Scaling of seismic and aseismic moments of natural and induced earthquakes

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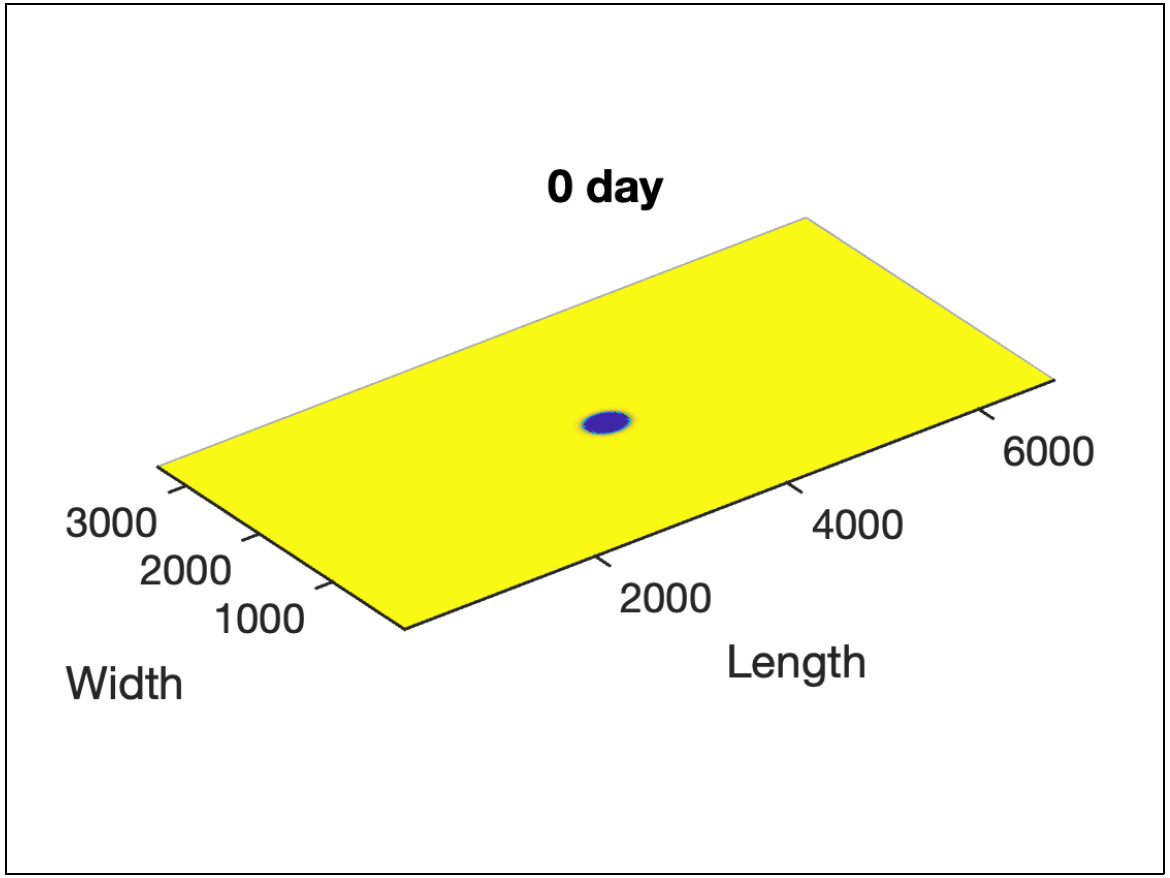
Aseismic and seismic scaling

M_0^{seis} - M_0^{geod}

- Database of slow slip transients + triggered seismicity:
  - Geodetic moments
  - Seismic moments of triggered seismicity
  - Duration
  - Source dimensions

- Source parameters of triggered seismicity only during slow slip transient

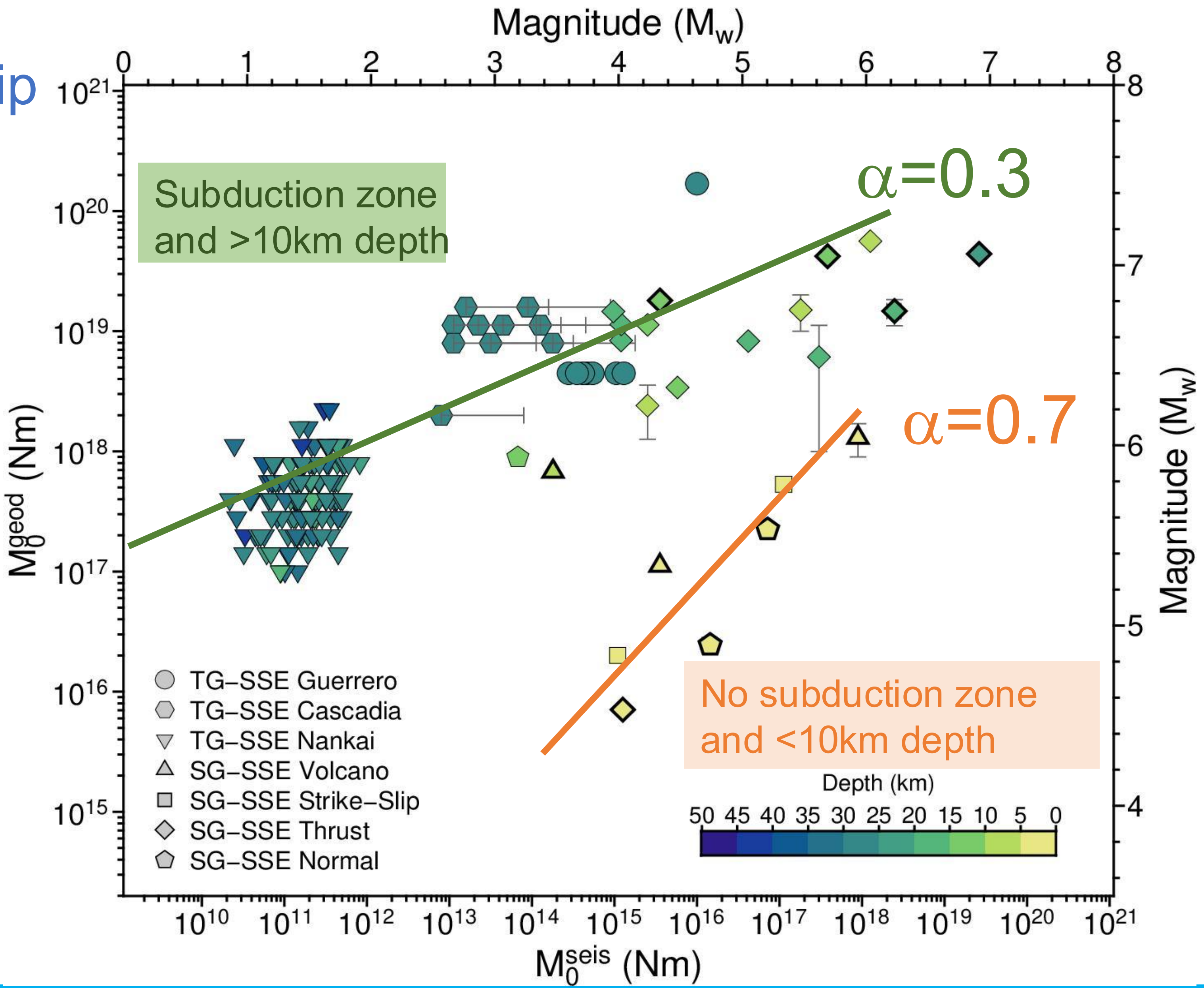


Aseismic and seismic moment release do scale during slow slip transients

$$M_0^{geod} = \beta (M_0^{seis})^{\alpha}$$

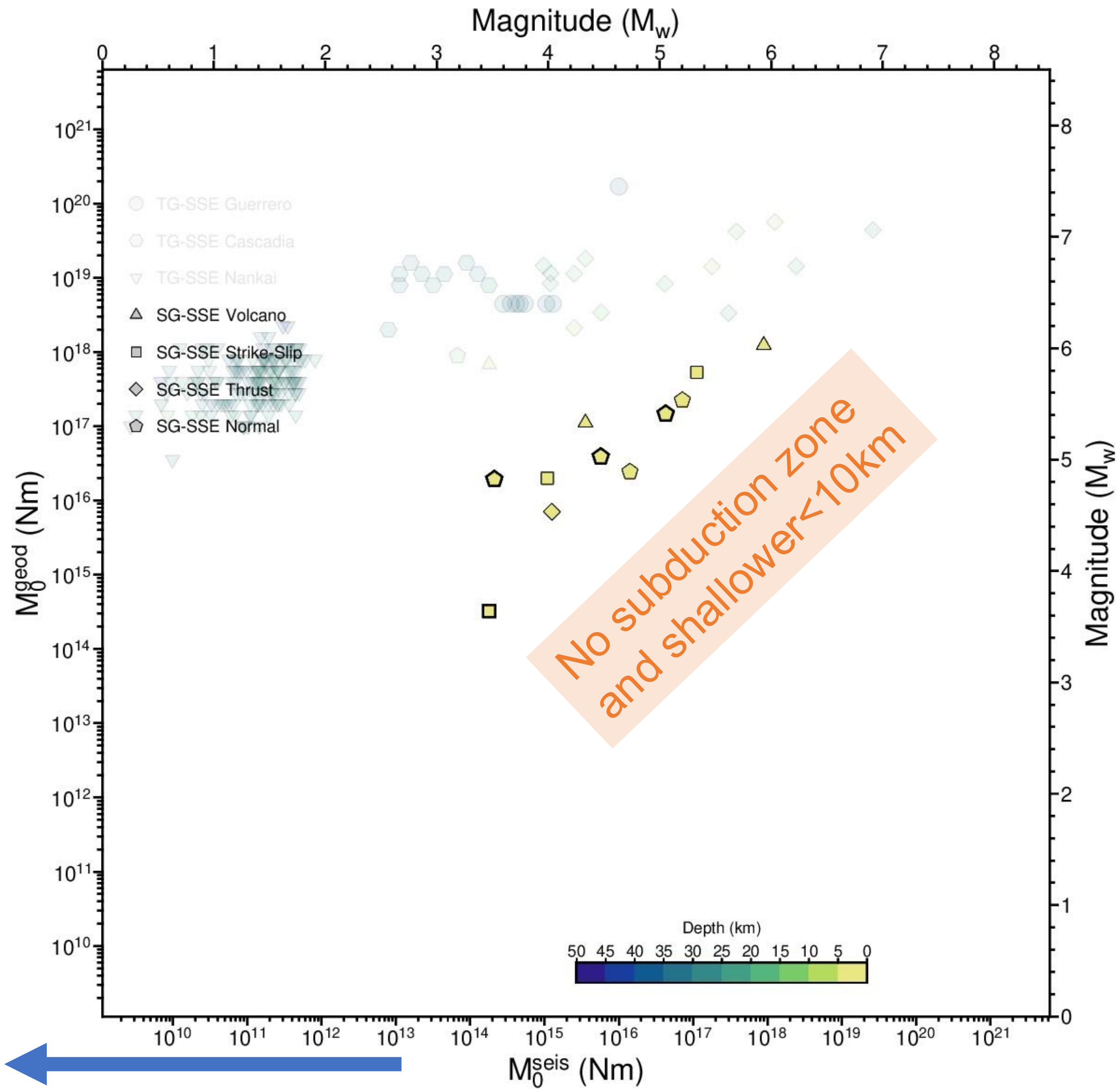
$$M_0^{geod} = M_0^{seis} + M_0^{aseis}$$

- TG–SSE Guerrero
- TG–SSE Cascadia
- TG–SSE Nankai
- SG–SSE Volcano
- SG–SSE Strike–Slip
- SG–SSE Thrust
- SG–SSE Normal



Passarelli et al., 2021 *Sci. Adv.*

Aseismic and seismic scaling



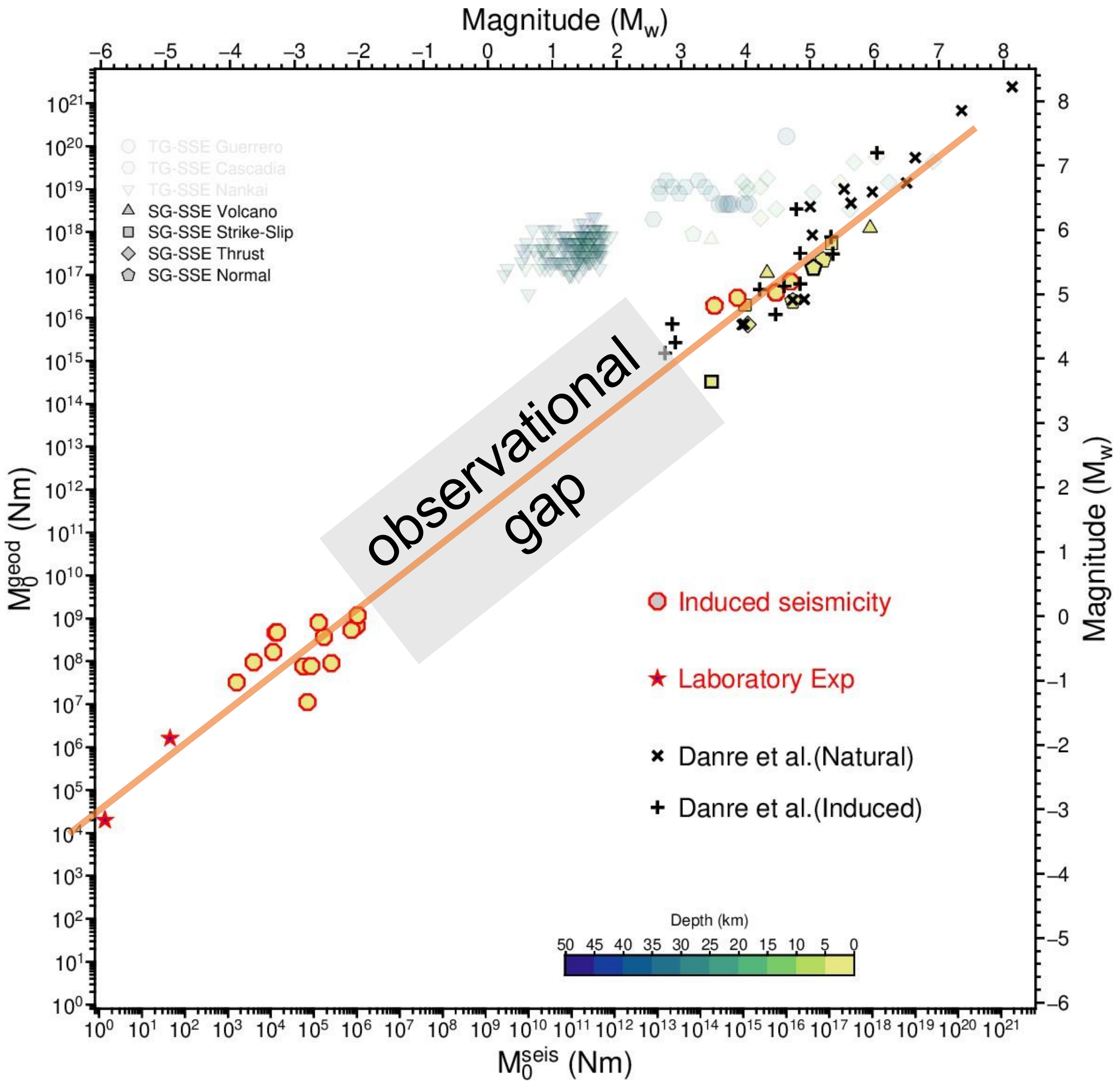
In-situ and Lab Exp

$$M_0^{geod} = \beta (M_0^{seis})^{\alpha}$$

Added new data:

- Natural SSEs
- In-situ field scale injection experiments
- Lab experiments
- Performed simulation

Aseismic and Seismic slip: From nature to lab



$$M_0^{geod} = \beta (M_0^{seis})^{\alpha}$$

α=0.7

x Natural (Danré et al., 2025)

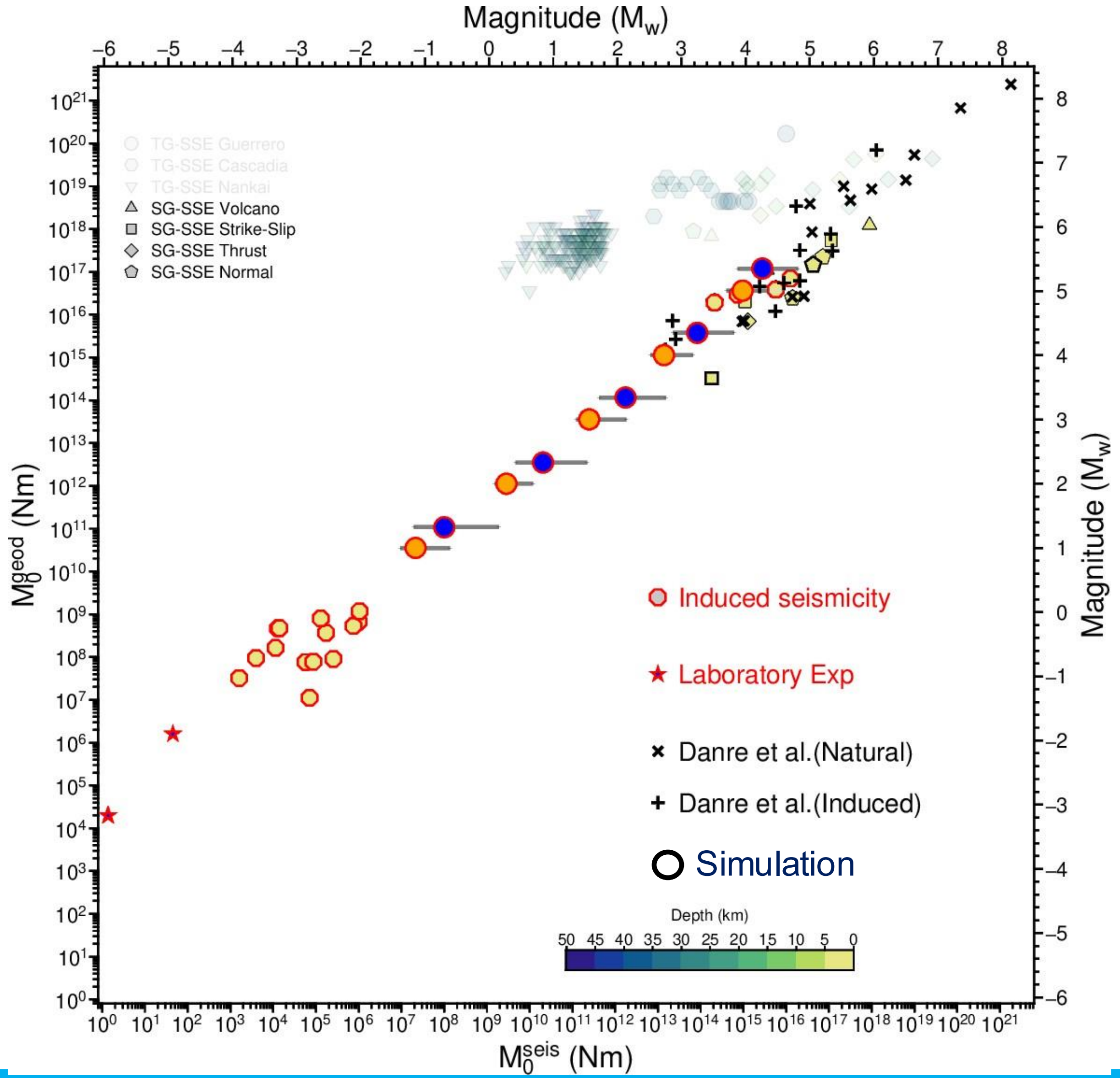
+ Induced (Danré et al., 2025)

★ Laboratory Exp

Aseismic and Seismic scaling

Geodetic vs Seismic Moment scaling:

$$M_0^{geod} = \beta (M_0^{seis})^\alpha$$



- Scaling -> The larger M_0^{geod} the larger the proportion of M_0^{seis}
- Scaling arises by a combination of:
- Confining stress increase with depth - > larger seismic moment release for deeper events
- Geometrical finiteness of the fault activated

