Seismic Anisotropy and Passive Monitoring of Seismogenic Zones

Jean-Paul Montagner, Maria Saade, Philippe Roux, Florent Brenguier, Stéphanie Durand, Paul Cupillard, Lucia Zaccarelli, …

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Frequency	**Mhz-kHz**	**10000-100Hz**	**100-10Hz**	**10Hz-1Hz**	**1-0.001Hz**
Domain	Laboratory acoustics	Underwater acoustics	Shallow seismic imaging	Seismic imaging	Seismology-large scale
Applications	NDT Monitoring	Tomography Source detection	Structure of shallow layers Geotechnical applications, land slides Monitoring	Natural resources Natural hazards Monitoring	Structure of the Earth, Earthquake risk zonation, Monitoring
Wave type	Acoustic/ elastic waves	Acoustic waves	Elastic waves	Elastic waves	Elastic waves

OUTLINE

- **Data: Seismic noise** (microseismic noise; seismic Hum)
- **Cross-correlation tensor: Seismic Anisotropy?**
- **Scientific Issues**:

- Structure of the Earth from Seismic Hum
- **Seismic monitoring:**
  Temporal changes of anisotropy in seismogenic zones
  Numerical modeling
- Interpretation of observed anisotropy

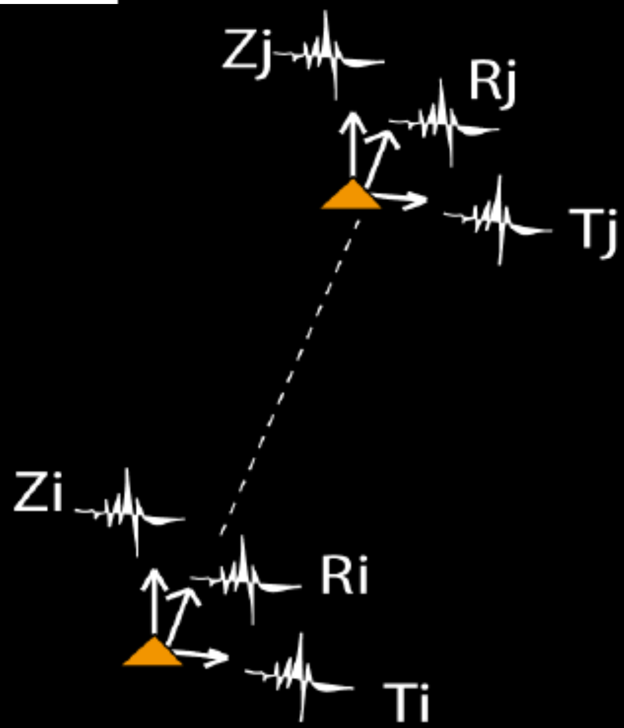
Cross-correlation tensor

for 2 stations i, j and 3 components k, l

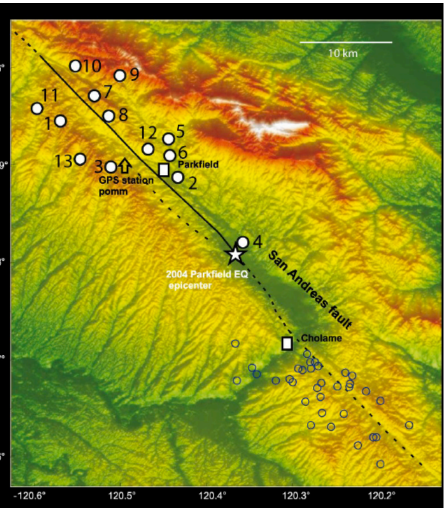
$$[C_{ij}(t)]_{kl} = \frac{\int_0^T S_{ik}(\tau)\, S_{jl}(t+\tau)\, d\tau}{\sqrt{\int_0^T S_{ik}^2(\tau) d\tau \int_0^T S_{jl}^2(\tau) d\tau}},$$

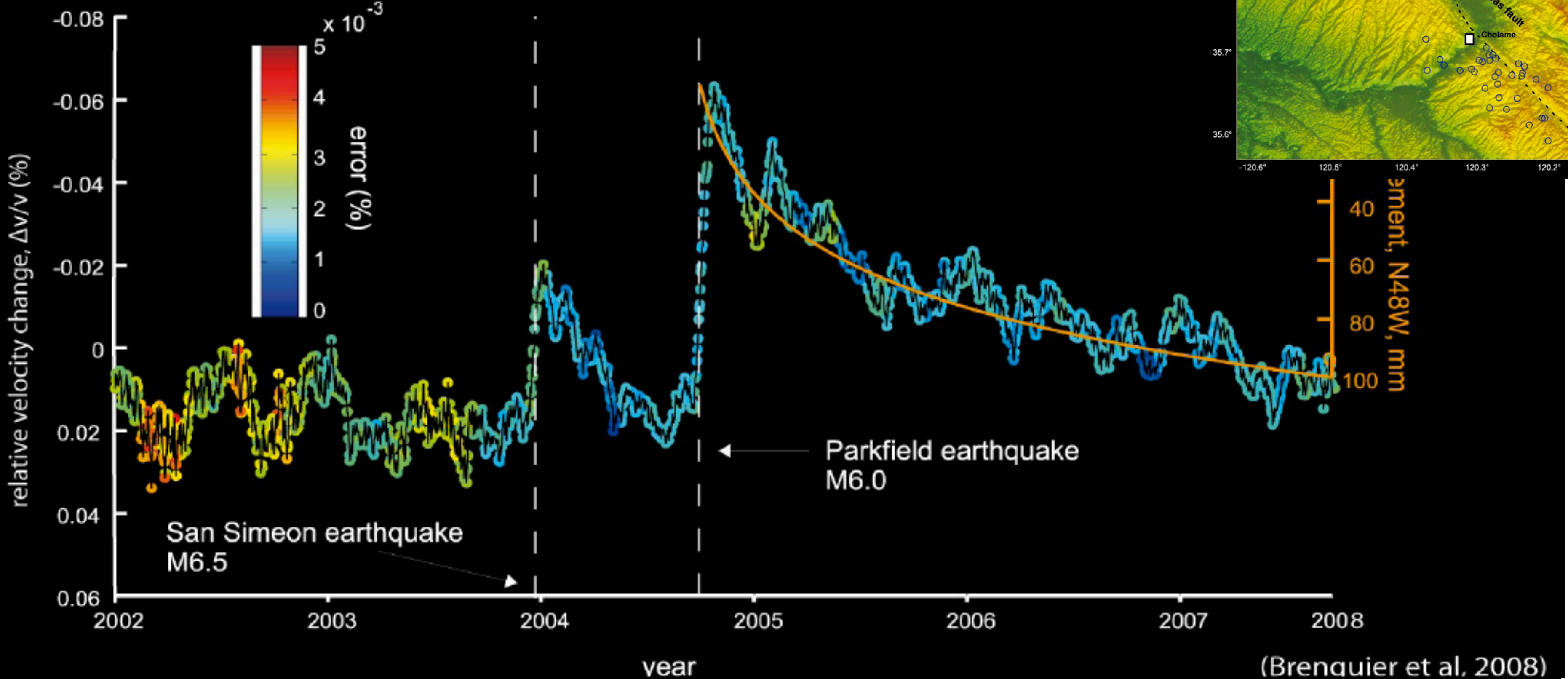
ZZ	ZR	ZT
RZ	RR	RT
TZ	TR	TT

Brenguier et al., 2008



Parkfield High Resolution Seismic Network (HRSN)

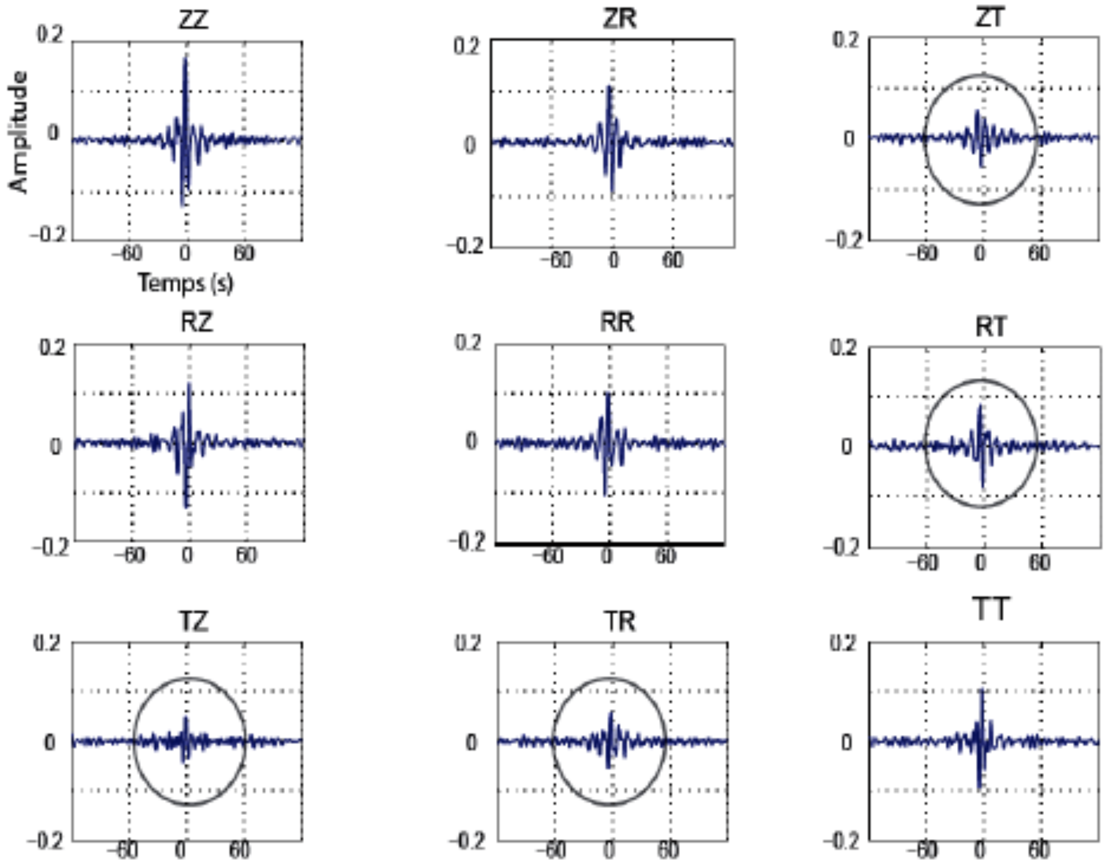




ZZ: Co-seismic and post-seismic relative velocity change (Brenguier et al., 2008)

Example of cross-correlation tensor

Parkfield HRSN – Stack (30days)



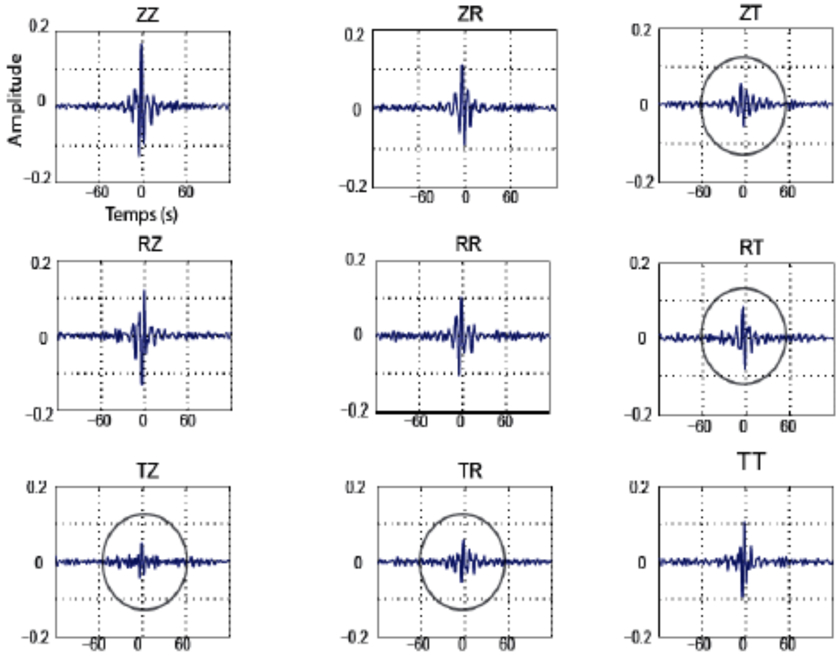
TZ, TR, ZT, RT ≠ 0

How can we explain the off-diagonal terms

of the cross-correlation tensor?

TZ, TR, ZT, RT ≠ 0

-Non uniform distribution of seismic noise sources?
-Lateral heterogeneities of Velocities?
-Seismic anisotropy?



Seismic Anisotropy is present at all scales

-From microscopic scale up to macroscopic scale

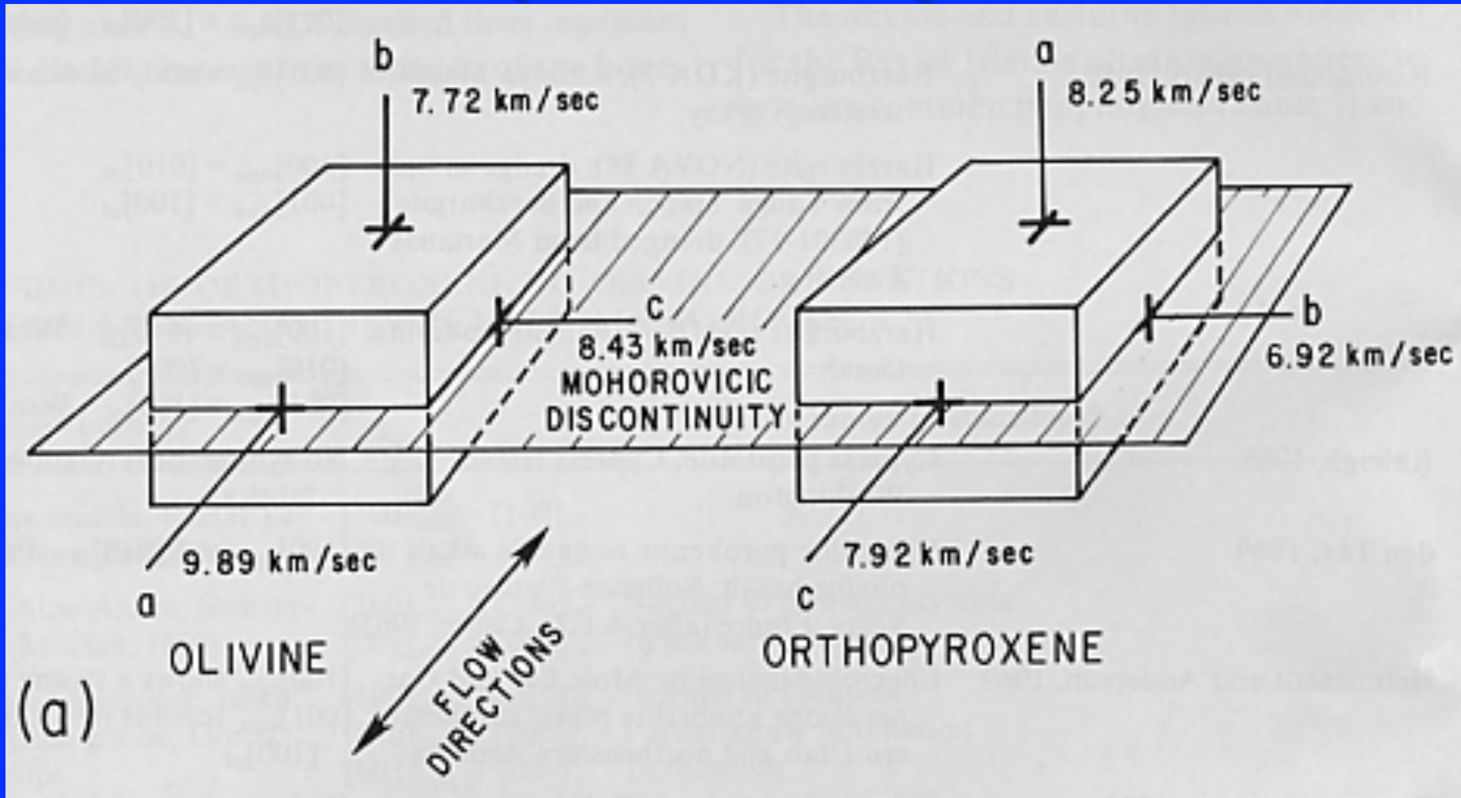
-Efficient mechanisms of alignment of minerals in the crust and upper mantle:

(L.P.O.: Lattice preferred orientation;
S.P.O.: Shape preferred orientation;
Fine Layering)

ANISOTROPY is the Rule not the Exception

Apparent (observed) anisotropy:
NON UNIQUE INTERPRETATION
in different depth ranges of the Earth

L.P.O. : Lattice Preferred Orientation (strain field)



