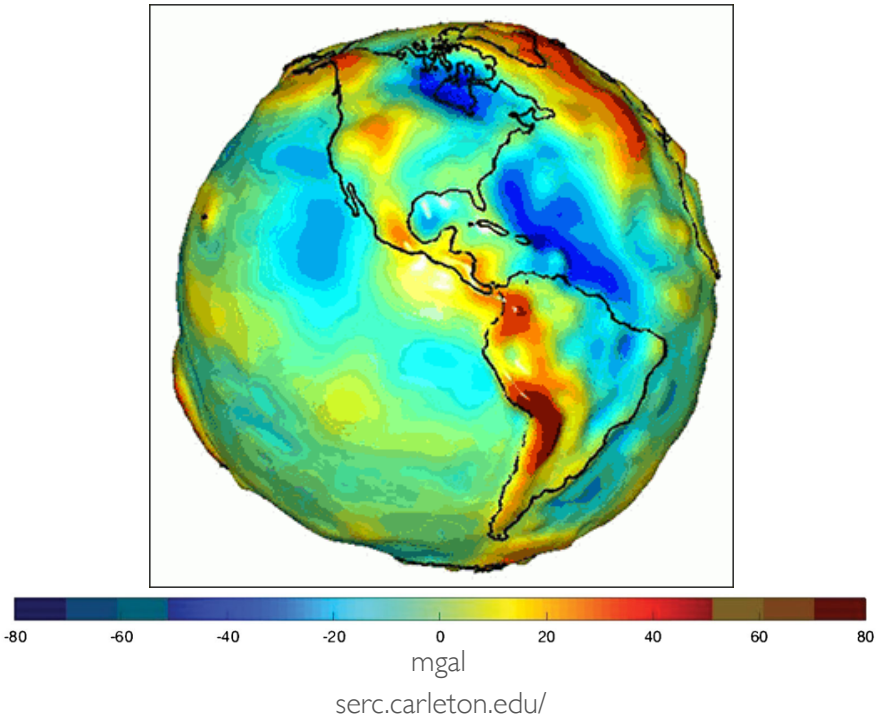
Physical Processes Behind Geodetic Deformation

Adriano Gualandi

UNIVERSITY OF CAMBRIDGE

INGV



serc.carleton.edu/

ICTP, Trieste

Workshop on
Mechanics of the Earthquake Cycle

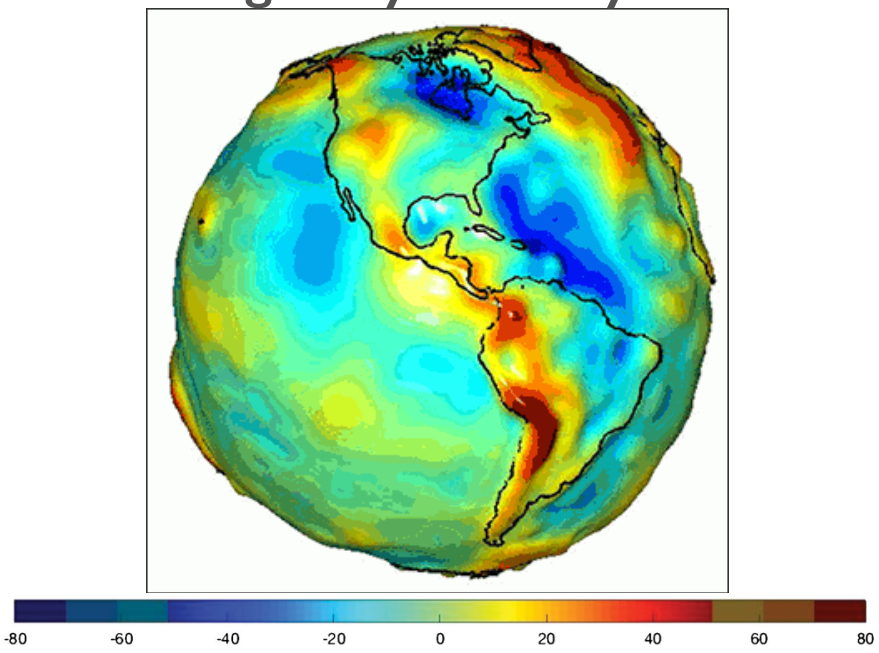
23 Oct 2023

What Is Geodesy ?

Geodesy:

from "*γεωδαισία*" (anc. Greek) or "geodaisia" meaning "division of the Earth"

gravity anomaly



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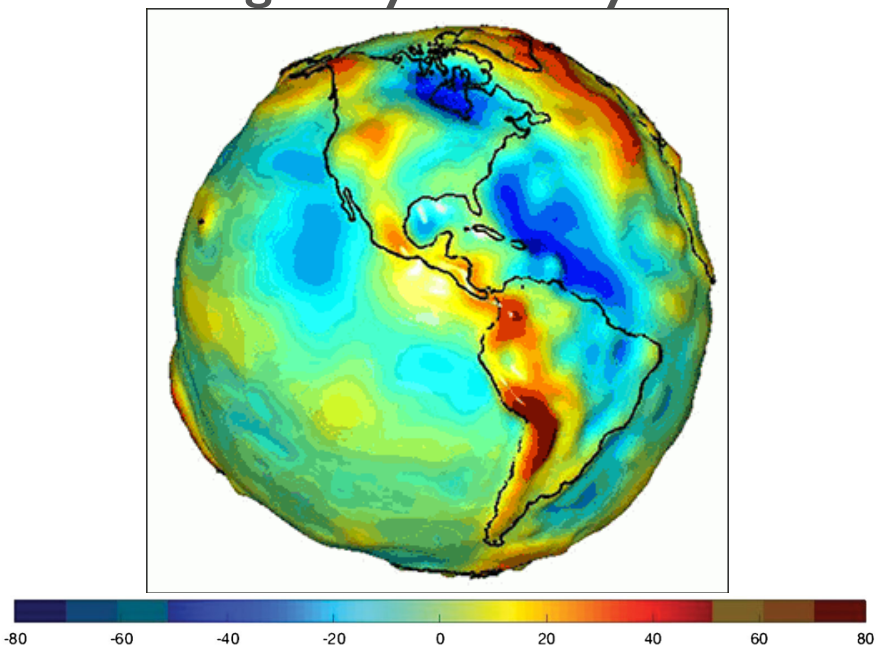
is the science of measuring the mass distribution, shape, and spatial orientation of the Earth

gravity anomaly



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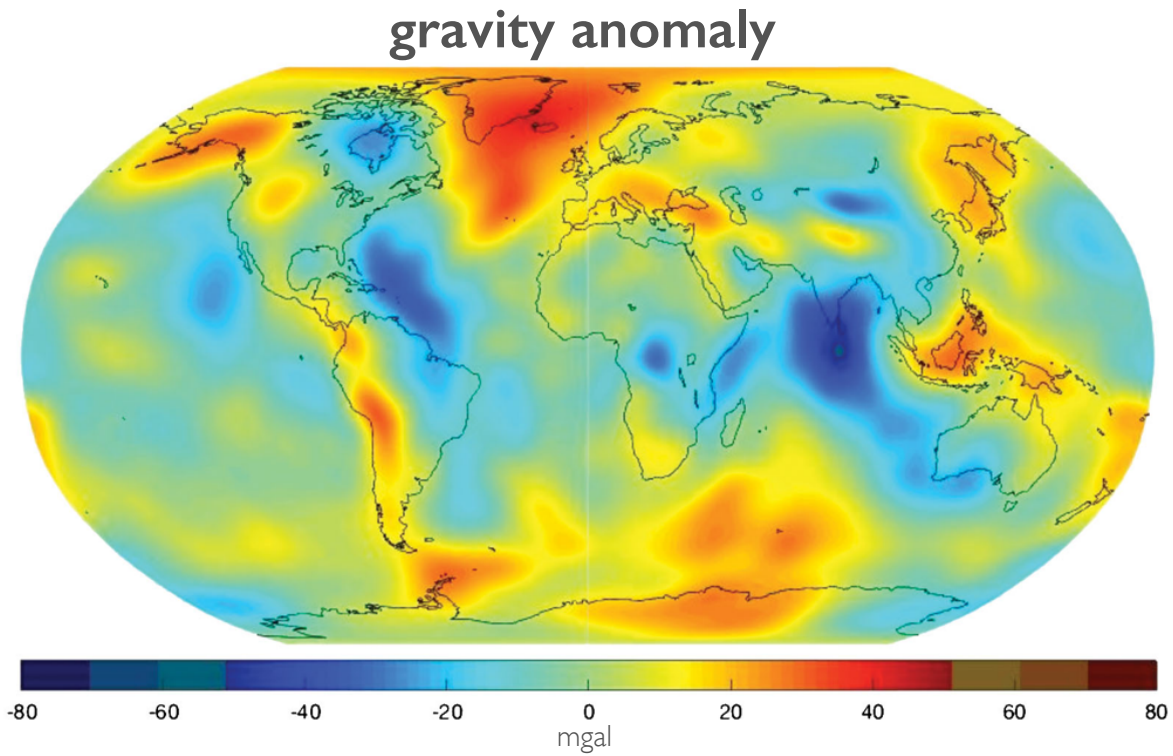
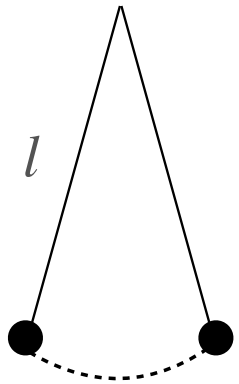
Gravity Measures

decades of satellite tracking



Absolute Gravity

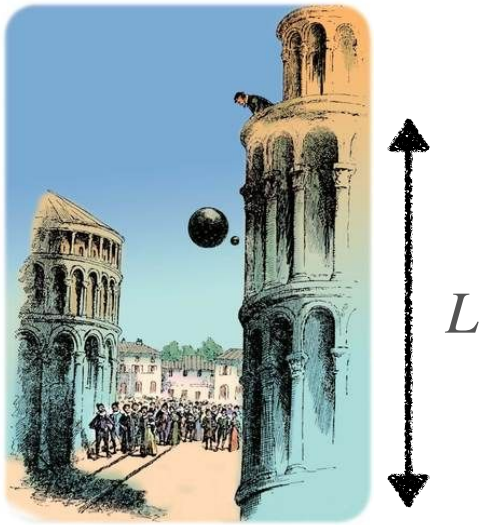
Pendulum



$$T = 2\pi\sqrt{\frac{l}{g}}$$

$$g = 4\pi^2\frac{l}{T^2}$$

Mass dropping

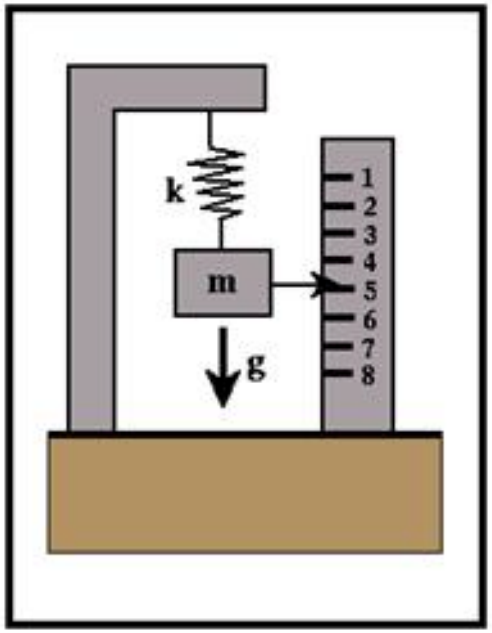


$$L = \frac{1}{2}g\Delta t^2$$

$$g = \frac{2L}{\Delta t^2}$$

Relative Gravity

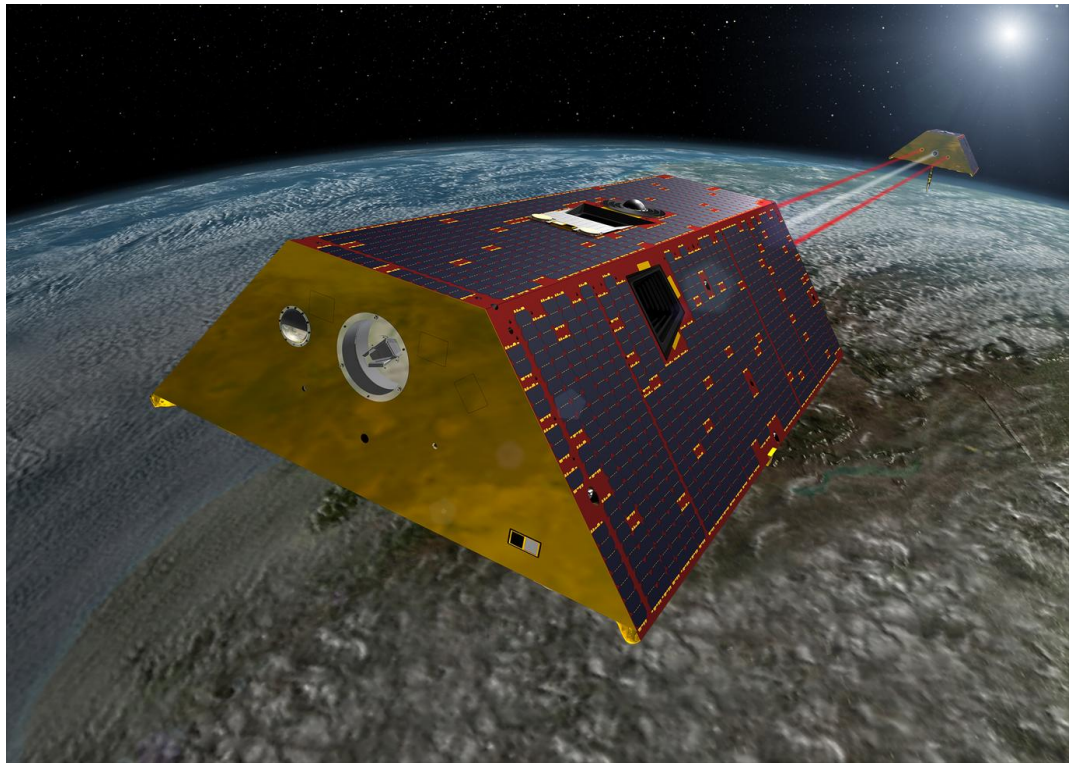
Gravimeter



www.ucl.ac.uk/

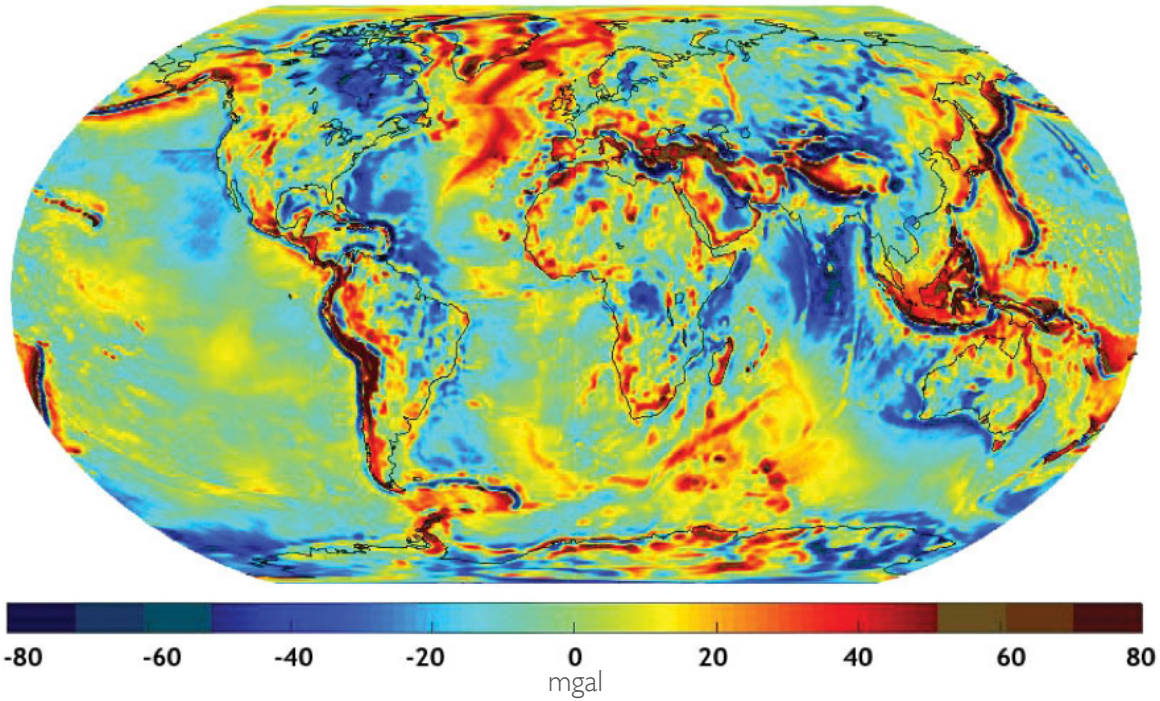
Gravity Anomaly

Gravity Recovery and Climate Experiment (GRACE & GRACE-FO)



Gravity Anomaly

10 yr of GRACE
4 yr of GOCE Gravity Field and Steady-State Ocean Circulation Explorer



www2.csr.utexas.edu

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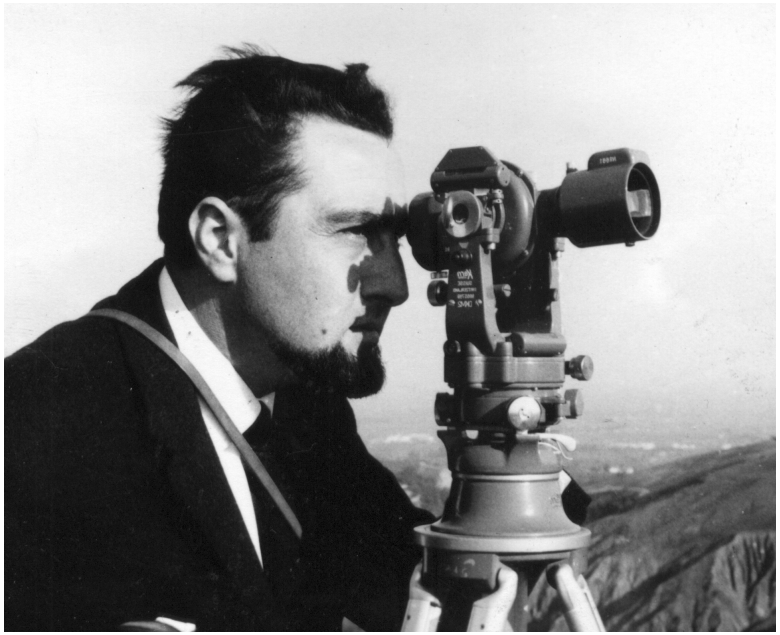
Theodolite

