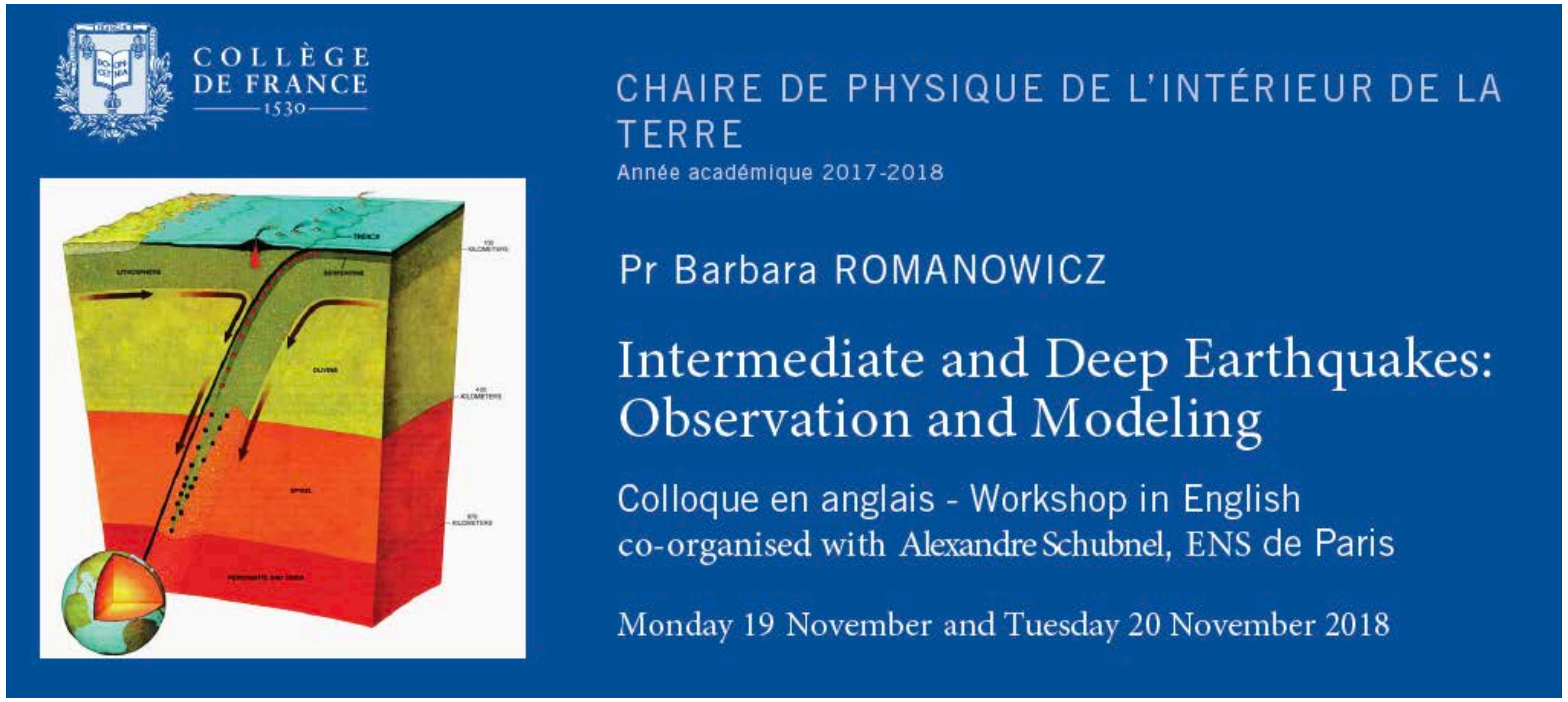
Intermediate and Deep Earthquakes: Observation and Modeling

Deep earthquakes in subducting slabs hosted in highly anisotropic rock fabric

Yingcai Zheng

Nov 20, 2018

with Jiaxuan Li, Leon Thomsen, Thomas Lapen, Xinding Fang



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Problem

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(e.g., Houston 2007TOG; Knopoff and Randall 1970; Kuge and Kawakatsu 1990, 1992,1993; Kuge and Lay 1994a,b; Frohlich 1994,1995; Julian et al., 1998; Richardson and Jordan, 2002BSSA; Vavrycuk 2004,2006; Okal et al., 2018; Romanowicz,2018; Li et al., 2018)

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Shear Slip + **Isotropic** Medium =

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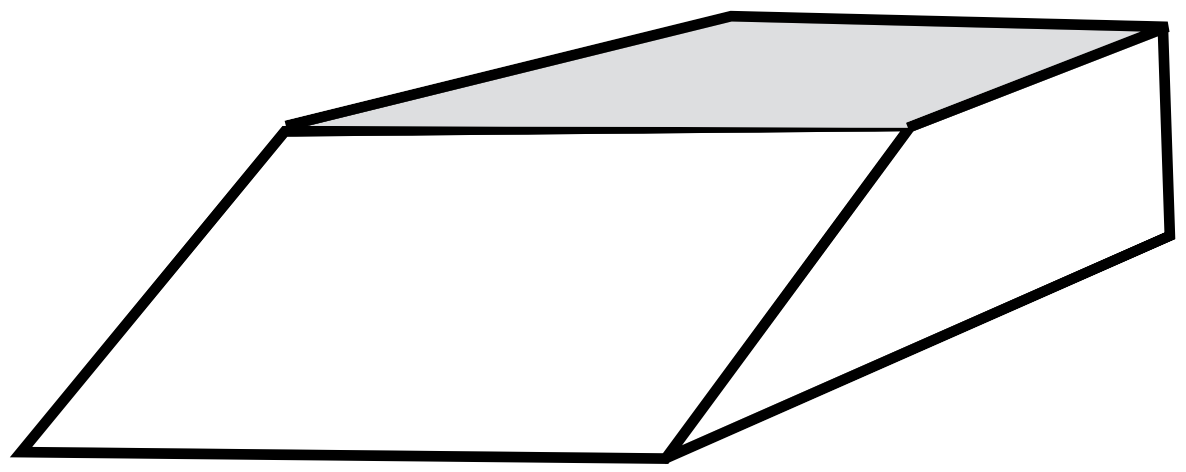

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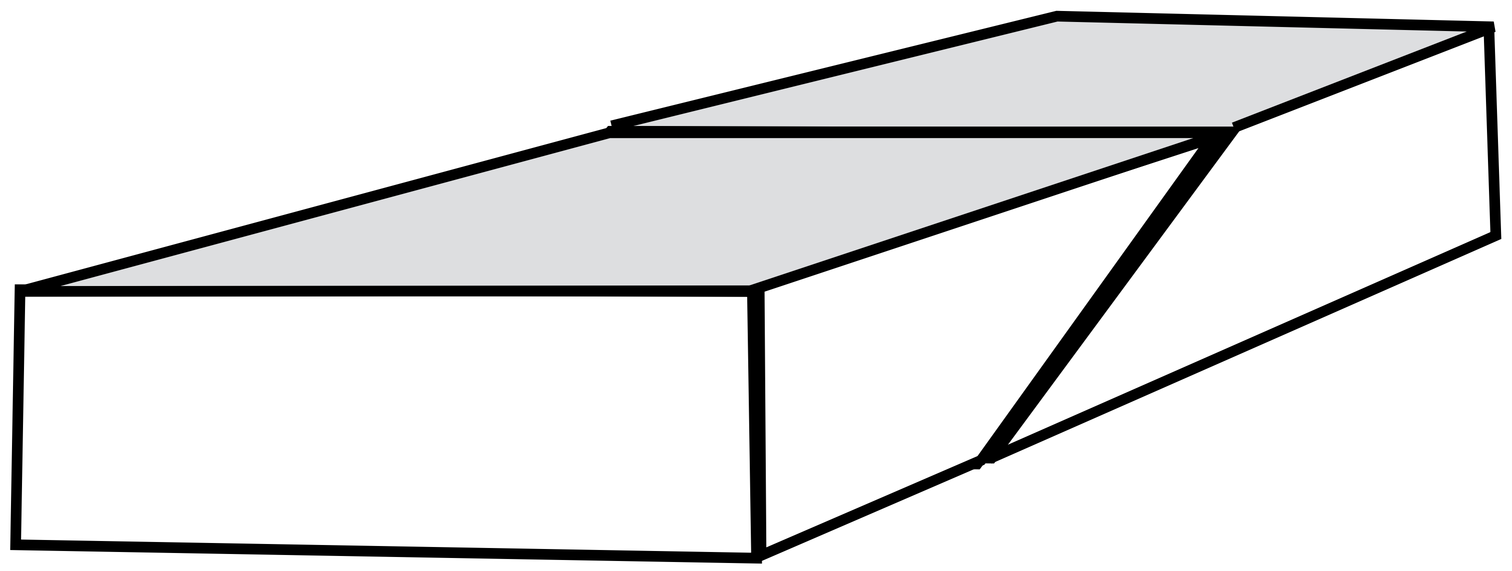

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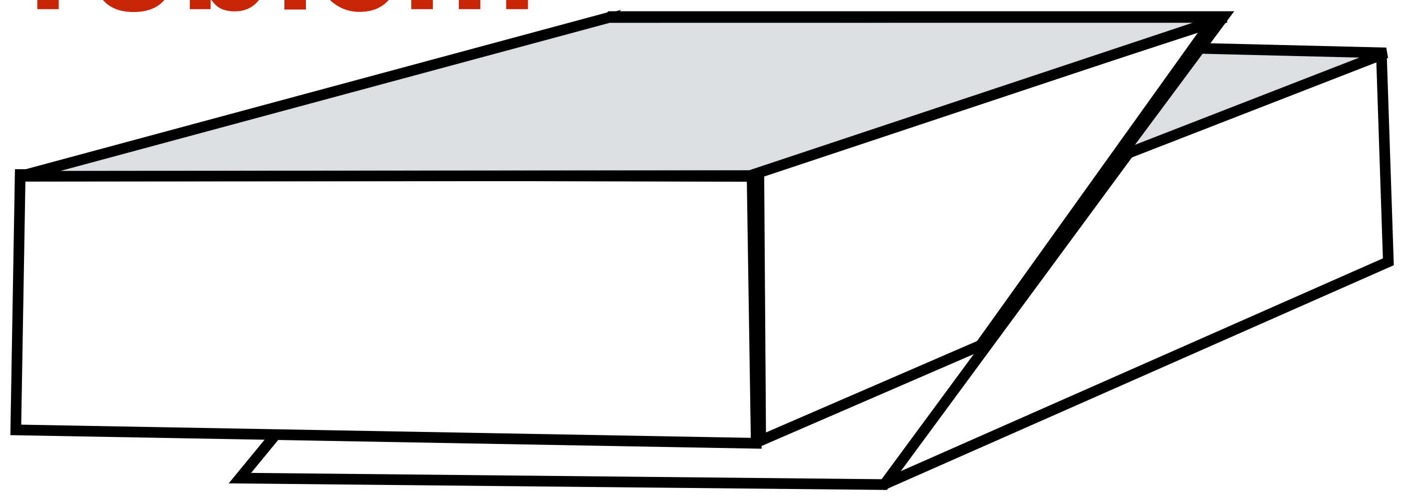

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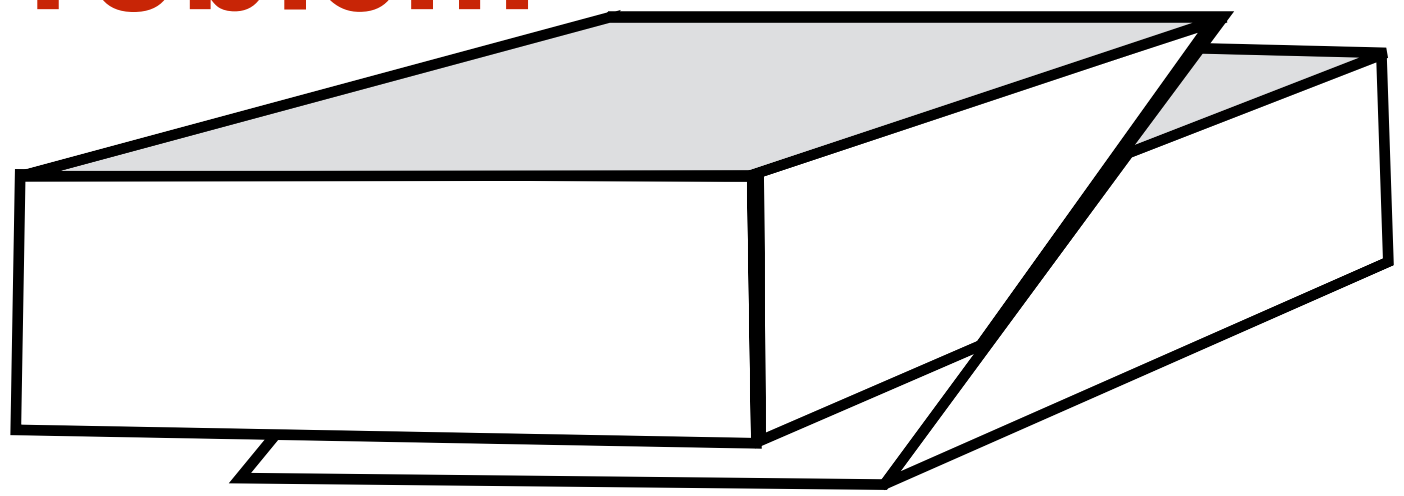

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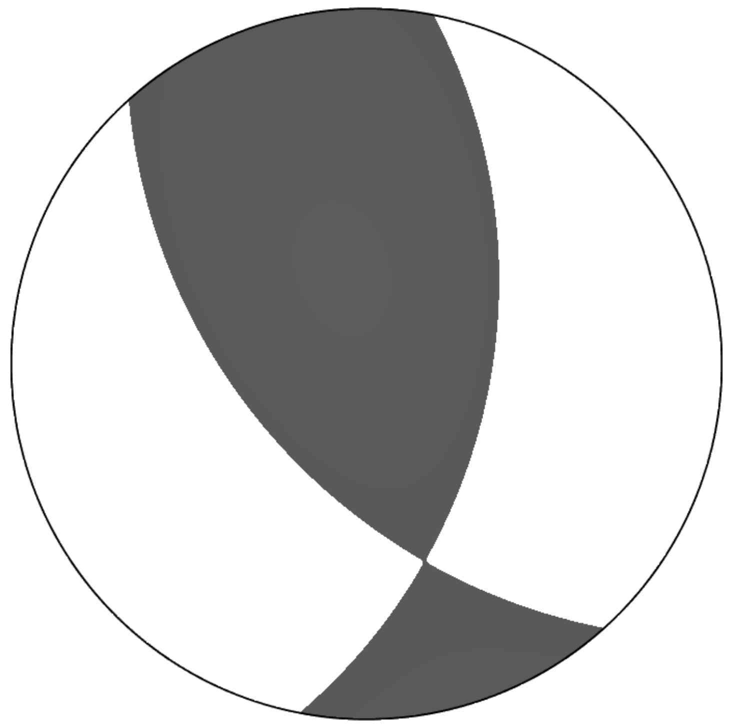

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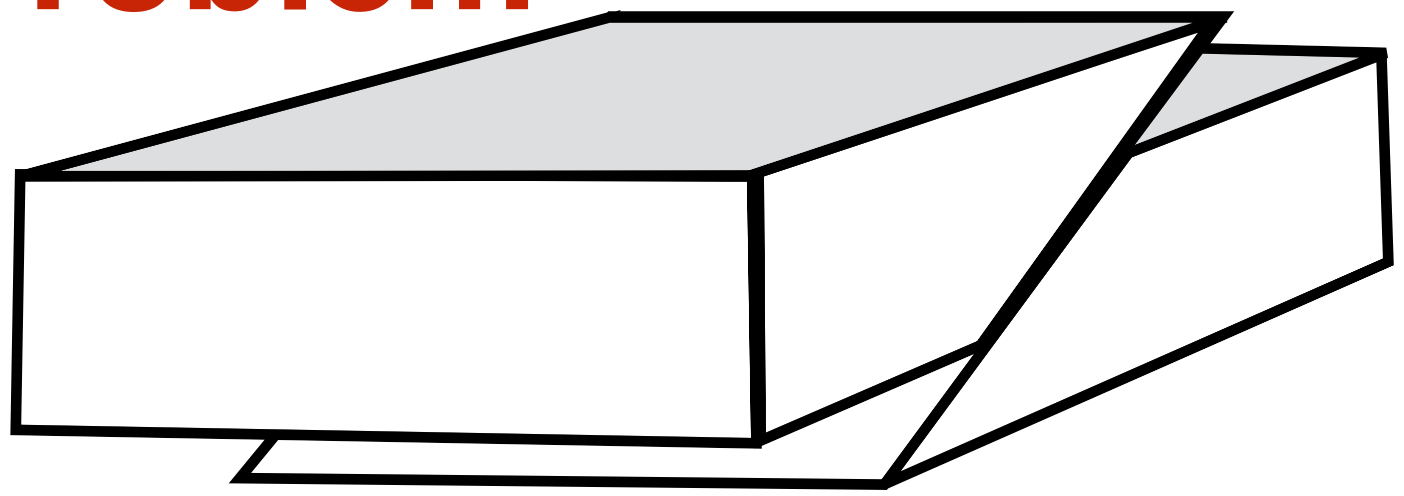

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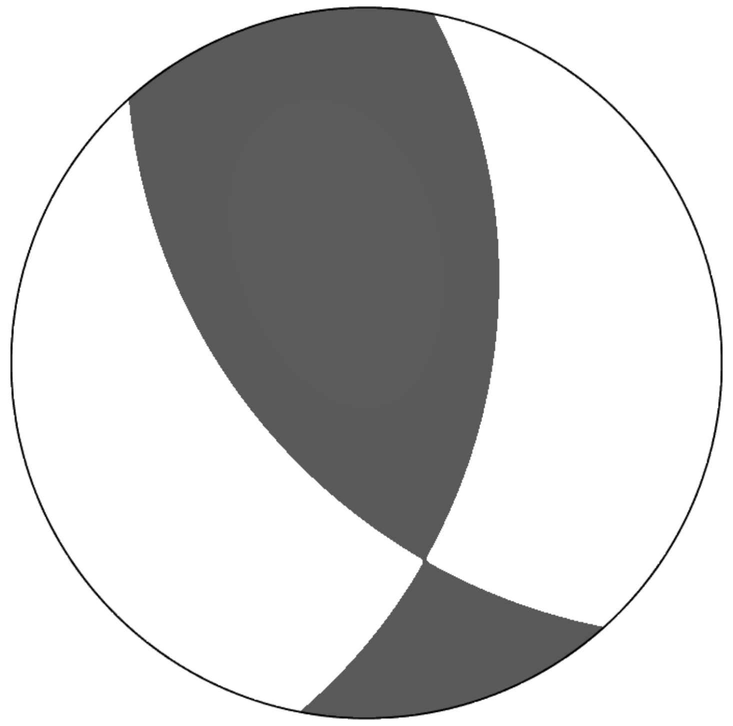

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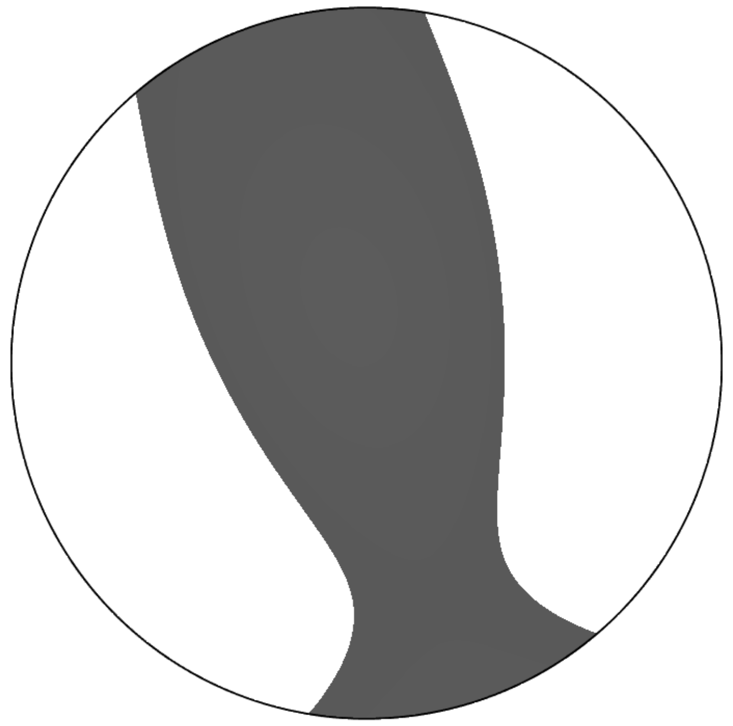

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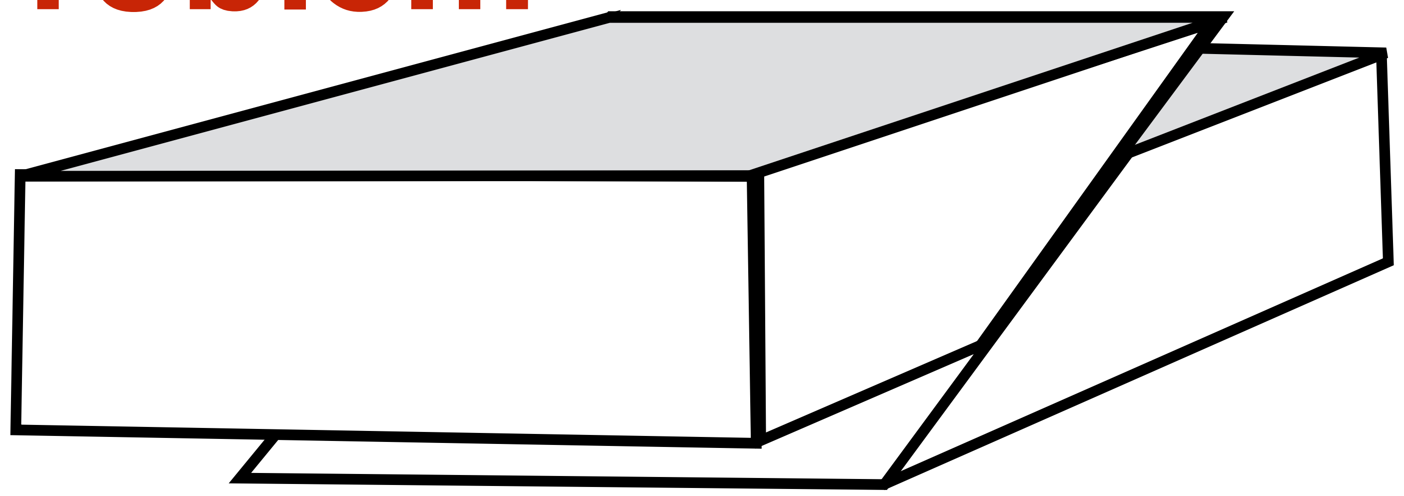

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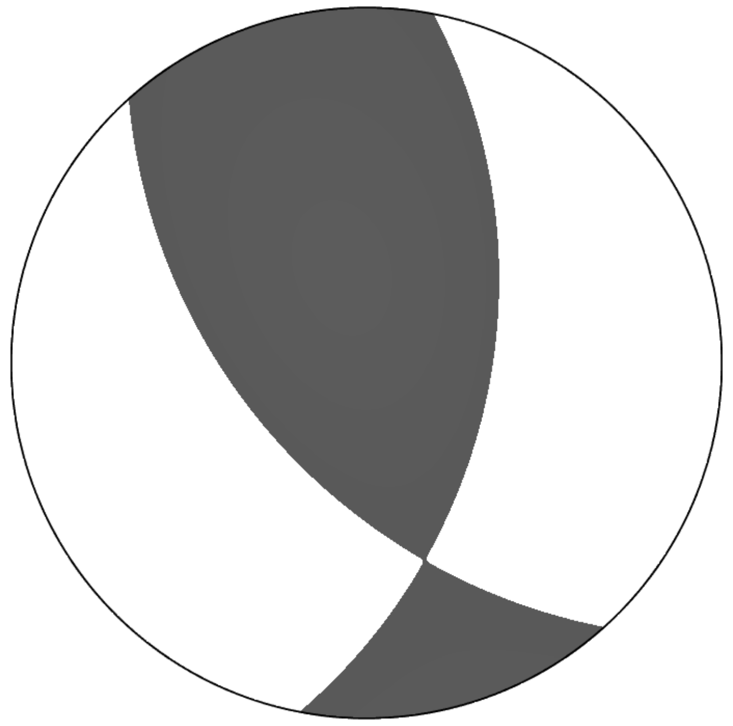

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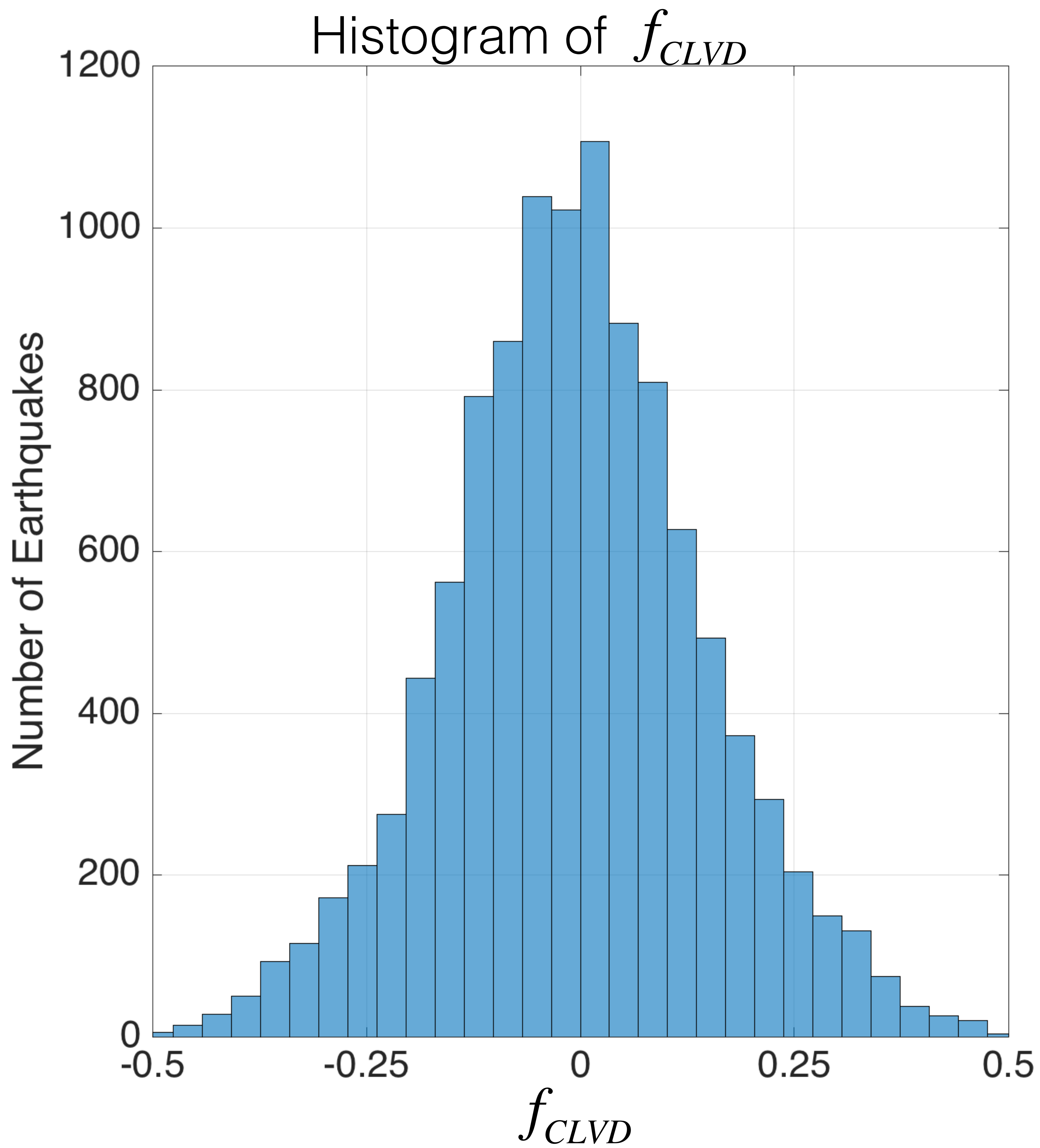

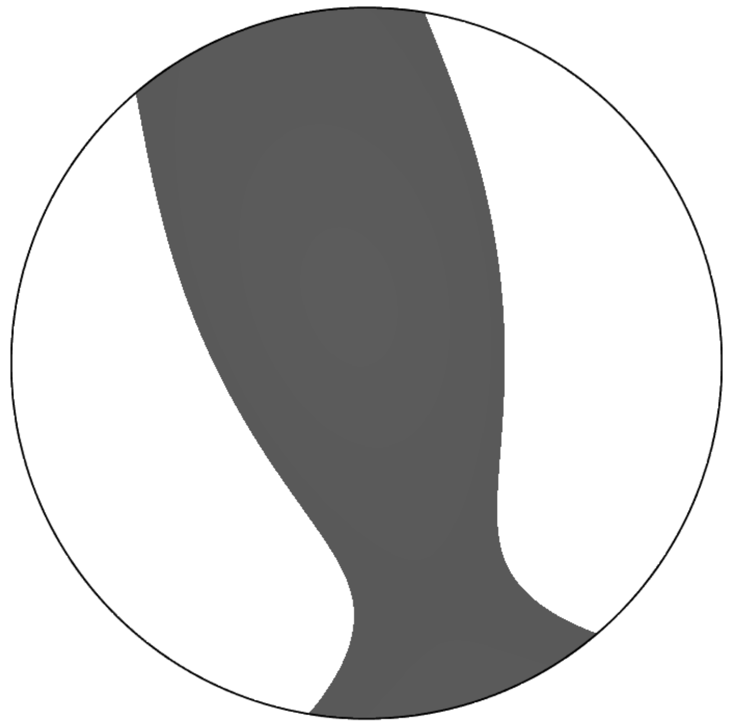

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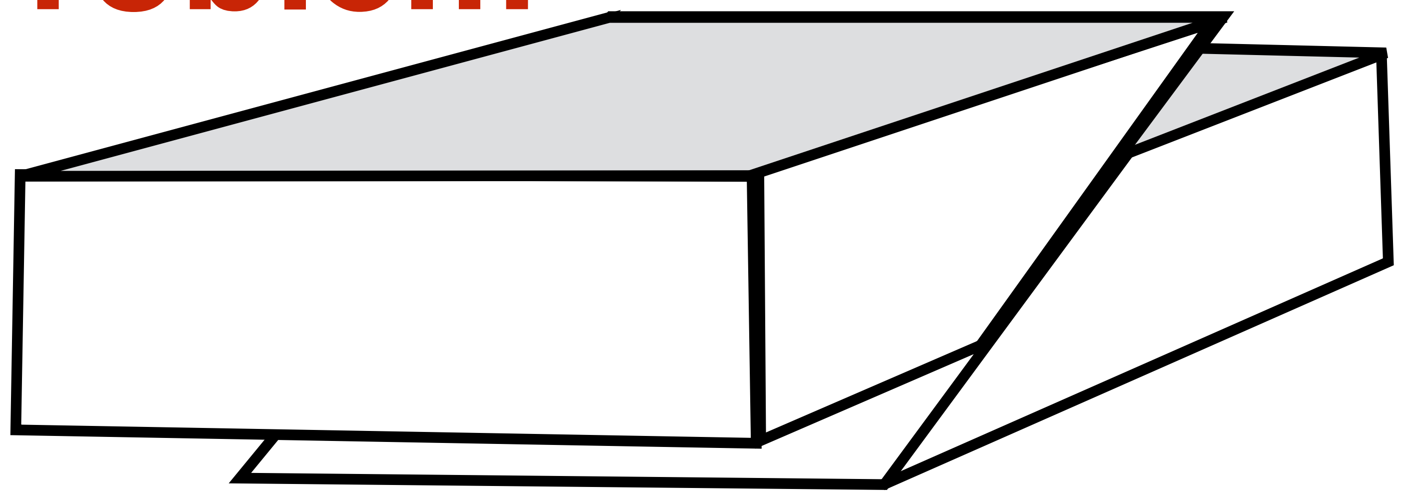

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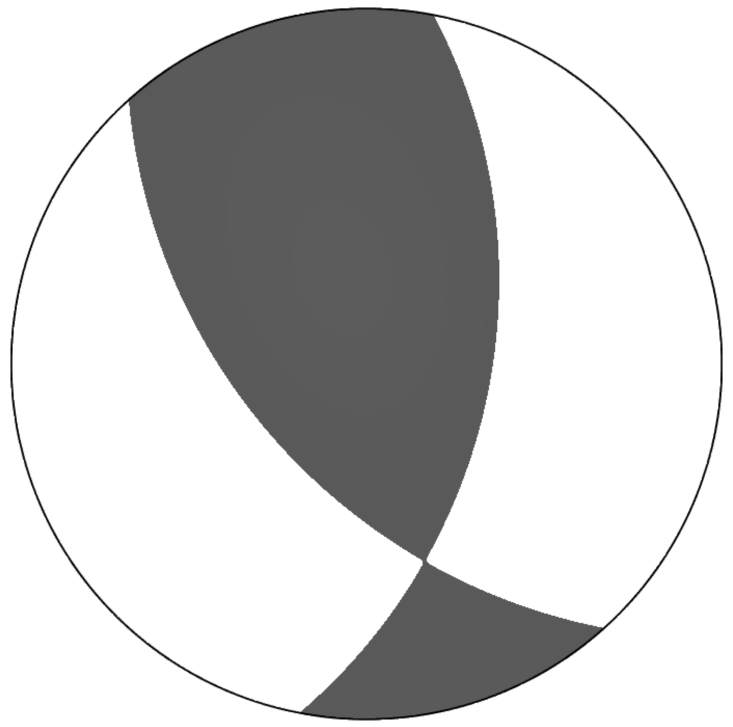

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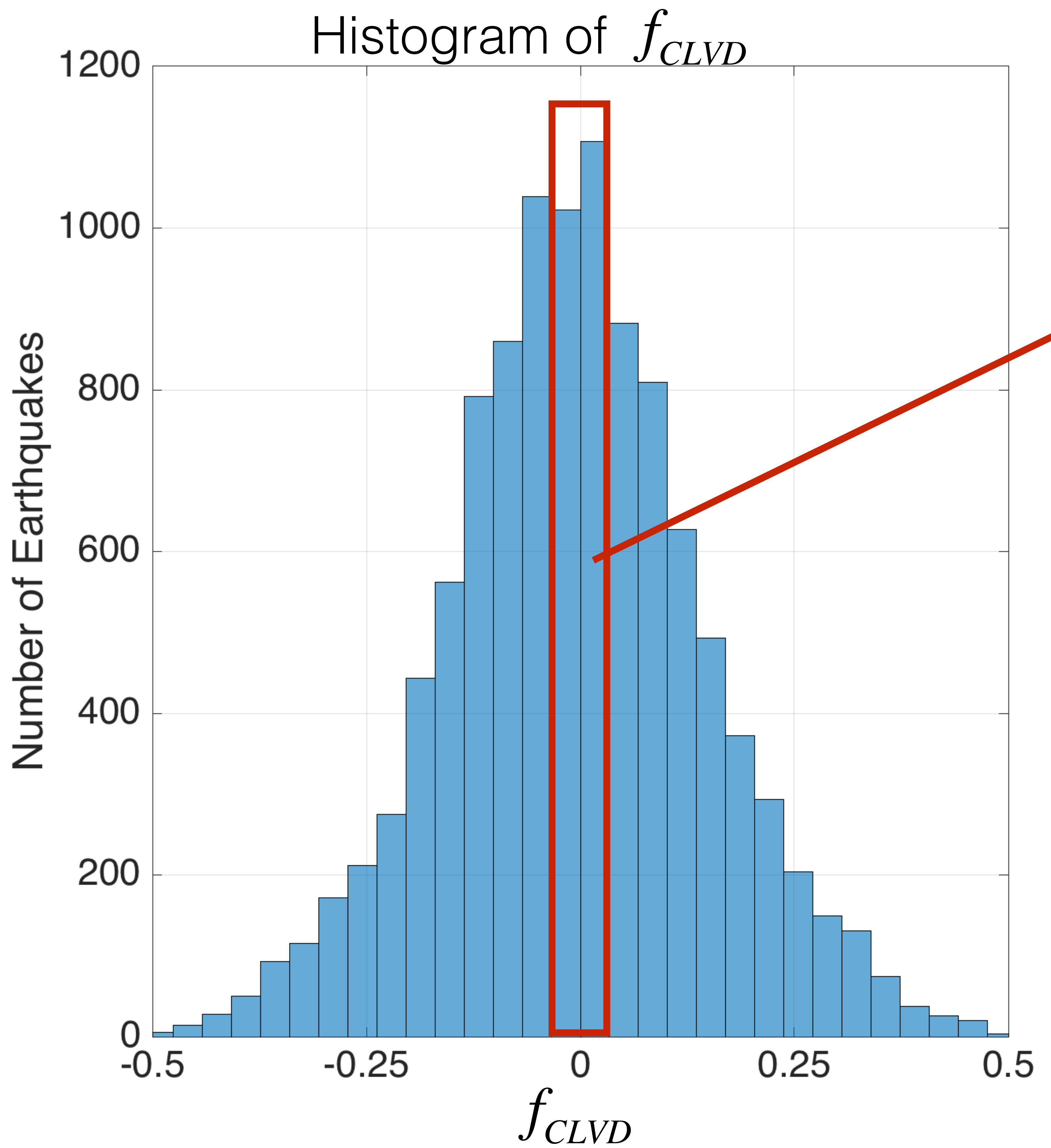

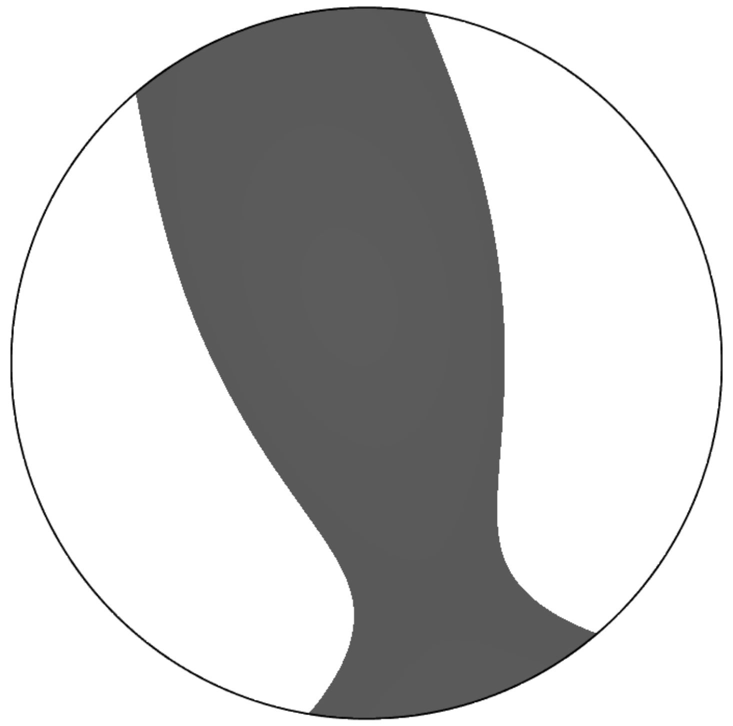

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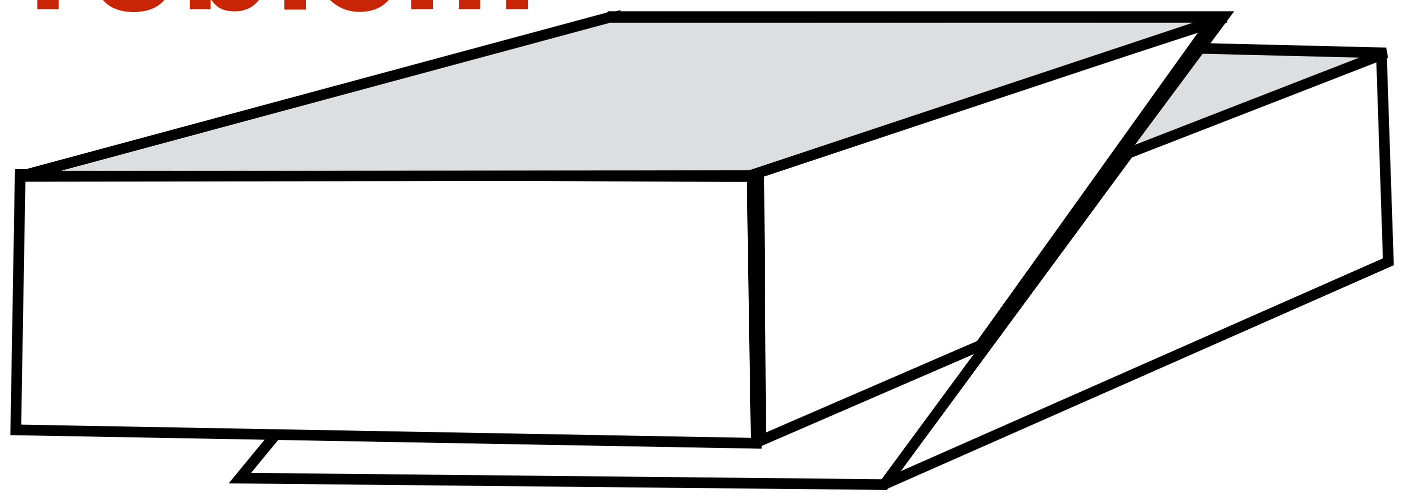

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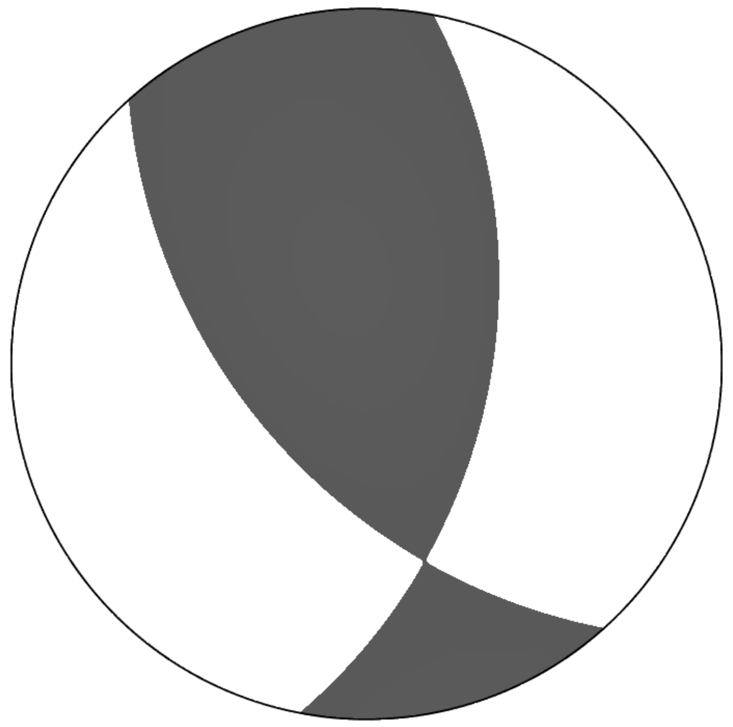

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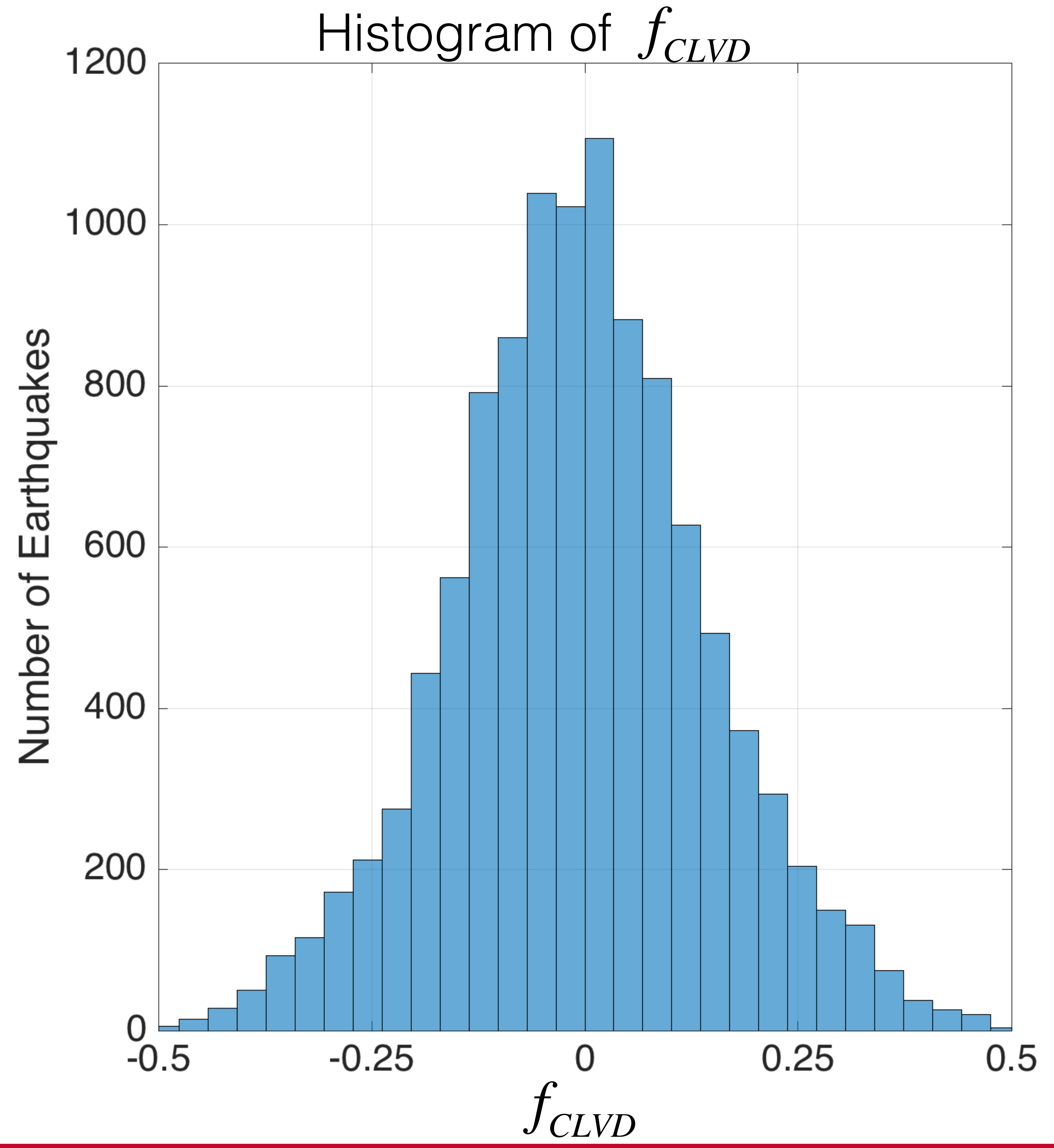