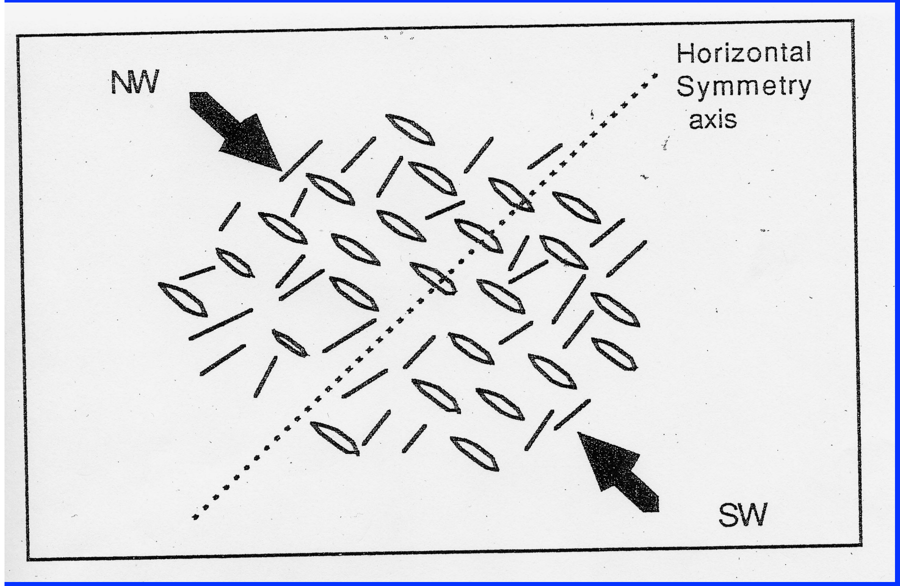
Christensen and Lundquist, 1982

→ ***STRAINMETER***

Mapping of mantle convection

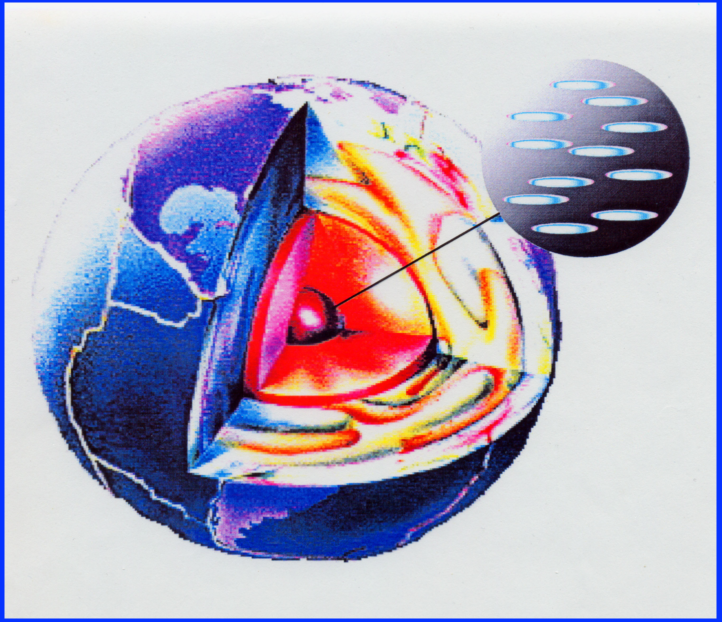
S.P.O.: Cracks, fluid inclusions, …
(Stress field)

Crust (+lithosphere)



(Babuska and Cara, 1991)

Inner core



(Singh et al., 2001)

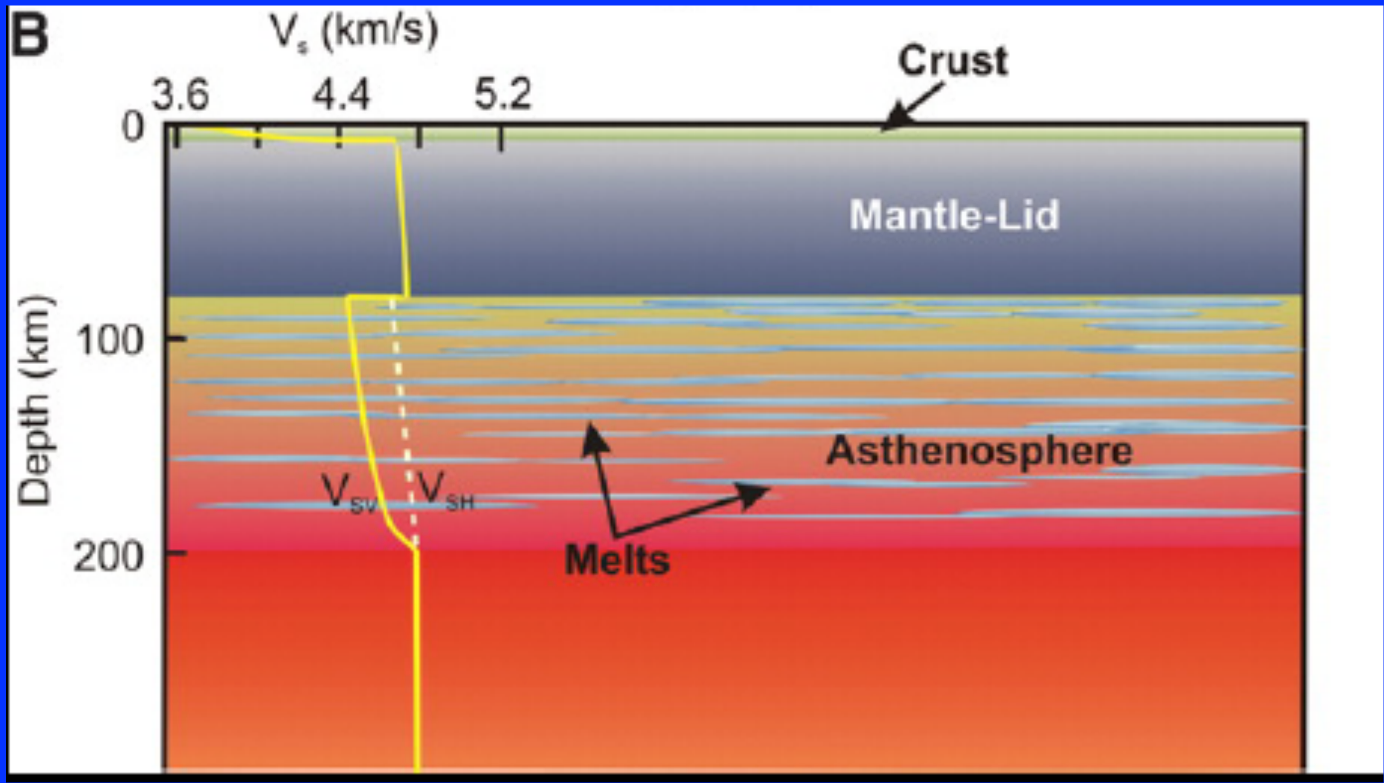
→ STRESSMETER

Temporal variations of anisotropy?

Monitoring of cracked, fractured zones

(seismogenic zones: Durand et al. 2011; Saade et al., 2013)

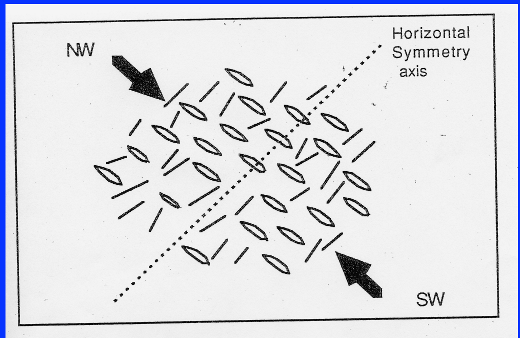
FINE LAYERING: Stratification Anisotropy
Mille-feuilles model (partial melting)

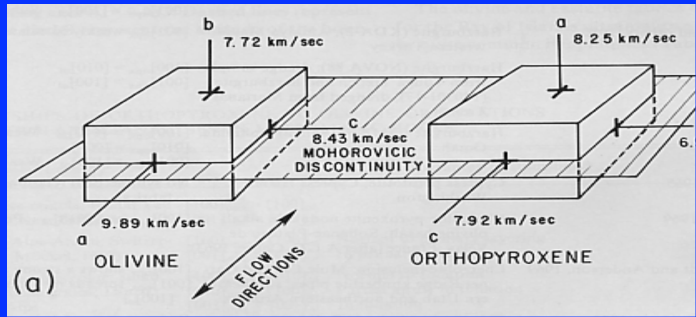


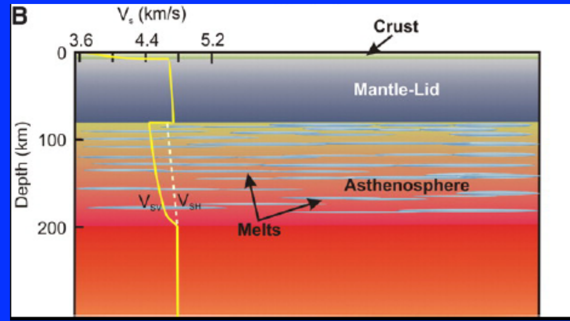
Radial anisotropy (Kawakatsu et al. 2009)
V.T.I. Vertical Transverse Isotropy medium: 5 parameters
($A=\rho\ V_{PH}^2$, $C=\rho\ V_{PV}^2$, F, $L= V_{SV}^2$, $N= V_{SH}^2$)

Different processes in different layers

-S.P.O. (stress)   -L.P.O.(strain)   Fine Layering







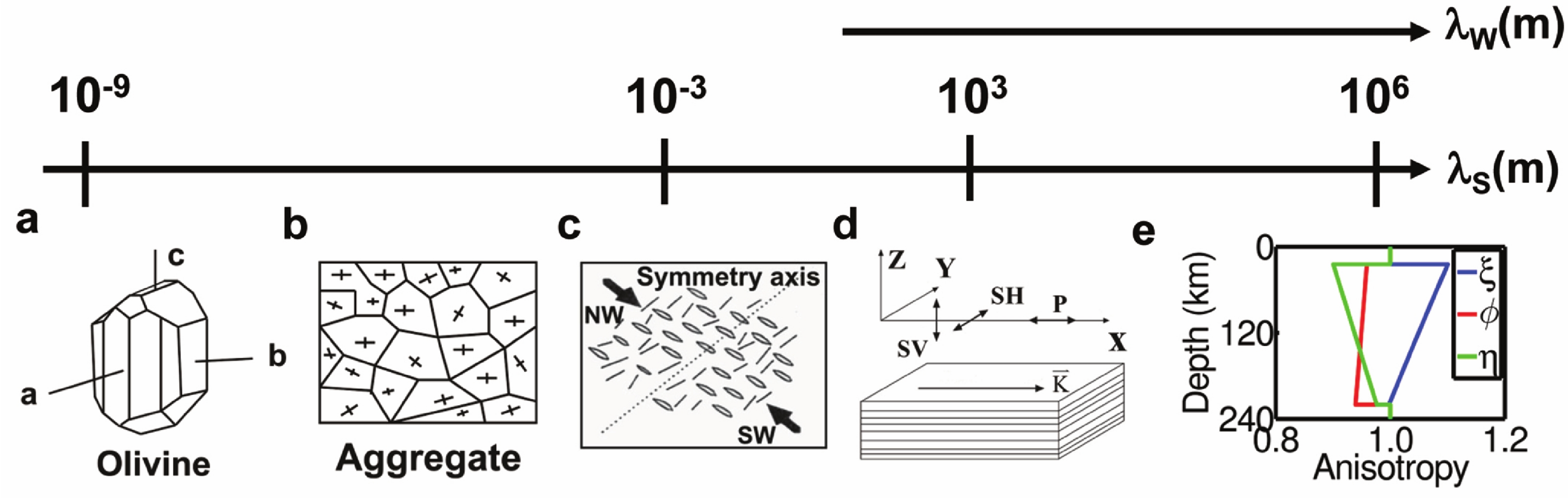
- *Mineralogy, Water and fluid content*
- *Present day tectonic, geodynamic processes*
- *Past processes (frozen anisotropy)*

Monitoring of stress and strain fields

Stratification of anisotropy in the crust & mantle
Separation of the different kinds of anisotropy in different layers => Different interpretations

Interpretation of observed (apparent) anisotropy: Intrinsic versus extrinsic anisotropy

(L.P.O., C.P.O. versus SPO, fine layering)



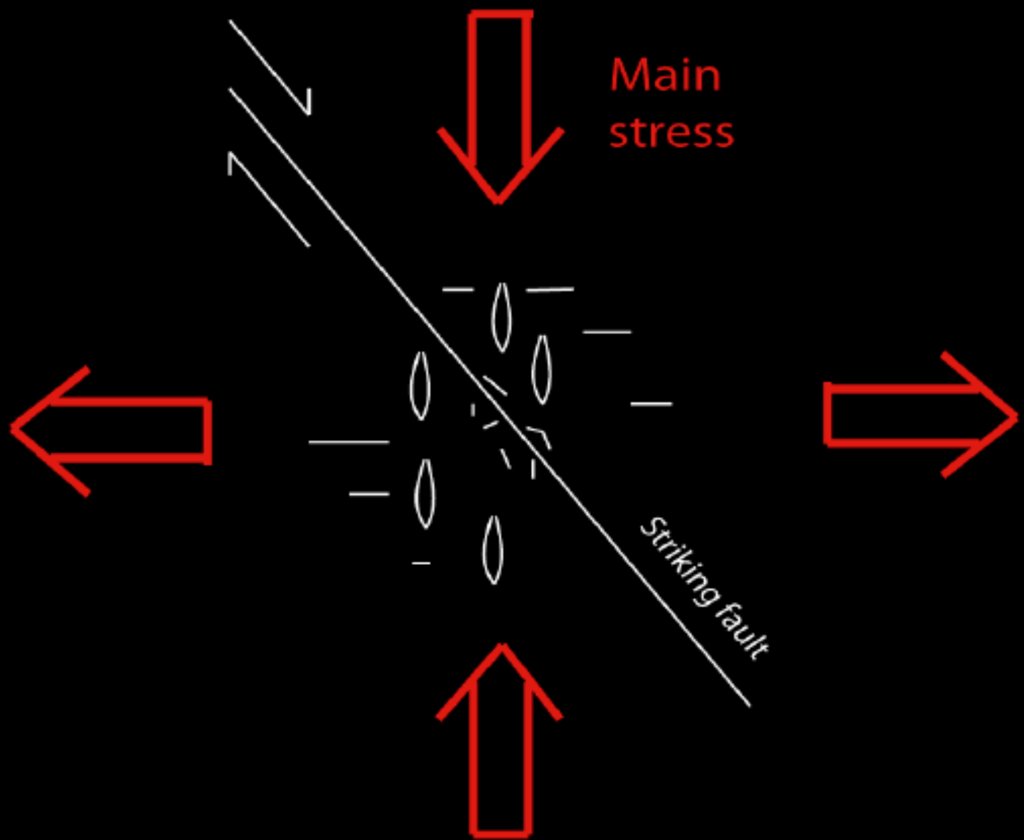
Intrinsic | Extrinsic | PREM

Case of VTI model (such as PREM): 1D-case

Alternative interpretations of PREM radial seismic anisotropy?

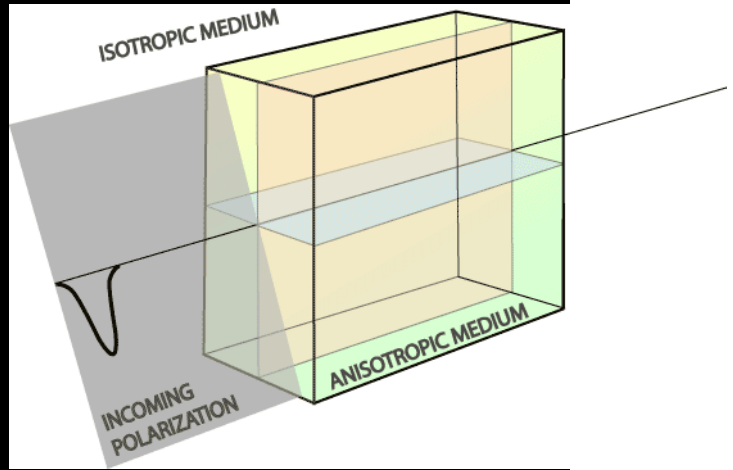
Seismic Anisotropy: Cracks, fluid inclusions

stress field rotations in the crust
⇒temporal variations of velocity
and anisotropy during seismic cycle?



