Guest Lecture ITS – 17 November 2023

Structure & dynamics of subduction zones from seismic tomography and anisotropy

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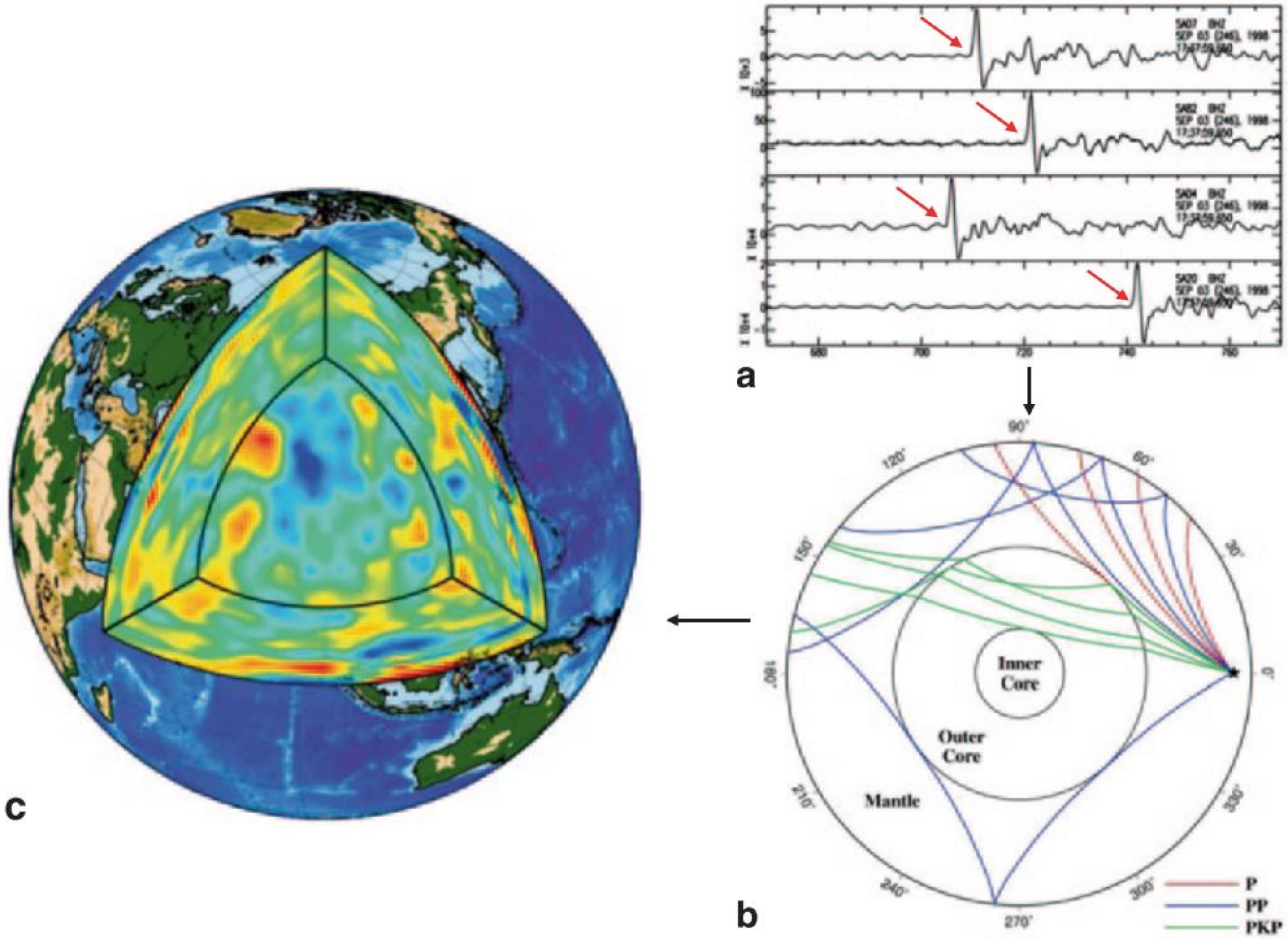
Seismic Tomography

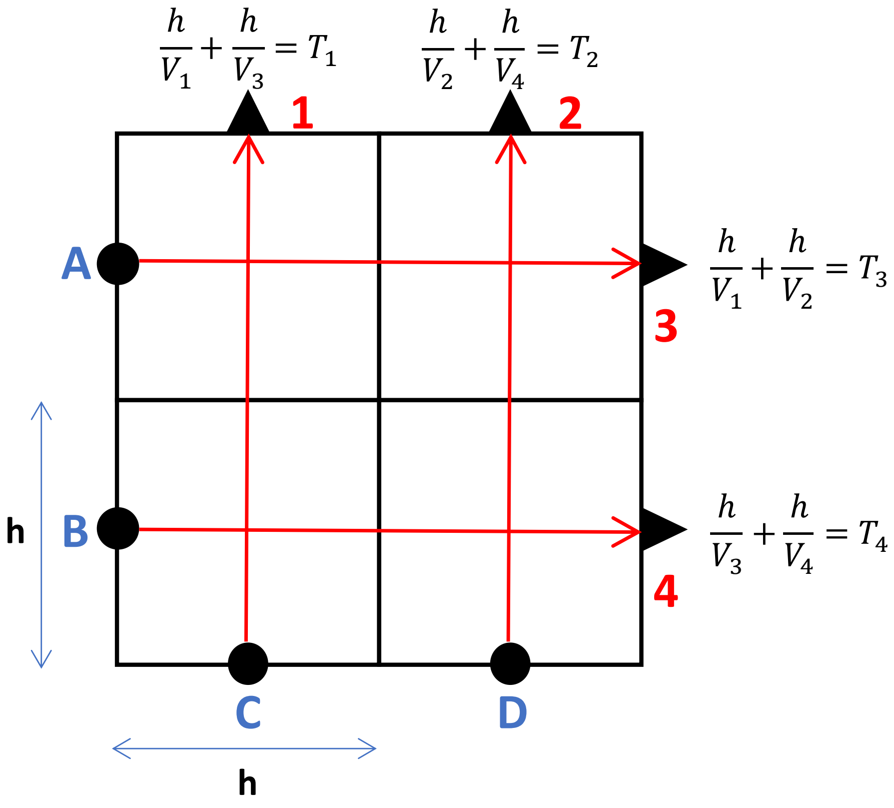
Seismic tomography is one geophysical tool that can provide the three-dimensional images of Earth's interior.

These 3-D models promise to answer some basic questions of geodynamics i.e., **the Earth's structure and processes**.



A conceptual diagram of seismic tomography (Zhao, 2007)

Basic Principle

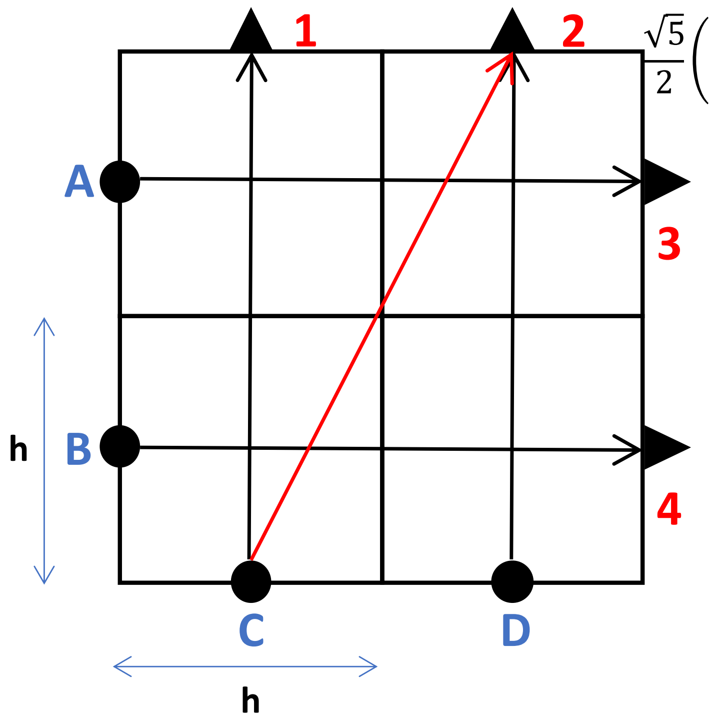


$$\frac{h}{V_1}+\frac{h}{V_3}=T_1$$

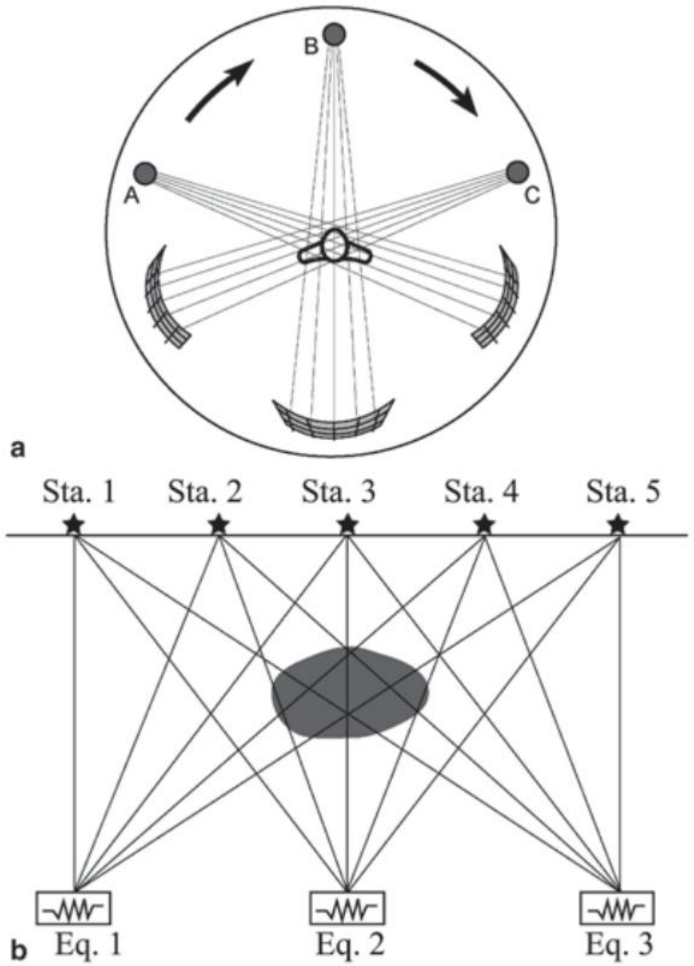
$$\frac{h}{V_2}+\frac{h}{V_4}=T_2$$

$$\frac{h}{V_1}+\frac{h}{V_2}=T_3$$

$$\frac{h}{V_3}+\frac{h}{V_4}=T_4$$



$$\frac{\sqrt{5}}{2}\left(\frac{h}{V_3}+\frac{h}{V_2}\right)=T_5$$



Schematic diagram of medical (**a**) CT-scan, and (**b**) seismic tomography

Classification of Seismic Tomography

Depending on the **seismic data** used:
- Body-wave tomography
- Surface-wave tomography
- Waveform tomography (FWI)

Depending on the **lateral scale** of the study area:
- Local tomography
- Regional tomography
- Global tomography

According to the **depth range** of the modelling space:
- Crustal tomography
- Mantle tomography
- Core tomography

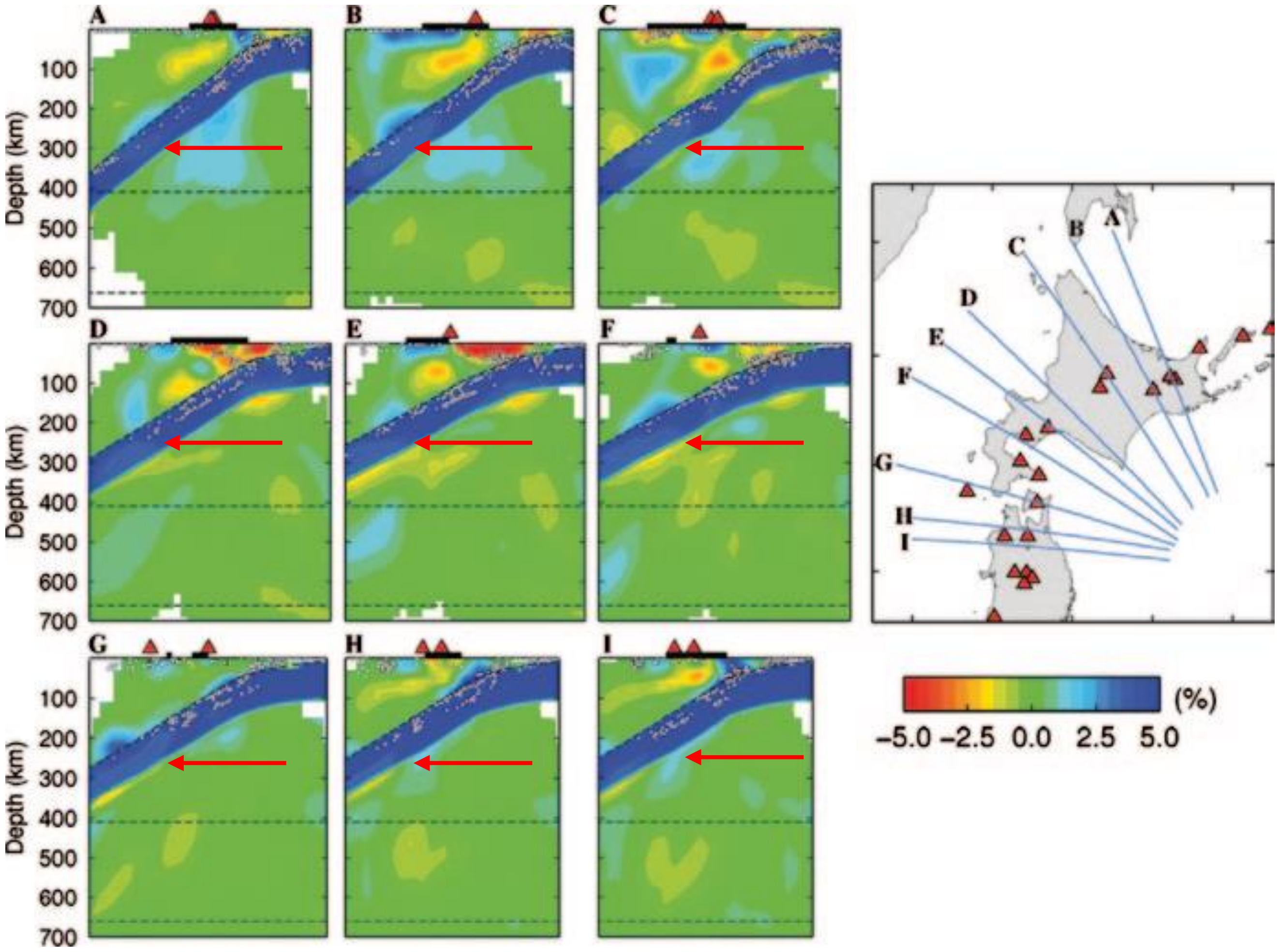
According to the **relative distance** between the seismic array:
- Local earthquake tomography (LET)
- Teleseismic tomography (TET)

Depending on the **physical parameters** to be determined:
- Seismic velocity tomography
- Seismic attenuation tomography
- Seismic anisotropy tomography

Depending on which **heavenly body** is being studied:
- Earth (terrestrial) tomography
- Lunar tomography
- Solar tomography

Interpretation of Seismic Tomography: Subduction Zones

Seismic Velocity



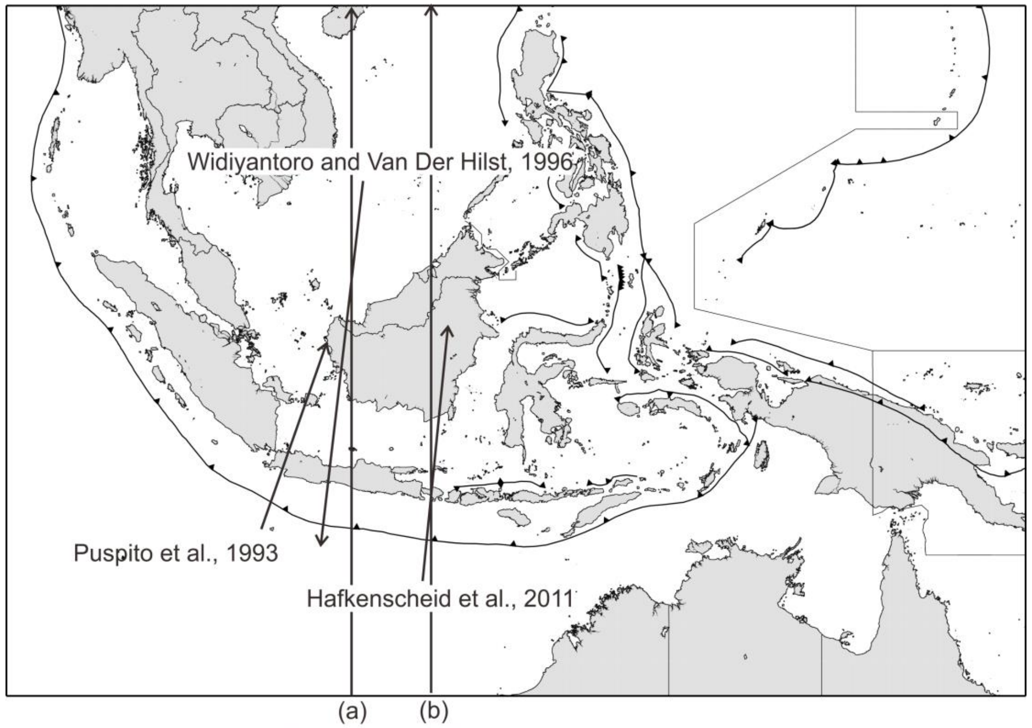
Vertical cross-sections of Vp imaged by seismic tomography along the profiles shown on the inset map of northern Japan (Zhao, 2015).