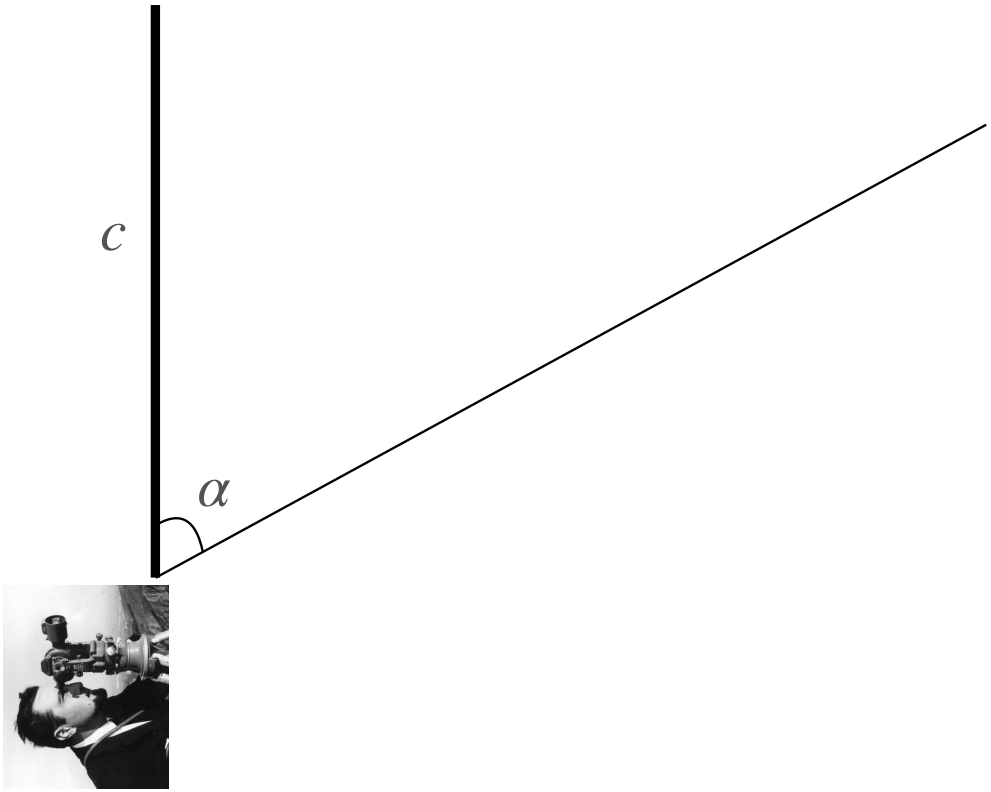


Enea Gualandi

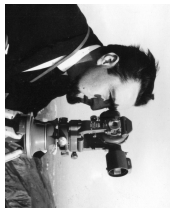
Invar stadia rod

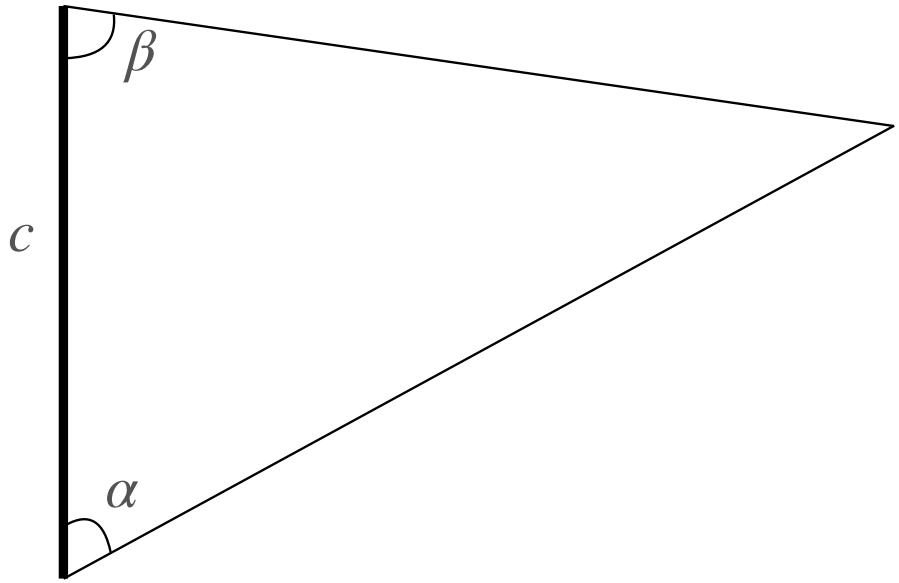
Sante Sassi

Triangulation



Triangulation



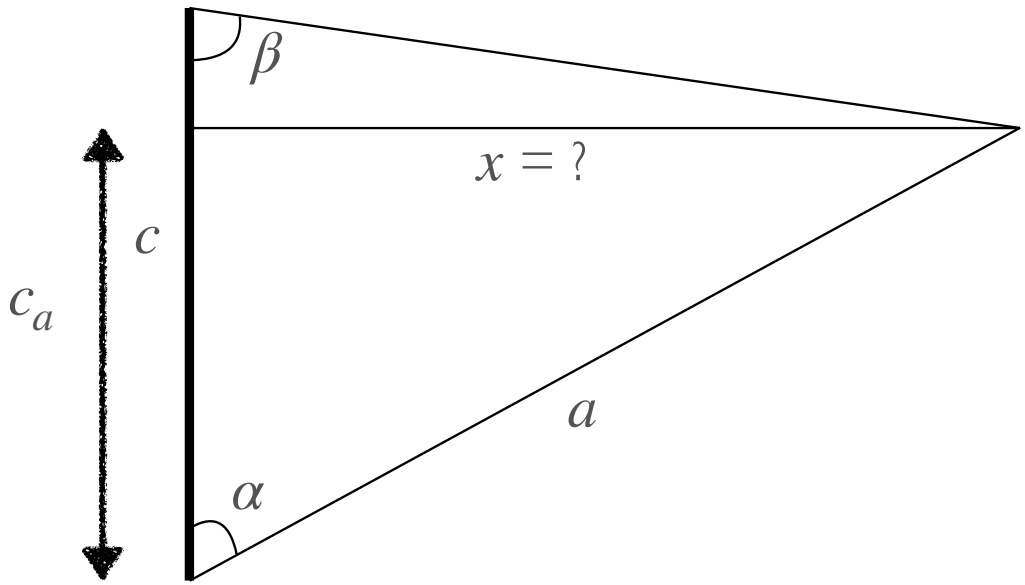


Triangulation

$$x = a \sin \alpha$$
$$c_a = a \cos \alpha$$

$$\frac{x}{c_a} = \tan \alpha$$

$$c_a = \frac{x}{\tan \alpha}$$

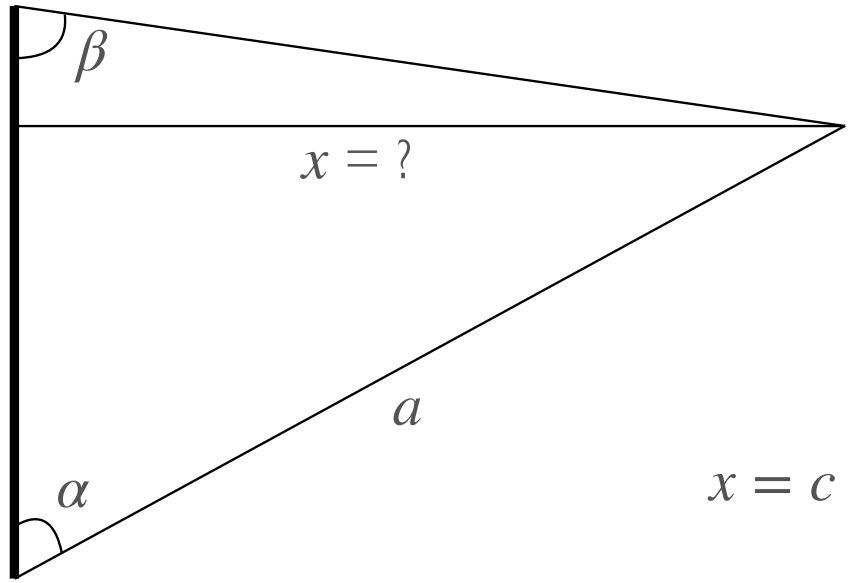


Triangulation

$$c = c_a + c_b = \frac{x}{\tan\alpha} + \frac{x}{\tan\beta} = \ldots = x\frac{\sin(\alpha+\beta)}{\sin\alpha\sin\beta}$$

$$c_b = \frac{x}{\tan\beta}$$

$$c_a = \frac{x}{\tan\alpha}$$



$$x = c\,\frac{\sin\alpha\sin\beta}{\sin(\alpha+\beta)}$$

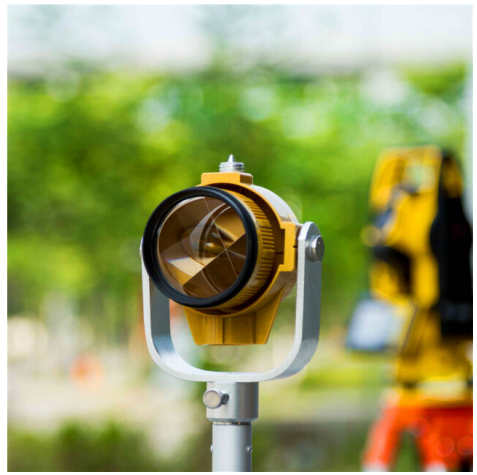
Trilateration

Total station

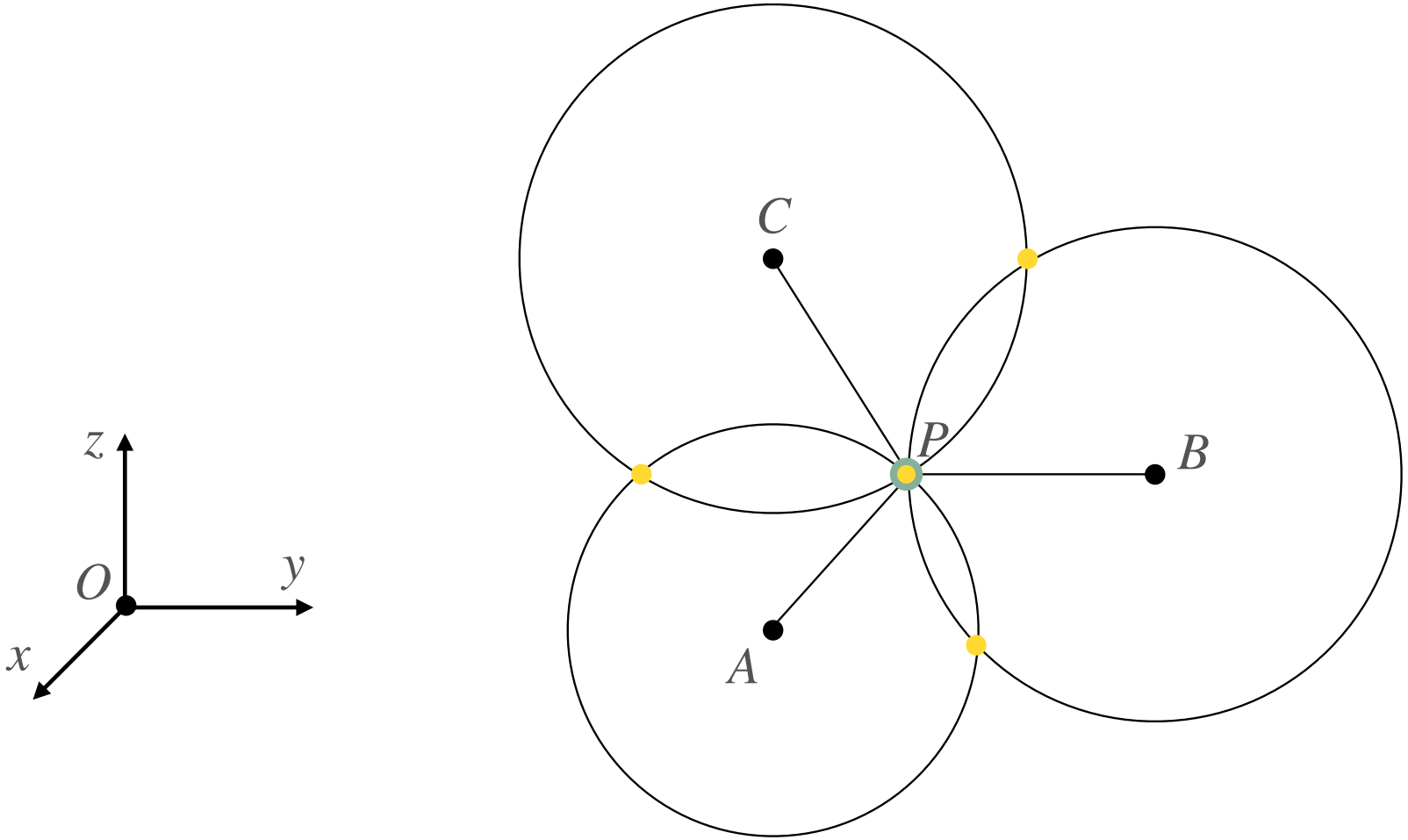
Elisabetta Ferrario

Leonardo Gualandi

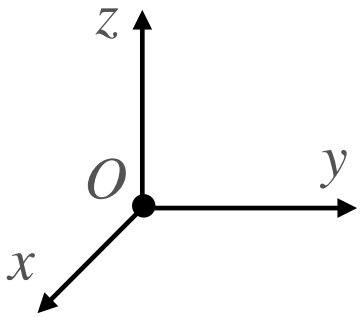
Prism

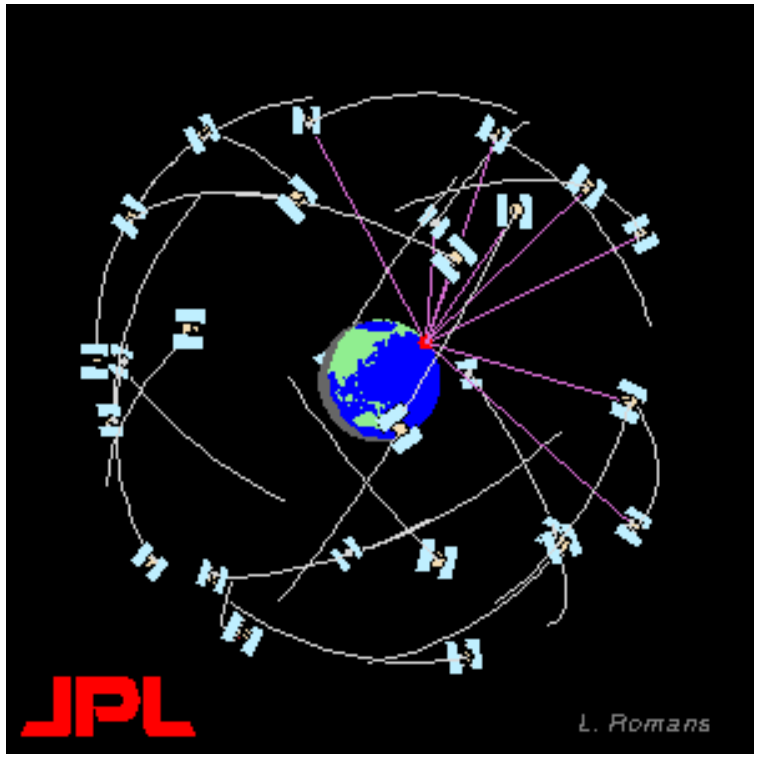


Trilateration



Global Navigation Satellite System





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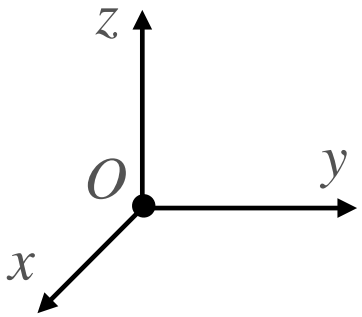
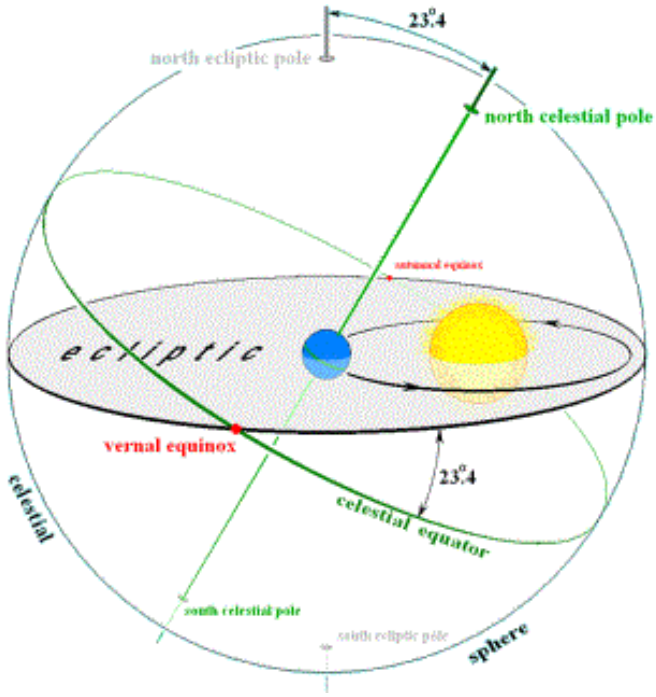
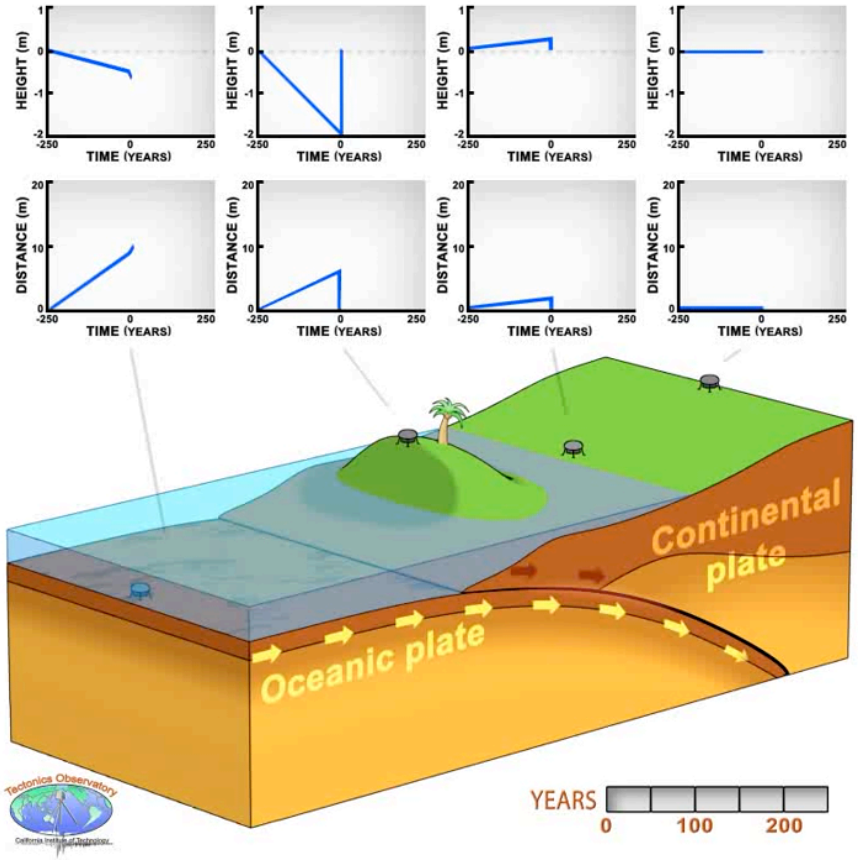




http://www.siranah.de

How To Apply Geodesy To Study Earthquakes ?