Different kinds of anisotropy effects on seismic waves

•Body waves: Shear wave splitting
(birefringence)



Courtesy of Ed. Garnero

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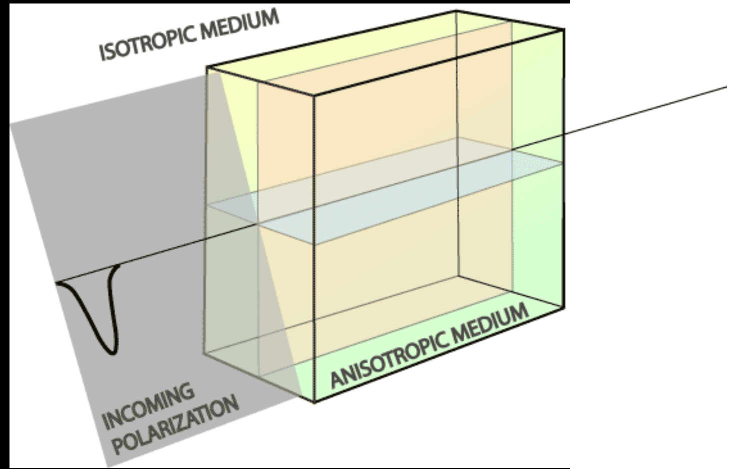


Courtesy of Ed. Garnero

•Body waves: Shear wave splitting (birefringence)

•Surface waves (Rayleigh and Love):

-Rayleigh-Love discrepancy (VTI model)

-Azimuthal variations of phase (or group) velocities, radial anisotropy

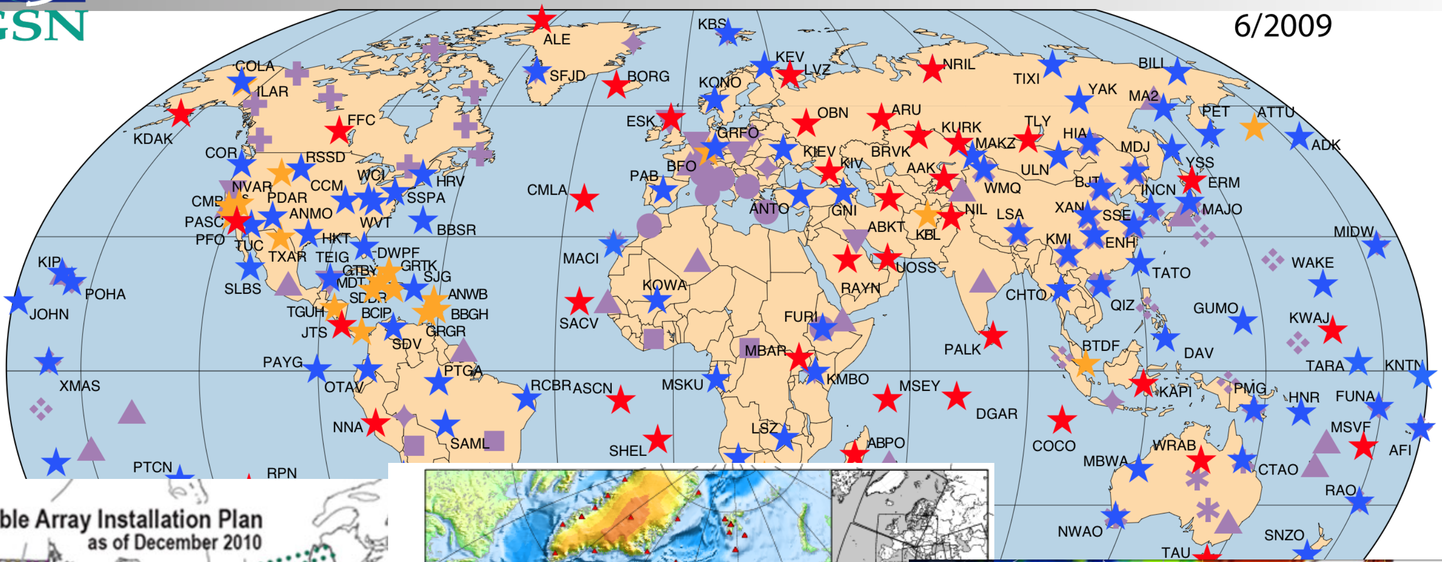
-Amplitude effects: Quasi-Rayleigh, Quasi-Love polarization anomalies

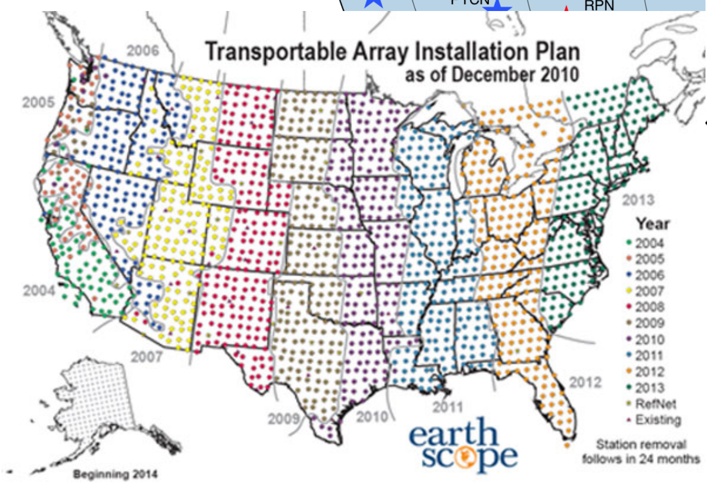
DATA?

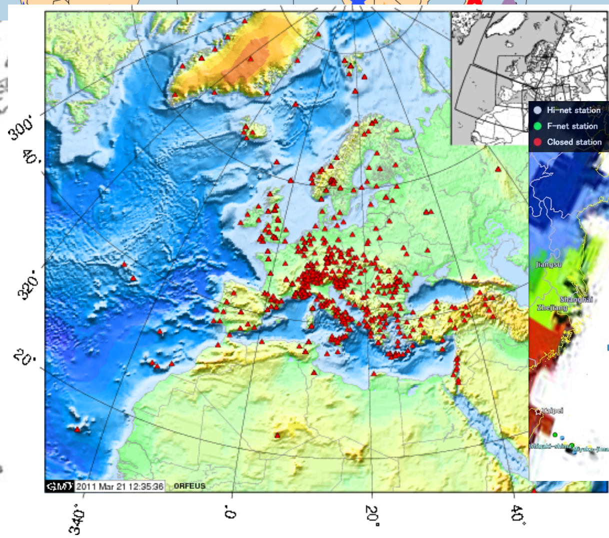
Broadband Seismic Data

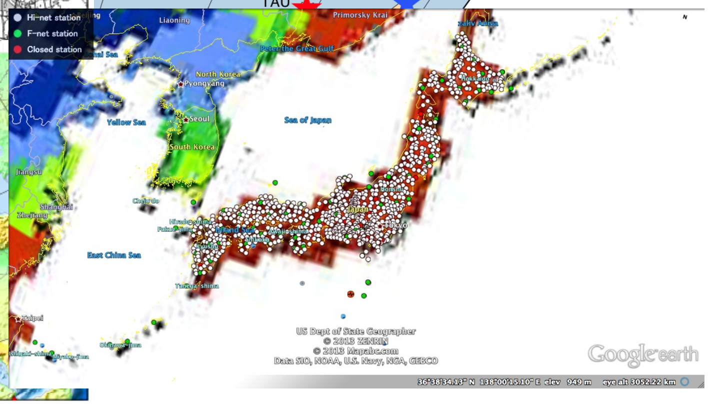
GLOBAL SEISMOGRAPHIC NETWORK
FEDERATION OF BROADBAND DIGITAL SEISMIC NETWORKS (FDSN)

6/2009



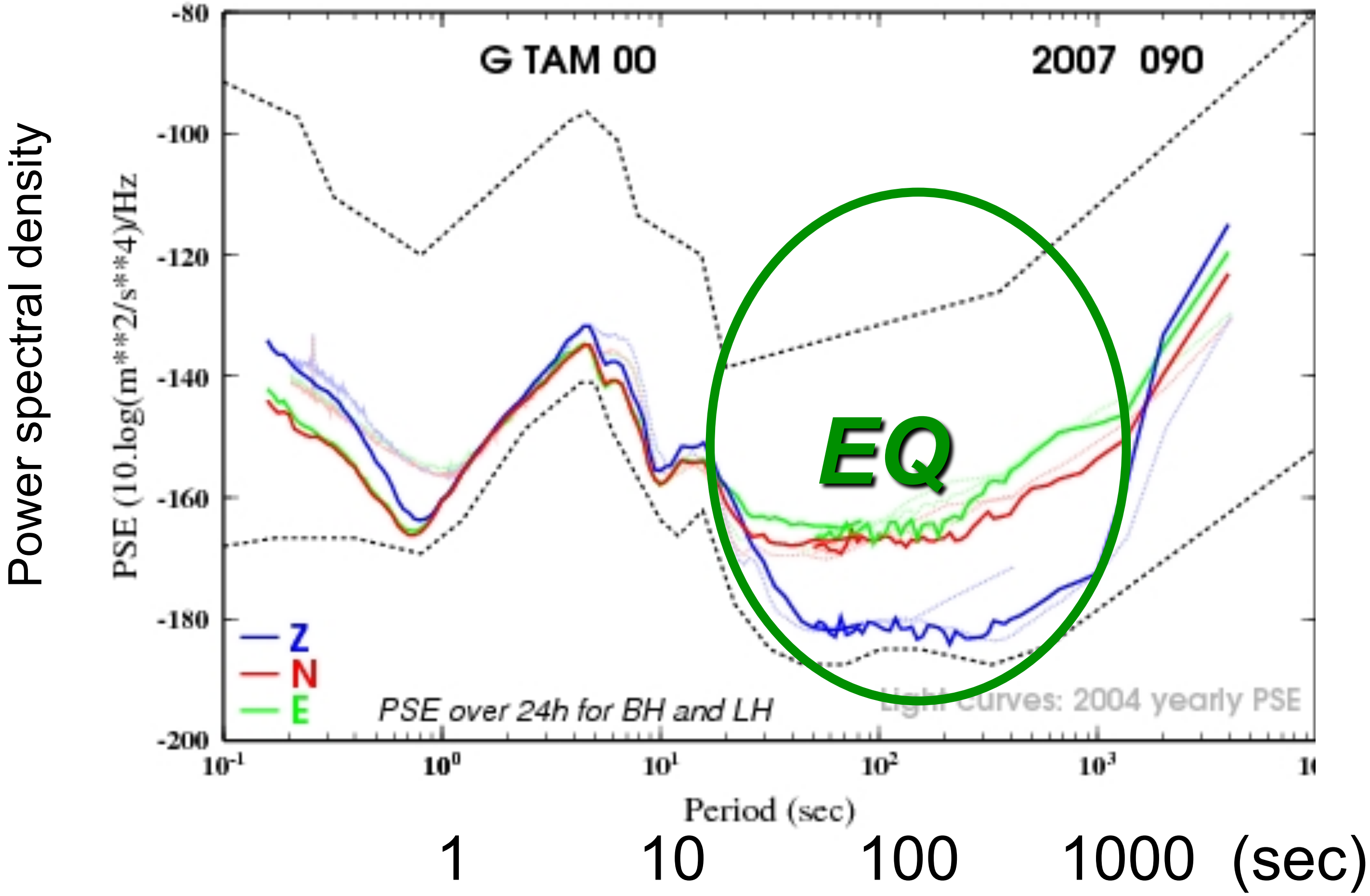






+ Regional BB seismic arrays: US-array, Vebsn, Hi-net, ….

Broadband Seismic Noise



TAM (Tamanrasset, Algeria)

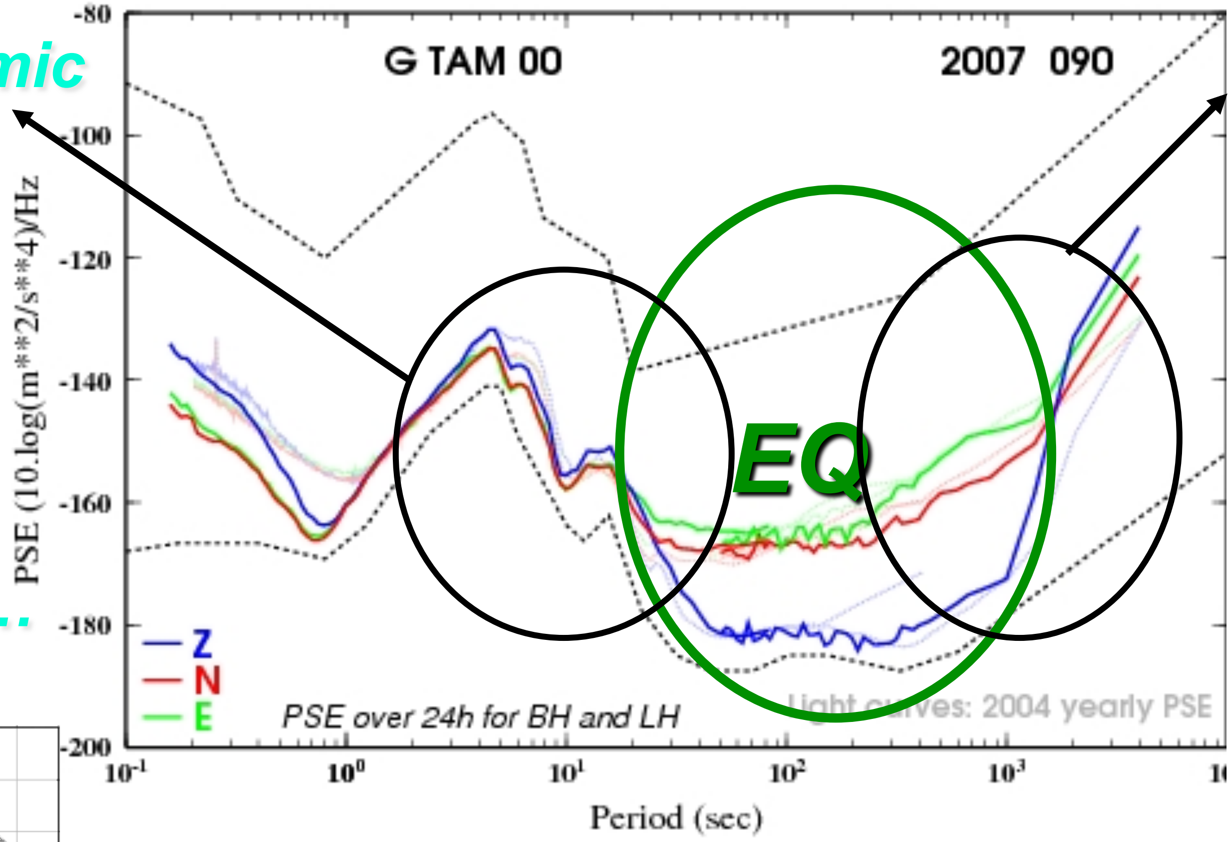
http://geoscope.ipgp.fr

Broadband Seismic Noise

Microseismic Noise

↓

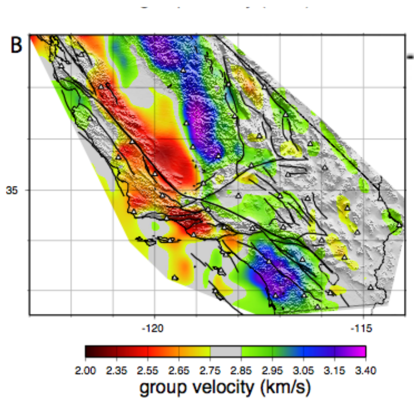
Shapiro, Campillo, Roux, Brenguier,…



VLP Noise (transient, Hum, …)

↓

Nishida, Montagner, Kawakatsu (2009)



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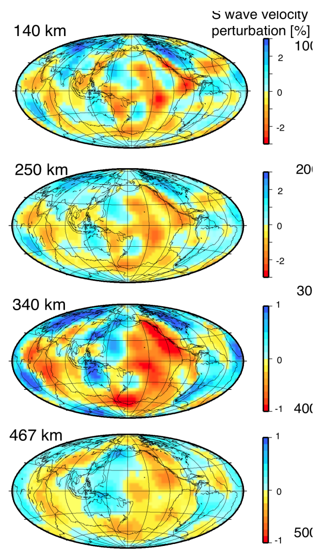
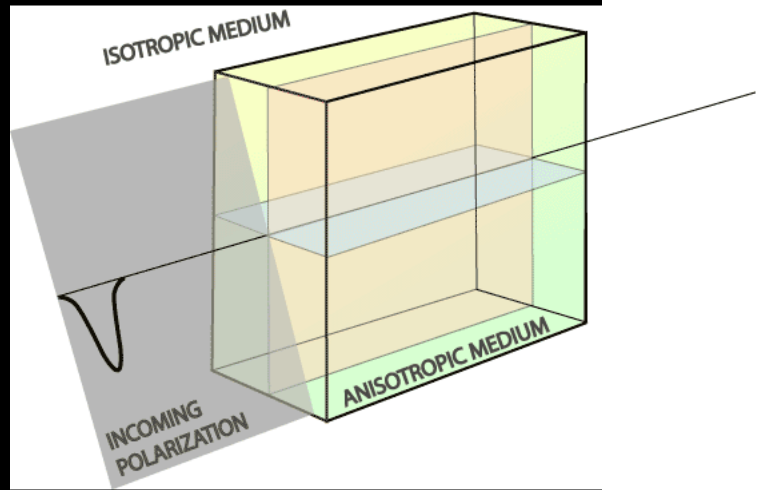


Different kinds of anisotropy effects on seismic waves

•Body waves: Shear wave splitting (birefringence)



•Surface waves (Rayleigh and Love):

- Rayleigh-Love discrepancy

-Azimuthal variations of phase (or group) velocities, radial anisotropy

Courtesy of Ed. Garnero

-Quasi-Rayleigh, Quasi-Love polarization anomalies

Effect of anisotropy on the phase of surface waves

Effect on eigenfrequency ω_k (Rayleigh's principle)

$$\frac{\delta\omega_k}{\omega_k} = \frac{\int_\Omega \varepsilon_{ij}^* \, \delta C_{ijkl} \, \varepsilon_{kl} \, d\Omega}{\int_\Omega \rho_0 \, u_r^* \, u_r \, d\Omega} = \left.\frac{\delta V}{V}\right|_k$$