Subducting slabs are colder than the surrounding mantle, so they always exhibit **high seismic velocity**

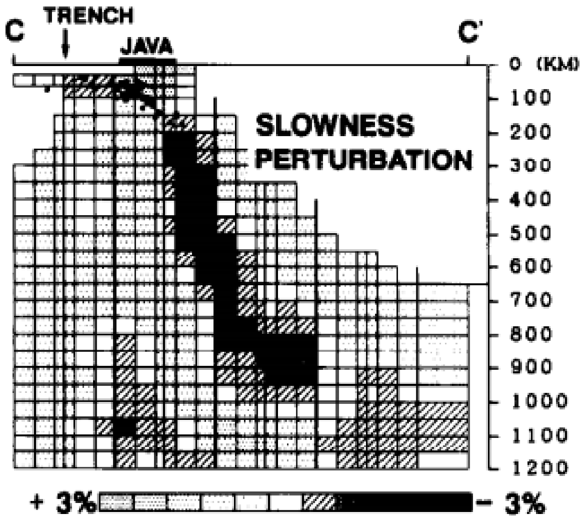
Interpretation of Seismic Tomography: Subduction Zones

SE Asia & Indonesia region:

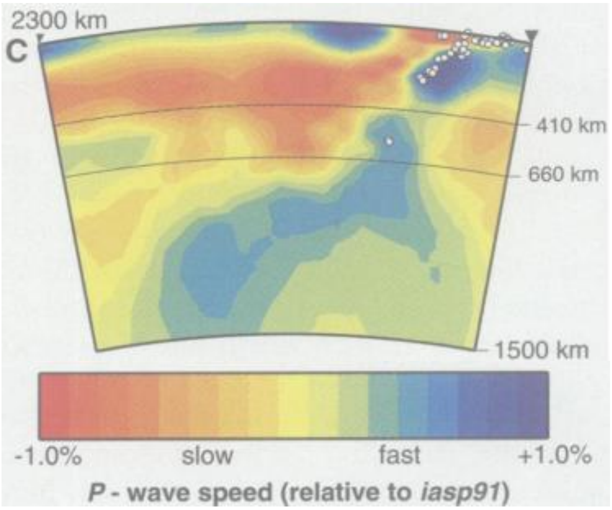
- Fukao et al., 1992
- Puspito et al., 1993
- Widiyantoro and Van Der Hilst, 1996, 1997
- Hafkenscheid et al., 2001
- Hall and Spakman, 2015
- Zenonos et al., 2019



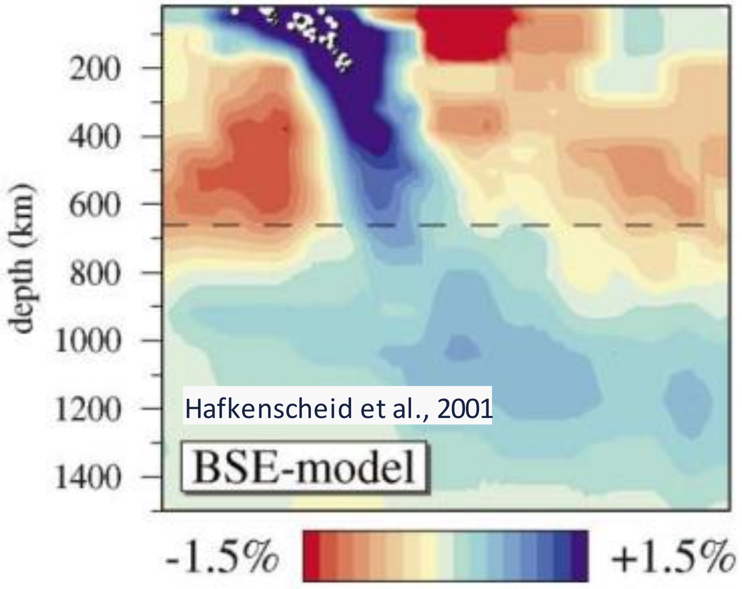
Zenonos et al., 2019



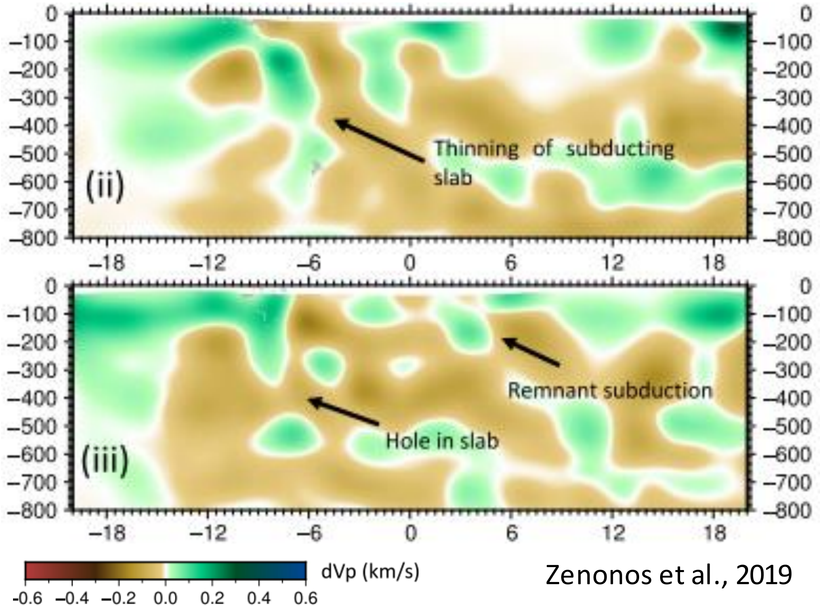
Puspito et al., 1993



Widiyantoro and Van Der Hilst, 1996



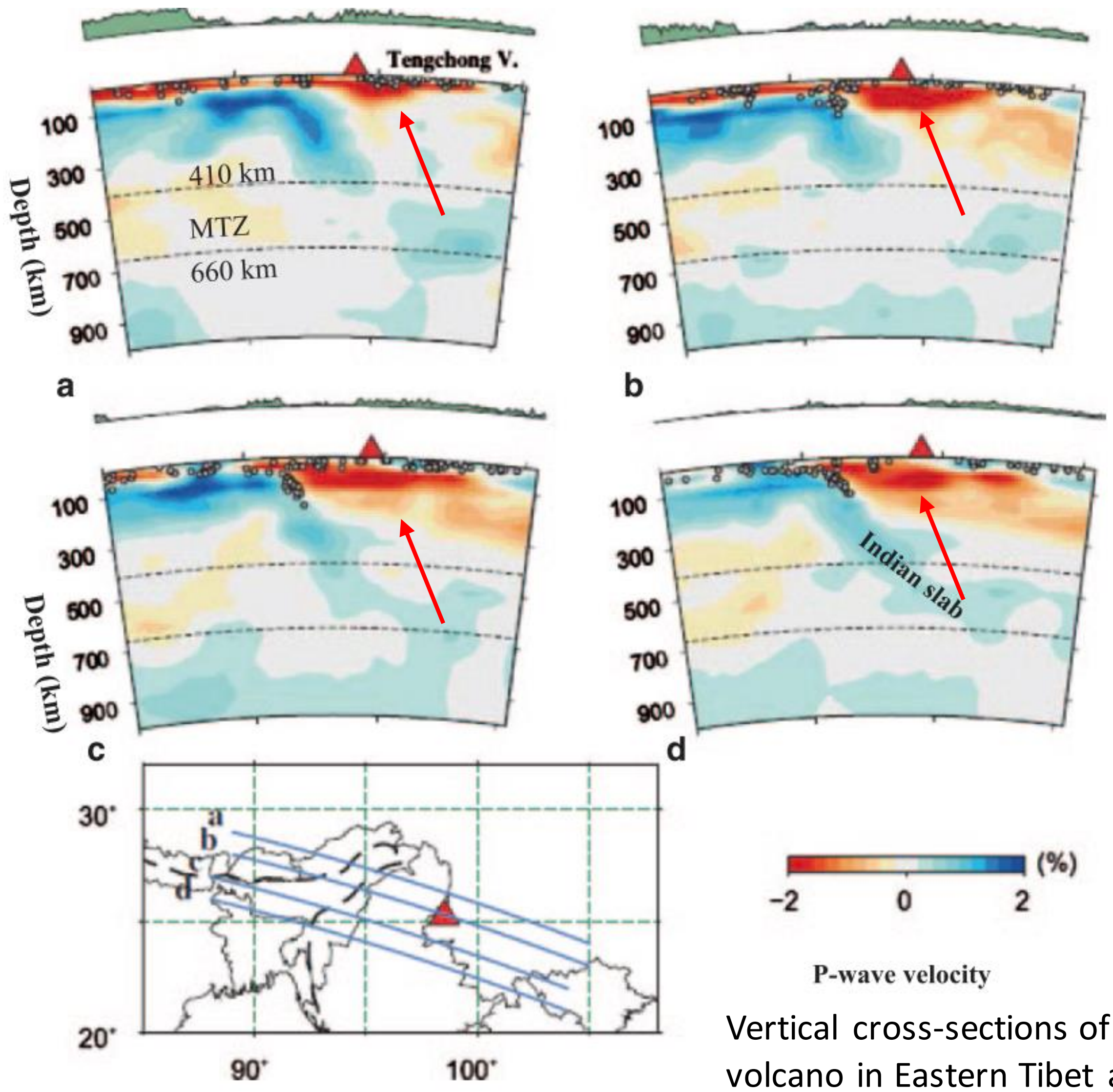
Hafkenscheid et al., 2001



Zenonos et al., 2019

Interpretation of Seismic Tomography: Subduction Zones

Seismic Velocity



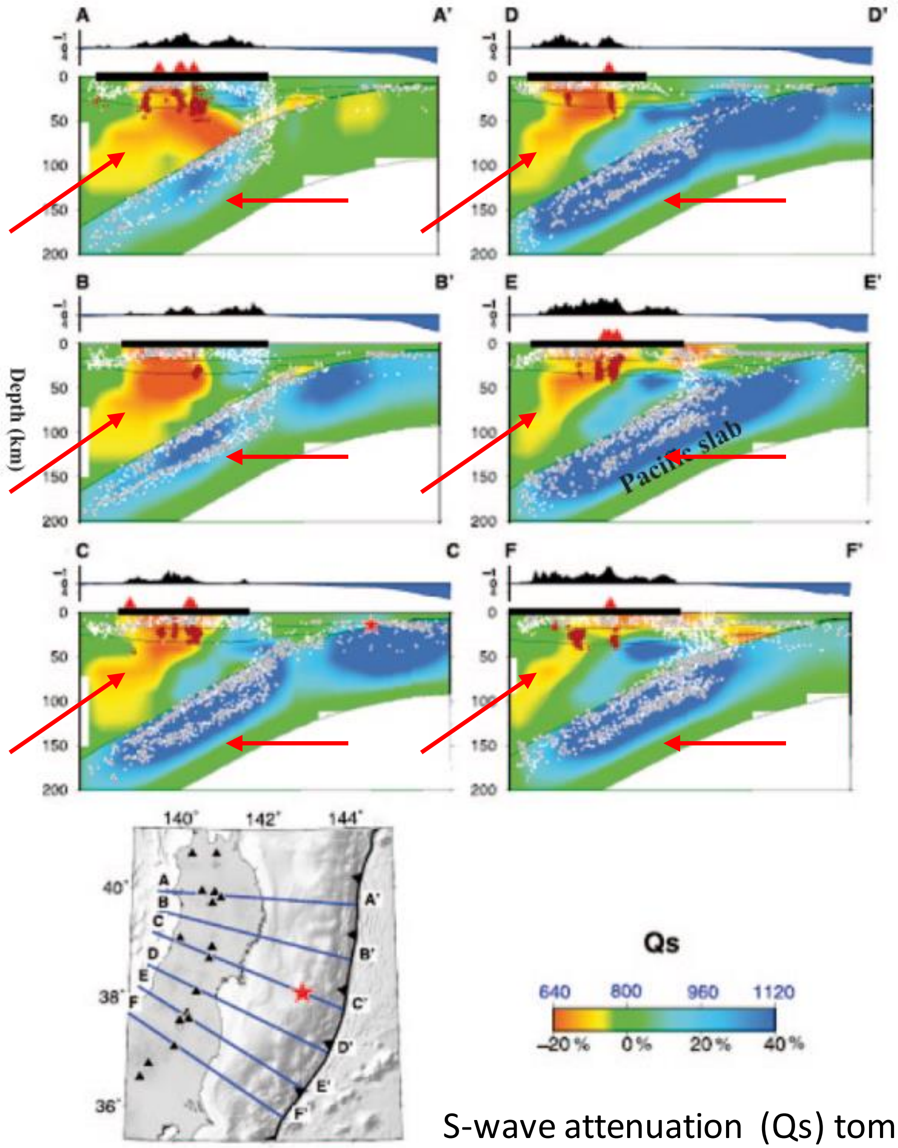
Vertical cross-sections of Vp under the active Tengchong volcano in Eastern Tibet and SW Chine (Wei et al, 2012).

Low seismic velocity anomalies in the mantle wedge beneath the volcanic front and back-arc areas reflect the source zone of **arc magmatism and volcanism.**

It is due to the joint effects of fluids from slab dehydration and corner flow in the mantle wedge (e.g. Hacker et al 2003).

Interpretation of Seismic Tomography: Subduction Zones

Seismic Attenuation



Seismic attenuation (Q) provides information on the physical properties and composition of materials in the crust and mantle. It sometimes more **sensitive to temperature variation and melts** than seismic velocity

Subducting slabs are generally indicated by **High-Q (weak attenuation)**

The mantle wedge and crust beneath the arc volcanoes reflect **Low-Q (strong attenuation)**

S-wave attenuation (Qs) tomography under NE Japan (Liu et al., 2014)

Interpretation of Seismic Tomography: Subduction Zones

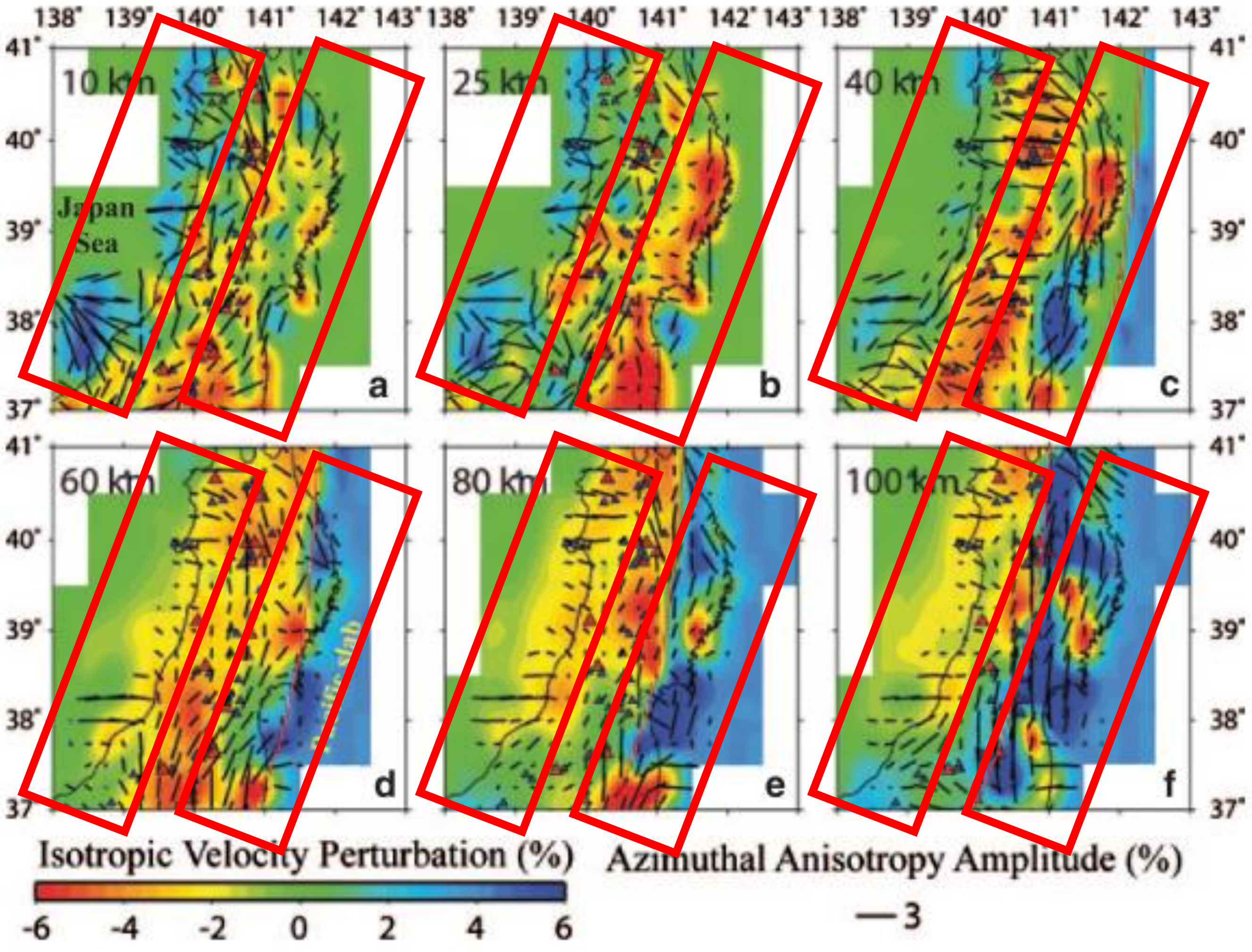
Seismic Anisotropy

Seismic anisotropy, seismic velocity's directional dependency, has widely employed to examine **the dynamic process and stress** of Earth's interior.

The body-wave methods include: **shear wave splitting, receiver functions, and P-wave anisotropy**

Trench-normal fast-velocity directions (FVDs) in the back-arc mantle wedge, reflecting **slab-driven corner flow** in the mantle wedge.

Trench-parallel FVDs are revealed in the fore-arc mantle wedge, suggesting the existence of a **B-type olivine fabric.**



Map views of P-wave anisotropy tomography under NE Japan (Wang and Zhao, 2013)

frontiers
in Earth Science

ORIGINAL RESEARCH
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Seismic Imaging of Lithospheric Structure Beneath Central-East Java Region, Indonesia: Relation to Recent Earthquakes

