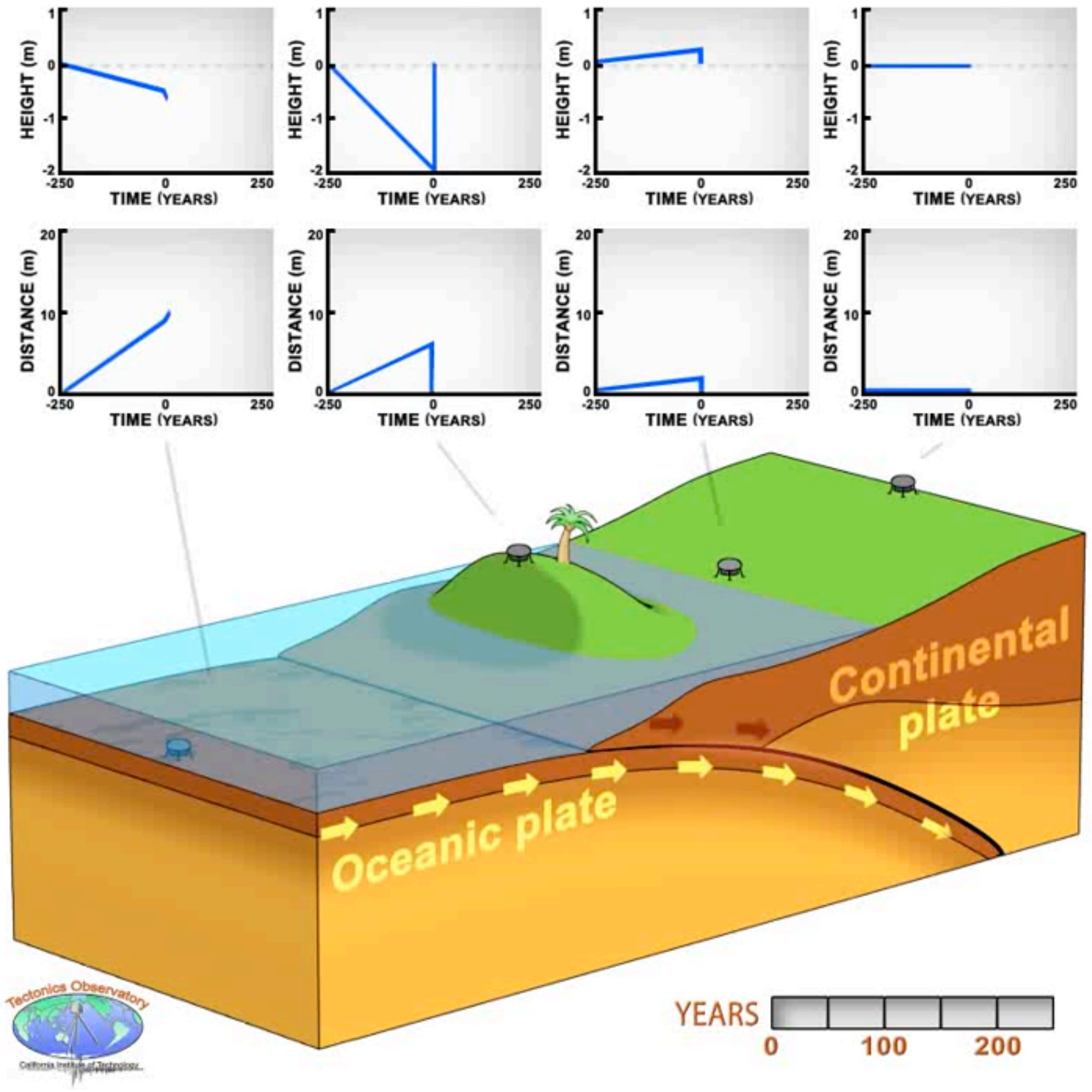
Tectonic Deformation: Kinematic and Dynamic Perspectives



Adriano Gualandi

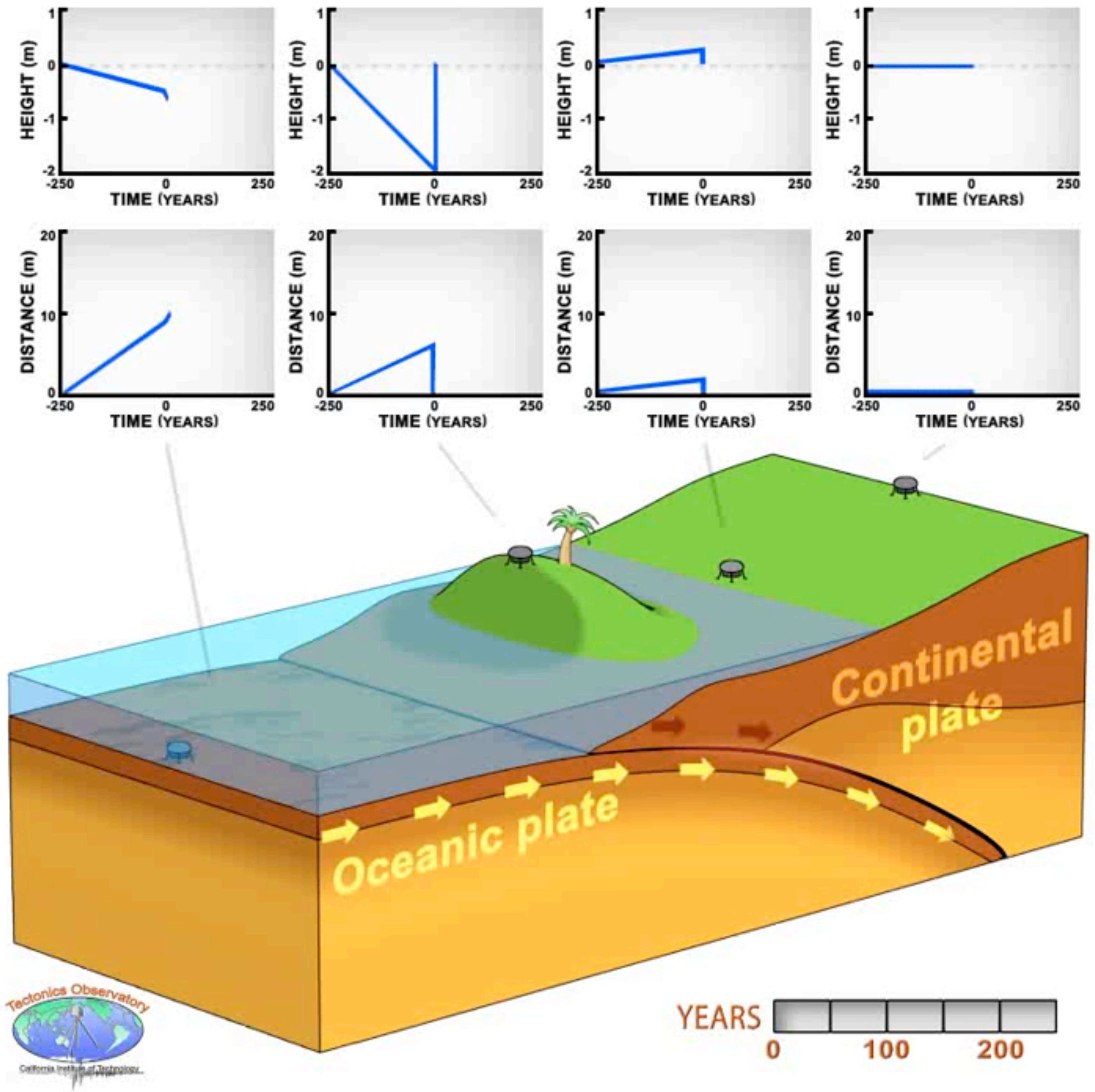
UNIVERSITY OF CAMBRIDGE

PEP

Cambridge

29 Nov 2023

The Seismic Cycle



The Seismic Cycle

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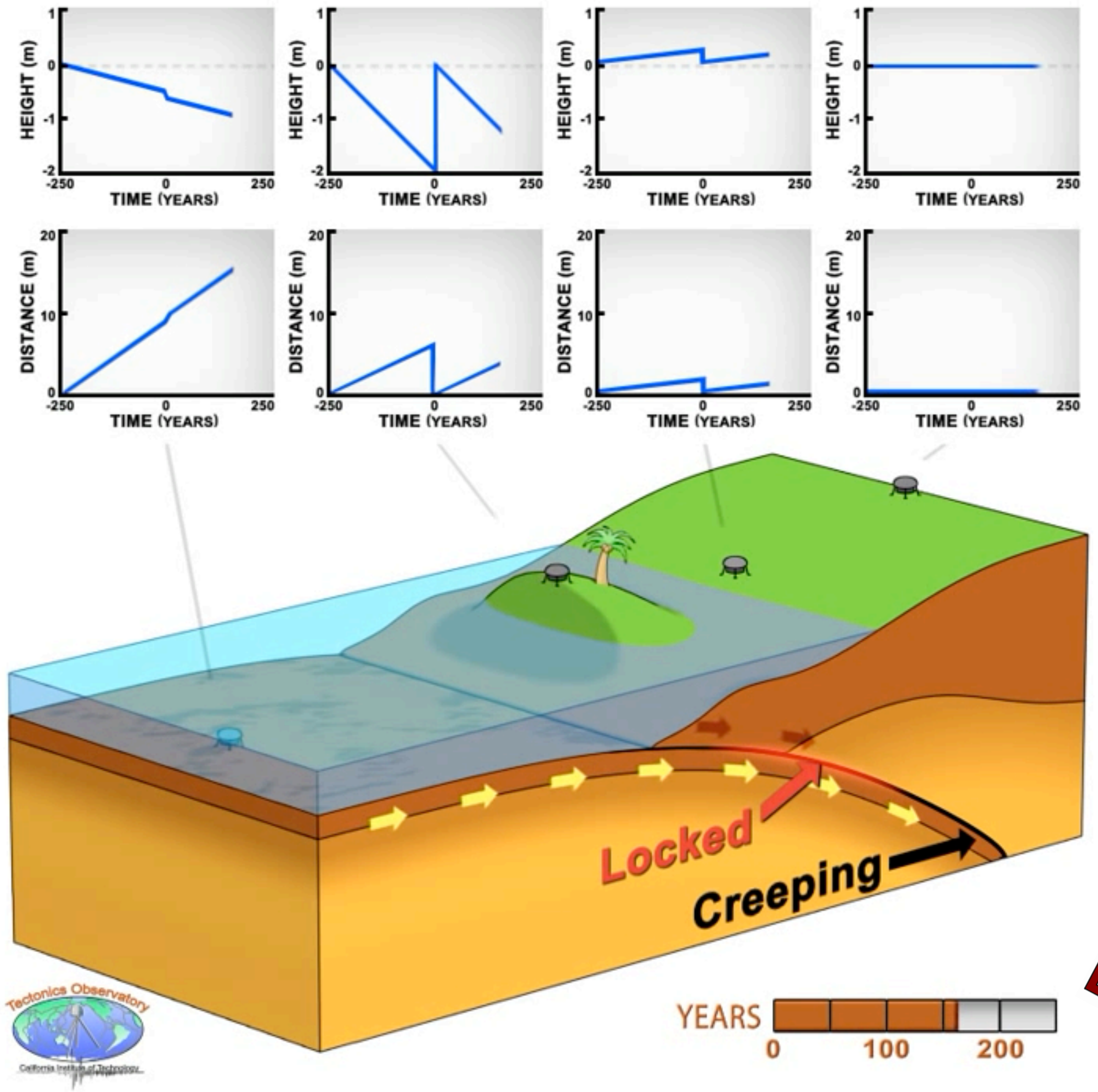

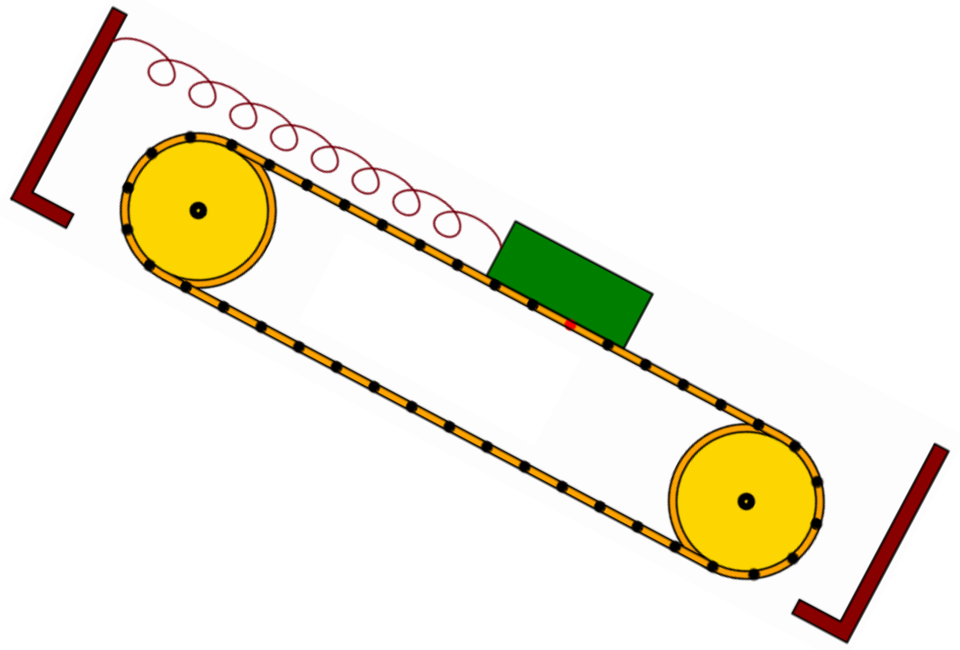

The Spring-Slider

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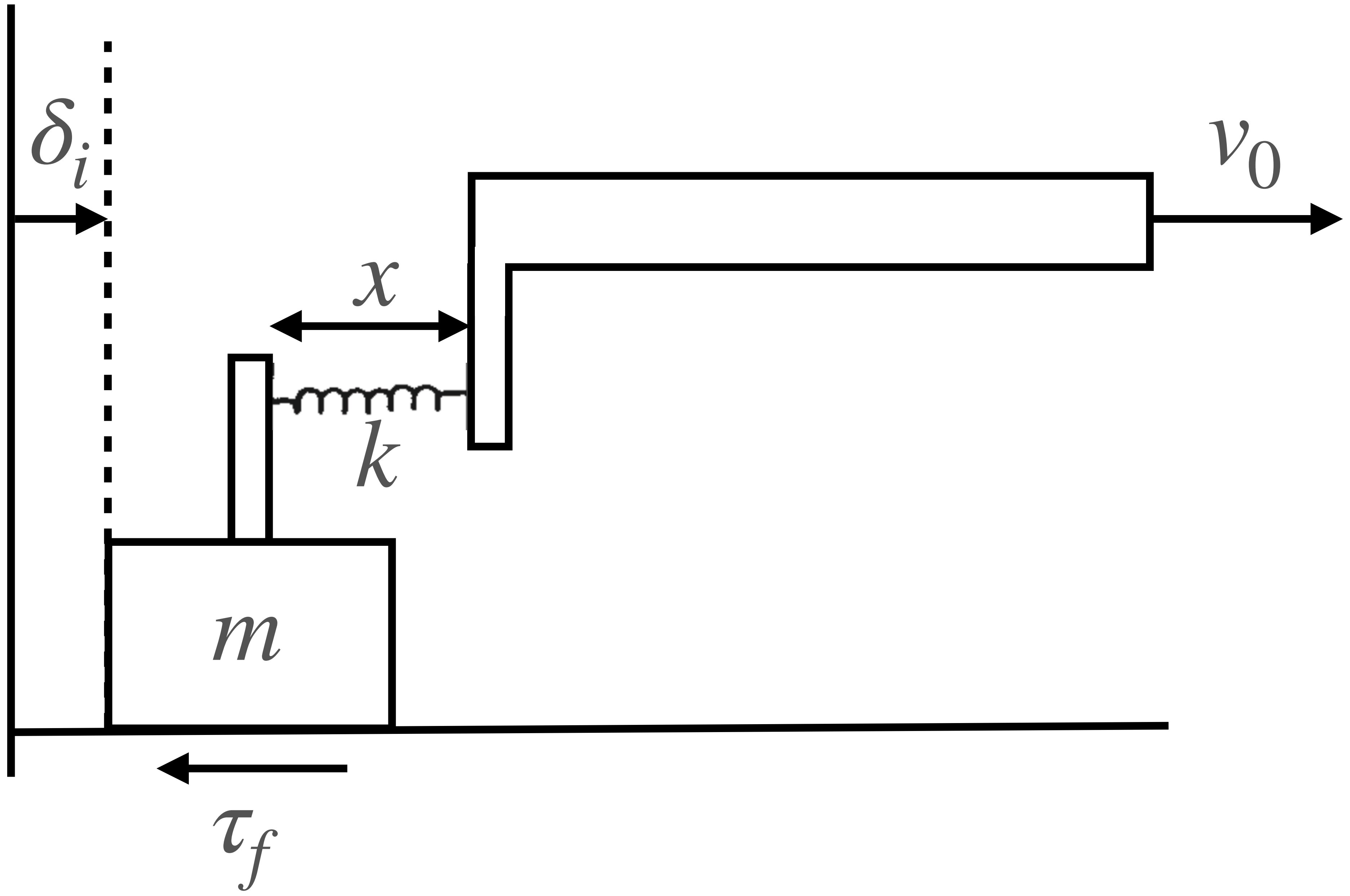

The Spring-Slider

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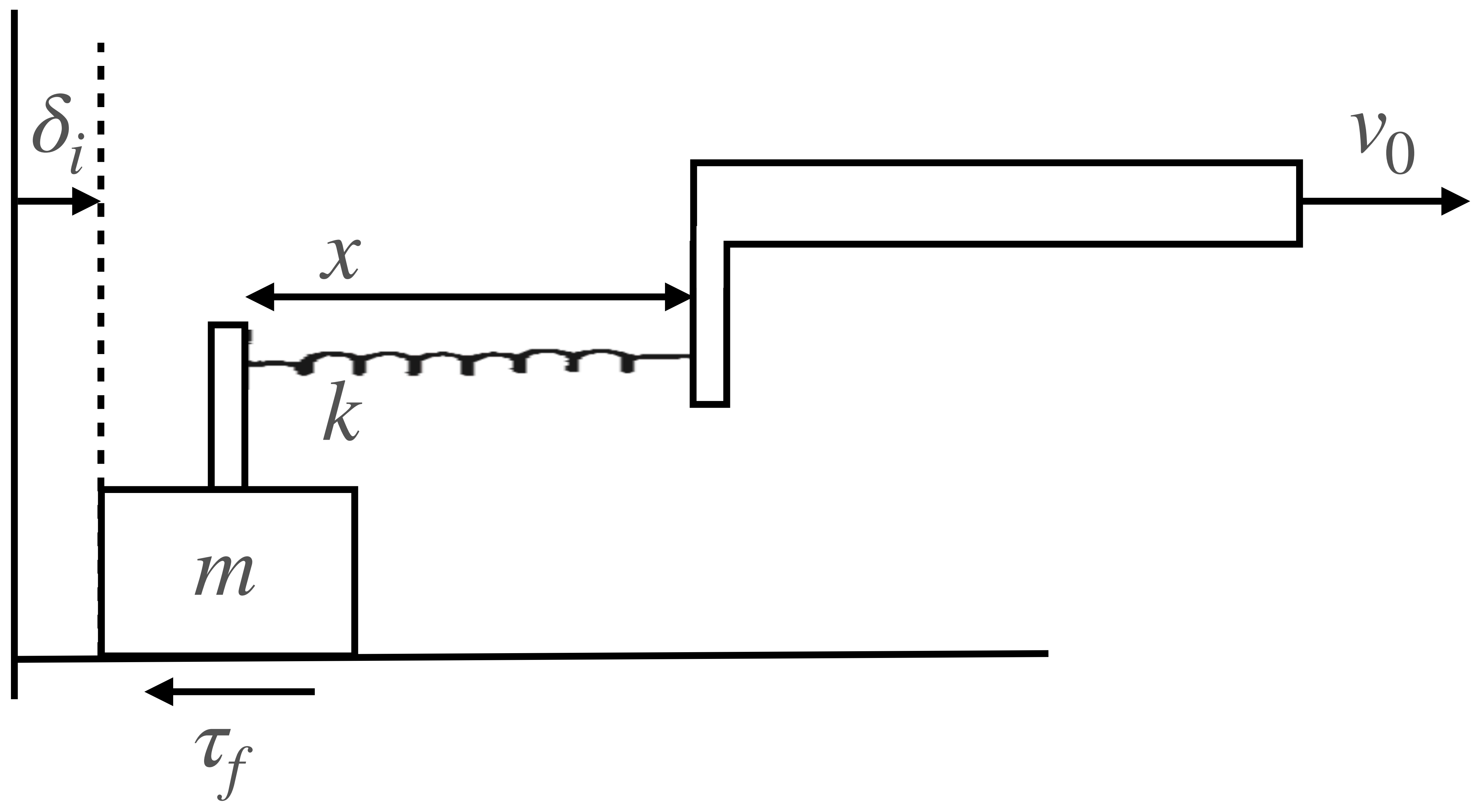

The Spring-Slider

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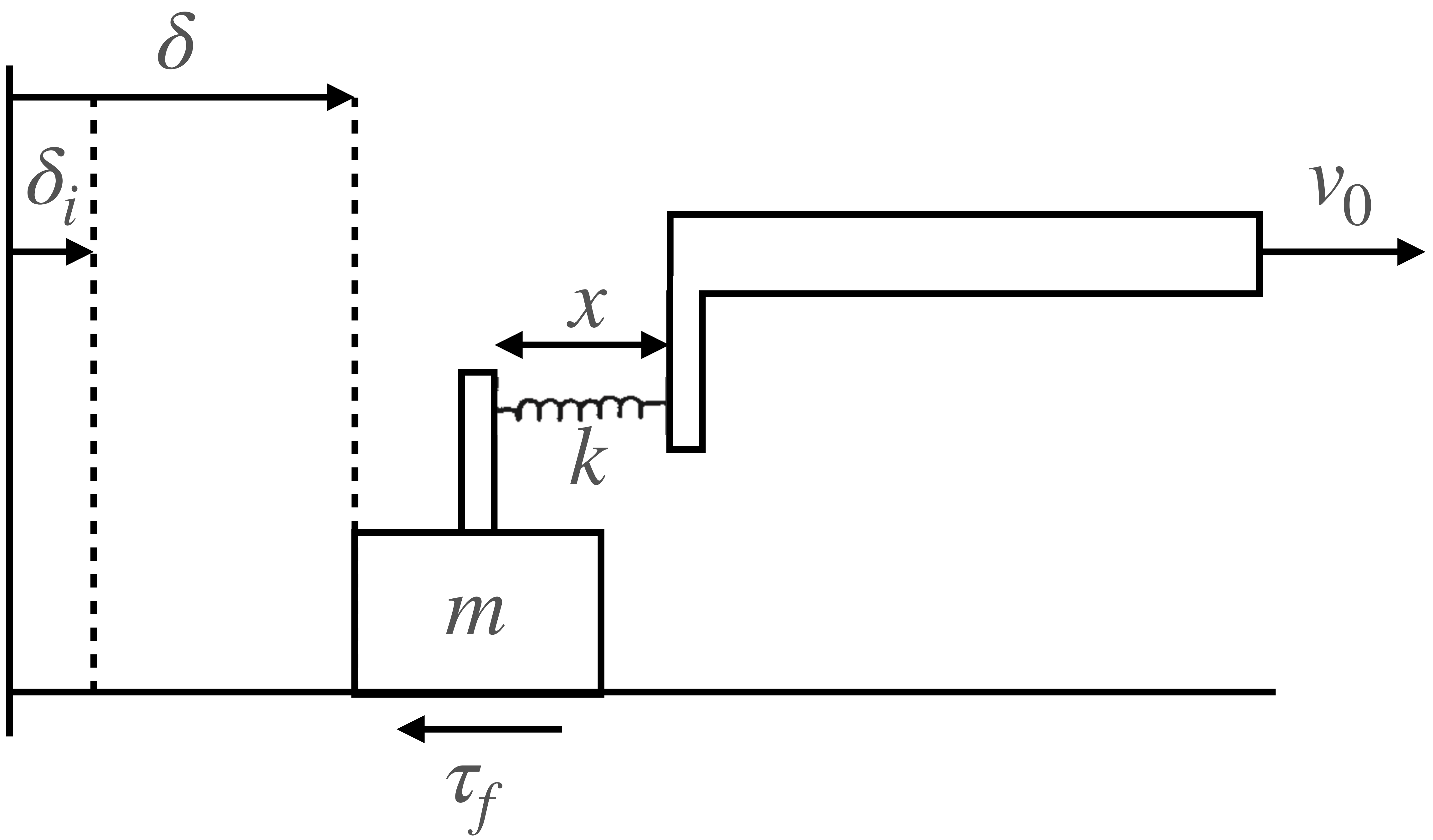

$$m\frac{\mathrm{d}v}{\mathrm{d}t} = \sum_j \tau_j = \tau_i + \tau_l - \tau_f + \Delta\tau(t)$$

The Seismic Cycle

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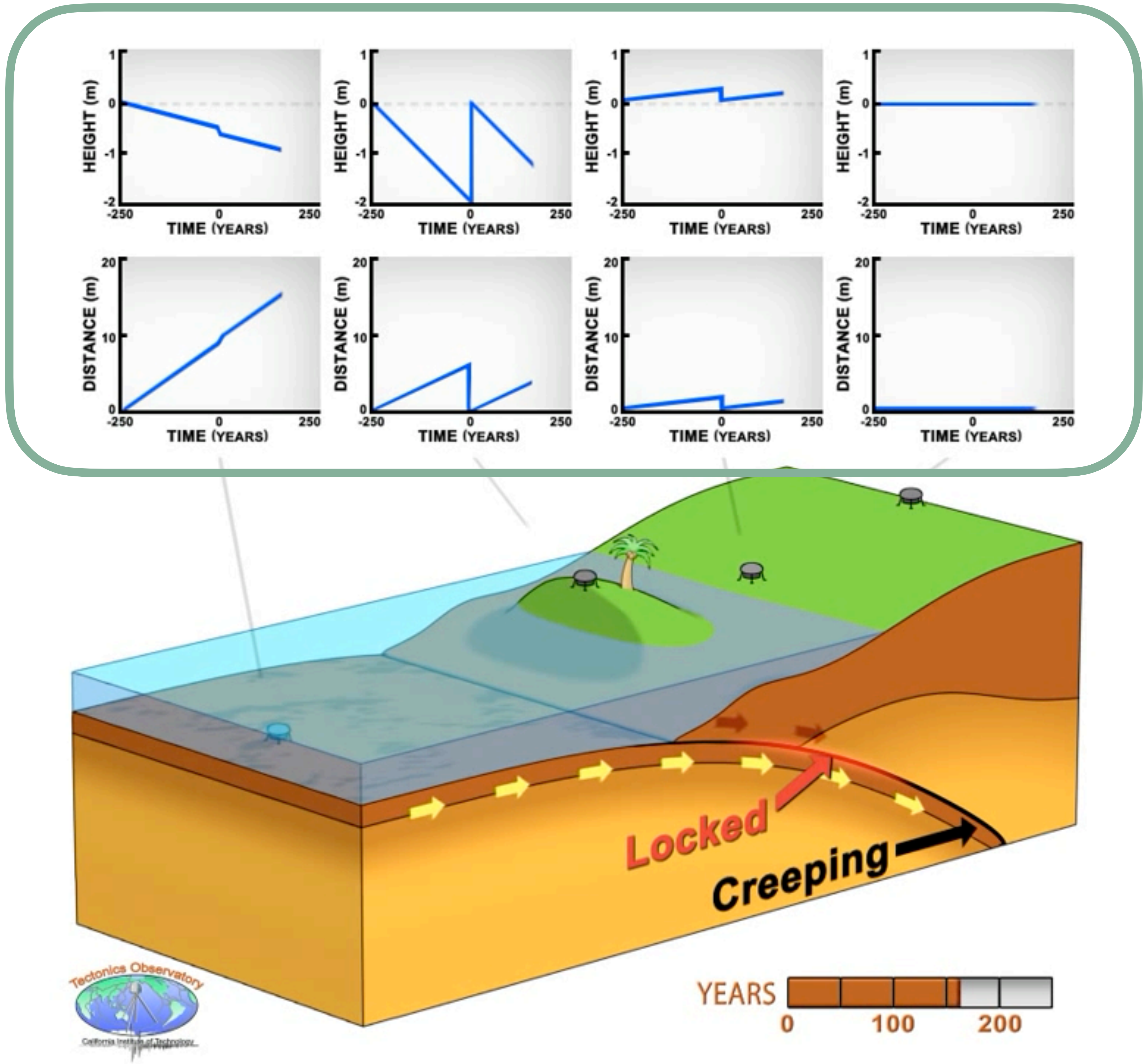

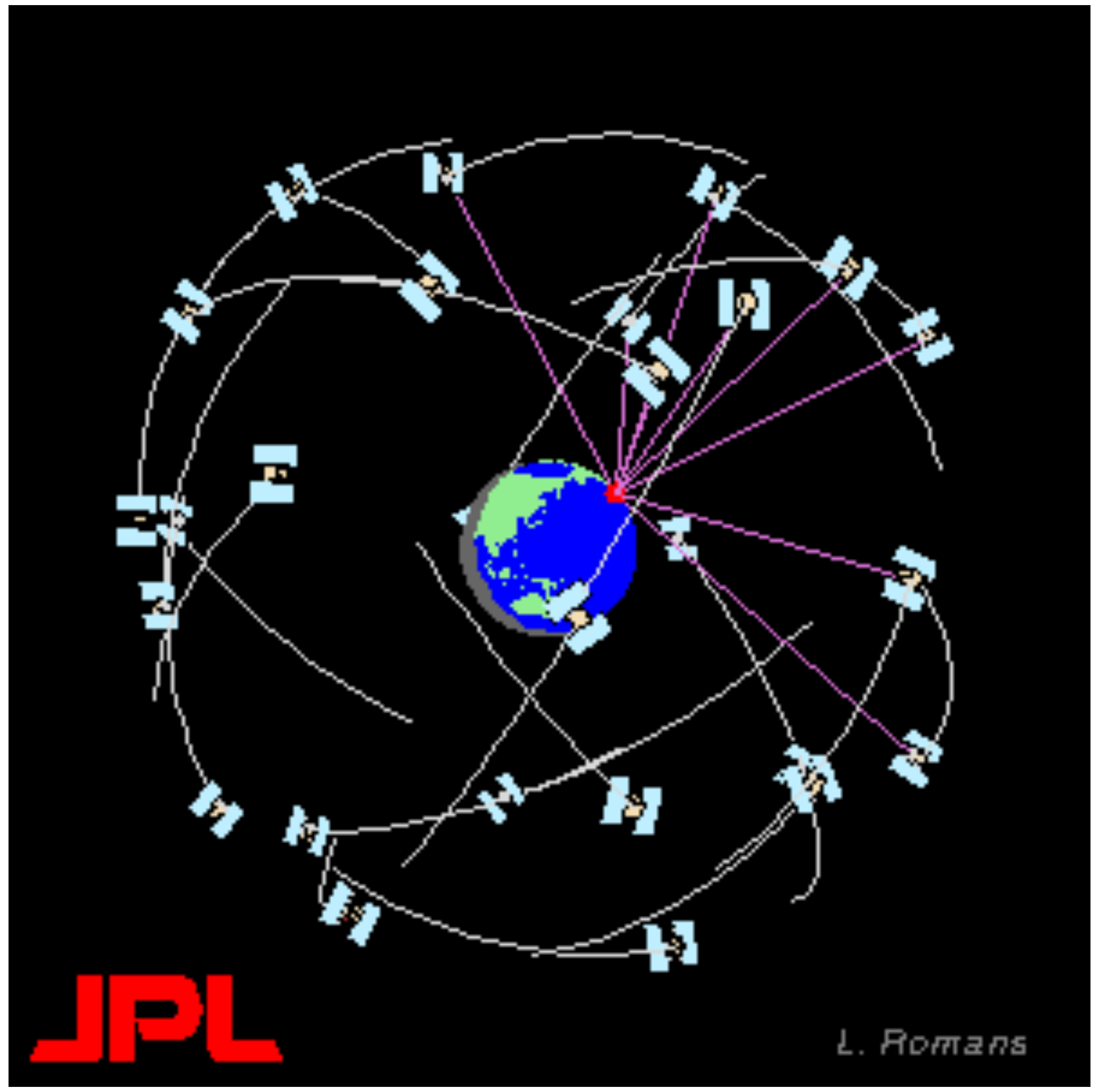

Daily GNSS Position Time Series

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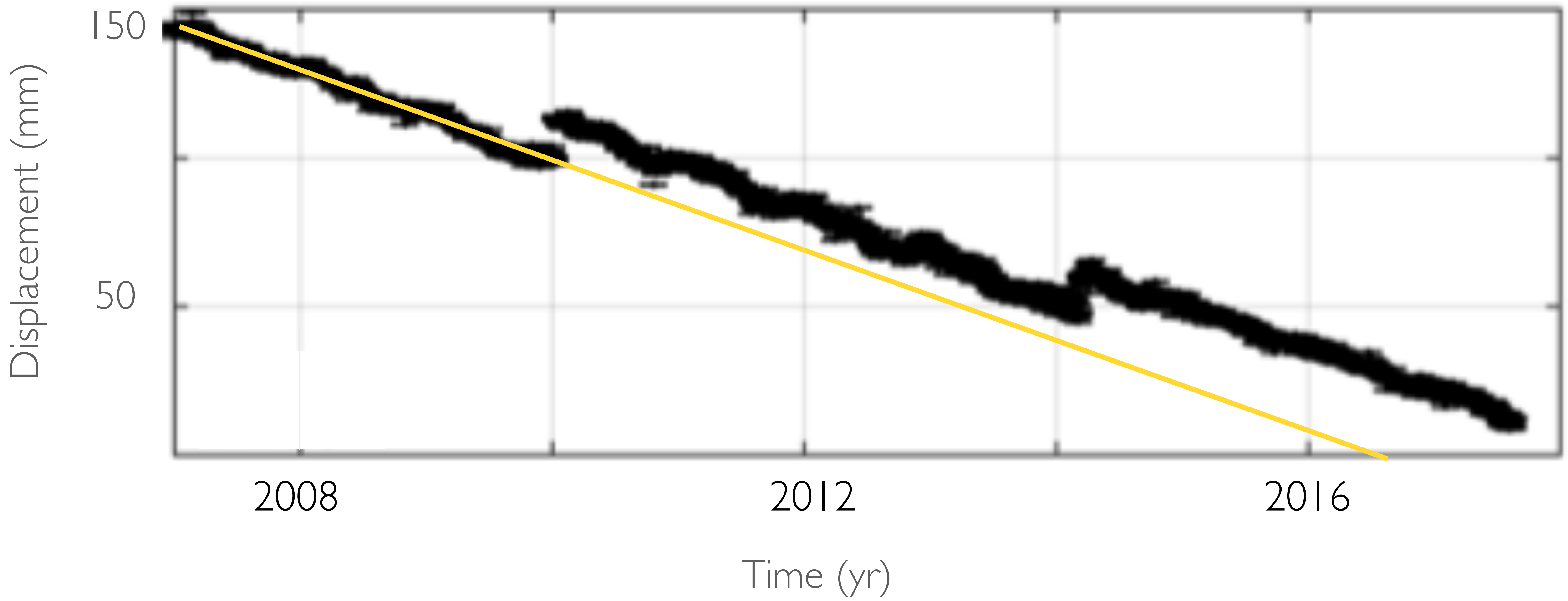
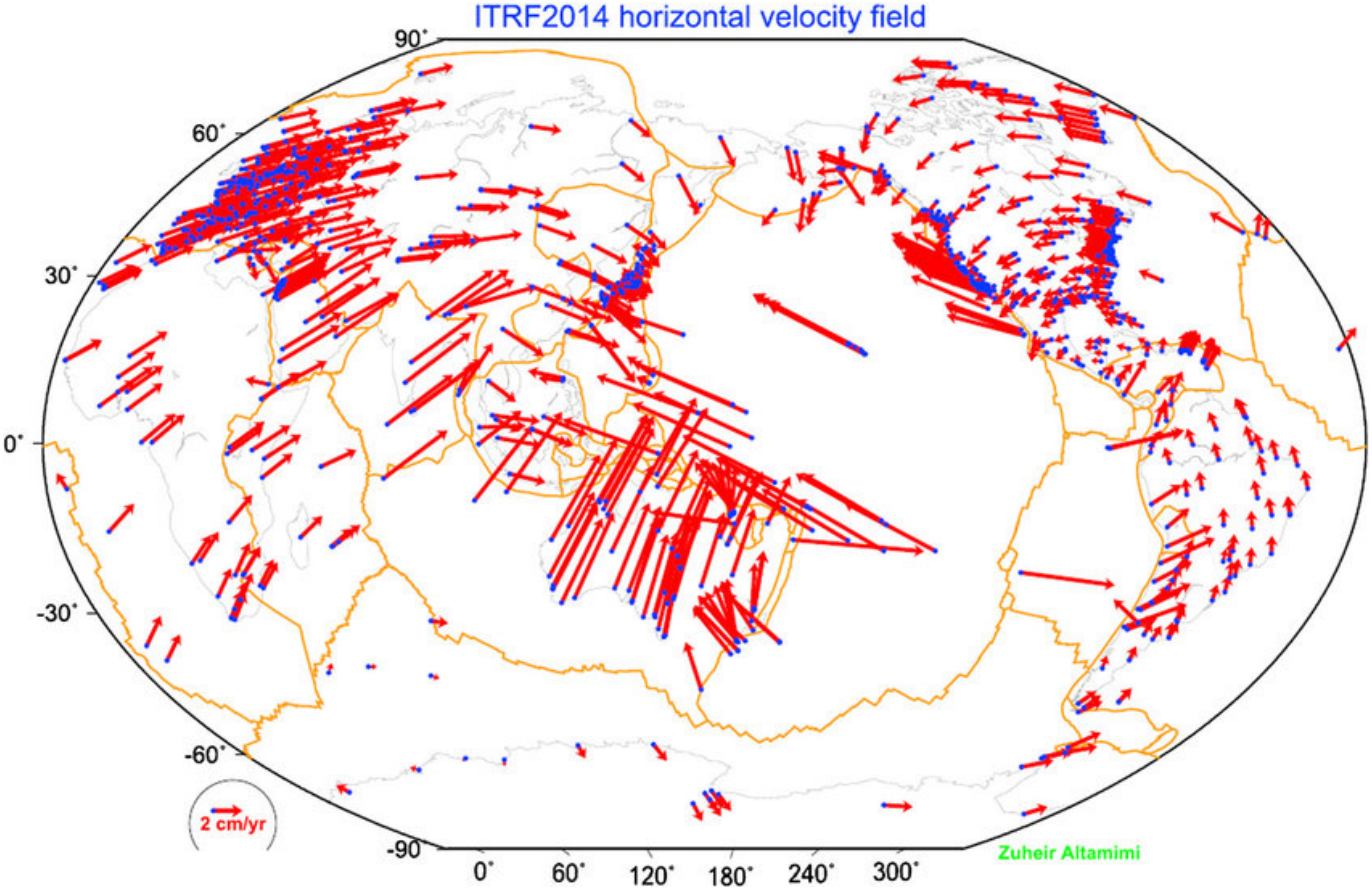
What model would you use to explain this time series ?

