Seismic Anisotropy

Monitoring of Seismogenic and Volcanic zones

Jean-Paul Montagner

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…

IPG-Paris, ISTerre-Grenoble, U. Nancy, ENS-Lyon, ERI-Tokyo

Frequency	Mhz-kHz	10000-100Hz	100-10Hz	10Hz-1Hz	1-0.01Hz
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 driven field: Seismic Data**
- **Cross-correlation tensor: Seismic Anisotropy?**
- **Seismic Anisotropy: many processes**

- **Scientific Issues**:

- 3D- Anisotropic Structure of the Earth
  Upper mantle – LAB

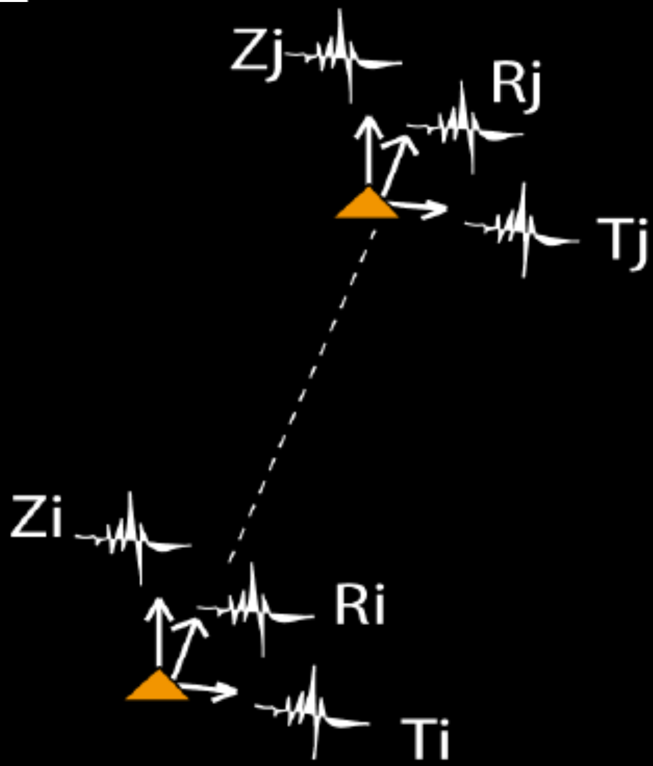
- Seismic monitoring:

  Temporal changes of anisotropy in
  - seismogenic zones (Northern Honshu – Japan)
  - volcanic zones (Mt Fuji)

Cross-correlation tensor C_{ij}
for 2 stations i, j and 3 components k, l
Seismic signals $S_{ik}(t)$, $S_{jl}(t)$

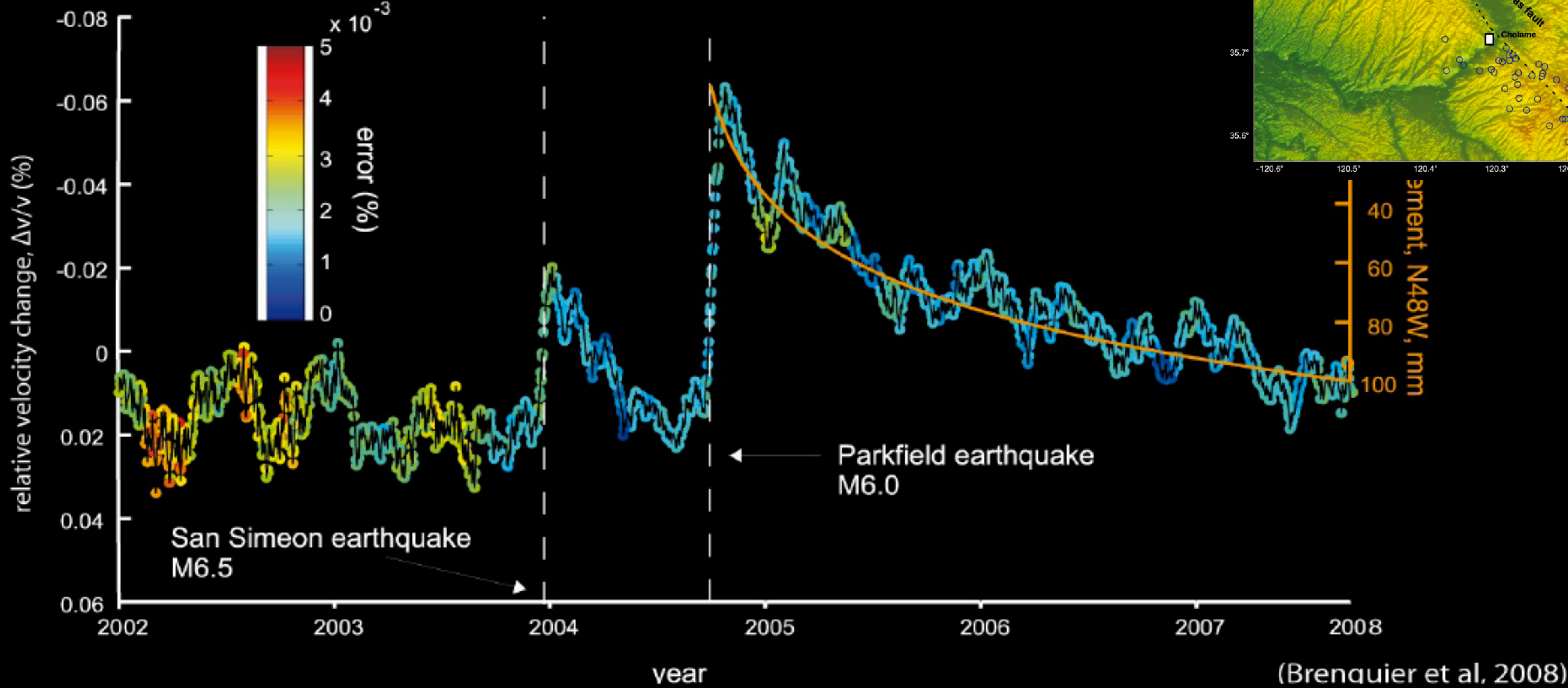
$$[C_{ij}(t)]_{kl} = \frac{\int_0^T S_{ik}(\tau) S_{jl}(t+\tau)\,d\tau}{\sqrt{\int_0^T S_{ik}^2(\tau)d\tau \int_0^T S_{jl}^2(\tau)d\tau}},$$

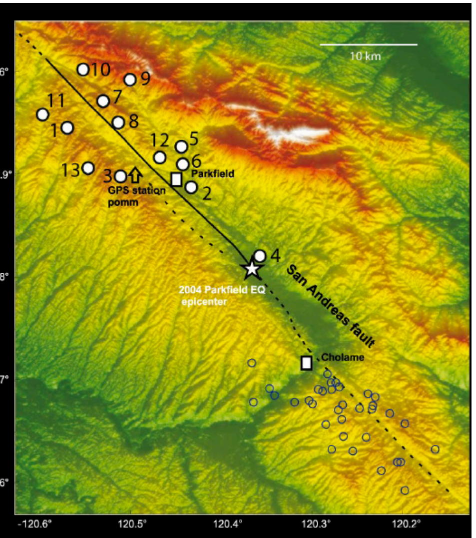
ZZ	ZR	ZT
RZ	RR	RT
TZ	TR	TT



Brenguier et al., 2008

Parkfield High Resolution Seismic Network (HRSN)

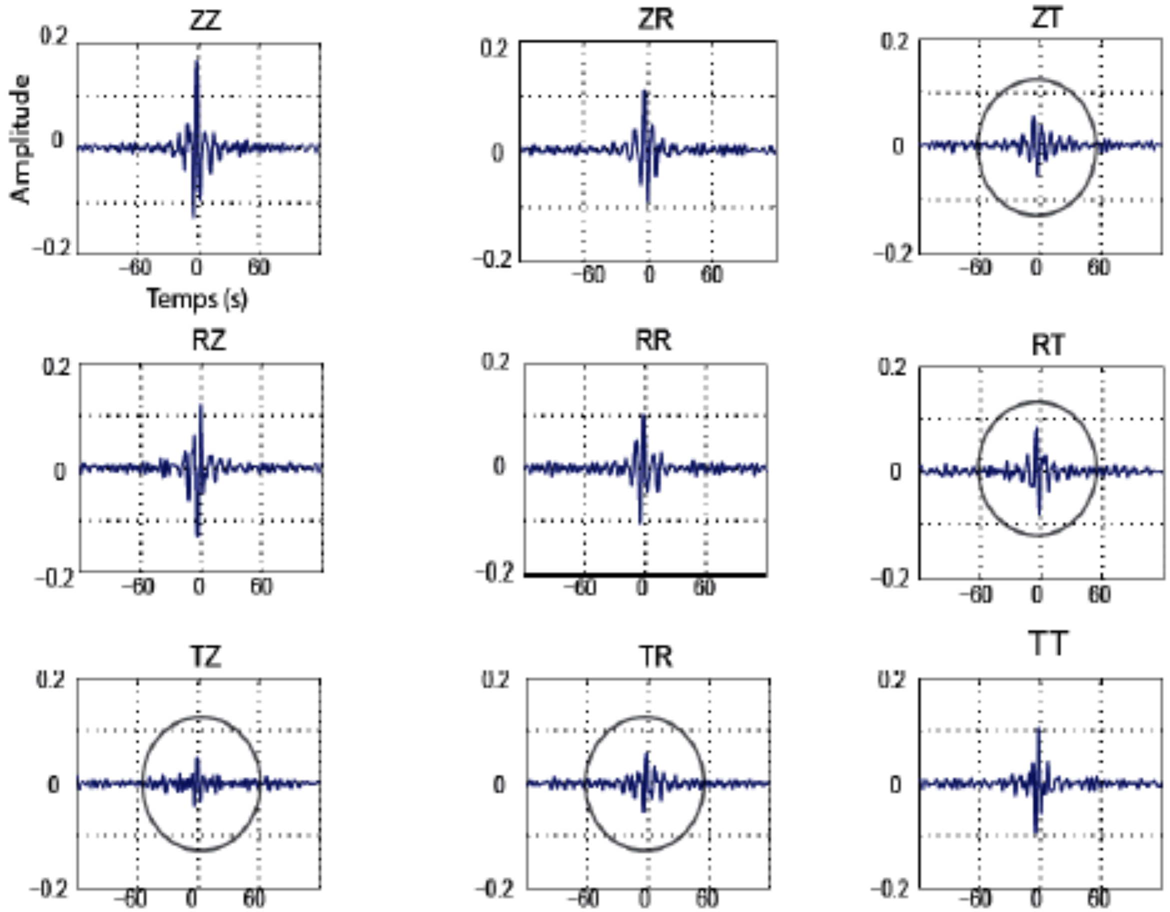




ZZ: Co-seismic and post-seismic relative velocity change (Brenguier et al., 2008)

Example of cross-correlation tensor

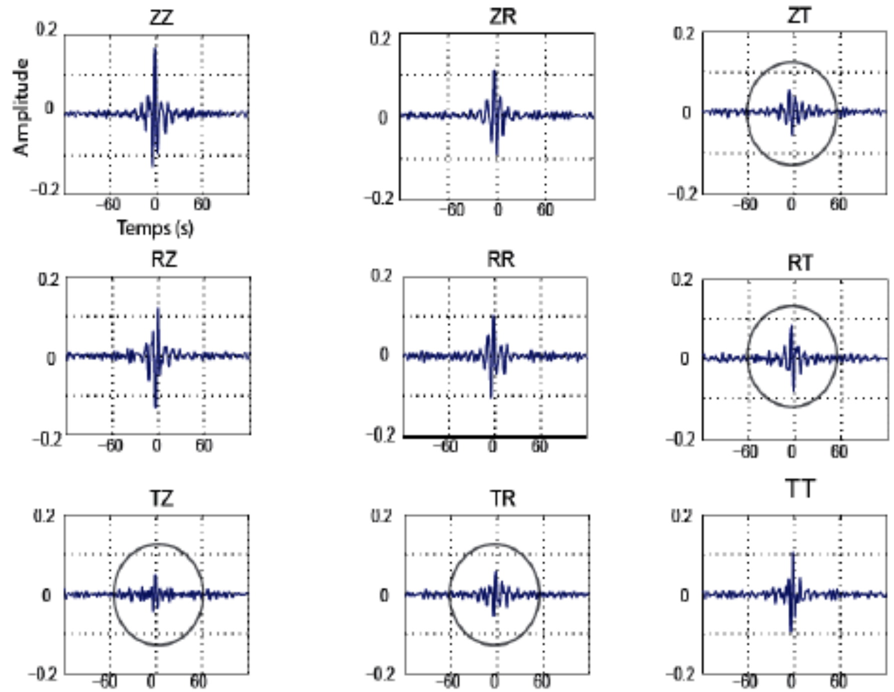
Parkfield HRSN – Stack (30days)



TZ, TR, ZT, RT ≠ 0

How can we explain the off-diagonal terms of the cross-correlation tensor?

TZ, TR, ZT, RT ≠ 0

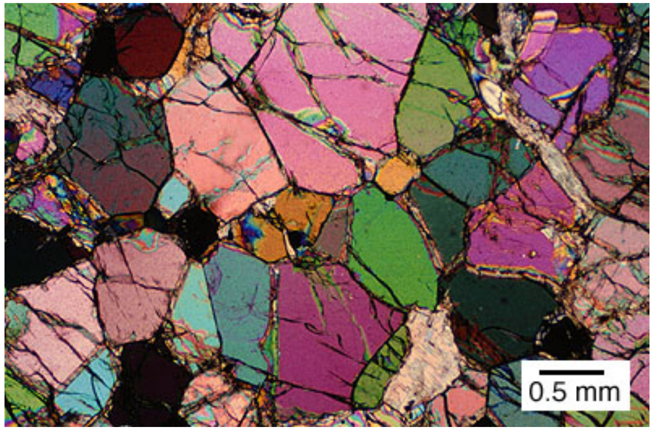


-Non uniform distribution of seismic noise sources?
-Lateral heterogeneities of Velocities?
-**Seismic anisotropy?**

To explain seismic data:
heterogeneities isotropic / anisotropic, anelasticity

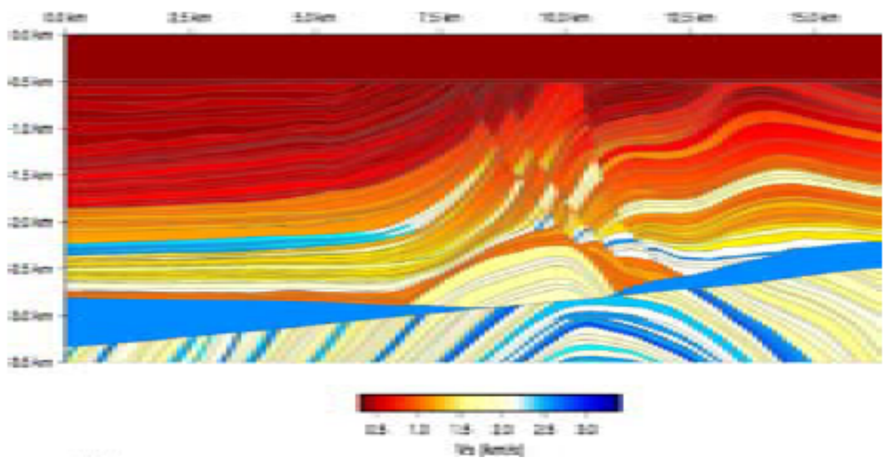
Confusion: Heterogeneity ≠ Anisotropy

-Homogeneous, anisotropic
(Olivine aggregates)



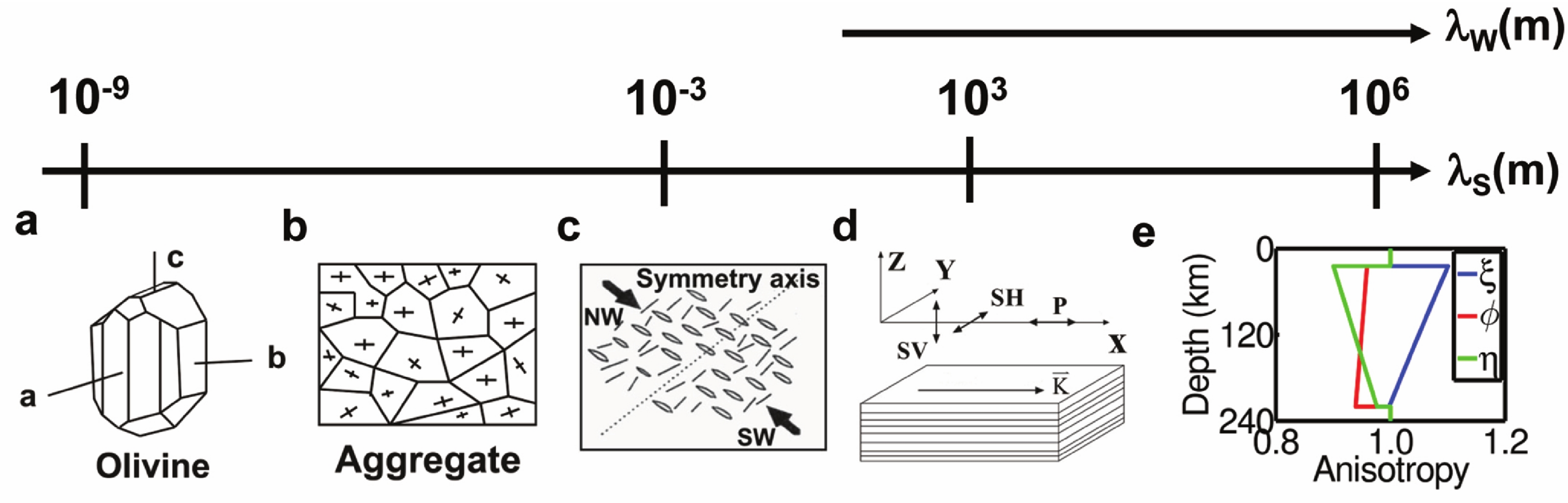
-Heterogeneous, isotropic

Marmousi



Solid Earth: heterogeneous + anisotropic + anelastic

Seismic Anisotropy at all scales



PREM

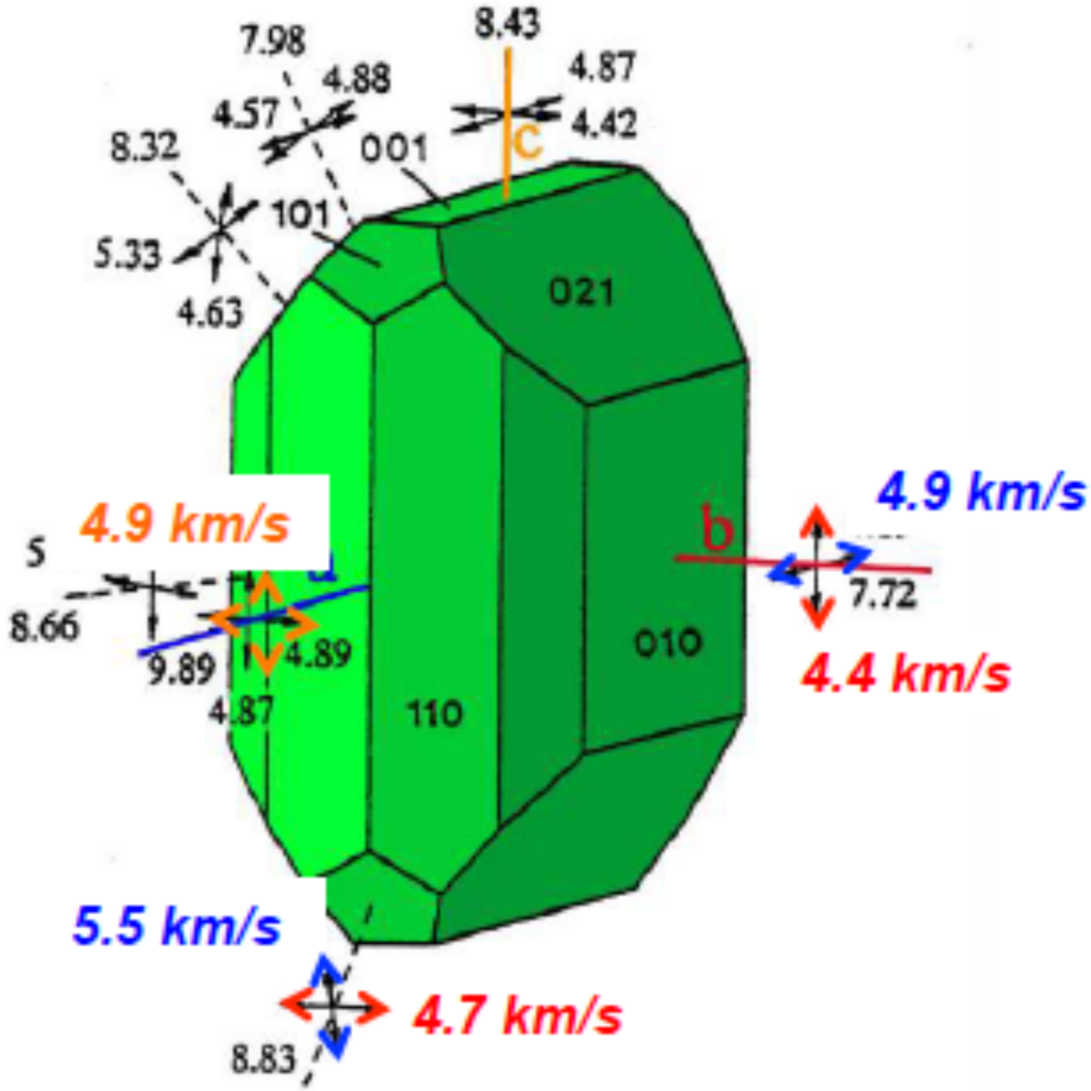
PREM: radial anisotropy: up to 10%

λ_W seismic wavelength

λ_S spatial scale

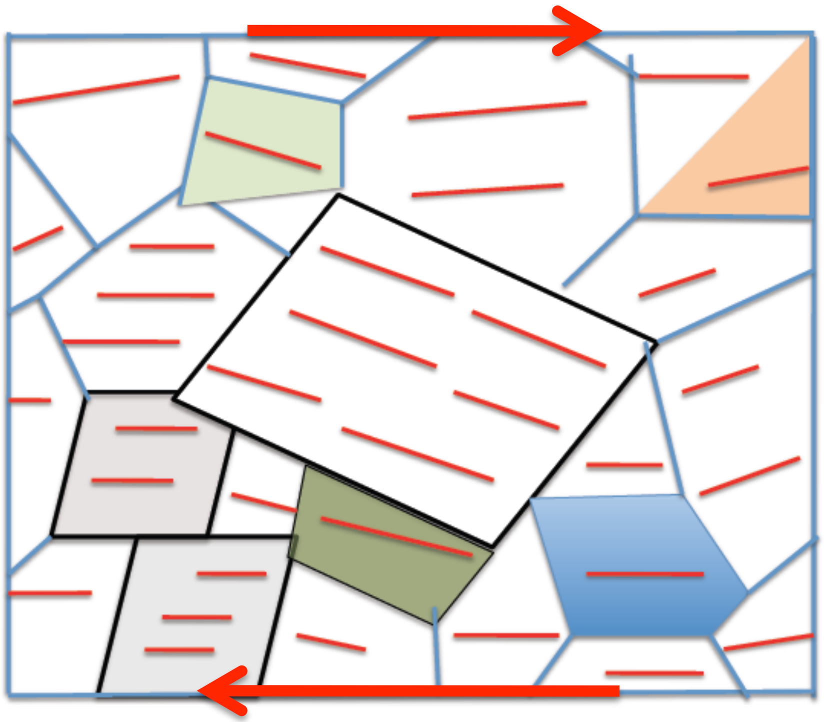
(Wang et al., 2013)