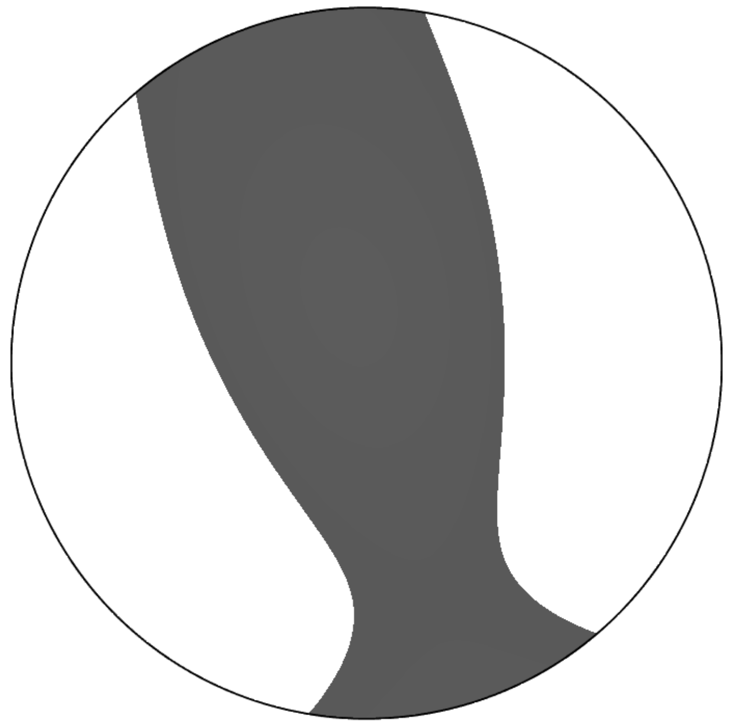

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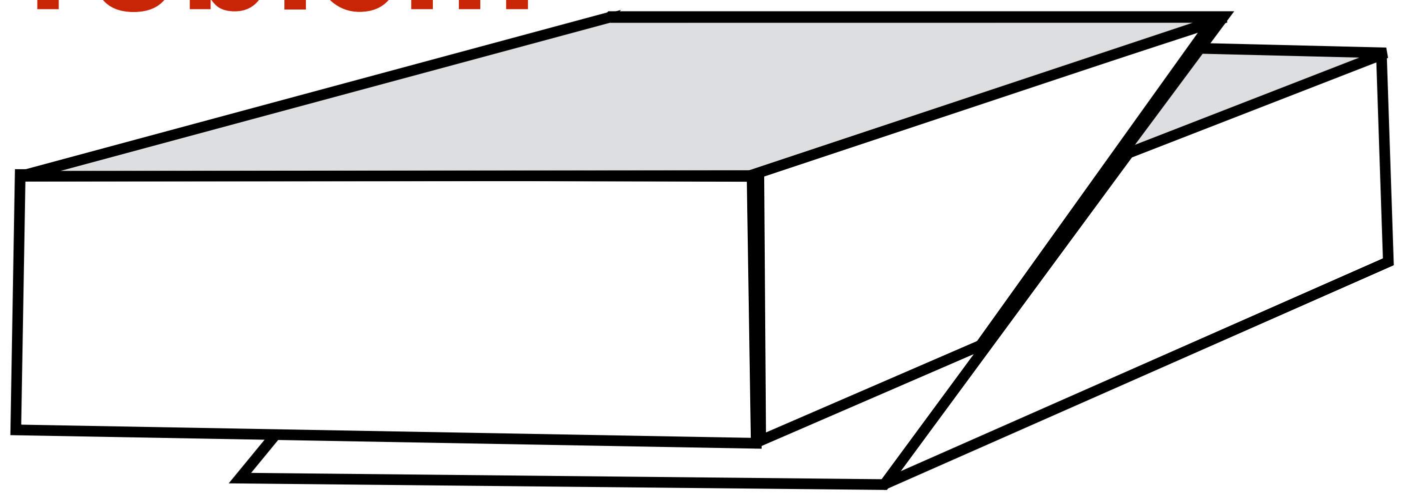

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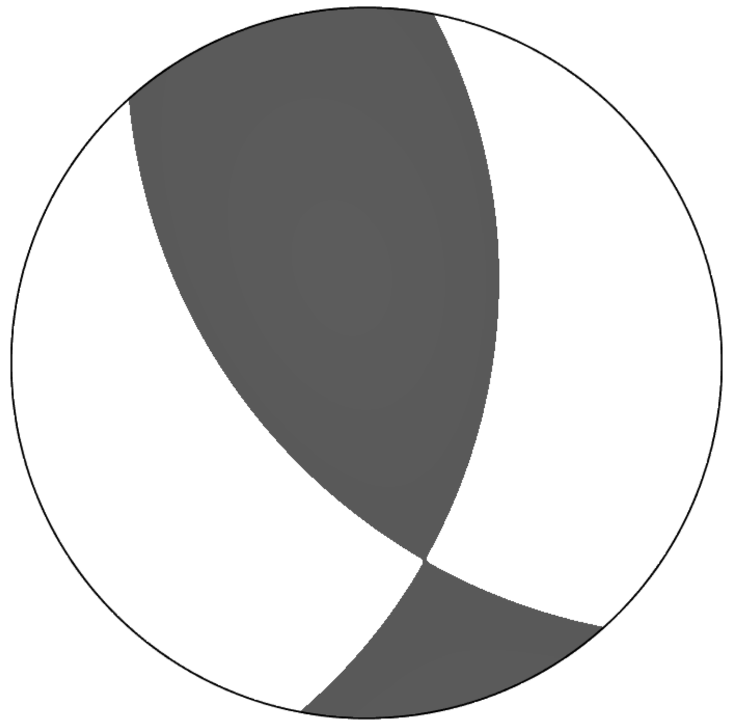

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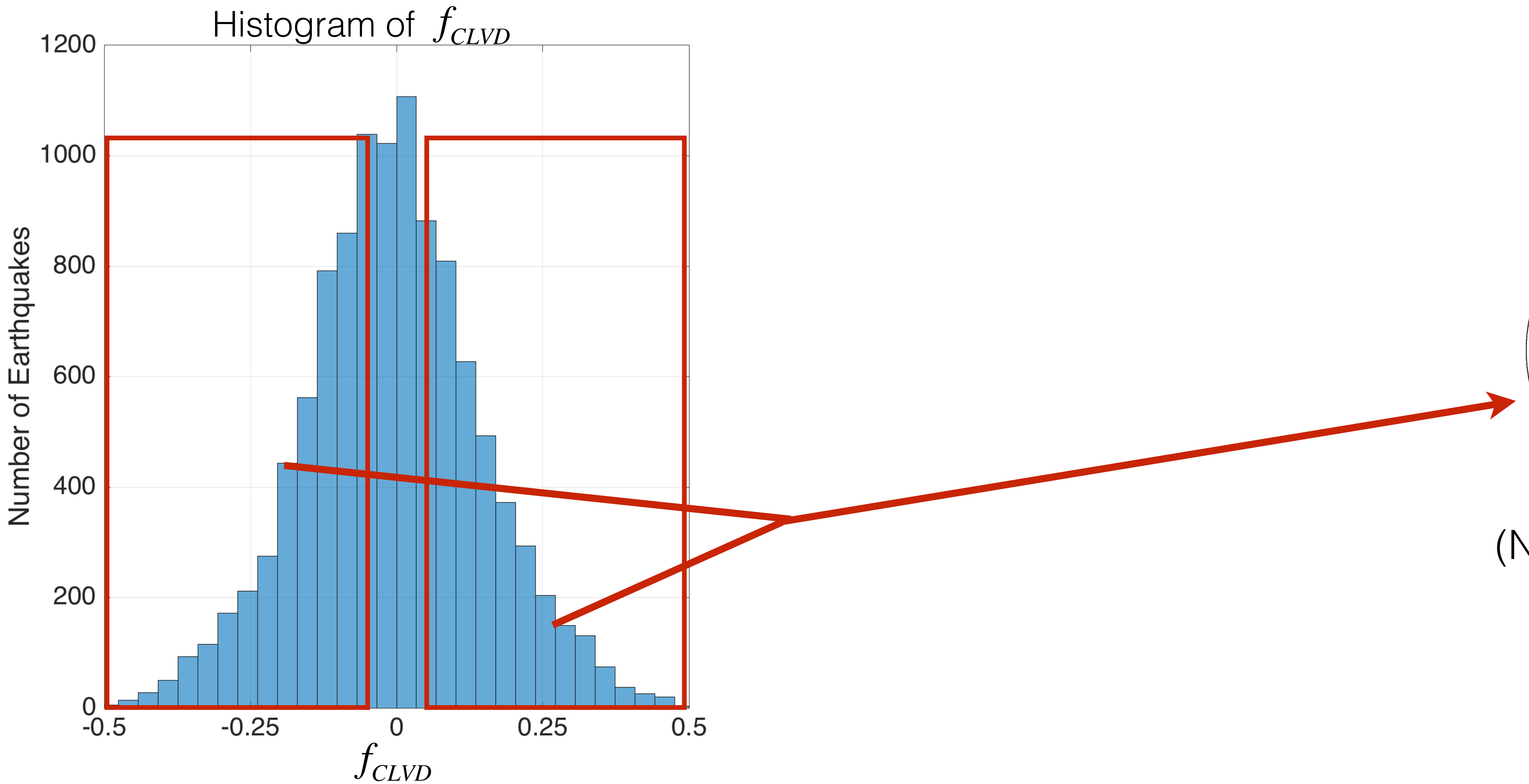

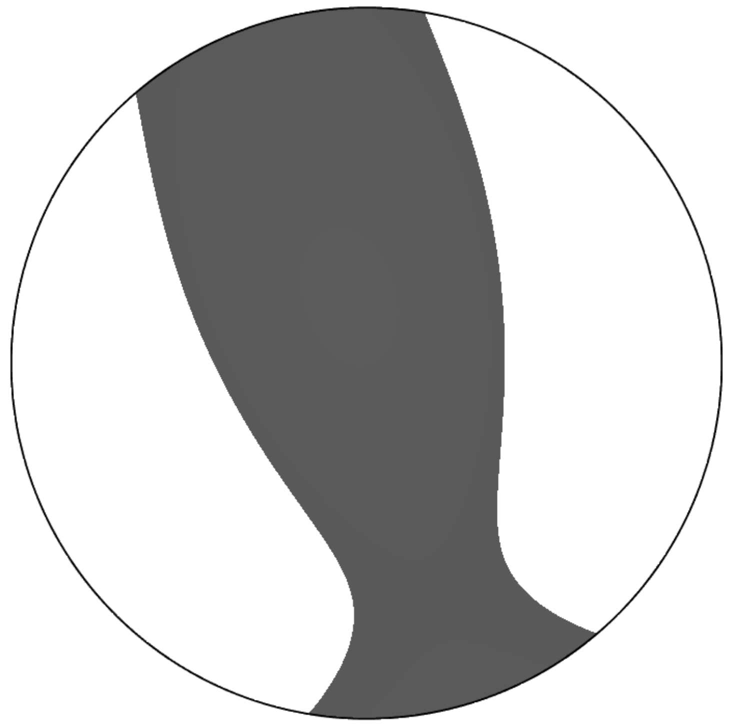

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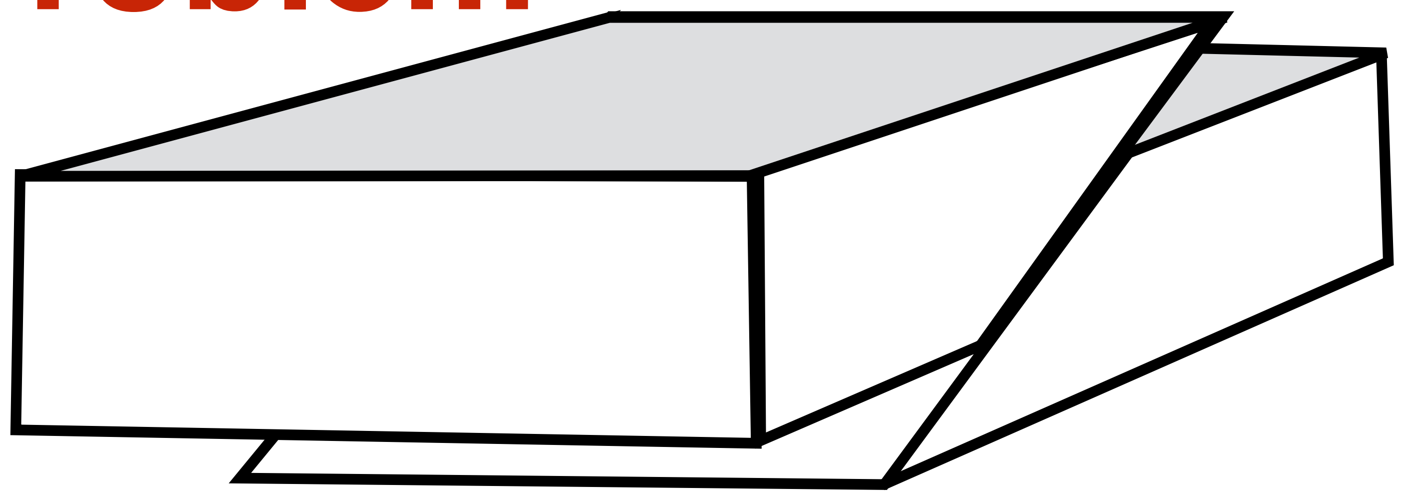

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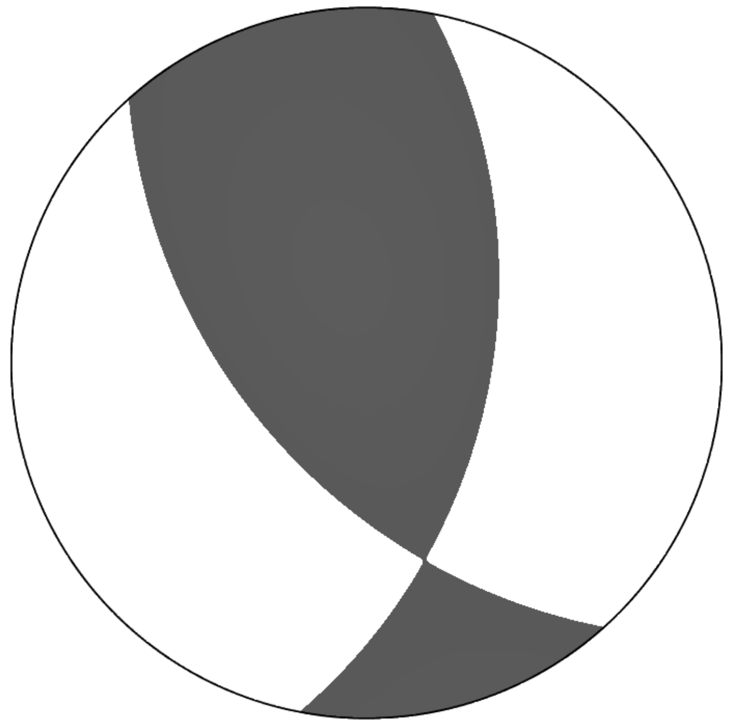

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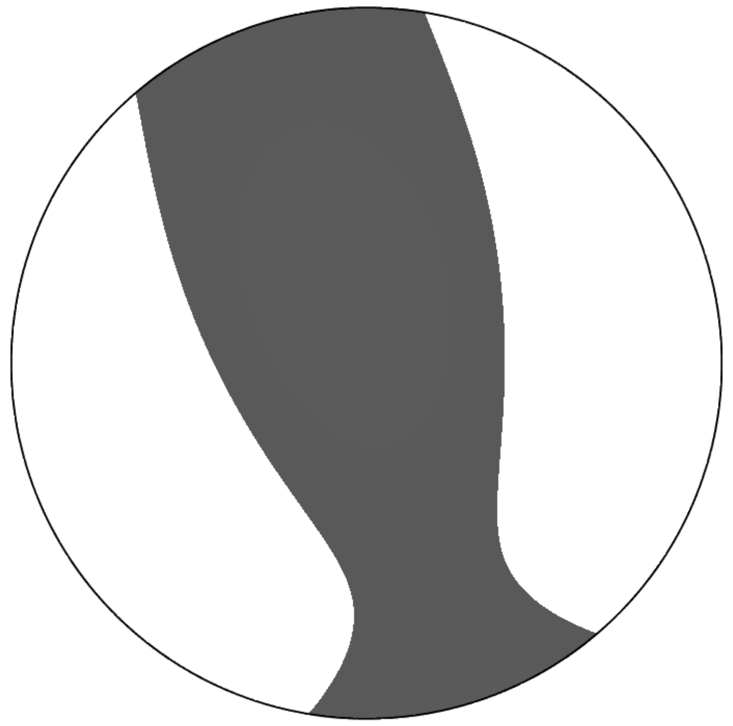

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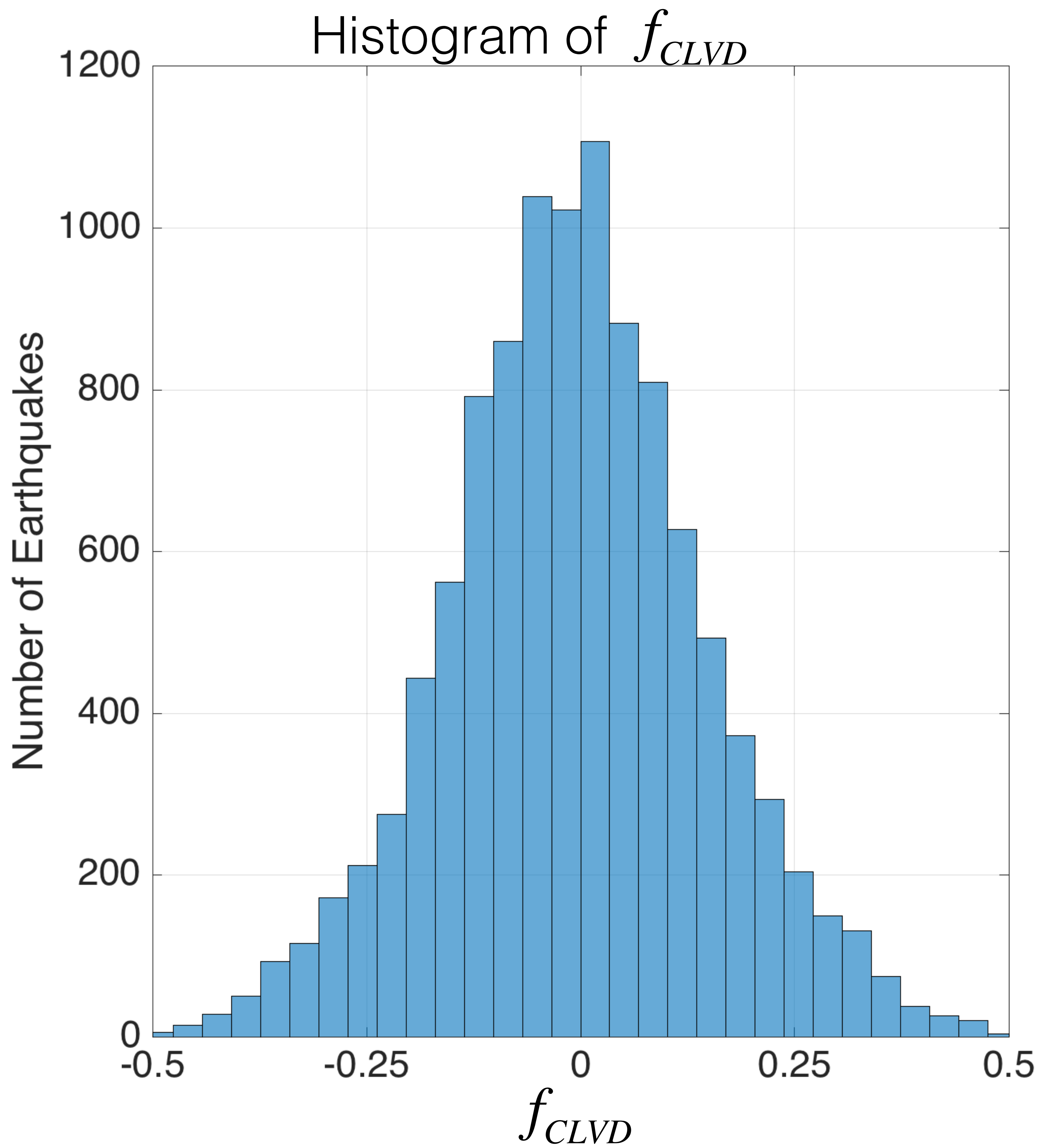

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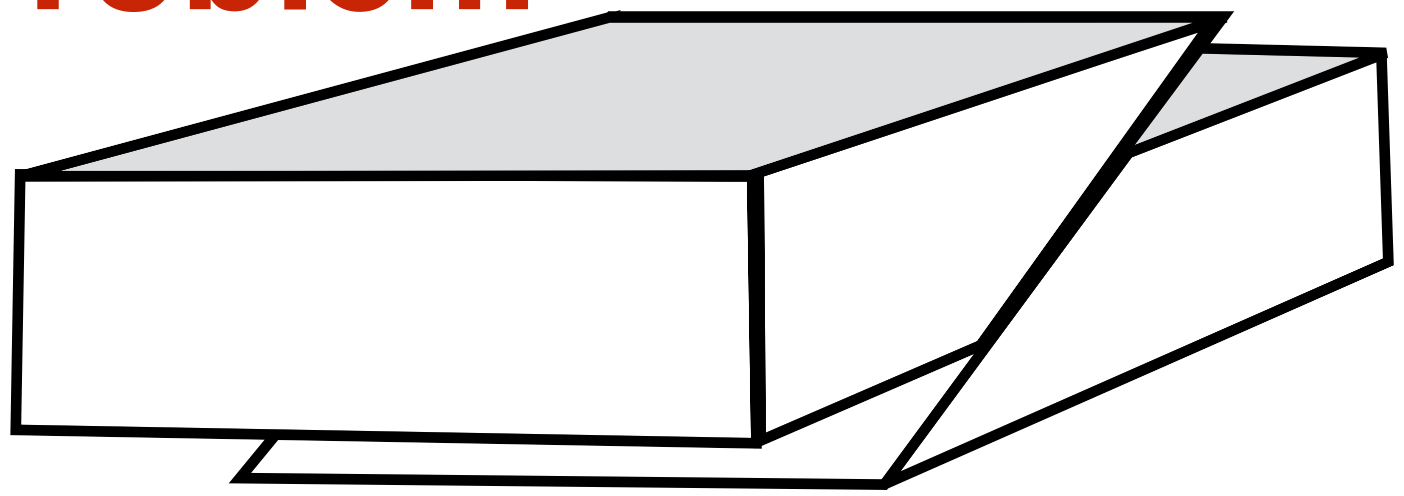

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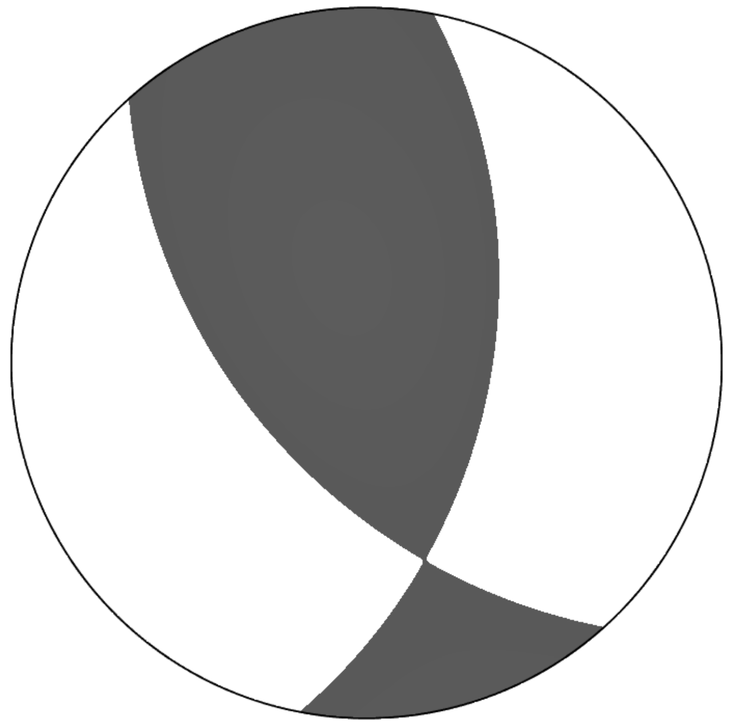

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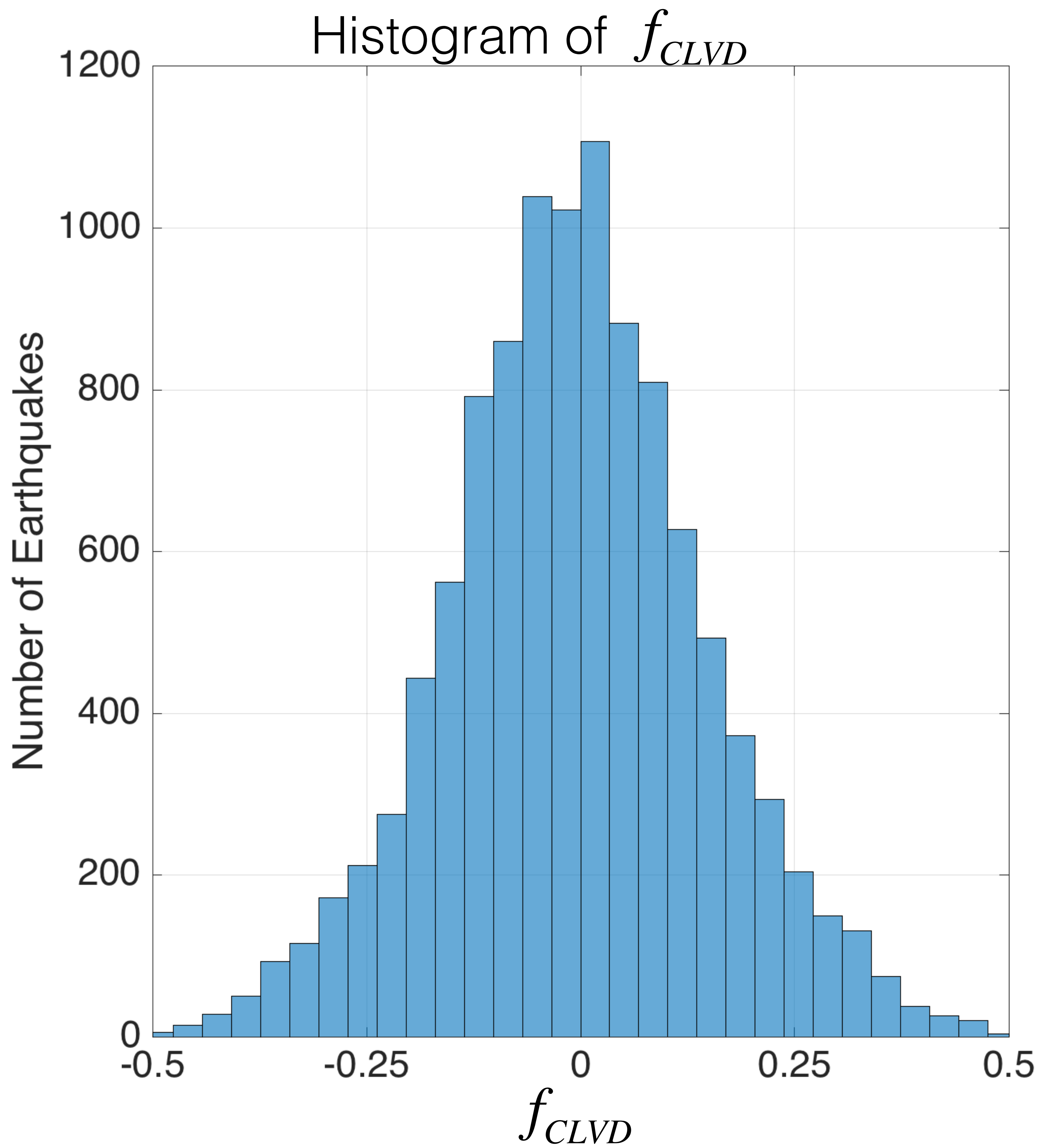

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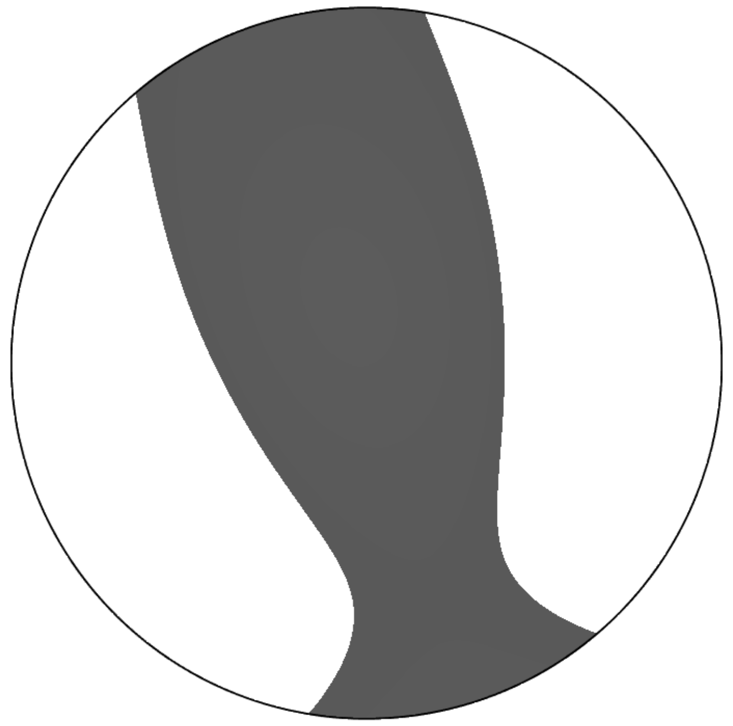

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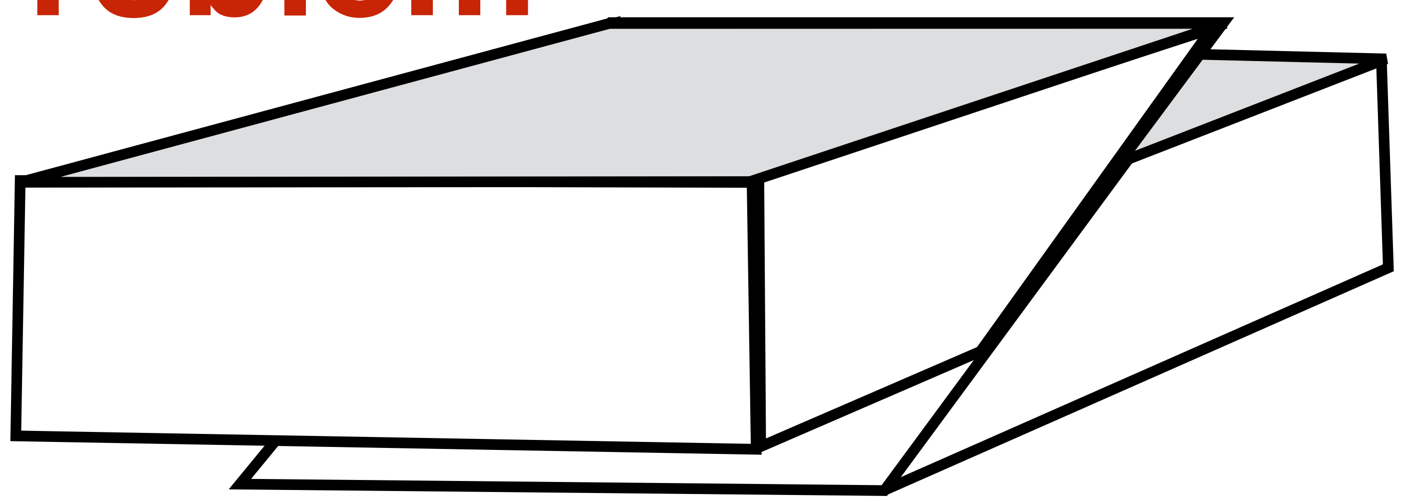

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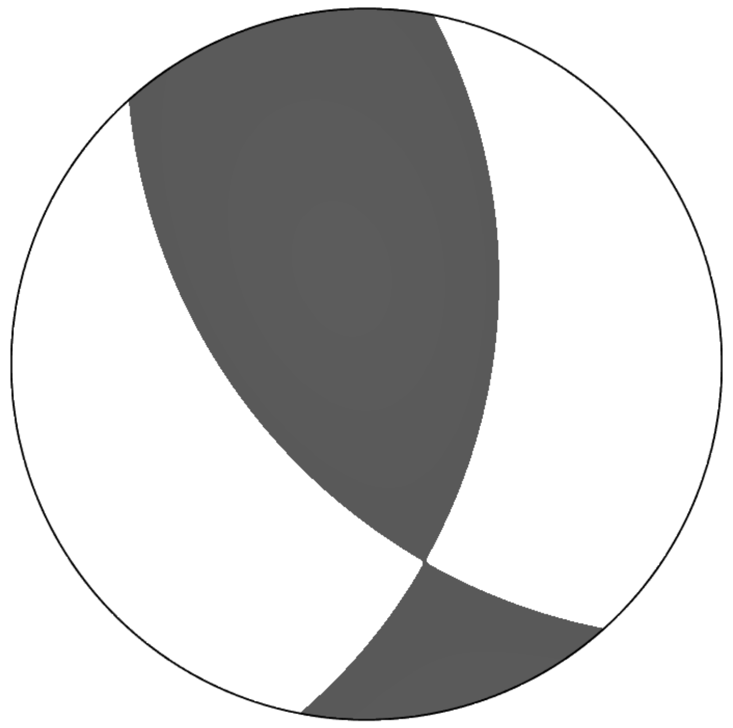

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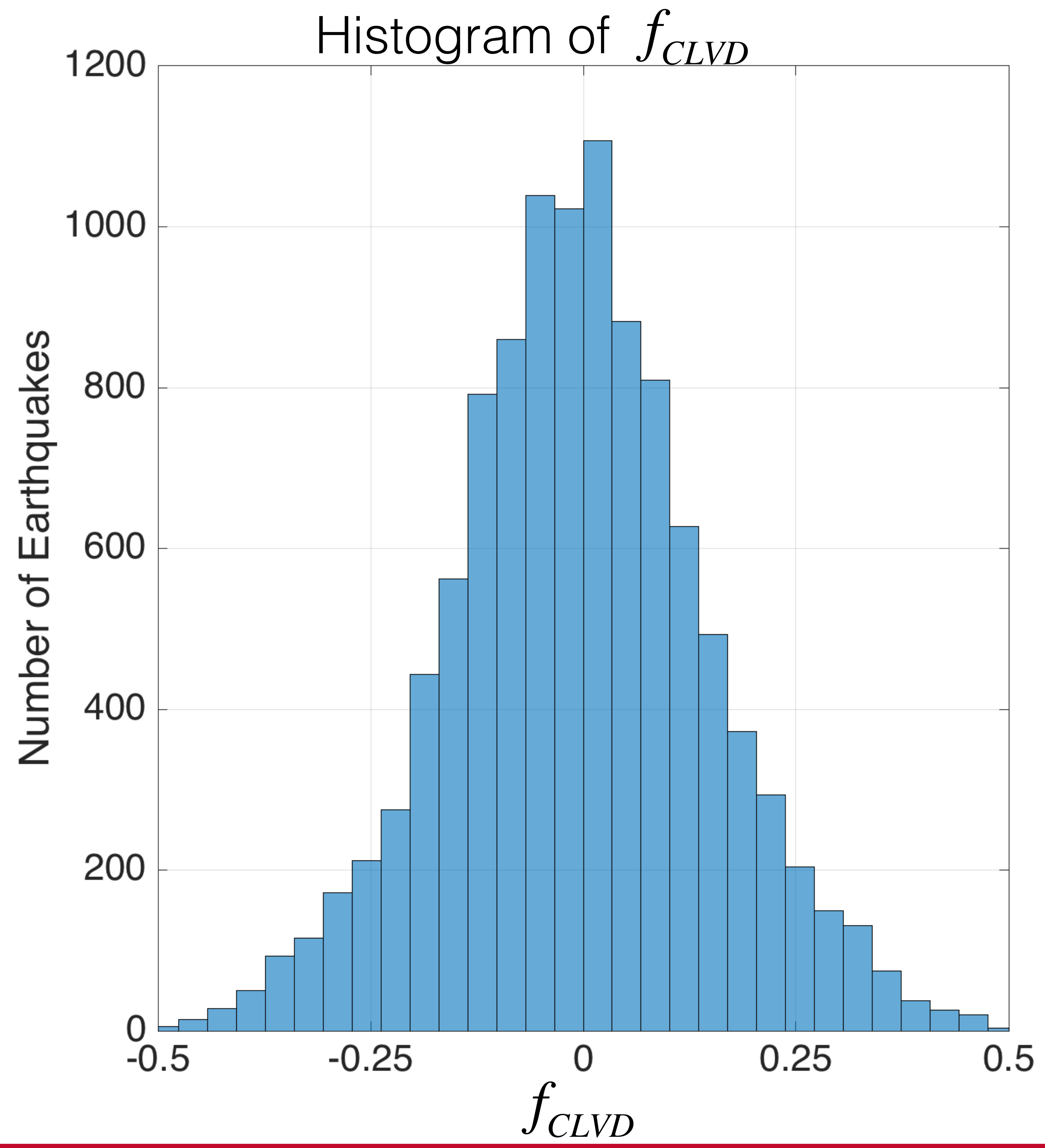

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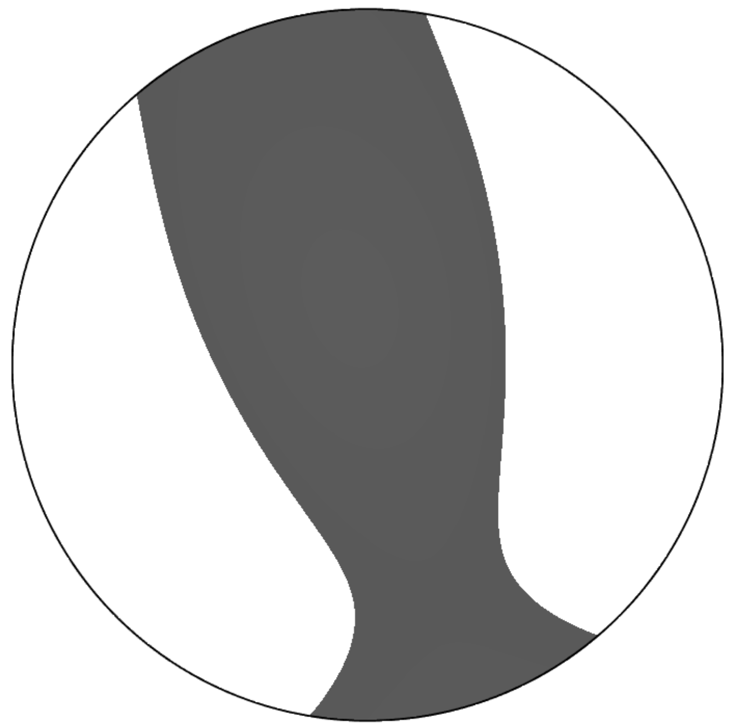

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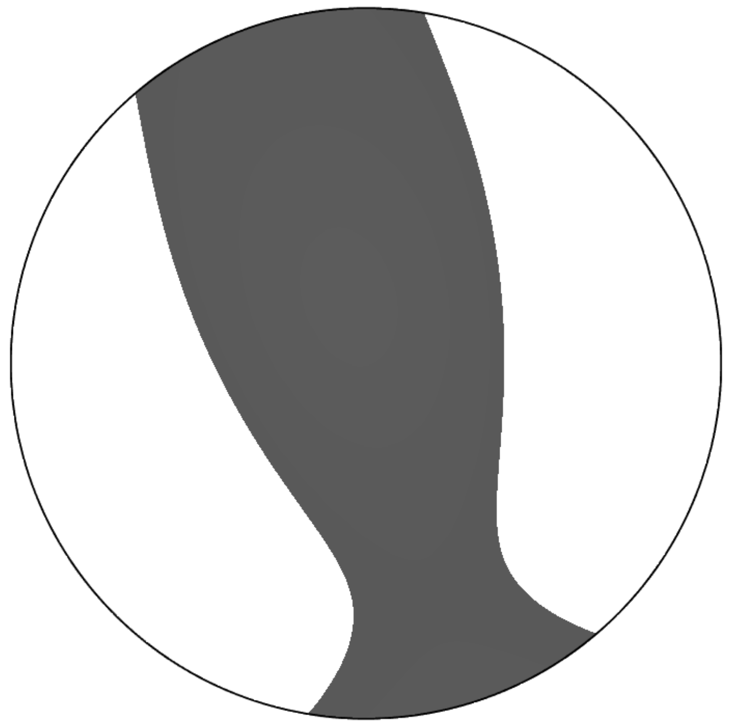
(Knopoff and Randall 1970; Kuge and Kawakatsu 1993; Kuge and Lay 1994; Frohlich 1994 Science; Julian et al., 1998; Vavrycuk 2004,2006; Li et al., 2018)

Proposed explanations

- sources are different such as implosion (e.g., Okal et al. 2018)?
- multi-faulting - rupture on nonplanar fault (e.g., Kuge et al. 1990,1992,1993,1994a,b)
- 3D path effect
- slab structure effect, high-velocity core, slow MOW
- station coverage effect
- anisotropy outside of the slab
- anisotropy around the EQs in the slab (e.g., Vavrycuk 2004,2006; Li et al., 2018natgeo)

Hypothesis: non-DC radiation patterns = DCs + a common medium anisotropy?



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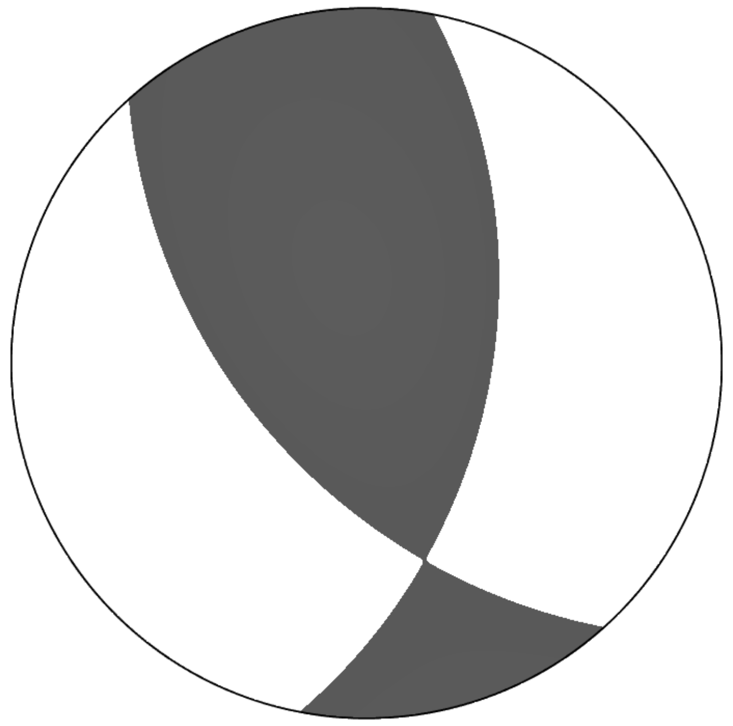

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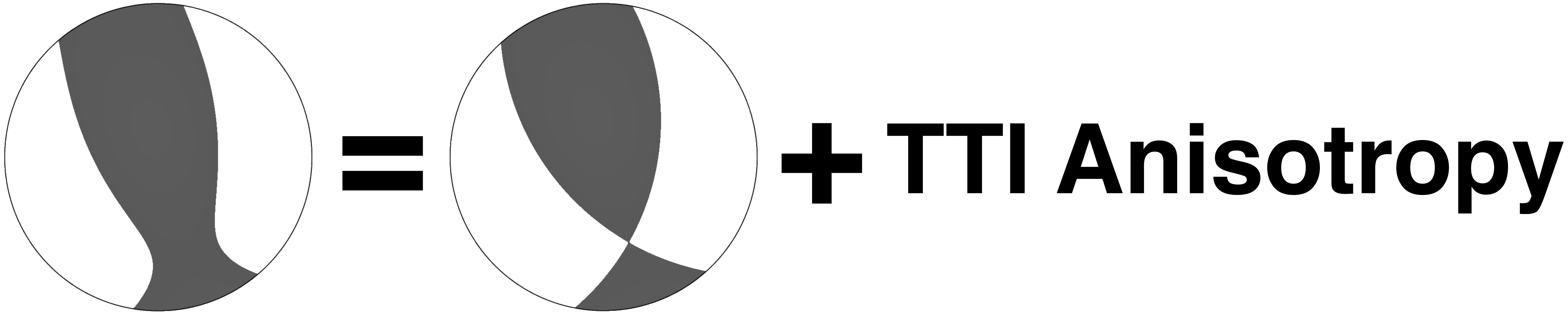

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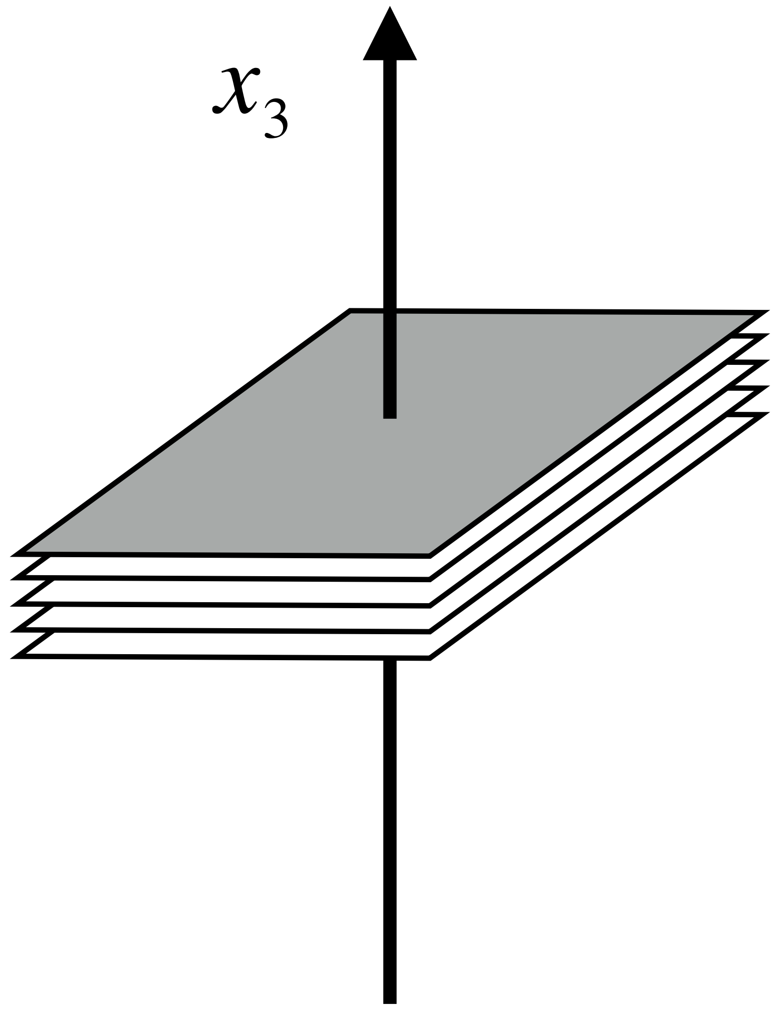

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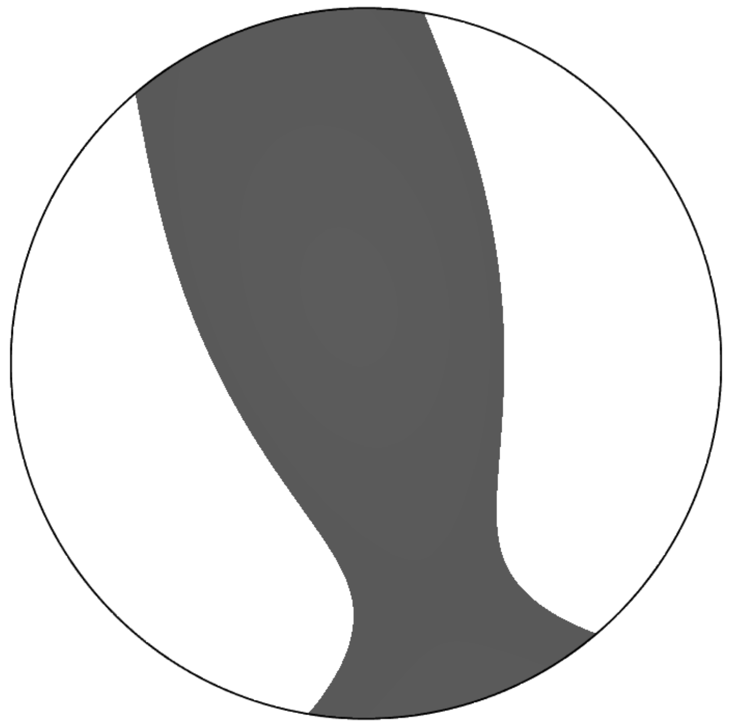

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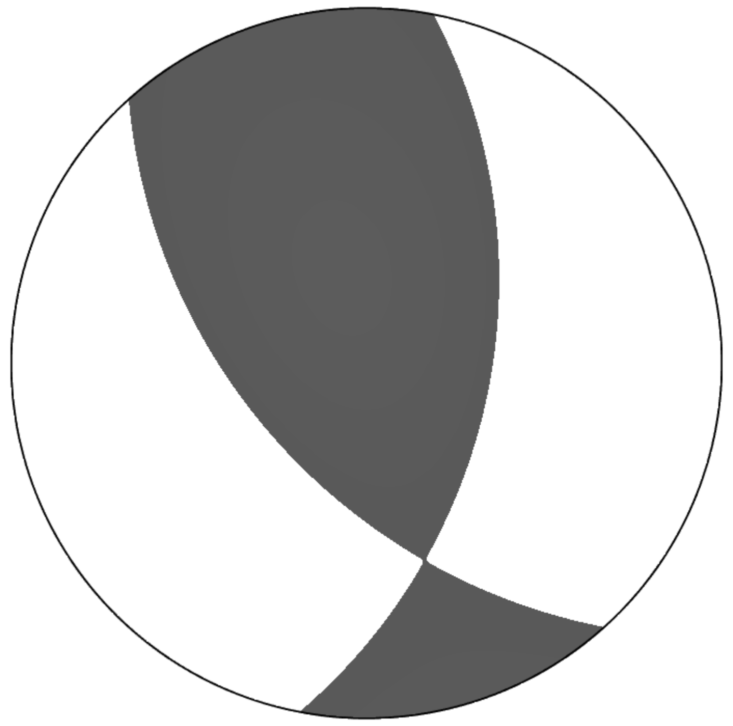

