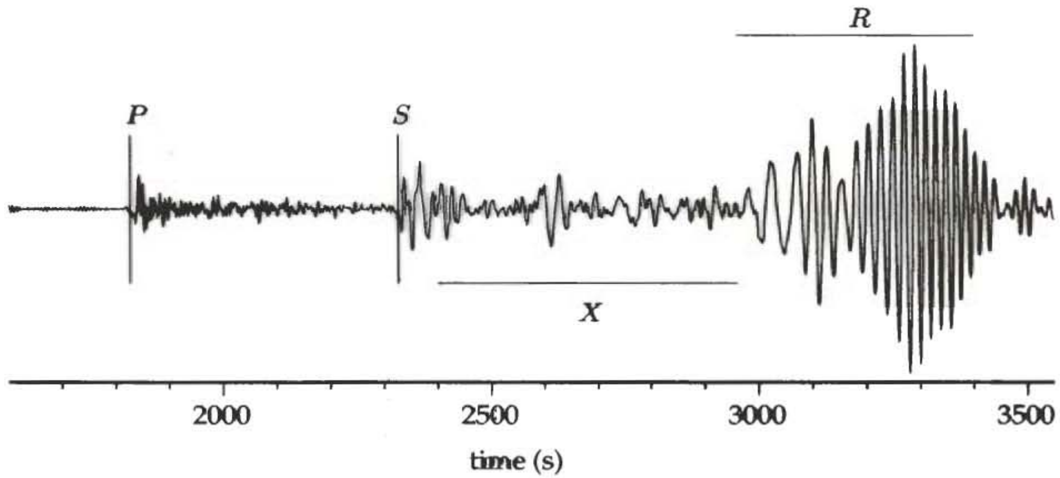
Chile Earthquake Jul. 1995



→ Dispersive waves,

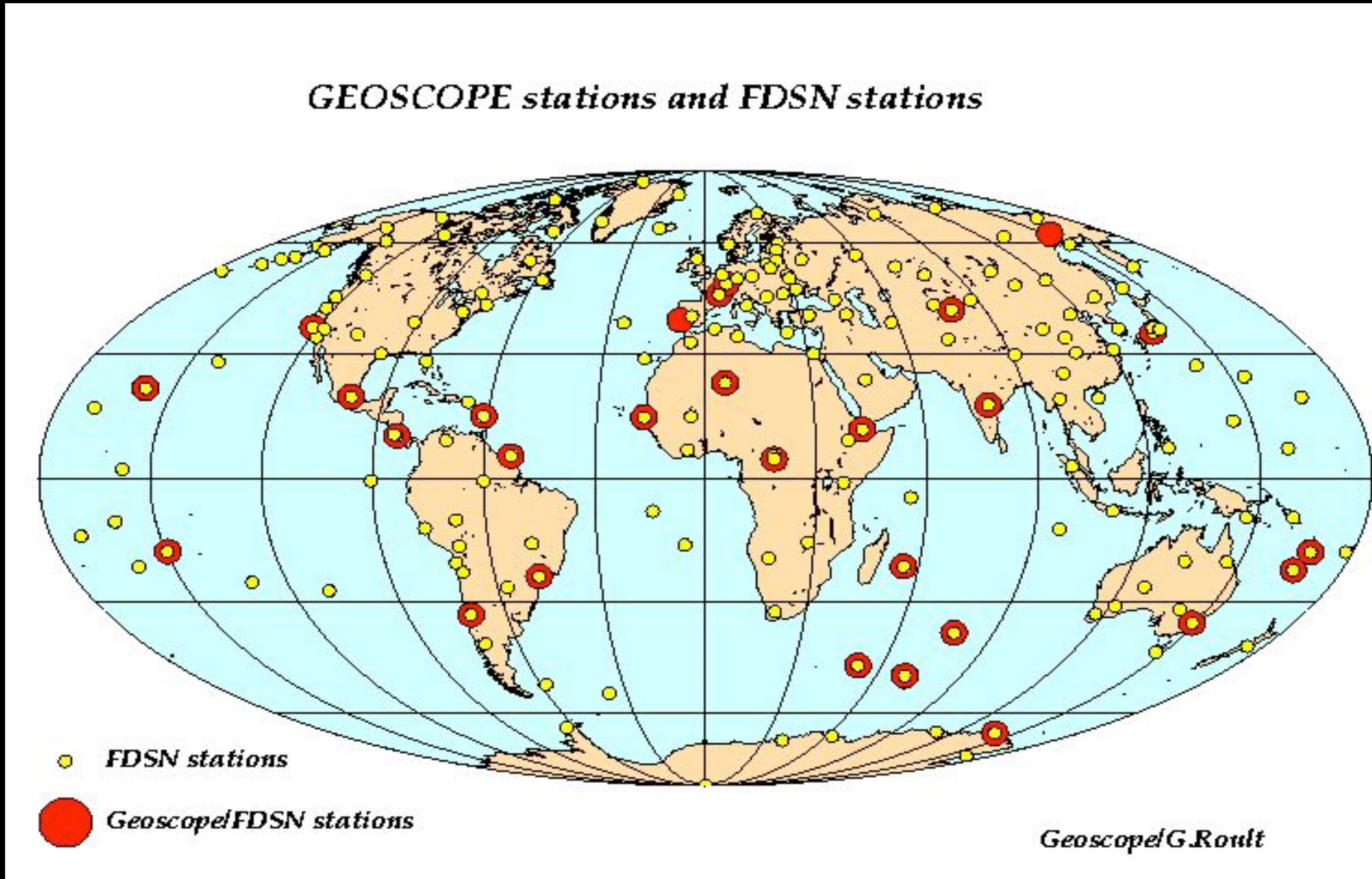
→ Good global coverage,

→ Large scale heterogeneities (min. 600 km).

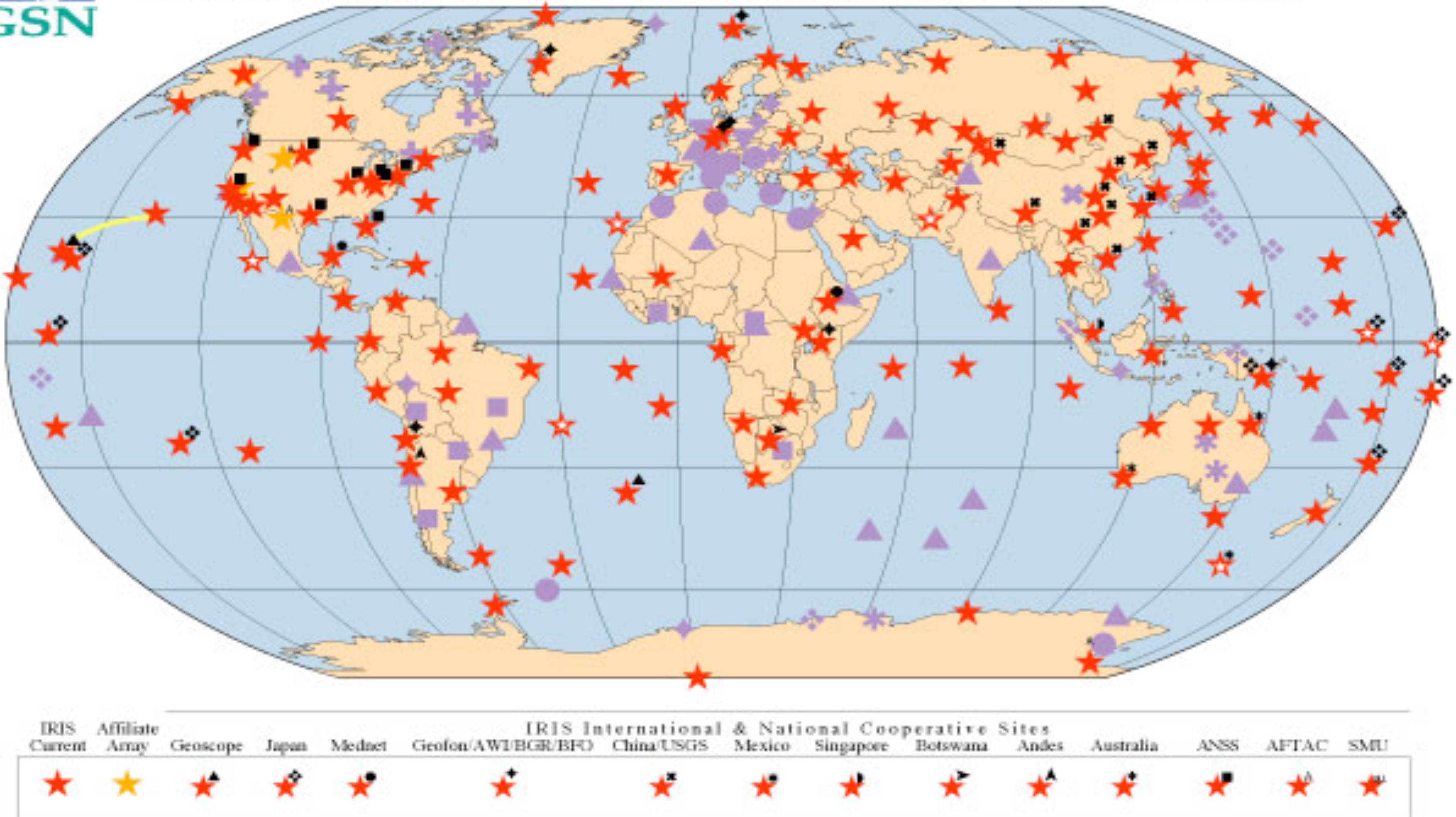


Vertical component of displacement field recorded at DRV station corresponding to the New-Guinea 05/16/1999 earthquake.

Global Networks



GLOBAL SEISMOGRAPHIC NETWORK
& FEDERATION OF DIGITAL BROADBAND SEISMIC NETWORKS



Ocean Bottom Observatories

=> International Ocean network (I.O.N.)

- 2/3 of the Earth are covered by water.
- seafloor seismometers enable:
  - To investigate oceanic regions with a better resolution
  - To fill gaps in the global coverage

NERO (joint French-Japanese Project)

IPGP

I.O.N.

International Ocean Network

ION (International Ocean network) France, Italy, Japan, UK, U.S.

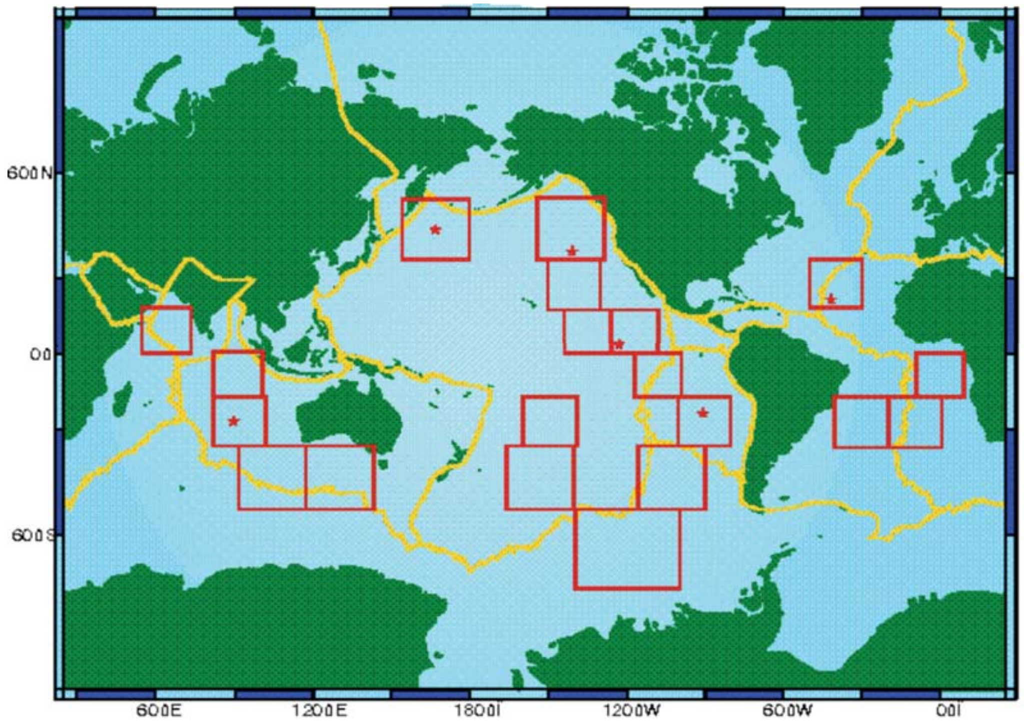
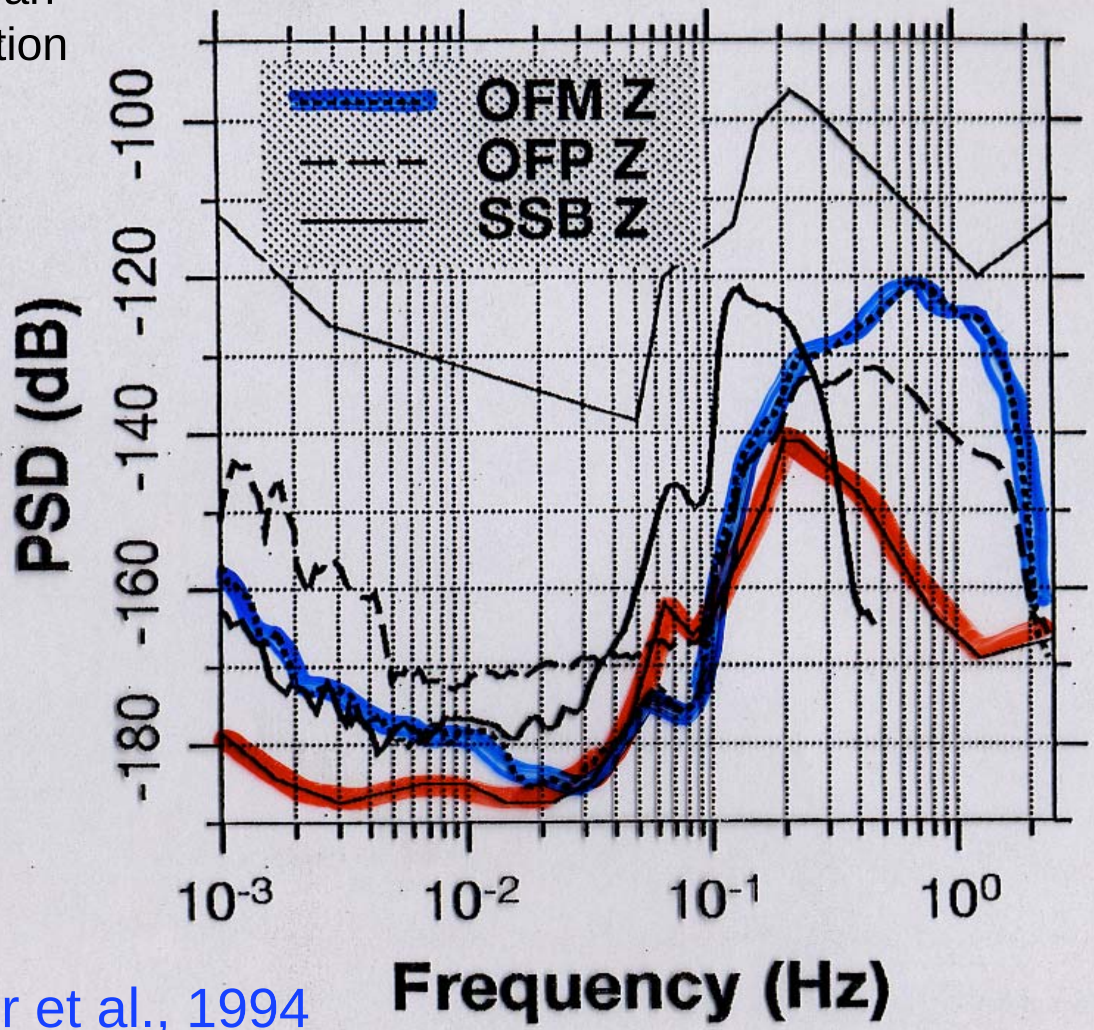


Figure 1: This map shows twenty regions which would require a seafloor seismic observatory in order to have 128 GSN stations evenly spaced around the globe (red boxes). The six starred boxes have been selected as preliminary test sites. The yellow lines mark plate boundaries.

OFM: Ocean bottom station



Montagner et al., 1994

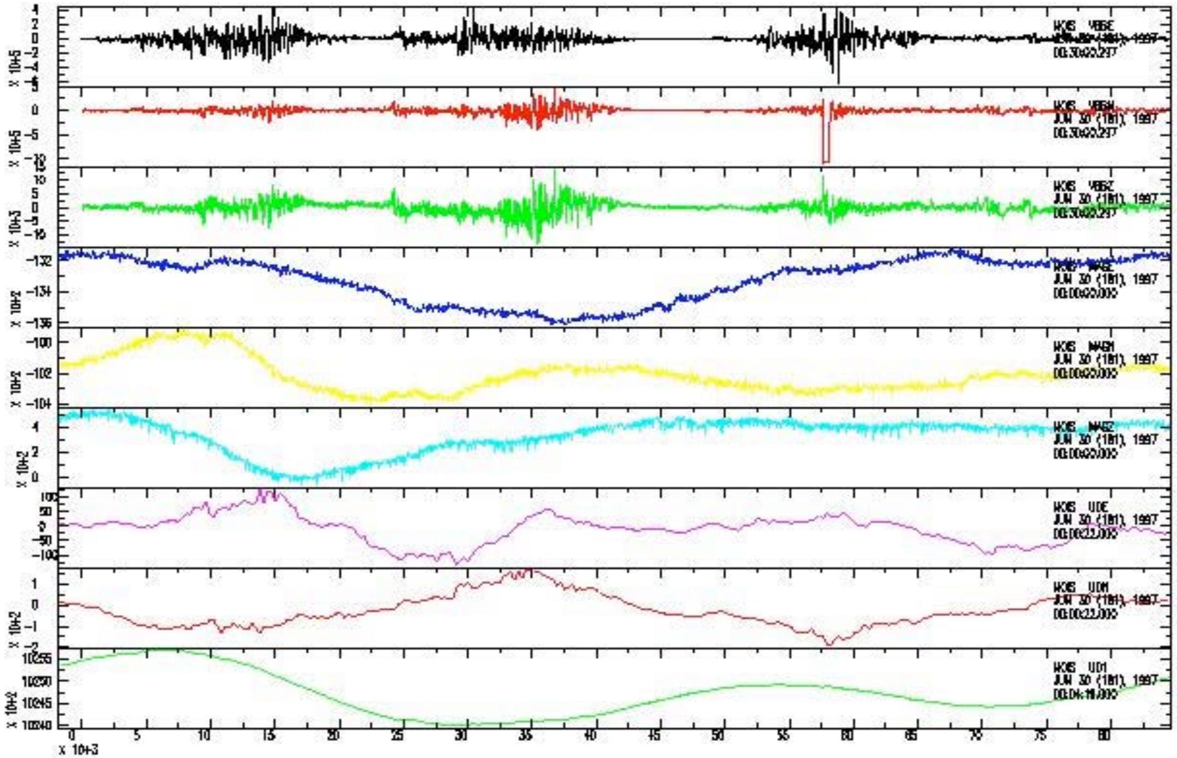
M.O.I.S.E (June-Sept. 1997)

(Monterey bay Ocean bottom International Experiment)

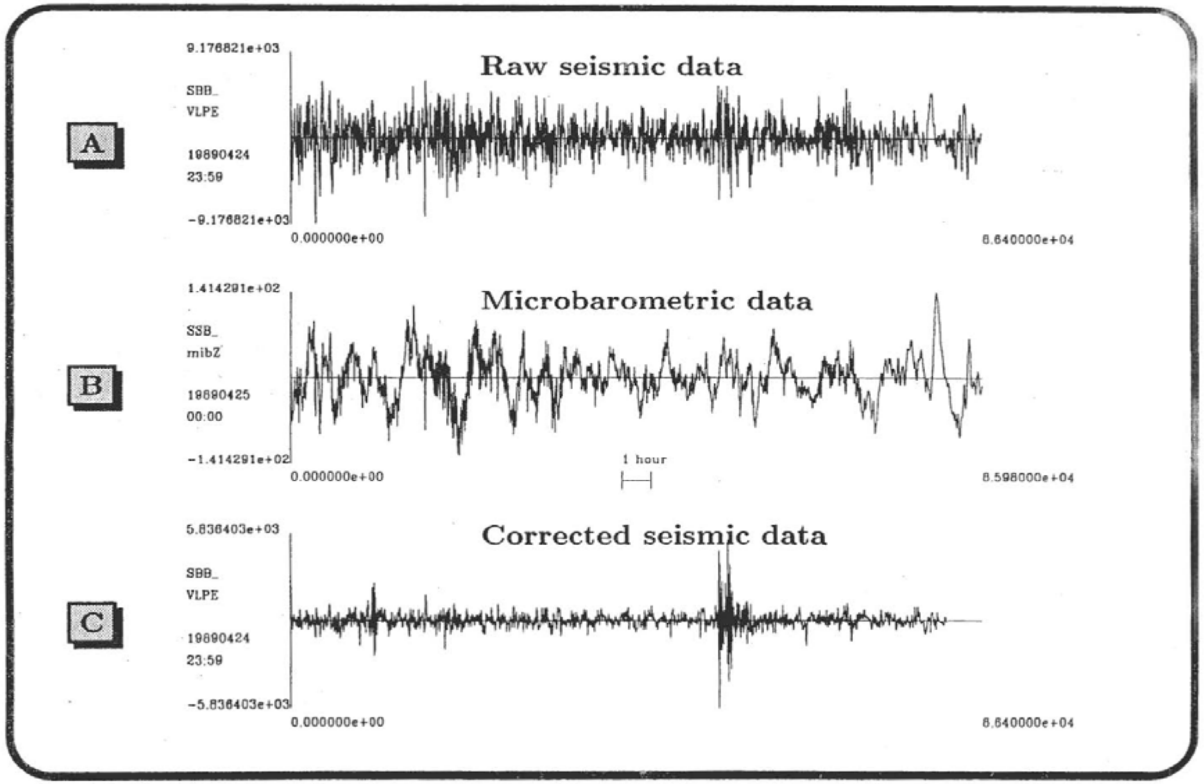
MBARI, UC Berkeley, IPG-Paris, UBO-Brest

iPGP
INSTITUT DE PHYSIQUE
DU GLOBE DE PARIS

Multiparameter signals



Deconvolution of the seismic signal from the pressure influence



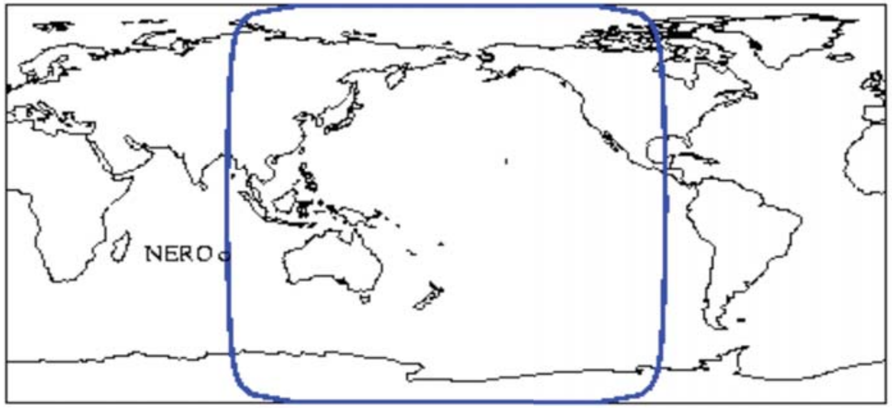
Beauduin et al.,1996

NERO:
Scientific Interest
Global scale

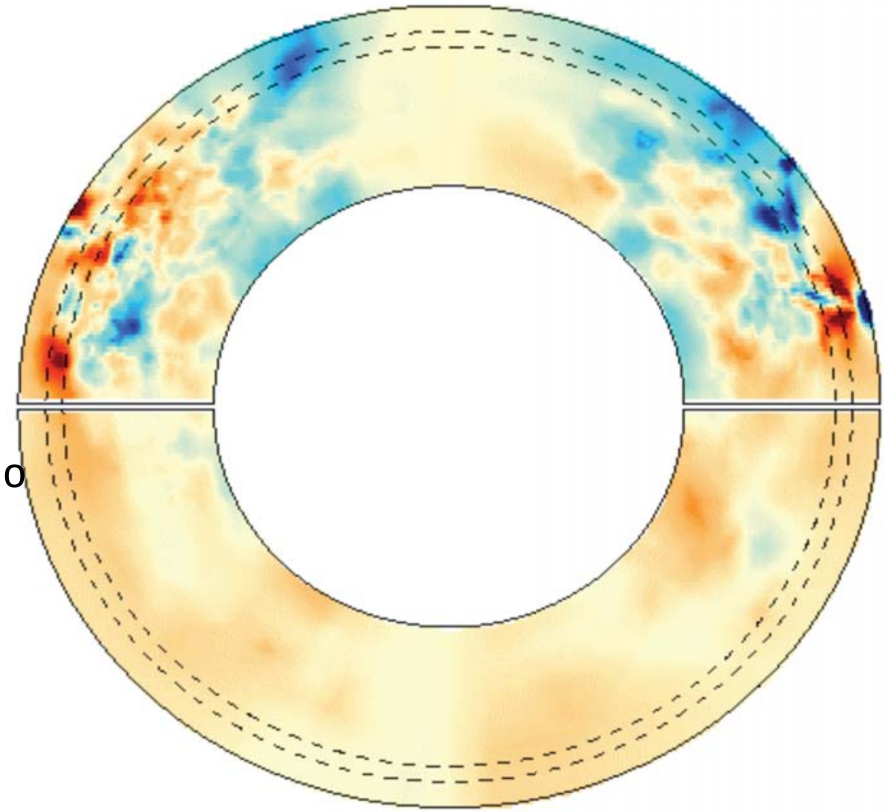
- To fill a gap in global station coverage

-To improve global tomographic model resolution

- To improve azimuthal distribution in determination of large earthquakes focal

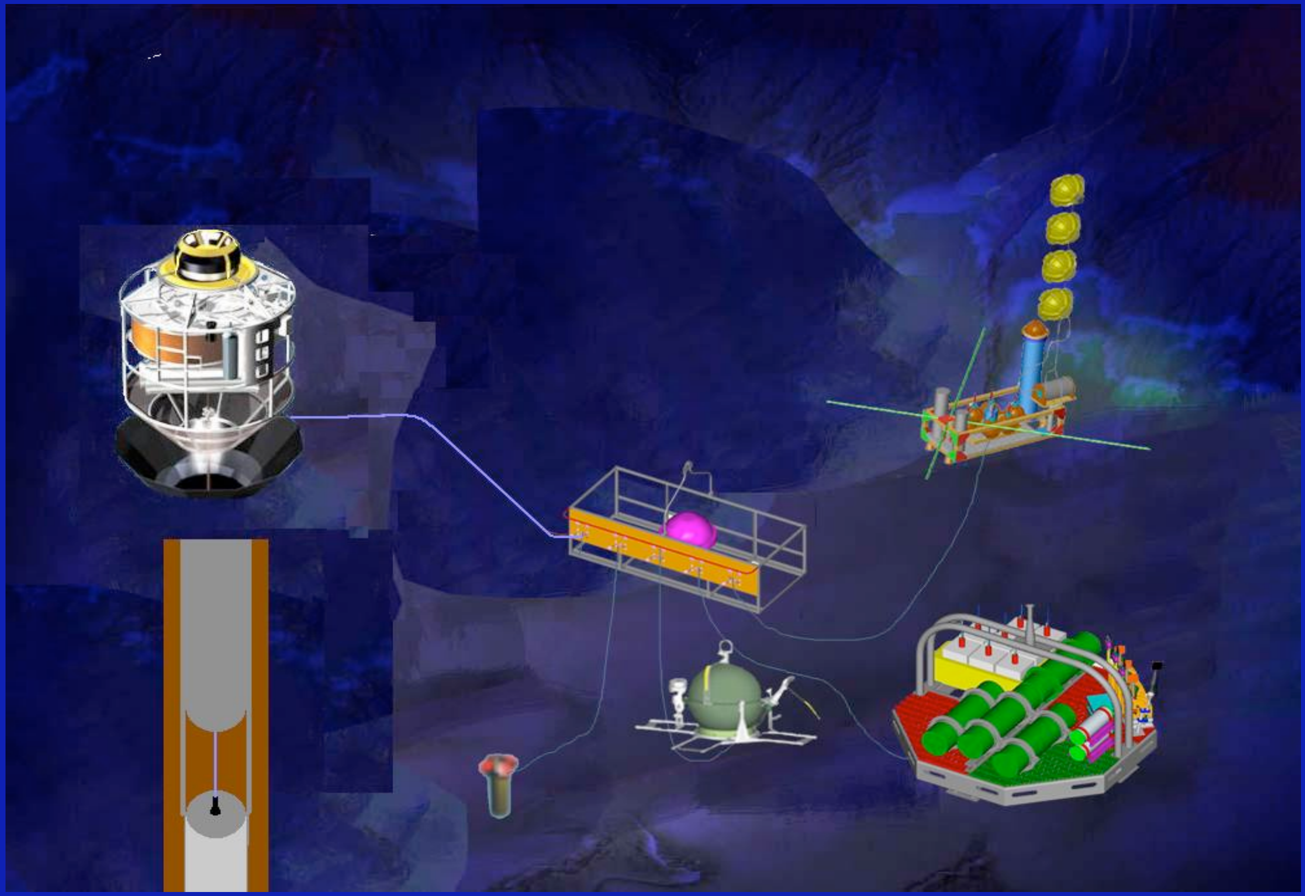


NERO o



Karason & van der Hilst, 2003

NERO observatory (in 2008)



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- Scientific Issues: earthquakes, structure of the Earth and planets
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- NM-SEM and time reversal

Hypothesis: Elastic Medium

$$s_{ij} = C_{ijkl}\, e_{kl}$$

Where e_{kl} **is the strain tensor,** s_{ij} **the stress tensor**

C_{ijkl} **the elastic tensor: 81 elastic moduli**

Symmetries of e_{kl}, s_{ij} **and of the strain energy**

W= 1/2 $\mathbf{S_{ij}}\, e_{ij}$ => 21 independent elements

Isotropic case:

$C_{ijkl} = l\ \ d_{ij}\, d_{kl} + m(d_{ik}\, d_{jl}\ + d_{il}\, d_{jk})$

l , mare Lamé parameters

Elastodynamic equation

$$\partial_j(C_{ijkl}\,\partial_k\, u_l) + \rho\,\omega^2\, u_i = 0$$

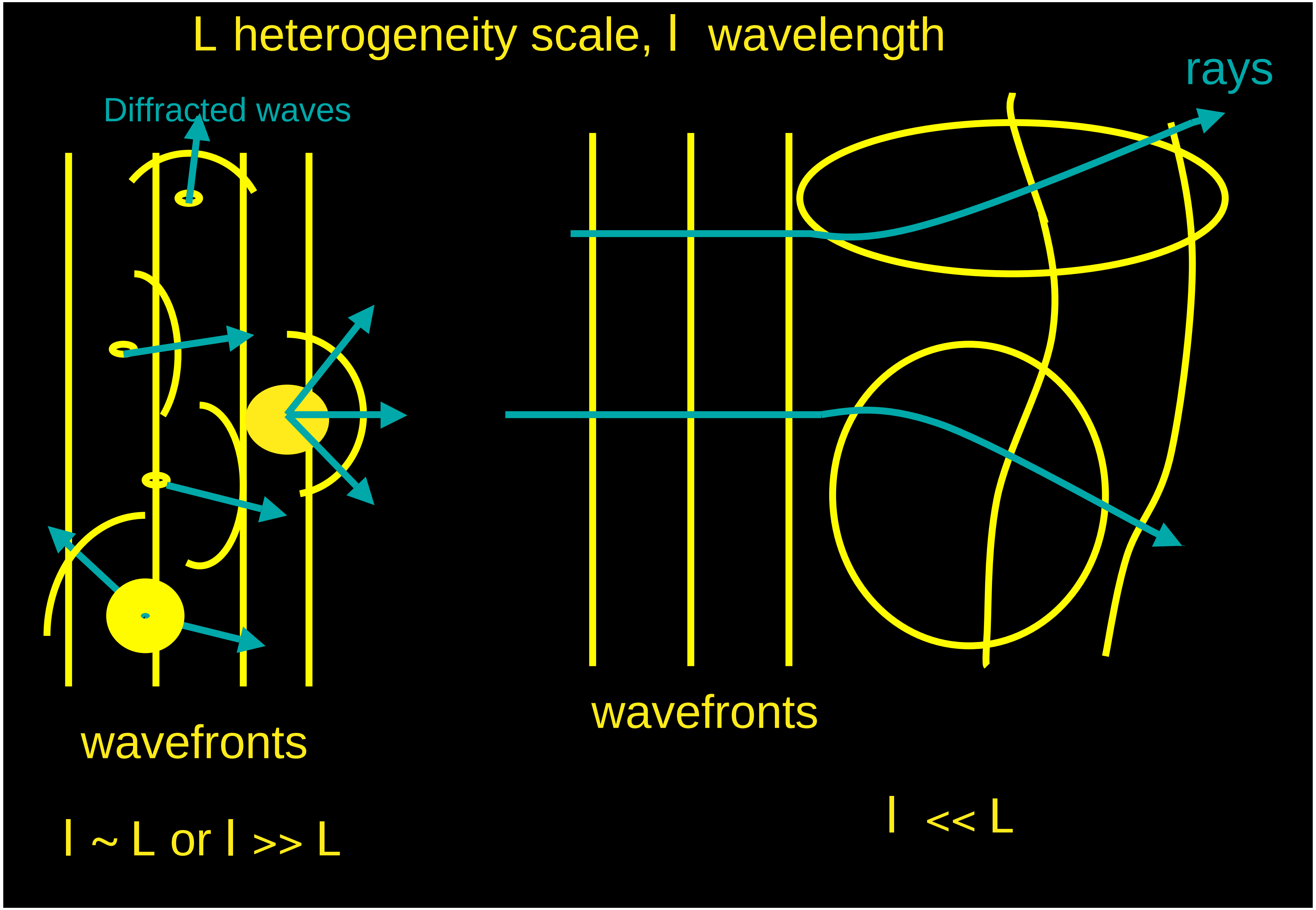
In the isotropic case, 2 solutions:

S-wave

P wave

In heterogeneous media, comparison between

Wavelength λ and scale of heterogeneity Λ


L heterogeneity scale, l wavelength
rays
Diffracted waves
wavefronts
wavefronts
l ~ L or l >> L
l << L

Duality wave - particle:

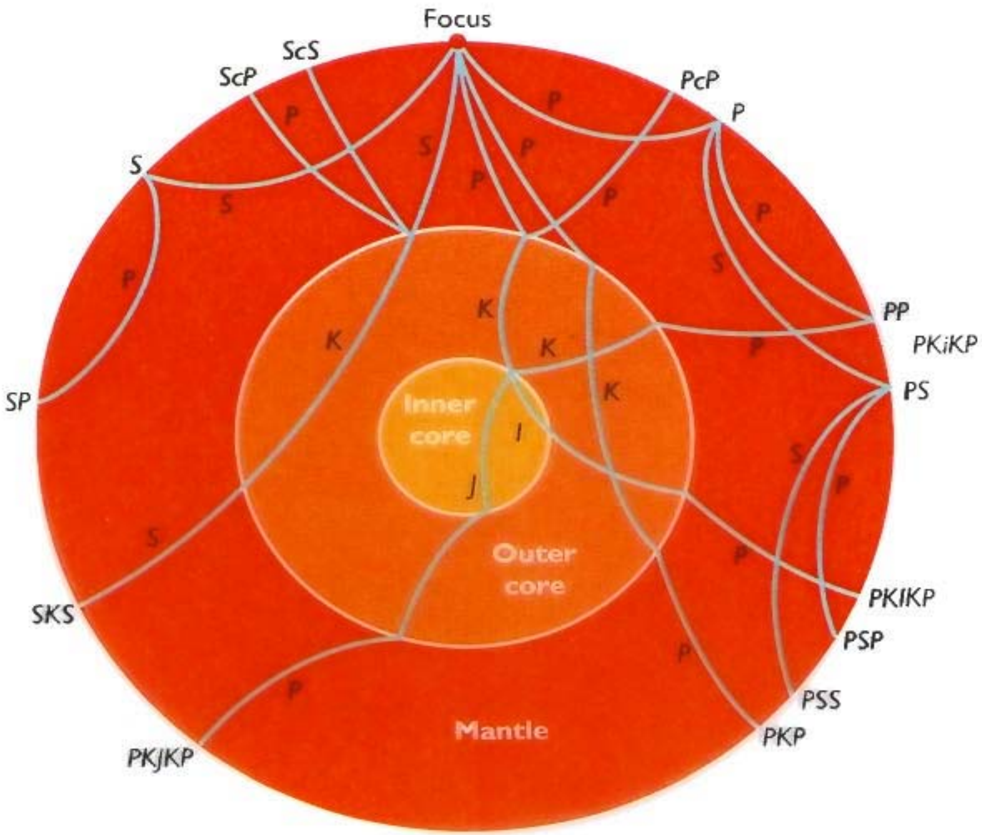
- l seismic wavelength
- L scale heterogeneity