Olivine : 20% anisotropy



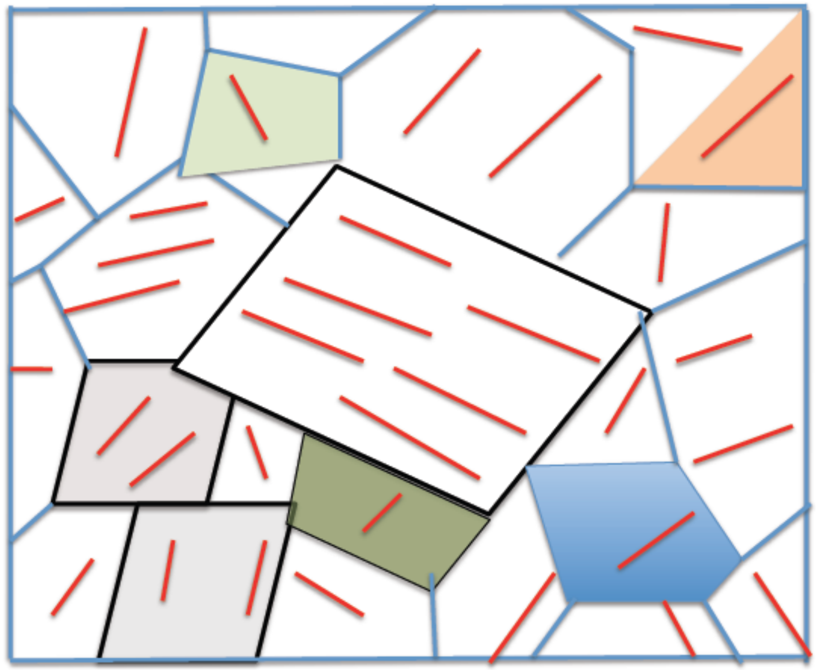
Coherent Strain field (convective process)
(L.P.O.: lattice preferred orientation)

Large-scale Seismic anisotropy ≠ 0



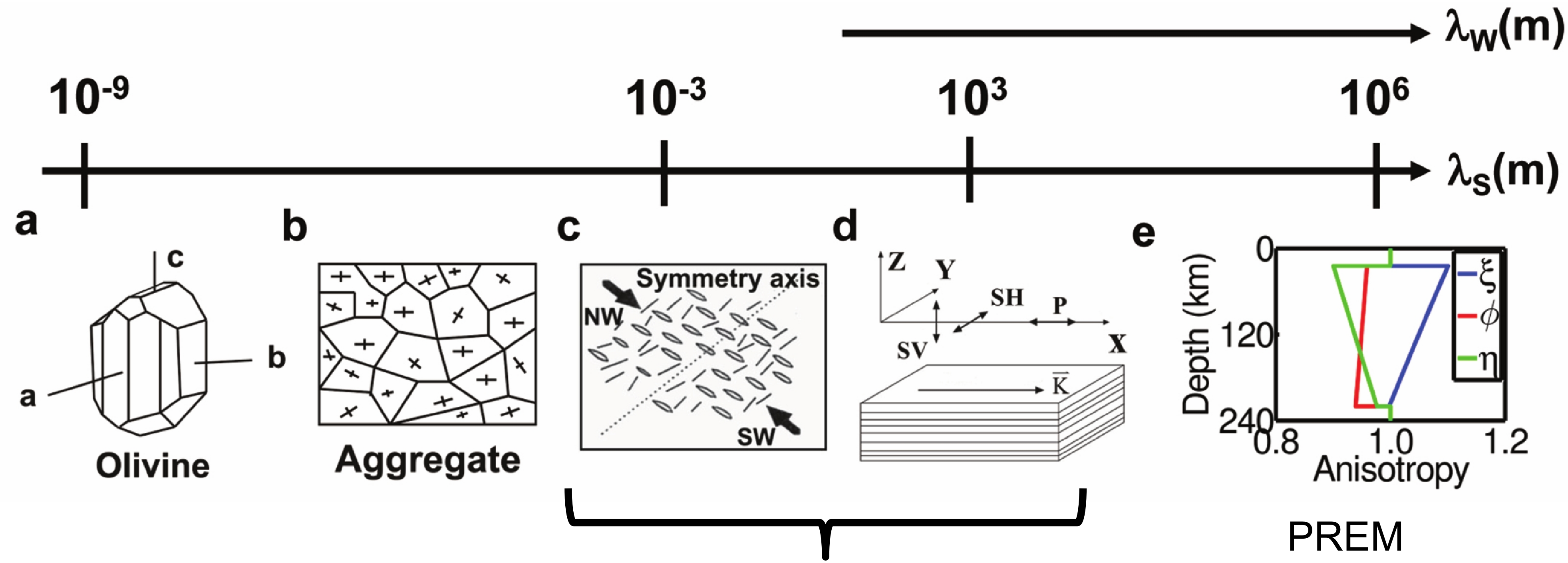
Incoherent Strain field
(random orientation)

Large-scale Seismic anisotropy ≈ 0



Inner Organization

Seismic Anisotropy at all scales



PREM: radial anisotropy: up to 10%

λ_W seismic wavelength

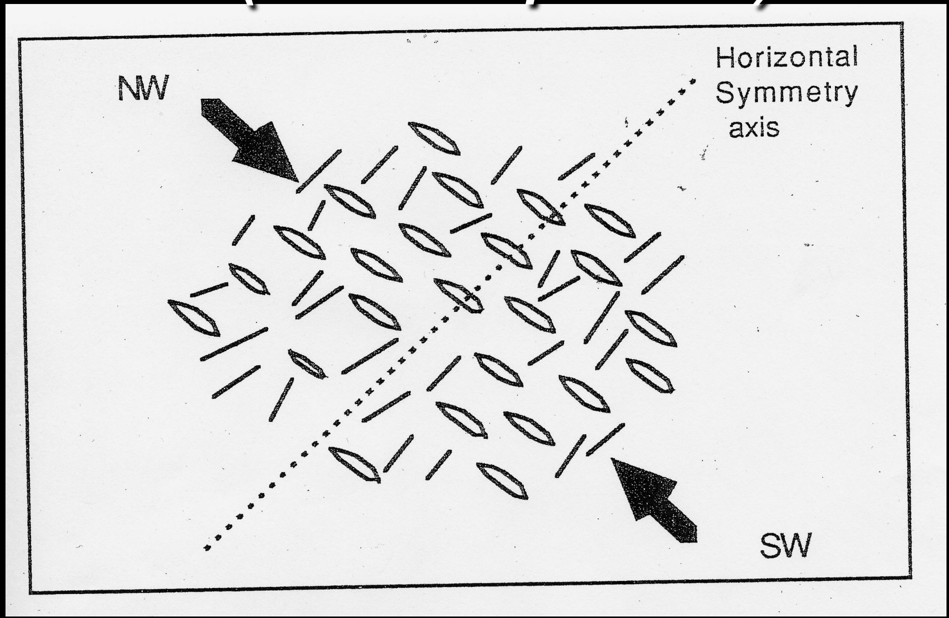
λ_S spatial scale

(Wang et al., 2013)

S.P.O.: Shape Preferred Orientation

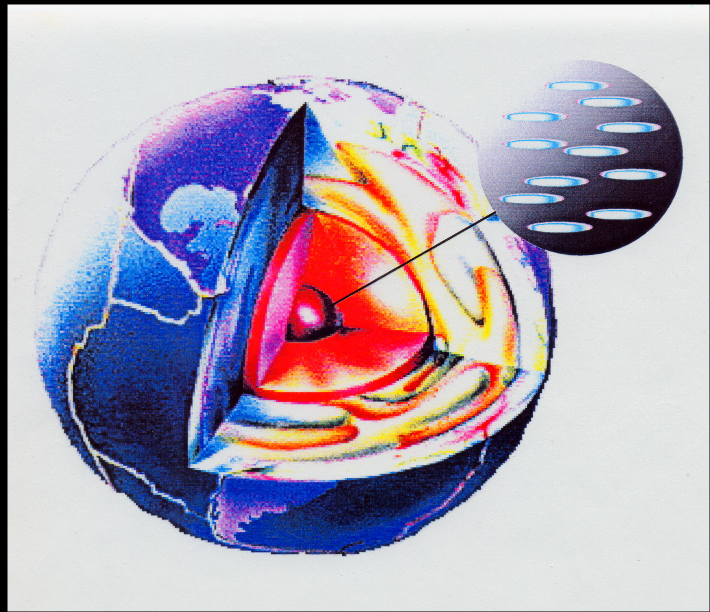
Cracks, fluid inclusions, … (Stress field)

Crust (+lithosphere)



(Babuska and Cara, 1991)

Inner core



(Singh et al., 2001)

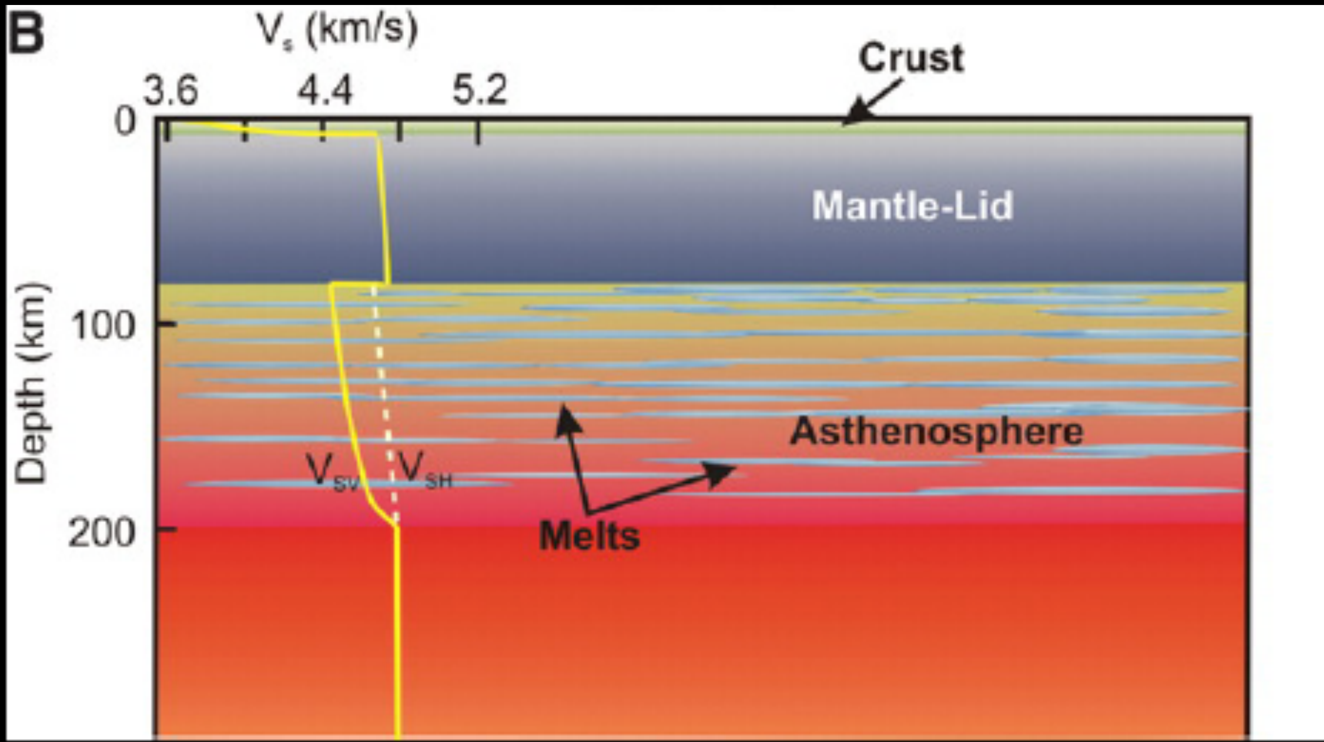
→ *STRESSMETER*

Temporal variations of anisotropy?

Monitoring of cracked, fractured zones

(seismogenic zones: Durand et al. 2011; Saade et al., 2014, 2017)

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



→ *Effective medium*

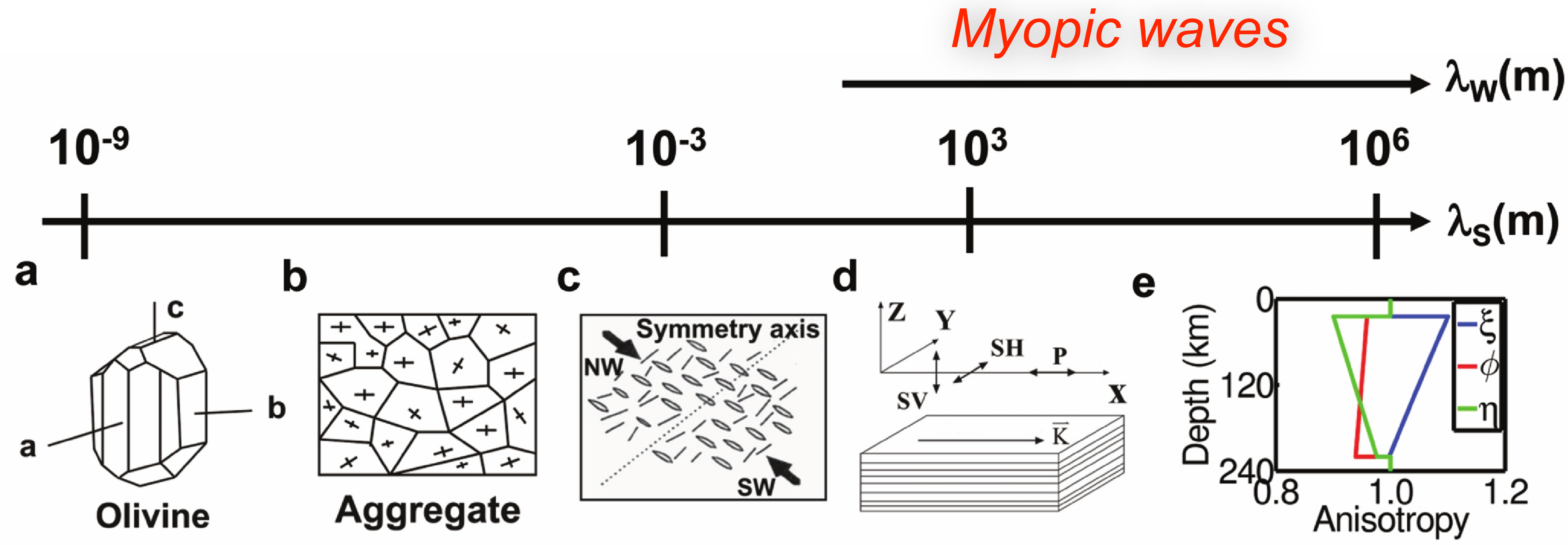
Radial anisotropy (Kawakatsu et al. 2009)

V.T.I. Vertical Transversely Isotropic medium:

5 parameters

($A=\rho V_{PH}^2$, $C=\rho V_{PV}^2$, F, $L= V_{SV}^2$, $N= V_{SH}^2$)

Seismic Anisotropy at all scales



Intrinsic **Extrinsic** PREM

Observed (apparent) anisotropy

Intrinsic versus Extrinsic anisotropy

$$\alpha = p\alpha^{int} + (1-p)\,\alpha^{ext}$$

NOT A SECOND ORDER EFFECT, different interpretations

Wave propagation in anisotropic medium

- Isotropic medium

$$\rho\frac{\partial^2 u_i}{\partial t^2} = \lambda\frac{\partial\Theta}{\partial x_i} + \mu\frac{\partial}{\partial x_j}(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i})$$

Where u is seismic displacement,
λ and μ Lamé parameters
$\Theta = \nabla.\mathbf{u}$

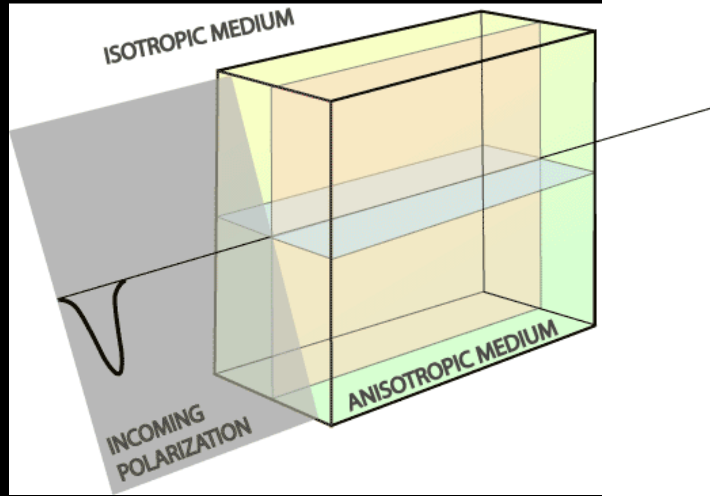
- Anisotropic medium

$$\rho\frac{\partial^2 u_i}{\partial t^2} = \frac{1}{2}\gamma_{ijkl}(u_{k,lj} + u_{l,kj})$$

γ_{ijkl} 4th-order elastic tensor

Different kinds of anisotropy effects on seismic waves

•Body waves: Shear wave splitting
(birefringence)



Courtesy of Ed. Garnero

Different kinds of anisotropy effects on seismic waves

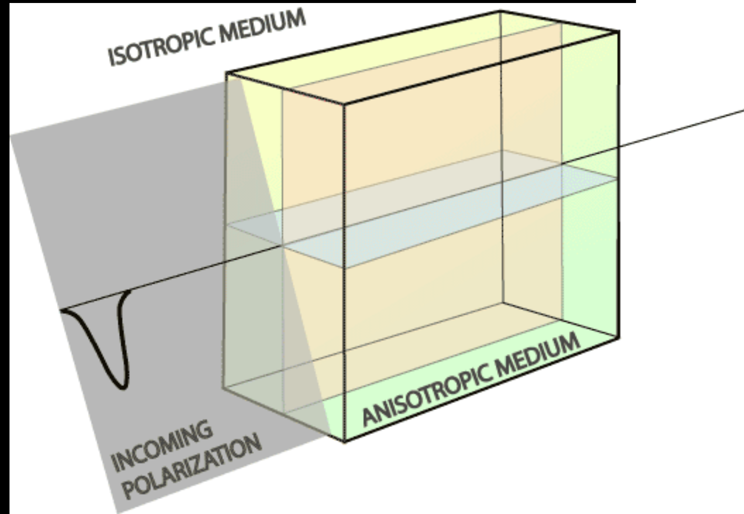
•Body waves: Shear wave splitting
(birefringence)

•Surface waves (Rayleigh and Love):

- Rayleigh-Love discrepancy

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

-Quasi-Rayleigh, Quasi-Love
polarization anomalies



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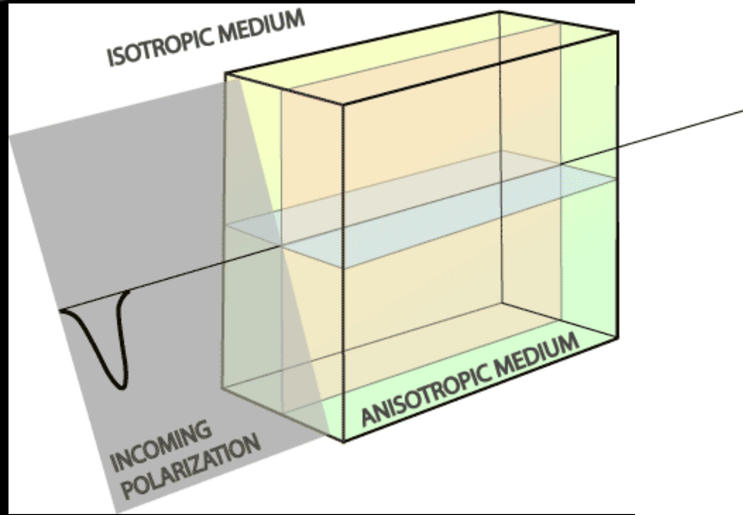