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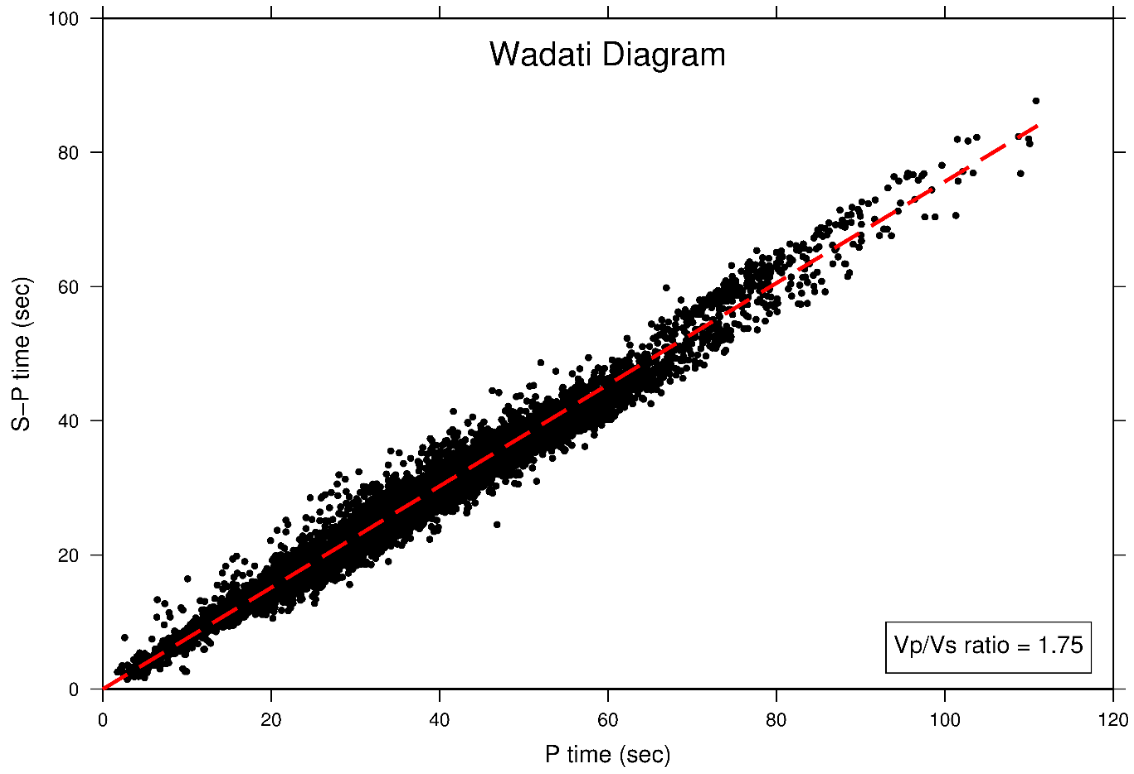
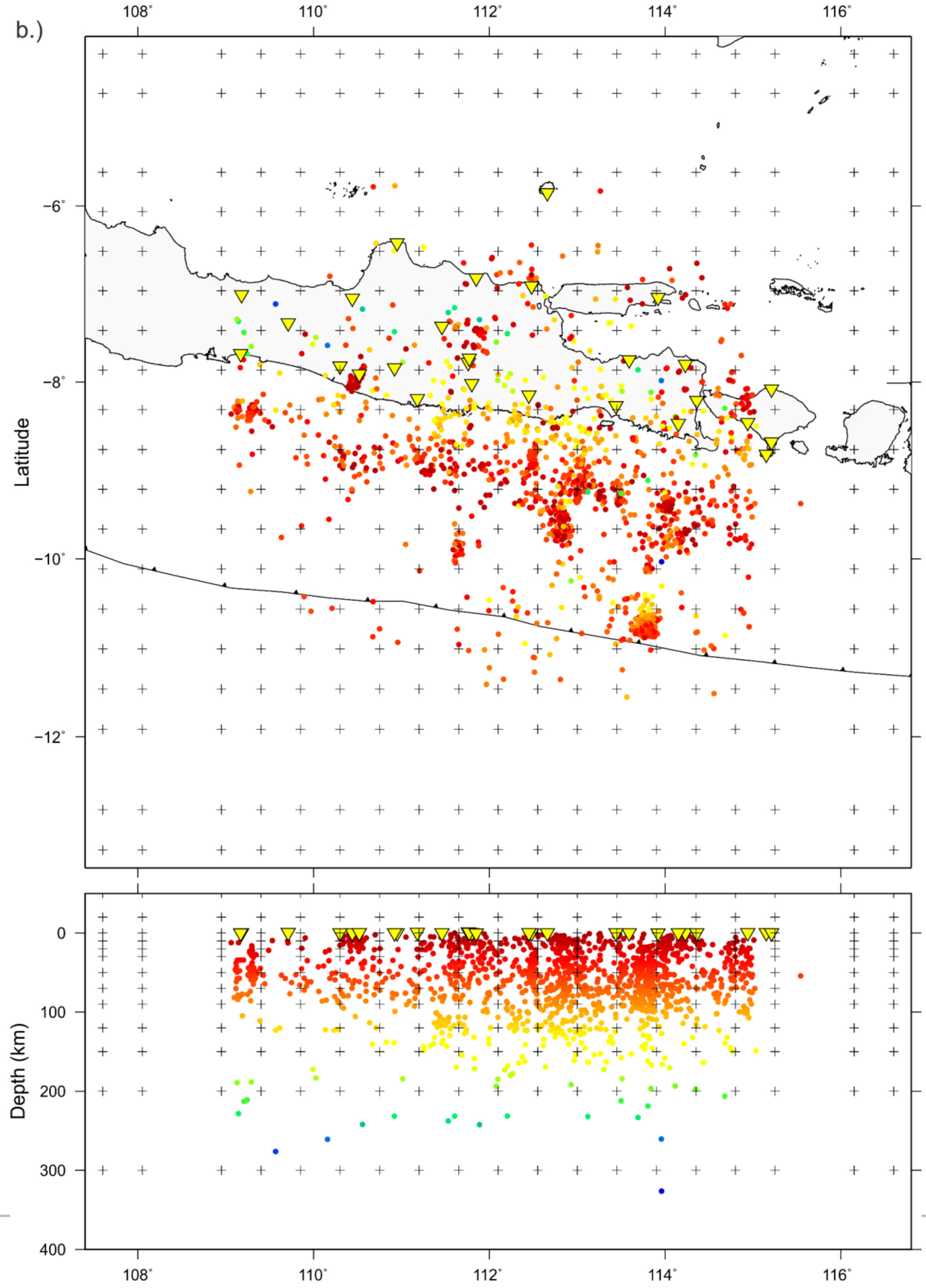
Data



We used re-picked arrival times and hypocenter location determined by previous study, with total:

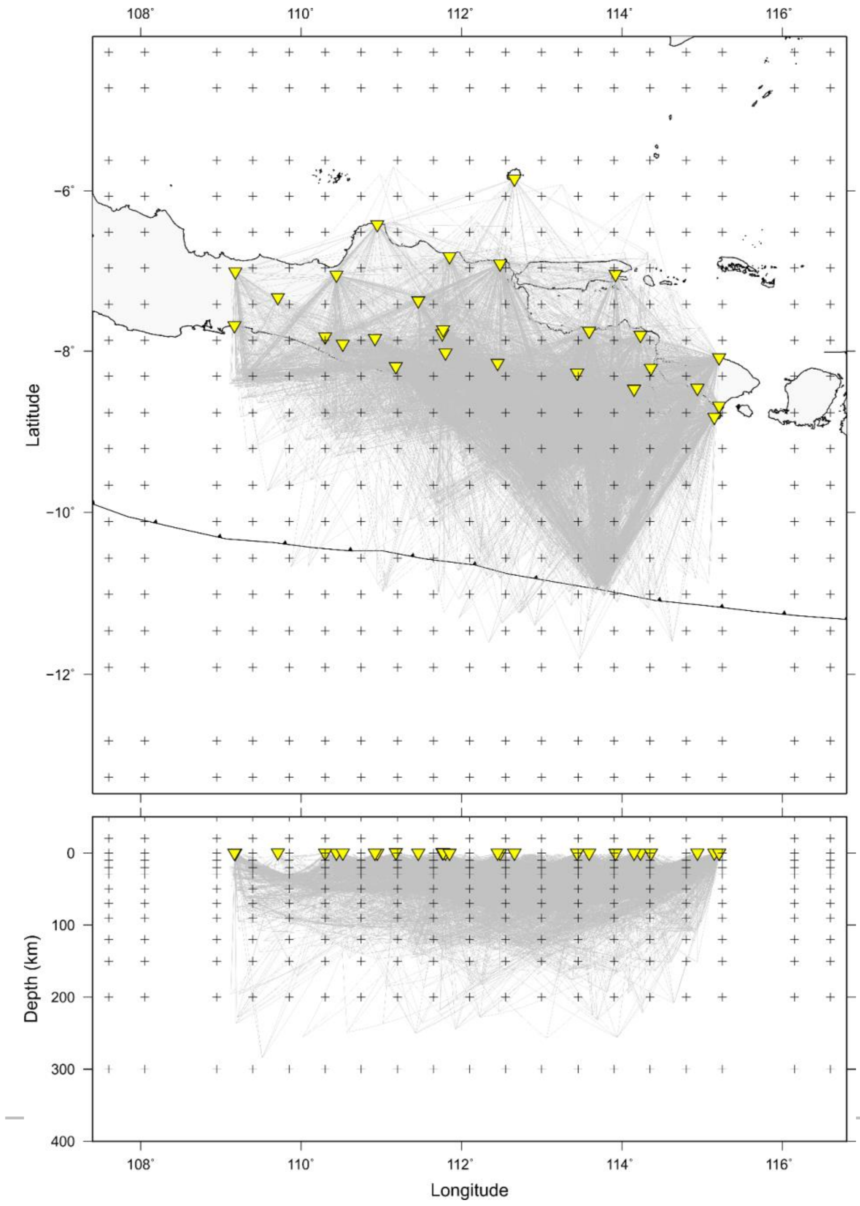
- 1,488 events in the time period of January 2009-September 2017
- > 20,000 P- and S-wave phases
- 27 stations of BMKG

The earthquake data was constrained to the longitude and latitude ranges of 108°-118°E and 5°-12°S, respectively, with at least six high-quality phase picks and magnitude (Mw) >3.



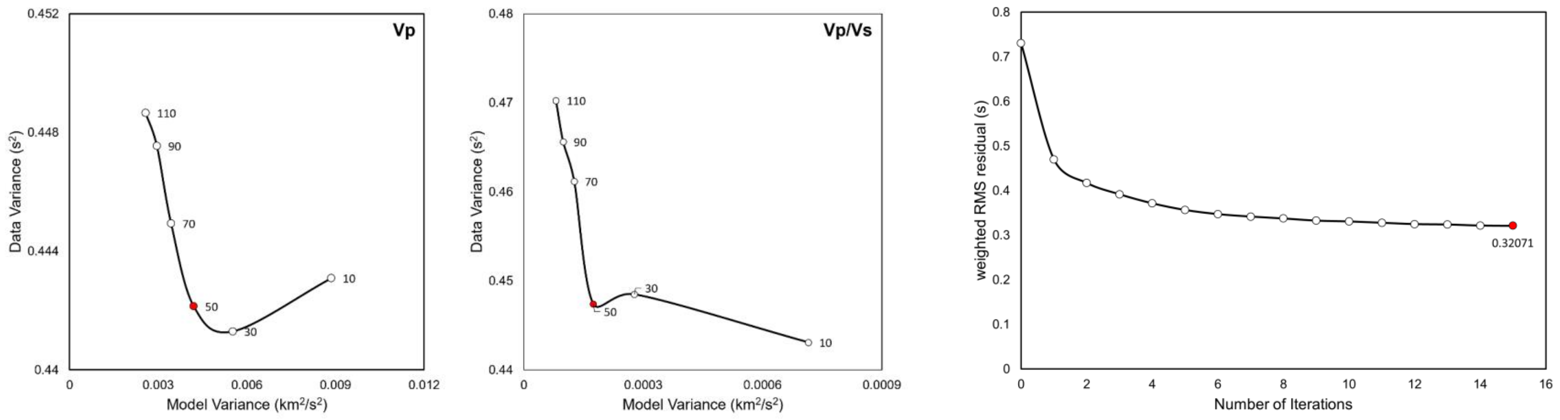
Ray Tracing and Tomographic Inversion

Ray paths distribution determined by using pseudo-bending method of Um and Thurber (1987)

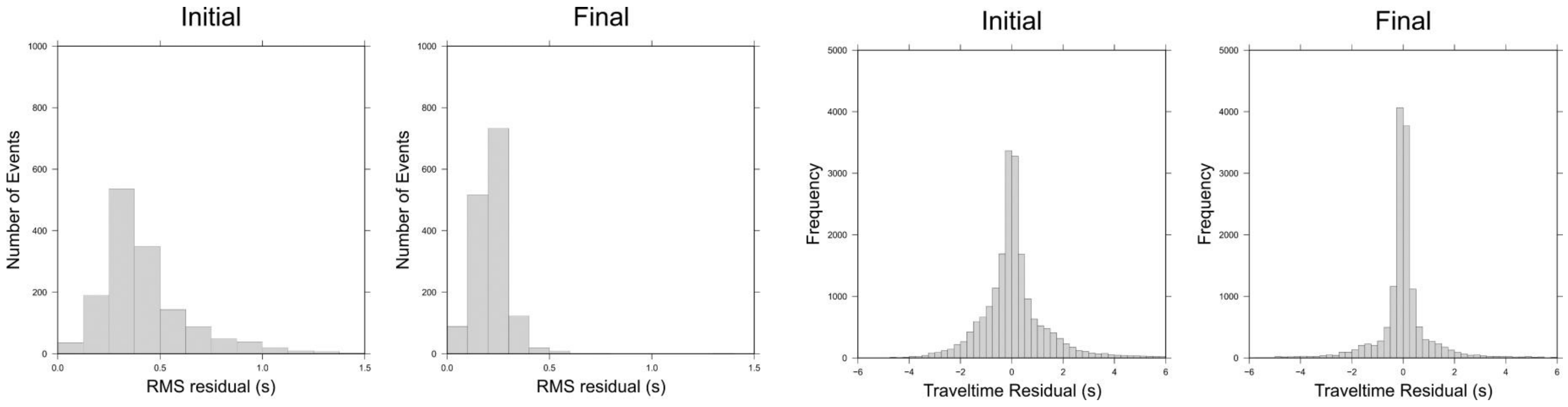


Tomographic Inversion

We applied SIMULPS12 code (Evans et al., 1994) to invert for both hypocenter relocation and velocity structure simultaneously, with the least-square (LSQR) inversion (Paige and Saunders, 1982).

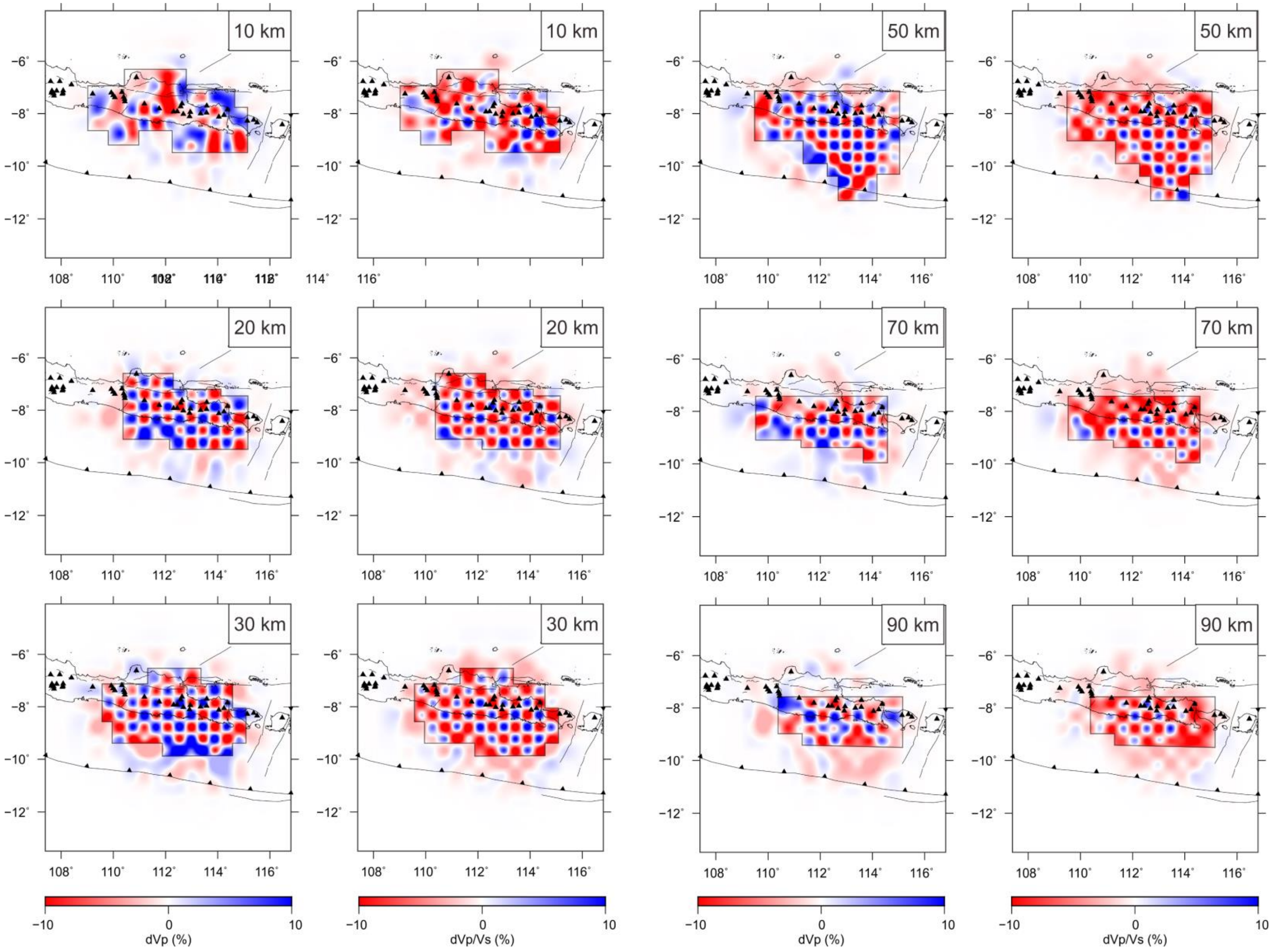


Trade-off curves showing model variance versus data variance for selecting optimal damping values in the inversions.