- Particle: Ray theory (XXth century)

l << L

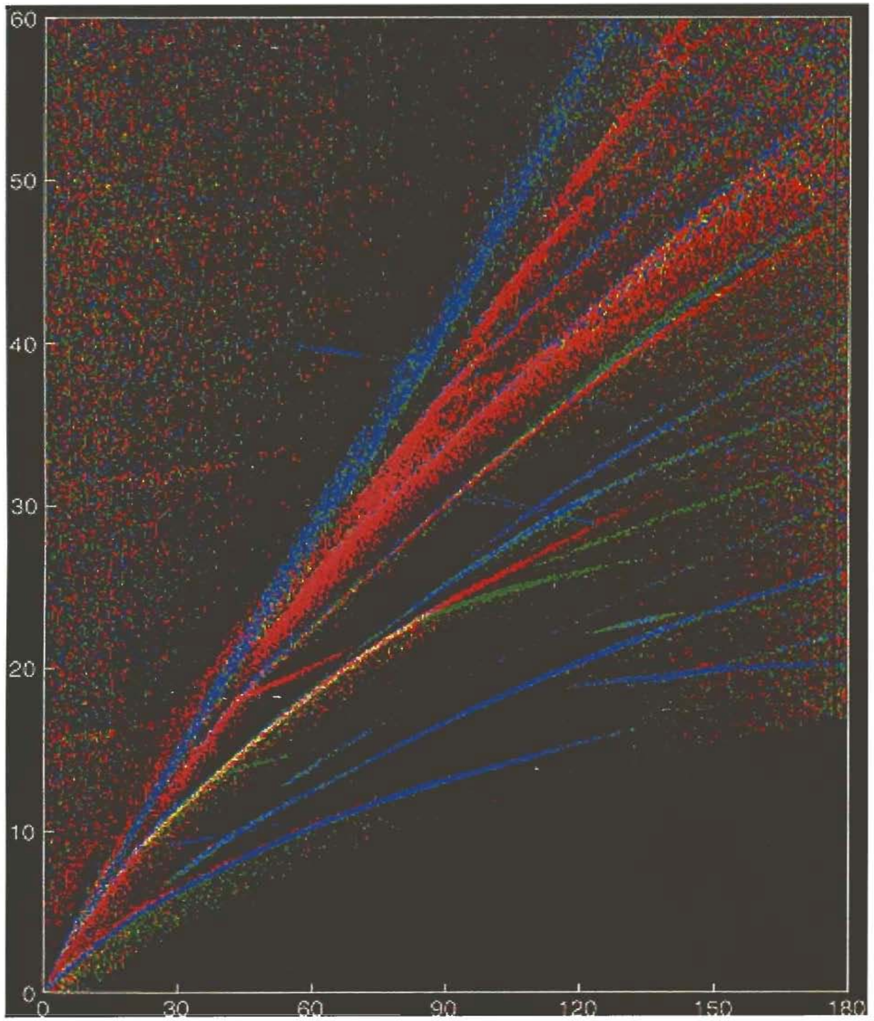
- Wave: Normal mode theory (>1970)

RAY PATHS INSIDE THE EARTH



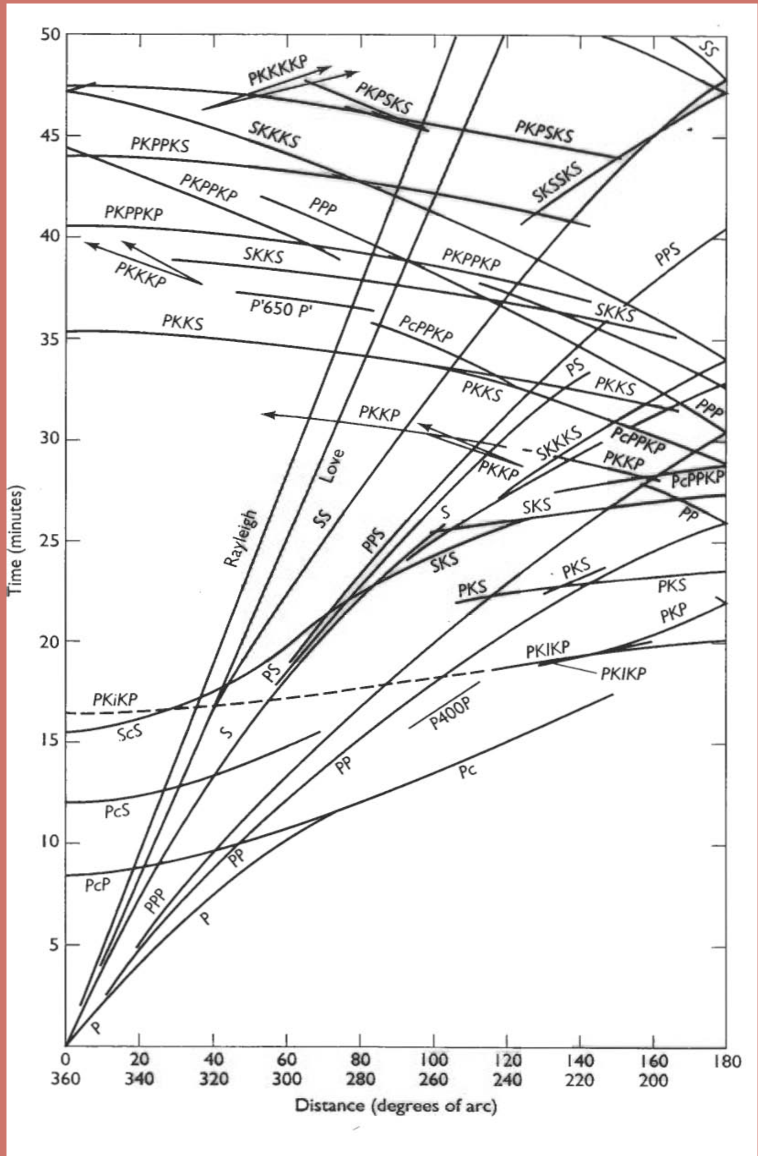
Bolt, 1993

Time



Epicentral distance

Shearer, 1997



Time (minutes)
Distance (degrees of arc)
0
20
40
60
80
100
120
140
160
180
360
340
320
300
280
260
240
220
200
5
10
15
20
25
30
35
40
45
50
PKKKKP
PKPSKS
PKPSKS
SKKKS
PKPPKS
SKSSKS
PKPPKP
PPP
PKPPKP
SKKS
PKPPKP
PKKKP
PPS
SKKS
P'650 P'
PcPPKP
PKKS
PKKS
PS
PKKS
PKKP
PPP
SKKKS
PcPPKP
PKKP
PKKP
PcPPKP
Love
SS
Rayleigh
PPS
S
SKS
PP
SKS
PKS
PKS
PKS
PKP
PS
PKIKP
PKIKP
PKiKP
ScS
S
P400P
PP
Pc
PcS
PP
PcP
PPP
P
P
SS

Duality wave - particle:

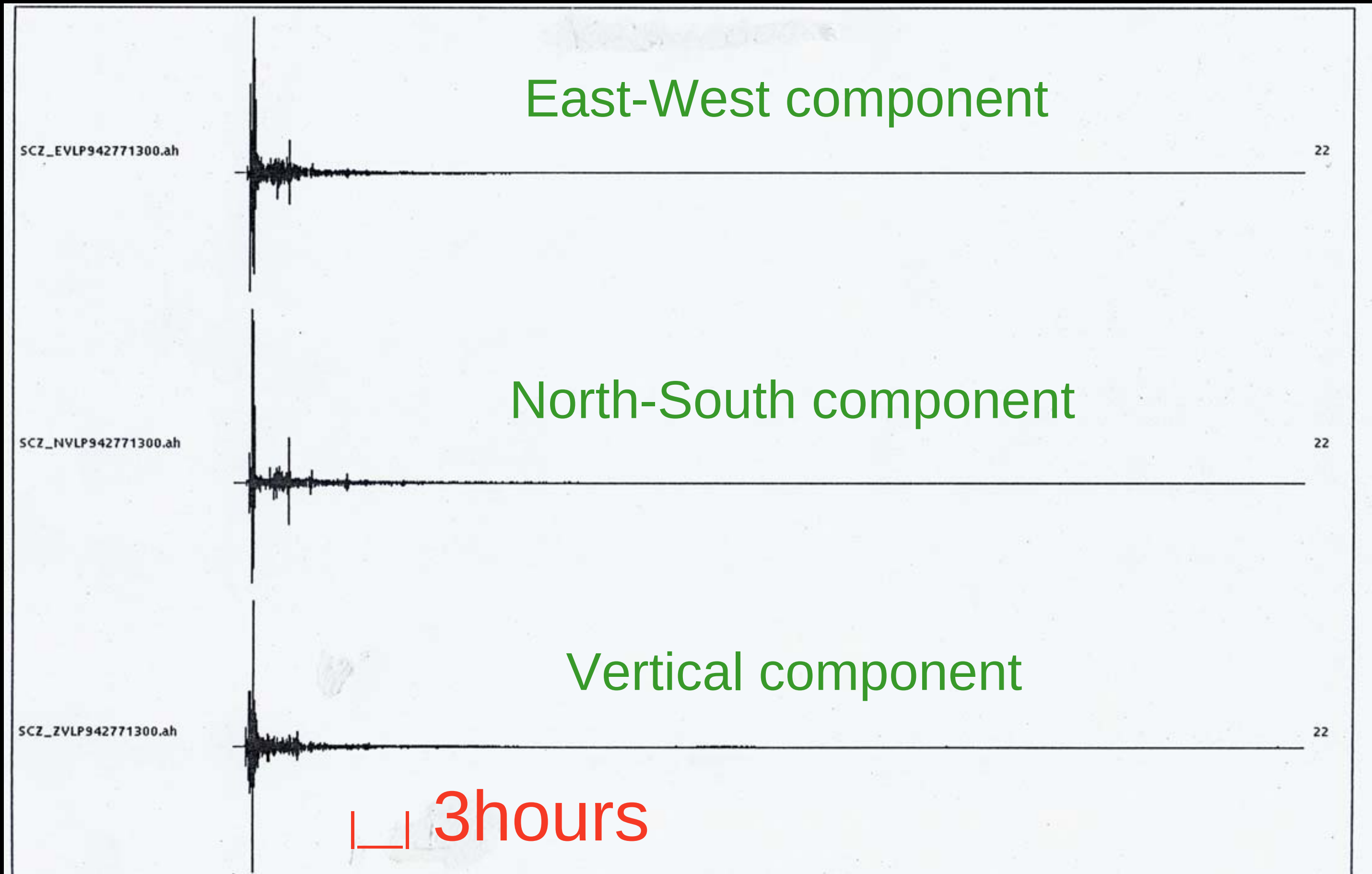
- l seismic wavelength
- L scale heterogeneity

- Particle: Ray theory (XXth century)

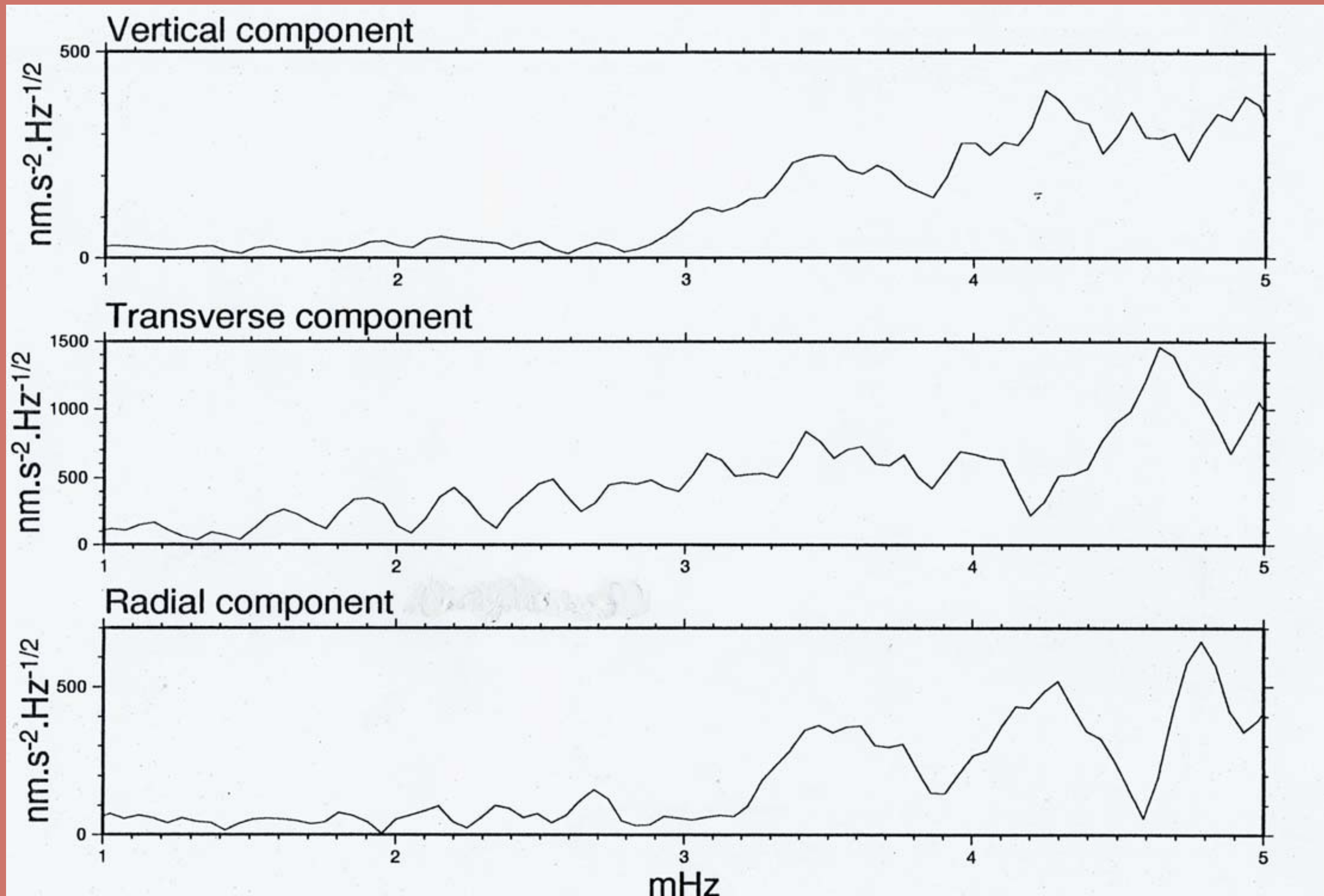
l << L

- Wave: Normal mode theory (>1970)

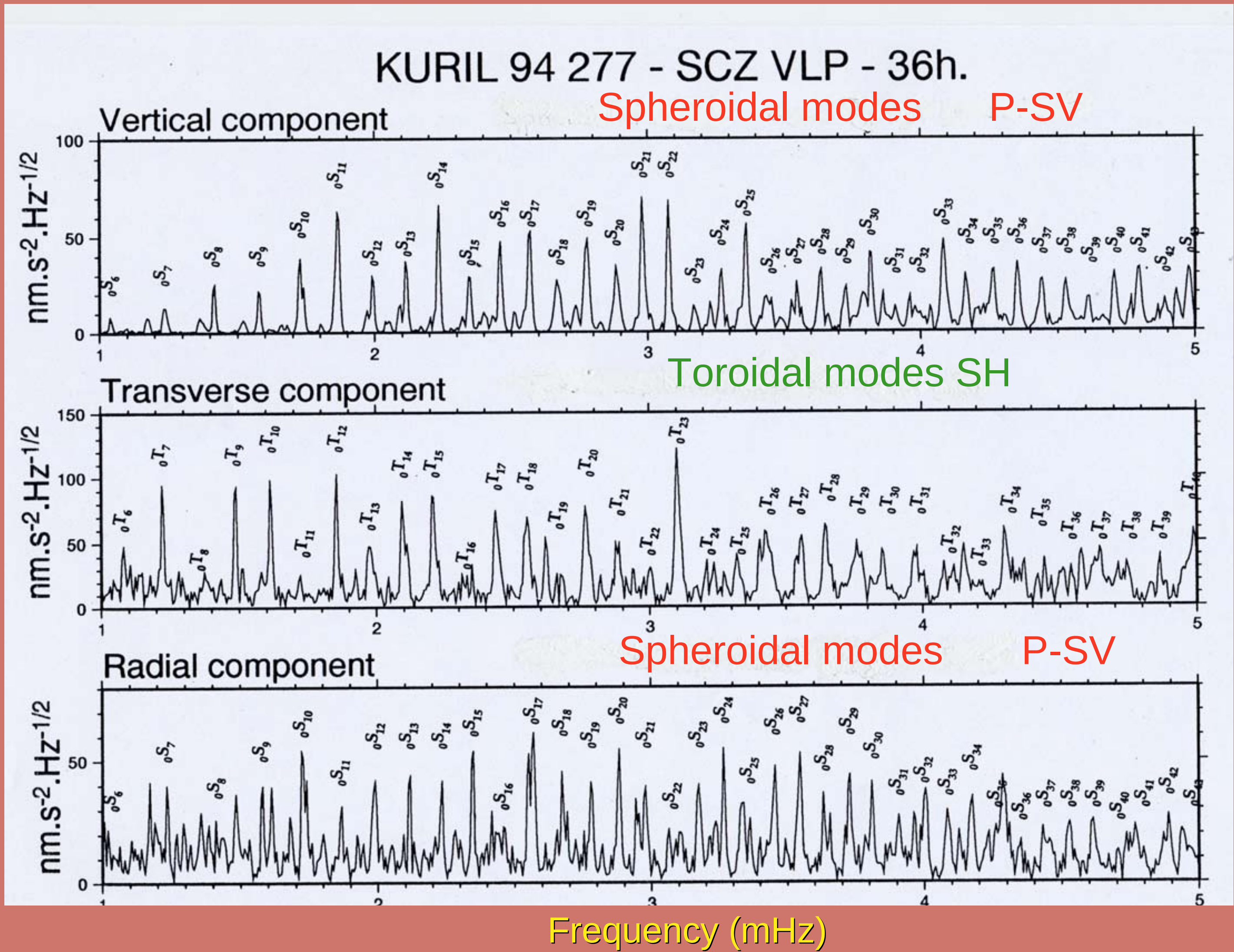
Kurils islands 1994-277 Ms=8.3



Kurils islands 1994-277 SCZ-VLP
Spectra 3 hours



Frequency (mHz)


KURIL 94 277 - SCZ VLP - 36h.
Vertical component
Spheroidal modes P-SV
Transverse component
Toroidal modes SH
Radial component
Spheroidal modes P-SV
nm.s-2.Hz-1/2
Frequency (mHz)

Elasto-dynamic equation

$r \leq_{tt} \mathbf{u}_{0i} = \leq_j \mathbf{s}_{\mathbf{ij}} + \mathbf{r}\ \mathbf{g_i} + \mathbf{F_i}\ \mathbf{(+\ Fs_i\ +\ldots)}$

Which can be rewritten:

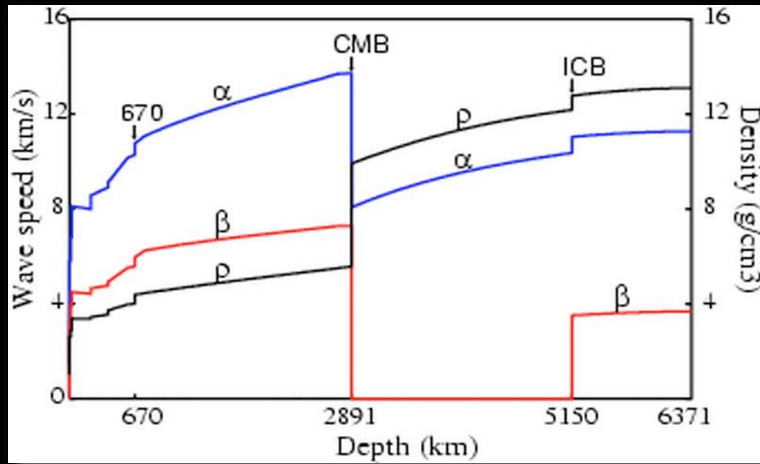
$r \leq_{tt} \mathbf{u}_0 = \mathbf{H_0 u_0}\ \ \mathbf{(+\ Fs)}$

H_0 is an integro-differential operator

1D-Reference Earth Model:

$M_0(r)$, r (r), $V_P(r)$, $V_s(r)$

(PREM, Dziewonski and Anderson, 1981
or IASP91, Kennett and Engdahl, 1991)



Eigenfrequencies: ${}_n w_l$

Eigenfunctions: ${}_n u_l^m$ (r,t)= |n,l,m>

$r \le_{tt} \mathbf{u}_0 = \mathbf{H_0 u_0}$ **(+ Fs)**

Eigenfrequencies: ${}_n w_l$

Eigenfunctions: ${}_n u_l^m\,(r,t) = |n,l,m>$

3 quantum numbers (k={n,l,m}) => $\mathbf{u}_k(r,t)$

$\le r\ \mathbf{u}_k^* \,.\, \mathbf{u}_k\ d^3x = d_{ij}$

$\mathbf{H_0}\,\mathbf{u}_k = r\ \ {}_n w_l^2\, \mathbf{u}_k$

Displacement:

$\mathbf{u}(\mathbf{r},t) = S_{n,l,m}\ \ {}_n\mathbf{a}_l^m\ |n,l,m> \exp(-i_n w_l t)$

$\mathbf{u}_k(r,t) = \{U(\,r\,)\,\mathbf{e}_r + V(r\,)\mathbf{e}_q \le_q + V(r\,)/\sin q\ \mathbf{e}_f \le_f\}\ Y_l^m\,(q,f\,)$

$\qquad + \{W(r\,)\,\mathbf{e}_q \le_f - W(r\,)\,\mathbf{e}_f \le_q\}\ Y_l^m\,(q,f\,)$

Spheroidal Modes

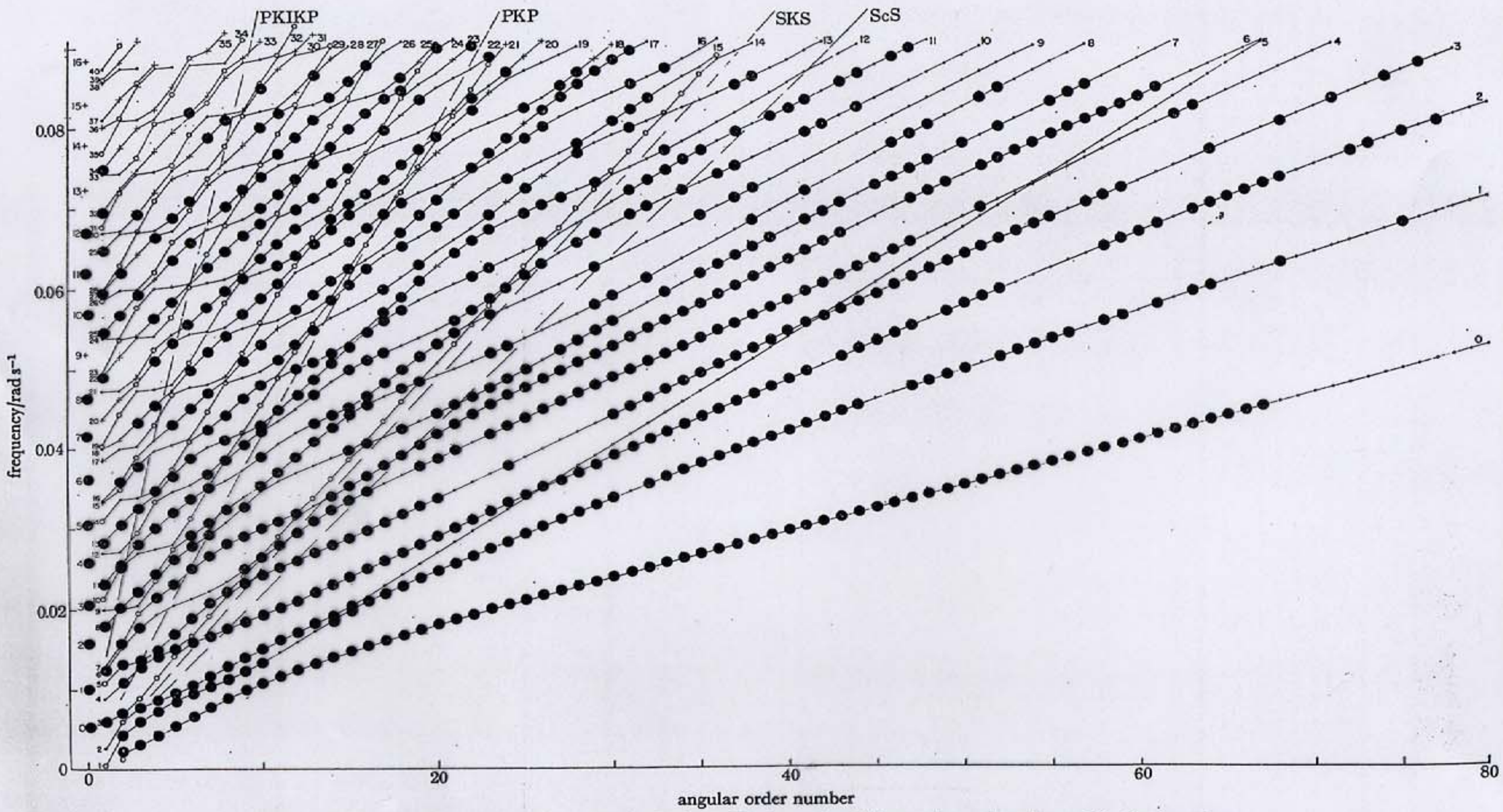


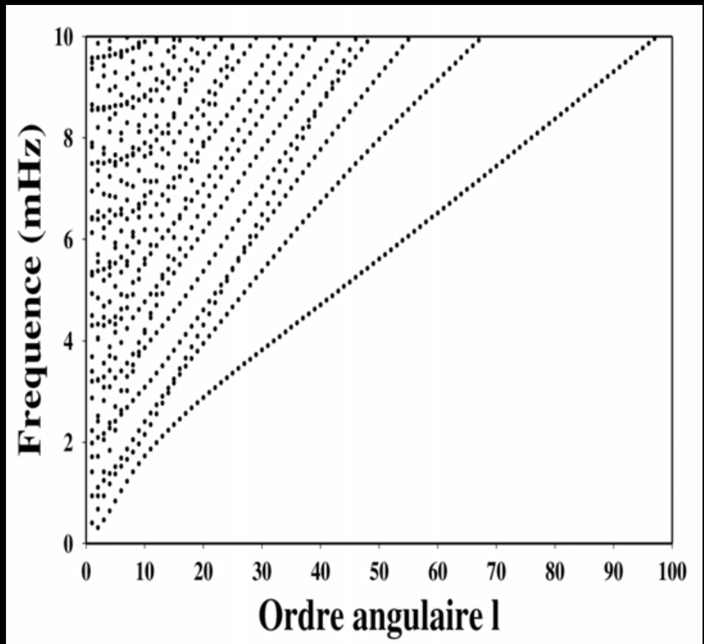
FIGURE 17. Spheroidal normal modes in the (ω, l) plane. The large dots indicate observed modes used in the inversions. For further details we refer the reader to §3 of Alaska II. •, $CE < 0.5$; +, $CE \geqslant 0.5$; ∘ core modes.

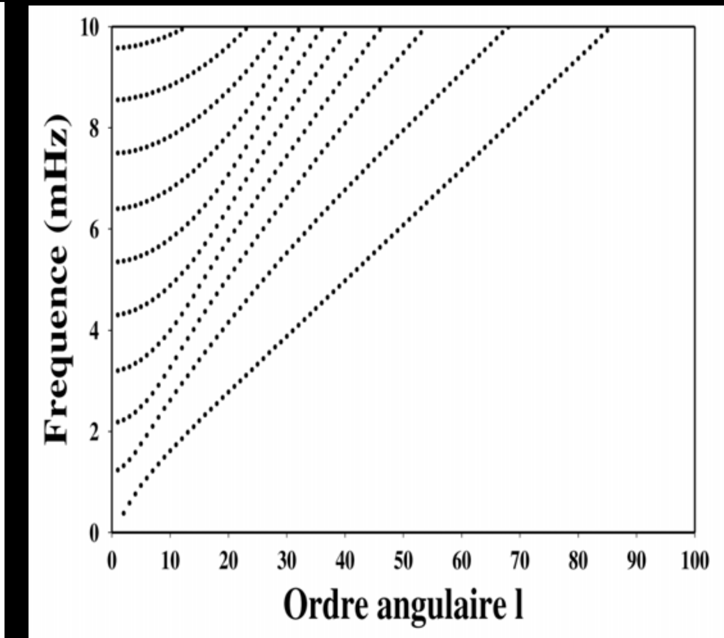
Spherical eigenfrequencies

Spheroïdal Modes $_nS_l$
(P-SV / Rayleigh)

Toroïdal modes $_nT_l$
(SH / Love)

Dispersion Branches

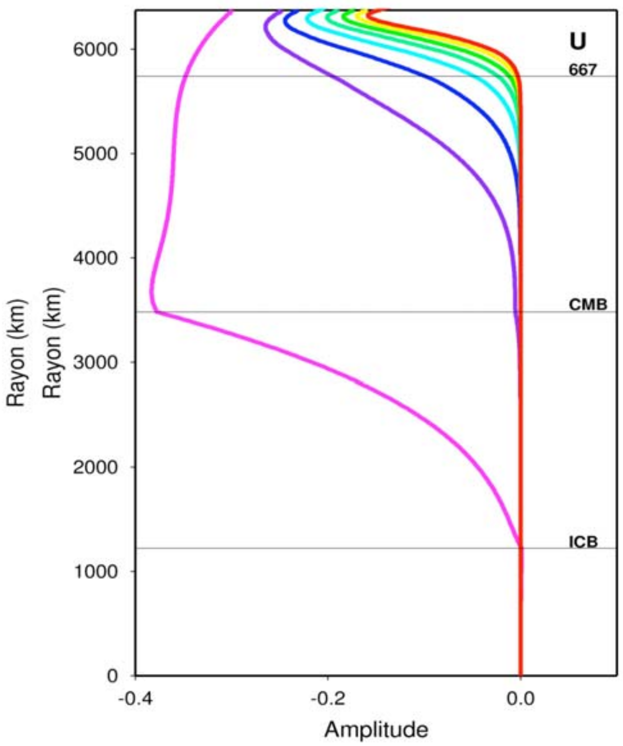




multiplet : (n,l) = 2l+1 singlets
singlet : (n,l,m)

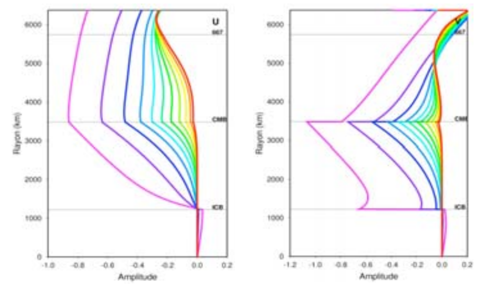
n : radial order
l : angular order
m : azimuthal order

Spherical eigenfunctions

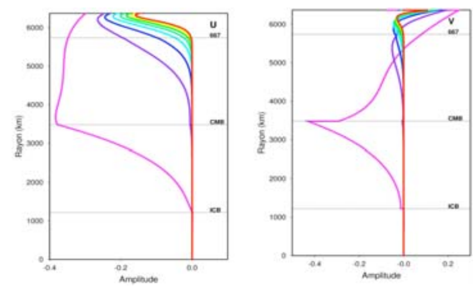


$_0$S branch

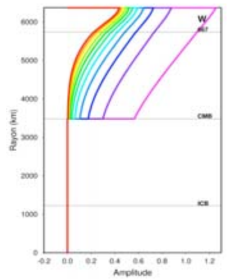
l= 2,3,4,5,6,7,8,9,10,11,12

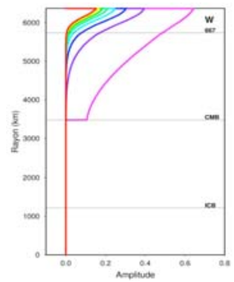


l= 5,15,25,35,45,55,65,75



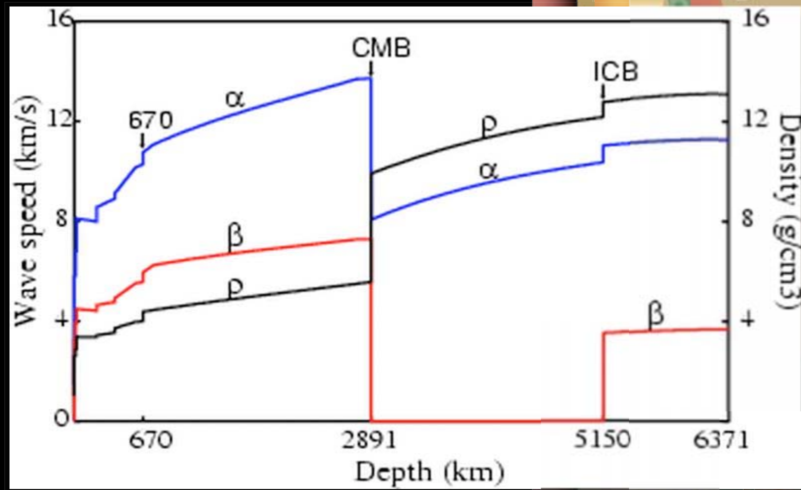
$_0$T branch





1D- Reference Earth Model

- Normal mode calculation (**eigenfrequencies** ${}_{n}\omega_{k}$ **eigenfunctions** ${}_{n}u_{l}(r,t)$)
- Synthetic Seismograms by normal mode summation ($k=\{n,l,m\}$).