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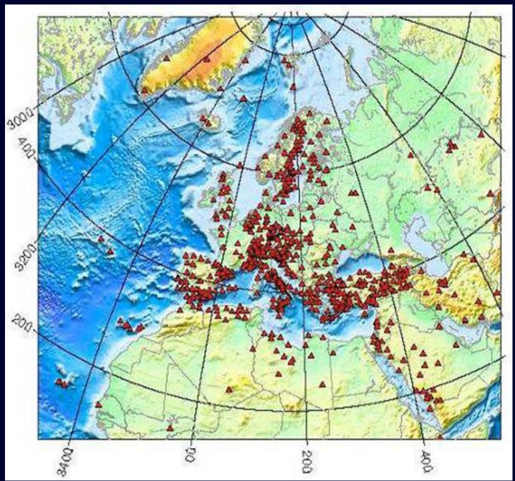
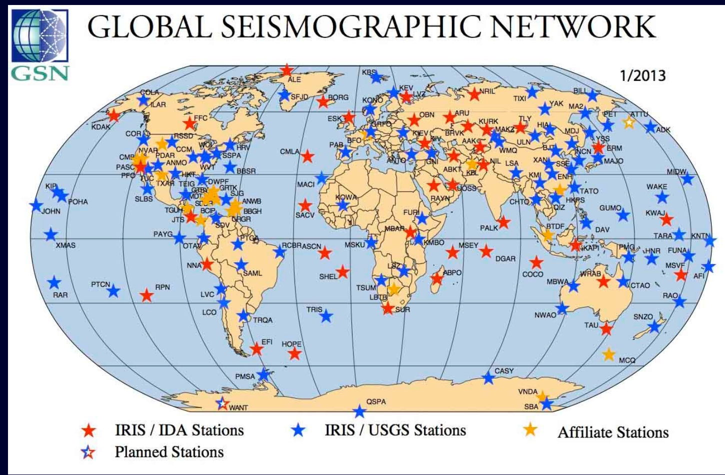
Courtesy of Ed. Garnero

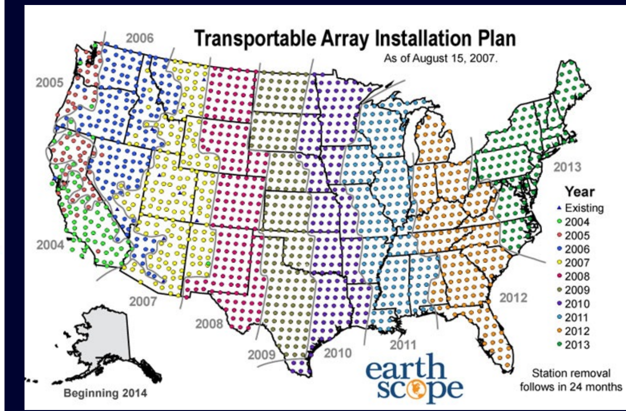
Data in Global & Regional Seismology



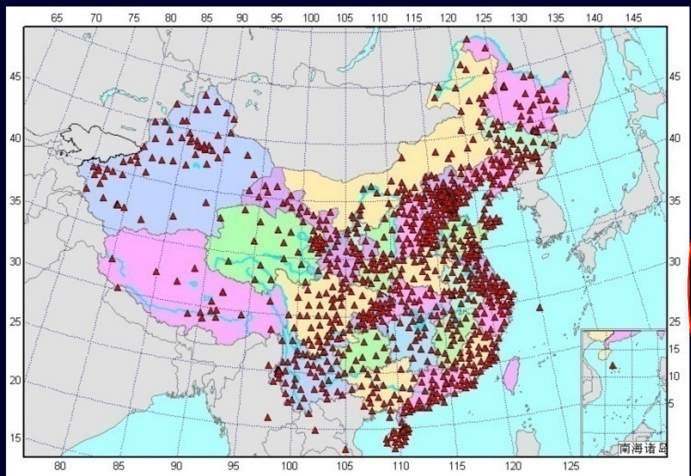
[www.geo.uib.no]



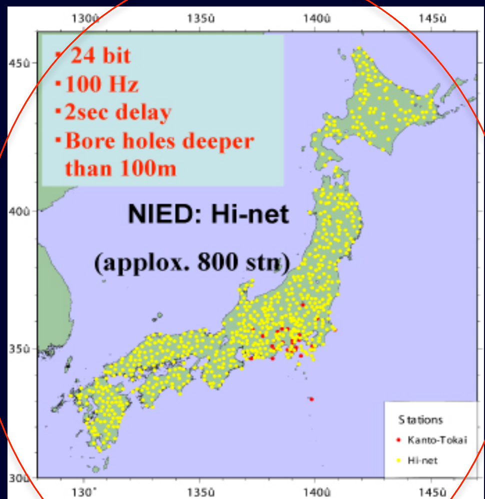
[www.iris.edu]



[web.mst.edu]



[data.earthquake.cn]



[drh.edm.bosai.go.jp]

Barruol et al., 2013

OUTLINE

- Data driven field: Seismic Data
- Cross-correlation tensor: Seismic Anisotropy?
- Seismic Anisotropy: many processes

- **Scientific Issues**:

  Seismic monitoring:

  Temporal changes of polarization anisotropy in:

  - seismogenic (Parkfield, Cal., USA; Iwate-Miyagi, Japan)

  - Volcanic zones (Mount Fuji, Japan)

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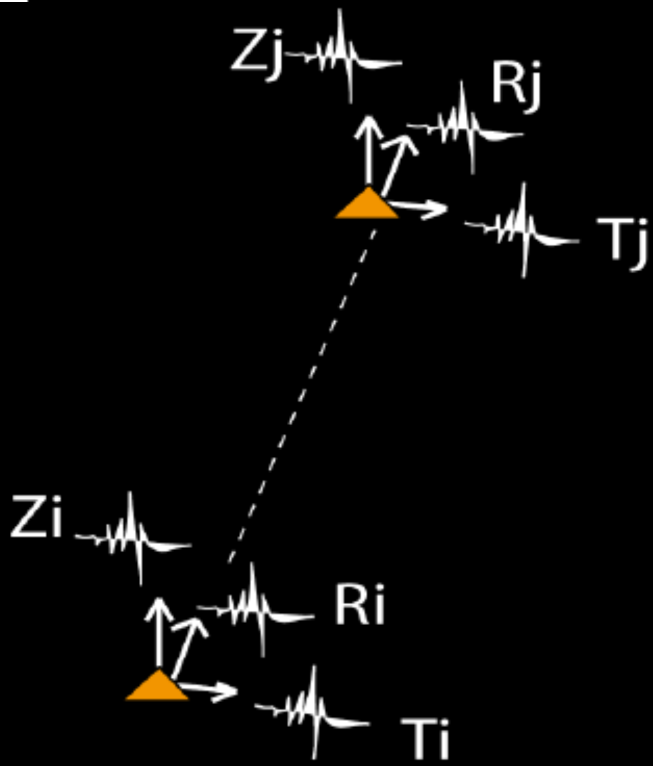

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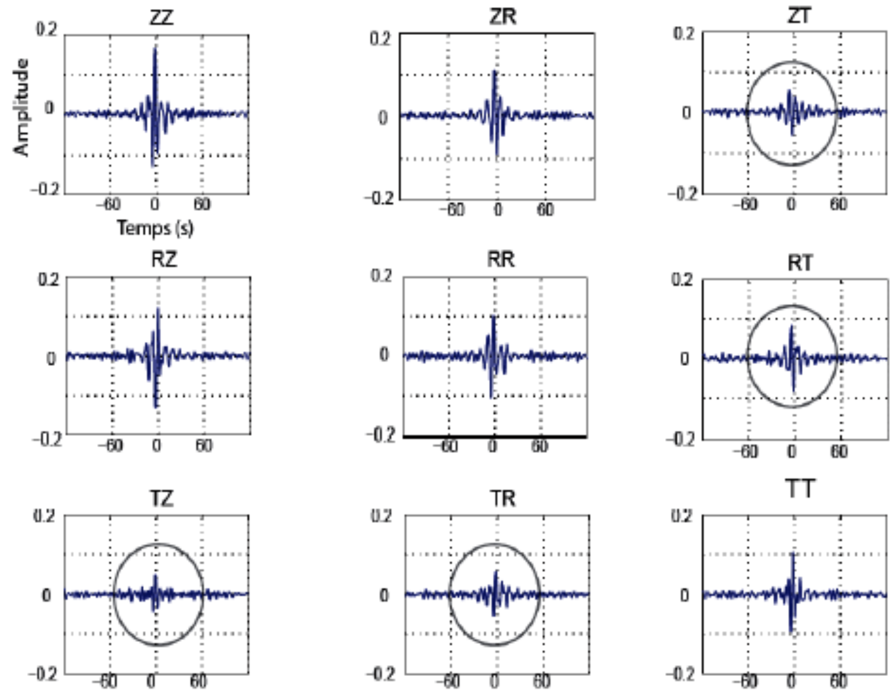
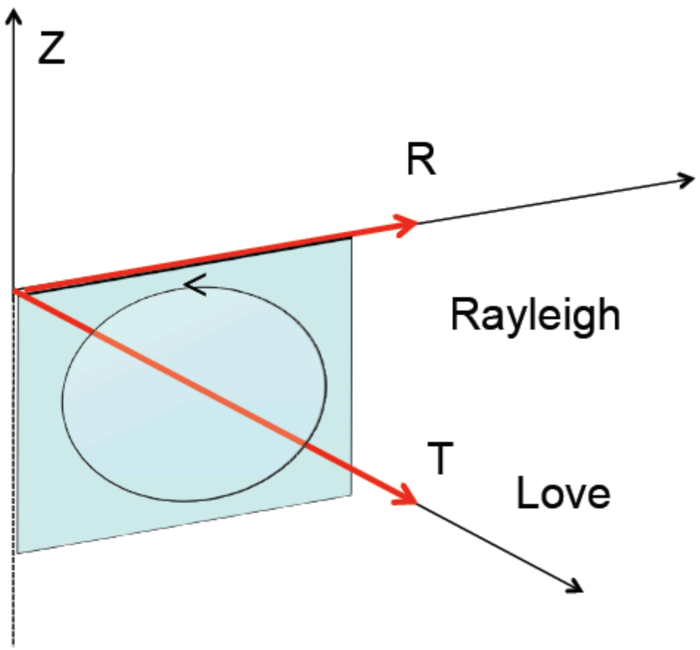
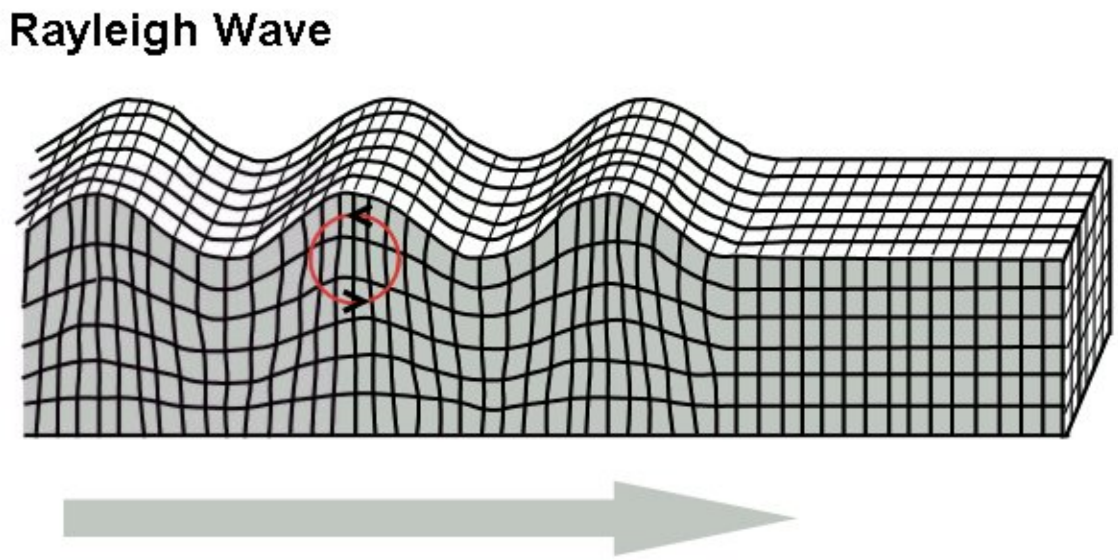


Effect of anisotropy on amplitude

Polarization of surface waves

ISOTROPIC MEDIUM





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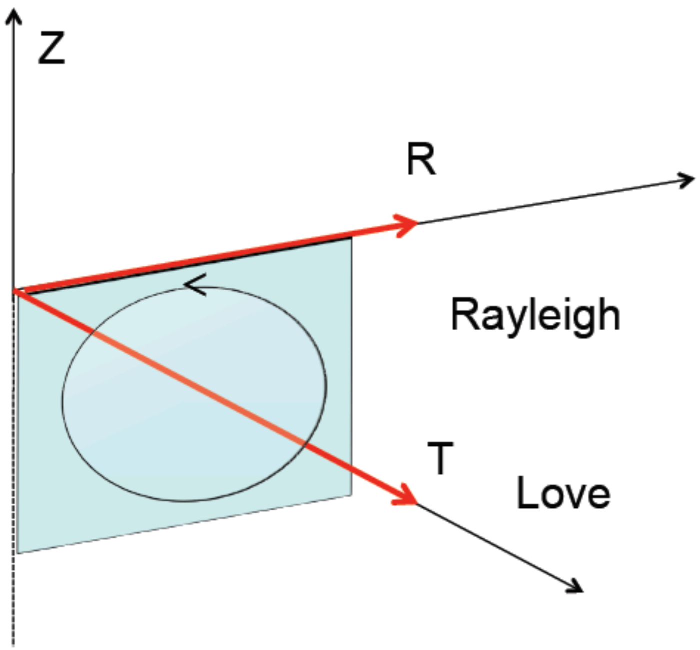
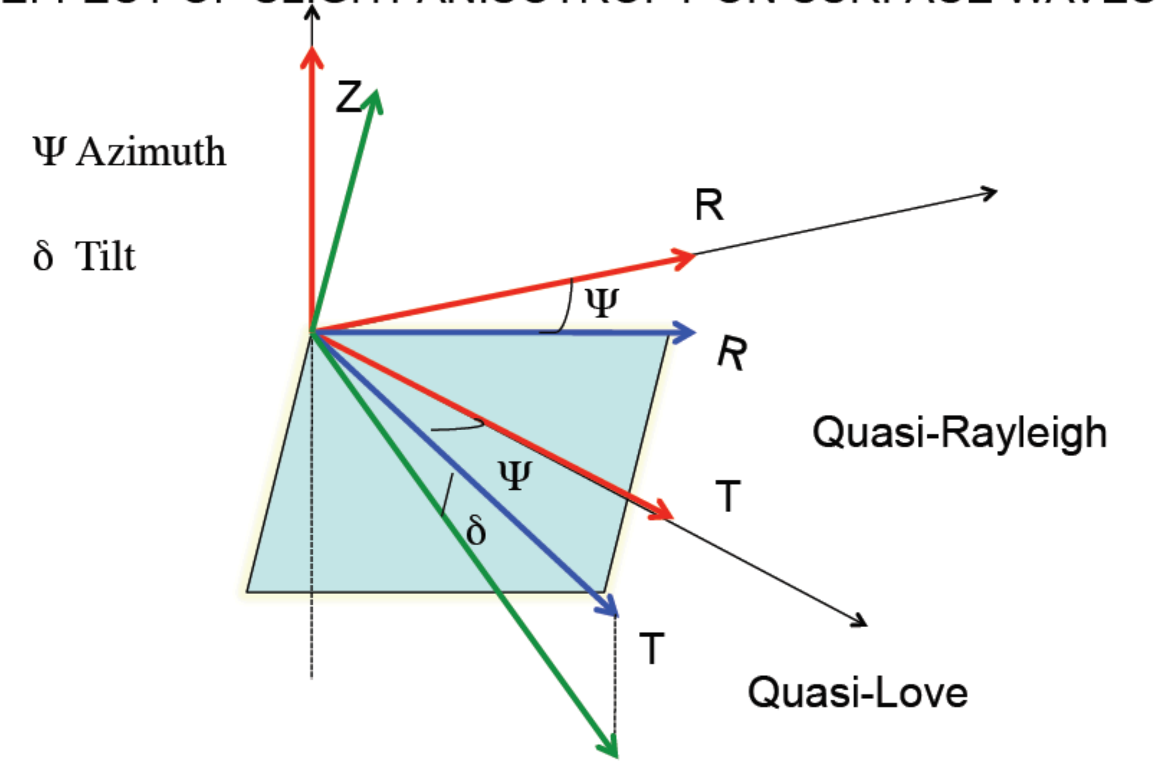


EFFECT OF SLIGHT ANISOTROPY ON SURFACE WAVES



New Observables Ψ, δ

THEORY

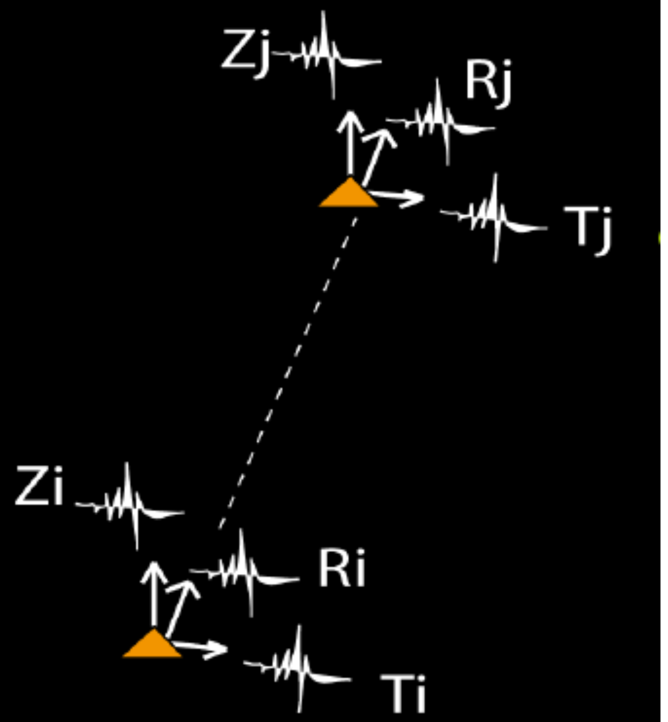
Cross-correlation for 2 stations i, j and 3 components k, l

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

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

Cross-Correlation Tensor

ZZ	ZR	ZT
RZ	RR	RT
TZ	TR	TT



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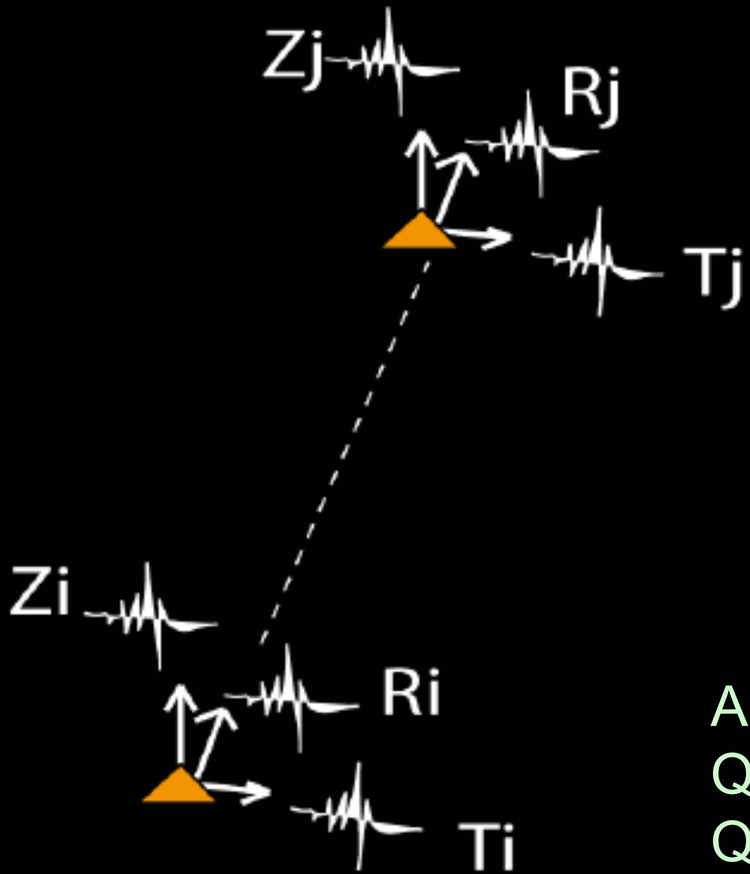
ZZ	ZR	~0
RZ	RR	~0
~0	~0	TT

ISOTROPIC MEDIUM
Rayleigh wave
Love wave



ZZ	ZR	ZT
RZ	RR	RT
TZ	TR	TT

ANISOTROPIC MEDIUM
Quasi-Rayleigh wave
Quasi-Love wave

THEORY

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

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

Azimuthal
Anisotropy
of Rayleigh
waves

Effect of anisotropy on C_{ij}

ZZ	ZR	ZT
RZ	RR	RT
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Joint Inversion
of Rayleigh
and Love waves:
Radial anisotropy

THEORY

Cross-correlation
for 2 stations i, j
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Effect of anisotropy on C_{ij}

ZZ	ZR	ZT
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Azimuthal
Anisotropy
of Rayleigh
waves