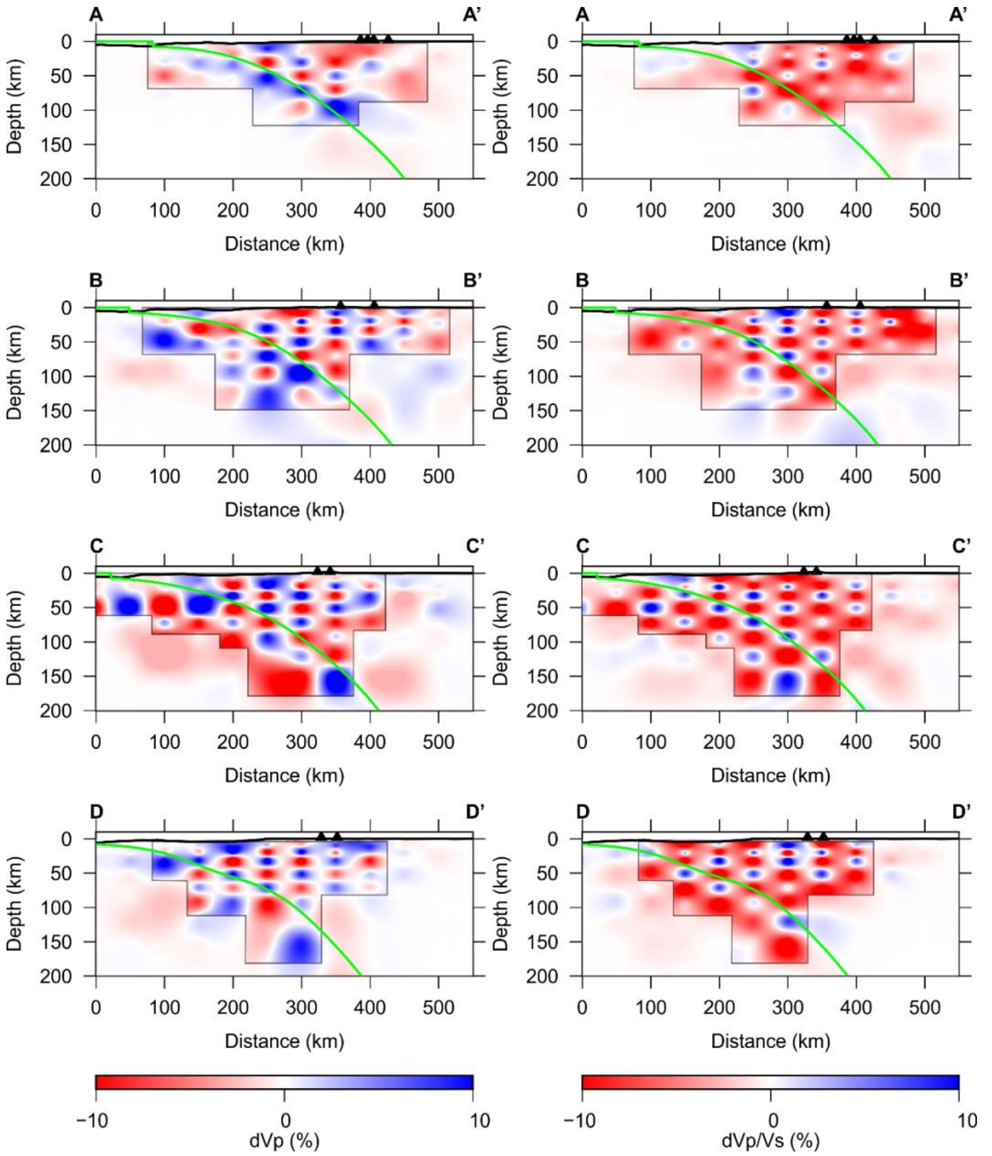


Checkerboard Resolution Test

Horizontal sections



Vertical sections



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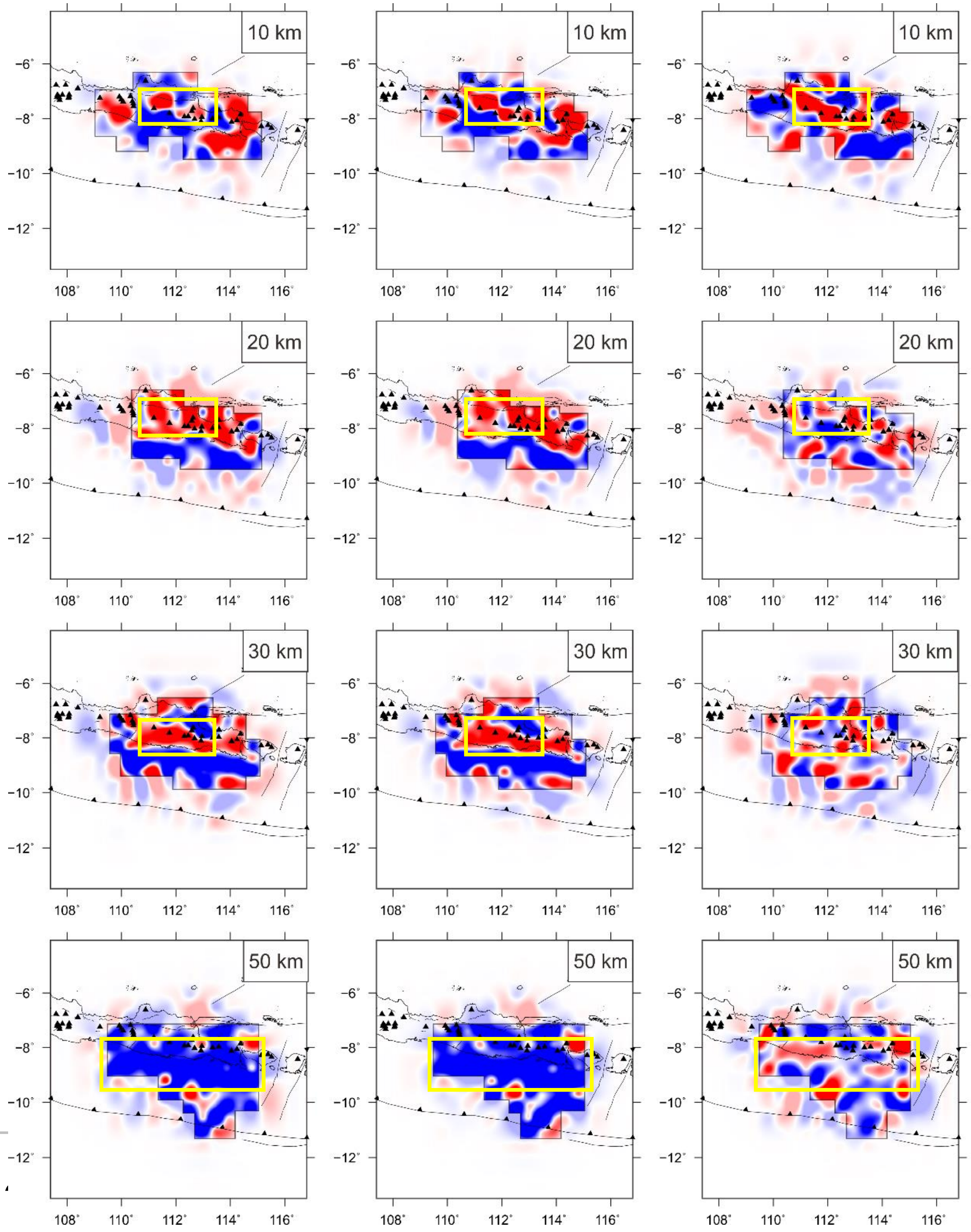
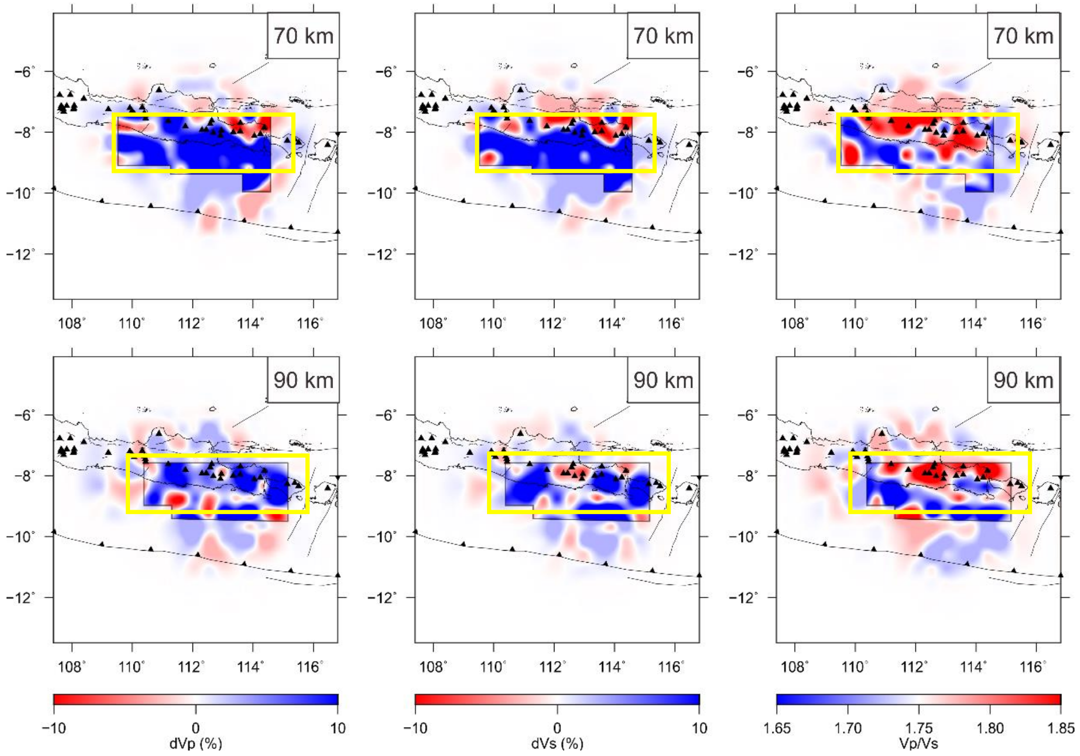
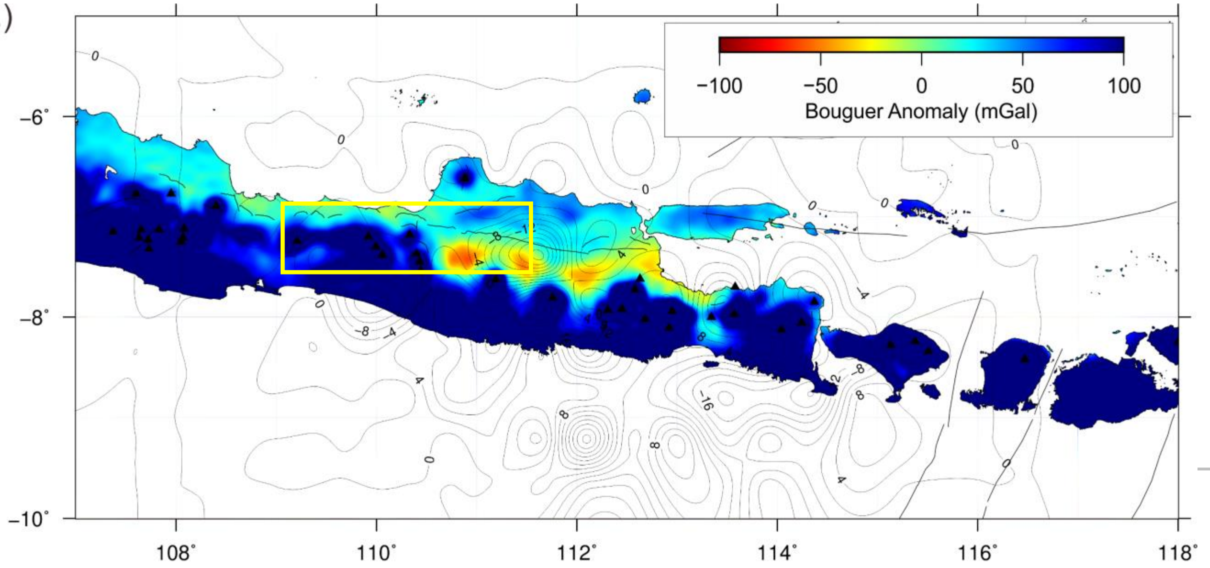
Results and Discussion



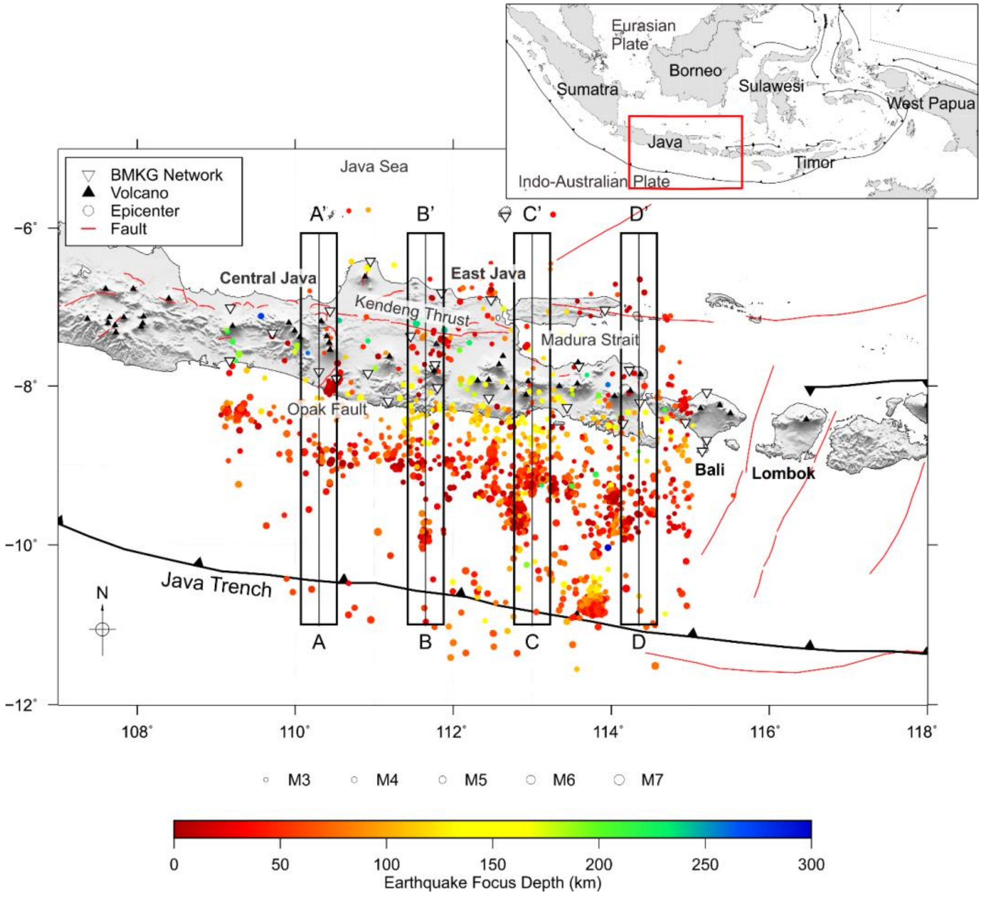


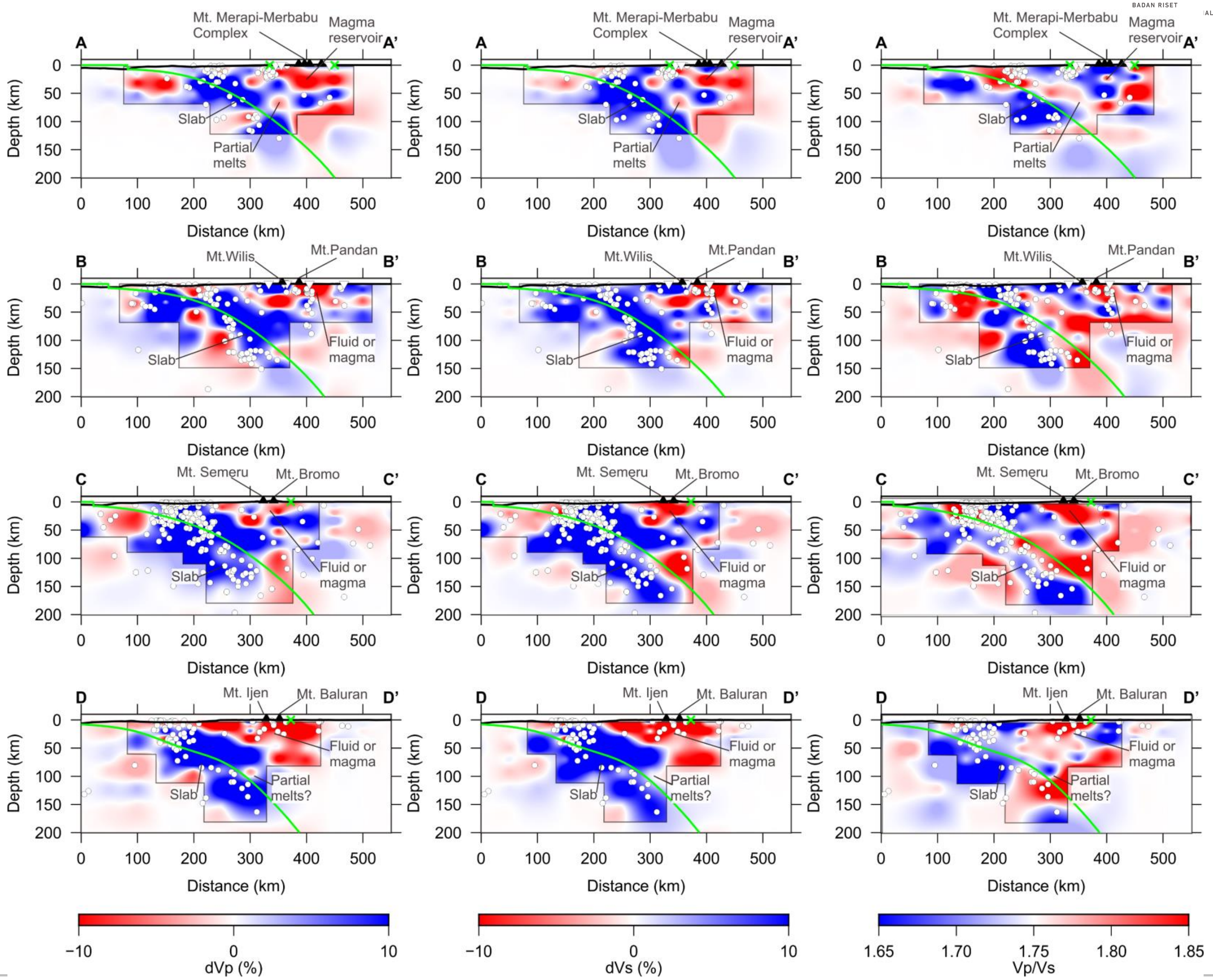
a.)



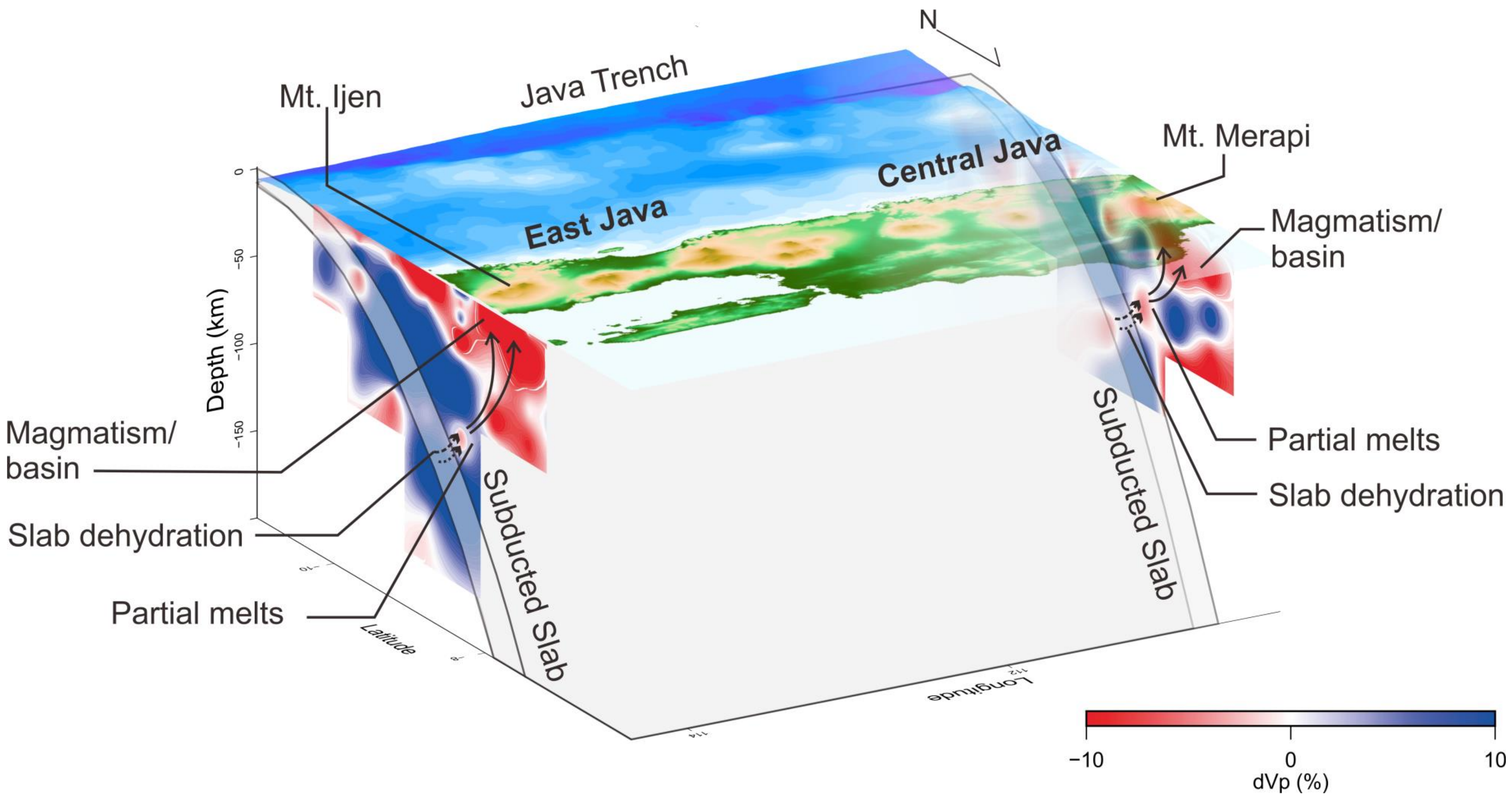
Center for Geological Survey (PSG)

Results and Discussion



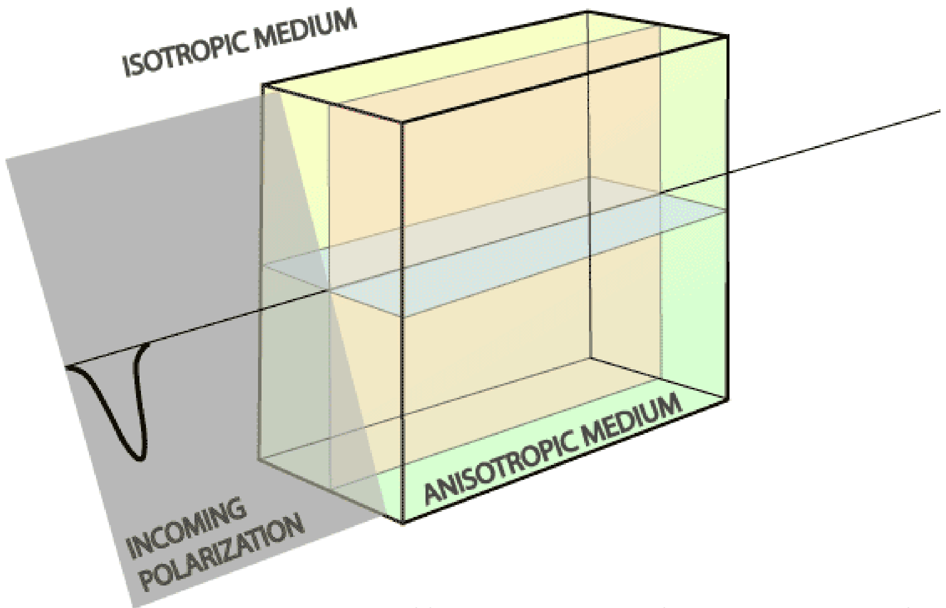


Results and Discussion



Interpretative cross-sections of the velocity structure from Vp beneath Central and East Java subduction zone. The tomography cross sections show Vp distributions which pass through Mt. Merapi-Merbabu and Mt. Ijen.