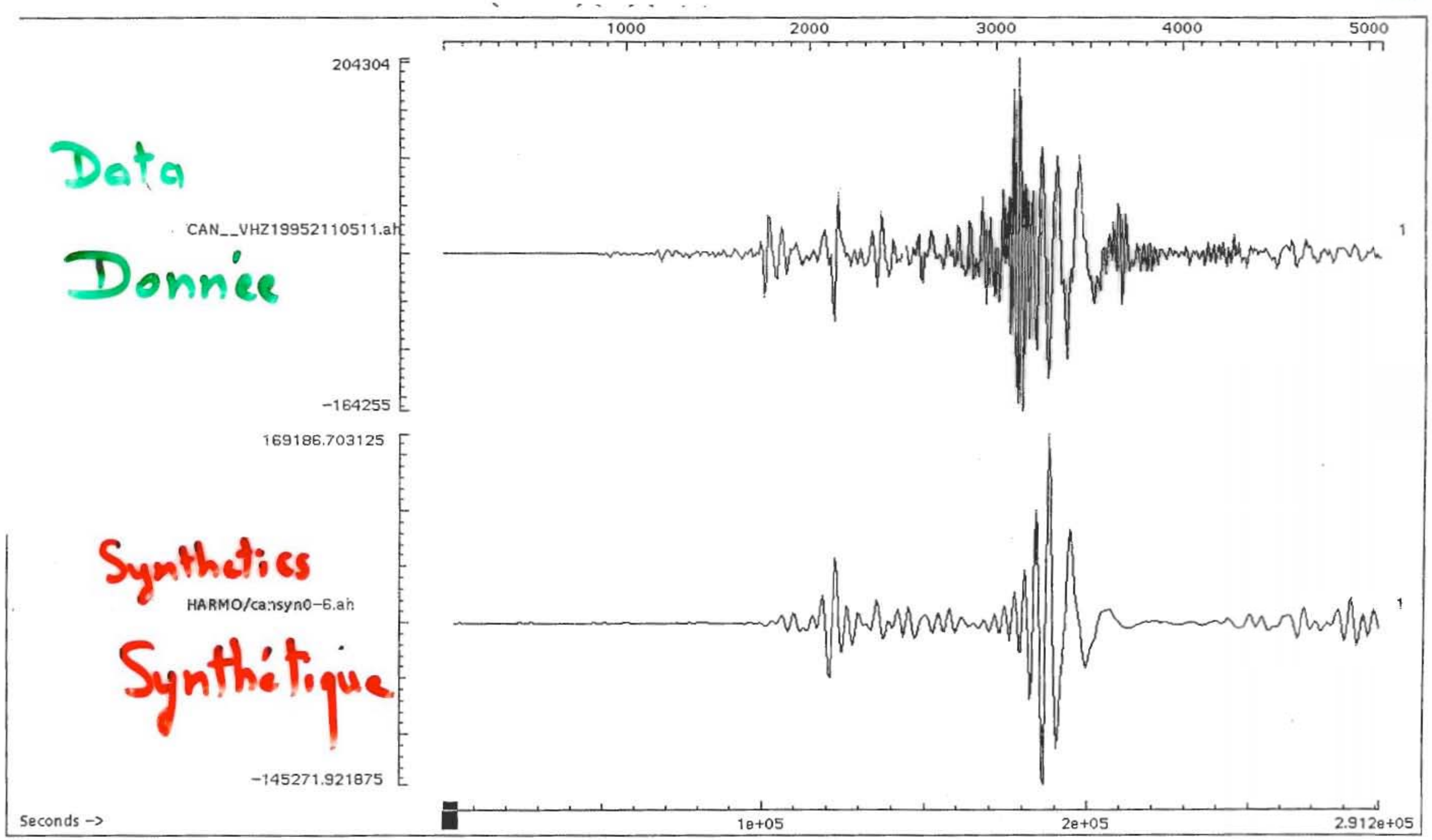


$\mathbf{u}(\mathbf{r},t)$ Displacement at point $\mathbf{r}$ at time t due to a force system $\mathbf{F}$ at point source $\mathbf{r}_s$

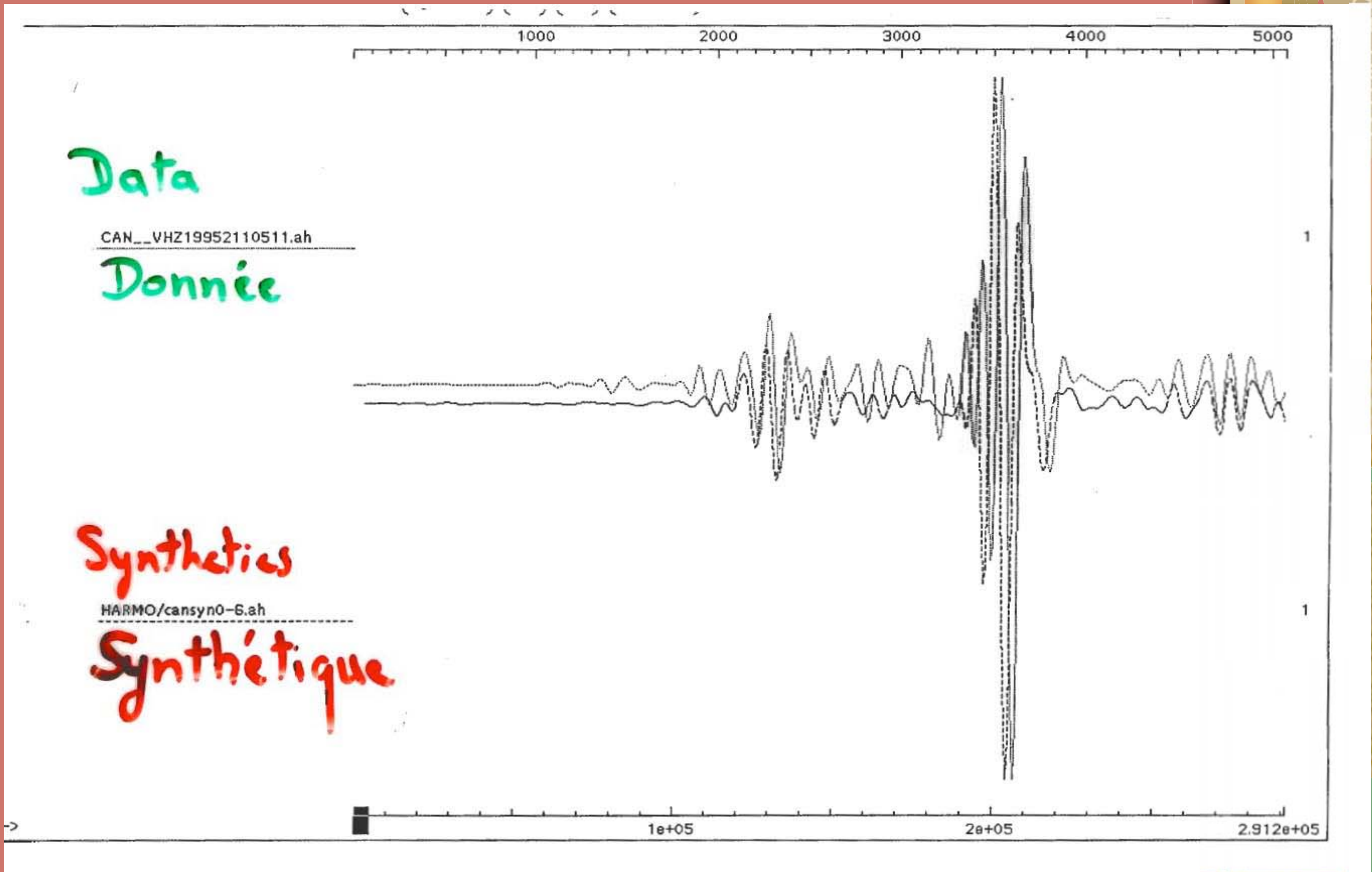
$$\mathbf{u}(\mathbf{r},t) = \Sigma_k\, u_k(r) \cos \omega_k t / \omega_k^2 \exp(-\omega_k t/2Q)\, (\mathbf{u}_k.\mathbf{F})_s$$

Source Term $(\mathbf{u}_k.\mathbf{F})_s = (\mathbf{M}:\mathbf{e})_s$

M Seismic moment tensor, **e** deformation tensor



1000
2000
3000
4000
5000
204304
Data
CAN__VHZ19952110511.ah
Donnée
1
-164255
169186.703125
Synthetics
HARMO/cansyn0-6.ah
Synthétique
1
-145271.921875
Seconds ->
1e+05
2e+05
2.912e+05



Data
CAN__VHZ19952110511.ah
Donnée
Synthetics
HARMO/cansyn0-6.ah
Synthétique
1000
2000
3000
4000
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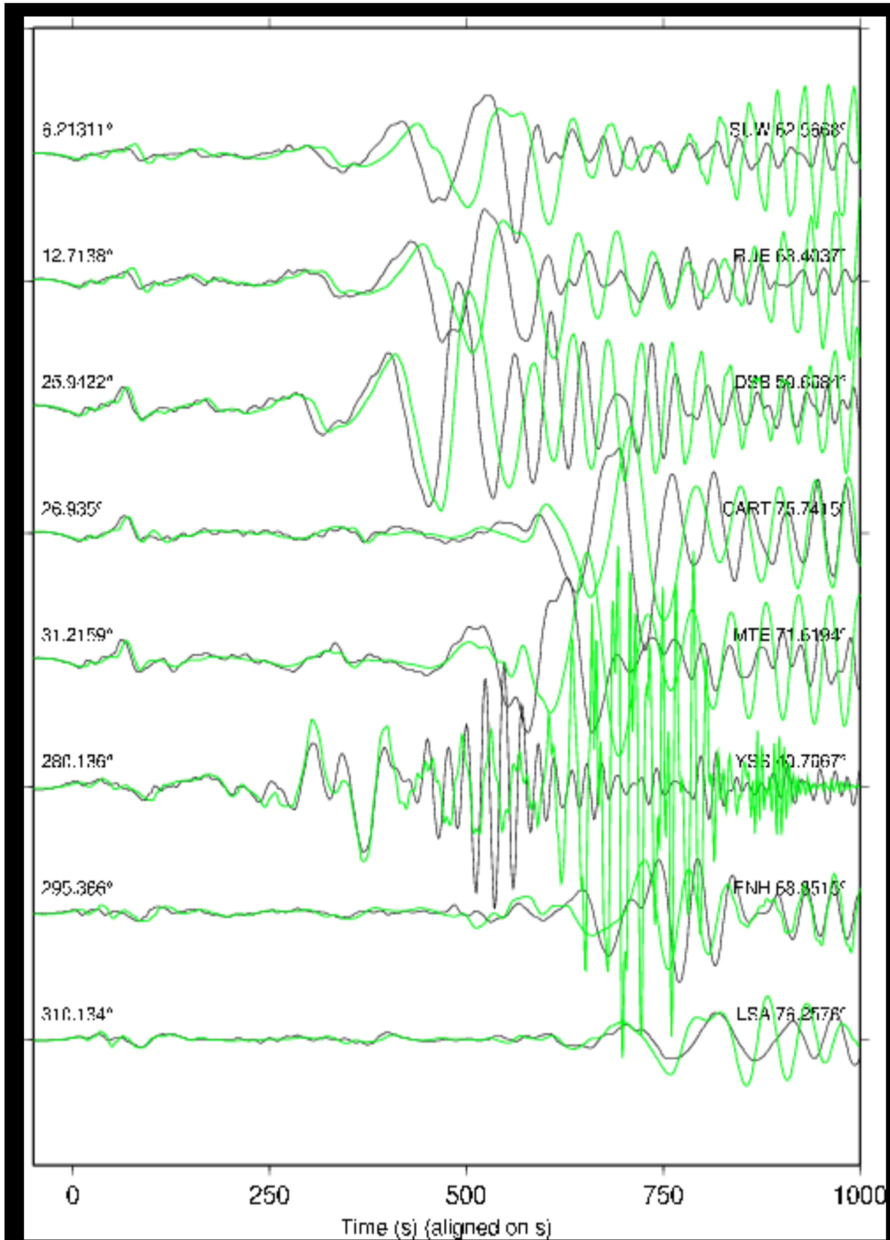
1e+05
2e+05
2.912e+05



Synthetic seismograms
By normal mode
summation

Denali-Alaska earthquake
(Nov. 2002)

Komatitsch and Tromp, 2003

Eigenfunction basis is a complete basis => any wave can be modelled by normal mode summation including surface waves and body waves.

Asymptotic form of $Y_l^m(q,f)$:

$Y_l^m(q,f)$: $= p^{-1} (\sin q)^{1/2} \cos[(l+1/2)q + 1/2\, mp - 1/4\, p]\, e^{imf}$

For a source at the pole, q plays the role of epicentral distance.

The horizontal wavenumber k is: $k=(l + 1/2)/a$

And phase velocity is $c(w) = {}^{w}/_{k}$

Ray parameter $p = a \sin i / V$ <=> horizontal slowness

$$p = a\, {}^{k}/_{w} = =(l + 1/2) / w$$

Duality wave - particle:

l seismic wavelength

L scale heterogeneity

Particle: Ray theory $l << L$

Wave: Normal mode theory (NM) +
Perturbation theories (small amplitude of 3D-heterogeneities) -> Global tomography

Numerical modelling of wave equation

Strong or weak forms: $l \leq L$

-Spectral Element Method (SEM)

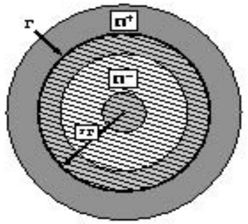
-Coupled SEM-NM method

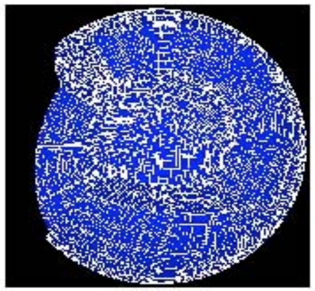
Spectral Element Method: D. Komatitsch (1999)

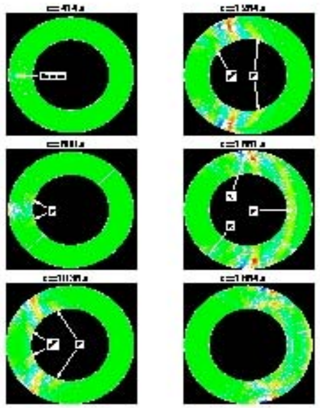
Coupled method of Spectral Elements and Modal Solution

Principle:

- Ω^+: Spectral Element area: 3D model
- Ω^-: Modal Solution area: 1D model







Capdeville et al., 2002

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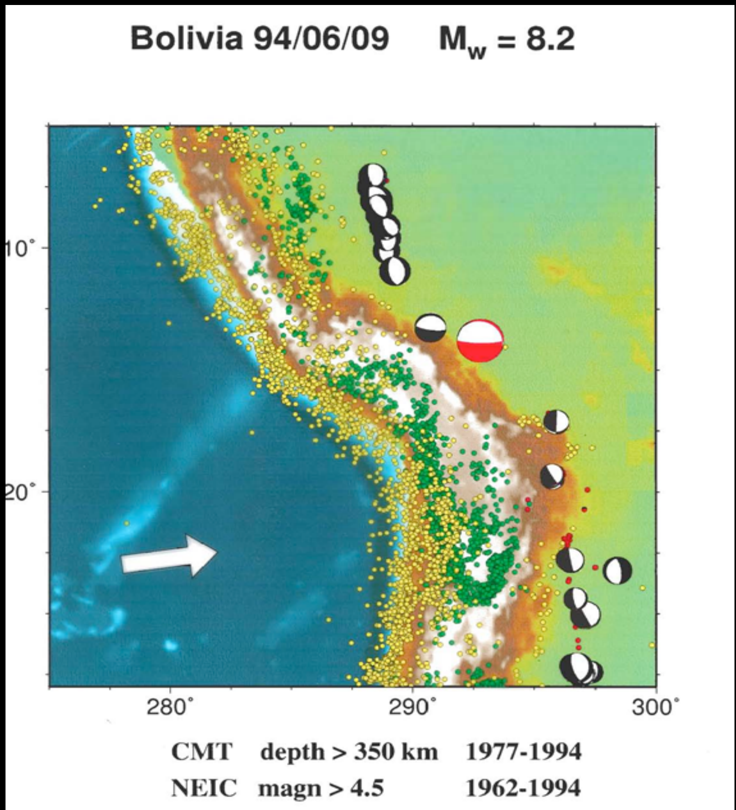
- Historical evolution: Ray theory, Normal mode theory, Numerical techniques (SEM, NM-SEM)
- Scientific Issues: earthquakes, structure of the Earth and planets
- Seismic Experiment: Plume detection
- NM-SEM and time reversal

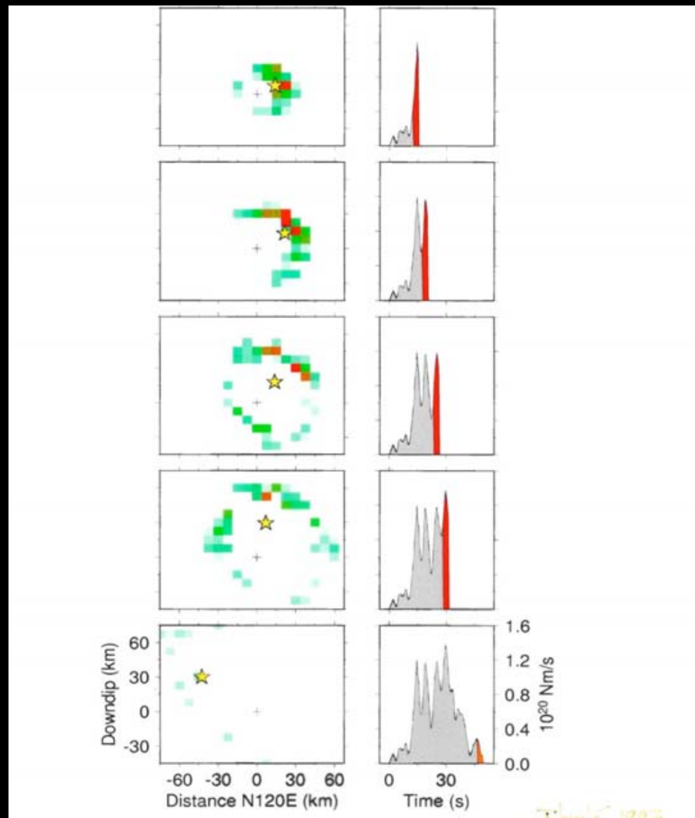
Seismic Source Studies

$\mathbf{u}(\mathbf{r},t) = S_k\ u_k\ (\ r\ )\cos w_k t\ / w_k^{\,2}\ \exp(-w_k t/2Q)\ (\mathbf{u}_k.\mathbf{F})_S$

Source Term $(\mathbf{u}_k\,.\mathbf{F})_S = (\mathbf{M}:\mathbf{e})_S$

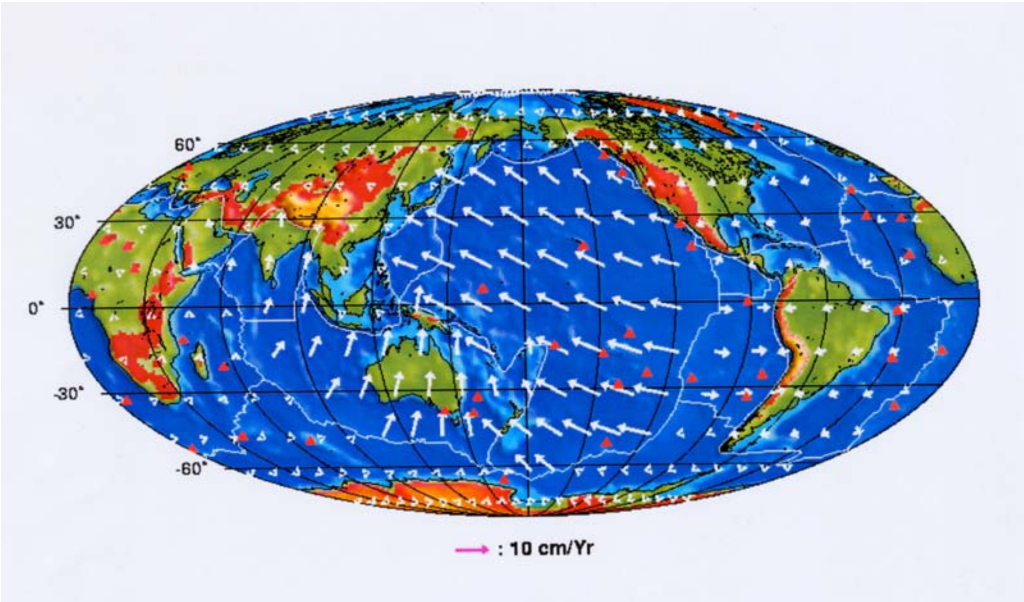
M Seismic moment tensor, **e** deformation tensor



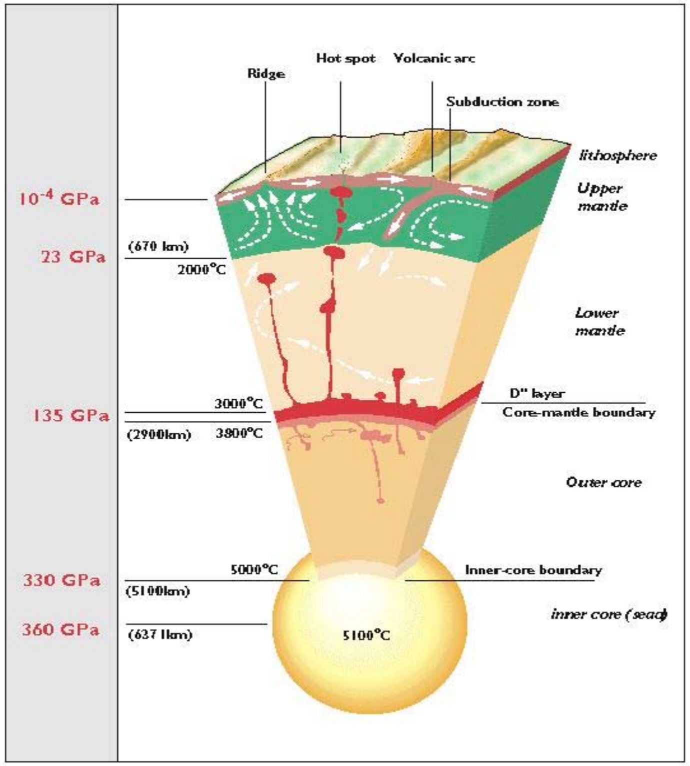


Structure of the Earth

Plate tectonics



Mantle Convection



Tomographic Technique

- Forward Problem: Theory **d**=**g**(**p**)

d data space, **p** parameter space

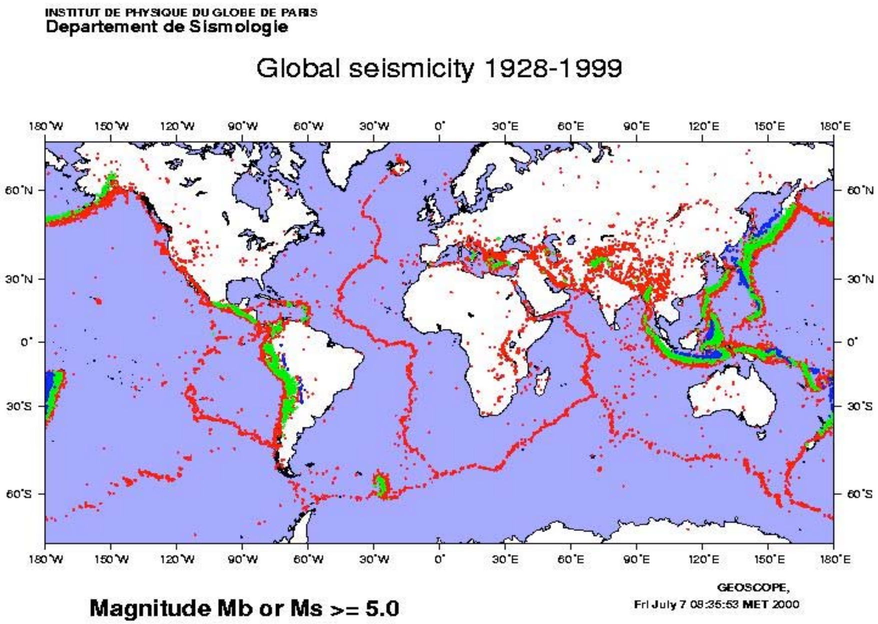
- Reference Earth model p_0:

$d_0 = g(p_0)$

- Kernels ≤g/≤p
- Cd function (or matrix) of covariance of data

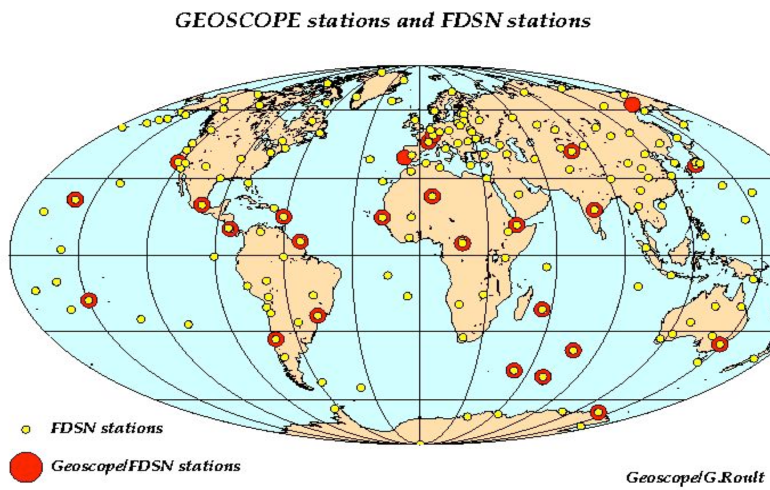
- Inverse Problem: $p-p_0 = \underline{g}^{-1} (d-d_0)$

- C_{p0} a priori Covariance function of parameters
- C_{pf} a posteriori Covariance function of parameters
- R Resolution



Receivers

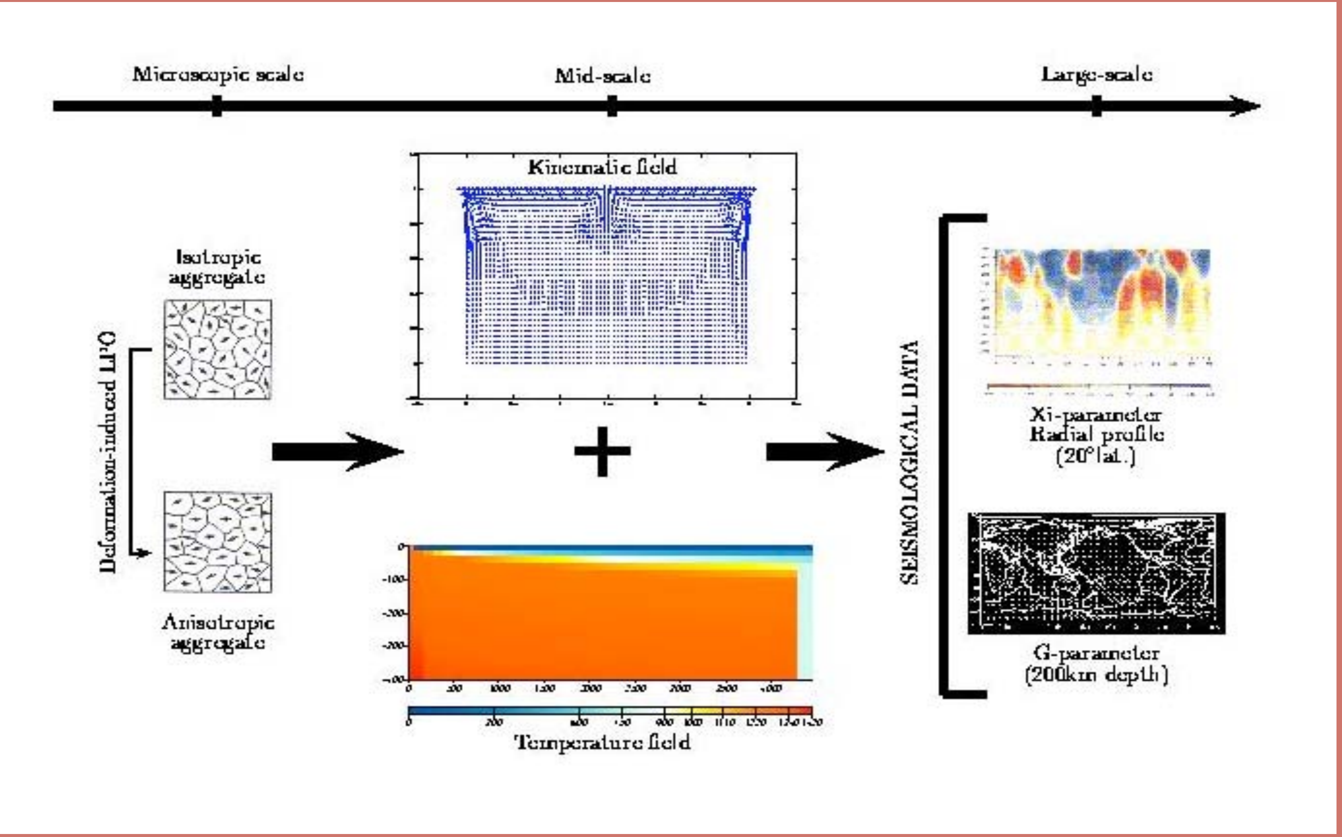
Seismic sources



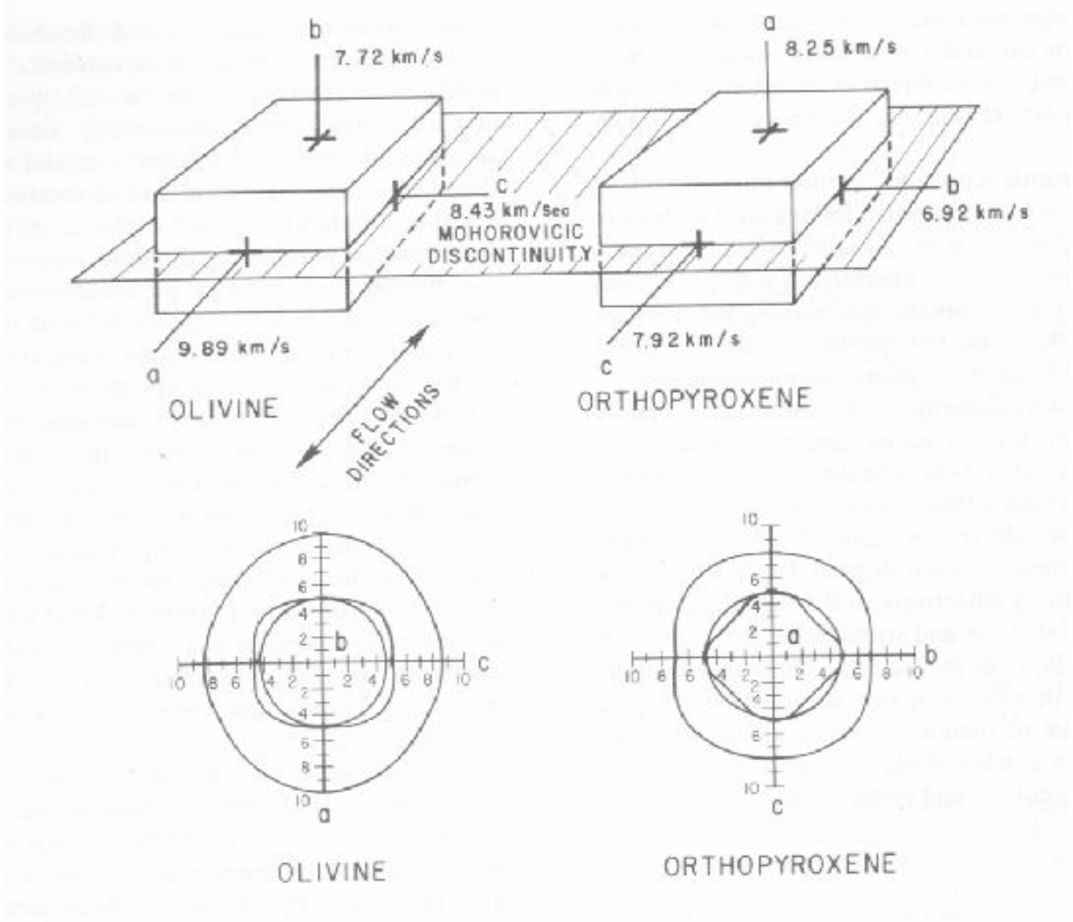
Importance of seismic anisotropy

ANISOTROPY is the Rule not the Exception

Seismic Anisotropy is present at all scales



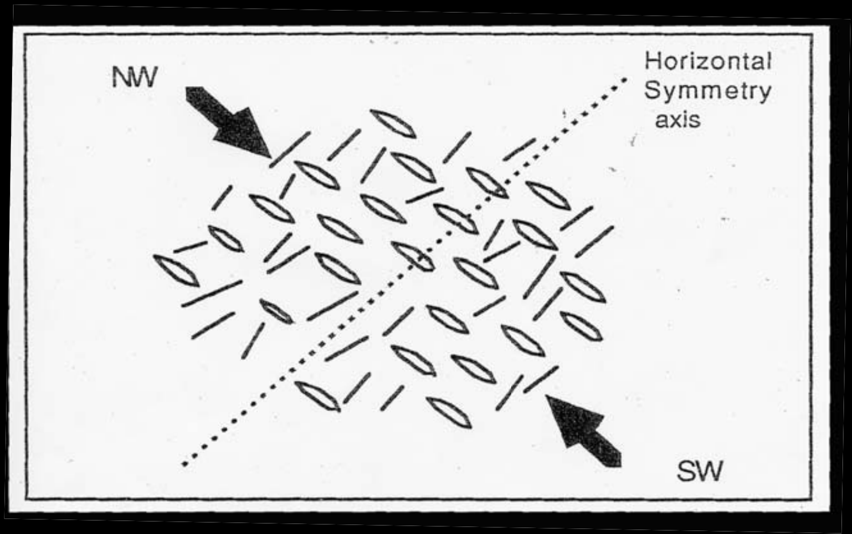
(Montagner and Guillot, 2001)



From Christensen and Lundquist, 1982

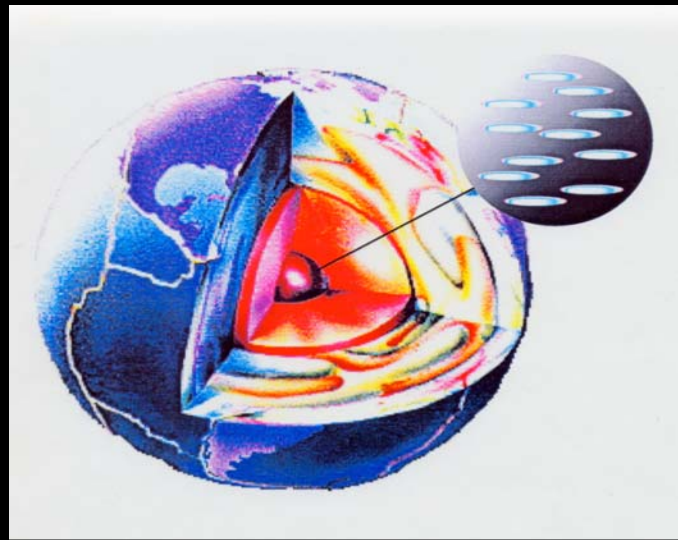
Cracks, fluid inclusions

Crust



(Babuska and Cara, 1991)

Inner core



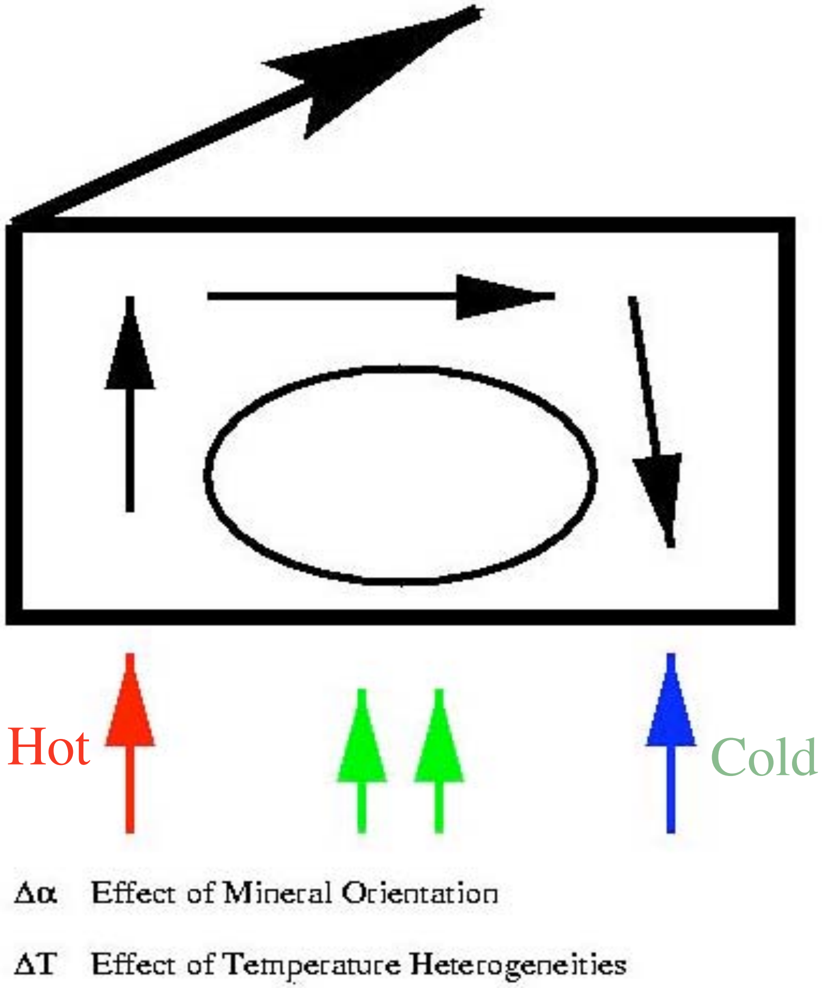
(Singh et al., 2001)

Importance of seismic anisotropy
ANISOTROPY is the Rule not the Exception

Anisotropy is present at all scales

-From microscopic scale up to macroscopic scale
-Efficient mechanisms of alignment
(L.P.O.: lattice preferred orientation
S.P.O.: shape preferred orientation; fine layering)