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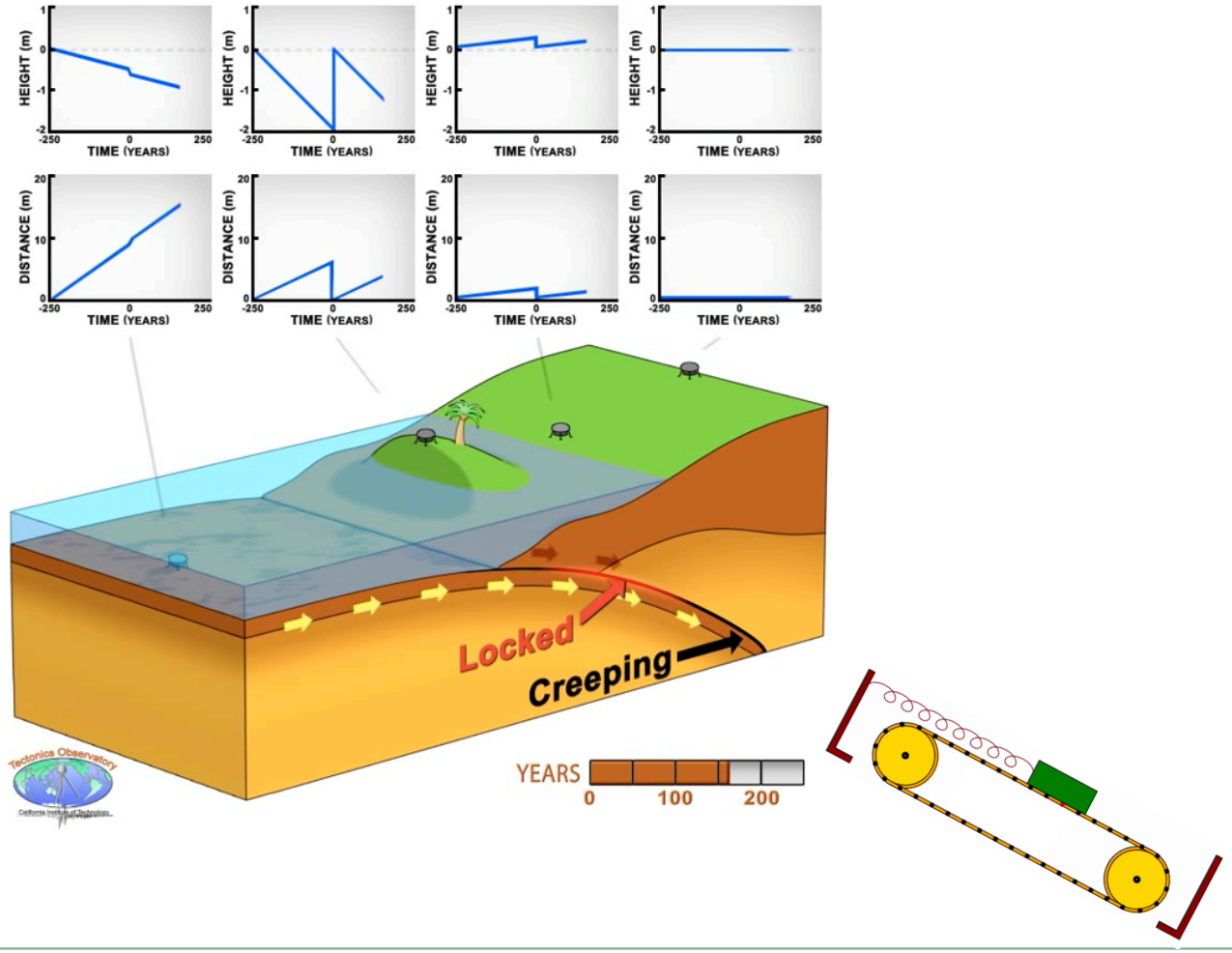
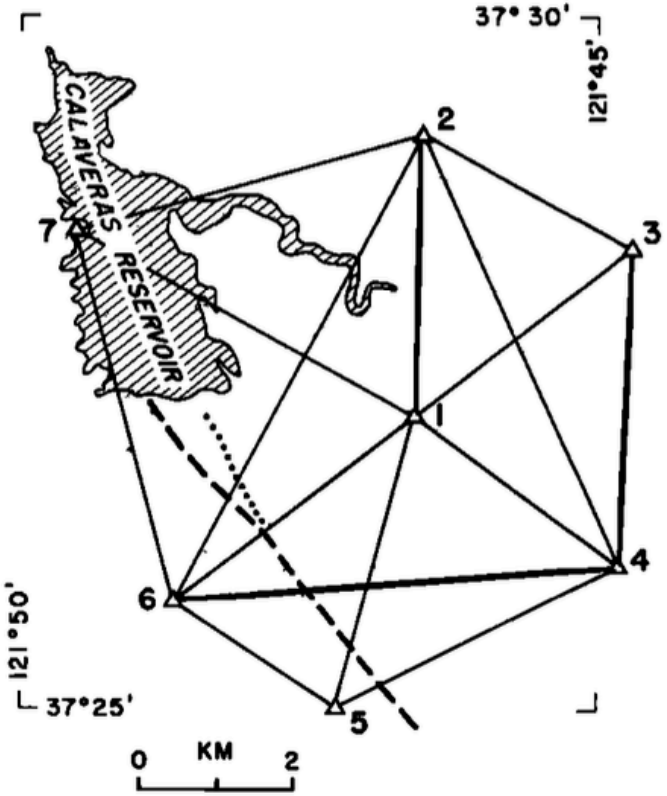


Strain Polygon

Trilateration network along San Andreas fault surveyed annually



Savage and Prescott, 1973, *JGR*

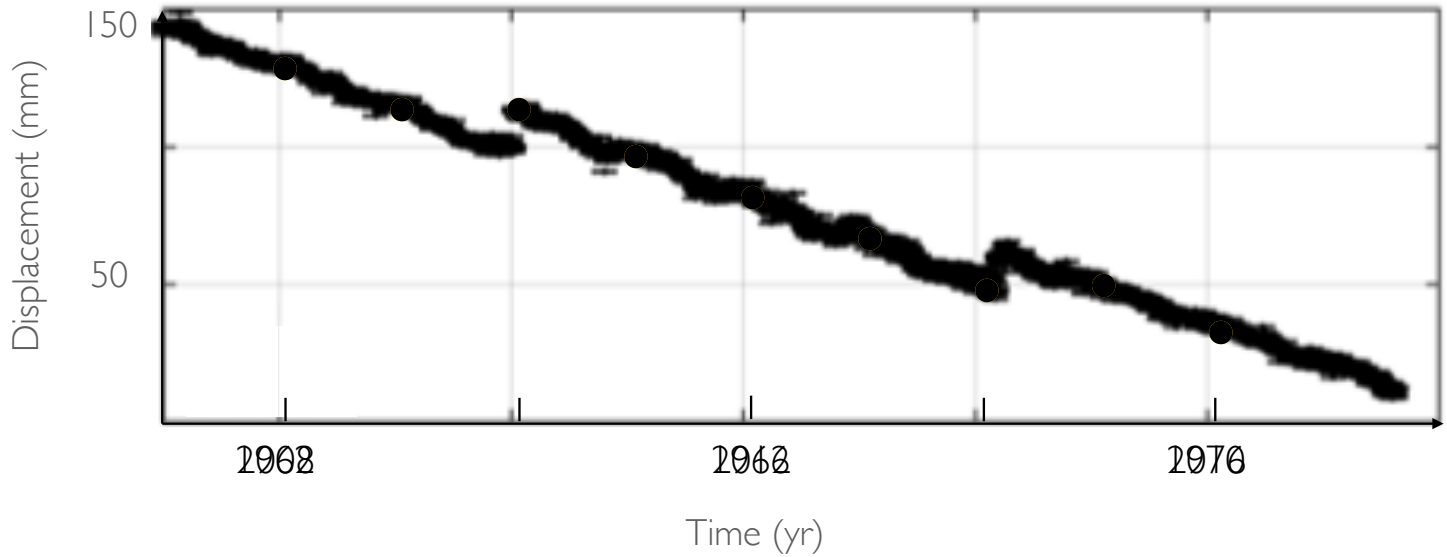
$$3 \text{ mm} \leq \sigma \leq 8 \text{ mm}$$

for

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

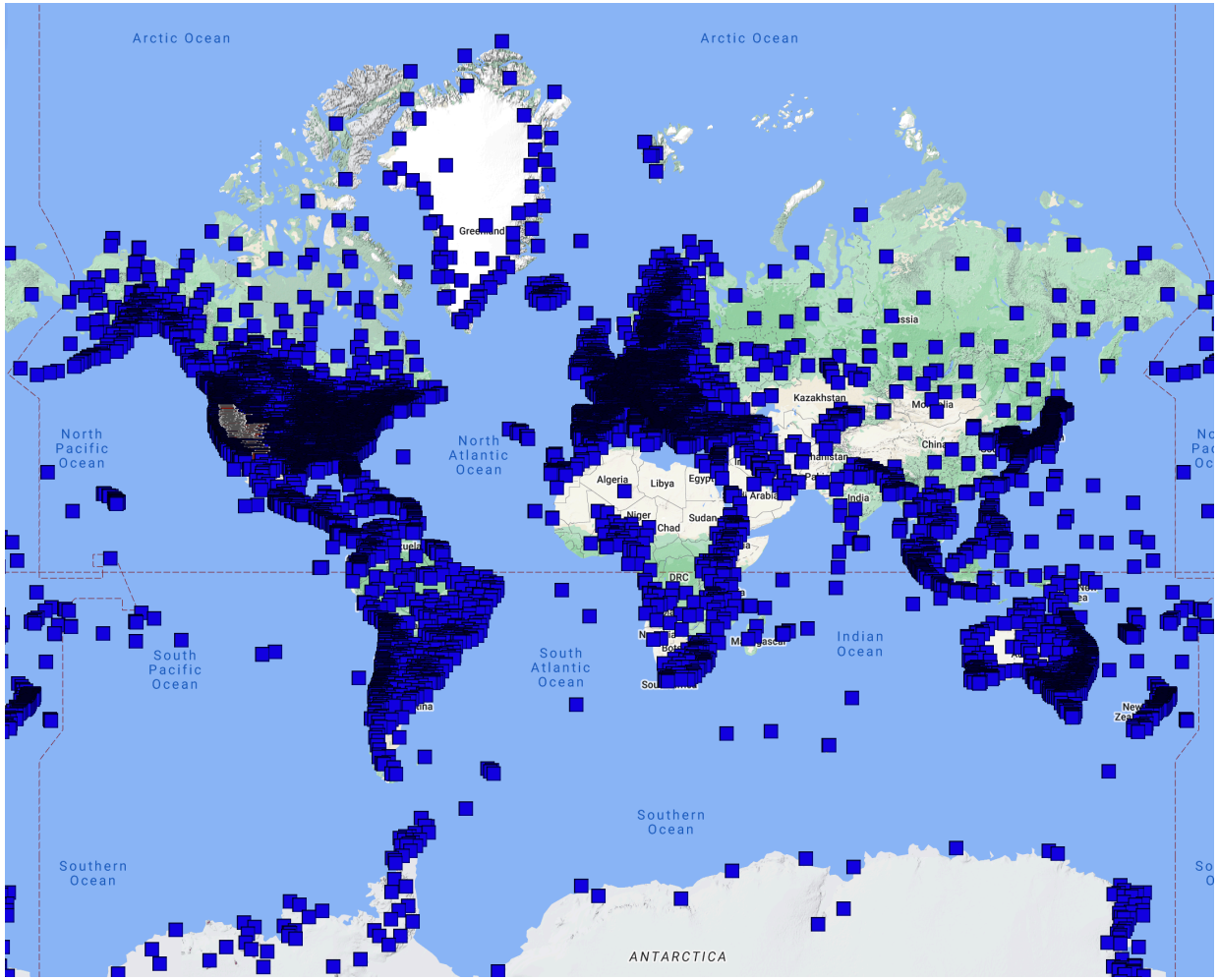
with corrections for atmospheric refractivity (aircraft measures of T and p)

Displacement Time Series



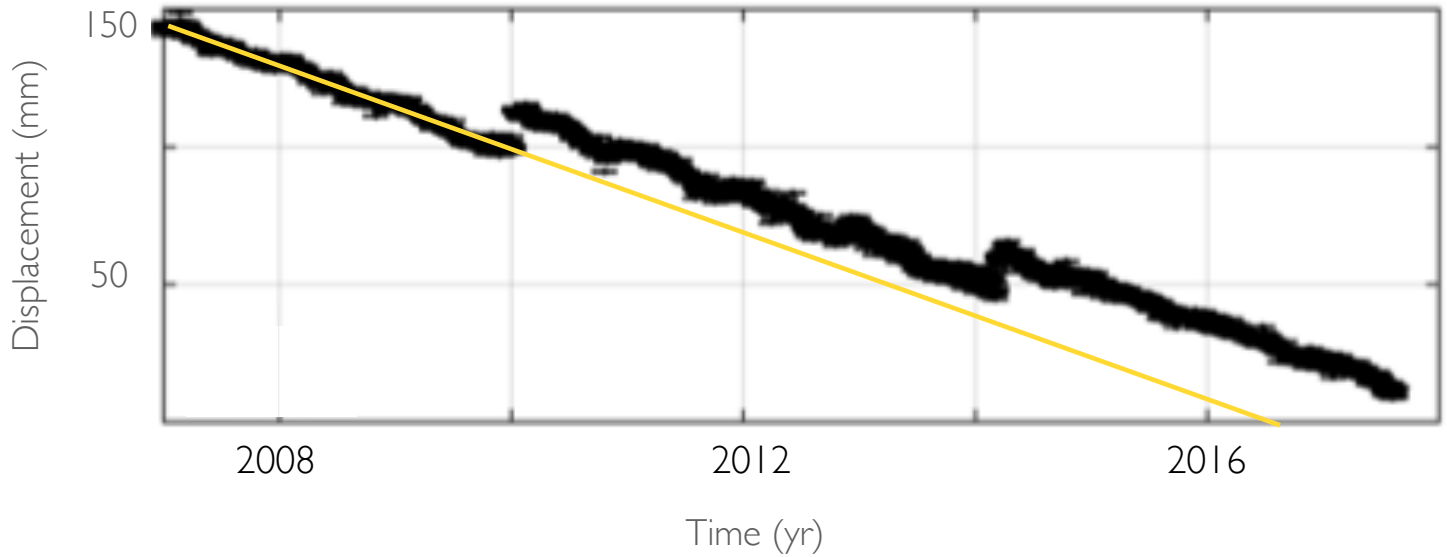
Michel et al., 2019a, *PAGEOPH*

Big Data



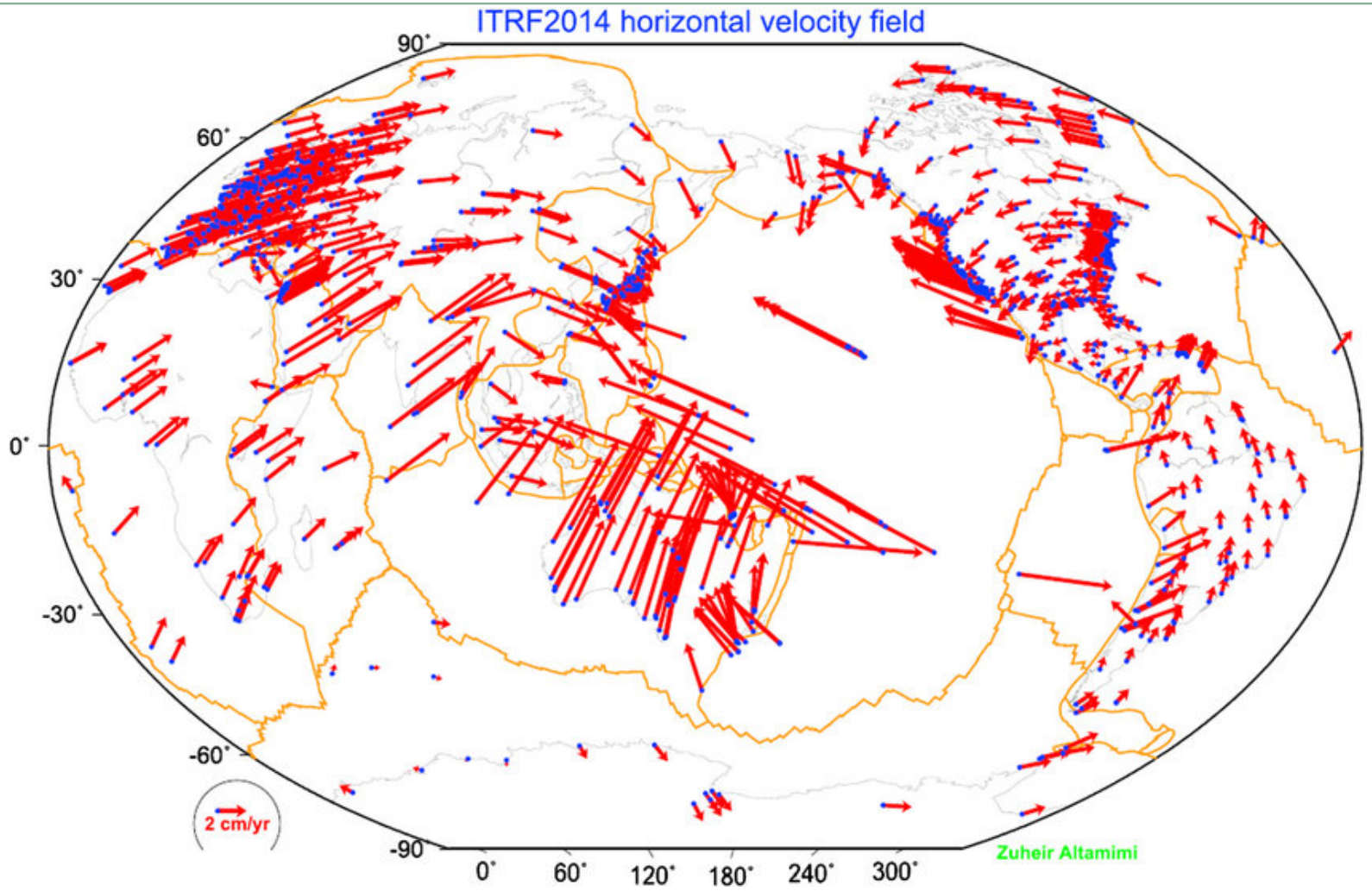
http://geodesy.unr.edu/
Blewitt et al., 2018, *Eos*