Shear Wave Splitting Analysis



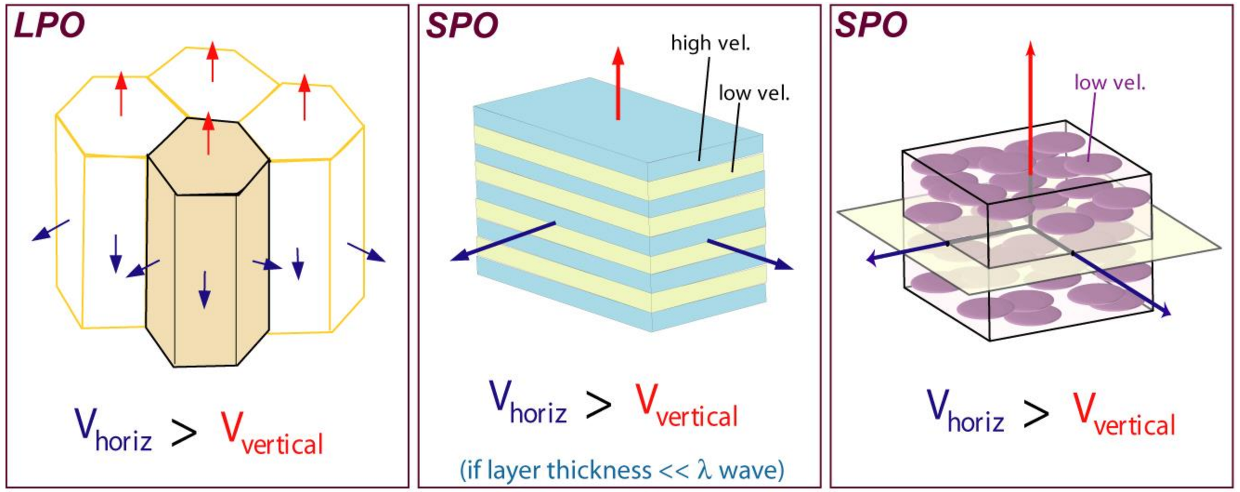
(http://garnero.asu.edu/research_images/images_anisotropy.html)

When a shear wave travels through an anisotropic medium, it is split into orthogonally polarized fast (blue) and slow (red) shear waves, causing shear wave splitting.

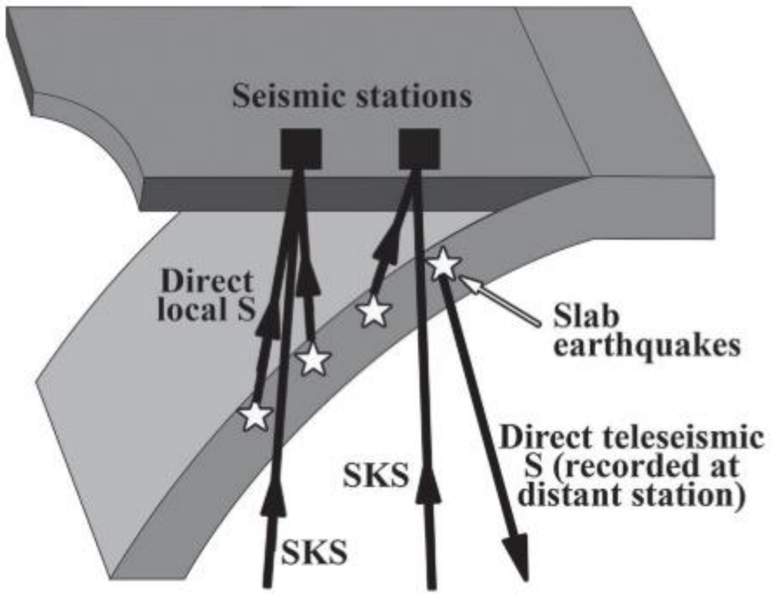
- the orientation of fast shear wave (ϕ)
- delay time between the two arrivals (δt)

SWS results from:

- **SPO:** caused by cracks in the crust, faults, melt-filled inclusions in the mantle, resulting the fast direction is polarized parallel to the direction of maximum stress.
- **LPO:** deformation leads to a preferred orientation of the mineral, under certain temperature and pressure conditions.

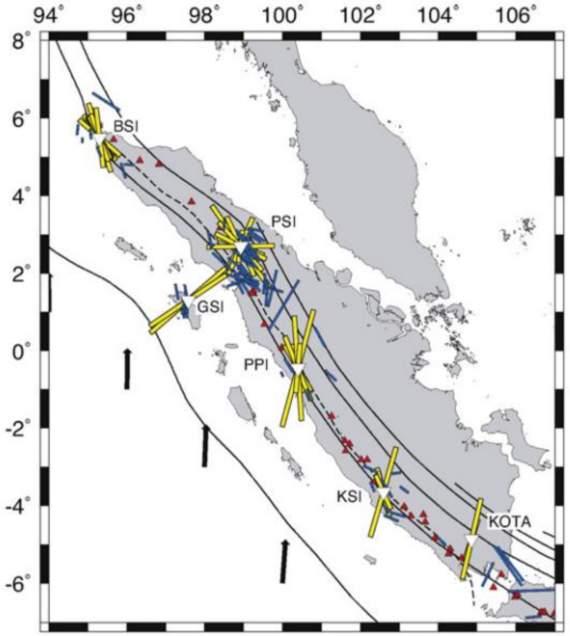


[after Moore,Garnero,Lay,Williams, JGR, 2004]

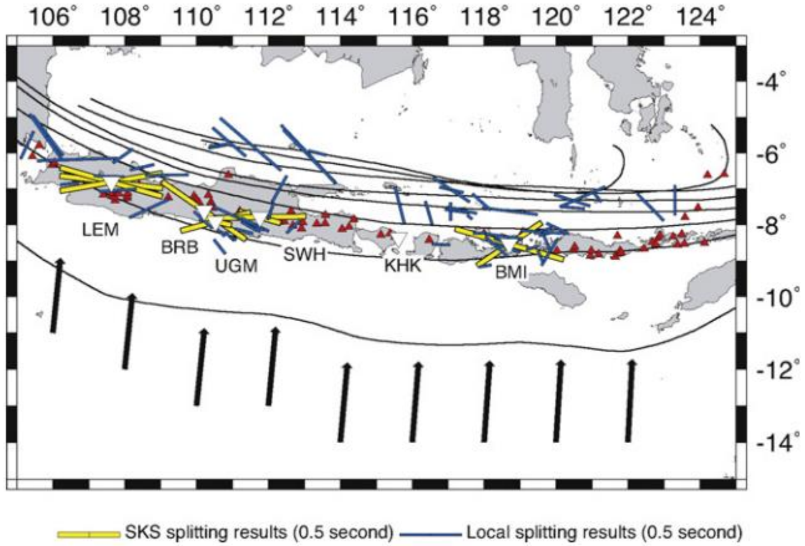


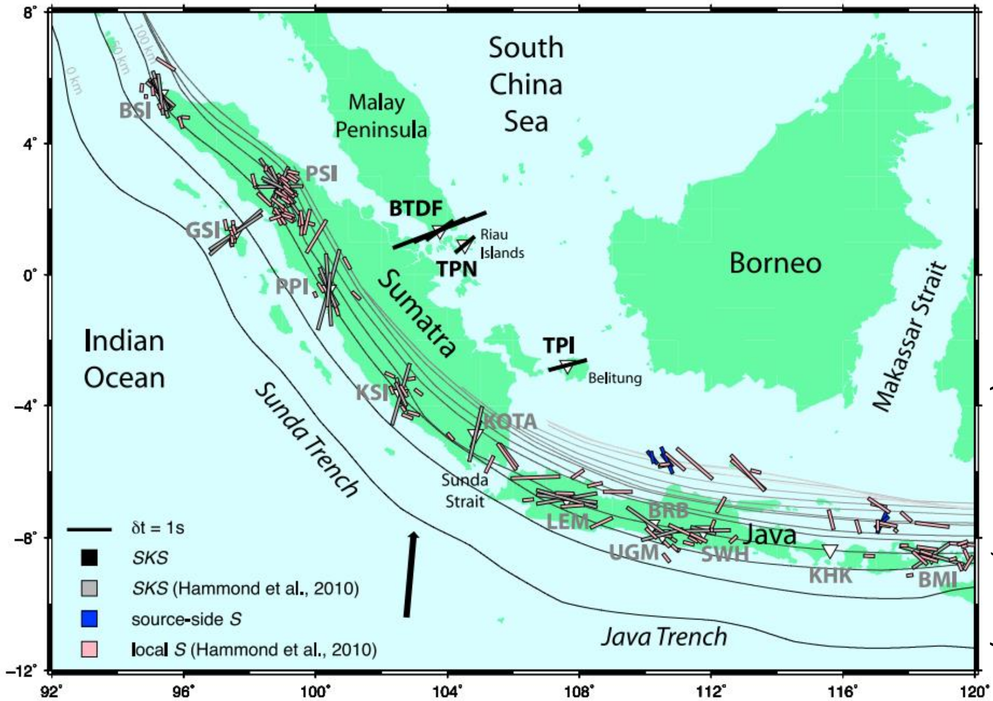
(Long, 2013)

Anisotropic studies in Indonesia from SWS analysis

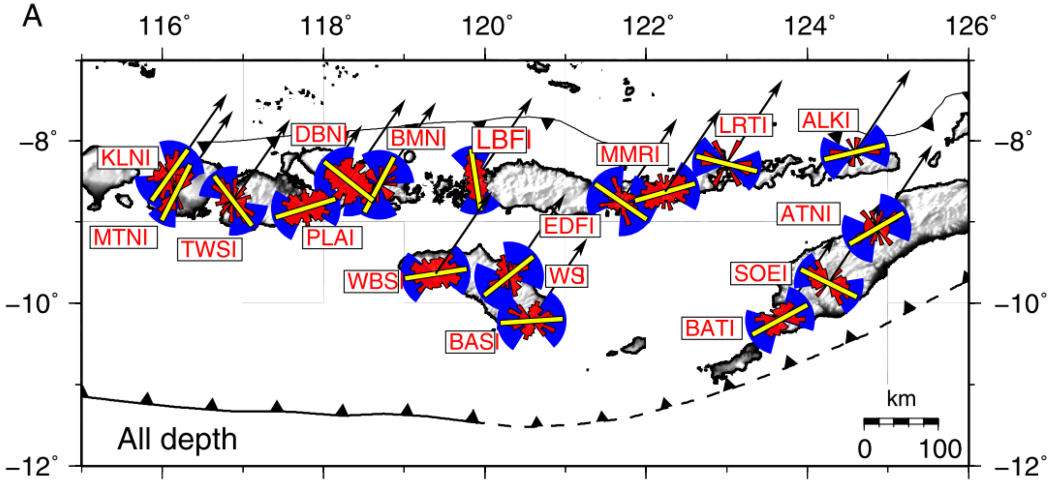


(Hammond et al., 2010)

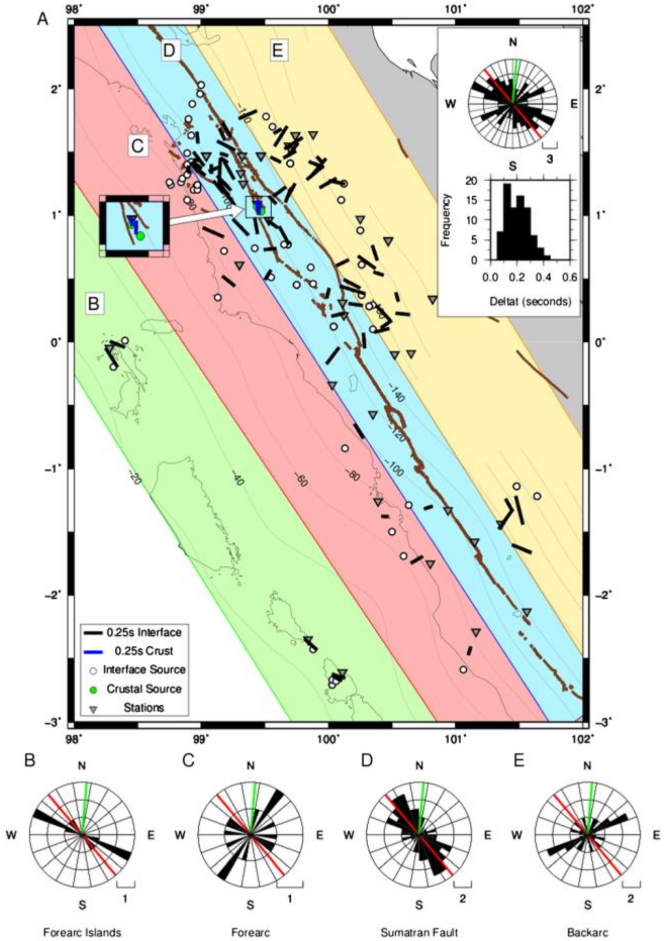




(Di Leo et al., 2012)



(Syuhada et al., 2020)



(Collings et al., 2013)

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Anisotropy variations in the continental crust of Central – East Java region, Indonesia from local shear wave splitting

Faiz Muttaqy [a,b,*], Andri Dian Nugraha [c], Syuhada Sy
Nanang Tyasbudi Puspito [c], Annisa Trisnia Sasmi [b,e],

[a] Research Center for Geological Disaster, National Research and Innovation Agency (BRIN
[b] Laboratory of Volcanology and Geothermal, Faculty of Mining and Petroleum Engineering,
[c] Global Geophysics Research Group, Faculty of Mining and Petroleum Engineering, Institut
[d] Disaster Prevention Research Institute, Kyoto University, Gokasho, Uji, Kyoto 611-0011, J
[e] Faculty of Geography, Universitas Muhammadiyah Surakarta, Central Java 57139, Indon
[f] Agency for Meteorology, Climatology, and Geophysics (BMKG), Jakarta 10610, Indonesia

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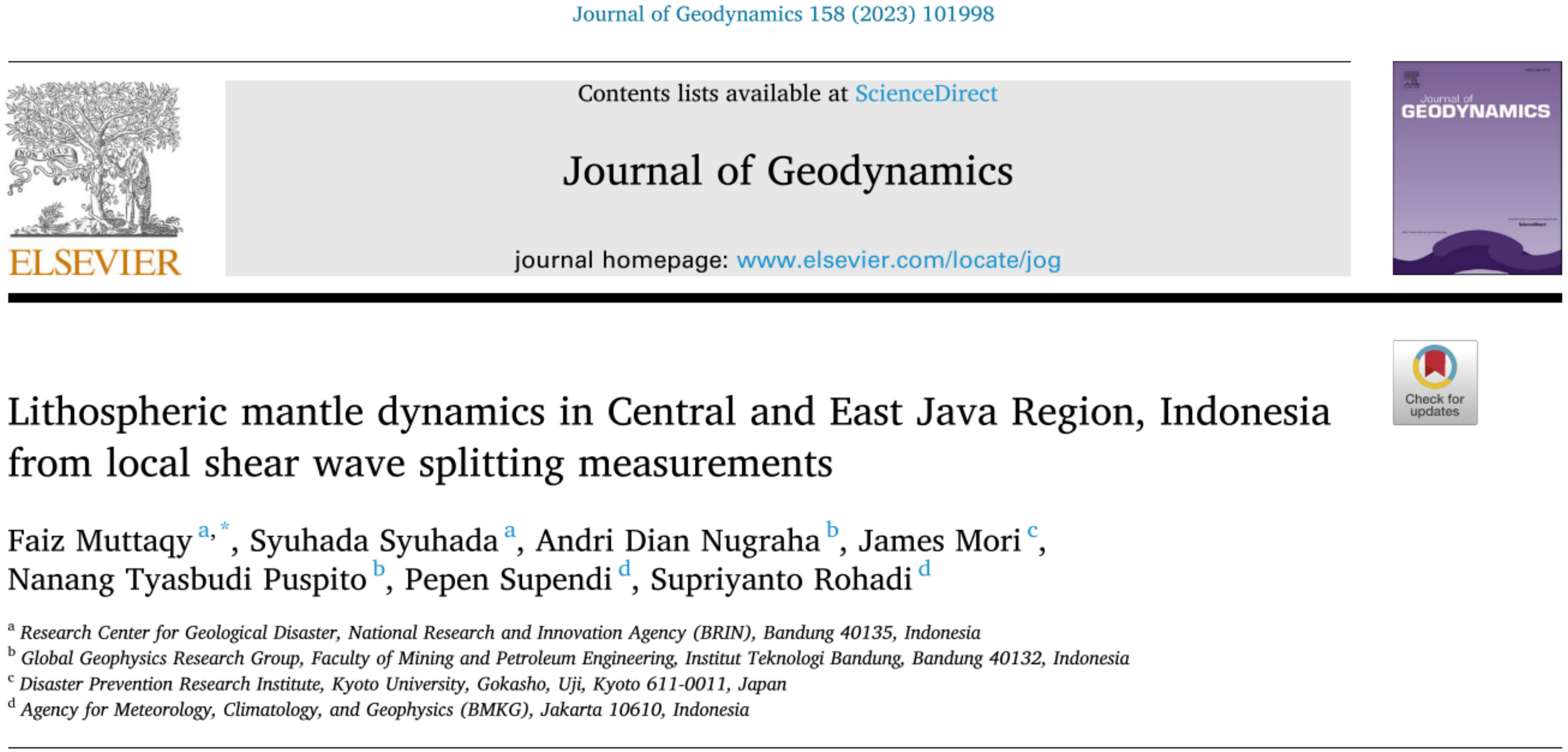