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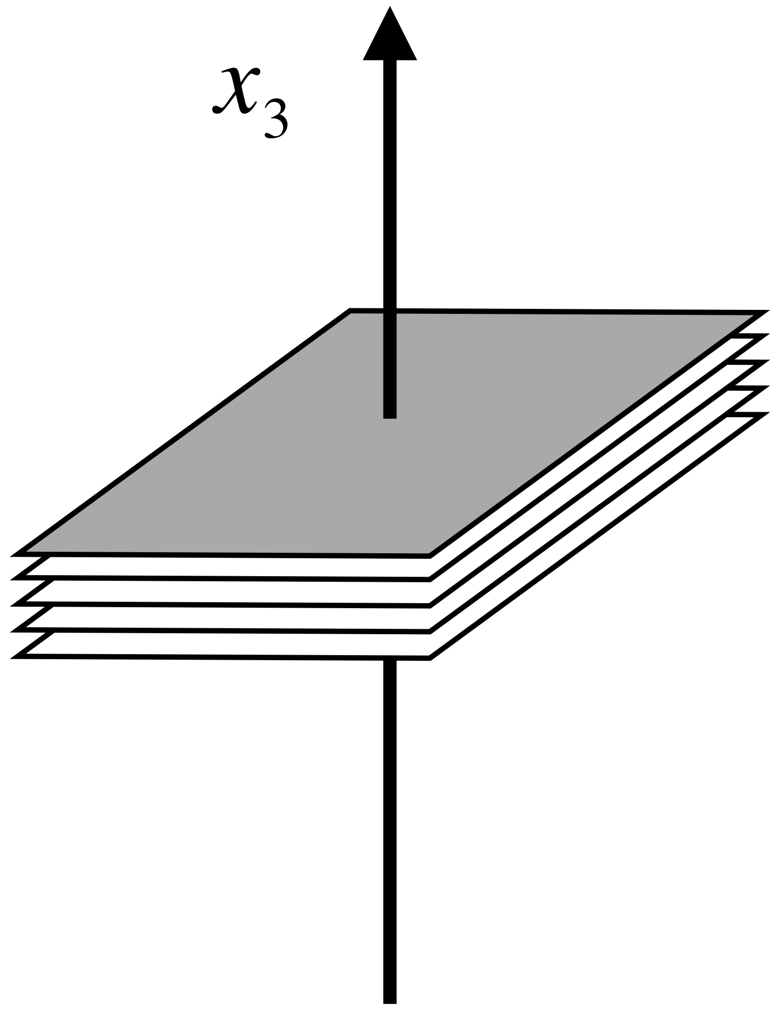

P and S wave velocities along the symmetry axis x_3:

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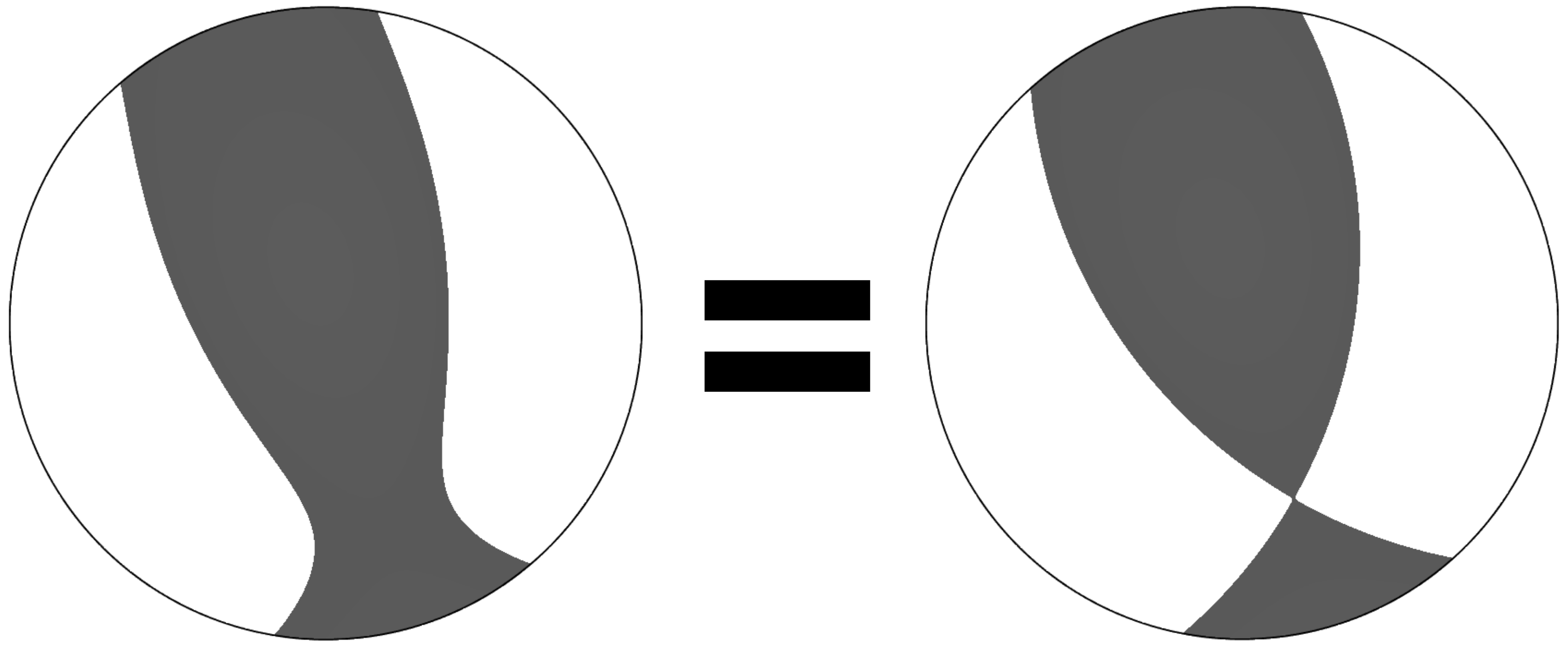

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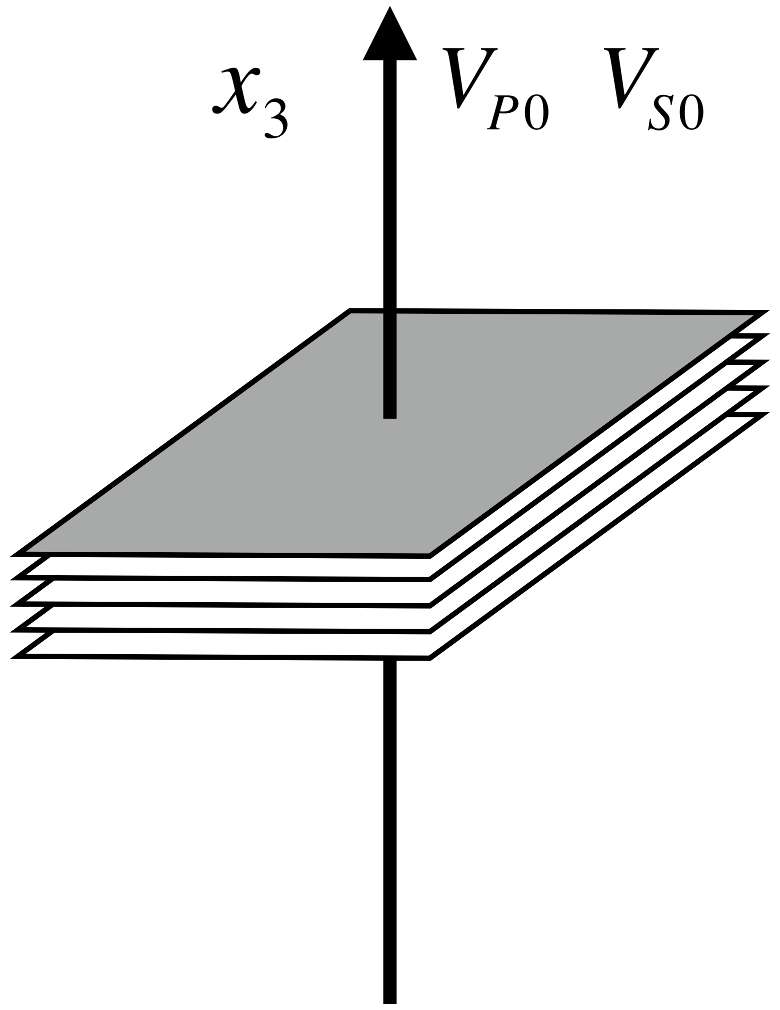

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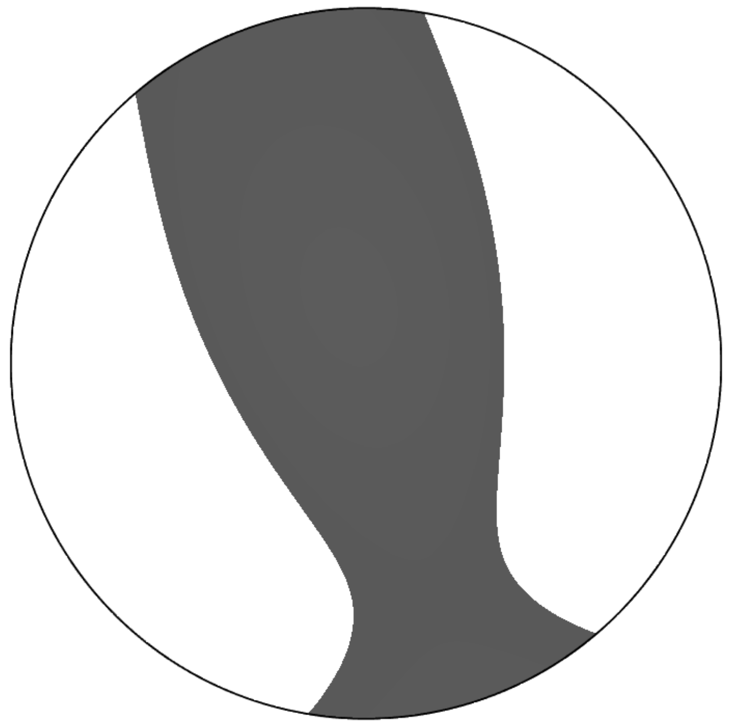

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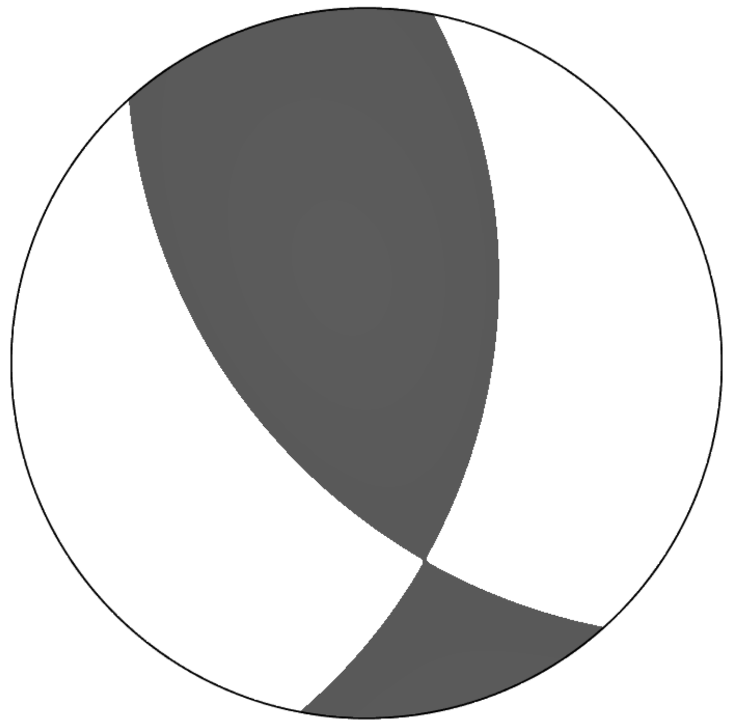

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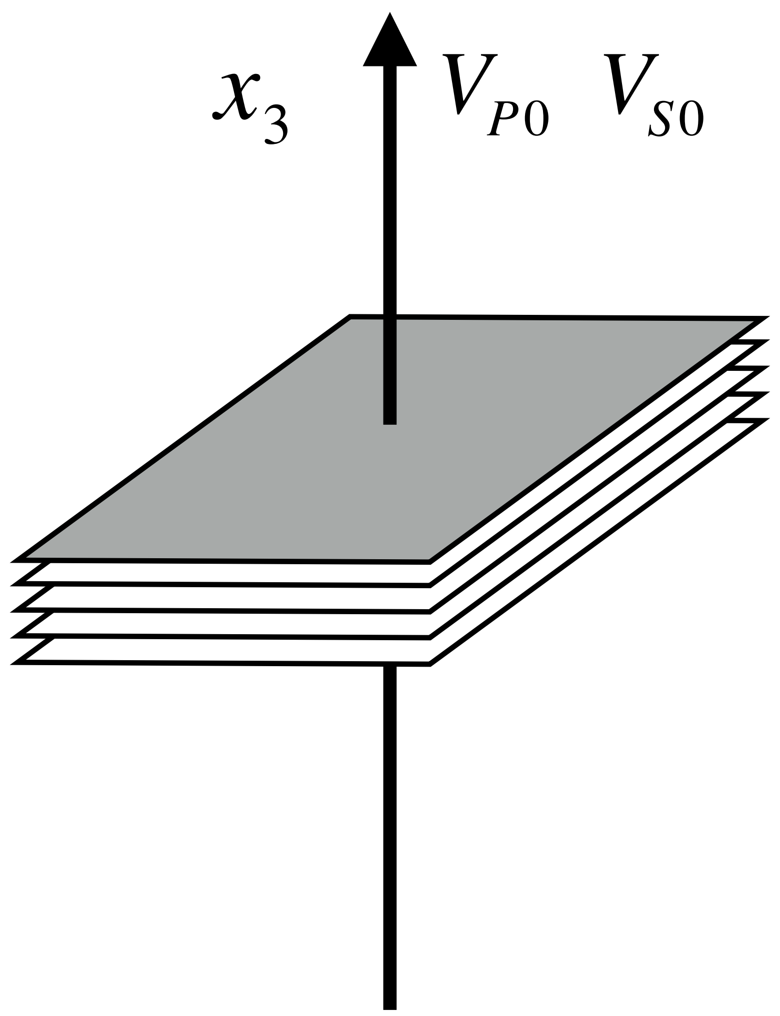

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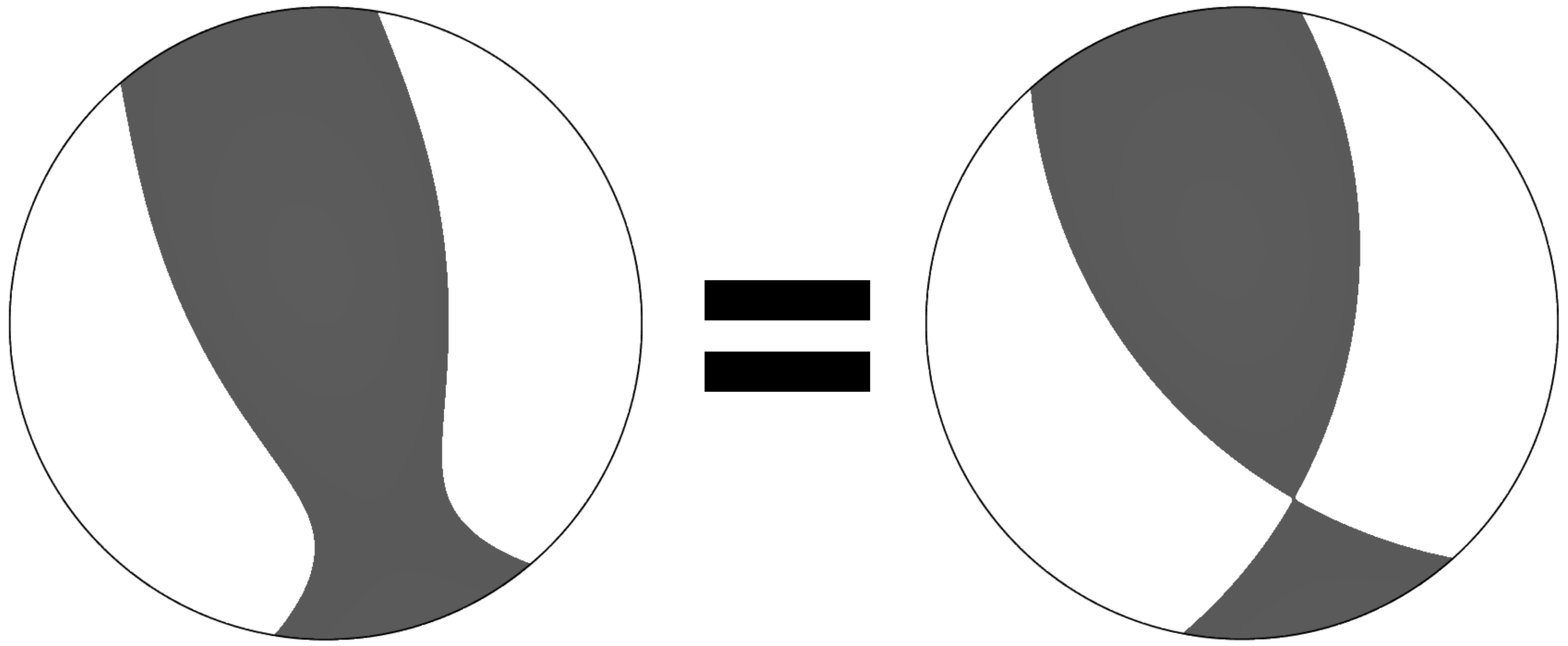

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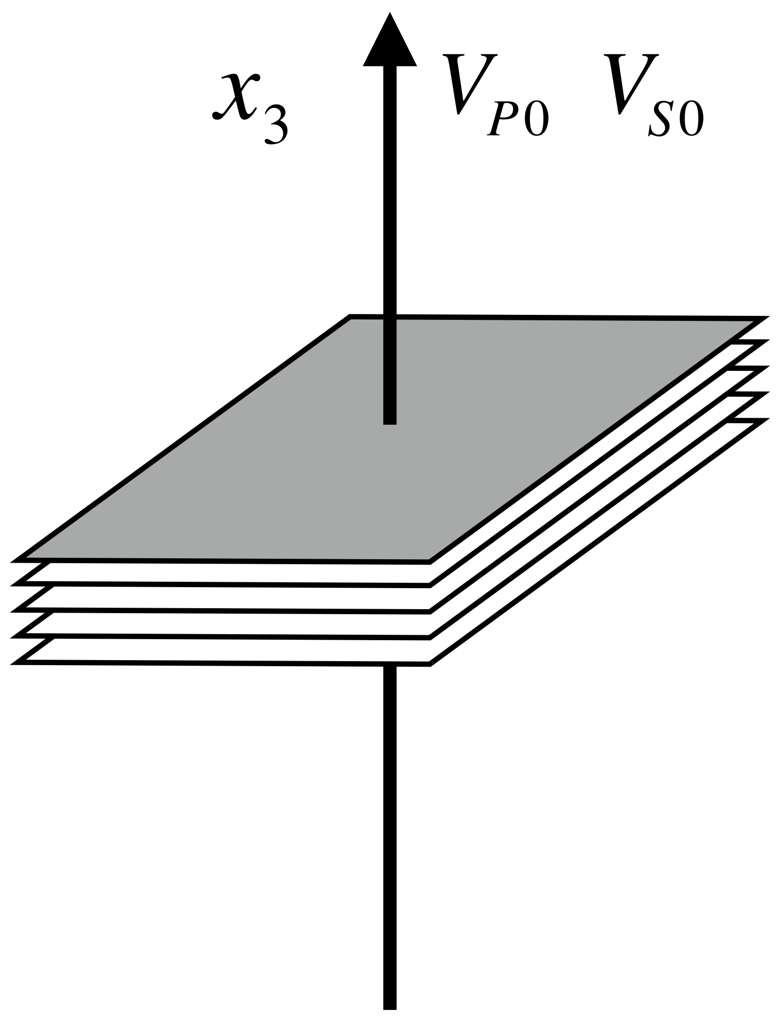

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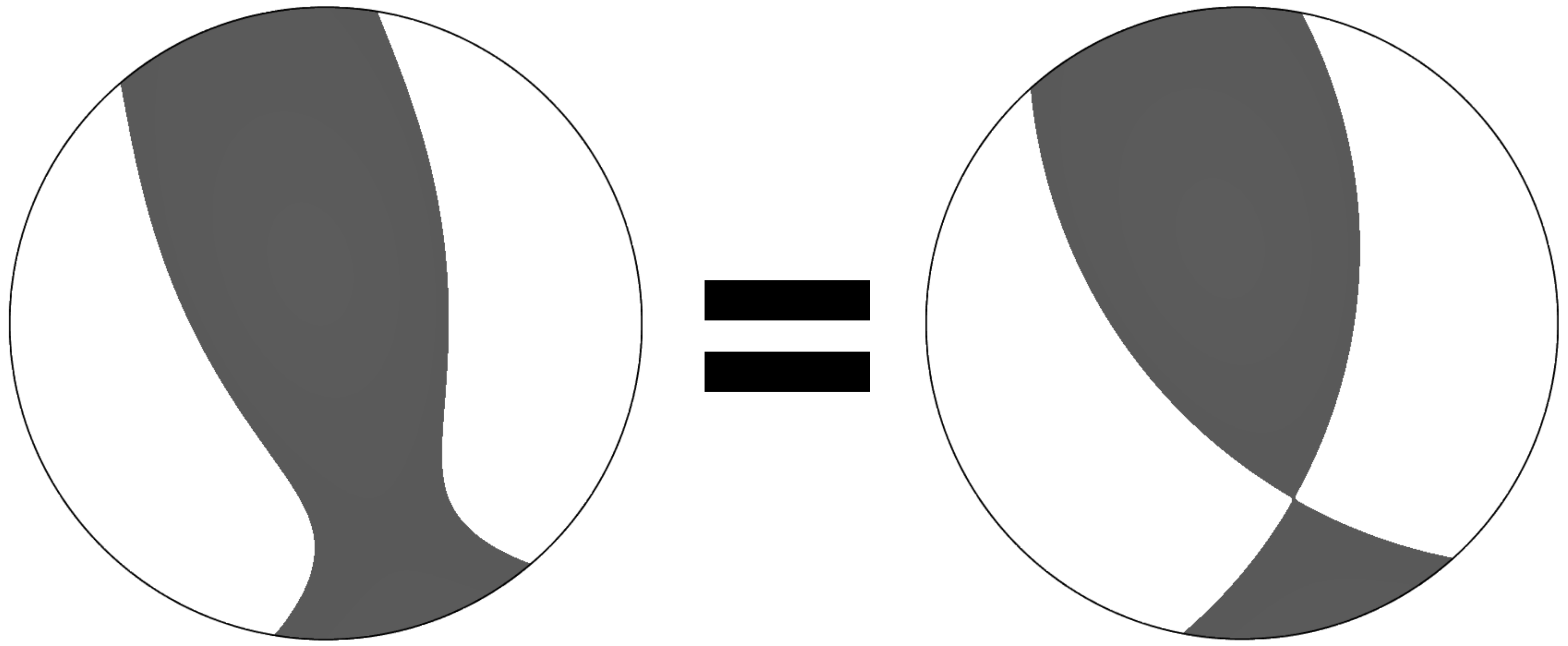

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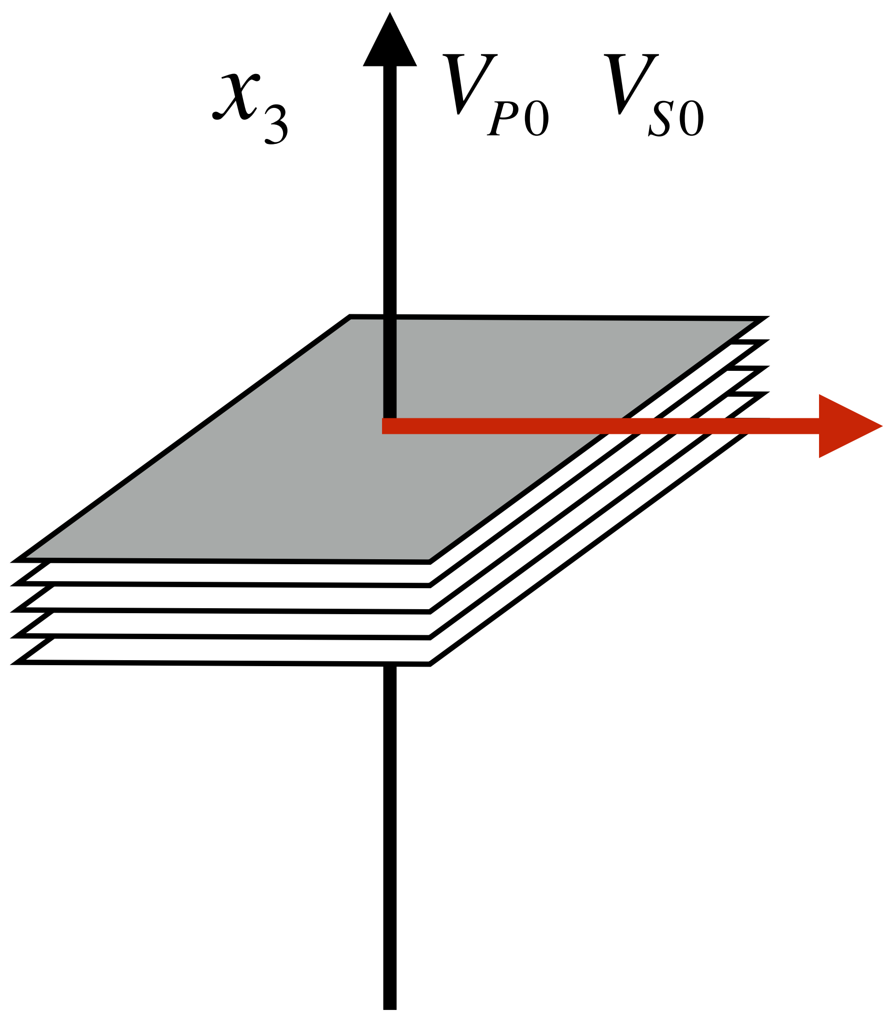

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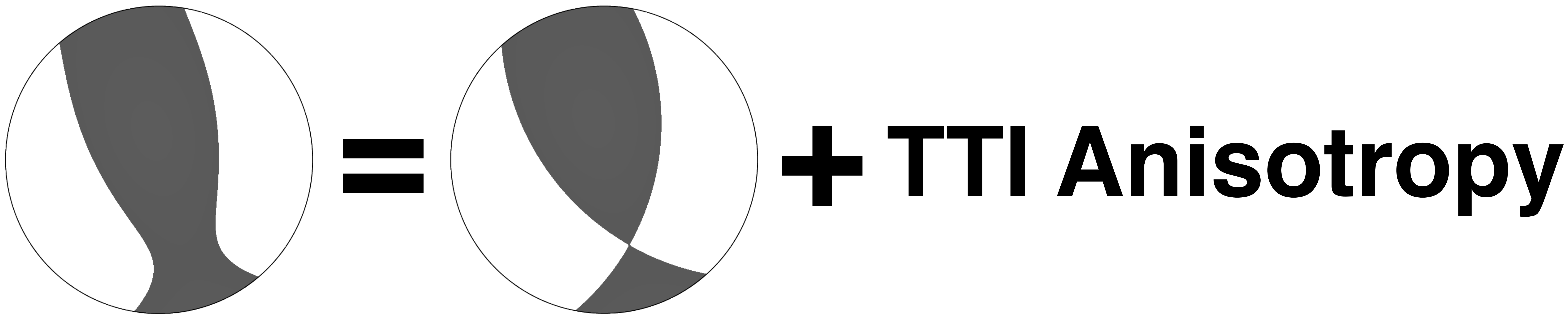

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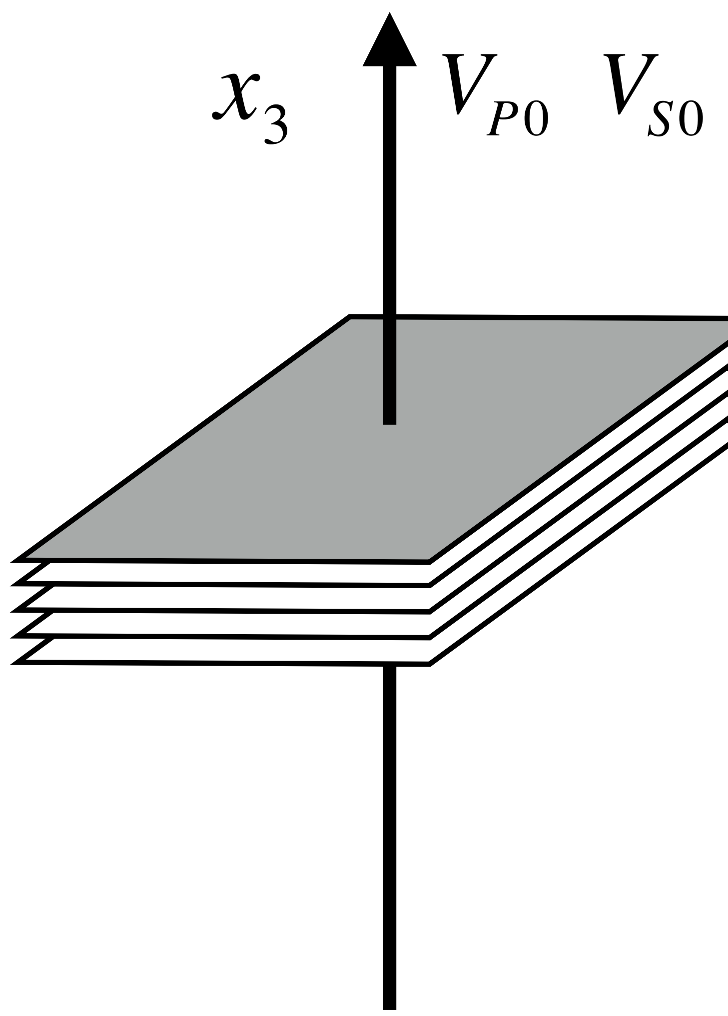

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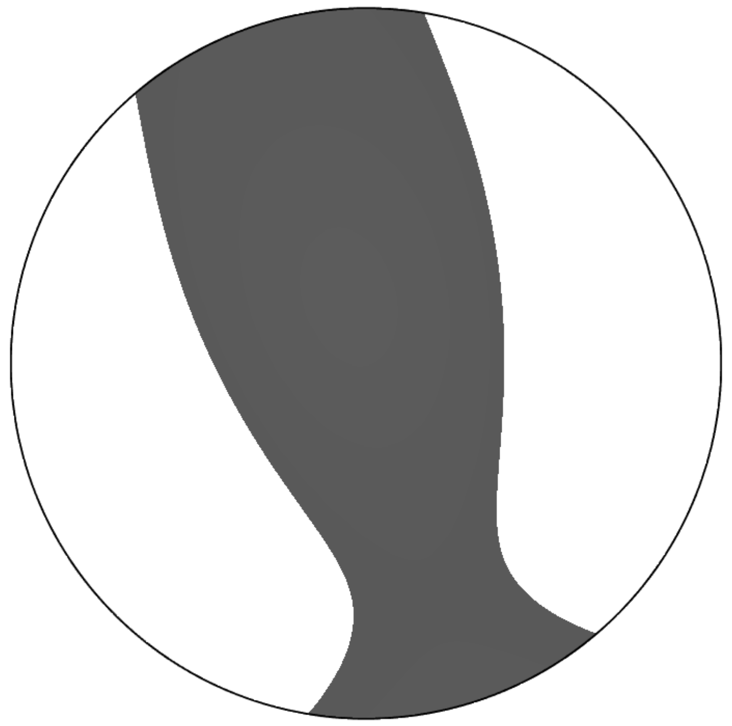

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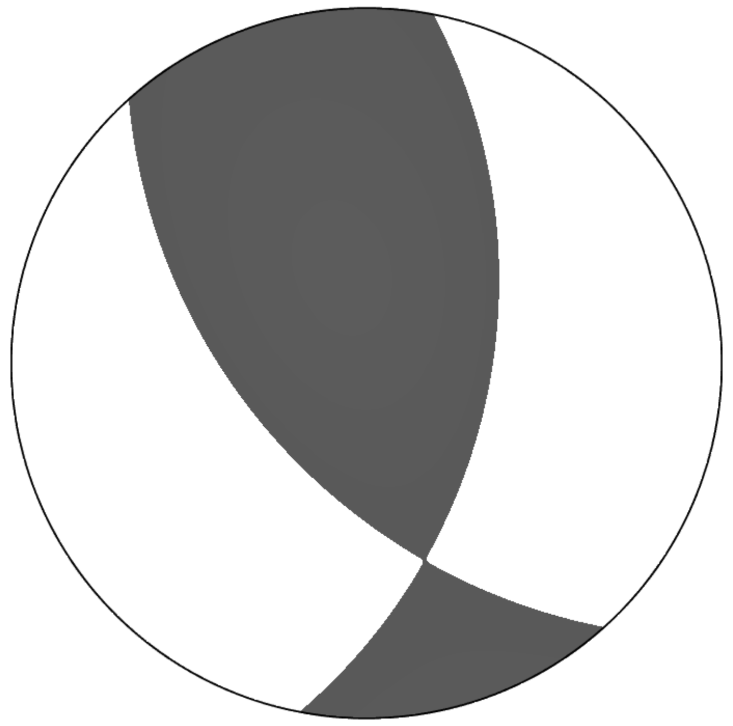

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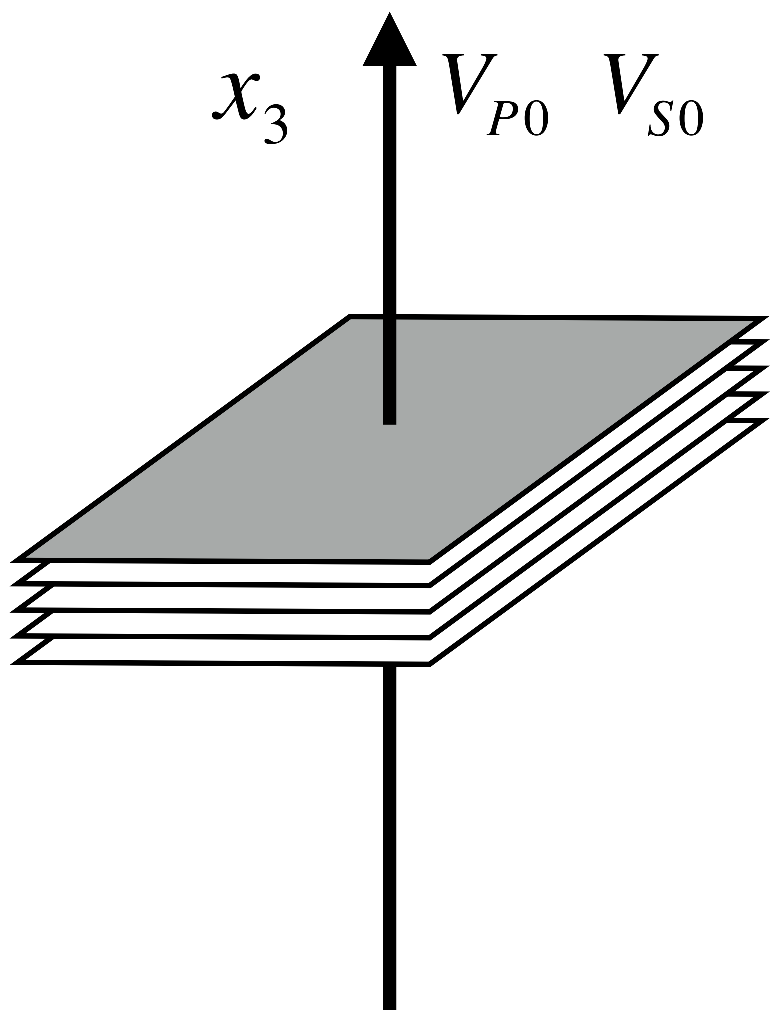

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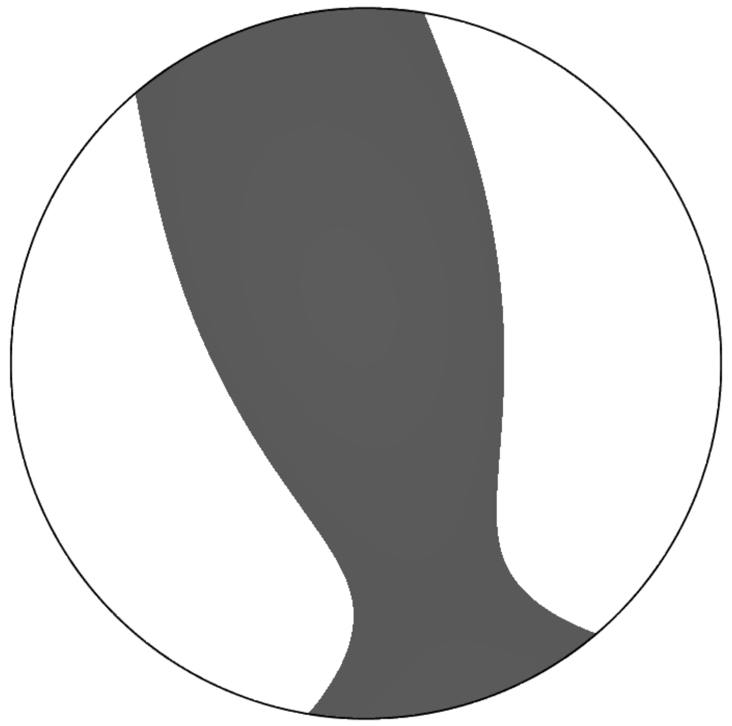

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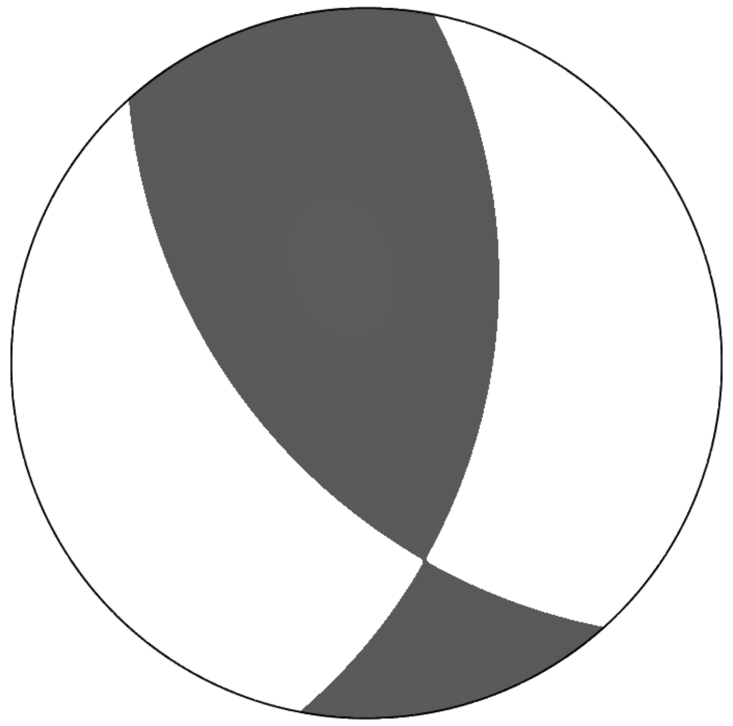

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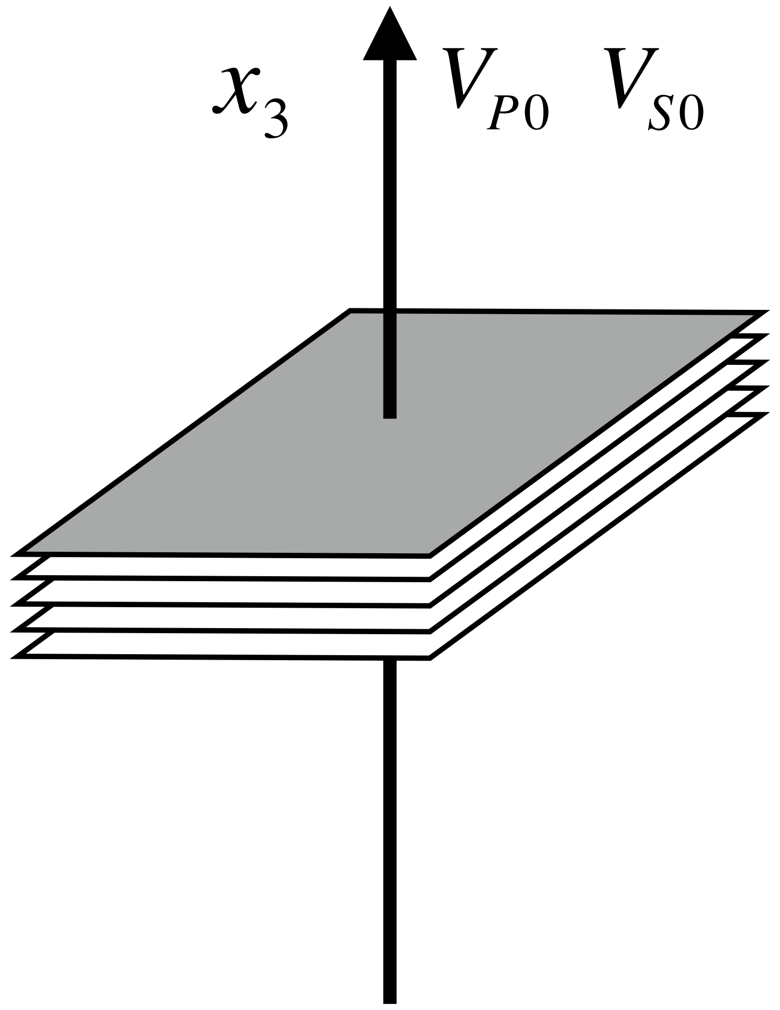

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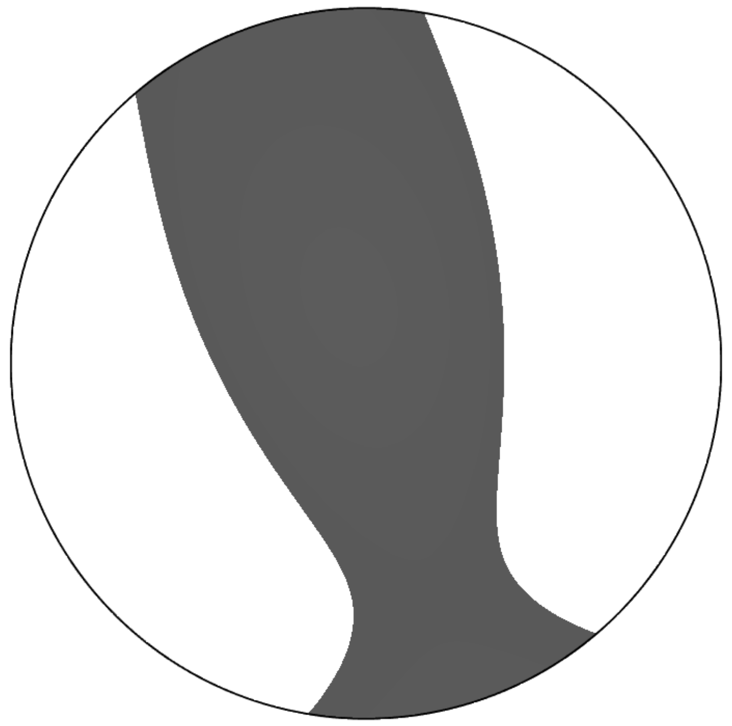
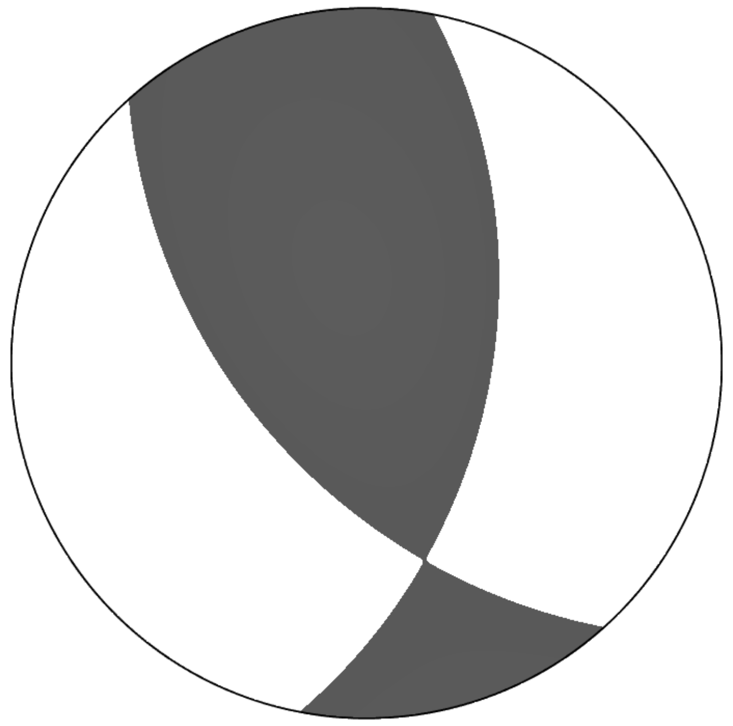


=  + TTI Anisotropy

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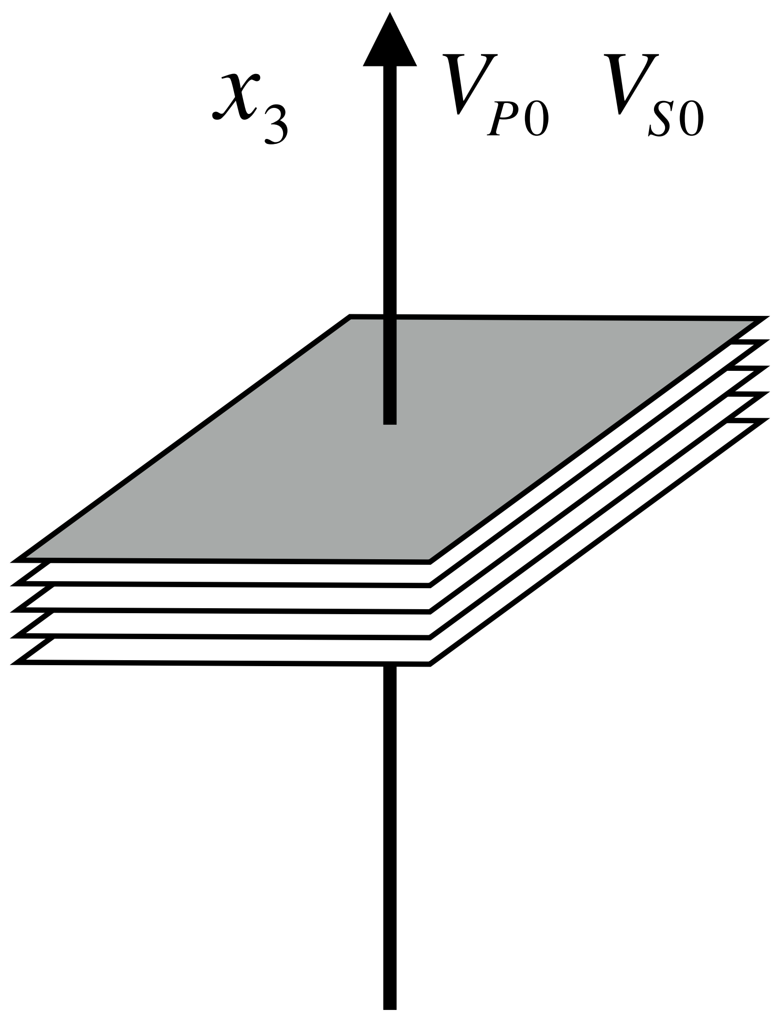