Displacement Time Series

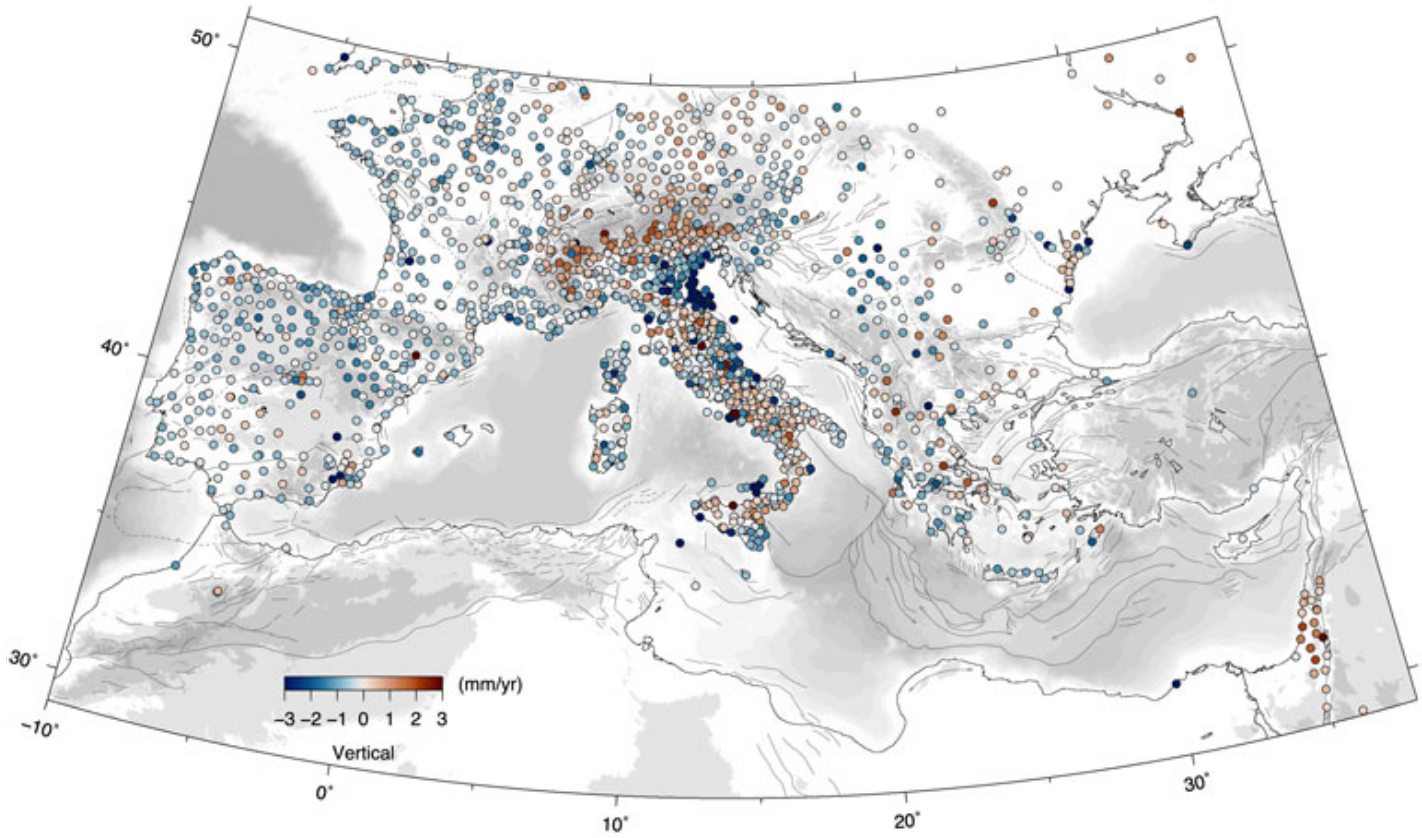


Michel et al., 2019a, *PAGEOPH*

Velocity Field

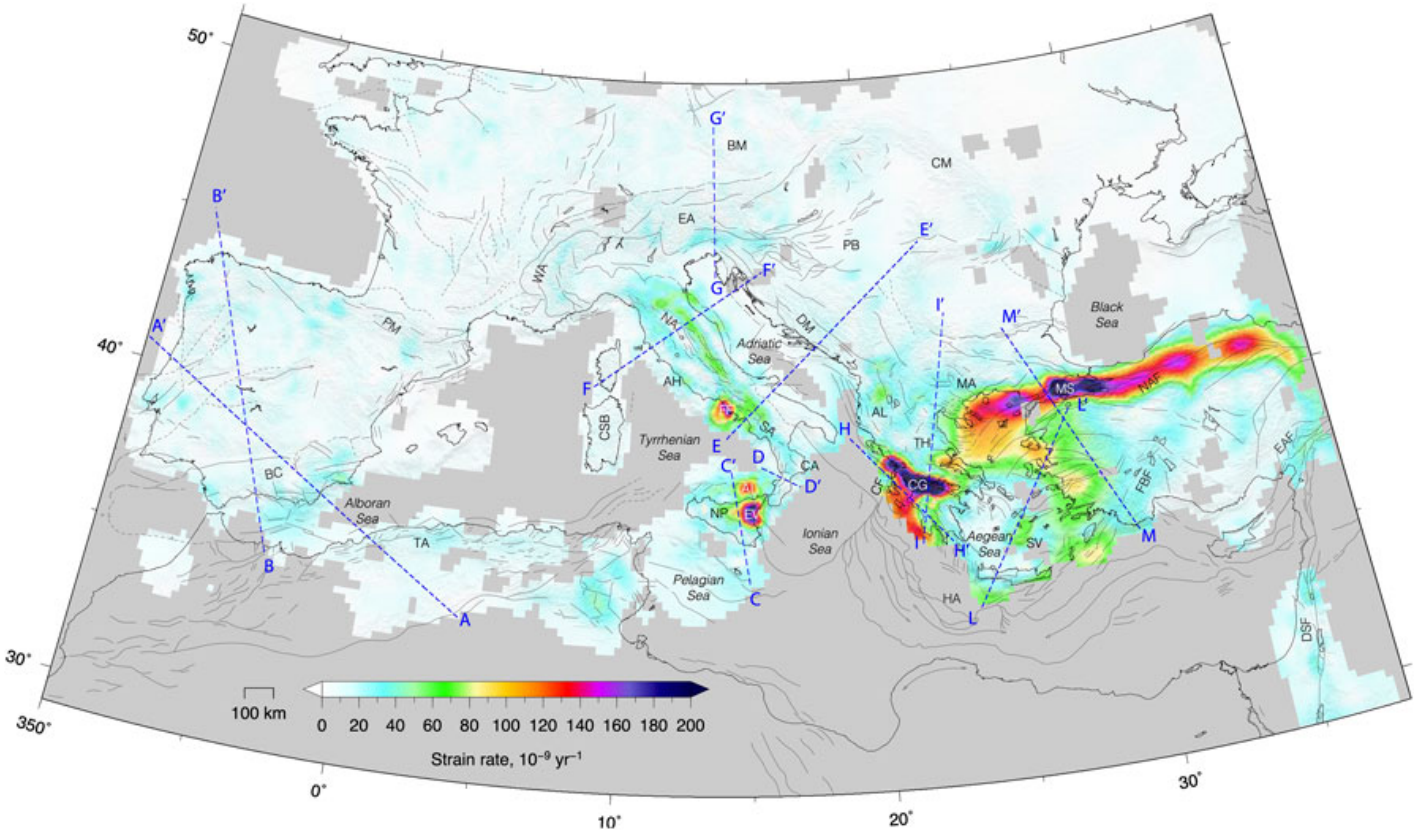


Velocity Field



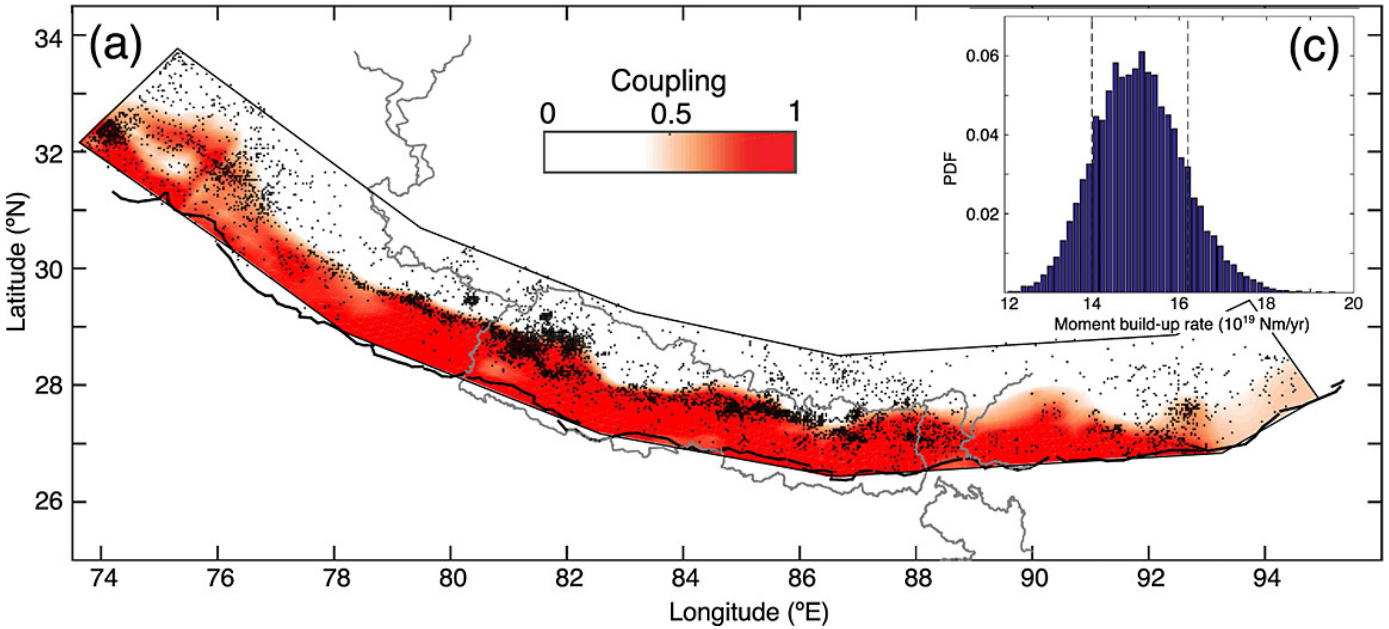
Serpelloni et al, 2022, *Front. Earth Sci.*

Strain Rate Field



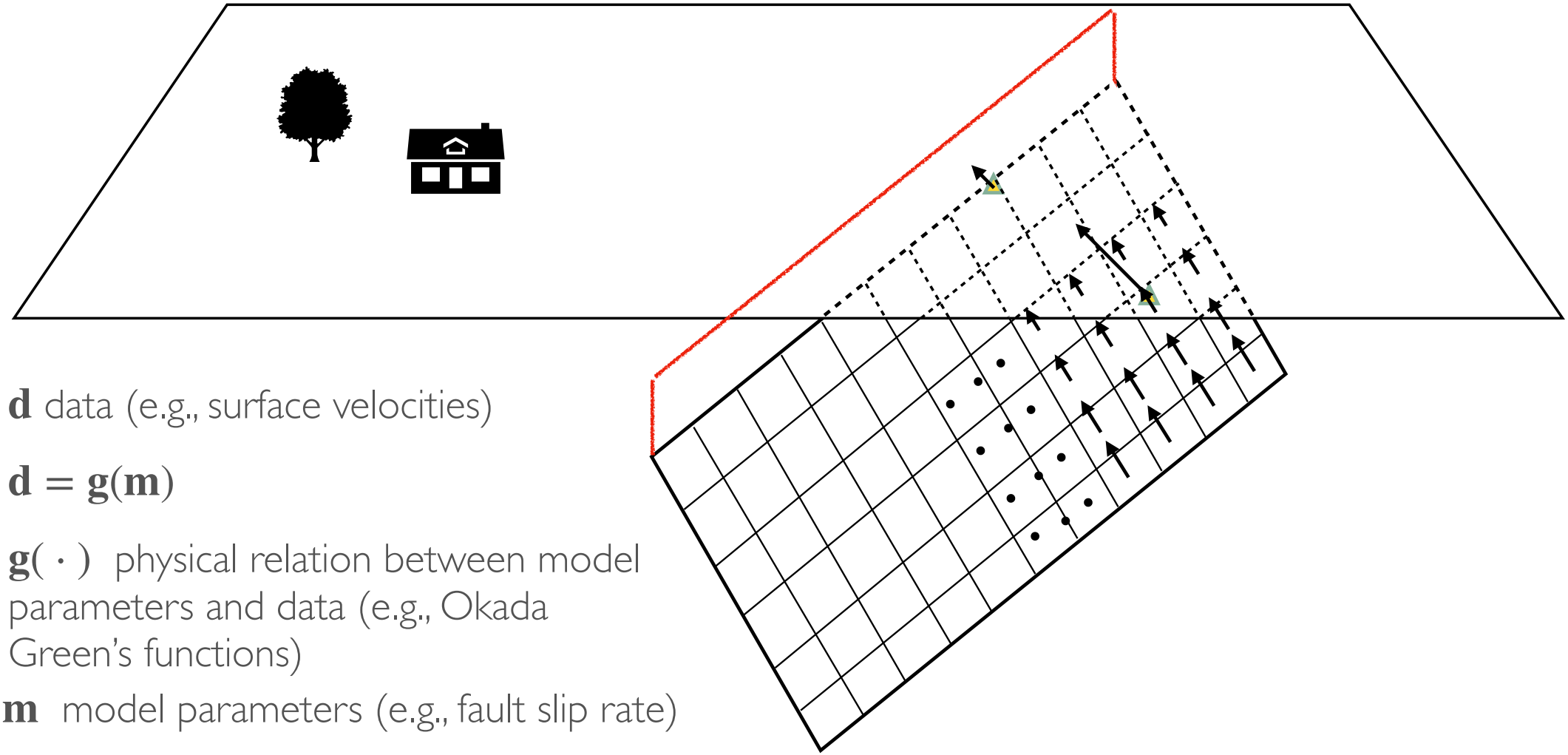
Serpelloni et al, 2022, *Front. Earth Sci.*

Coupling Map



Stevens and Avouac, 2015, *GRL*

Coupling Map



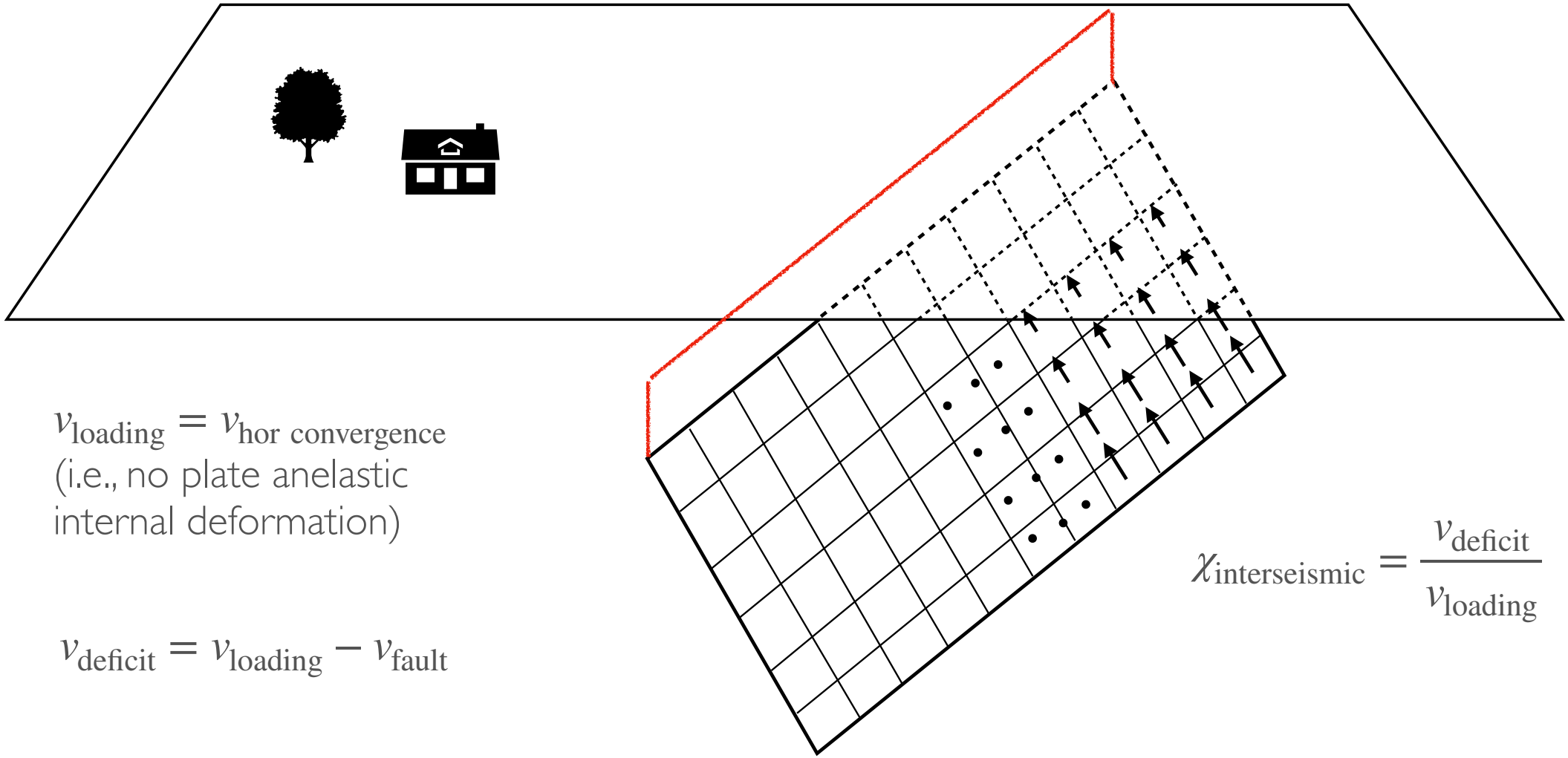
$\mathbf{d}$ data (e.g., surface velocities)

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

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

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

Coupling Map

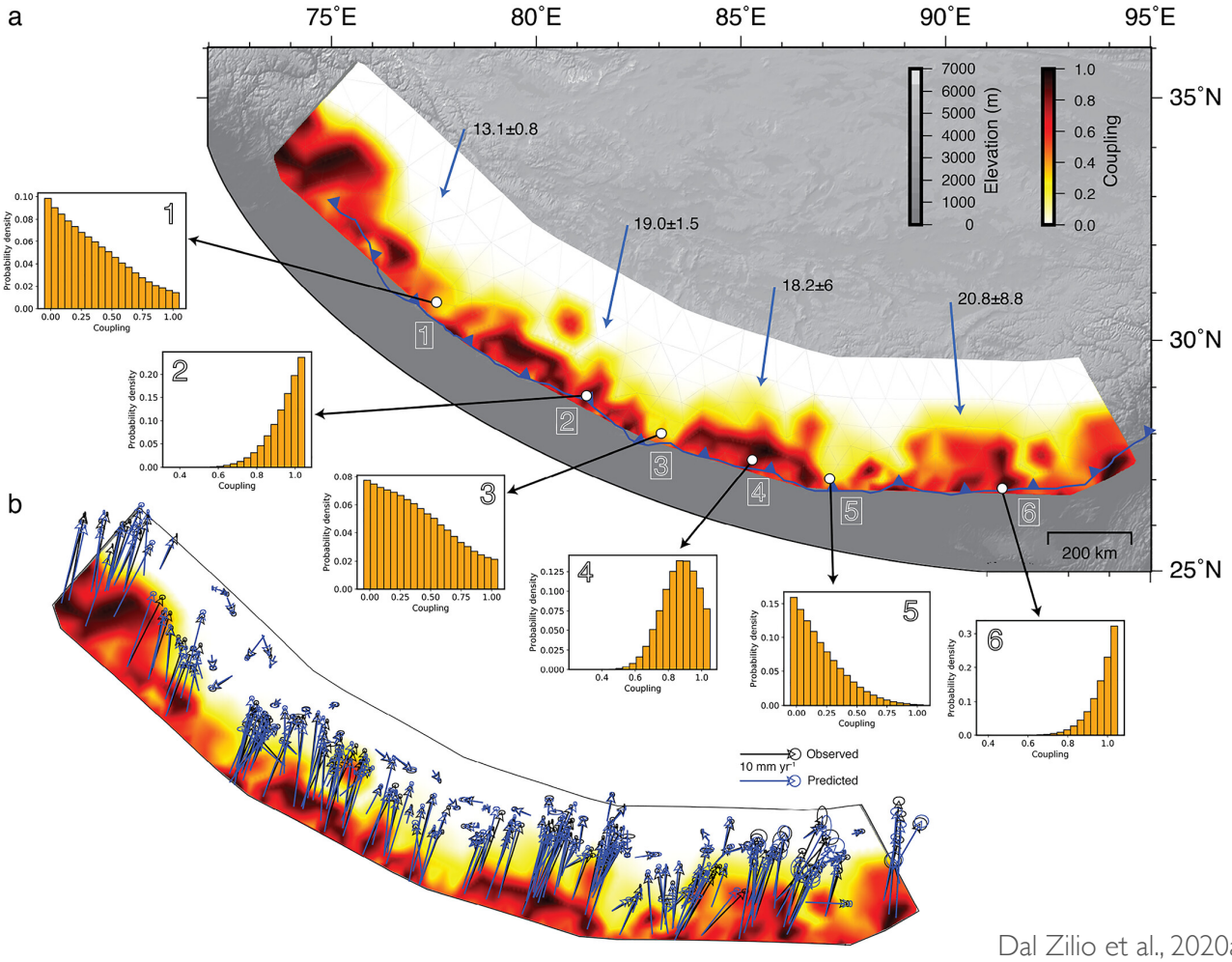


$v_{\text{loading}} = v_{\text{hor convergence}}$
(i.e., no plate anelastic internal deformation)