$$x(t) = x_{\text{linear}}(t)$$

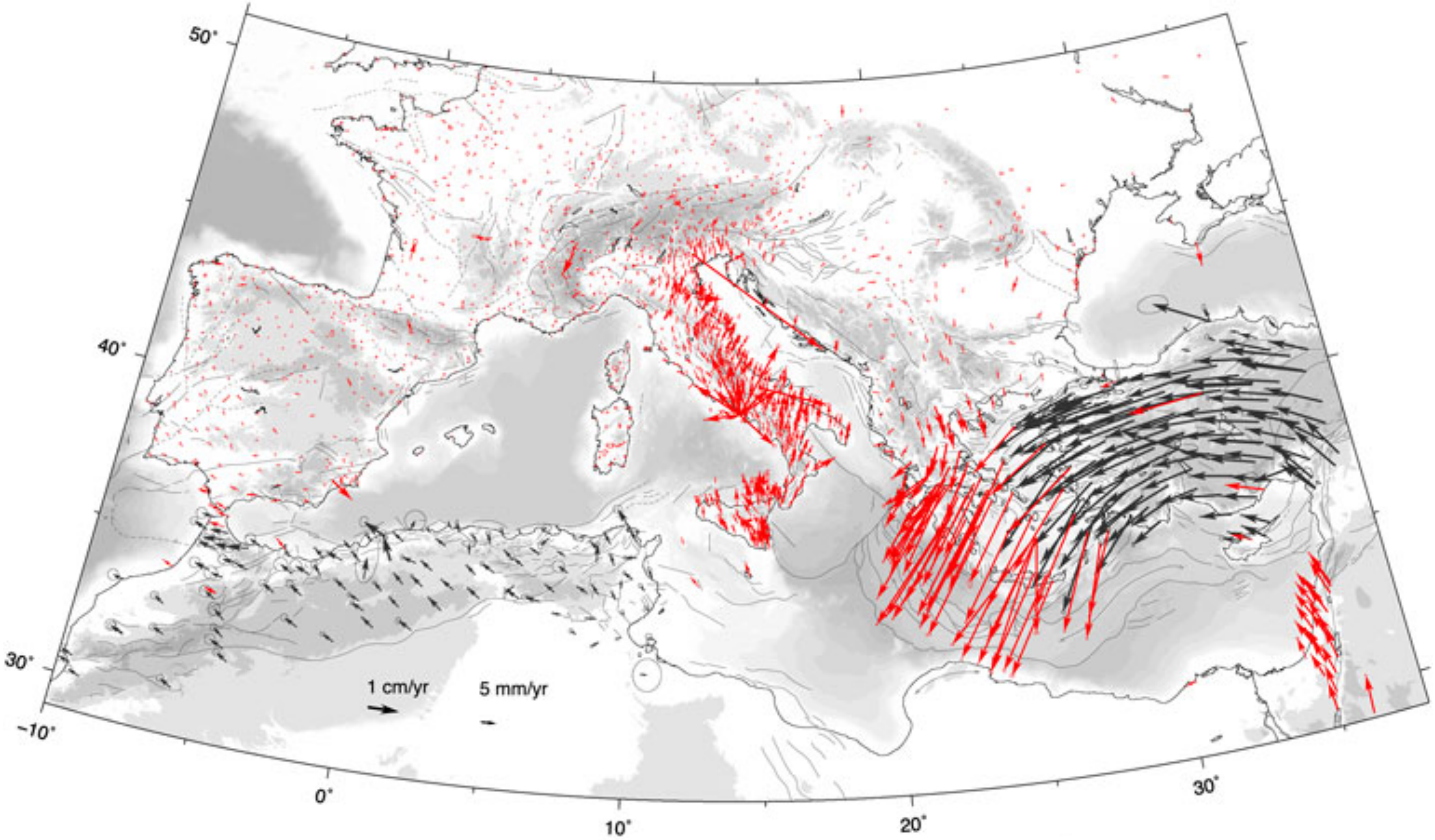


Michel et al., 2019a, *PAGEOPH*

Kinematic Description



Horizontal



Serpelloni et al, 2022, *Front. Earth Sci.*

Coupling Map

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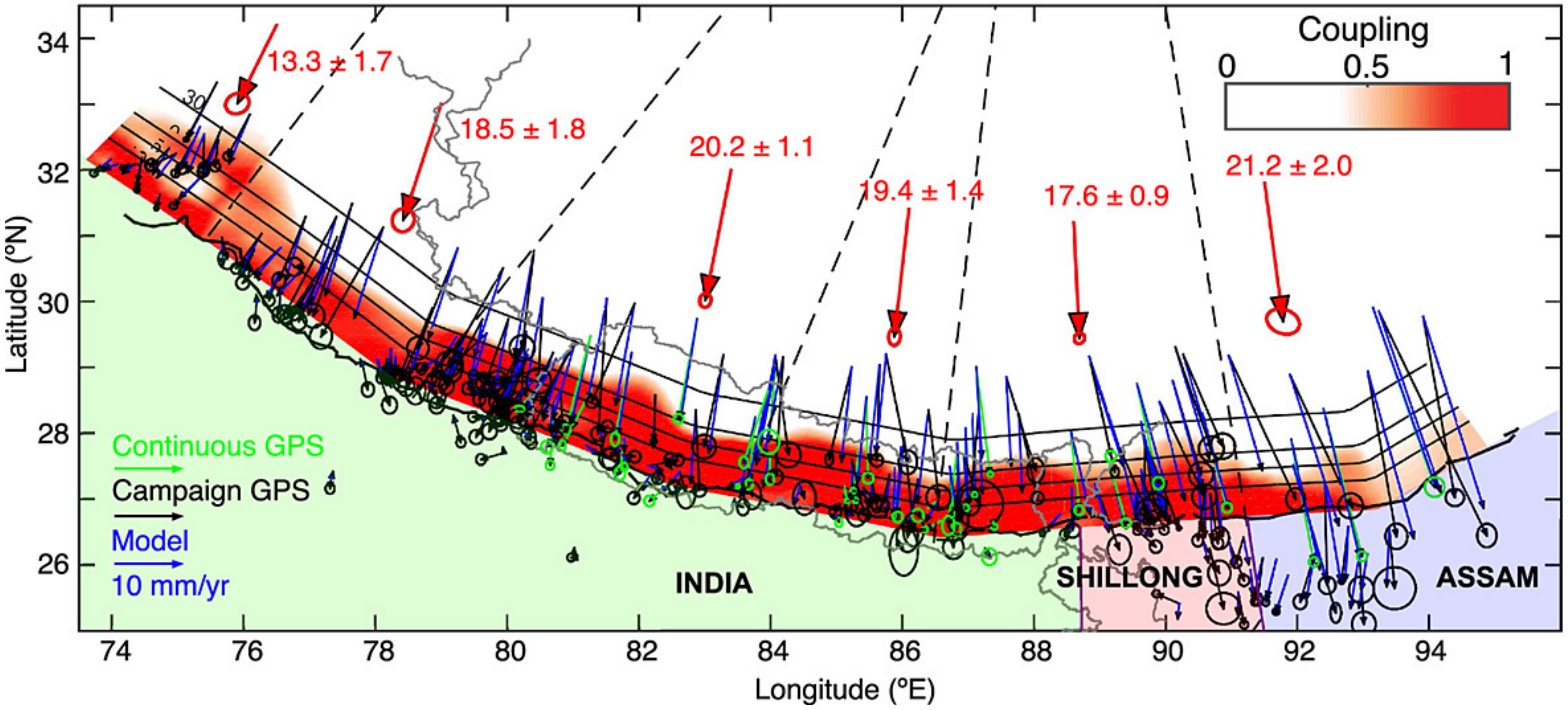

Stevens and Avouac, 2015, *GRL*

Coupling Map

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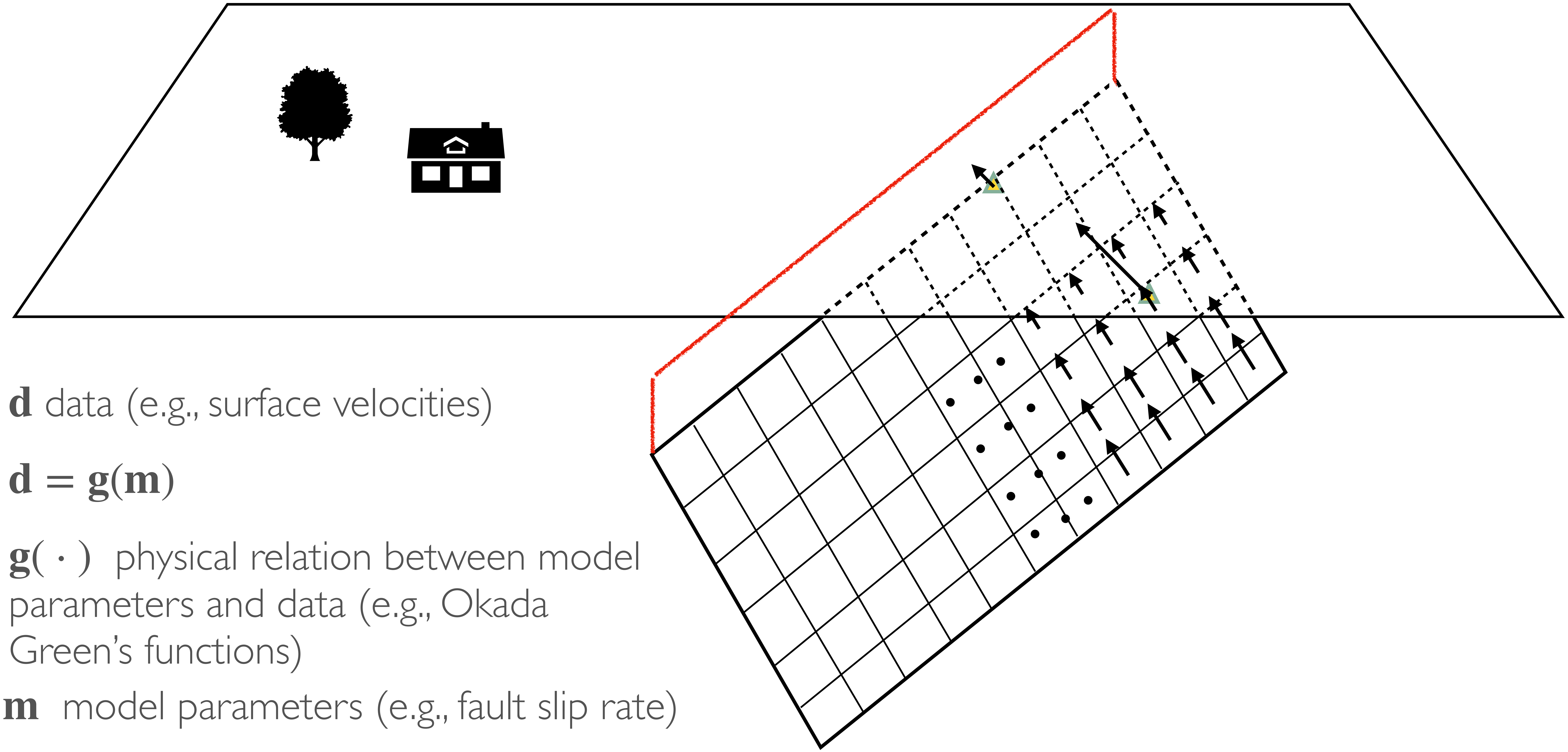

$\mathbf{d}$ data (e.g., surface velocities)

$\mathbf{d} = \mathbf{g}(\mathbf{m})$

$\mathbf{g}(\cdot)$ physical relation between model parameters and data (e.g., Okada Green's functions)

$\mathbf{m}$ model parameters (e.g., fault slip rate)

Coupling Map

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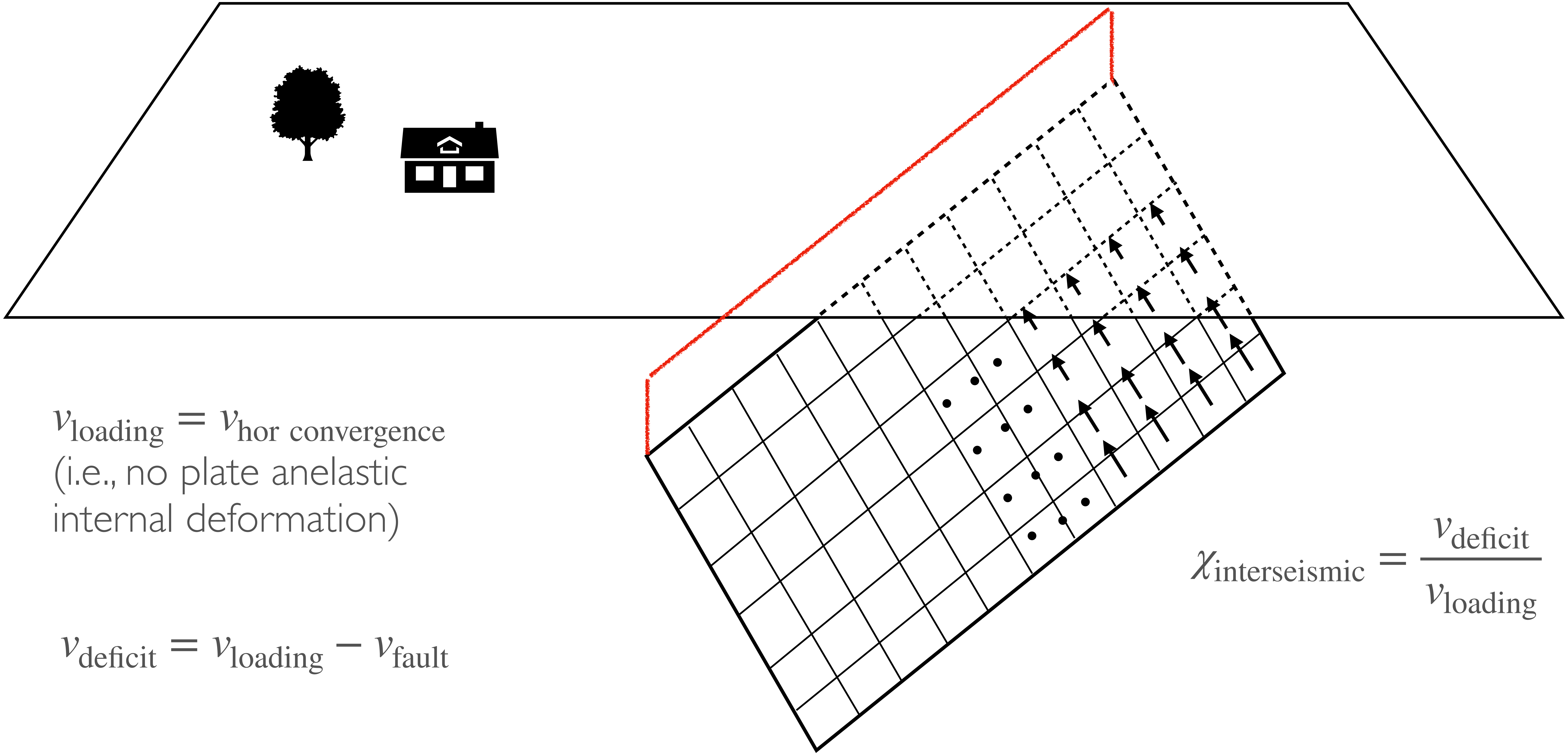

$v_{\text{loading}} = v_{\text{hor convergence}}$
(i.e., no plate anelastic internal deformation)

$v_{\text{deficit}} = v_{\text{loading}} - v_{\text{fault}}$

$$\chi_{\text{interseismic}} = \frac{v_{\text{deficit}}}{v_{\text{loading}}}$$

Coupling Map

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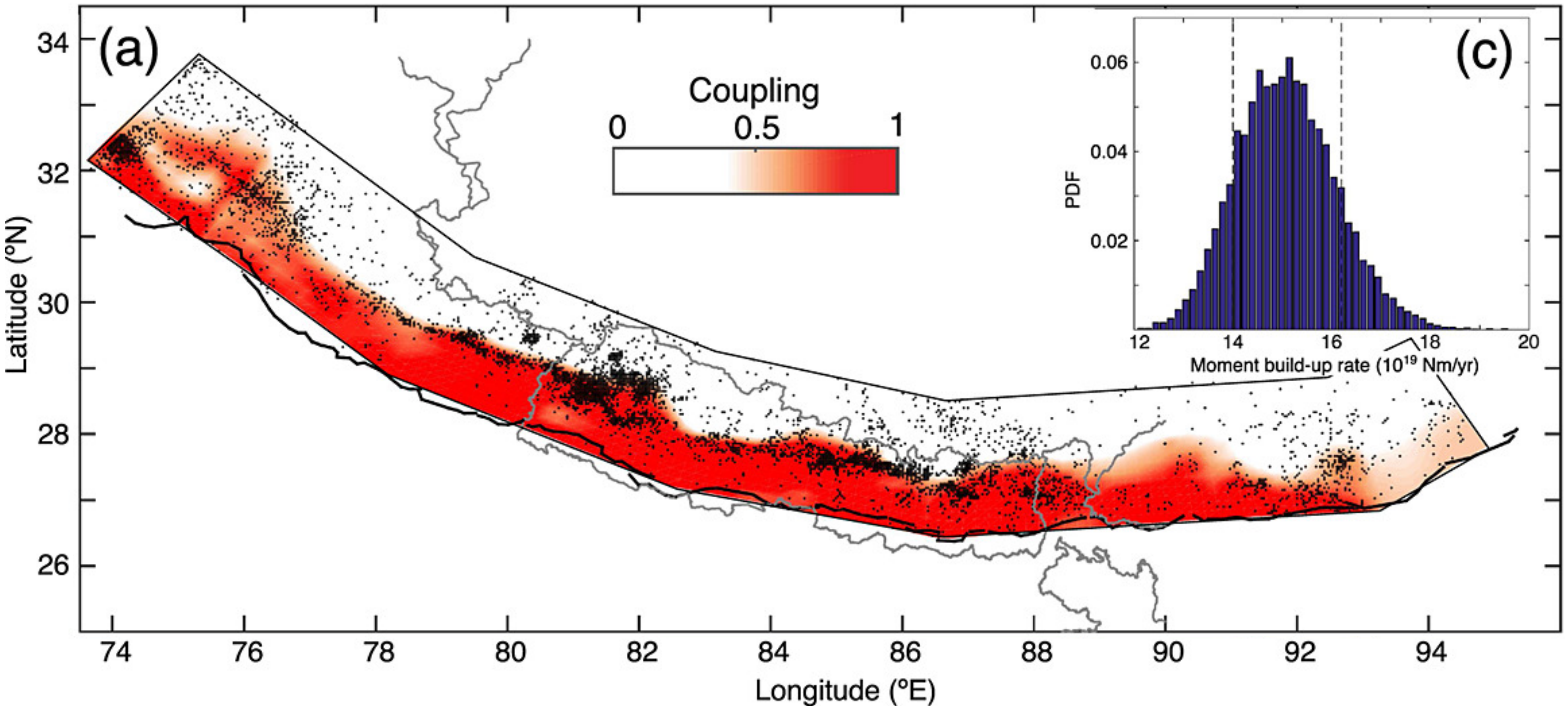

Stevens and Avouac, 2015, *GRL*

Dynamics Description

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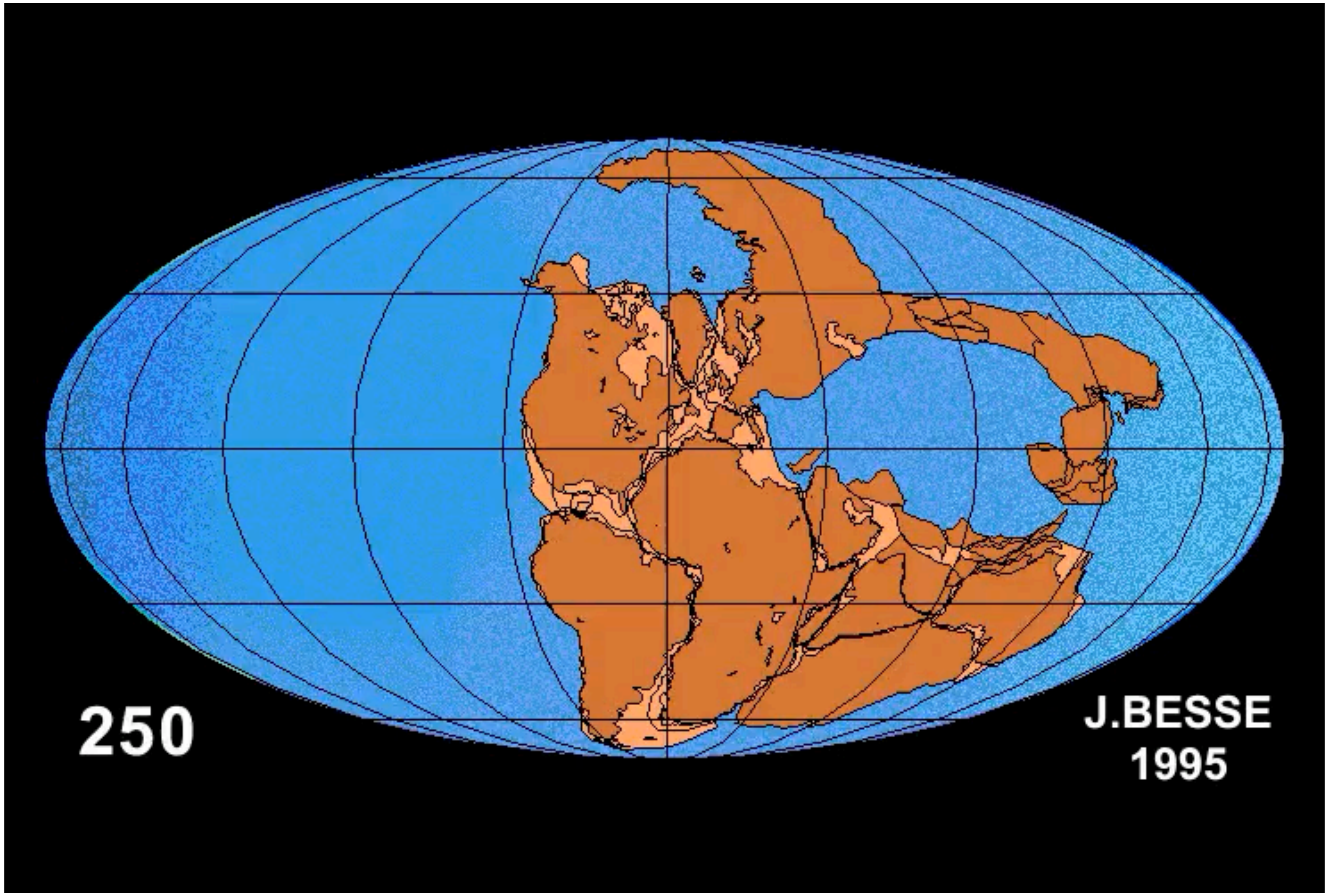
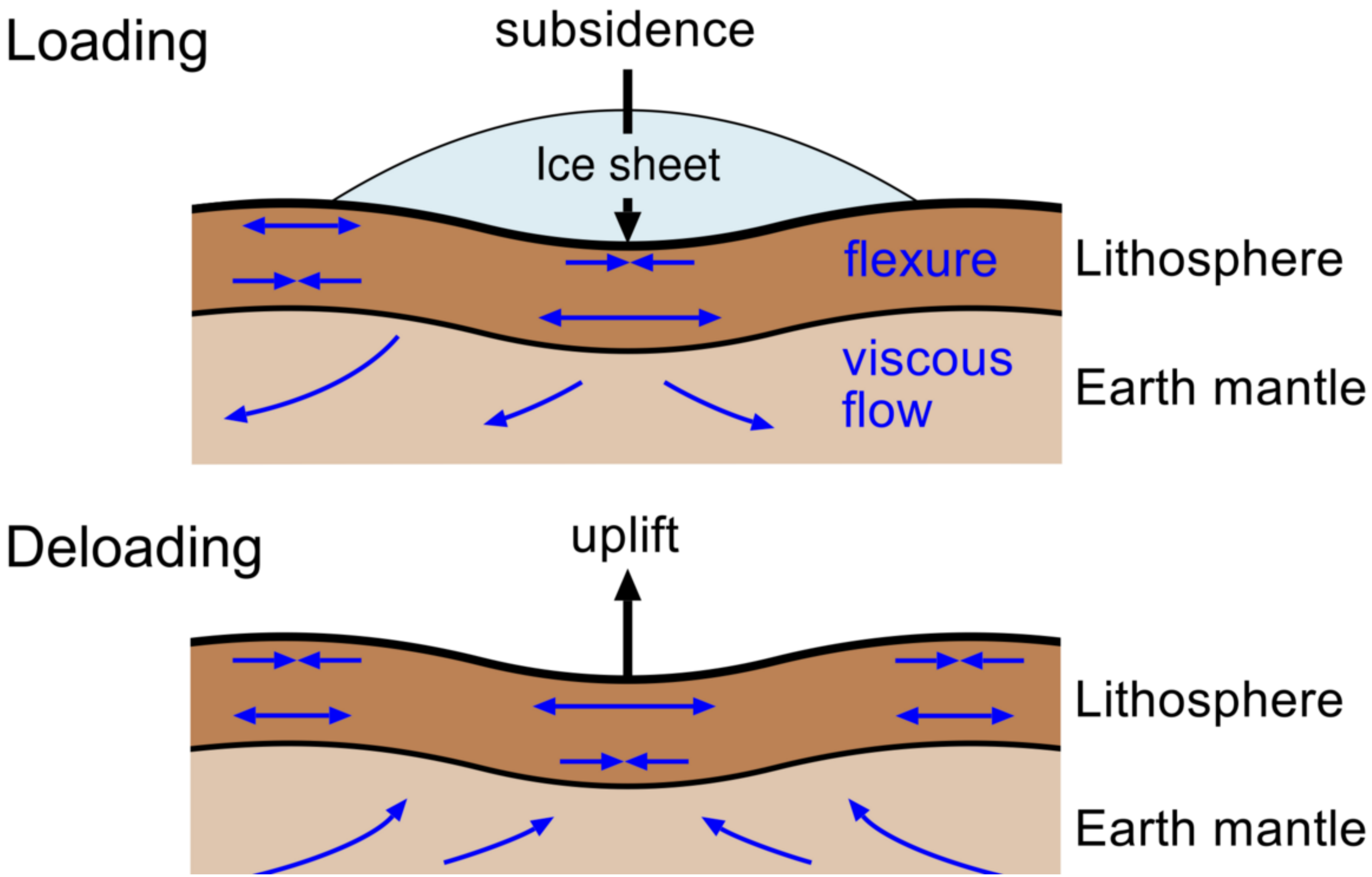


tectonics.caltech.edu

Viscoelastic Mantle



Hüttl, 2011, *Our surprising planet*

Offsets

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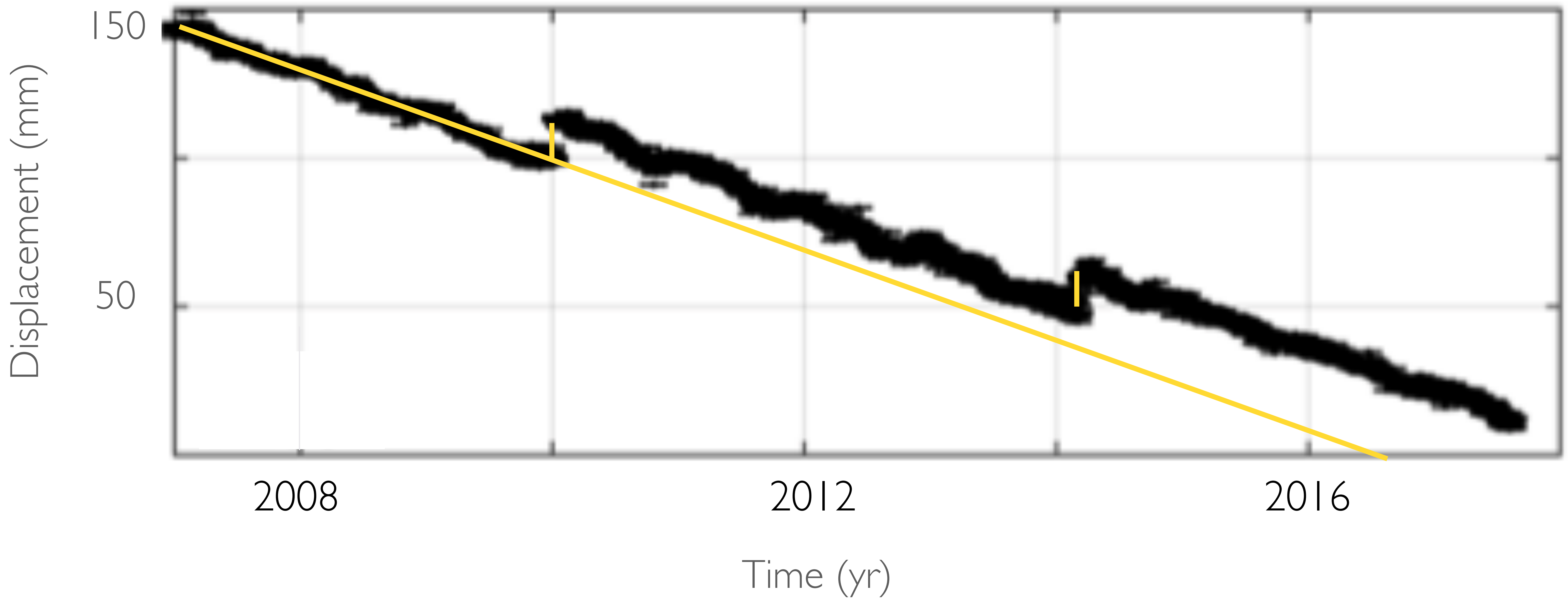
What model would you use to explain this time series ?

$$x(t) = x_{\text{linear}}(t) + x_{\text{offsets}}(t)$$



What can generate an offset ?

Michel et al., 2019a, *PAGEOPH*

Offsets

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What can generate an offset ?