P and S wave velocities along the symmetry axis x_3:

V_{P0} V_{S0}

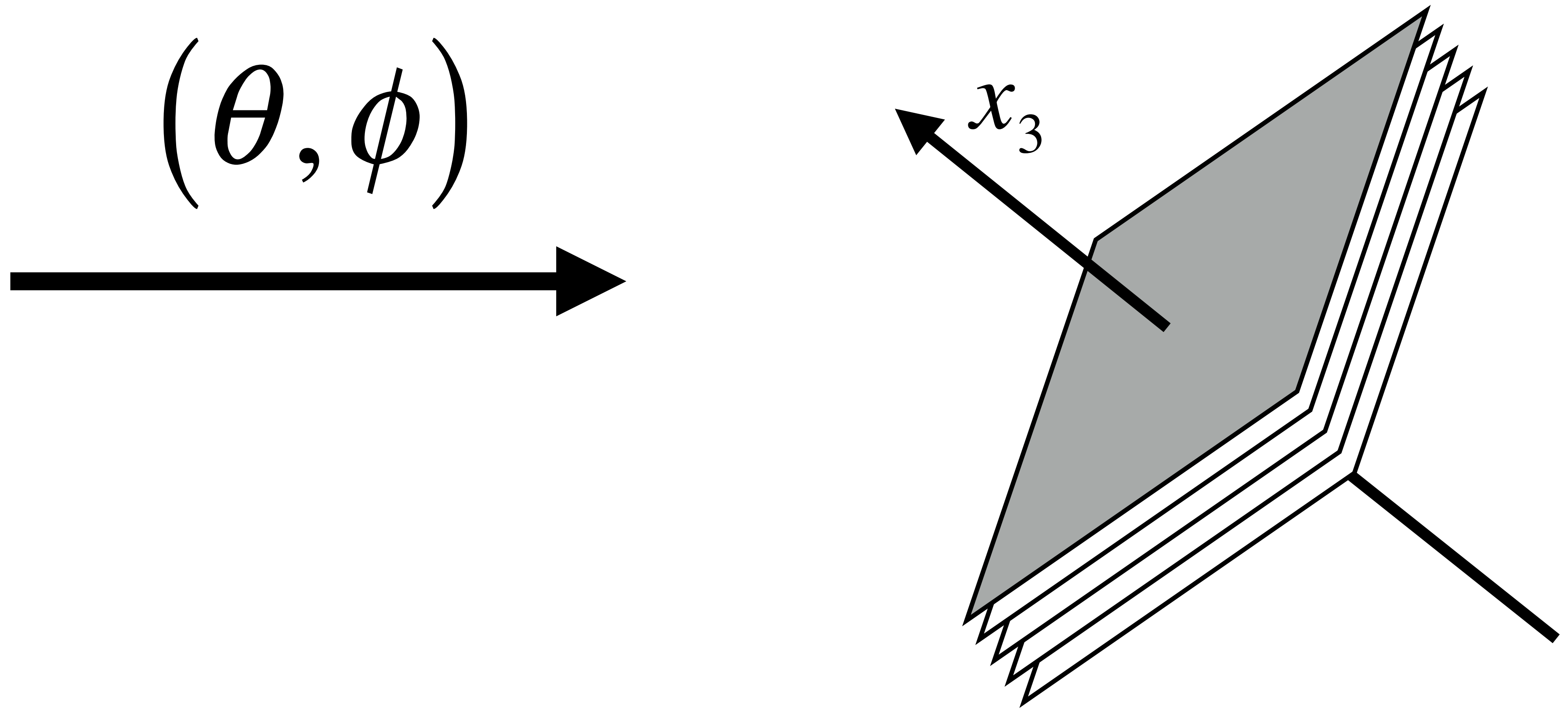
Thomsen Parameters:

ε : P wave anisotropy

γ : S wave anisotropy

δ : Affect both P and S wave anisotropy

TTI:



(Thomsen 1986)

Moment tensor

$$m_{ij} = \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix}$$

non-double-couple component

$$f_{clvd} = -\frac{\lambda_2}{\max\{|\lambda_1|, |\lambda_3|\}}$$

$$-0.5 \le f_{clvd} \le 0.5$$

Methods

Methods

(Vavrycuk 2004,2006; Aki and Richards, 1980)

$$m_{ij} = u\,S\,C_{ijkl}\,n_k\,v_l$$

Methods

(Vavrycuk 2004,2006; Aki and Richards, 1980)

$$m_{ij} = u\, S\, C_{ijkl}\, n_k\, v_l$$

moment tensor

Methods

(Vavrycuk 2004,2006; Aki and Richards, 1980)

$$m_{ij} = u\,S\,C_{ijkl}\,n_k\,v_l$$

moment tensor

displacement x fault area

Methods

(Vavrycuk 2004,2006; Aki and Richards, 1980)

$$m_{ij} = u\,S\,C_{ijkl}\,n_k\,v_l$$

- m_{ij}: **moment tensor**
- $u\,S$: **displacement x fault area**
- C_{ijkl}: **elastic tensor**

Methods

(Vavrycuk 2004,2006; Aki and Richards, 1980)

$$m_{ij} = u\,S\,C_{ijkl}\,n_k\,v_l$$

- m_{ij}: moment tensor
- $u\,S$: displacement x fault area
- C_{ijkl}: elastic tensor
- $n_k\,v_l$: normal vector x slip vector

Methods

(Vavrycuk 2004,2006; Aki and Richards, 1980)

$$m_{ij} = u\,S\,C_{ijkl}\,n_k\,v_l$$

- m_{ij} → moment tensor
- $u\,S$ → displacement x fault area
- C_{ijkl} → elastic tensor
- $n_k\,v_l$ → normal vector x slip vector

Methods

(Vavrycuk 2004,2006; Aki and Richards, 1980)

$$m_{ij} = u\,S\,C_{ijkl}\,n_k\,v_l$$

- m_{ij}: moment tensor
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Methods

(Vavrycuk 2004,2006; Aki and Richards, 1980)

$$m_{ij} = u\,S\,C_{ijkl}\,n_k\,v_l$$

- m_{ij}: moment tensor
- $u\,S$: displacement x fault area
- C_{ijkl}: elastic tensor
- $n_k\,v_l$: normal vector x slip vector

1. First invert for the TTI symmetry axis orientation

Methods

(Vavrycuk 2004,2006; Aki and Richards, 1980)

$$m_{ij} = u\,S\,C_{ijkl}\,n_k\,v_l$$

- m_{ij}: moment tensor
- $u\,S$: displacement x fault area
- C_{ijkl}: elastic tensor
- $n_k\,v_l$: normal vector x slip vector

1. First invert for the TTI symmetry axis orientation

2. Anisotropy strength at this TTI symmetry axis

Inversion For Real Data from CMT Catalog

http://www.globalcmt.org/

(Dziewonski, Chou & Woodhouse 1981; Ekström,Nettles, and Dziewonski, 2012)

Data/Moment tensor Selection

Data/Moment tensor Selection

- **We finally choose <u>1,057</u> earthquakes worldwide**

Data/Moment tensor Selection

- We finally choose 1,057 earthquakes worldwide
- Focal depth Range >100km

Data/Moment tensor Selection

- **We finally choose 1,057 earthquakes worldwide**
- **Focal depth Range >100km**
- **Mw~5-6.6**

Data/Moment tensor Selection

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- **Focal depth Range >100km**
- **Mw~5-6.6**
- **From 1976 to 2013**

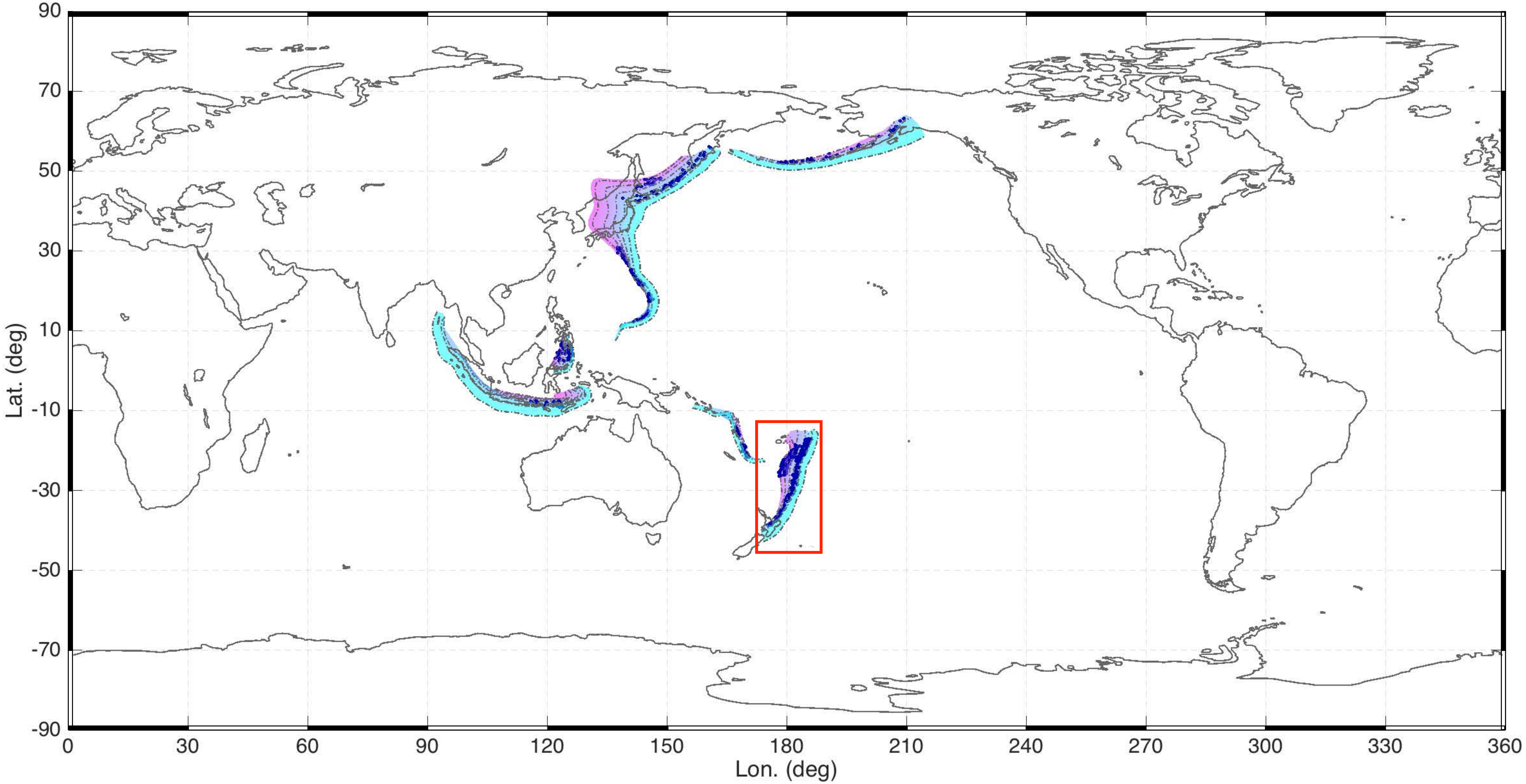
Data/Moment tensor Selection

- **We finally choose 1,057 earthquakes worldwide**
- **Focal depth Range >100km**
- **Mw~5-6.6**
- **From 1976 to 2013**
- **In the vicinity of subducting slabs (**Gudmundsson et al. 1998**)**

Data/Moment tensor Selection

- **We finally choose 1,057 earthquakes worldwide**
- **Focal depth Range >100km**
- **Mw~5-6.6**
- **From 1976 to 2013**
- **In the vicinity of subducting slabs (**Gudmundsson et al. 1998**)**
- **Frohlich's criteria of selecting 'better-determined' mechanisms** (Frohlich and Davis, 1999)

Tonga



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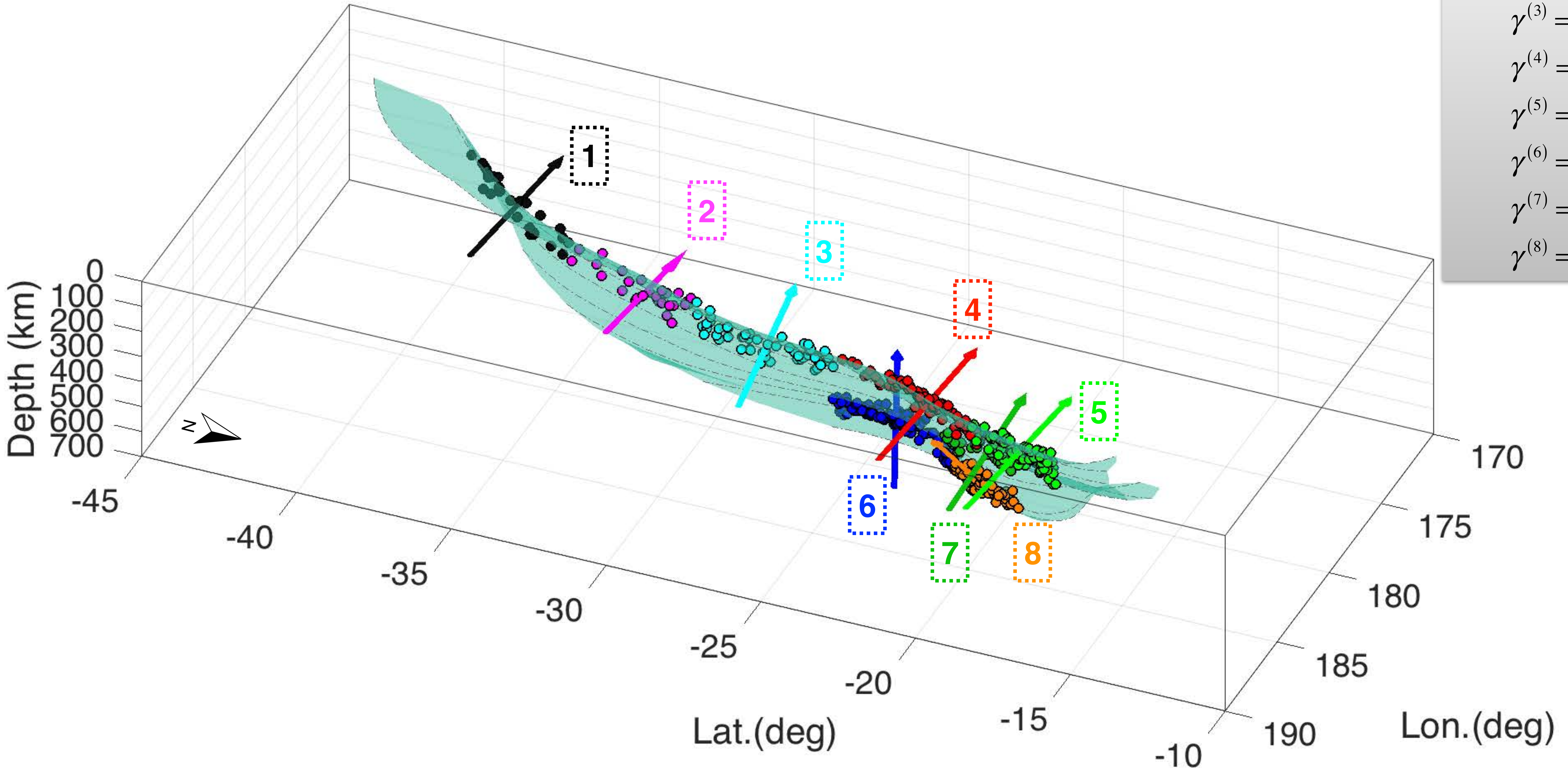
Tonga



Thomsen Parameter:

$\gamma^{(1)} = 24 \pm 5\%$

$\gamma^{(2)} = 26 \pm 2\%$

$\gamma^{(3)} = 27 \pm 3\%$

$\gamma^{(4)} = 30 \pm 3\%$

$\gamma^{(5)} = 35 \pm 4\%$

$\gamma^{(6)} = 30 \pm 4\%$

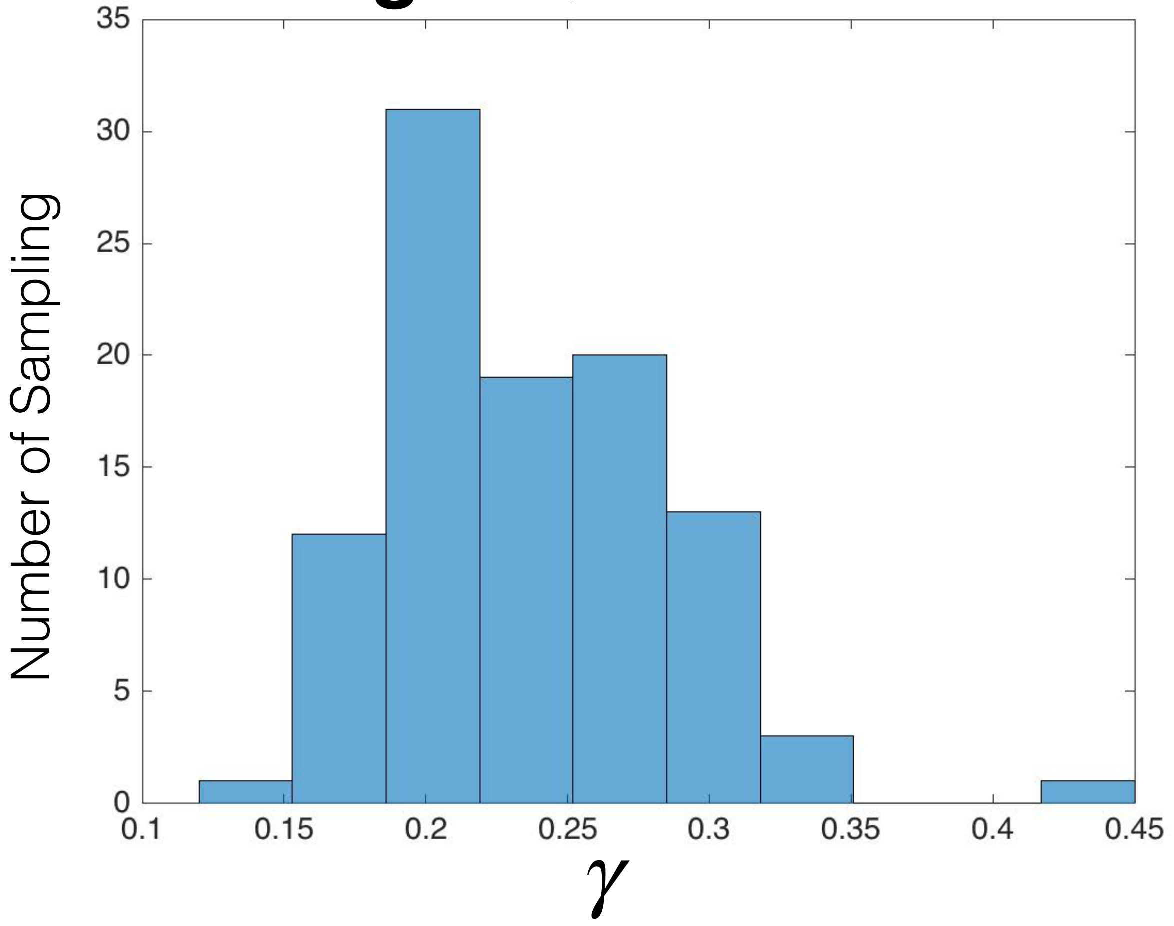
$\gamma^{(7)} = 46 \pm 4\%$

$\gamma^{(8)} = 23 \pm 2\%$

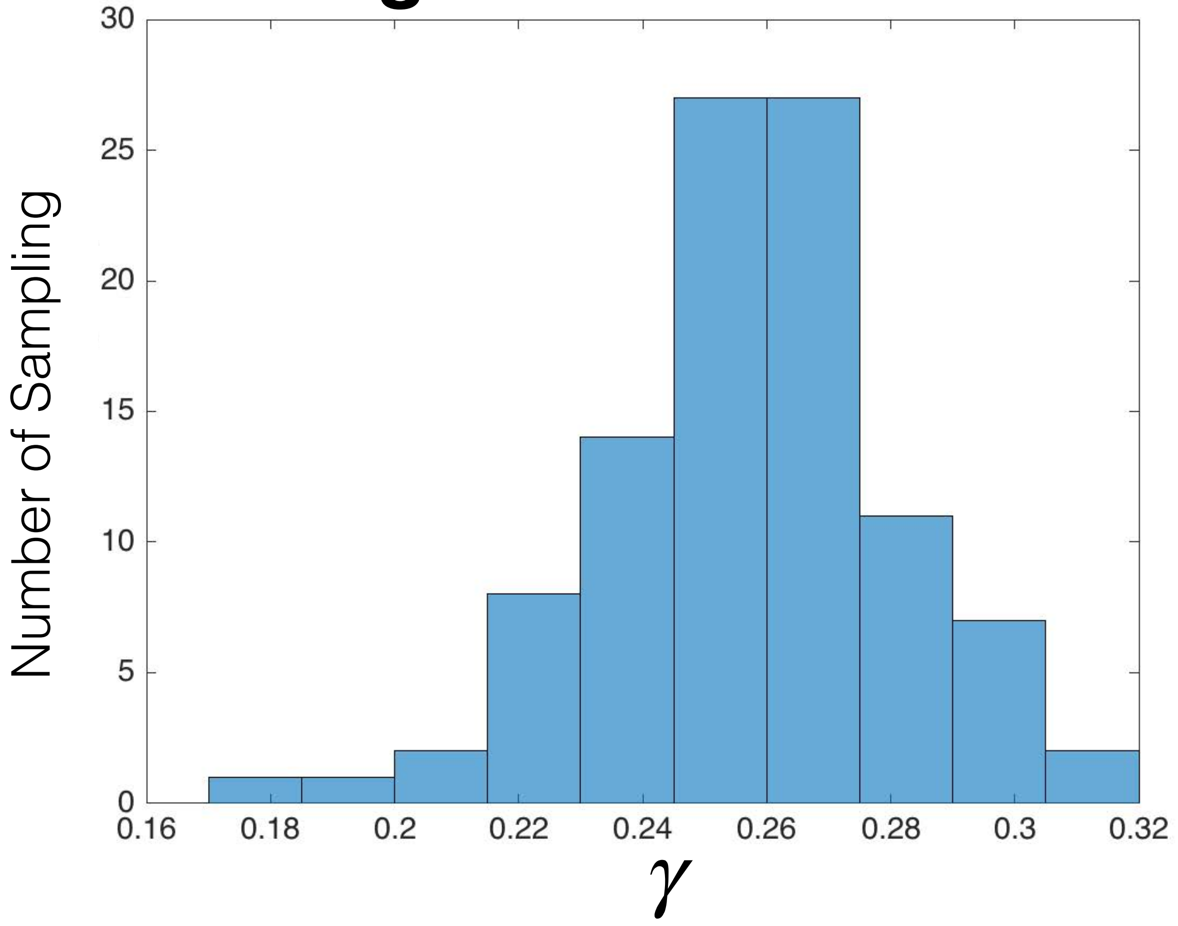
Tonga

Tonga

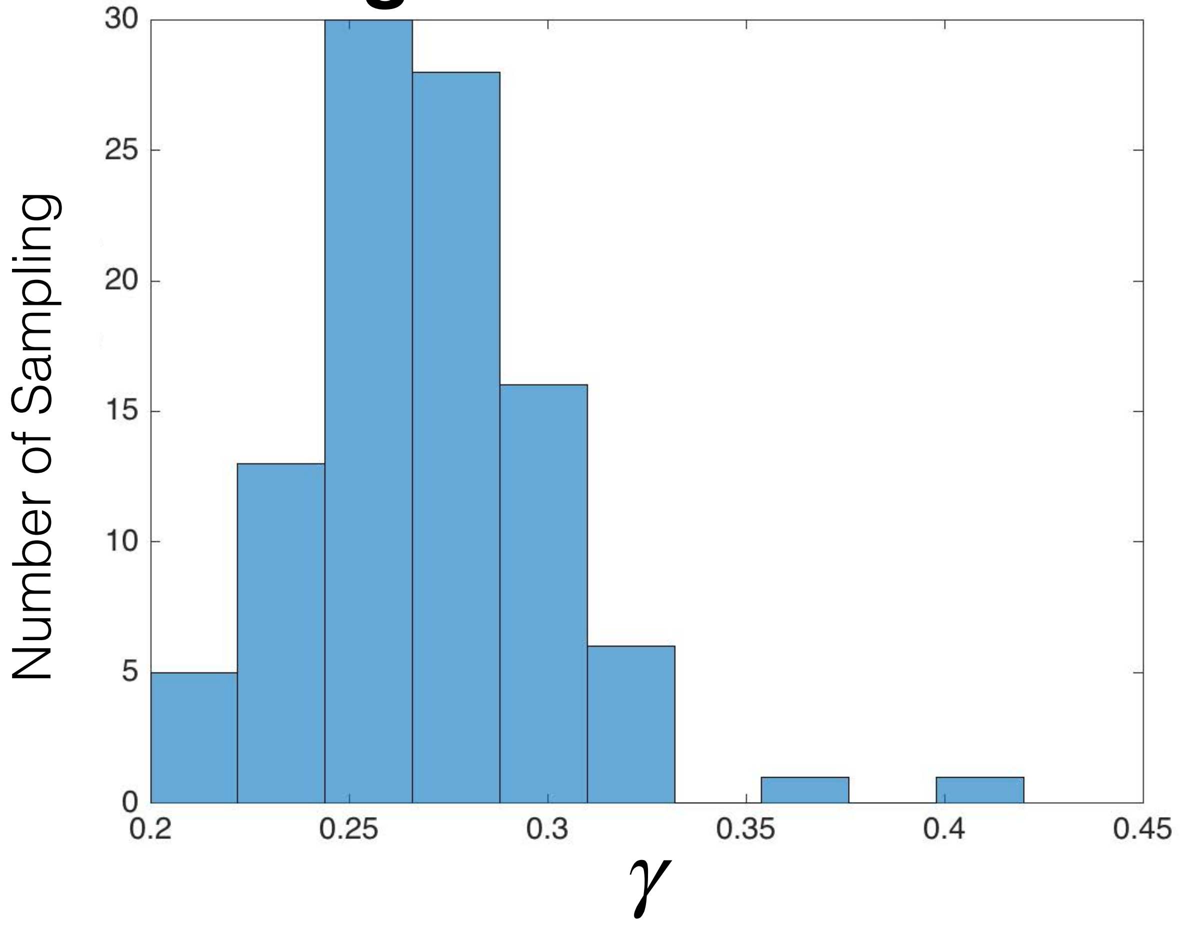
Tonga1: $\gamma = 0.24 \pm 0.05$



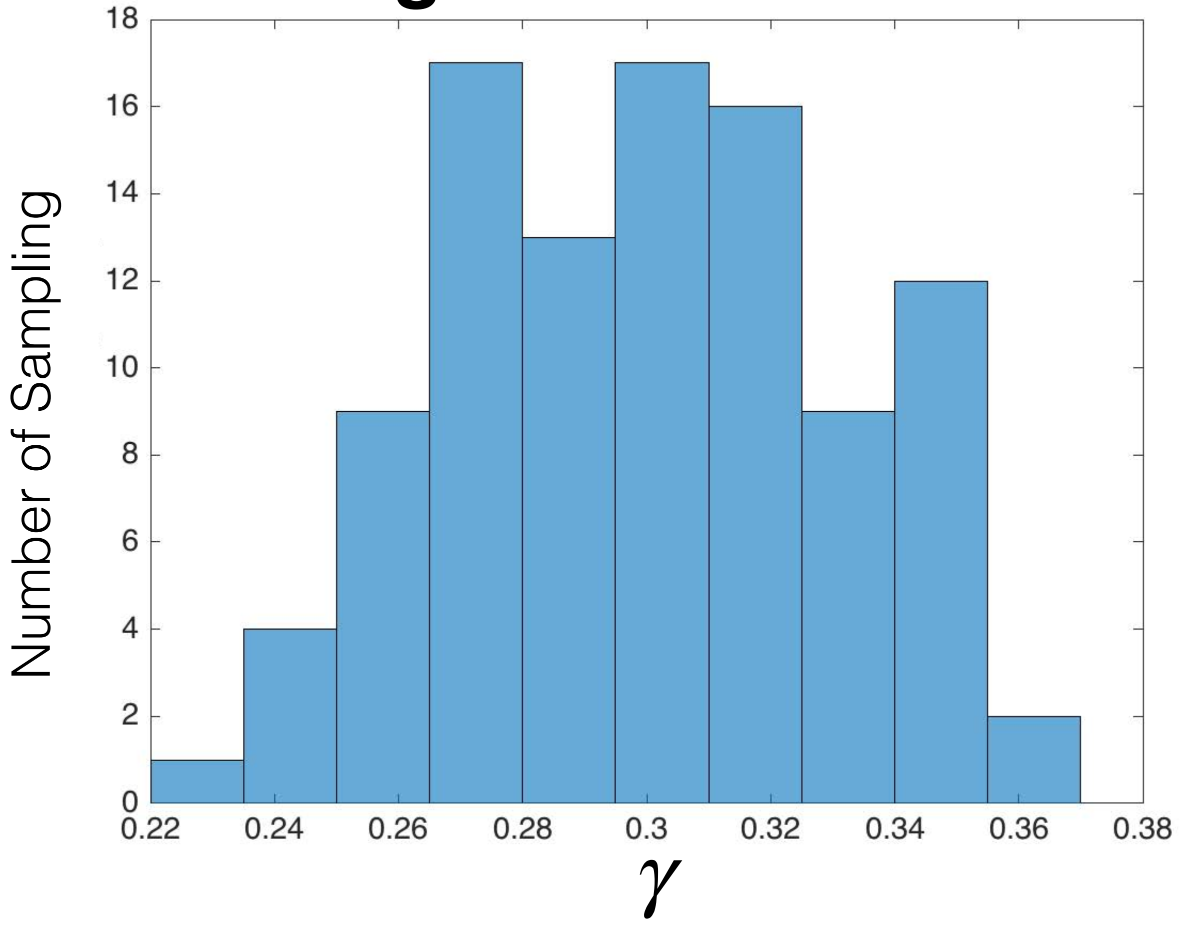
Tonga2: $\gamma = 0.26 \pm 0.02$



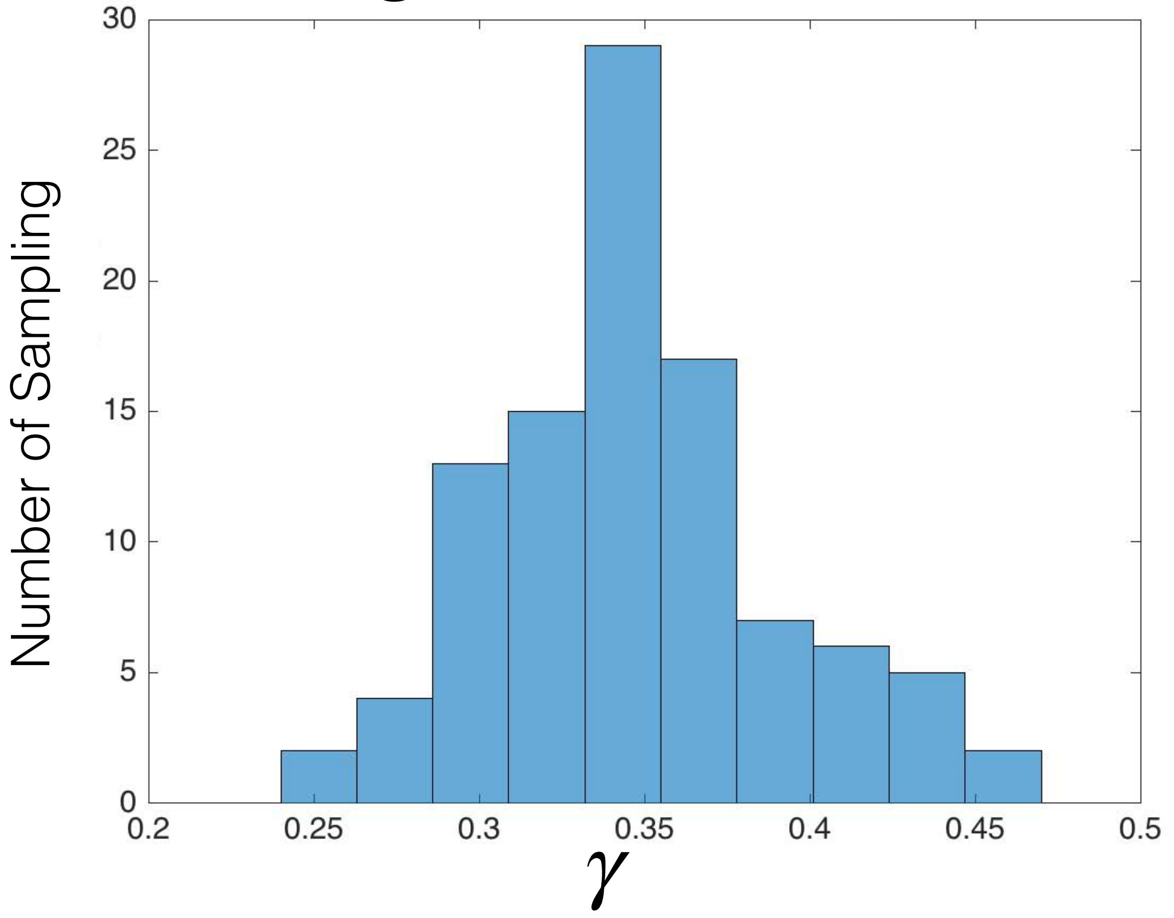
Tonga3: $\gamma = 0.27 \pm 0.03$



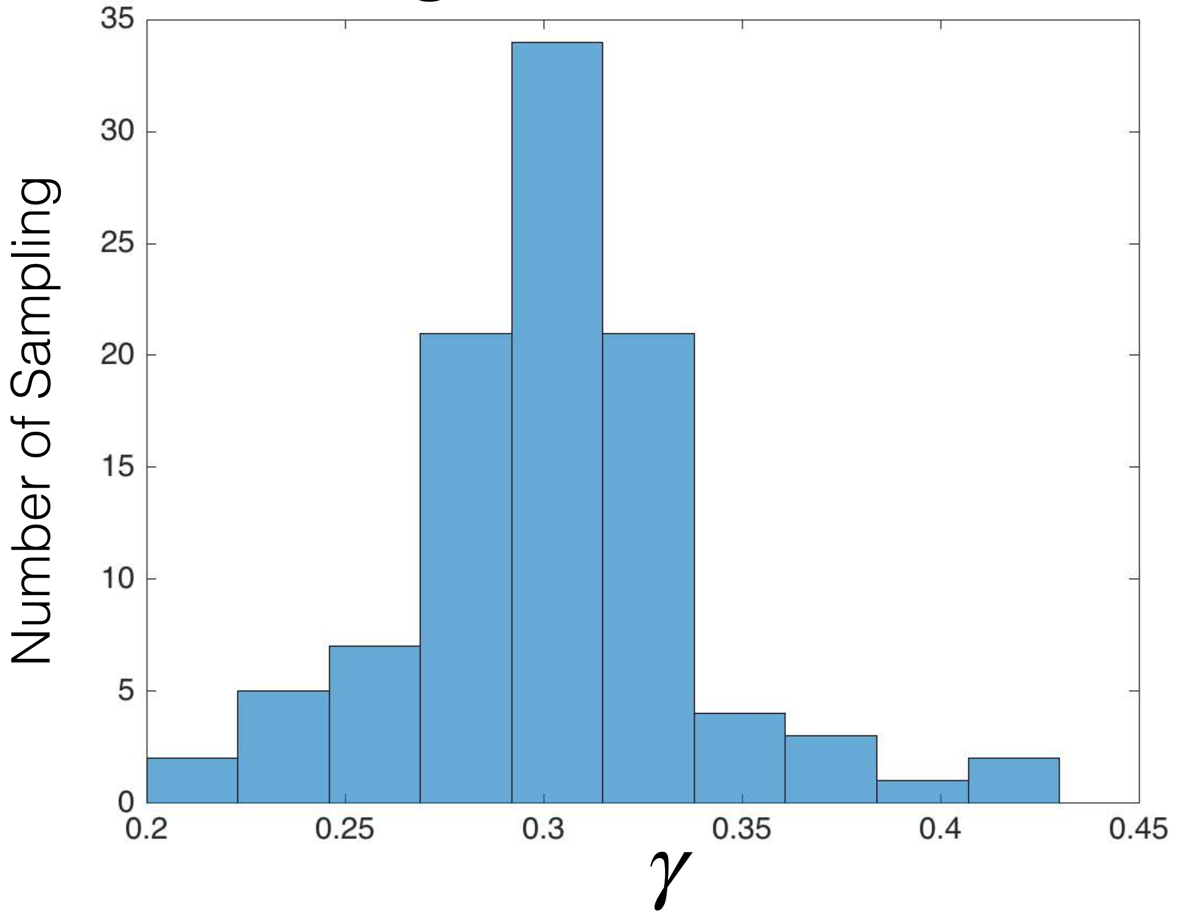
Tonga4: $\gamma = 0.30 \pm 0.03$



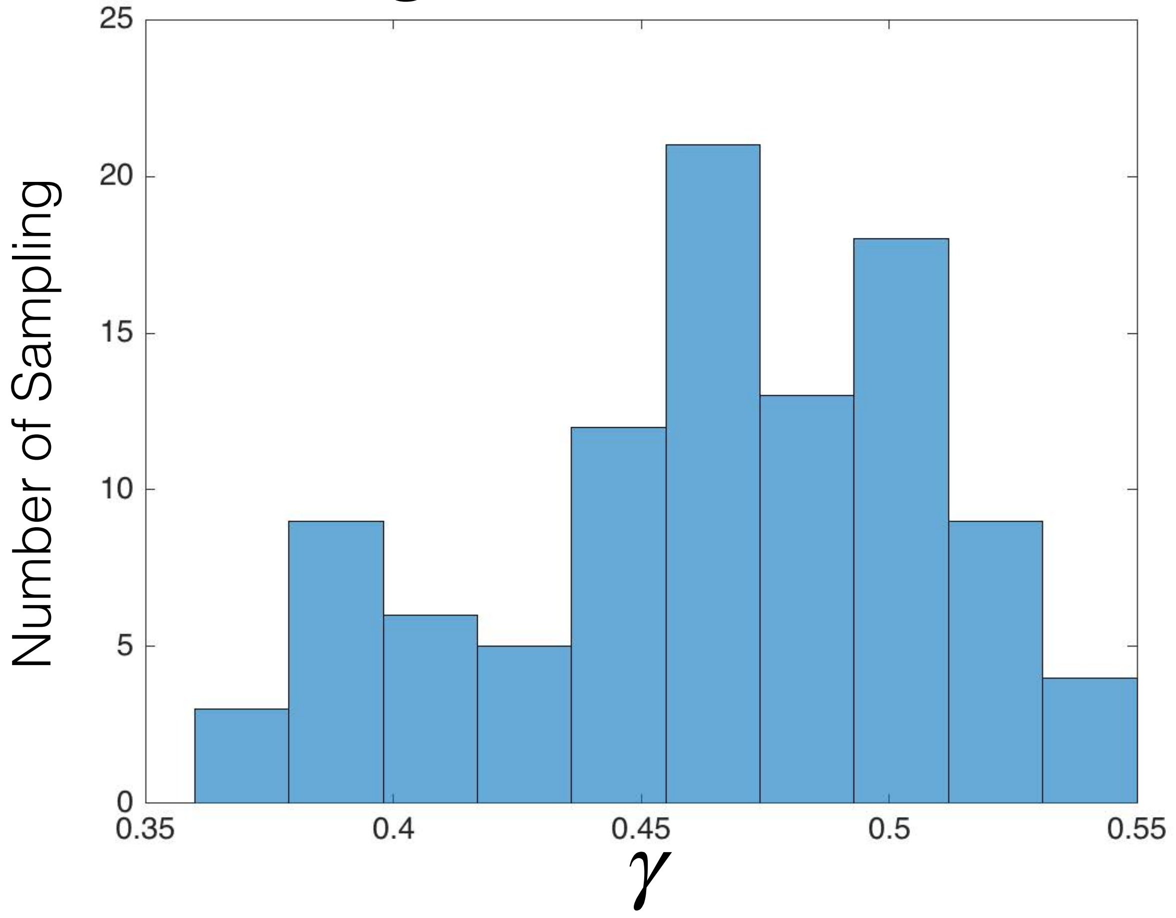
Tonga5: $\gamma = 0.35 \pm 0.04$



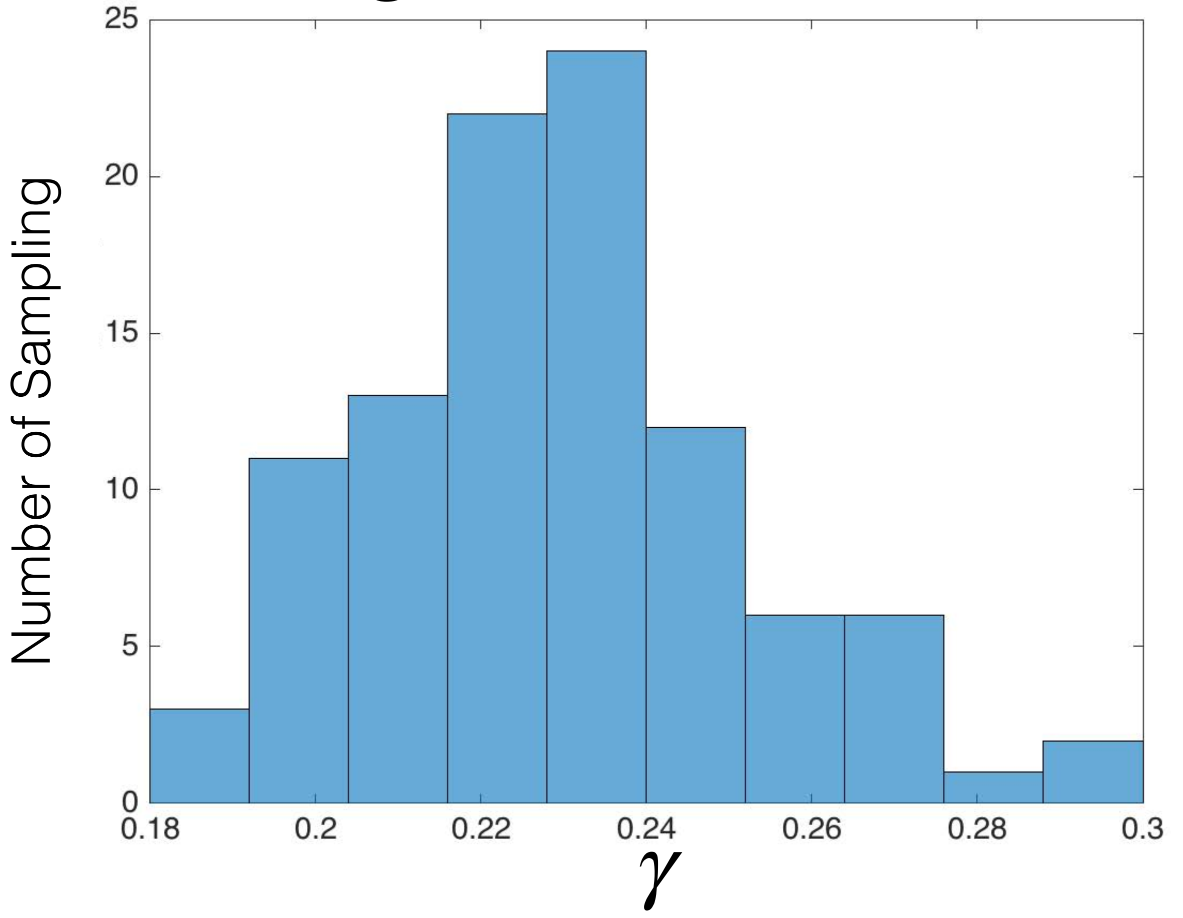
Tonga6: $\gamma = 0.30 \pm 0.04$



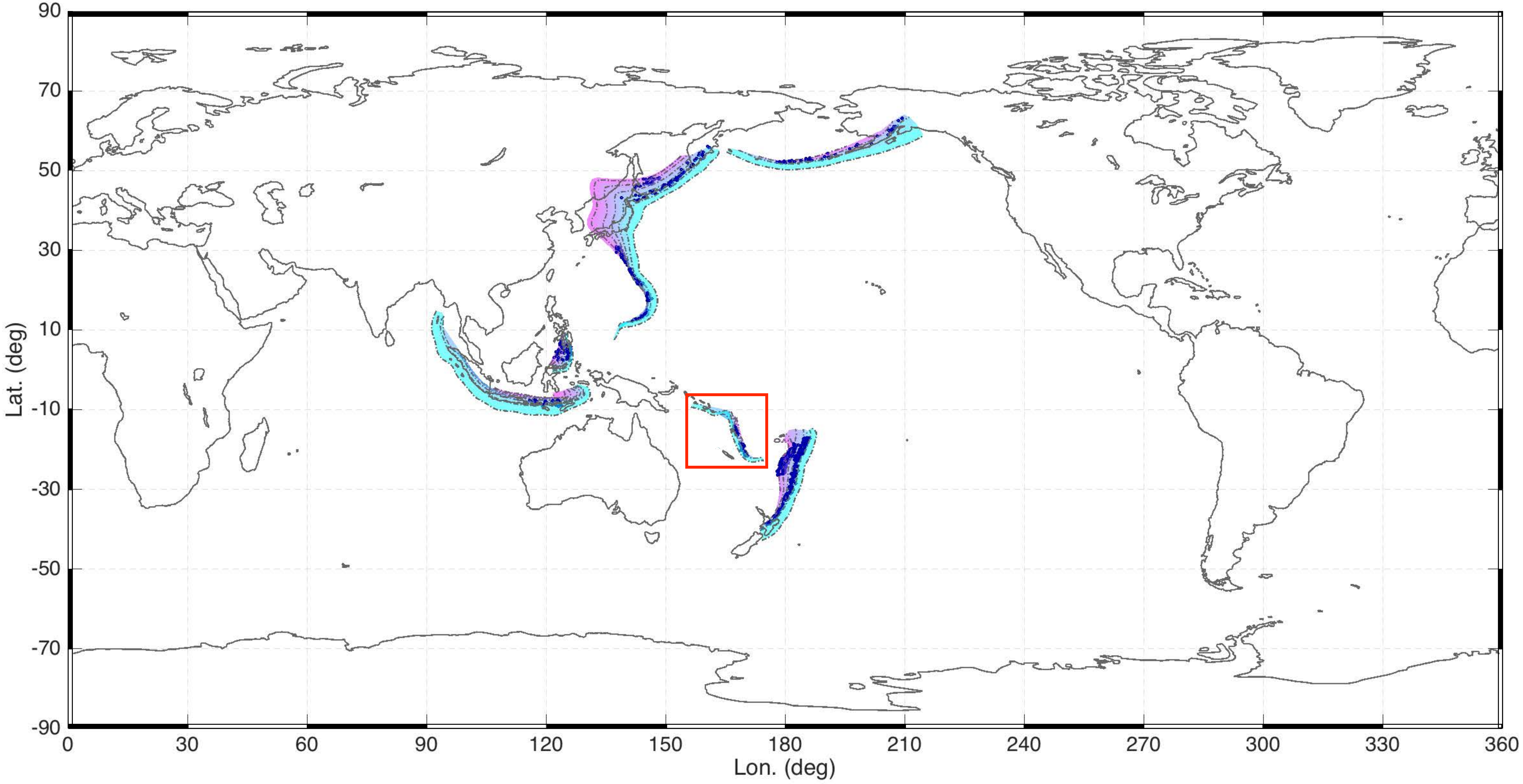
Tonga7: $\gamma = 0.46 \pm 0.04$



Tonga8: $\gamma = 0.23 \pm 0.02$



Vanuatu



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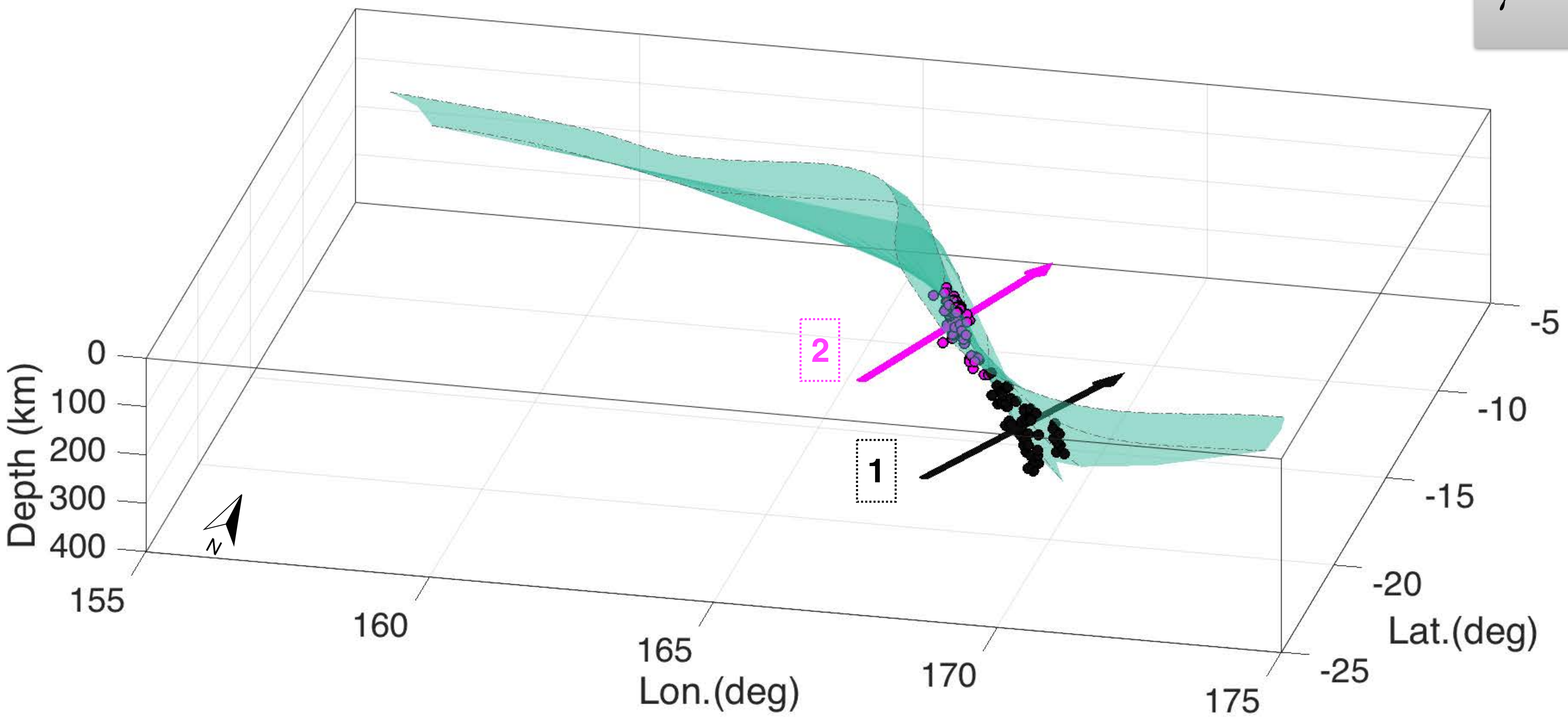
Lon. (deg)