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

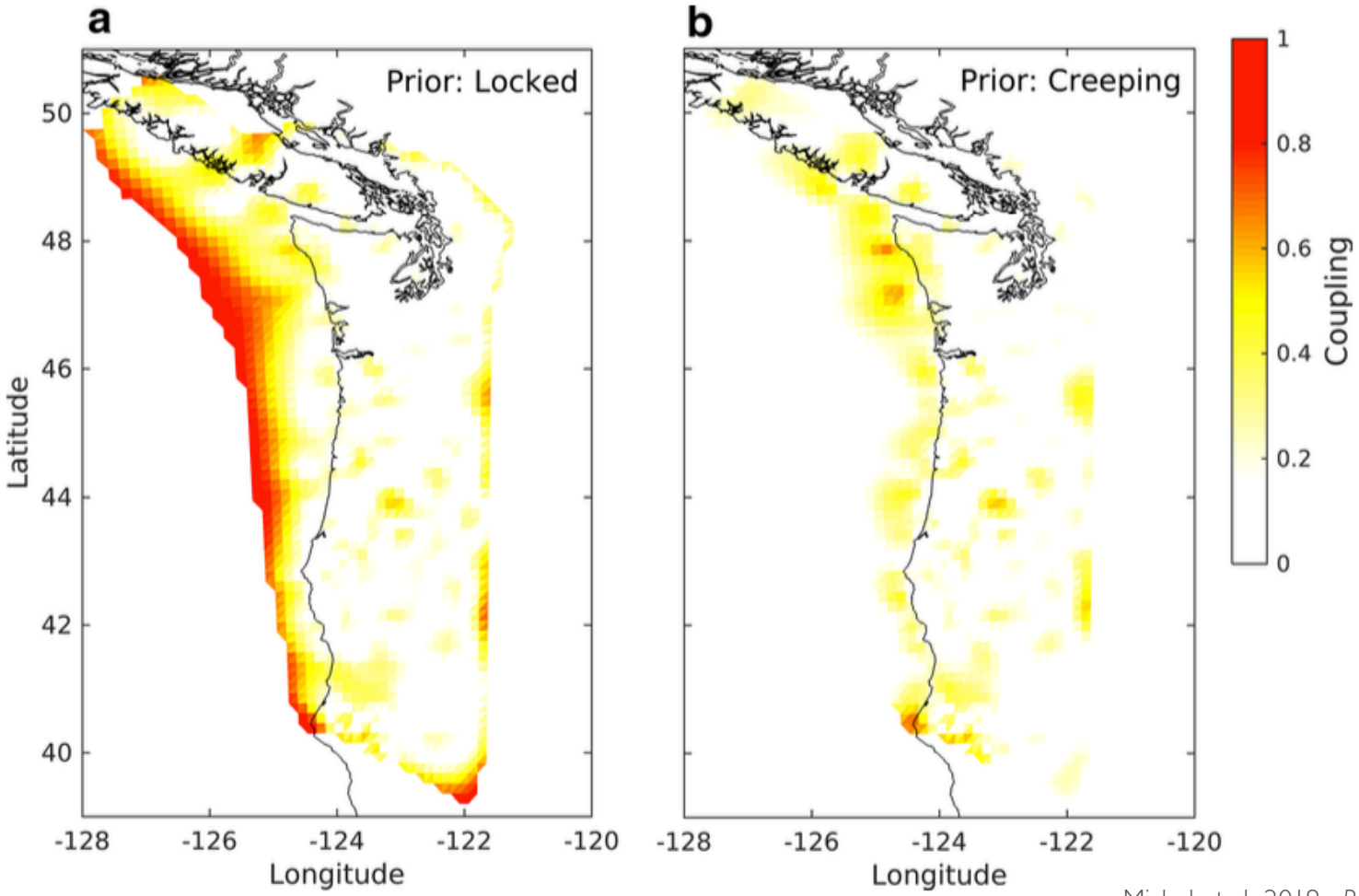
$$\chi_{\text{interseismic}} = \frac{v_{\text{deficit}}}{v_{\text{loading}}}$$

Coupling Map



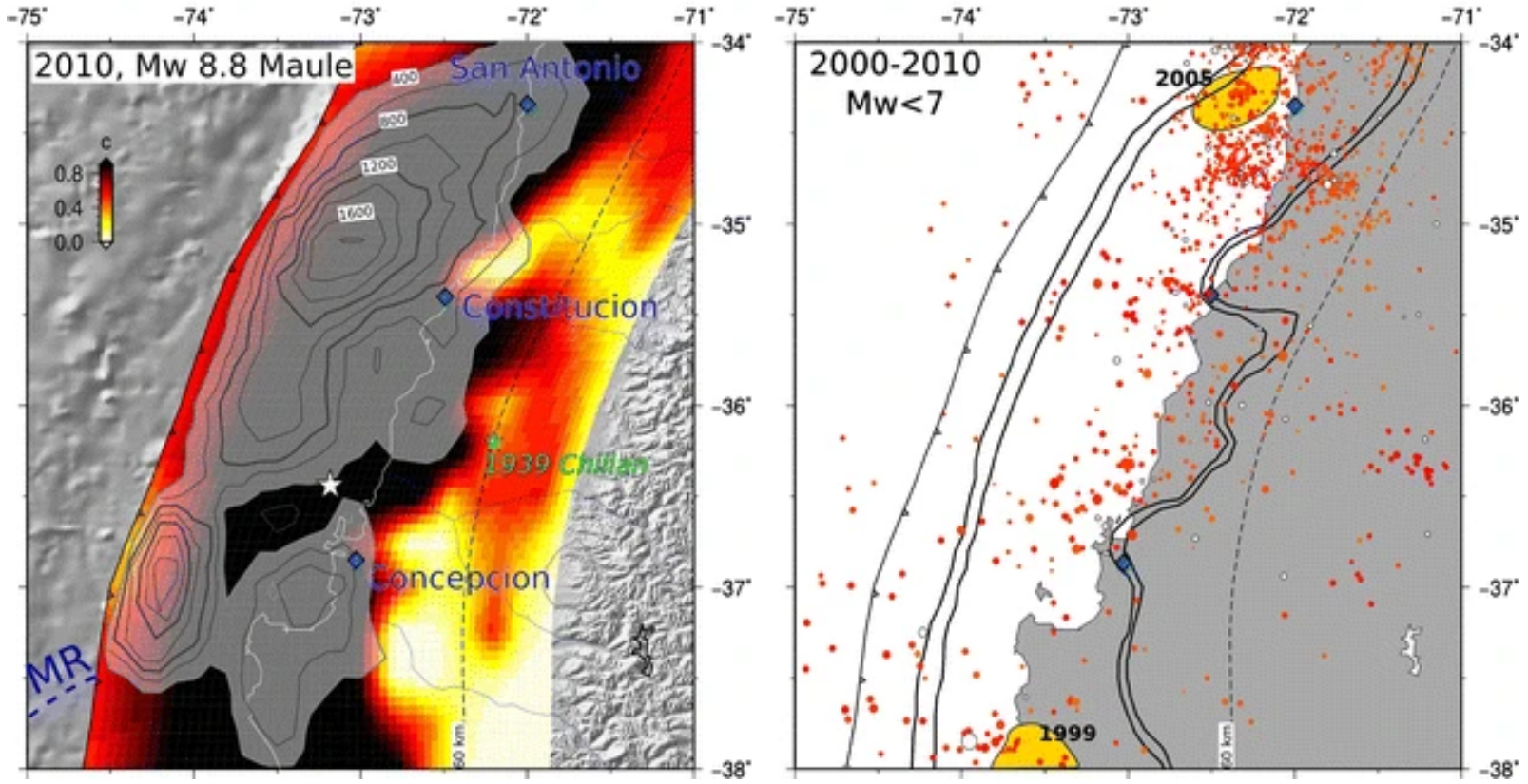
Dal Zilio et al., 2020a, *GRL*

Coupling Map



Michel et al., 2019a, *PAGEOPH*

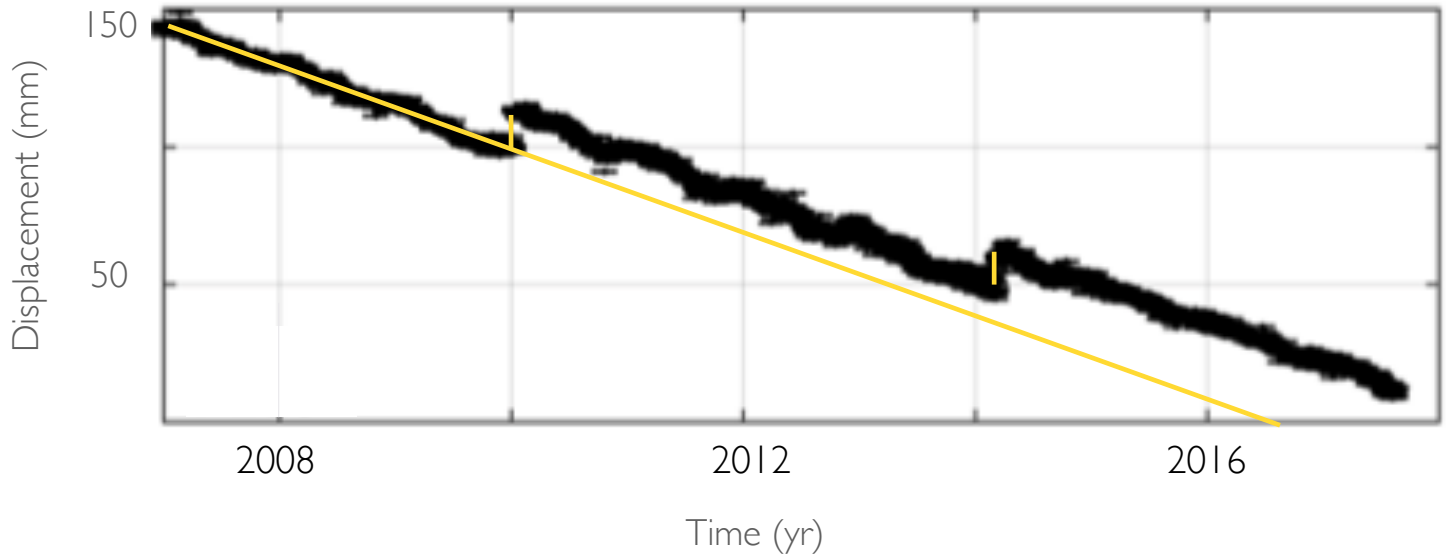
Coupling Map



Metois et al., 2016, *PAGEOPH*

Offsets

What can generate an offset ?



Michel et al., 2019a, *PAGEOPH*

Offsets

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Earthquakes

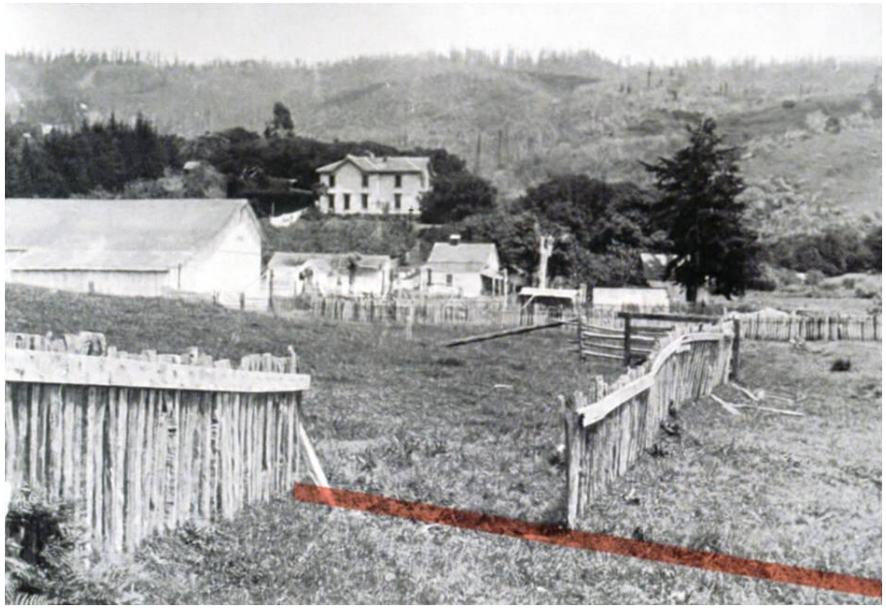
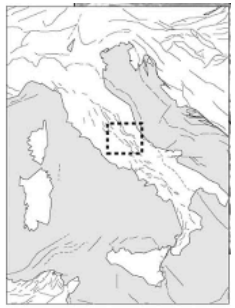