Earthquakes

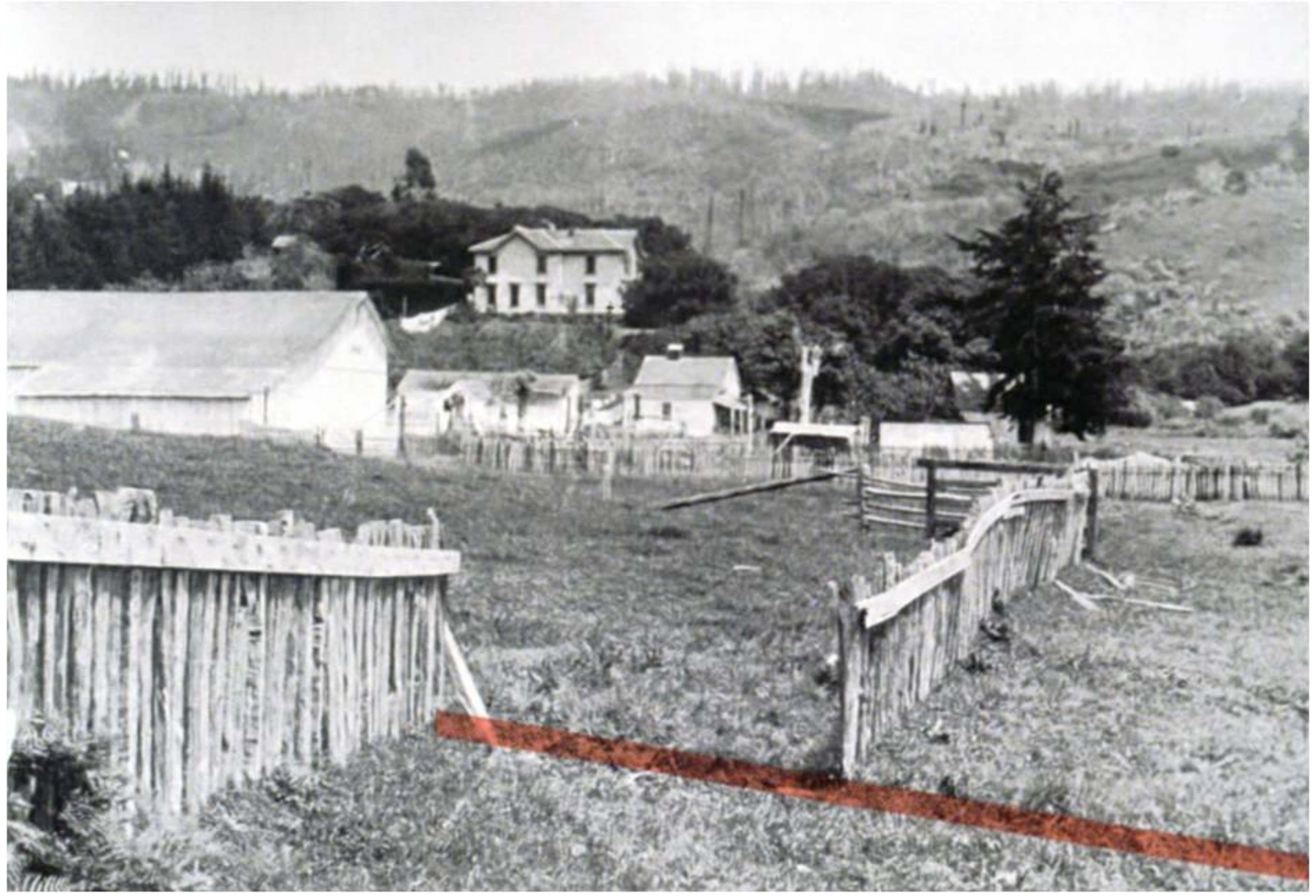

Photo by G.K. Gilbert

1906 San Francisco: $\sim$ 3 m

Antenna change / firmware update

Static Inverse Problem

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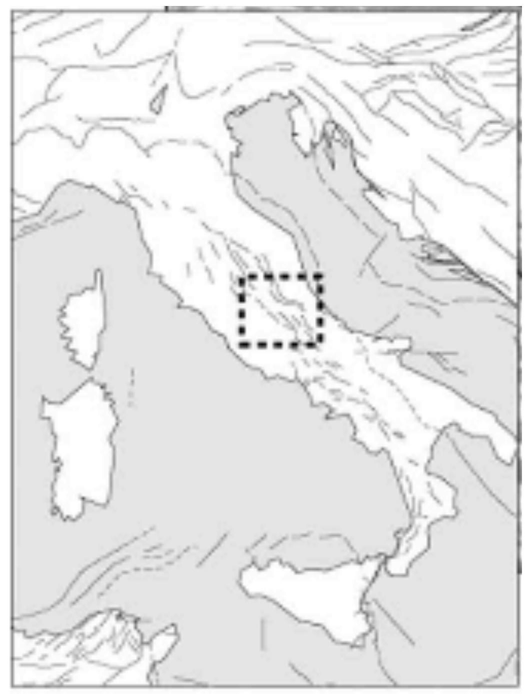
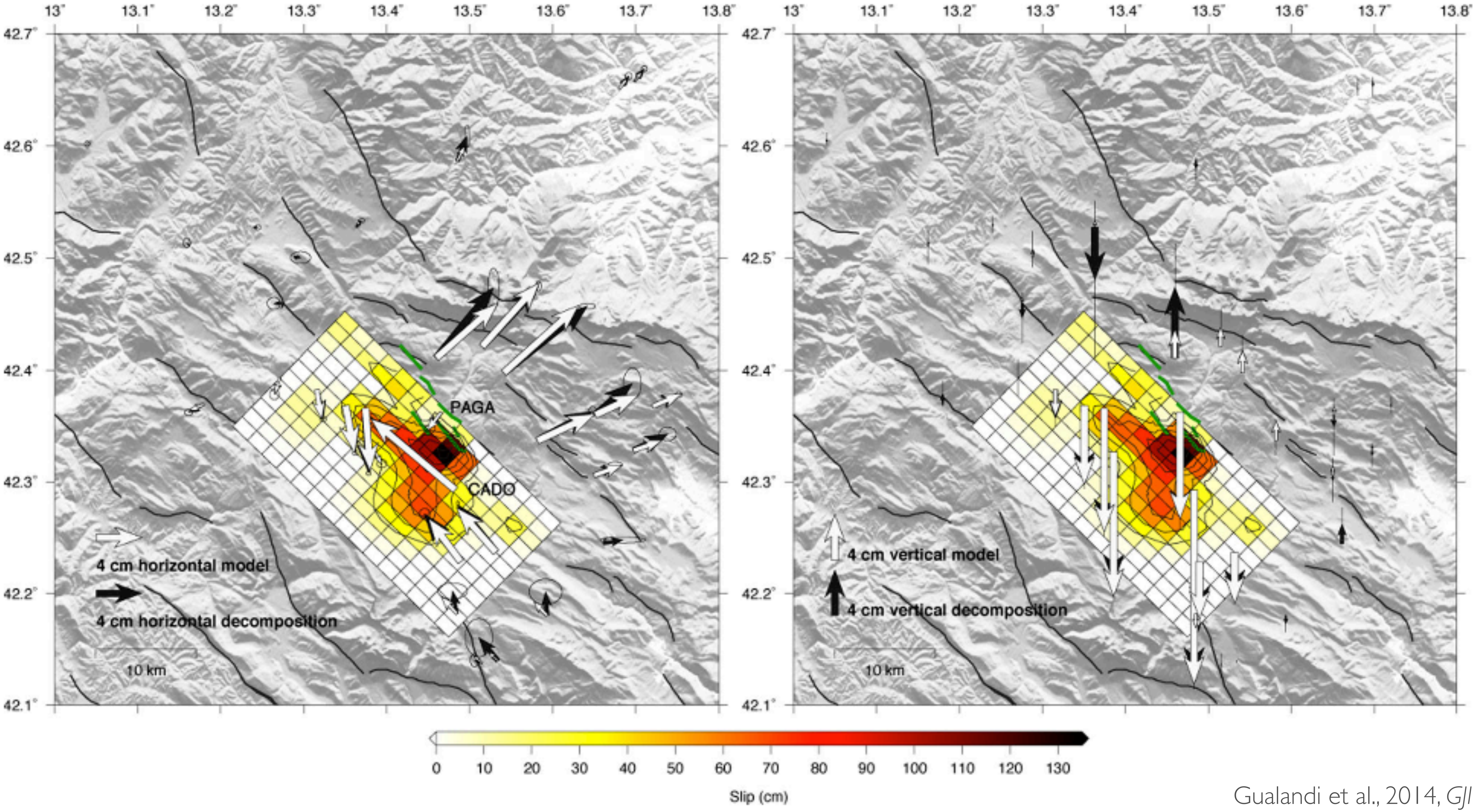


$M_w 6.3$
L'Aquila earthquake (2009)



Gualandi et al., 2014, *GJI*

Coupling Map

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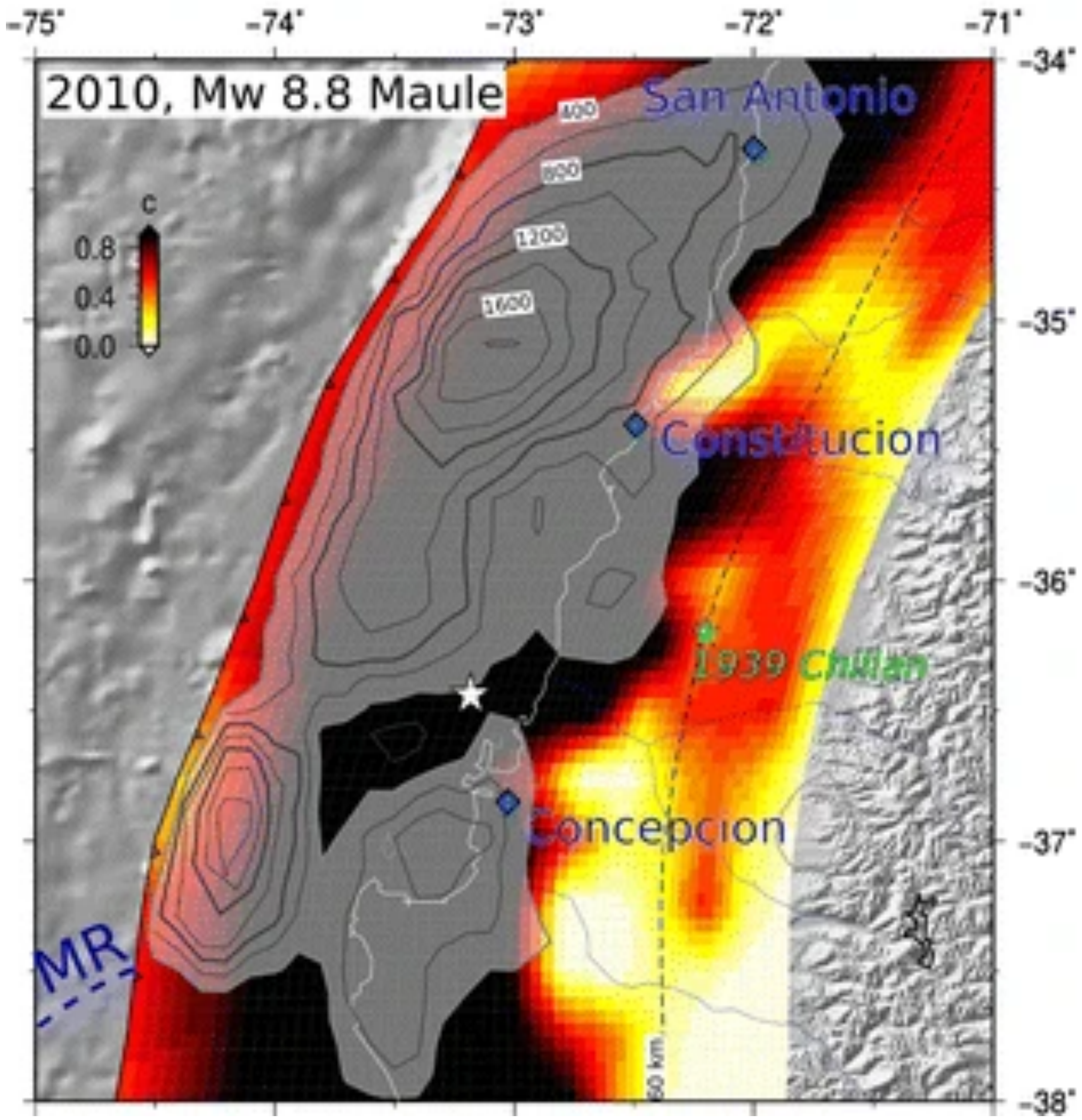

Metois et al., 2016, *PAGEOPH*

Dynamic Effects

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Dynamics Model

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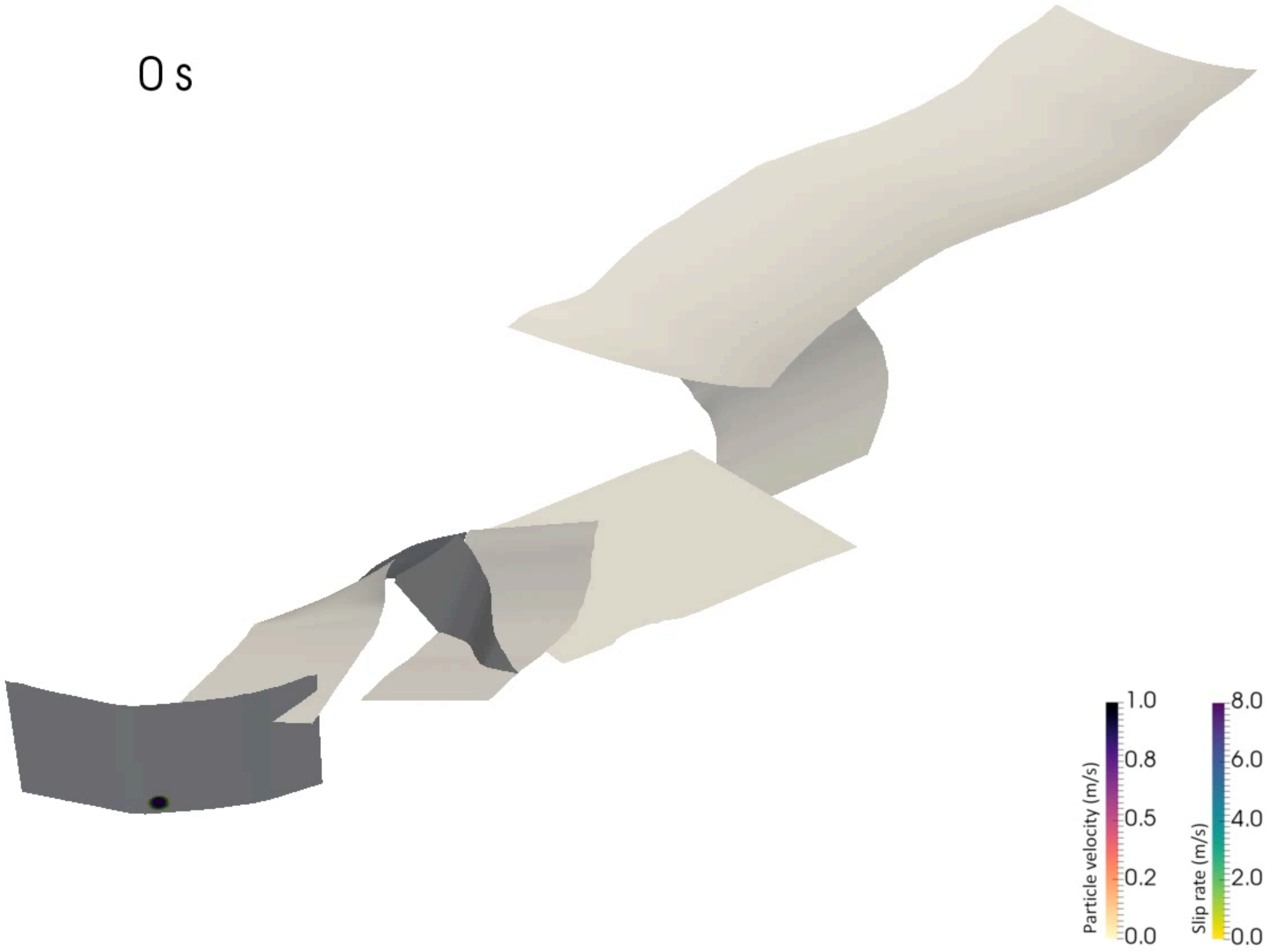
M_w7.8
Kaikōura
earthquake
(2016)



Ulrich et al., 2019, *Nat. Comm.*

High-Rate GNSS

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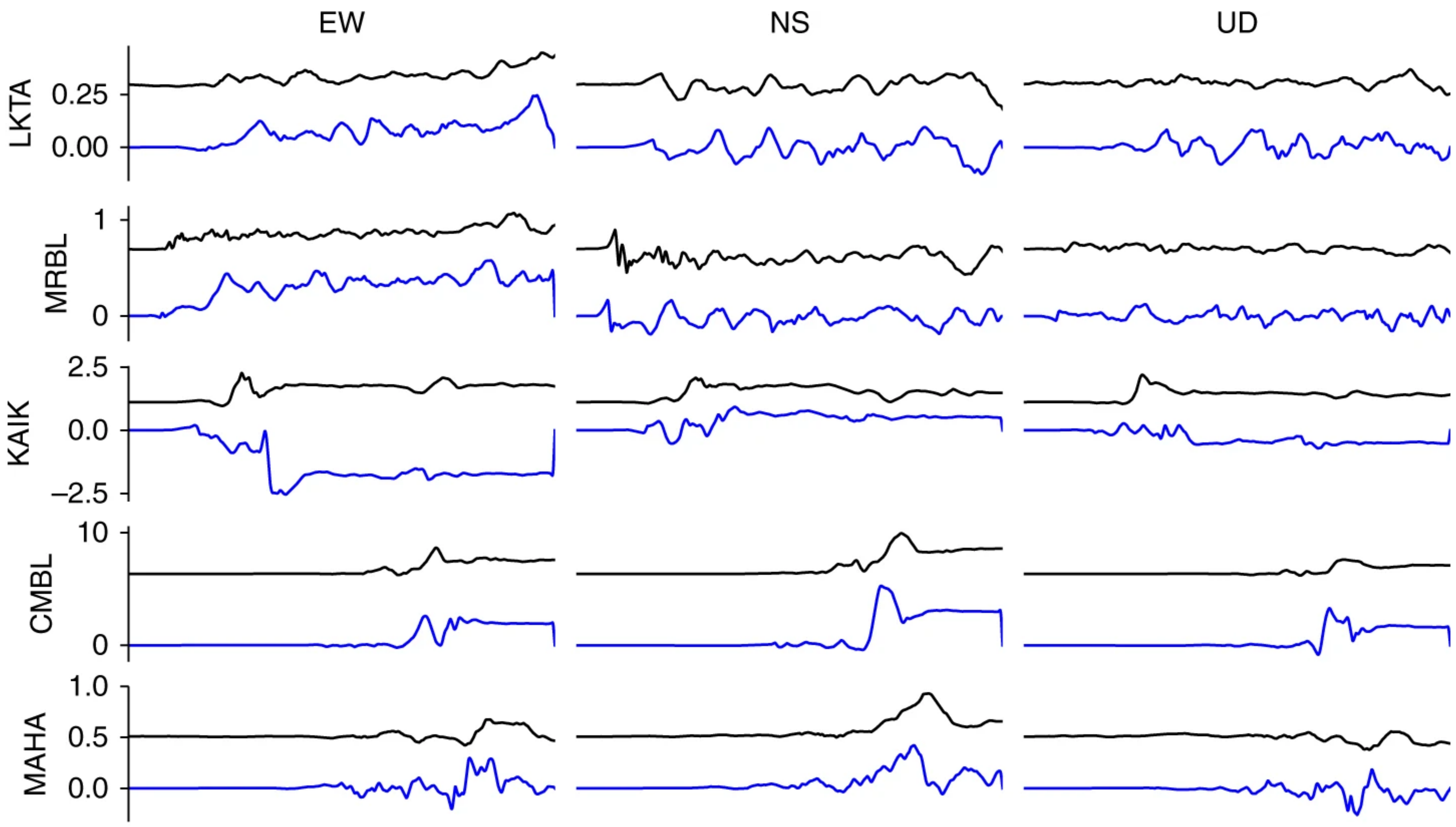

Ulrich et al., 2019, *Nat. Comm.*

High-Rate GNSS

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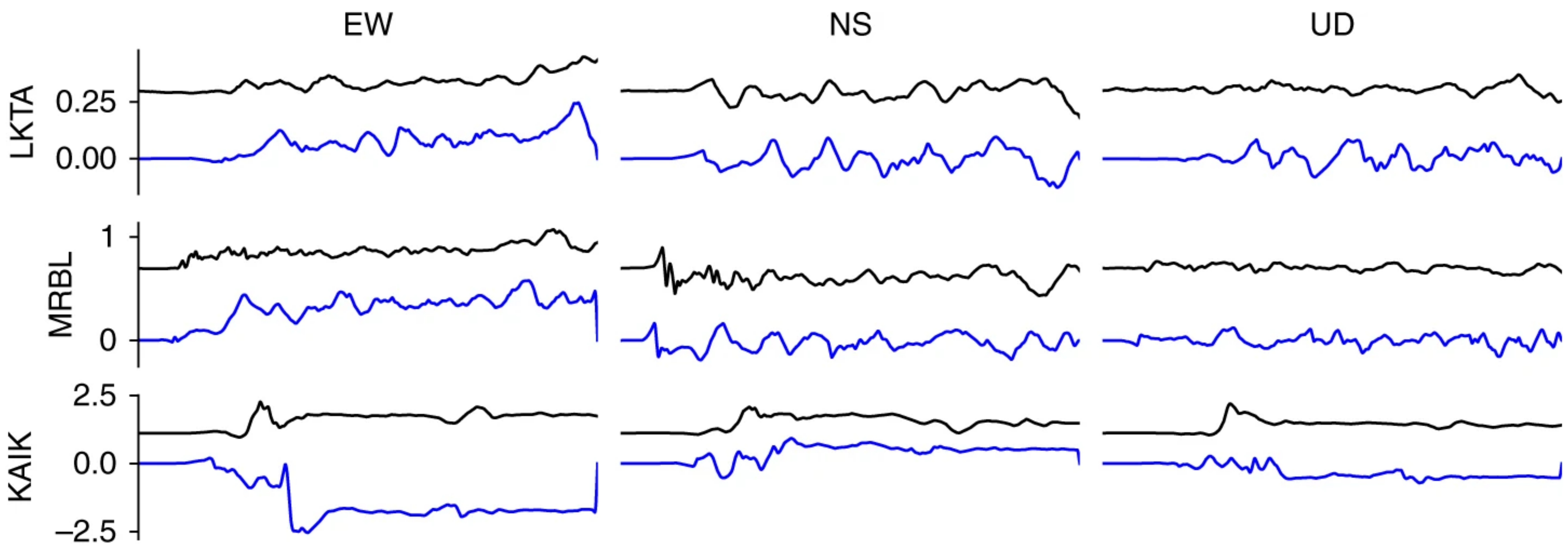

"Due to the close distance of some of the stations to the faults [...], a close match of synthetic and observed waveforms is not expected."

Ulrich et al., 2019, *Nat. Comm.*

Daily GNSS Position Time Series

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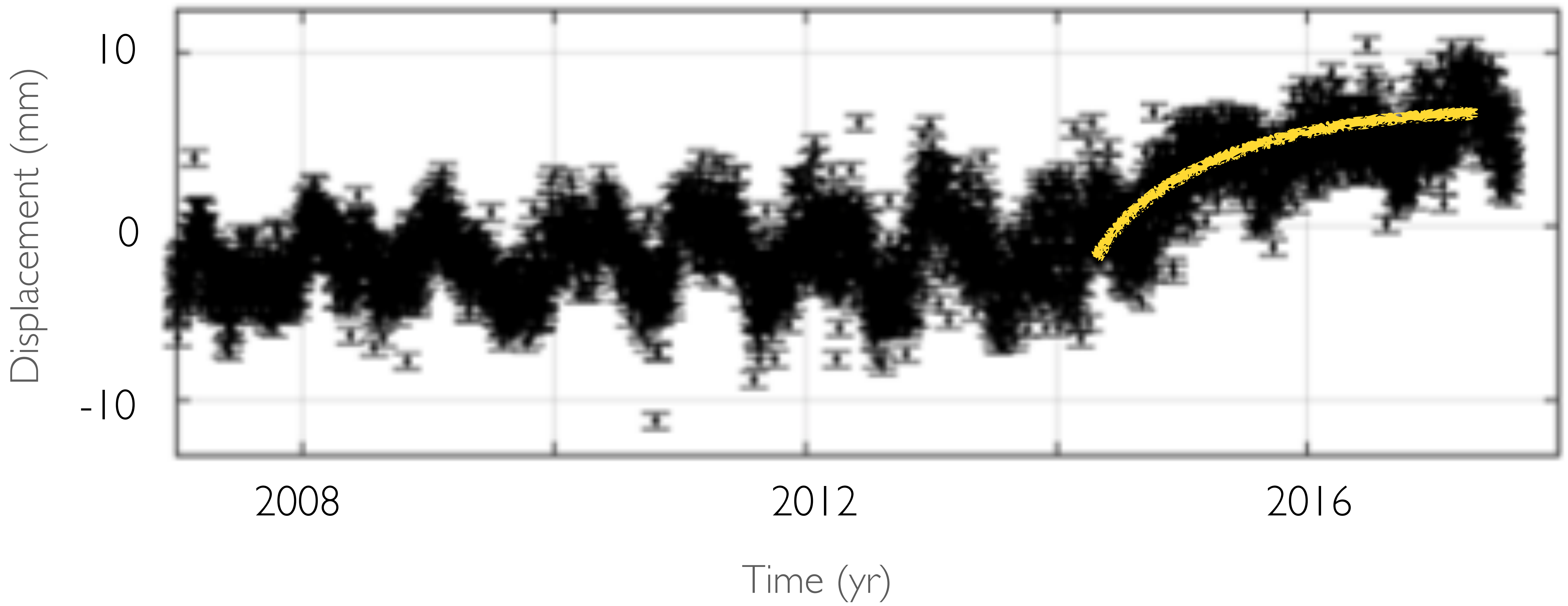
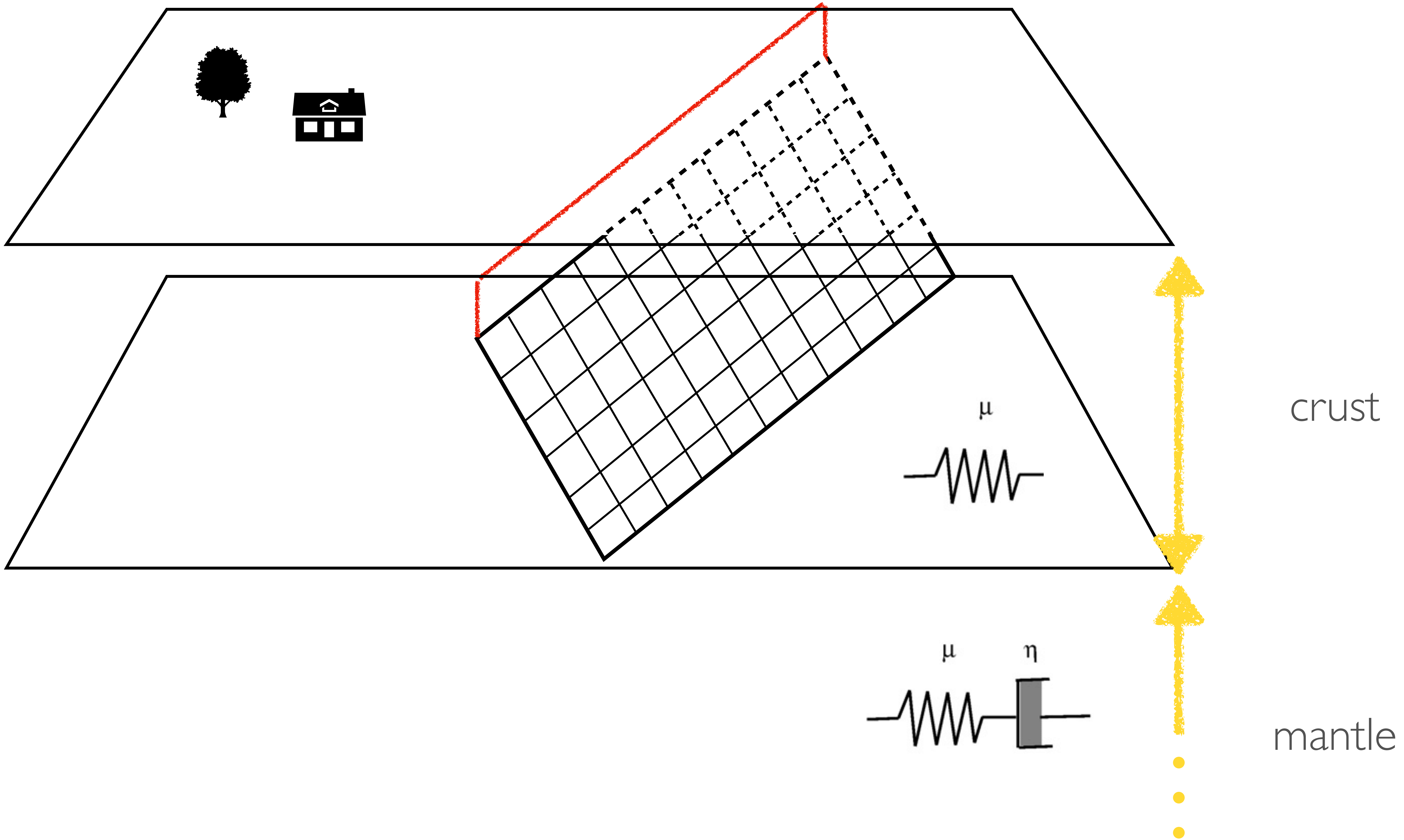
What can generate post-seismic deformation ?

$$x(t) = x_{\mathrm{linear}}(t) + x_{\mathrm{offsets}}(t) + x_{\mathrm{post-seismic}}(t)$$



Michel et al., 2019a, *PAGEOPH*

Viscoelastic Mantle



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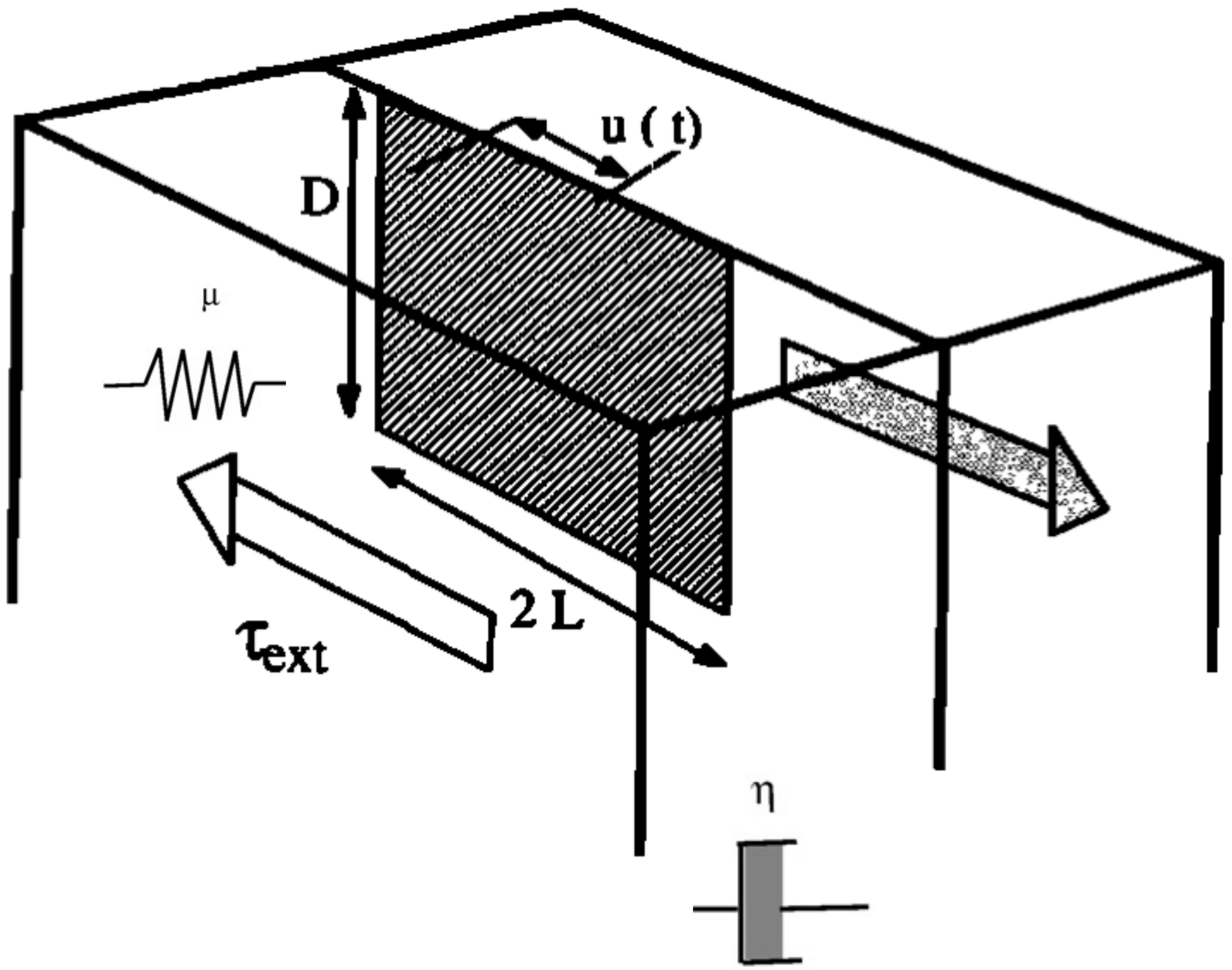
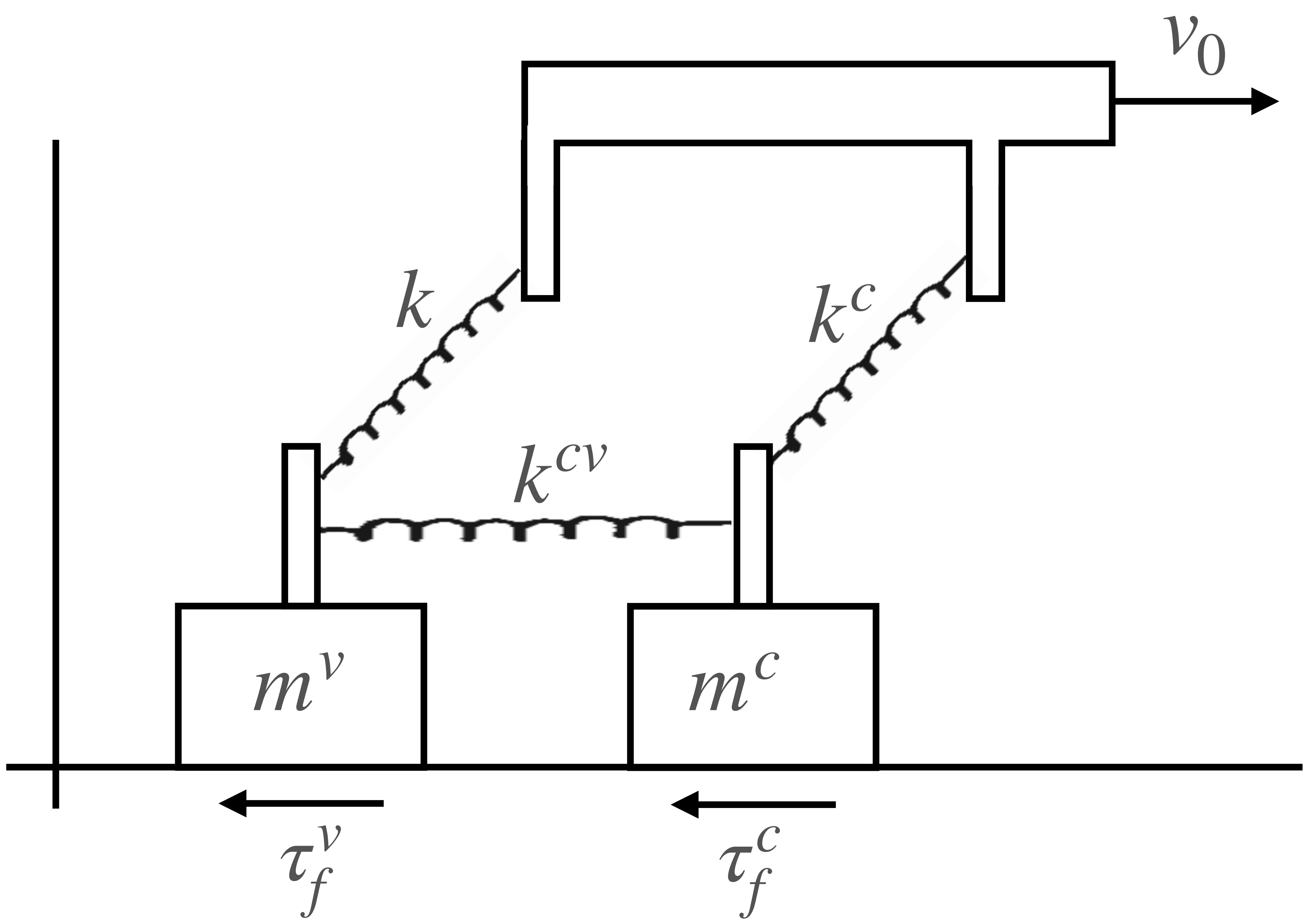
Viscous Resistance To Slip