ε strain tensor, u displacement, δC_{ijkl} elastic tensor perturbation (21 elastic moduli), V phase velocity

Phase velocity pertubation $\boldsymbol{\delta V(T,\theta,\phi,\Psi)}$ at point r (θ,ϕ)

(Smith & Dahlen, 1973; Montagner & Nataf, 1986)

Ψ Azimuth (angle between North and wave vector)

$$\delta V(T,\theta,\phi,\Psi)/_V = \alpha_0(T,\theta,\phi) + \alpha_1(T,\theta,\phi)\cos 2\Psi + \alpha_2(T,\theta,\phi)\sin 2\Psi + \alpha_3(T,\theta,\phi)\cos 4\Psi + \alpha_4(T,\theta,\phi)\sin 4\Psi$$

- ***Cijkl 21 elastic moduli***
- ***VTI Model*** *(transversely isotropy with vertical symmetry axis)*

0-ψ term: **5 parameters A, C, F, L, N (PREM)**

- ***Best resolved parameters from surface waves*** *(among 13 parameters when including azimuthal anisotropy 2ψ, 4ψ)*

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

$\xi = N/L = (V_{SH}/V_{SV})^2$ *Radial Anisotropy*

$G,\ \Psi_G$ *Azimuthal Anisotropy of V_{SV}, also related to SKS splitting (when horizontal symmetry axis, vertical propagation, Montagner et al., 2000)*

- ***Body waves*** *(Crampin, 1984)*

$$\rho V_{SV}^2 = L + G_c \cos 2\Psi + G_s \sin 2\Psi$$

$$\rho V_{SH}^2 = N - E_c \cos 4\Psi - E_s \sin 4\Psi$$

Effect of anisotropy on the phase of surface waves

Effect on eigenfrequency ω_k (Rayleigh's principle)

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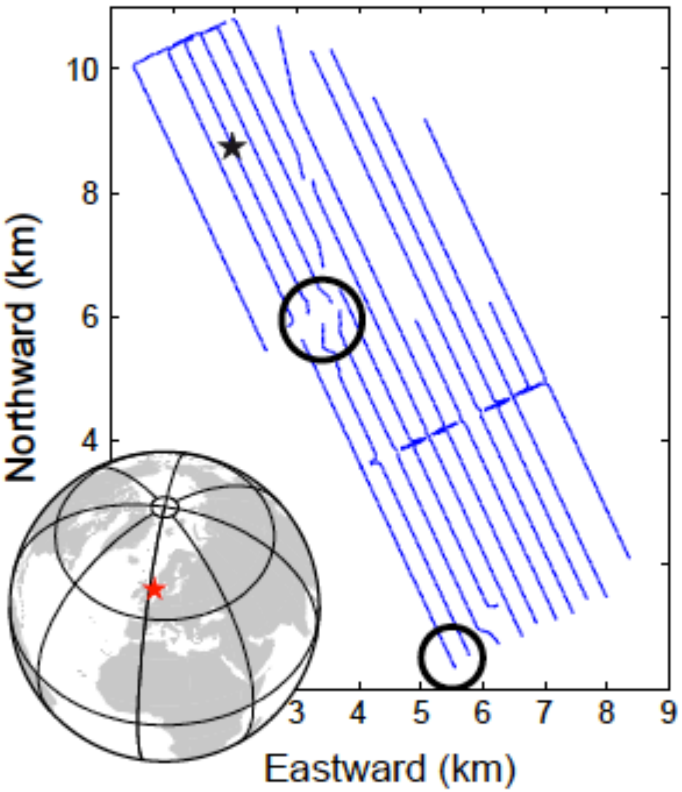
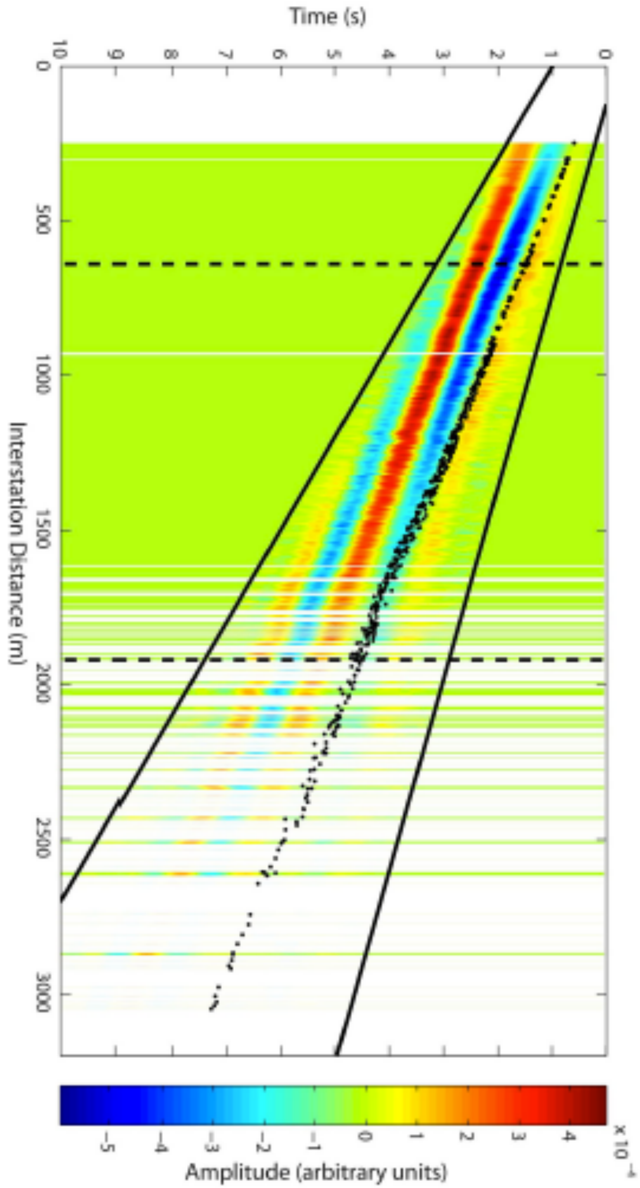
Global, regional, local scales

Rayleigh wave (seismic noise): Azimuthal variation on ZZ-component

Valhall LoFS network

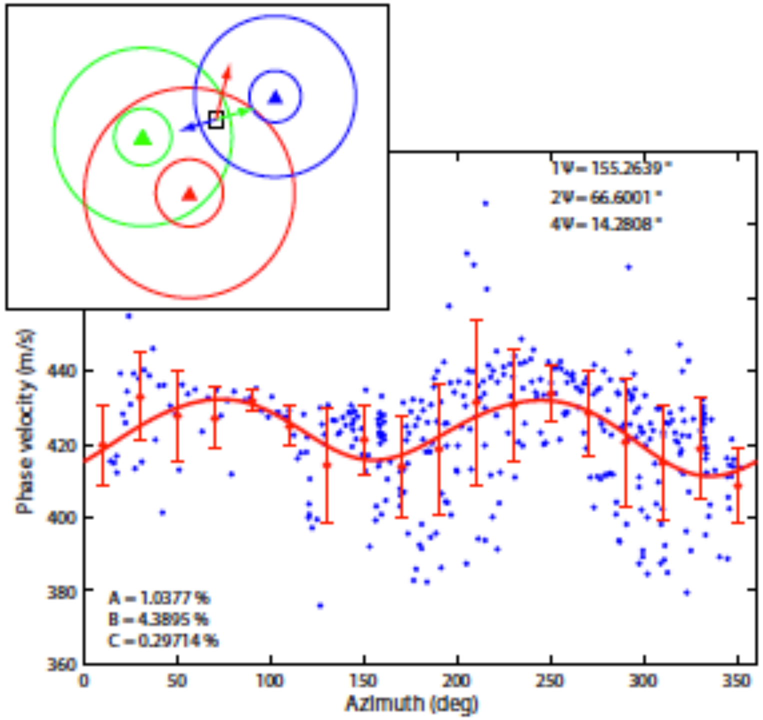




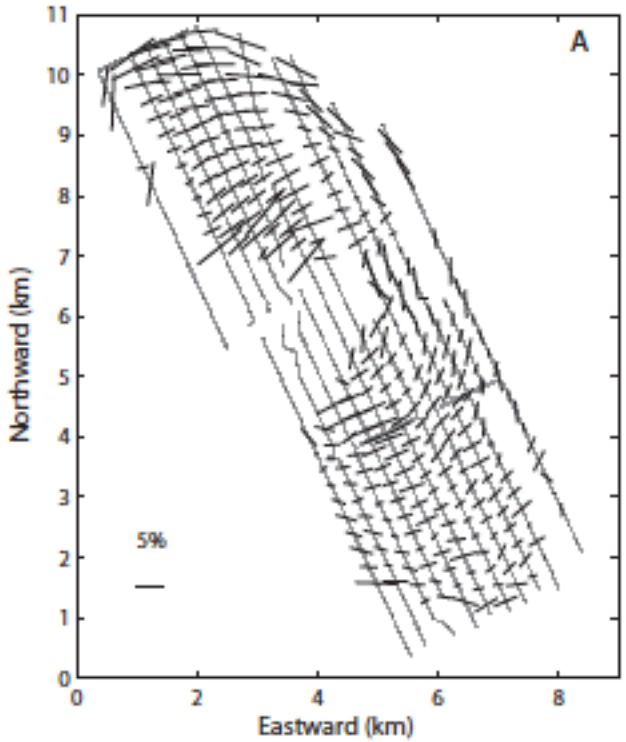
Mordret et al., 2013 (poster)

Rayleigh wave:
Azimuthal variation on ZZ-component (1-2-4-Ψ terms

At T=0.8s



Valhall LoFS: 2-Ψ term

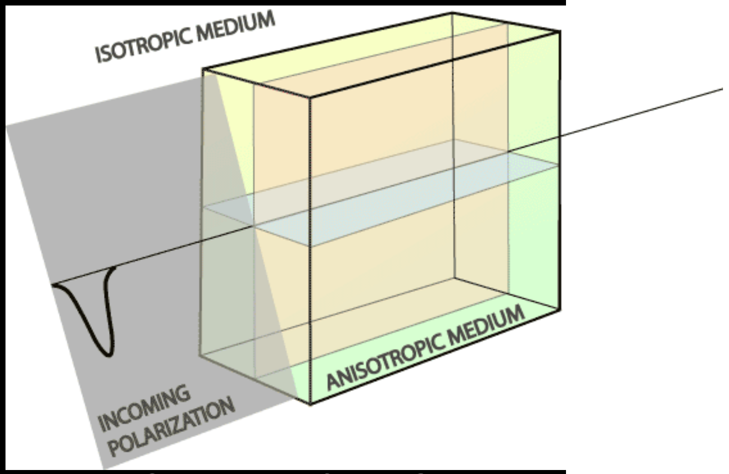


Mordret et al., 2013

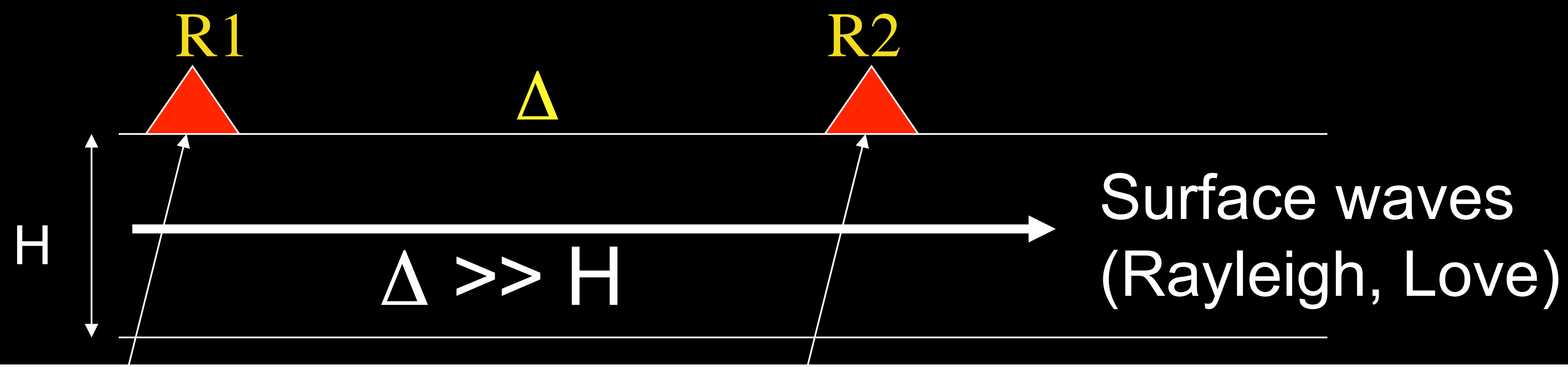
Different kinds of anisotropy effects on seismic waves

•Body waves: Shear wave splitting (birefringence)

•Surface waves:
-Azimuthal variations of phase (or group) velocities, radial anisotropy
-Quasi-Rayleigh, Quasi-Love polarization anomalies



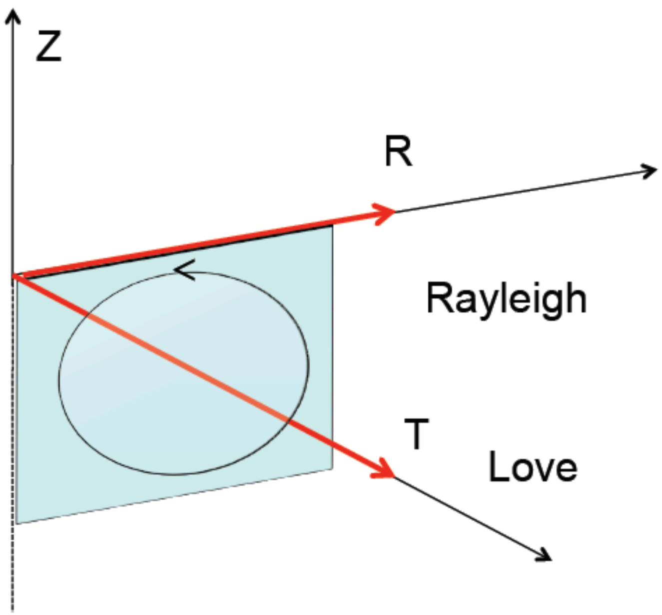
Courtesy of Ed. Garnero



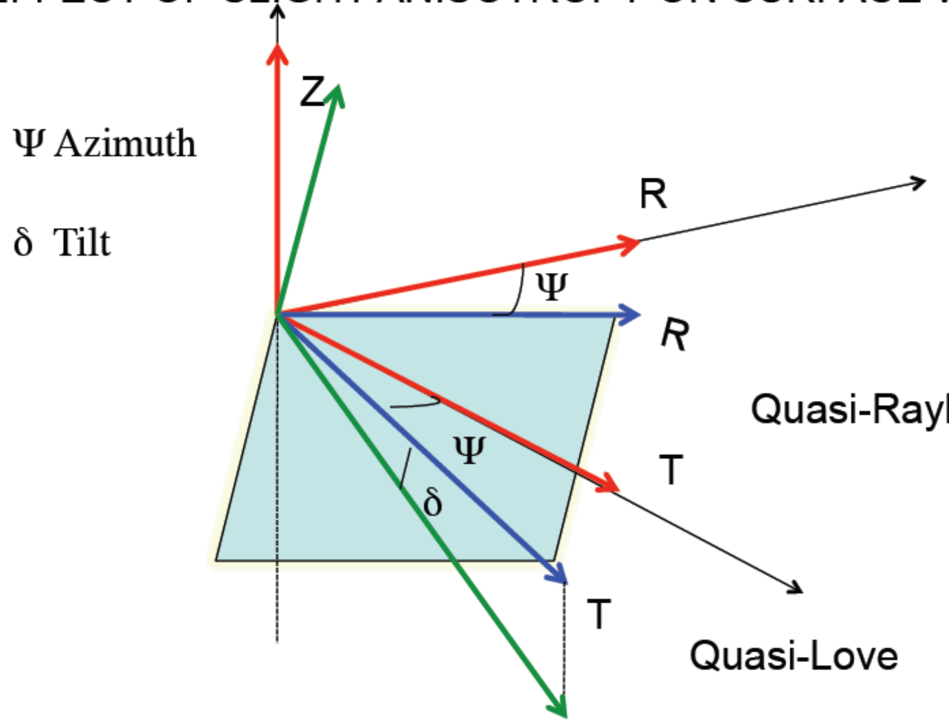
Effect of anisotropy on amplitude

Polarization of surface waves

ISOTROPIC MEDIUM



EFFECT OF SLIGHT ANISOTROPY ON SURFACE WAVES



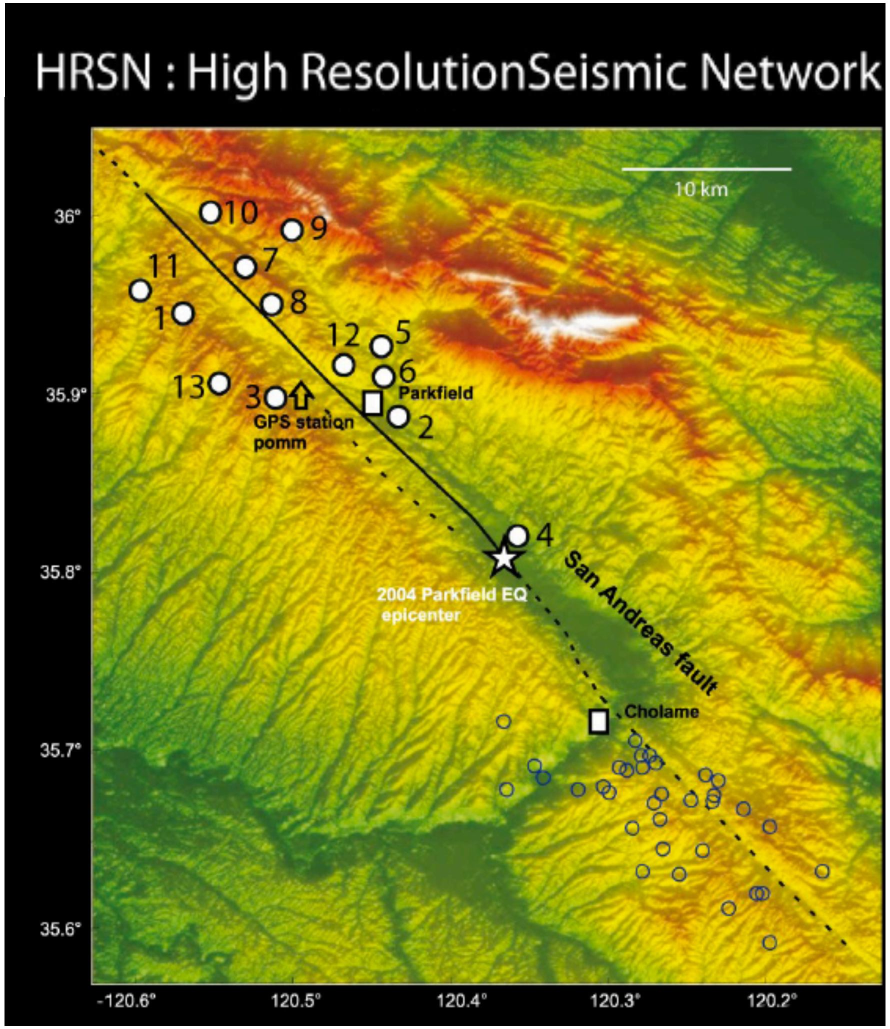
Monitoring of seismogenic zones by ambient noise