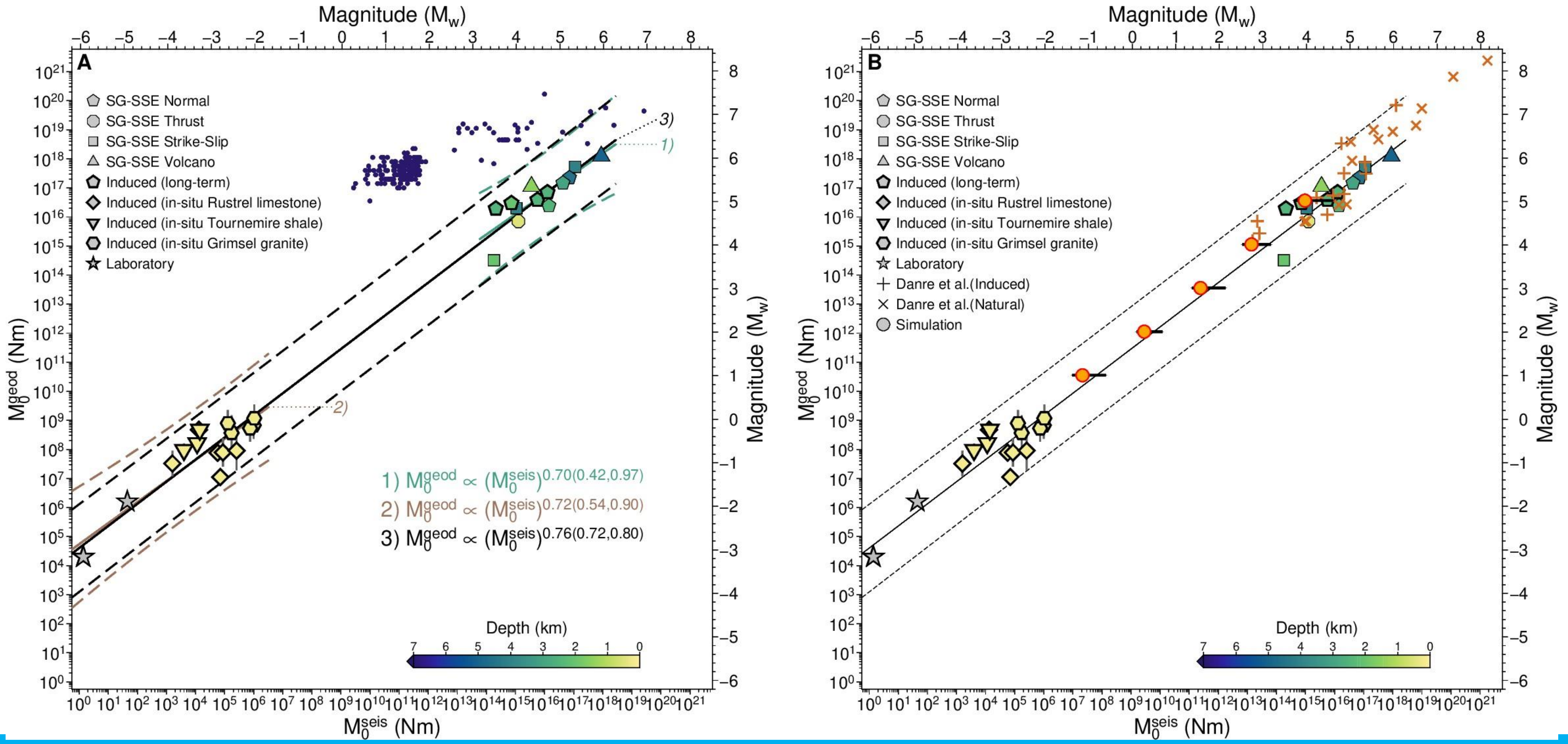
Results

Aseismic and Seismic scaling

Geodetic vs Seismic Moment scaling

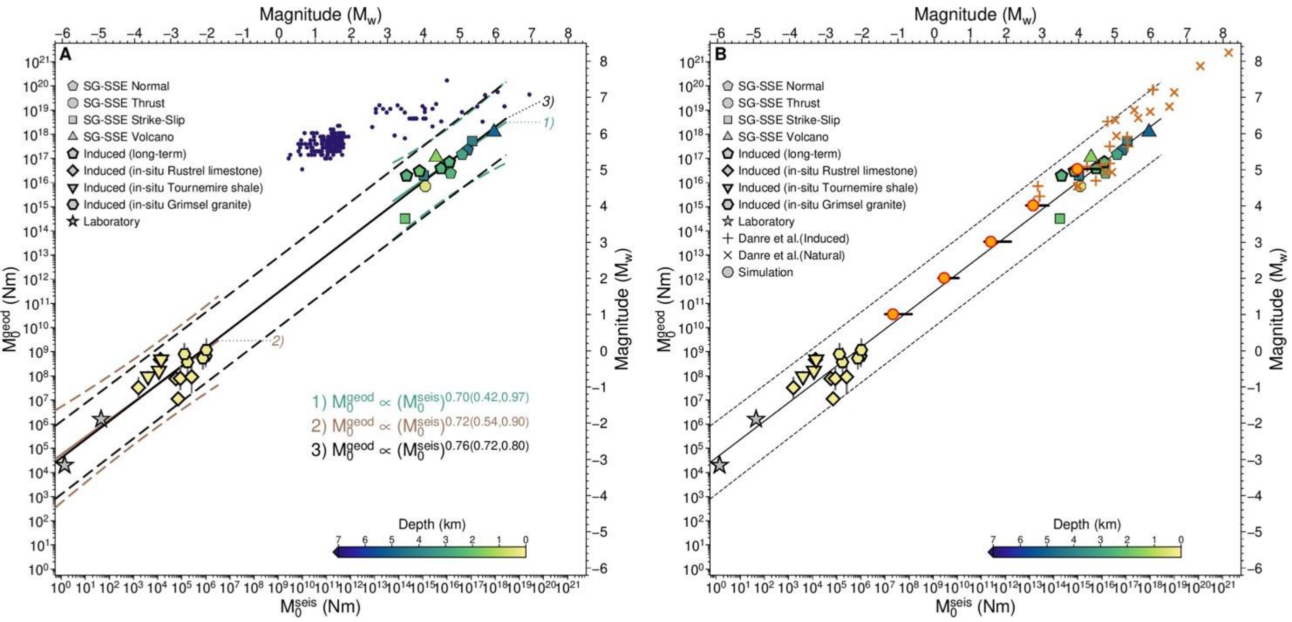
$$M_0^{geod} = 10^{4.6}(M_0^{seis})^{0.76}$$

$$M_0^{geod} = \beta(M_0^{seis})^{\alpha} \equiv if\ and\ only\ if\ M_0^{seis}\exists$$



Aseismic and Seismic scaling

Geodetic vs Seismic Moment scaling



$$M_0^{geod} = \beta (M_0^{seis})^{\alpha}$$

$$\equiv if\ and\ only\ if\ \ M_0^{seis} \exists$$

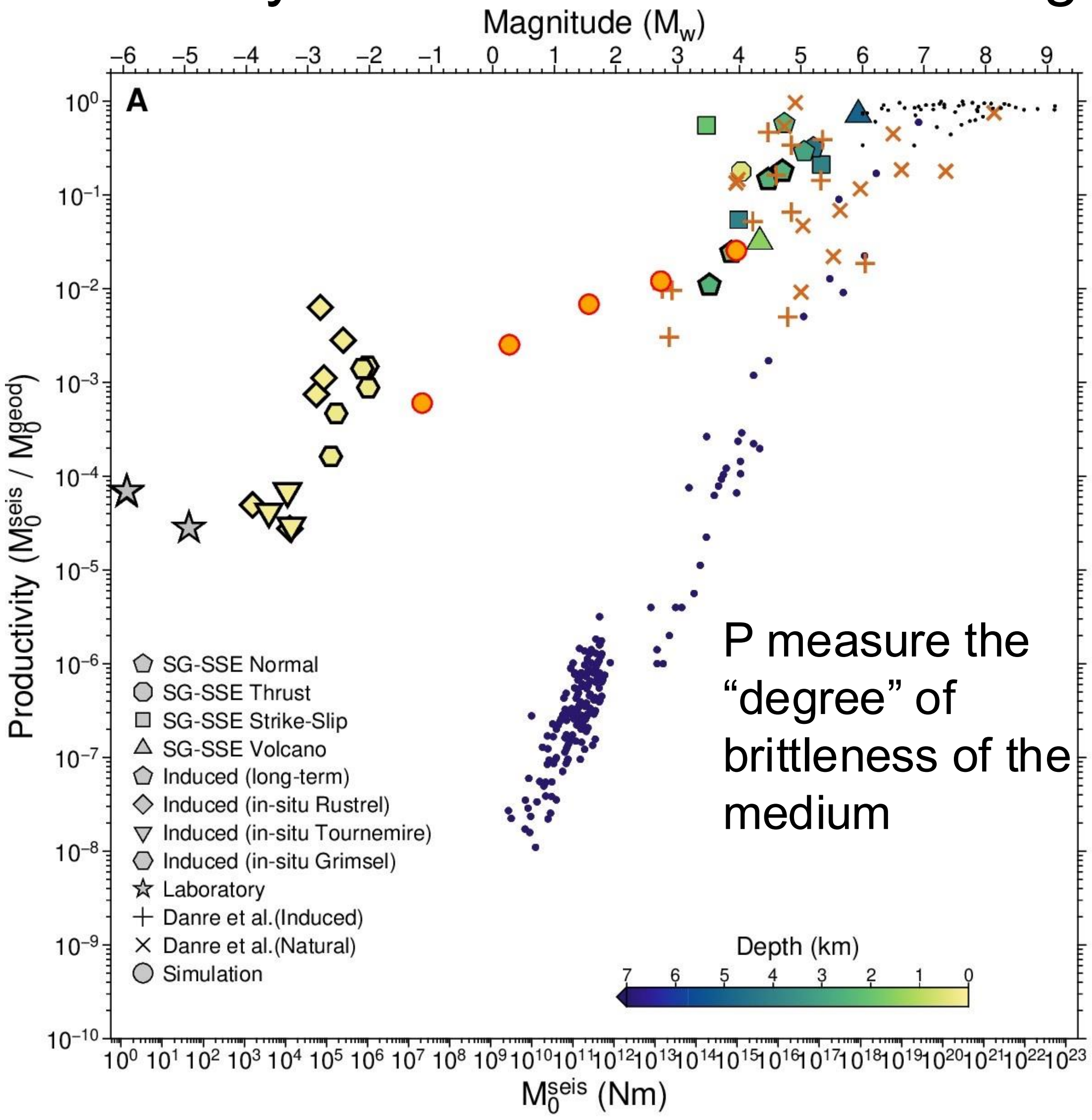
Eq. holds only for seismogenic slow slip transients

$$M_0^{geod} = M_0^{seis} + M_0^{aseis}$$

$$M_0^{geod} = \beta M_0^{seis}\ if\ \alpha=1$$

Aseismic and Seismic scaling

Productivity vs Seismic Moment scaling:



P measure the "degree" of brittleness of the medium

$$M_0^{geod} = \beta (M_0^{seis})^{\alpha}$$

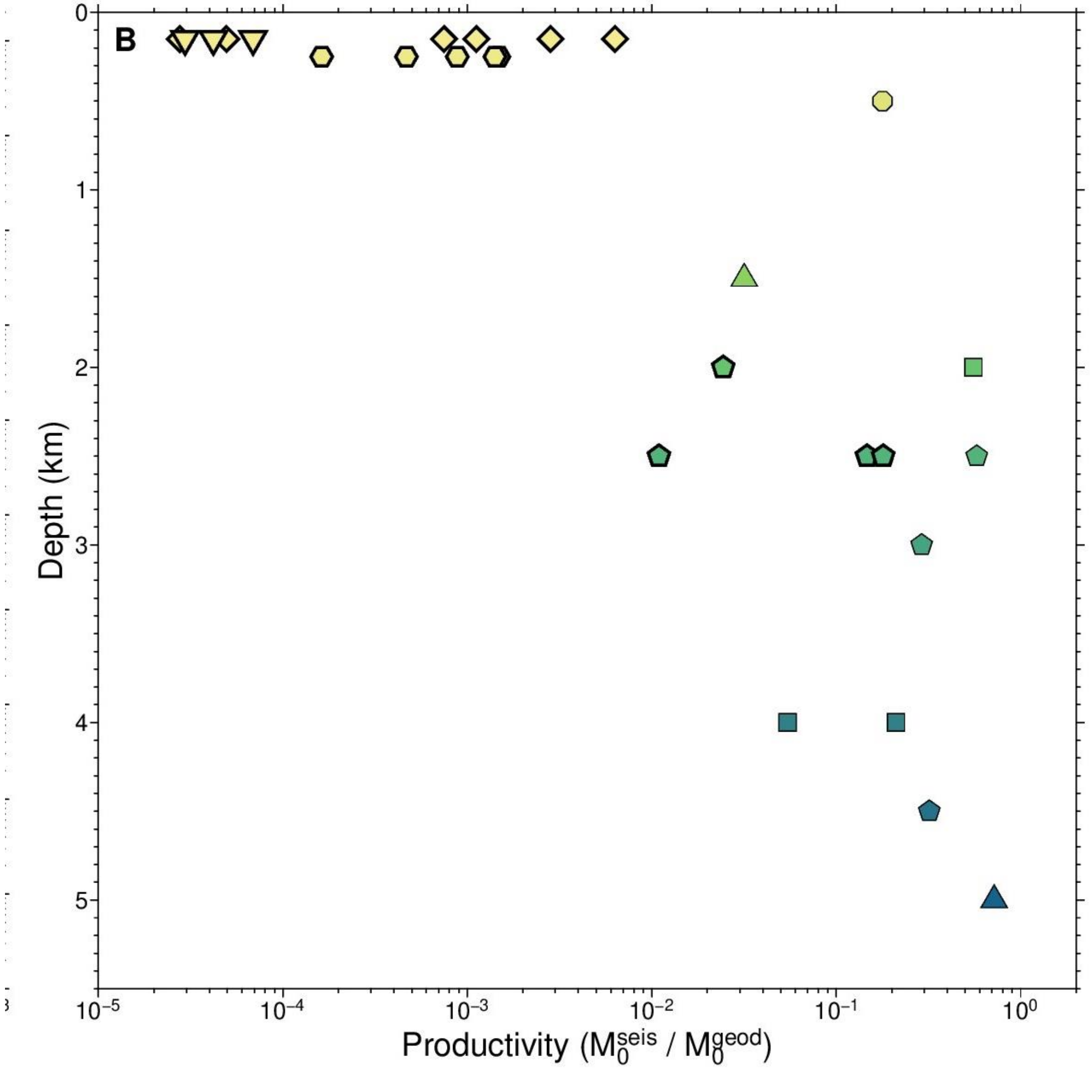
$$P = \frac{M_0^{seis}}{M_0^{geod}} = \frac{M_0^{seis}}{M_0^{seis} + M_0^{aseis}} = \frac{(M_0^{seis})^{1-\alpha}}{\beta}$$

P:

- $M_0^{seis} \gg M_0^{aseis}$ → $P \sim 1$
- $M_0^{seis} = M_0^{aseis}$ → $P = 0.5$
- $M_0^{aseis} \gg M_0^{seis}$ → $P \sim \frac{1}{M_0^{aseis}}$

Aseismic and Seismic scaling

Productivity vs Seismic Moment scaling:



$$Depth \sim P$$

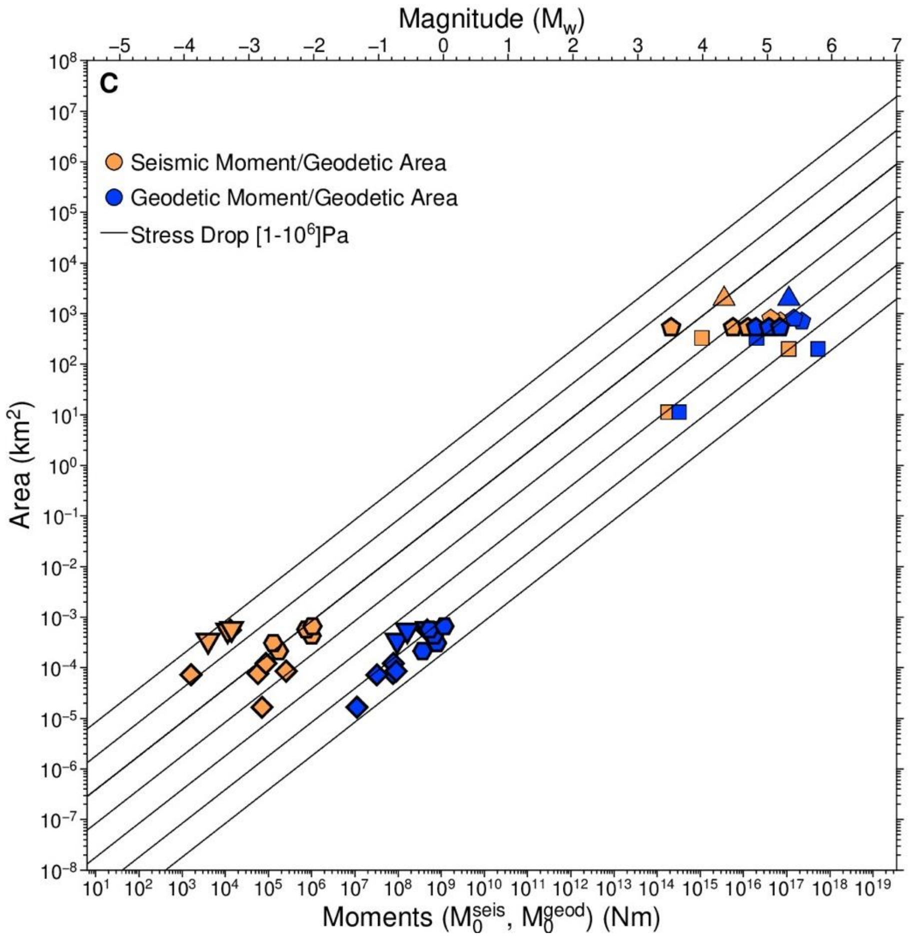
The deeper SSE the more seismic productive they are

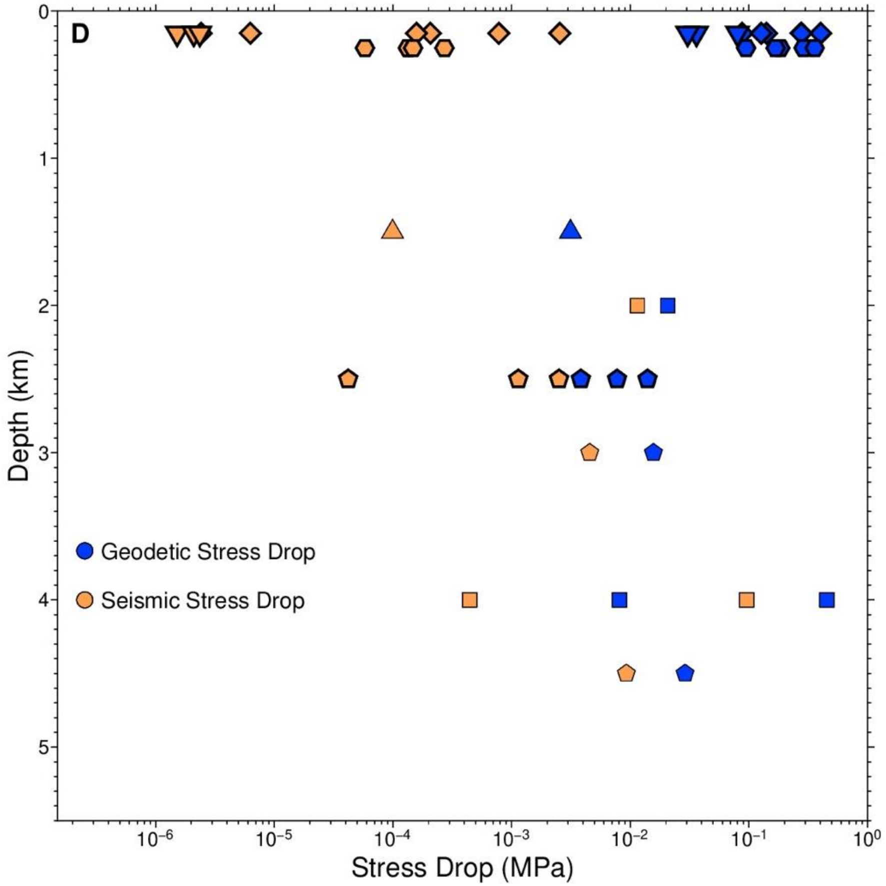
$$M_0^{seis} \lesssim M_0^{aseis}$$

Spearman Correlation ~ 0.85

Stress drop

$$\tau_{s,g} = \frac{7}{16}\frac{M_0^{s,g}}{L_{geod}^3}$$



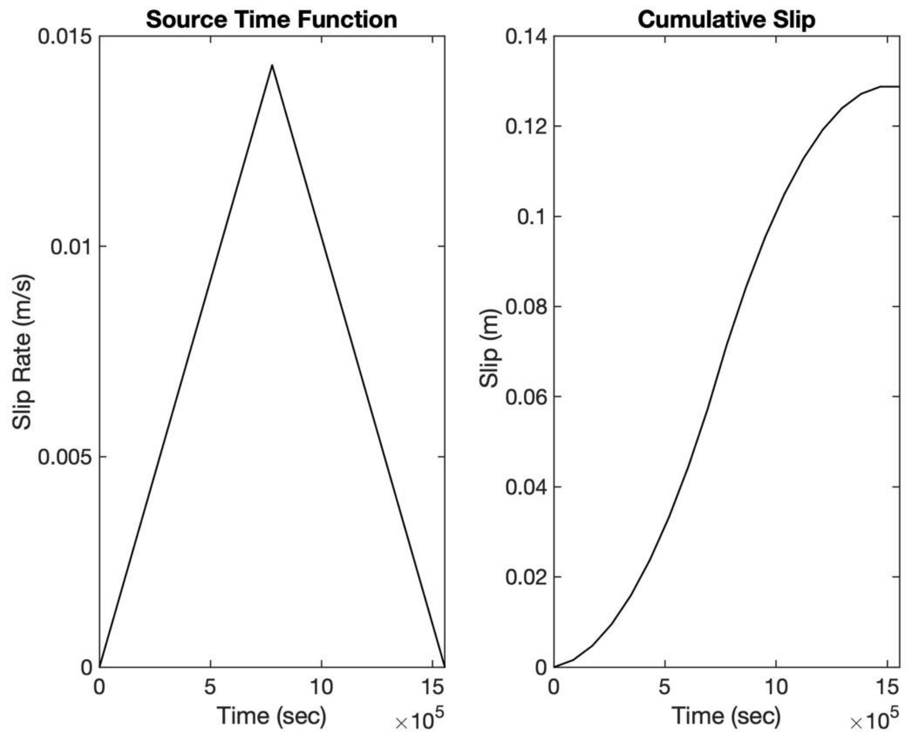


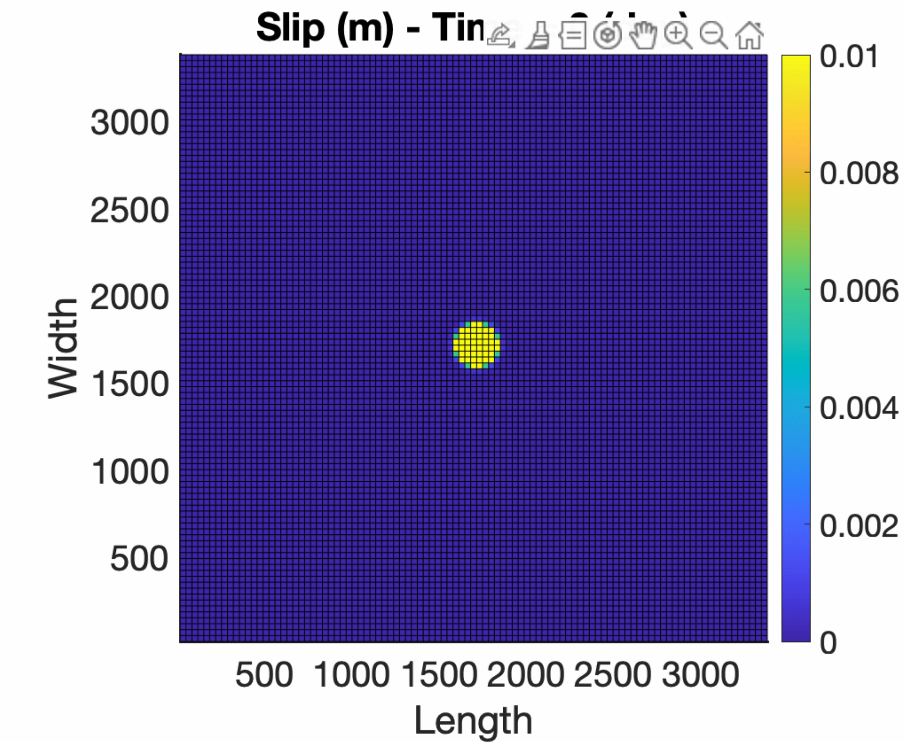
$$\tau \sim P$$

Simulation: Aseismic and Seismic slip

Poroelastic model (Wang and Kümpel, 2003)