Wesson, 1988, *JGR*

Viscous Resistance To Slip

$$m^v \frac{\mathrm{d}v}{\mathrm{d}t} = \sum_j \tau_j^v = \tau_i^v + \tau_l^v - \tau_f^v + \Delta\tau^v(t)$$

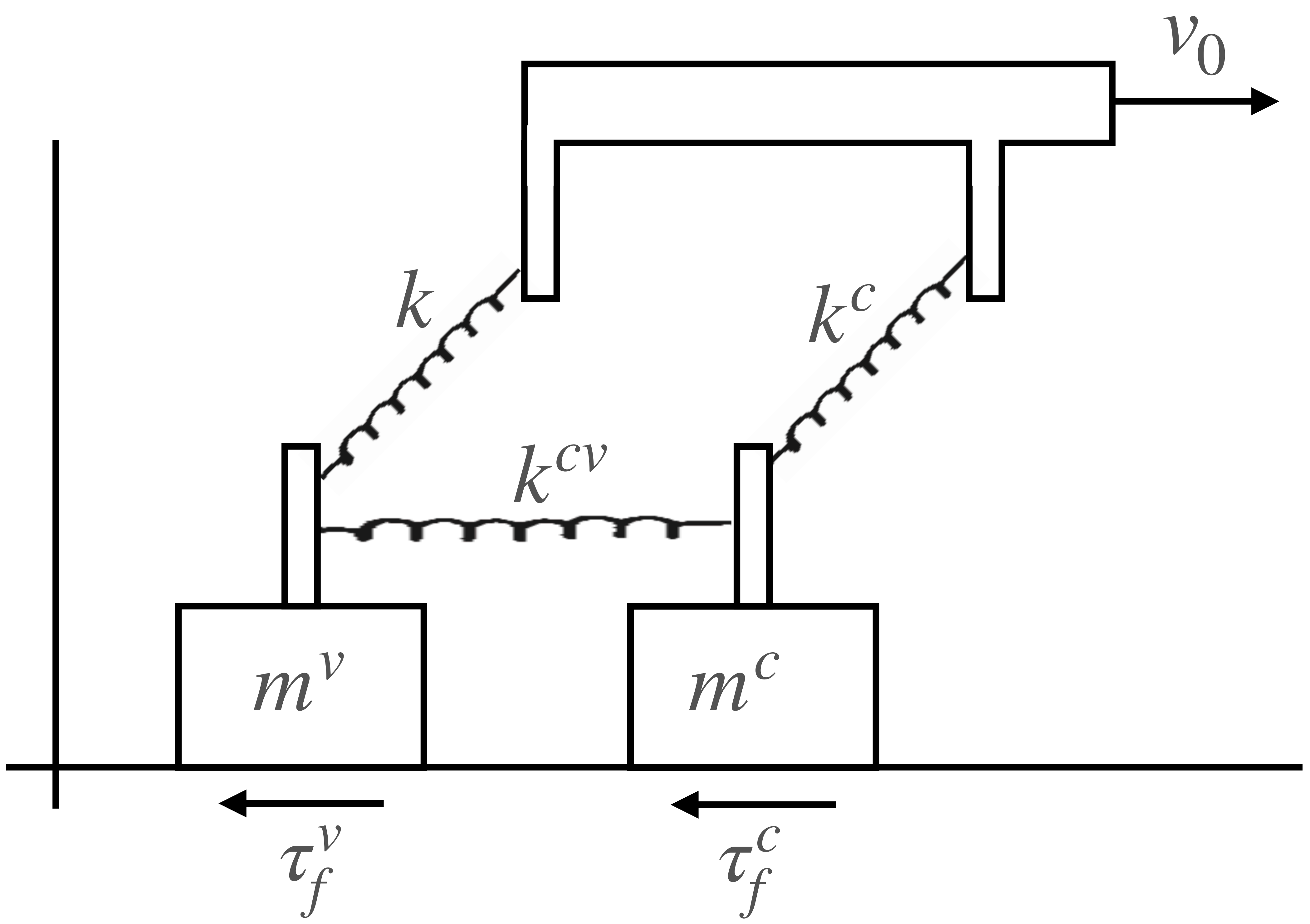
$$\tau_l^v = k(v_0 t - \delta^v)$$

$$\tau_f^v = \eta v^v$$

$$\Delta\tau^v(t) = \Delta\tau^{cv}\mathrm{H}(t - t_{eq})$$

Quasi-static approximation:

$$0 = \tau_i + \tau_l - \tau_f + \Delta\tau(t)$$



Viscous Resistance To Slip

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Quasi-static approximation:

$$0 = \tau_i + \tau_l - \tau_f + \Delta\tau \mathrm{H}(t)$$

$$t = t_0 = 0$$
$$\delta = \delta_i = 0$$
$$v = v_i = v_0$$

$$0 = \tau_i + 0 - \eta v_0 + 0 \qquad \tau_i = \eta v_0$$

$$\tau_l = k(v_0 t - \delta)$$

$$\tau_f = \eta v$$

$$0 = \eta v_0 + k \boxed{\left[\frac{\Delta\tau}{k}\mathrm{H}(t) + v_0 t - \delta\right]} - \eta v$$

$$u = \frac{\Delta\tau}{k}\mathrm{H}(t) + v_0 t - \delta$$

$$\dot{u} = \frac{\Delta\tau}{k}\delta_{\mathrm{Dirac}}(t) + v_0 - v$$

$$0 = \eta v_0 + ku - \eta\left[\frac{\Delta\tau}{k}\delta_{\mathrm{Dirac}}(t) + v_0 - \dot{u}\right]$$

$$\eta\dot{u} + ku = \eta(v_0 - v_0) + \frac{\eta}{k}\Delta\tau\delta_{\mathrm{Dirac}}(t)$$

Viscous Resistance To Slip

$$\eta\dot{u} + ku = \eta(\cancel{v_0} - \cancel{v_0}) + \frac{\eta}{k}\Delta\tau\delta_{\mathrm{Dirac}}(t)$$

$$u = \frac{\Delta\tau}{k}\mathrm{H}(t) + v_0 t - \delta$$

Viscous Resistance To Slip

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$$\dot{u} + \frac{k}{\eta}u = \frac{\Delta\tau}{k}\delta_{\mathrm{Dirac}}(t)$$

$$u = \frac{\Delta\tau}{k}\mathrm{H}(t) + v_0 t - \delta$$

$$\dot{u} + \frac{k}{\eta}u = 0$$

for $t > 0$

$$u_{0+} = \frac{\Delta\tau}{k}$$

$$\frac{\mathrm{d}u}{u} = -\frac{k}{\eta}\mathrm{d}t$$

$$\int_{u_{0+}}^{u(t)} \frac{\mathrm{d}u'}{u'} = -\frac{k}{\eta}\int_{0+}^{t} \mathrm{d}t$$

$$u = u_{0+}\exp\left(-\frac{k}{\eta}t\right)$$

$$u = \frac{\Delta\tau}{k}\exp\left(-\frac{k}{\eta}t\right)$$

$$\delta(t) = \frac{\Delta\tau}{k}\mathrm{H}(t) + v_0 t - u \quad = v_0 t + \frac{\Delta\tau}{k}\left[1 - \exp\left(-\frac{k}{\eta}t\right)\right]$$

$$t_r = \frac{\eta}{k}$$

Afterslip

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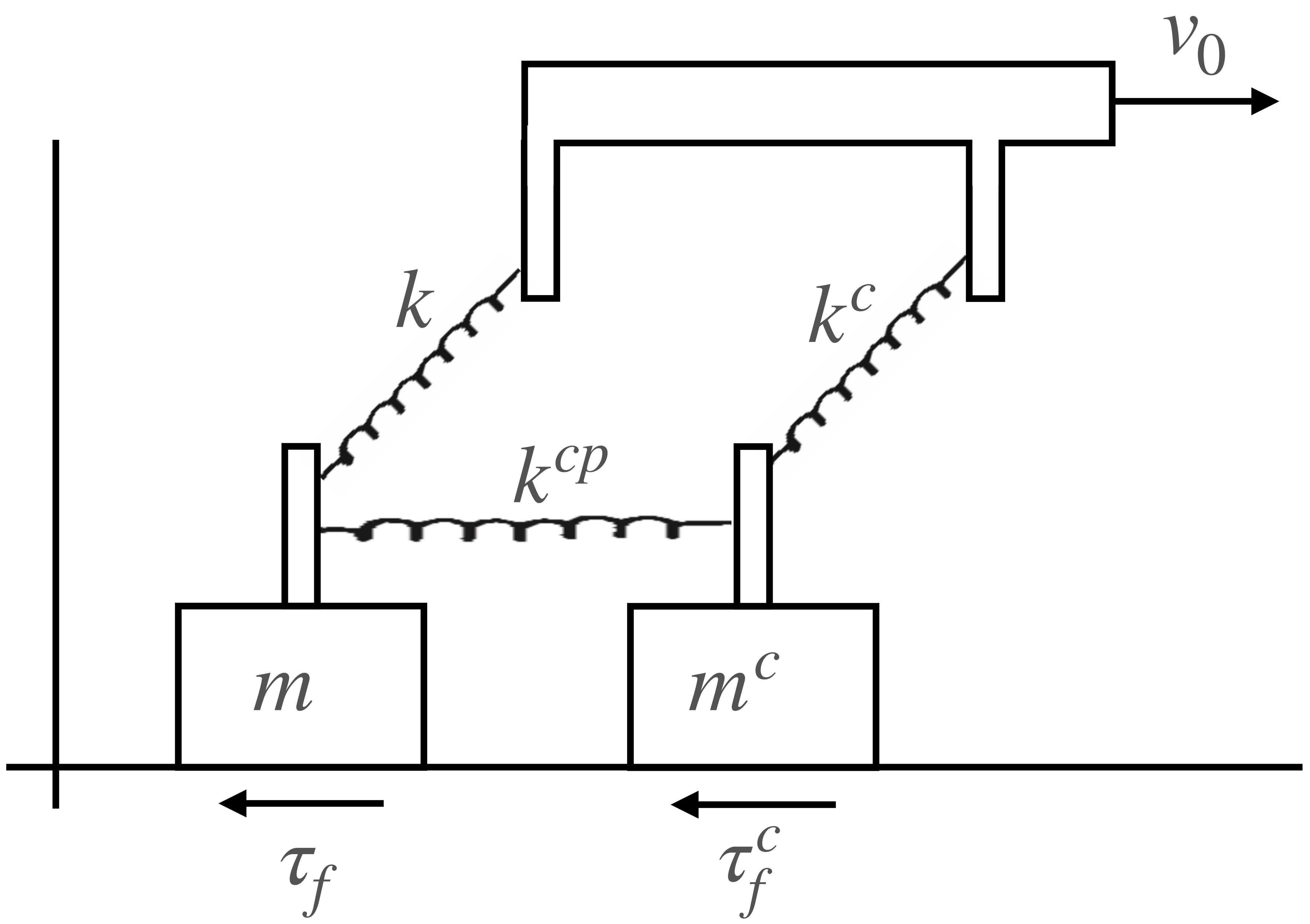
$$m\frac{\mathrm{d}v}{\mathrm{d}t} = \sum_j \tau_j = \tau_i + \tau_l - \tau_f + \Delta\tau(t)$$

$$\tau_l = k(v_0 t - \delta)$$

$$\tau_f = \sigma_n \mu \ = \sigma_n \left[\mu_0 + a \ln\frac{v}{v_*} + b \ln\frac{v_*\theta}{L}\right]$$

Dieterich, 1979, *JGR*



Afterslip

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$$m\frac{\mathrm{d}v}{\mathrm{d}t} = \sum_j \tau_j = \tau_i + \tau_l - \tau_f + \Delta\tau(t)$$

$$\tau_l = k(v_0 t - \delta)$$

$$\tau_f = \sigma_n \mu = \sigma_n \left[\mu_0 + a \ln\frac{v}{v_*} + b \ln\frac{v_* \theta}{L}\right] \overset{\theta = \theta_{ss}}{=} \sigma_n \left[\mu_0 + (a-b)\ln\frac{v}{v_*}\right]$$

Dieterich, 1979, *JGR*

$$\Delta\tau(t) = \Delta\tau \mathrm{H}(t - t_{eq})$$

Quasi-static approximation:

$$0 = \tau_i + \tau_l - \tau_f + \Delta\tau(t)$$

Afterslip

$$0 = \tau_i + k(v_0 t - \delta) - \sigma_n \left[\mu_0 + (a-b)\ln\frac{v}{v_*} \right] + \Delta\tau \mathrm{H}(t)$$

$$t = t_0 = 0$$
$$\delta = \delta_i = 0$$
$$v = v_i$$

$$0 = \tau_i + k(\cancel{v_0 t_0} - \cancel{\delta_i}) - \sigma_n \left[\mu_0 + (a-b)\ln\frac{v_i}{v_*} \right] + \Delta\tau \cancel{\mathrm{H}(t_0)}$$

$$\tau_i = \sigma_n \left[\mu_0 + (a-b)\ln\frac{v_i}{v_*} \right]$$

$$0 = k(v_0 t - \delta) - (a-b)\sigma_n \ln\frac{v}{v_i} + \Delta\tau \mathrm{H}(t)$$

$$v = \dot{\delta}$$

$$(a-b)\sigma_n \ln\frac{\dot{\delta}}{v_i} = k(v_0 t - \delta) + \Delta\tau \mathrm{H}(t)$$

Perfettini and Avouac, 2004a, *JGR*

Afterslip

$$(a-b)\sigma_n \ln \frac{\dot{\delta}}{v_i} = k(v_0 t - \delta) + \Delta\tau \mathrm{H}(t)$$

$$\ln \frac{\dot{\delta}}{v_i} = \frac{k}{(a-b)\sigma_n}(v_0 t - \delta) + \frac{\Delta\tau}{(a-b)\sigma_n}\mathrm{H}(t) \qquad c = \frac{k}{(a-b)\sigma_n}$$

$$\dot{\delta} = v_i \exp\left[c(v_0 t - \delta) + \frac{\Delta\tau}{(a-b)\sigma_n}\mathrm{H}(t)\right] \qquad t_r = \frac{1}{c v_0} = \frac{(a-b)\sigma_n}{k v_0}$$

$$e^{c\delta}\dot{\delta} = v_i f(t) \qquad f(t) = \exp\left[\frac{t}{t_r} + \frac{\Delta\tau}{(a-b)\sigma_n}\mathrm{H}(t)\right]$$

$$\int_{0^+}^{t} e^{c\delta}\dot{\delta}\mathrm{d}t' = v_i \int_{0^+}^{t} f(t')\mathrm{d}t' = v_i F(t)$$

Perfettini and Avouac, 2004a, *JGR*

Afterslip

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$$e^{c\delta}\dot{\delta} = v_i f(t) \qquad f(t) = \exp\left[\frac{t}{t_r} + \frac{\Delta\tau}{(a-b)\sigma_n}\mathrm{H}(t)\right] \qquad c = \frac{k}{(a-b)\sigma_n}$$

$$\int_{0^+}^{t} e^{c\delta}\dot{\delta}\mathrm{d}t' = v_i \int_{0^+}^{t} f(t')\mathrm{d}t' \;\; = v_i F(t) \qquad t_r = \frac{1}{cv_0} = \frac{(a-b)\sigma_n}{kv_0}$$

$$\parallel$$

$$\int_{0^+}^{t} e^{c\delta}\frac{\mathrm{d}\delta}{\mathrm{d}t'}\mathrm{d}t' \qquad \delta(t) = \frac{1}{c}\ln\left[1 + cv_i F(t)\right]$$

$$F(t) = \exp\left(\frac{\Delta\tau}{(a-b)\sigma_n}\right)\int_{0^+}^{t}\exp\left(\frac{t'}{t_r}\right)\mathrm{d}t' \;\; = \exp\left(\frac{\Delta\tau}{(a-b)\sigma_n}\right) t_r \exp\left(\frac{t'}{t_r}\right)\Bigg|_{0^+}^{t}$$

$$= \exp\left(\frac{\Delta\tau}{(a-b)\sigma_n}\right) t_r \left[\exp\left(\frac{t}{t_r}\right) - 1\right]$$

Perfettini and Avouac, 2004a, *JGR*

Afterslip

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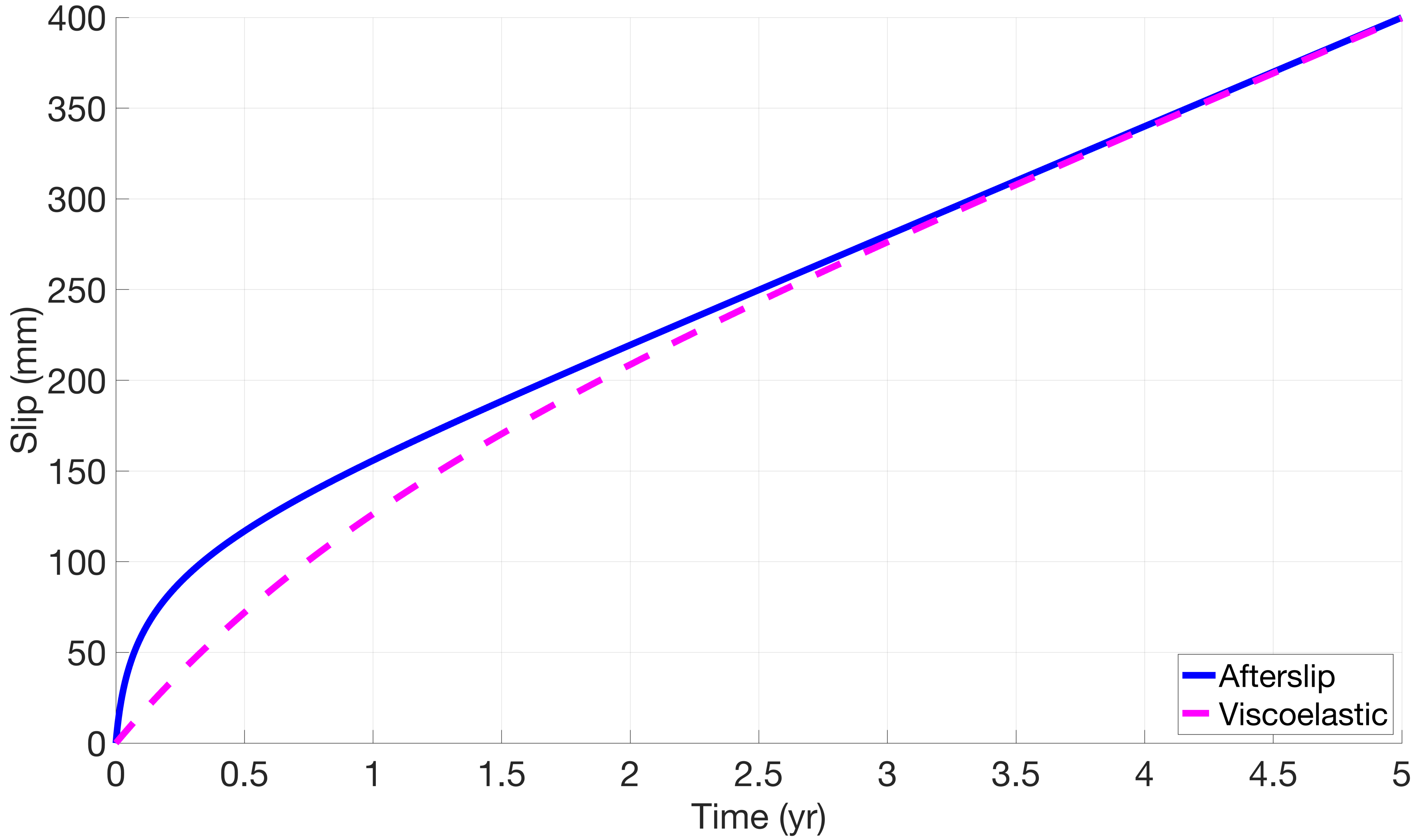
$$\delta(t) = \frac{1}{c}\ln\left[1+\frac{v_i}{v_0}\exp\left(\frac{\Delta\tau}{(a-b)\sigma_n}\right)\left(\exp\left(\frac{t}{t_r}\right)-1\right)\right]$$

$$c = \frac{k}{(a-b)\sigma_n}$$

$$t_r = \frac{1}{cv_0} = \frac{(a-b)\sigma_n}{kv_0}$$

Perfettini and Avouac, 2004a, *JGR*

Viscoelastic Relaxation vs Afterslip



Viscoelastic Relaxation vs Afterslip

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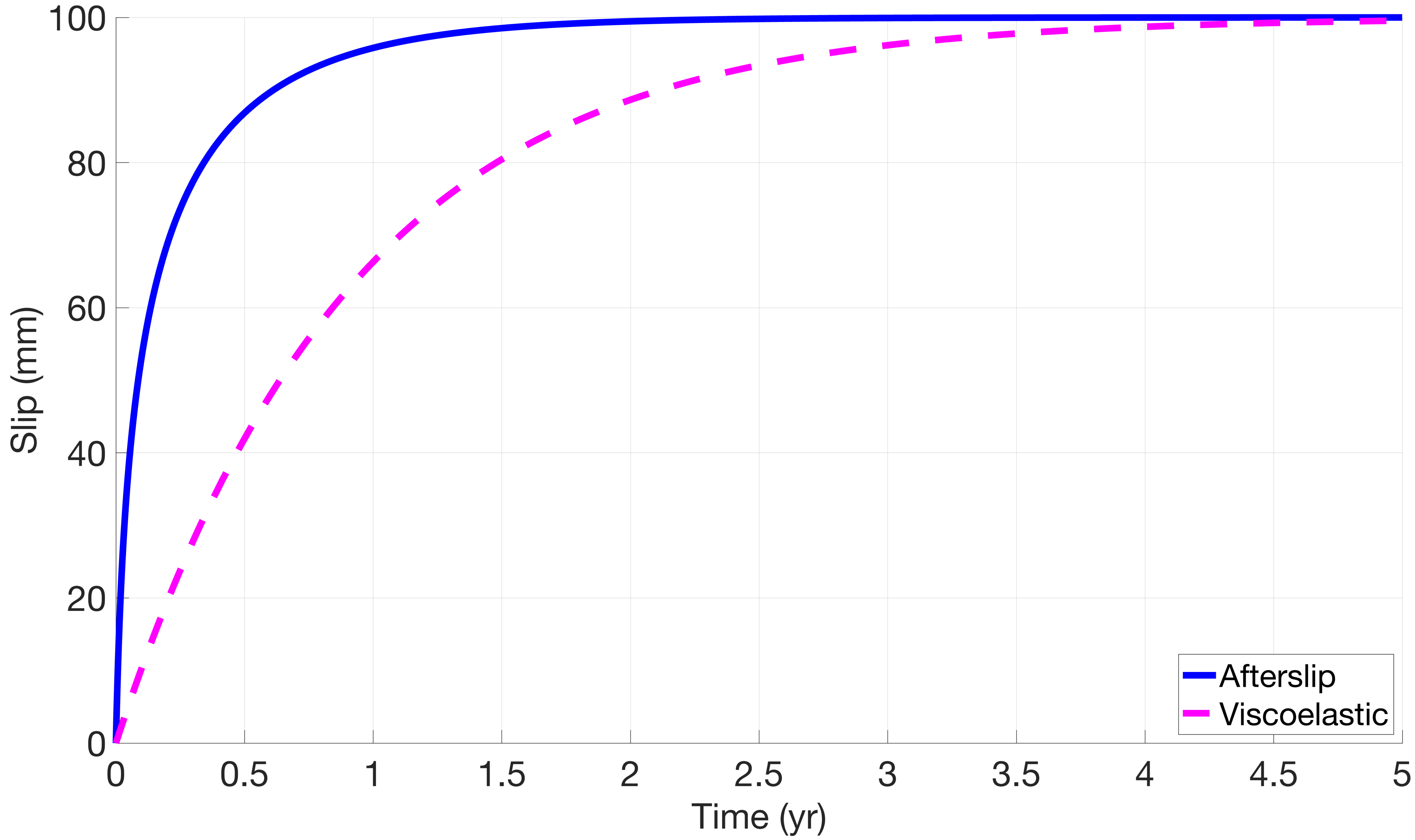

Independent Component Analysis

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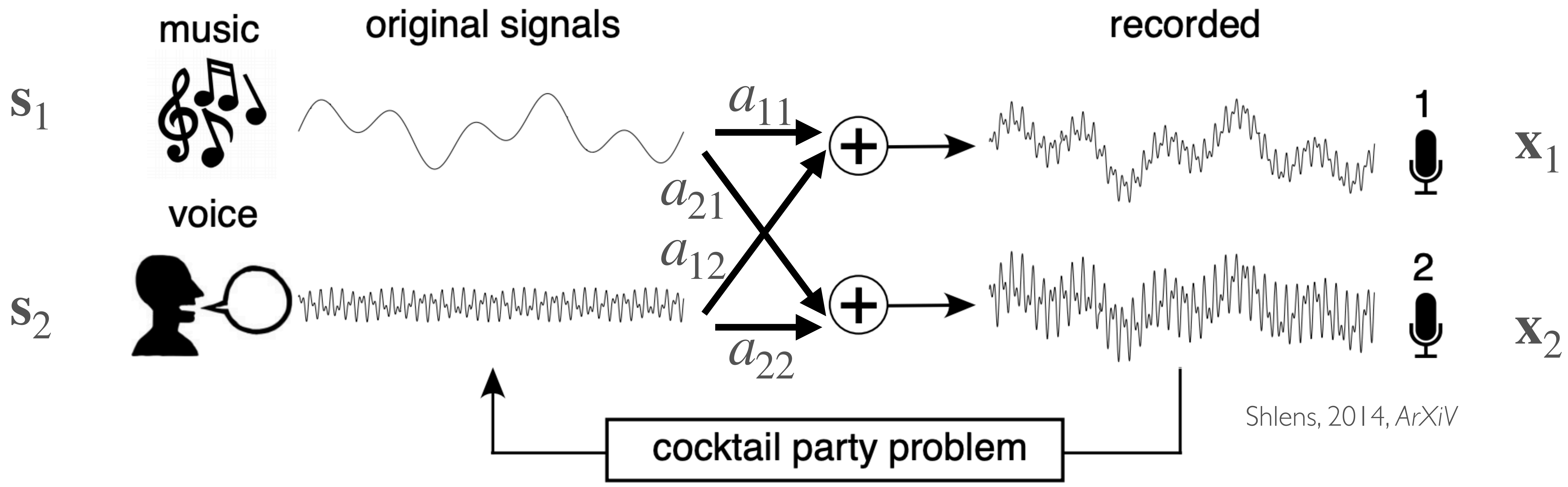
How can we disentangle two sources ?



Shlens, 2014, *ArXiV*

$X = AS$ $\mathbf{s}_1$ and $\mathbf{s}_2$ are independent

Viscoelastic Relaxation vs Afterslip

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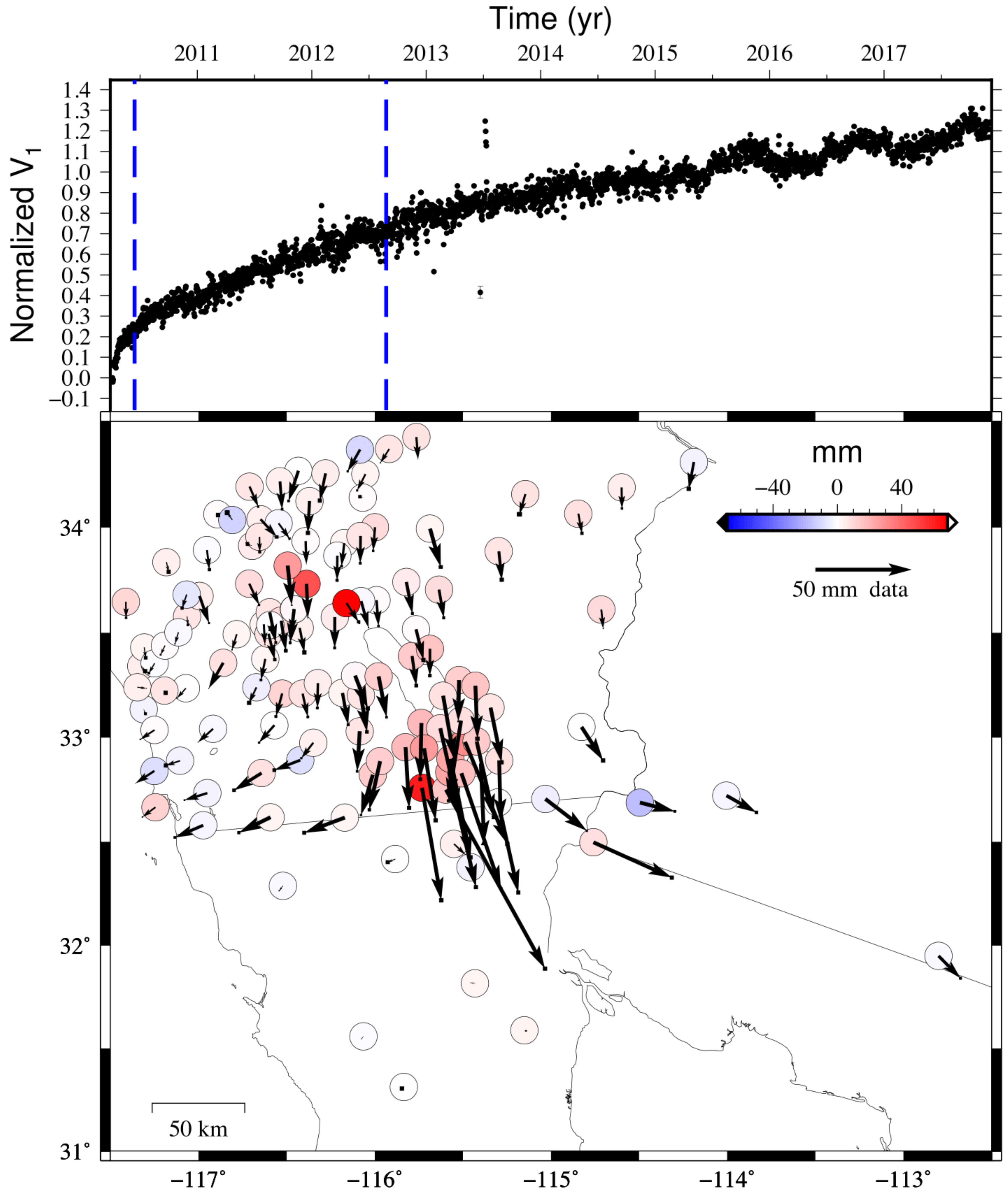