Surface waves recovered by ambient noise cross-correlation

ADVANTAGES

- Surface waves instead of body waves
- Independent of seismicity
- Continuous noise = continuous monitoring

- Application to the Parkfield area
- 3Component HRSN
- 28 Sept. 2004: Parkfield event, Mw=6.0
- 2005: No significant local earthquake (>4)



THEORY

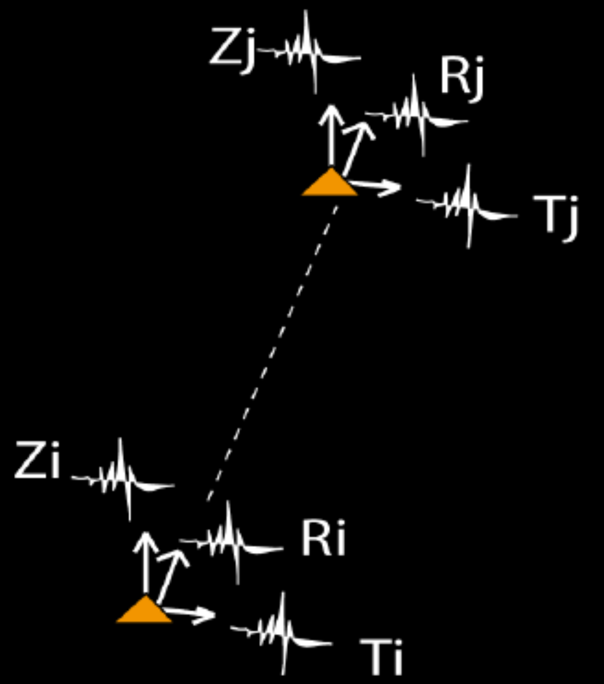
Cross-correlation for 2 stations i, j and 3 components k, l

$$[C_{ij}(t)]_{kl} = \frac{\int_0^T S_{ik}(\tau)\, S_{jl}(t+\tau)\, d\tau}{\sqrt{\int_0^T S_{ik}^2(\tau) d\tau \int_0^T S_{jl}^2(\tau) d\tau}}$$

→ Random sources:
Related to Green's tensor i,j
Medium response

Cross-Correlation Tensor

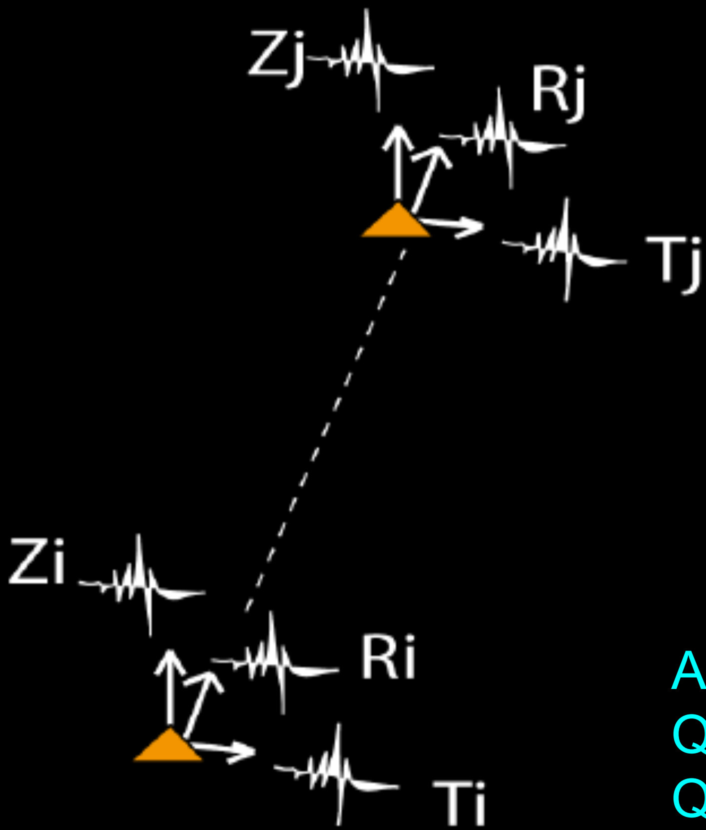
ZZ	ZR	ZT
RZ	RR	RT
TZ	TR	TT



$$[C_{ij}(t)]_{kl} = \frac{\int_0^T S_{ik}(\tau) S_{jl}(t+\tau)\, d\tau}{\sqrt{\int_0^T S_{ik}^2(\tau) d\tau \int_0^T S_{jl}^2(\tau) d\tau}},$$

ZZ	ZR	~0
RZ	RR	~0
~0	~0	TT

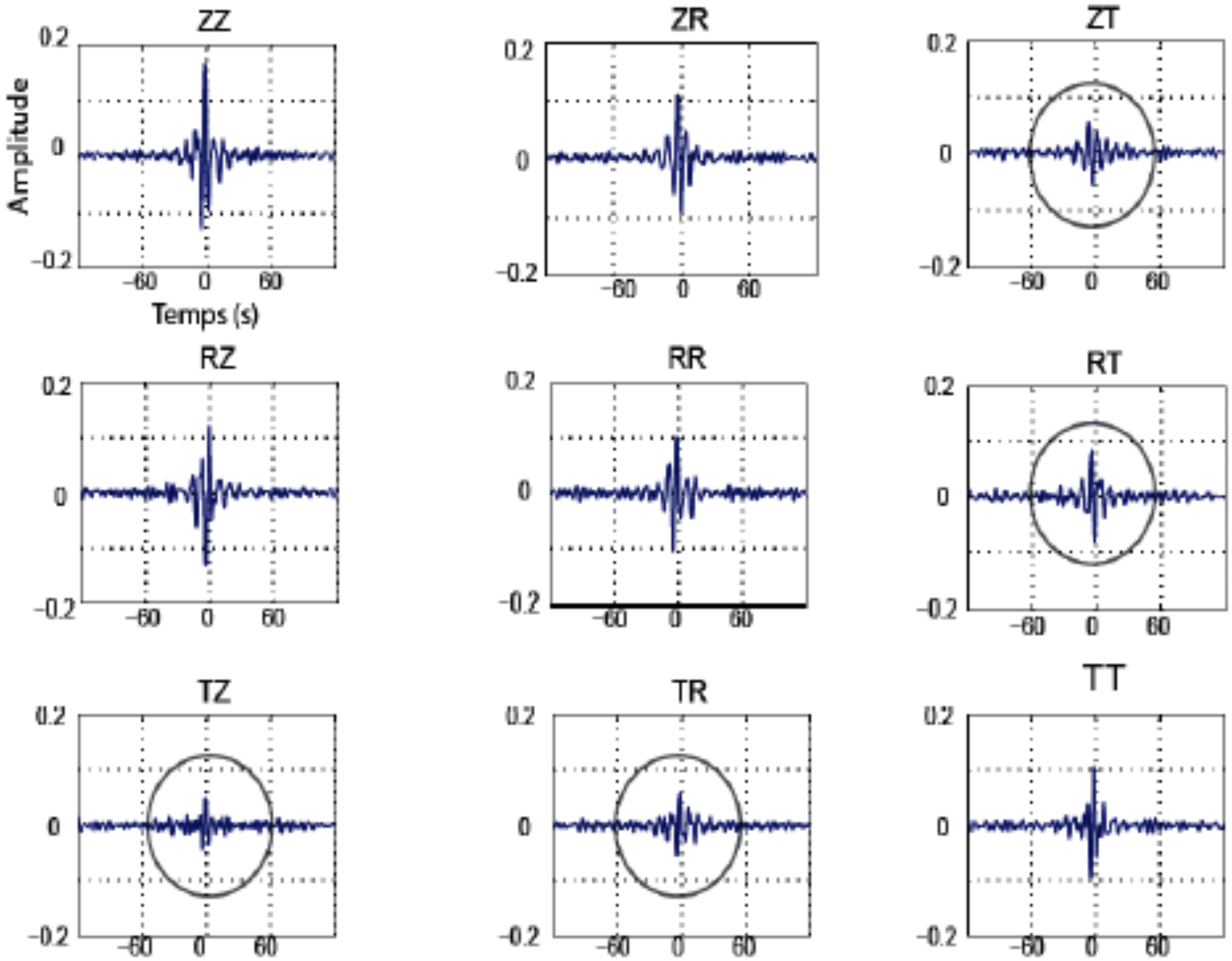
ISOTROPIC MEDIUM
Rayleigh wave
Love wave



ZZ	ZR	ZT
RZ	RR	RT
TZ	TR	TT

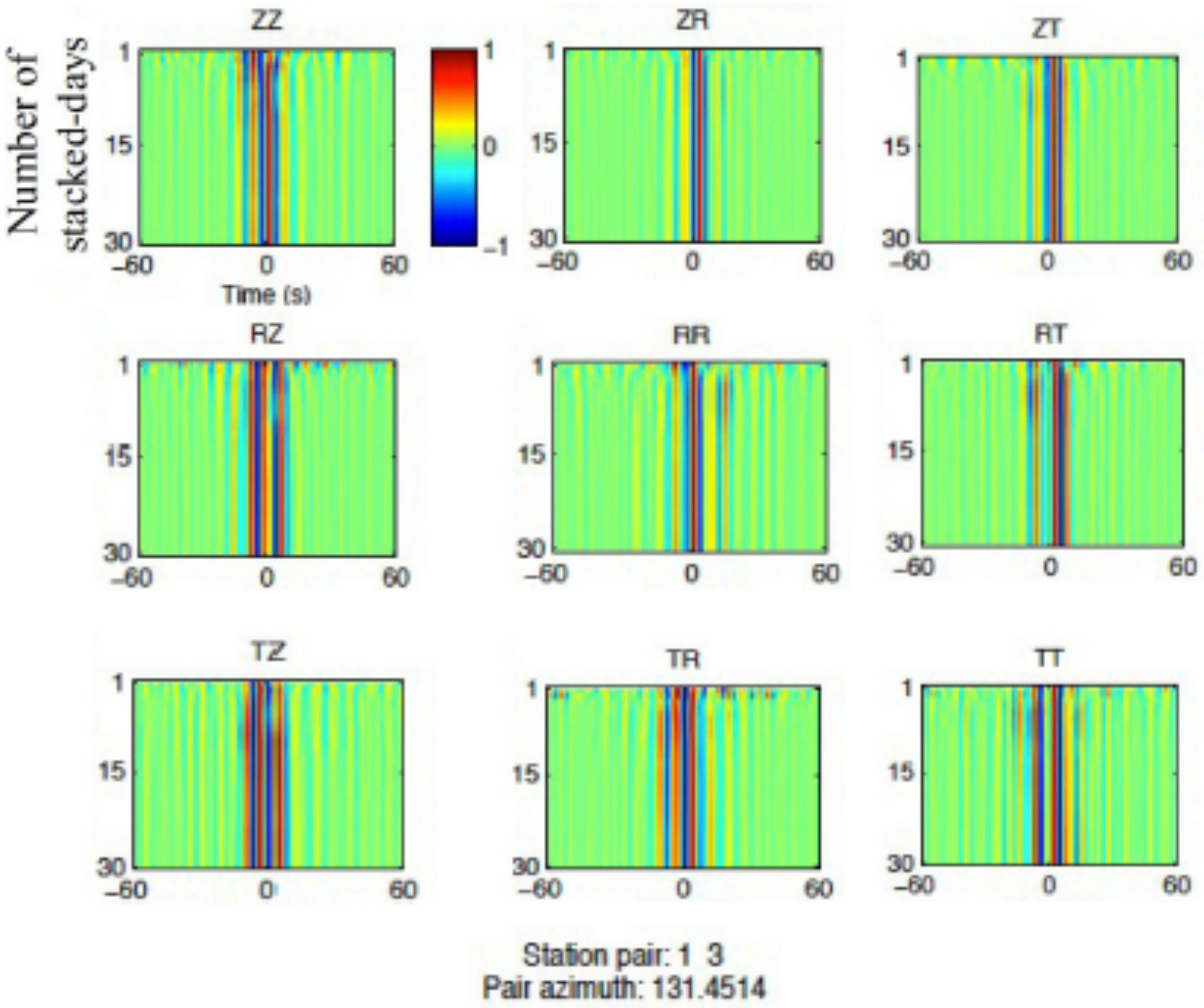
ANISOTROPIC MEDIUM
Quasi-Rayleigh wave
Quasi-Love wave

Example of cross-correlation tensor



TZ, TR, ZT, RT ≠ 0

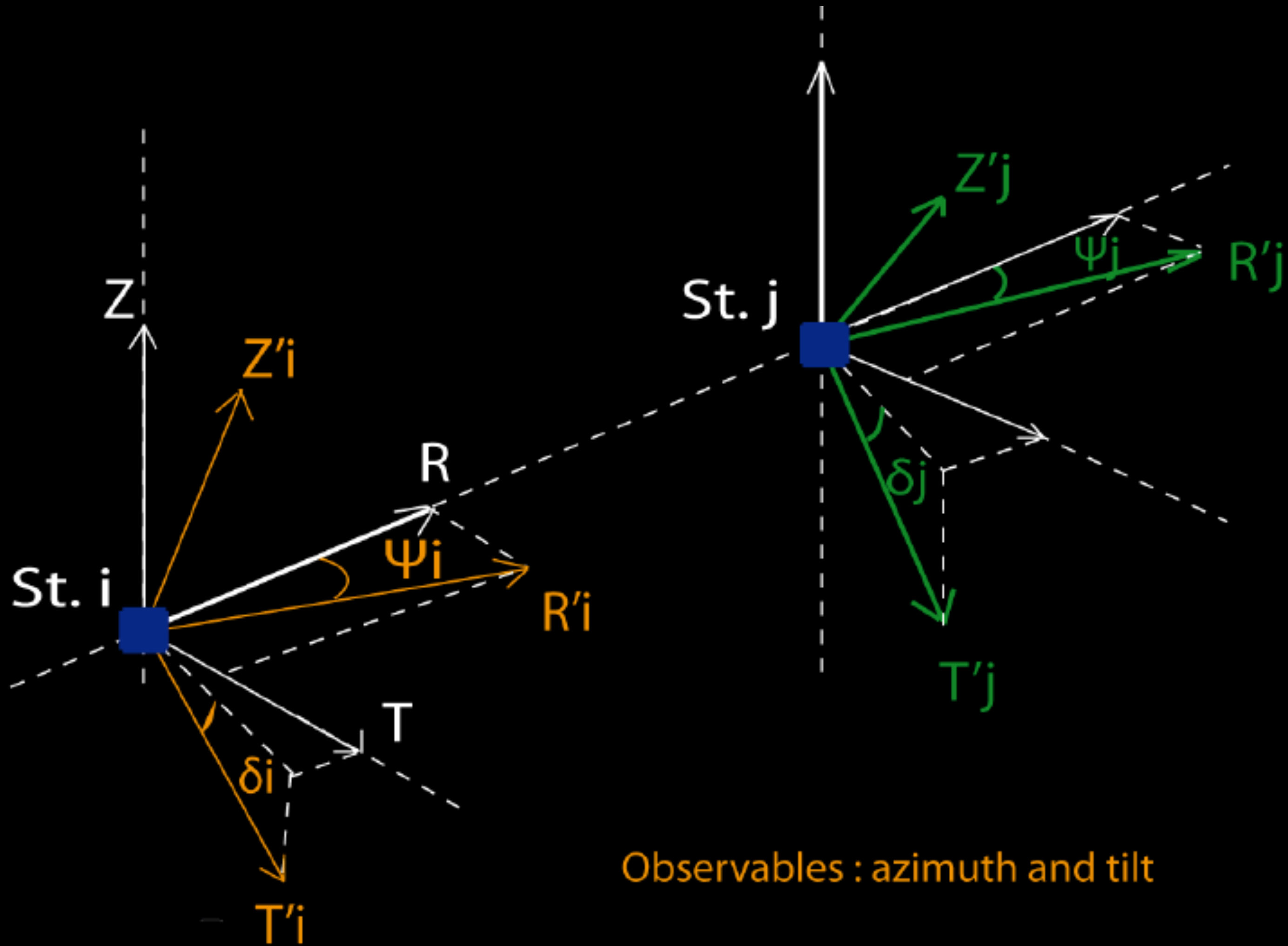
Stability of stack: 15-30days



ORA: Optimal Rotation Algorithm (Roux, GJI, 2010)