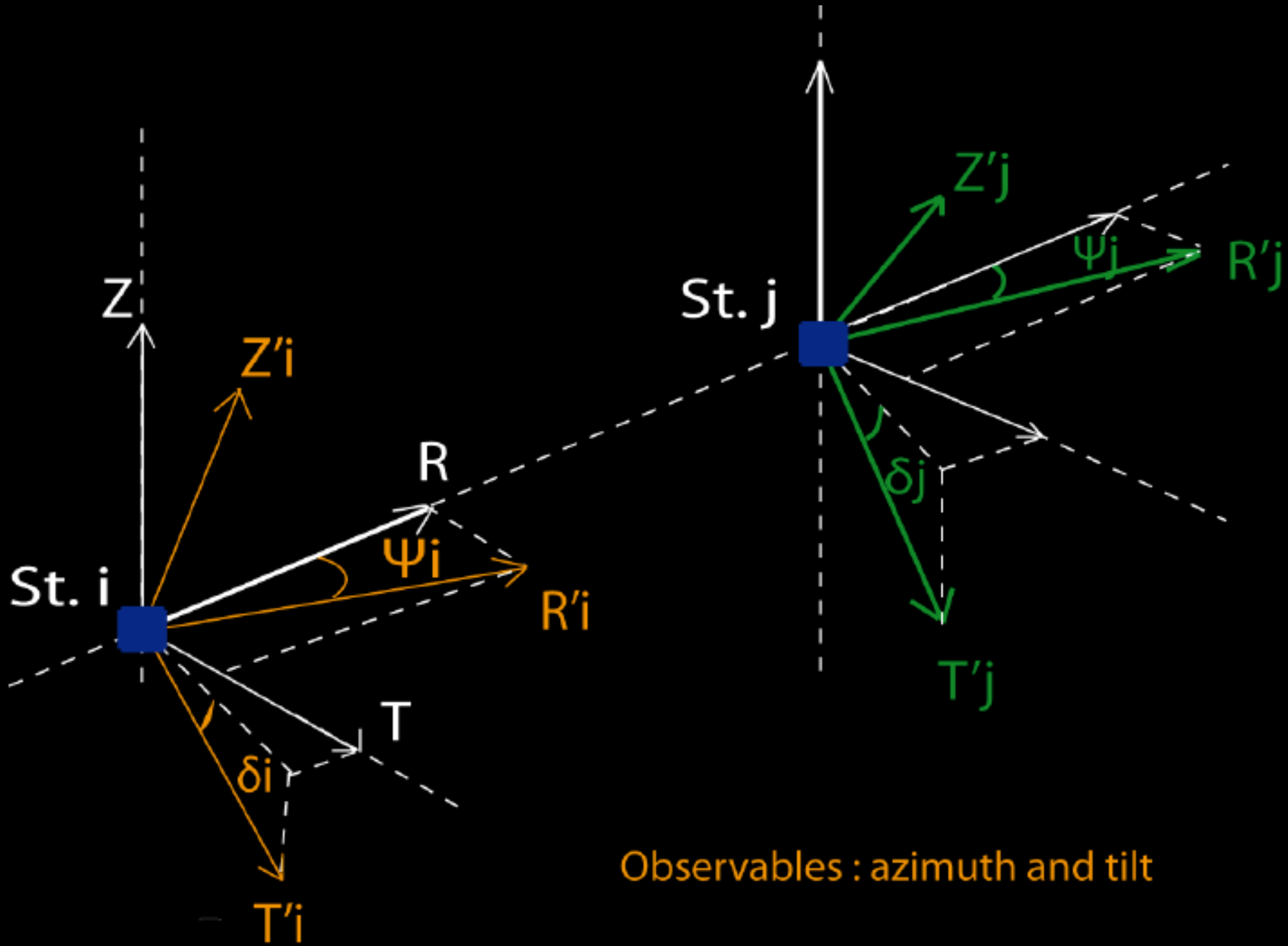
Quasi-Rayleigh
Quasi-Love
waves:
polarization
anomalies

Joint Inversion
of Rayleigh
and Love waves:
Radial anisotropy

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

Minimization of the RT, TR, ZT and TZ components

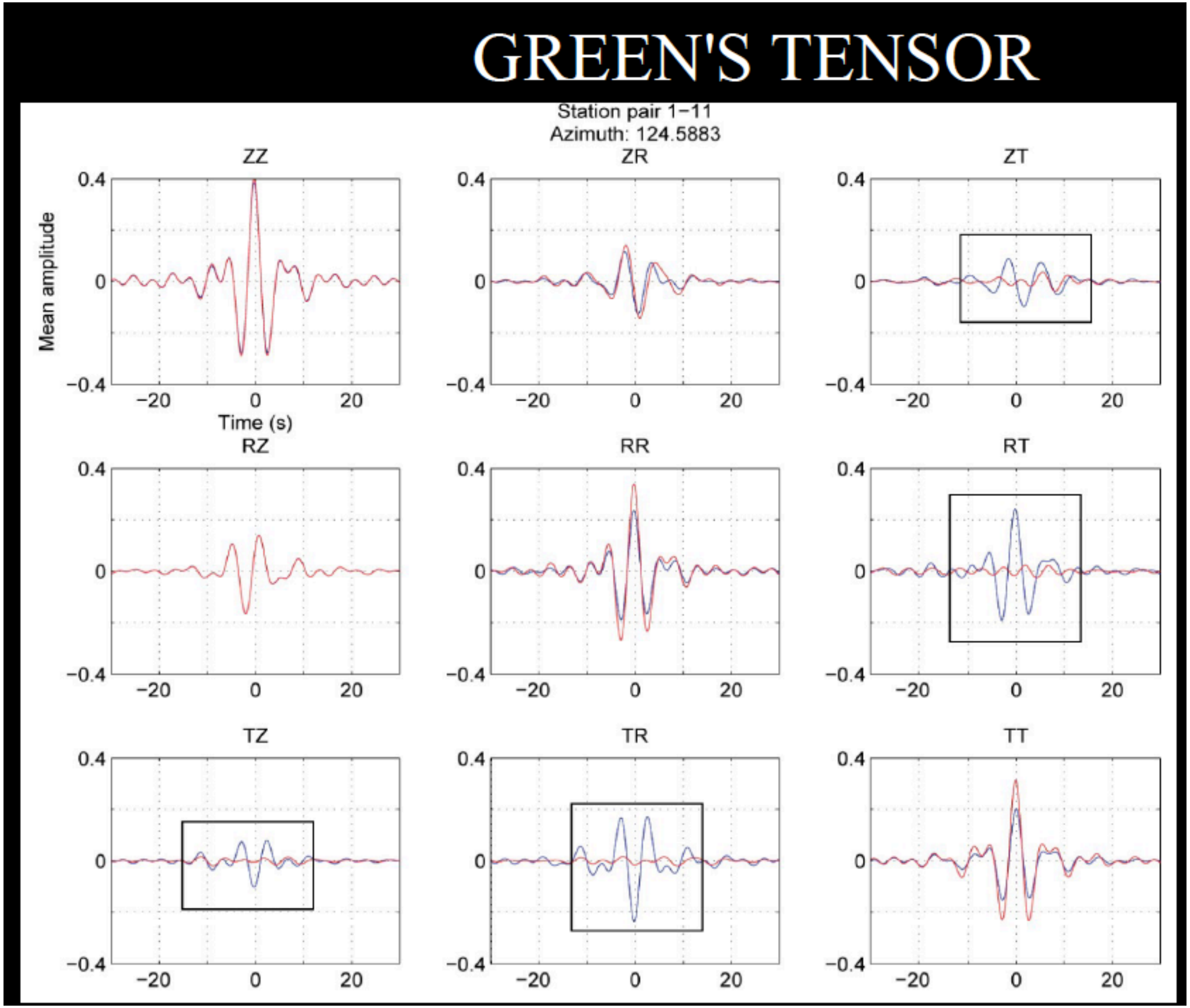
ZZ	ZR	~~ZT~~
RZ	RR	~~RT~~
~~TZ~~	~~TR~~	TT



Observables : azimuth and tilt

Ψ δ

Efficiency of Optimal Rotation Algorithm (ORA)



Time (s) Time (s) Time (s)

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:

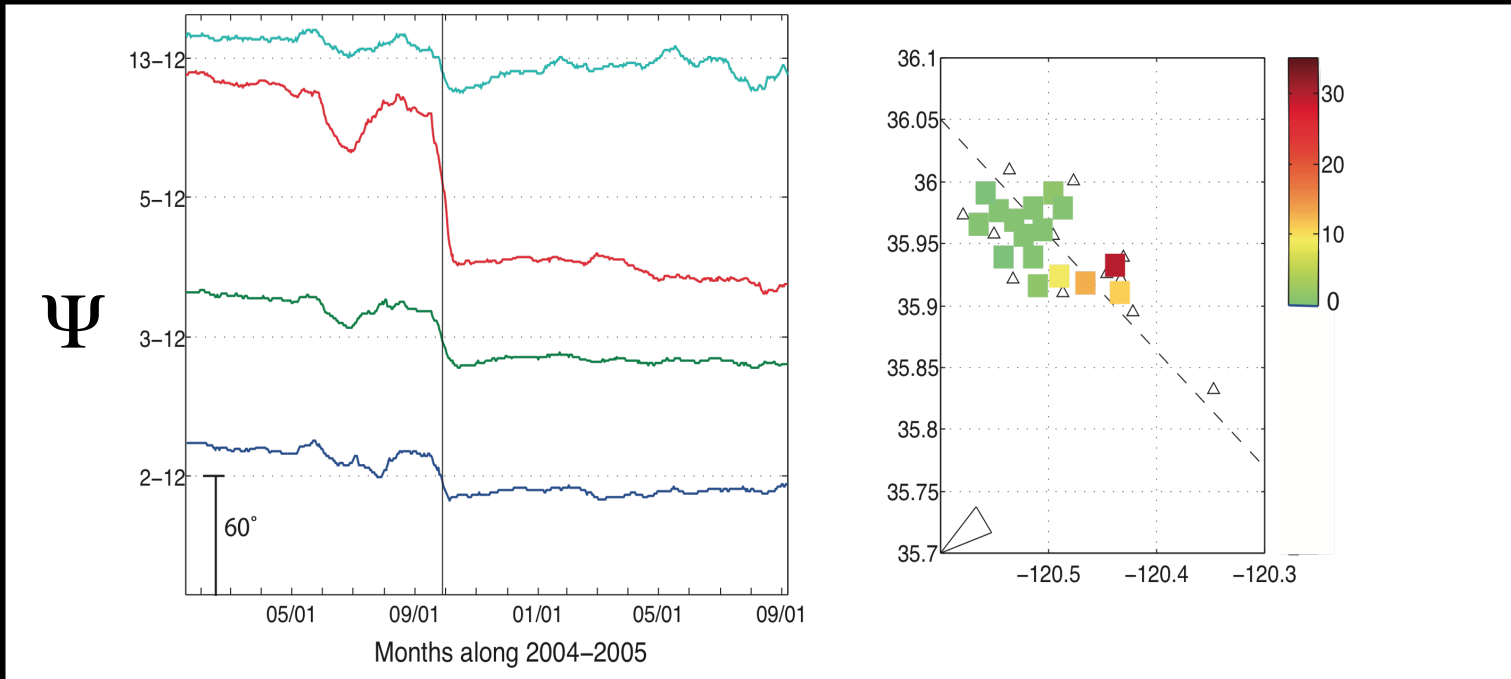
- Non-random distribution of seismic sources

→ seasonal variations (beamforming analysis)

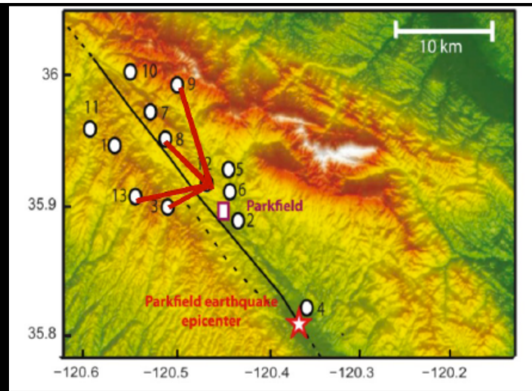
- ANISOTROPY changes

→ Stress field temporal variations

Time variations of Ψ angle after noise removal



Significant co-seismic jumps for station pairs containing station 12



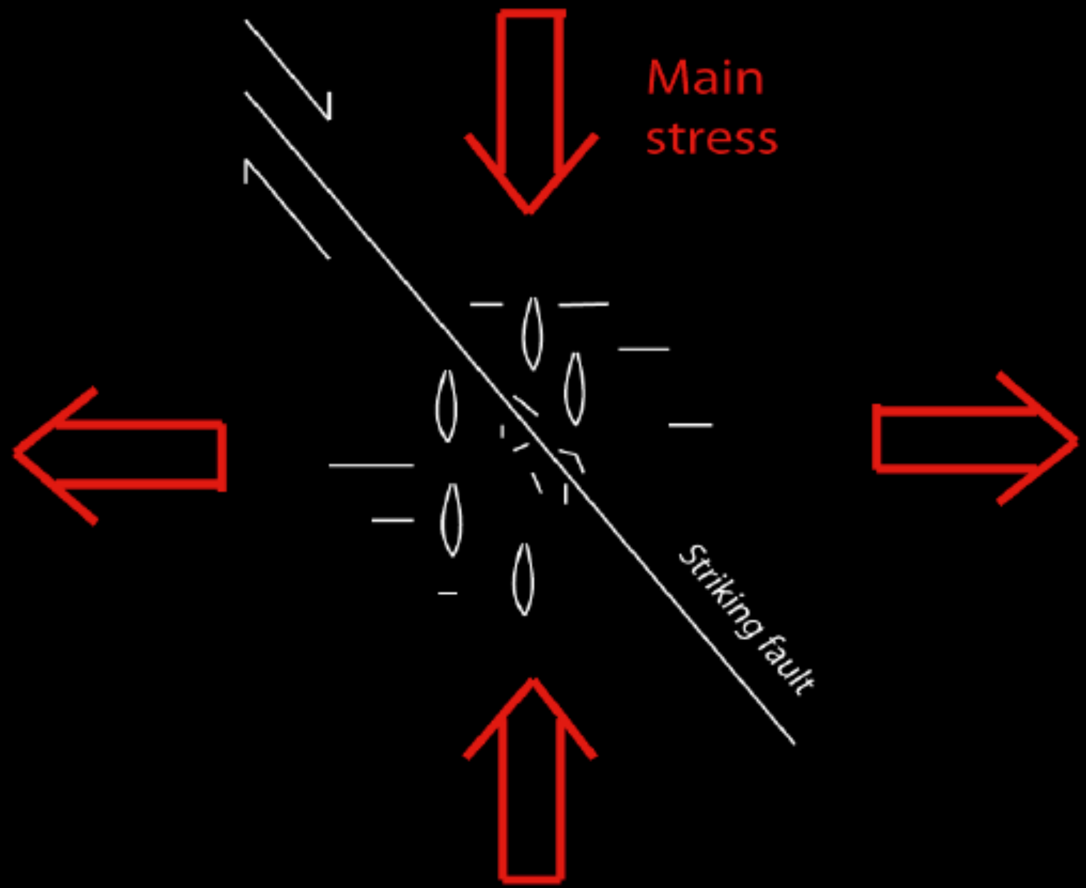
Tentative (reasonable) interpretation:

stress rotation => apparent rotation of the crack distribution

Durand et al., 2011

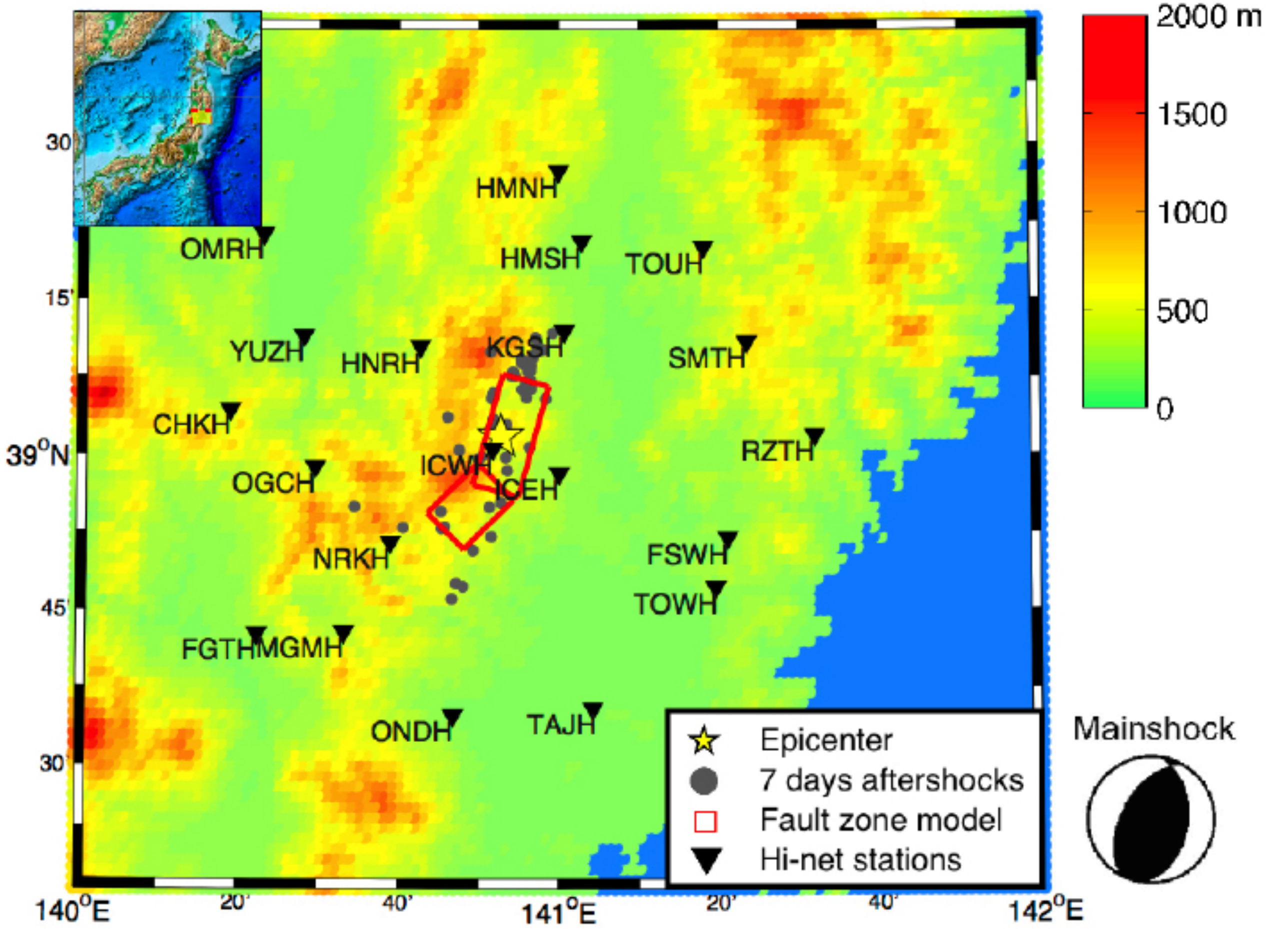
Seismic Anisotropy: Cracks, fluid inclusions

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



Other Tectonic context

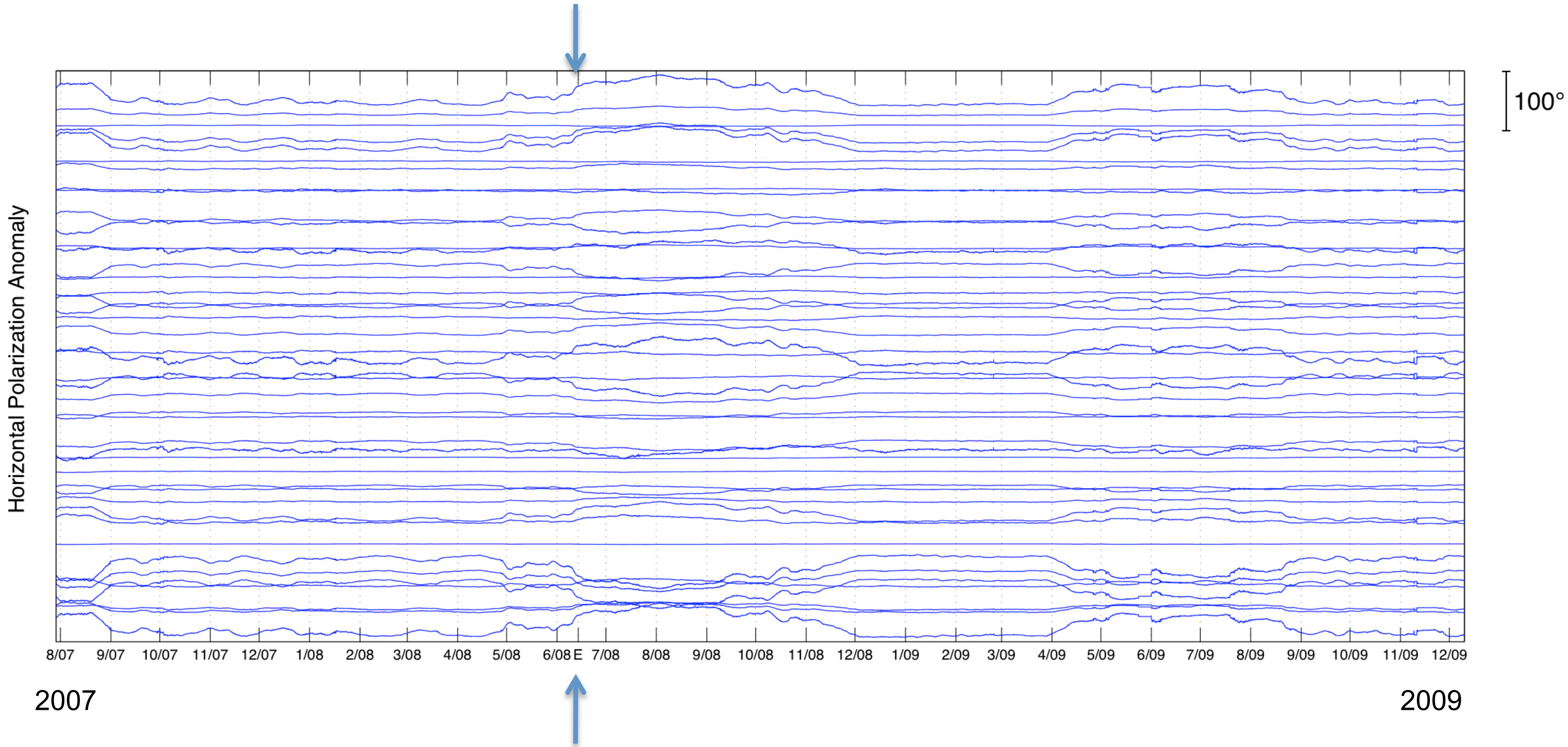
Iwate – Miyagi earthquake (14/06/08)