Montagner & Guillot, 2001

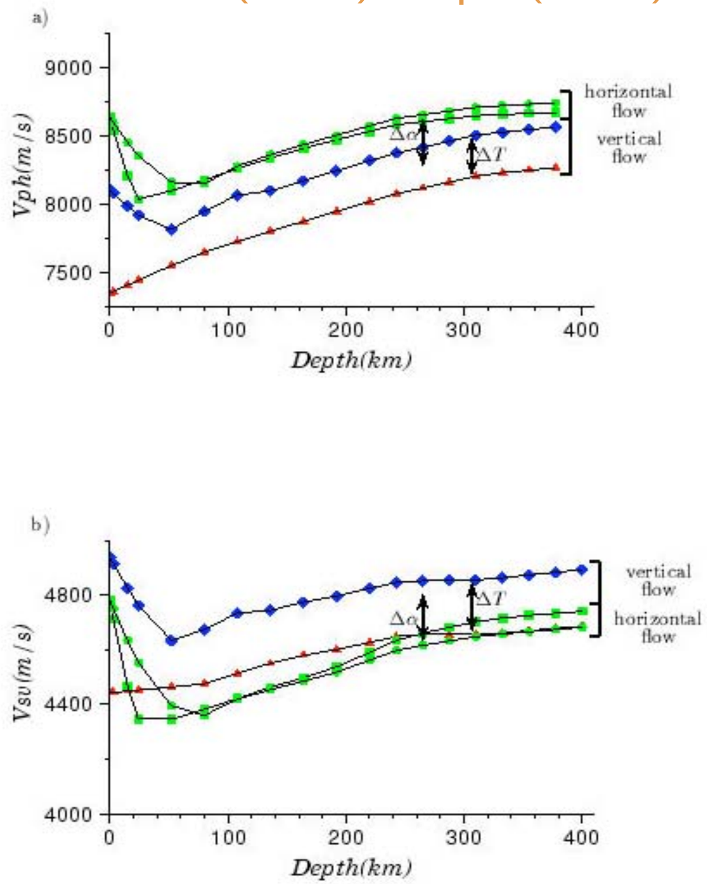


Da: Anisotropy Effect

DT: Temperature Effect

Da ≈ DT

Ol (60%) +Opx (40%)



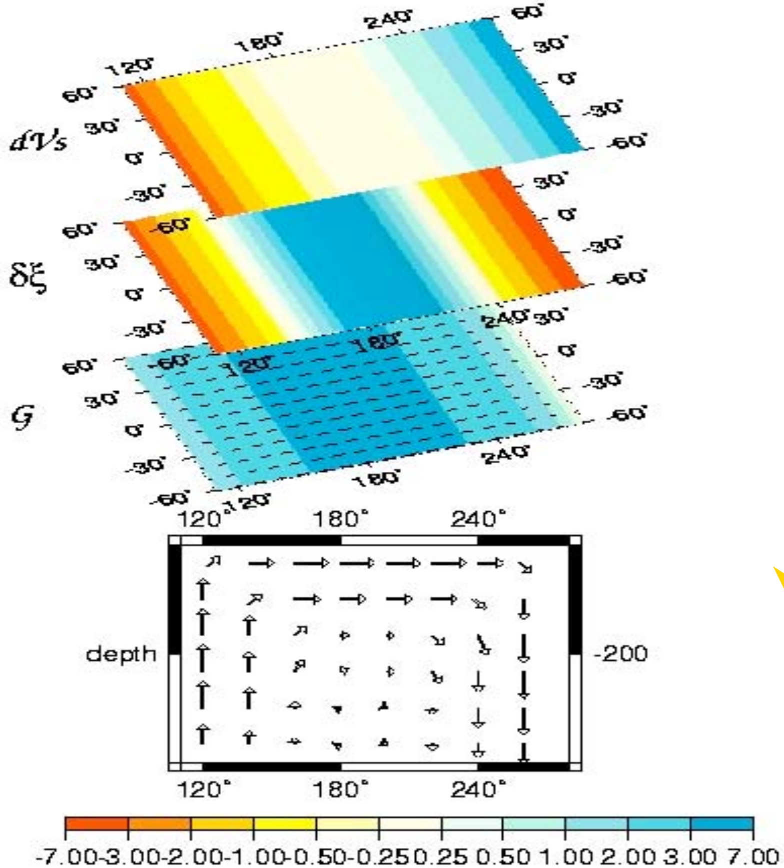
Montagner &Guillot, 2001

Convective cell: anisotropic parameters

S- Velocity

Radial Anisotropy

Azimuthal Anisotropy



Interpretation

Anisotropy is observed on different kinds of seismic waves

- Body waves (Pn, Shear wave splitting)
- Surface waves (Rayleigh-Love discrepancy; Azimuthal anisotropy)

Importance of seismic anisotropy
ANISOTROPY is the Rule not the Exception

Anisotropy is present at all scales

- from microscopic scale to macroscopic scale
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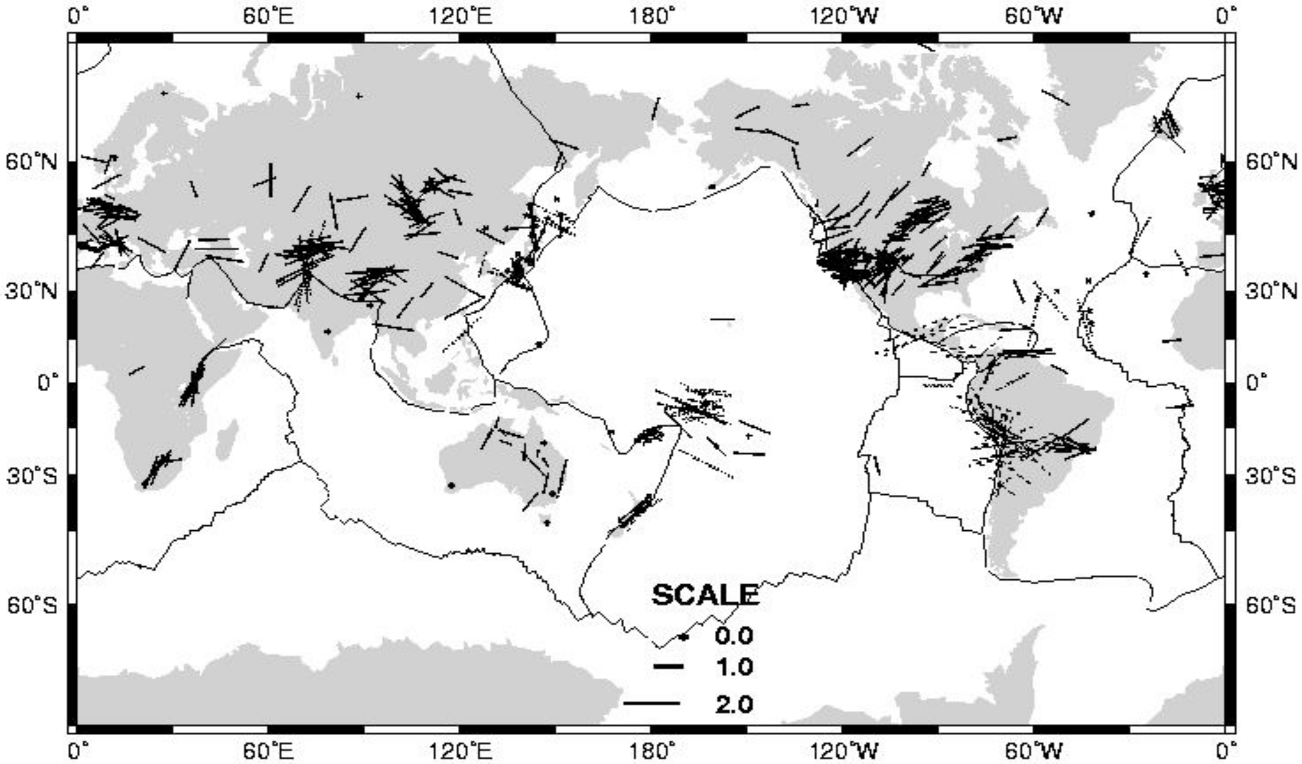
Anisotropy is observed on different kinds of seismic waves
-Body waves (Pn; S-wave splitting)
-Surface waves (Rayleigh-Love discrepancy, azimuthal anisotropy)

ANISOTROPY REFLECTS AN INNER ORGANIZATION

ANISOTROPY IS NOT A SECOND ORDER EFFECT

Compilation of S-wave splitting measurements



Savage, Rev. Geophys., 1999

Effect of anisotropy on surface waves

$$\frac{\delta\omega_k}{\omega_k} = \frac{\int_V \epsilon^*_{ij}\delta C_{ijpq}\epsilon_{pq}dV}{\int_V \rho_0 u^*_r u_r dV}$$

ω_k eigenfrequency corresponding to multiplet $k = \{n, l, m\}$

ϵ strain tensor, u displacement, δC elastic tensor perturbation.

- Phase velocity $v(\omega, \theta, \phi, \Psi)$ at $\mathbf{r}(\theta, \phi, r)$ (*Smith & Dahlen*, 1973)

$$\begin{aligned} v(\omega,\theta,\phi,\Psi) = \quad & A_0(\omega,\theta,\phi) + A_1(\omega,\theta,\phi)cos2\Psi + A_2(\omega,\theta,\phi)sin2\Psi + \\ & A_3(\omega,\theta,\phi)cos4\Psi + A_4(\omega,\theta,\phi)sin4\Psi \end{aligned}$$

Ψ azimuth (angle between North and wave vector).

E

The first order perturbation in Love wave phase velocity $\delta C_L(k,\Psi)$ can be expressed as:

$$\delta C_L(k,\Psi) = \frac{1}{2C_{0L}(k)}[L_1(k) + L_2(k)cos2\Psi + L_3(k)sin2\Psi + L_4(k)cos4\Psi + L_5(k)sin4\Psi$$

where

$$L_0(k) = \int_0^\infty \rho W^2 dz$$

$$0\Psi \leftarrow L_1(k) = \frac{1}{L_0}\int_0^\infty (W^2 dN + \frac{W'^2}{k^2} dL)dz$$

$$2\Psi \leftarrow \begin{cases} L_2(k) = \frac{1}{L_0}\int_0^\infty -G_c(\frac{W'^2}{k^2})dz \\ L_3(k) = \frac{1}{L_0}\int_0^\infty -G_s(\frac{W'^2}{k^2})dz \end{cases}$$

$$4\Psi \leftarrow \begin{cases} L_4(k) = \frac{1}{L_0}\int_0^\infty -E_c.W^2 dz \\ L_5(k) = \frac{1}{L_0}\int_0^\infty -E_s.W^2 dz \end{cases}$$

The same procedure holds for Rayleigh waves, starting from the displacement given previously.

$$\delta C_R(k,\Psi) = \frac{1}{2C_{0R}(k)}[R_1(k) + R_2(k)cos2\Psi + R_3(k)sin2\Psi + R_4(k)cos4\Psi + R_5(k)sin4\Psi$$

where

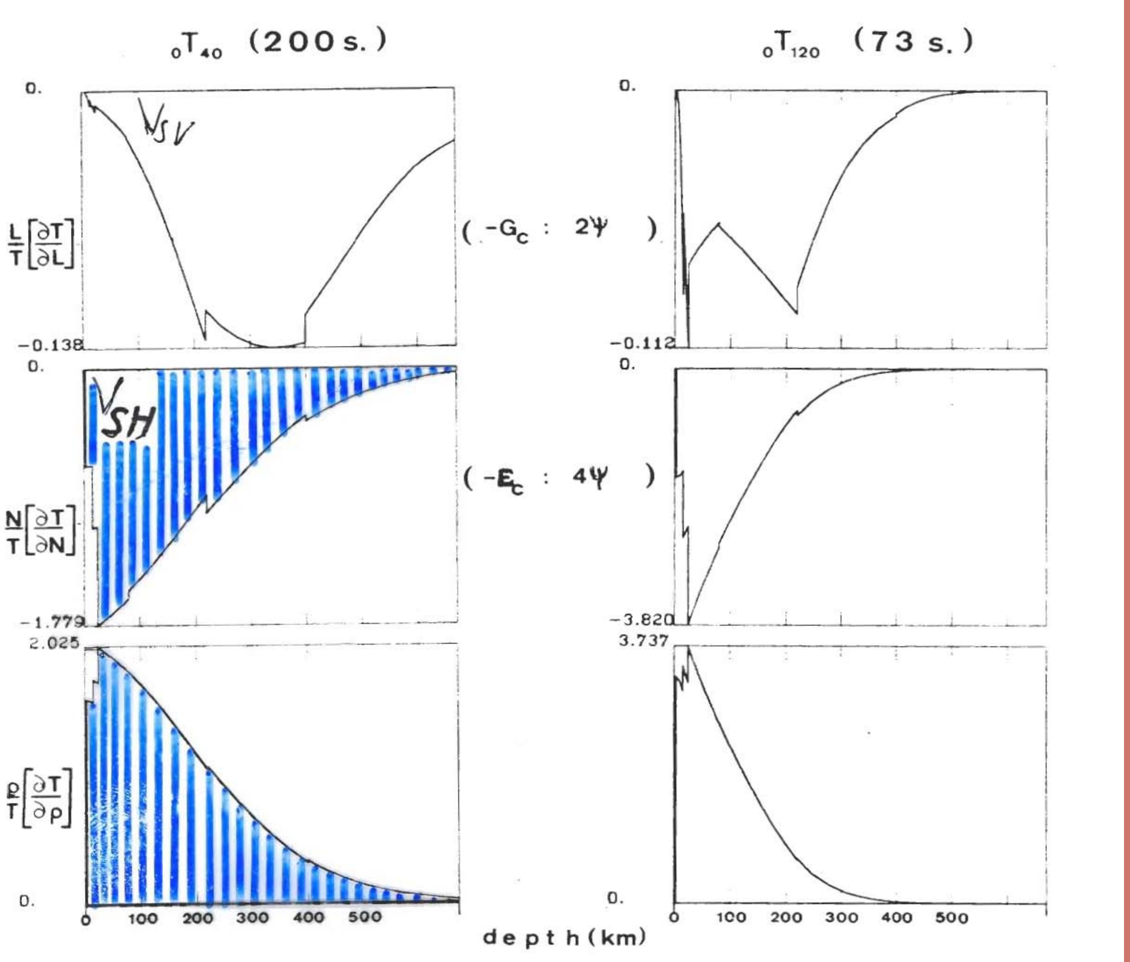
$$R_0(k) = \int_0^\infty \rho(U^2 + V^2)dz$$
$$R_1(k) = \frac{1}{R_0}\int_0^\infty [V^2 dA + \frac{U'^2}{k^2}.dC + \frac{2U'V}{k}.dF + (\frac{V'}{k} - U)^2 dL]dz$$
$$R_2(k) = \frac{1}{R_0}\int_0^\infty [V^2.B_c + \frac{2U'V}{k}.H_c + (\frac{V'}{k} - U)^2 G_c]dz$$
$$R_3(k) = \frac{1}{R_0}\int_0^\infty [V^2.B_s + \frac{2U'V}{k}.H_s + (\frac{V'}{k} - U)^2 G_s]dz$$
$$R_4(k) = \frac{1}{R_0}\int_0^\infty E_c.V^2 dz$$
$$R_5(k) = \frac{1}{R_0}\int_0^\infty E_s.V^2 dz$$

The 13 depth-functions $A, C, F, L, N, B_c, B_s, H_c, H_s, G_c, G_s, E_c, E_s$ are linear combinations of the elastic coefficients C_{ij} and are explicitly given as follows:

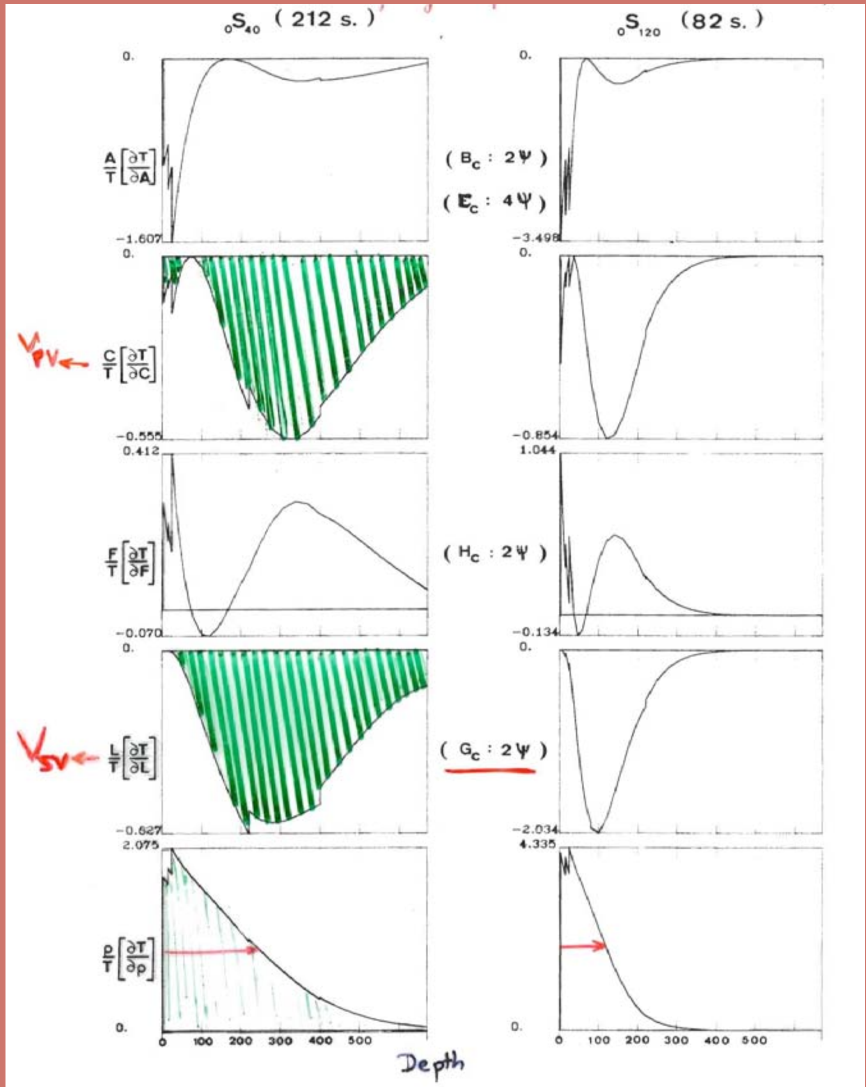
Table 1: Calculation of the various $c_{ij}\epsilon_i\epsilon_j$ for Love waves
$\alpha = cos\Psi$; $\beta = sin\Psi$

n	ij	$c_{ij}\epsilon_i\epsilon_j$
1	11	$c_{11}\alpha^2\beta^2.k^2W^2$
1	22	$c_{22}\alpha^2\beta^2.k^2W^2$
1	33	0
2	12	$-c_{12}\alpha^2\beta^2.k^2W^2$
2	13	0
2	23	0
2	24	
4	14	$c_{14}(-i\alpha^2\beta).\frac{kWW'}{2}$
4	15	$c_{15}(i\alpha^2\beta).\frac{kWW'}{2}$
4	16	$c_{16}(-\alpha\beta)(\alpha^2-\beta^2).\frac{k^2W^2}{2}$
4	24	$c_{24}(-i\alpha^2\beta).\frac{kWW'}{2}$
4	25	$c_{25}(-i\alpha\beta^2).\frac{kWW'}{2}$
4	26	$c_{26}(\alpha\beta)(\alpha^2-\beta^2).\frac{k^2W^2}{2}$
4	34	0
4	35	0
4	36	0
4	44	$c_{44}\alpha^2.\frac{W'^2}{4}$
8	45	$c_{45}(-\alpha\beta).\frac{W'^2}{4}$
8	46	$c_{46}(-i\alpha)(\alpha^2-\beta^2).\frac{kWW'}{2}$
4	55	$c_{55}\beta^2.\frac{W'^2}{4}$
8	56	$c_{56}(i\beta)(\alpha^2-\beta^2).\frac{kWW'}{2}$
4	66	$c_{66}(\alpha^2-\beta^2).\frac{k^2W^2}{4}$

Love wave partial derivatives



Rayleigh wave partial derivatives



0Ψ term	$A = \frac{3}{8}(C_{11} + C_{22}) + \frac{1}{4} C_{12} + \frac{1}{2} C_{66} \rightarrow$ $C = C_{33} \rightarrow$ $F = \frac{1}{2}(C_{13} + C_{23})$ $L = \frac{1}{2}(C_{44} + C_{55}) \rightarrow$ $N = \frac{1}{8}(C_{11} + C_{22}) - \frac{1}{4} C_{12} + \frac{1}{2} C_{66} \rightarrow$	V_{PH} V_{PV} V_{SV} V_{SH}
	cos	sin
2Ψ term	$B_c = \frac{1}{2}(C_{11} - C_{22})$ $G_c = \frac{1}{2}(C_{55} - C_{44})$ $H_c = \frac{1}{2}(C_{13} - C_{23})$	$B_s = C_{16} + c_{26} \rightarrow B$ $G_s = C_{54} \rightarrow G$ $H_s = C_{36} \rightarrow H$
4Ψ term	$E_c = \frac{1}{8}(C_{11} + C_{22}) - \frac{1}{4} C_{12} - \frac{1}{2} C_{66}$	$E_s = \frac{1}{2}(C_{16} - C_{26}) \rightarrow E$

1: horizontal direction North

2: horizontal direction perpendicular to 1-axis

3: vertical direction

$$B = \sqrt{B_c^2 + B_s^2}$$

$$G = \sqrt{G_c^2 + G_s^2}$$

$$H = \sqrt{H_c^2 + H_s^2}$$

$$E = \sqrt{E_c^2 + E_s^2}$$

Montagner and Nataf, 1986

- Best Resolved parameters for Surface Waves

$\mathbf{L} = \rho V_{SV}^2$ Isotropic part of V_{SV}.

$\xi = \frac{N}{L} = \frac{V_{SH}^2}{V_{SV}^2}$ Radial Anisotropy.

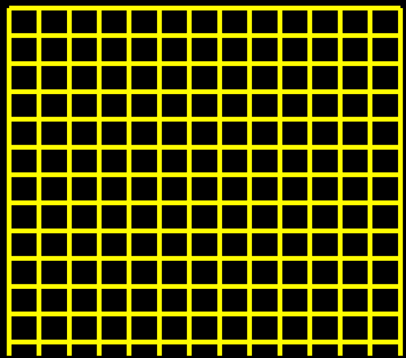
G, Ψ_G Azimuthal Anisotropy of V_{SV}, also related to SKS splitting (when horizontal symmetry axis).

- Body Waves (*Crampin*, 1984)

$\rho V_{qSV}^2 = L + G_c cos2\Psi + G_s sin2\Psi$

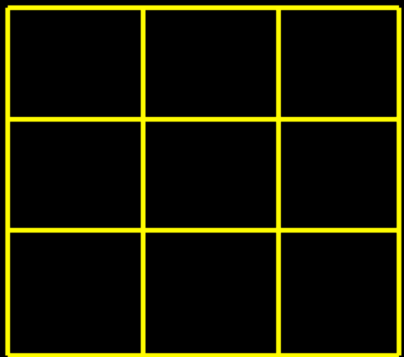
$\rho V_{qSH}^2 = N - E_c cos4\Psi - E_s sin4\Psi$

Isotropic Inversion



N independent parameters
0-Y term
VR1
Variance reduction

Anisotropic inversion



3N’ = N

0+2 Y term
VR2

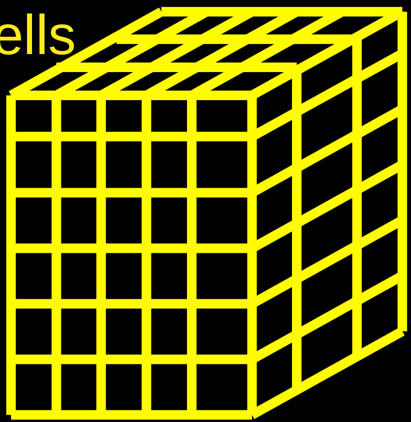
VR2>VR1 => the anisotropic model can be simpler than the isotropic model

Parameter Space

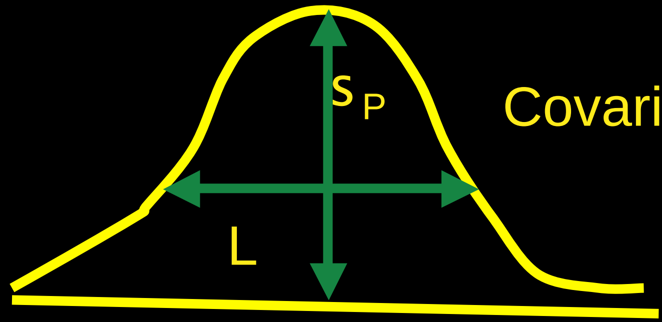
Physical parameters: r + 13 physical parameters

Geographical parameterization: **p**(r,q,f)

Cells



Continuous parameterization



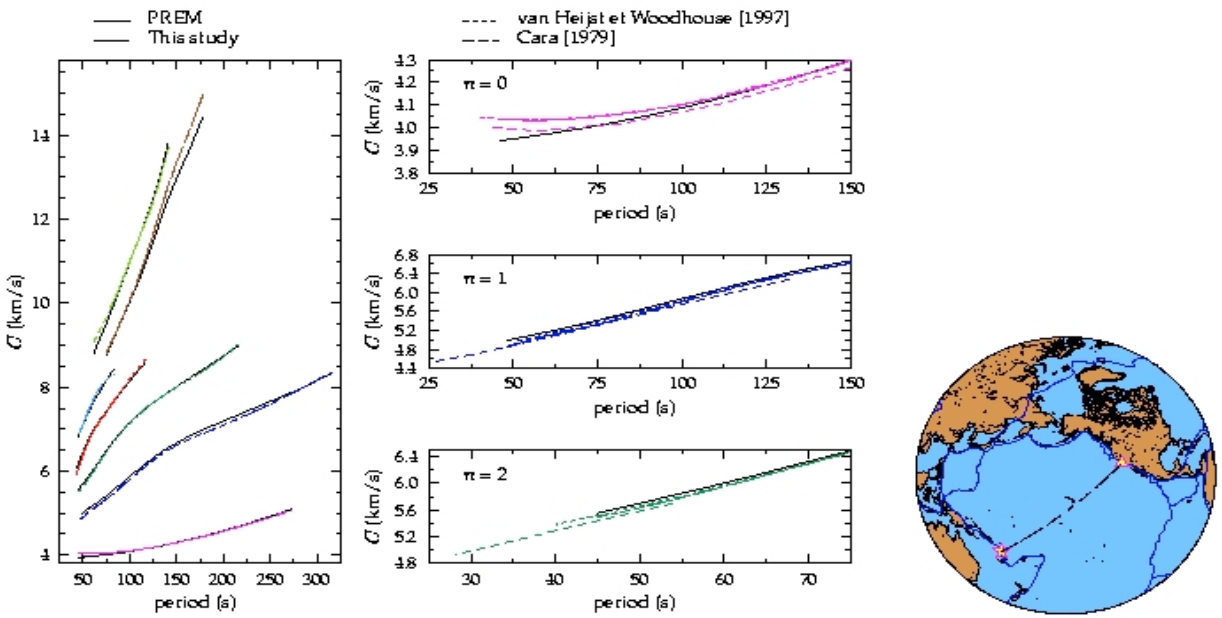
Covariance fonction

- Spherical harmonic expansion

- Lateral resolution:

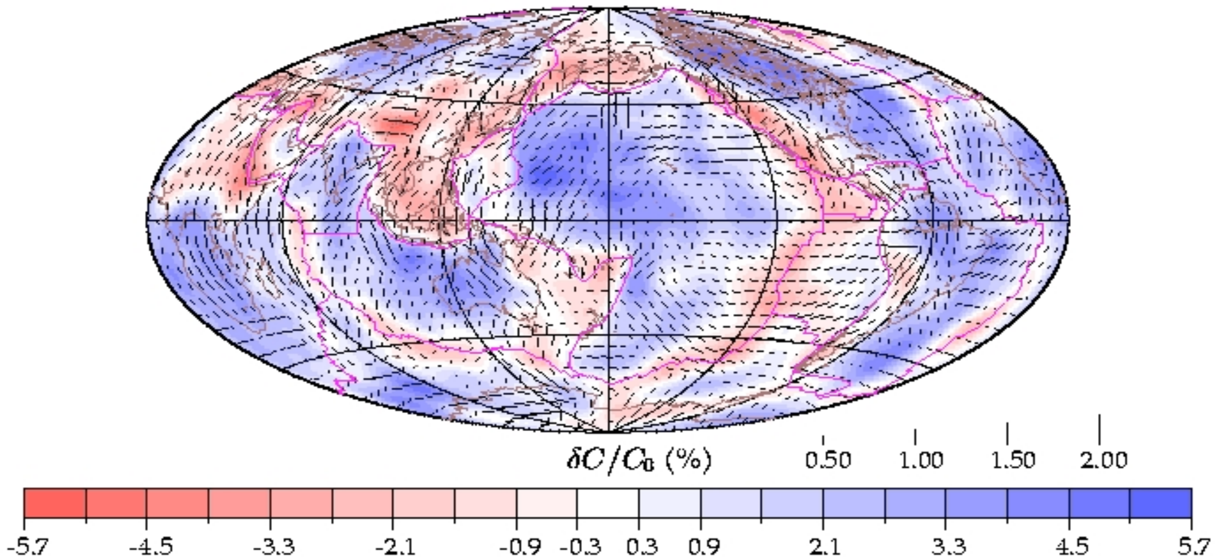
Hor 1000km, Rad 50km => 500*60*14 ≤ 420,000 parameters

Calculation of dispersion curves: Fundamental modes and higher modes



Comparison with previous results along the Vanuatu-California path.

Beucler et al., 2002

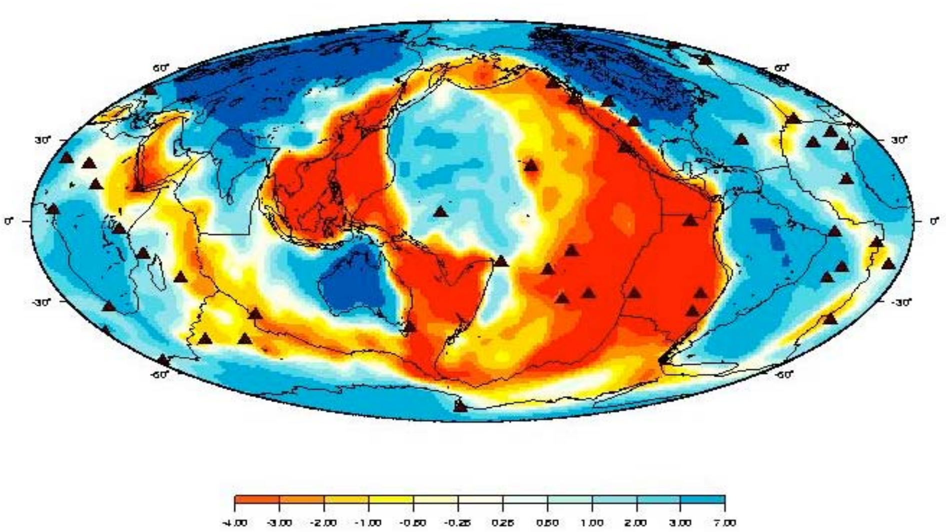


Anisotropic model resulting from phase velocities inversion (C.L.A.S.H., including 2Ψ and 4Ψ terms), $n = 0$, $T = 50$ s.