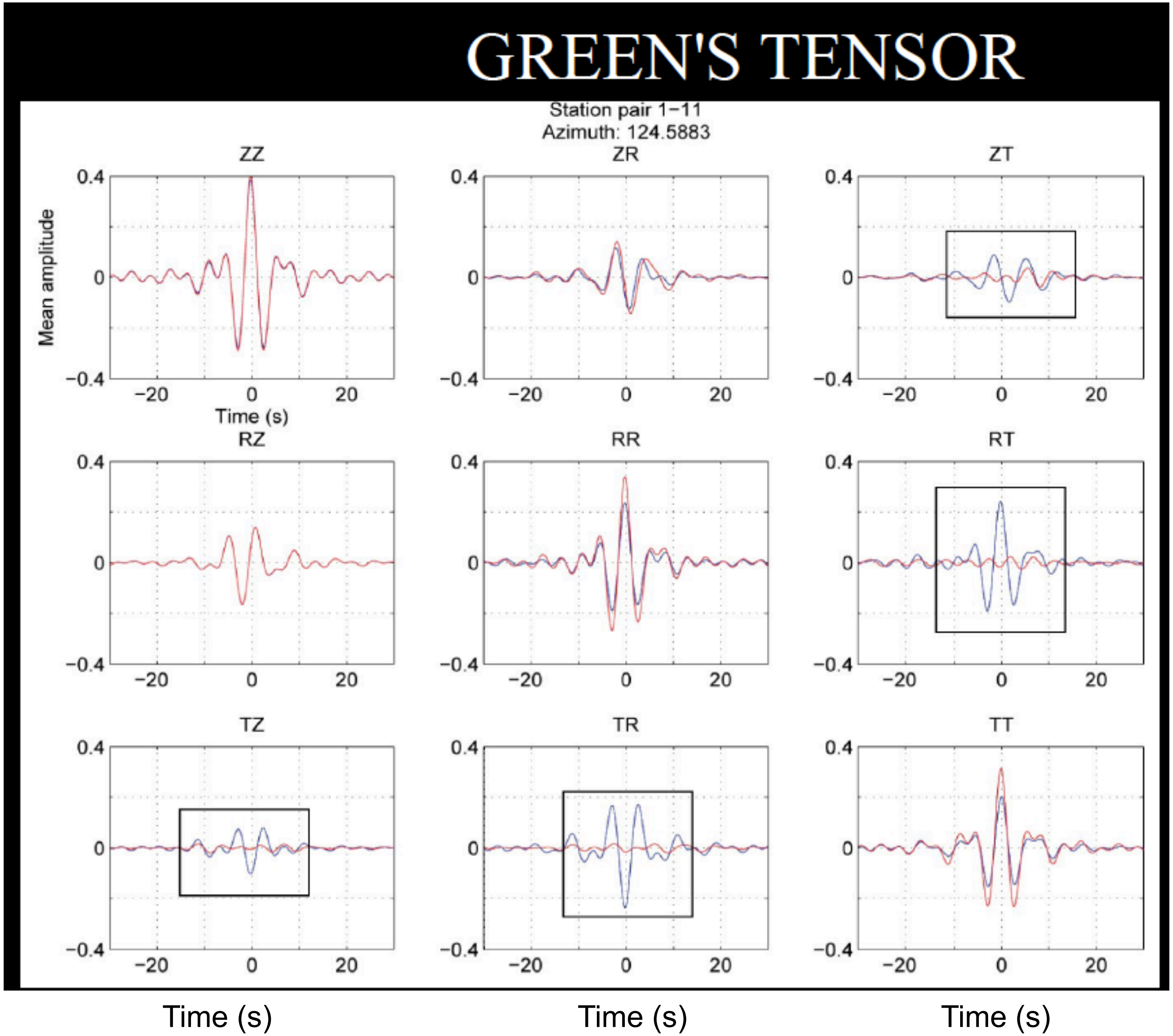
Minimization of the RT, TR, ZT and TZ components

ZZ	ZR	~~ZT~~
RZ	RR	~~RT~~
~~TZ~~	~~TR~~	TT



Observables : azimuth and tilt

Ψ δ



Before ORA

After ORA

=> Quasi-Rayleigh

New observables:
Ψ and δ

Temporal Changes of Ψ and δ ?

Temporal changes of Cross-correlations (polarization angle Ψ)

2 effects:

- Non-random distribution of seismic sources

→ seasonal variations (beamforming analysis)

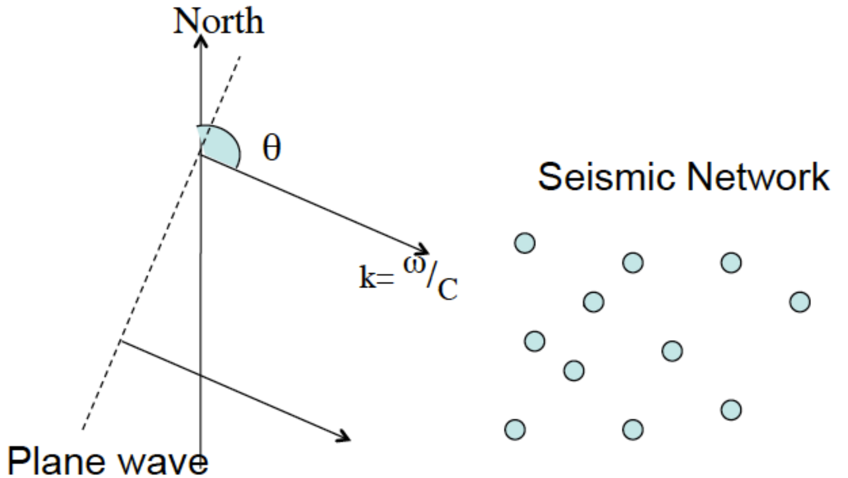
- ANISOTROPY changes

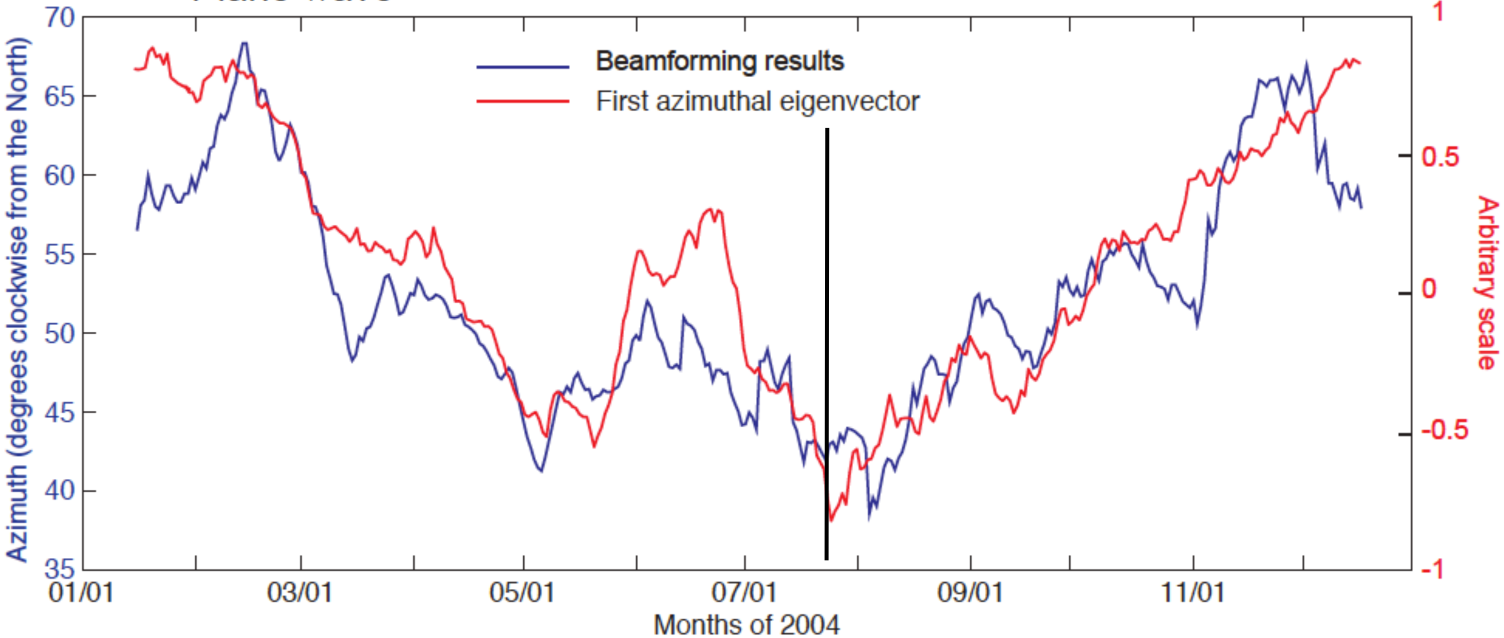
→ Stress field temporal variations

Seasonal Changes

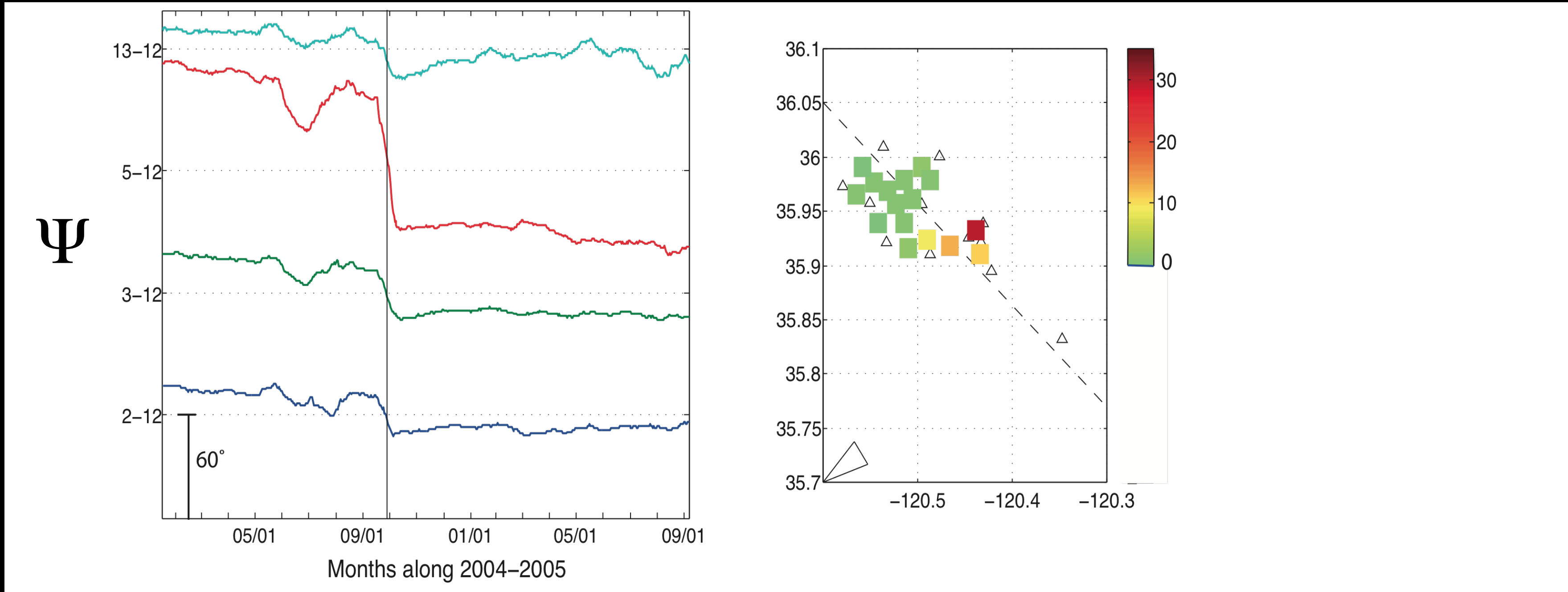
Origin of seismic sources: Beamforming (Roux, 2009)

$$B(\theta, c) = \frac{1}{\Delta\omega} \int_{\omega_c - \Delta\omega/2}^{\omega_c + \Delta\omega/2} \left| \sum_{i=1}^{N} \tilde{S}_i(\omega) \exp\left[i\frac{\omega}{c}(x_i \sin\theta + y_i \cos\theta) \right] \right|^2 d\omega$$

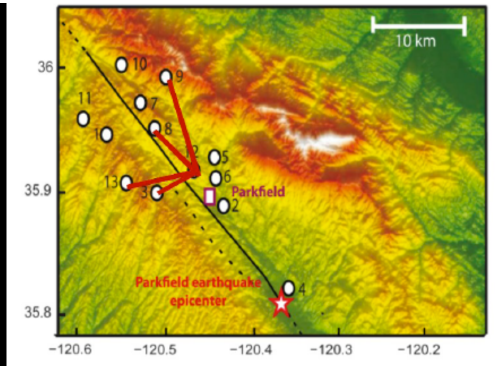




Time variations of Ψ angle after noise removal



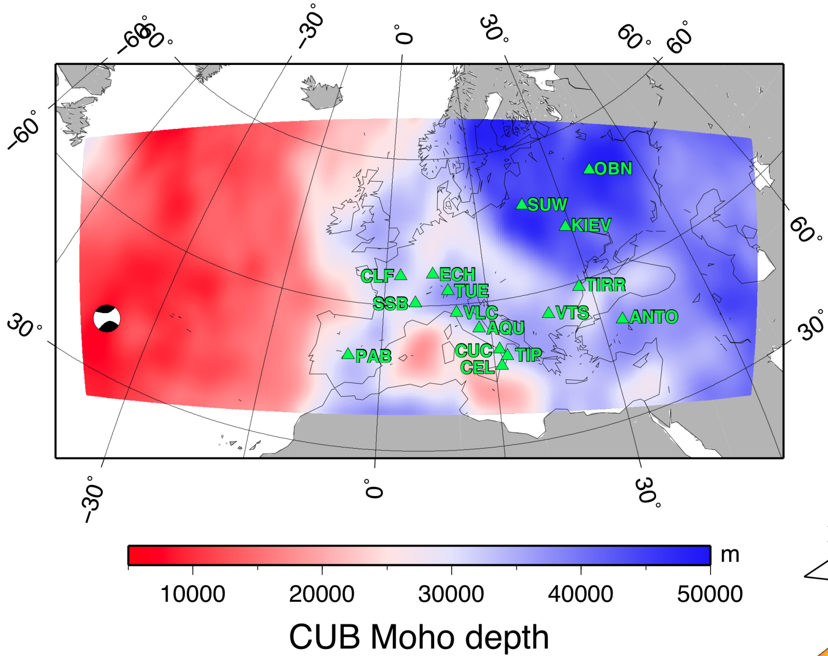
Significant co-seismic jumps for station pairs containing station 12