Aseismic Source (SSE) w/ triangular Source Time Function and Gaussian slip…





…and calculate poro-elastic stresses in a homogeneous half-space

Simulation: Aseismic and Seismic slip

Physics-based stochastic earthquake simulator (SEED)
(Rinaldi and Nespoli, 2017)

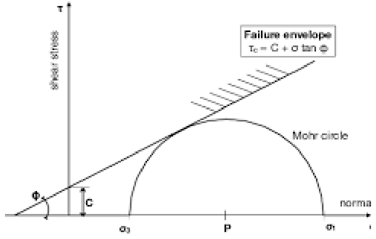
SEED = point source eqk

Initial random position (x,y,z)

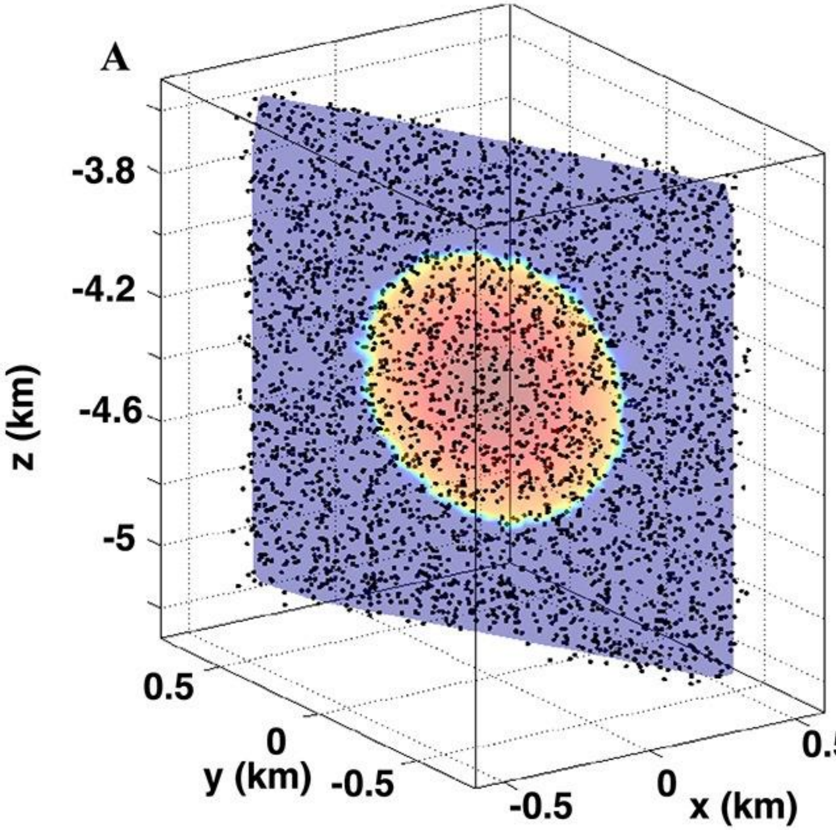
Random Focal Mechanism

Initial random stress state $\Delta\sigma$

SEED fails according Coulomb failure criterion

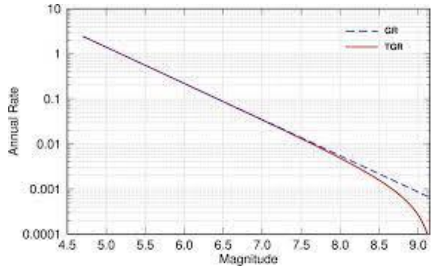


b-value
b-value ~ $\Delta\sigma$
b-value = 1



Catalli et al., 2016

Magnitude Truncated GR



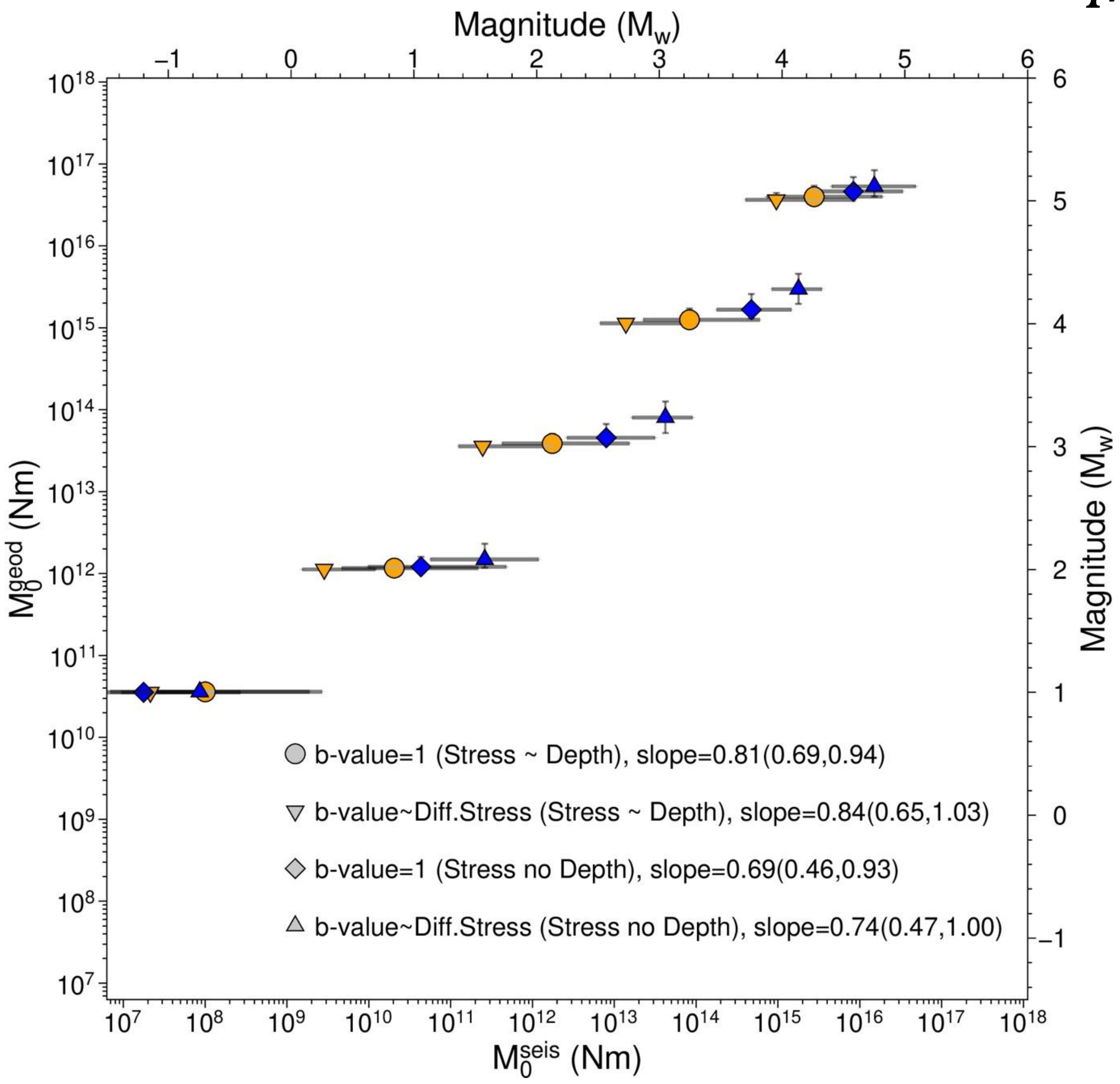
Geodetic vs Seismic Moment scaling:

$$M_0^{geod} = \beta (M_0^{seis})^{\alpha}$$

SSE magnitude (source):

Mw = 1, 2, 3, 4, 5

- Computational domain scales w/ Mw
- SEED density constant
- Mmax(eqks) = Mw(SSE)
- 200 catalogs for each magnitude class



Simulation:

b ~ $\Delta\sigma$ and *b = 1*

w/ Depth-dependent stress or not

Finiteness of the fault matters, i.e. truncated GR

Aseismic and seismic scaling

Physical explanation

Shallower $M_0^{geod} = \beta (M_0^{seis})^{0.7}$

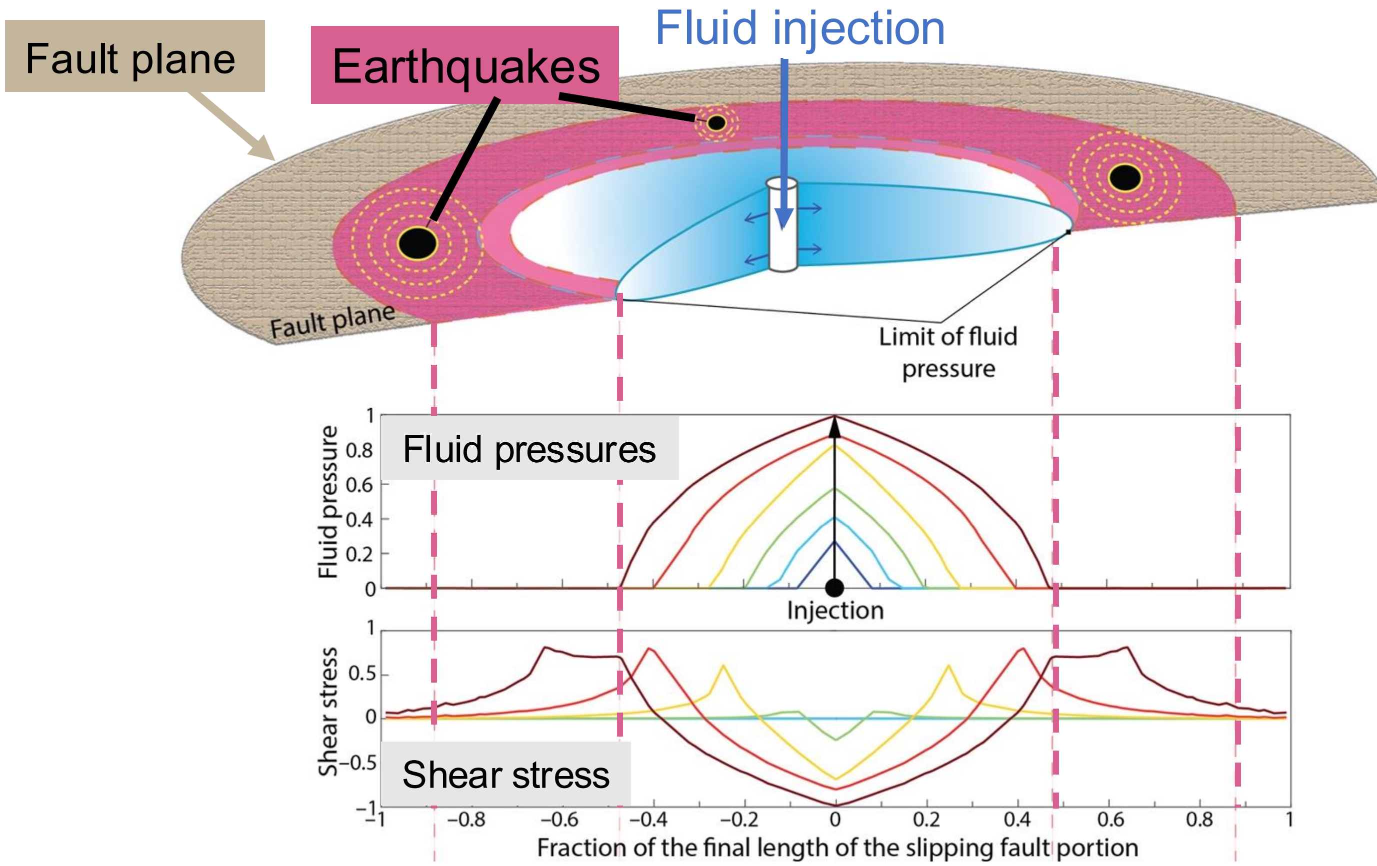
(outside subduction zones)

Physical mechanisms: fault pressurization (unclamping)

Pressure unclamps the fault and produces aseismic slip

High-pressure induces aseismic slip to expand (around the injection point)

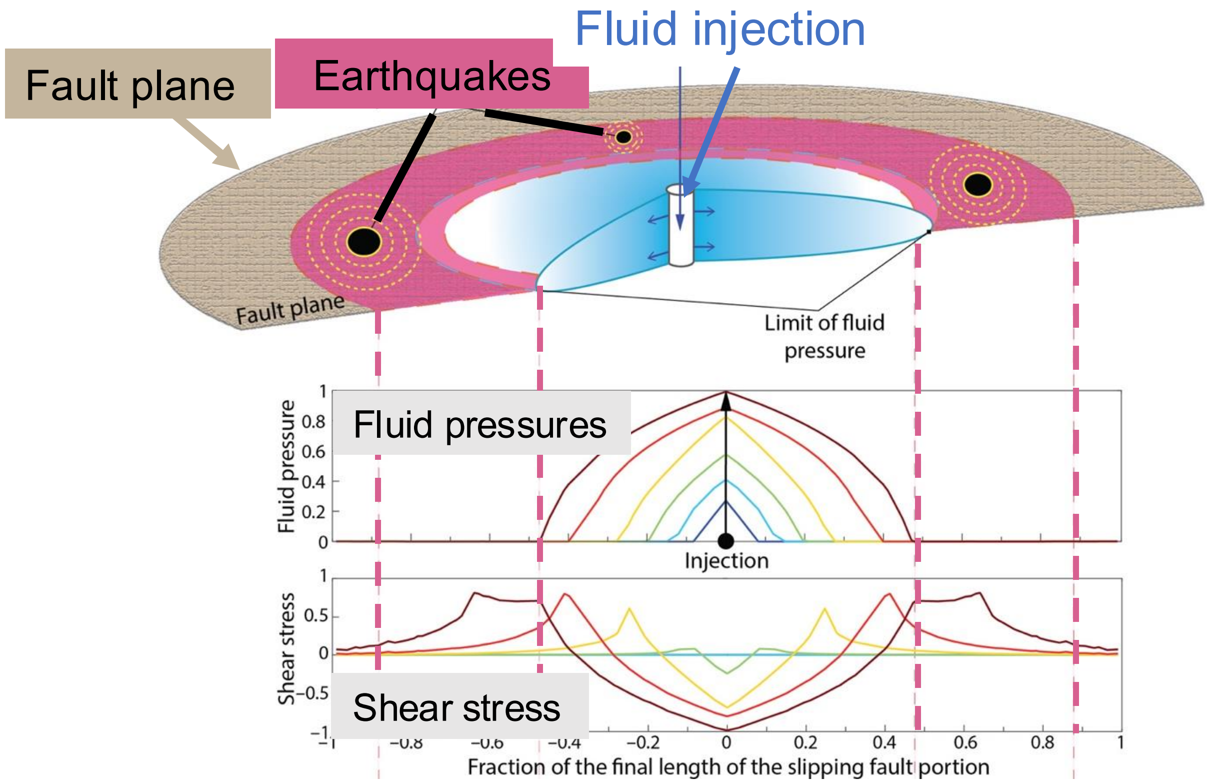
Propagation of the aseismic rupture triggers seismicity due to shear stress increase at the rupture edges



Cappa et al., 2019

Conclusions

- Seismic to aseismic moment scaling over 14-18 orders of magnitude (but observational gap??)
- If $M_a >> M_s$ scaling holds over large range of orders of magnitude
- Geometrical finiteness of the fault constrains aseismic and seismic moment release
- Fluid-induced pressurization of fault is a viable mechanisms to trigger slow and fast slip

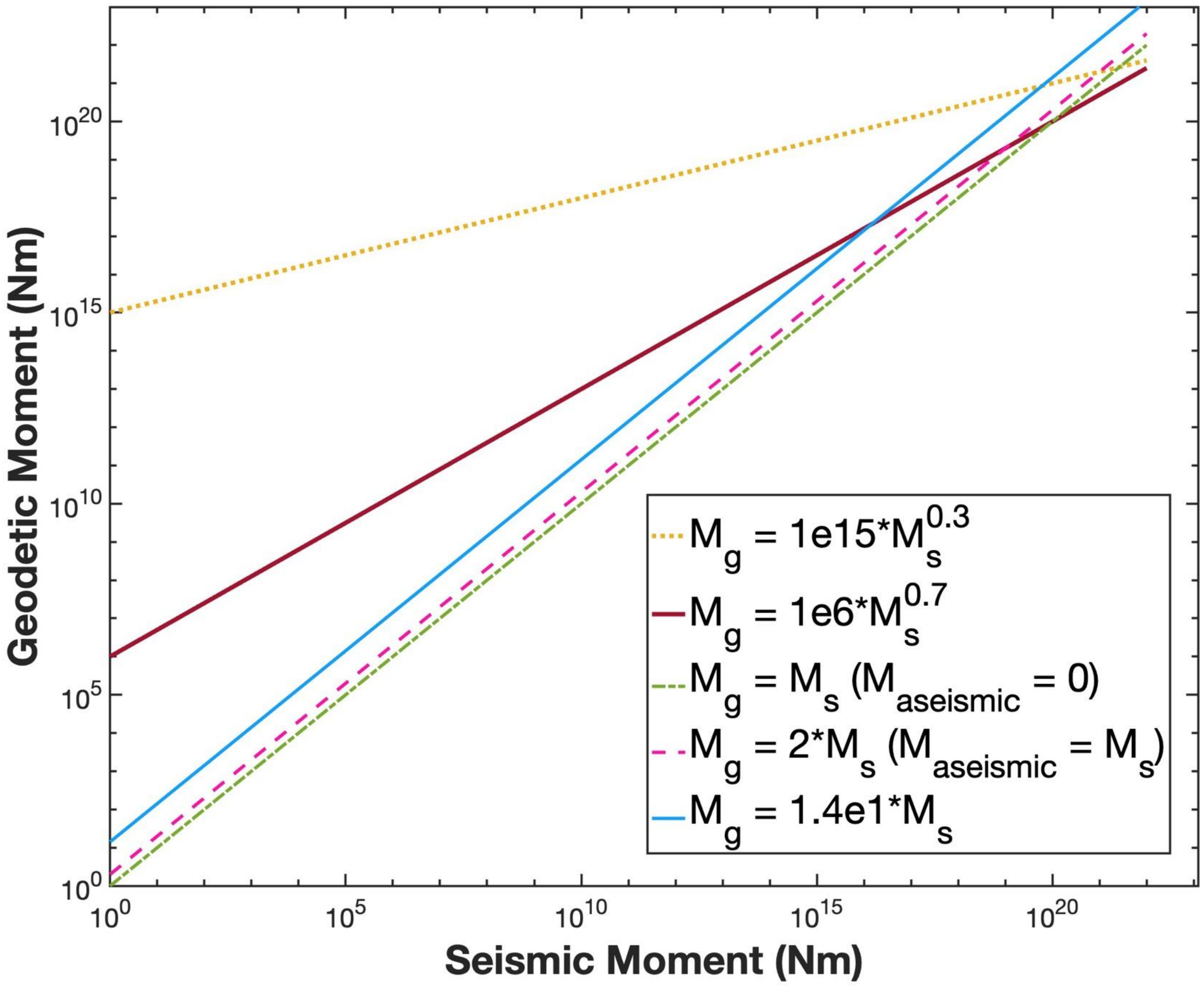


Cappa et al., 2019

Thank you

START OF BACK UP SLIDES:

please contact me at luigi.passarelli@ingv.it for further explanation since slides are very minimalistic

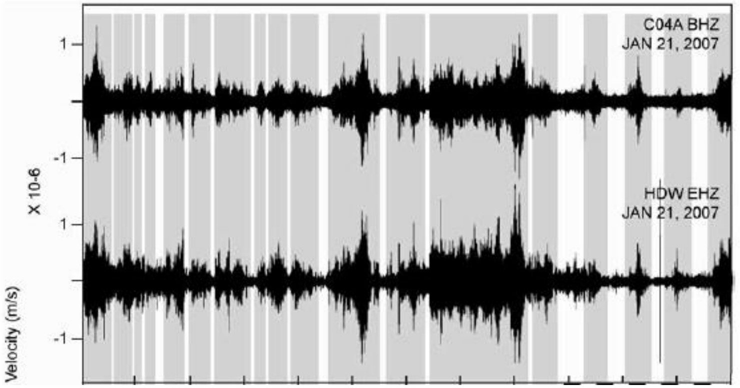


Geodetic Moment (Nm)
Seismic Moment (Nm)
10^{0}
10^{5}
10^{10}
10^{15}
10^{20}
$M_g = 1e15*M_s^{0.3}$
$M_g = 1e6*M_s^{0.7}$
$M_g = M_s$ ($M_{aseismic} = 0$)
$M_g = 2*M_s$ ($M_{aseismic} = M_s$)
$M_g = 1.4e1*M_s$

Slow Slip Transients aka Slow Slip Events (SSEs)

Slow slip transients are rupture that do not excite seismic wave and are often "associated" w/ *"seismic"* events:

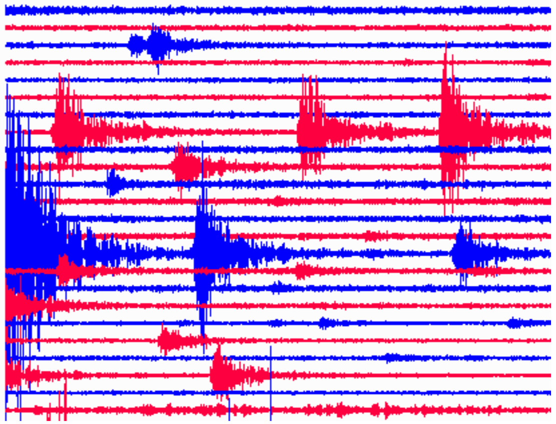
Non-volcanic Tremor
(many tiny earthquakes)