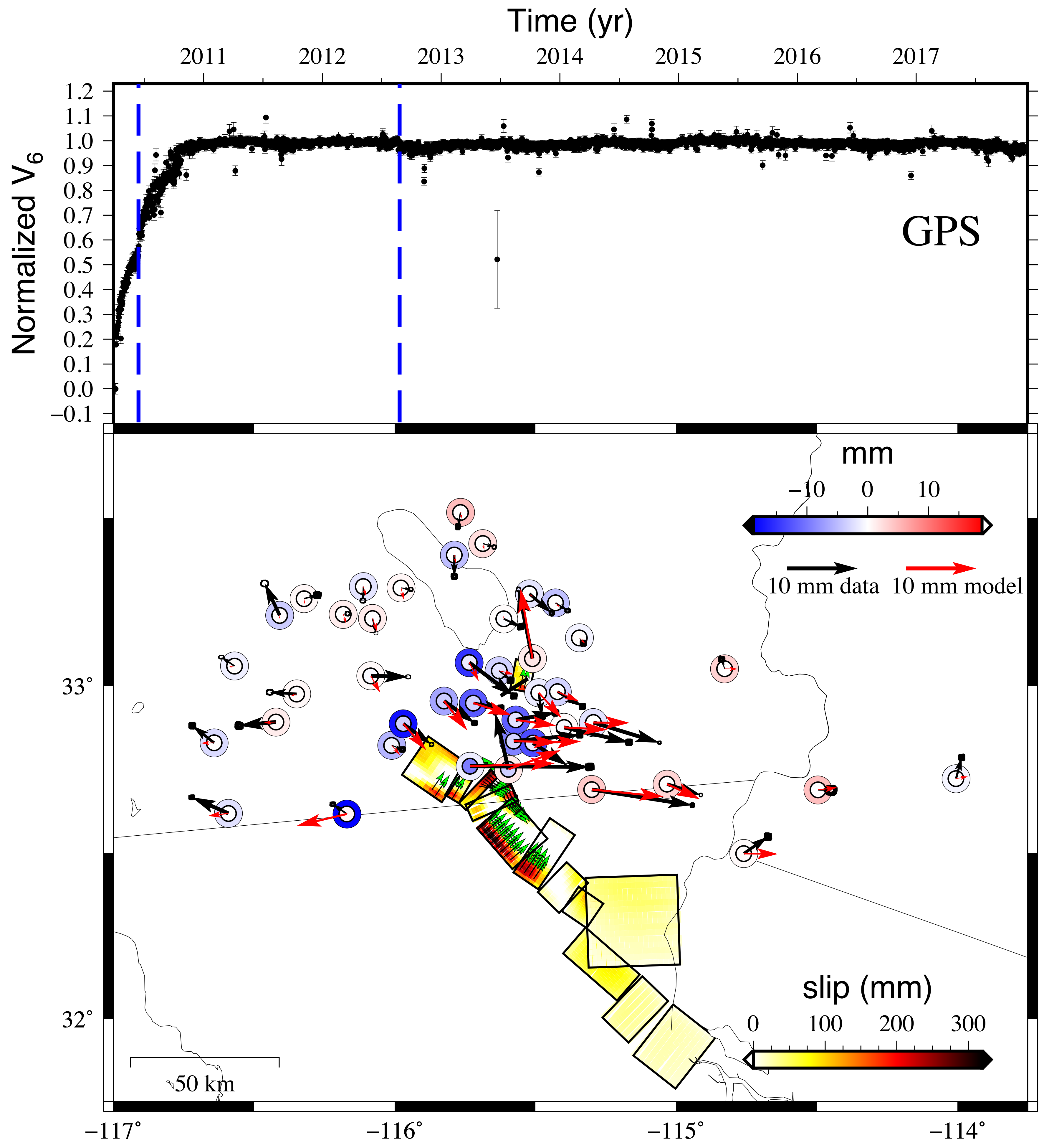

Gualandi et al., 2020a, *EPSL*

Post-Seismic Deformation

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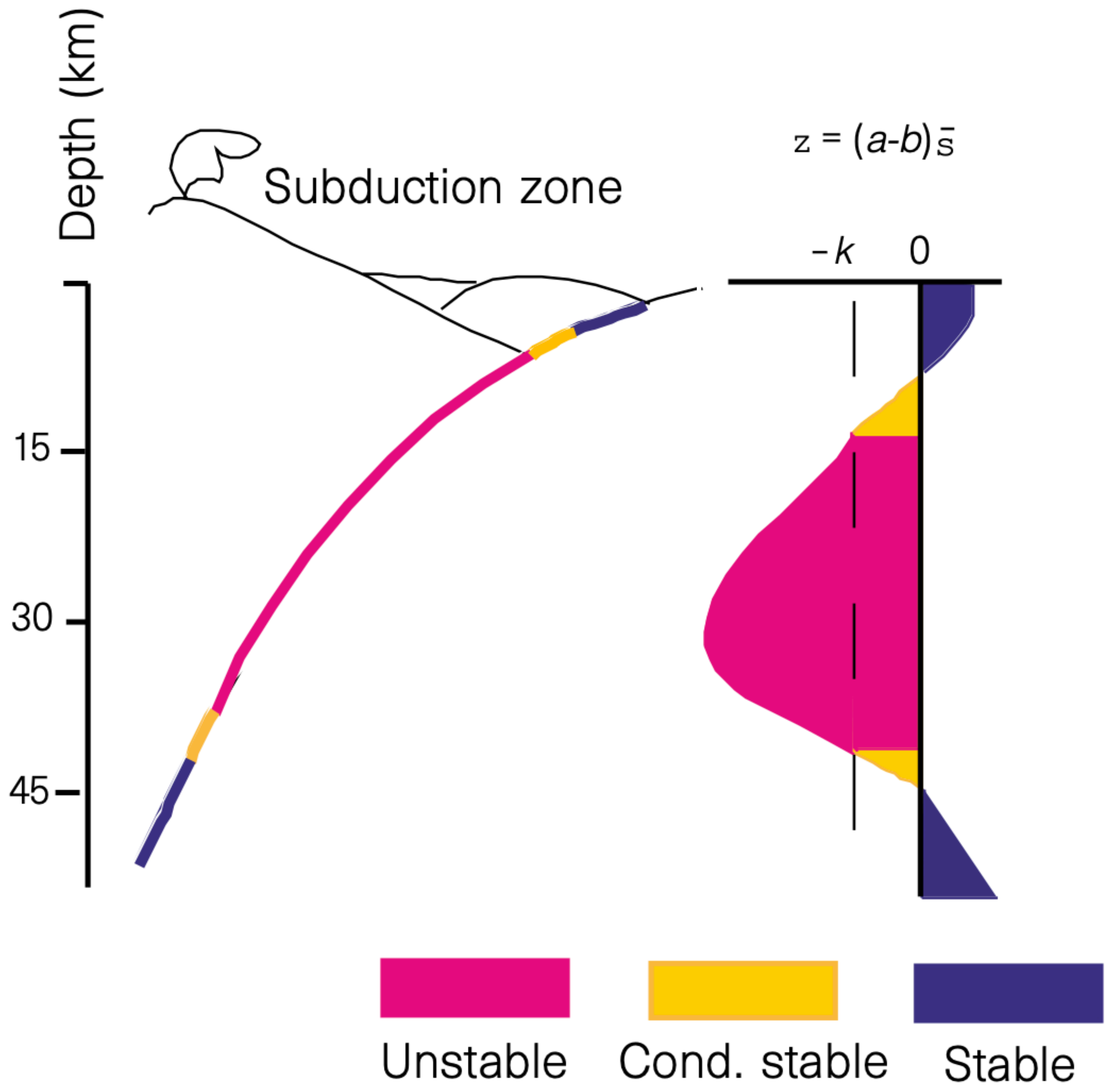

$$\tau_f = \sigma_n \mu = \sigma_n \left[\mu_0 + a \ln \frac{v}{v_*} + b \ln \frac{v_* \theta}{L} \right]$$

Dieterich, 1979, *JGR*

Scholz, 1998, *Nature*

Afterslip

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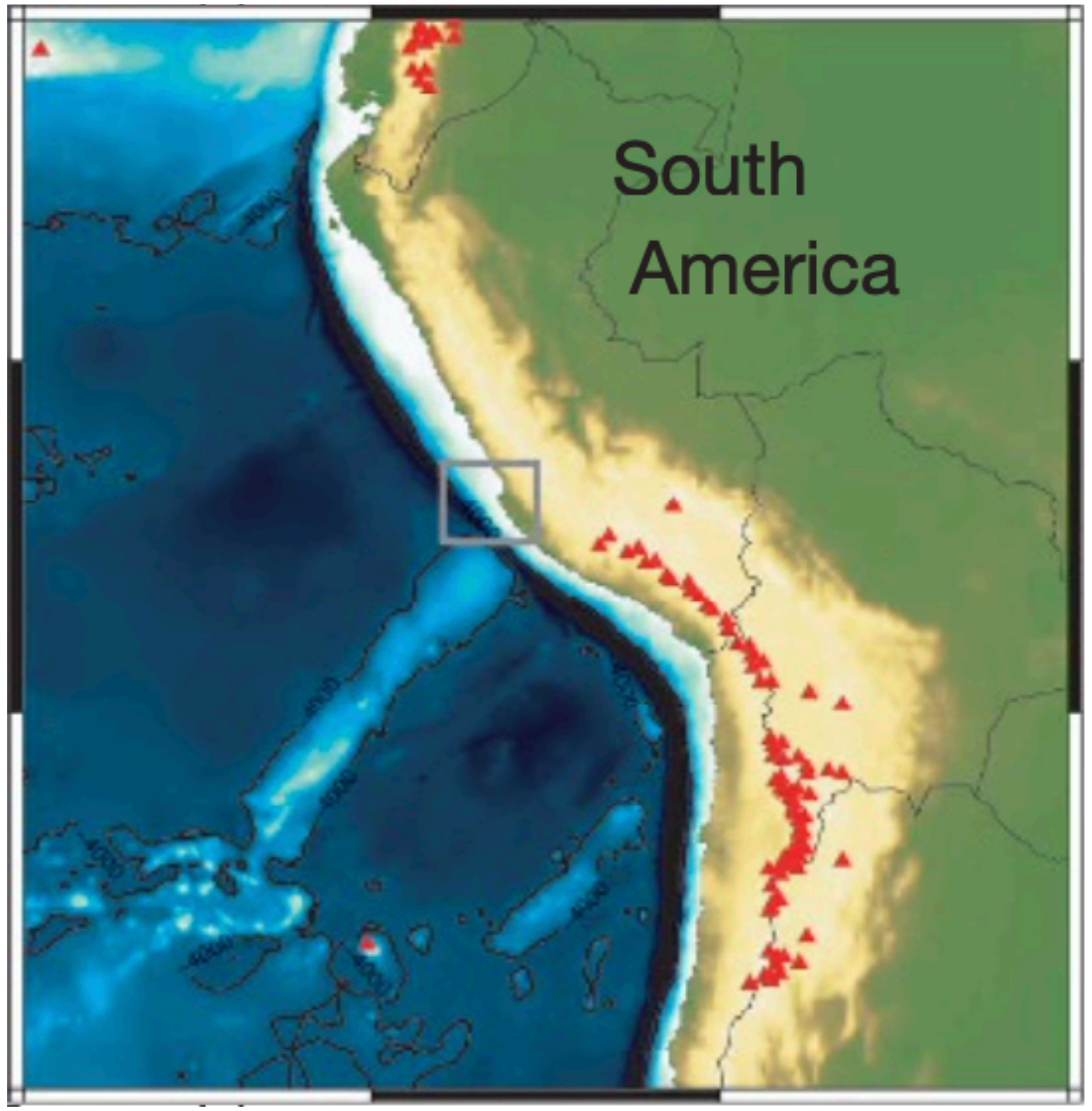
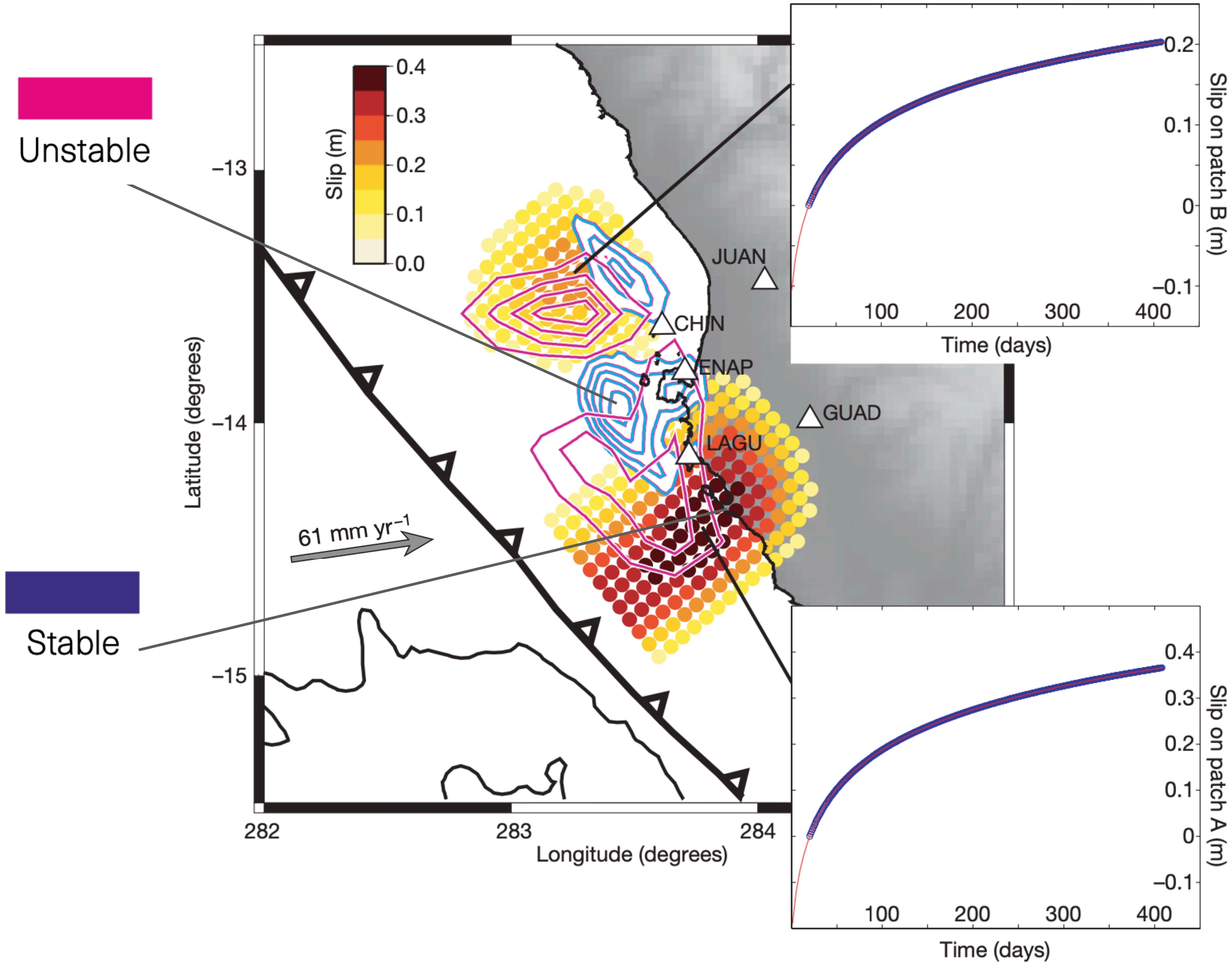
subduction



$M_w 8.0$ Pisco earthquake (2007)



Perfettini et al., 2010, *Nature*

Fault Heterogeneities

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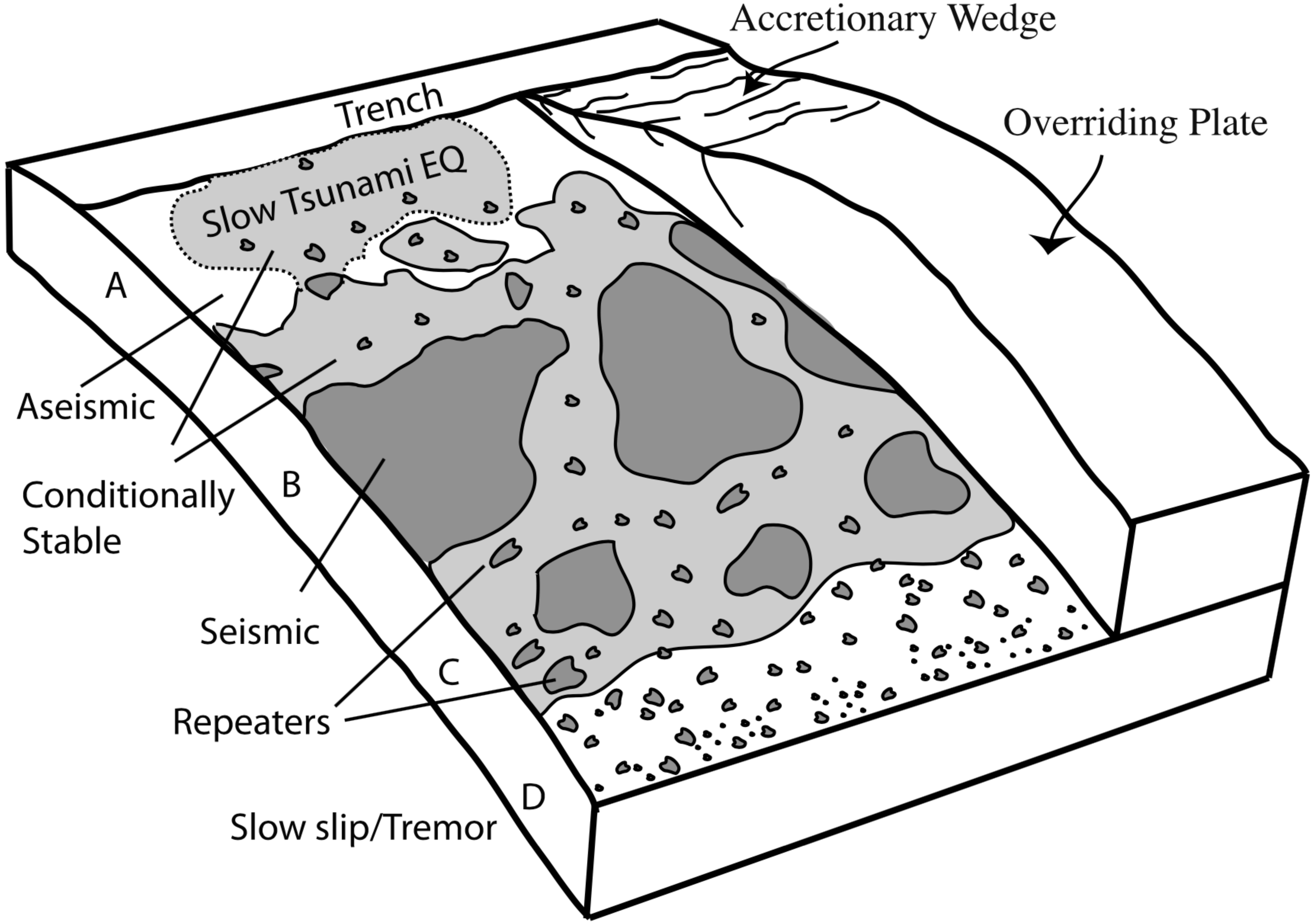

Lay et al., 2012, *JGR*.

Slow Slip Events

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Animation credit: Eric Vantroyen, Sylvain Michel, Adriano Gualandi, Jean-Philippe Avouac

Conclusions

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Kinematics

- Lower misfit with observations
- Useful for seismic hazard
- We can retrieve rheological parameters
- Can provide insights on the dynamics

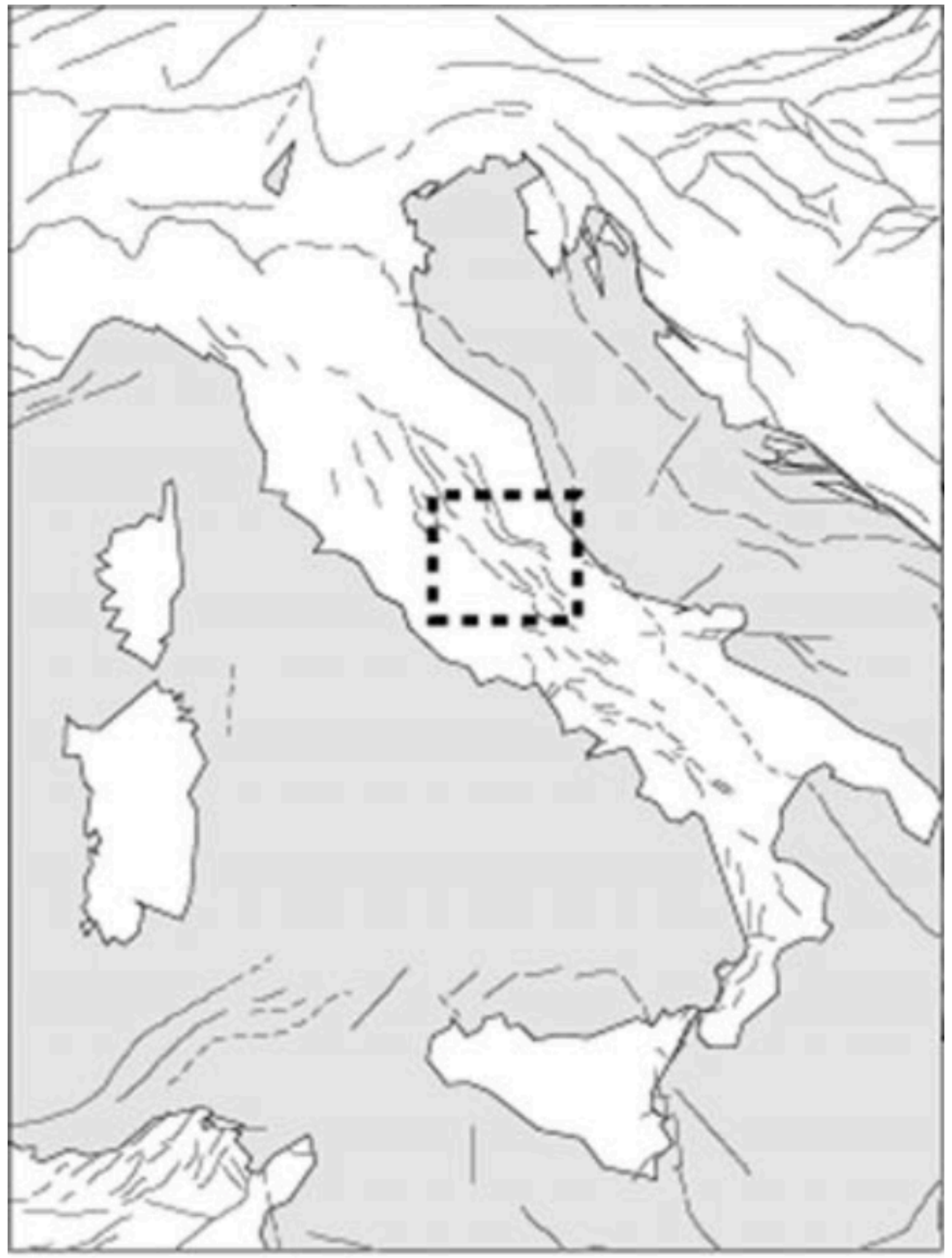
Dynamics

- Higher misfit with observations
- Physical laws, not only geometrical constraints
- Typically uses estimated rheological parameters
- Insights into multiple cycles

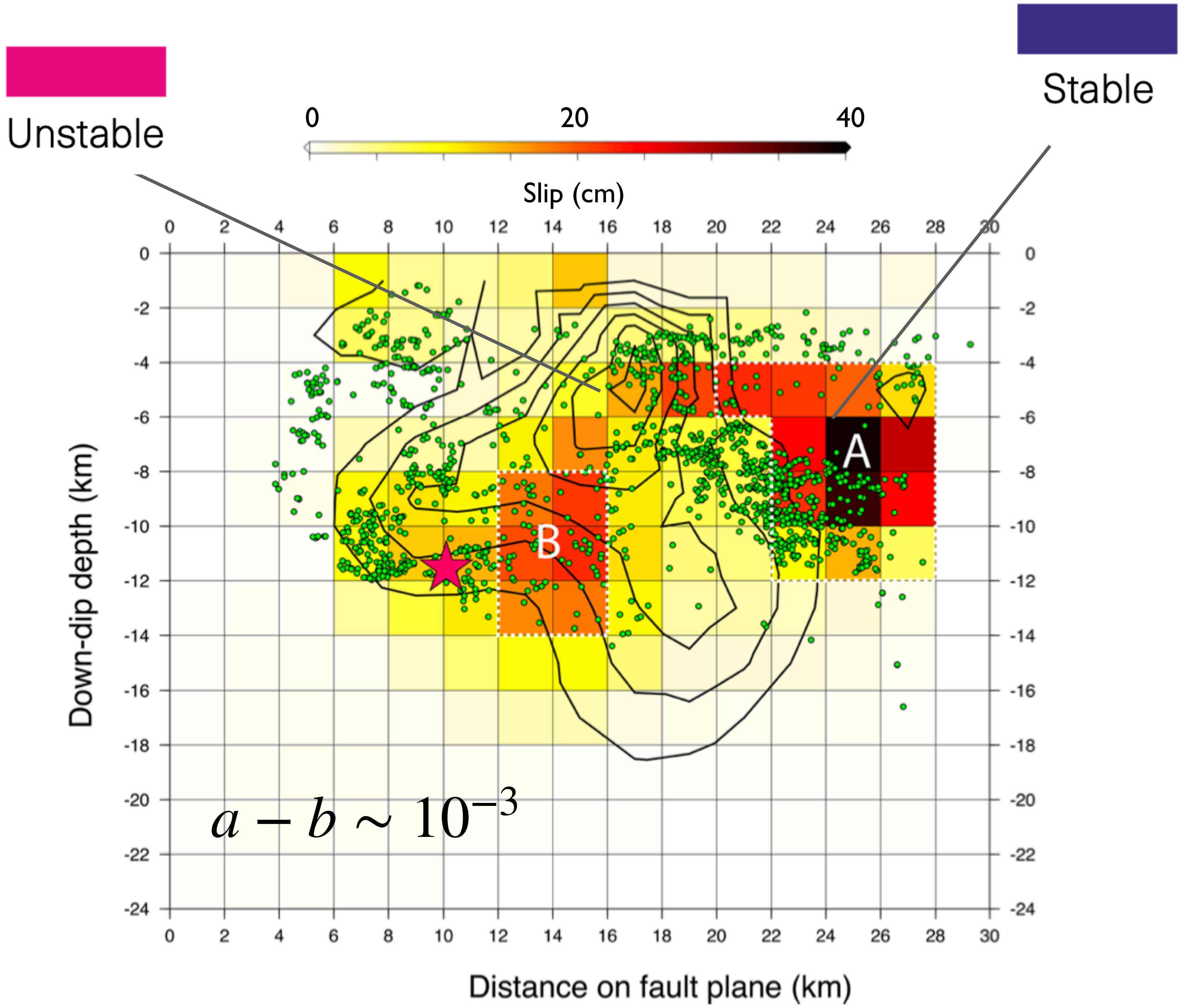
Extra Slides

Afterslip

intraplate



M_w6.3 L'Aquila earthquake (2009)



Gualandi et al., 2014, *GJI*

Strain Polygon

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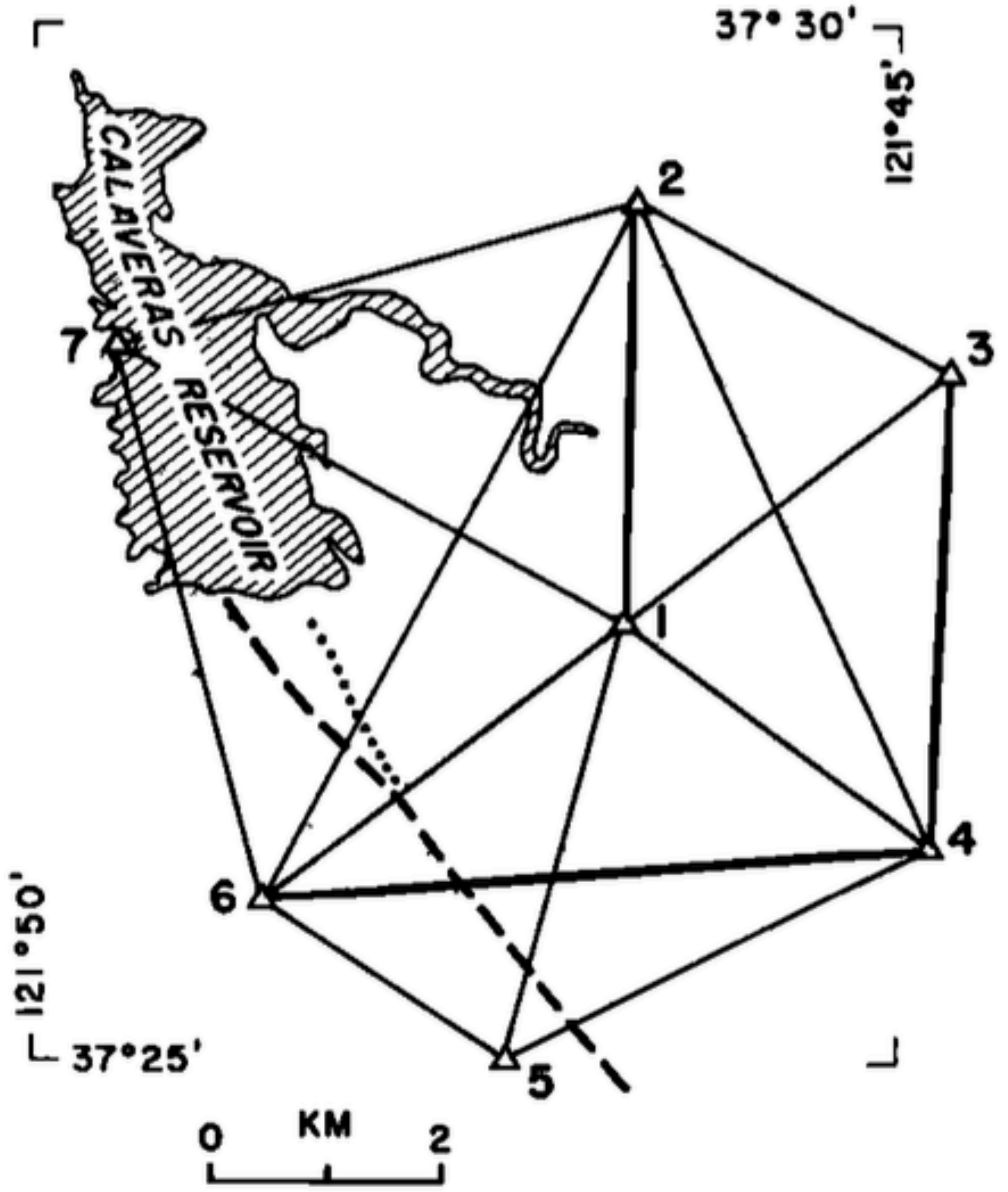
Trilateration network along San Andreas fault surveyed annually



Savage and Prescott, 1973, *JGR*

$$3 \text{ mm} \leq \sigma \leq 8 \text{ mm}$$

for

$$1 \text{ km} \leq L \leq 37 \text{ km}$$

with corrections for atmospheric refractivity (aircraft measures of T and p)

Strain Rate Field

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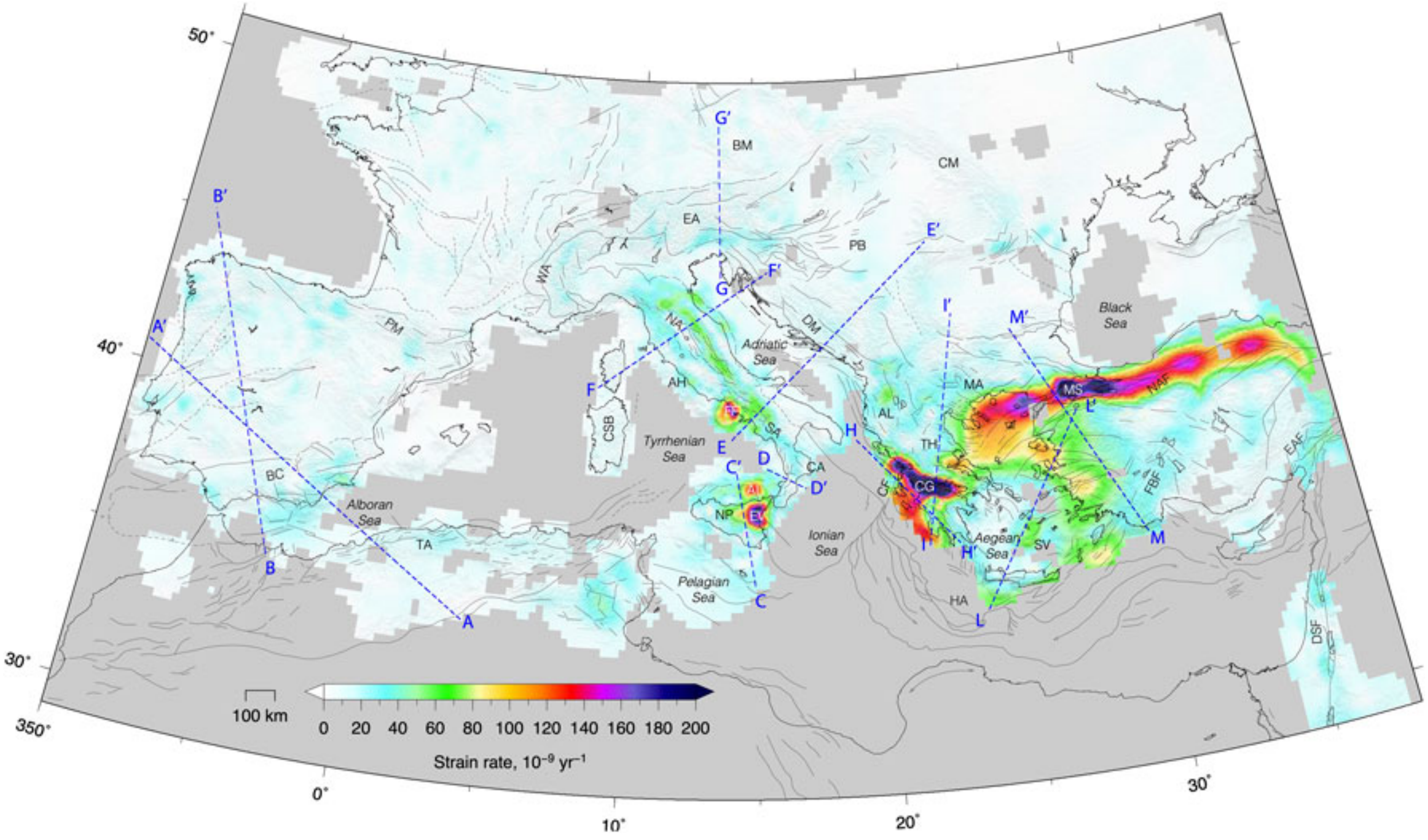

Serpelloni et al, 2022, *Front. Earth Sci.*

Mantle Dynamics

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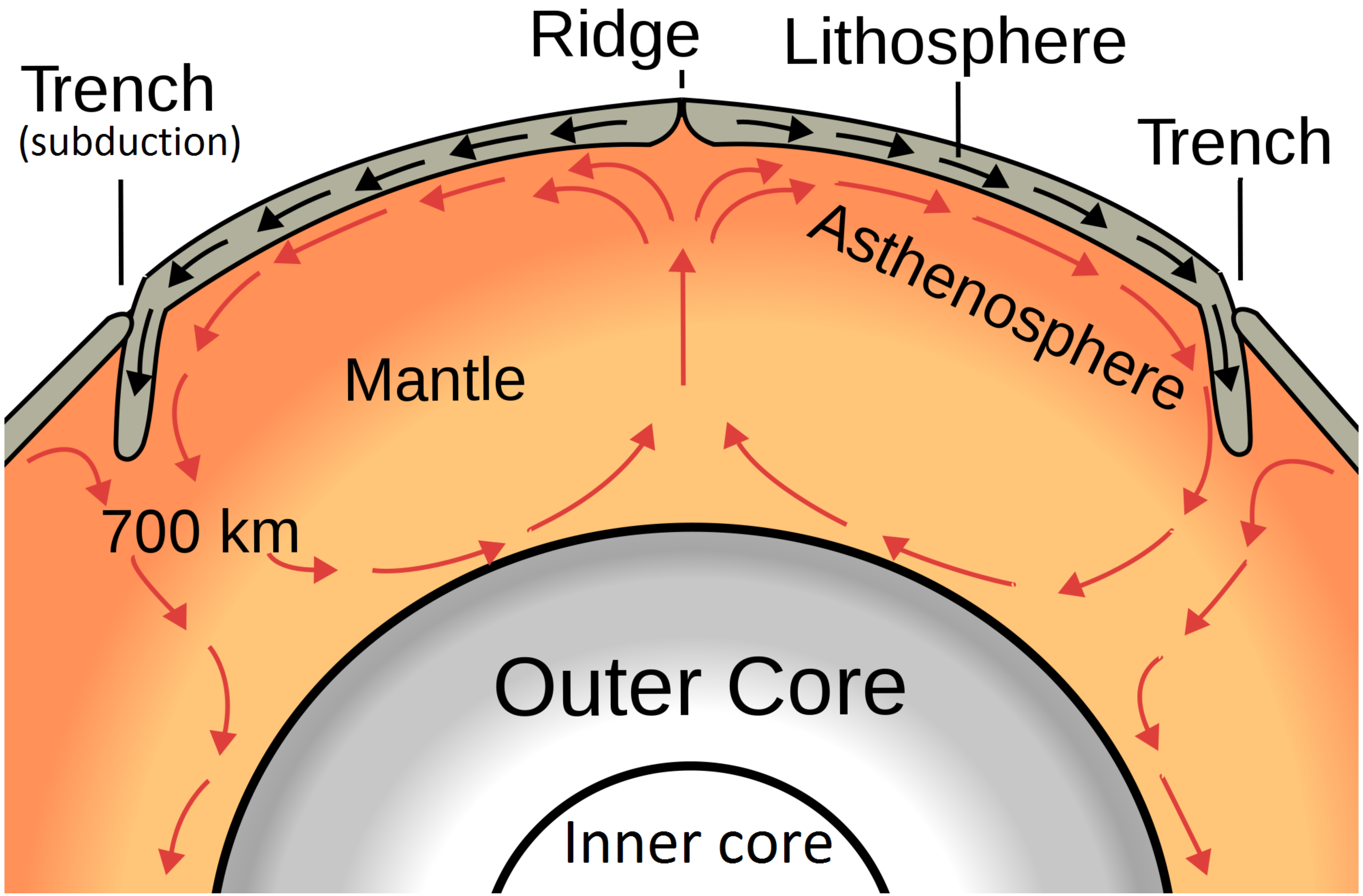

openeducationalberta.ca

Afterslip

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$$\delta(t) \overset{t \ll t_r}{\simeq} \frac{1}{c} \ln \left[1 + \frac{v_i}{v_0} \exp\left(\frac{\Delta\tau}{(a-b)\sigma_n} \right) \left(\cancel{1} + \frac{t}{t_r} \cancel{-1} \right) \right]$$

$$= \frac{1}{c} \ln \left[1 + \frac{v_i}{v_0} \frac{1}{t_r} \exp\left(\frac{\Delta\tau}{(a-b)\sigma_n} \right) t \right] = \frac{1}{c} \ln \left[1 + \frac{t}{t_{as}} \right]$$

$$c = \frac{k}{(a-b)\sigma_n}$$

$$t_r = \frac{1}{c v_0} = \frac{(a-b)\sigma_n}{k v_0}$$

$$\delta(t) \simeq v_0 t_r \ln\left(1 + \frac{t}{t_{as}} \right)$$

$$t_{as} = \frac{v_0 t_r}{v_i} \exp\left(-\frac{\Delta\tau}{(a-b)\sigma_n} \right)$$