Journal of Geodynamics 158 (2023) 101998

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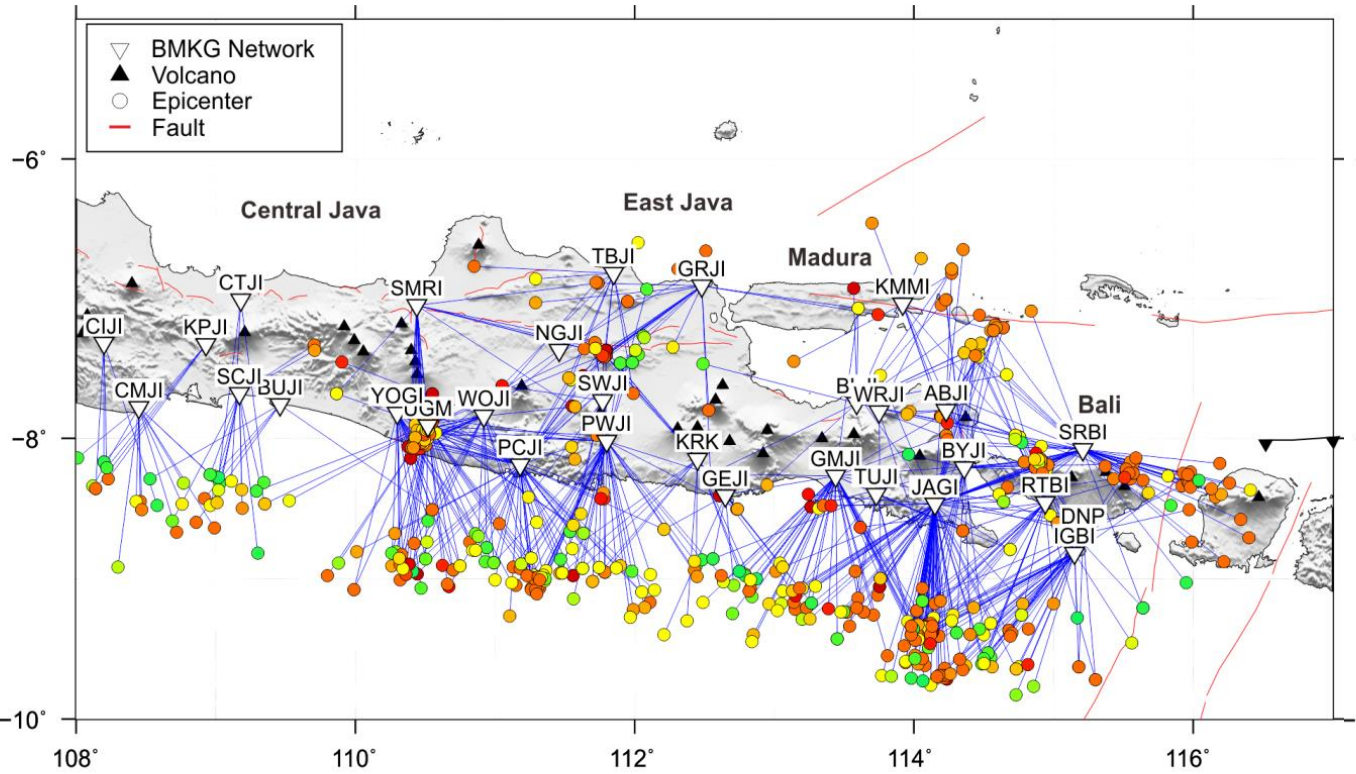
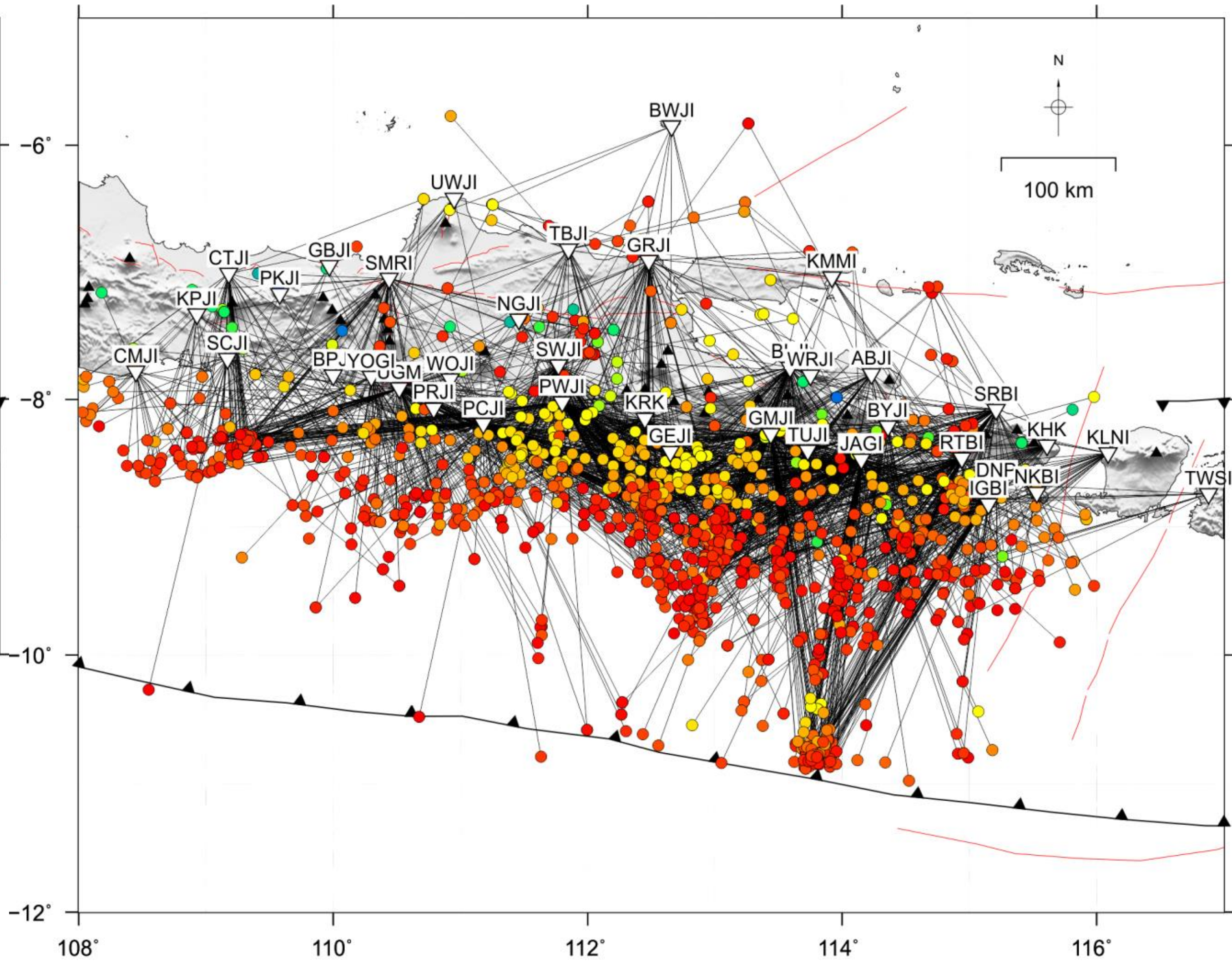
Lithospheric mantle dynamics in Central and East Java Region, Indonesia from local shear wave splitting measurements

Faiz Muttaqy [a,*], Syuhada Syuhada [a], Andri Dian Nugraha [b], James Mori [c],
Nanang Tyasbudi Puspito [b], Pepen Supendi [d], Supriyanto Rohadi [d]

[a] Research Center for Geological Disaster, National Research and Innovation Agency (BRIN), Bandung 40135, Indonesia
[b] Global Geophysics Research Group, Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung, Bandung 40132, Indonesia
[c] Disaster Prevention Research Institute, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan
[d] Agency for Meteorology, Climatology, and Geophysics (BMKG), Jakarta 10610, Indonesia

Data





We investigate shear wave splitting using local S phases within 2009-2020

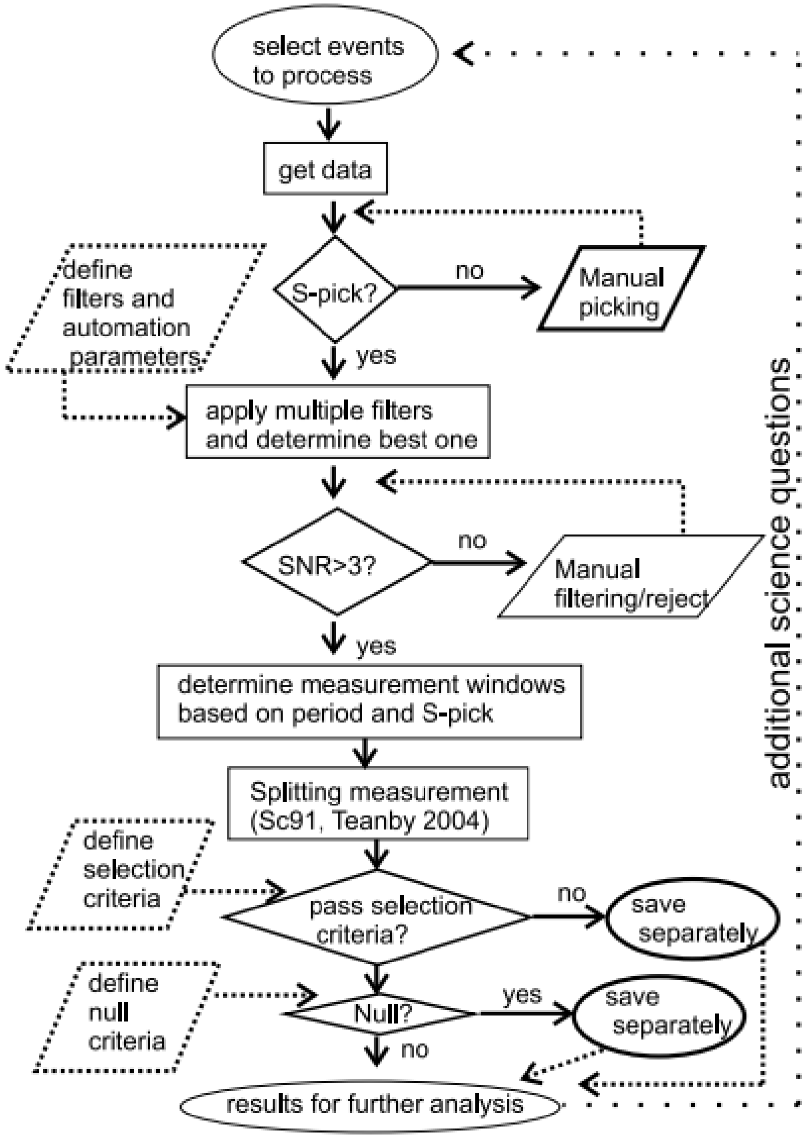
Crustal anisotropy:

- Seismograms from 30 BMKG stations
- event depths < 30 km, Mw >3
- radius 150 km from each recorded station

Upper mantle anisotropy:

- 38 BMKG stations
- event depths 30-300 km, Mw >3
- radius 300 km

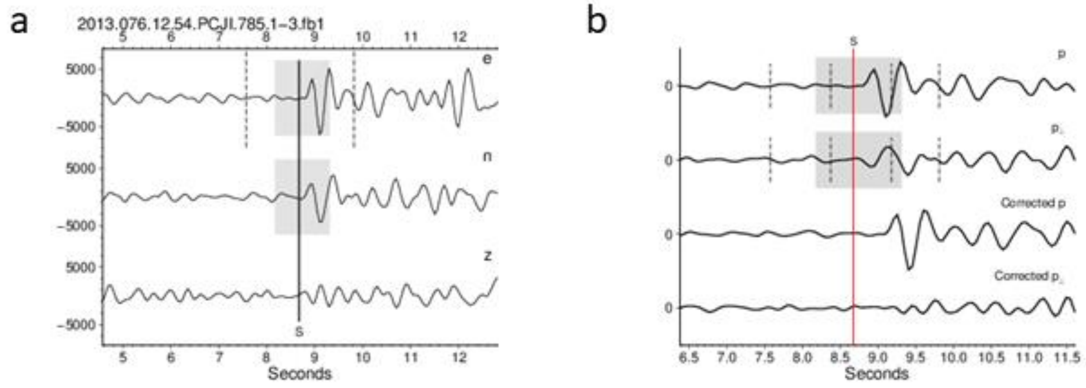
Method



Flowchart of MFAST package (Savage et al., 2010)

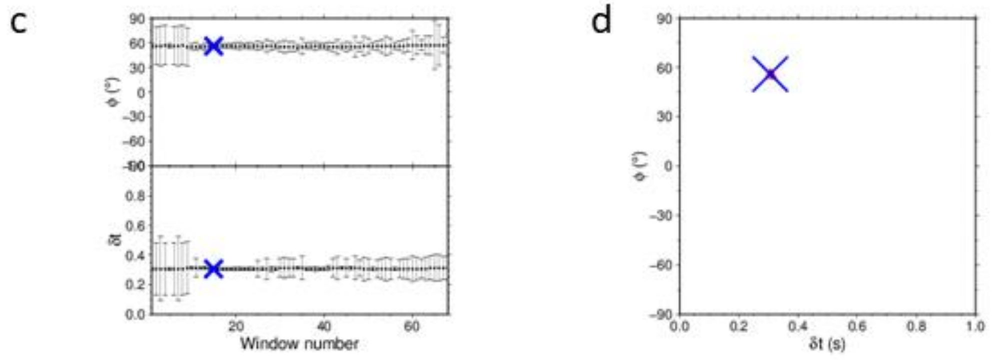
MFAST package
(Savage et al. 2010)

- The extension to the SC91 and Teanby et al (2004) techniques which simplify the processing of large datasets, with the only manual step in picking S arrival.

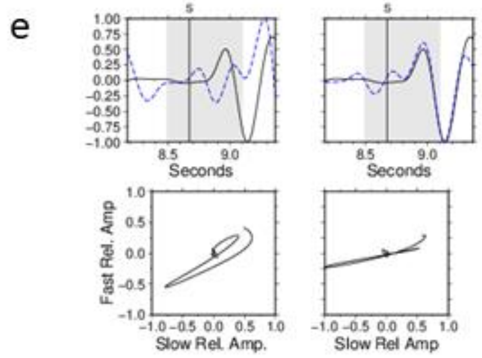


Filtered waveforms

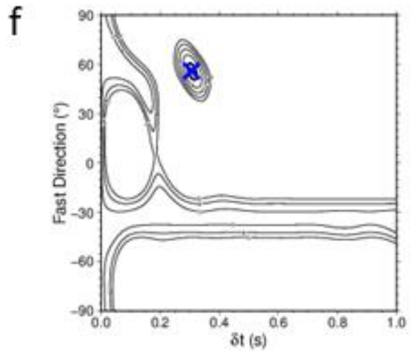
Rotated waveforms



Parameters obtained from cluster analysis (Teanby, et al., 2004)



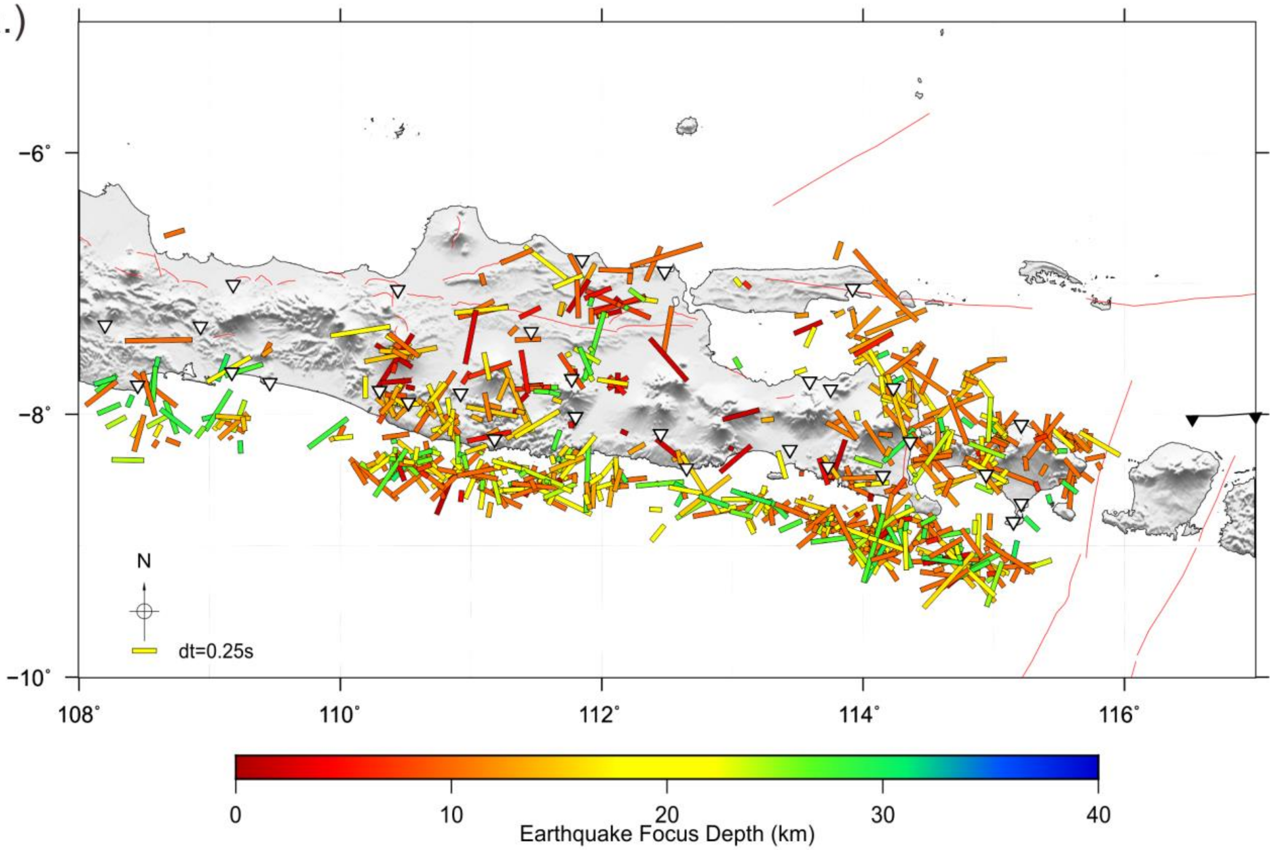
Particle motion plot before and after the correction