Aguiar et al., 2009

and/or

Swarms of "ordinary" (larger) earthquakes

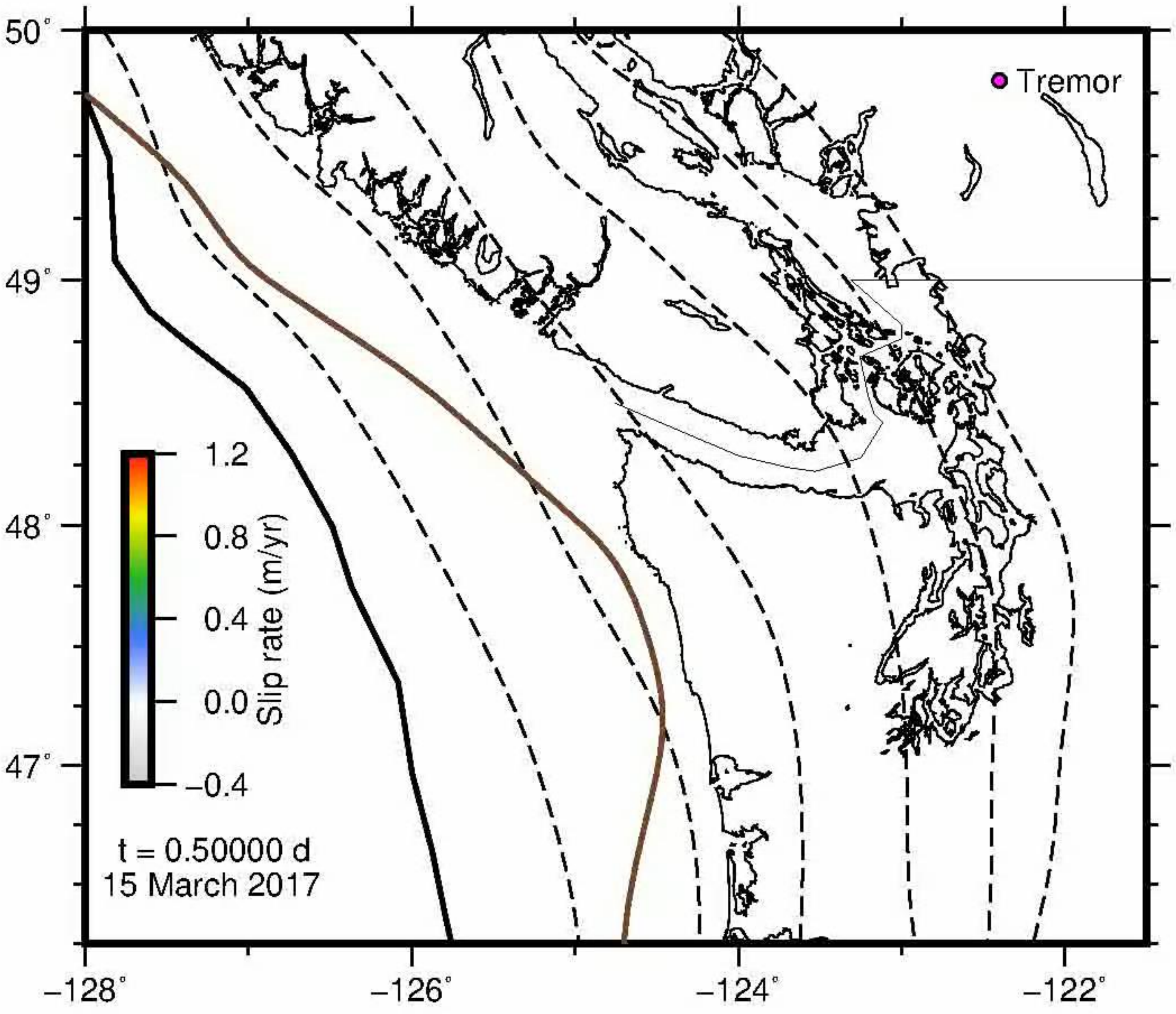


GEOFON TNTI stazione

Tremor-Genic Slow Slip Events
TG-SSEs

Swarm-Genic Slow Slip Events
SG-SSEs

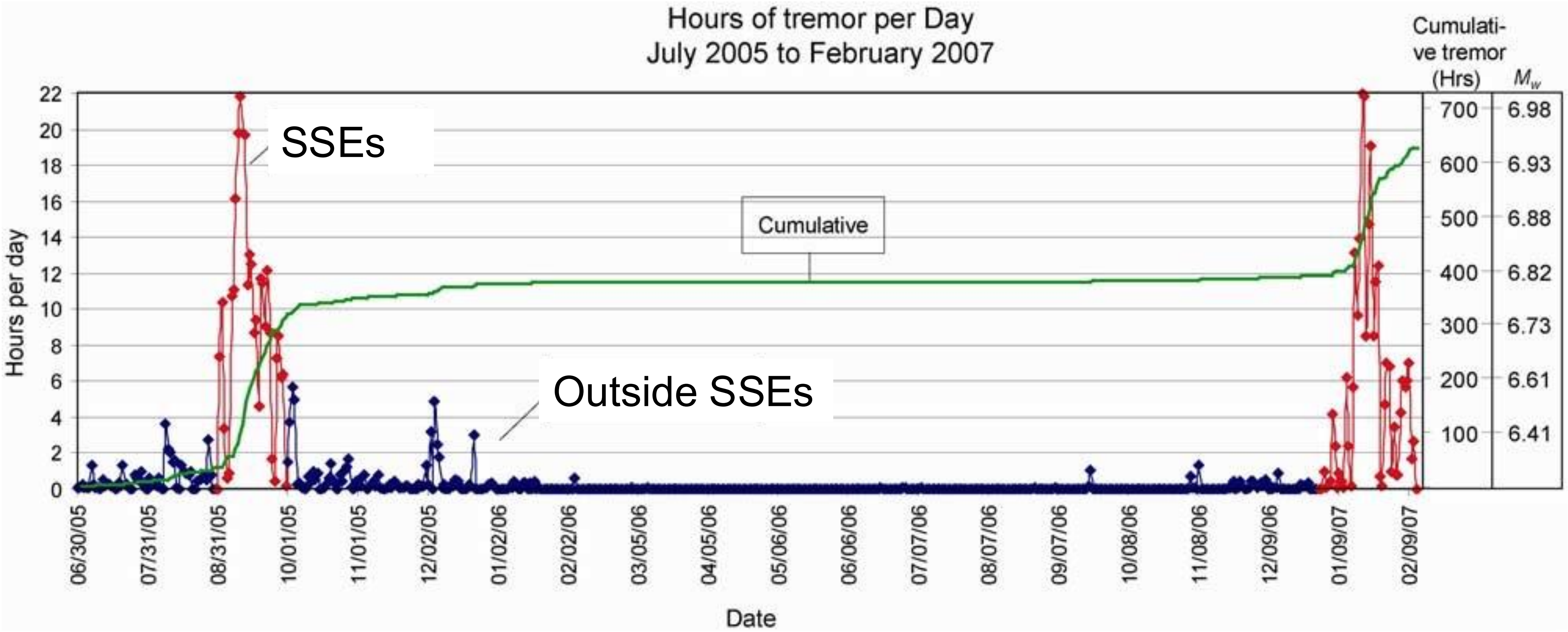
Slow Slip Events (SSEs): Phemenology



Itoh et al., 2022

Slow Slip Events (SSEs)

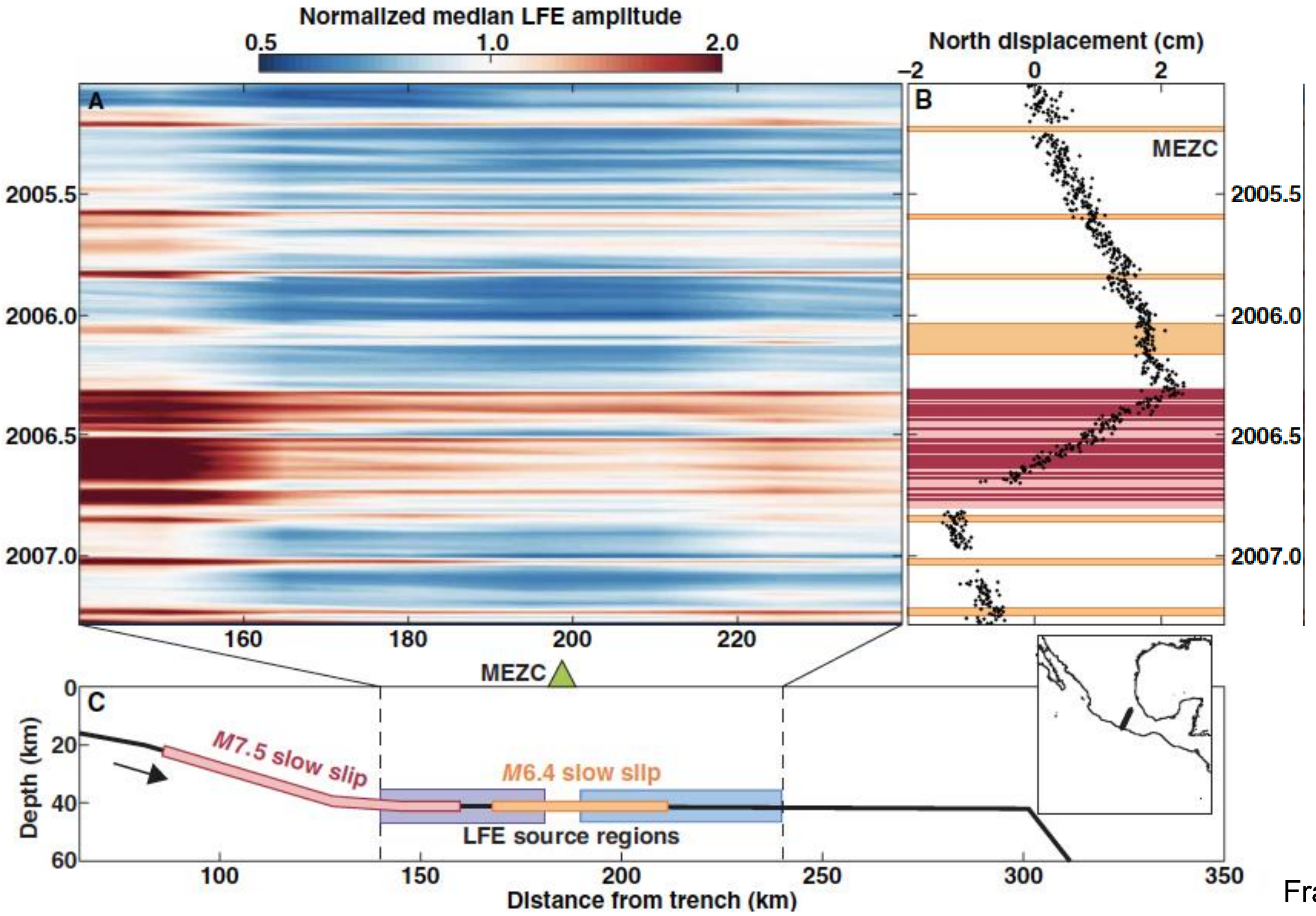
Tremor or LFEs counts increases during SSEs



Aguiar et al., 2009

Slow Slip Events (SSEs)

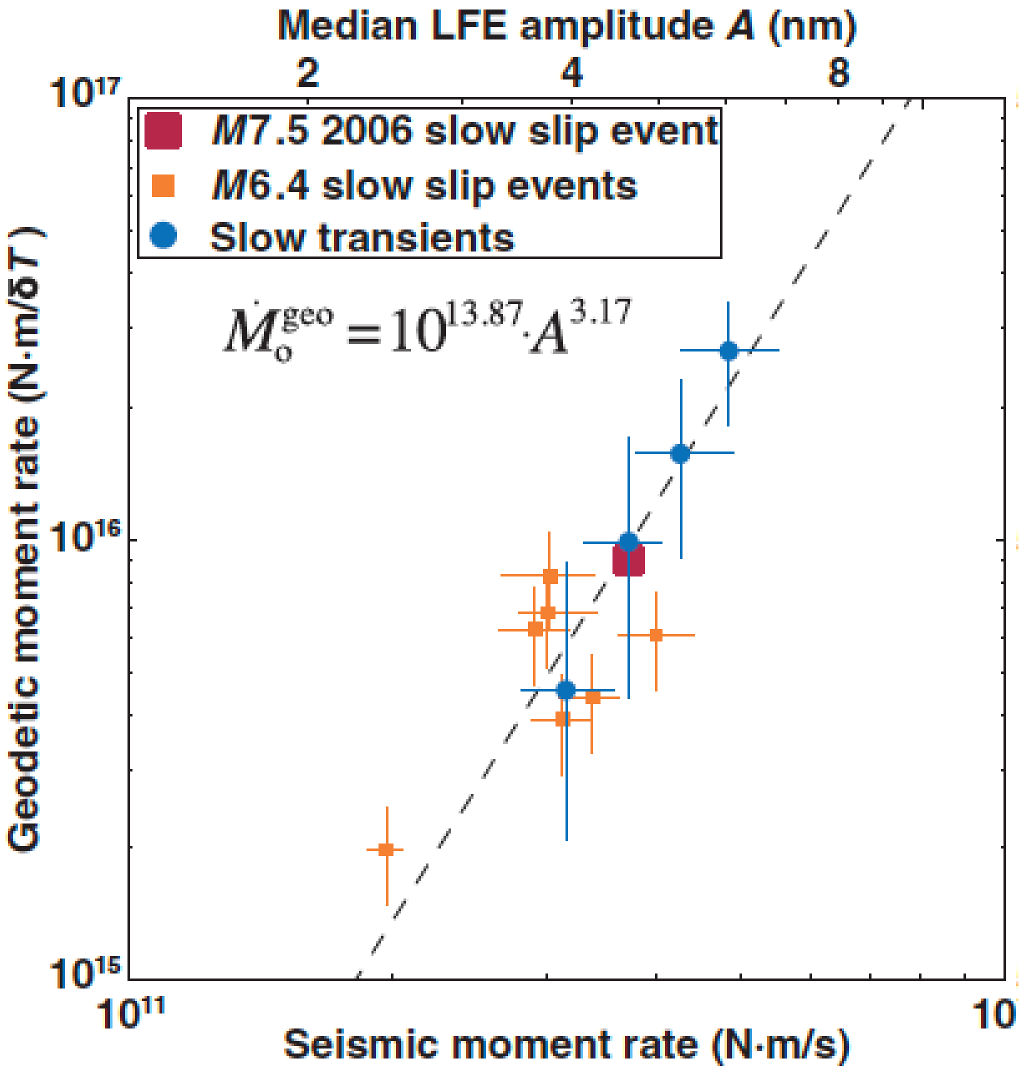
Tremor or LFEs amplitudes (energy) increase during SSEs



Frank and Brodsky 2019

Slow Slip Events (SSEs): TG-SSEs

Tremor or LFEs moment (slip) rate correlates with moment (slip) rate of SSEs



Frank and Brodsky 2019

Fast and Slow Slip — Physical processes

⇒ Fault structures where *slow and aseismic* and *fast and seismic* slip can be accommodated at the same time

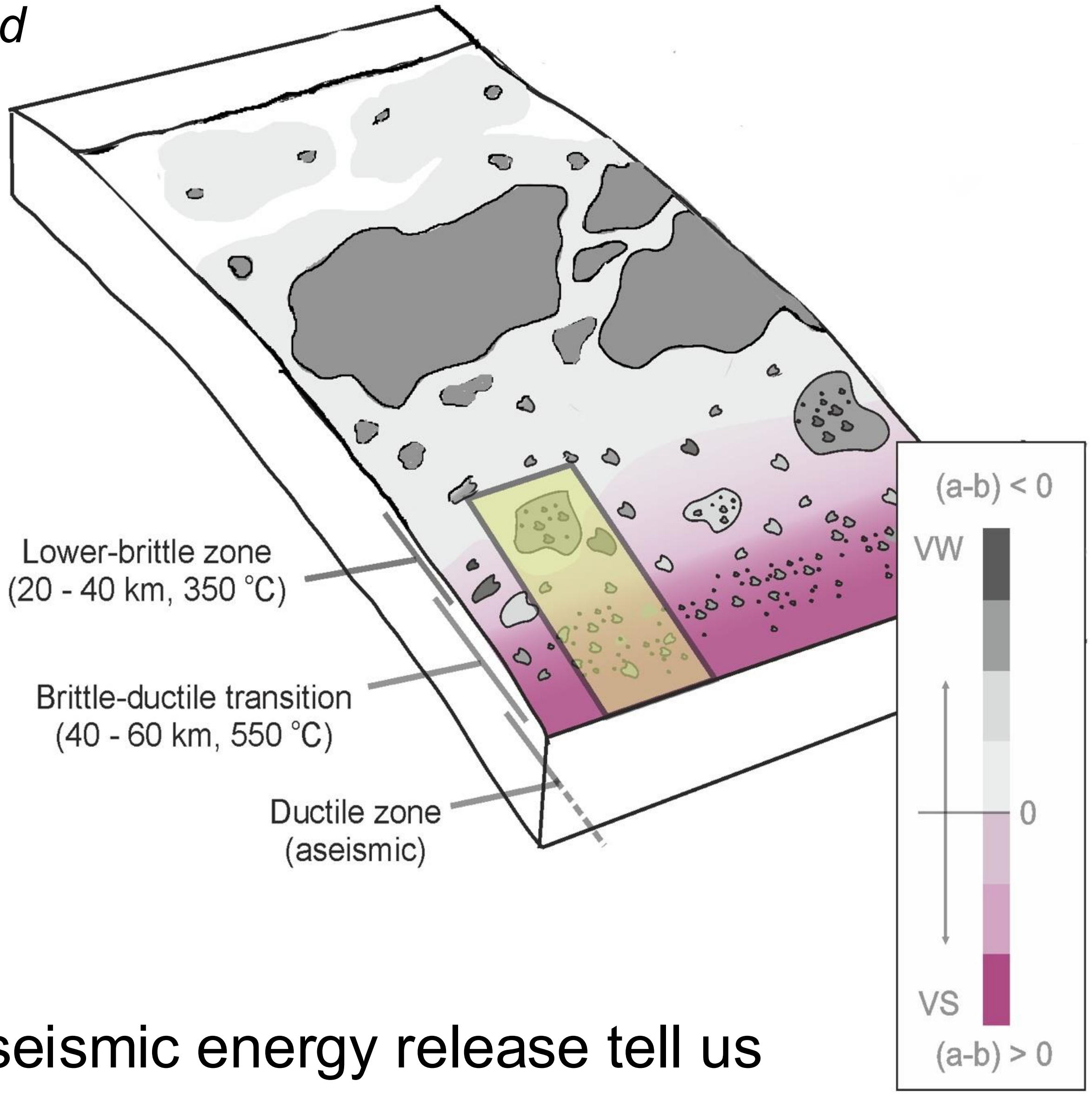
⇒ Conceptual model:
Brittle asperities (darker gray) embedded within conditionally stable (light gray) and stable sliding regions (pinkish)

⇒ Mechanical condition:

Heterogeneous frictional properties

Pronounced fault roughness

High pore pressure condition (low effective normal stress)



Does the proportion of aseismic and seismic energy release tell us about the mechanical condition at the source?

Aseismic and seismic scaling

Physical explanation

Physical mechanisms: fault pressurization (unclamping)

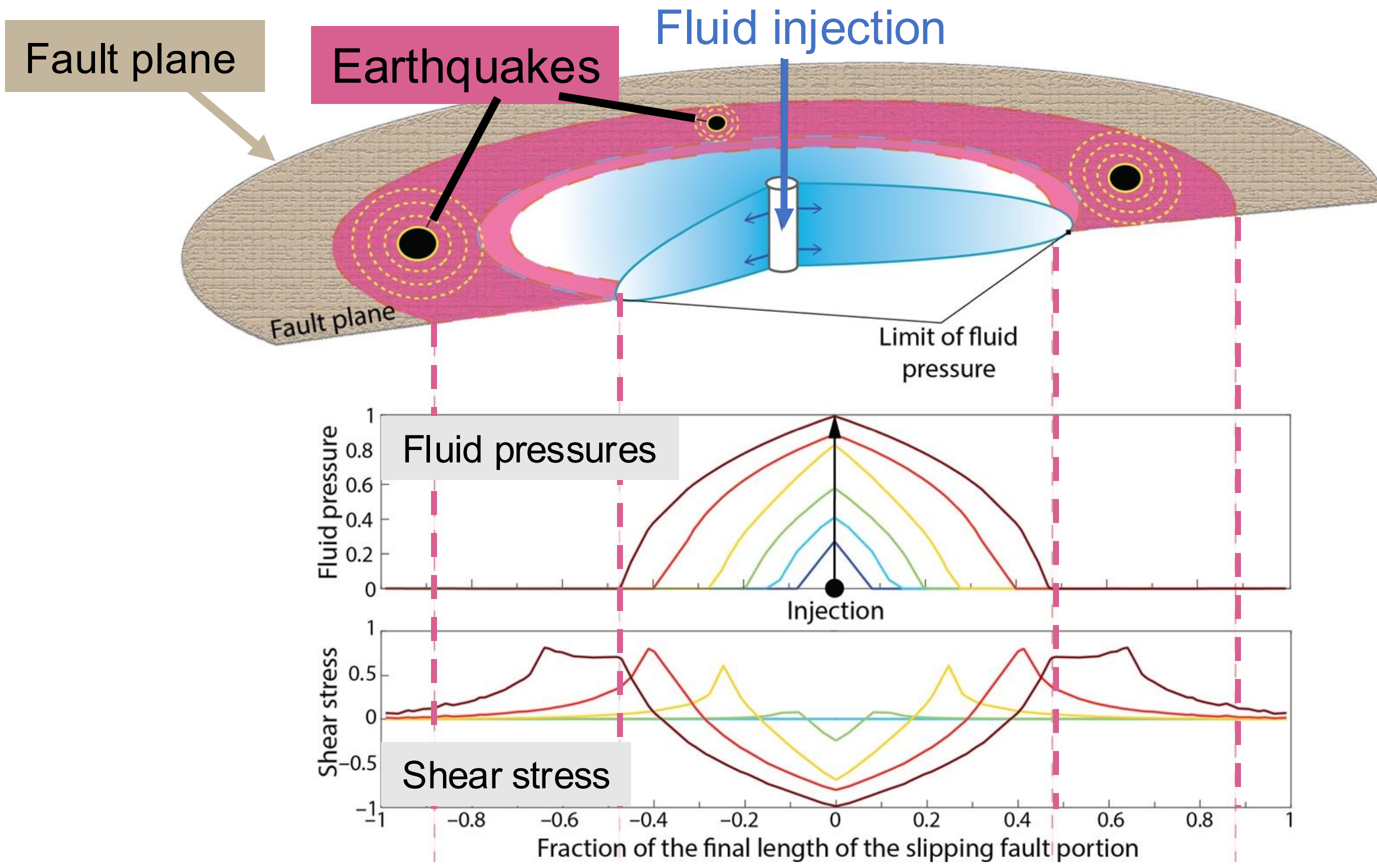
Shallower $M_0^{geod} = \beta (M_0^{seis})^{0.7}$