Global Tomography

Scale L≤ 2000km (degree 20)
Seismic wavelength l ≤ 500km
Ray theory applies

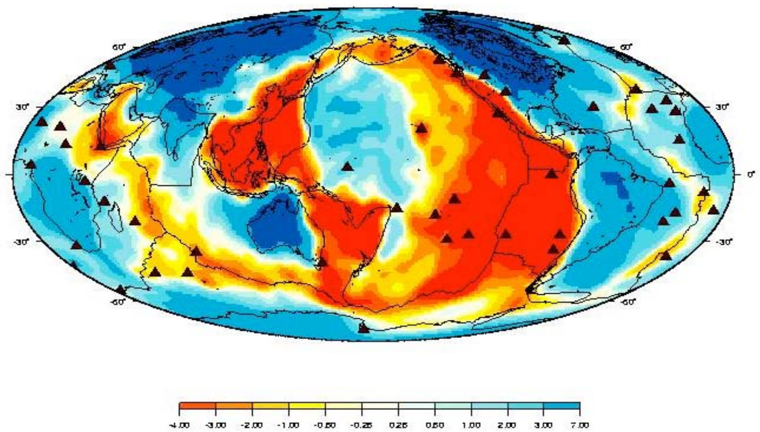
Shear wave velocities - depth = 100km

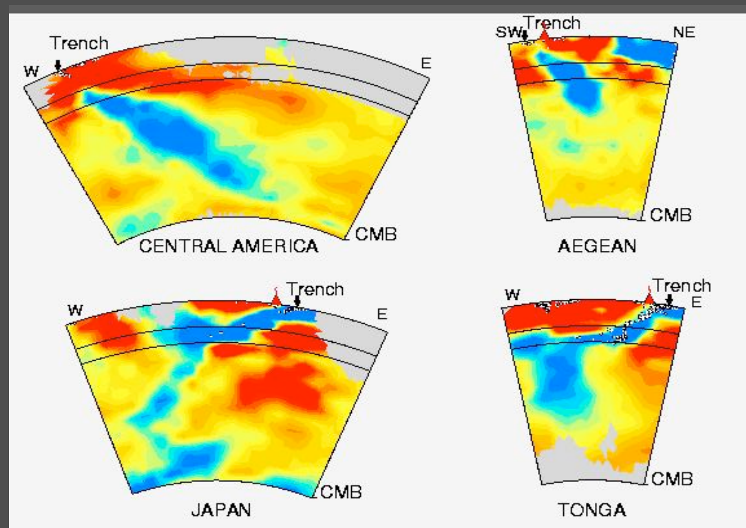


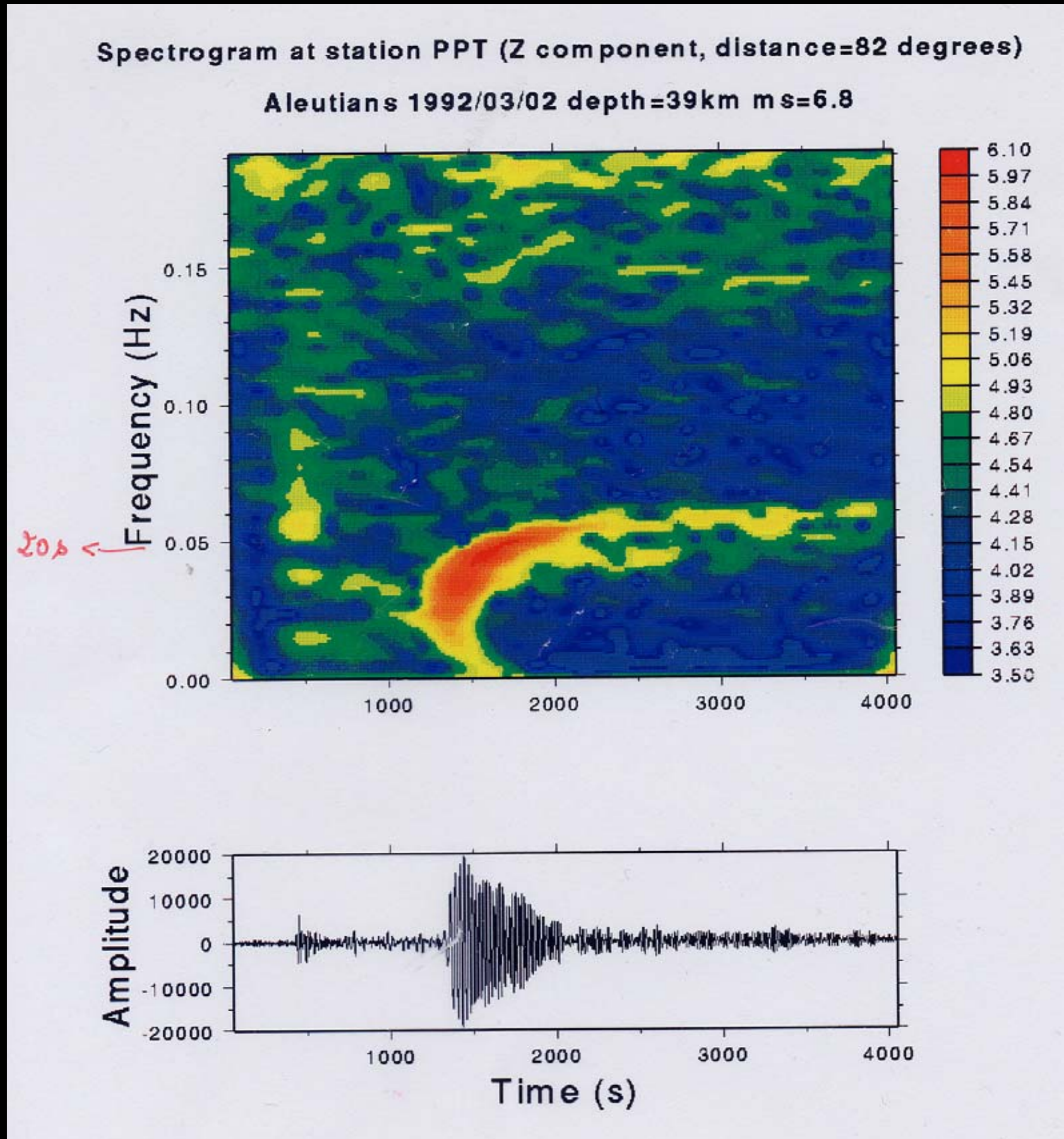
From Global Scale to Regional scale

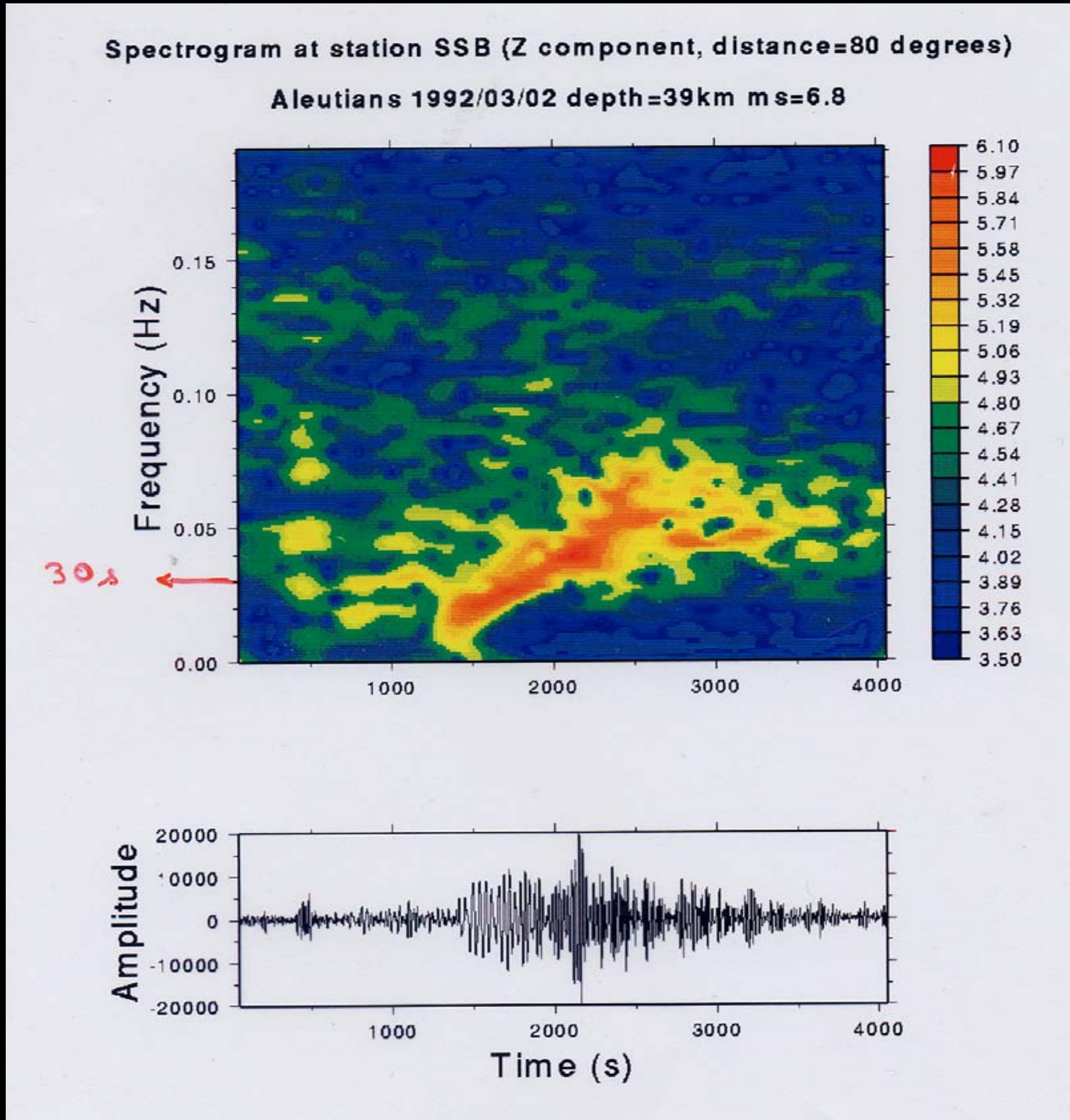
Scale L≤ 200-500km
Seismic wavelength   20km ≤ l ≤ 500km

S-wave velocity -
depth = 100km



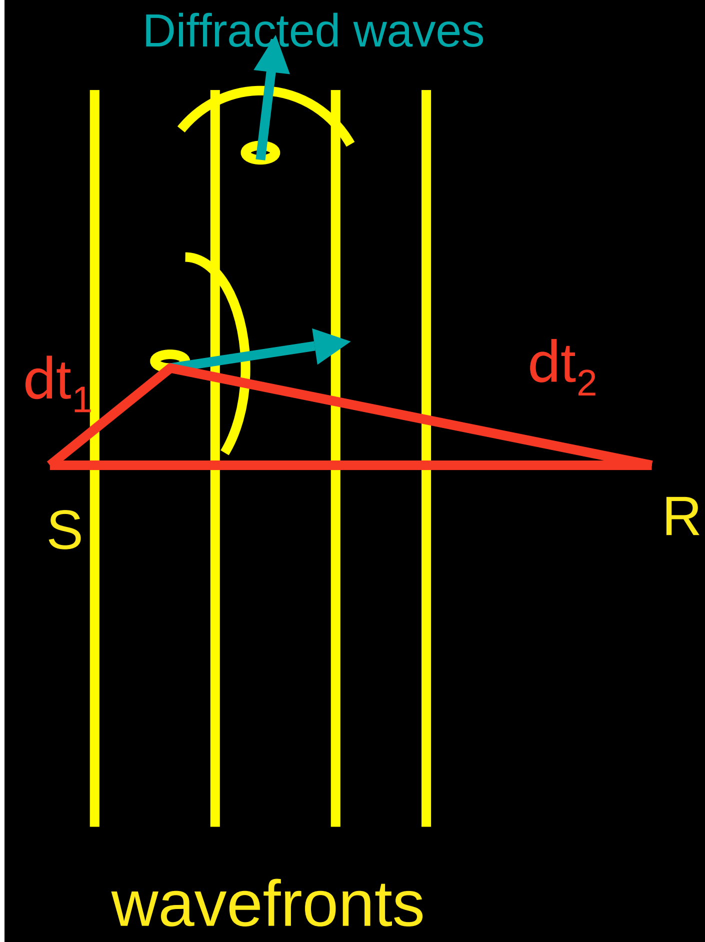


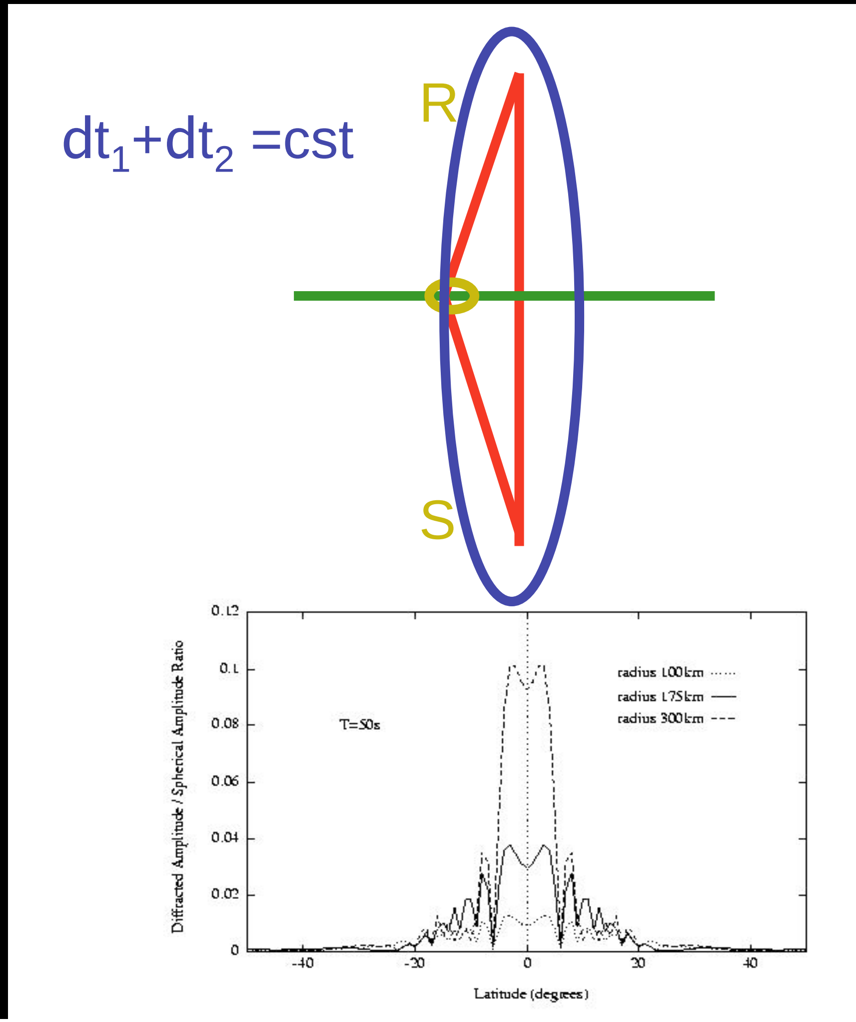

Spectrogram at station PPT (Z component, distance=82 degrees)
Aleutians 1992/03/02 depth=39km ms=6.8
Frequency (Hz)
0.15
0.10
0.05
0.00
20s
1000
2000
3000
4000
6.10
5.97
5.84
5.71
5.58
5.45
5.32
5.19
5.06
4.93
4.80
4.67
4.54
4.41
4.28
4.15
4.02
3.89
3.76
3.63
3.50
Amplitude
20000
10000
0
-10000
-20000
1000
2000
3000
4000
Time (s)


Spectrogram at station SSB (Z component, distance=80 degrees)
Aleutians 1992/03/02 depth=39km ms=6.8
Frequency (Hz)
0.15
0.10
0.05
0.00
30s
1000
2000
3000
4000
6.10
5.97
5.84
5.71
5.58
5.45
5.32
5.19
5.06
4.93
4.80
4.67
4.54
4.41
4.28
4.15
4.02
3.89
3.76
3.63
3.50
Amplitude
20000
10000
0
-10000
-20000
Time (s)

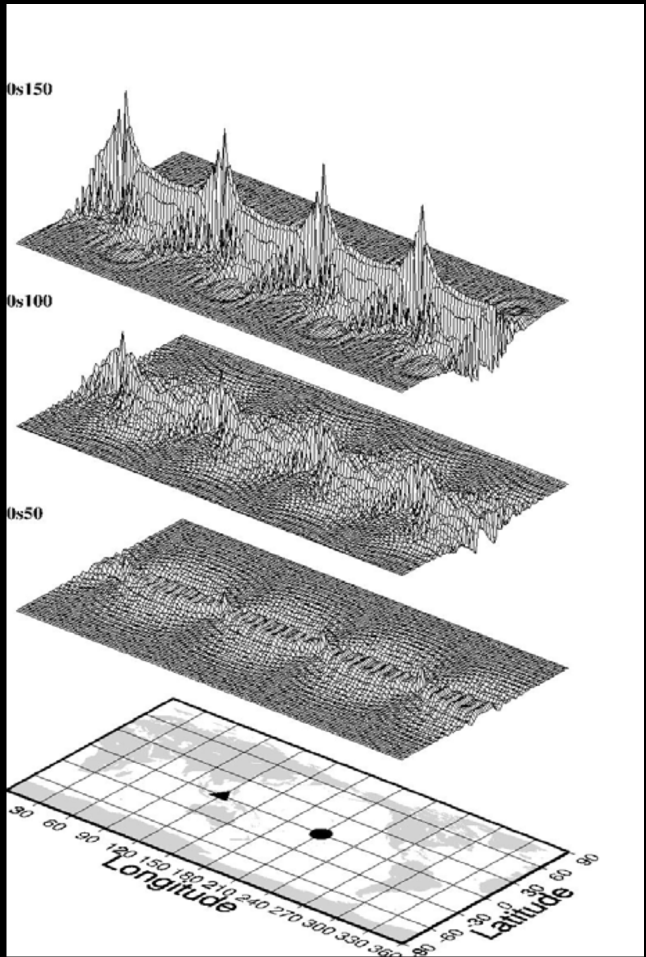
L heterogeneity scale, l wavelength

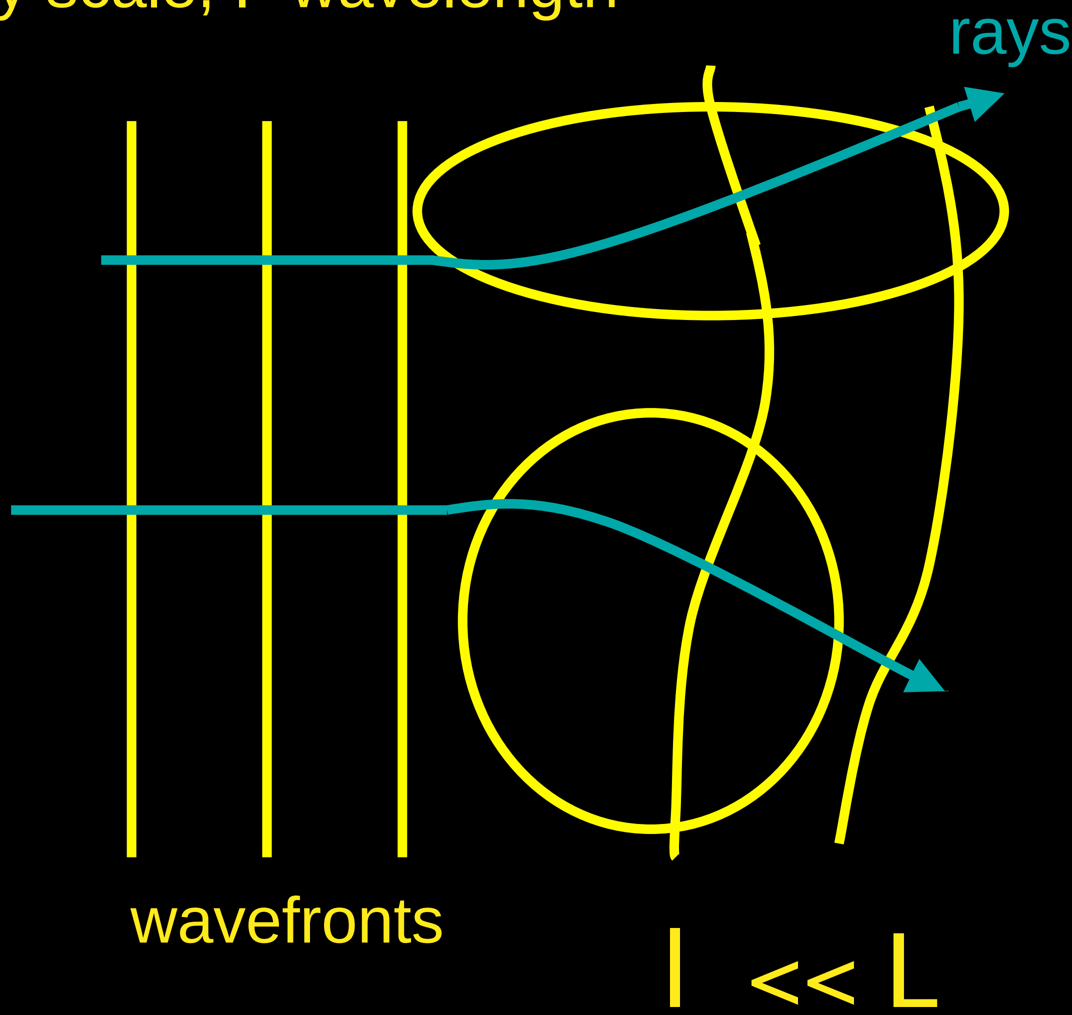
l ~ L or l >> L





L heterogeneity scale, l wavelength





Typical scales L≤2,000km, l ≤ 500km

Overview
Large scale Seismology: an observational field

- Data (Seismic source) + Instrument (Seismometer) -> Observations (seismograms)
- Historical evolution: Ray theory, Normal mode theory, Numerical techniques (SEM, NM-SEM)
- Scientific Issues: earthquakes, structure of the Earth and planets
- **Seismic Experiment: Plume detection**
- NM-SEM and time reversal

Hotspots - Plumes

EXPLANATION

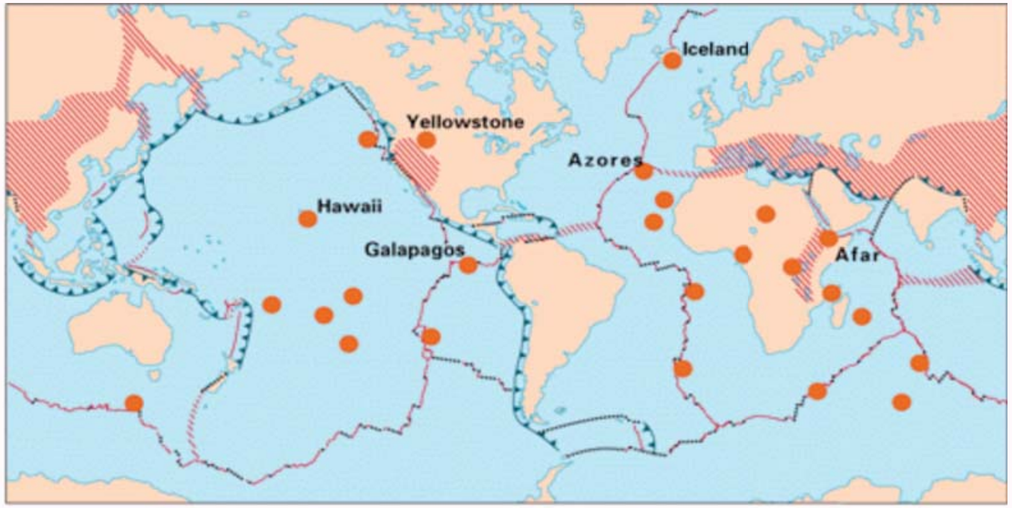
Divergent plate boundaries— Where new crust is generated as the plates pull away from each other.

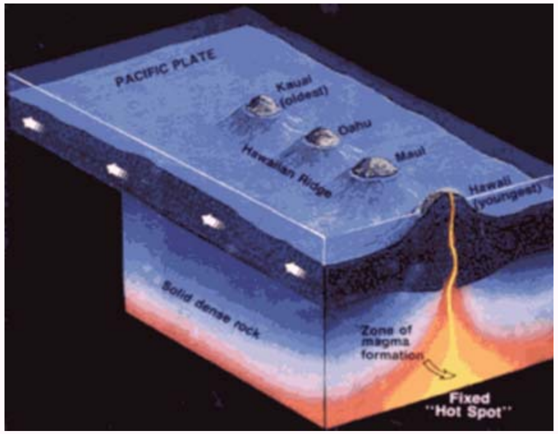
Convergent plate boundaries— Where crust is consumed in the Earth's interior as one plate dives under another.

Transform plate boundaries— Where crust is neither produced nor destroyed as plates slide horizontally past each other.

Plate boundary zones—Broad belts in which deformation is diffuse and boundaries are not well defined.

Selected prominent hotspots





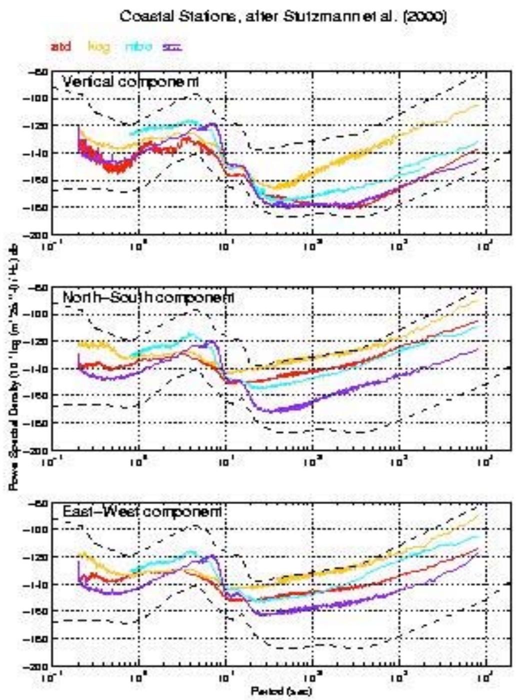
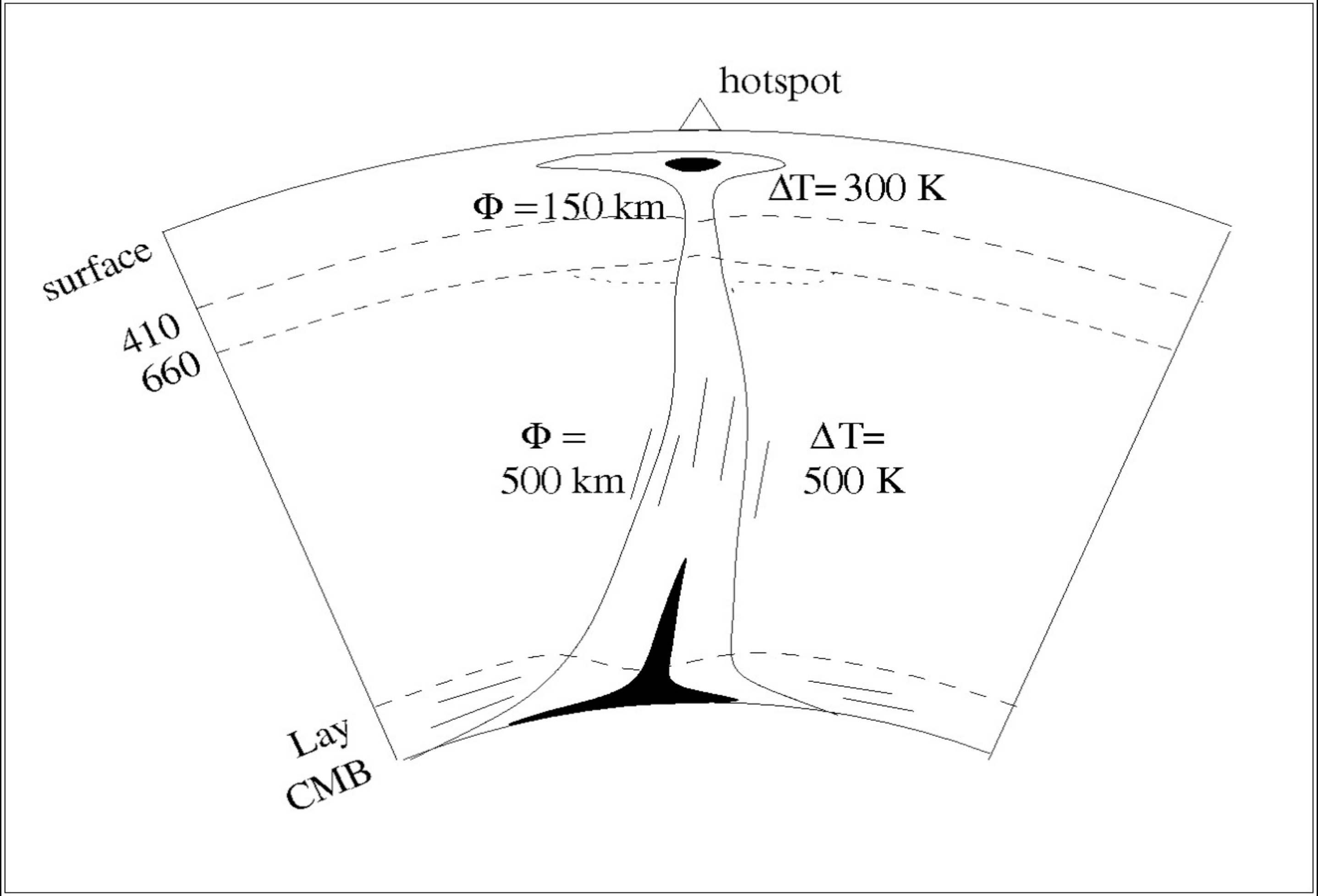


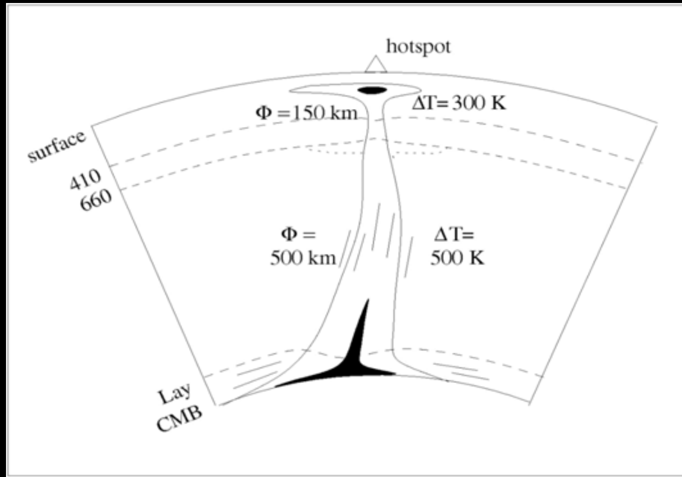
Figure 5c. Power spectral density estimated over noise data from the year 1995 for the three components (vertical: top, North-South: middle and East-West: bottom) of all coastal GEOSCOPE stations.


10 5:42
Th. Staudacher
OVPF / IPGP

Classical Plume Model (Nataf, 1999)



Definition of plume: thermal instability in a boundary layer:
- Core-mantle boundary
- Transition Zone (400-660- 1000km)?
- Asthenosphere- lithosphere?



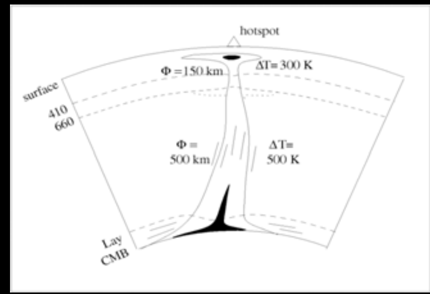
But

-Is the plume model correct?
-What is their geodynamical role?
-What is their biological role?

-What is their structure, their origin at depth?

-Are there really several types of plumes?

Detection of a Plume



Expected Effects of plume on seismic data

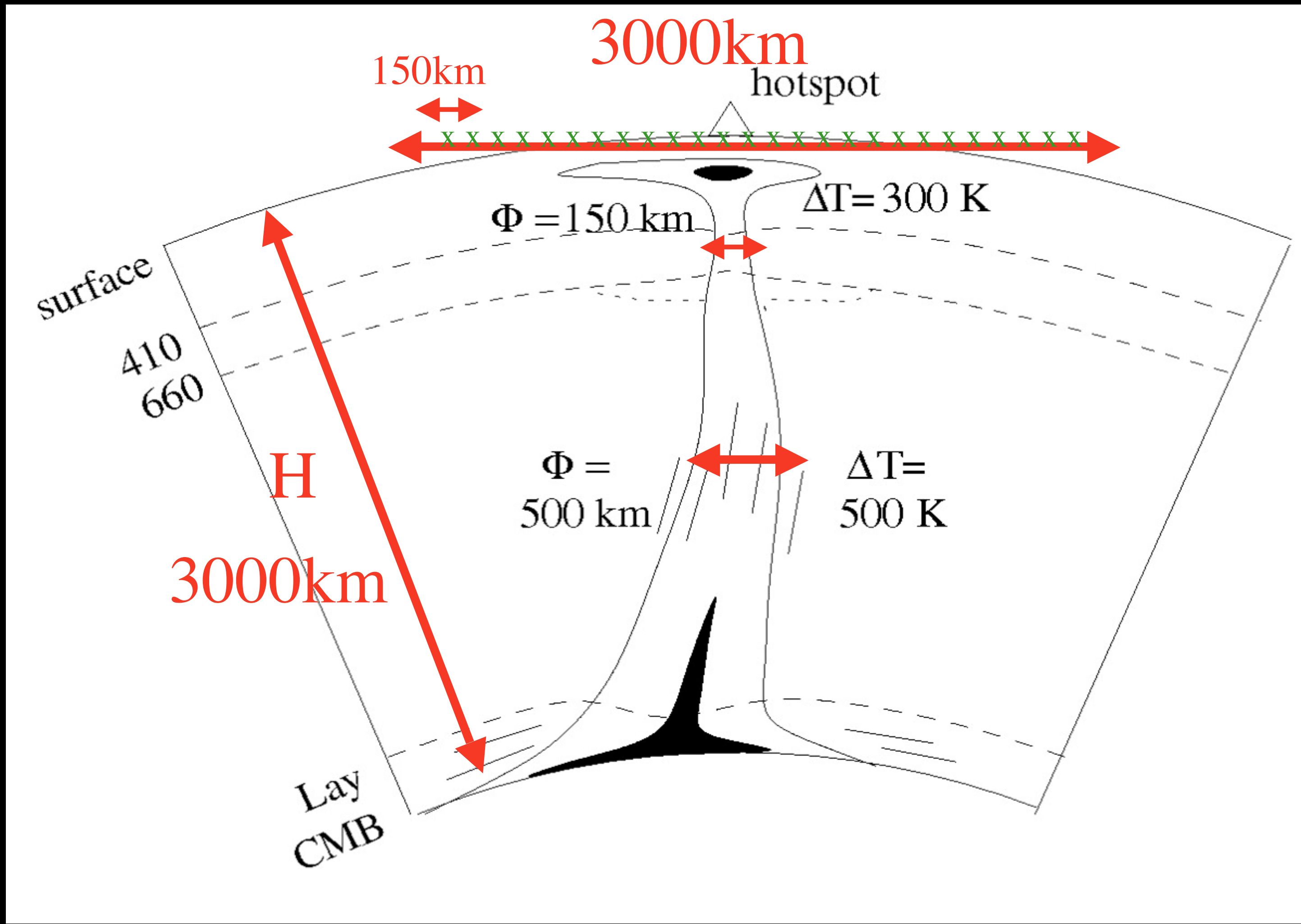
- Thermal effect: DT>0 => dV_S<0, dV_P<0

- Upwelling flow =>crystal alignment by LPO
Weak azimuthal seismic anisotropy,
V_{SV}>V_{SH} (x<1: radial seismic anisotropy)

- Large attenuation => low quality factor Q

- Thinning of the Transition zone thickness
(410km deflected downward, 660km upward)

H/F » 20 => at least 40 stations (2 per l)

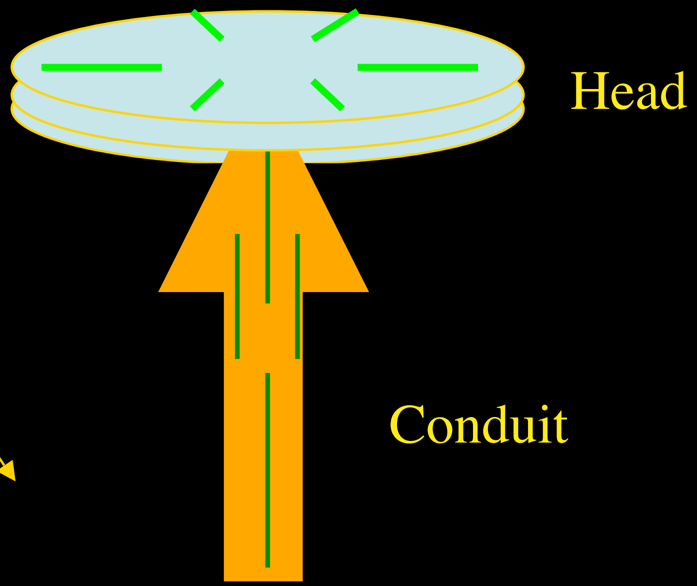


Plume affects not only S-wave velocity distribution but also seismic anisotropy

Plume affects not only S-wave distribution but also seismic anisotropy

- Head: Not a problem

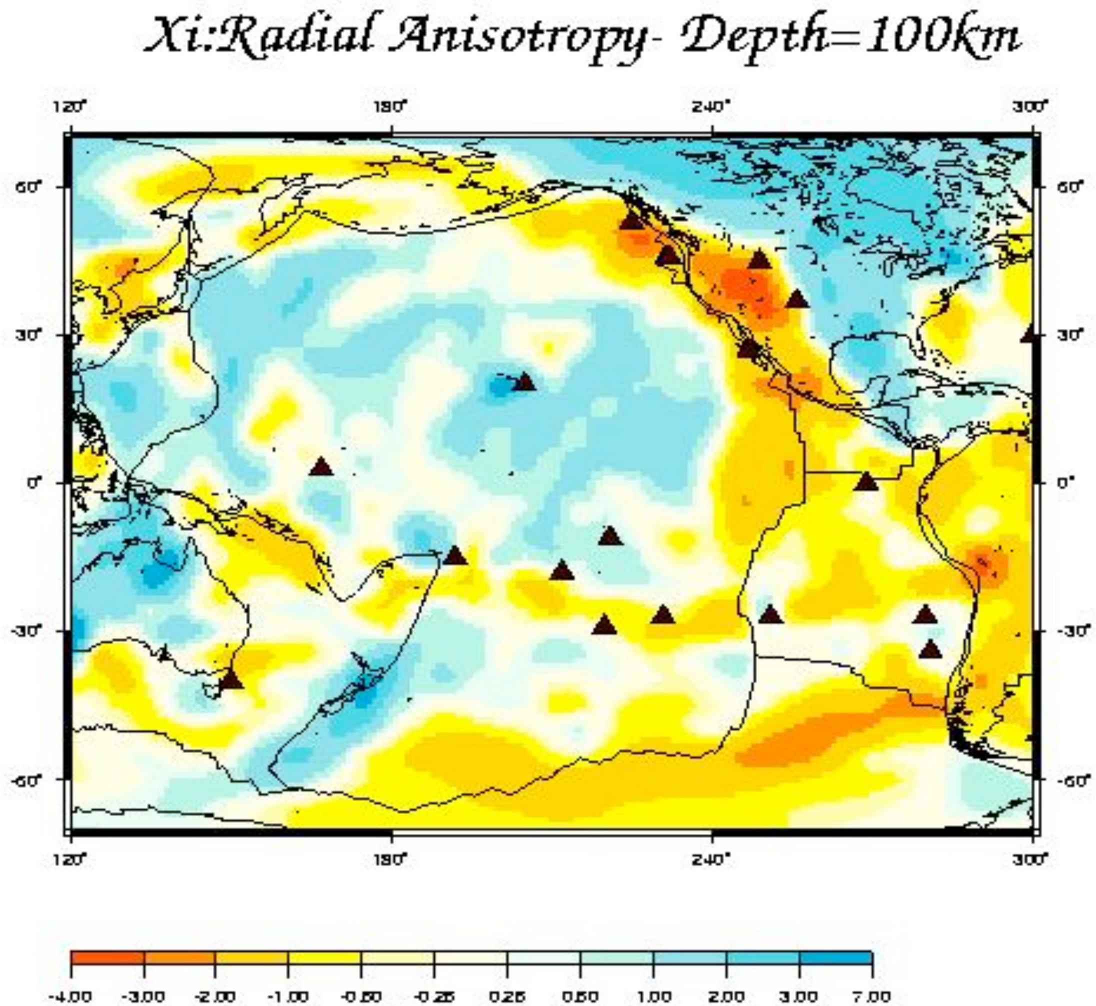
- Conduit: difficult to detect



Da: Anisotropy Effect => V_{SV} ↗

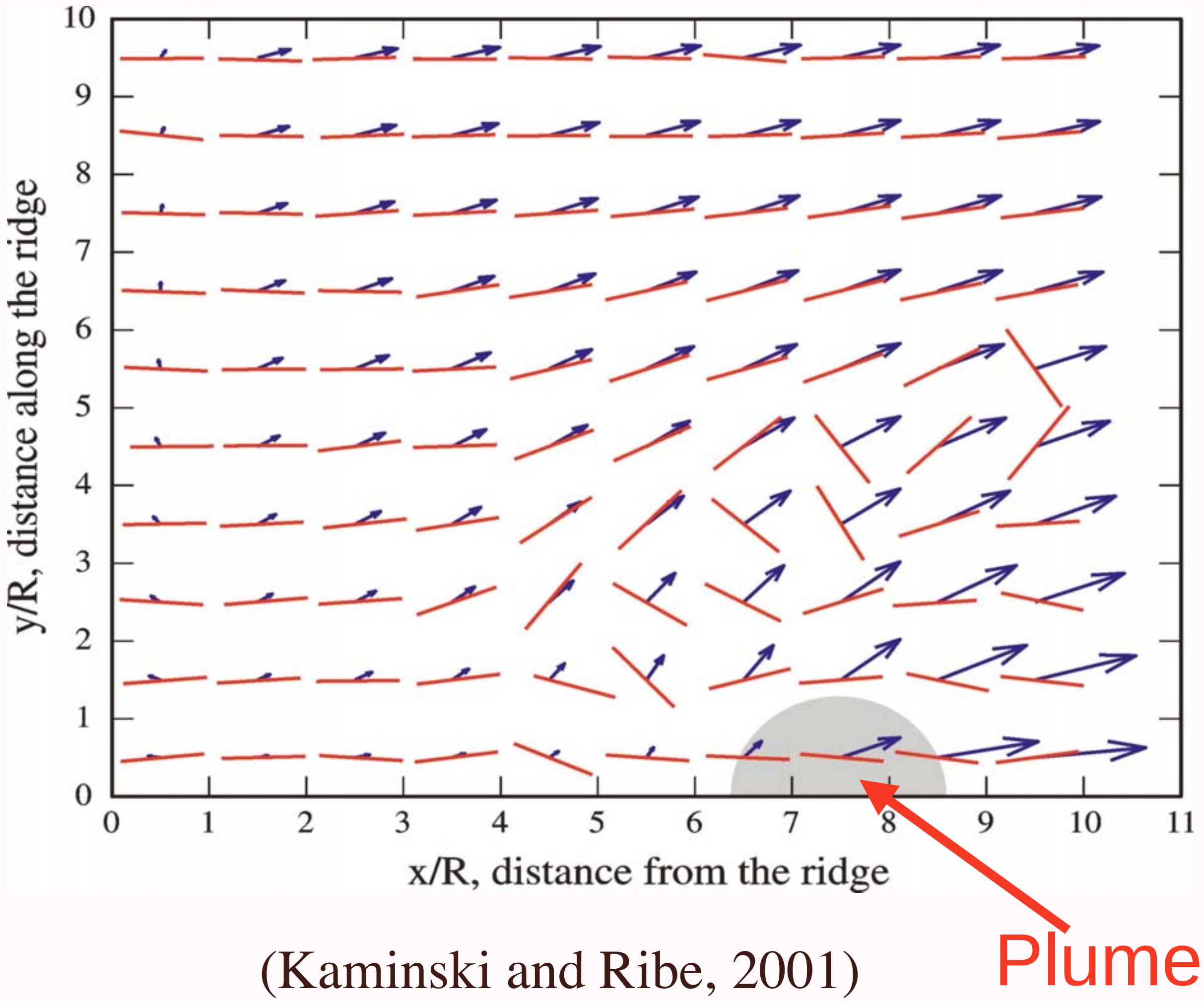
DT: Temperature Effect => V_{SV} ↘

Opposite effects



(Montagner, 2002)