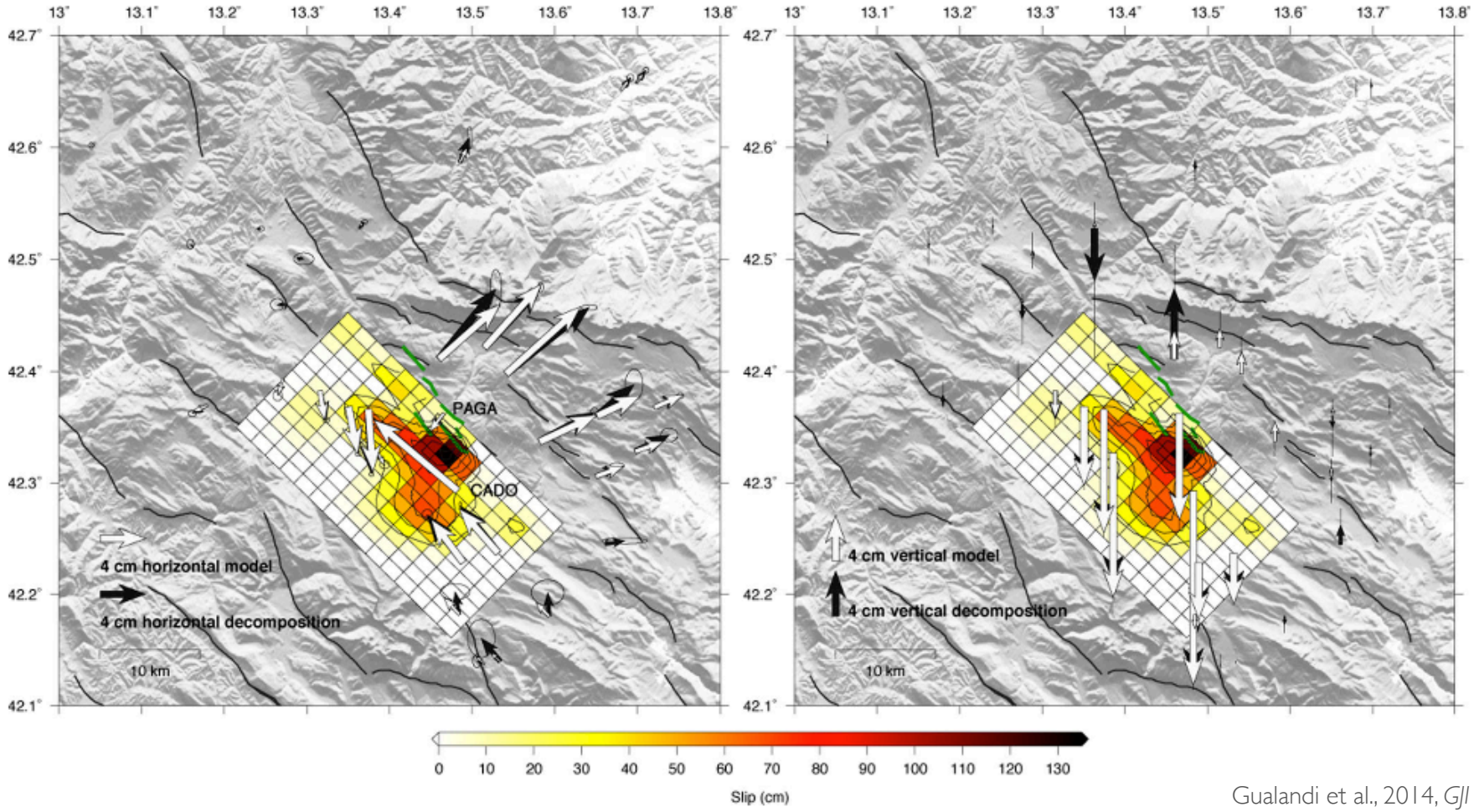
Photo by G.K. Gilbert

1906 San Francisco: ~ 3 m

Antenna change / firmware update

Static Inverse Problem

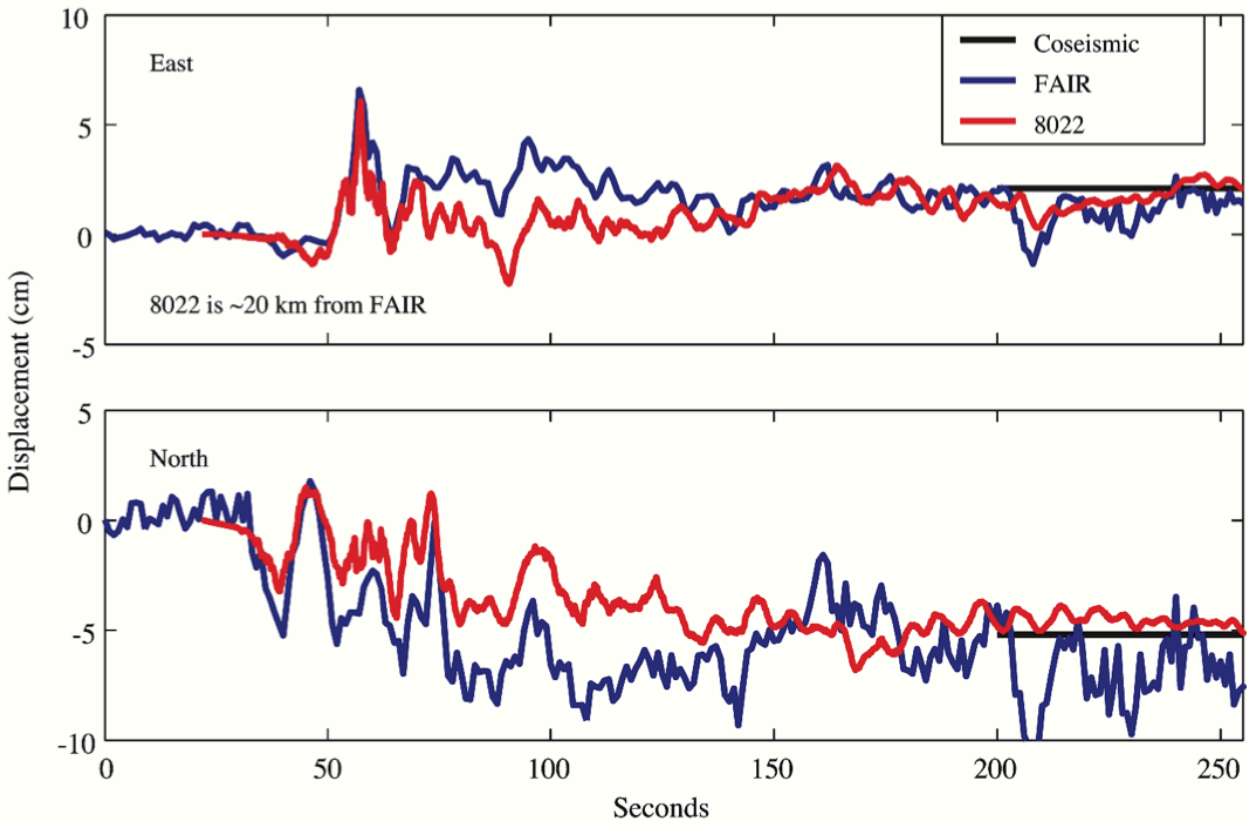




Gualandi et al., 2014, *GJI*

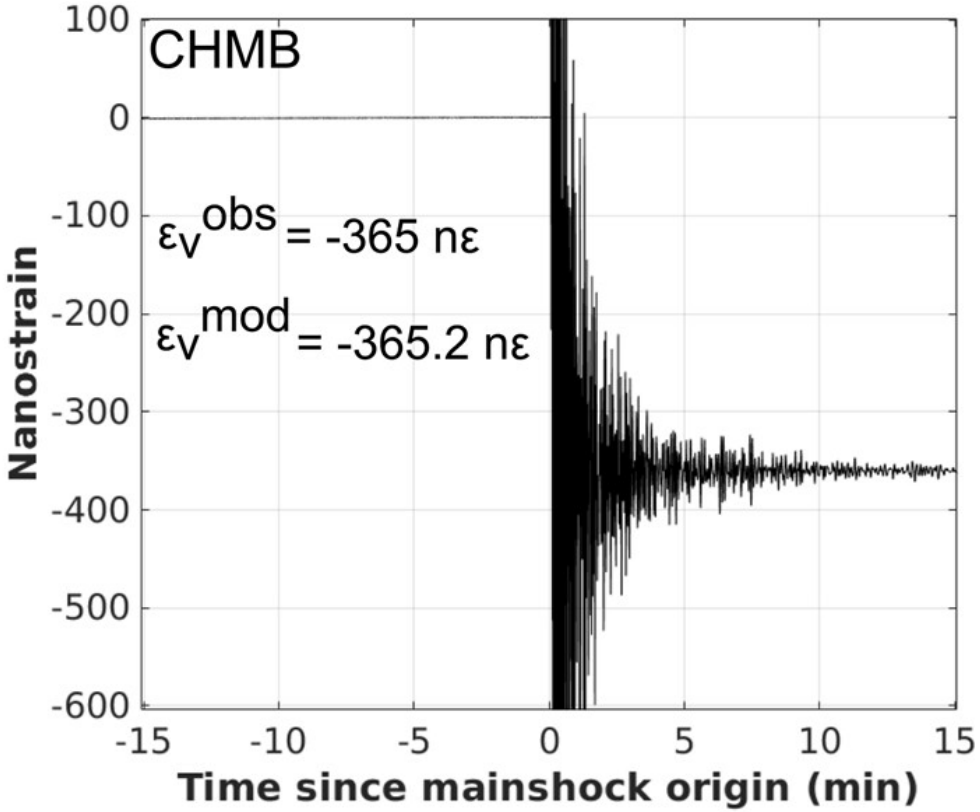
Dynamic Effects

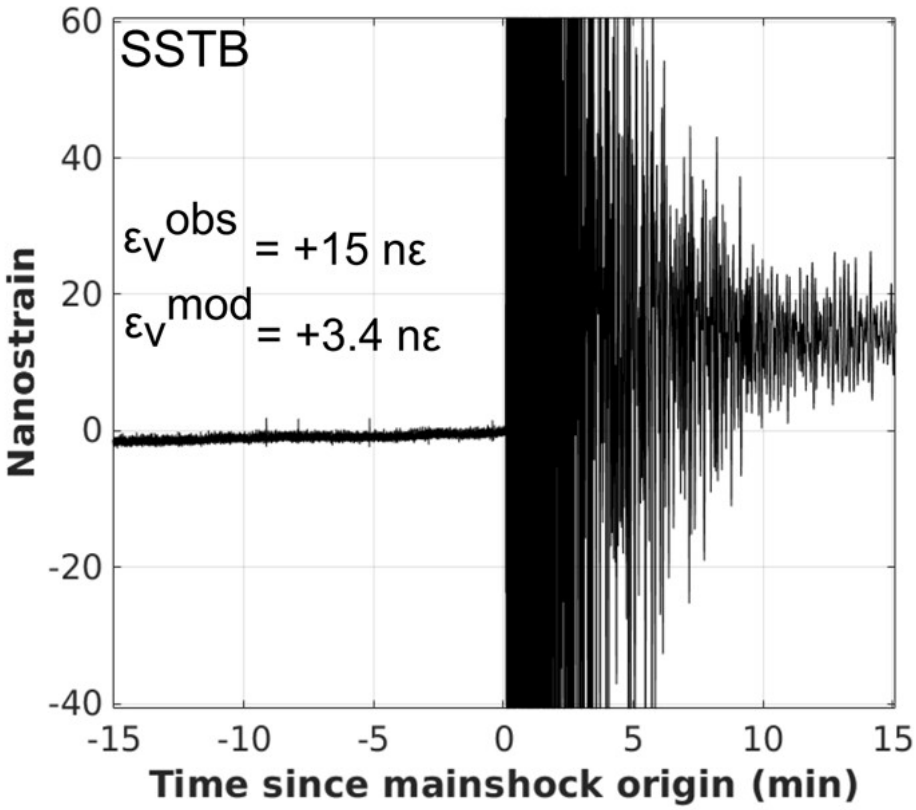
High-Rate Displacement



Larson et al., 2003, *Science*

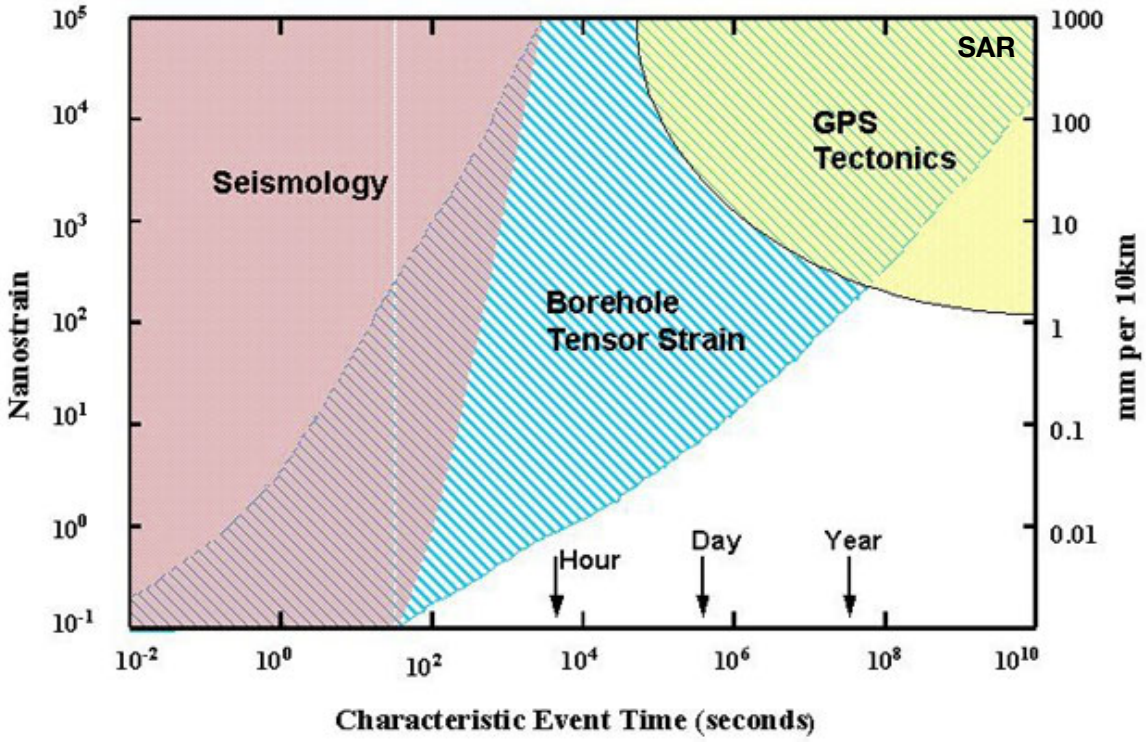
High-Rate Strain





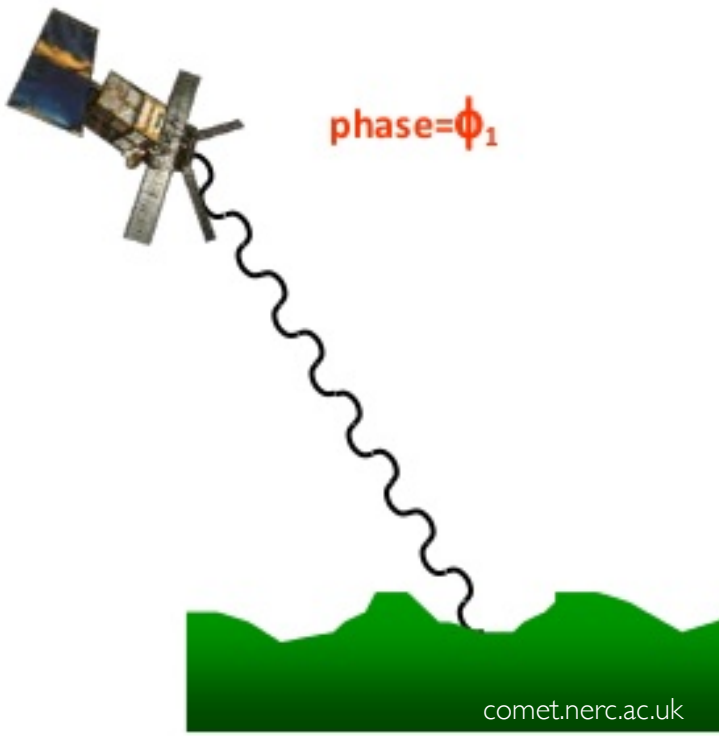
Lin et al., 2023, *JGR Solid Earth*

Sensitivity



Earthscope

Synthetic Aperture Radar (SAR)



Spatial resolution depends on $\frac{\lambda}{L}$

λ sensor wavelength

L length of the sensor's antenna

If $\lambda \sim 5$ cm $\Rightarrow$ $L \sim 4.25$ km

to get a spatial resolution of ~ 10 m

www.earthdata.nasa.gov/

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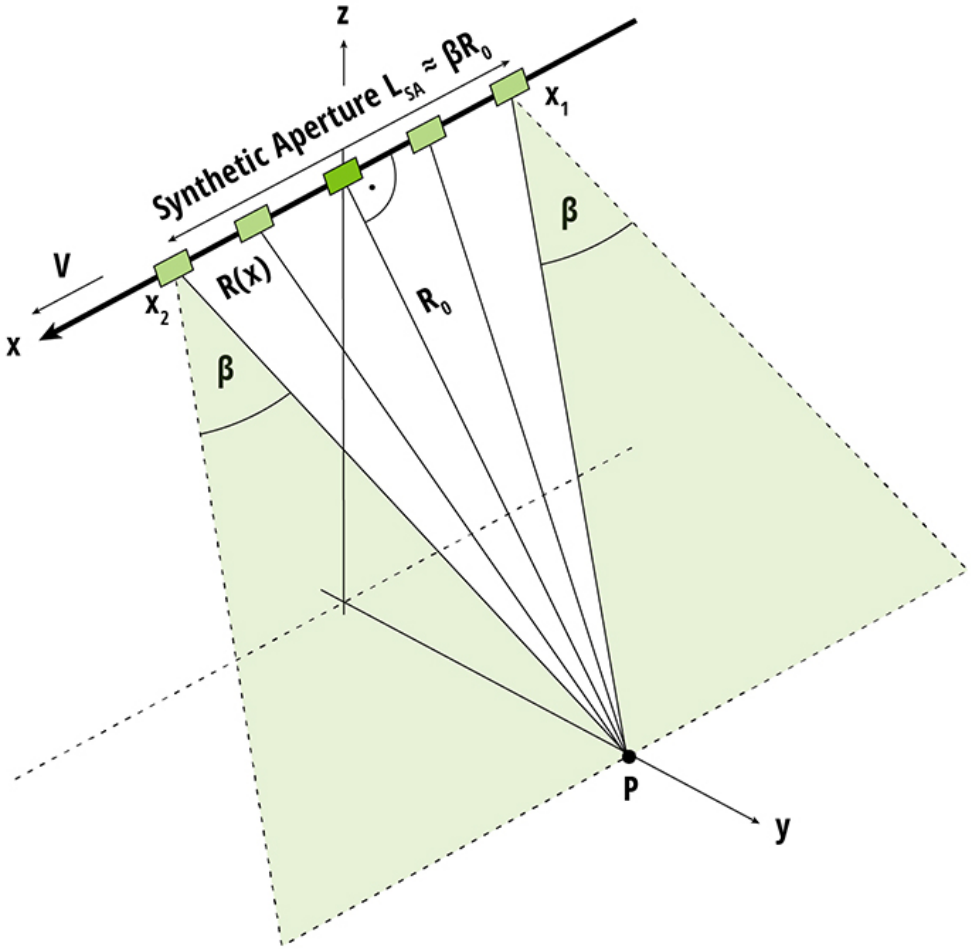

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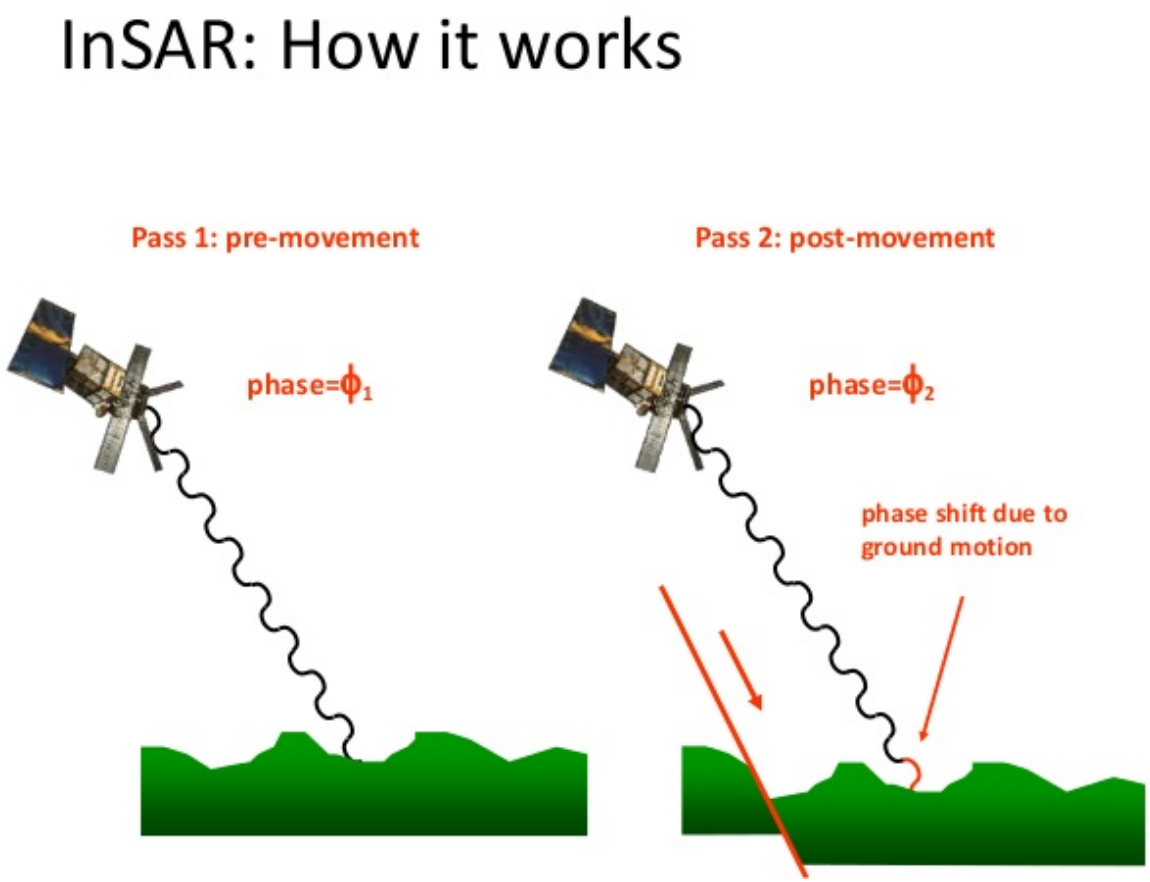
Wavelengths

Band	Frequency	Wavelength	Typical Application
Ka	27–40 GHz	1.1–0.8 cm	Rarely used for SAR (airport surveillance)
K	18–27 GHz	1.7–1.1 cm	rarely used (H_2O absorption)
Ku	12–18 GHz	2.4–1.7 cm	rarely used for SAR (satellite altimetry)
X	8–12 GHz	3.8–2.4 cm	High resolution SAR (urban monitoring,; ice and snow, little penetration into vegetation cover; fast coherence decay in vegetated areas)
C	4–8 GHz	7.5–3.8 cm	SAR Workhorse (global mapping; change detection; monitoring of areas with low to moderate penetration; higher coherence); ice, ocean maritime navigation
S	2–4 GHz	15–7.5 cm	Little but increasing use for SAR-based Earth observation; agriculture monitoring (NISAR will carry an S-band channel; expends C-band applications to higher vegetation density)
L	1–2 GHz	30–15 cm	Medium resolution SAR (geophysical monitoring; biomass and vegetation mapping; high penetration, InSAR)
P	0.3–1 GHz	100–30 cm	Biomass. First p-band spaceborne SAR will be launched ~2020; vegetation mapping and assessment. Experimental SAR.

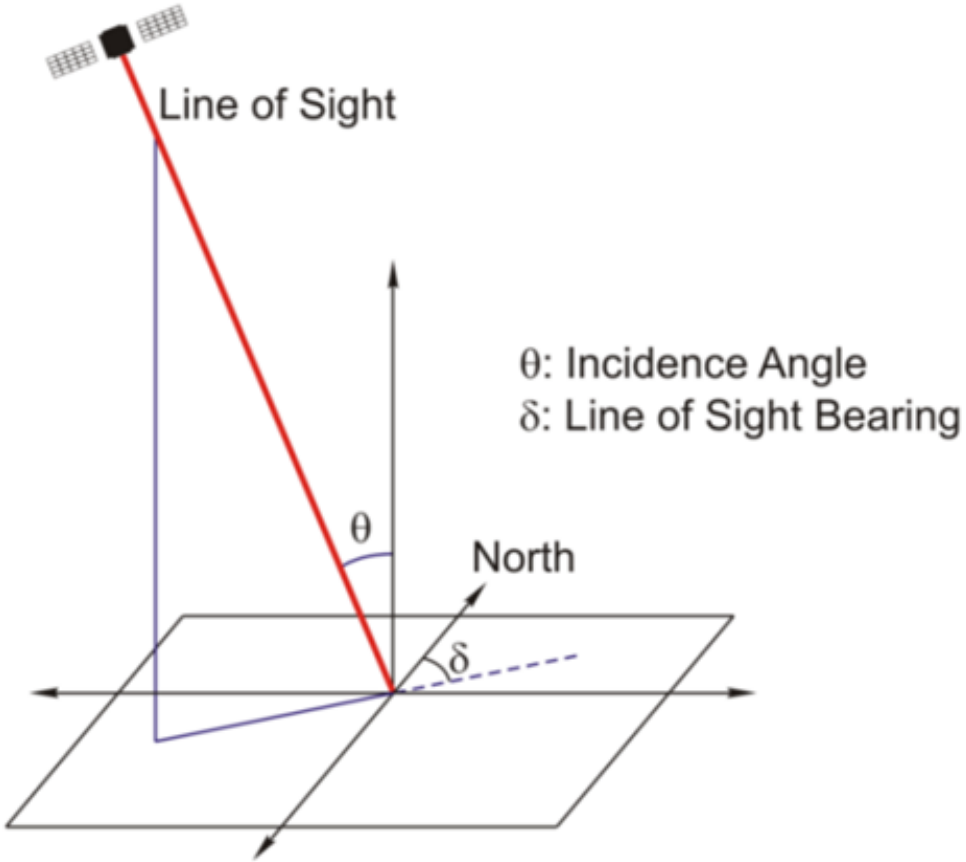
www.earthdata.nasa.gov/

Interferometric SAR (InSAR)