Vanuatu

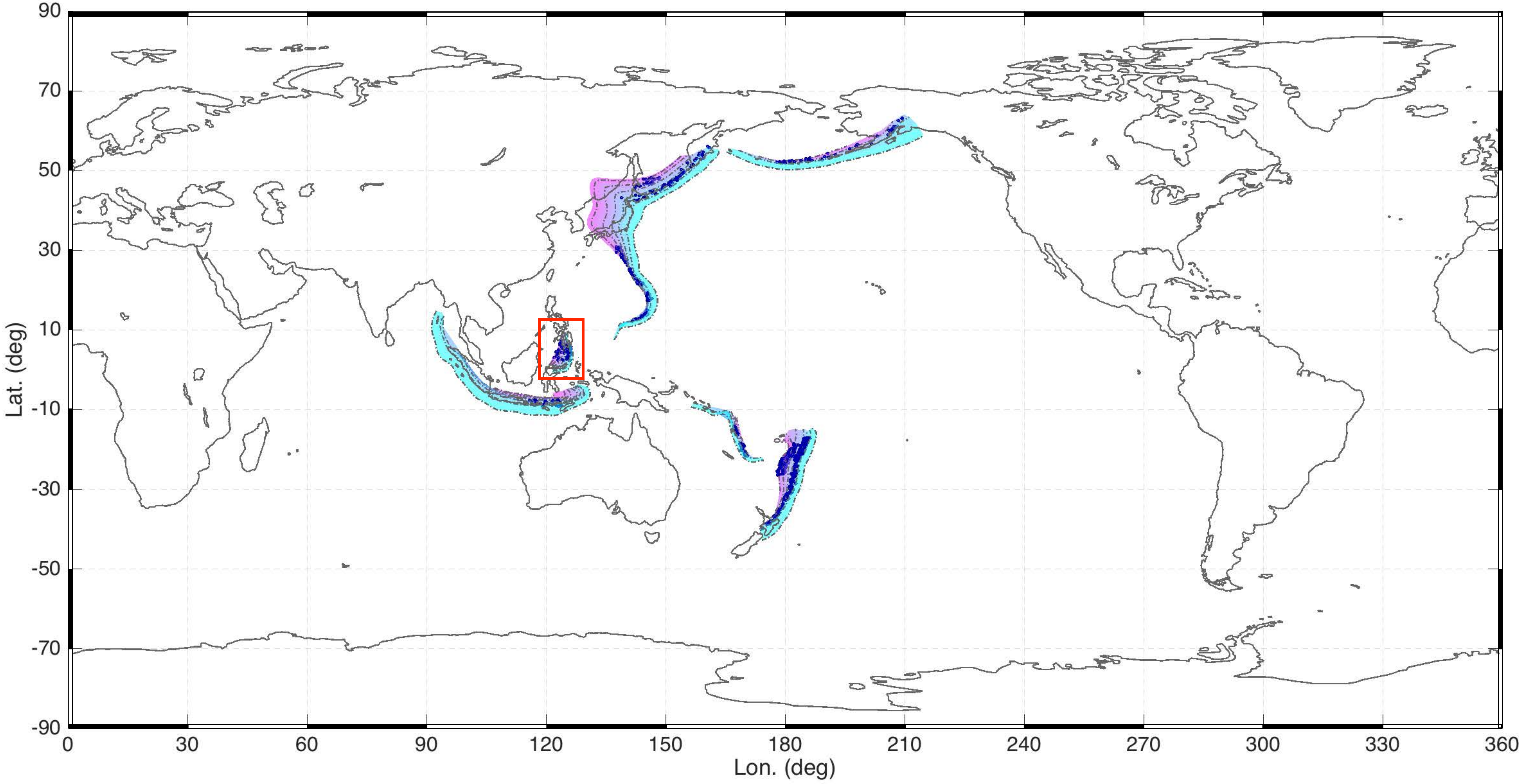
Thomsen Parameter:

$\gamma^{(1)} = 25 \pm 5\%$

$\gamma^{(2)} = 14 \pm 3\%$



Molucca



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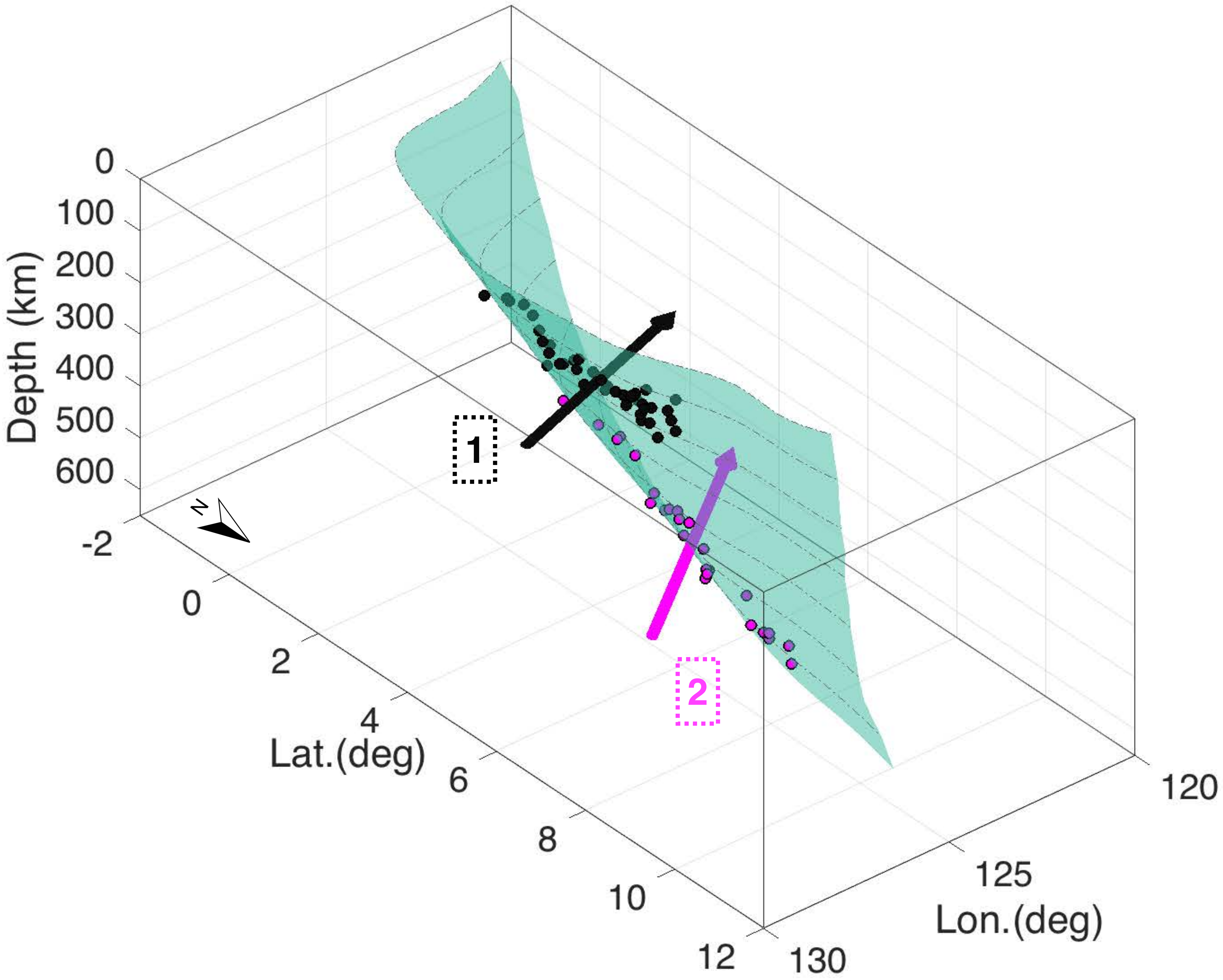
Molucca

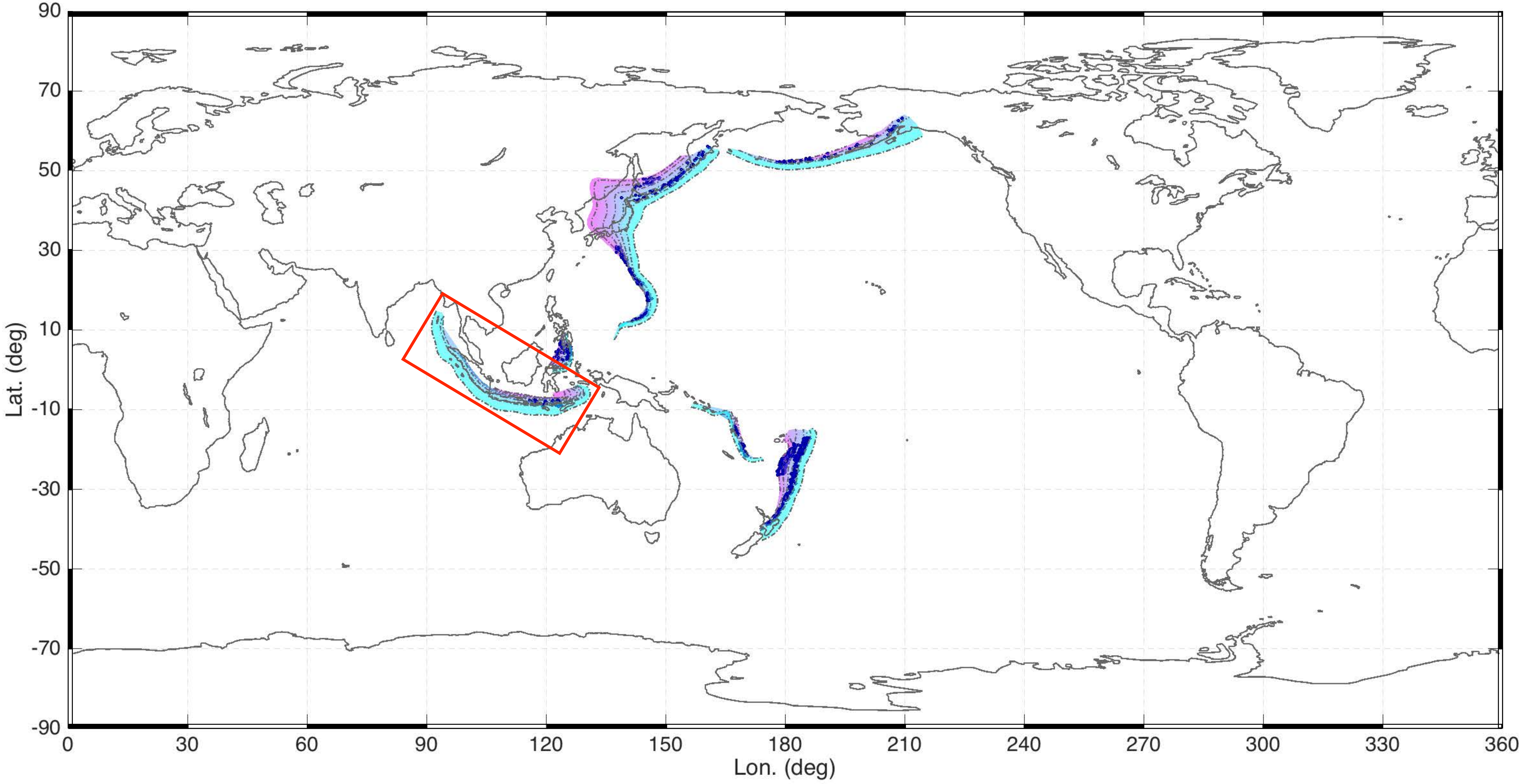
Thomsen Parameter:

$\gamma^{(1)} = 29 \pm 4\%$

$\gamma^{(2)} = 30 \pm 4\%$



Indonesia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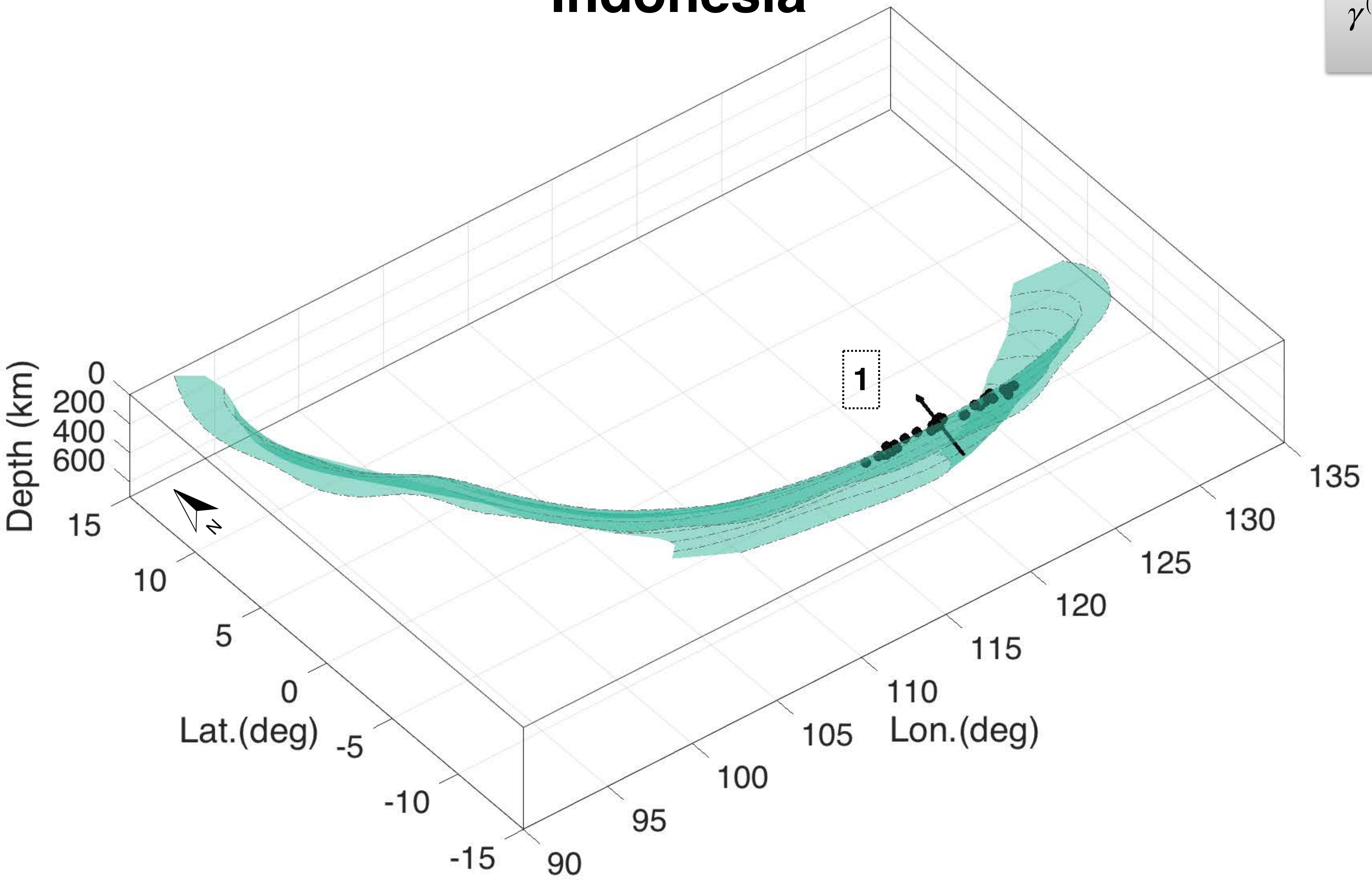
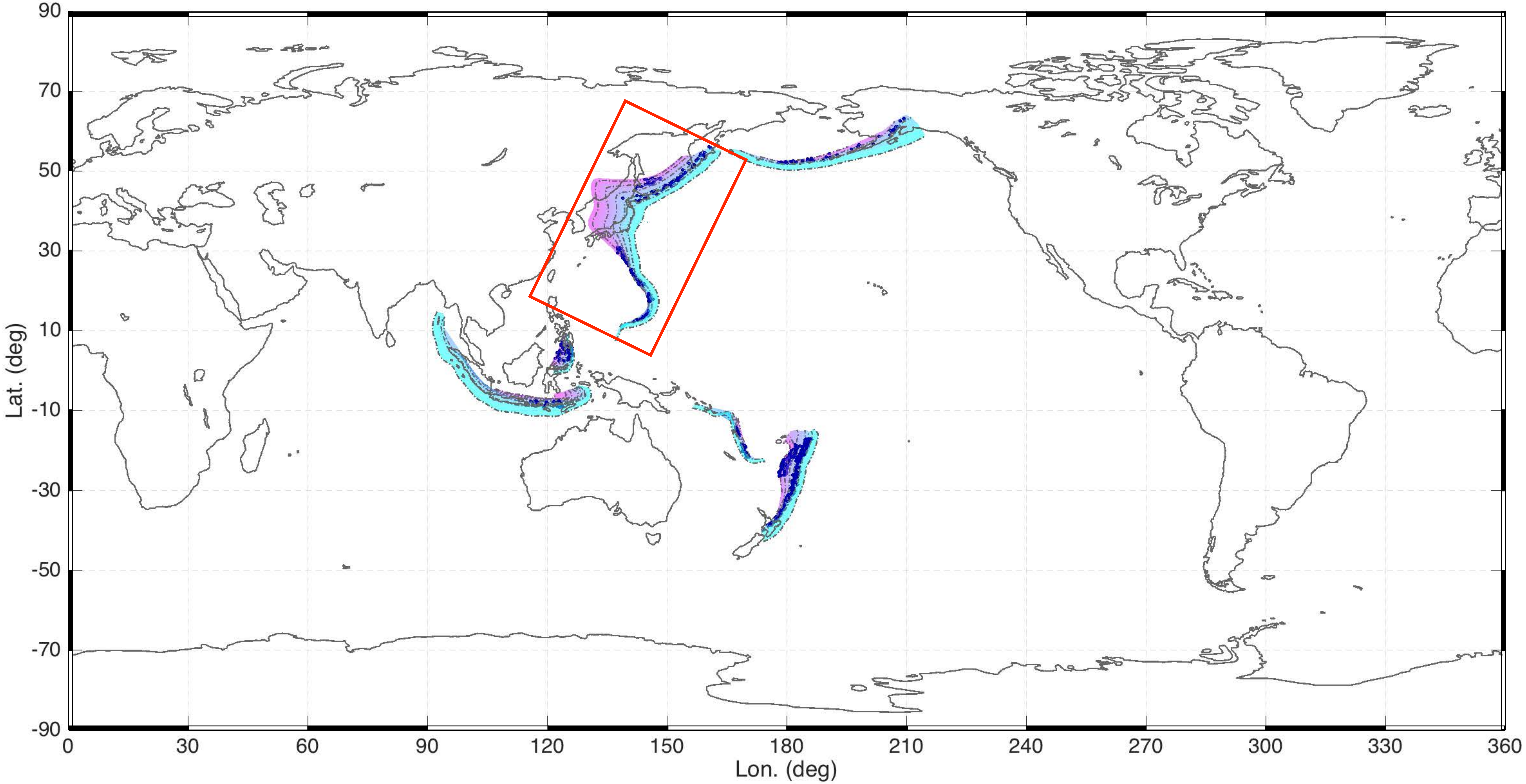
Thomsen Parameter:

$\gamma^{(1)} = 31 \pm 5\%$

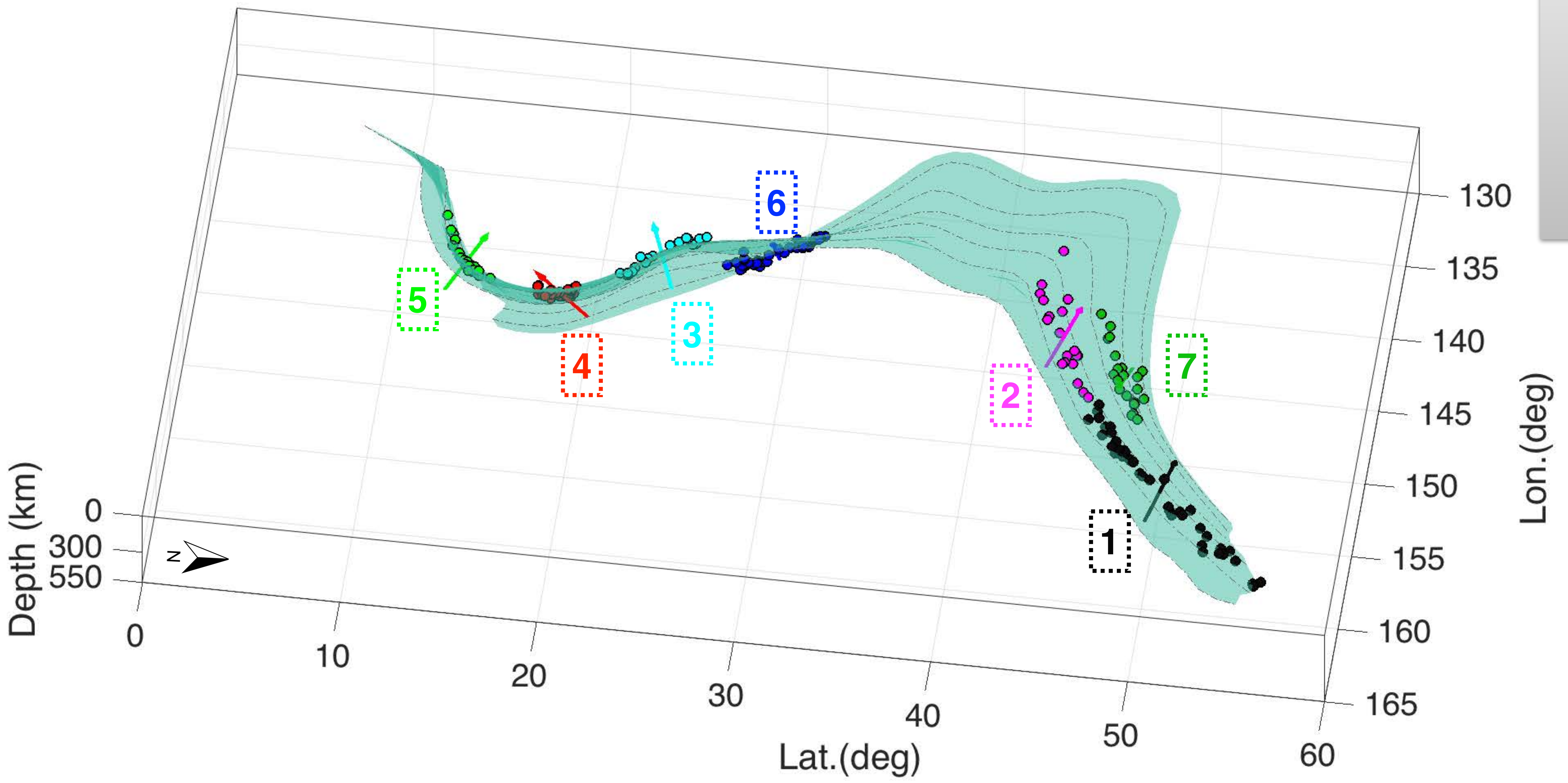
Indonesia



Mariana-Japan-Kuril



Mariana-Japan-Kuril



Thomsen Parameter:

$\gamma^{(1)} = 33 \pm 5\%$

$\gamma^{(2)} = 22 \pm 7\%$

$\gamma^{(3)} = 34 \pm 7\%$

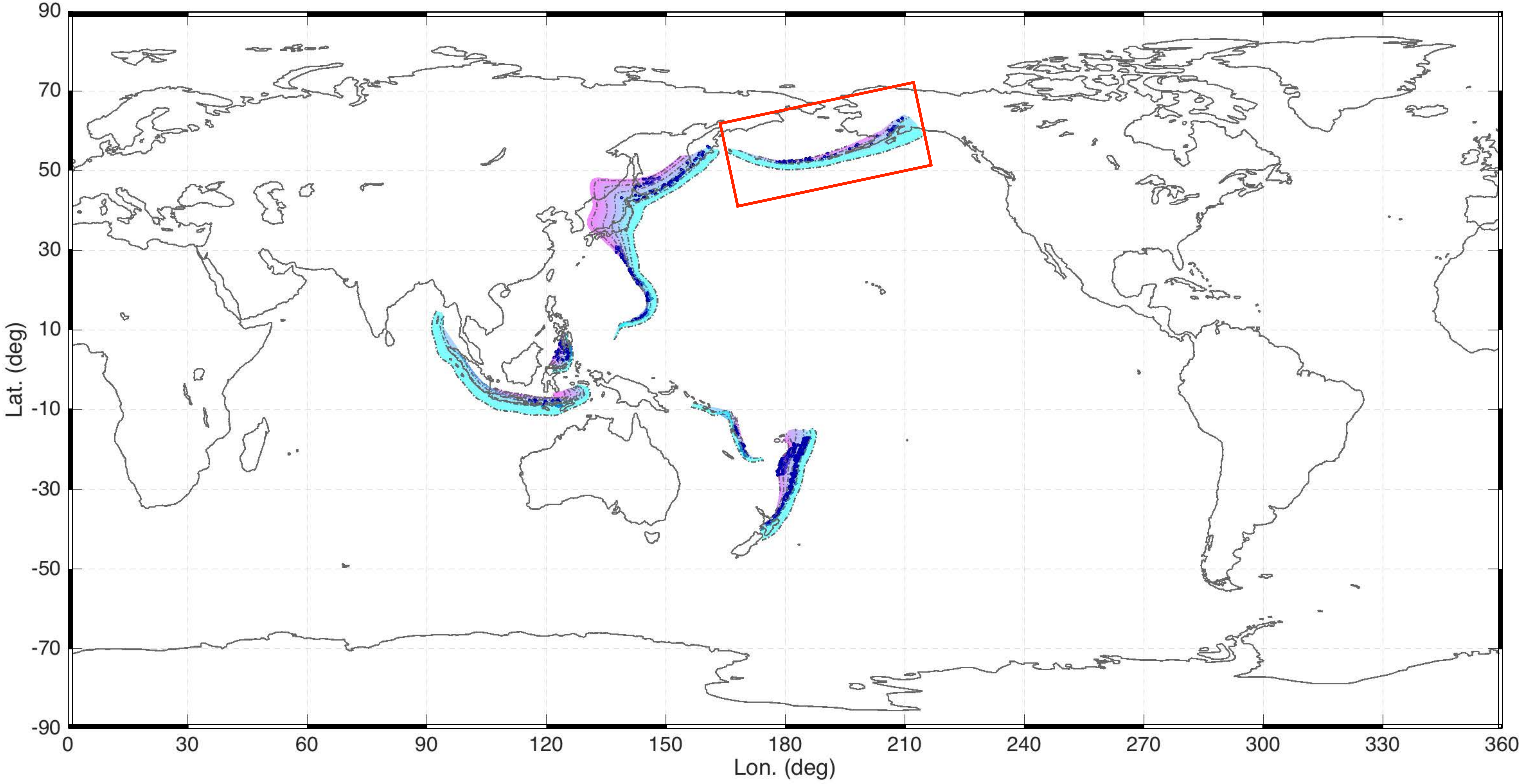
$\gamma^{(4)} = 6 \pm 5\%$

$\gamma^{(5)} = 27 \pm 5\%$

$\gamma^{(6)} = 15 \pm 2\%$

$\gamma^{(7)} = 25 \pm 5\%$

Aleutian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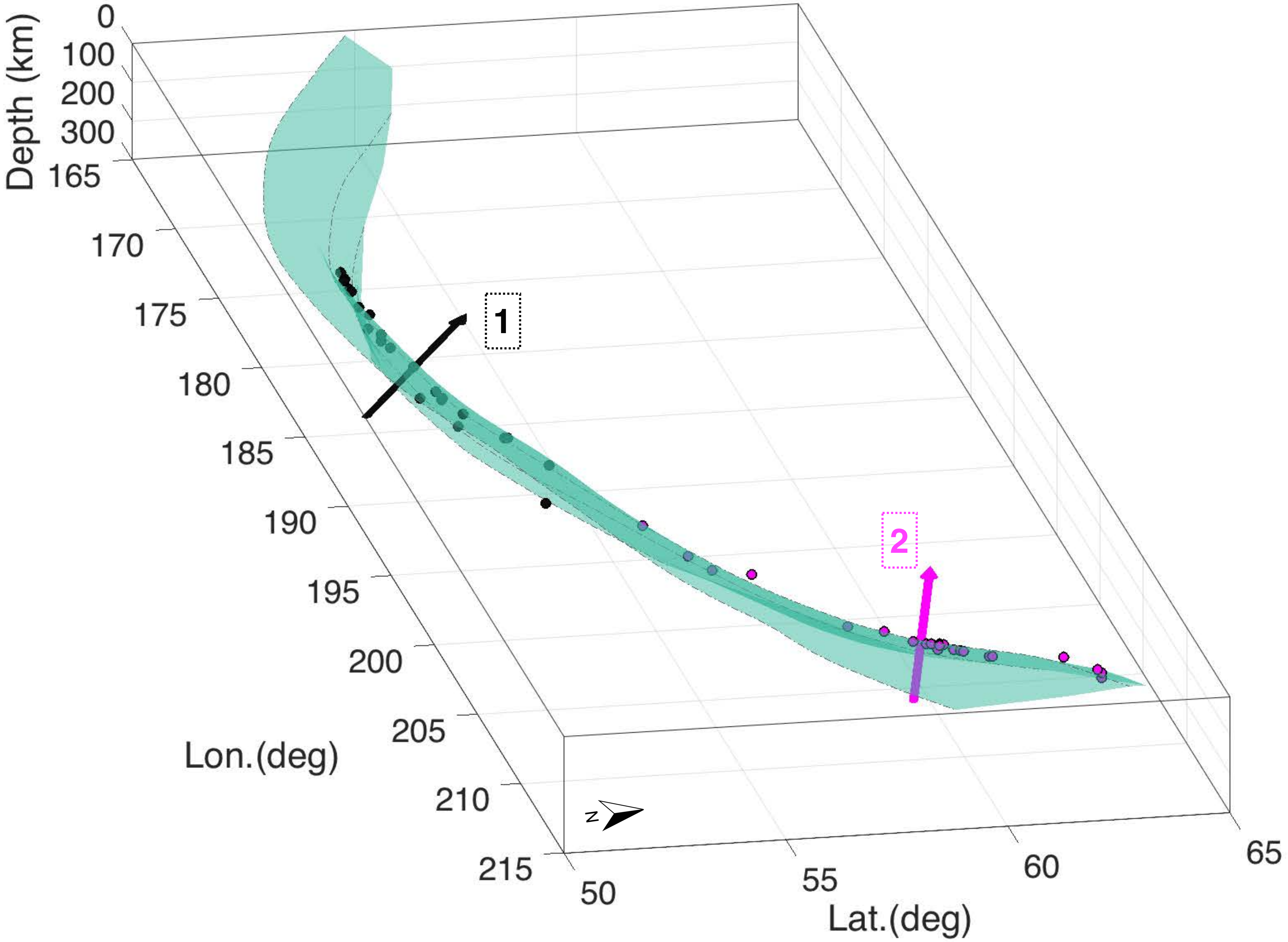
Thomsen Parameter:

$\gamma^{(1)} = 35 \pm 6\%$

$\gamma^{(2)} = 36 \pm 5\%$

Aleutian

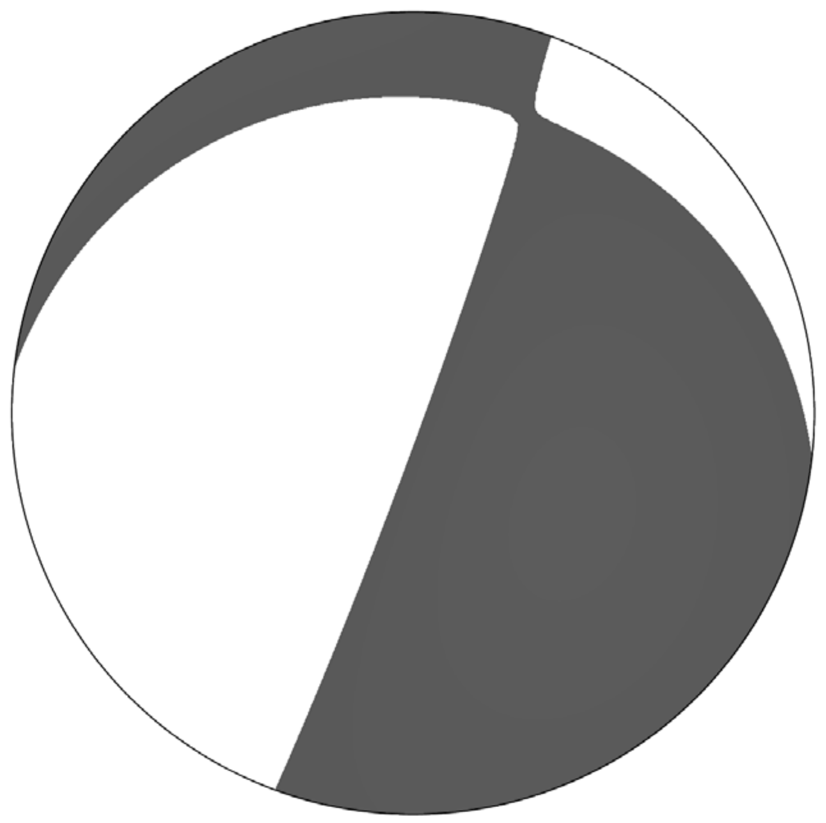


Radiation Pattern Fitting

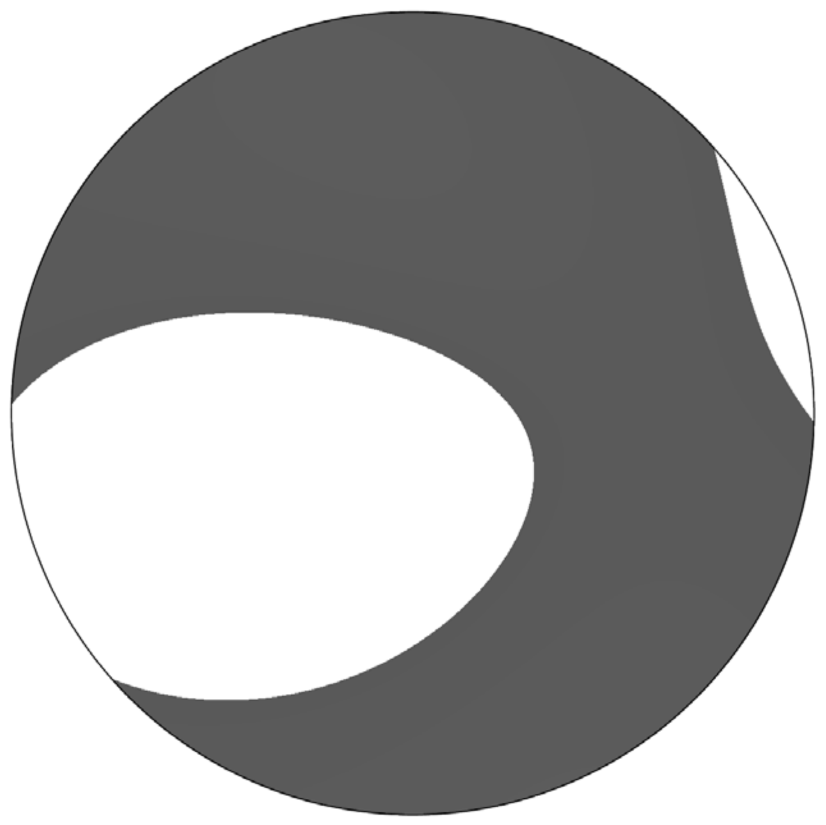
Tonga4

Radiation Pattern Fitting

Observed



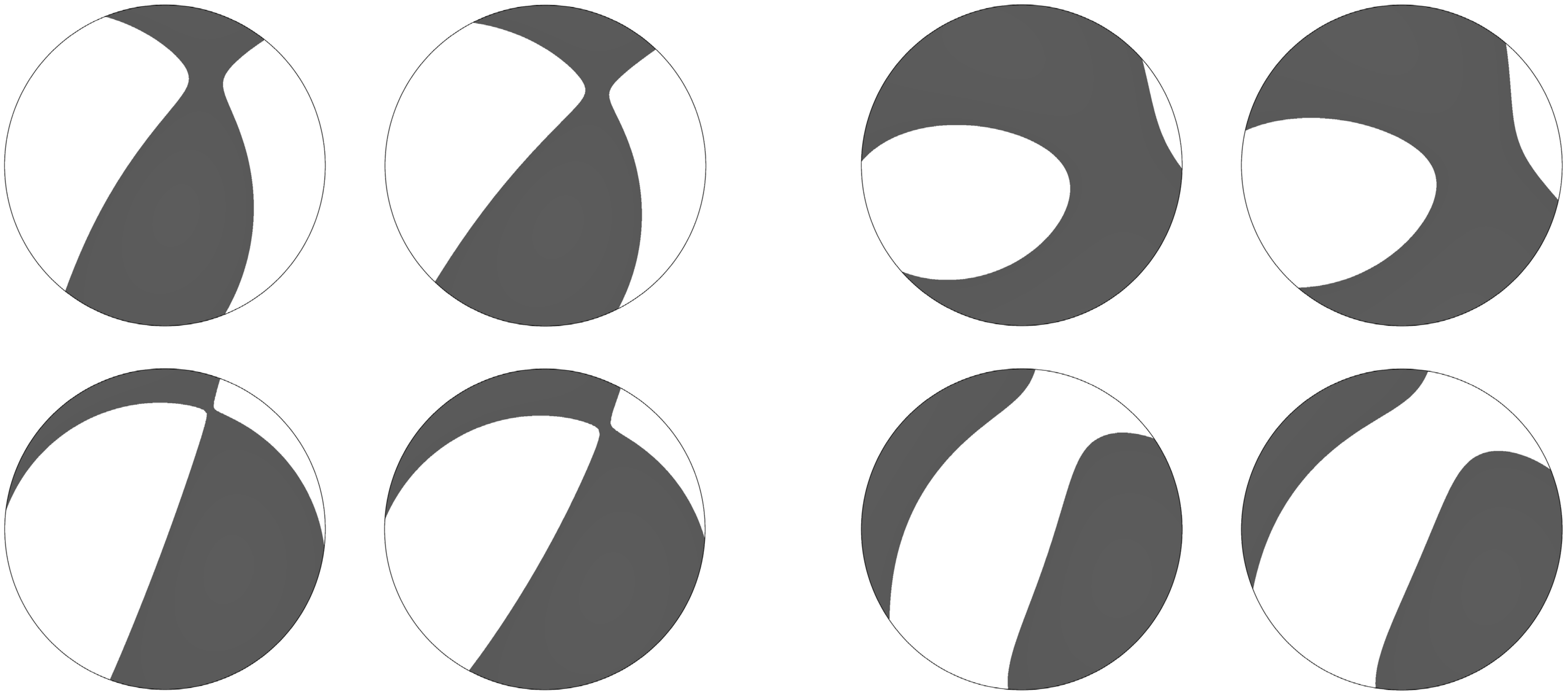
Observed



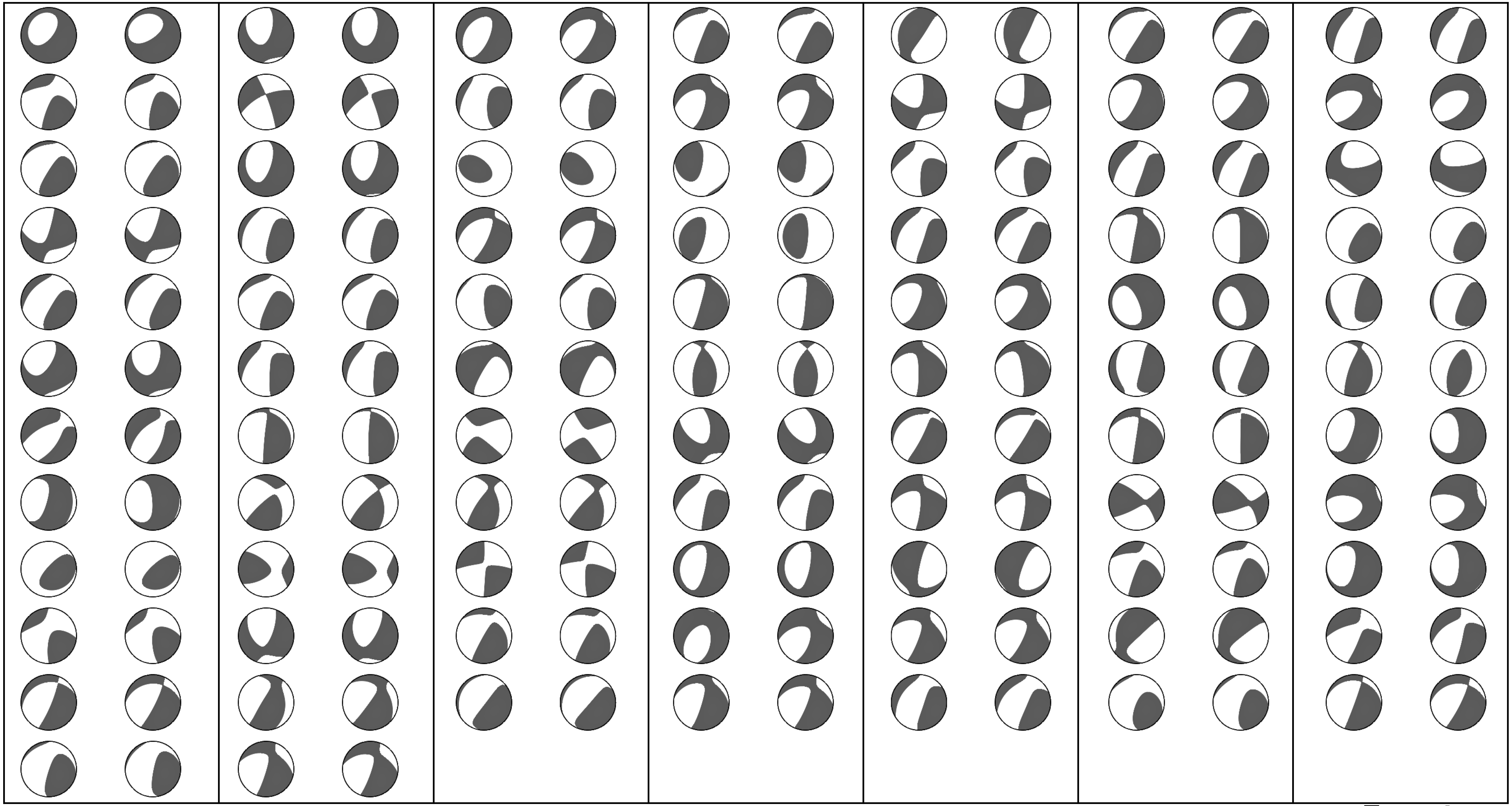
Tonga4

Radiation Pattern Fitting

Observed **Synthetic** **Observed** **Synthetic**

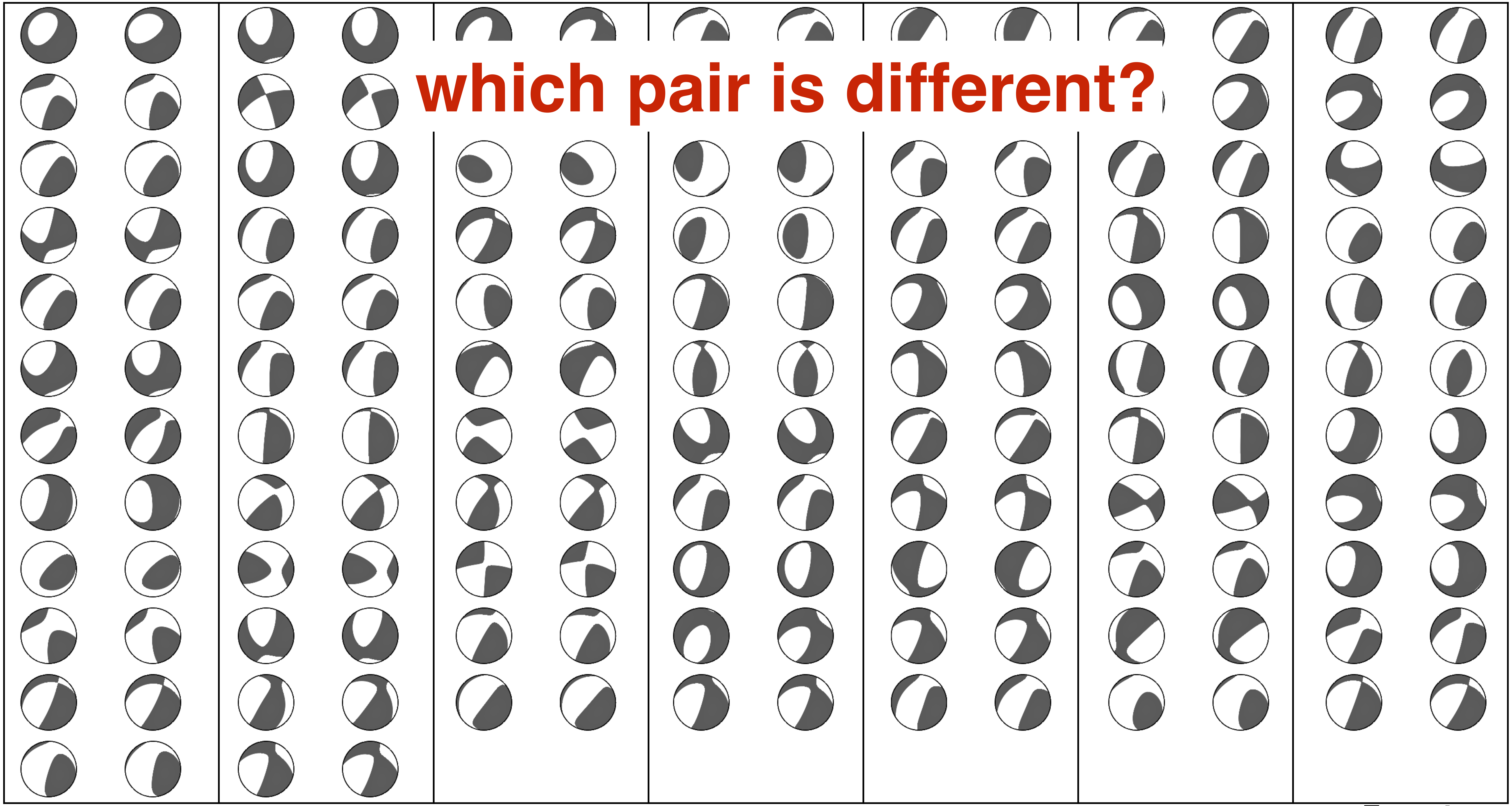


Tonga4



Tonga4

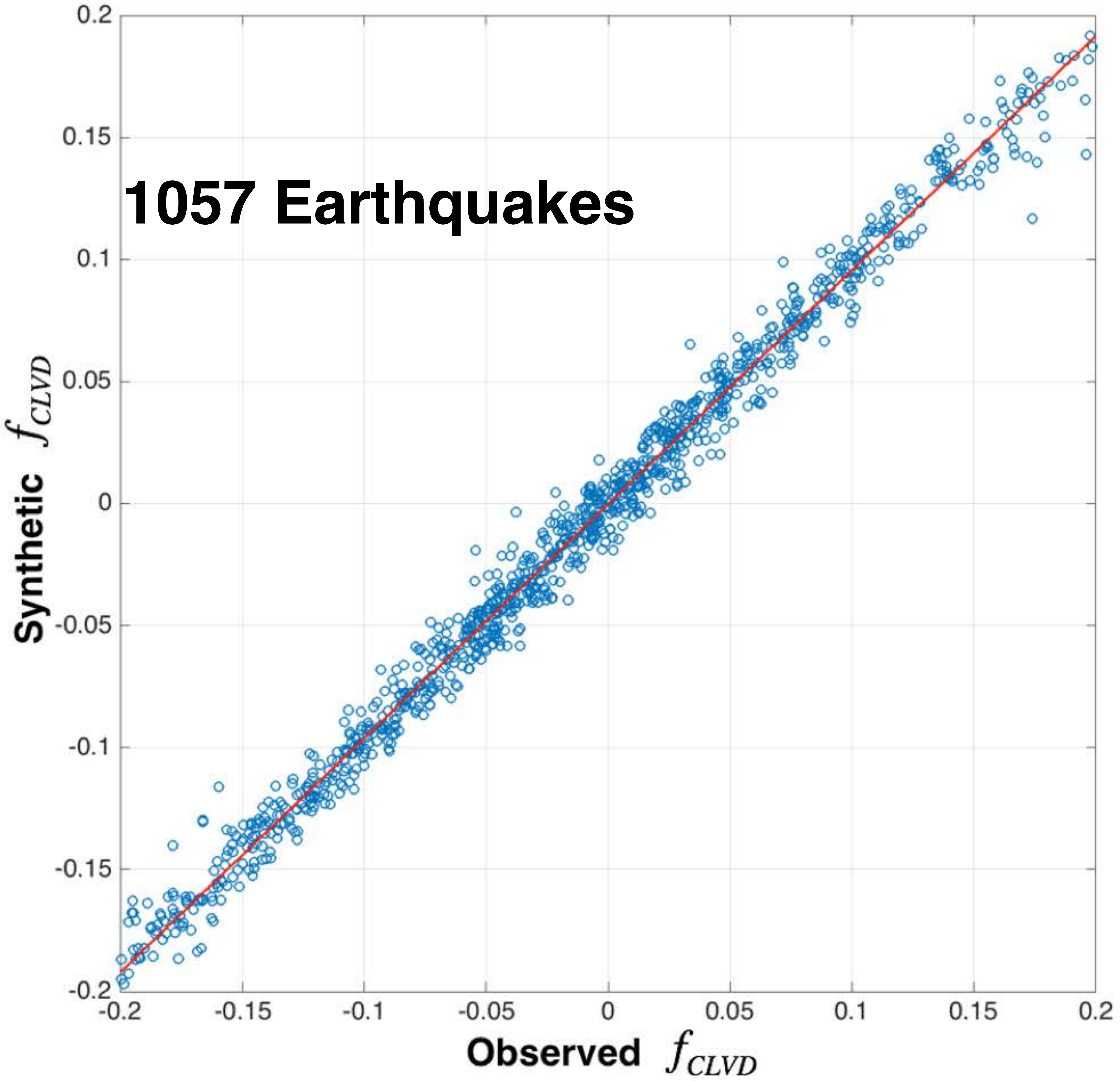
which pair is different?