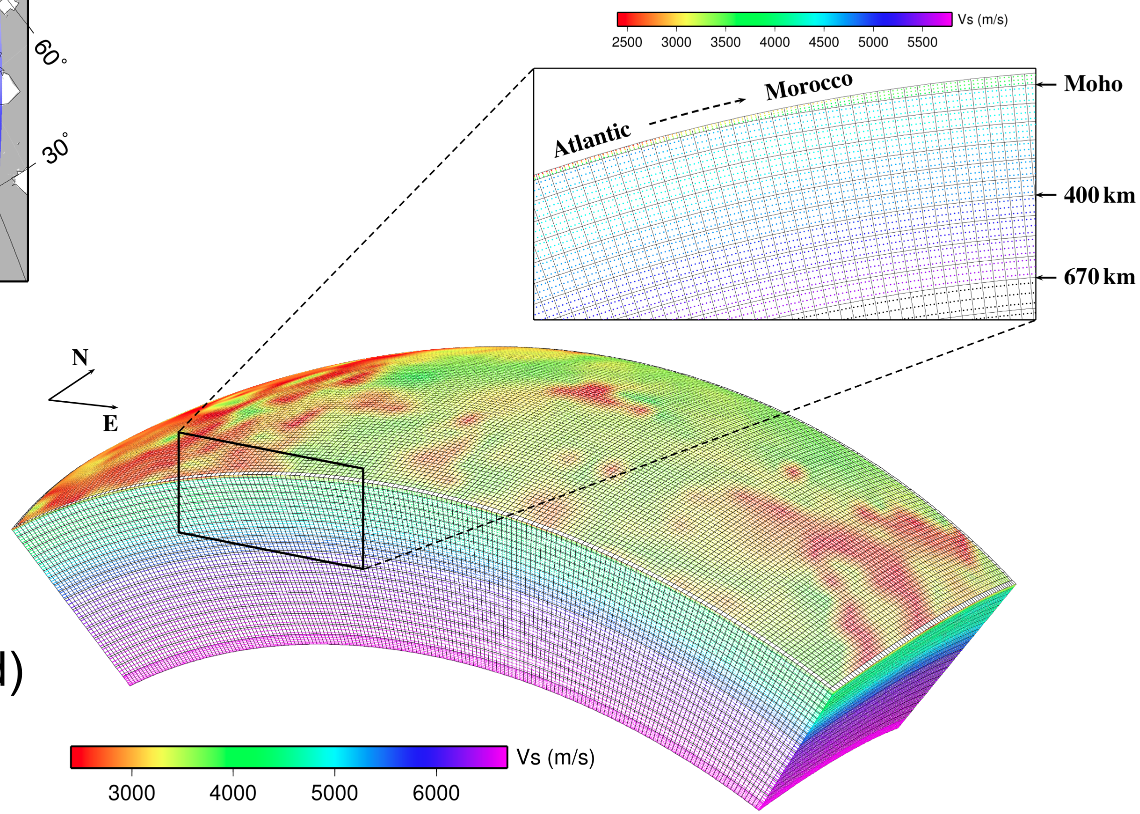


Tentative (reasonable) interpretation:
stress rotation => rotation of the crack distribution

NUMERICAL MODELING: regional and local scales

Wave propagation in fully anisotropic medium

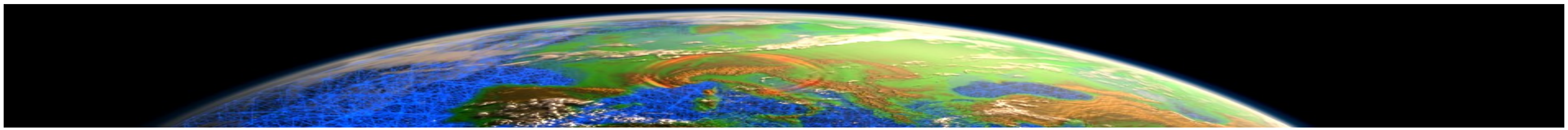




RegSEM code

(Regional Spectral Element Method)

Cupillard et al. (2012)



HTI medium

Transversely Isotropic medium with Horizontal symmetry axis

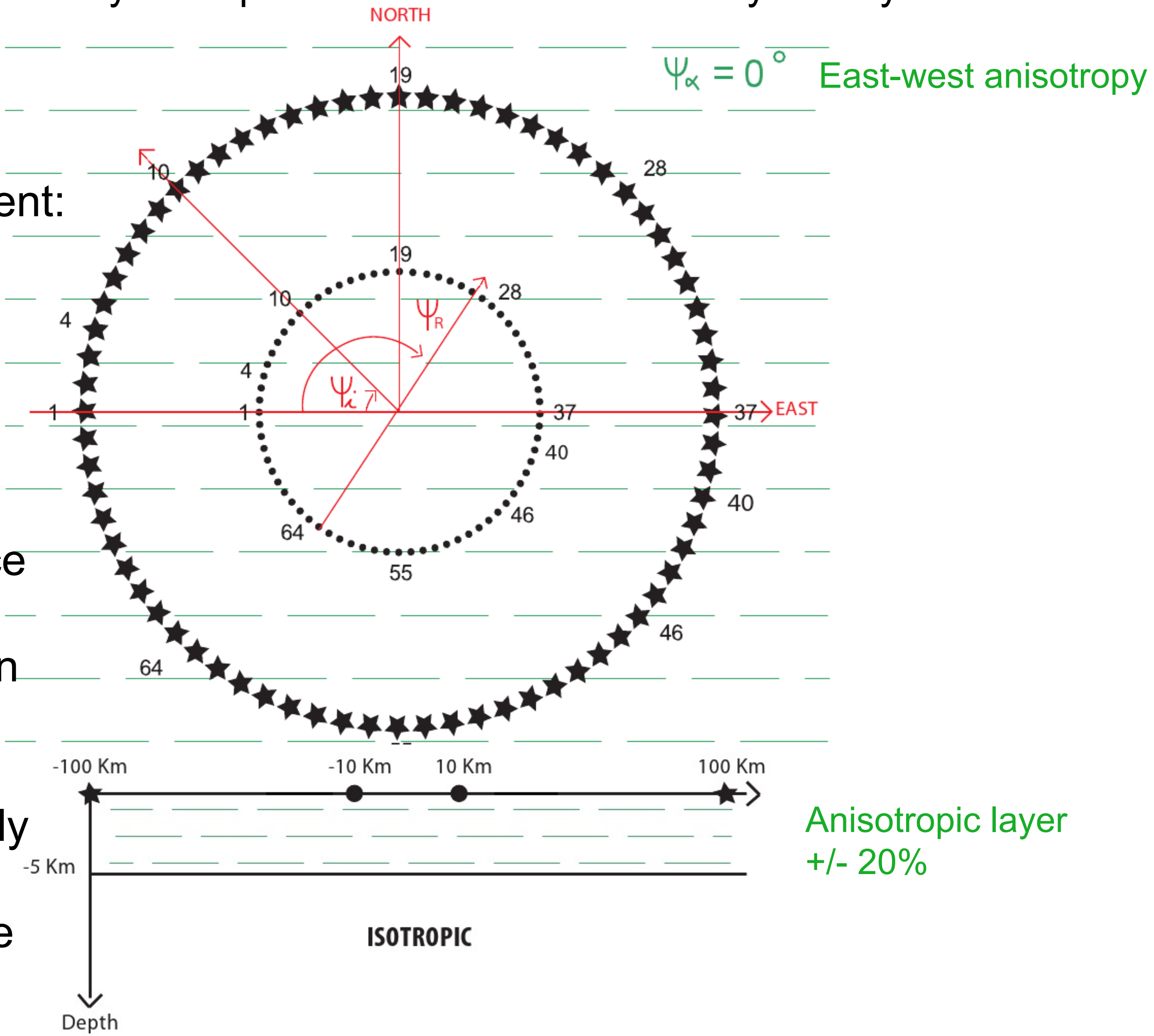
Numerical experiment:

72 sources ★

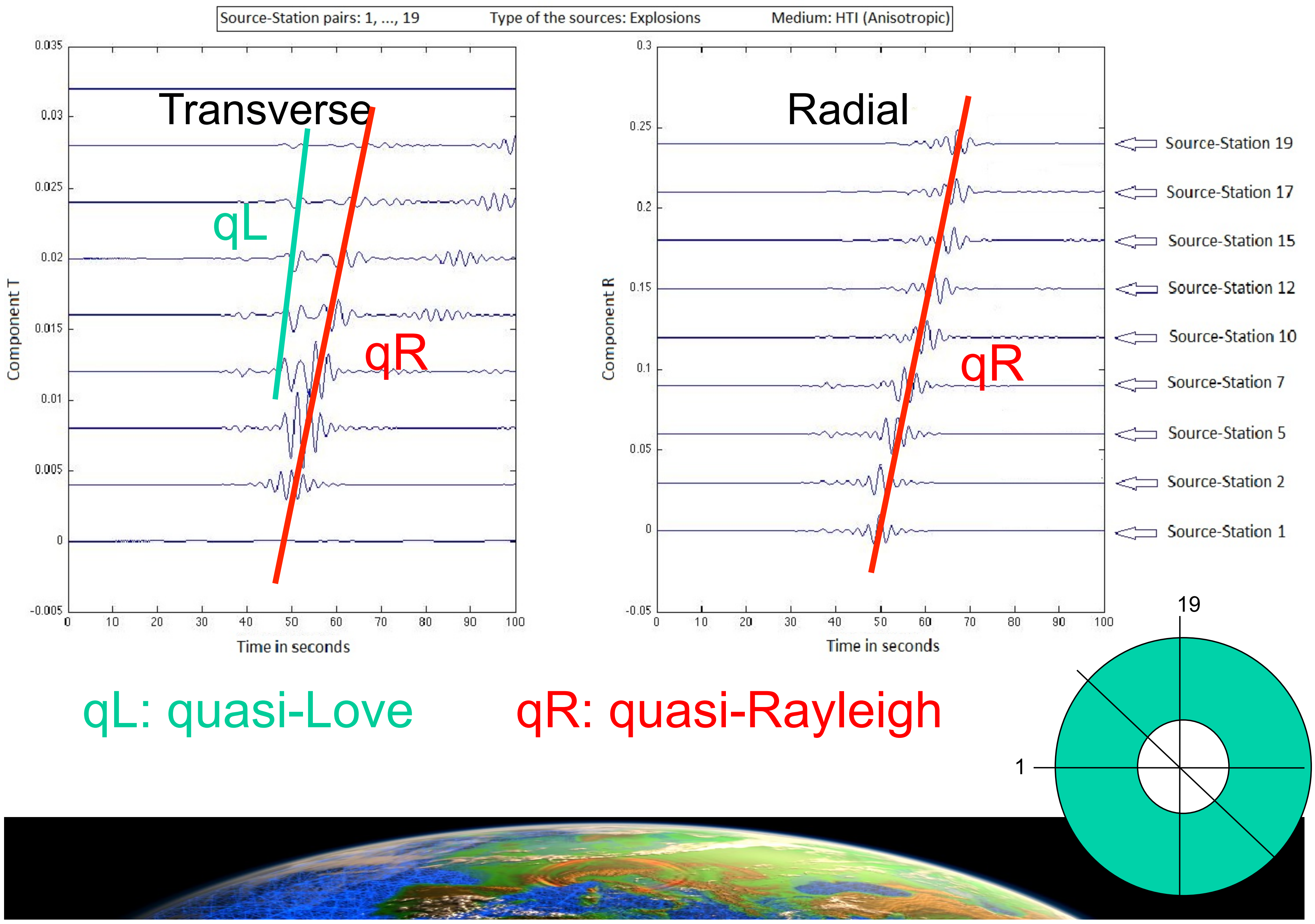
72 receivers •

Ψ_i azimuth of source
Ψ_R azimuth of path between receivers n and n+36
Ψ_W azimuth of polarization anomaly