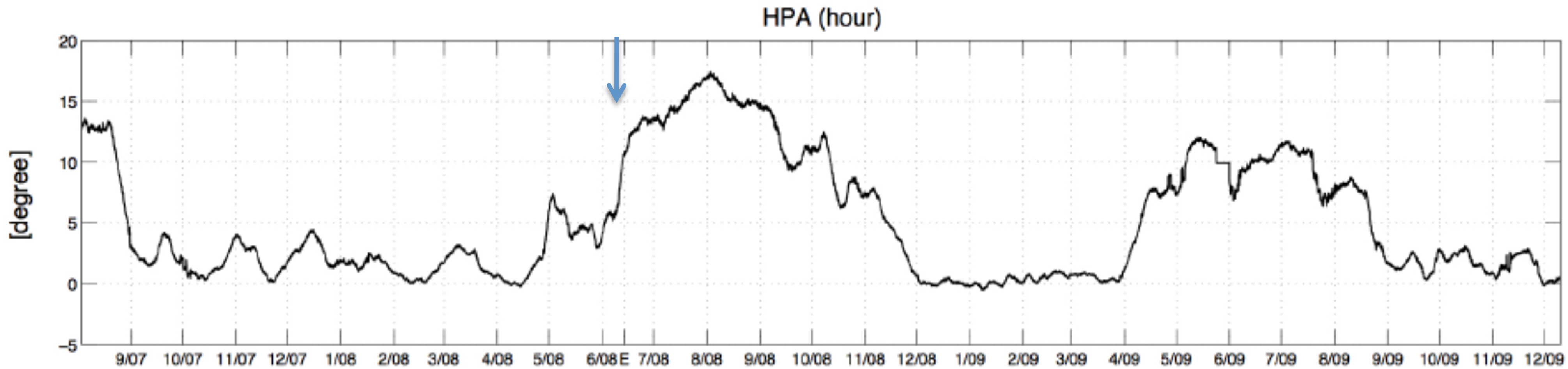
Data: Jul. 2007- Dec. 2009 NIED

Saadé et al., 2017

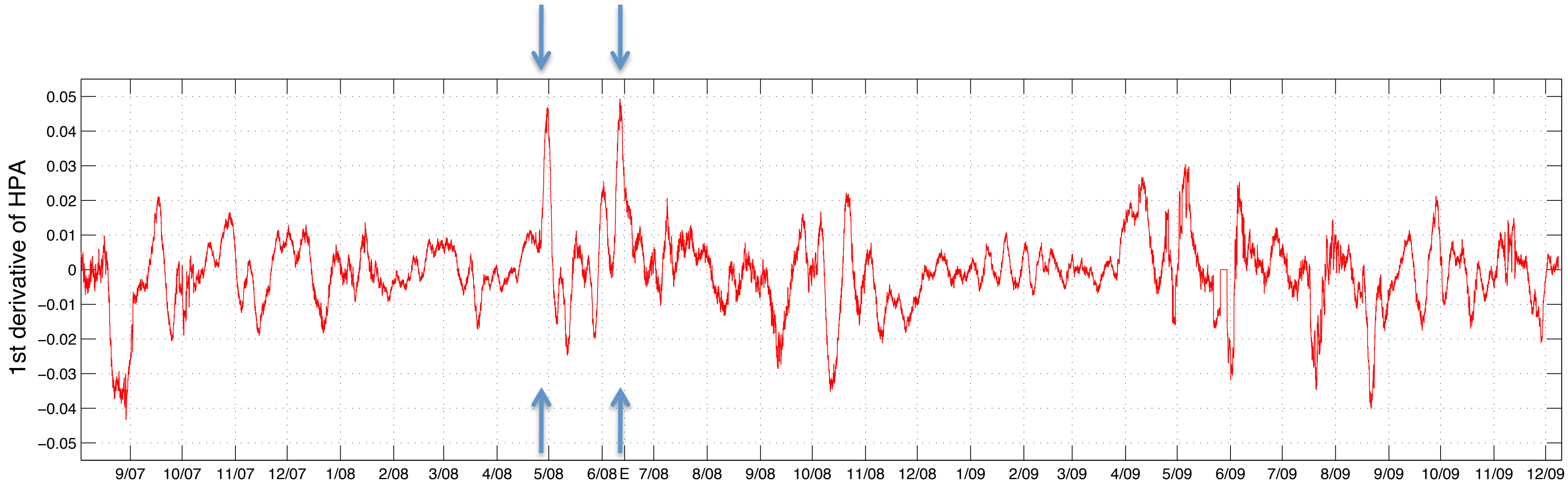
Horizontal Polarization Anomaly Ψ



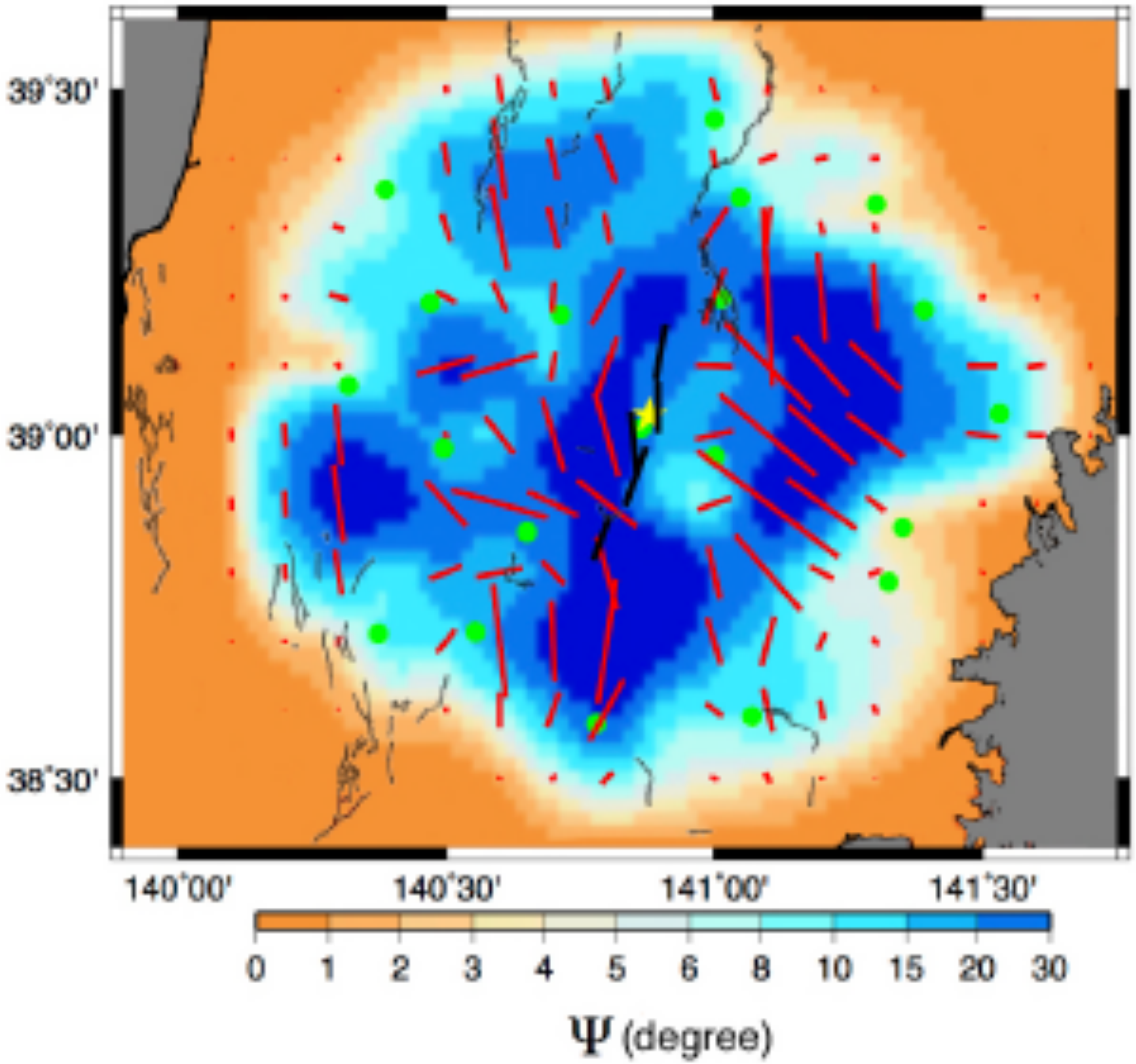
Average of the Horizontal Polarization Anomaly Ψ (HPA)



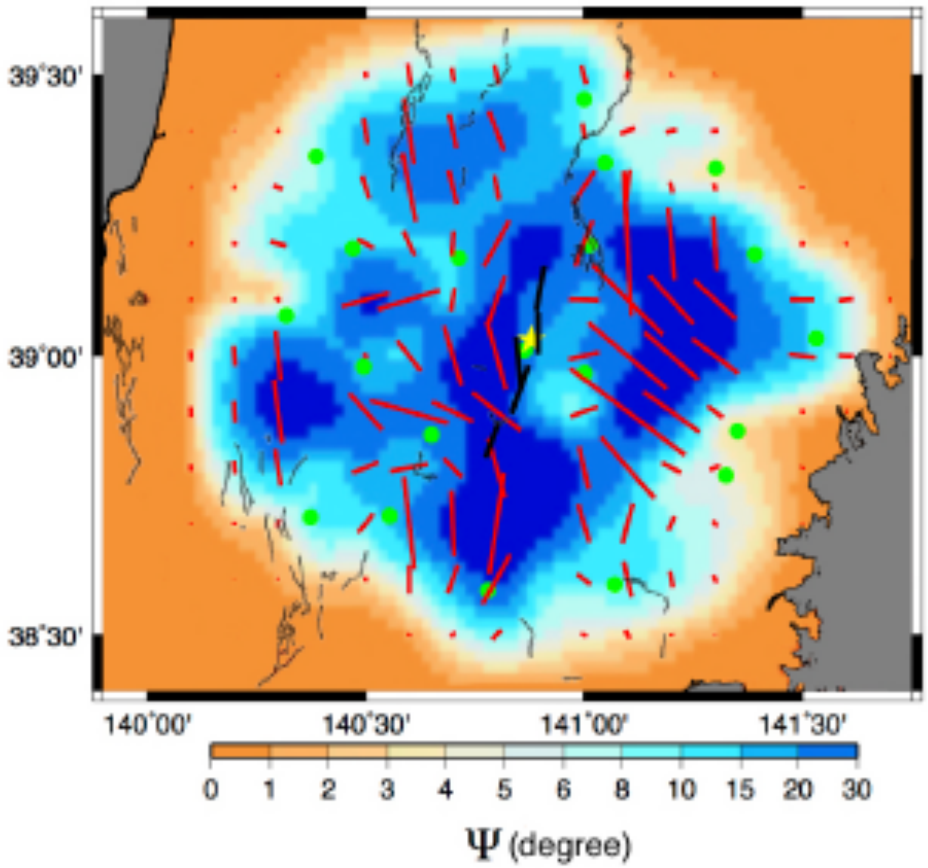
Time derivative of HPA

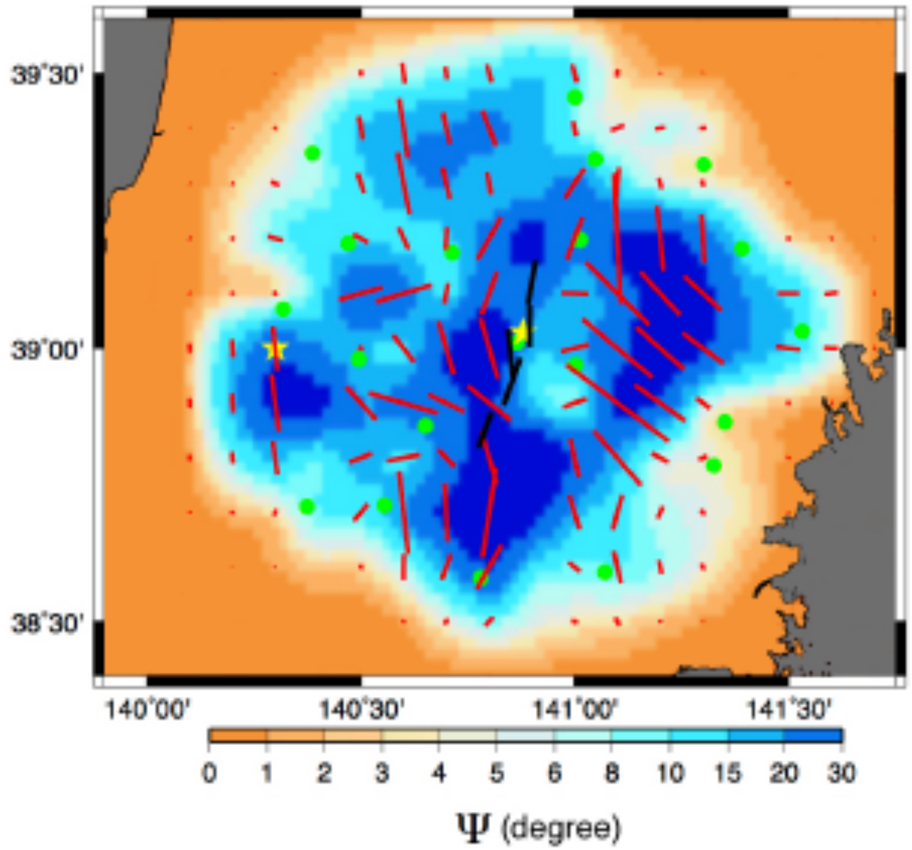


Horizontal Polarization change Ψ at the time of the EQ
June 13, 2008



Horizontal Polarization change Ψ
at the time of the EQ and at the end of April

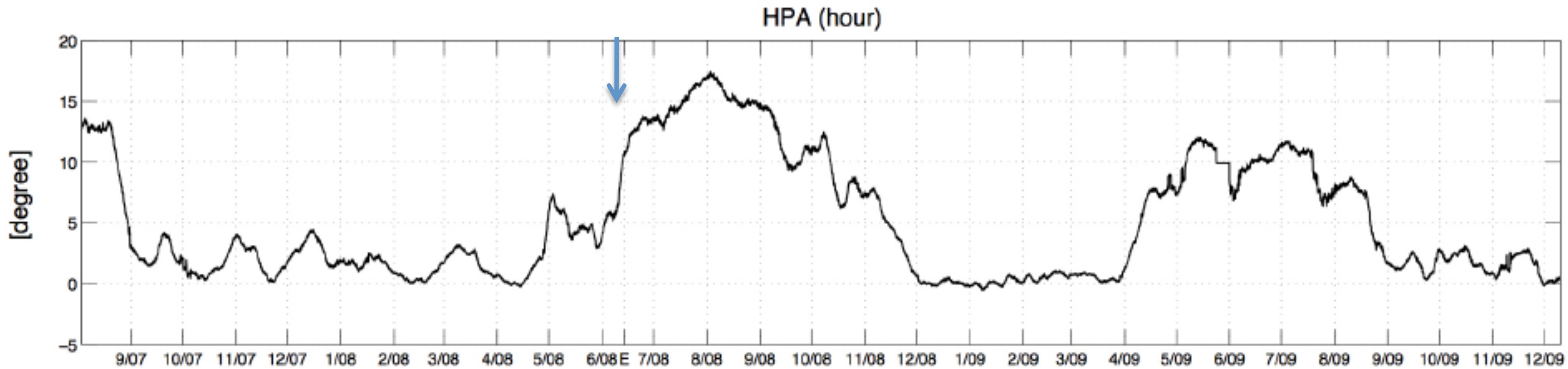




Many similarities for variations of the polarization anomaly for both events
(deep earthquake on April 17, 2008; Mw= 5.7)

Z! correlation does not mean causality

Average of the Horizontal Polarization Anomaly Ψ (HPA)



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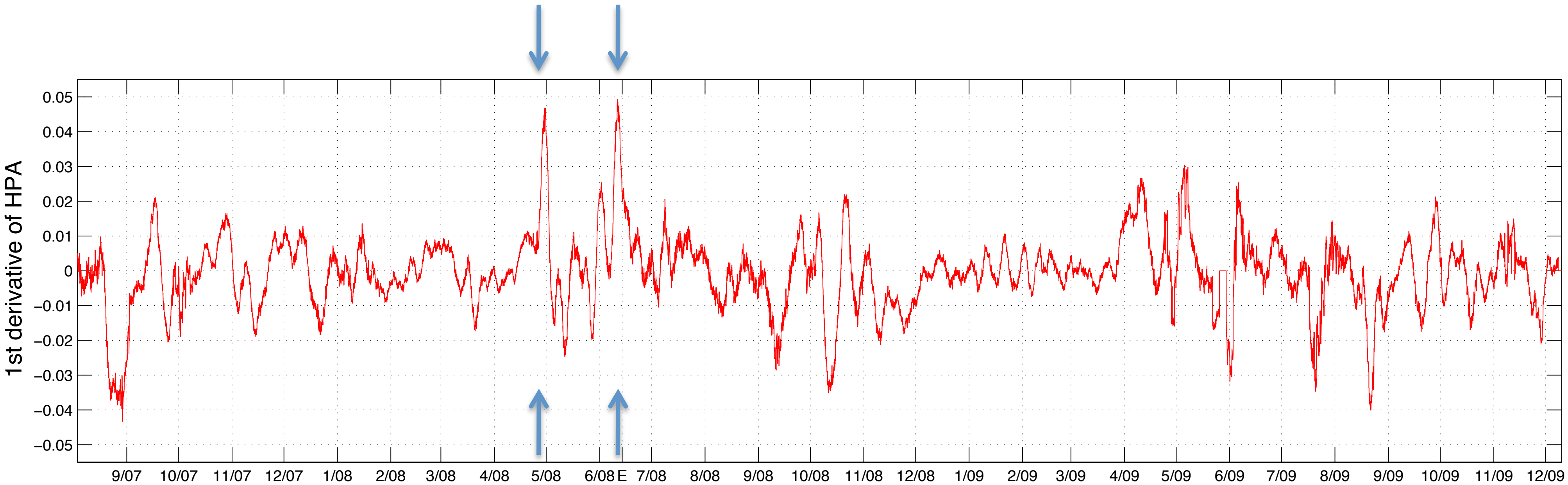

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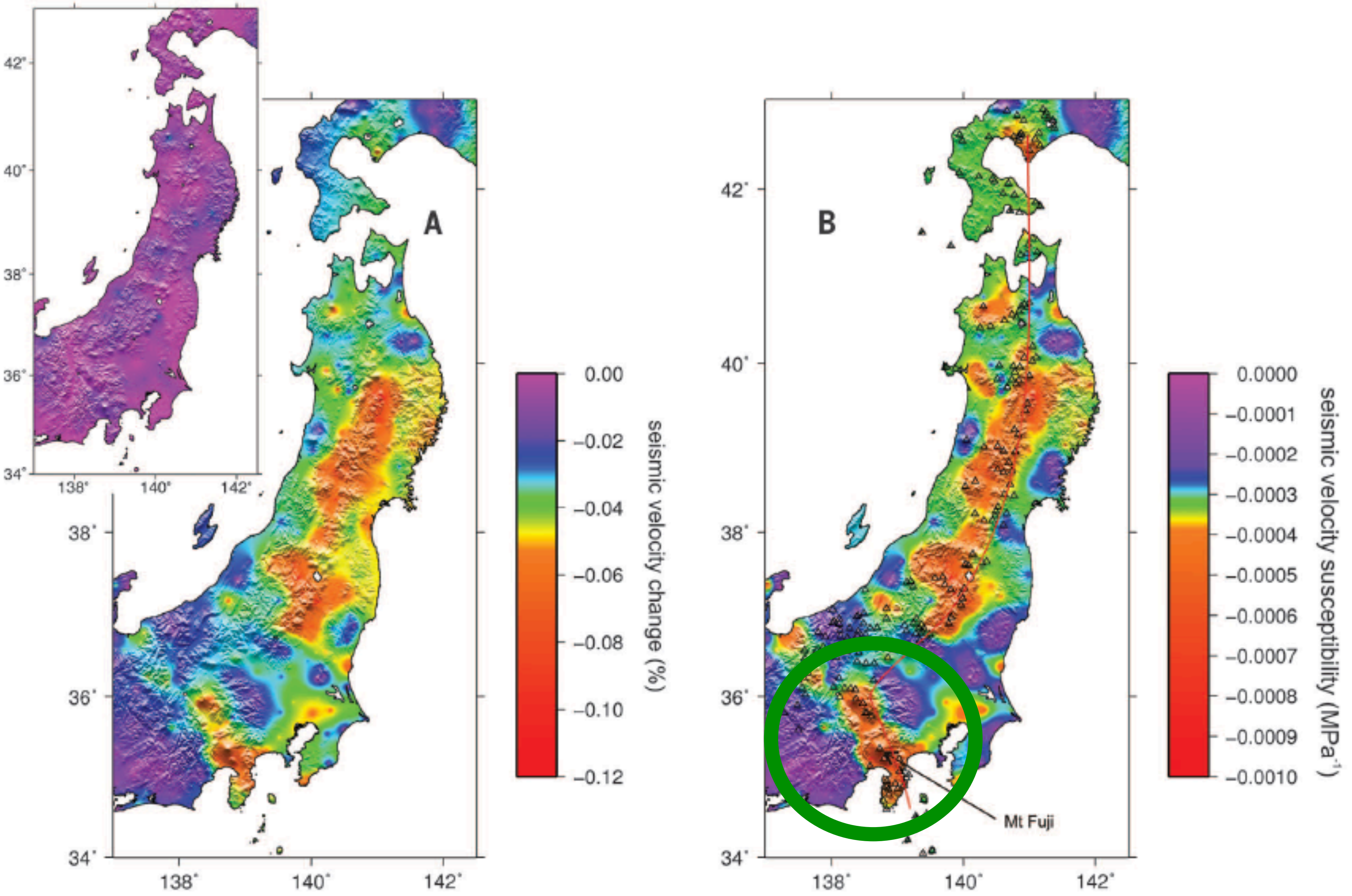
Seismic monitoring:

Temporal changes of polarization anisotropy in:

- seismogenic (Parkfield, Cal., USA; Iwate-Miyagi, Japan)