Perfettini and Avouac, 2004a, *JGR*

Daily GNSS Position Time Series

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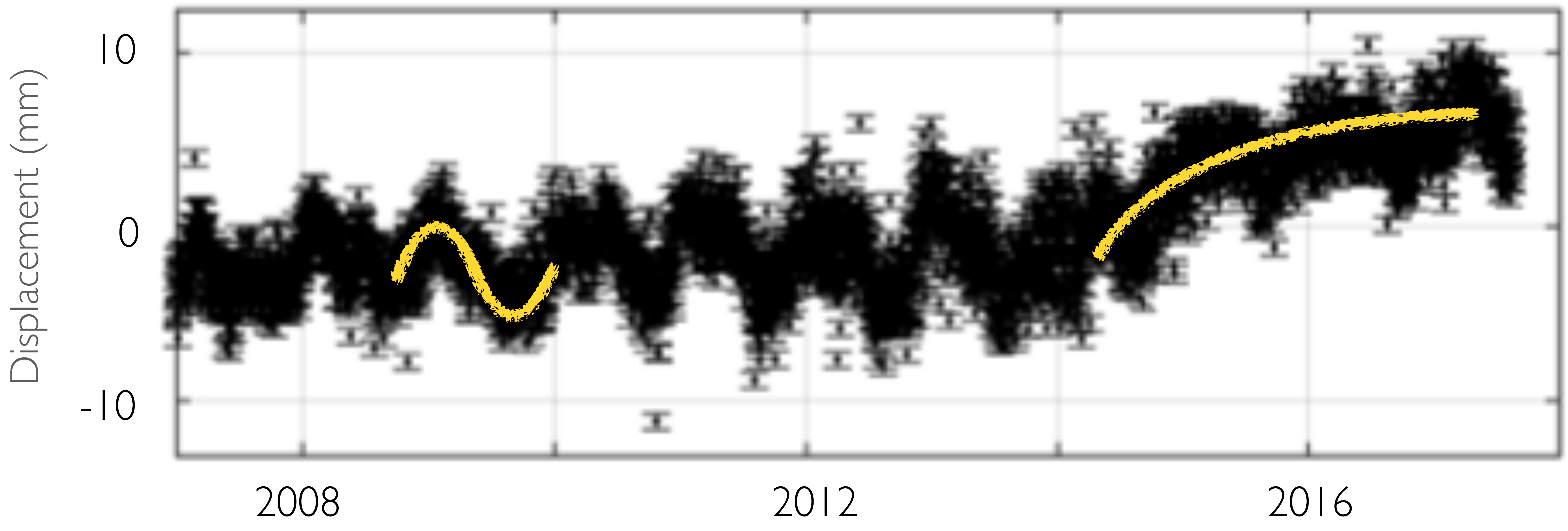
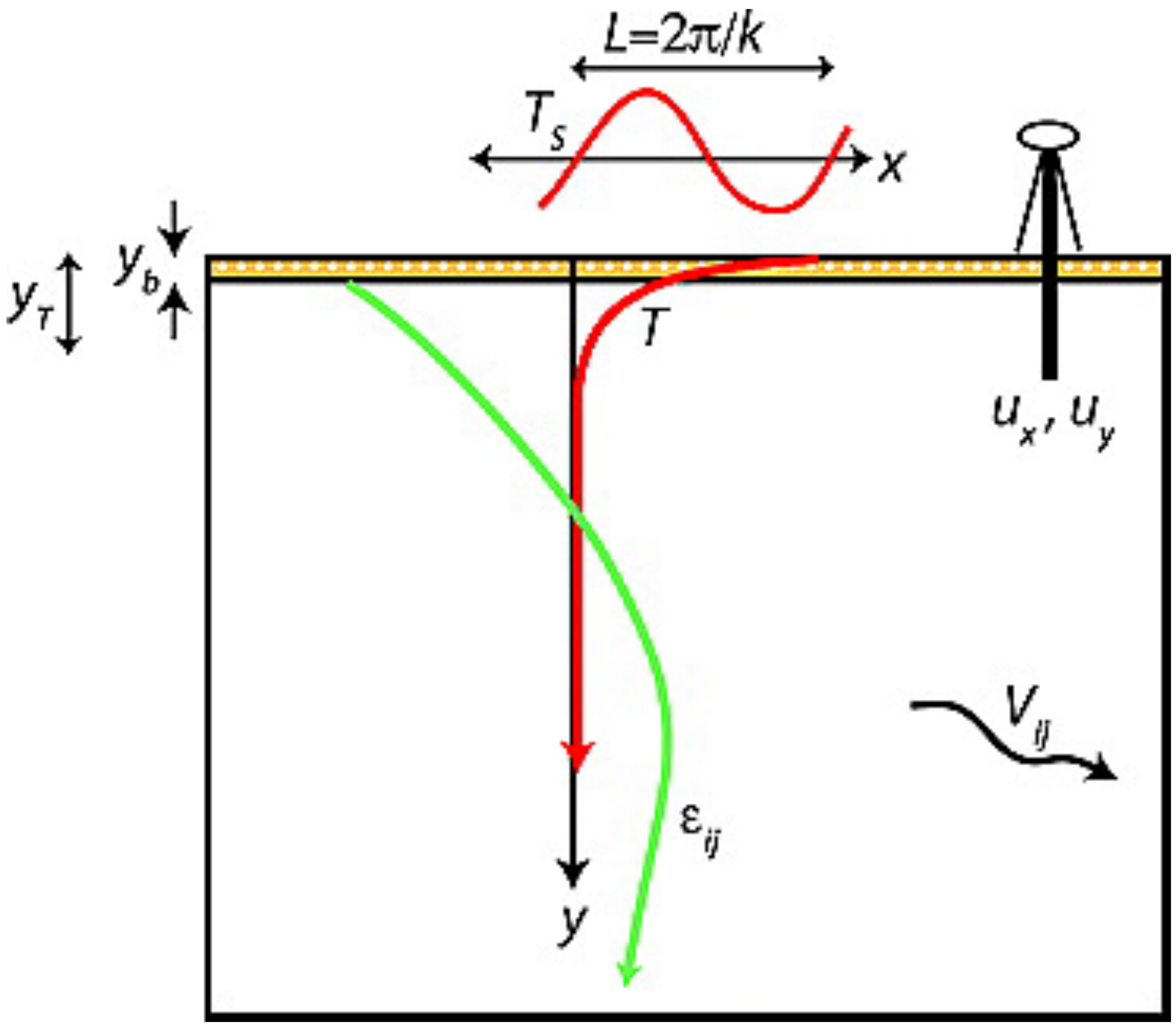
What can generate oscillations ?

$$x(t) = x_{\text{linear}}(t) + x_{\text{offsets}}(t) + x_{\text{post-seismic}}(t) + x_{\text{seasonal}}(t)$$



Michel et al., 2019a, *PAGEOPH*

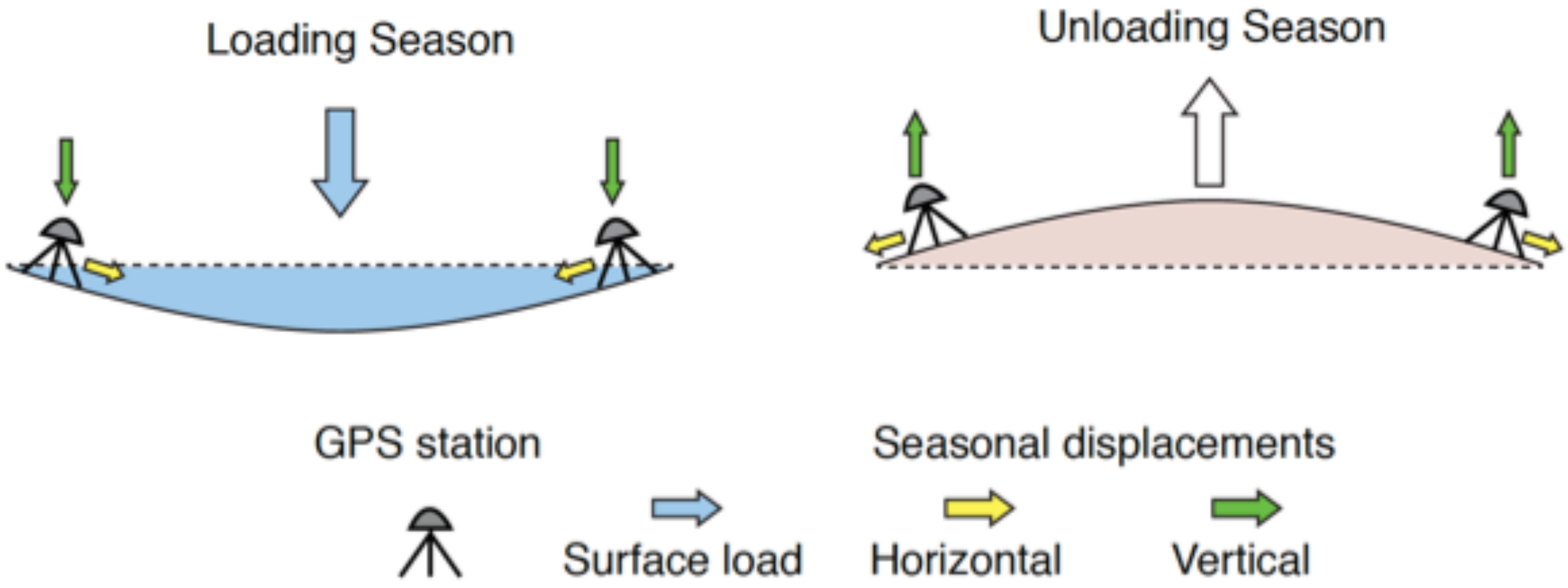
Thermal Dilation



competent layer

Tsai, 2011, *JGR*

Hydrological Load



Bettinelli et al., 2008, *EPSL*
Chanard et al., 2015, *JGR*

Daily GNSS Position Time Series

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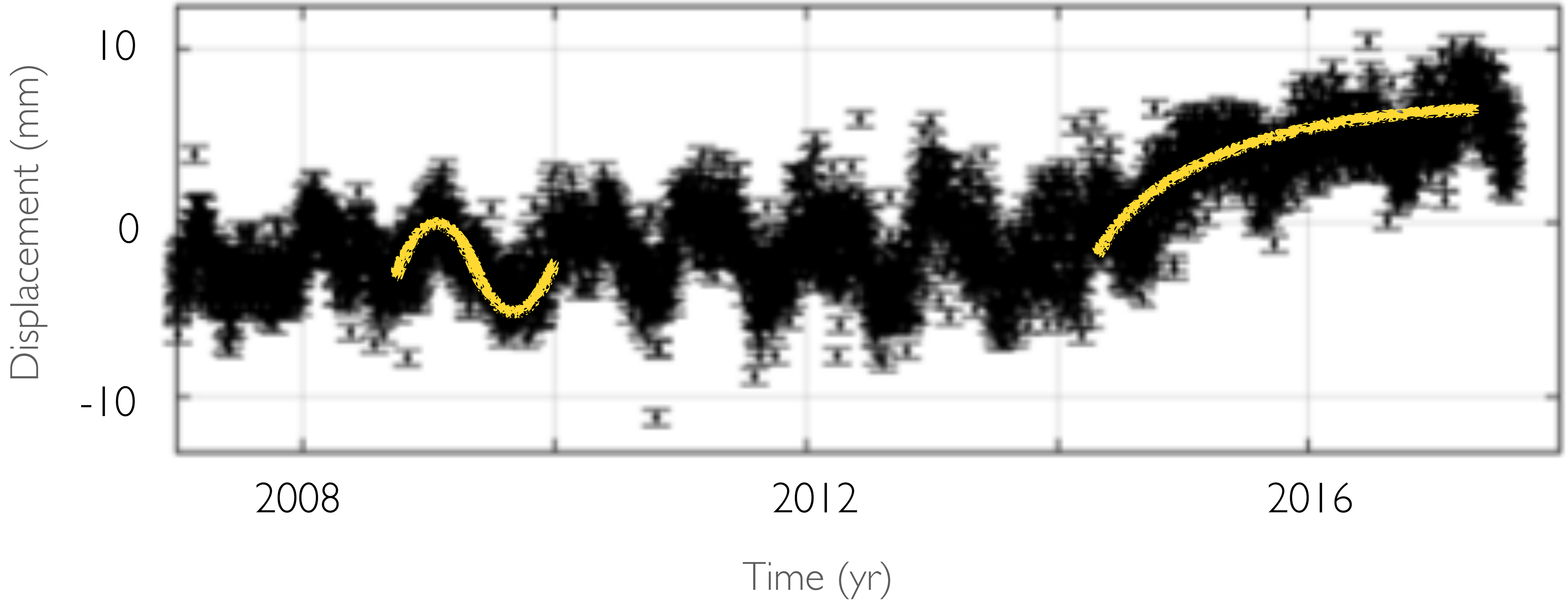
Other sources of deformation ?

$$x(t) = x_{\text{linear}}(t) + x_{\text{offsets}}(t) + x_{\text{post-seismic}}(t) + x_{\text{seasonal}}(t) + ?$$



Michel et al., 2019a, *PAGEOPH*

Pore Pressure Variations

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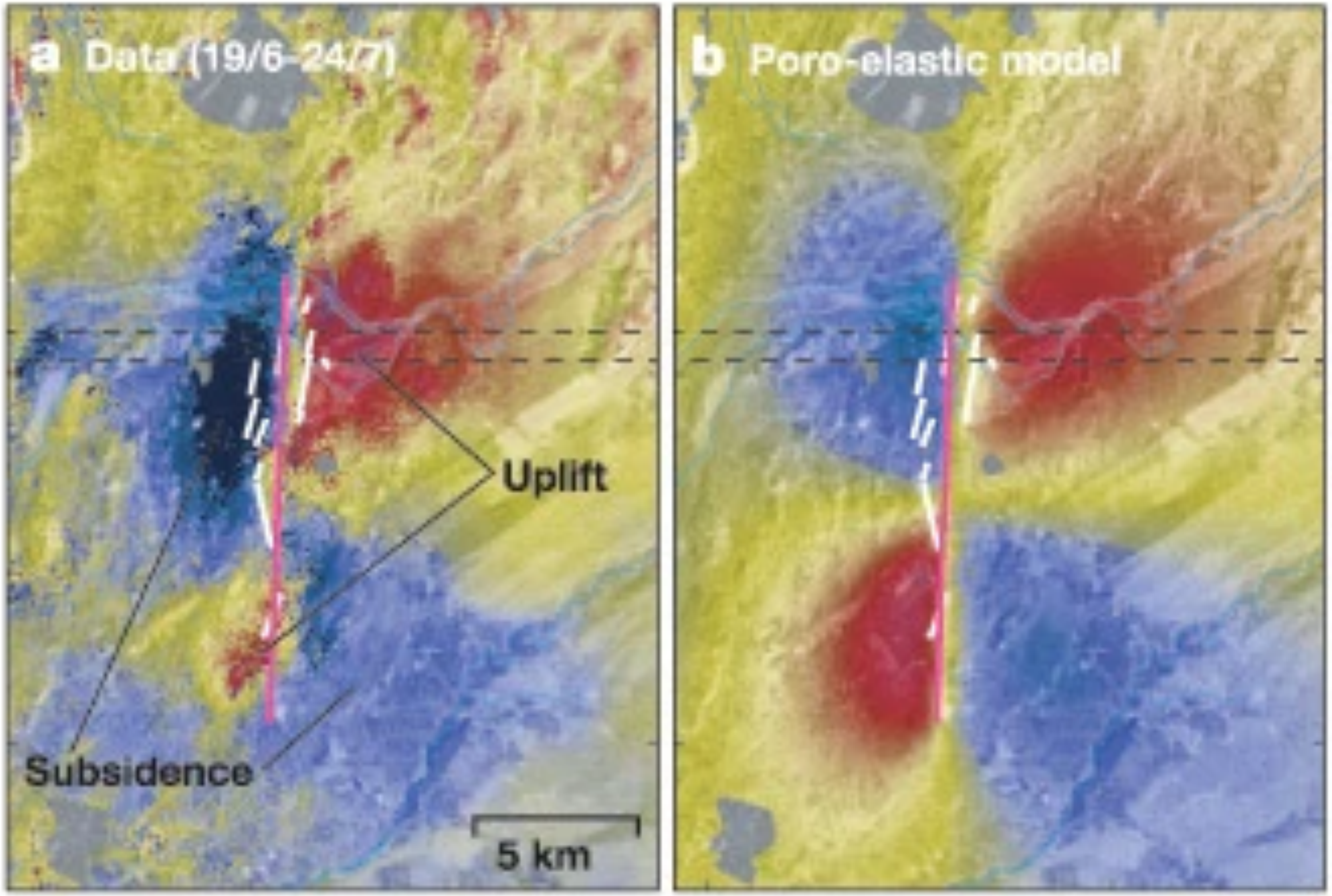
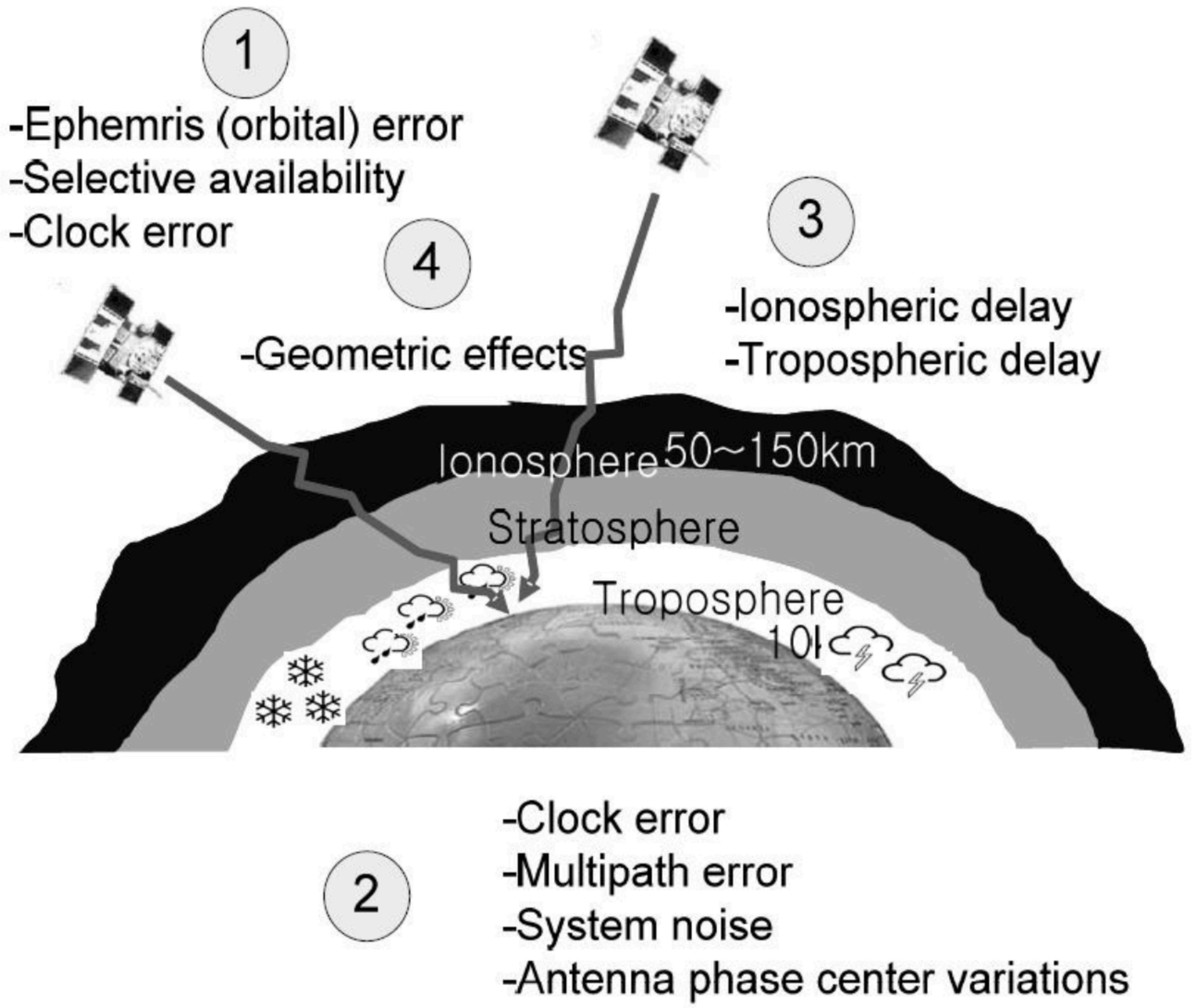


Jónsson et al., 2003, *Nature*

Errors



Jeong et al., 2007, *J. Astron. Space Sci.*

Slow Slip Events

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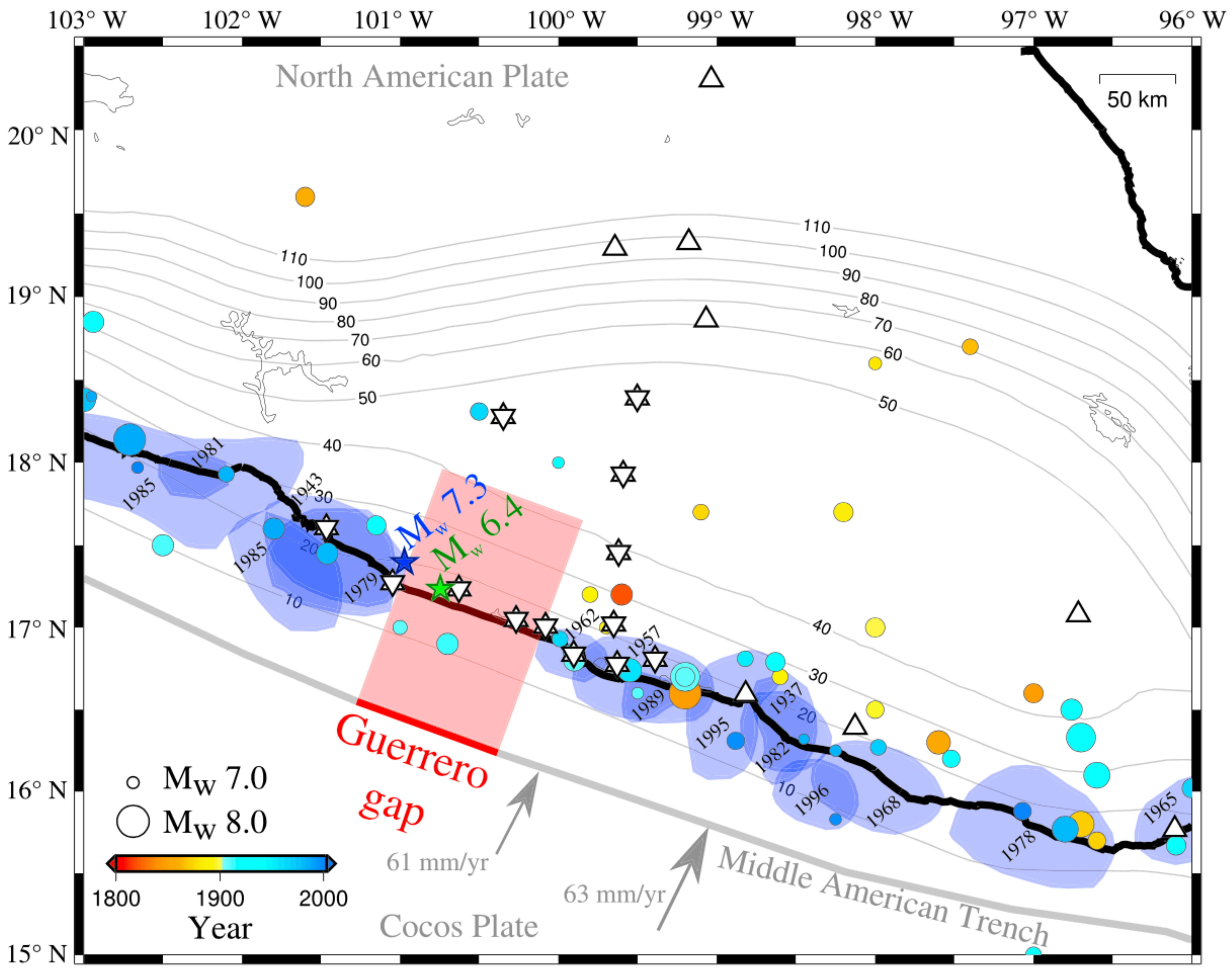

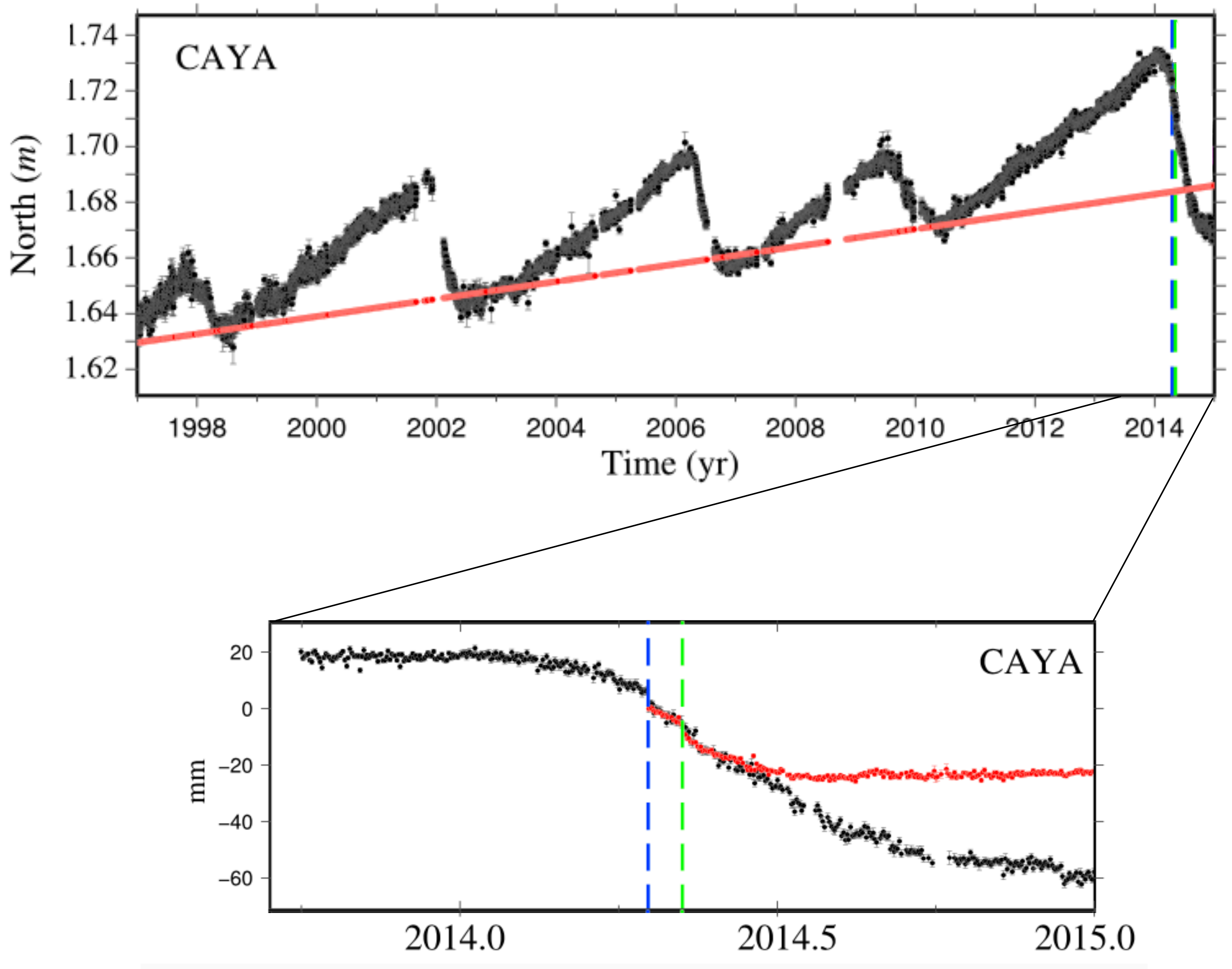

★ Mainshock ($M_w = 7.3$)

★ Largest aftershock ($M_w = 6.4$)

Gualandi et al., 2017b, *GRL*

Slow Slip Events

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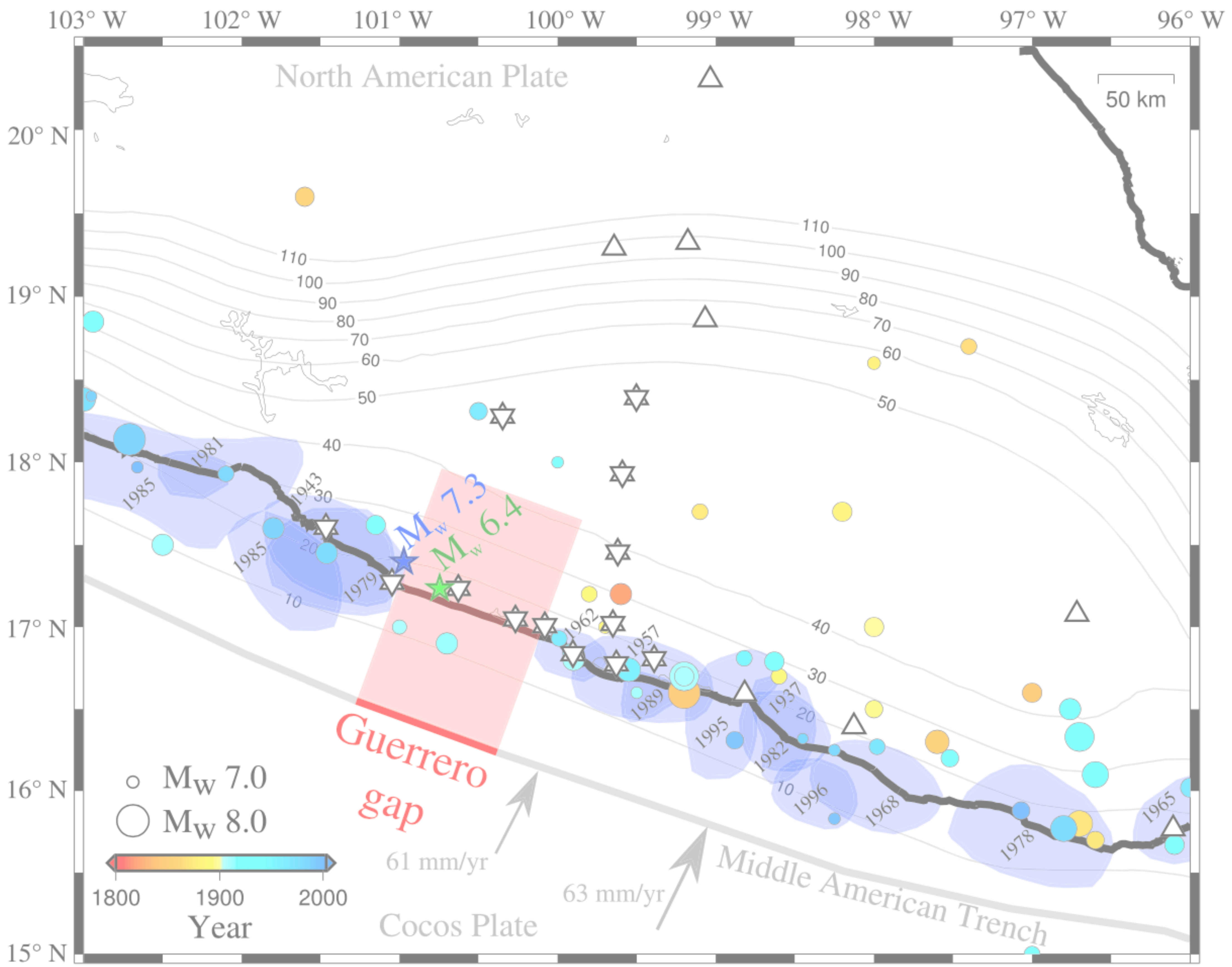