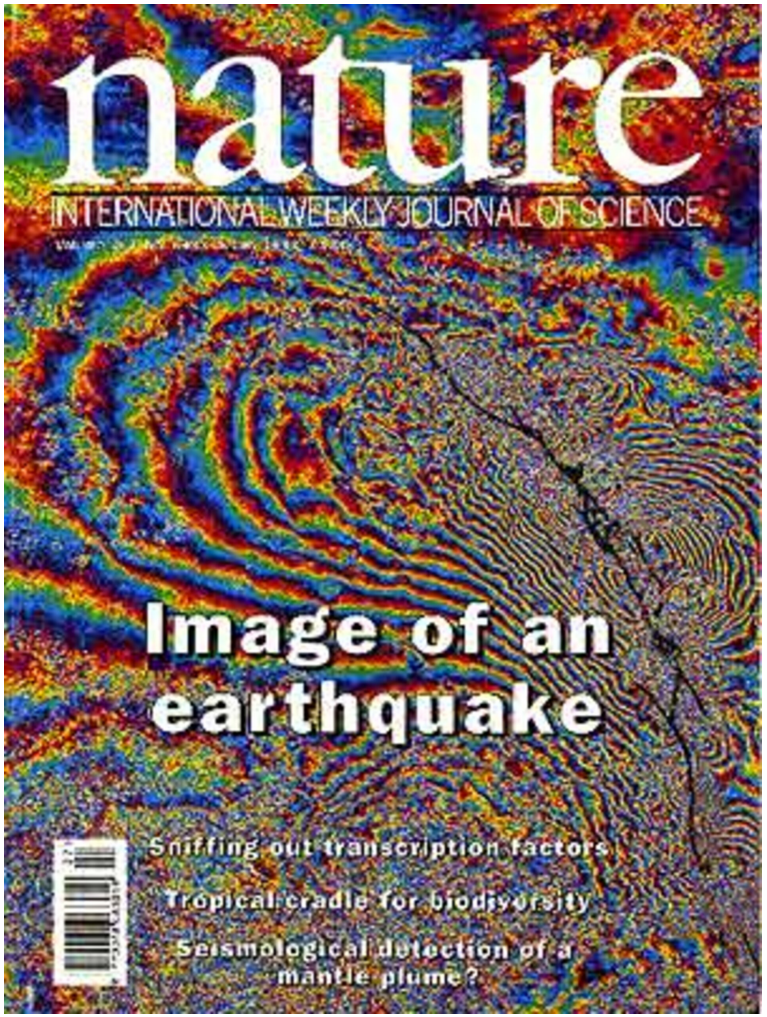
comet.nerc.ac.uk

Line of Sight (LOS)



satelliteblog.cgg.com- Image © CGG

InSAR and Earthquakes



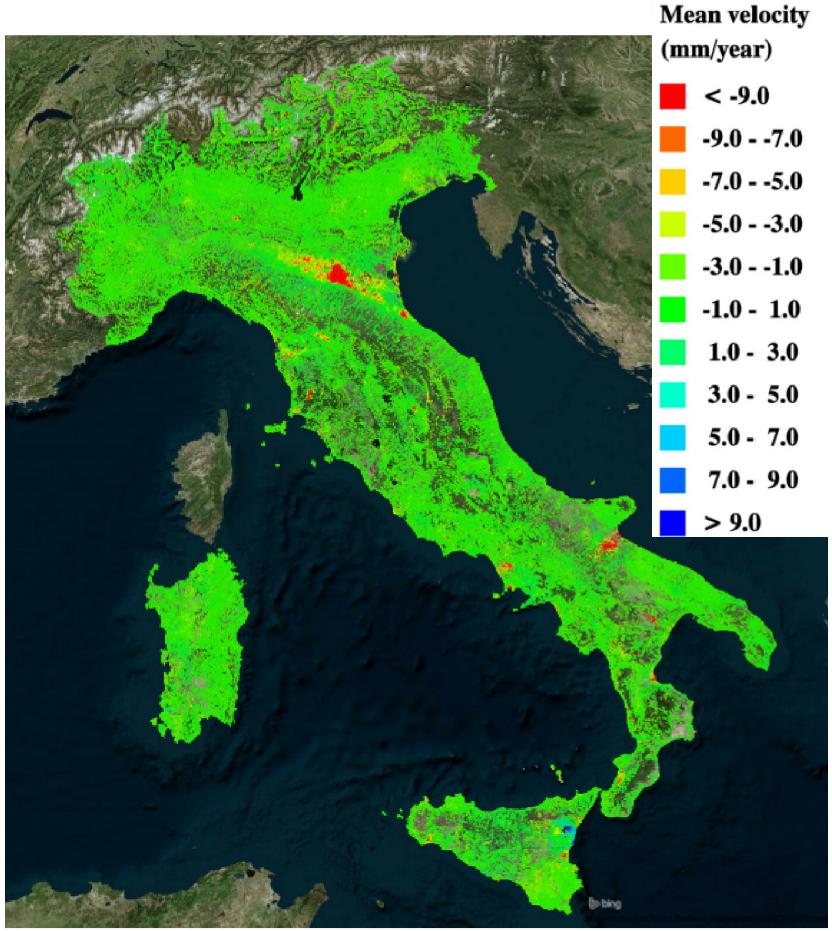
1 cycle = λ

Moving towards satellite

Moving away from satellite

Massonnet et al., 1993, *Nature*

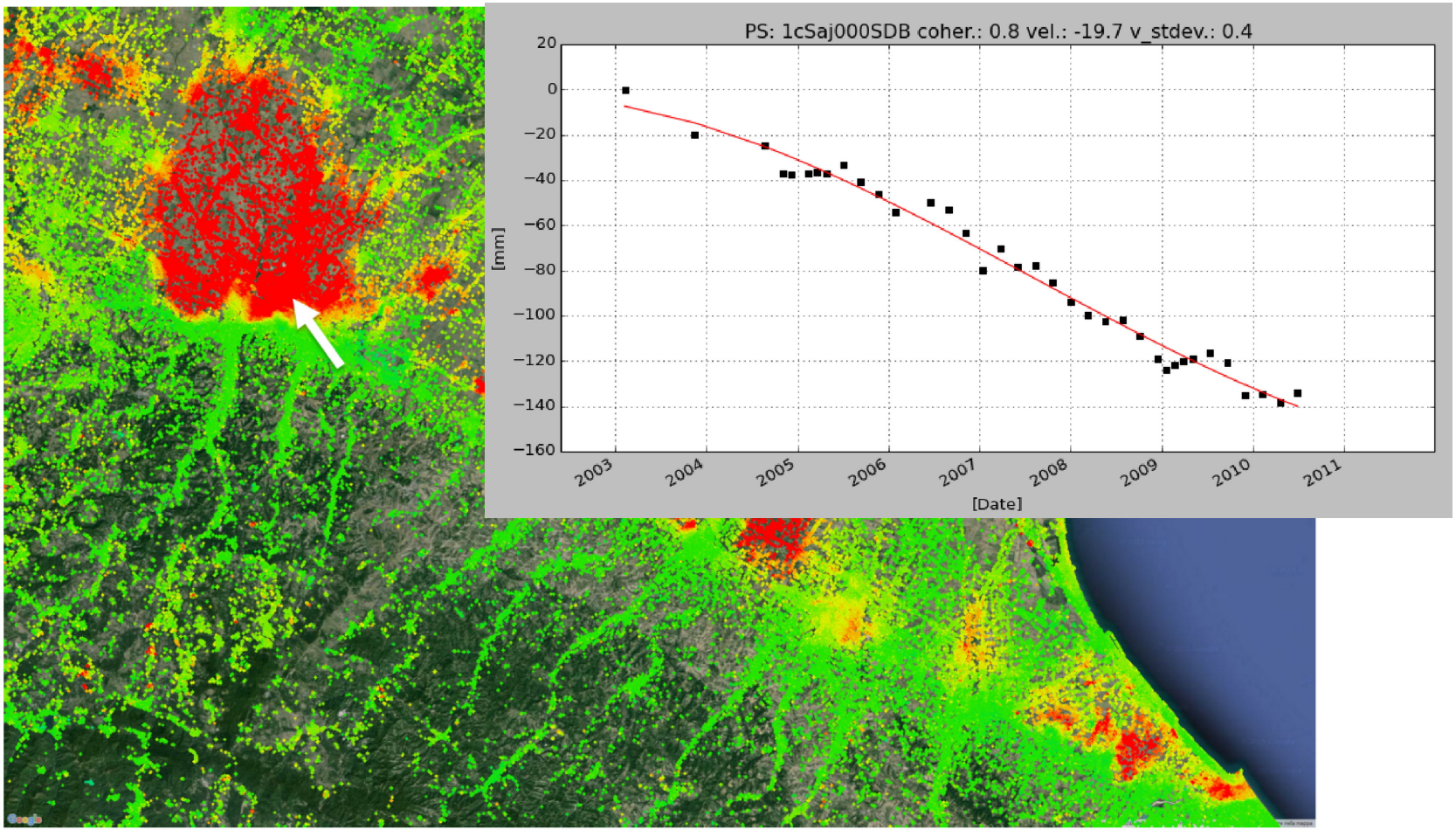
Velocity Field



ERS descending

Costantini et al., 2017, *Remote Sensing of Environment*

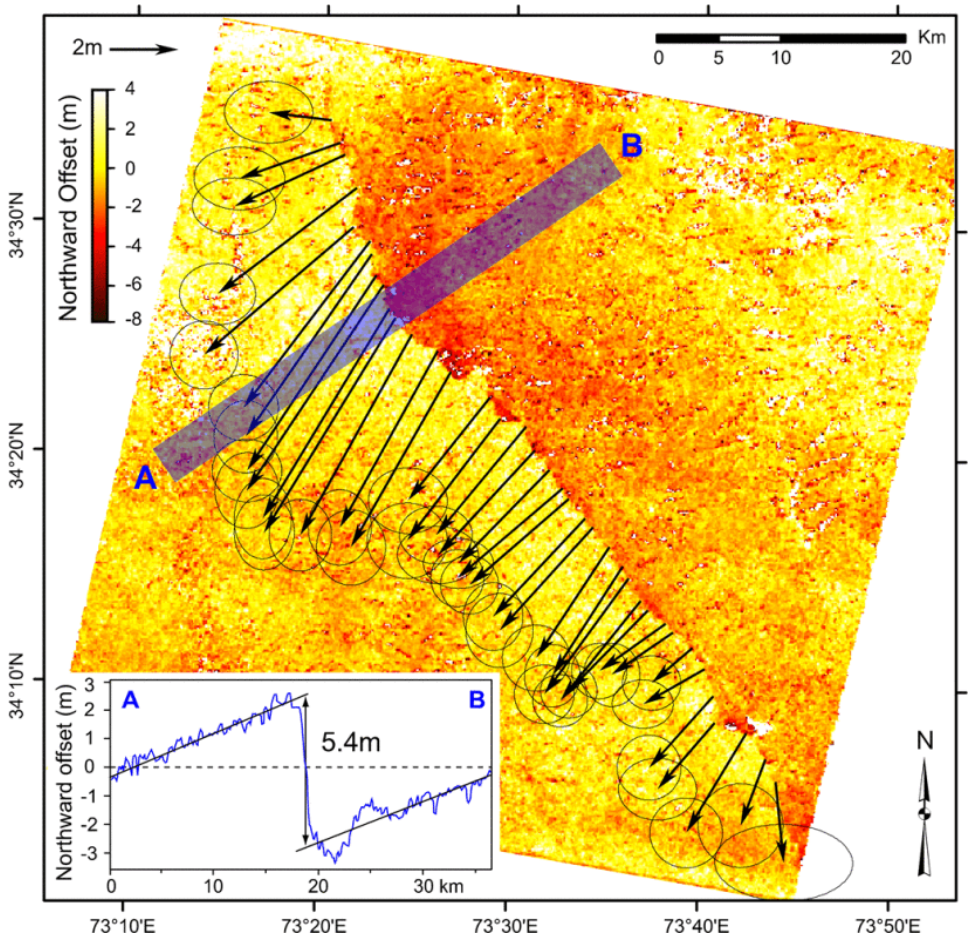
Velocity Field



Envisat descending (2003-2010)

Costantini et al., 2017, *Remote Sensing of Environment*

Photogrammetry

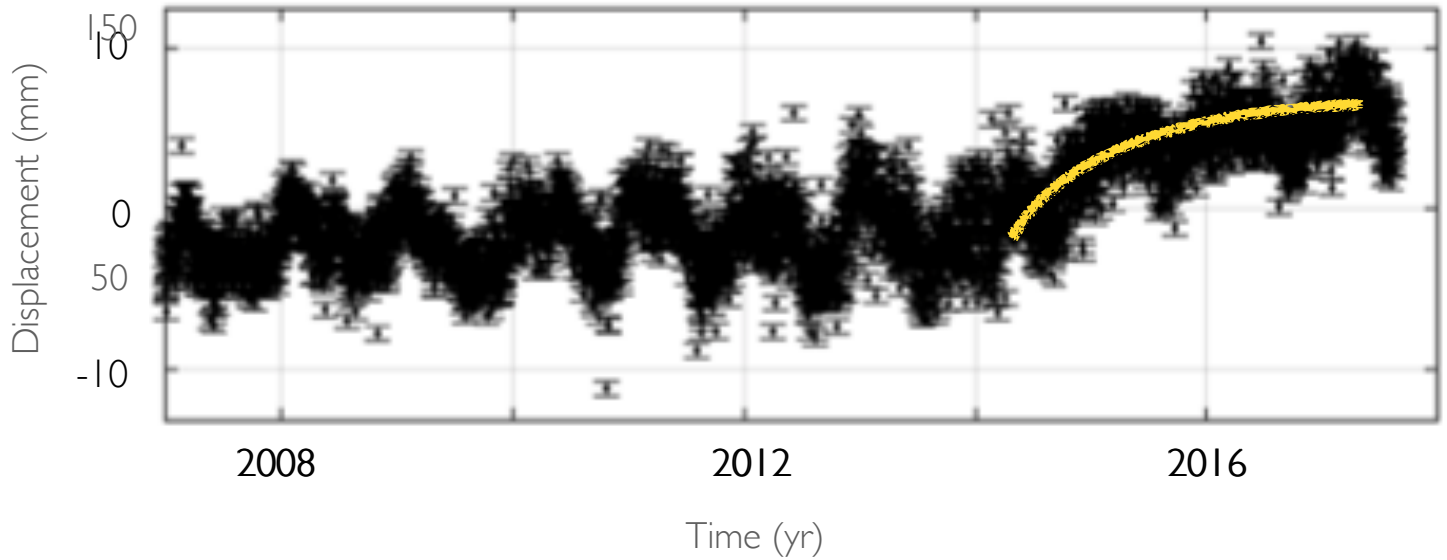


M_w 7.6 Kashmir earthquake (2005)

Leprince et al., 2007, *IEEE (IGARSS)*

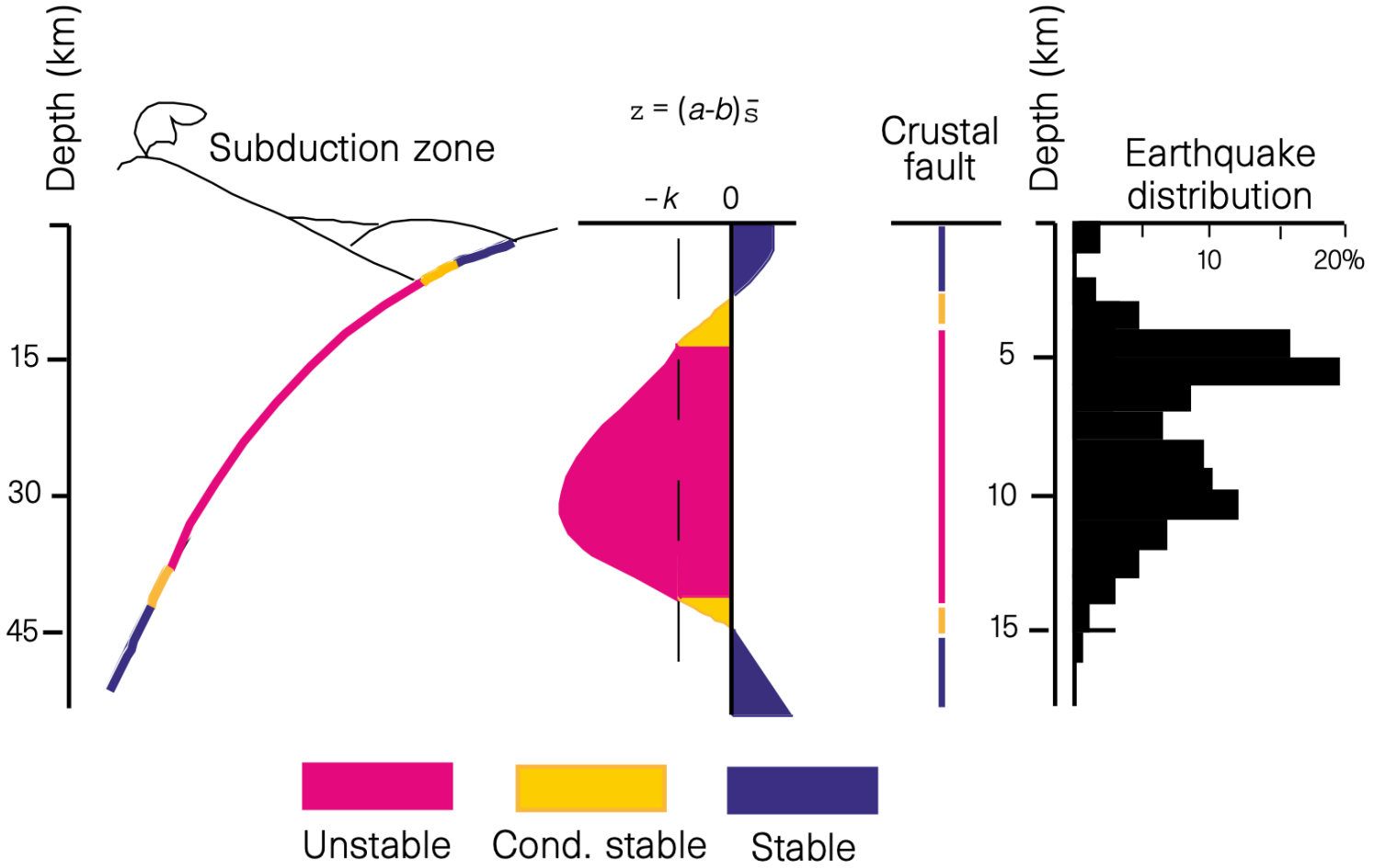
Daily GNSS Position Time Series

What can generate post-seismic deformation ?