(outside subduction zones)

Pressure <u>unclamps</u> the fault and produces aseismic slip

High-pressure induces <u>aseismic slip</u> to expand (around the injection point)

Propagation of the <u>aseismic rupture triggers seismicity</u> due to shear stress increase at the rupture edges

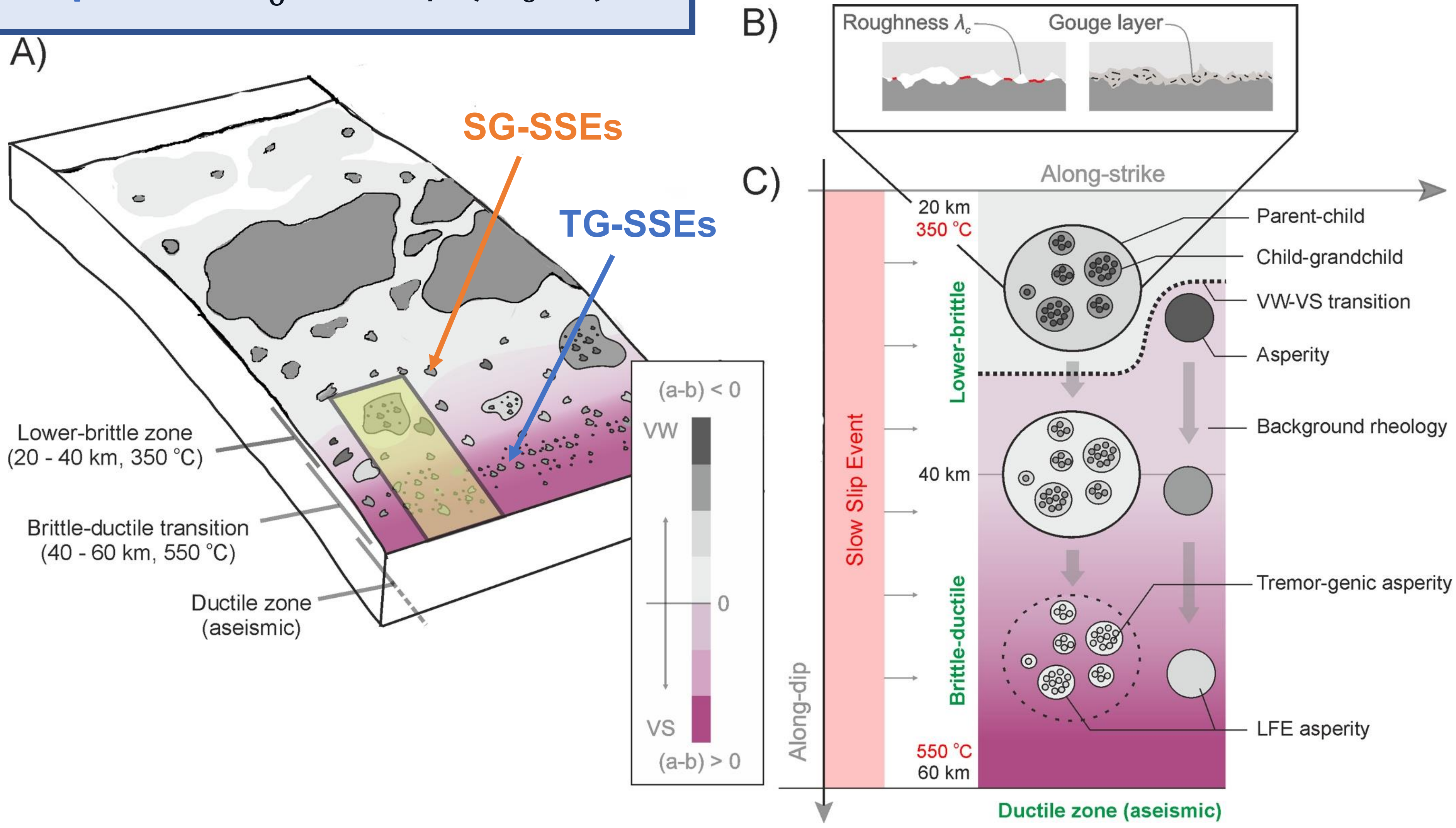


Cappa et al., 2019

Aseismic and seismic scaling

Physical explanation

Deeper $M_0^{geod} = \beta(M_0^{seis})^{0.3}$



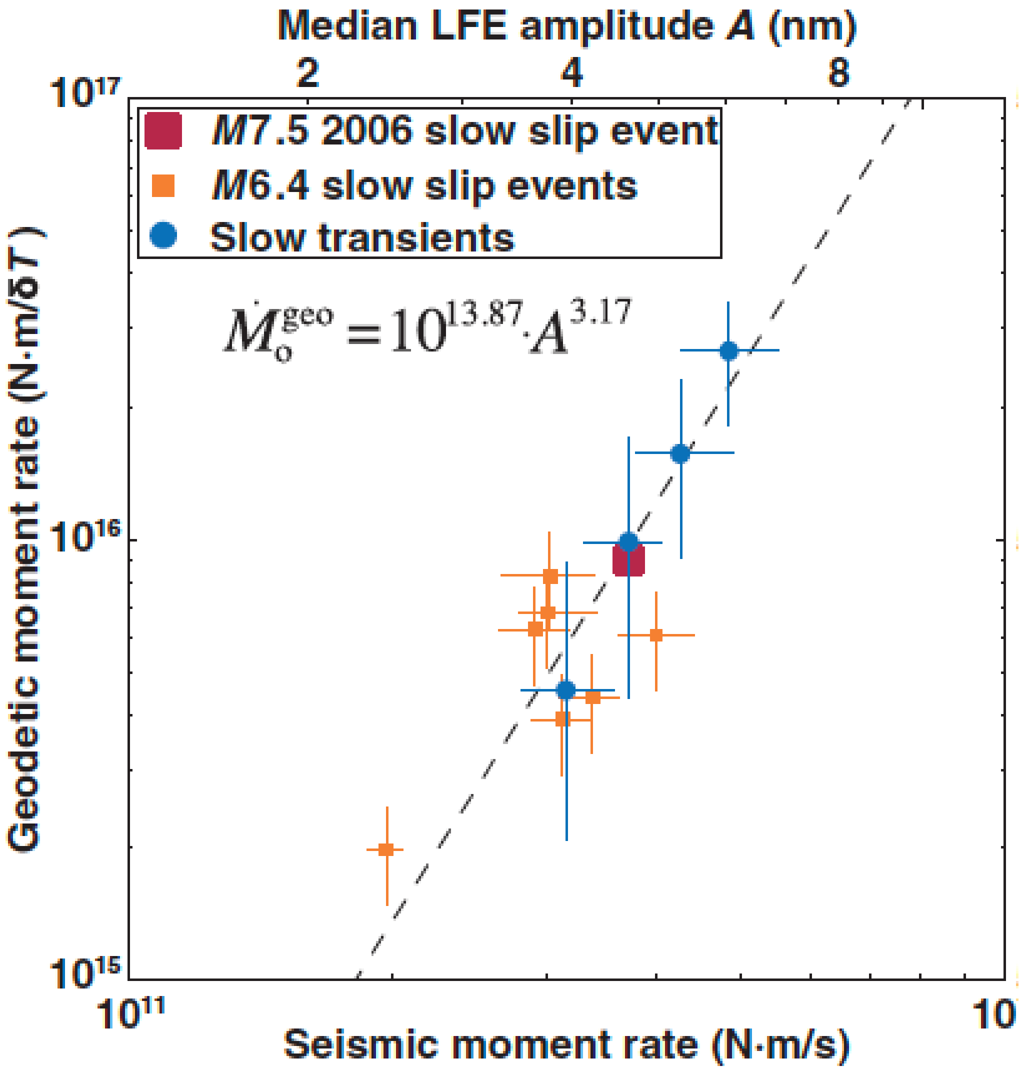
Pronounced fault roughness

High pore pressure

Heterogeneous frictional properties dependent on temperature

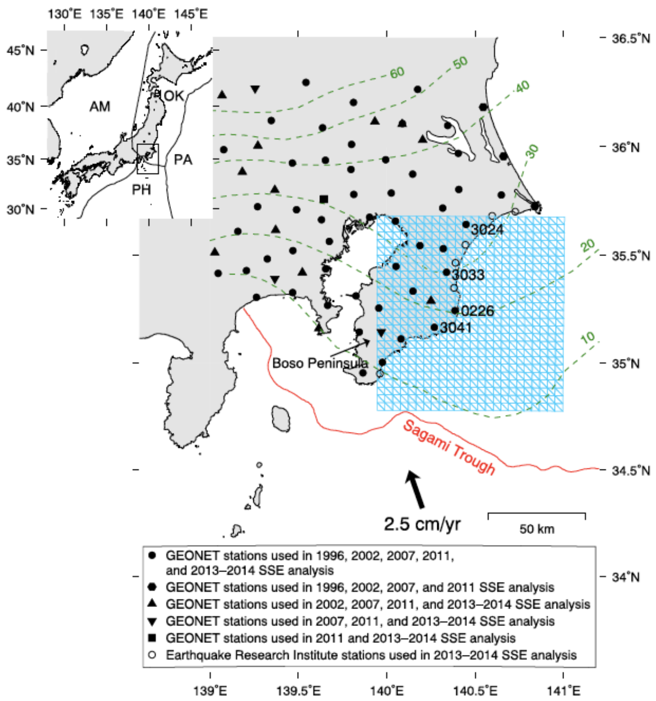
Slow Slip Events (SSEs): TG-SSEs

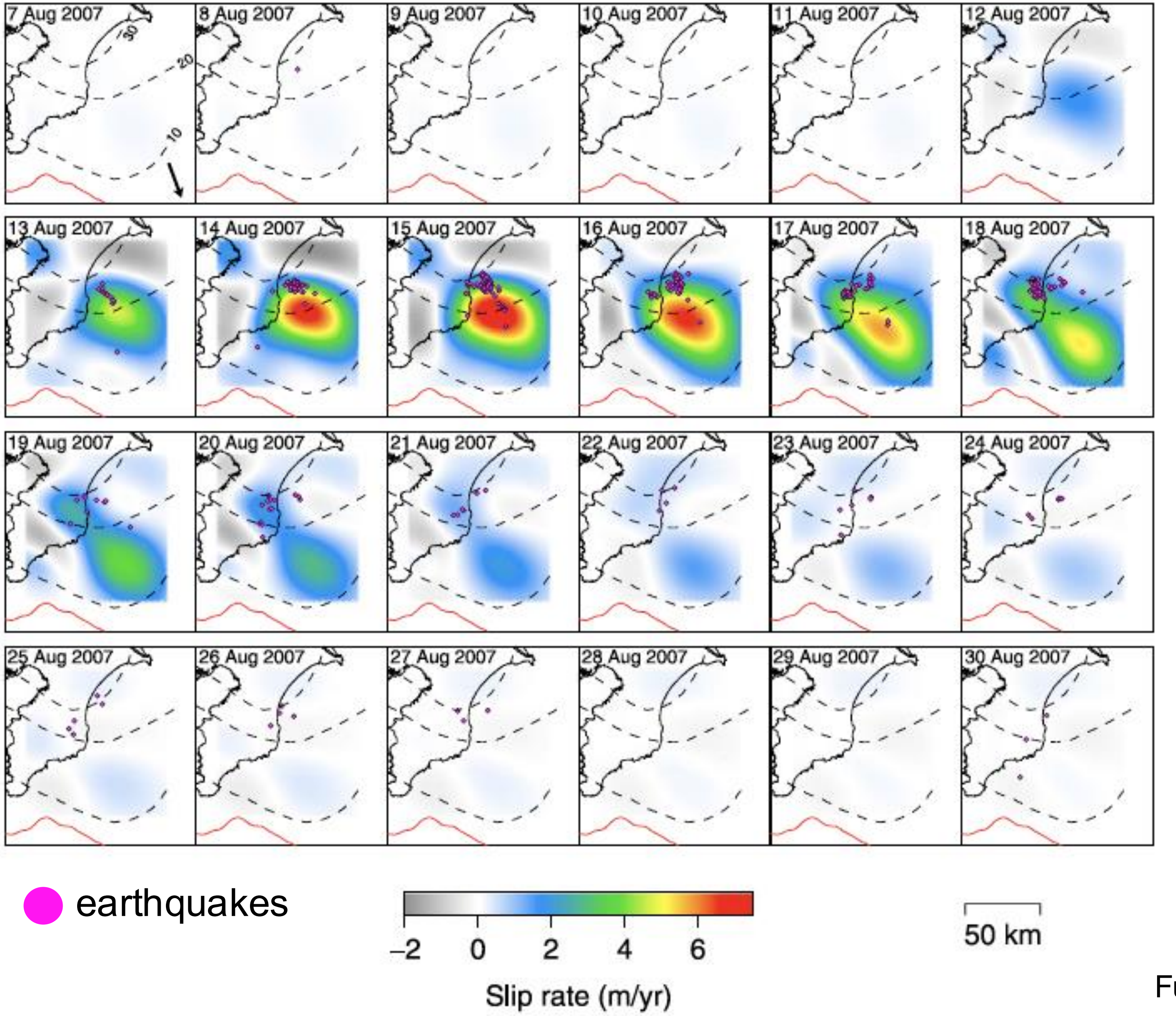
Tremor or LFEs moment (slip) rate correlates with moment (slip) rate of SSEs



Frank and Brodsky 2019

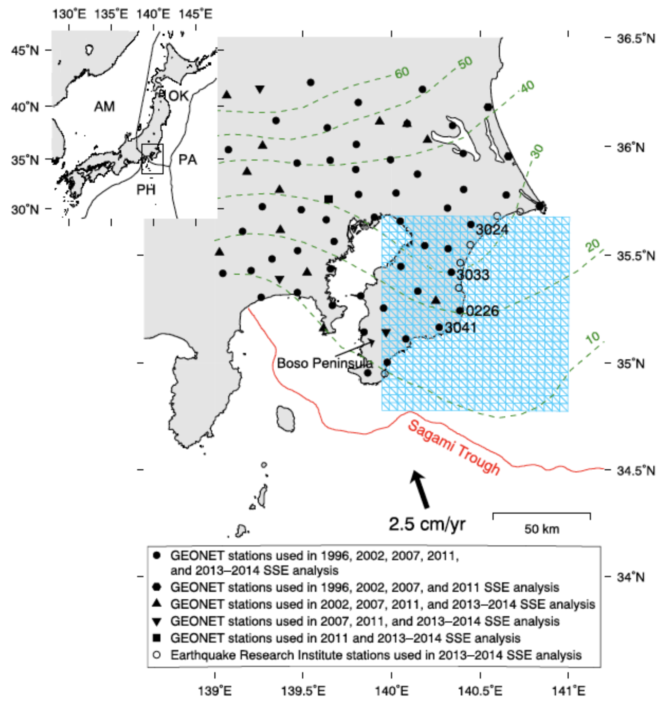
Slow Slip Events (SSEs): SG-SSEs

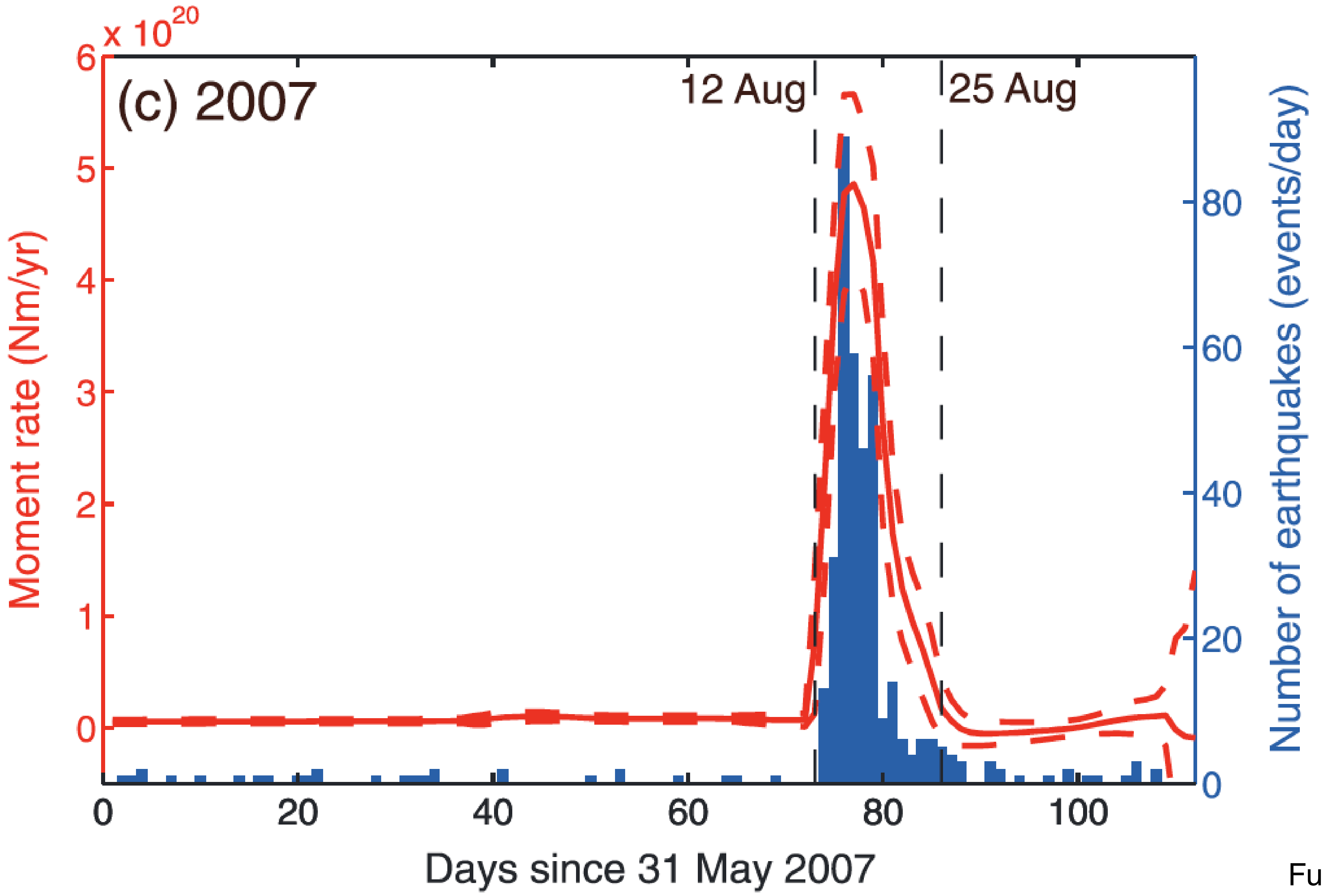




SG-SSEs in 2007 underneath Boso peninsula, Japan

Fukuda, 2018





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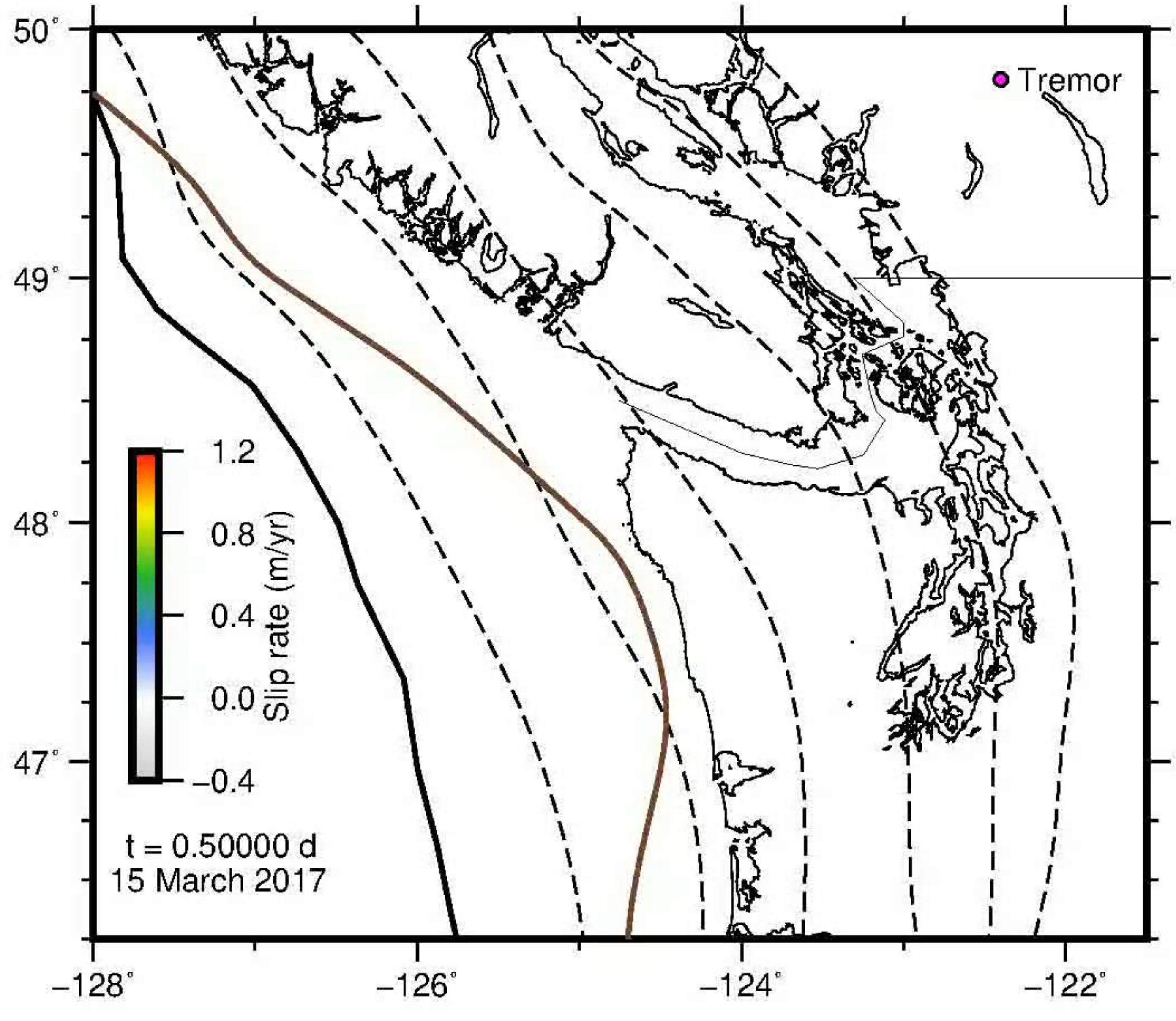
Fukuda, 2018