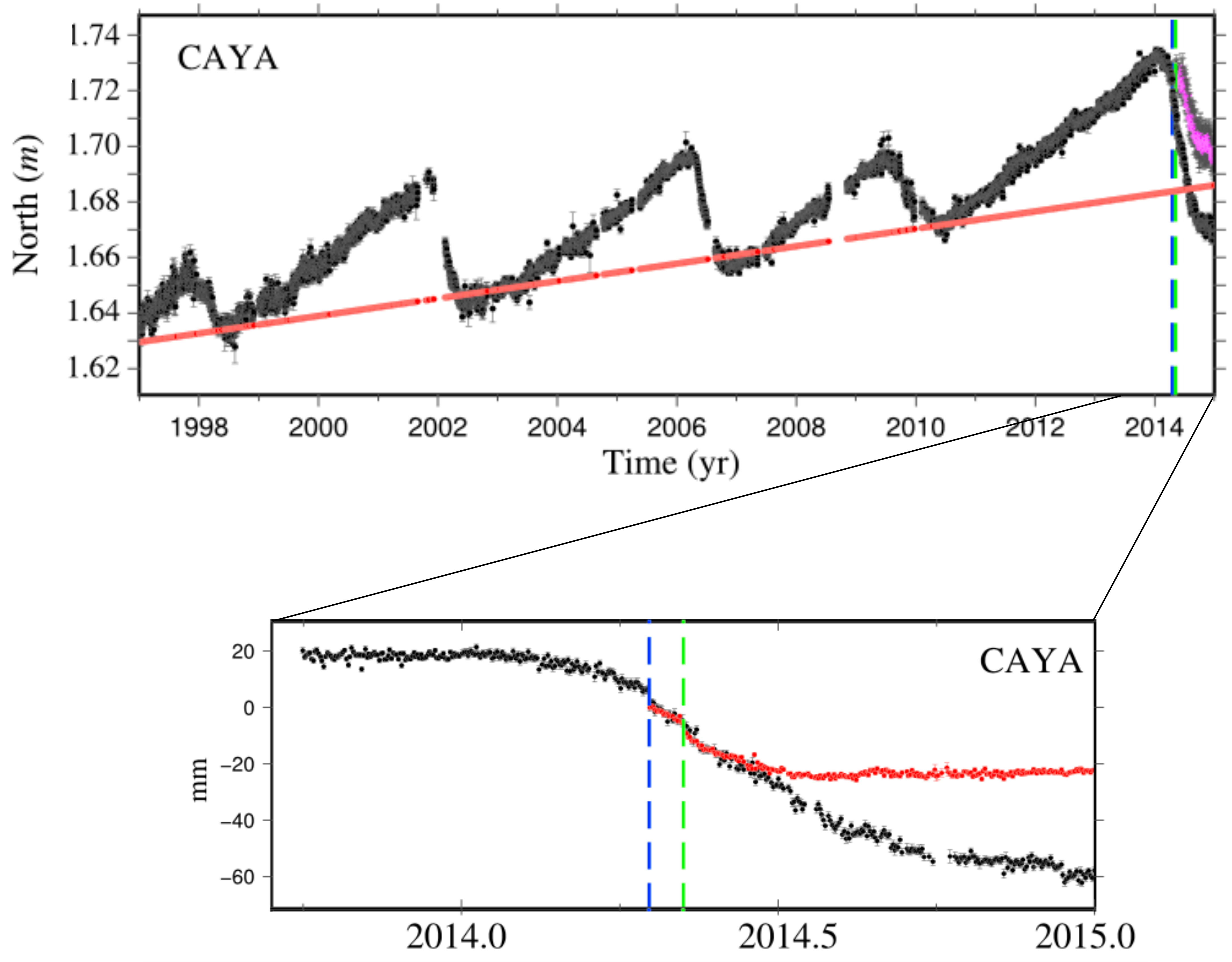

★ Mainshock ($M_w = 7.3$)

★ Largest aftershock ($M_w = 6.4$)

Gualandi et al., 2017b, *GRL*

Slow Slip Events

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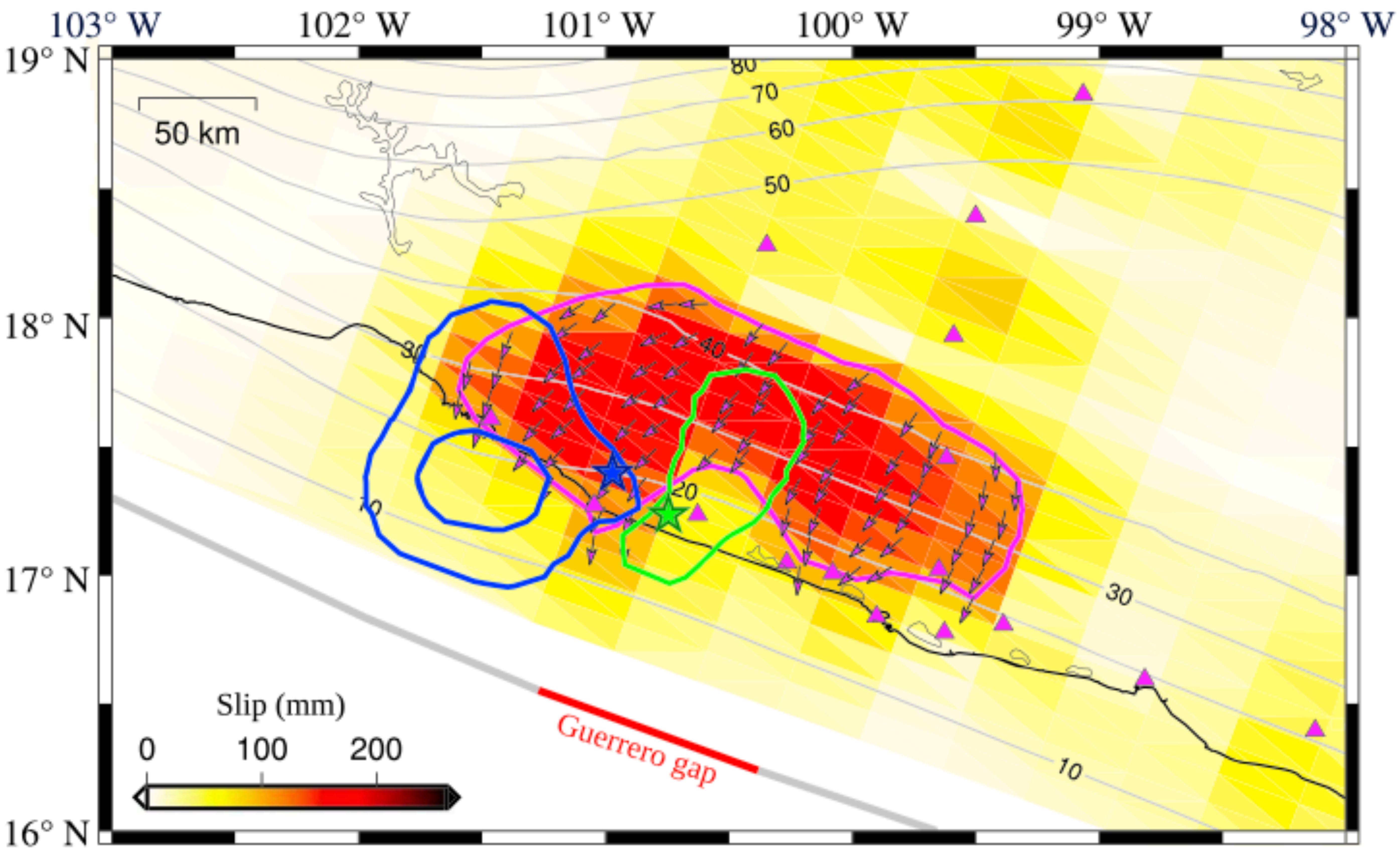
co-seismic

post-seismic

slow-slip



Gualandi et al., 2017b, *GRL*

Kinematics of Slow Earthquakes

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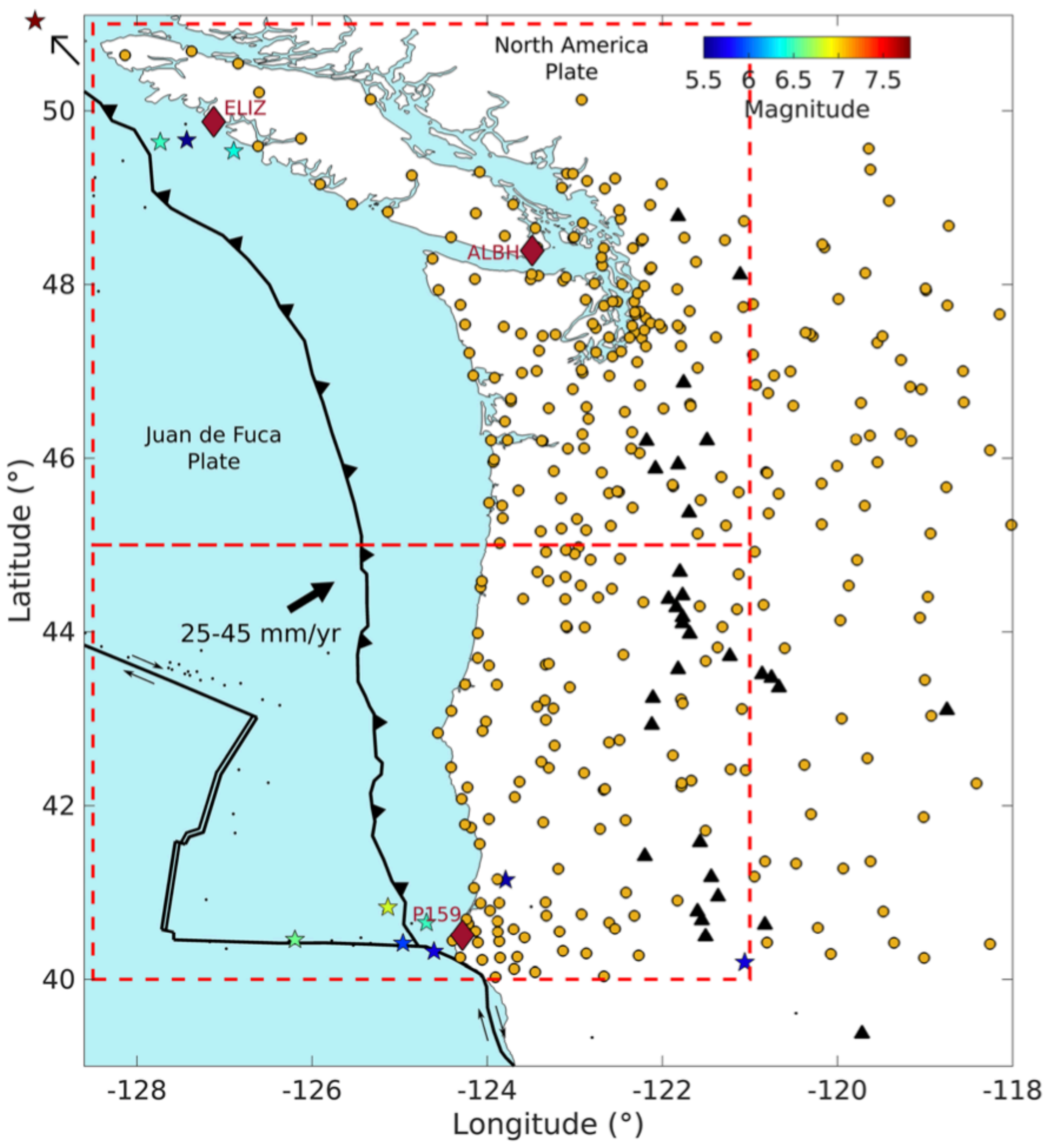
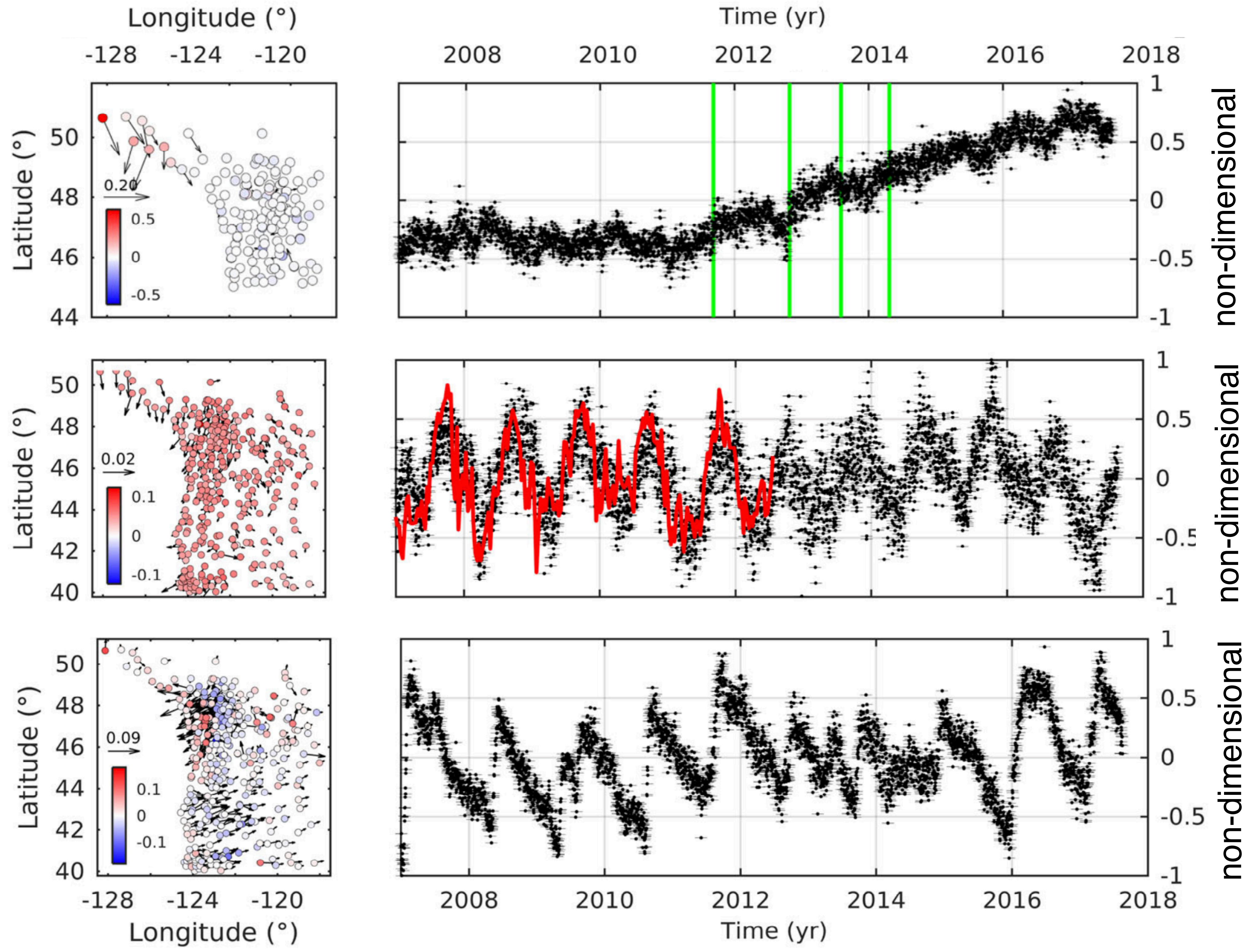
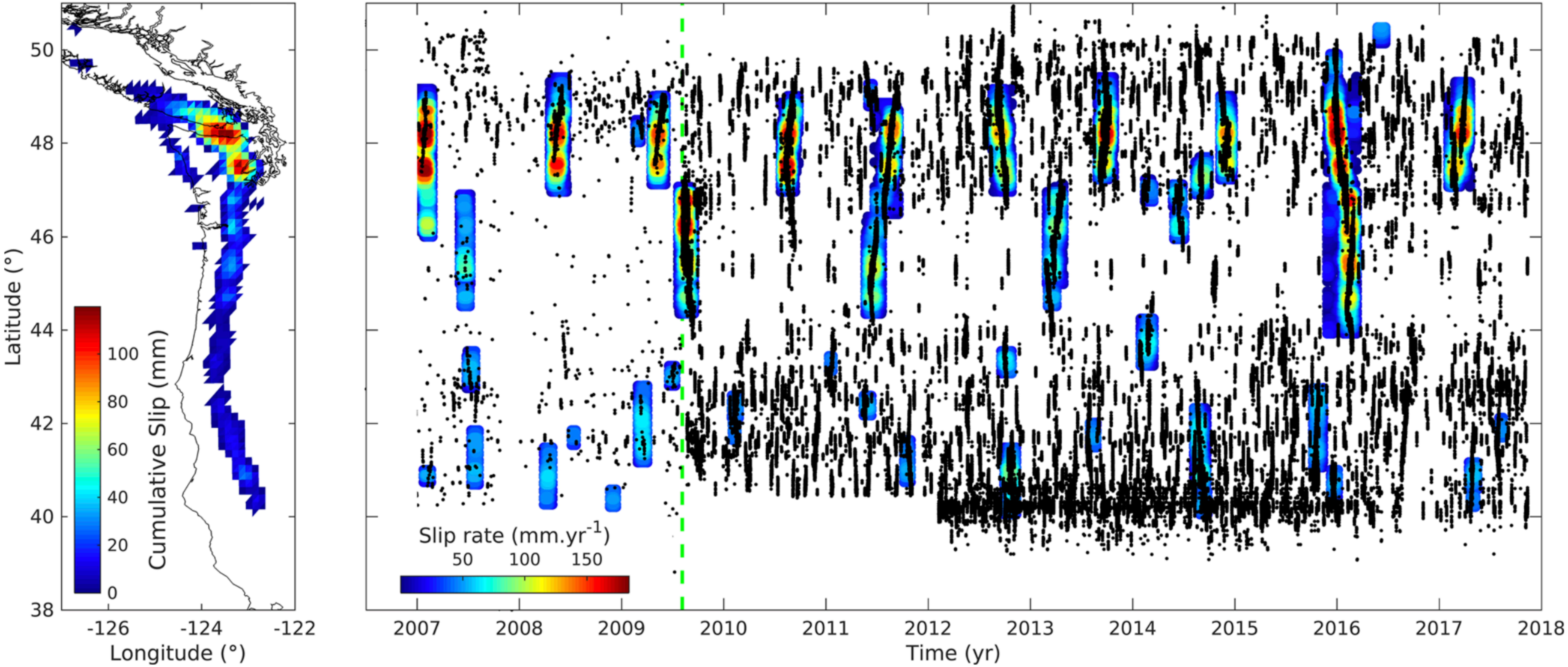


Michel et al., 2019a, *PAGEOPH*



Kinematic of Slow Earthquakes



Michel et al., 2019a, *PAGEOPH*

Regular vs Slow Earthquakes

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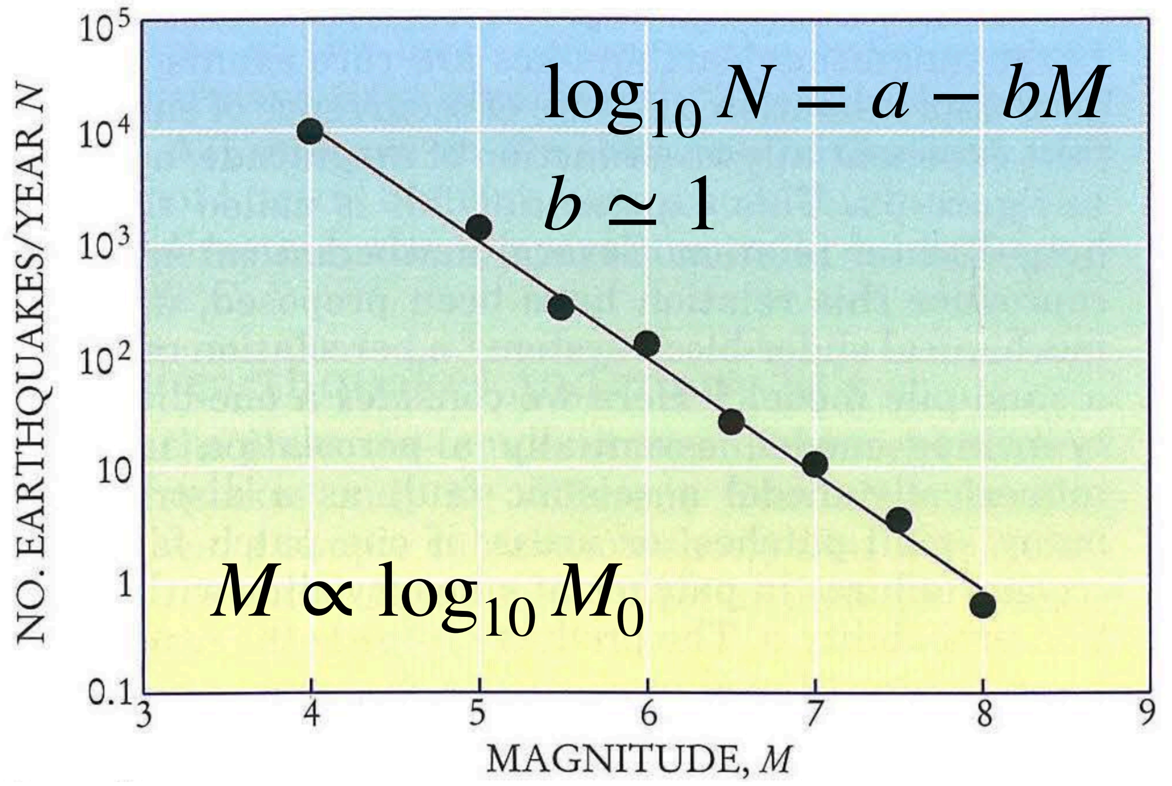
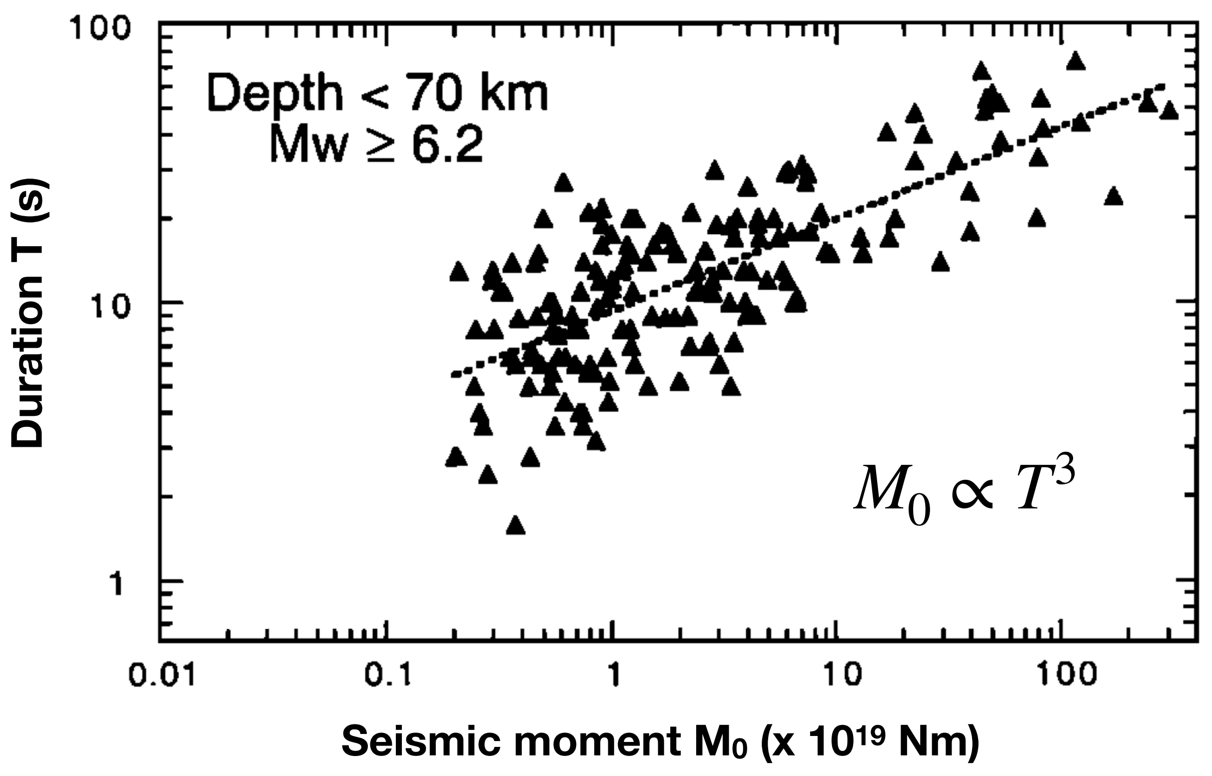
	Gutenberg-Richter law	Moment-duration law	Moment-area law