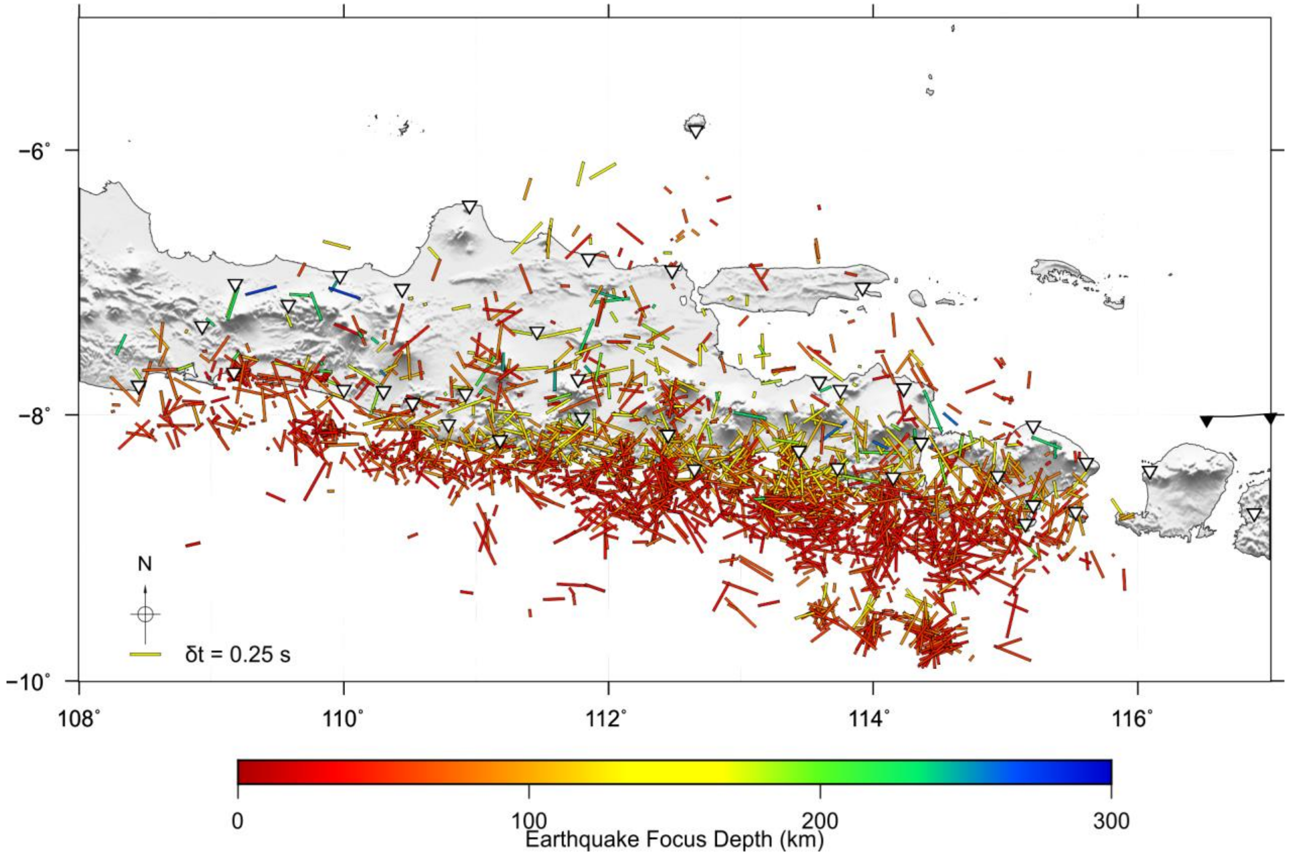
the contours of the smallest eigenvalue of the covariance matrix for the final chosen SC91 measurement

Results

a.)



721 splitting measurements for crustal anisotropy.

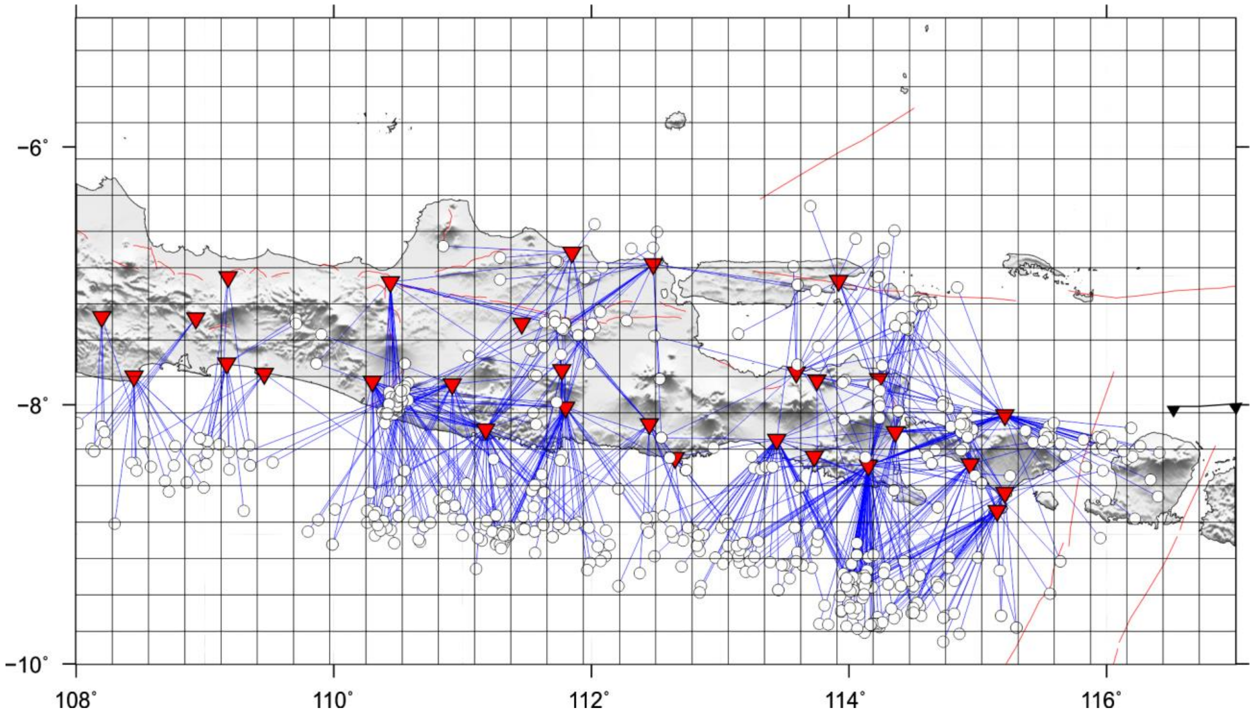


2,338 splitting measurements for uppermantle anisotropy.

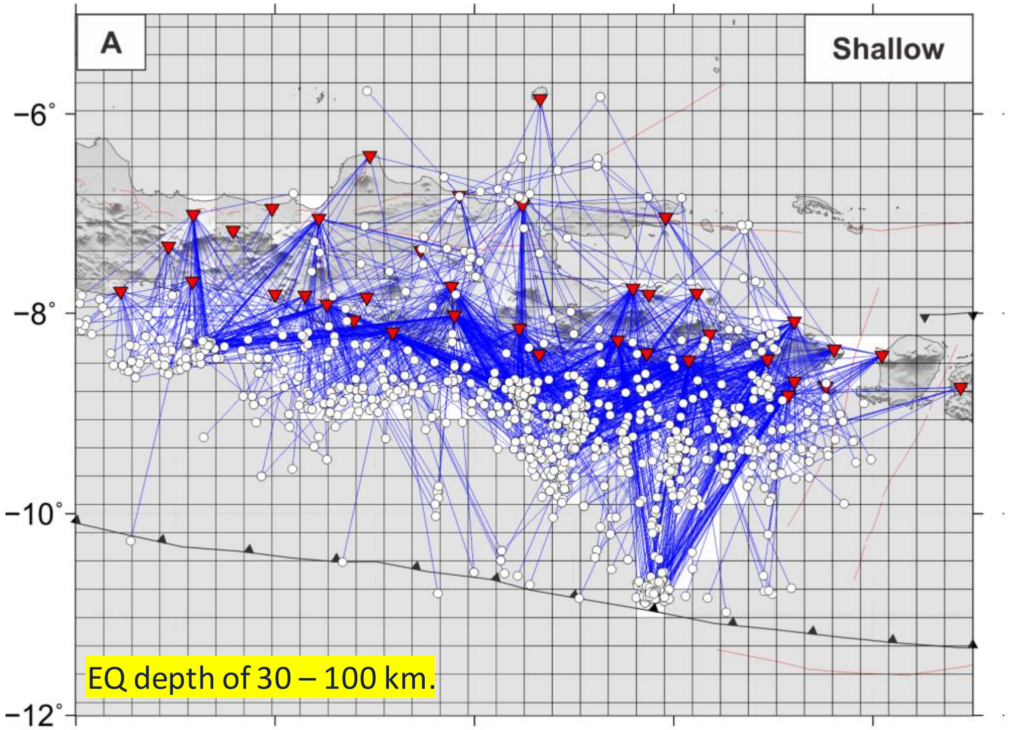
2-D Delay Time Tomography and Spatial Averages

TESSA package (Johnson et al. 2011)

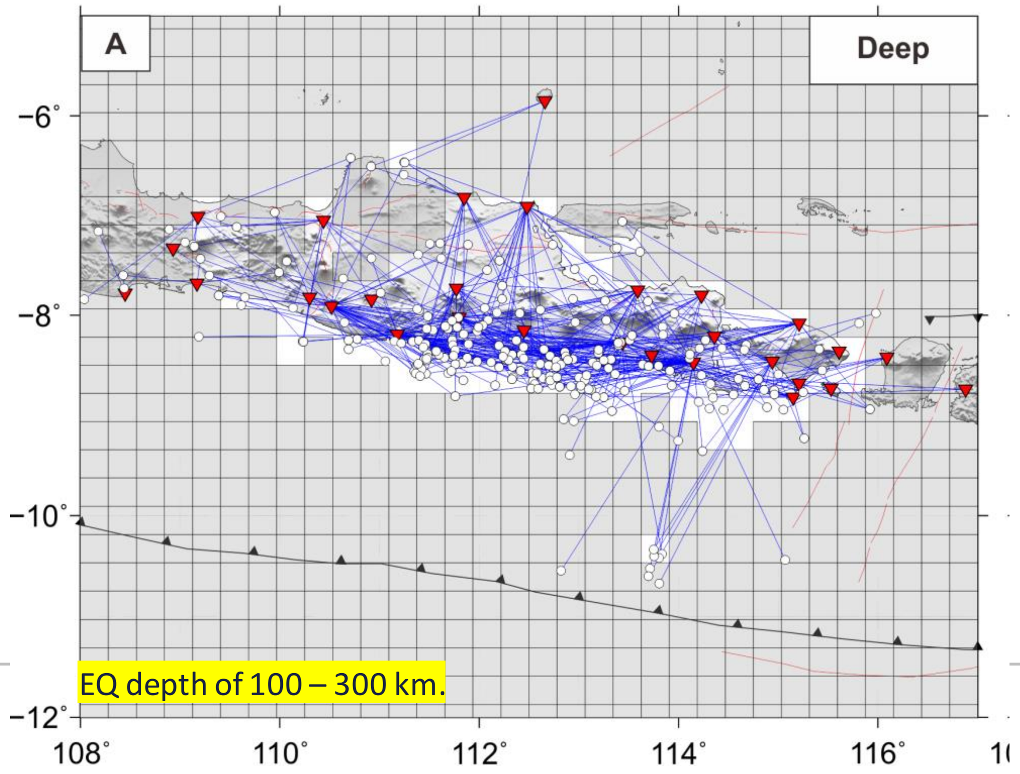
- The delay time (δt) from a single measurement is assumed to be accumulated along the ray path, and it is proportional to the path length of the ray through the anisotropic medium (Silver, 1996).



EQ depth of < 30 km.

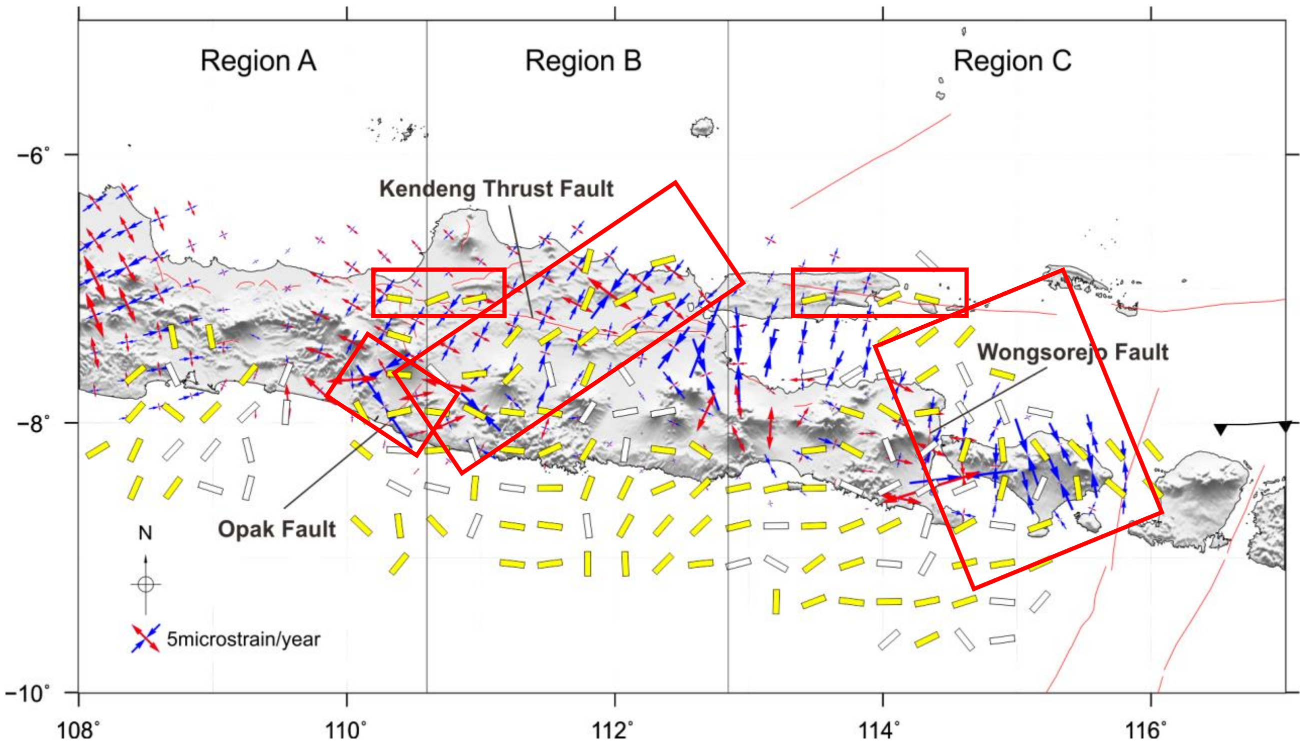


EQ depth of 30 – 100 km.

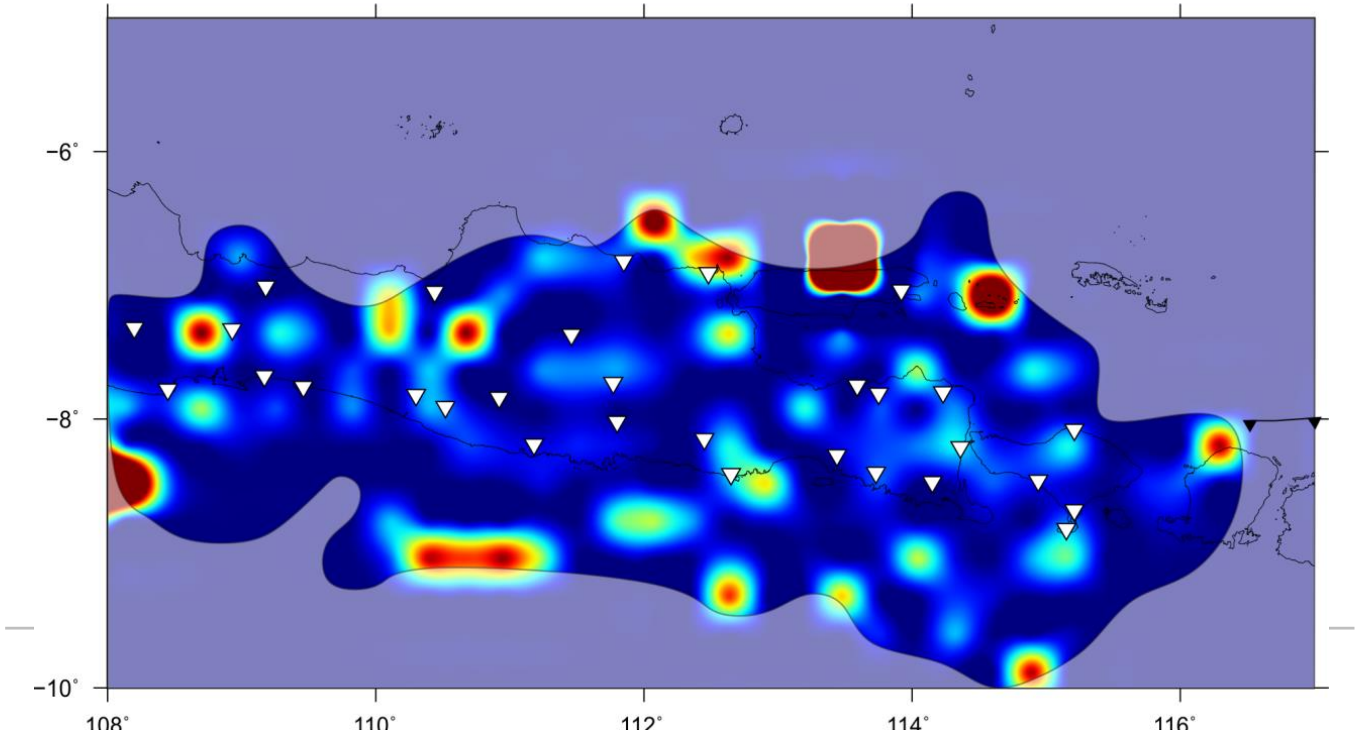


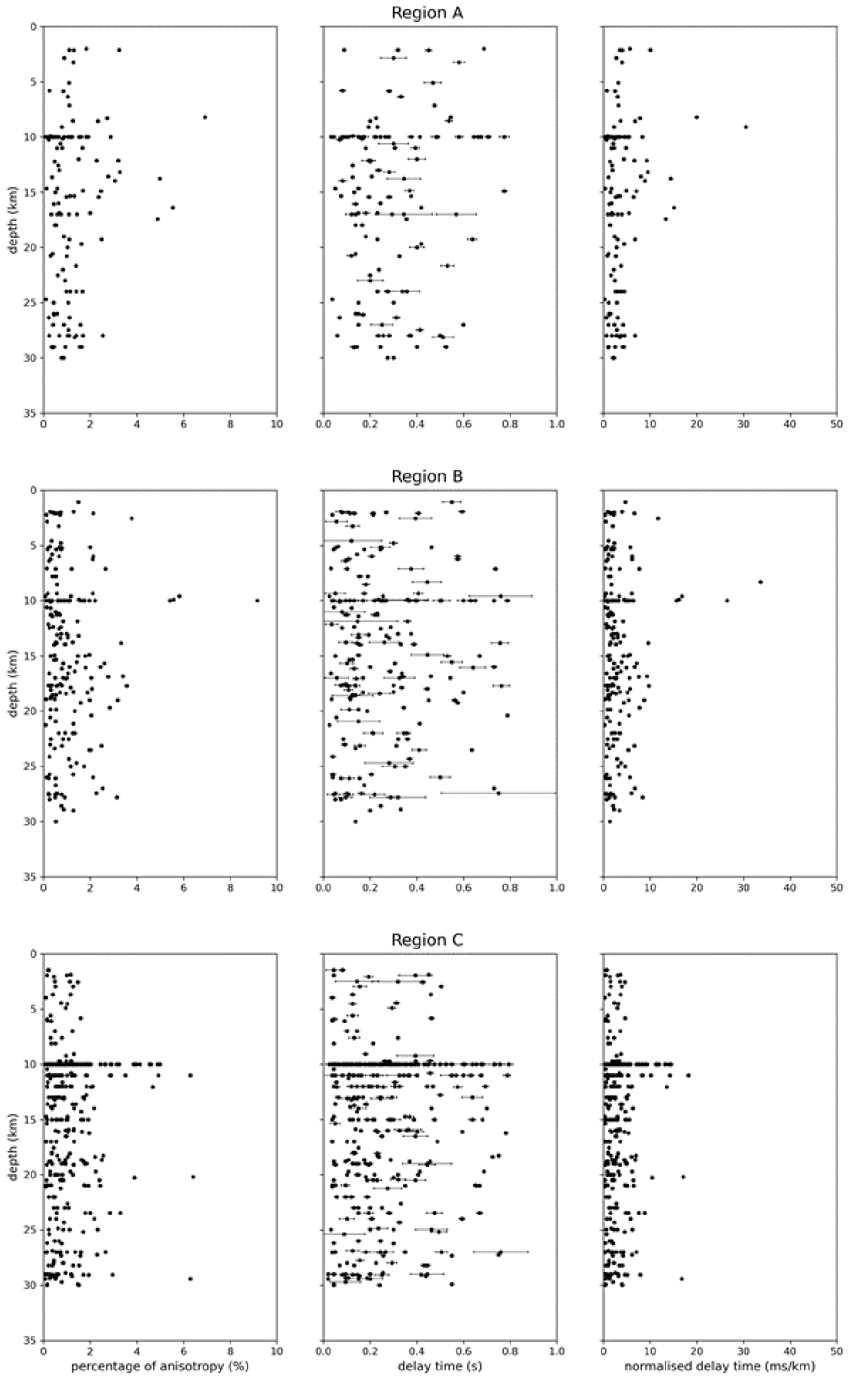
EQ depth of 100 – 300 km.