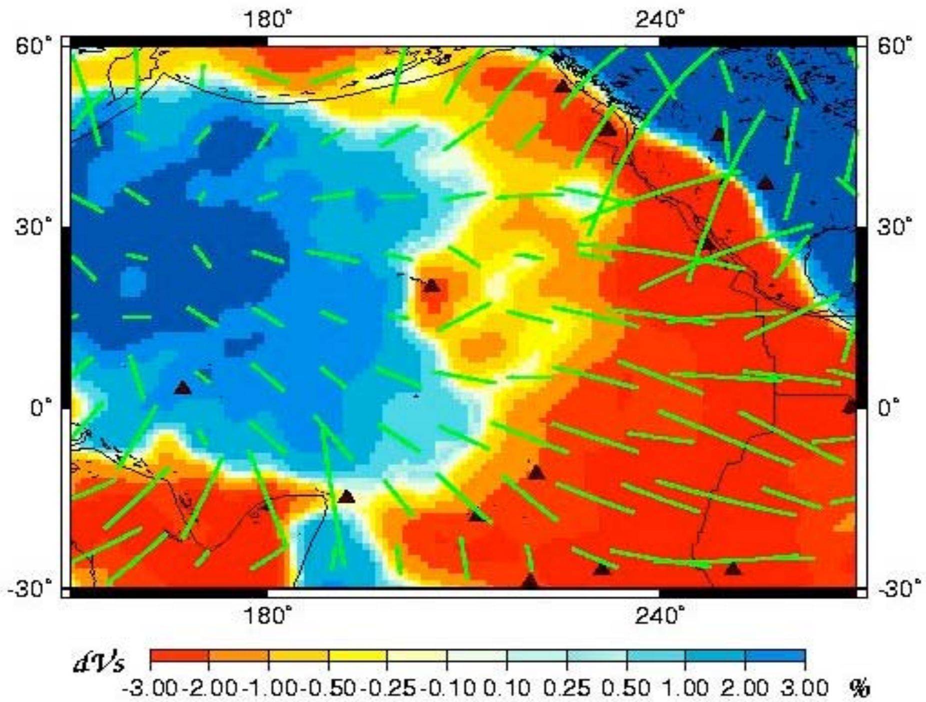
Azimuthal anisotropy



(Kaminski and Ribe, 2001)

S-wave velocity + Azimuthal Anisotropy

Depth=120 km



A plume is very difficult to detect below asthenosphere (narrow conduit ∂150km, small velocity contrast ∂1-2%)

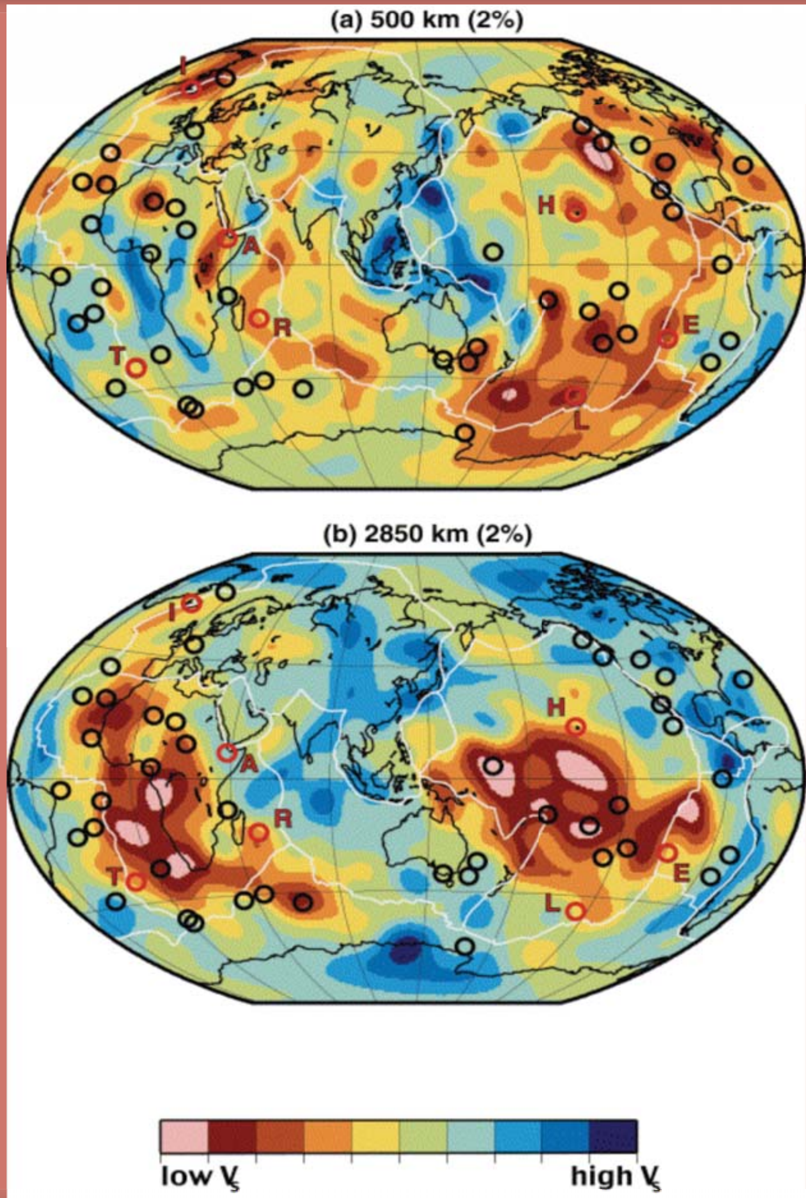
Head is easier to detect: large lateral extent, interaction with lithosphere, asthenosphere, or continent

Indirect detection through the perturbation of flow pattern around plume

Several regional investigations: Resolution 500km

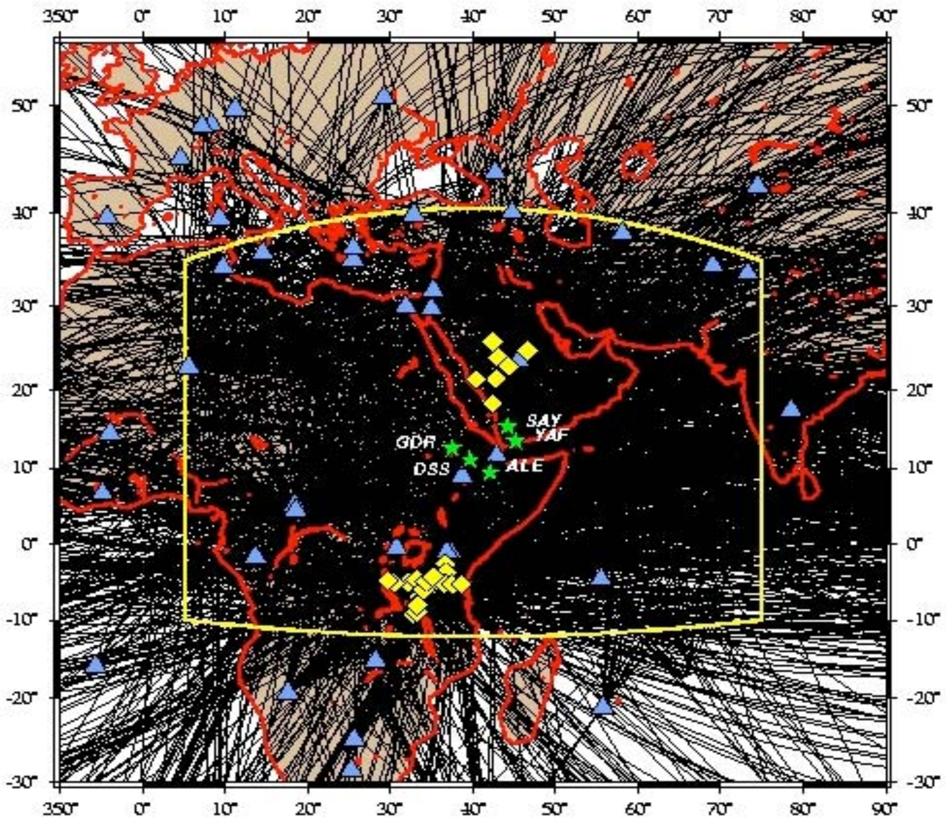
Horn of Africa (Debayle et al., 2000; Sicilia et al., 2003)

Global Scale



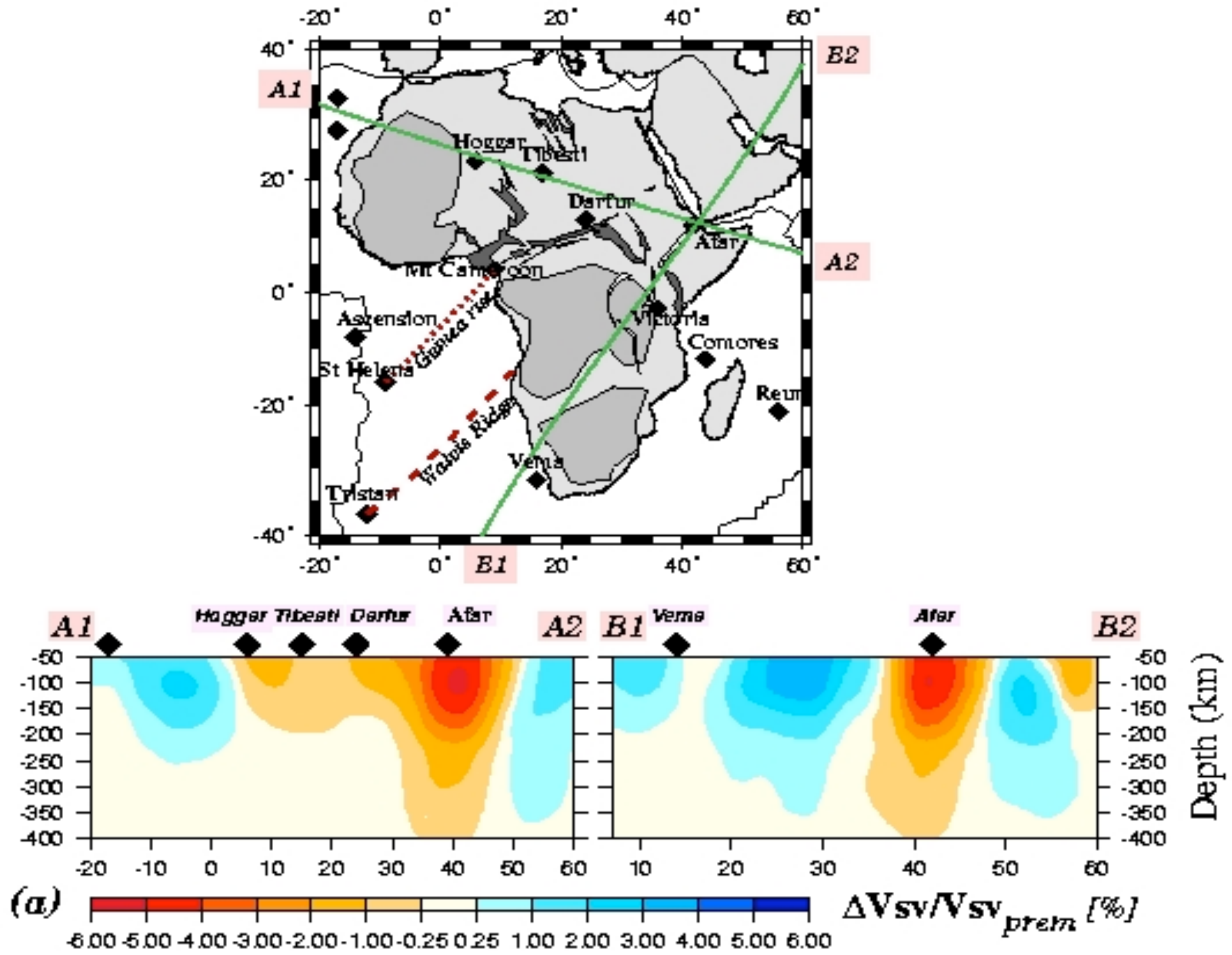
Ritsema et al., 2000

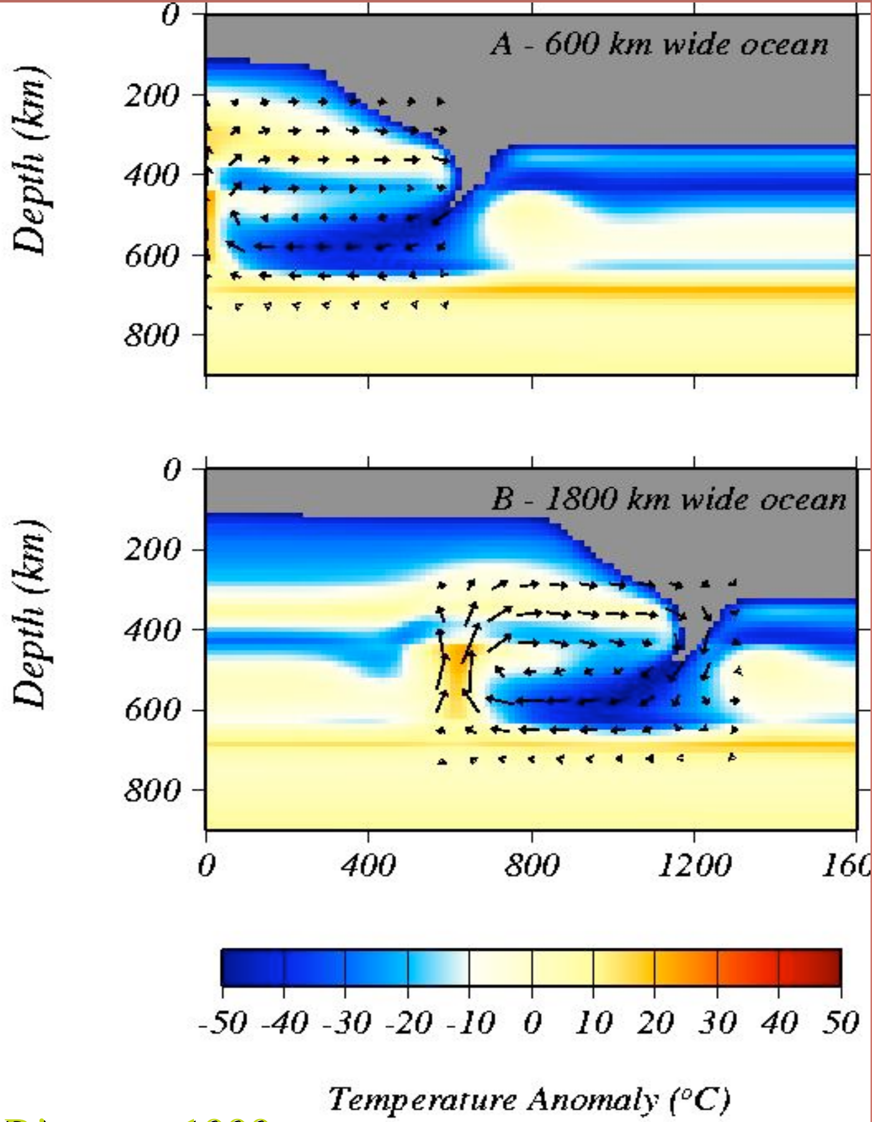
Horn of Africa



(Sicilia et al., 2003)

(Sebai et al., 2003)



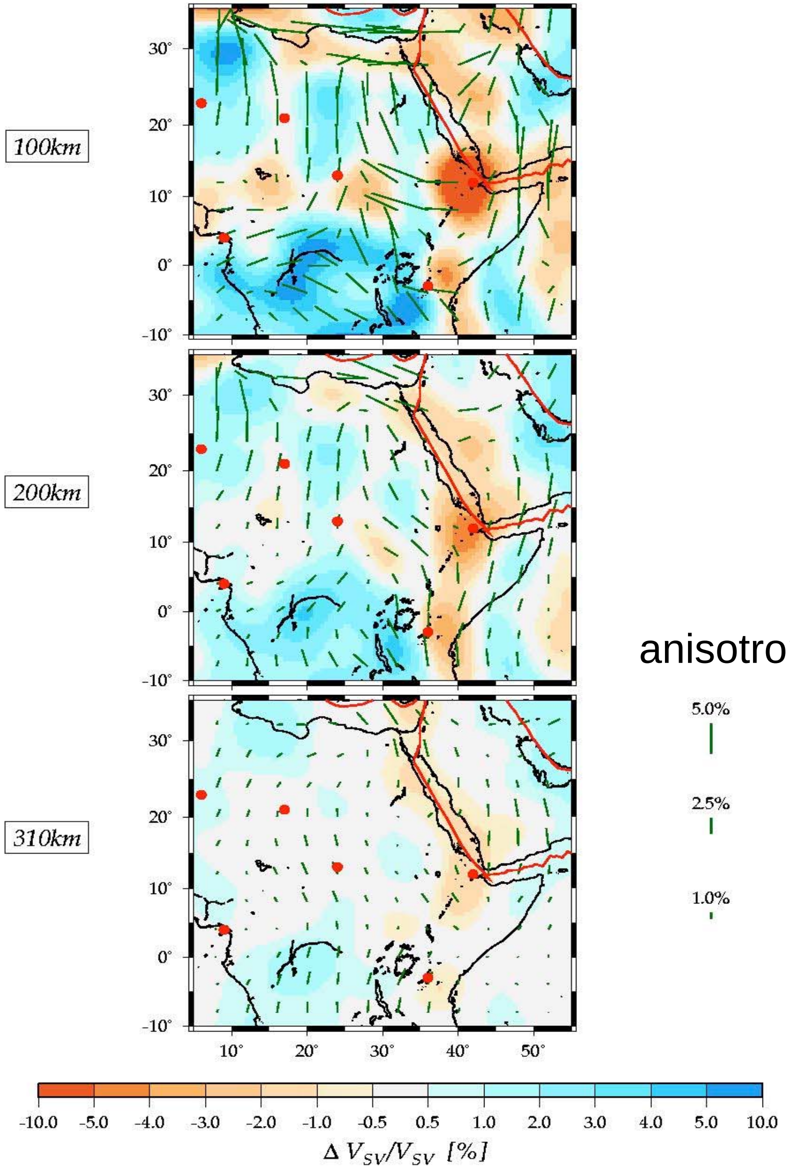


King & Ritsema, 1999

Depth=

Depth=

Depth=

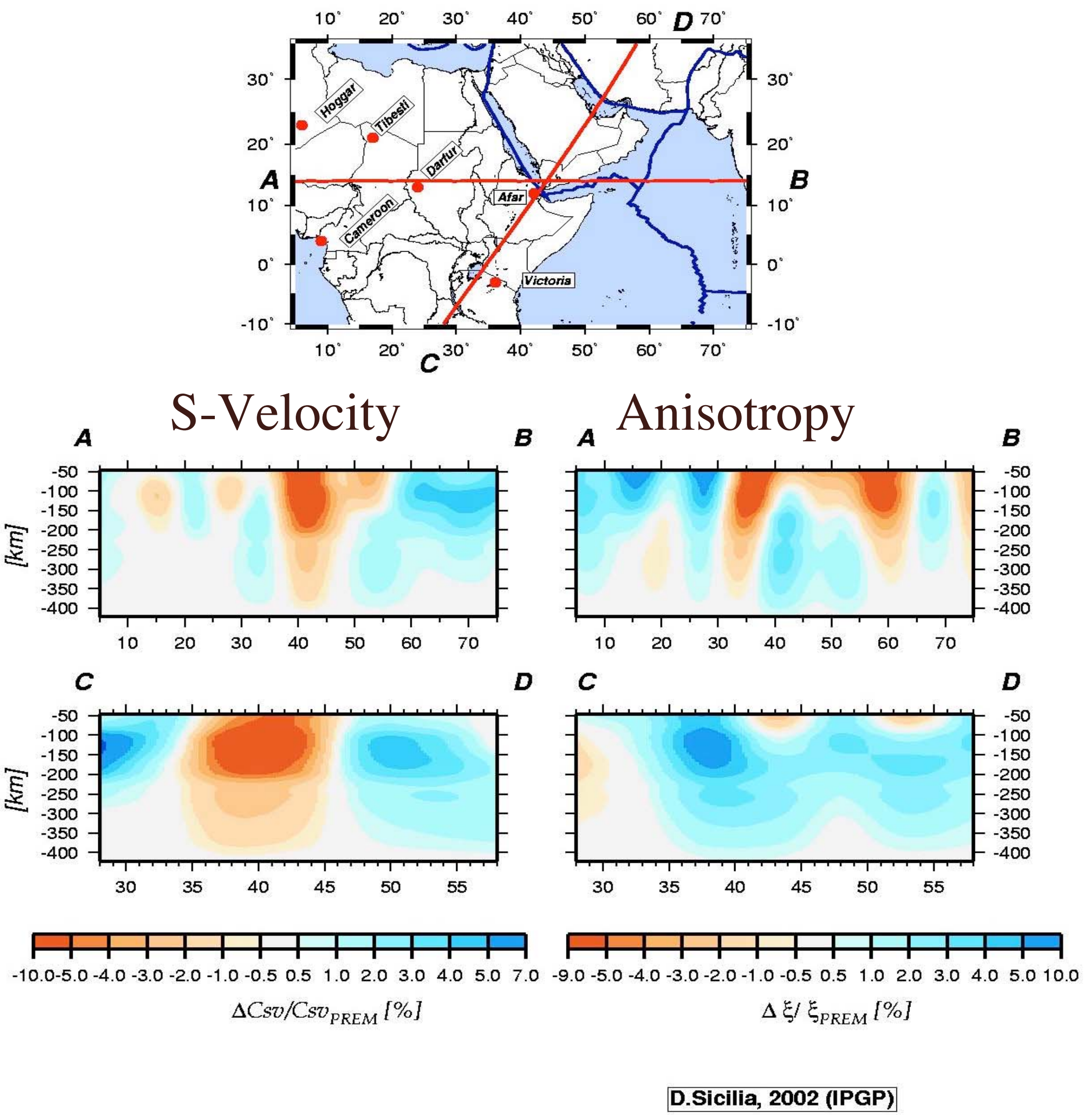


anisotropy

S-velocity

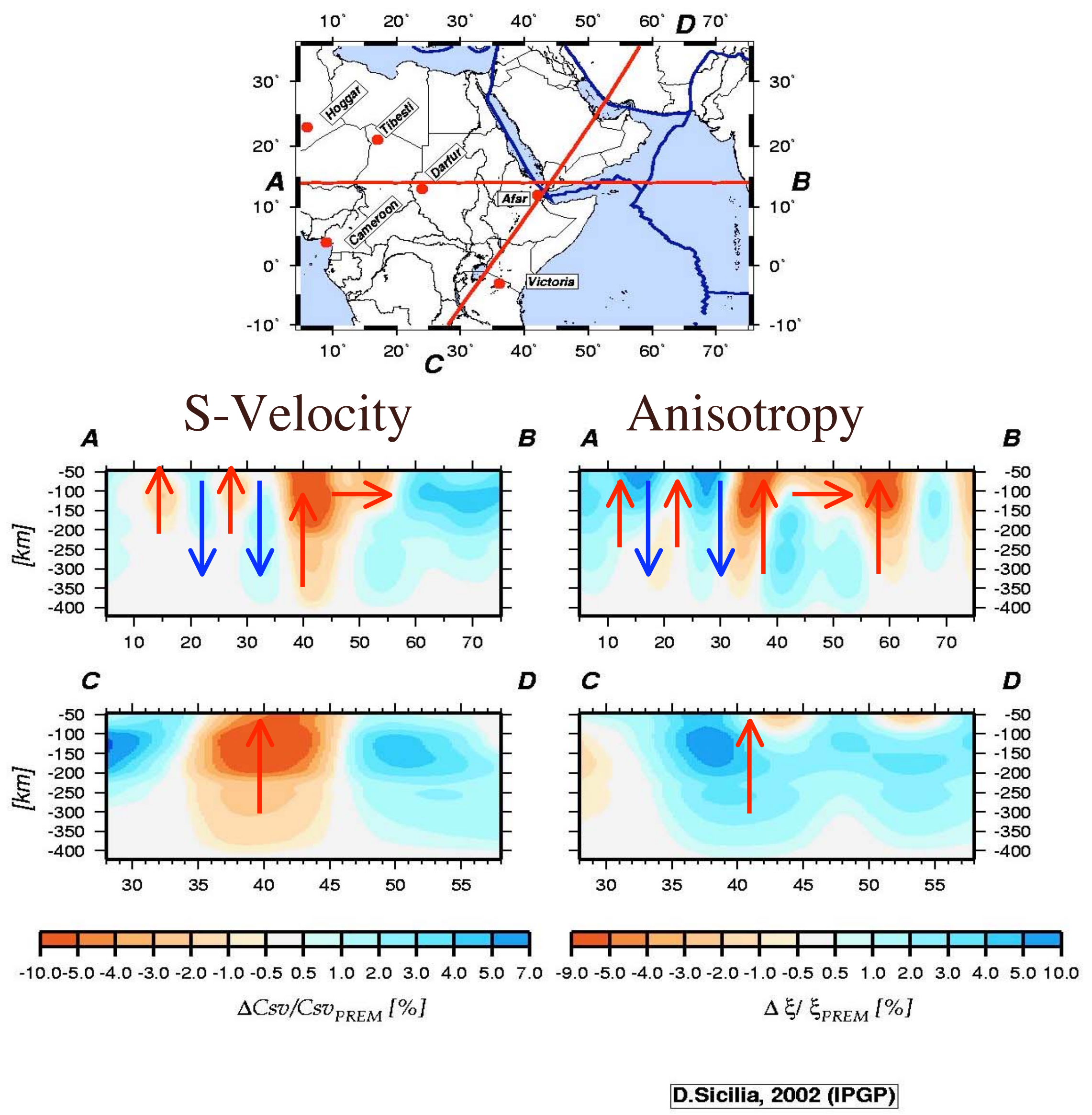
E-W

N-S

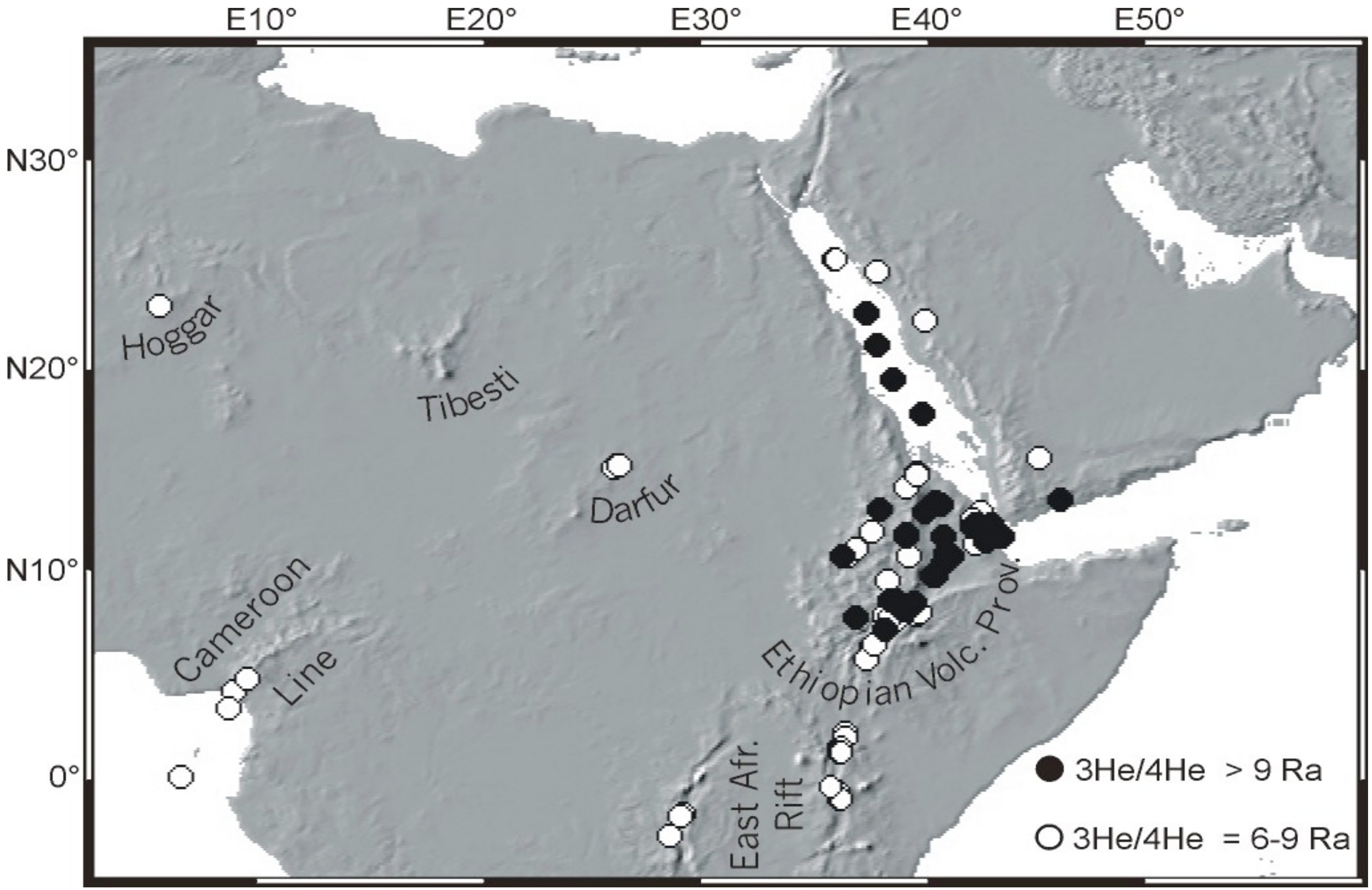

Hoggar
Tibesti
Darfur
Afar
Cameroon
Victoria
A
B
C
D
S-Velocity
Anisotropy
[km]
ΔCsv/Csv_PREM [%]
Δ ξ/ ξ_PREM [%]
D.Sicilia, 2002 (IPGP)

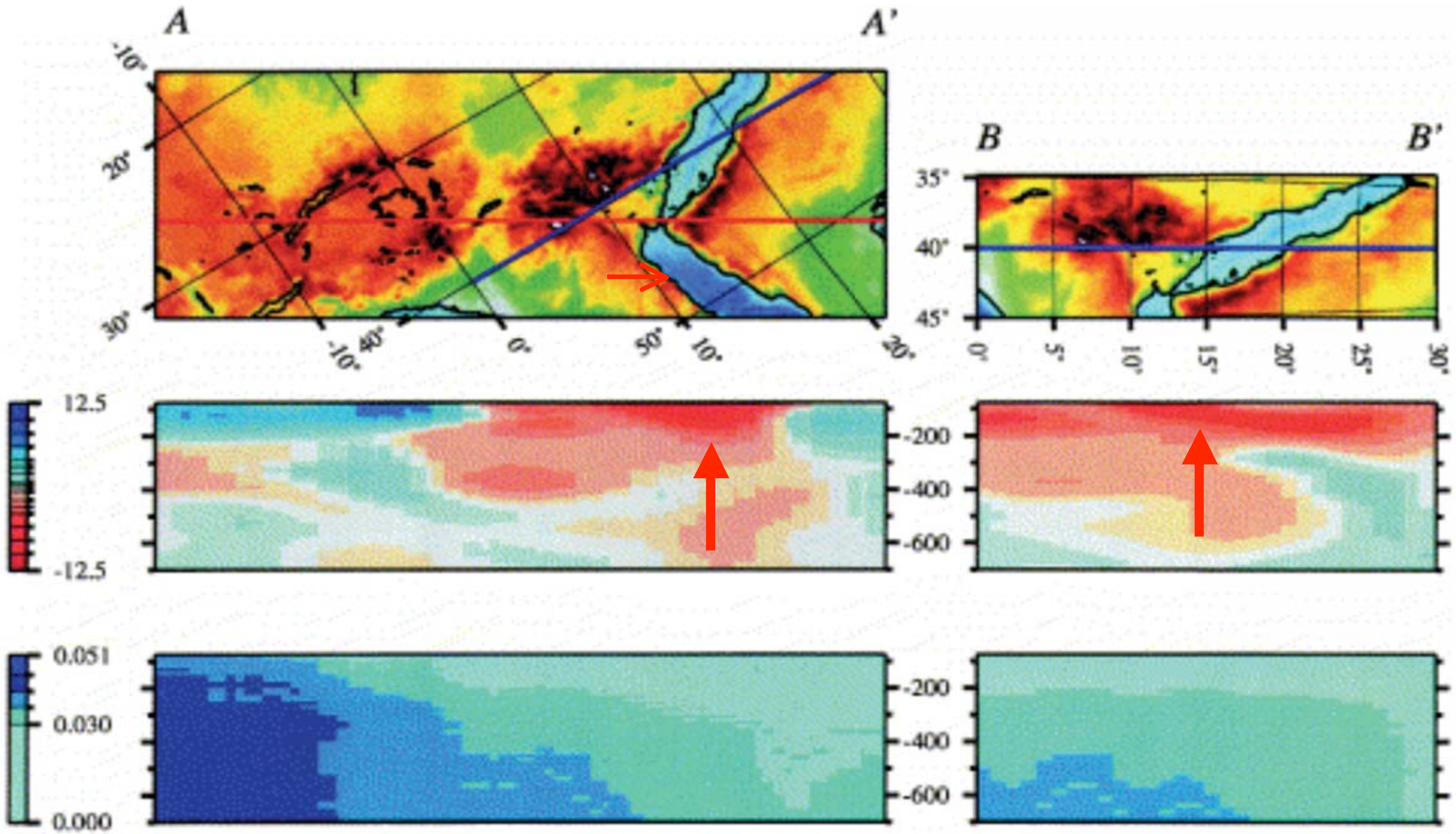
E-W

N-S



Hoggar
Tibesti
Darfur
Afar
Cameroon
Victoria
A
B
C
D
S-Velocity
Anisotropy
[km]
-10.0 -5.0 -4.0 -3.0 -2.0 -1.0 -0.5 0.5 1.0 2.0 3.0 4.0 5.0 7.0
ΔCsv/Csv PREM [%]
-9.0 -5.0 -4.0 -3.0 -2.0 -1.0 -0.5 0.5 1.0 2.0 3.0 4.0 5.0 10.0
Δ ξ/ ξ PREM [%]
D.Sicilia, 2002 (IPGP)