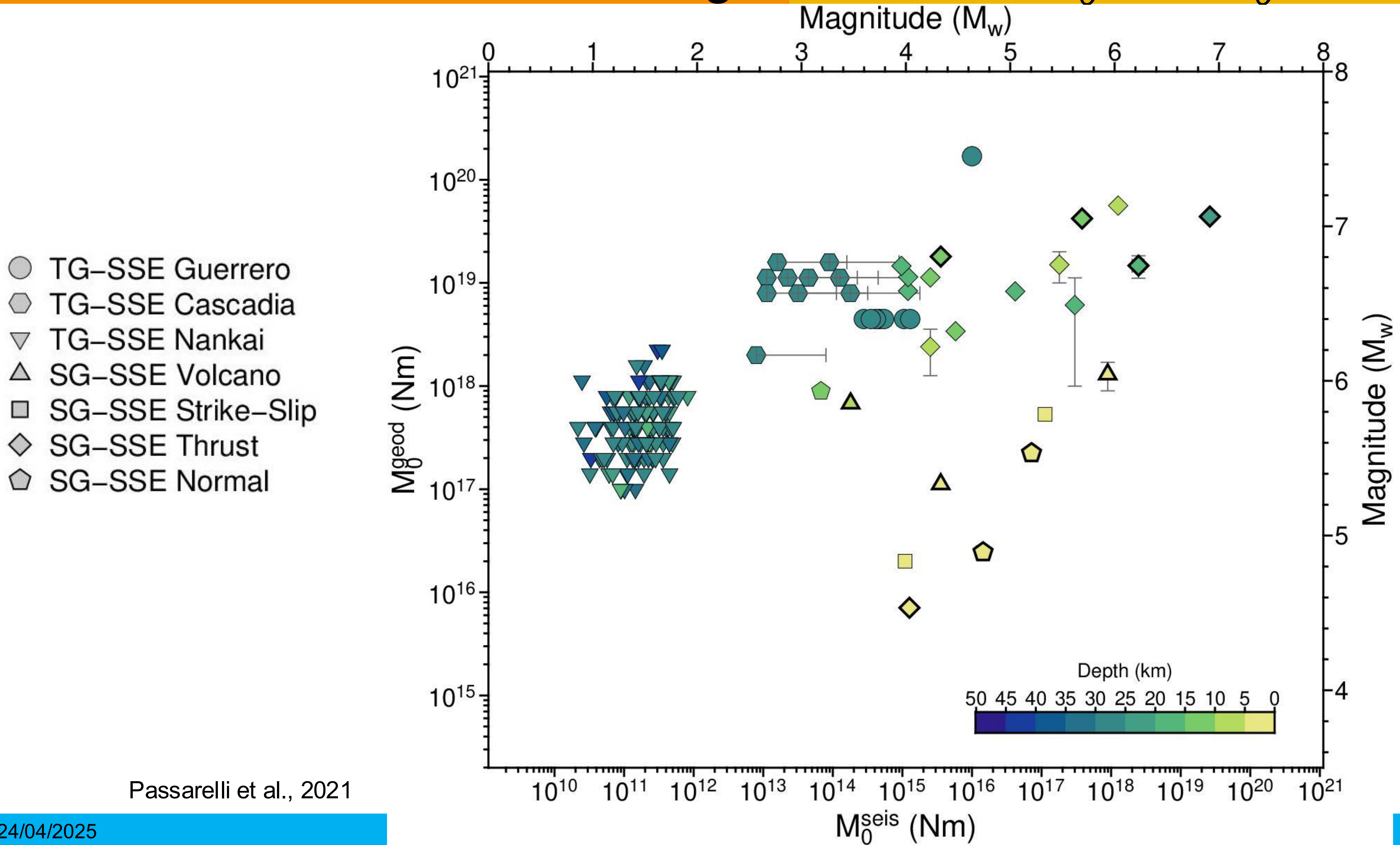
Slow Slip Events (SSEs): Phemenology



Itoh et al., 2022

Aseismic and seismic scaling

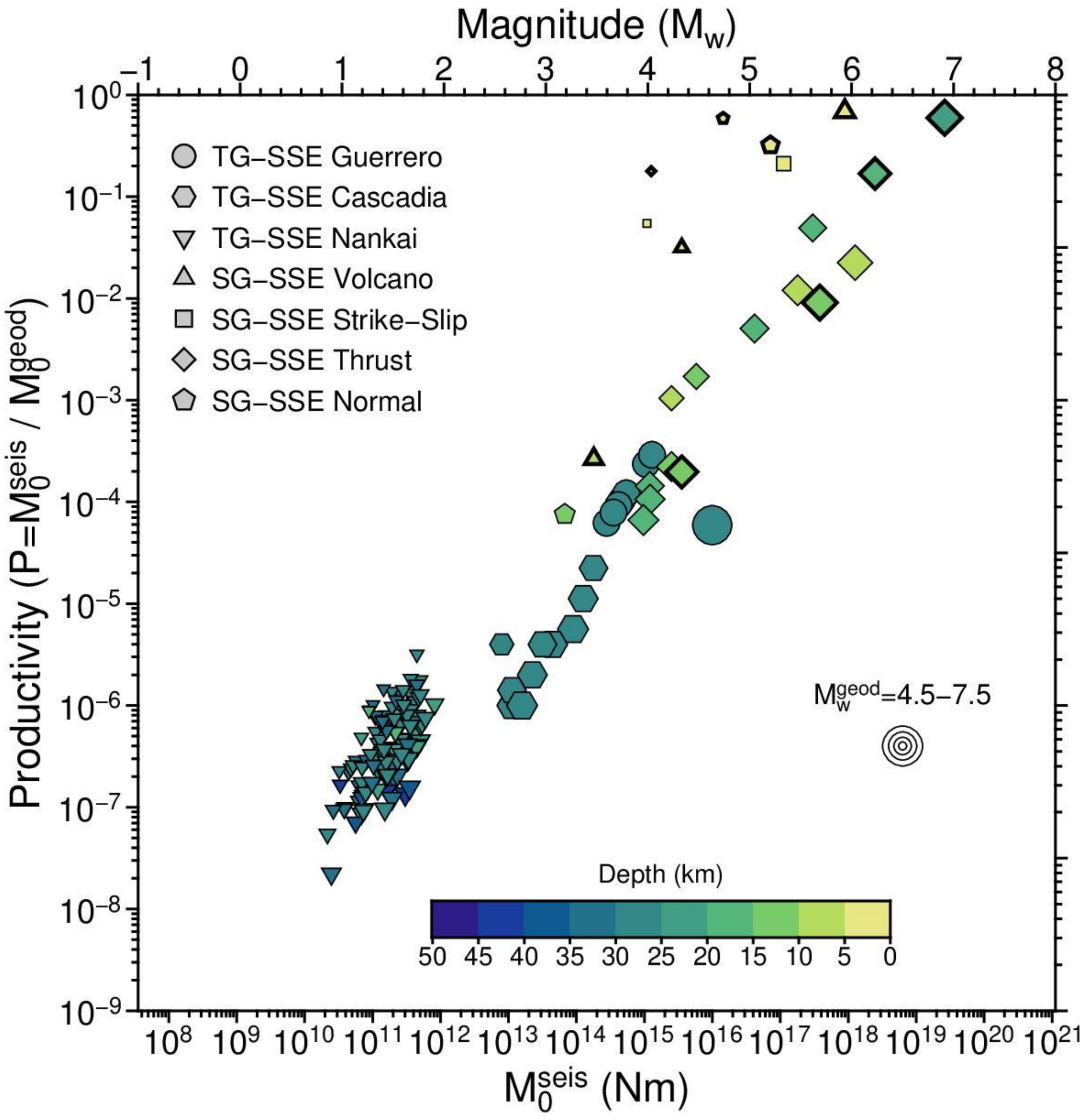
M_0^{seis} - M_0^{geod}



Passarelli et al., 2021

Aseismic and seismic scaling

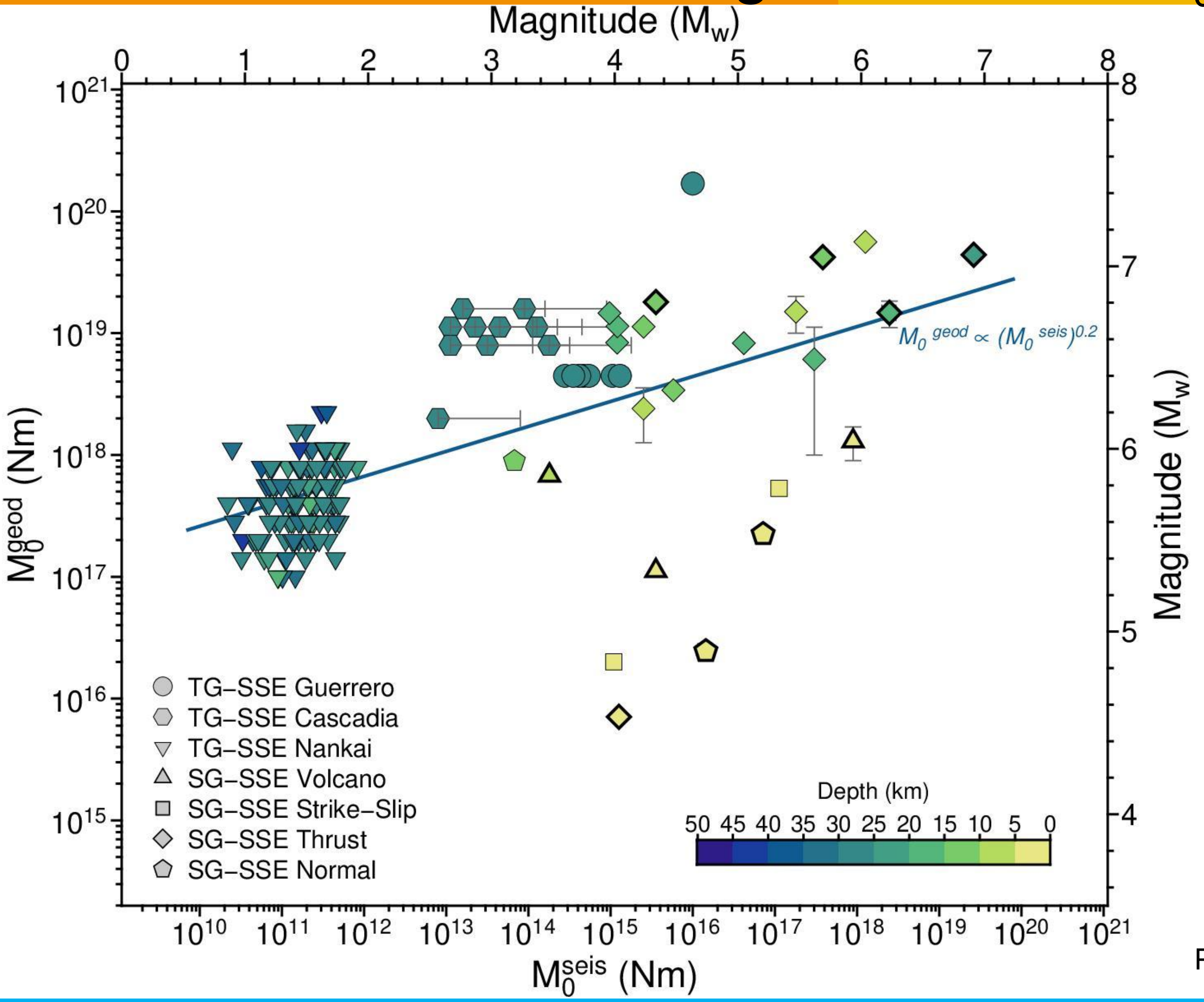
M_0^{seis} - M_0^{geod}



Passarelli et al., 2021 *Sci. Adv.*

Aseismic and seismic scaling

M_0^{seis} - M_0^{geod}



$$M_0^{geod} = \beta (M_0^{seis})^{\alpha}$$

α=0.2

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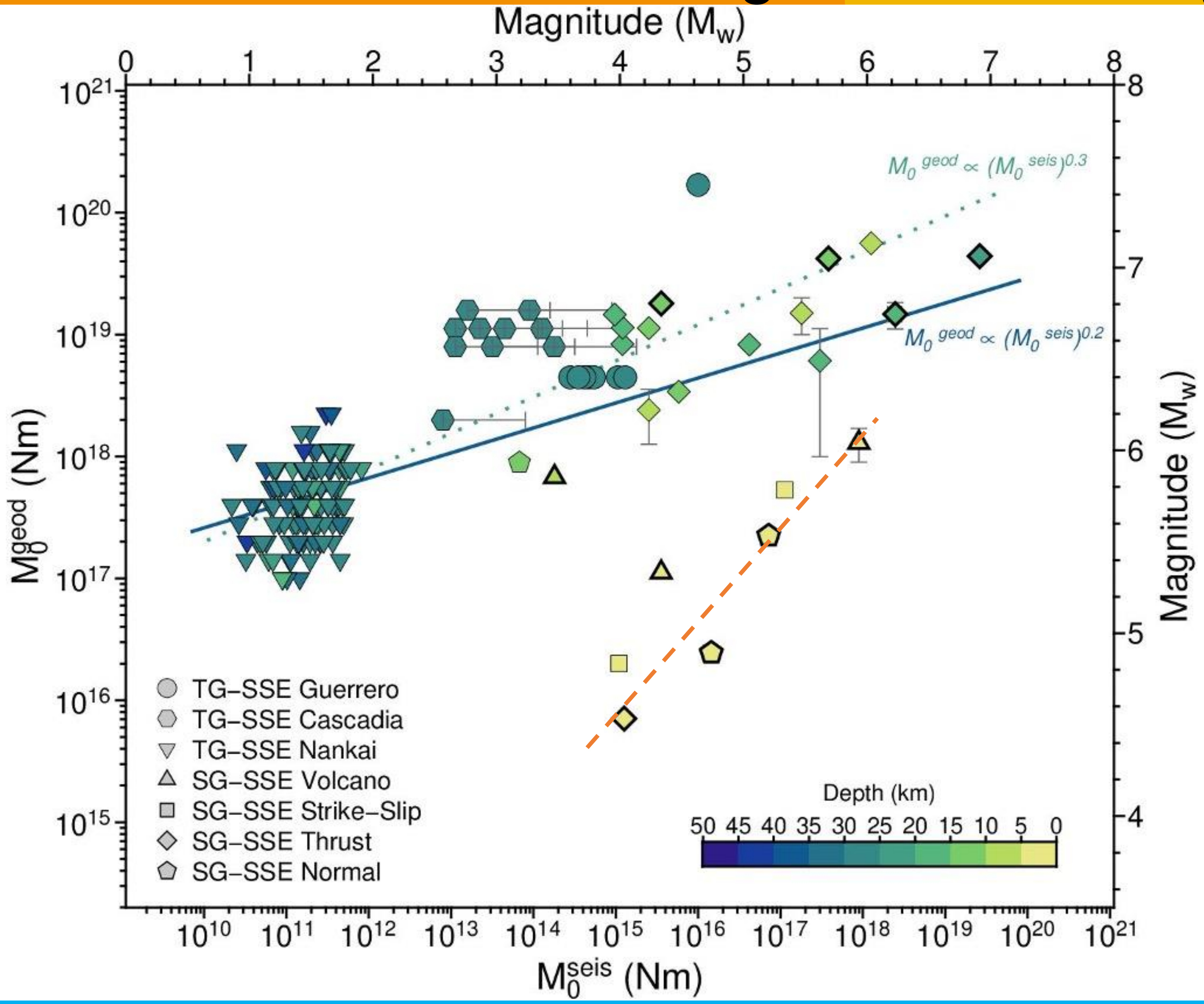
Aseismic and seismic scaling

M_0^{seis} - M_0^{geod}



$$M_0^{geod} = \beta (M_0^{seis})^{\alpha}$$

α=0.3

α=0.7

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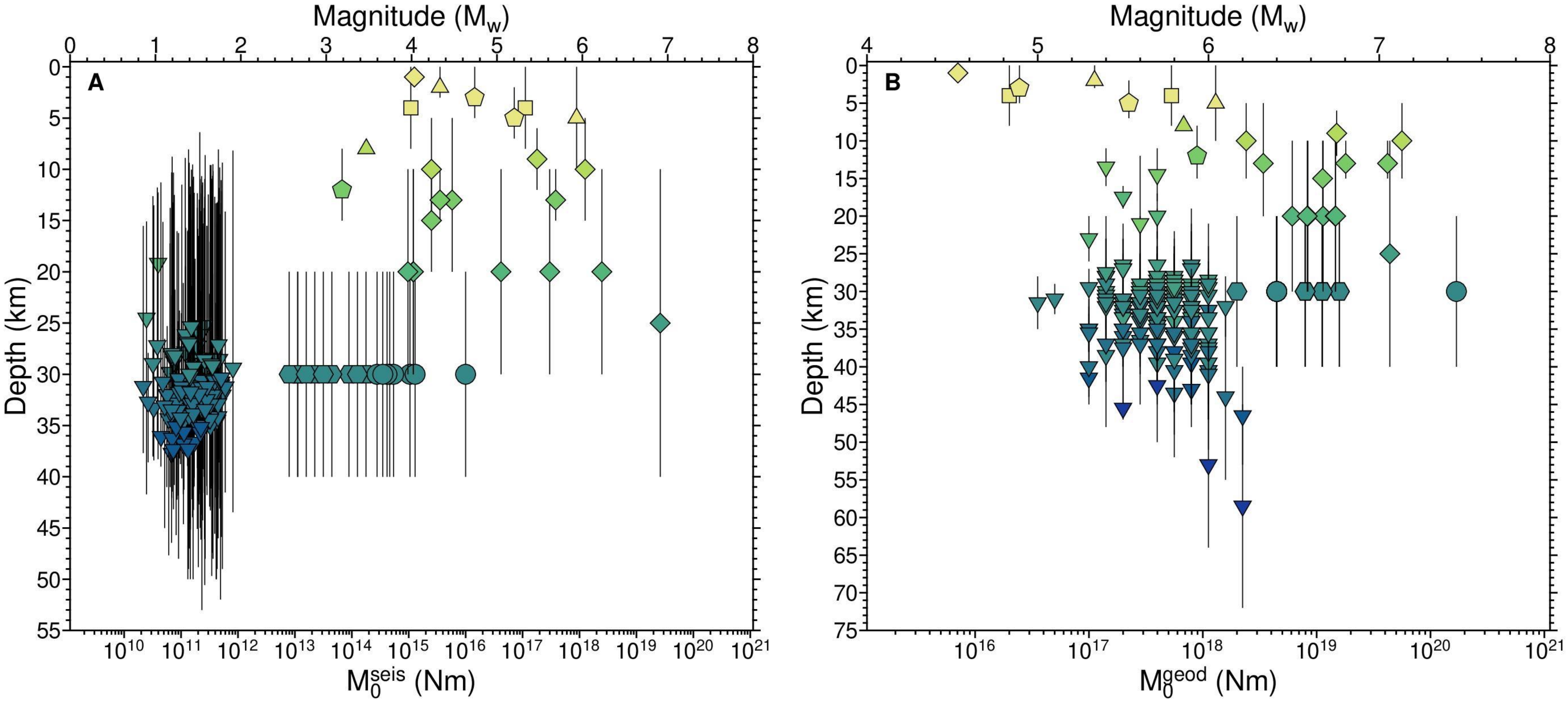
Aseismic and seismic scaling