Possible Causes of Crustal Anisotropy



Strain distribution from (Gunawan and Widiyantoro, 2019)





1-5 microstrain/yr, with
train.

with deformation in the

arallel to the plane of
l strain orientation.

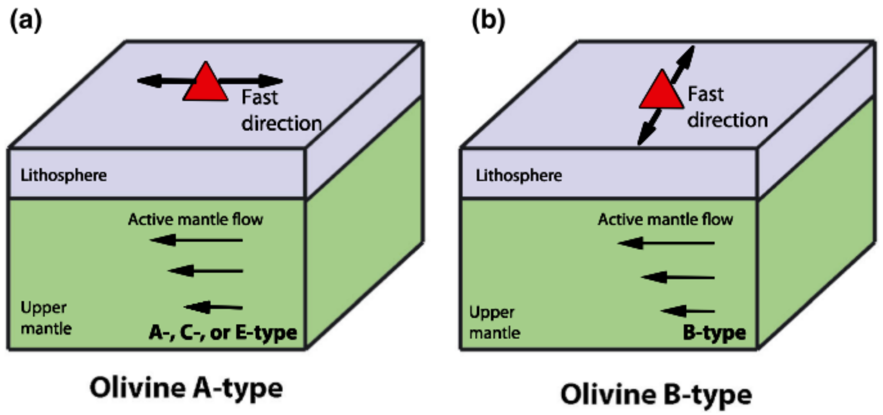
ntain fluids at high pore
ressional strain.

Percentage of anisotropy (Brustel, 2012):

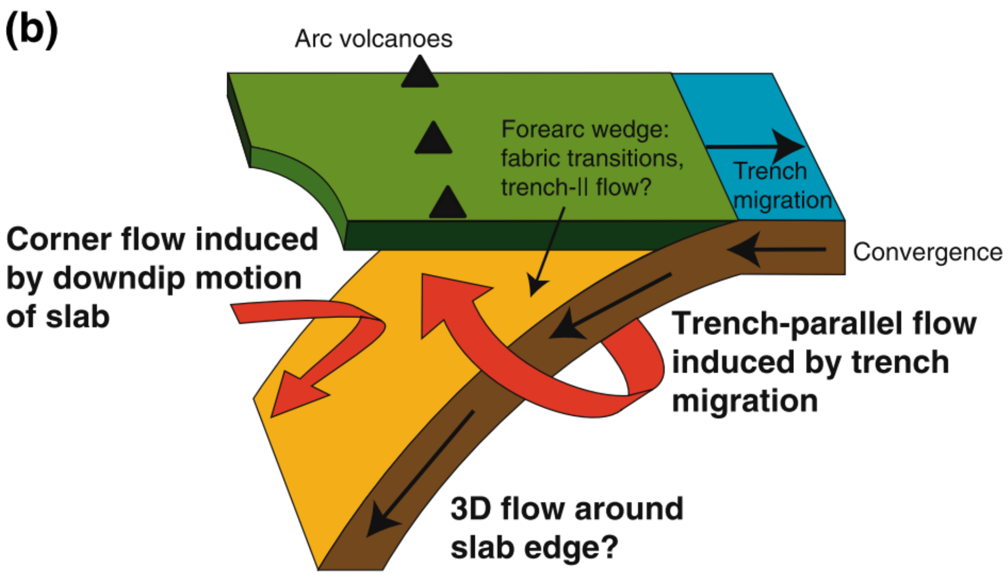
$$\xi = [(\delta t \times Vs)/d] \times 100\ \%$$

Higher delay times (0.6-0.8 s) at depth of 10-20 km with <4% anisotropy, indicating that the crustal rocks are not heavily fractured (Crampin and Peacock, 2008)

Linking Shear Wave Splitting to Mantle Processes



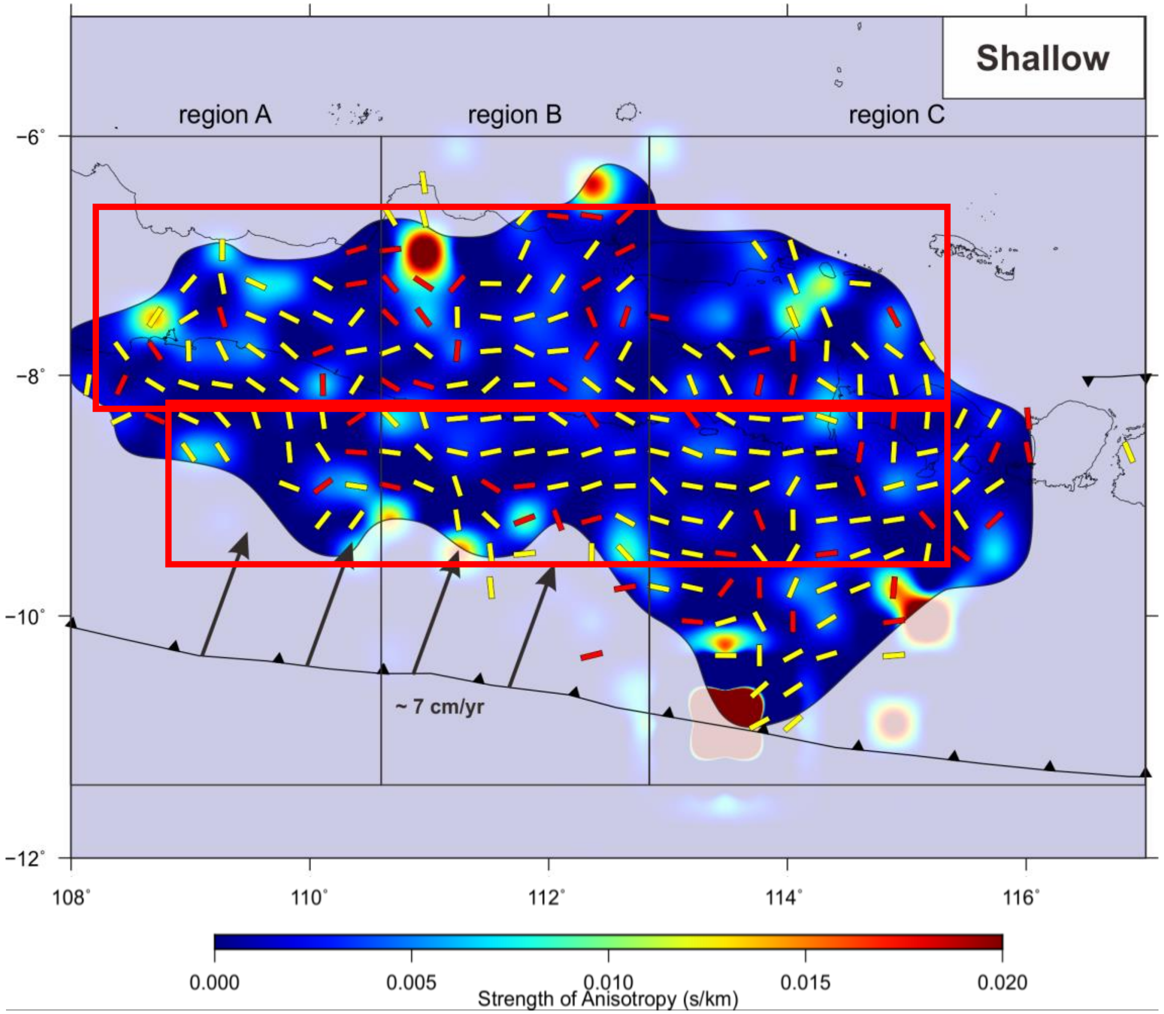
The sketch of the effect of B-type olivine fabric on the interpretation of shear wave splitting measurements in terms of mantle flow (Long, 2013)



Schematic diagram summarizing some of the mantle processes and the resulting anisotropy (Long and Silver, 2008)

Fast Shear Wave Pattern	Possible Causes	Subduction Area
Trench-Parallel (Forearc)	• As a result of slab rollback • B-type olivine developing in 2D corner flow (high water condition) • Magma filled cracks within mantle wedge • Cracks in the slab • Fossil Anisotropy	• Tonga, Caribbean, Central America • Ryukyu, Aleutian • Central Japan, Cascadia, South America • NE Japan, Sumatra-Java • NE Japan, Sumatra-Java
Trench-Perpendicular/Normal (Backarc)	• Mantle deformation due to plates interaction • Mantle flow aligned with plate motion • 2D corner flow in mantle wedge	• Tonga • Hikurangi (NZ) • NE Japan, Kamchatka

Possible Cause of Uppermantle Anisotropy



Spatial averages of splitting parameters at < 100 km depth.

Trench-perpendicular anisotropy:

- the presence of 2-D corner flow in the mantle wedge induced by the downdip motion of subducting slab that allows A-type olivine fabric to develop and align with the plate motion or perpendicular to the trench.

Trench-parallel anisotropy:

- the presence of a serpentinized mantle wedge. It promotes the change in olivine fabric geometry under several factors, such as water saturation, stress, temperature, and the presence of melt, producing B-type olivine fabric.

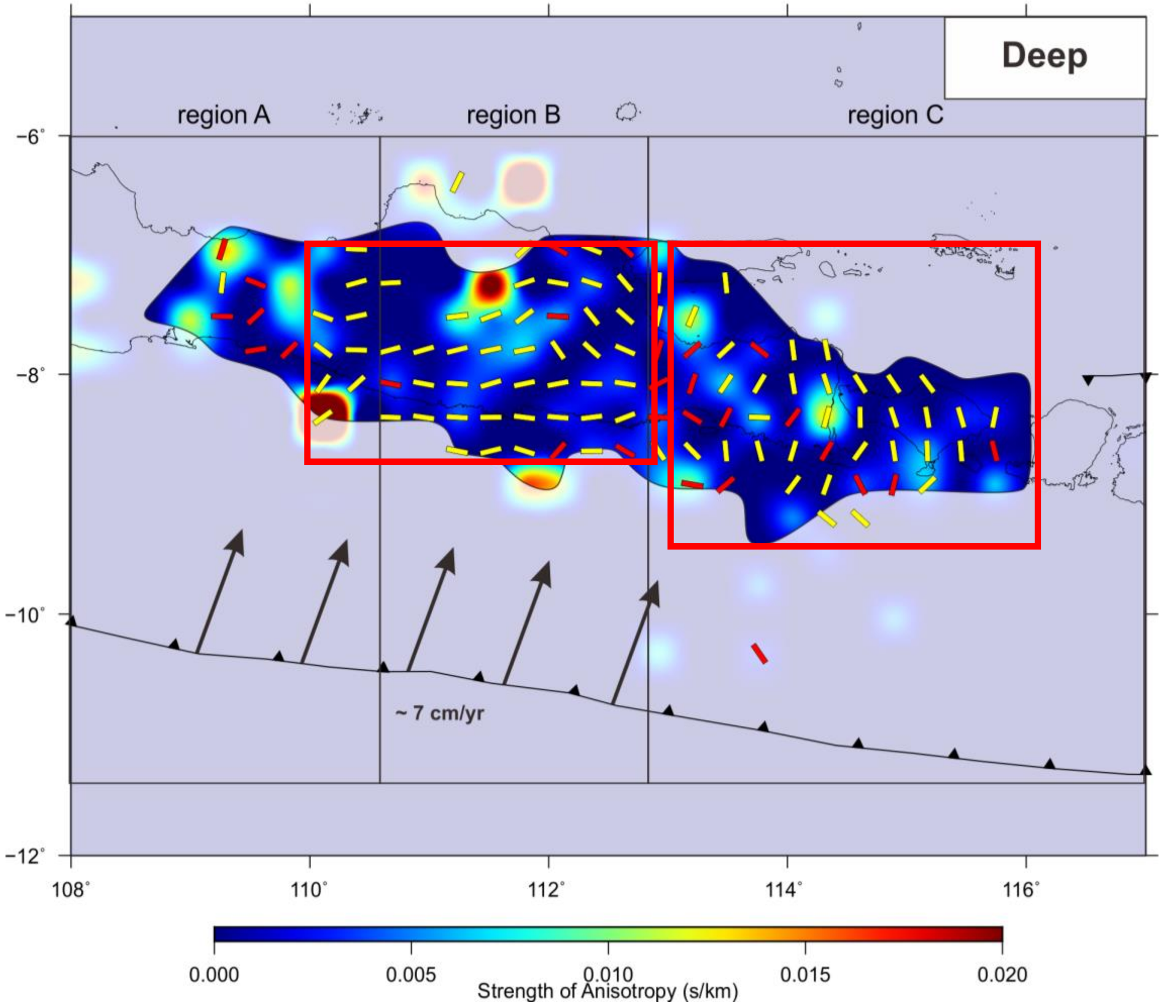
Discussion (Uppermantle Anisotropy)

Trench-parallel anisotropy:

- the presence of 3D corner flow in the mantle wedge, especially if the slab hole exist between Java-Sumatra subduction.
- Fossil anisotropy. The Australian plate was moving eastward in 74-119 Ma, while the oceanic slab subducting underneath Java Island originated in 80-140 Ma, causing orientations of east-west anisotropy at >100 km depth.

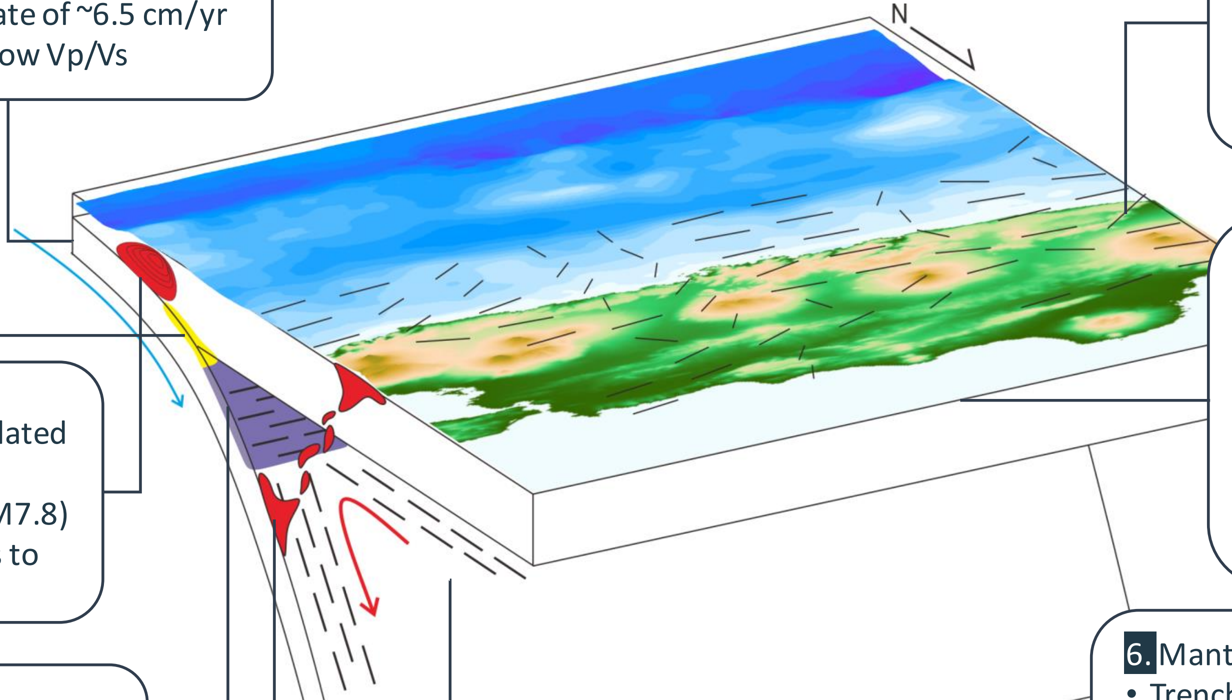
Trench-perpendicular anisotropy:

- the presence of 2-D mantle flow induced anisotropy



Spatial averages of splitting parameters at > 100 km depth.

Structure and Dynamics beneath Central-East Java Region



1. Oceanic slab
- Convergence rate of ~6.5 cm/yr
- High-velocity, low Vp/Vs

2. Seismogenic zone
- Clustered seismicity, includes the 2021 Malang EQ (M6.1)

3. Subducted seamount
- Low-velocity at 50 km depth, uplift, and isolated gravity anomaly
- Responsible for the 1994 Banyuwangi EQ (M7.8)
- Combination of stress and structural effects to the anisotropy with SPO mechanism

4. Serpentinized mantle
- Develops B-type olivine fabric orientated perpendicular to the direction of mantle flow (trench-parallel anisotropy)

5. Partial melting
- Low-velocity at 100 km depth
- joint effects between heat convection in the mantle wedge and fluids from slab dehydration
- the ascending fluids and melts migrate upward to feed the volcanoes above

6. Mantle wedge
- Trench-perpendicular anisotropy in the north suggesting corner flow in the mantle wedge with LPO mechanism
- Or, SPO of the partial melting that affect the olivine fabric orientation.

7. Continental crust
- North: > 1microstrain/yr ; South: < 1 microstrain/yr
- Crustal anisotropy of Java is caused by cracks and micro-cracks or stress-induced in the upper 10-15 km crust, which results in the aligned fast direction with maximum stress
- Low percentage of anisotropy (< 4%)

8. Opak fault
- Responsible for the 2006 Yogyakarta EQ (M6.3)
- Contrast velocity
- An exceptional large strain rate
- Fault parallel anisotropy

fmuttaqy - 2023

Thank you.

Faiz Muttaqy

fmuttaqy

BRIN
BADAN RISET
DAN INOVASI NASIONAL