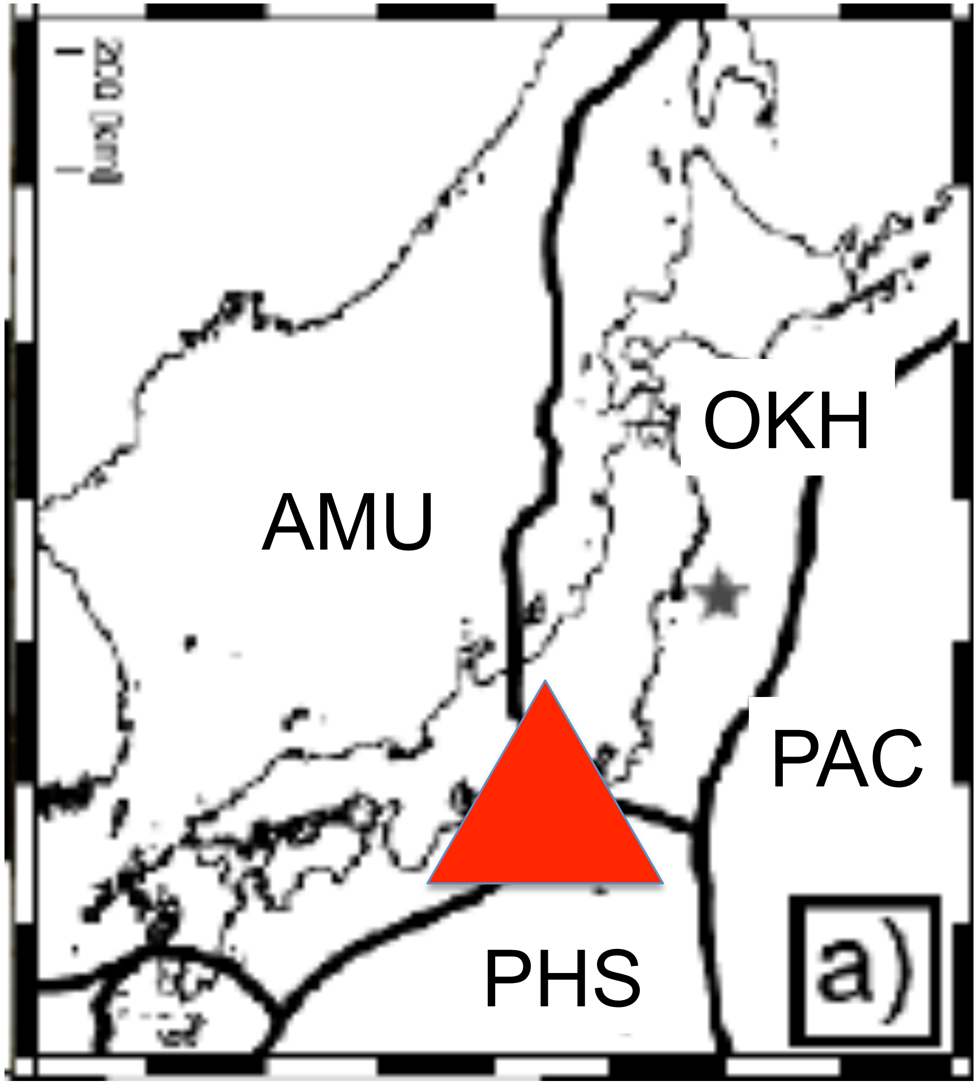
- Volcanic zones (Mount Fuji, Japan)

Volcanic zones: after the Tohoku-oki earthquake (11 march 2011)



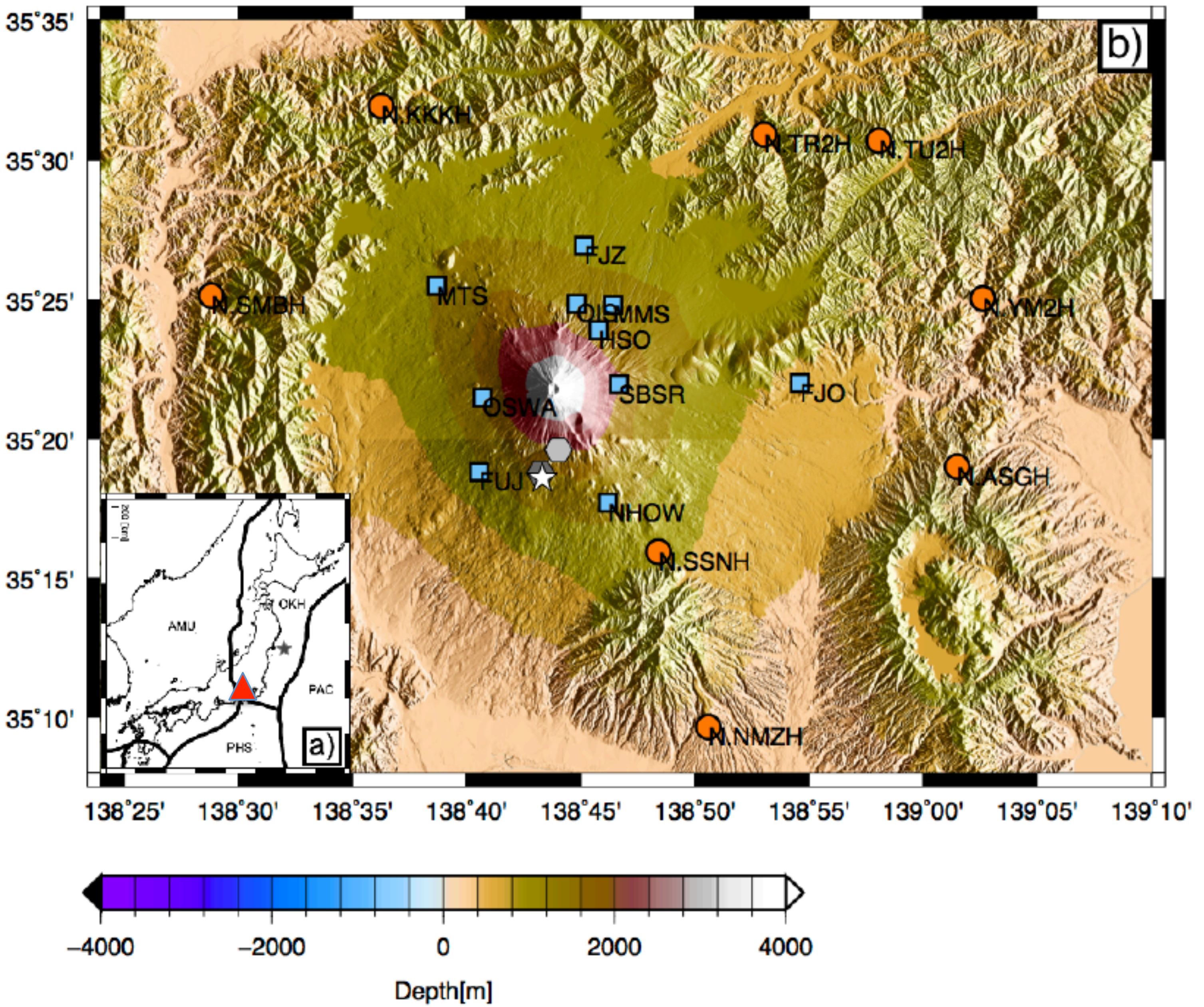
Brenguier et al., 2014

Monitoring of volcanic zones: Mount Fuji (+Hakone)

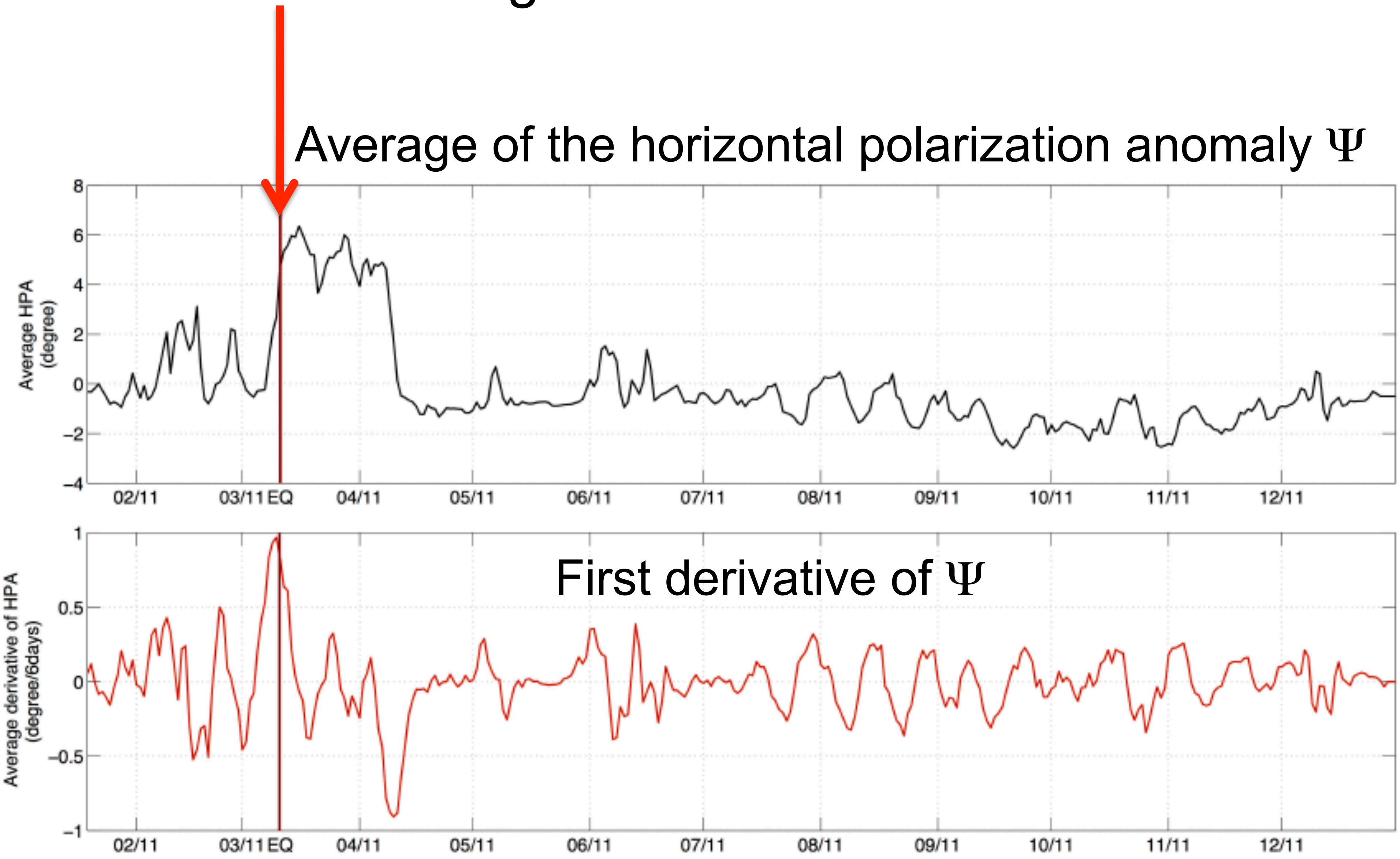


Hiroshige, 1858

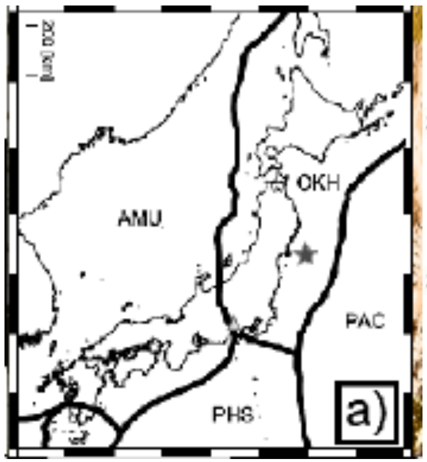
Monitoring of volcanic zones: Mount Fuji