$M_0^{seis,geod}$ - Depth

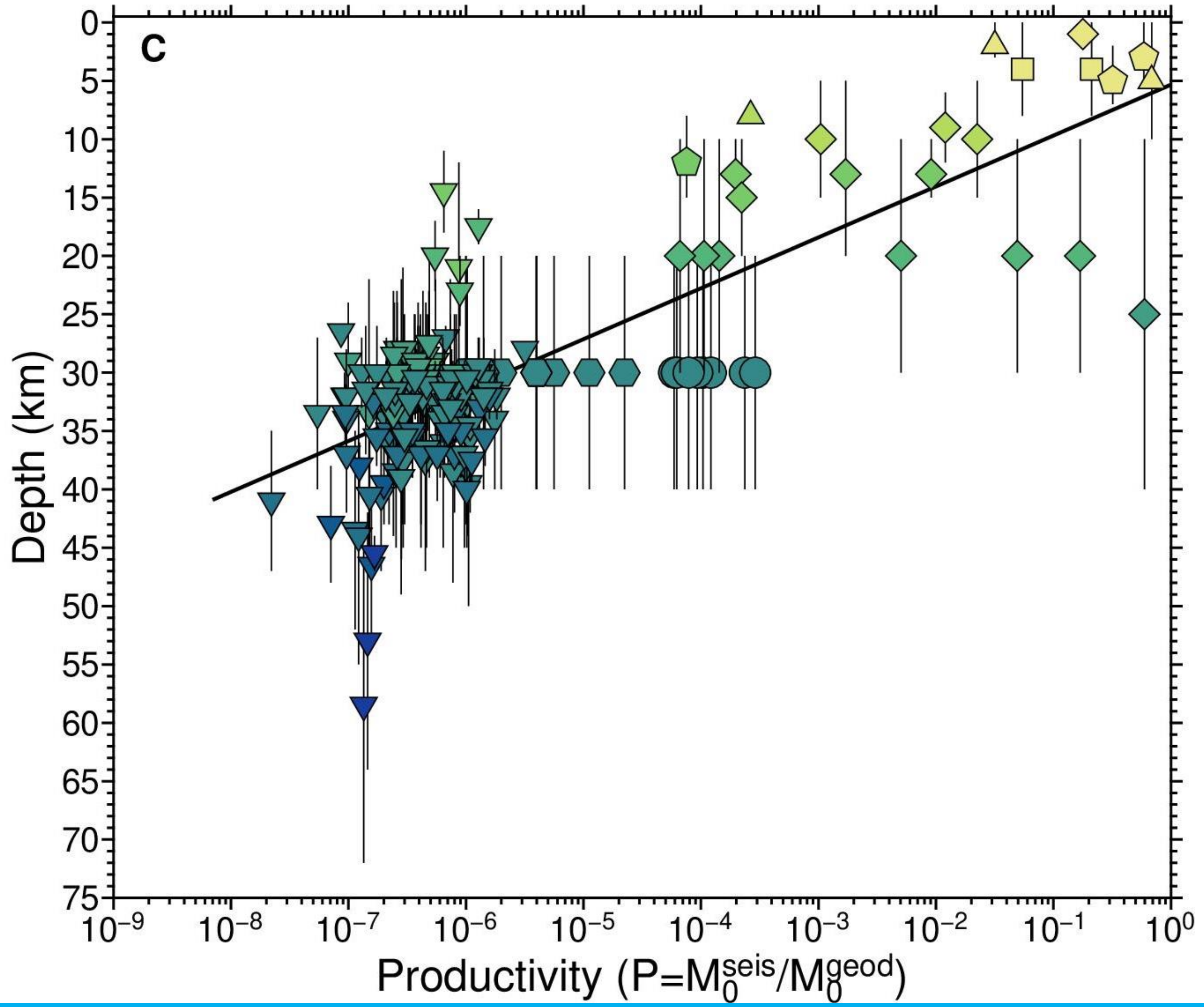
Seismic Moment

Geodetic Moment



Passarelli et al., 2021

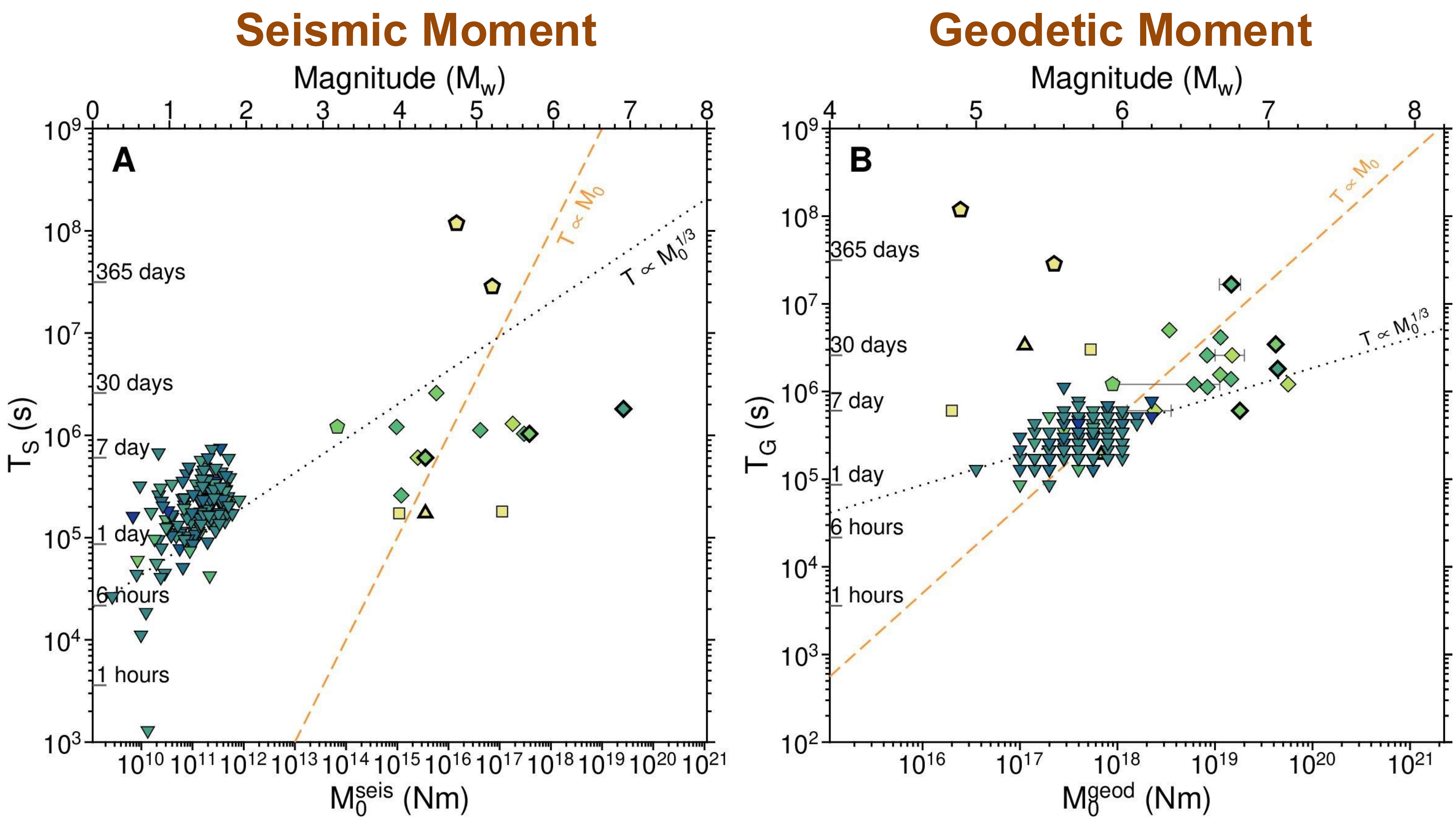
Earthquake productivity *P - Depth*



$$P = \frac{M_0^{seis}}{M_0^{geod}} \propto Depth$$

Passarelli et al., 2021

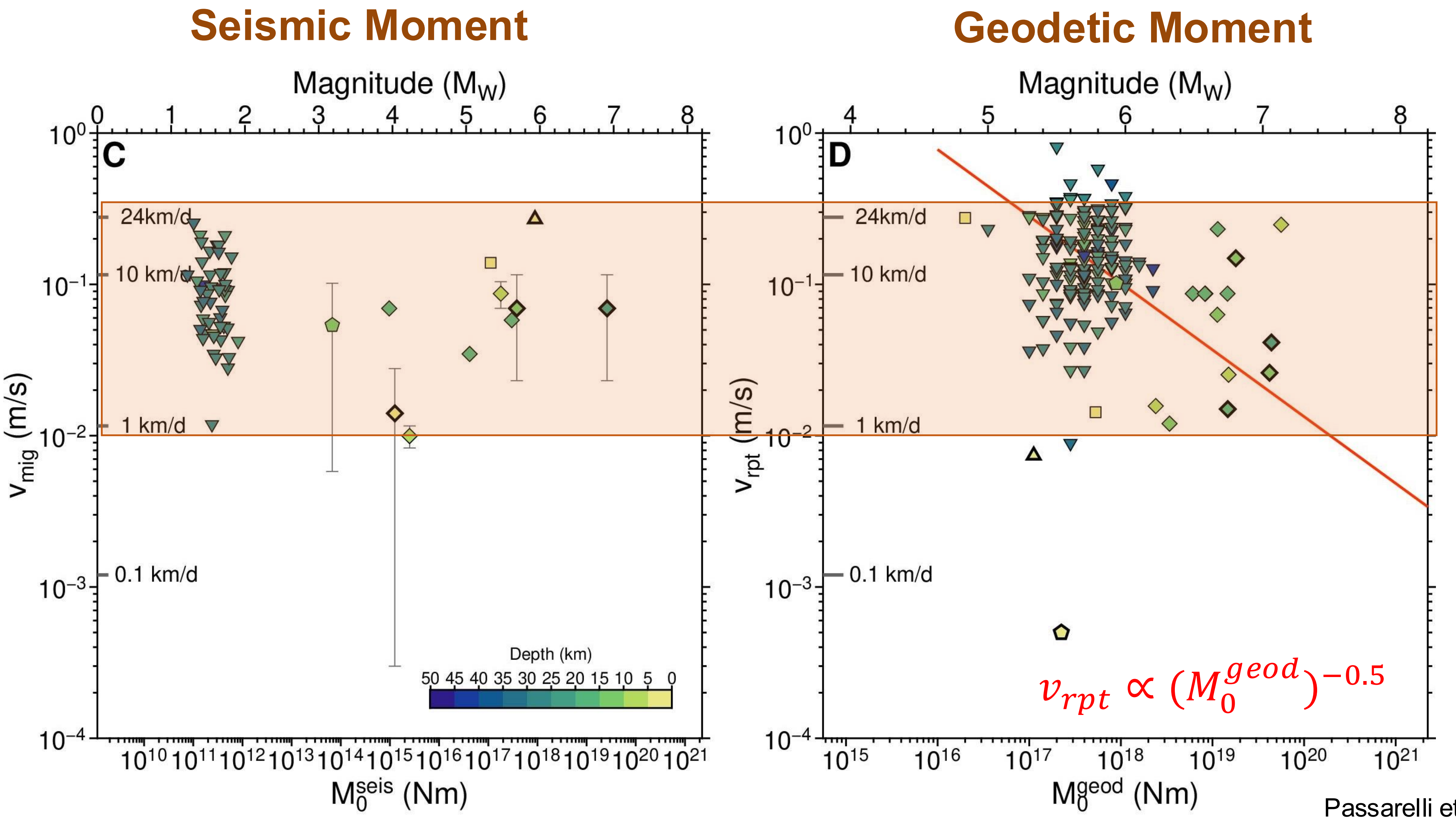
Aseismic and seismic scaling | $M_0^{seis,geod}$ - Duration



Passarelli et al., 2021

Aseismic and seismic scaling

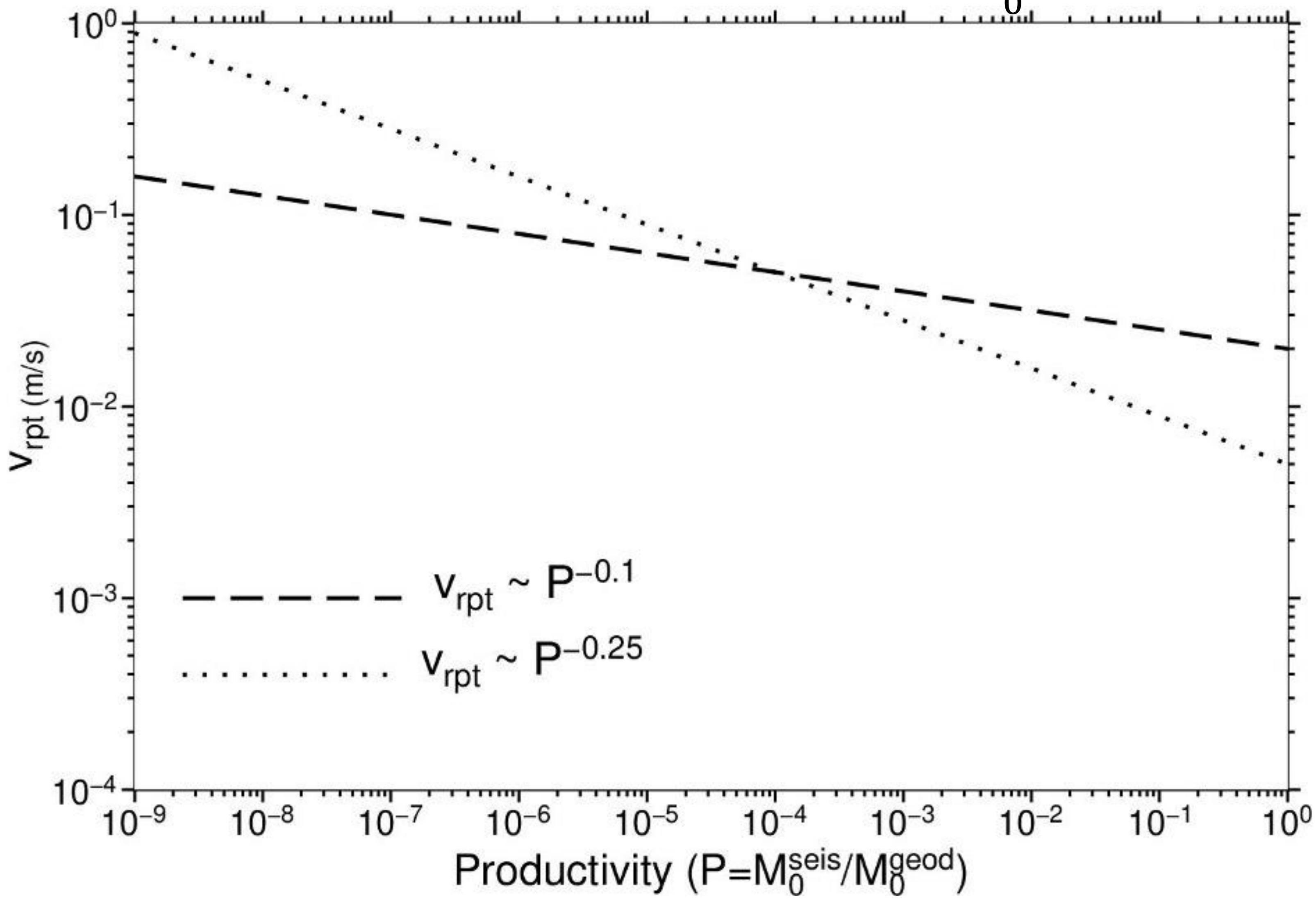
$M_0^{seis,geod} - v_{rpt,mig}$



Passarelli et al., 2021

$P - v_{rpt}$

$v_{rpt} \propto (M_0^{geod})^{-\delta}$ + $P(M_0^{geod}) = \frac{M_0^{seis}}{M_0^{geod}} \propto (M_0^{geod})^{\frac{1-\alpha}{\alpha}}$



$$v_{rpt} \propto P^{-\gamma}$$

$$\gamma = \frac{\delta(1-\alpha)}{\alpha}$$

if
α=(0.2-0.3) *(this study)*
δ = (0.4,0.6) *(Gao et al., 2010)*

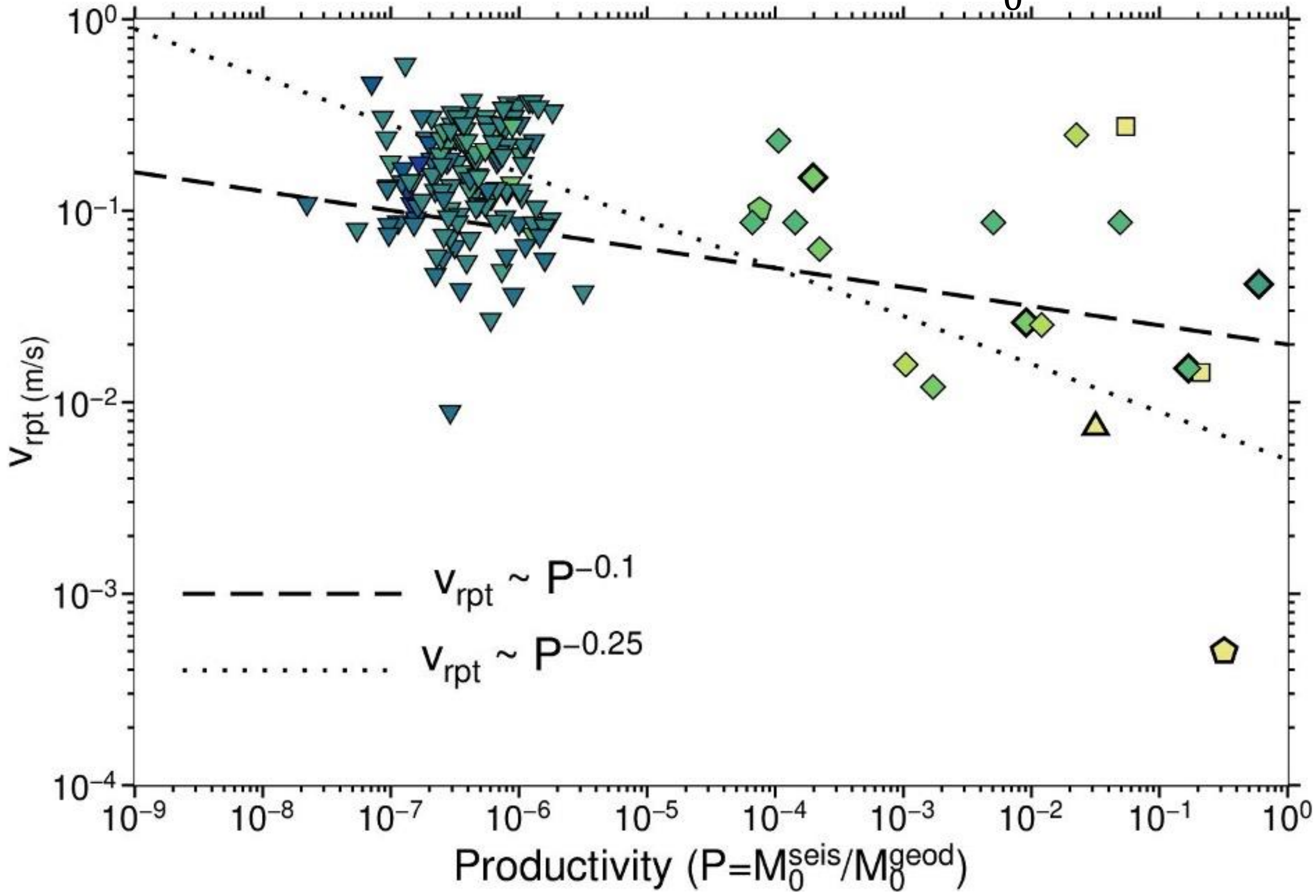
γ = (0.1,0.25)

Passarelli et al., 2021

Aseismic and seismic scaling

$P - v_{rpt}$

$$v_{rpt} \propto (M_0^{geod})^{-\delta} \quad + \quad P(M_0^{geod}) = \frac{M_0^{seis}}{M_0^{geod}} \propto (M_0^{geod})^{\frac{1-\alpha}{\alpha}}$$



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γ = (0.1,0.25)

Passarelli et al., 2021

Aseismic and seismic scaling — Recap

SG- and TG-SSEs have robust moment scaling

Deeper → $M_0^{geod} = \beta(M_0^{seis})^{0.3}$ lower *P*

Shallower → $M_0^{geod} = \beta(M_0^{seis})^{0.7}$ higher *P*

Earthquake productivity *P* scale consistently with *depth*

$$P = \frac{M_0^{seis}}{M_0^{geod}} \propto Depth$$

Data are inconclusive for M_0^{geod} - T_G scaling

$$M_0^{geod} - T^3 \ or M_0^{geod} - T \ ??$$

No M_0^{seis} - T_s (duration of seismicity) scaling

$$M_0^{seis} \not\approx T_S^n$$

Aseismic and seismic scaling — Recap

No $v_{mig} - M_0^{seis}$ scaling

$$v_{mig} \not\propto M_0^{seis}$$

Our data compatible w/ the $v_{rpt} - M_0^{geod}$ scaling

$$v_{rpt} \propto (M_0^{geod})^{-0.5}$$

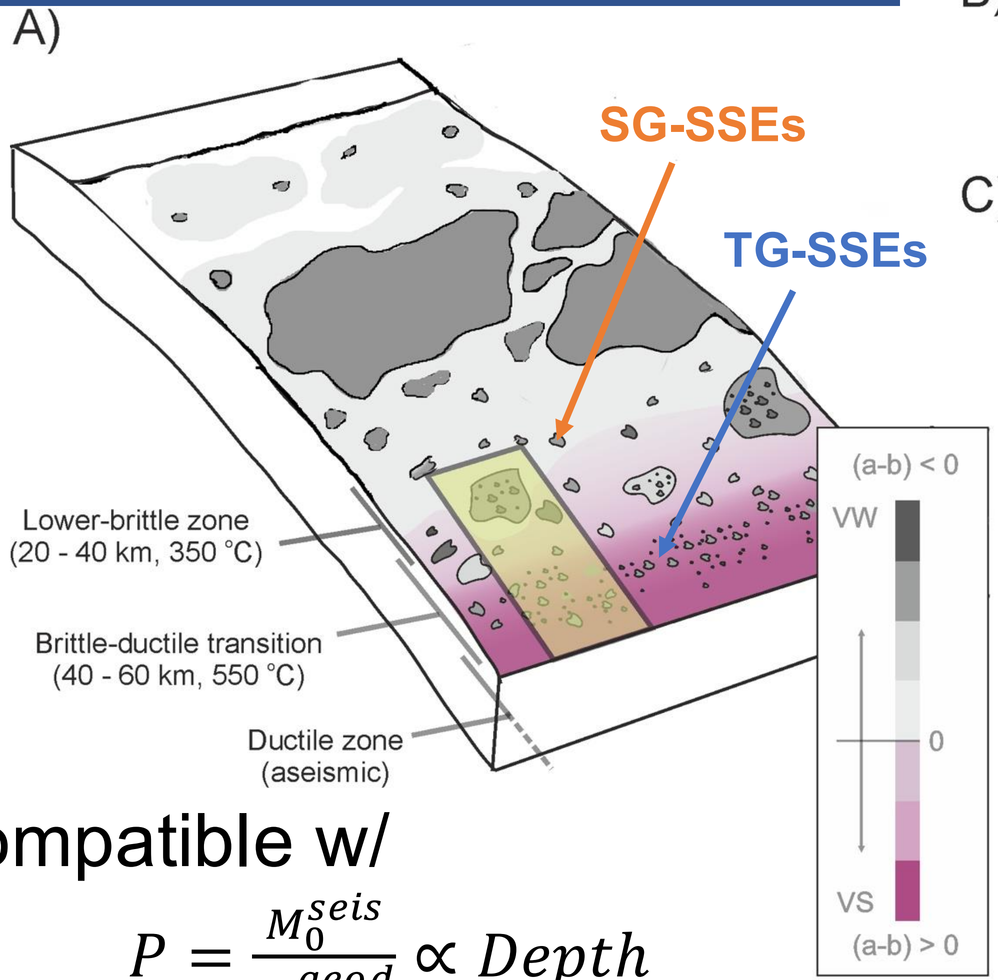
Earthquake productivity *P* scale consistently w/ v_{rpt}