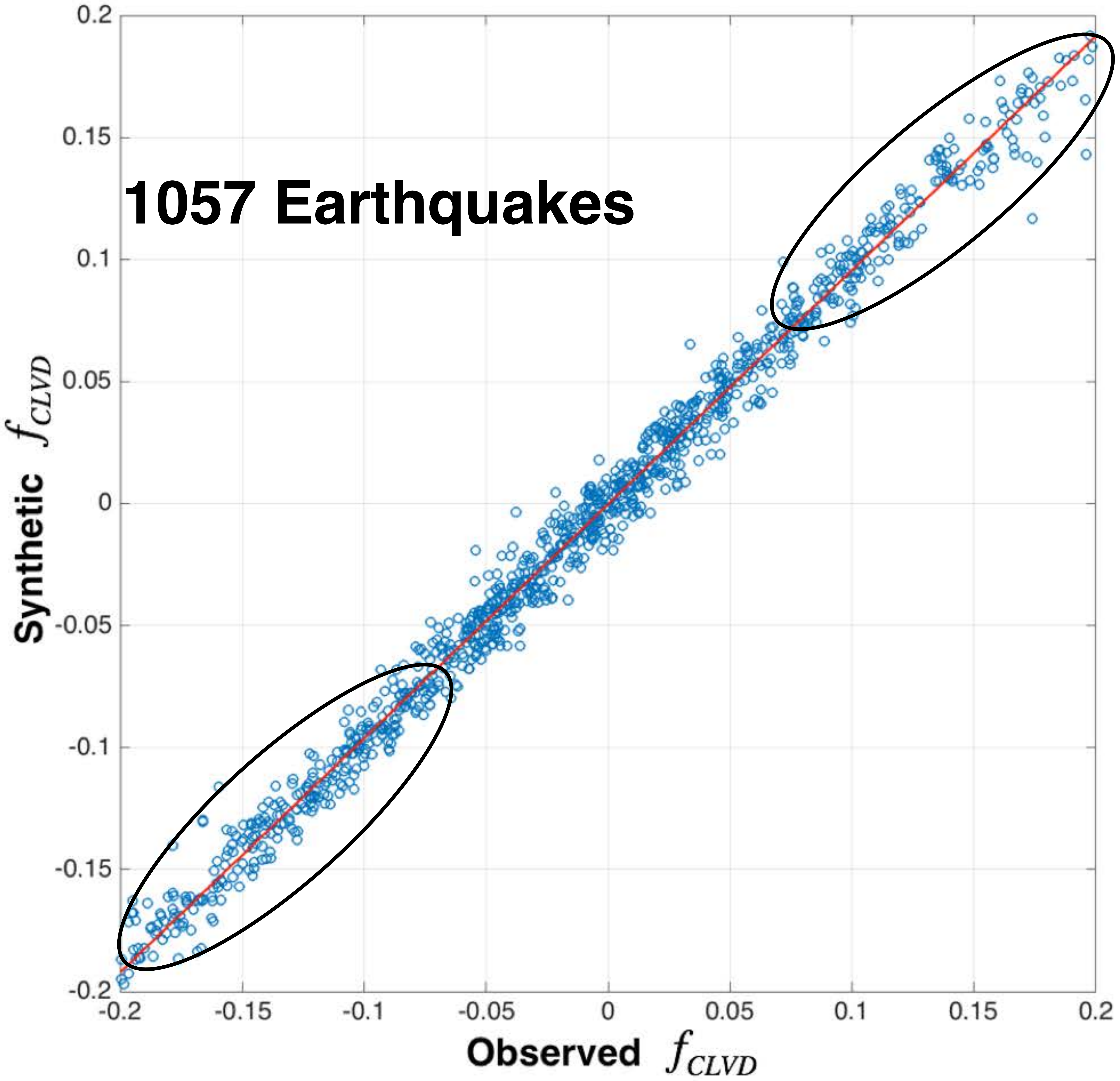
Tonga4

Non-double-couple Component Fitting

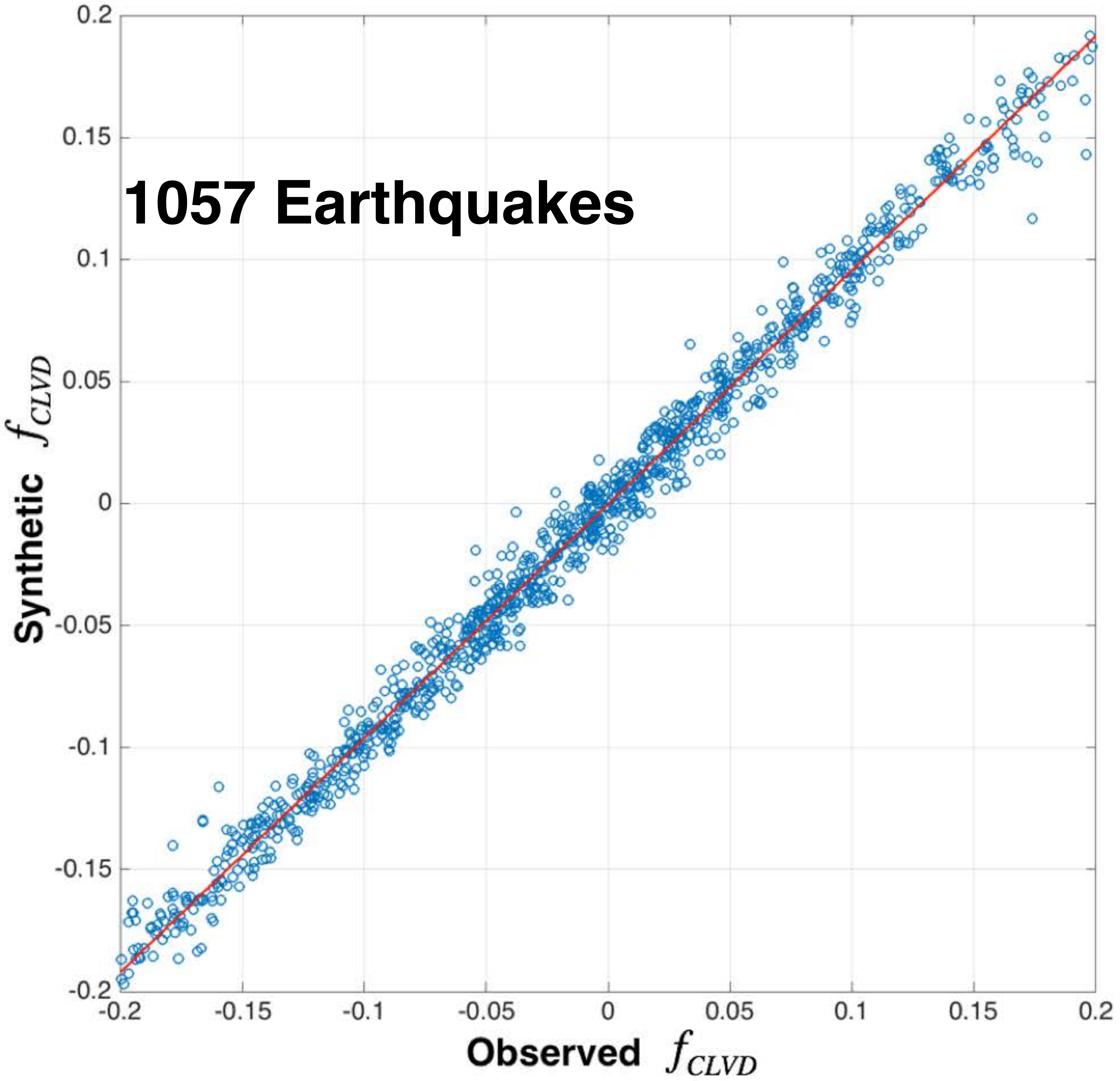
Non-double-couple Component Fitting



Non-double-couple Component Fitting



Non-double-couple Component Fitting



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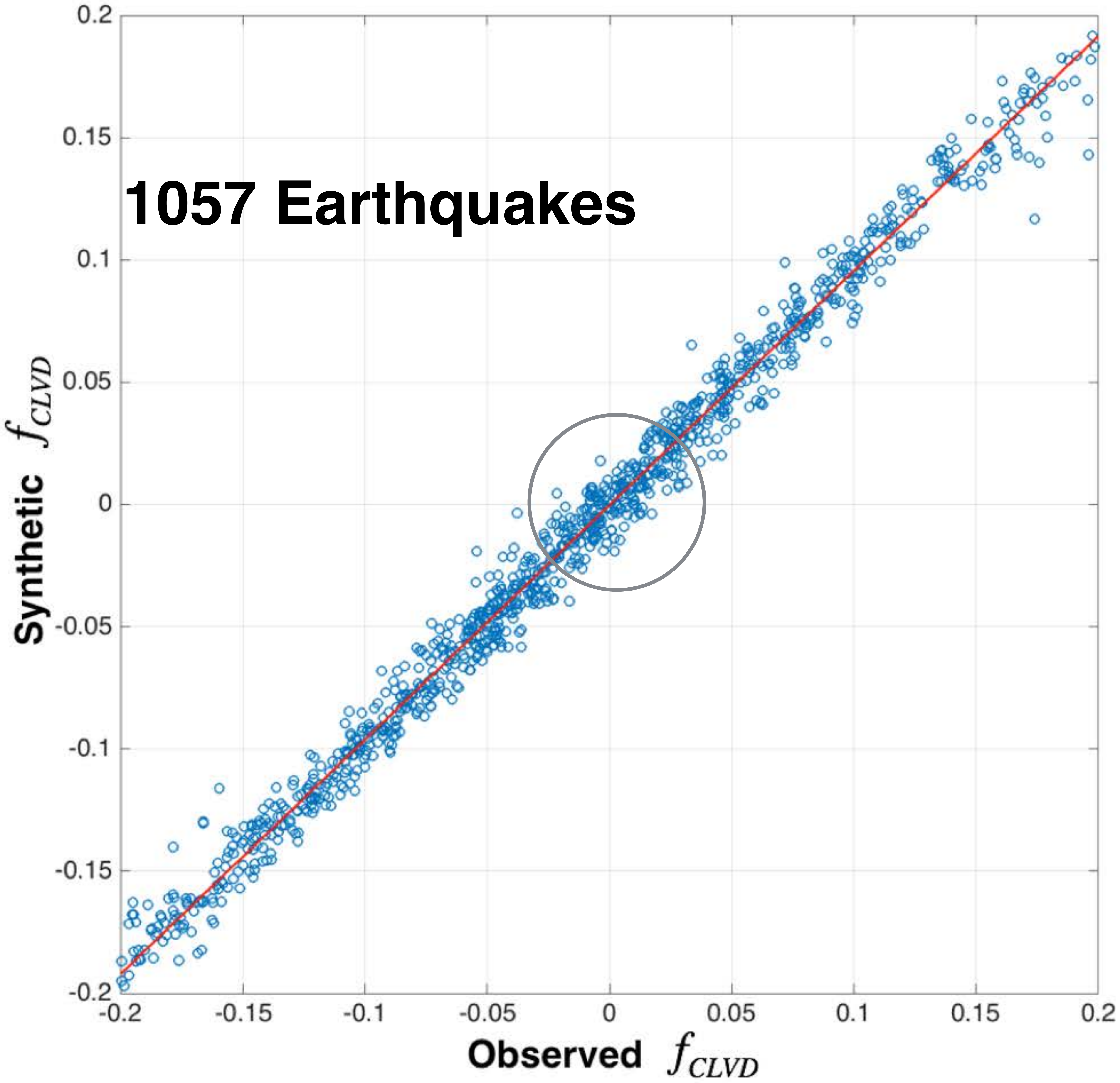
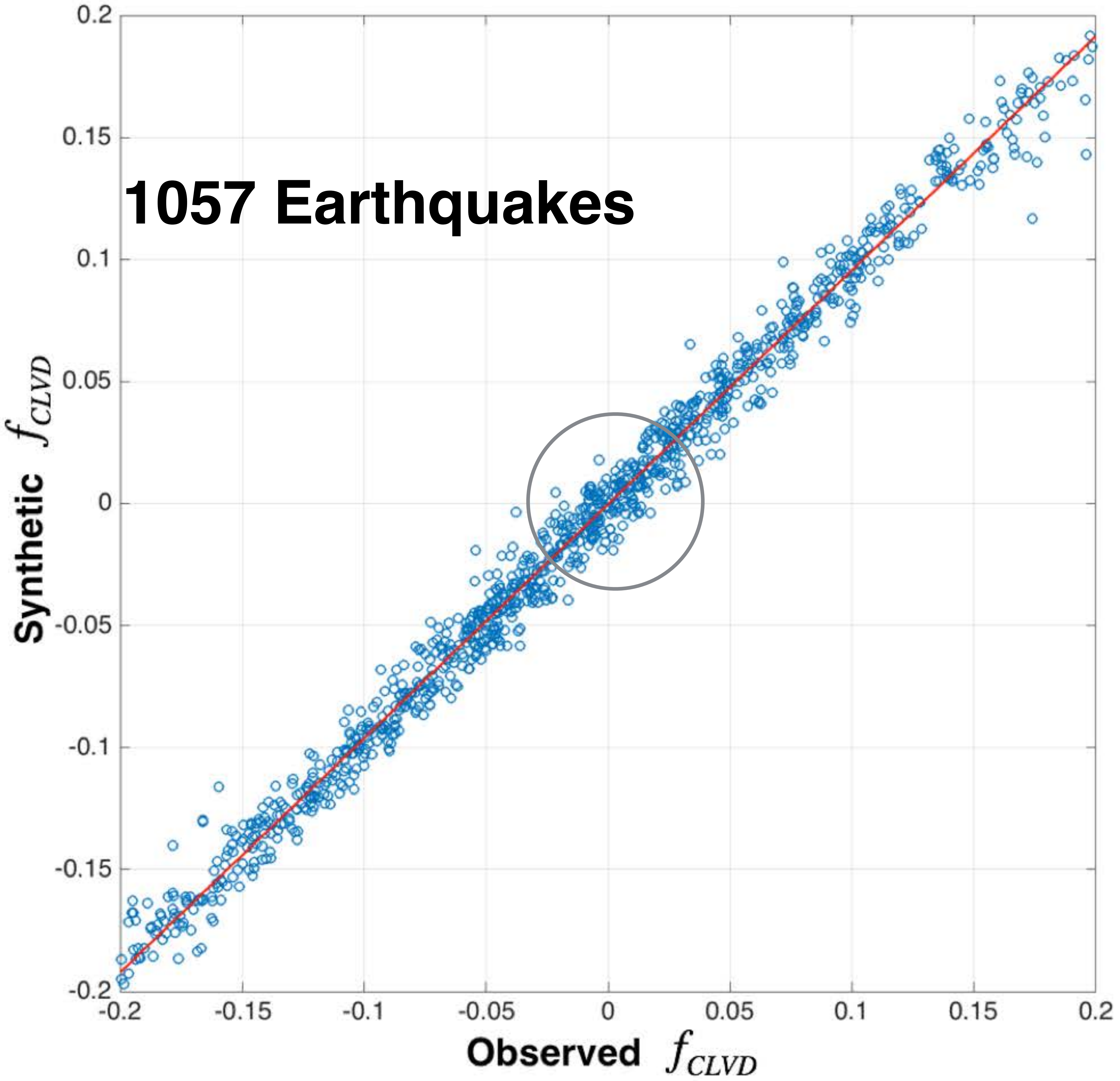
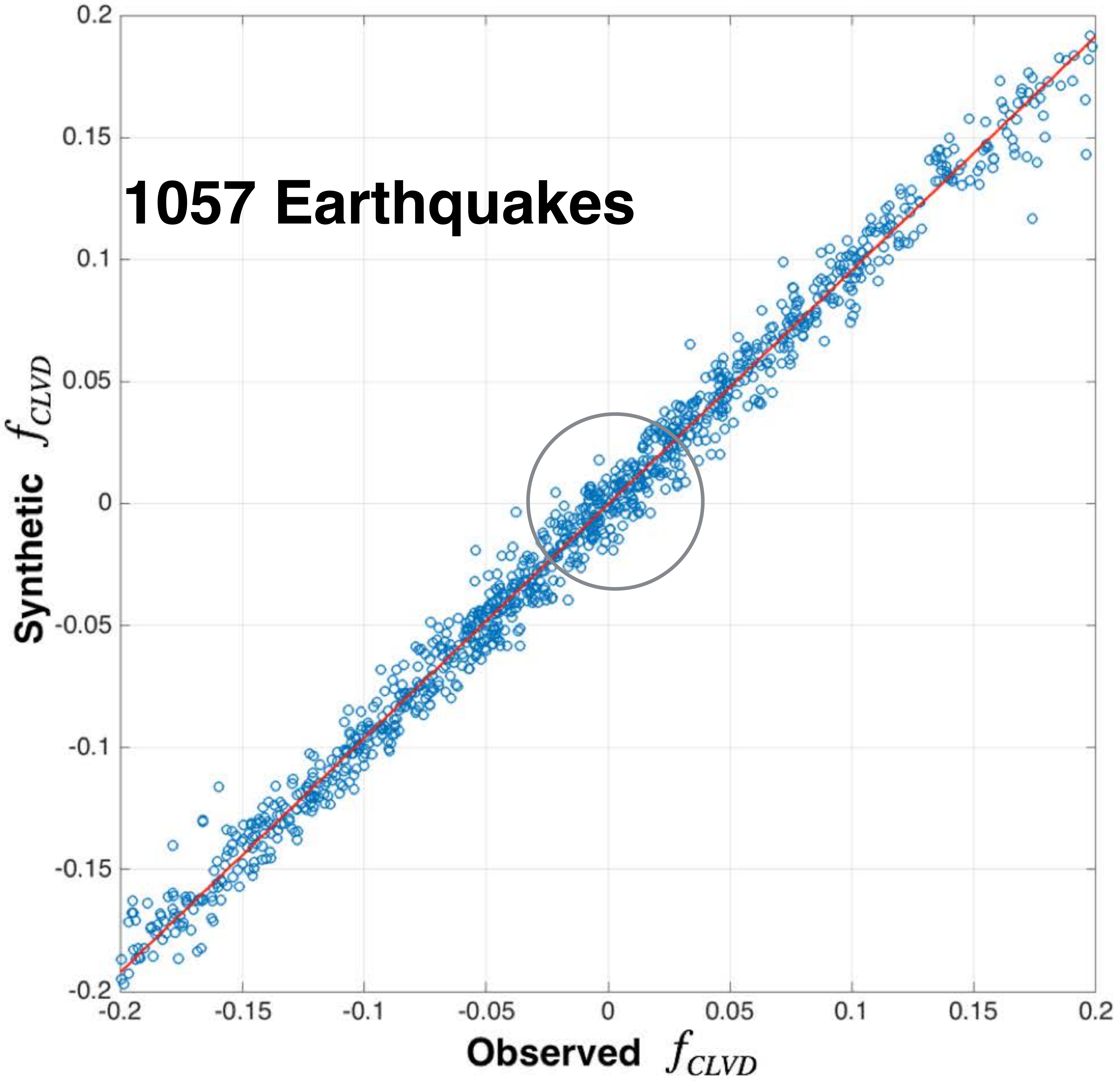


Non-double-couple Component Fitting



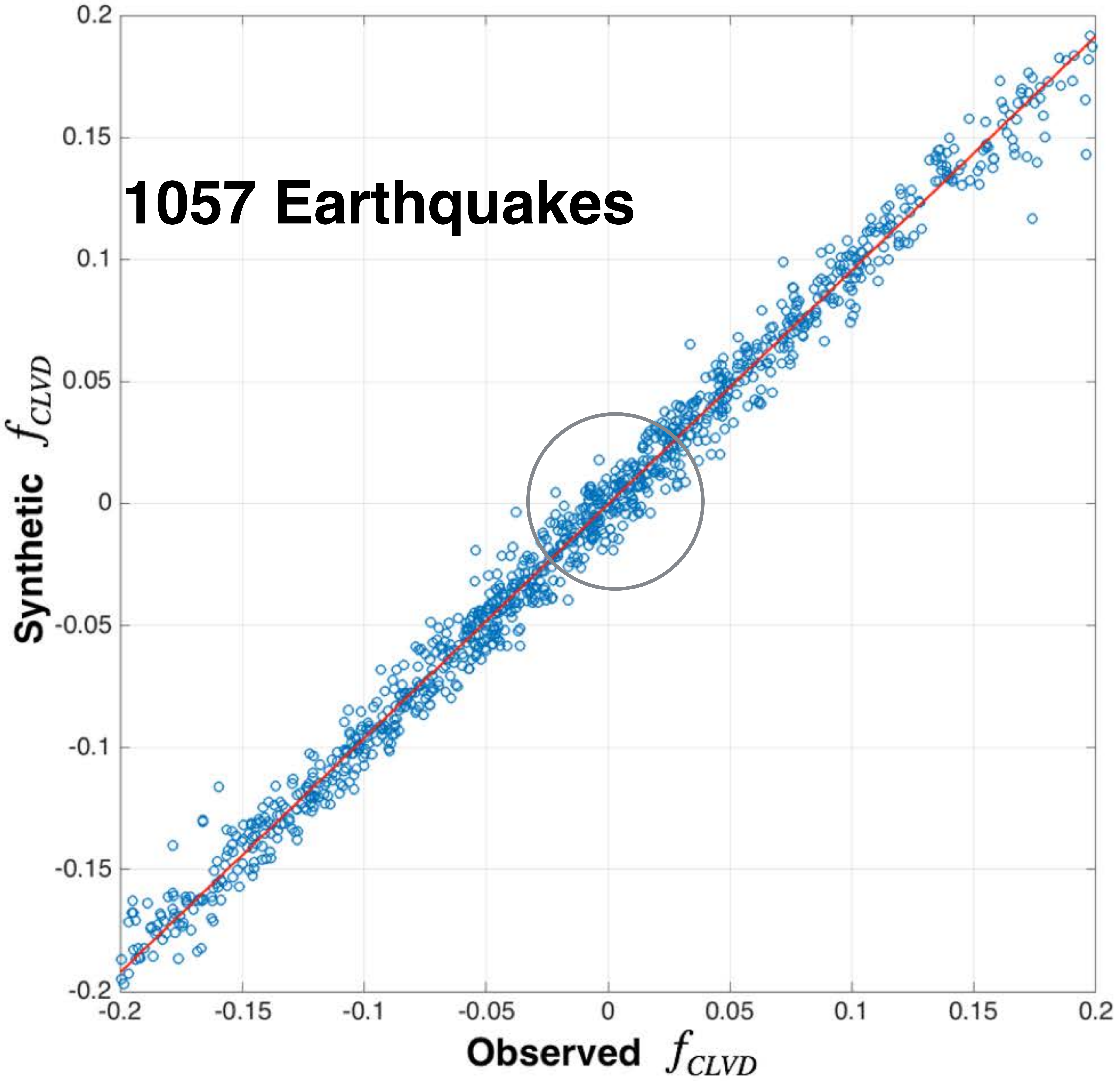
- **We can reproduce the non-DC component using shear dislocation source in tilted laminated anisotropy.**

Non-double-couple Component Fitting



- **We can reproduce the non-DC component using shear dislocation source in tilted laminated anisotropy.**
- **For 1057 deep earthquakes.**

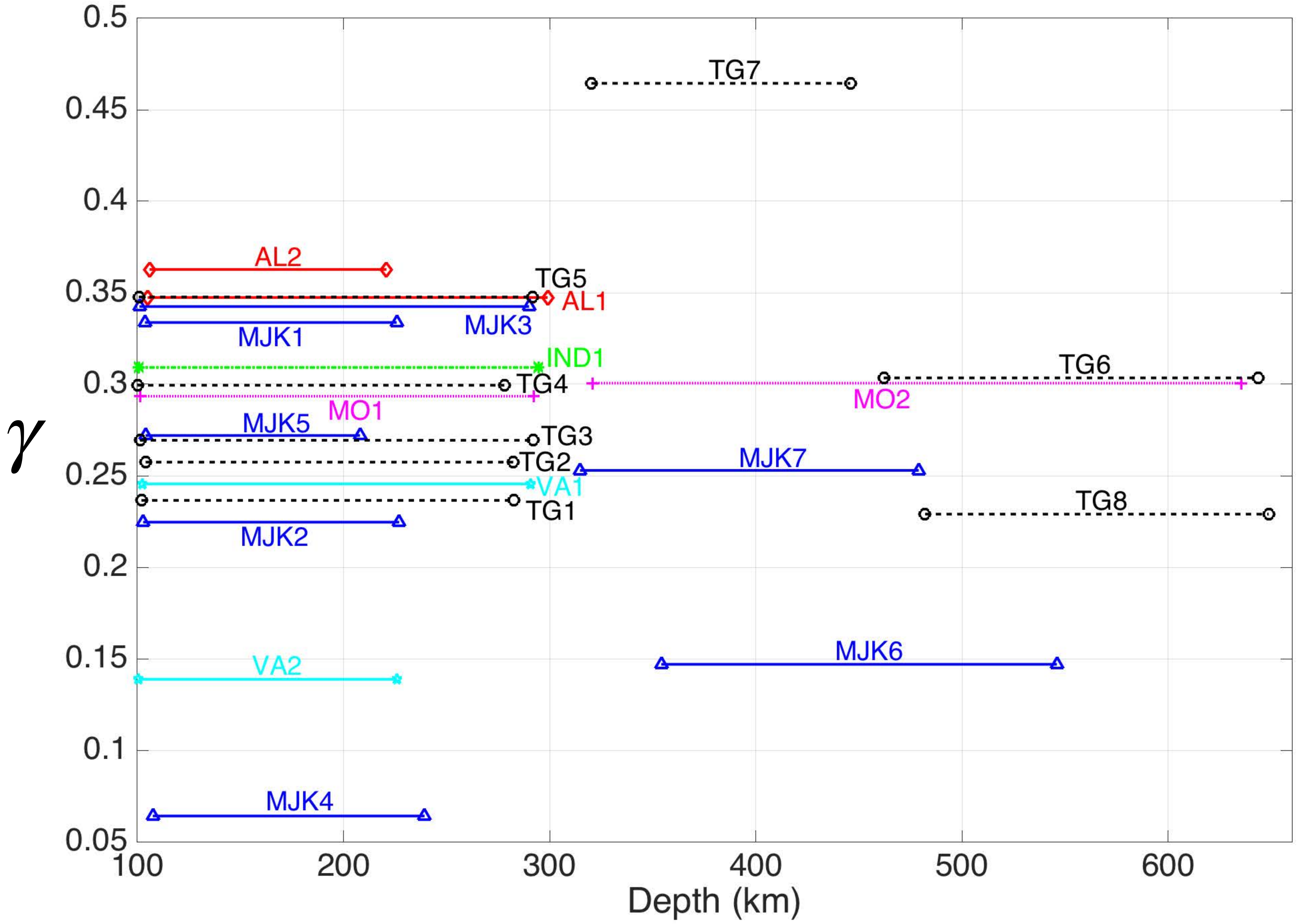
Non-double-couple Component Fitting



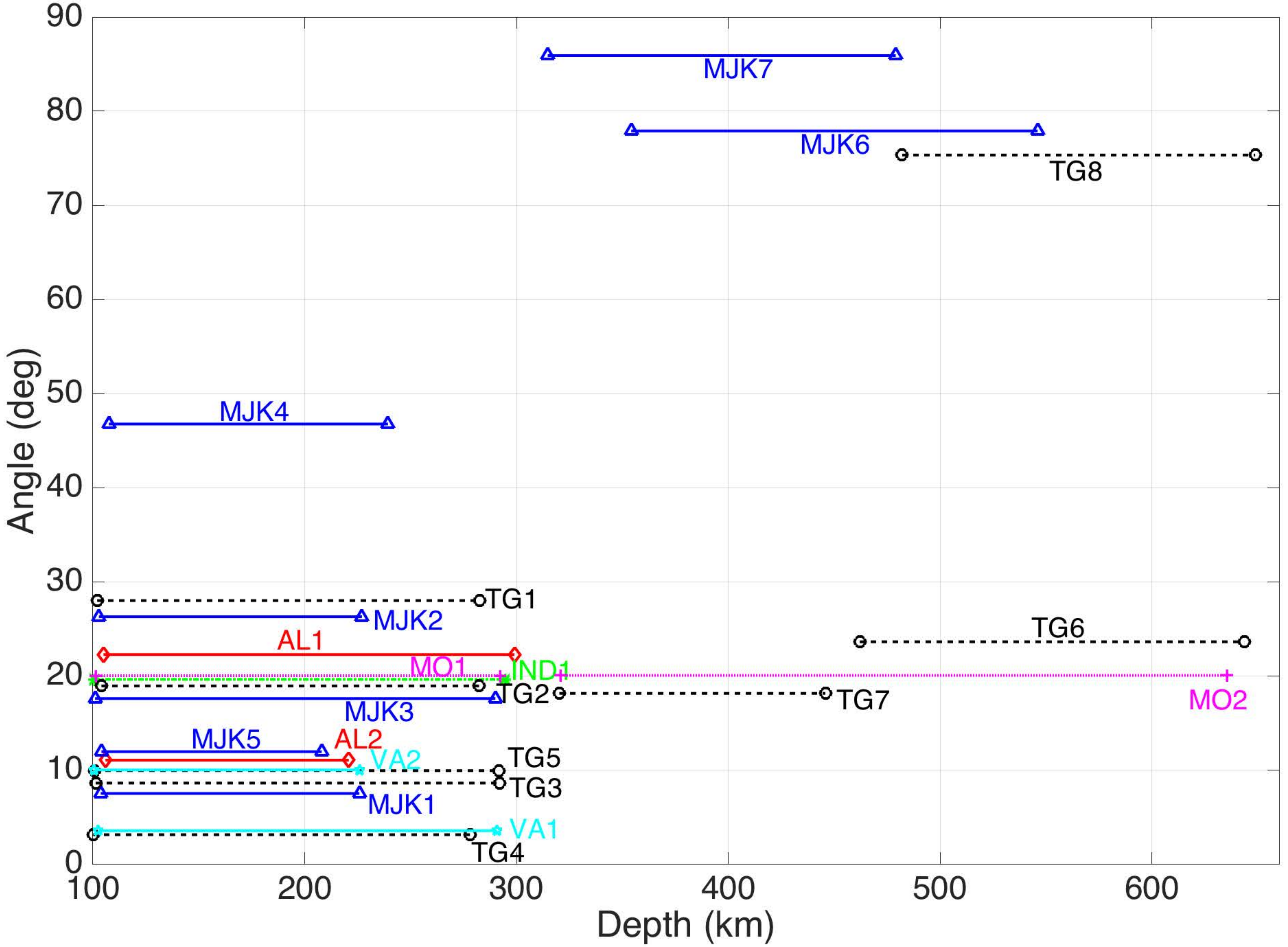
- **We can reproduce the non-DC component using shear dislocation source in tilted laminated anisotropy.**
- **For 1057 deep earthquakes.**
- **We can fit both large non-DC and small non-DC simultaneously.**

Inversion summary

Gamma (S anisotropy)-Depth

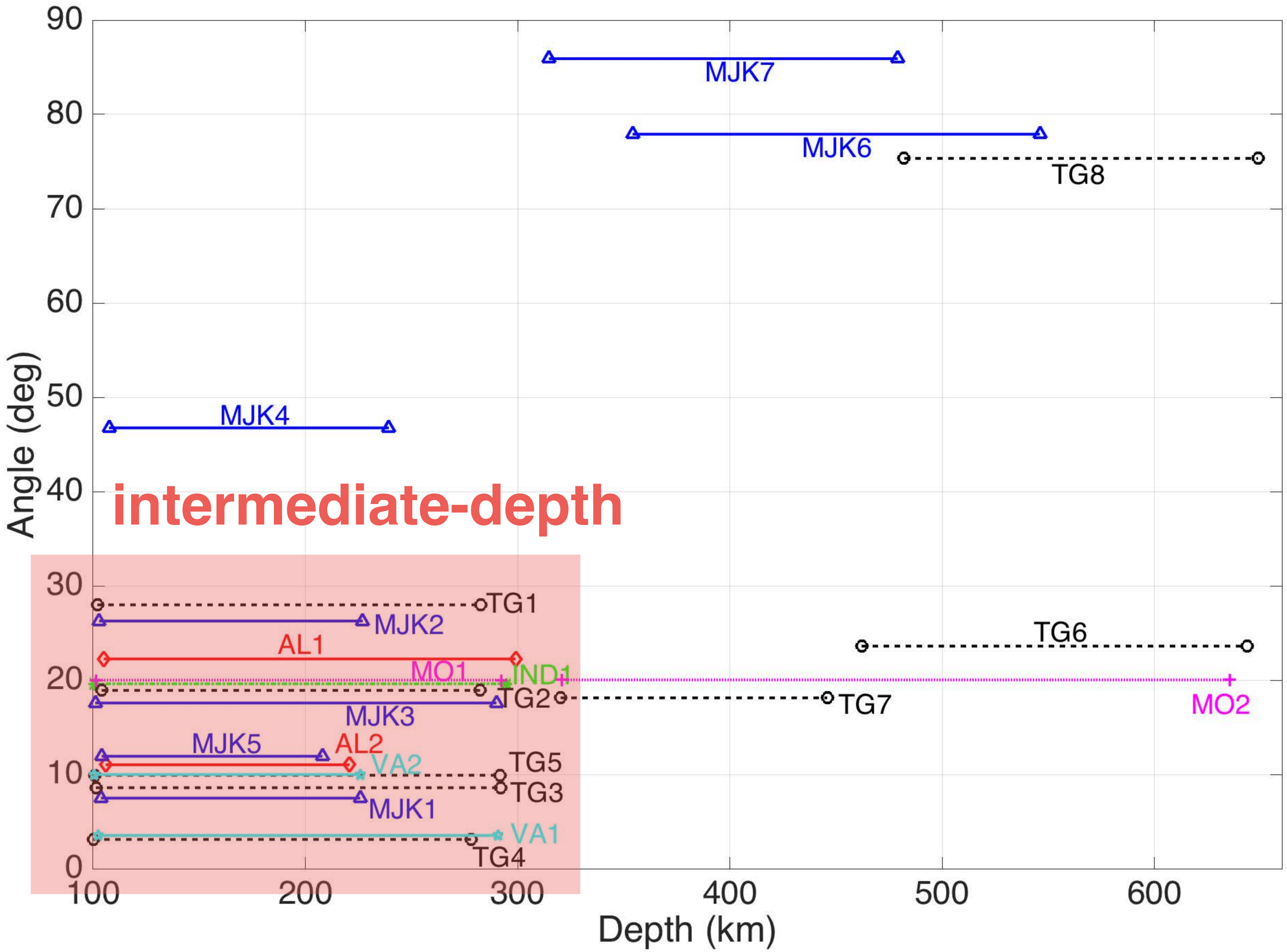


Angle-Depth



TG: Tonga
MJK: Mariana-Japan-Kuril
AL: Aleutian
MO: Molucca
VA: Vanuatu
IND: Indonesia

Angle-Depth



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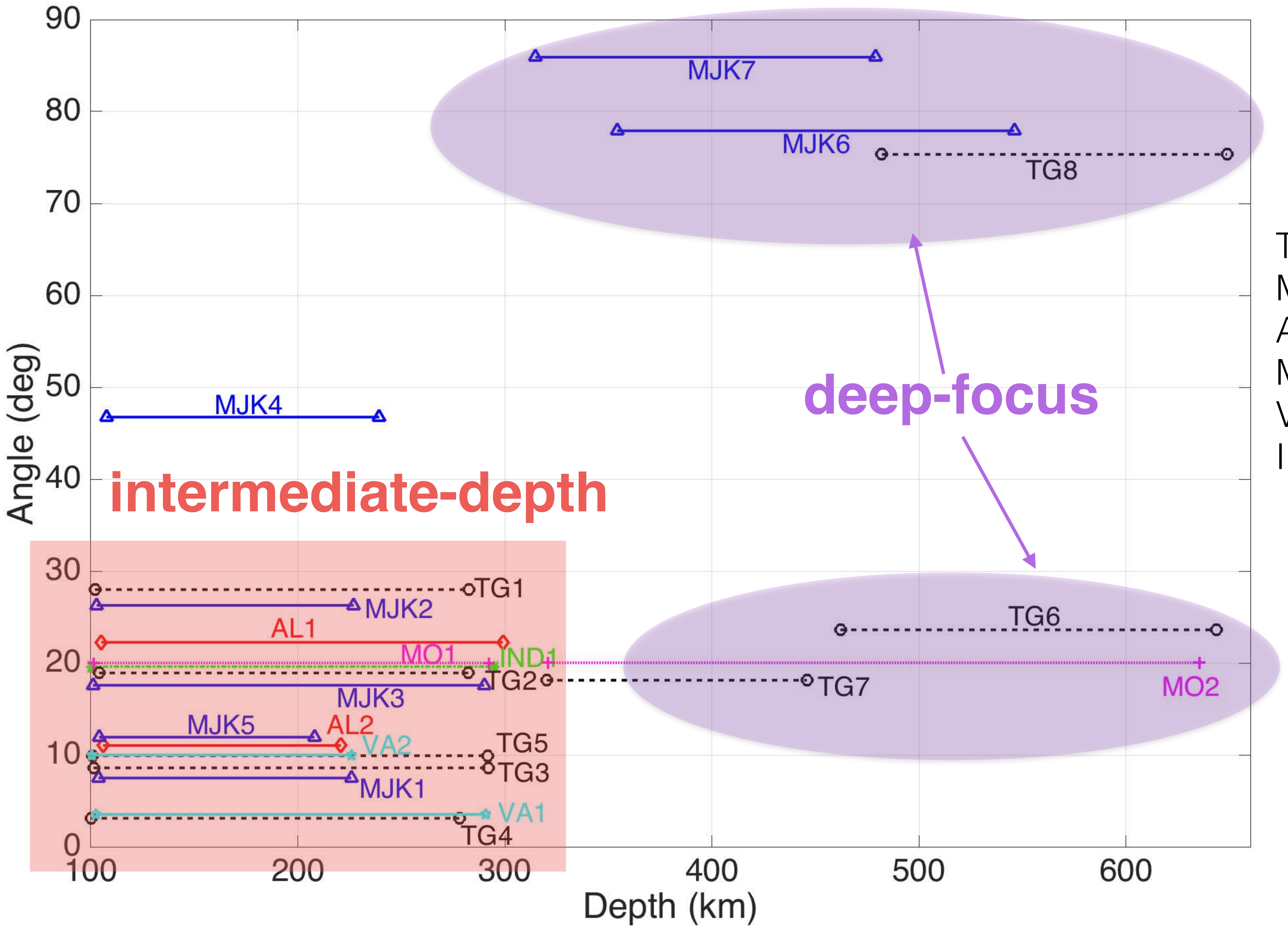
Angle-Depth



TG: Tonga
MJK: Mariana-Japan-Kuril
AL: Aleutian
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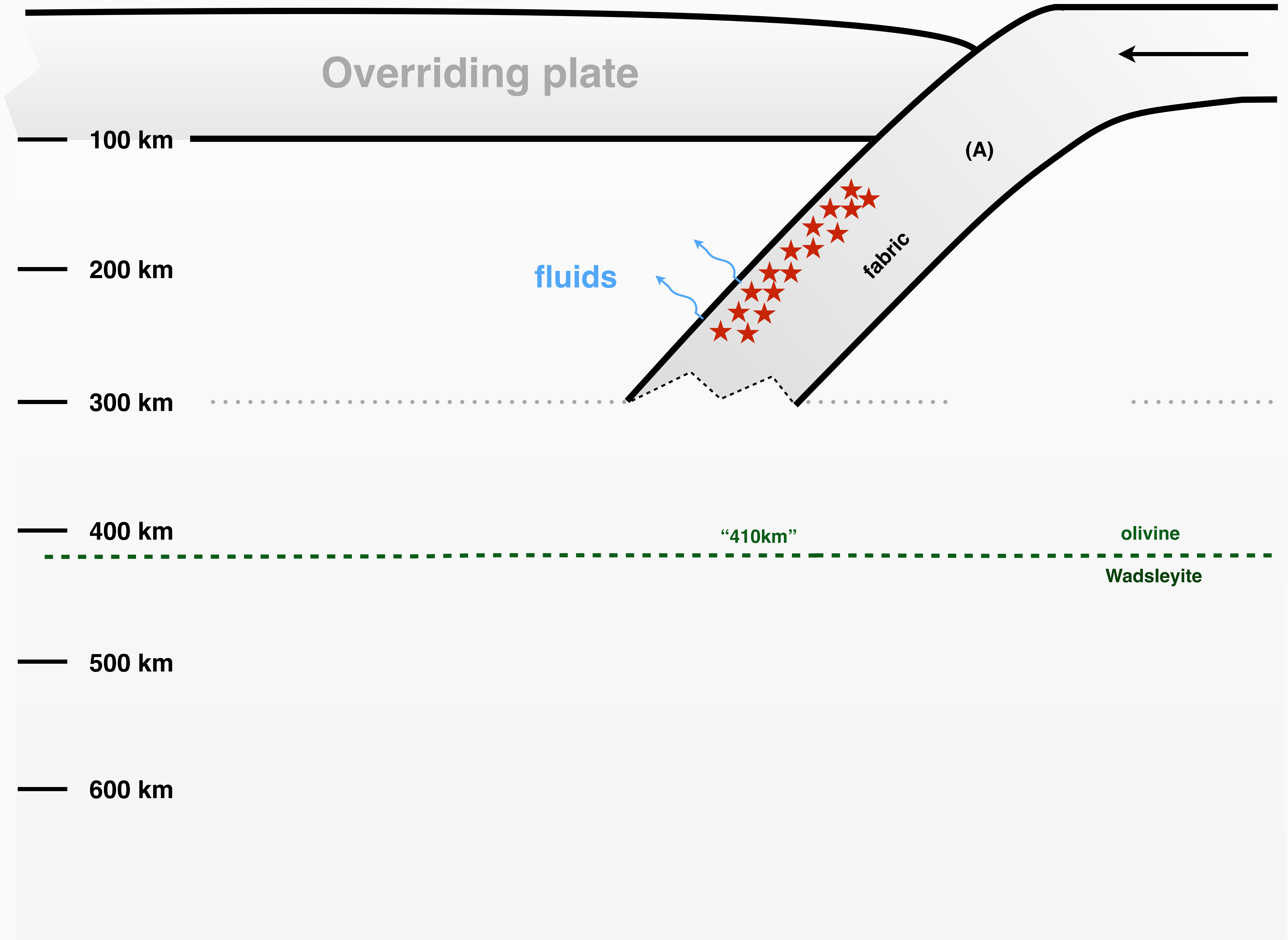
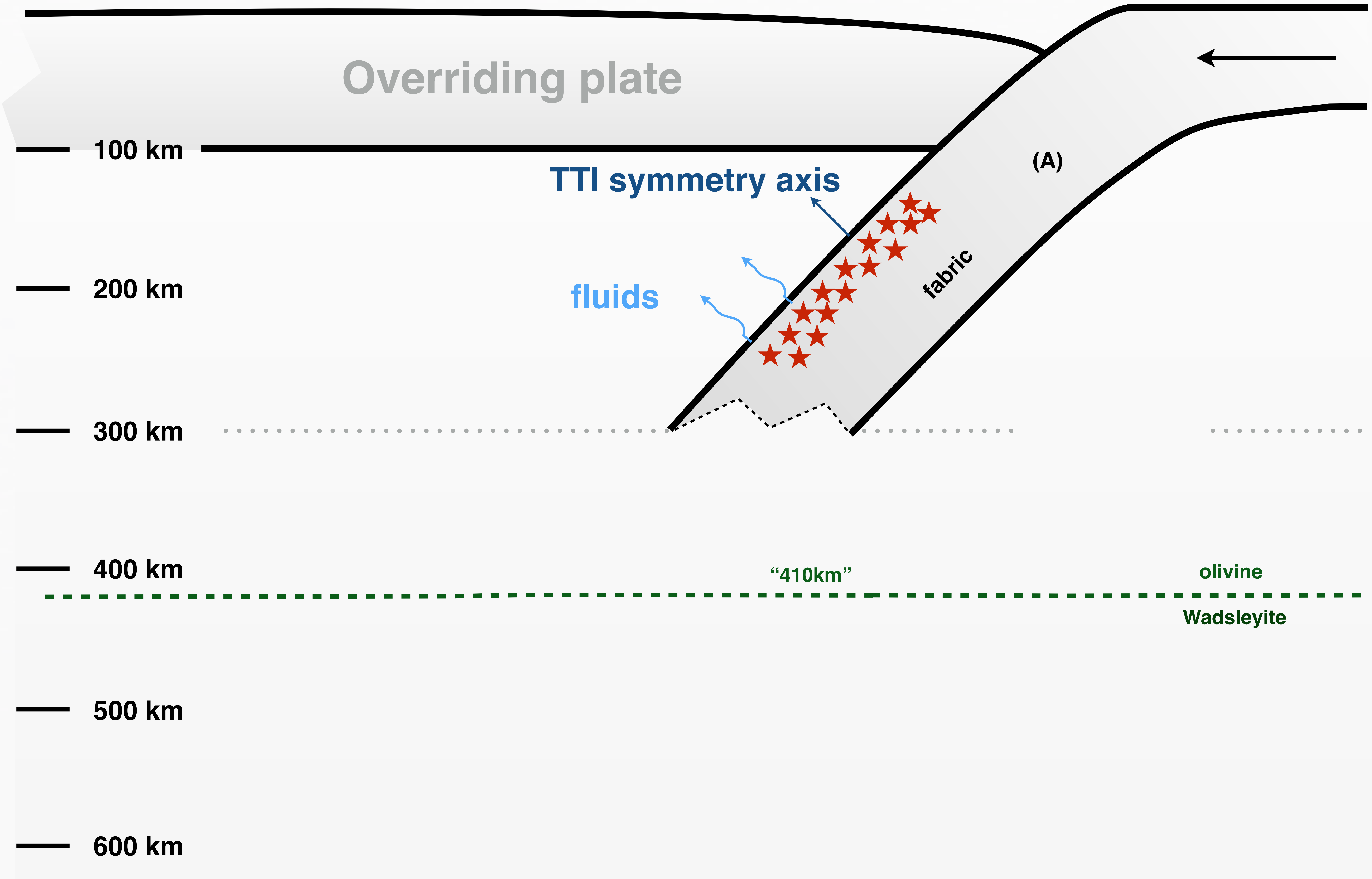
Schematic Diagram