E10°
E20°
E30°
E40°
E50°
N30°
N20°
N10°
0°
Hoggar
Tibesti
Darfur
Cameroon
Line
Ethiopian Volc. Prov.
East Afr.
Rift
3He/4He > 9 Ra
3He/4He = 6-9 Ra



(Debayle et al., 2001)

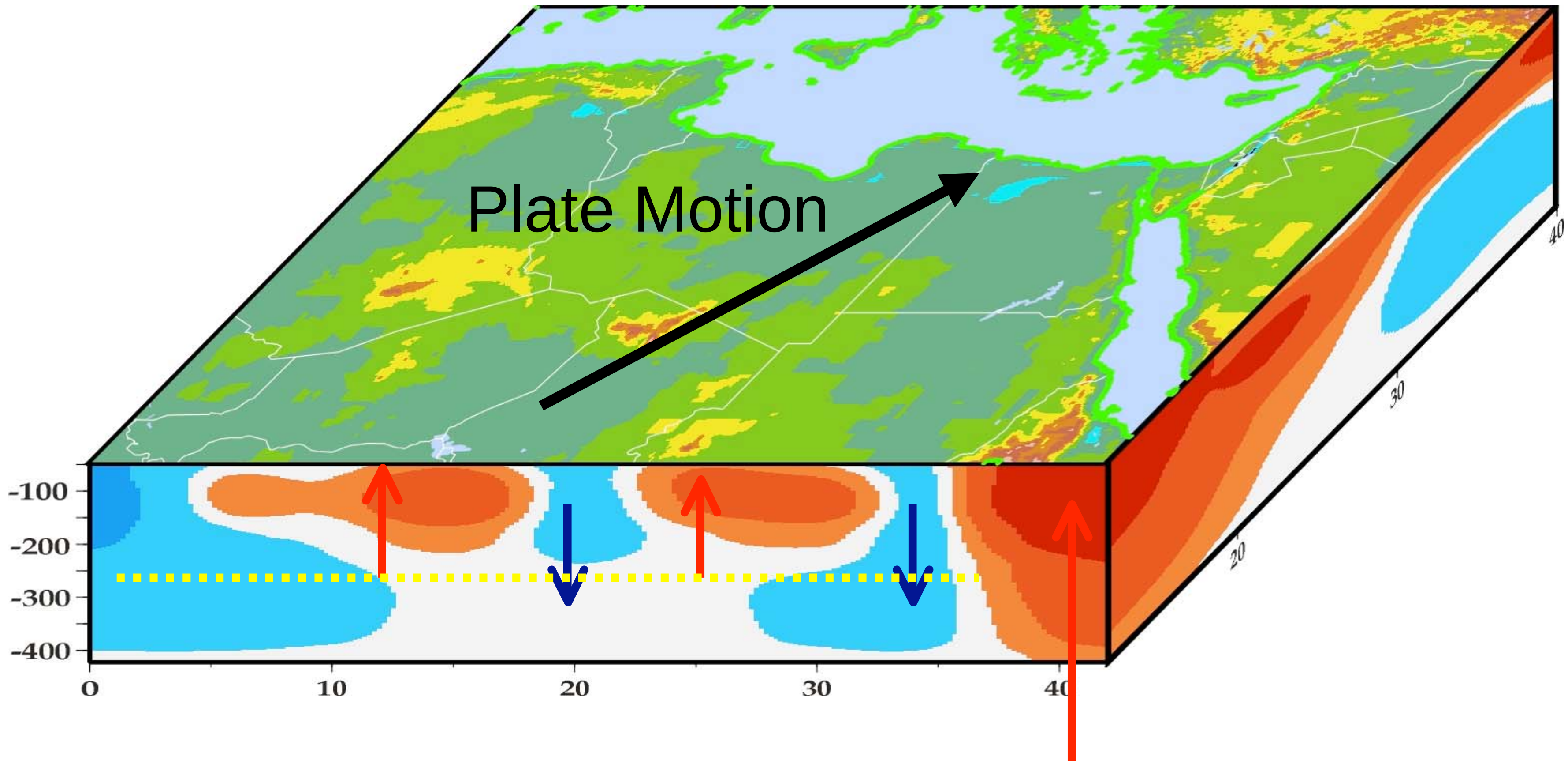
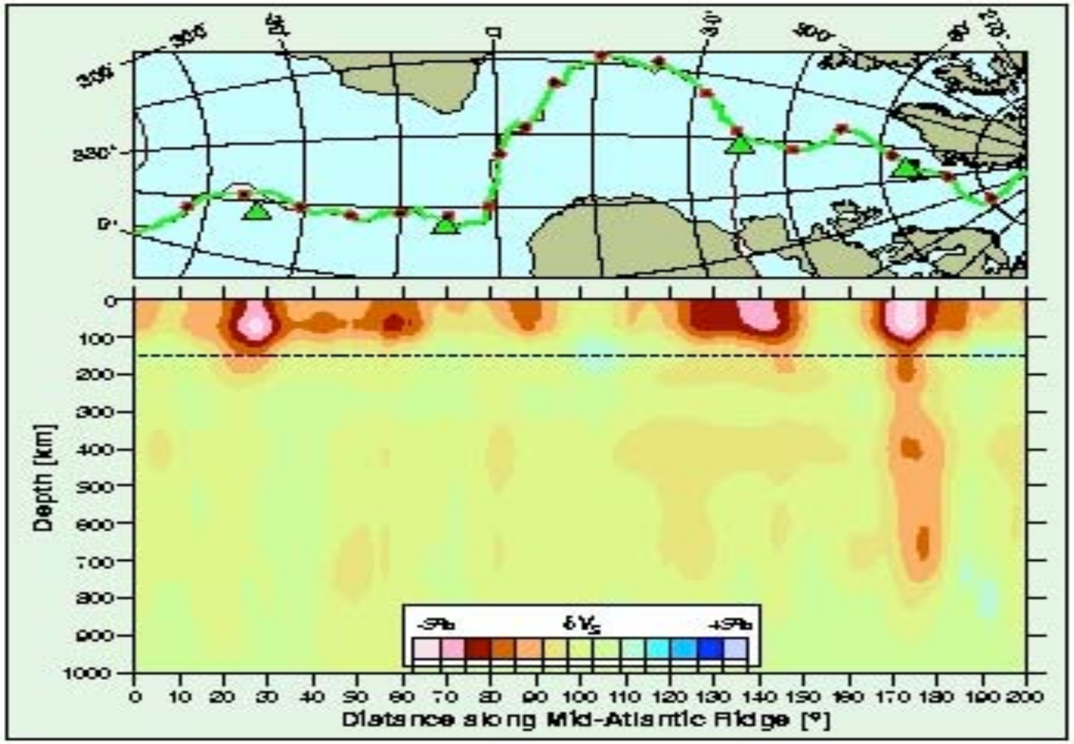
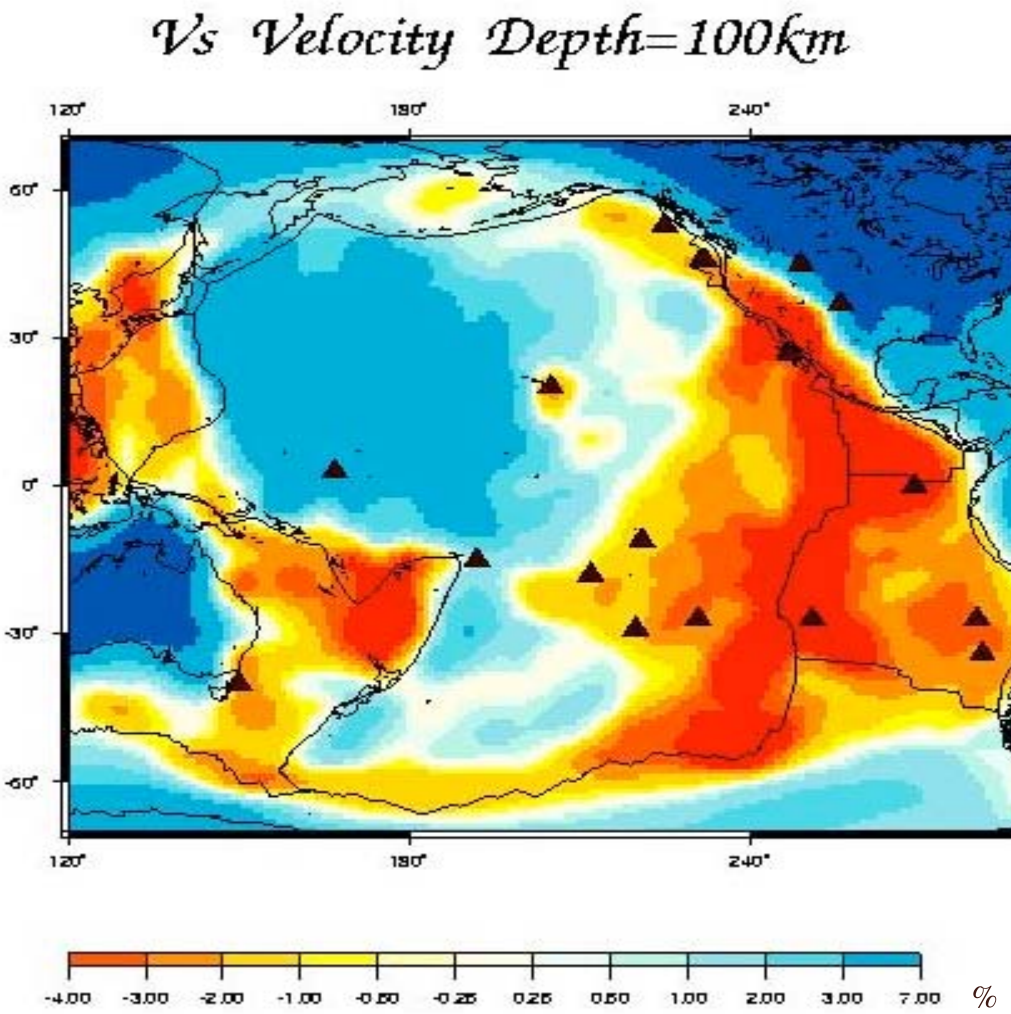


Plate Motion
-100
-200
-300
-400
0
10
20
30
40
20
30
40



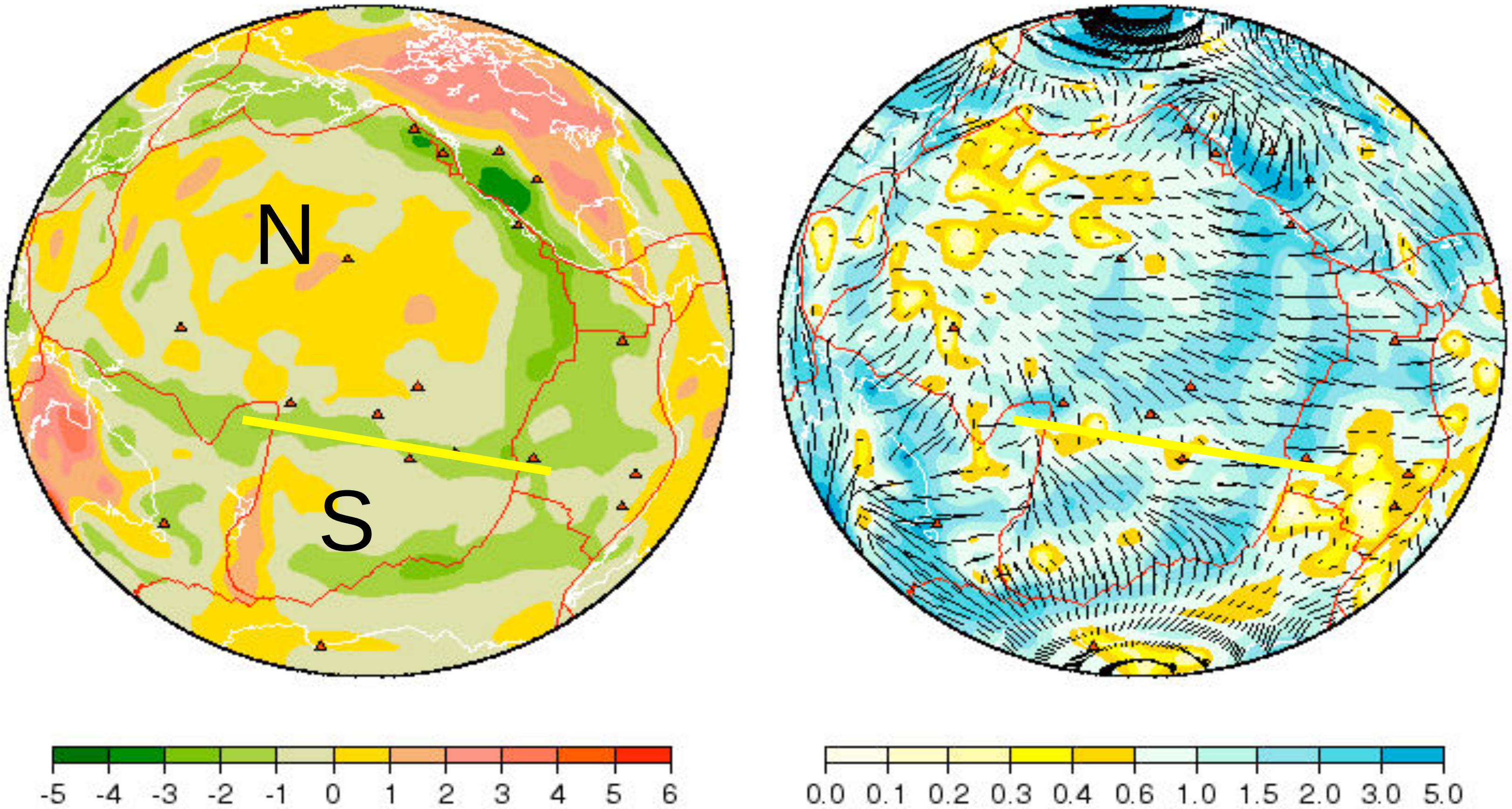
(Montagner and Ritsema, 2001)



(Montagner, 2002)

Future ridge between North and South Pacific ?

PREM (3SMAC) 2002 model - 140 km

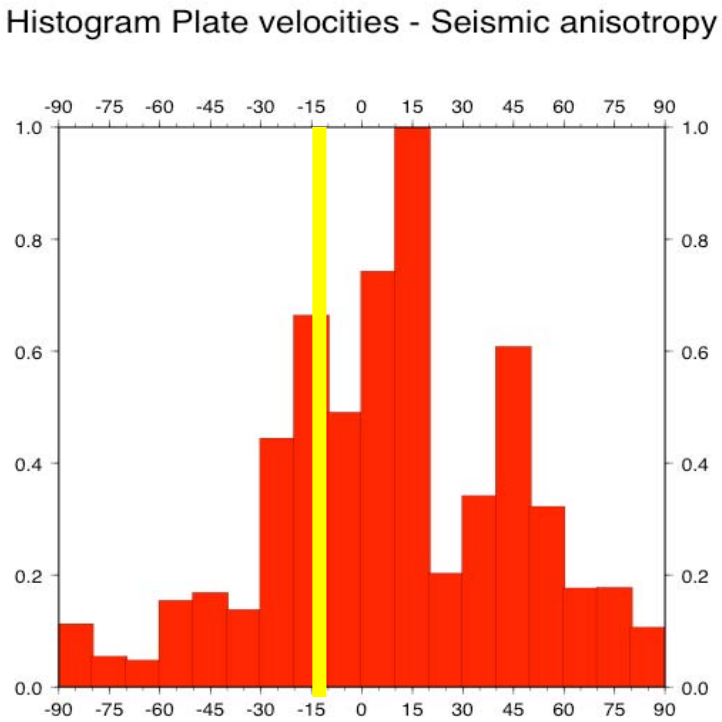


(a) Radial anisotropy

(b) Azimutal Anisotropy

Future Plate boundary within the Pacific plate?

Pacific Plate

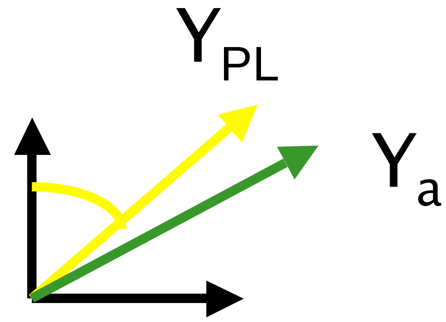


$Y_a \quad - \quad Y_{PL}$

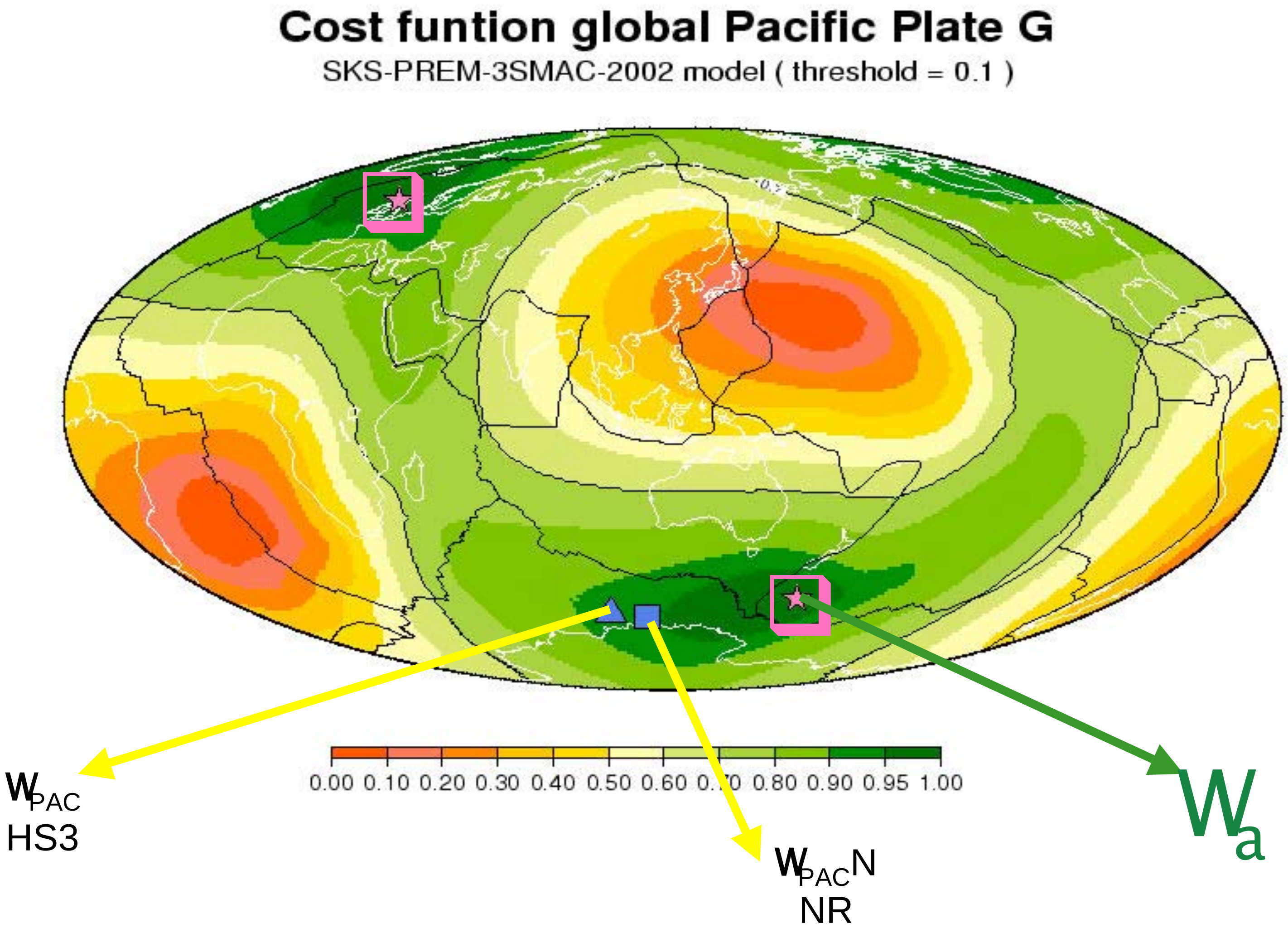
Angular difference (in degrees)

$$\mathbf{V}_{PL} = \mathbf{W}_{PL} \times \mathbf{OM}$$

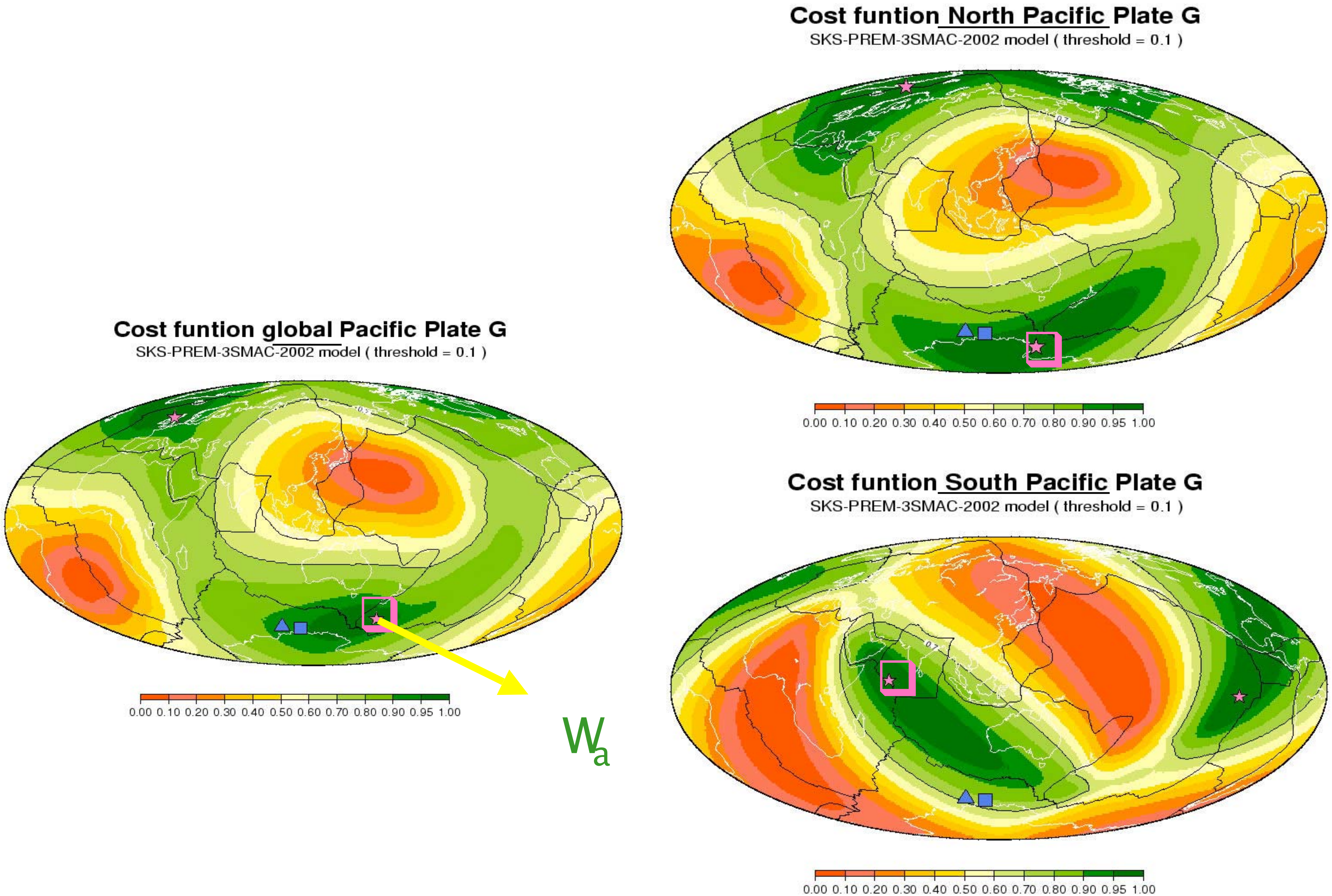
$\downarrow$



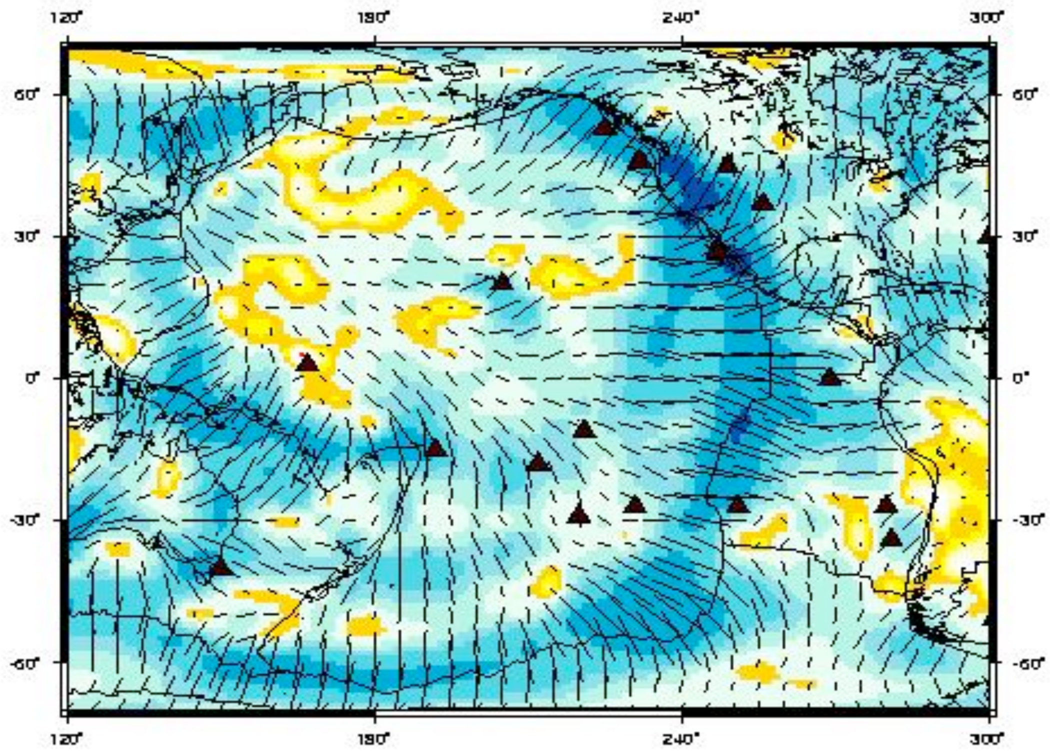
$$Y_a \longrightarrow (\mathbf{W}_a\,,\ \mathbf{W}_a^{antip})$$

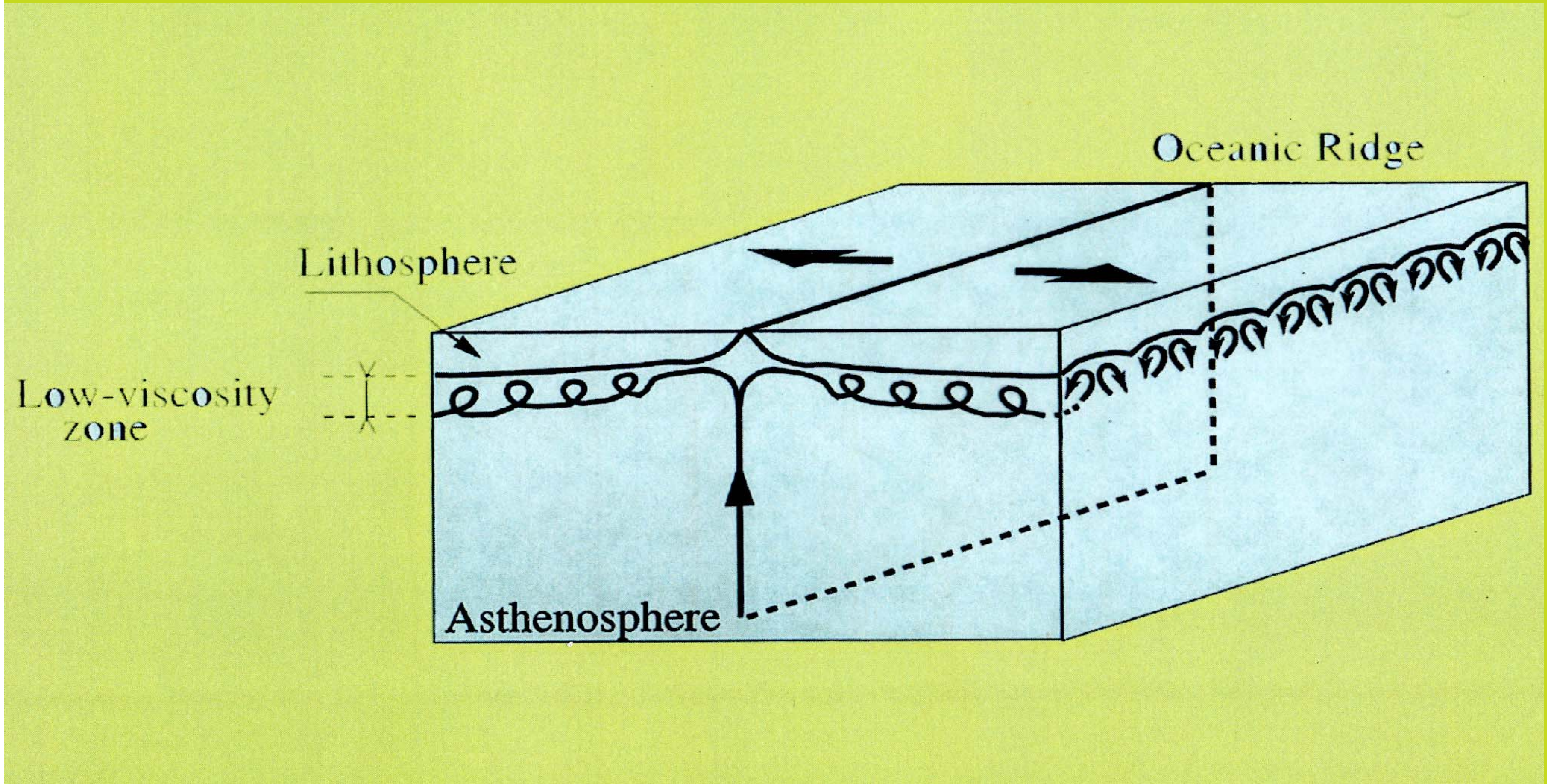


Cost funtion global Pacific Plate G
SKS-PREM-3SMAC-2002 model (threshold = 0.1)
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.80 0.90 0.95 1.00
W PAC
HS3
W PAC N
NR
Wa


Cost funtion North Pacific Plate G
SKS-PREM-3SMAC-2002 model (threshold = 0.1)
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 0.95 1.00
Cost funtion global Pacific Plate G
SKS-PREM-3SMAC-2002 model (threshold = 0.1)
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 0.95 1.00
W_a
Cost funtion South Pacific Plate G
SKS-PREM-3SMAC-2002 model (threshold = 0.1)
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 0.95 1.00

G:Azim. Anis. Depth=100km

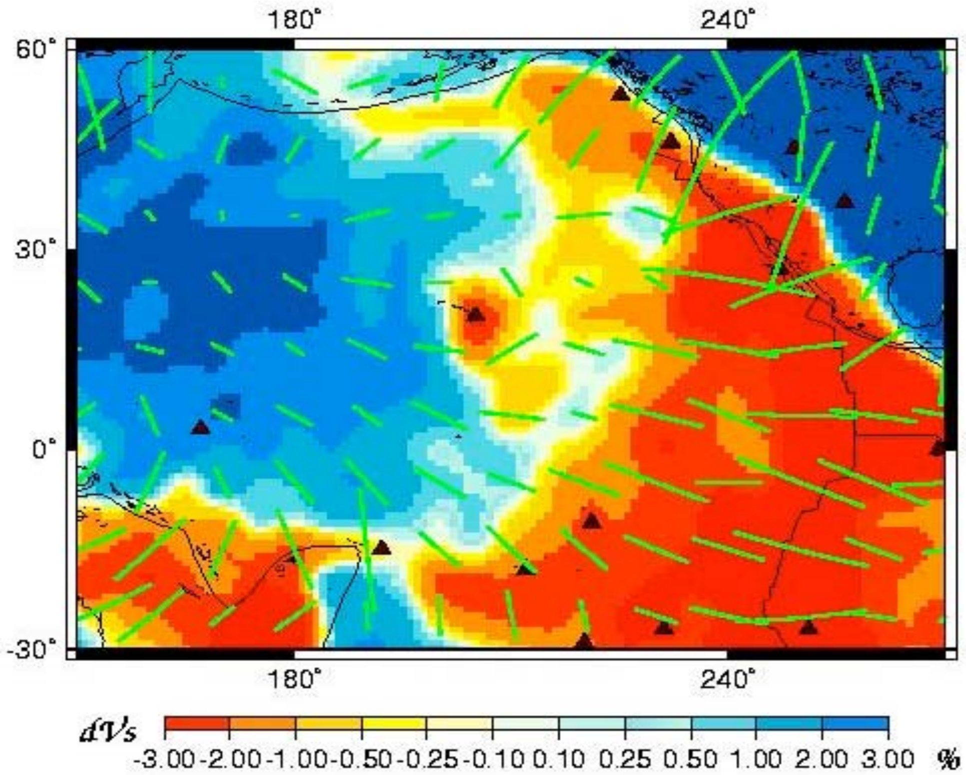


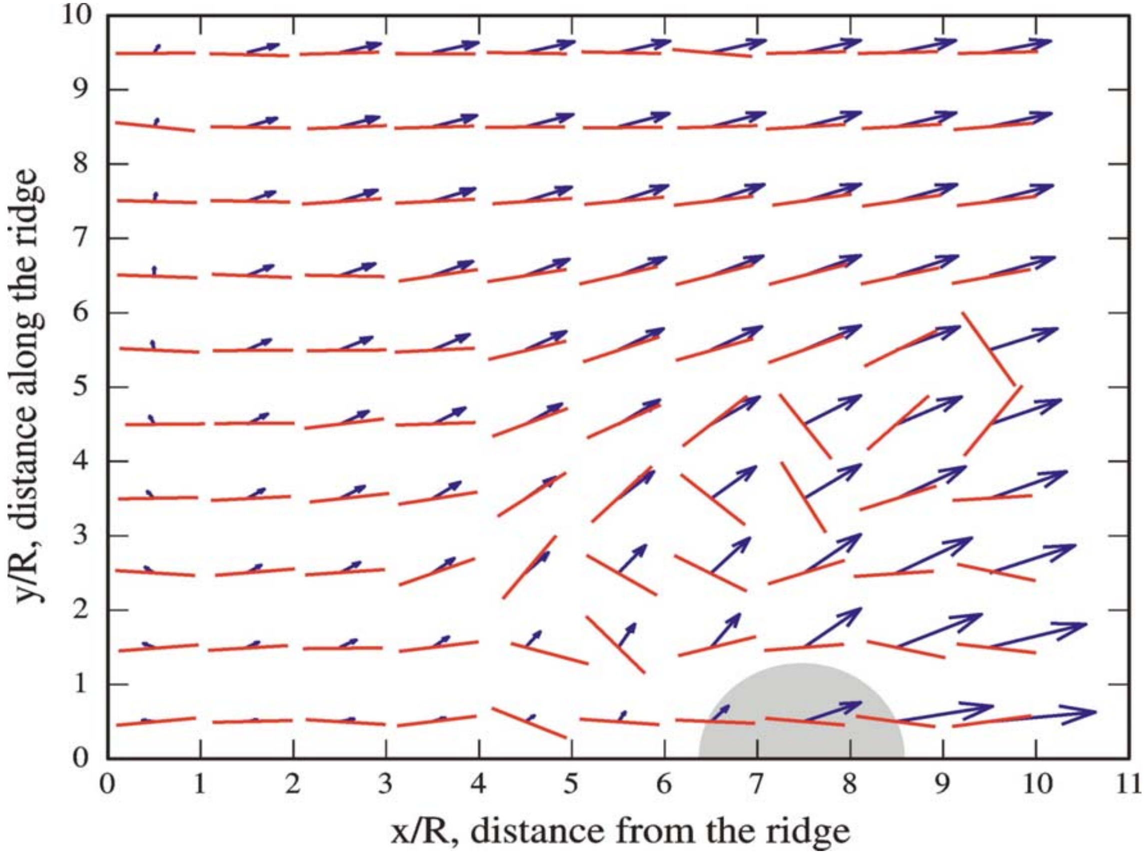


(Crambes and Davaille, 2002)

S-wave velocity + Azimuthal Anisotropy

Depth=120 km





$8\xi = D$

ξ

$D \approx 2000\text{km} \Rightarrow d \approx 250\text{km}$

(Kaminski and Ribe, 2001)

Plume Detection

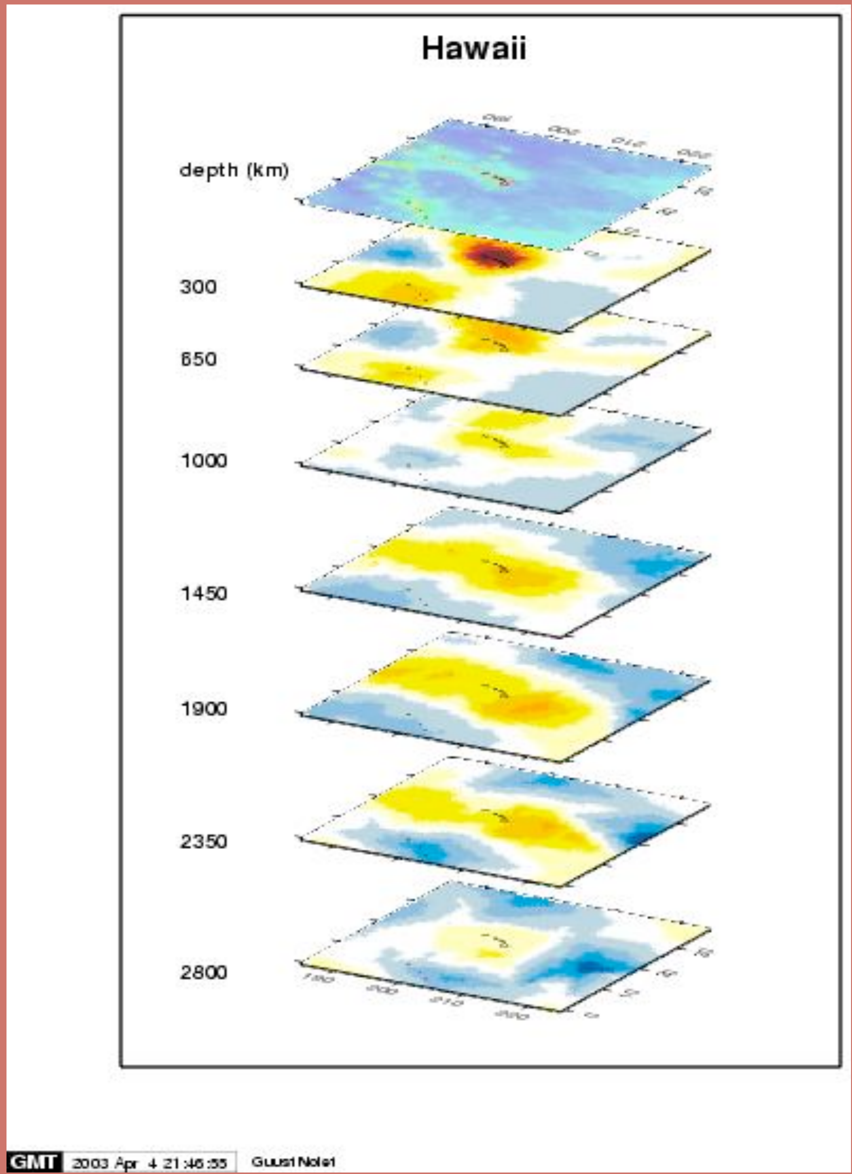
- Indirect detection of plumes through Azimuthal and Radial anisotropies.
- Two families of plumes have been detected:

- 1st kind is a consequence of small scale convection (<300km).
- 2nd kind originates from deep in the mantle: transition zone (410-660km).