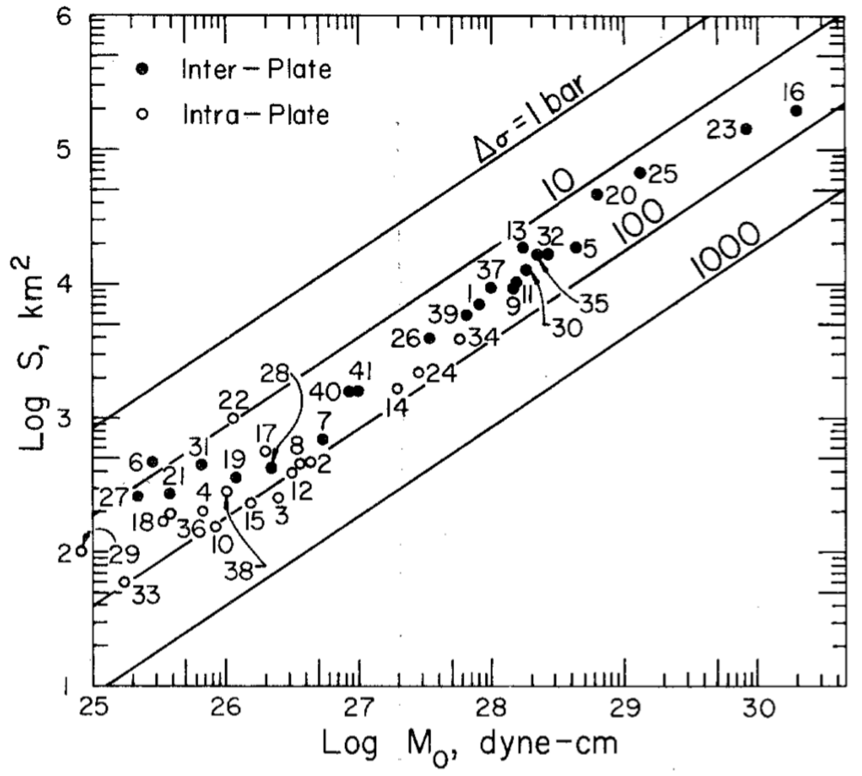
Regular



Kanamori and Brodsky, 2001, *Physics Today*

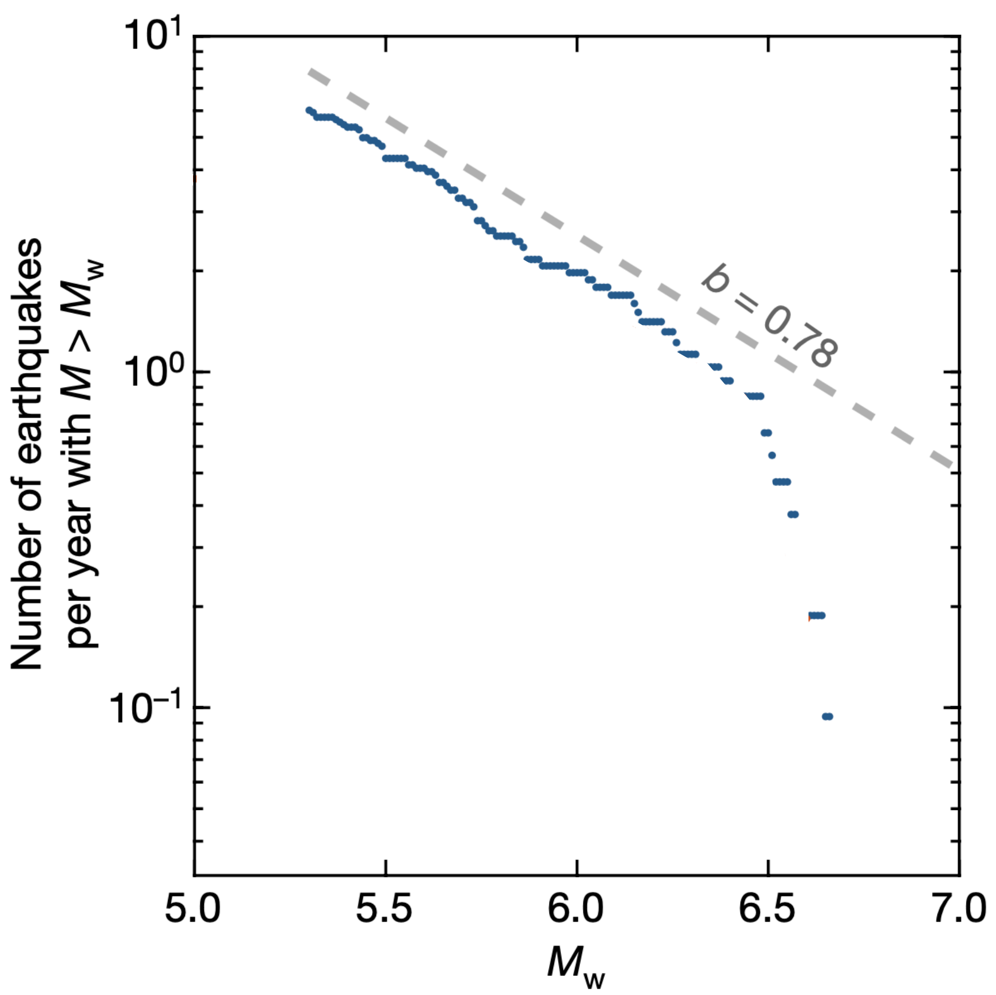


Houston, 2001, *JGR*

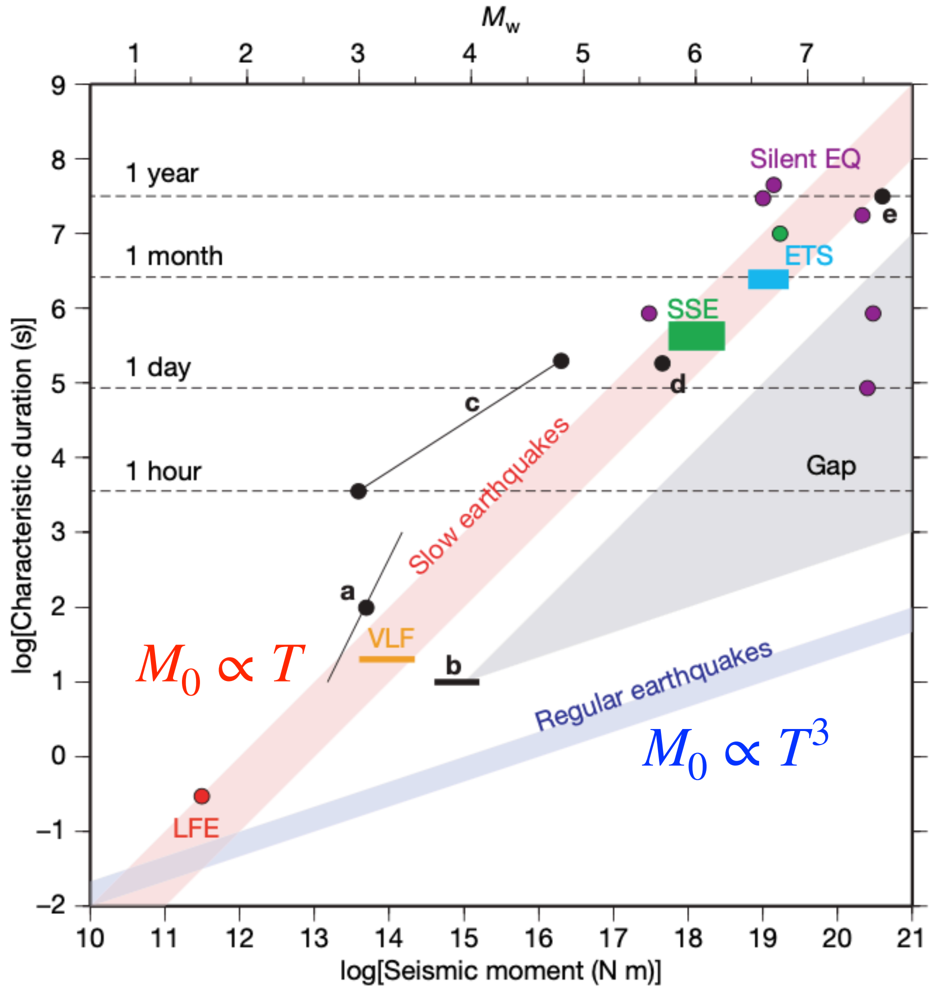


Kanamori and Anderson, 1975, *BSSA*

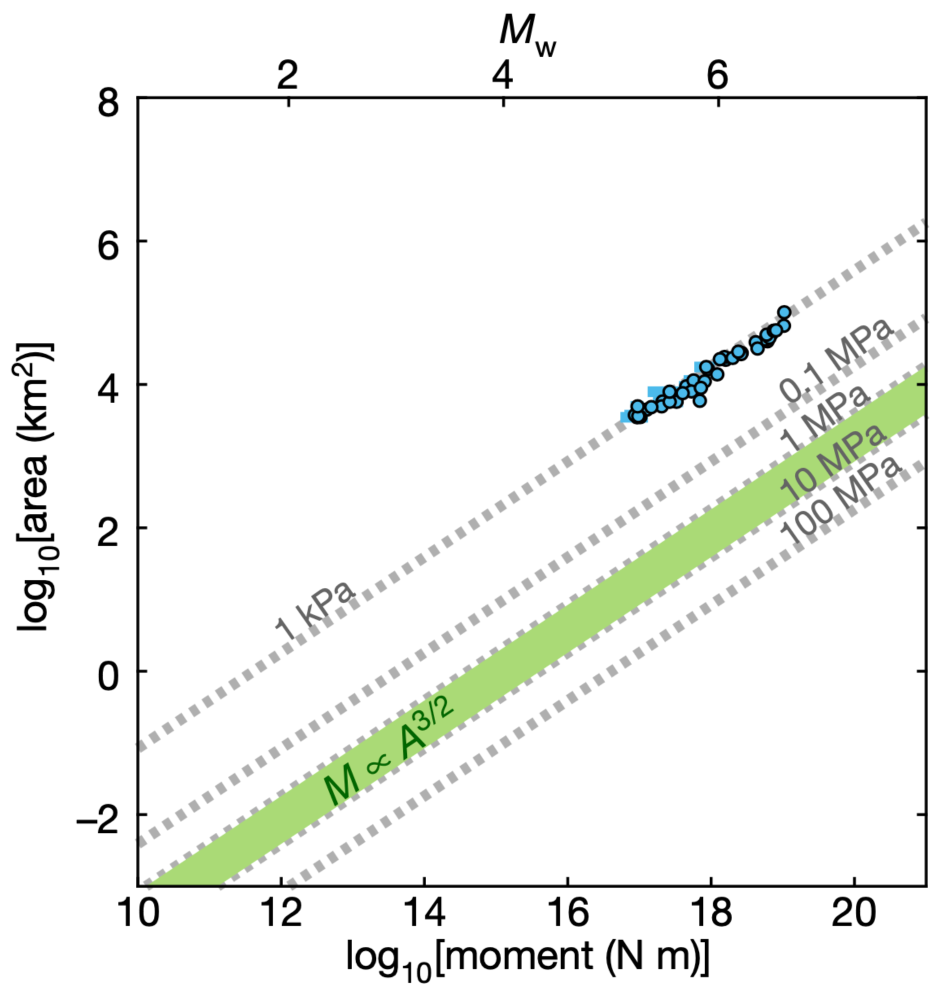
Slow



Michel et al., 2019b, *Nature*



Ide et al., 2007, *Nature*



Michel et al., 2019b, *Nature*

Regular vs Slow Earthquakes

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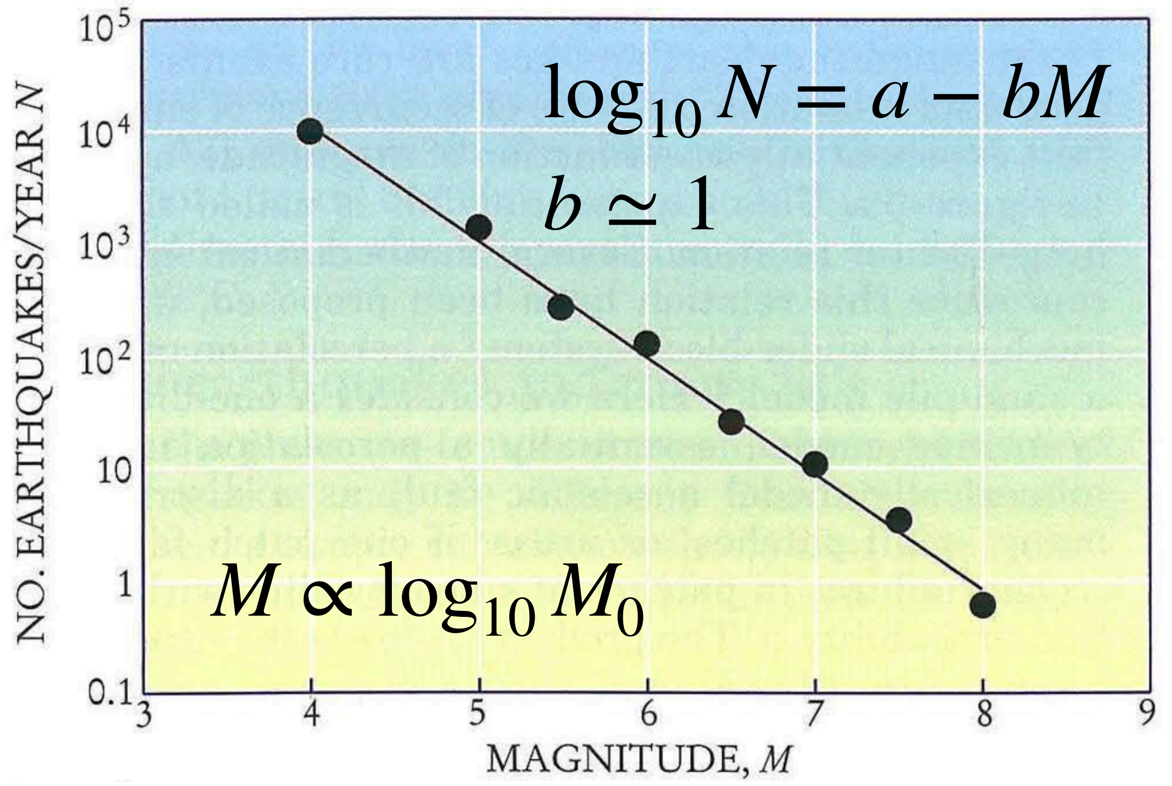
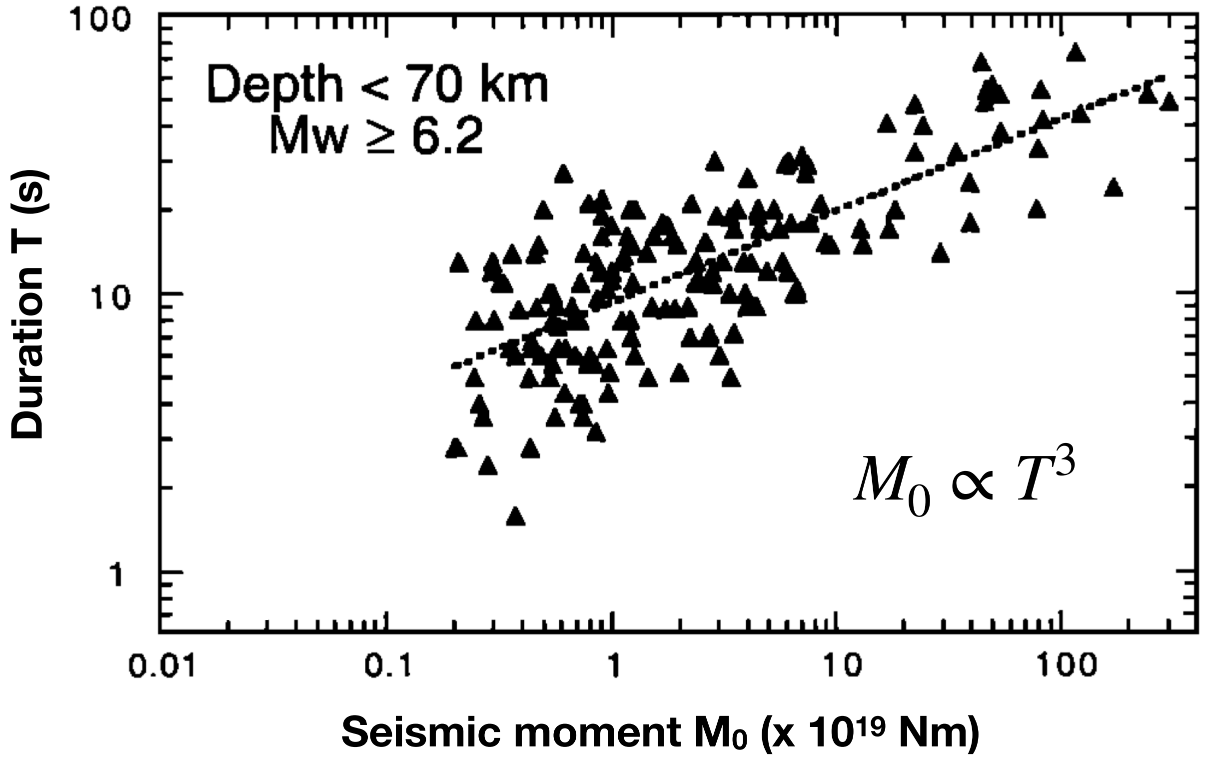
	Gutenberg-Richter law	Moment-duration law	Moment-area law

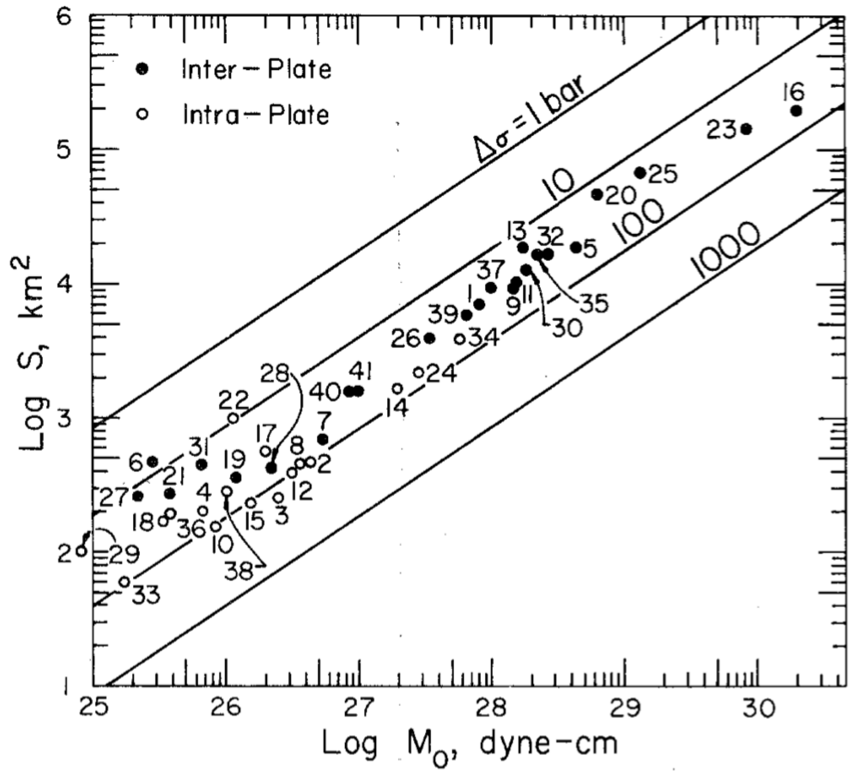
Regular



Kanamori and Brodsky, 2001, *Physics Today*

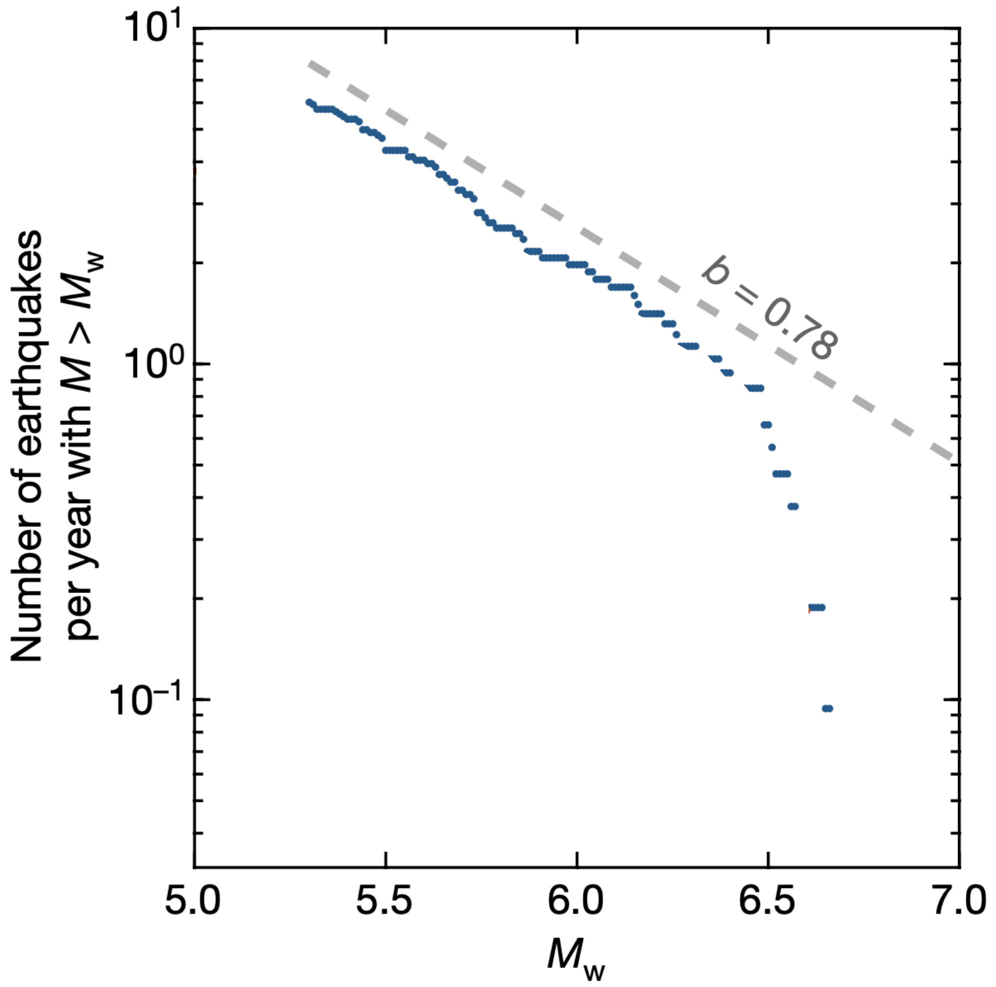


Houston, 2001, *JGR*

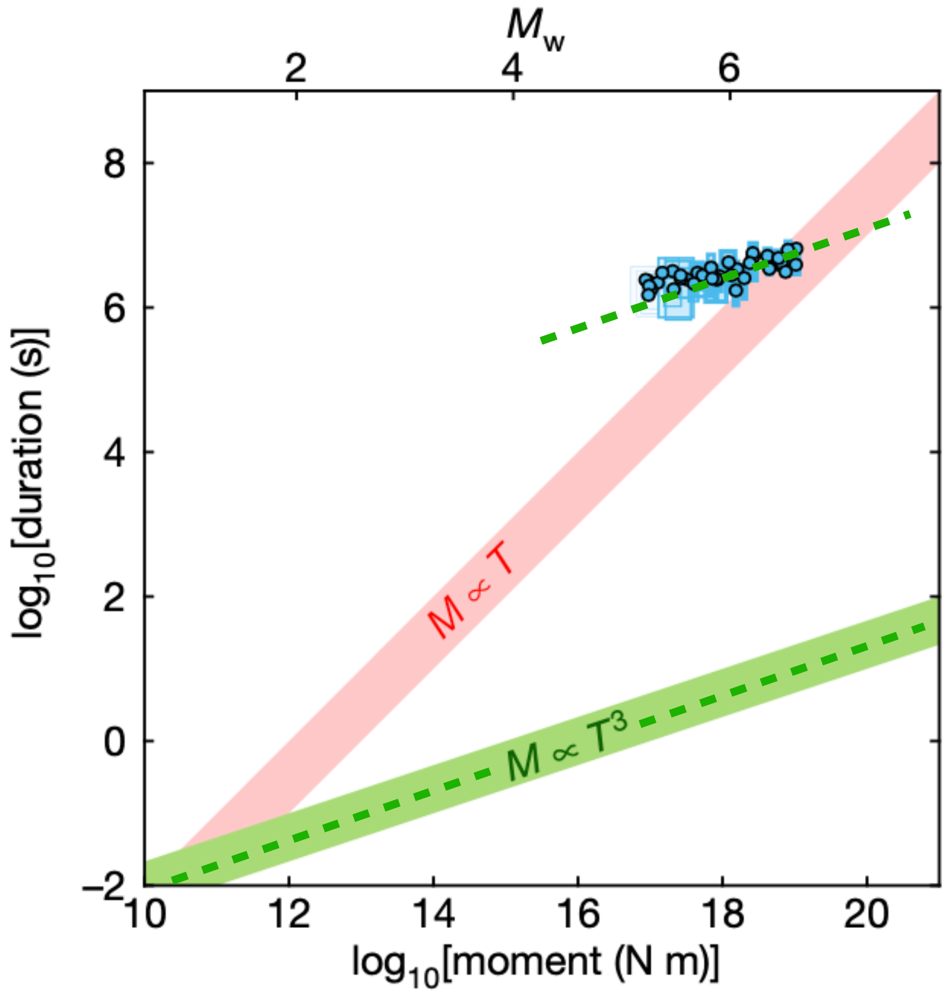


Kanamori and Anderson, 1975, *BSSA*

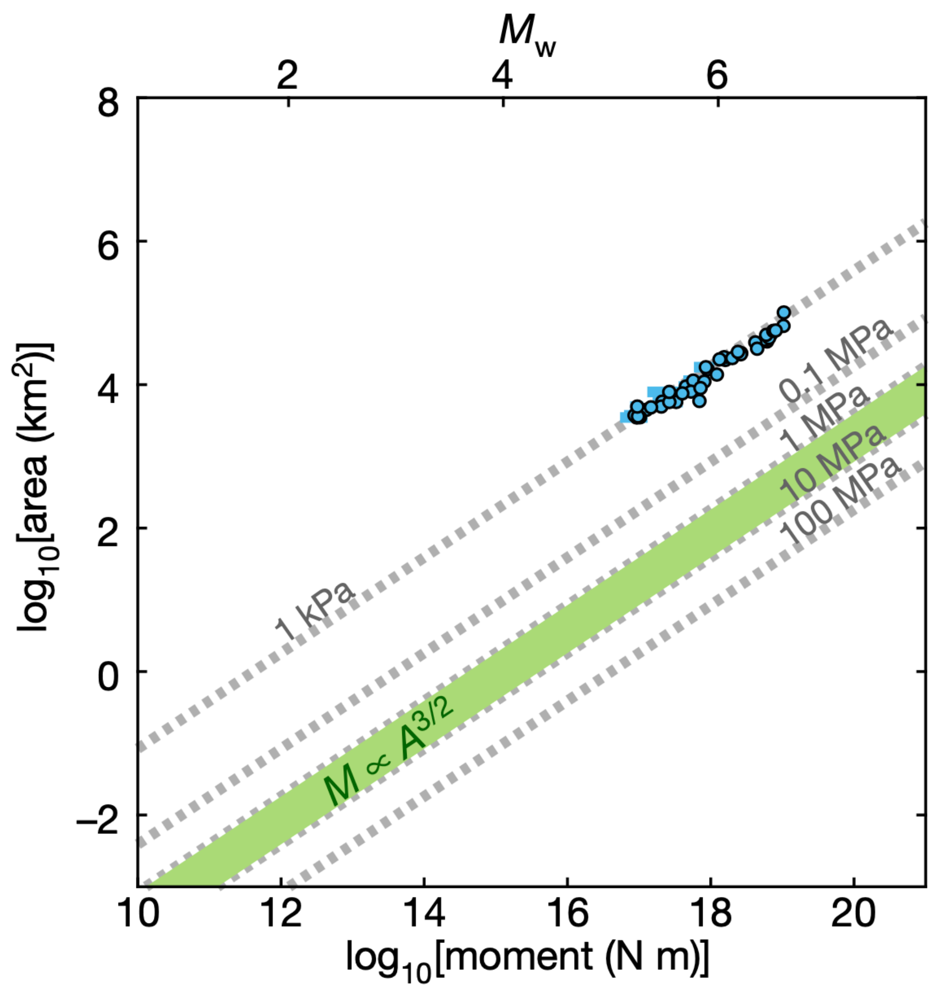
Slow



Michel et al., 2019b, *Nature*

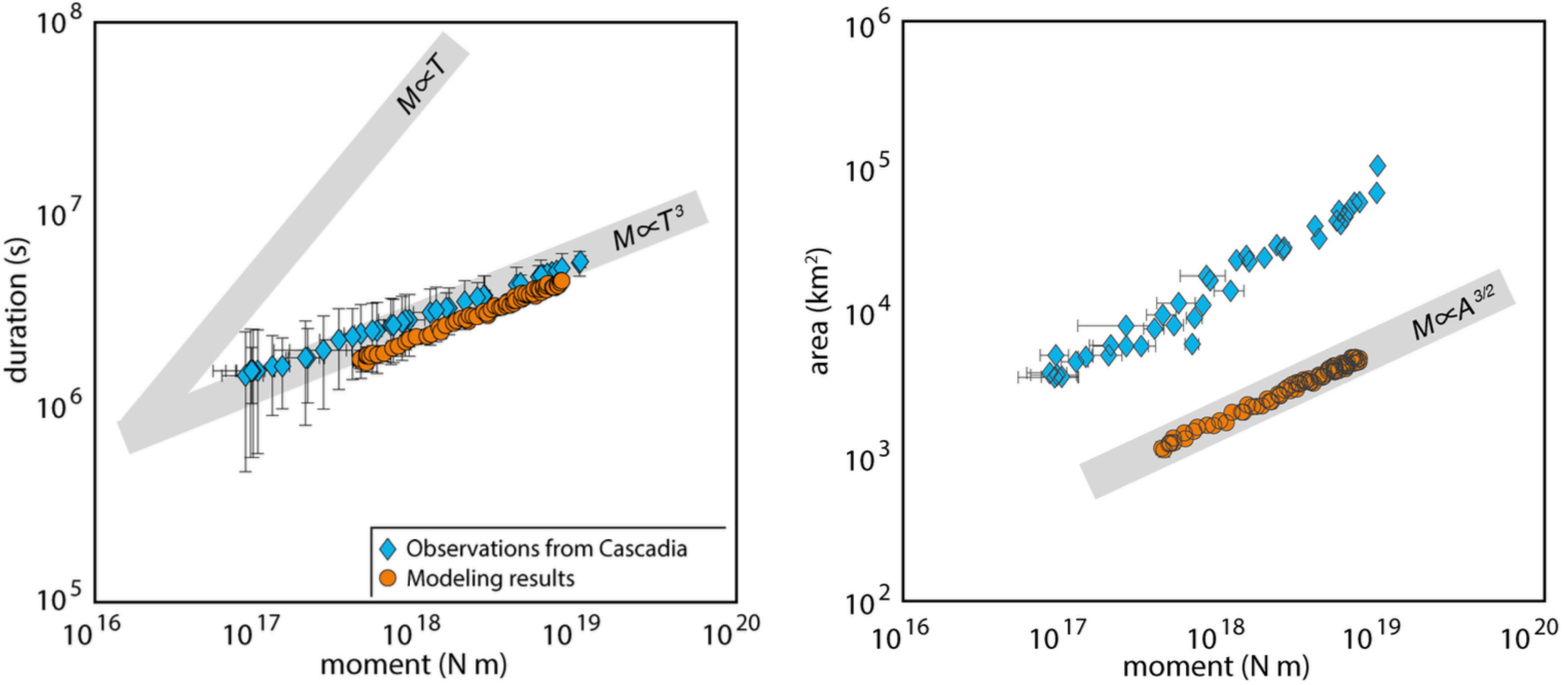


Michel et al., 2019b, *Nature*



Michel et al., 2019b, *Nature*

Slow Earthquakes Dynamics



Dal Zilio et al., 2020, *GRL*

Dynamics Information From Kinematics

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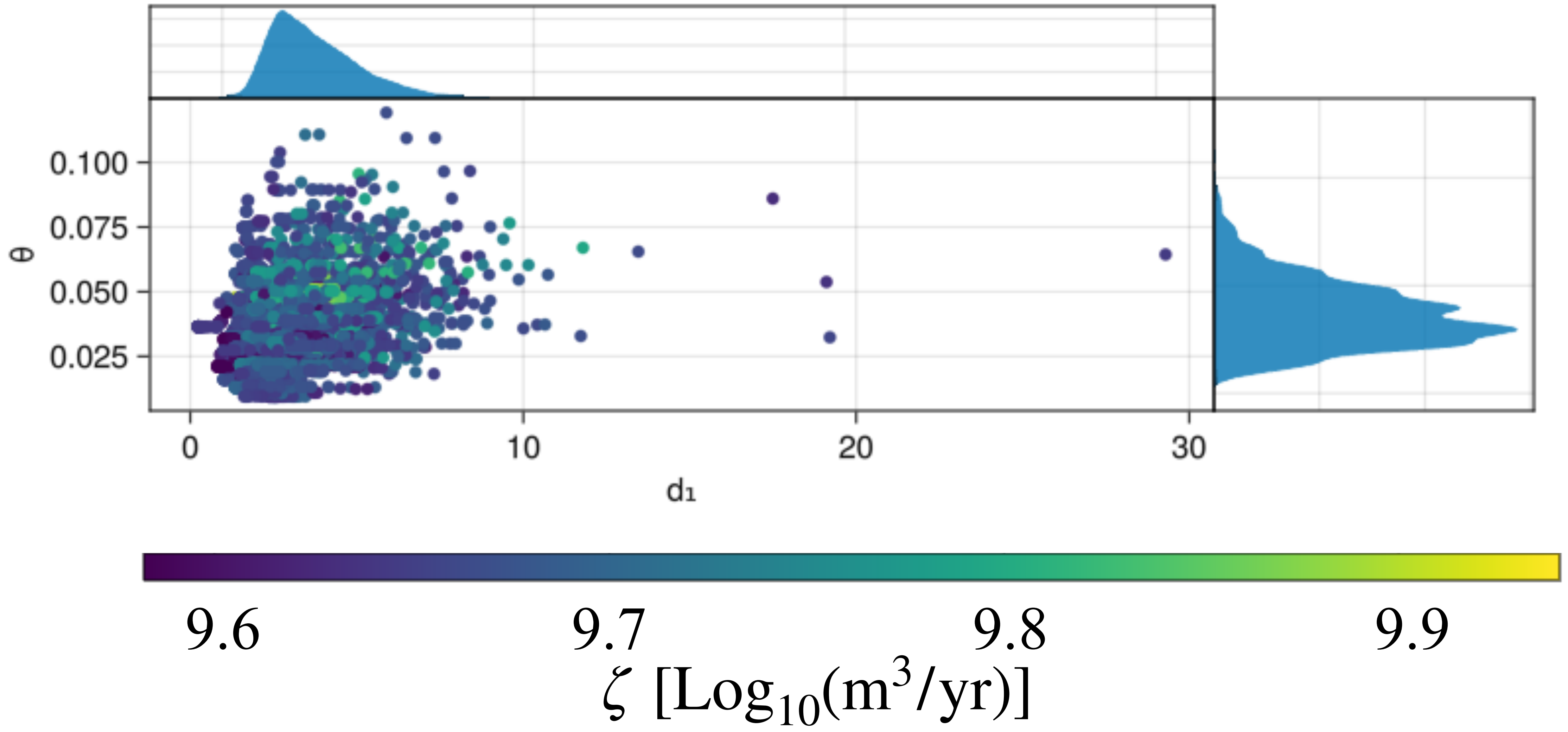
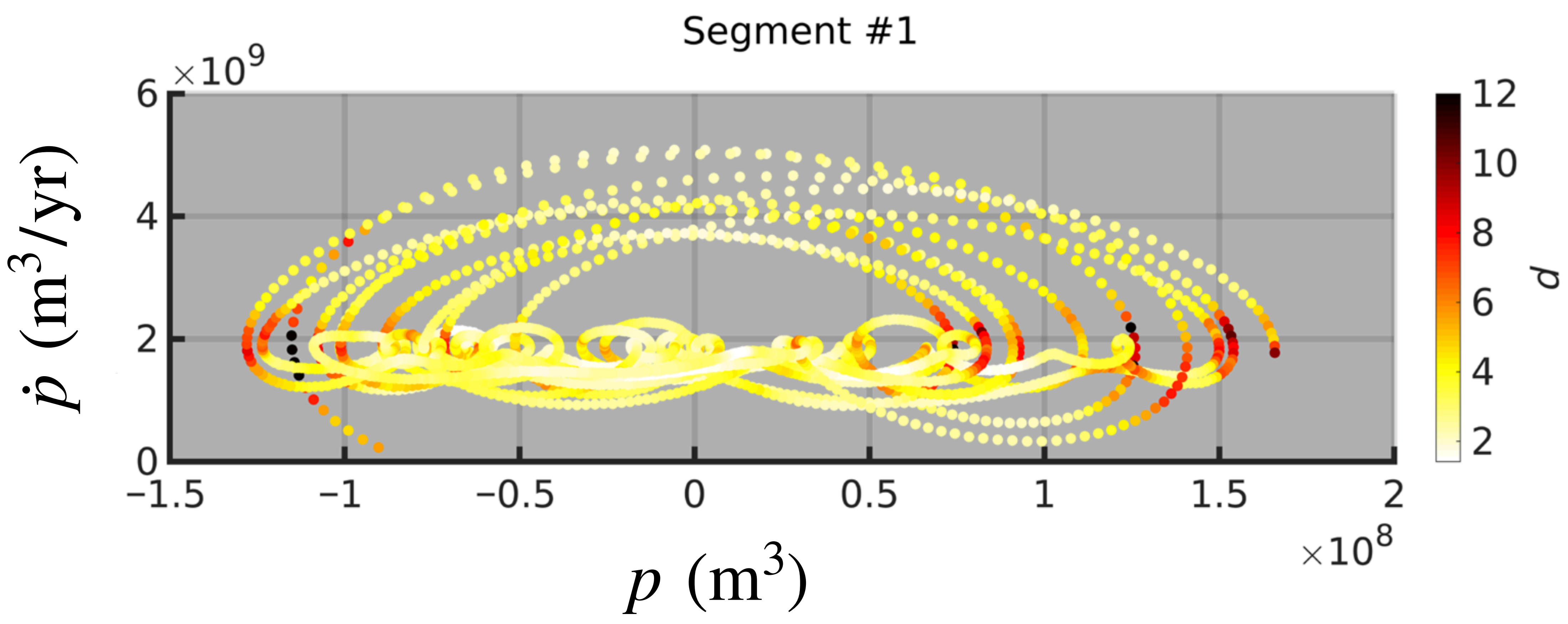
Cascadia





Dynamics Information From Kinematics

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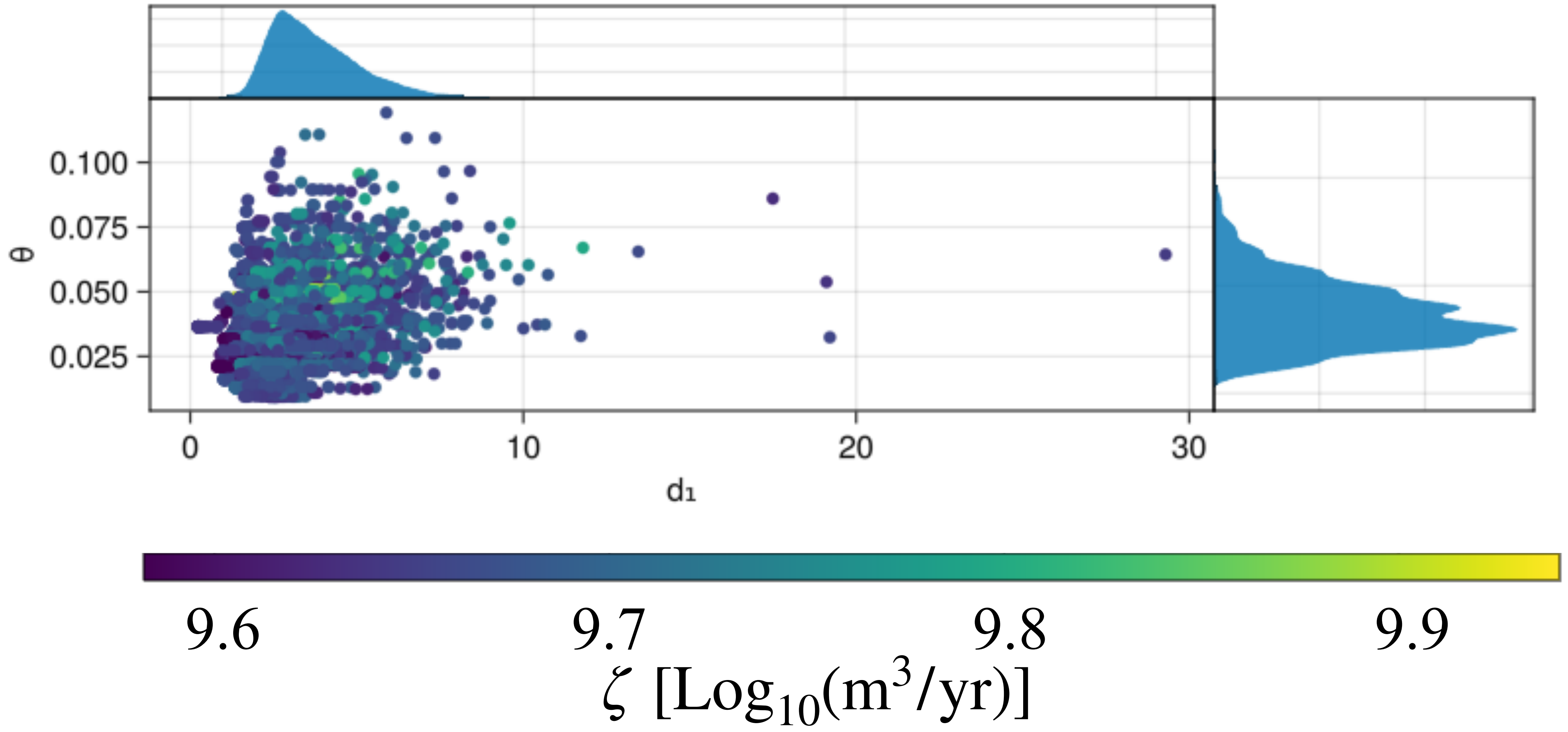
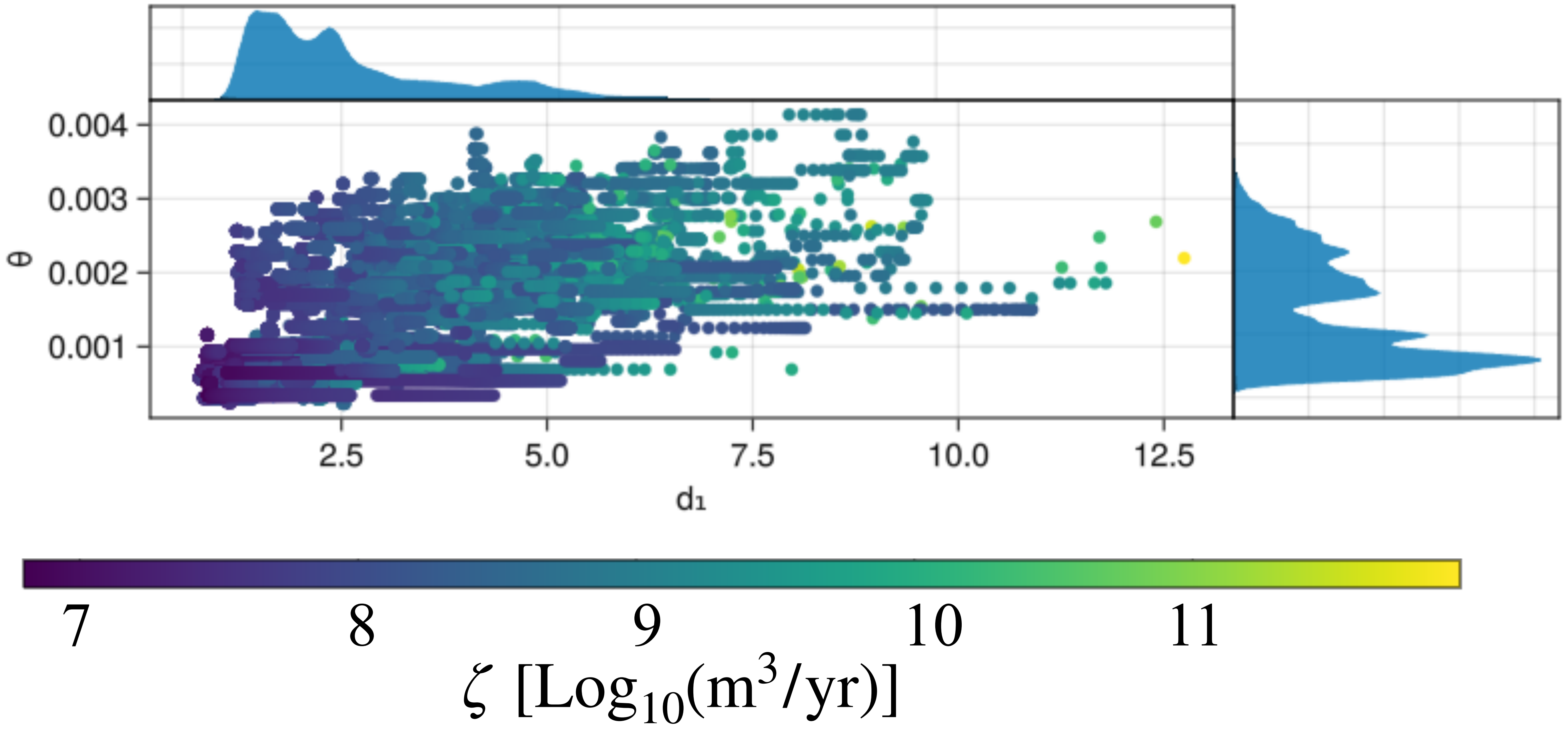
Cascadia



PDE



Part III - Nonlinear Dynamical Systems and Chaos in Geophysics