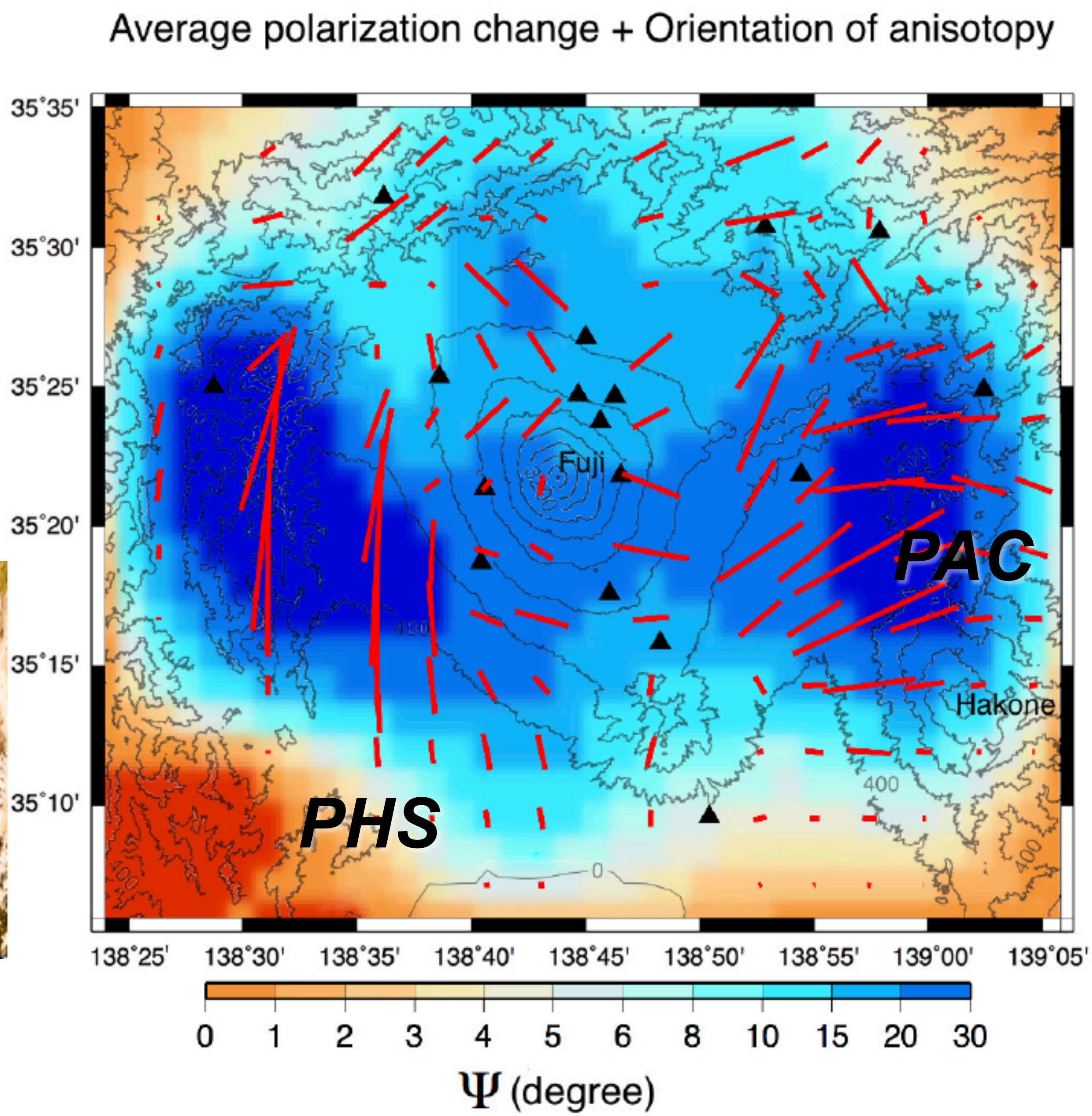


Monitoring of volcanic zones



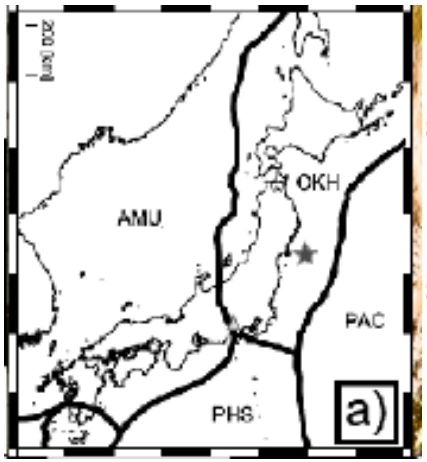
Monitoring of volcanic zones

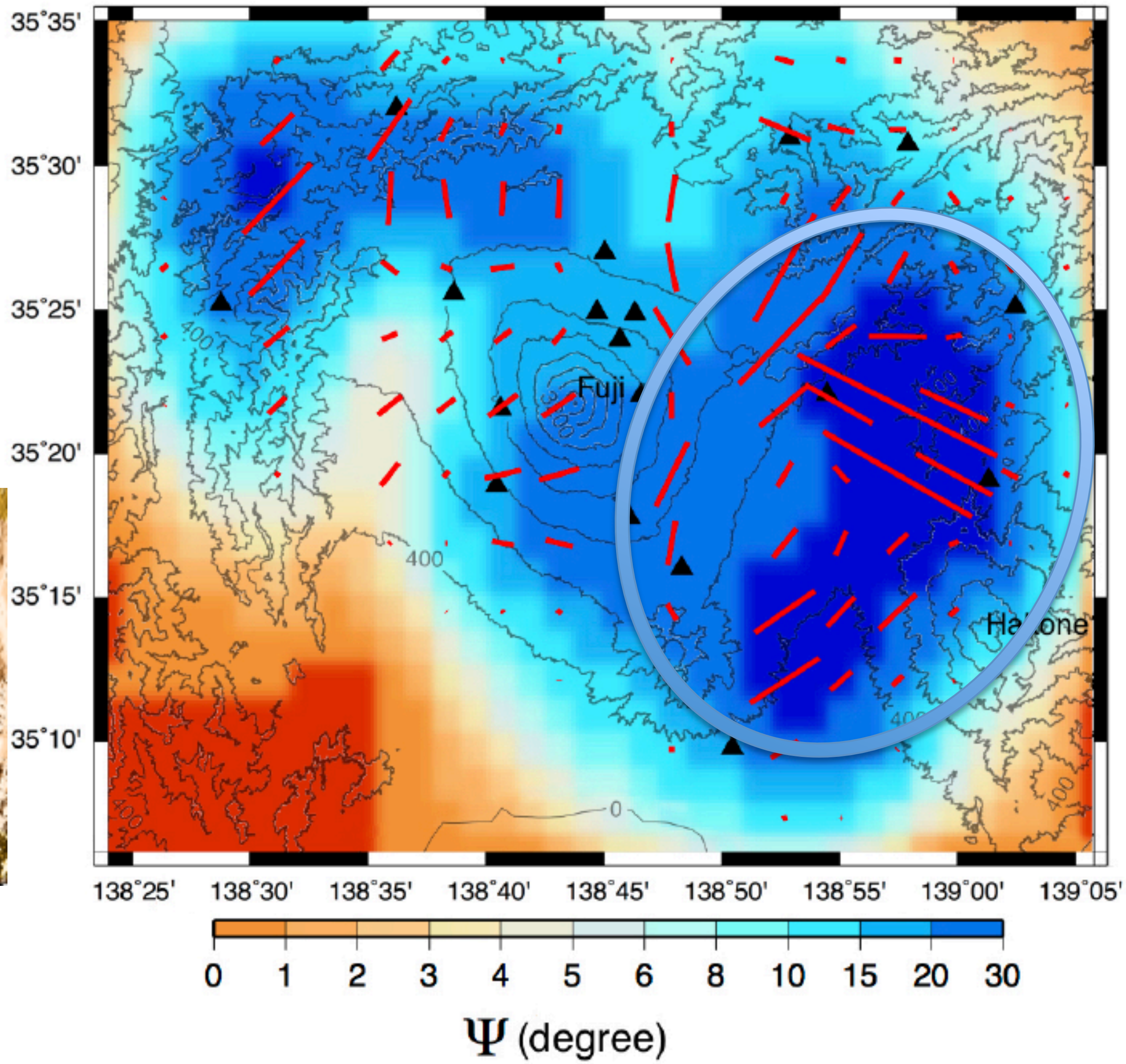




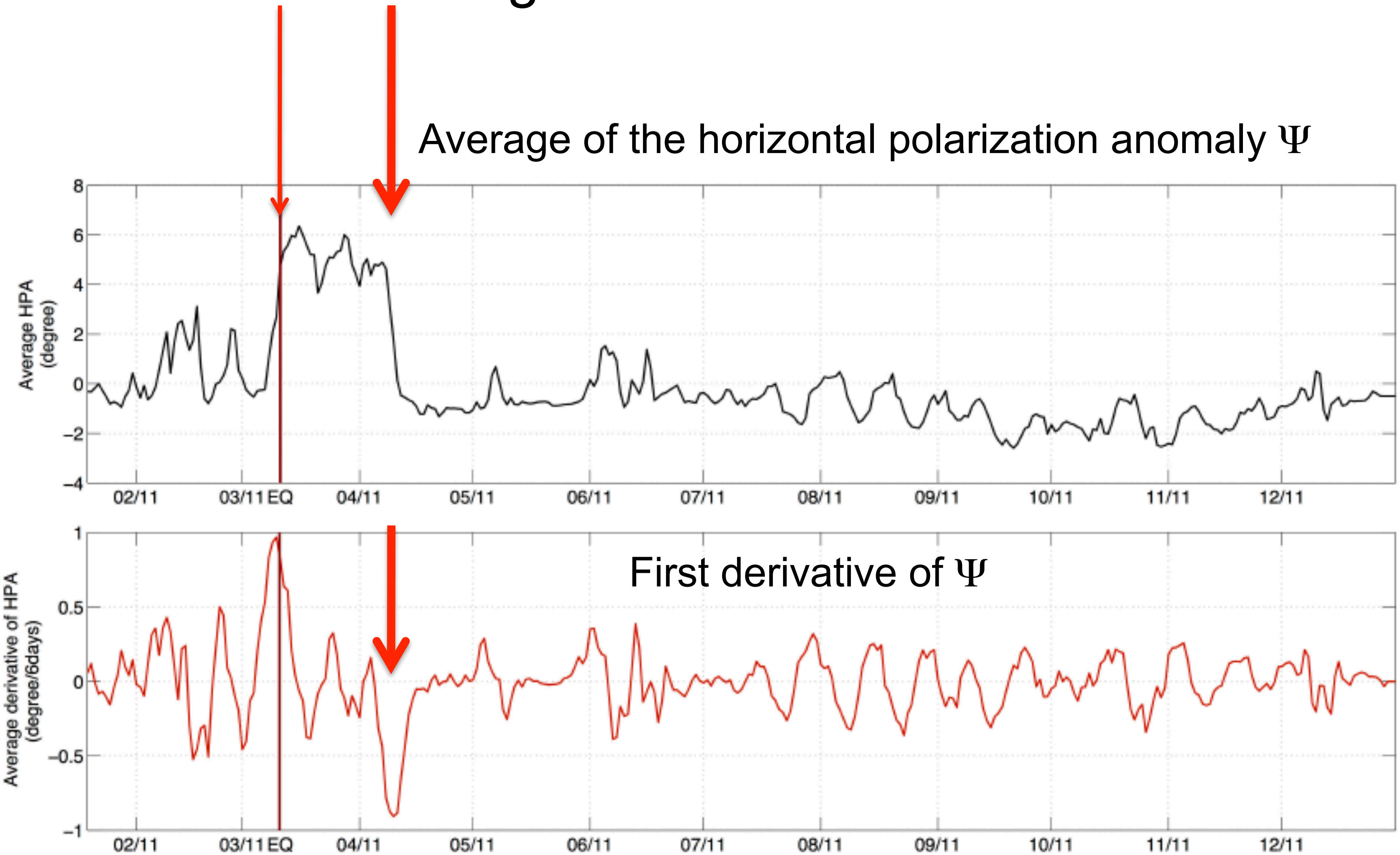
Monitoring of volcanic zones

Polarization and anisotropy change at the time of the EQ

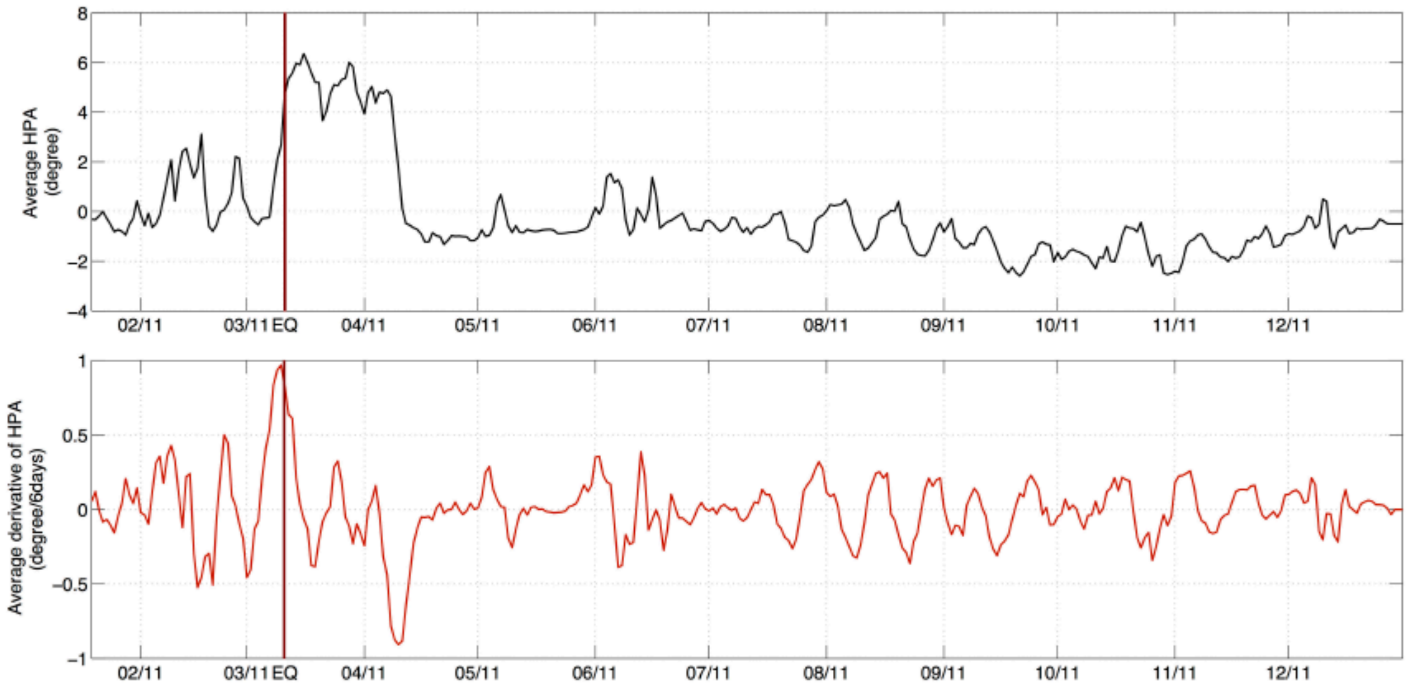


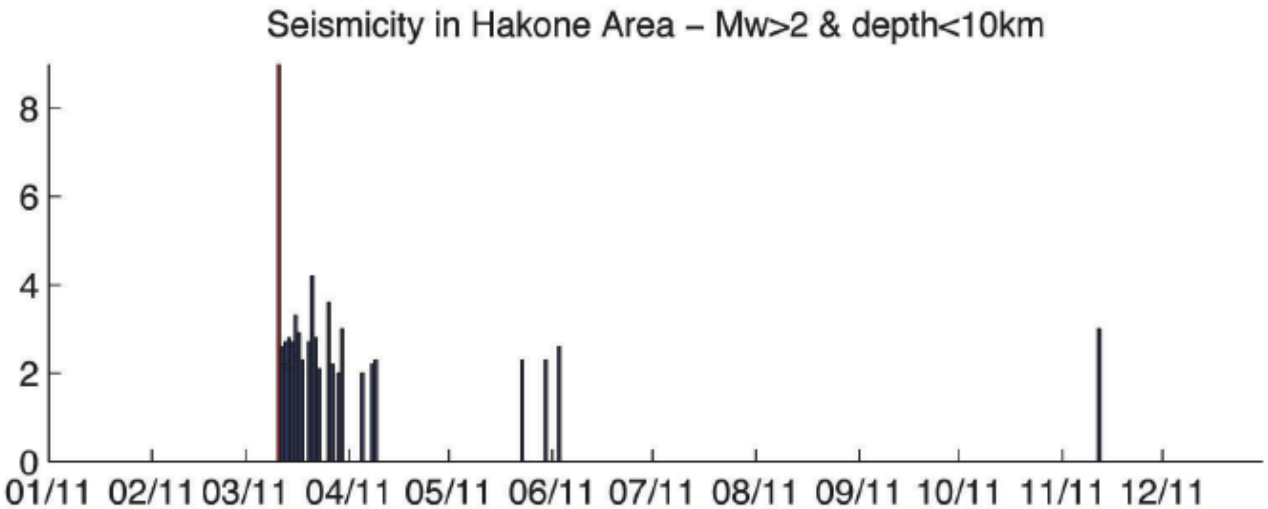


Monitoring of volcanic zones

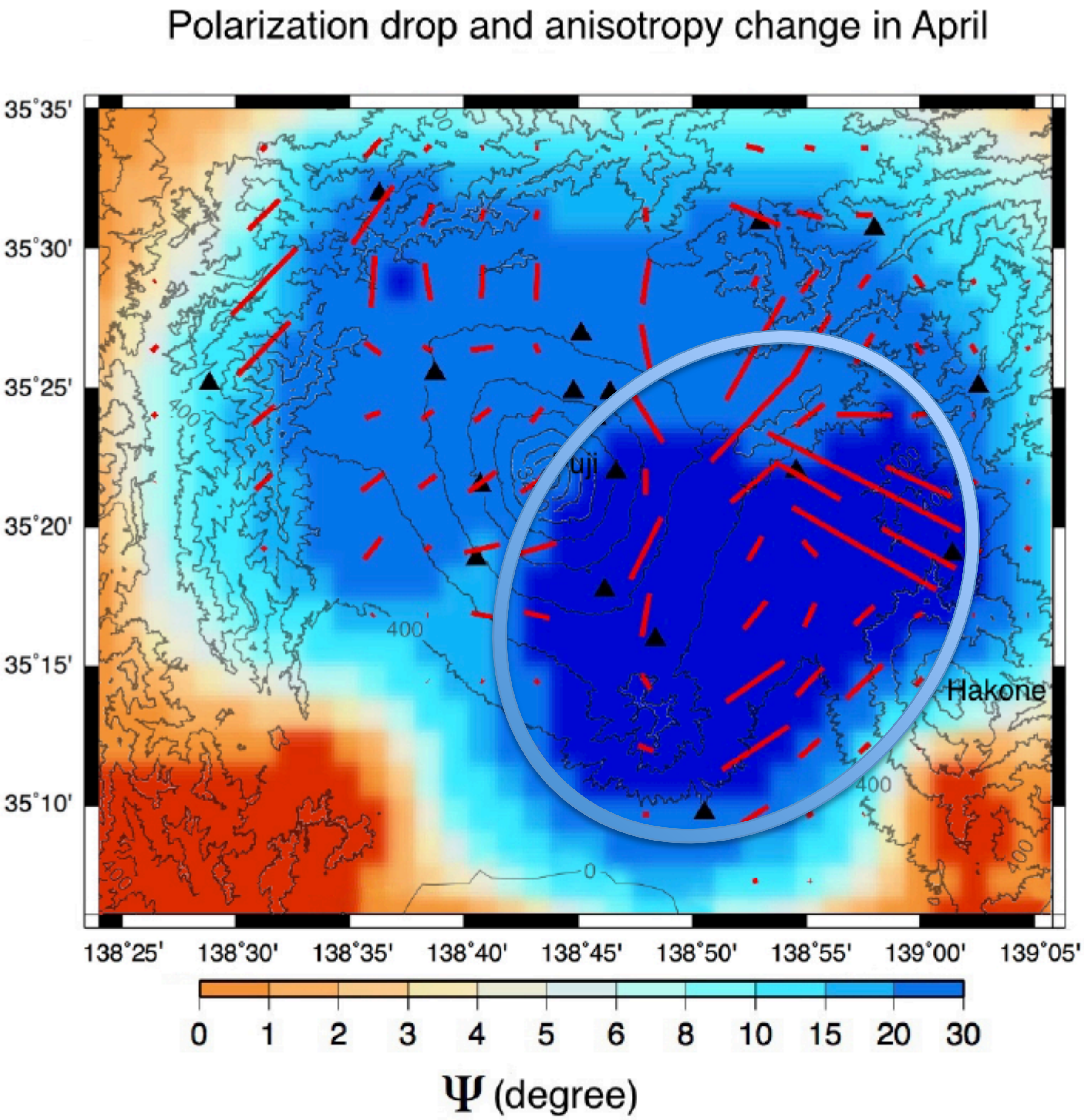


Monitoring of volcanic zones

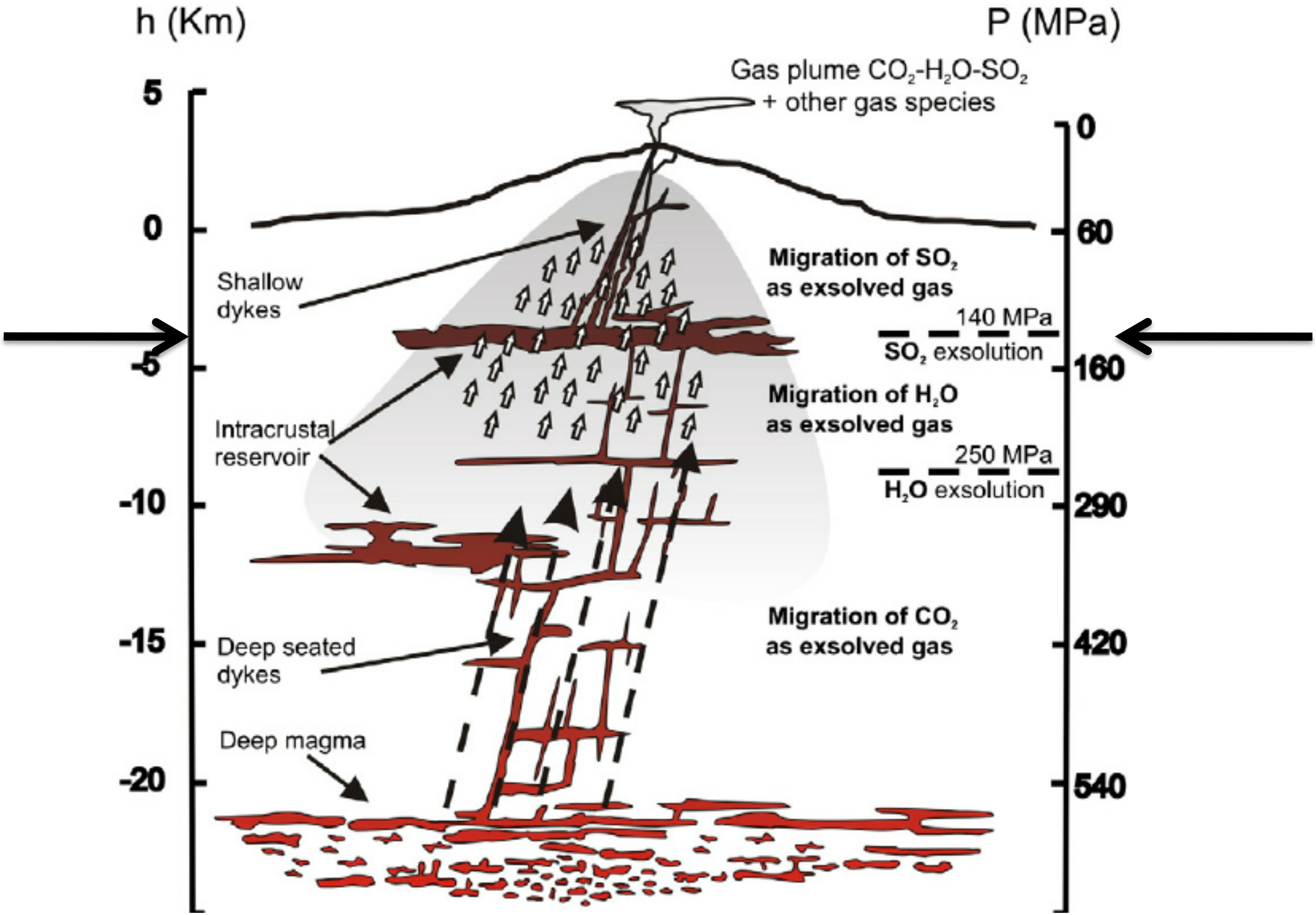




Monitoring of volcanic zones

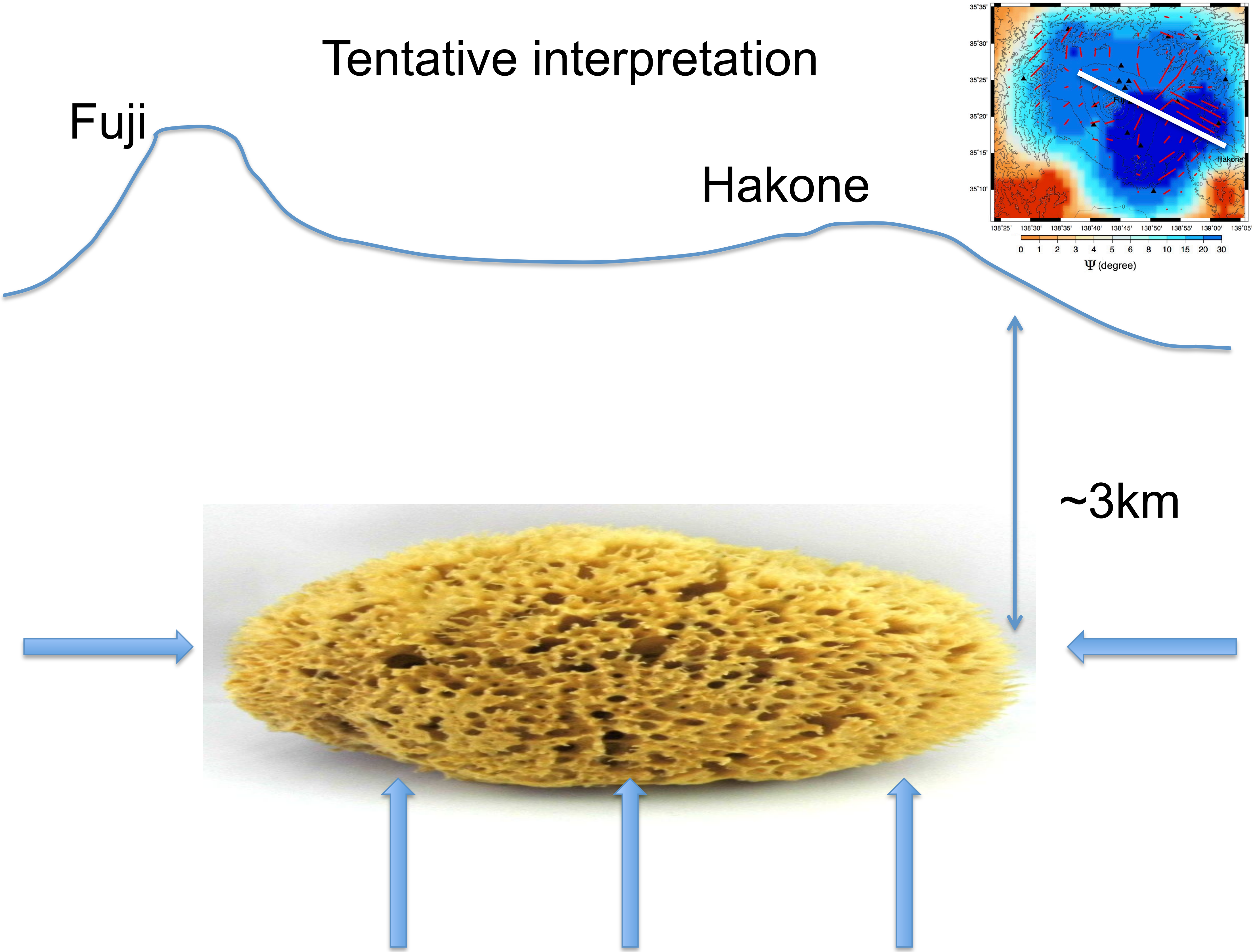


Plumbing System

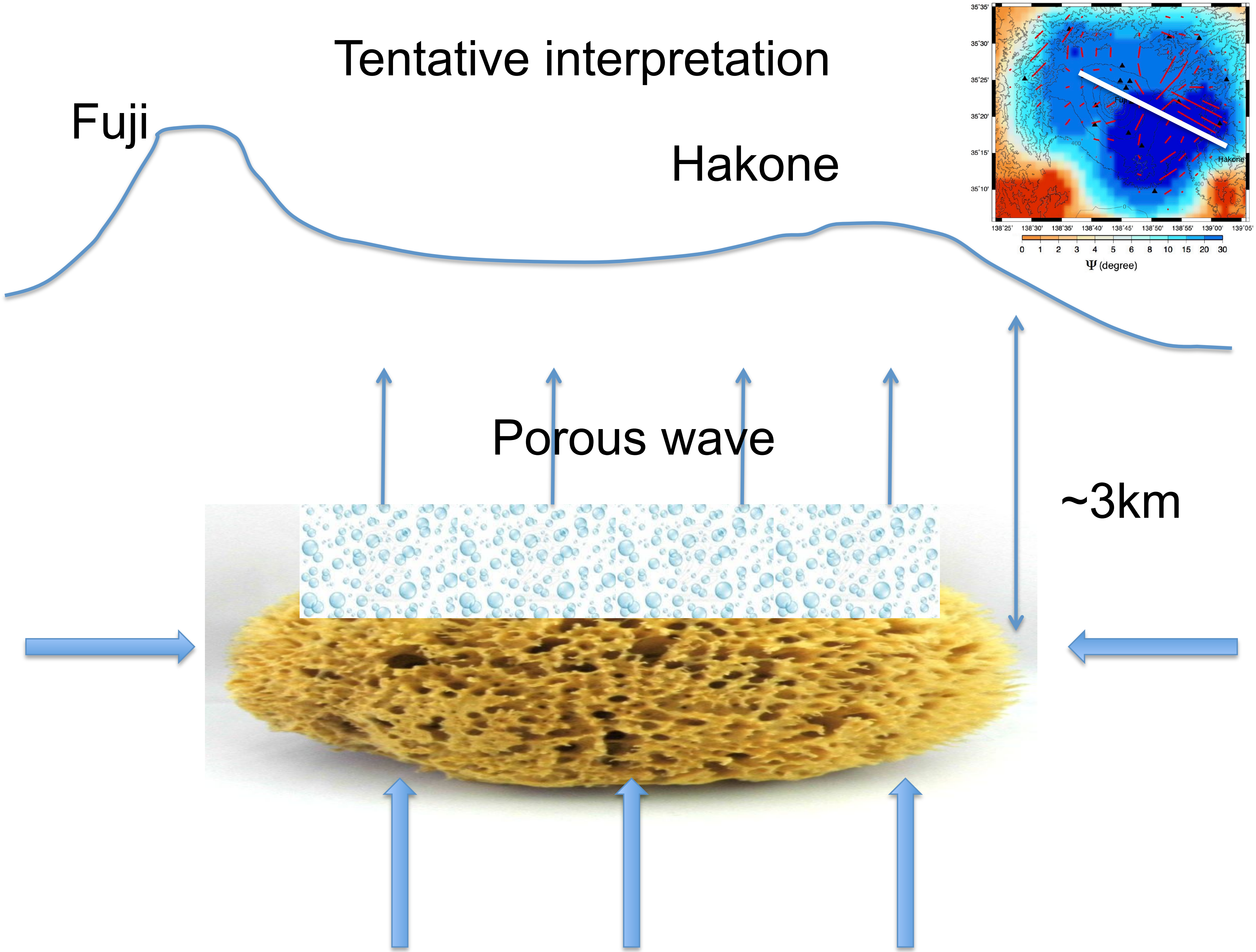


Ferlito et al., 2014

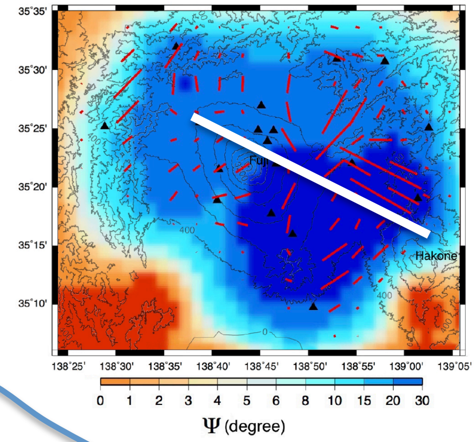
Tentative interpretation

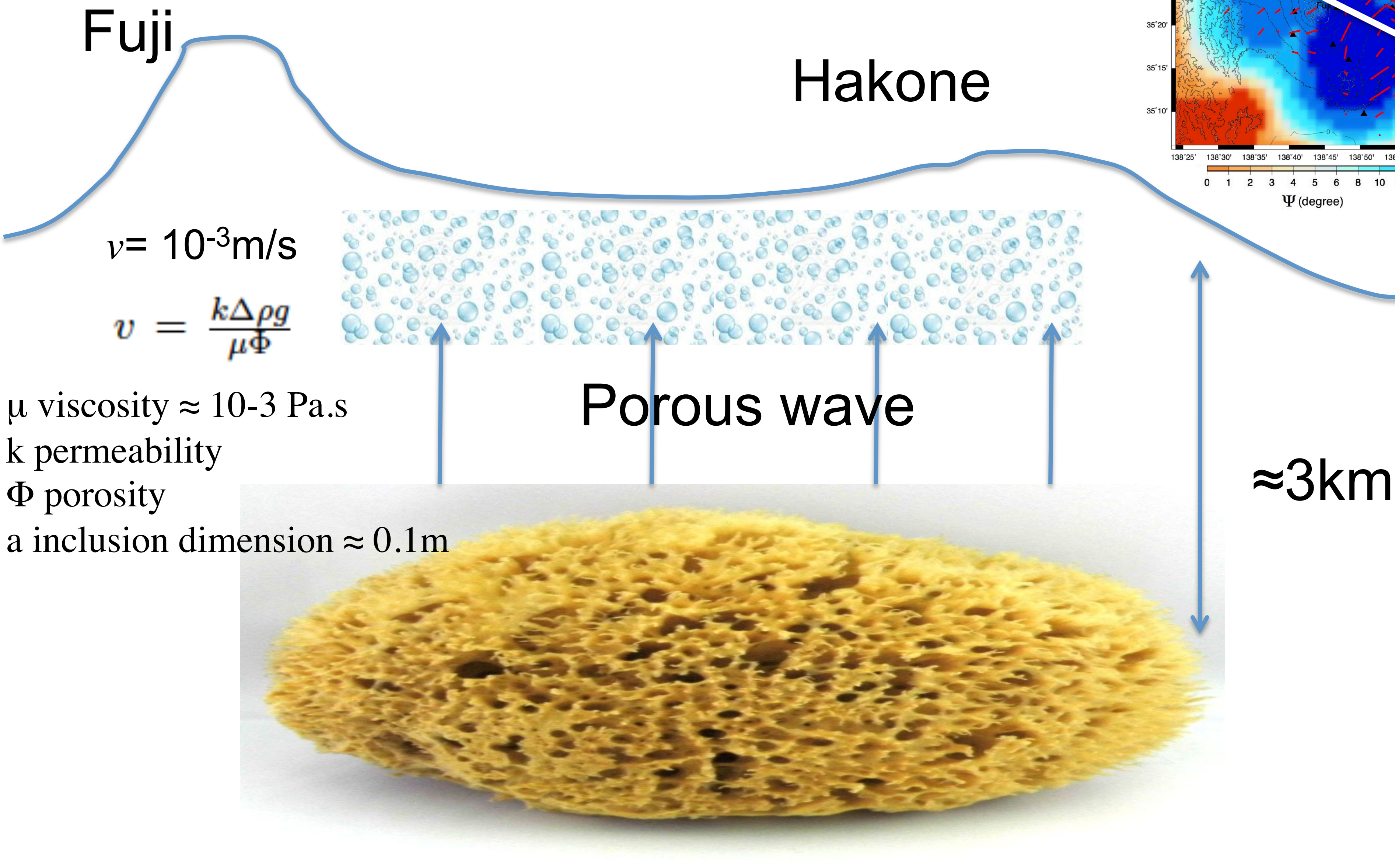


Tentative interpretation

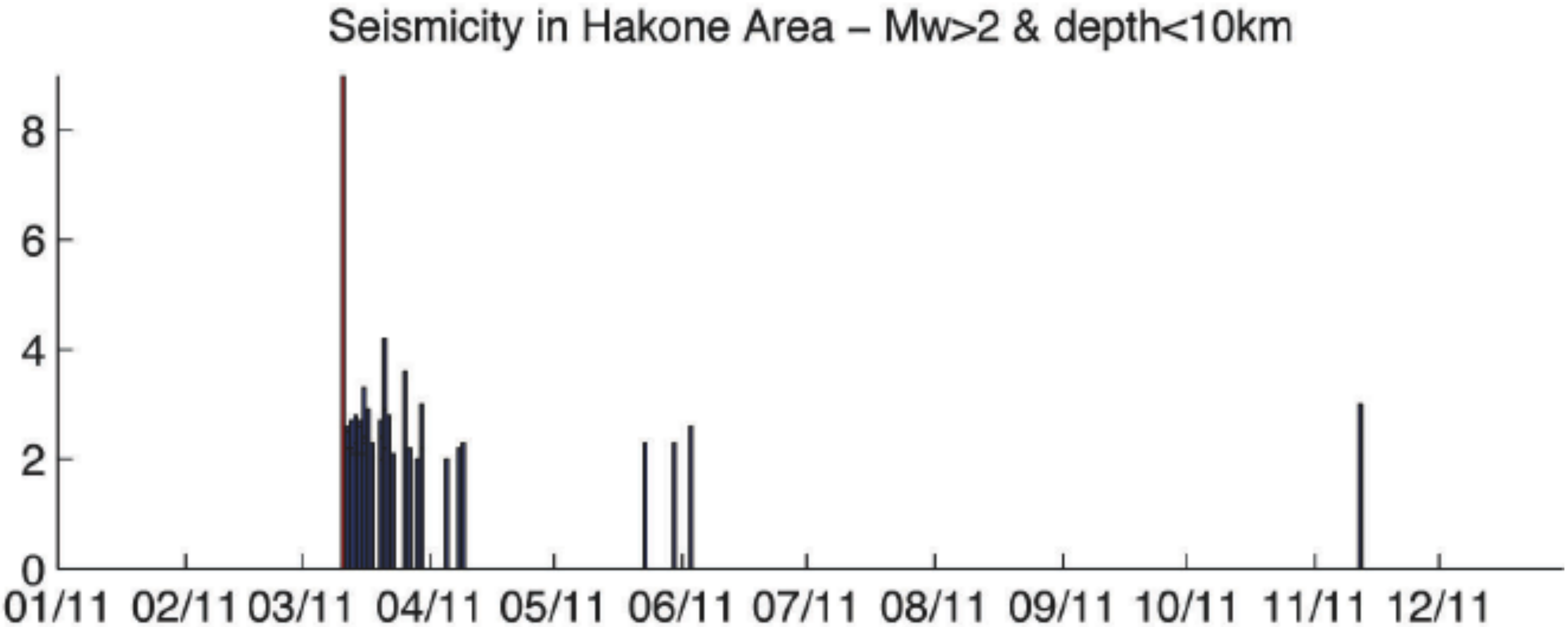


Tentative interpretation





Monitoring of volcanic zones



Conclusions

Seismic anisotropy is necessary to explain seismic data
It provides new information on many geophysical processes

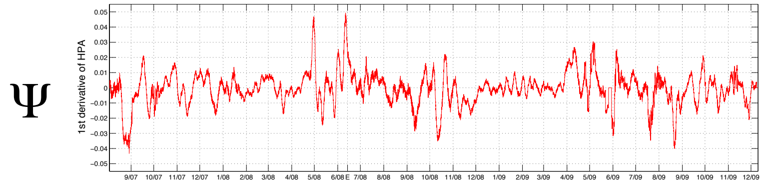
•New Method for continuous monitoring of the stress field in:

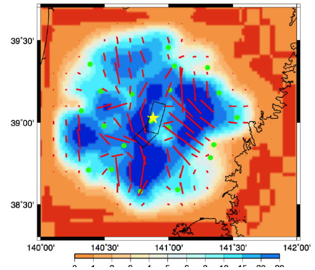
-Seismogenic zones
Significant temporal change of Ψ observed in parts of the cracked zone

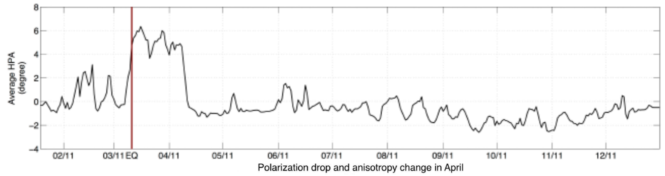
- Volcanic zones: Porous wave

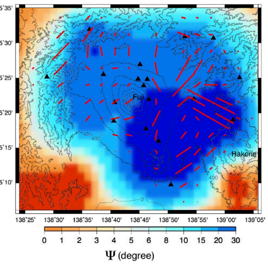
-Interpretation in terms of anisotropy variations and stress changes

- Other applications in oil/gas reservoirs
(Mordret et al., 2013; Tomar et al., 2016)









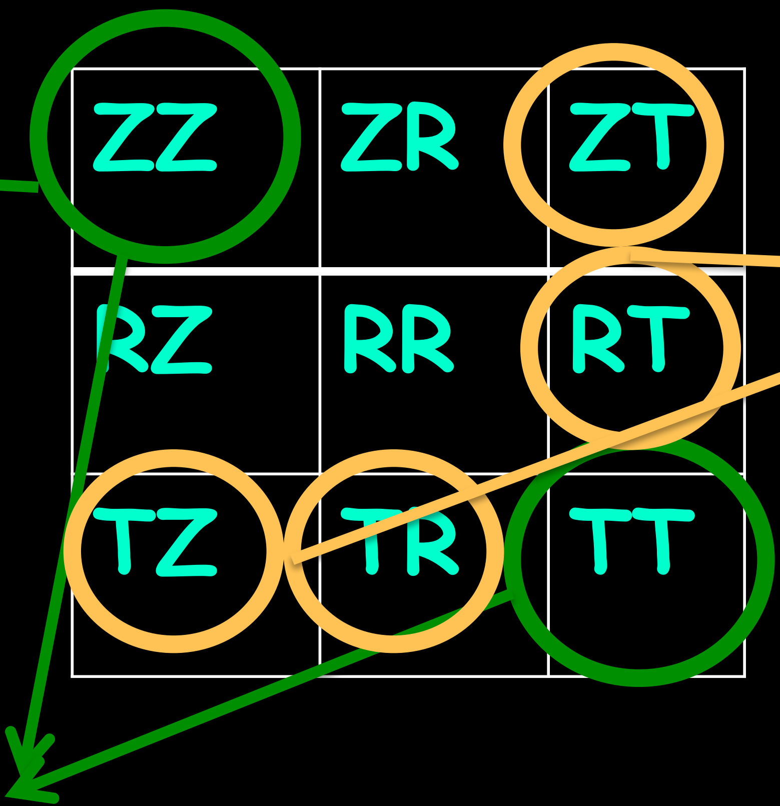
THEORY

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

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

Effect of anisotropy on C_{ij}

Azimuthal Anisotropy of Rayleigh waves

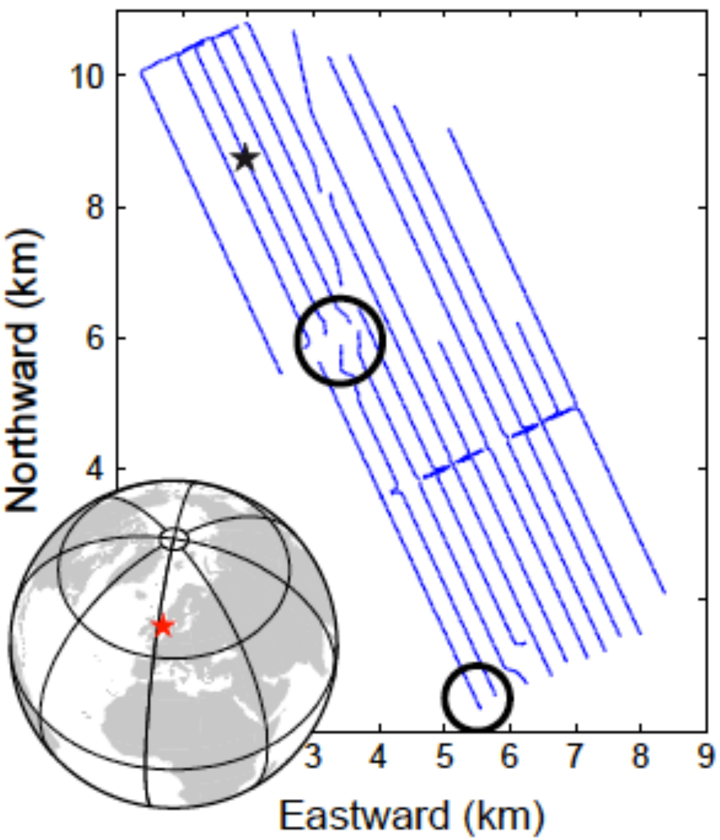


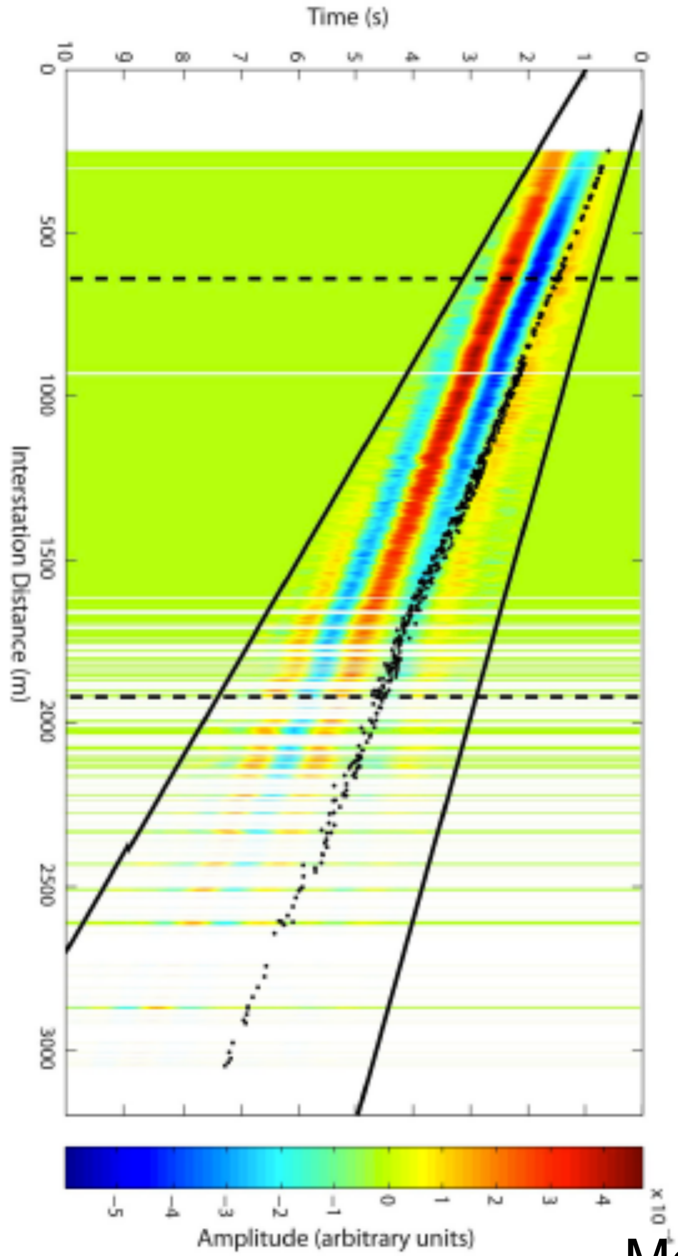
Quasi-Rayleigh
Quasi-Love
waves
polarization
anomalies

Joint Inversion of Rayleigh and Love waves: Radial anisotropy

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

Valhall LoFS network

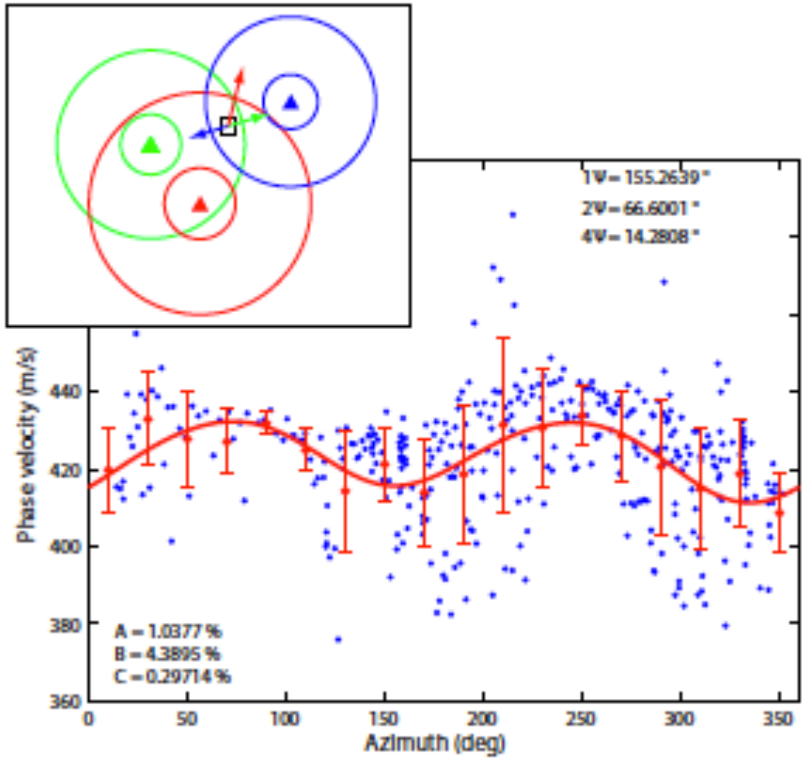




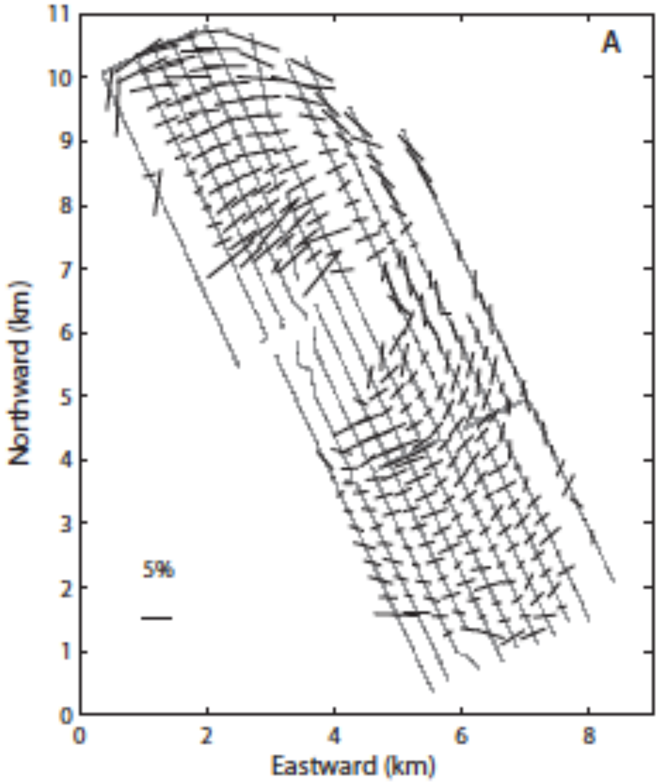
Mordret et al., 2013

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

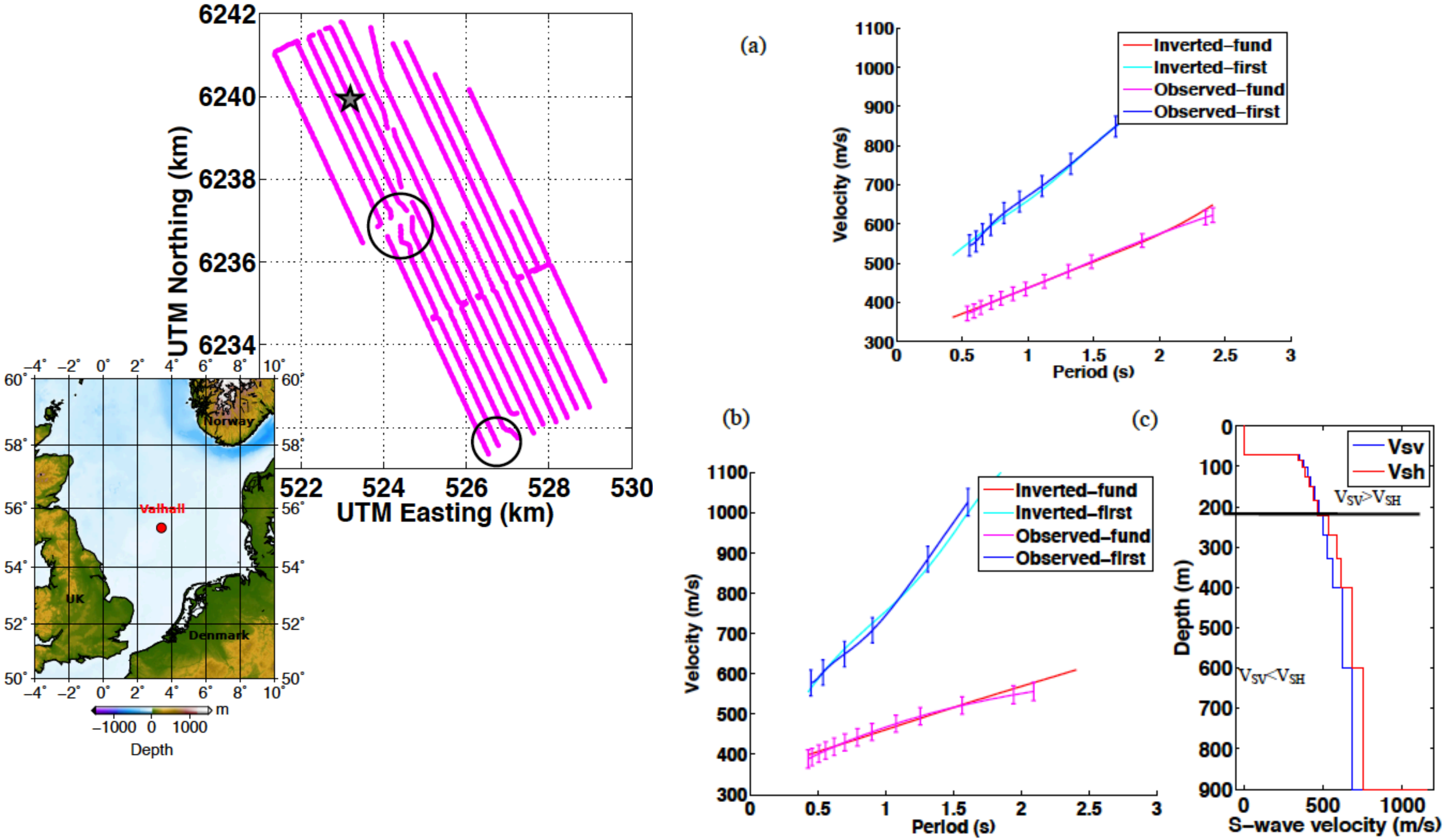
At T=0.8s



Valhall LoFS: 2-Ψ term



Mordret et al., 2013



Tomar et al., 2016