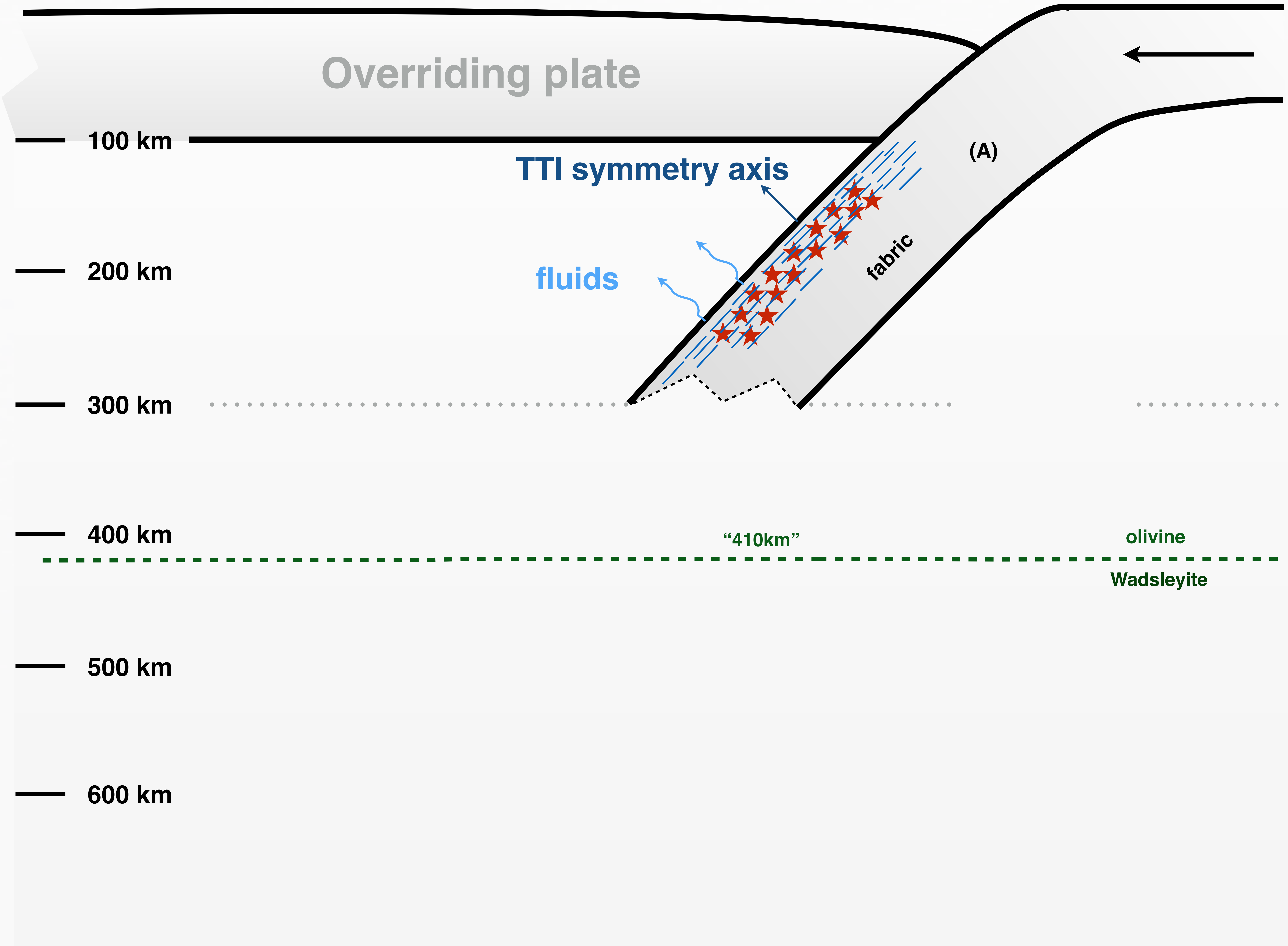
Schematic Diagram



Schematic Diagram

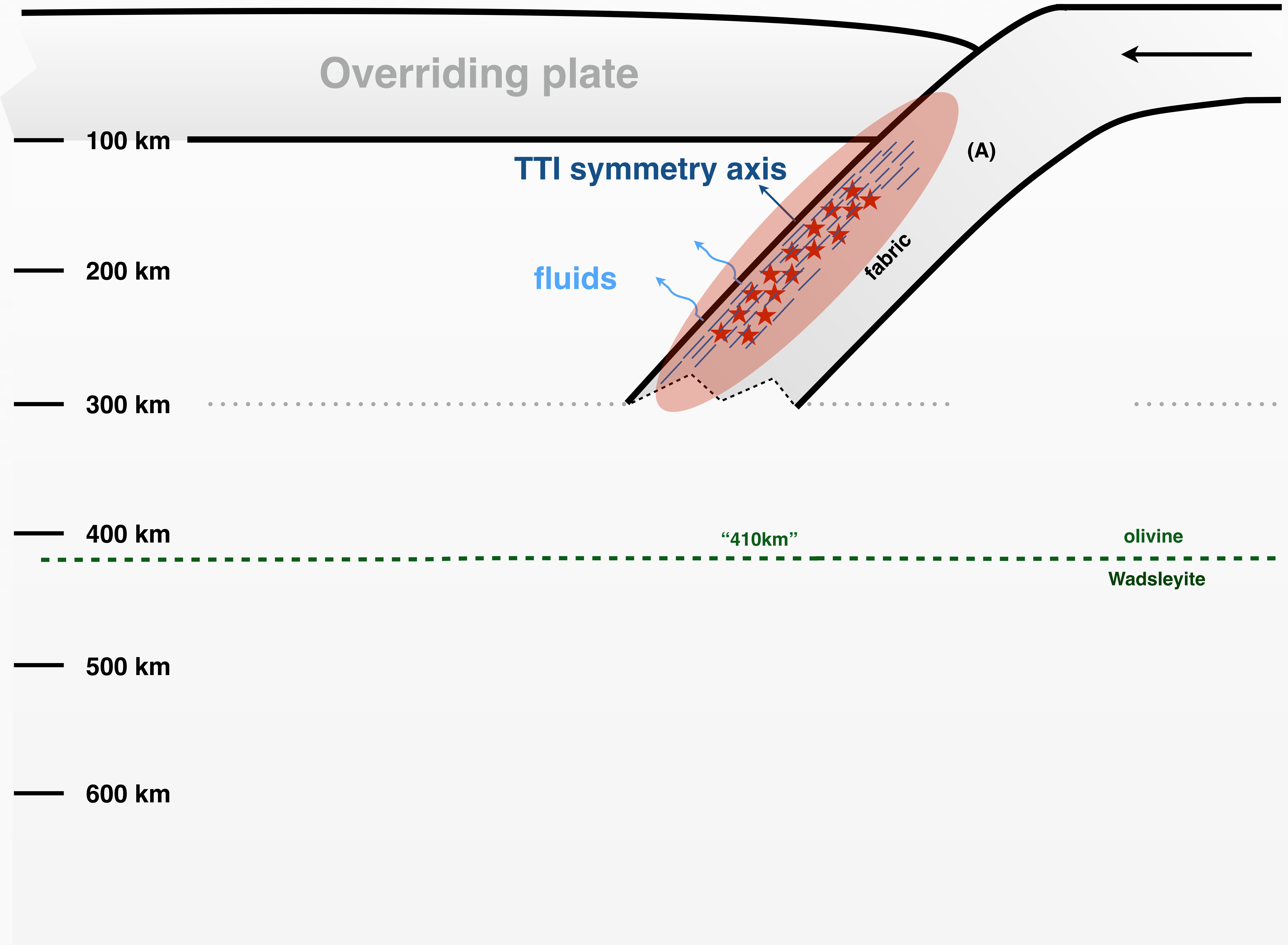


Schematic Diagram



(Hacker et al., 2003
Mainprice et al., 2009;
Brownlee et al., 2013;
Yang et al., 2014;)

Schematic Diagram



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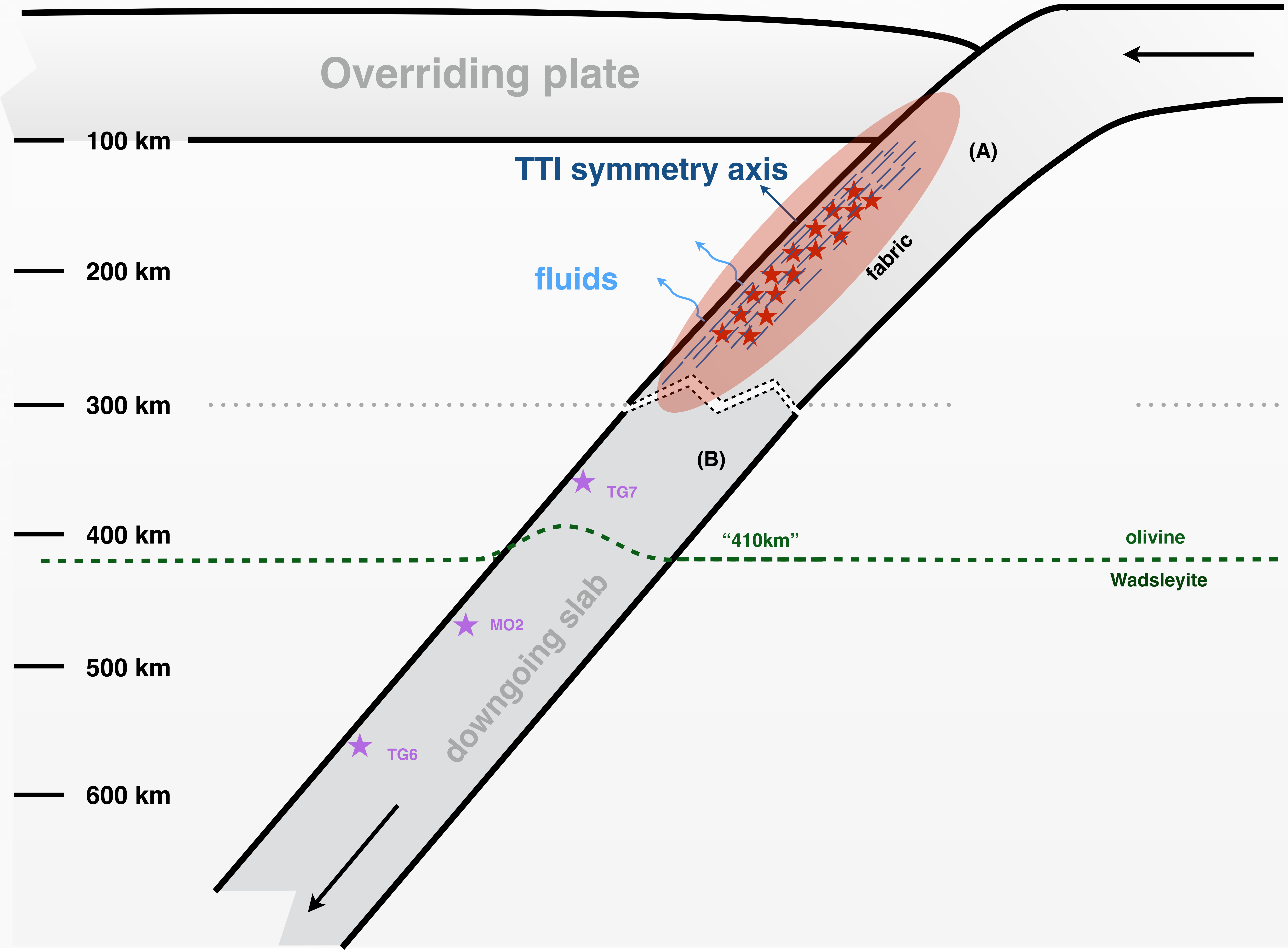
Schematic Diagram



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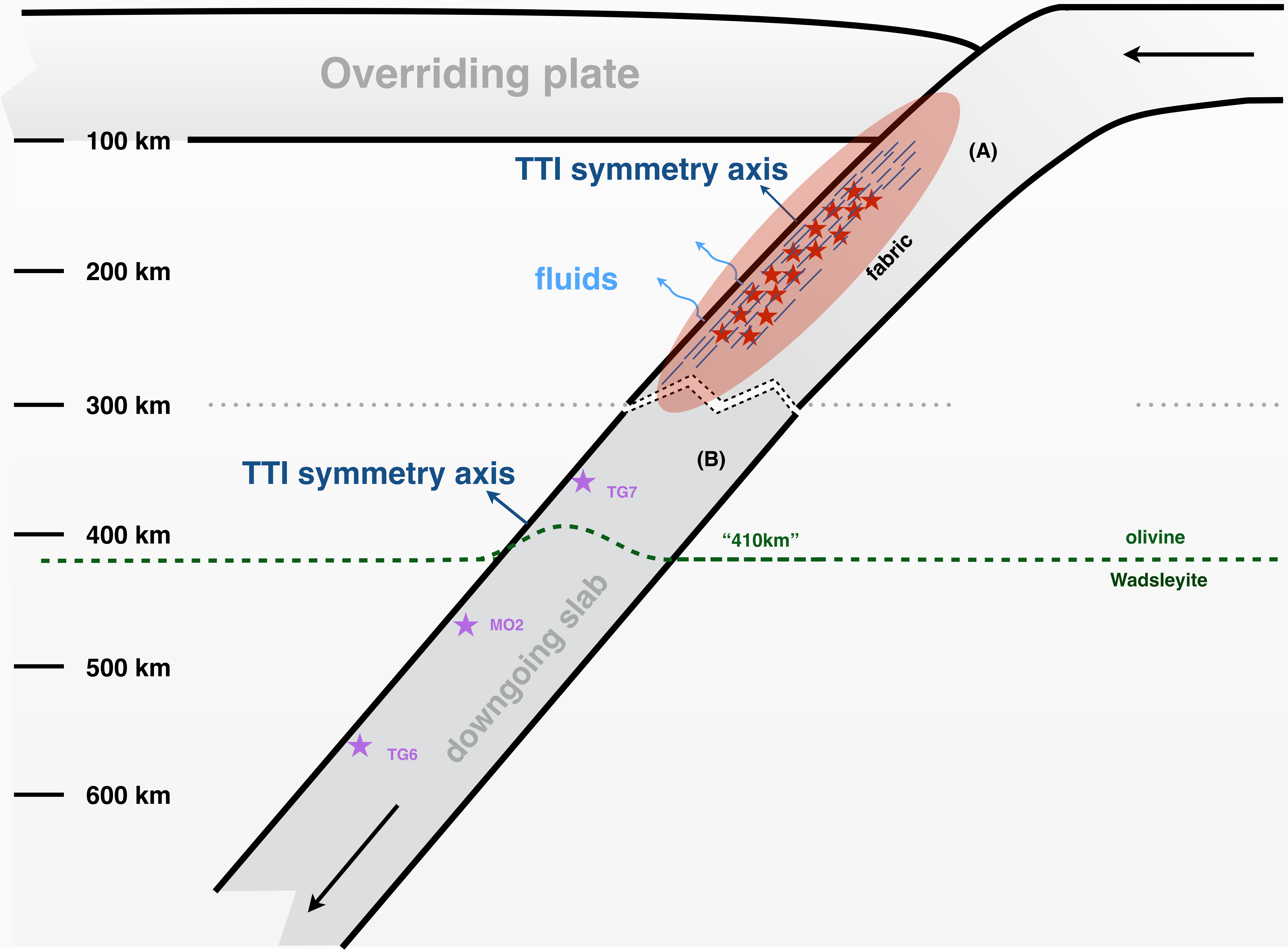
Schematic Diagram



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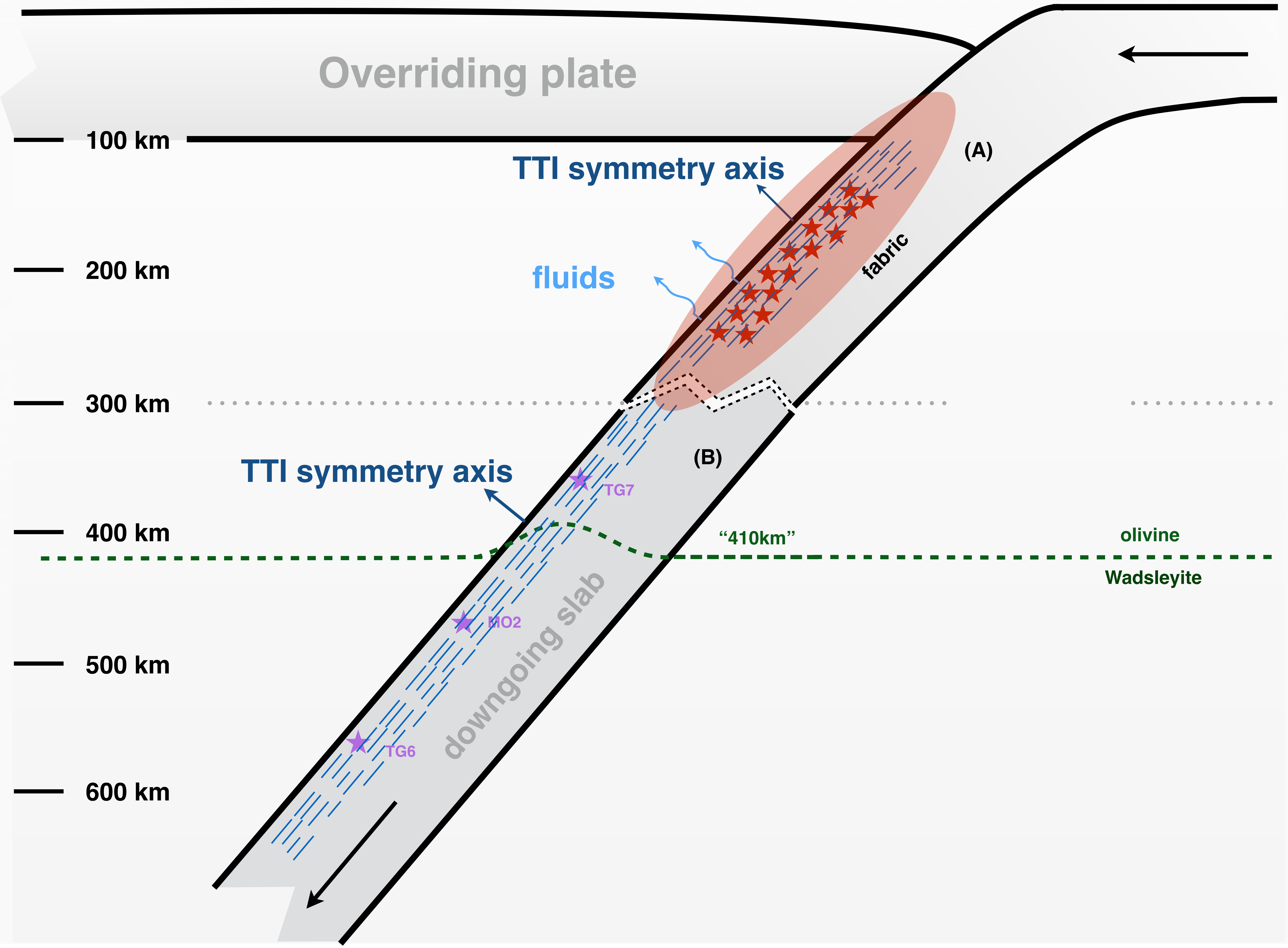
Schematic Diagram



(Hacker et al., 2003
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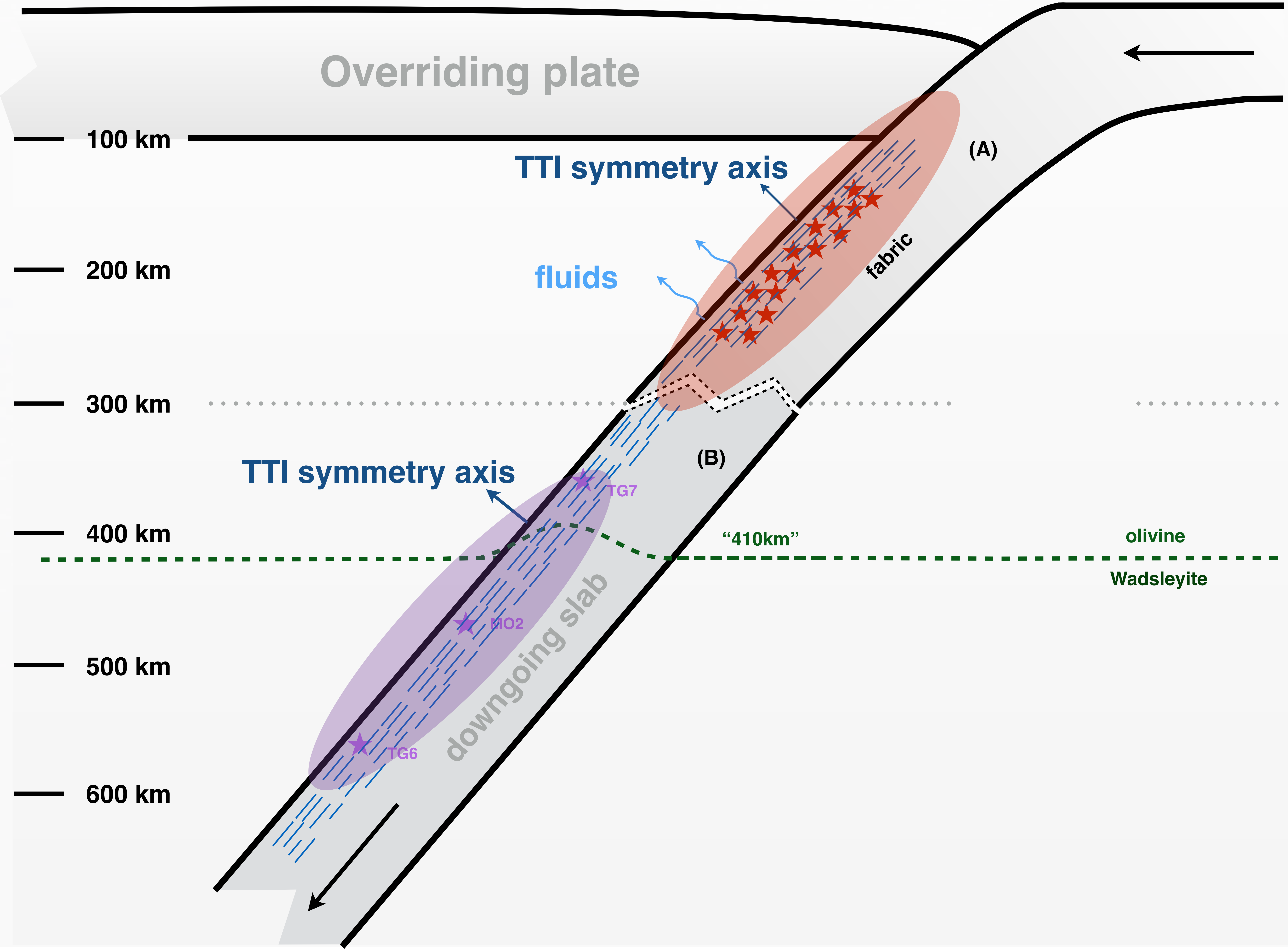
Schematic Diagram



(Hacker et al., 2003
Mainprice et al., 2009;
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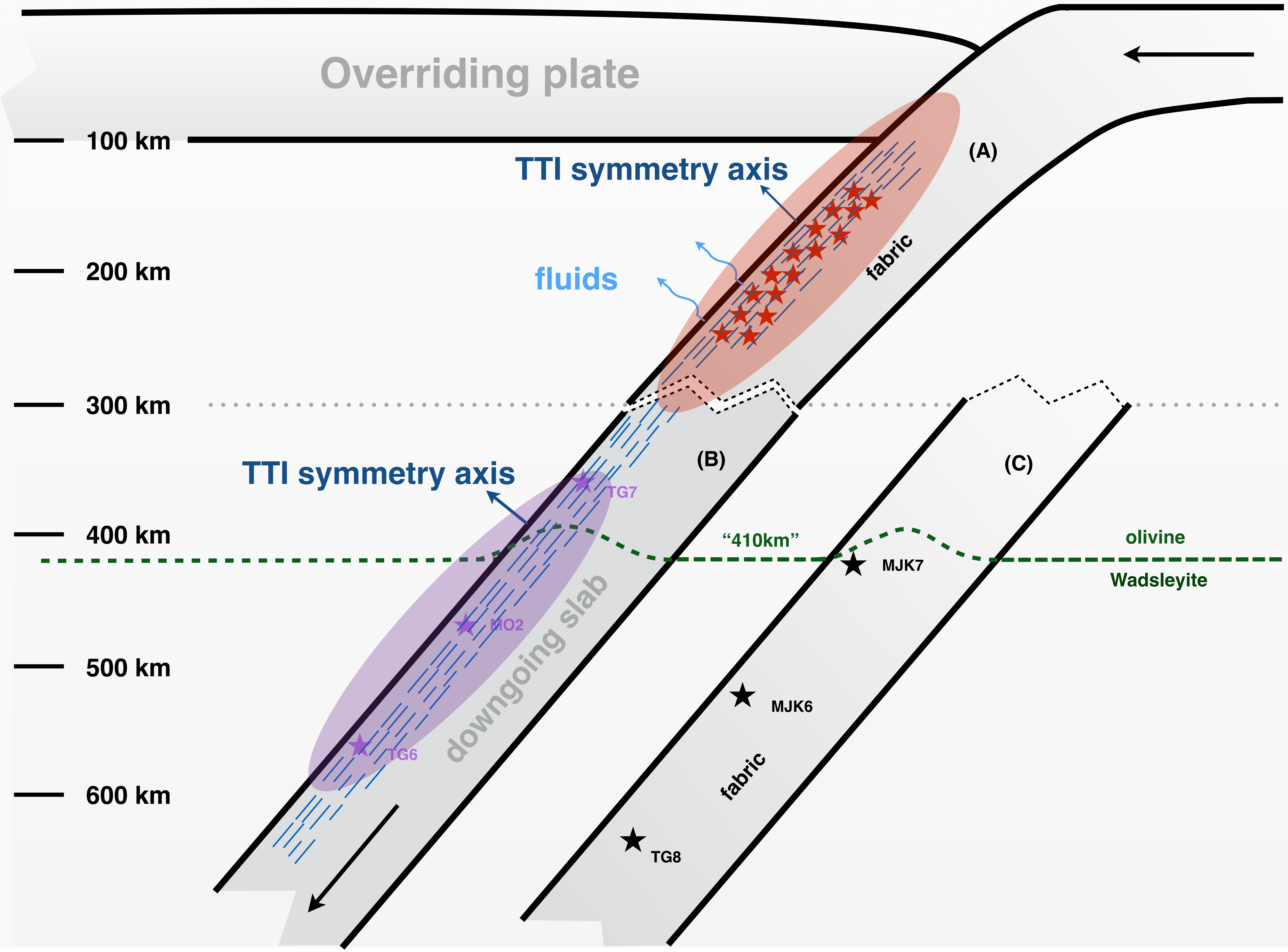
Schematic Diagram



(Hacker et al., 2003
Mainprice et al., 2009;
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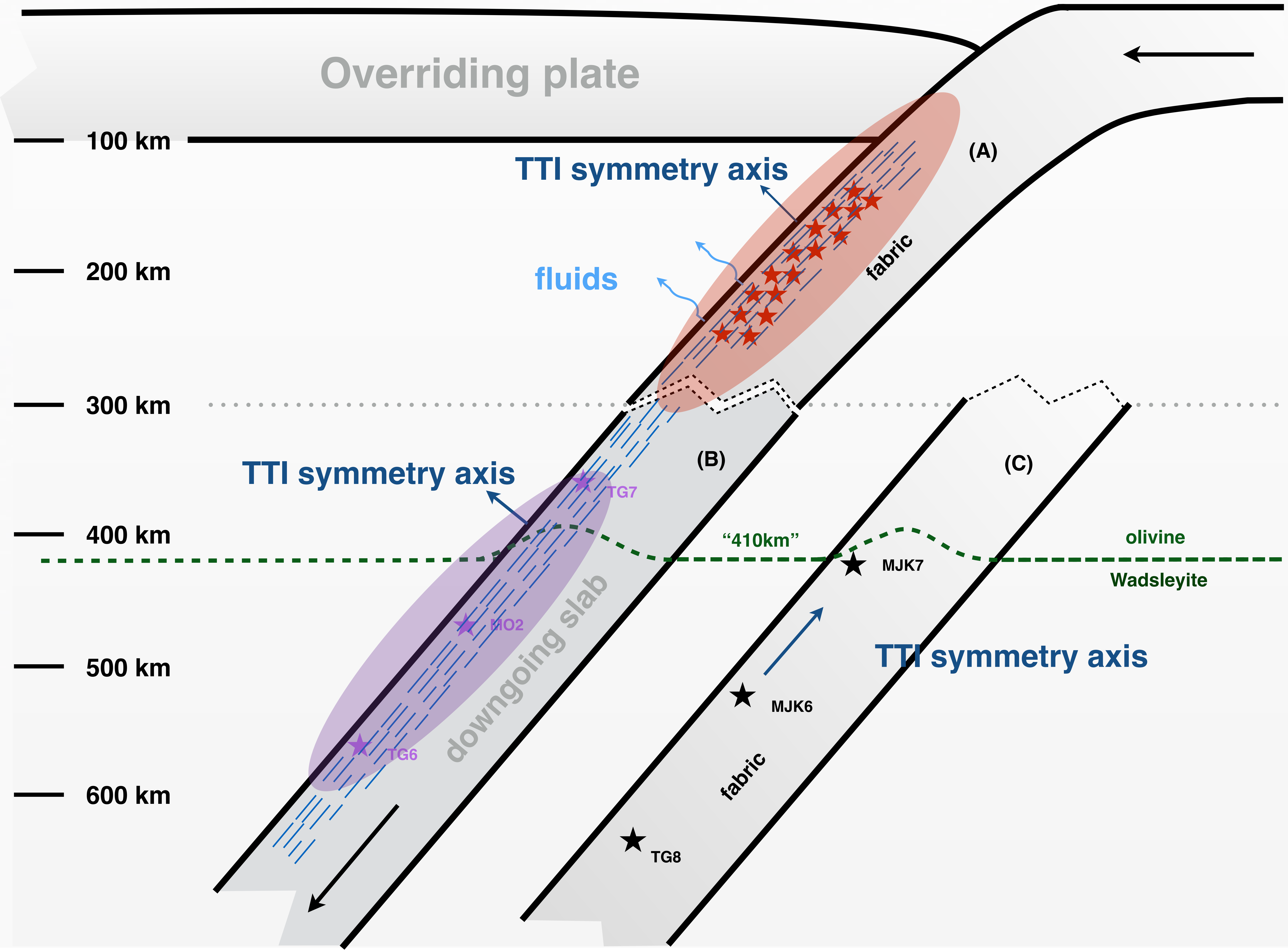
Schematic Diagram



(Hacker et al., 2003
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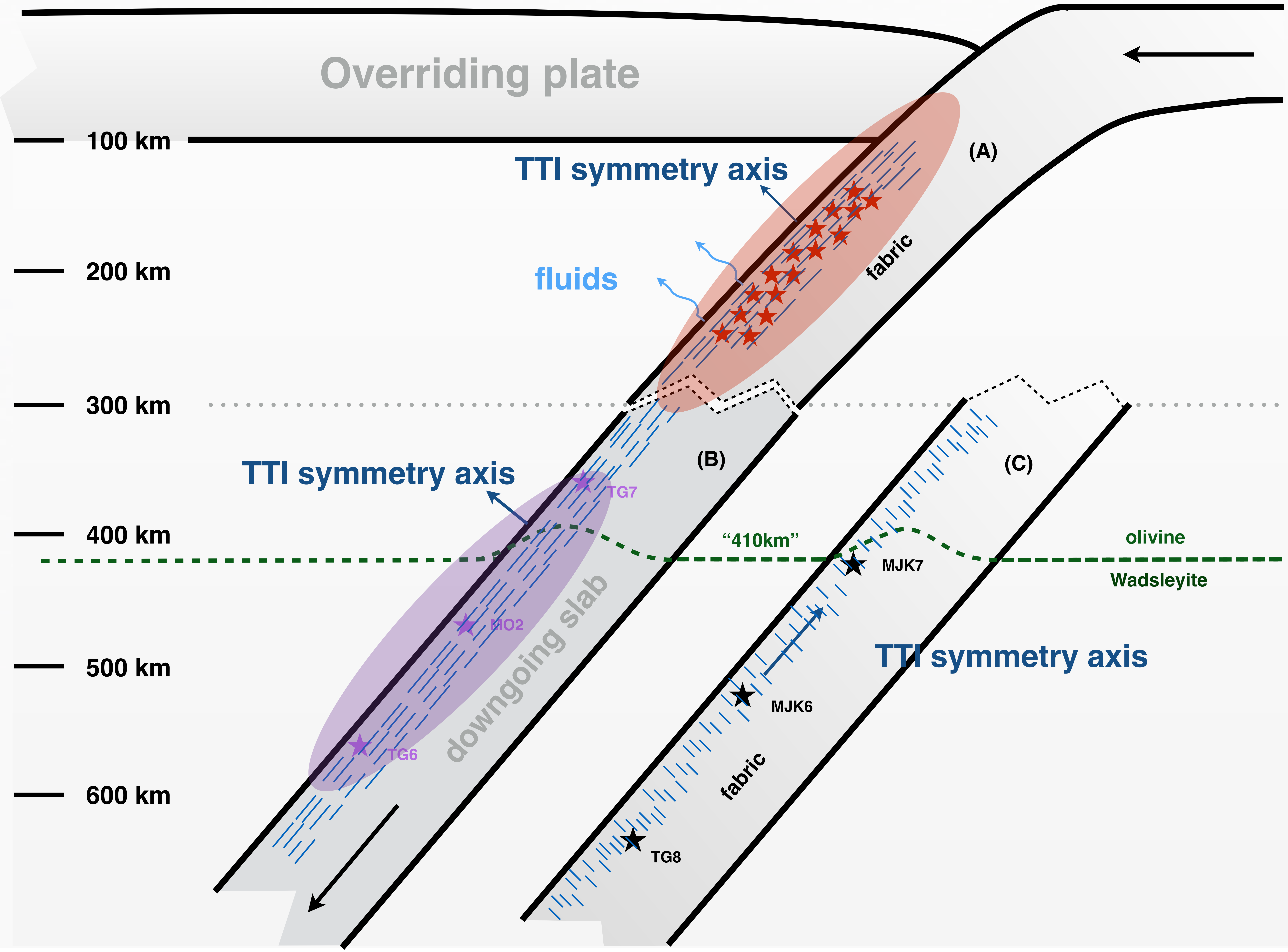
Yang et al., 2014;)

Schematic Diagram



(Hacker et al., 2003
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Yang et al., 2014;)

Magnesite

(Holyoke et al., 2014;
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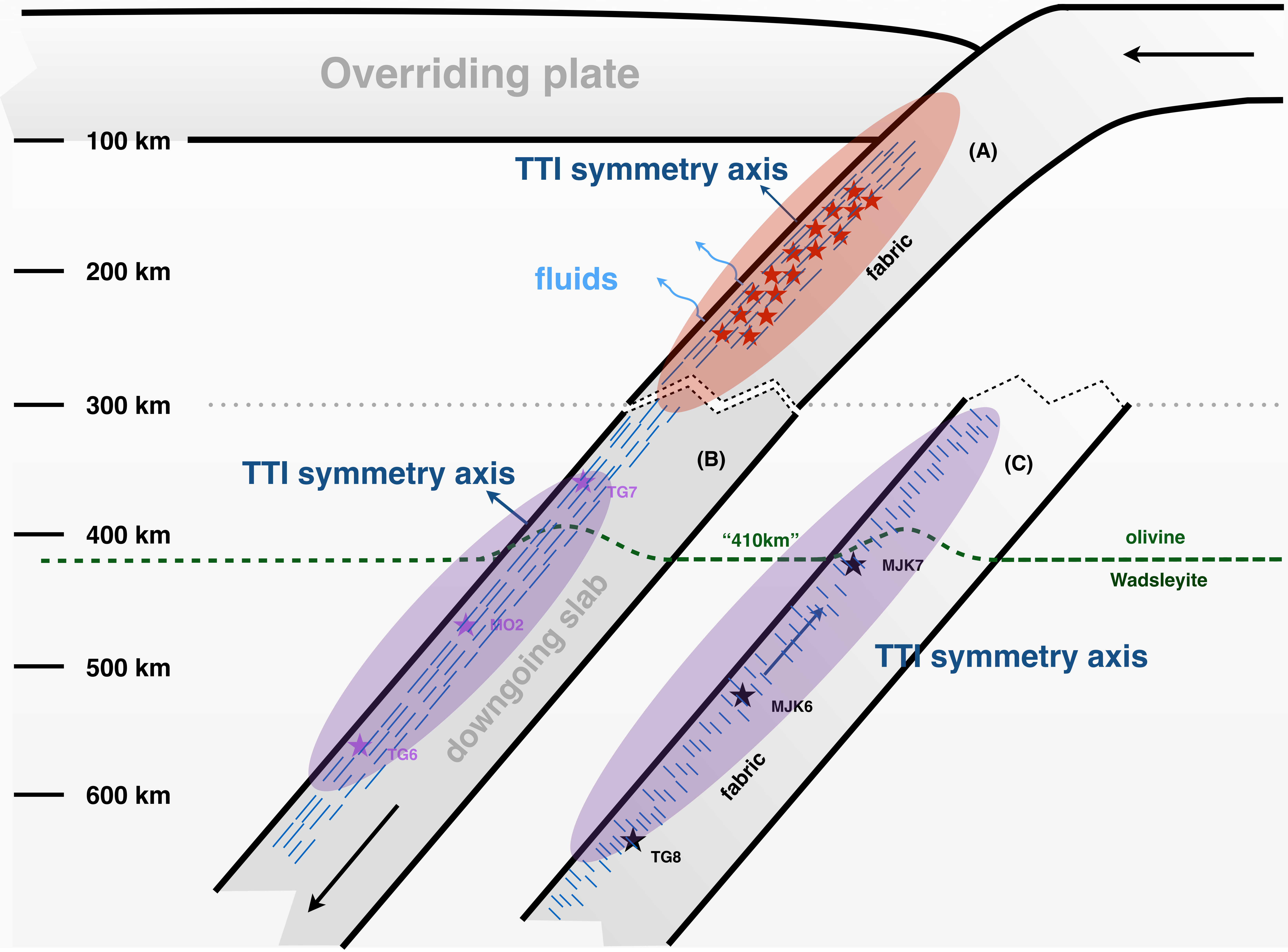

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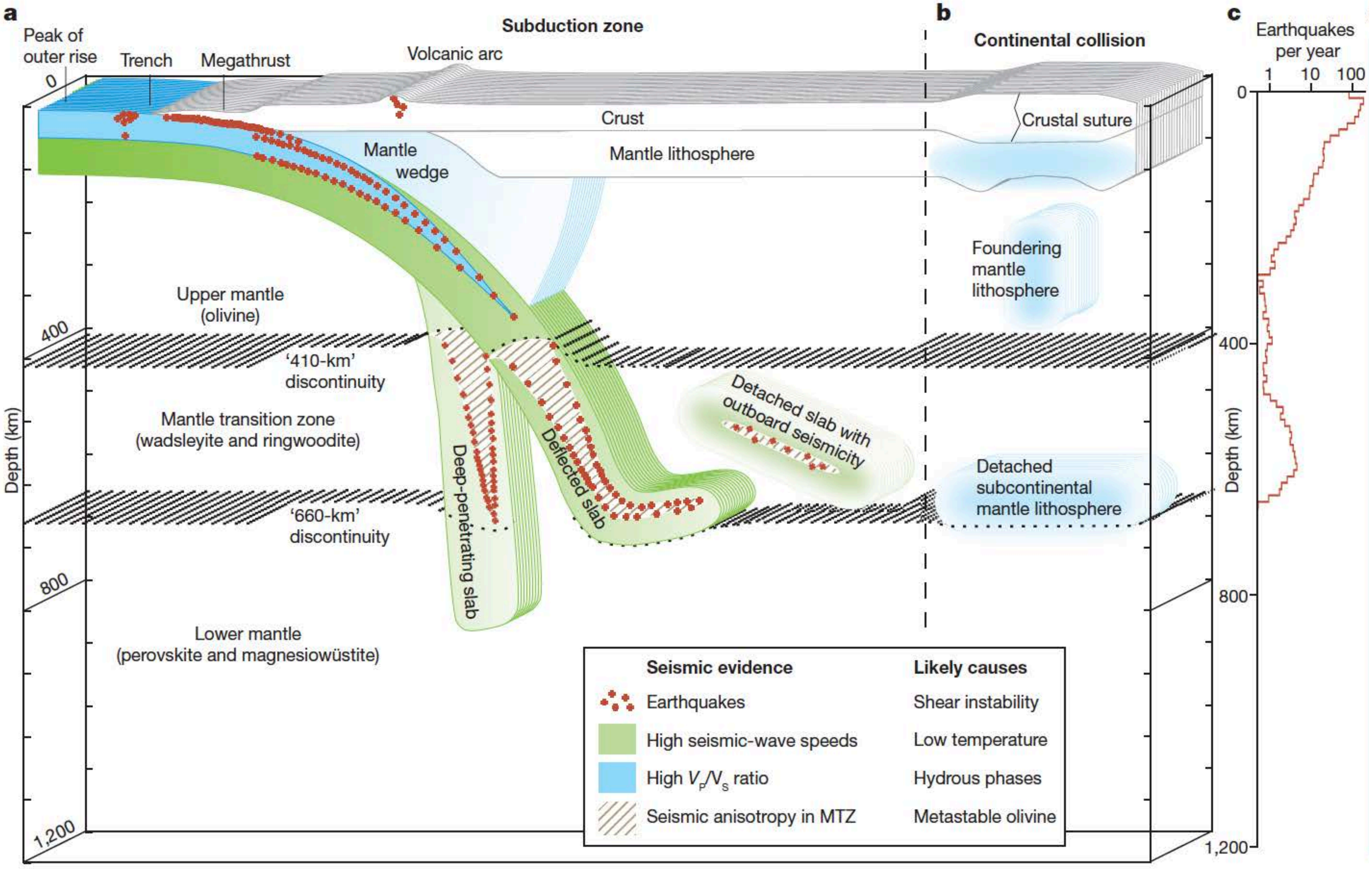
deep-focus earthquakes: phase change?



(Green, Chen, Brundzinski 2010 Nature)

(Zheng et al., 2007 Science)

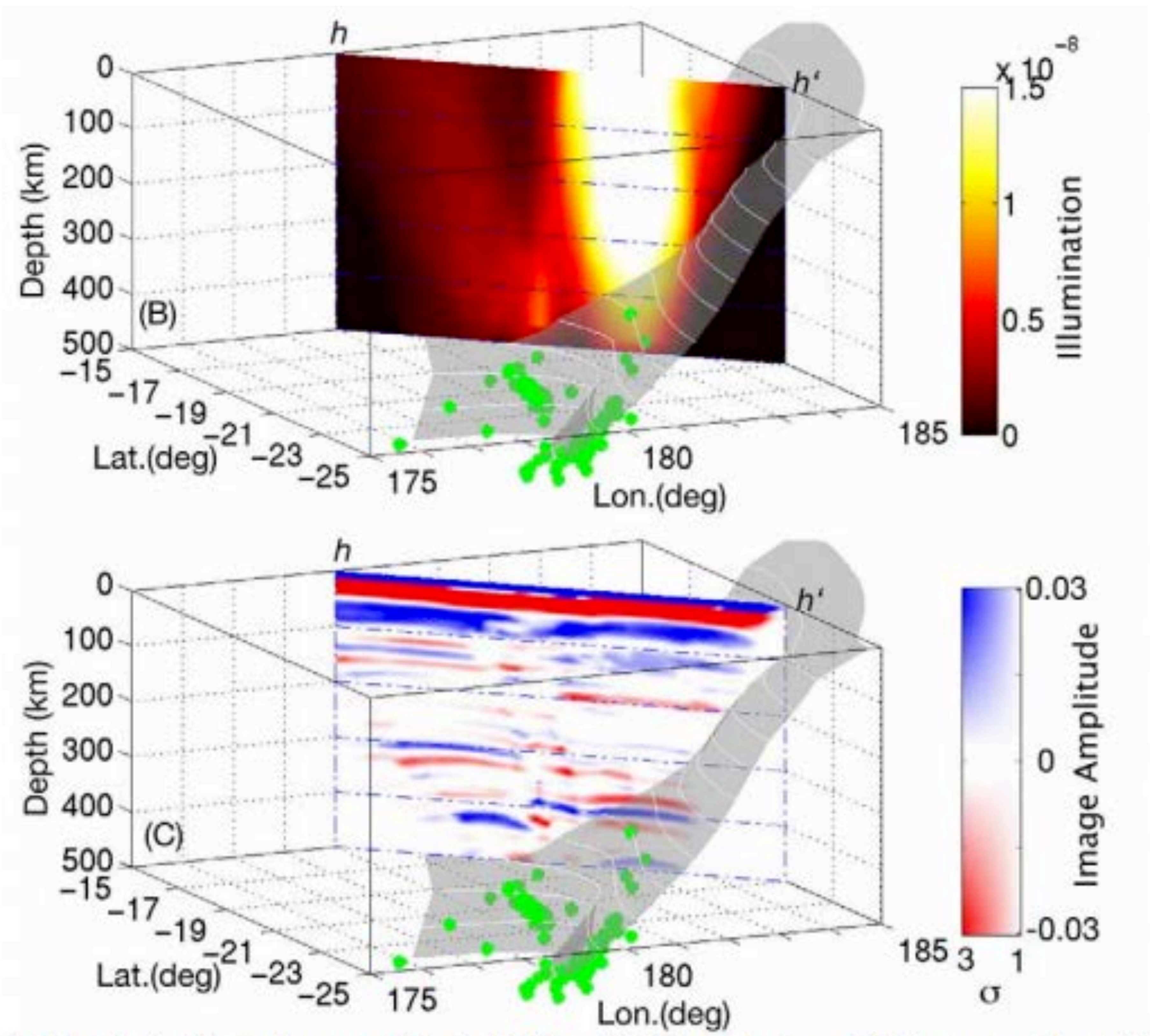


Fig.S5. Vertical slices along profile *h-h'* (fig. S1) through the $s_X SH$ image volume (A and C) and the corresponding illumination volume (B). Image (A) is shown with no scaling of the color hues relative to resolution, whereas image (C) is weighted according to the standard deviations above the mean (σ) of the signal at each pixel obtained by the boostrap method, as done in all other figures. The illumination depends on earthquake double-couple radiation pattern and the geometrical spreading factor, with higher values indicating well sampled and illuminated regions in this cross section. The strong illumination region mainly reflect the dense path distribution to North America.

the “410-km” discontinuity can be imaged clearly, no meta-stable olivine ?!