Poster Maria Saade

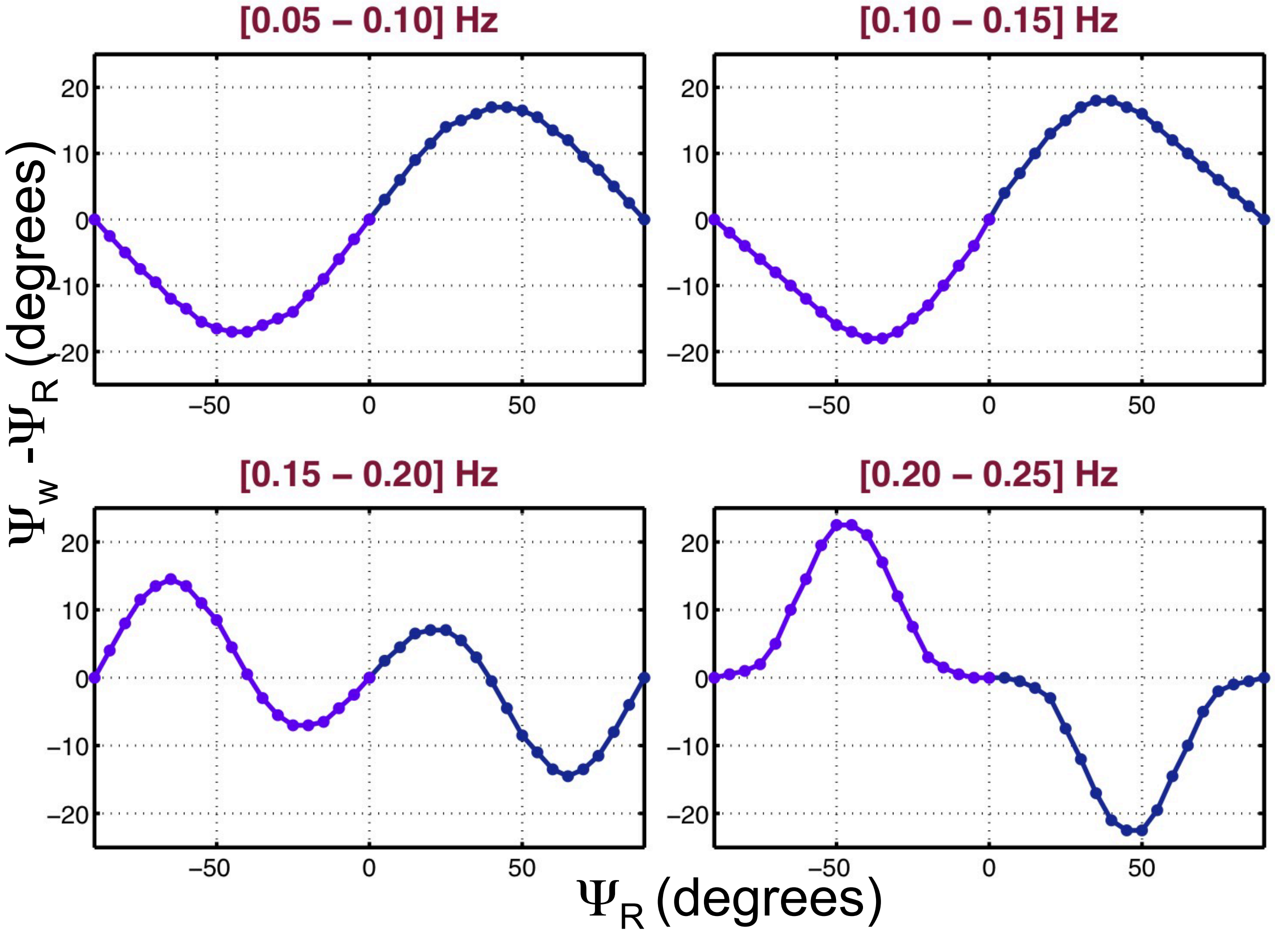


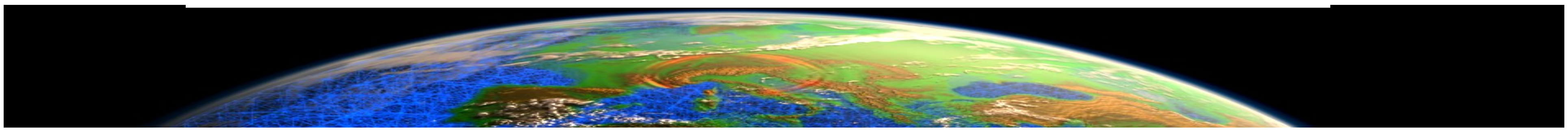
Source: explosion



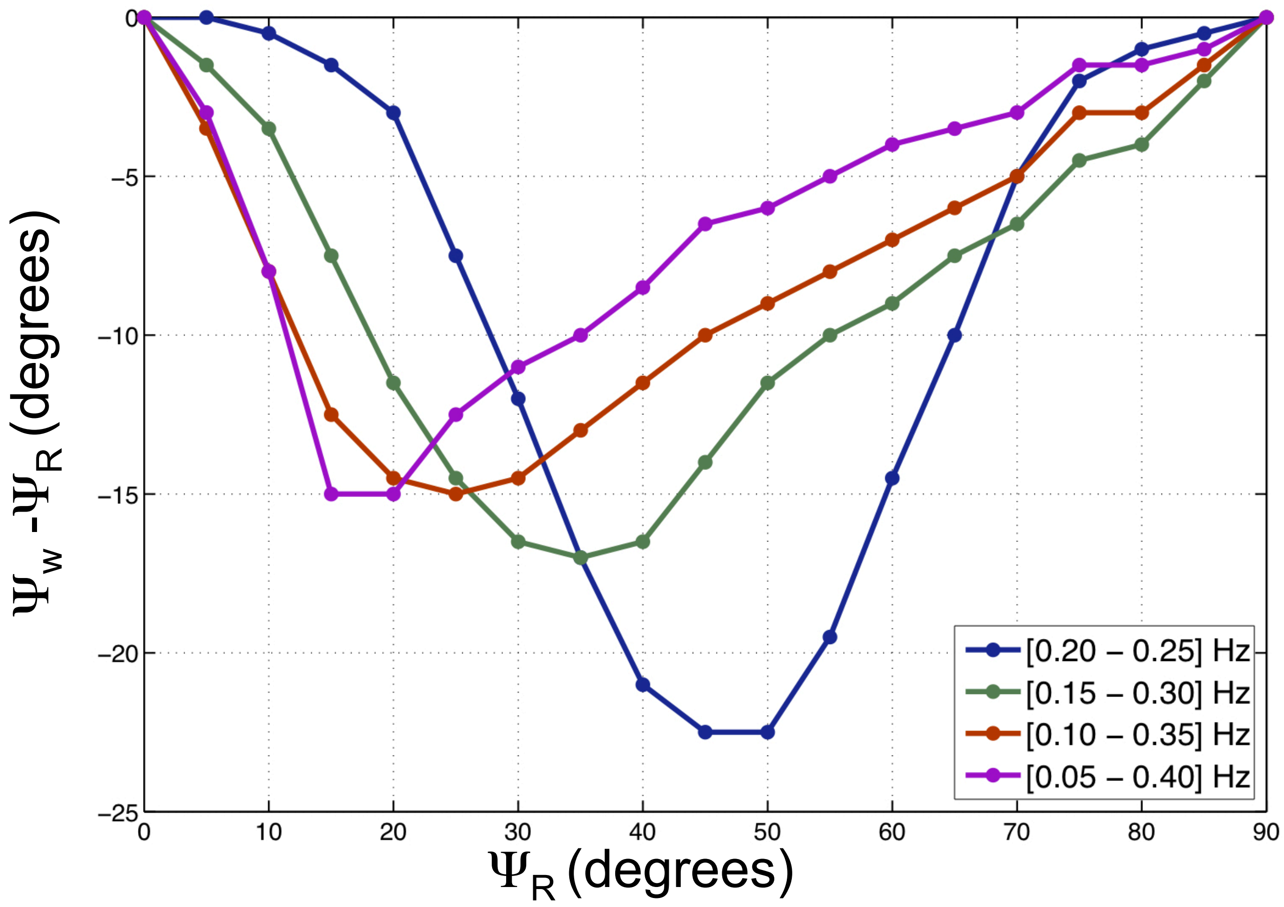
Cross-correlations

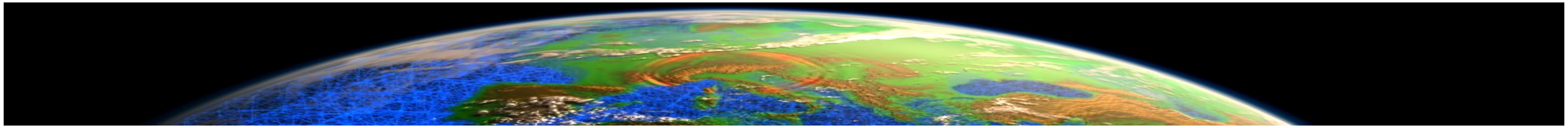
Variations of the horizontal polarization anomaly Ψ_w angle as a function of the incidence Ψ_R of the receiver pairs, for different frequency bands



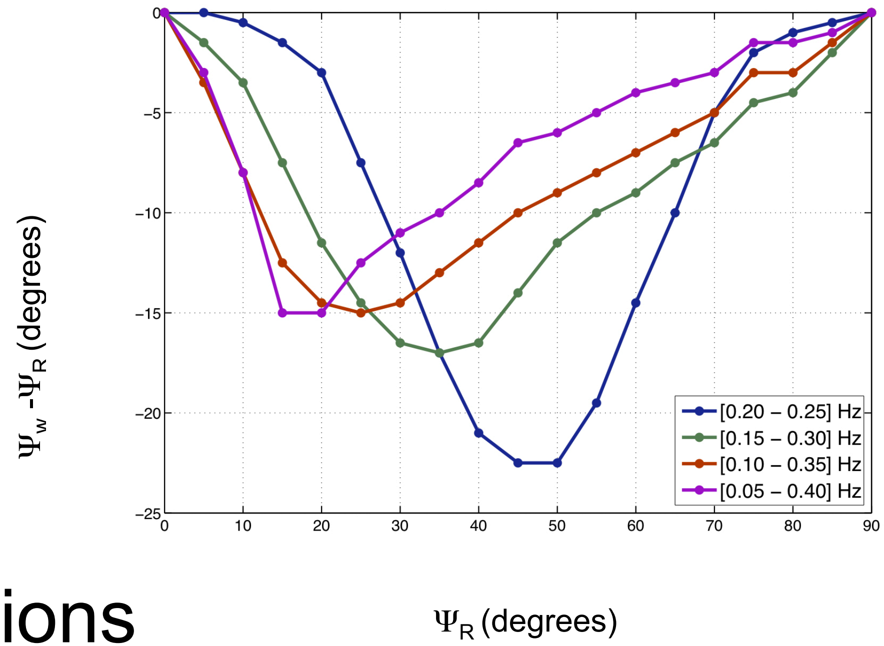


Displacement of the maximum of polarisation anomaly Ψ_w when increasing the bandwidth





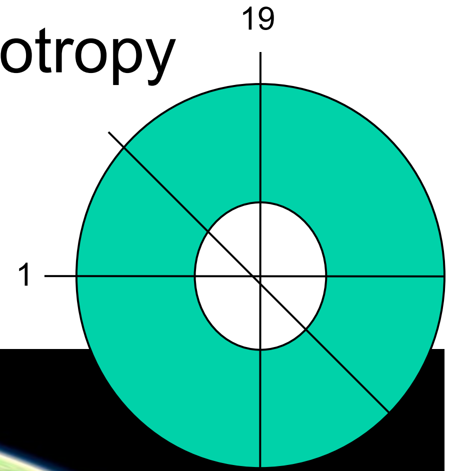
Polarization angle Ψ_w
Azimuth of path Ψ_R



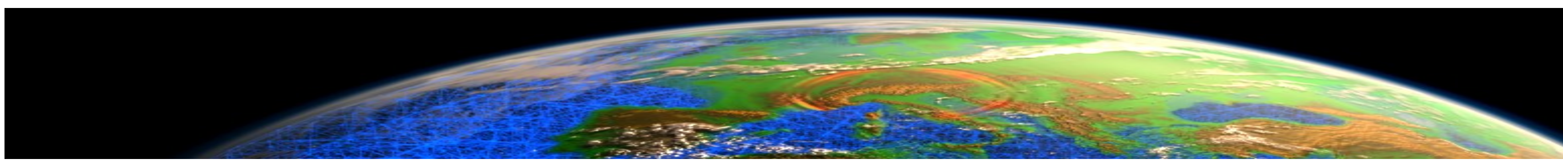
Reinterpretation of observations

(anisotropy Ψ_A fixed, but variable path azimuths Ψ_R)

- Rotation of the stress field before and after the event
- Approximate EW orientation of crack-induced anisotropy

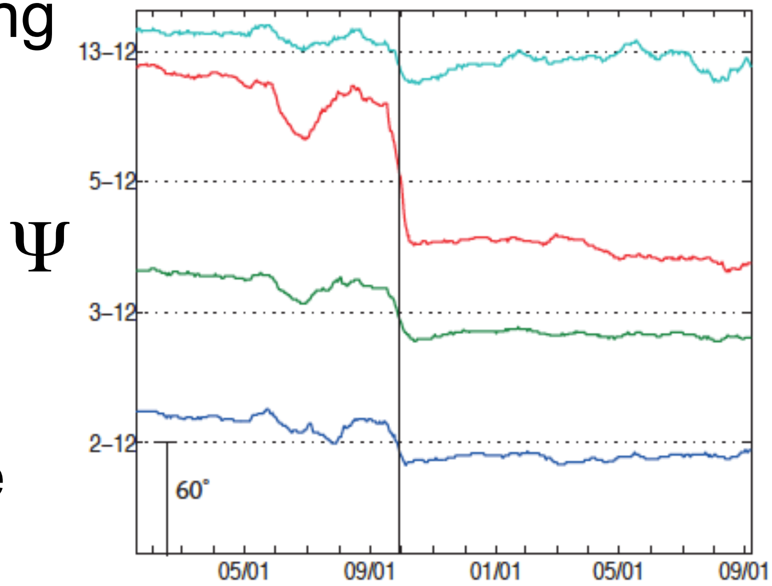


(Saade et al., 2013)



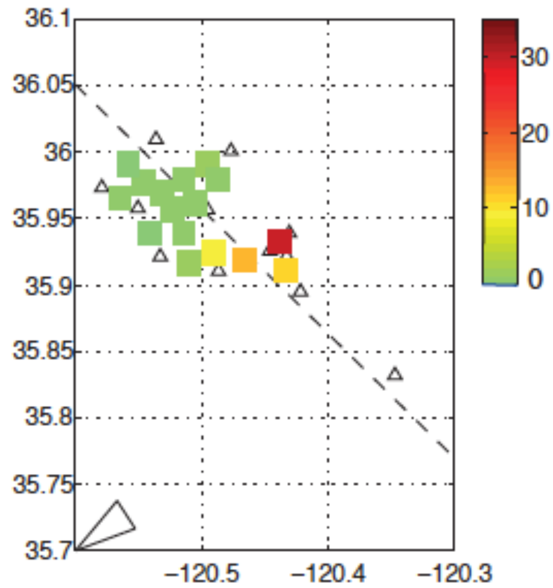
Conclusions

•New Method for continuous monitoring of the stress field
•Noise correlations sensitive to:
-1) Noise source location
-2) Anisotropy (stressmeter)
•Significant temporal change of Ψ observed in parts of the cracked zone
•Interpretation in terms of anisotropy variation



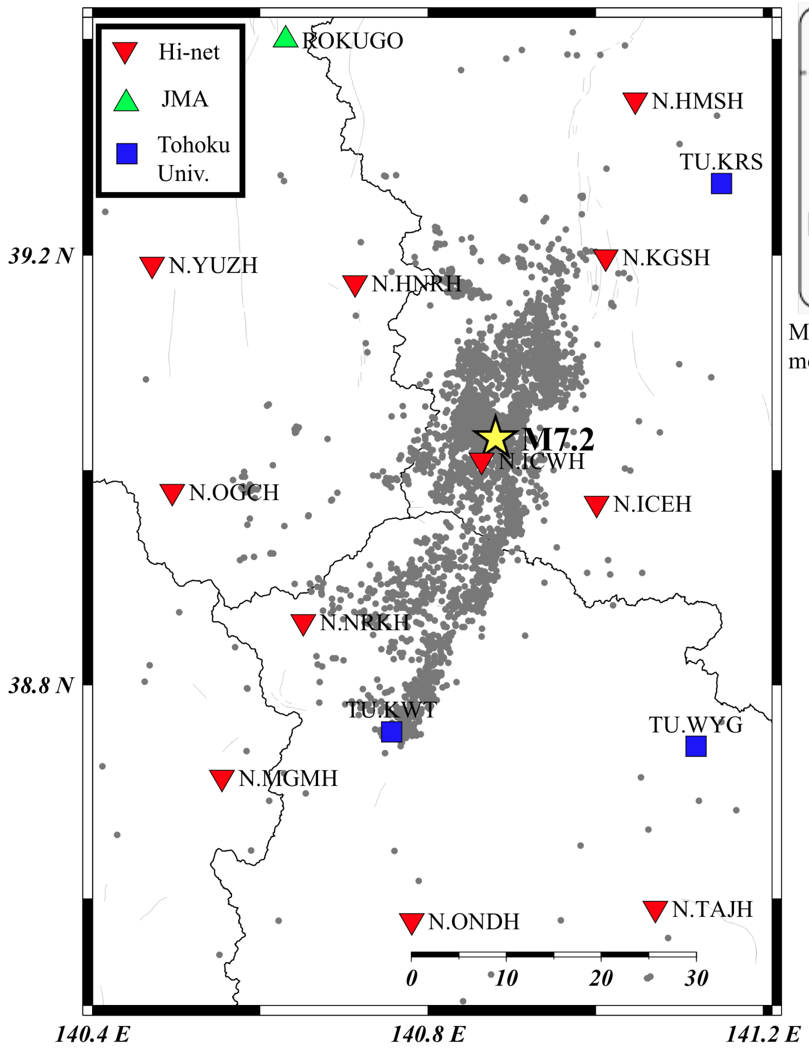
Future

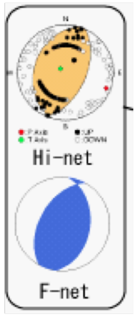
•Application to other tectonic contexts (Japan, Chile…)
•Application to fractured-cracked zones (oil/gas reservoirs)



Iwate – Miyagi earthquake (14/06/08)

Tohoku earthquake (11/03/11)

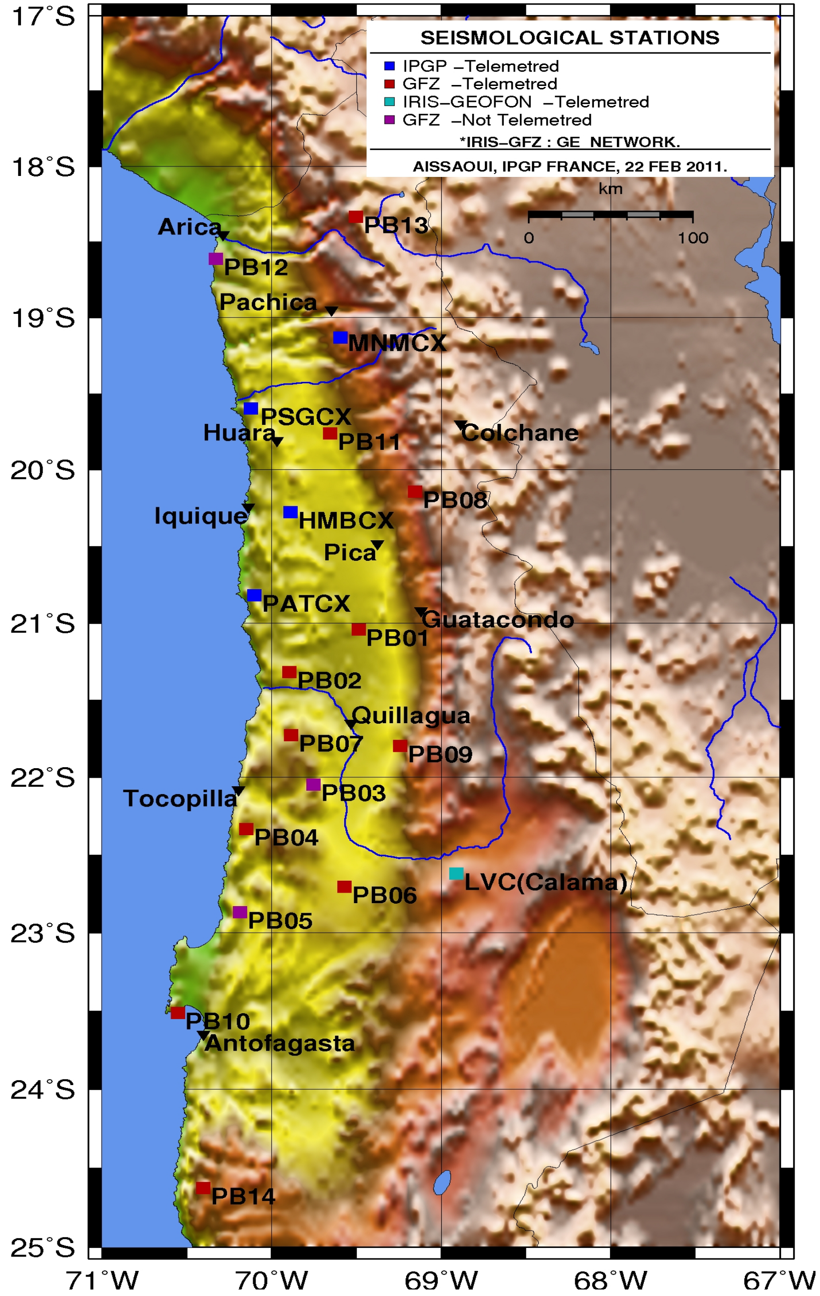




Mainshock focal mechanism

NIED

CX Network –North Chile



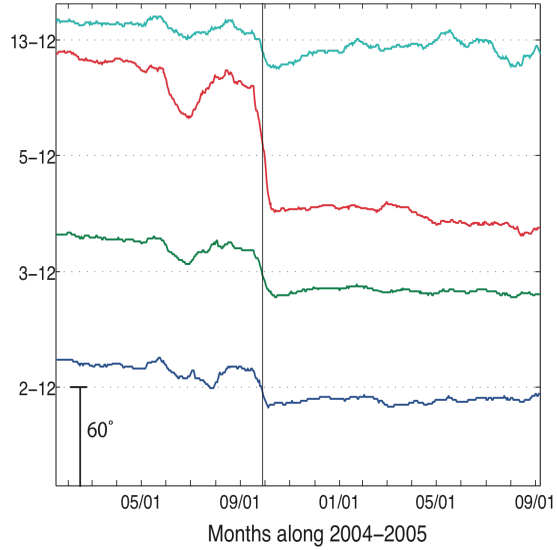
Tocopilla, Chile (14/11/07;7.7; 16/12/07, Mw=6.8)

Maule, Chile, 27/02/10?

Conclusions

•New Method to:
Continuously monitor stress field

•Significant co-seismic signal observed in specific parts of the faults:
• crack-induced anisotropy?



New developments

•Application in other tectonic contexts
•To fractured reservoirs
•Quantitative interpretation of apparent anisotropy