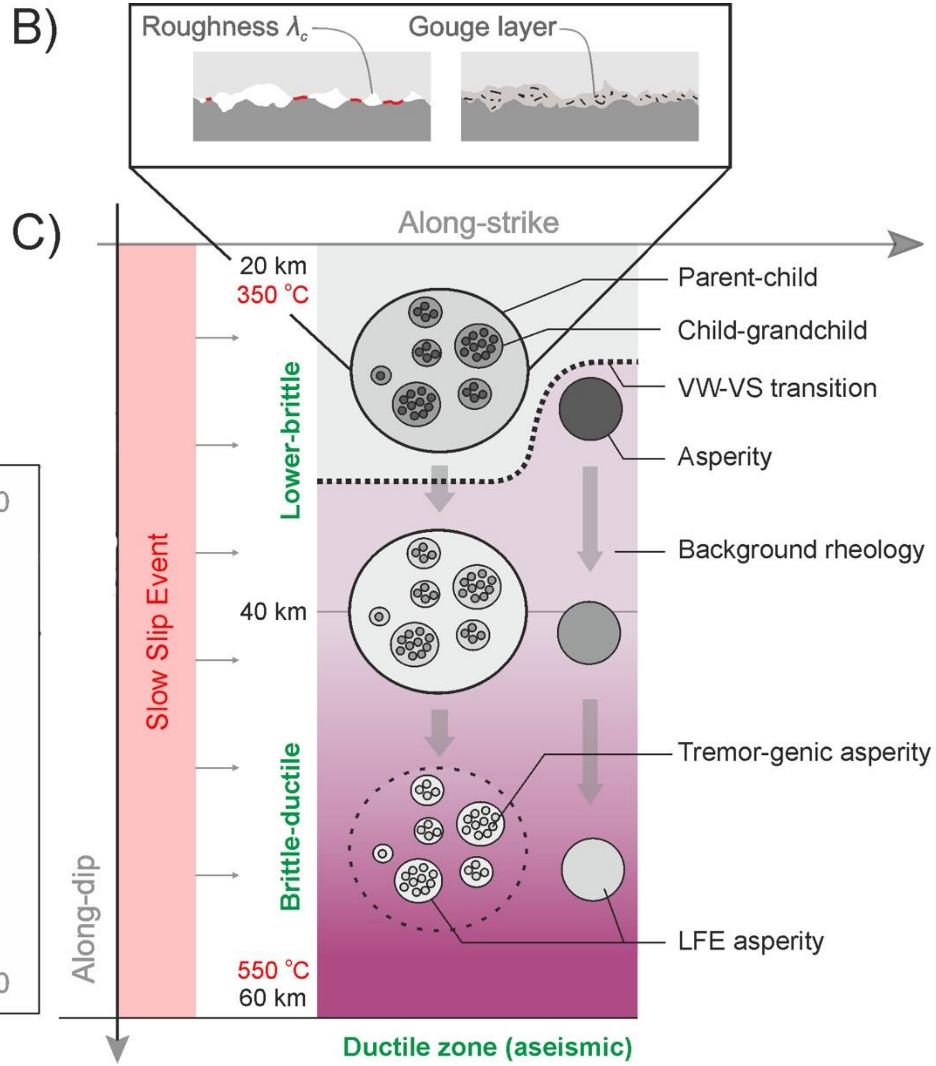
$$v_{rpt} \propto P^{-\gamma}$$

Aseismic and seismic scaling

Physical explanation

Deeper $M_0^{geod} = \beta (M_0^{seis})^{0.3}$





Pronounced fault <u>roughness</u>

<u>High pore pressure</u>

Compatible w/

$$P = \frac{M_0^{seis}}{M_0^{geod}} \propto Depth$$

$$v_{rpt} \propto P^{-\gamma}$$

Heterogeneous <u>frictional</u> properties dependent on temperature

Aseismic and seismic scaling

Source parameters

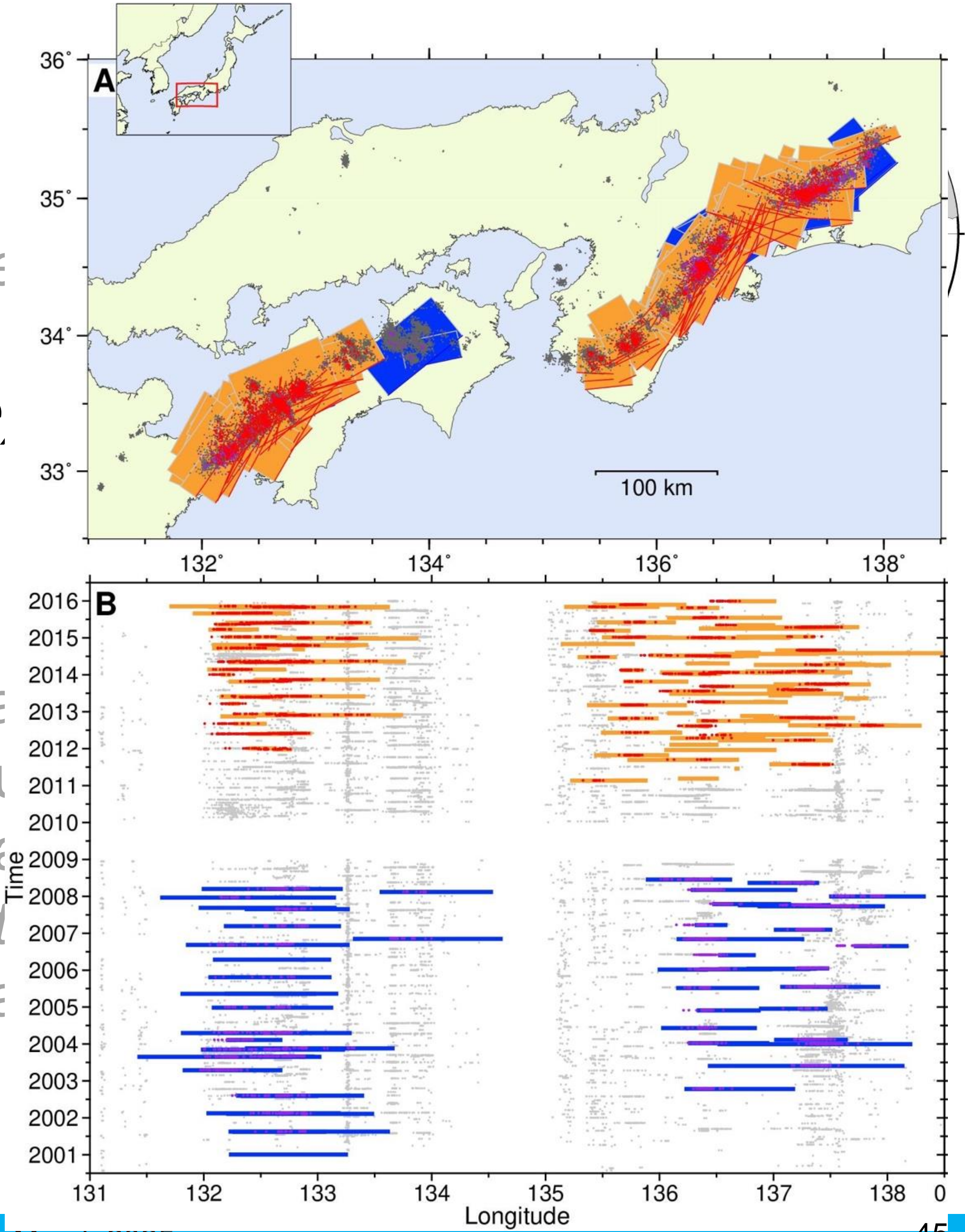
TG-SSEs:

- 10 SSEs at Cascadia subduction zone (*literature*
- 8 SSEs at Guerrero subduction zone (*literature*)
- 174 SSEs at Nankai subduction zone (*database*

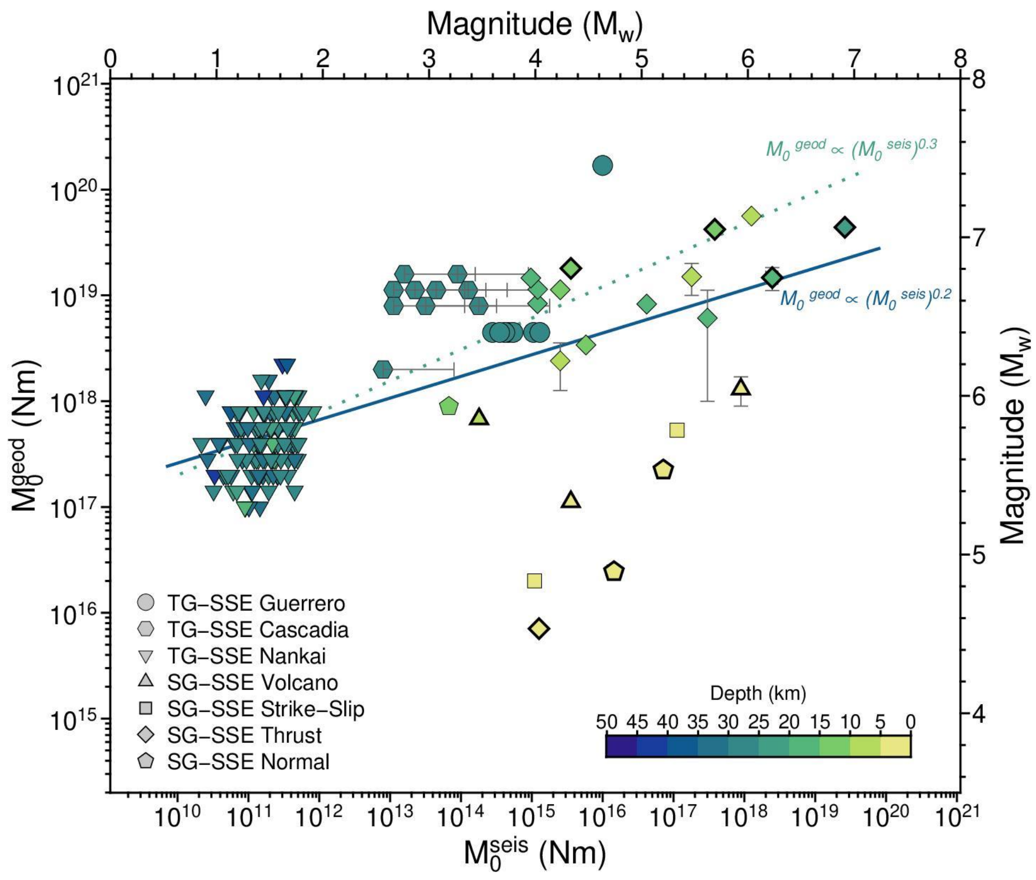
SG-SSEs:

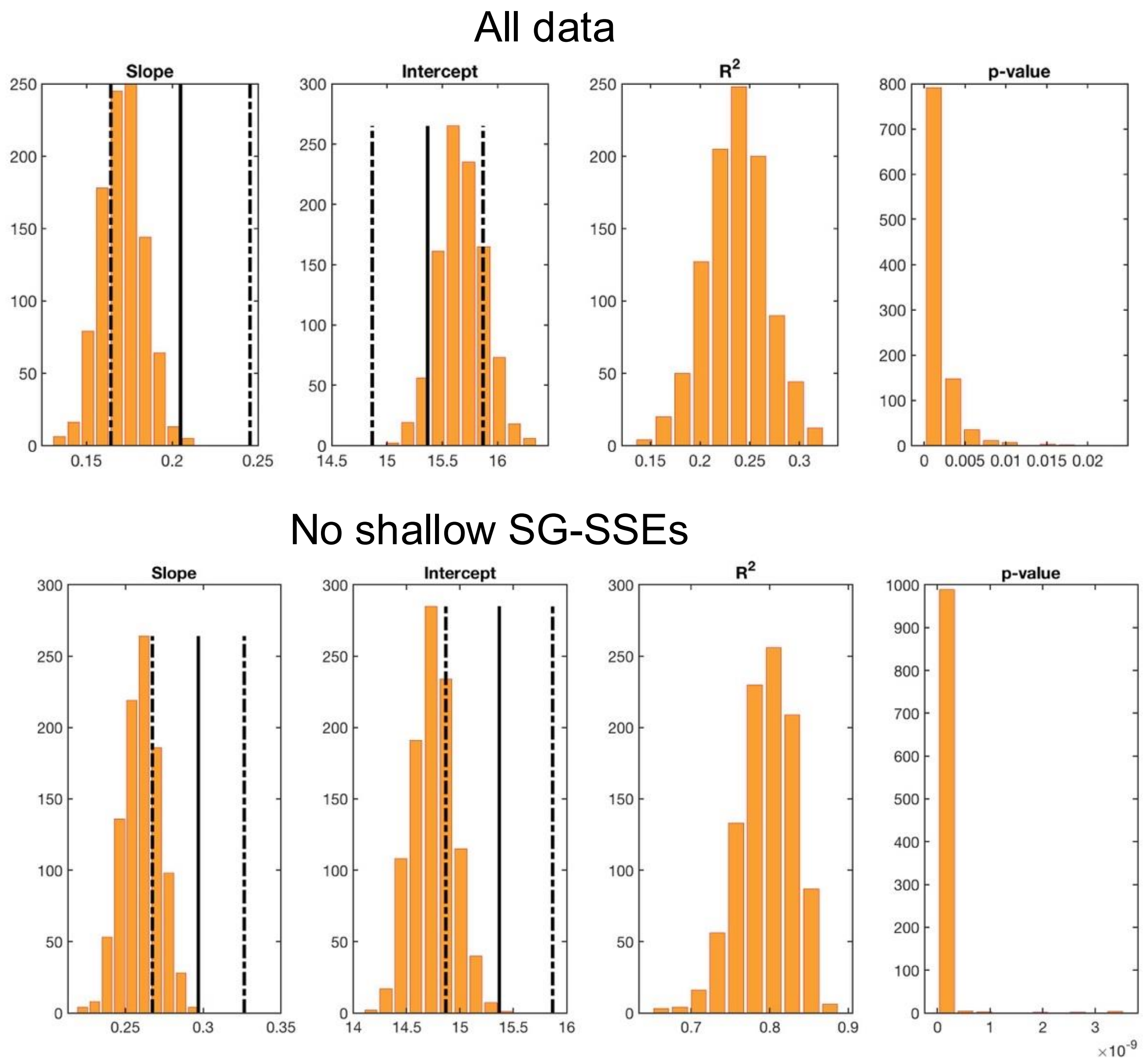
- 3 SSEs at volcanoes (Kilauea, Mt Etna and Miya
- 2 Strike-slip fault (San Andreas and Salton Throu
- 3 Normal fault (Pollino, Alto Tiberina and L'Aquila
- 1 Thrust (Wood Island Washington State) (*literat*
- 14 Thrust in subduction zone (Ecuador, Chile, Ja

Database dominated by events in subduction zone

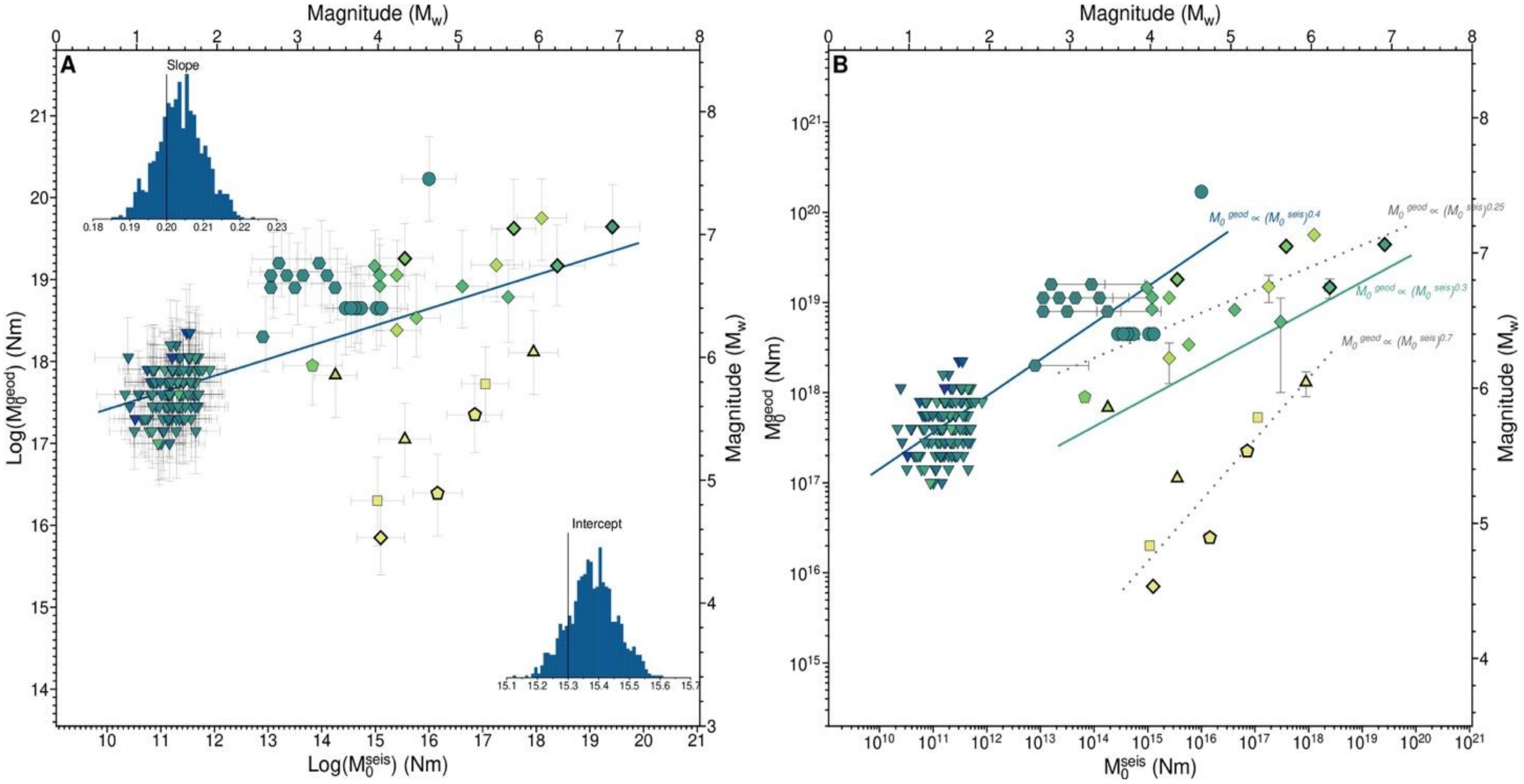


Statistical test



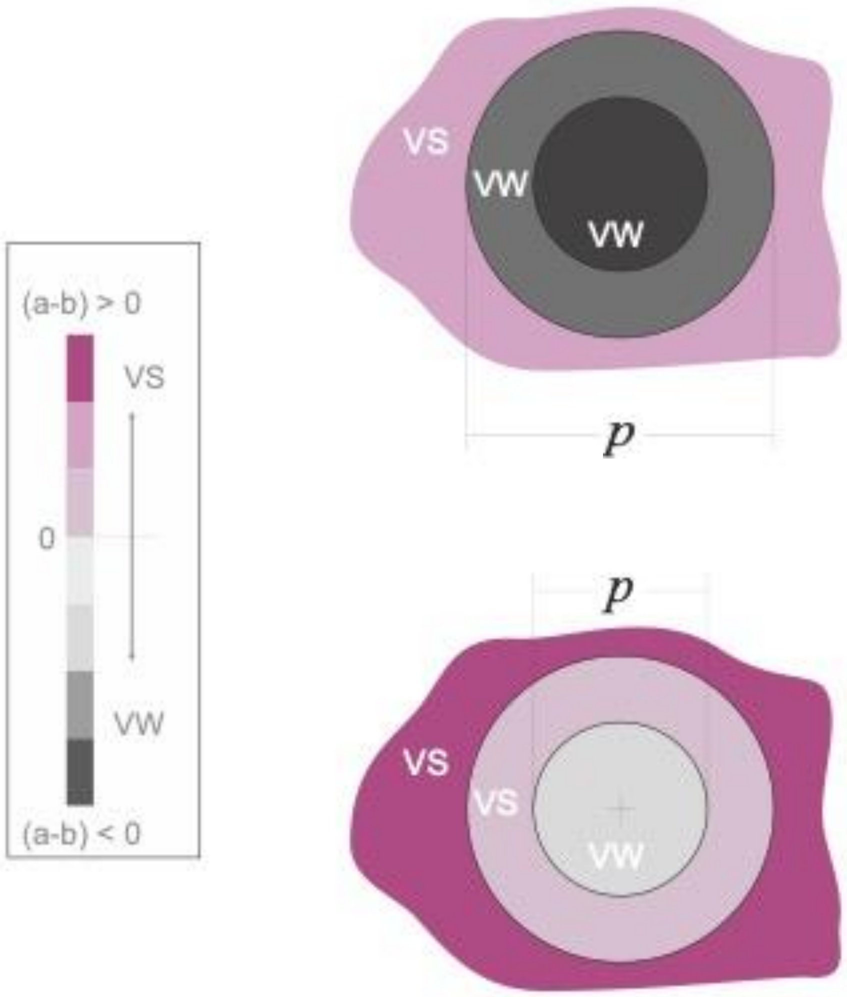


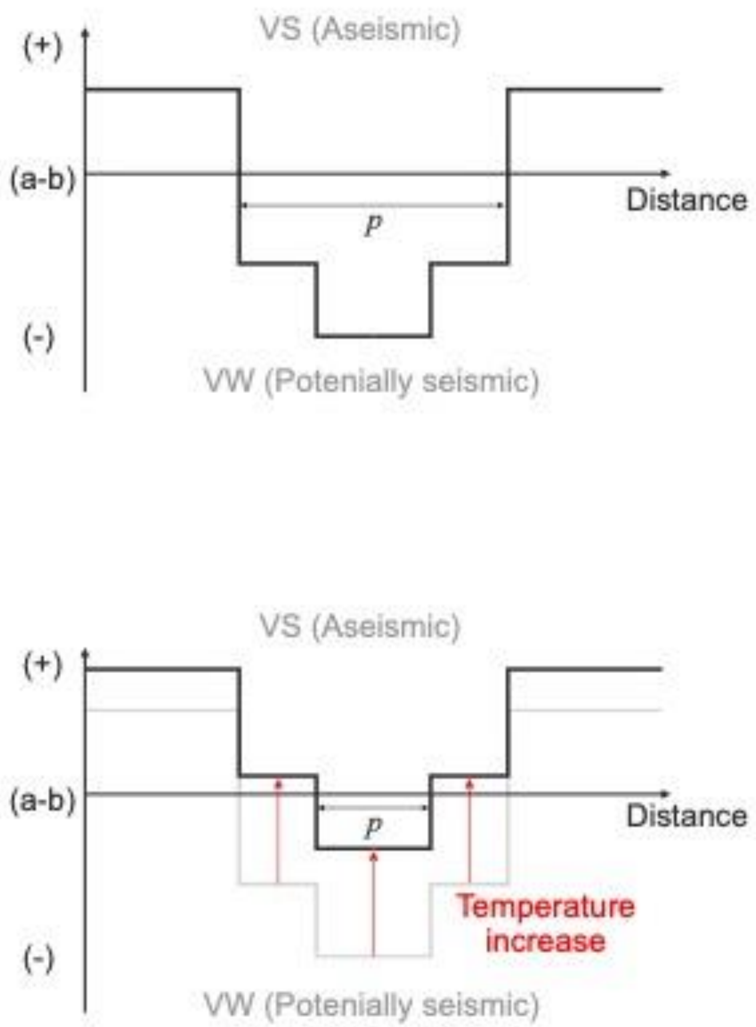
Statistical test



Aseismic and seismic scaling

Physical explanation





Aseismic and seismic scaling

Physical explanation