Discussion:
possible role of carbonates in generating deep-focus EQs?

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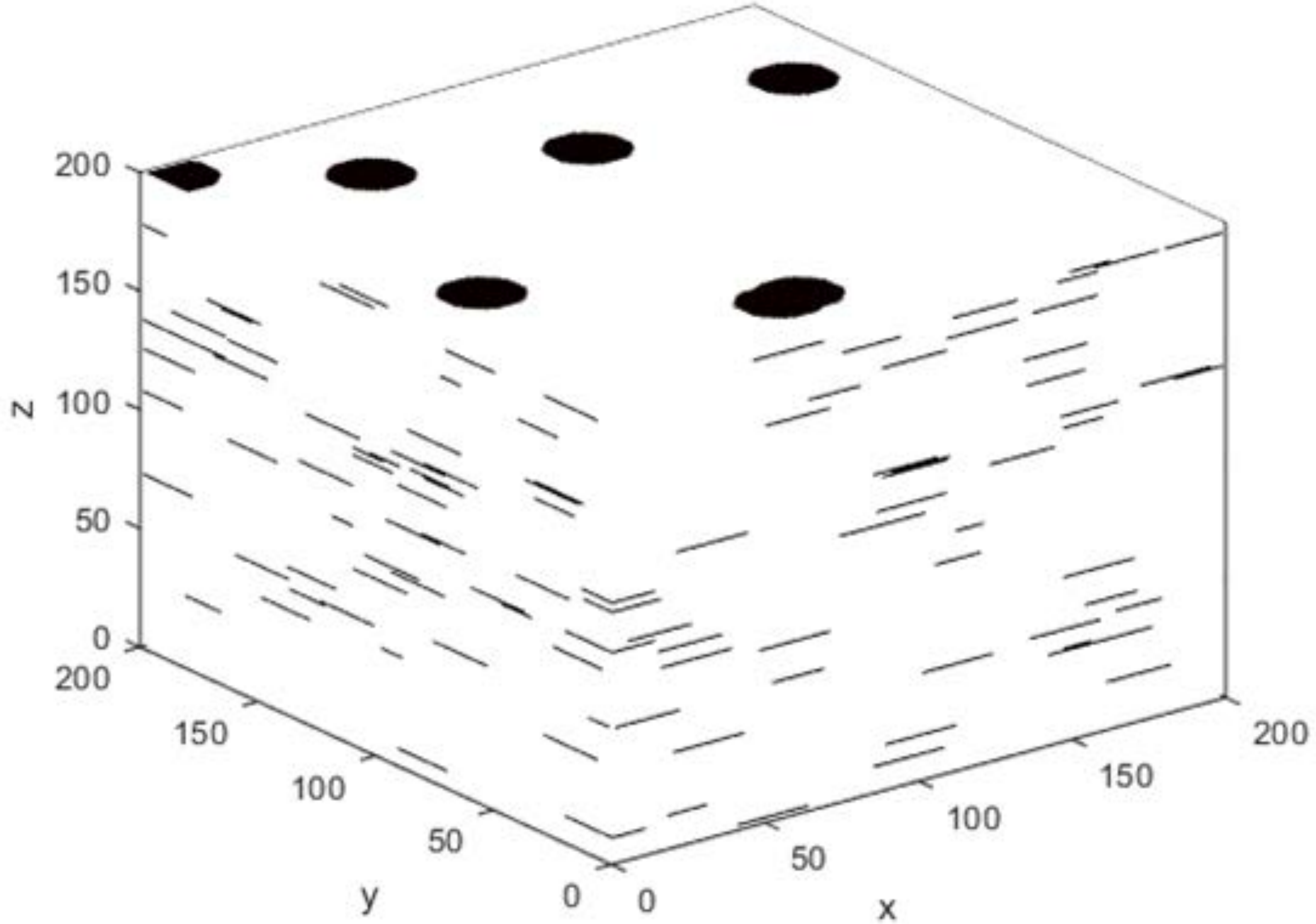
- show ductile-to-brittle transition behavior (similar to serpentines), e.g., Holyoke et al., 2014 JGR
- single-grain anisotropy is high, > 40% (Yang et al., 2014 EPSL)

Origin of anisotropy

inclusion model

Hard matrix + weak inclusions

Finite element stress-strain modeling



(Garboczi,1998, NIST)

matrix Vp=8km/s, Vs=4km/s; density 3400kg/m^3

inclusion Vp=8km/s, Vs=??; density 3400kg/m^3

How much <u>inclusion</u> do we need to produce such a high anisotropy?

very weak inclusions (melt/fluid)

$$\gamma \sim \frac{8}{7}\eta_c$$

$$\eta_c = \frac{3}{4\pi}\frac{\phi}{e}$$

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$$\phi = 0.02, e = 0.01 \longrightarrow \boxed{\gamma = 0.5}$$

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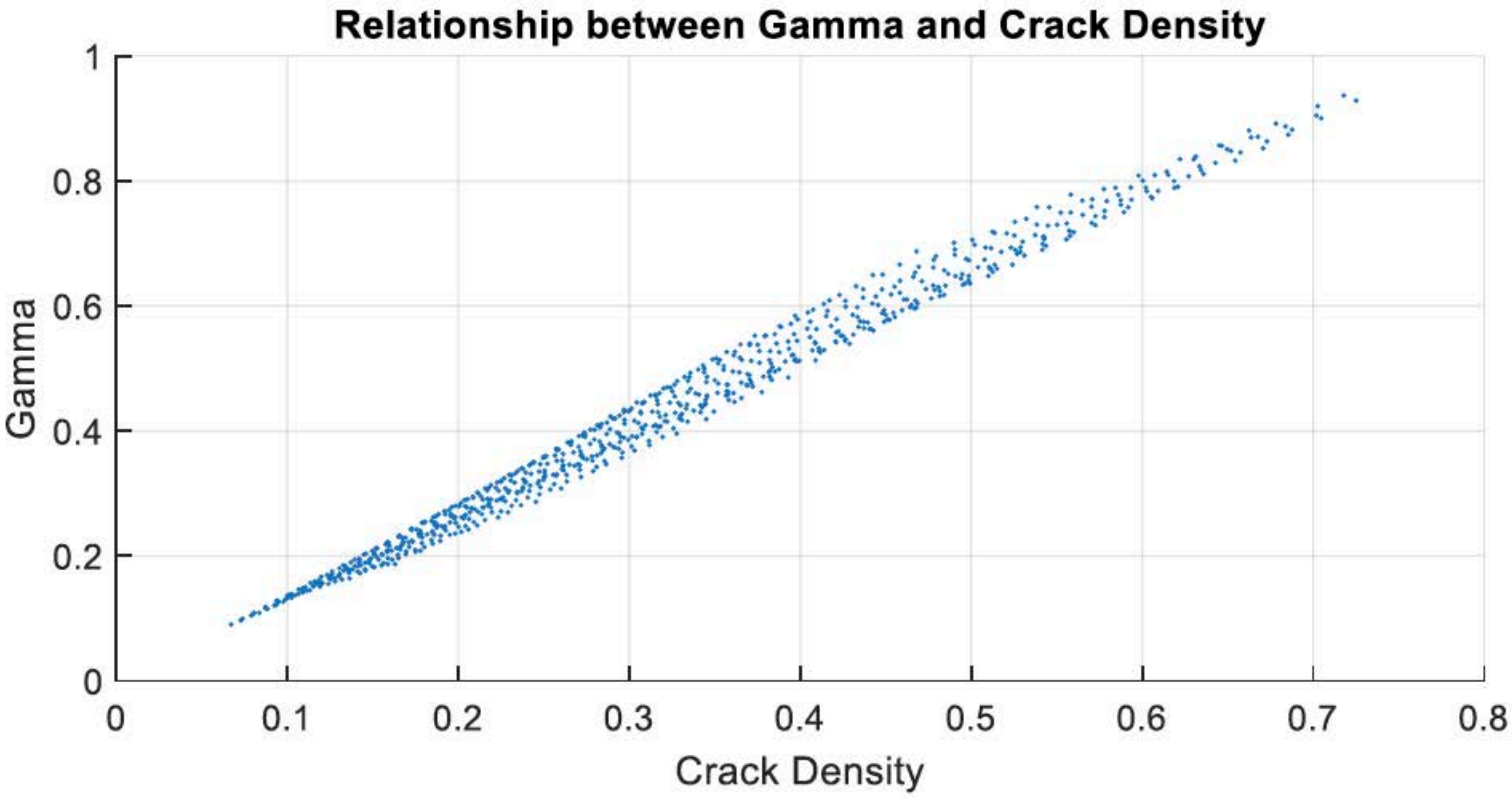
ϕ: volume fraction

e: aspect ratio

Thomsen, L. (1995), Elastic anisotropy due to aligned cracks in porous rock, *Geophysical Prospecting*, *43*(6), 805-829.

weak inclusion   inclusion Vs = 10% matrix Vs



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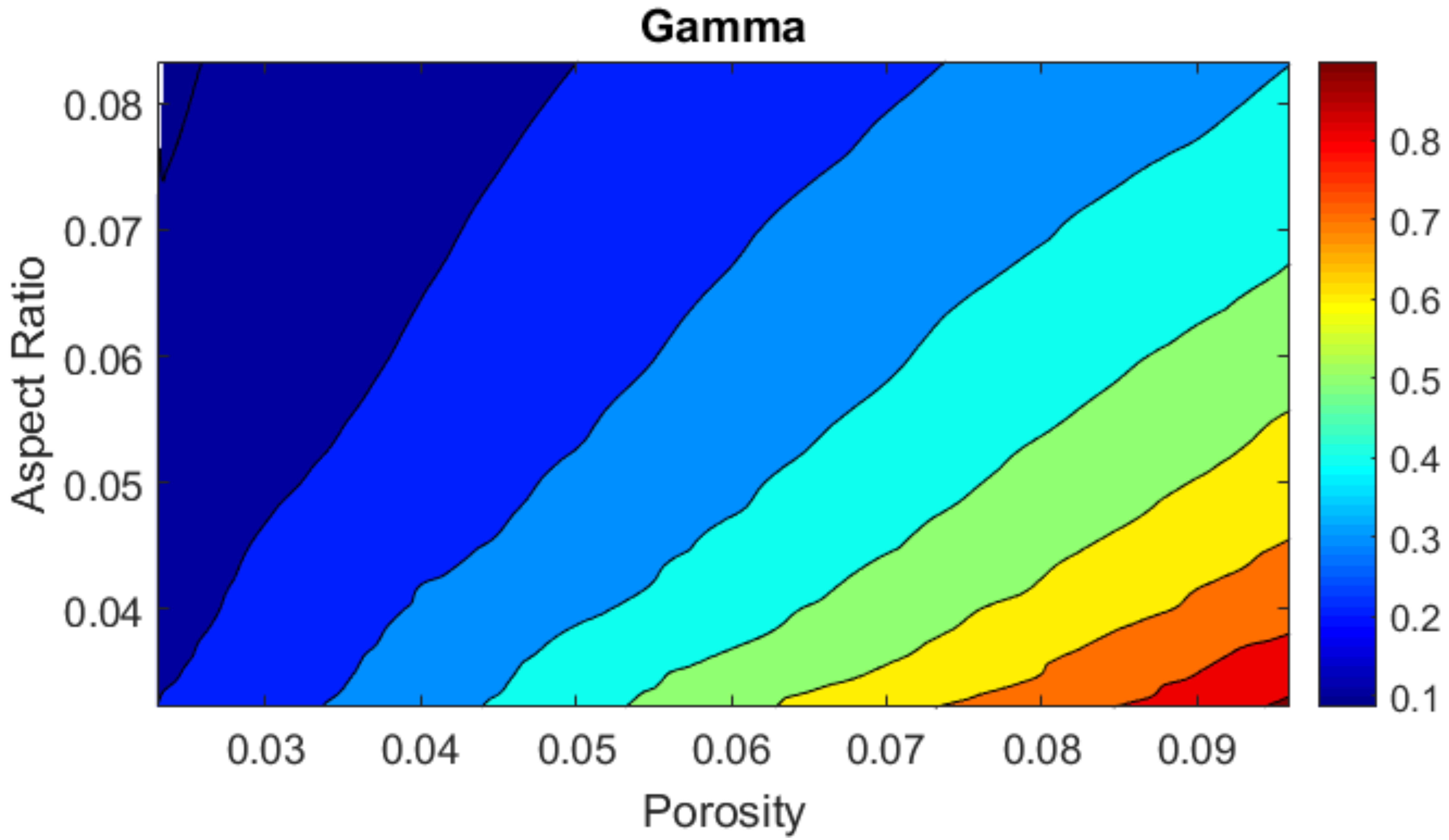
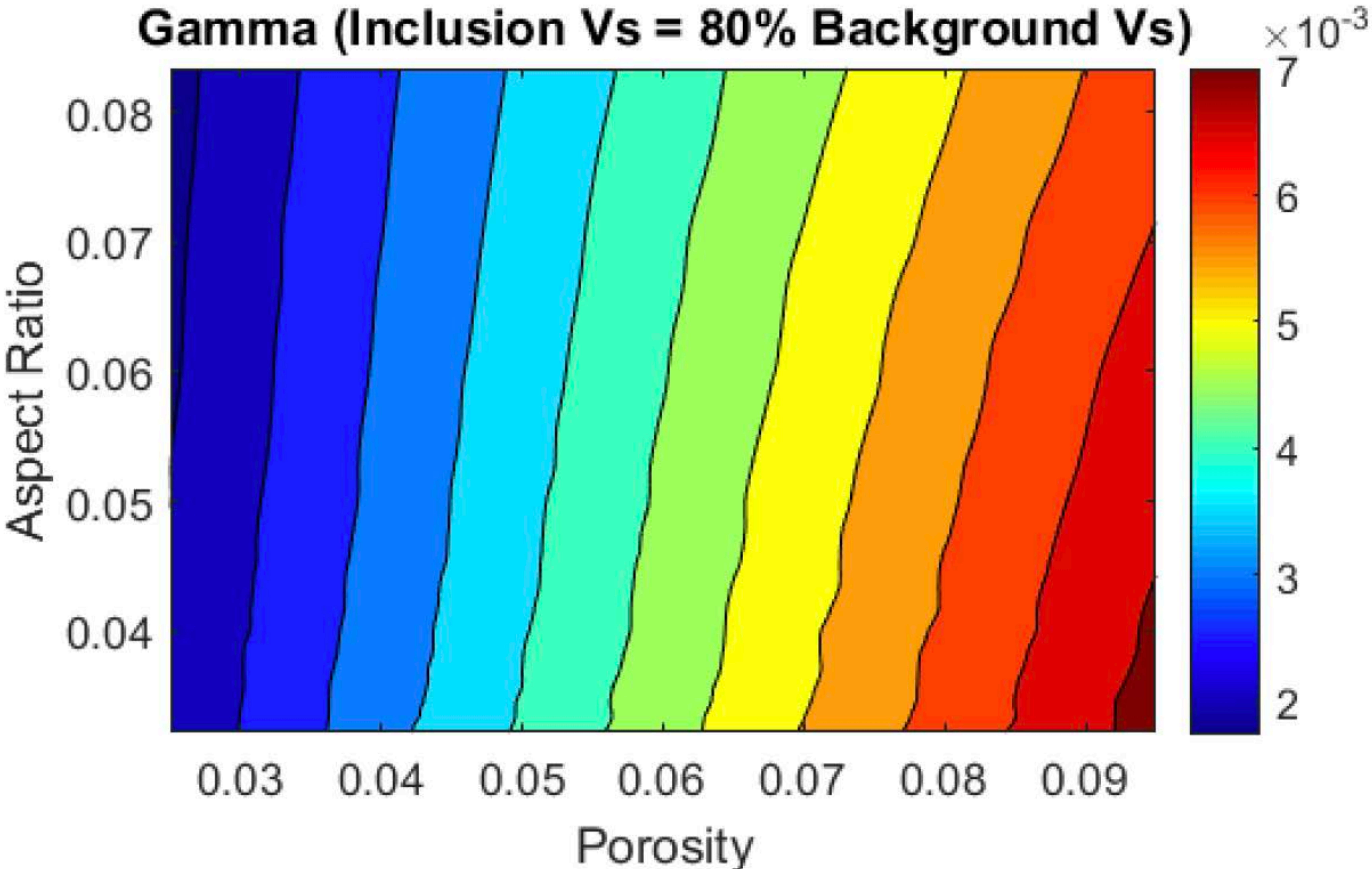
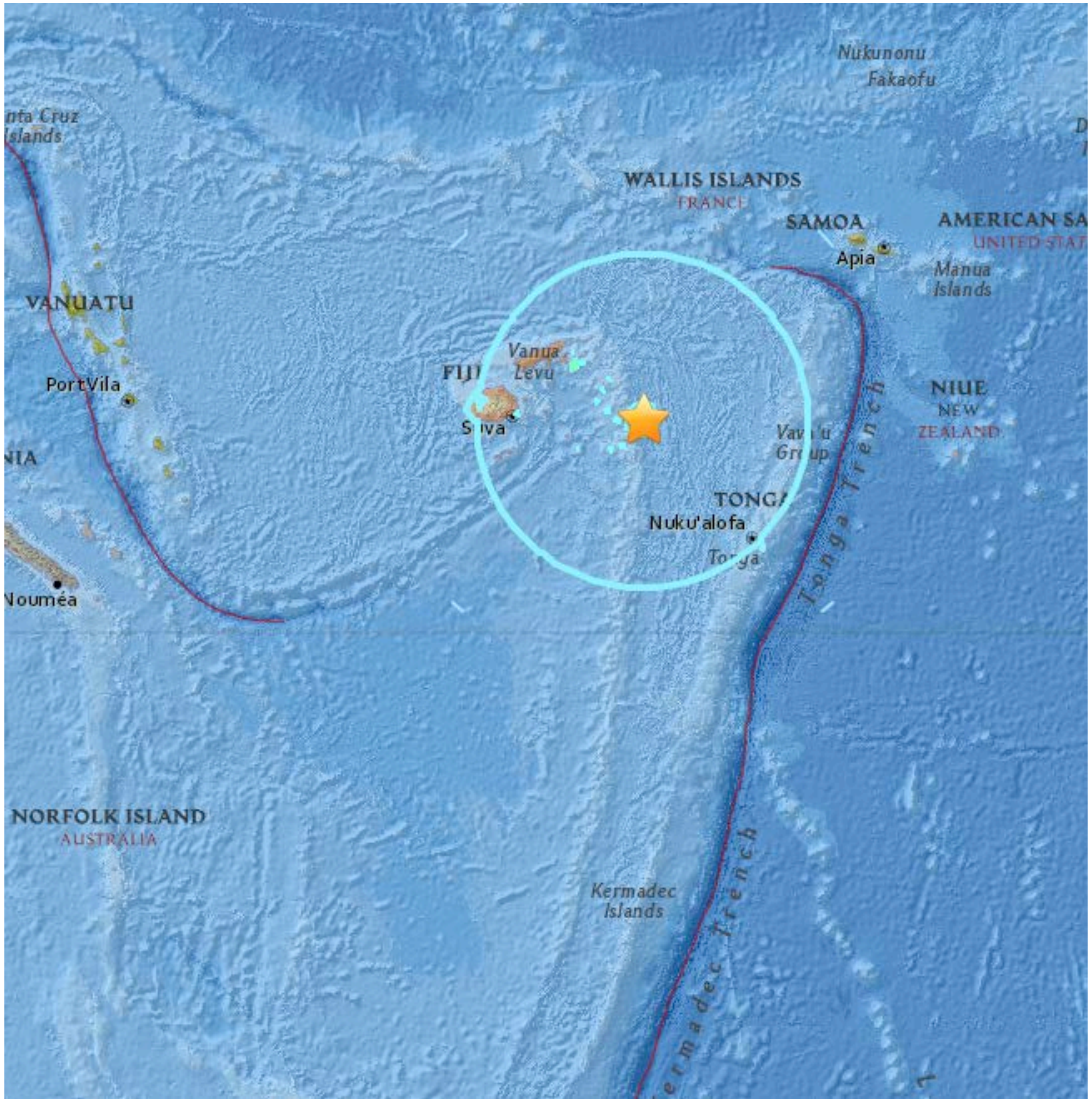


Strong inclusion: CANNOT get large anisotropy!

meta-stable ol inclusion?



Prediction



FIJI Event 2018-08-19 00:19:37 UTC M8.2

M 8.2 - 280km NNE of Ndoi Island, Fiji

2018-08-19 00:19:37 UTC | 18.178°S 178.111°W | 563.4 km depth

2018
M8.2

Moment Tensor

Back to Technical

Contributed by US[3] last updated 2018-08-19 01:15:12 (UTC)

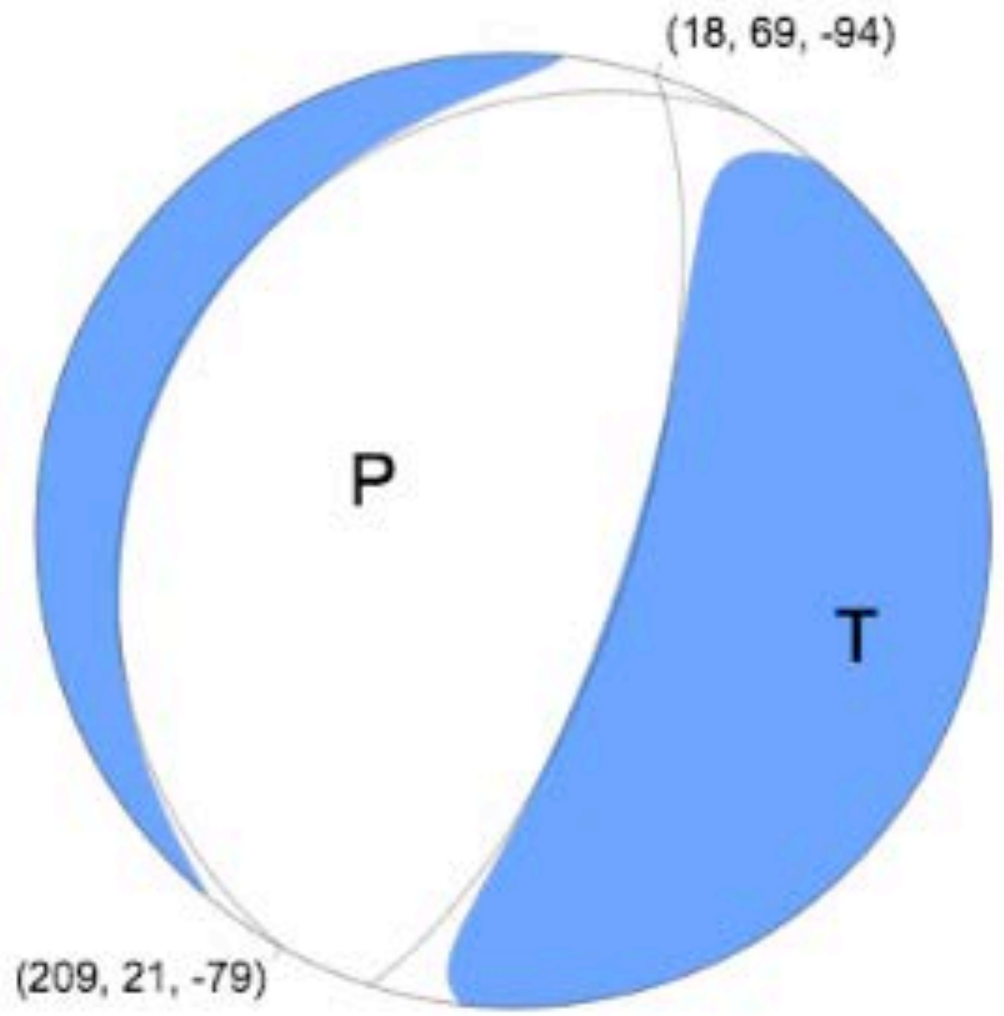
✓ The data below are the most preferred data available
✓ The data below have been reviewed by a scientist

W-phase Moment Tensor (Mww)

Moment	2.553e+21 N-m
Magnitude	8.2 Mww
Depth	580.5 km
Percent DC	89 %
Half Duration	32.4 s
Catalog	US
Data Source	US[3]
Contributor	US[3]

Nodal Planes

Plane	Strike	Dip	Rake
NP1	209°	21°	-79°
NP2	18°	69°	-94°



M 7.6 - Fiji region

1994-03-09 23:28:06 UTC | 18.039°S 178.413°W | 562.5 km depth

Moment Tensor

Back to Technical

Contributed by US[4] DUPUTEL[1] last updated 2015-02-12 16:21:17 (UTC)

✓ The data below are the most preferred data available
✓ The data below have been reviewed by a scientist

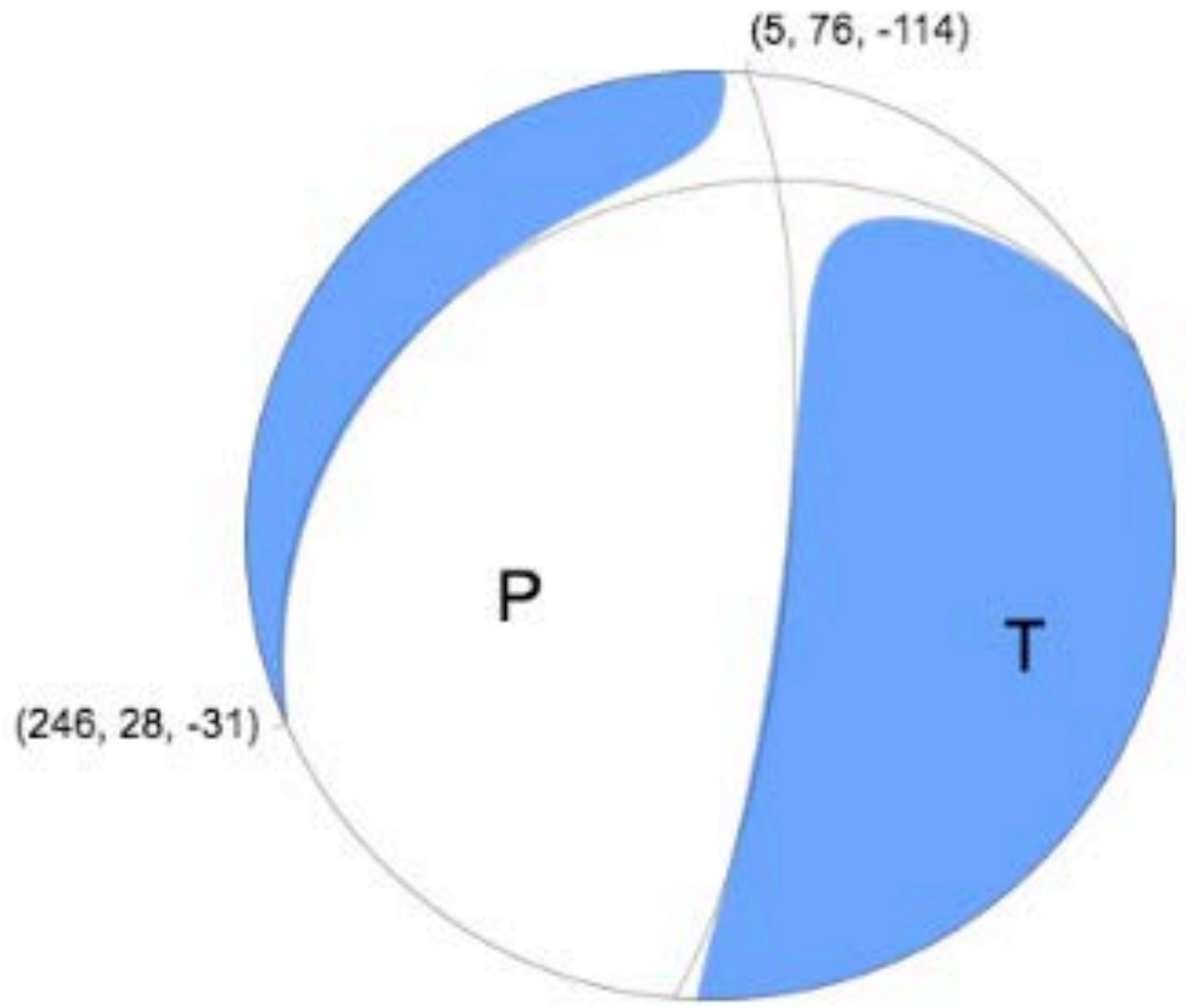
W-phase Moment Tensor (Mww)

Moment	2.928e+20 N-m
Magnitude	7.6 Mww
Depth	560.5 km
Percent DC	89 %
Half Duration	10 s
Catalog	DUPUTEL
Data Source	DUPUTEL[1]
Contributor	US[4]

Nodal Planes

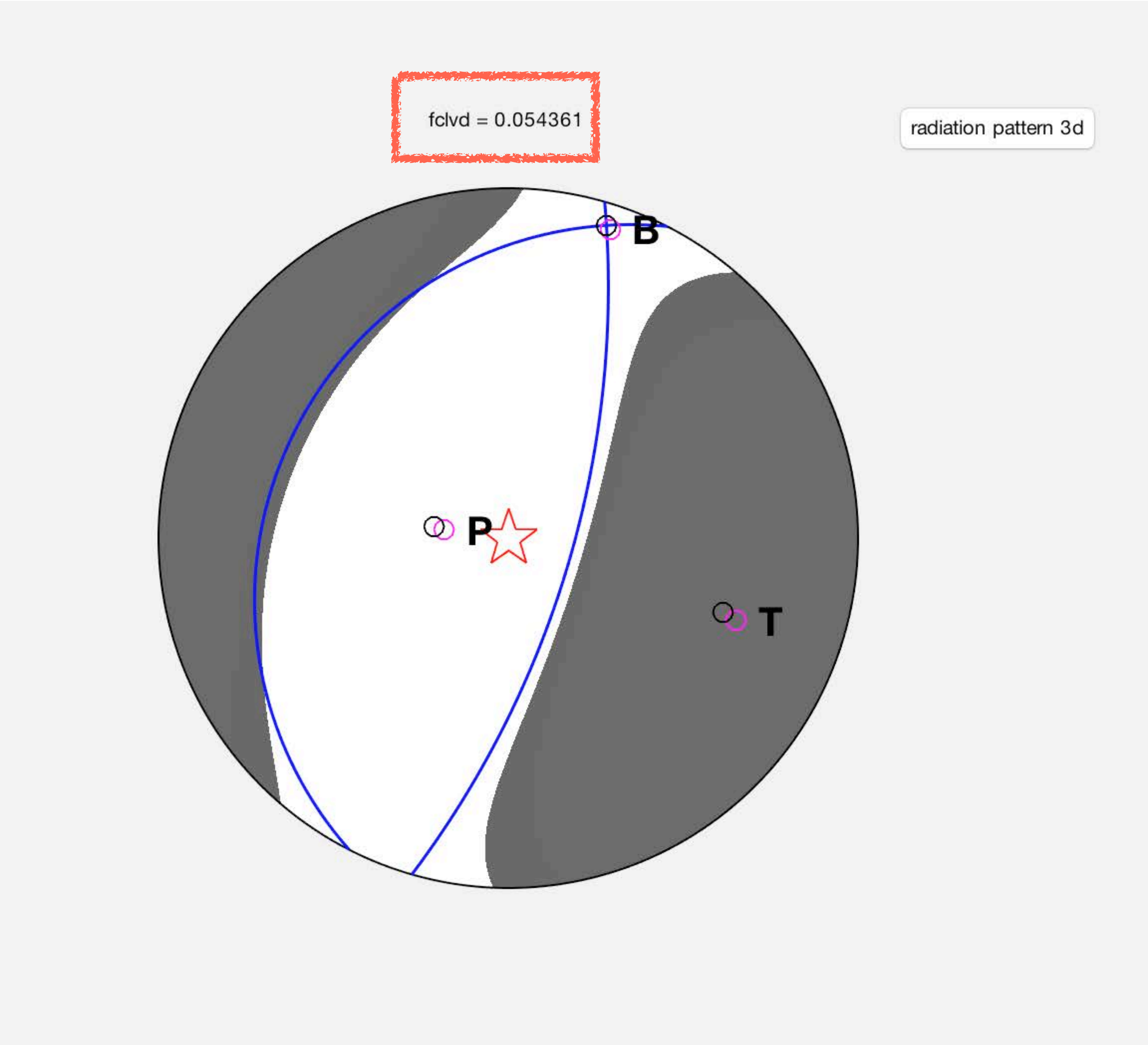
Plane	Strike	Dip	Rake
NP1	246°	28°	-31°
NP2	5°	76°	-114°

1994
M7.6



Historical earthquake
(similar location; focal mechanism, & non-DC)

- Using the anisotropy information (Thomsen gamma=0.2 for shear anisotropy), we can fit the “beach ball” well and the P,B, T axes.
- Shear rupture in the anisotropy can produce 11% non-DC component shown in the W-phase moment tensor inversion.



Conclusions

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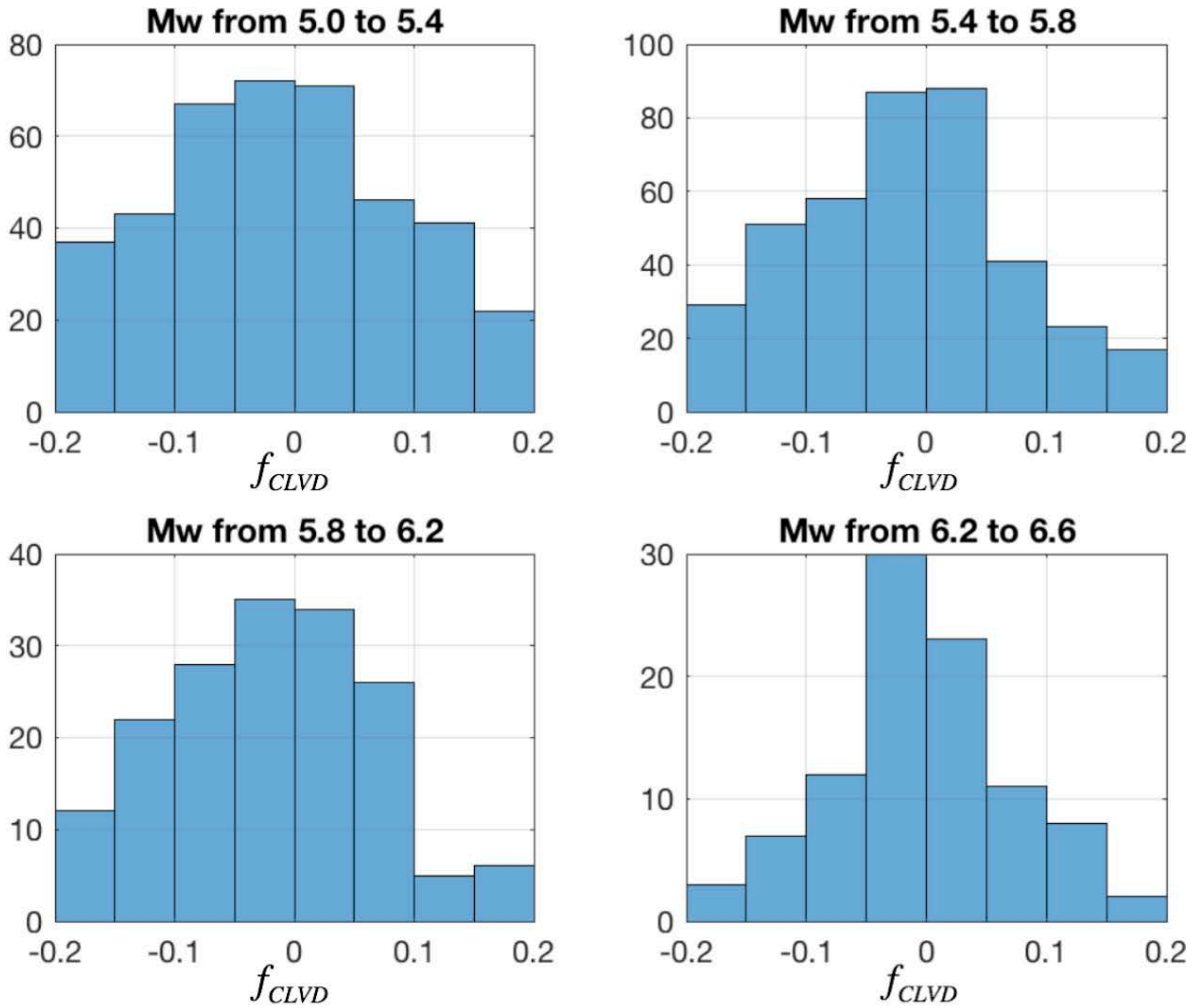
backup slides

histogram of fclvd as a function of Mw



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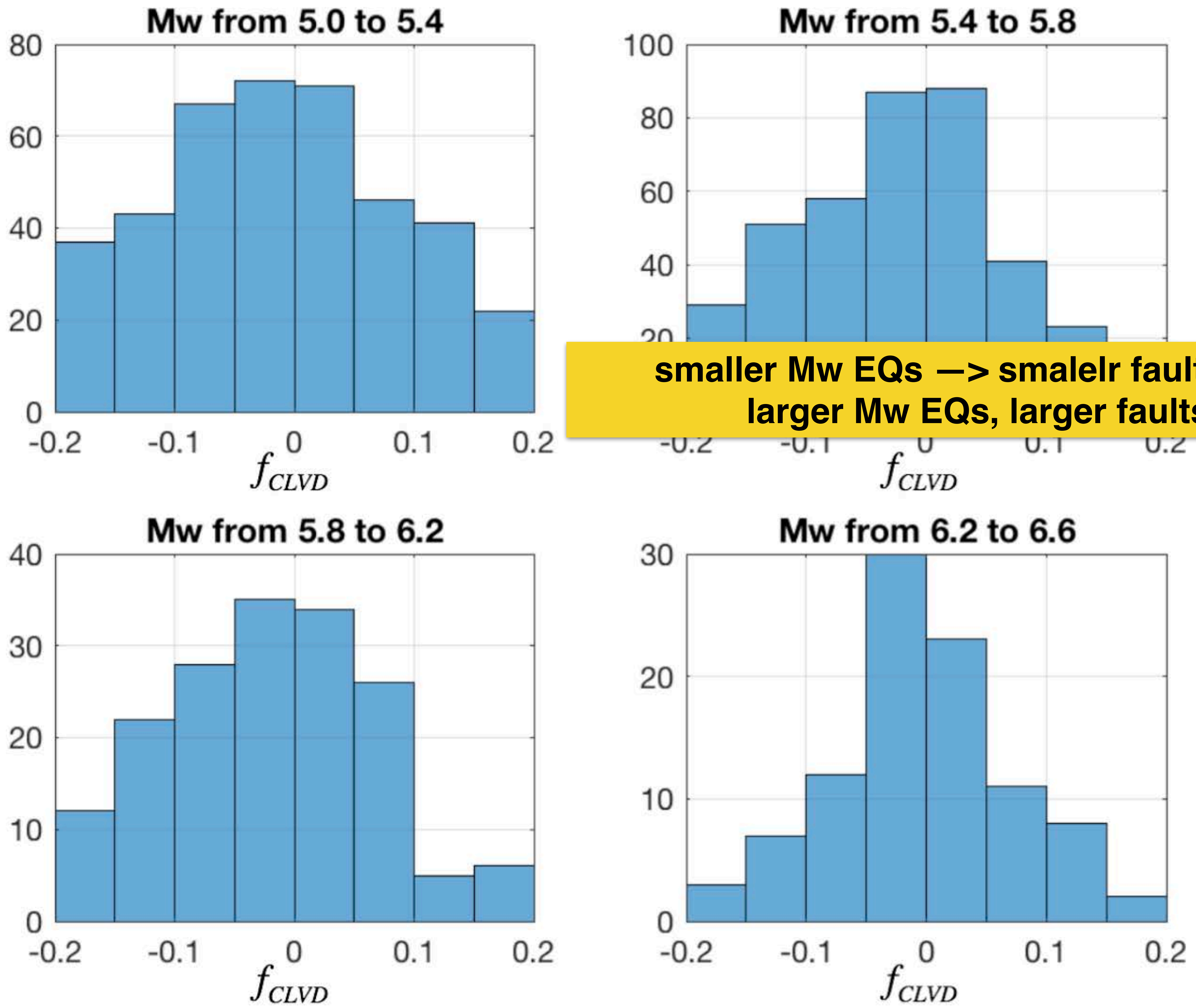
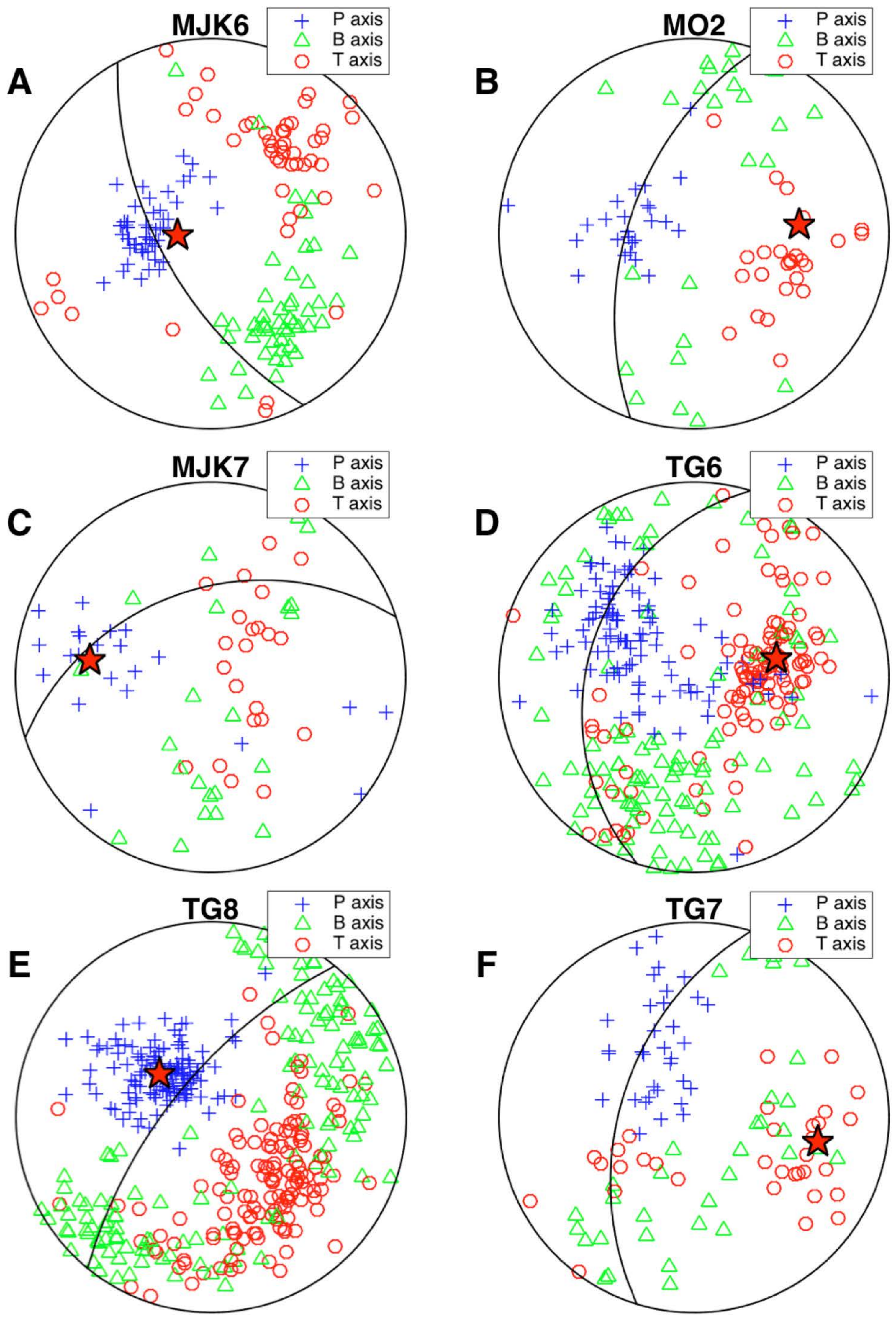
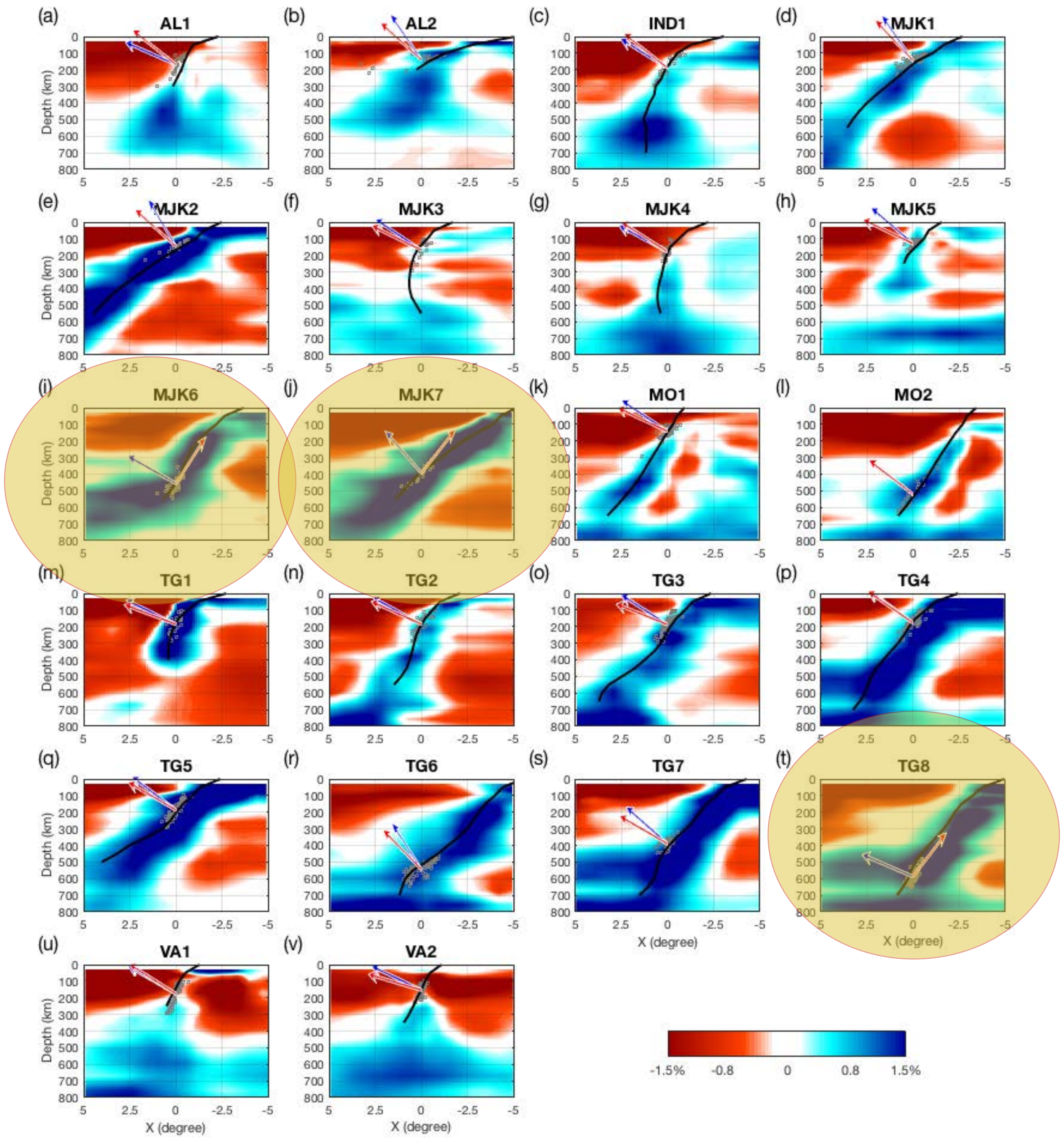


smaller Mw EQs —> smalelr faults: more non-DC?
larger Mw EQs, larger faults: more DC?

Optimized TTI Symmetry Axis and P Axes



Cross-Section



GAP_P4 Model
Fukao and Obayashi (2013)

Li et al. (2018 natgeo)