- Complex interaction Plume-lithosphere-asthenosphere:secondary scale of convection.
- Active hotspots in central Pacific and Africa participate to the reorganization of plate boundaries (New Plate boundaries).
- Lower Mantle plume not yet clearly detected because it cannot be detected with present seismic data
- Theoretical and Observational challenges

Banana-Doughnut Theory
(Dahlen et al.)

Application to global tomography
(Montelli et al., Science, 2004)



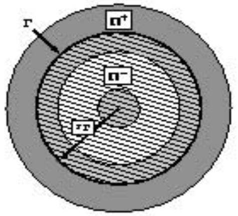
Overview
Large scale Seismology:

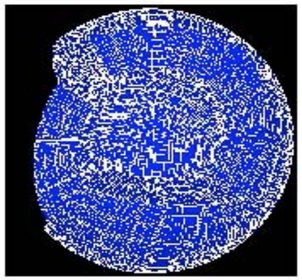
- Data (Seismic source) + Instrument (Seismometer) -> Observations (seismograms)
- Historical evolution: Ray theory, Normal mode theory, Numerical techniques (SEM, NM-SEM)
- Scientific Issues: earthquakes, structure of the Earth and planets
- Seismic Experiment: Plume dectection
- NM-SEM and time reversal

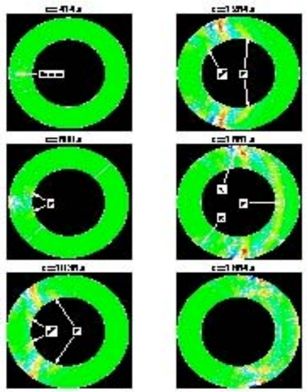
Coupled method of Spectral Elements and Modal Solution

Principle:

- Ω^+: Spectral Element area: 3D model
- Ω^-: Modal Solution area: 1D model

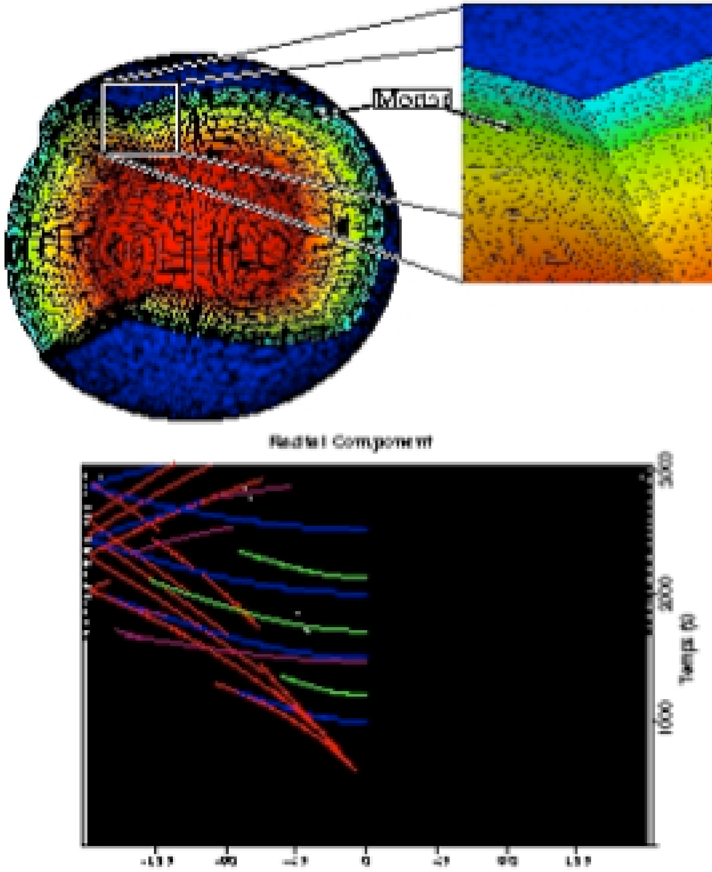


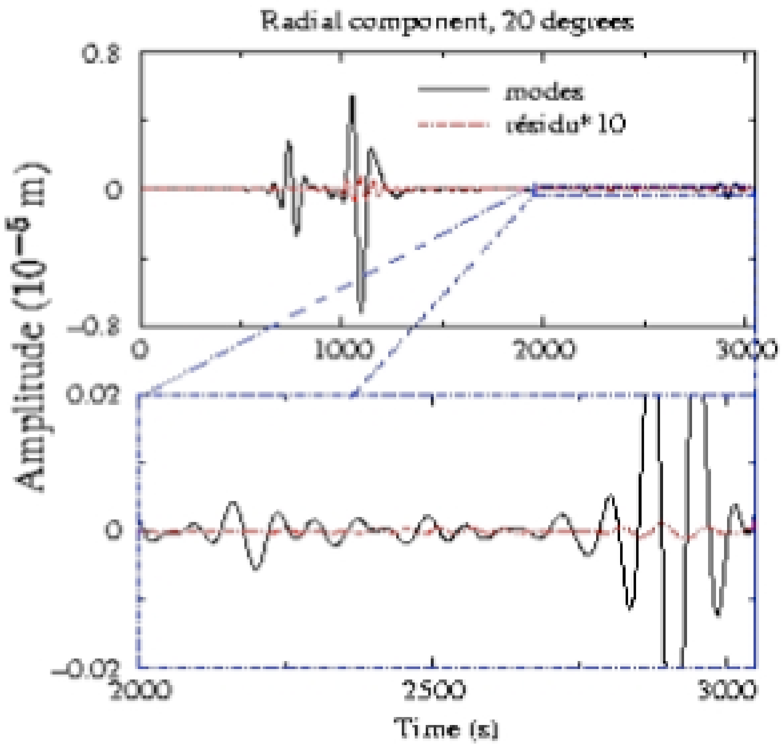




Capdeville et al., 2003

Example: PREM





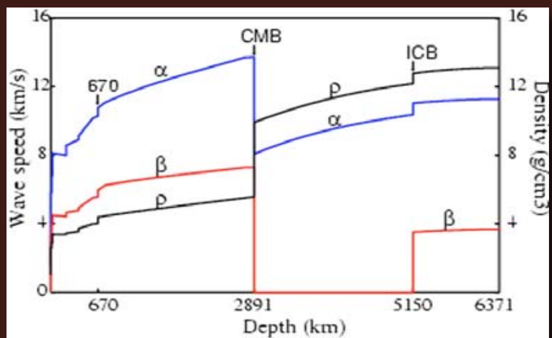
Time Reversal

1. Seismic displacement field **u**(r,t) can be calculated everywhere by SEM-NM method

$$\partial^2 u/\partial t^2 = H.u$$

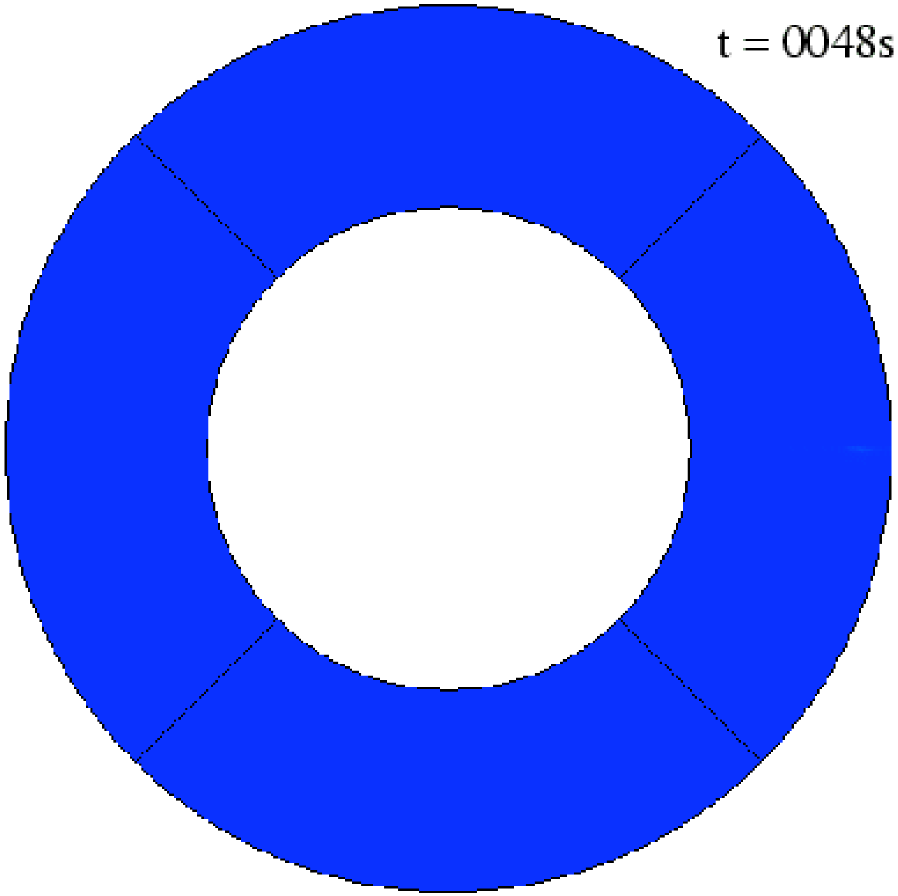
2. In the absence of attenuation, if u(t) is solution, u(-t) is also solution.
3. It is possible to backpropagate u(r,-t)

1D PREM



Larmat et al., 2004

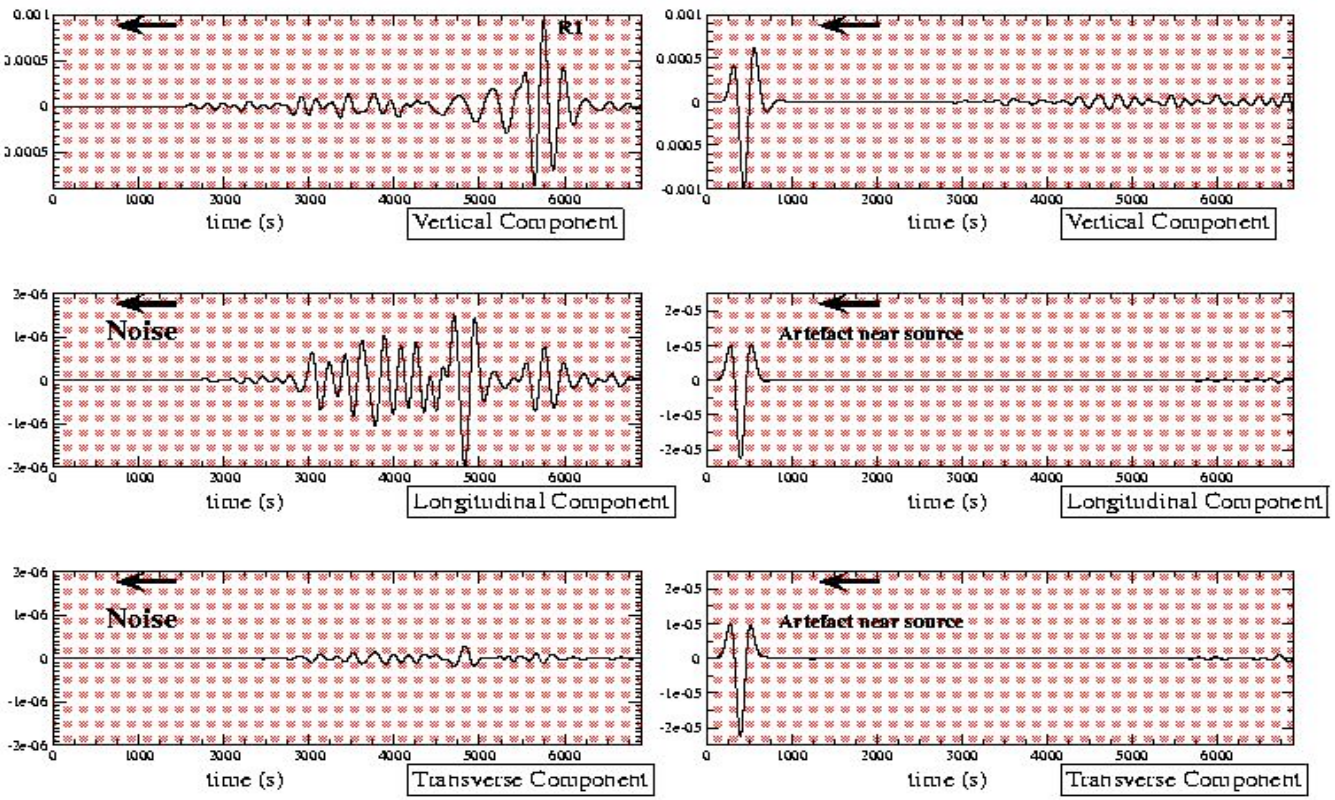
Forward Problem

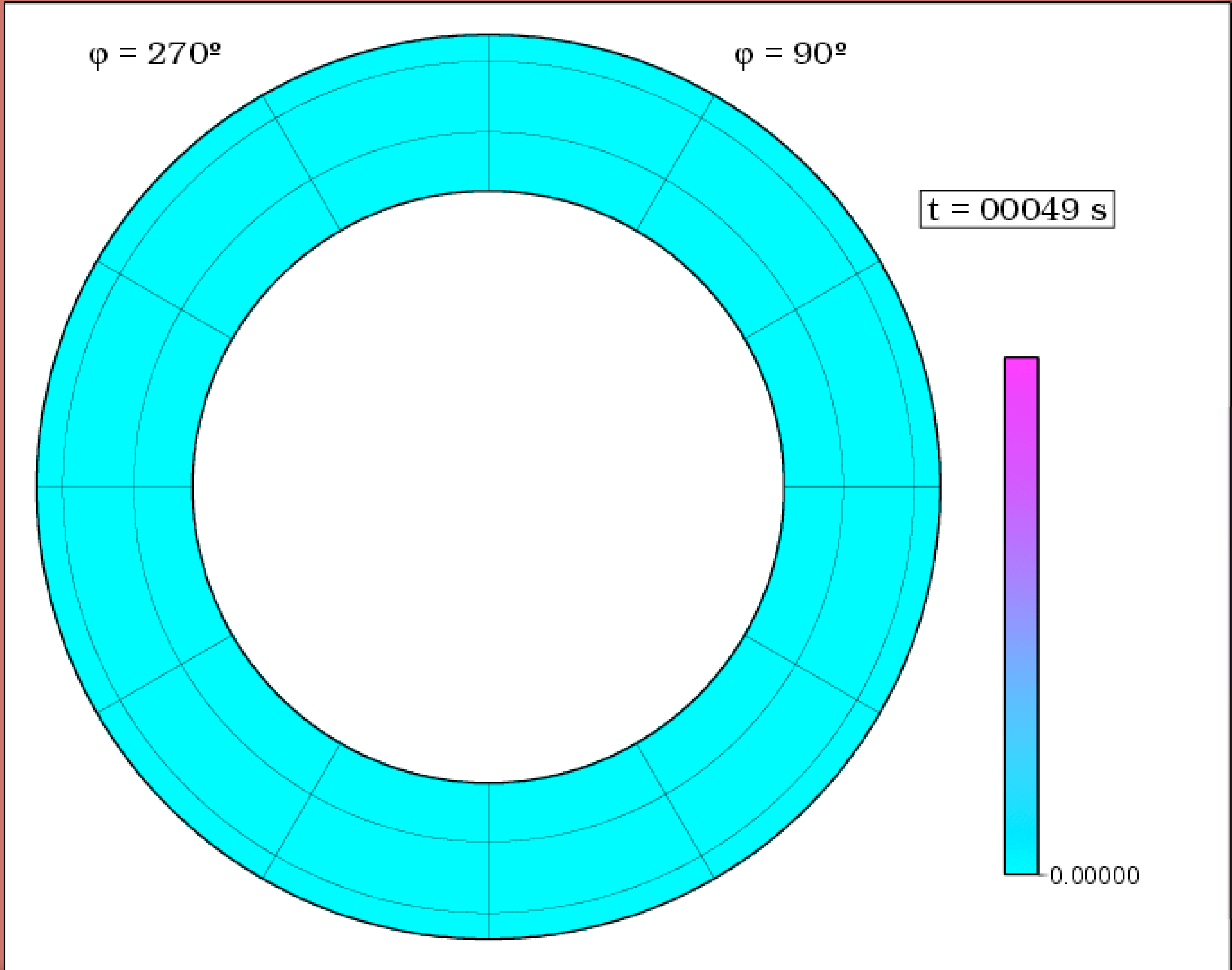


How much Information is backpropagated (PREM exp.)?

Antipode :

Epicentre :

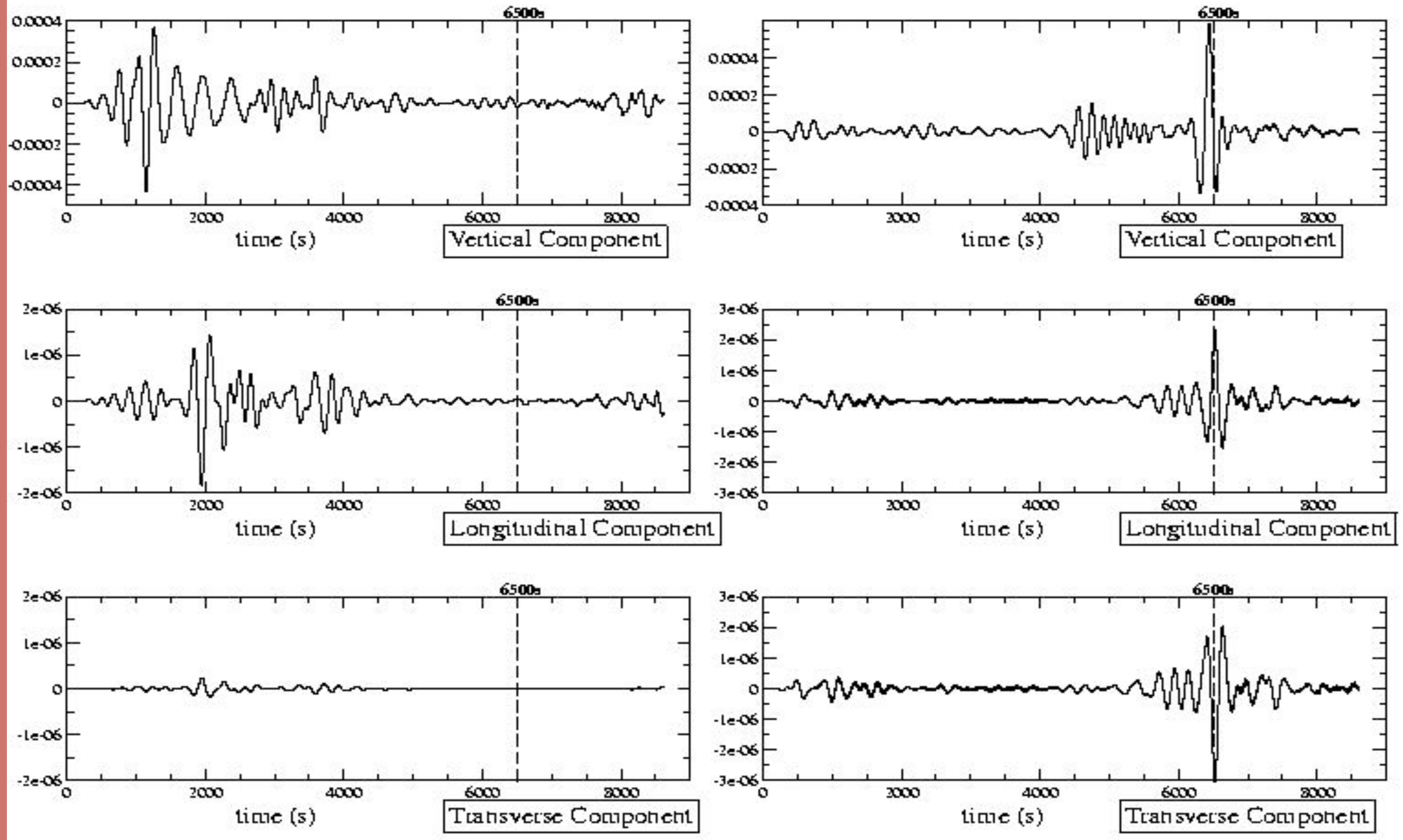



φ = 270º
φ = 90º
t = 00049 s
0.00000

Time–reversed wave measurements – from all the points of the mesh (PREM

Antipode (p=398 km):

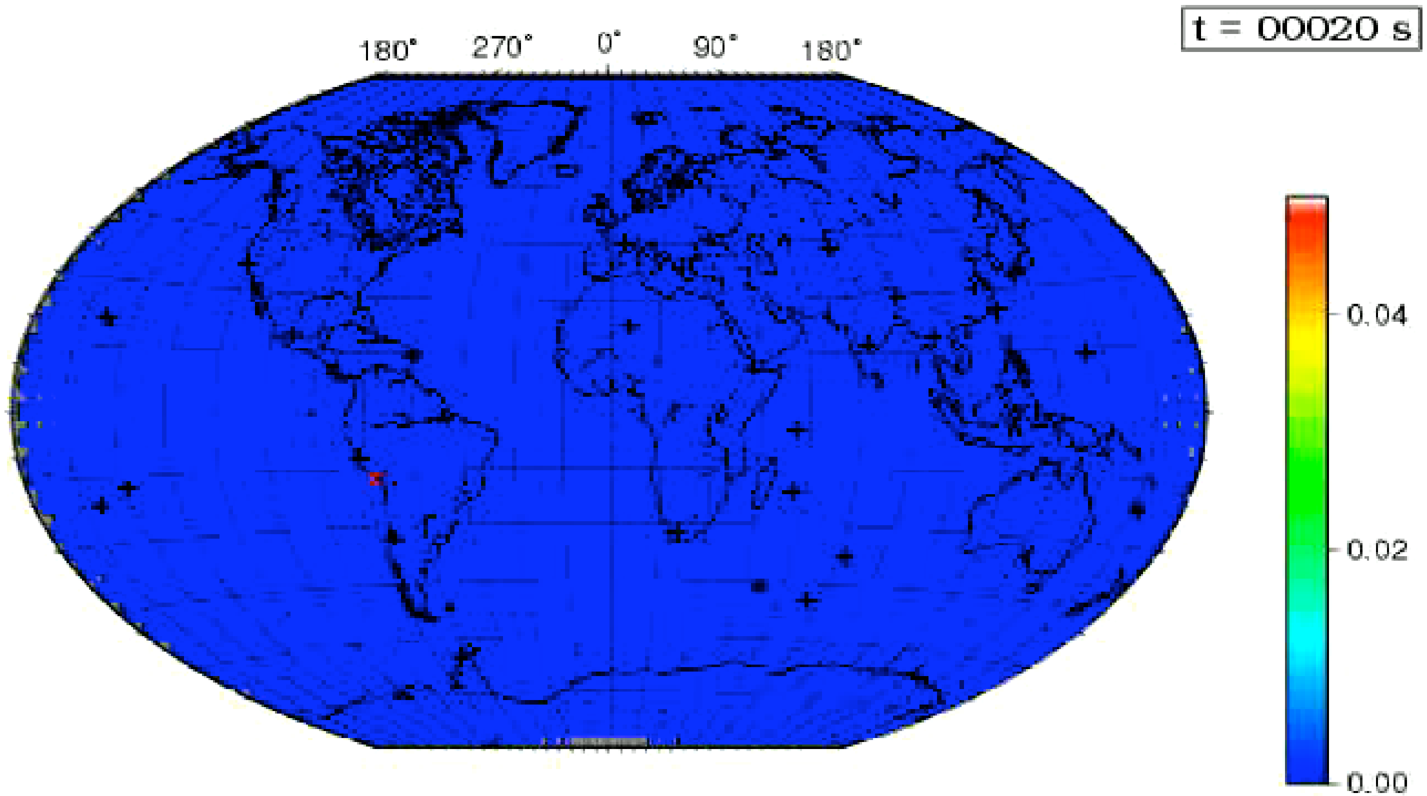
Source Point (p=398 km) :



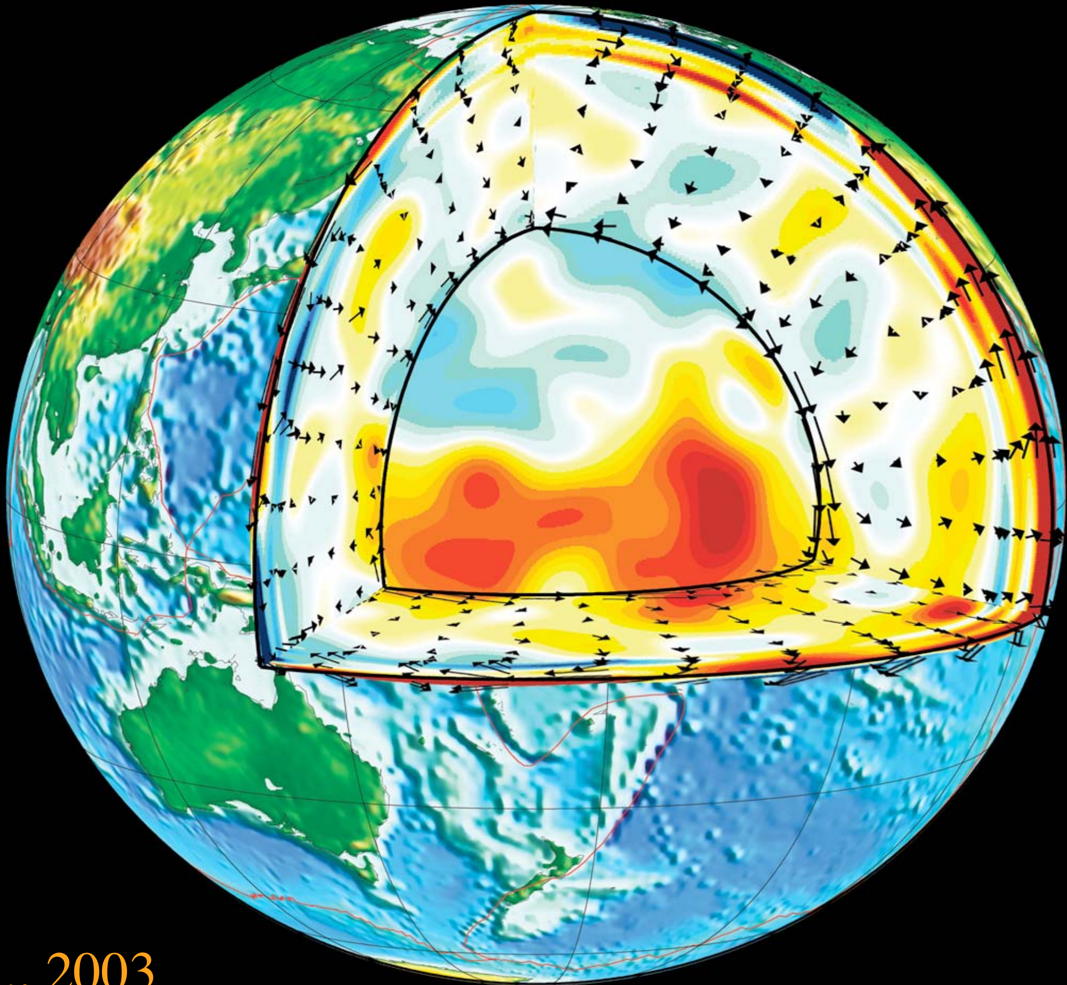
Time Reversal

- Application to real seismograms with a real earthquake with a distribution of present seismic stations
- Detection of unknown seismic sources (quiet earthquakes, origin of “seismic hum”)
- Detection of mantle plume

Peru Earthquake (2002)



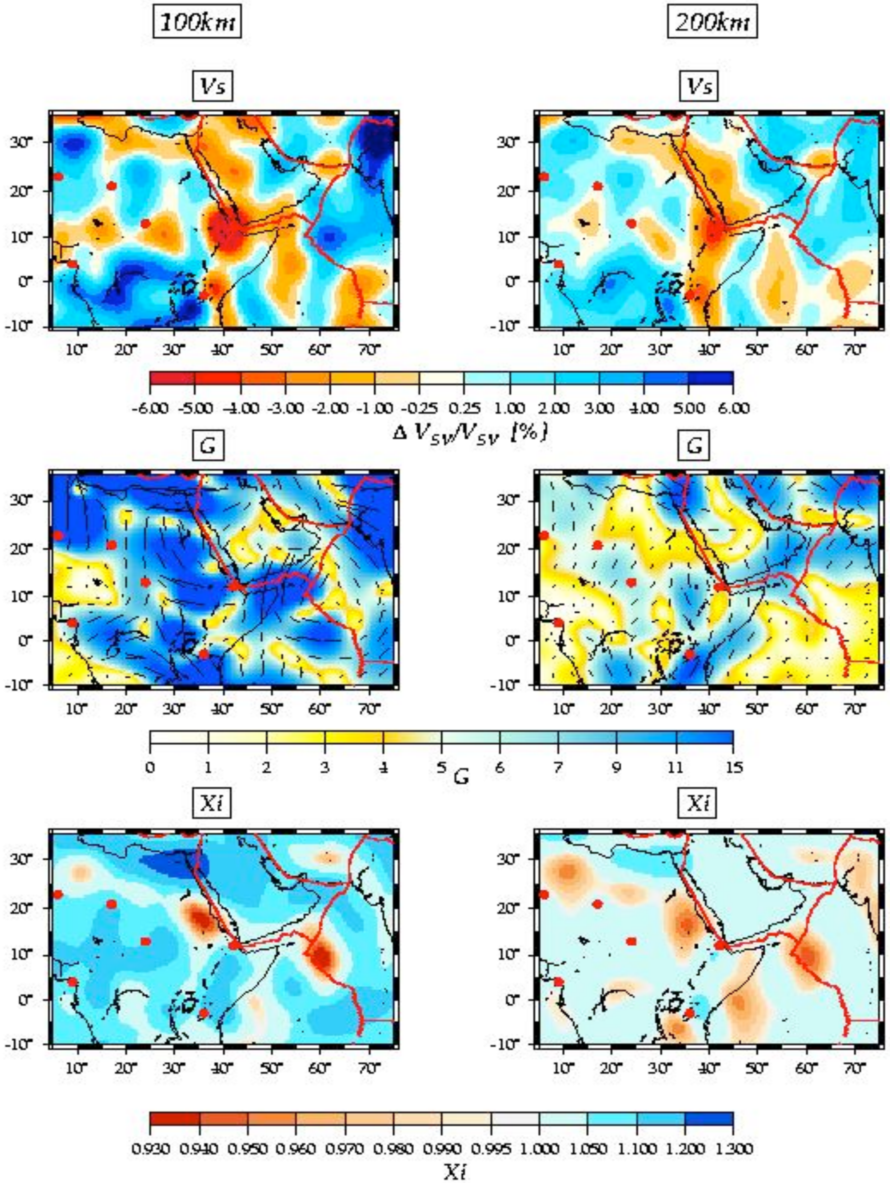
Anisotropy- Geodynamics Relationship



Gaboret et al., 2003

CONCLUSIONS

- Progress in instrumentation (Ocean bottom, Planet Mars; Spatial exploration)
- Ray Theory - Normal Modes -> Numerical Methods more and more powerful and accurate de by using more and more powerful computers.
- From Global scale towards regional scale- Incorporation of new parameters (anisotropy, anelasticity) in tomography
- Systematic Multidisciplinary Approach: Confrontation of seismological results with numerical and laboratory experiments



S-wave velocity

Azimuthal anisotropy

Radial Anisotropy

$$\mathbf{D = 1 - (dV_{SH}/V_{SV})^2}$$