Michel et al., 2019a, *PAGEOPH*

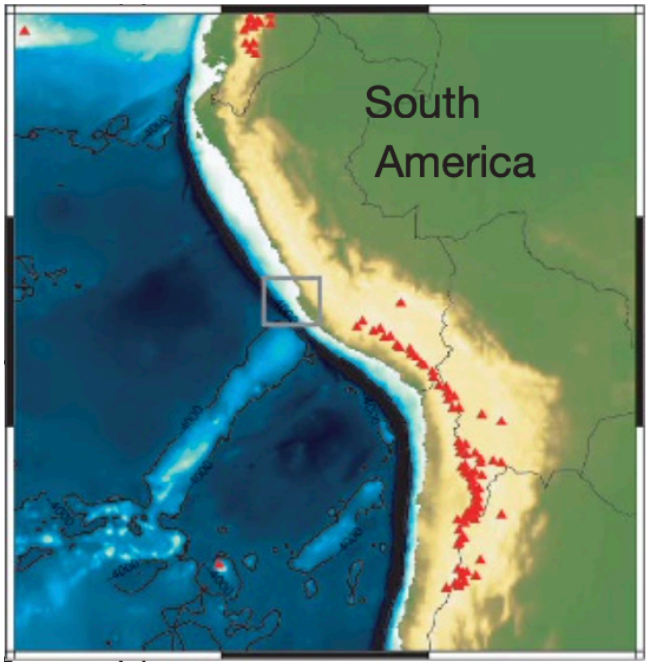
Post-Seismic Deformation

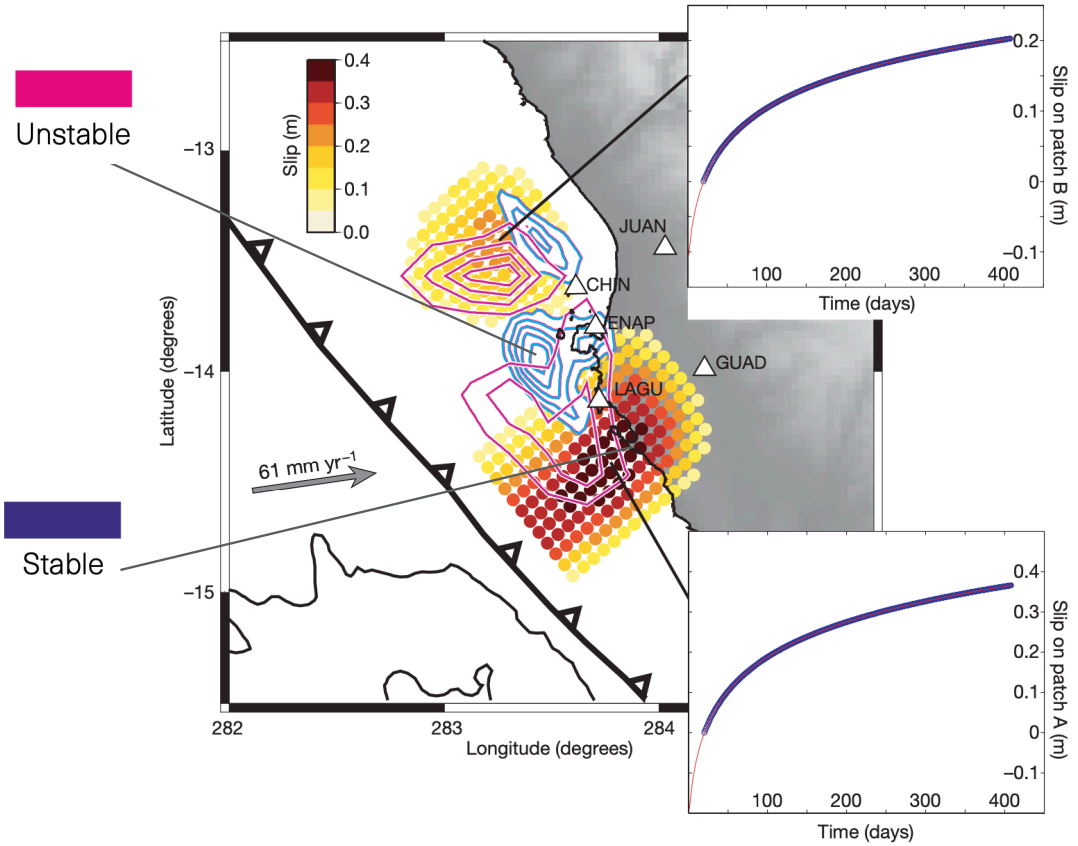


Scholz, 1998, *Nature*

Afterslip

subduction

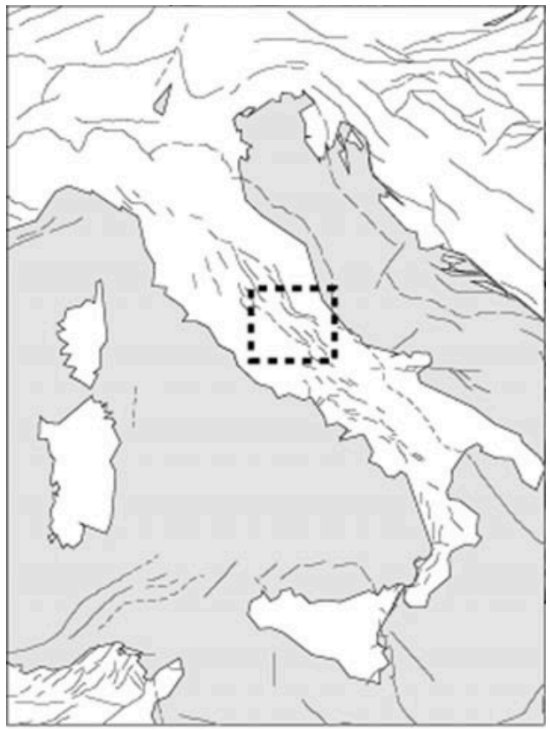


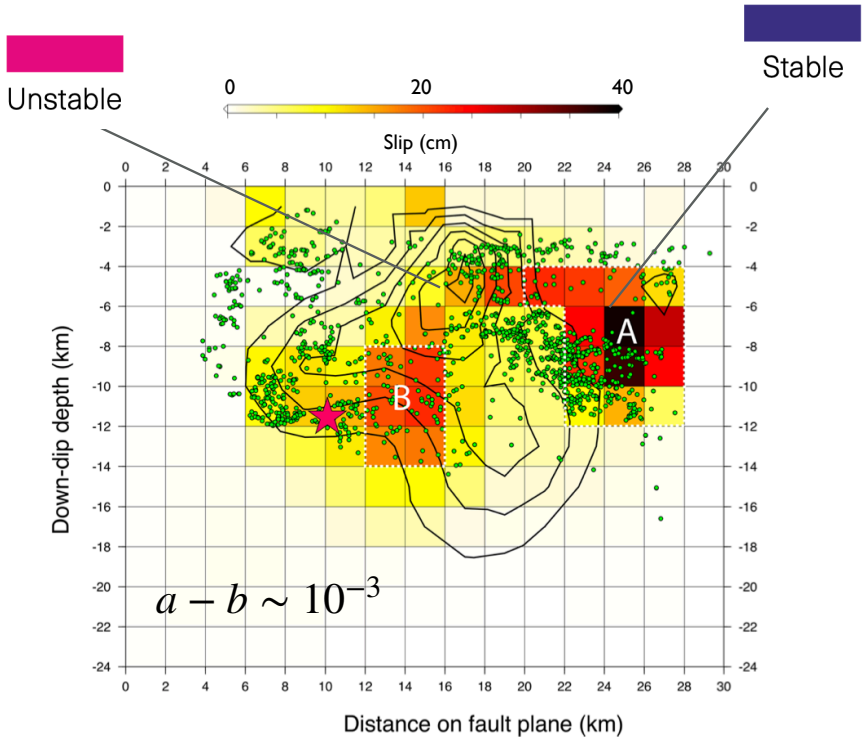


Perfettini et al., 2010, *Nature*

Afterslip

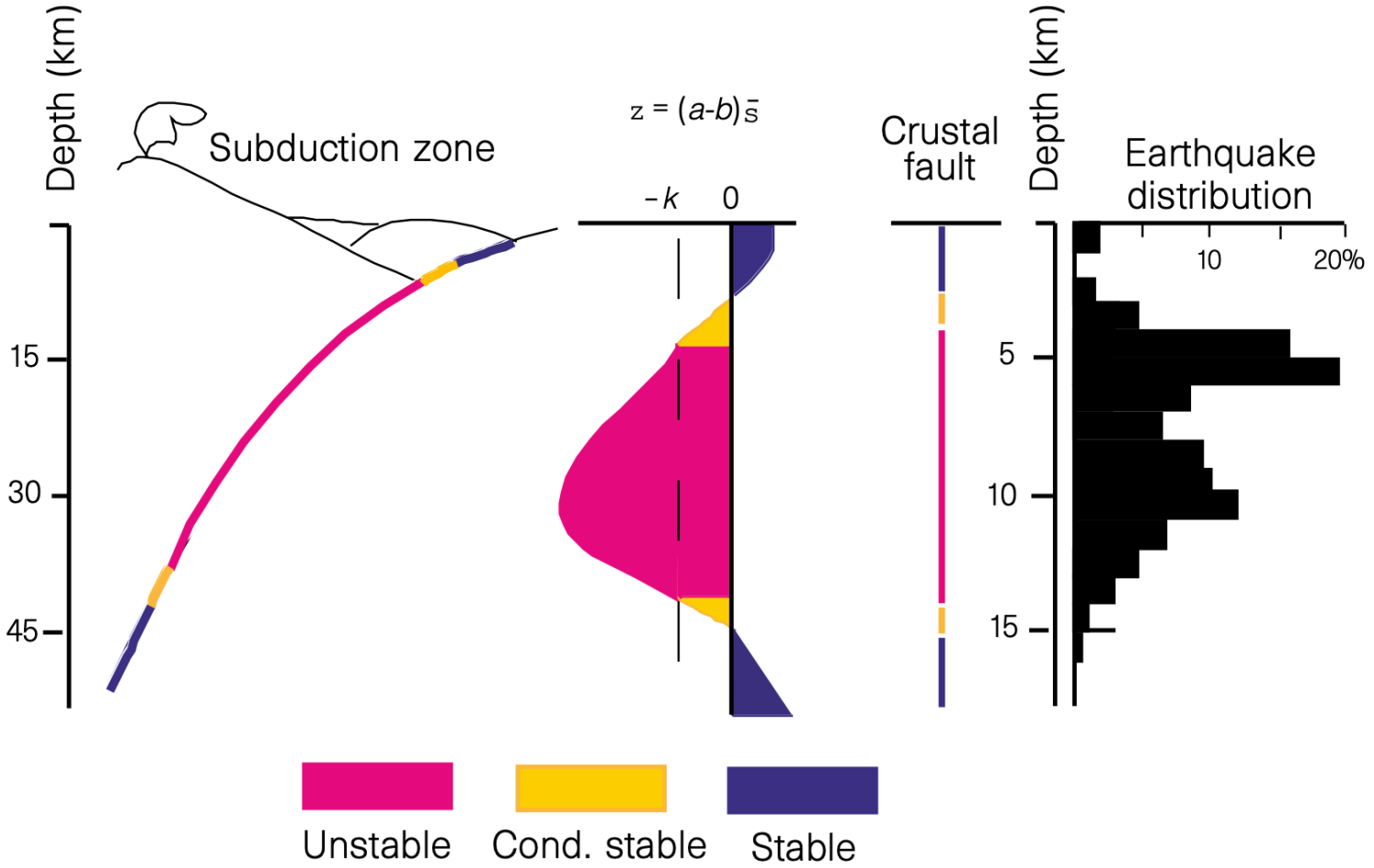
intraplate





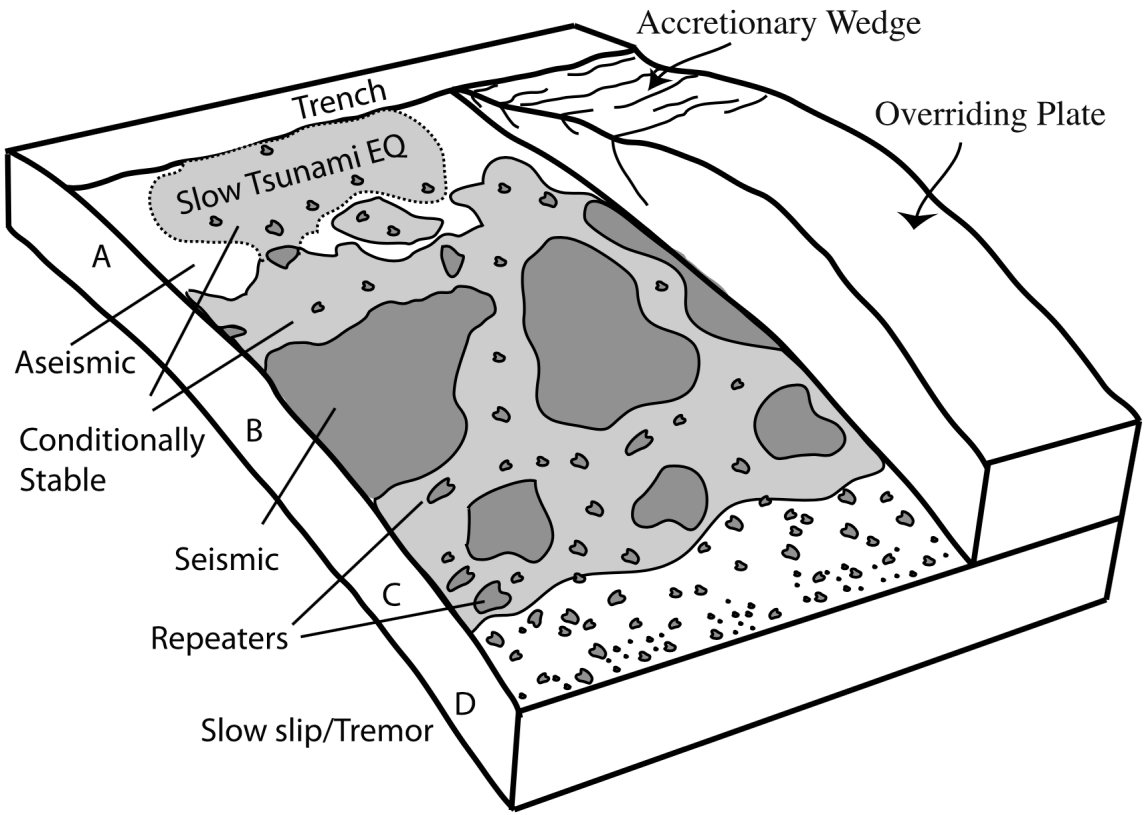
Gualandi et al., 2014, *GJI*

Fault Heterogeneities



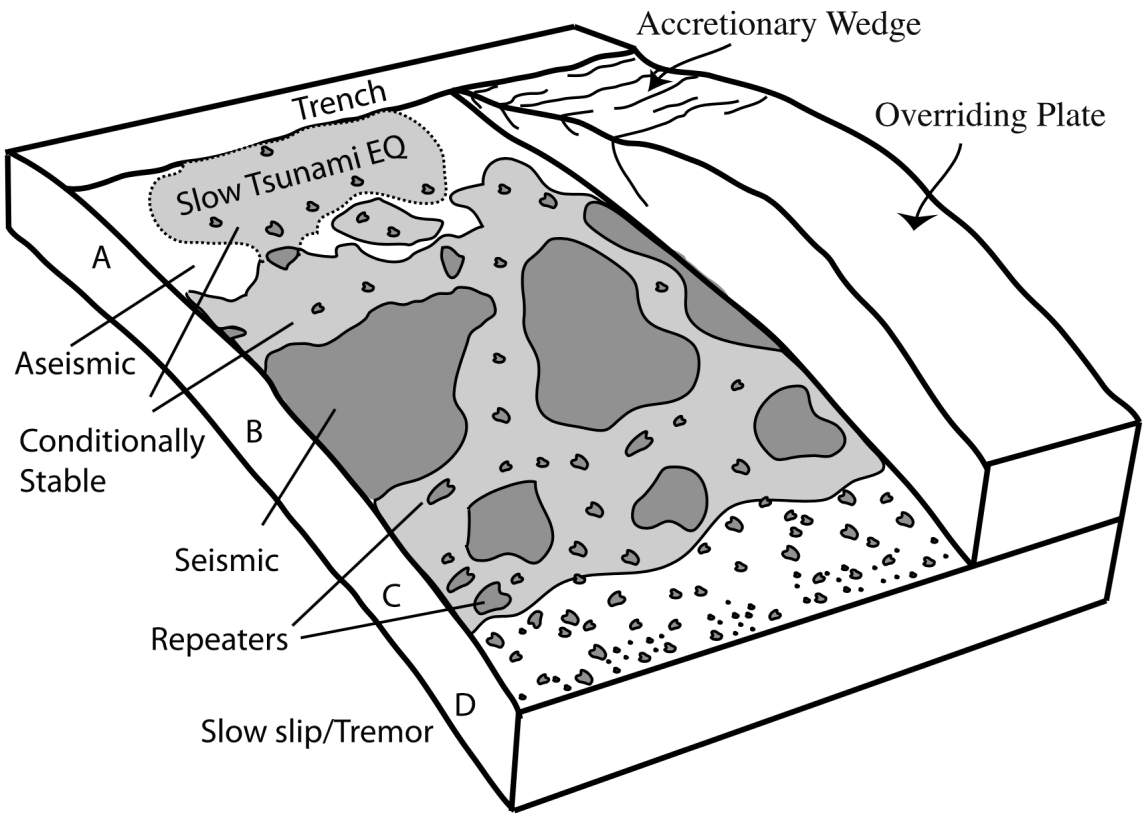
Scholz, 1998, *Nature*

Fault Heterogeneities

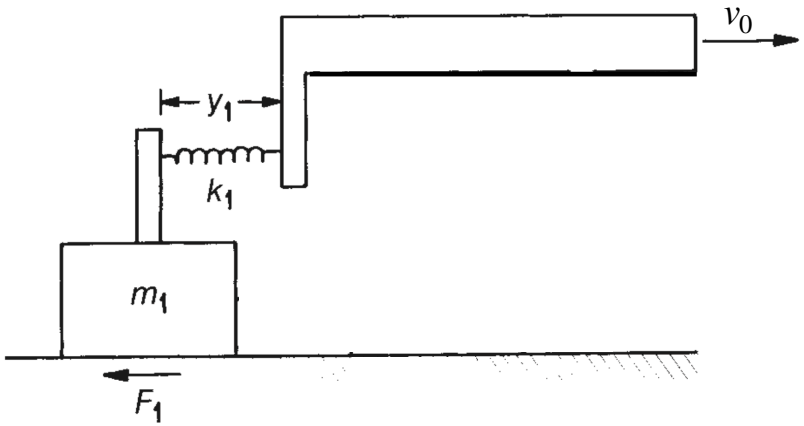


Lay et al., 2012, *JGR*.

Friction Law

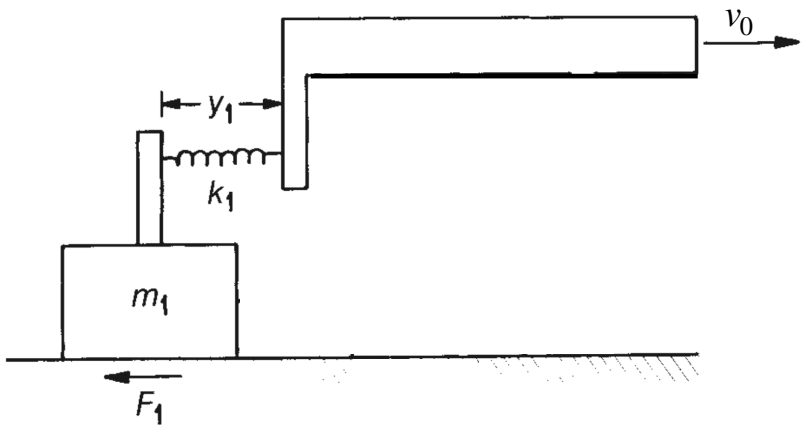


Lay et al., 2012, *JGR*.



Huang and Turcotte, 1990, *Nature*

Friction Law

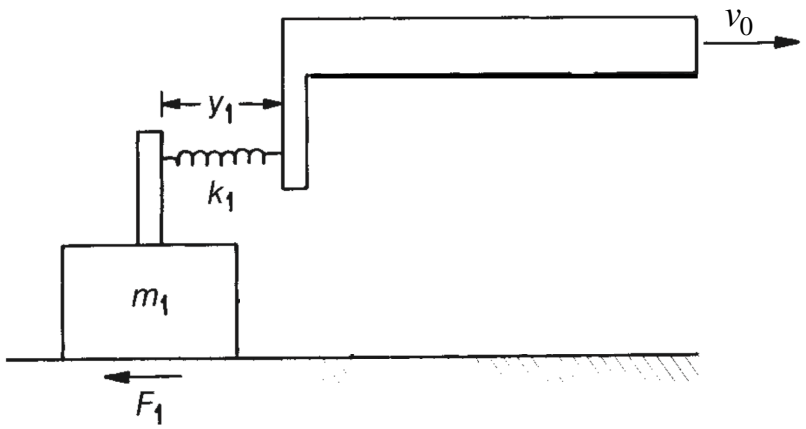


Huang and Turcotte, 1990, *Nature*

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

Perfettini and Avouac, 2004a, *JGR*

Friction Law



Huang and Turcotte, 1990, *Nature*

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

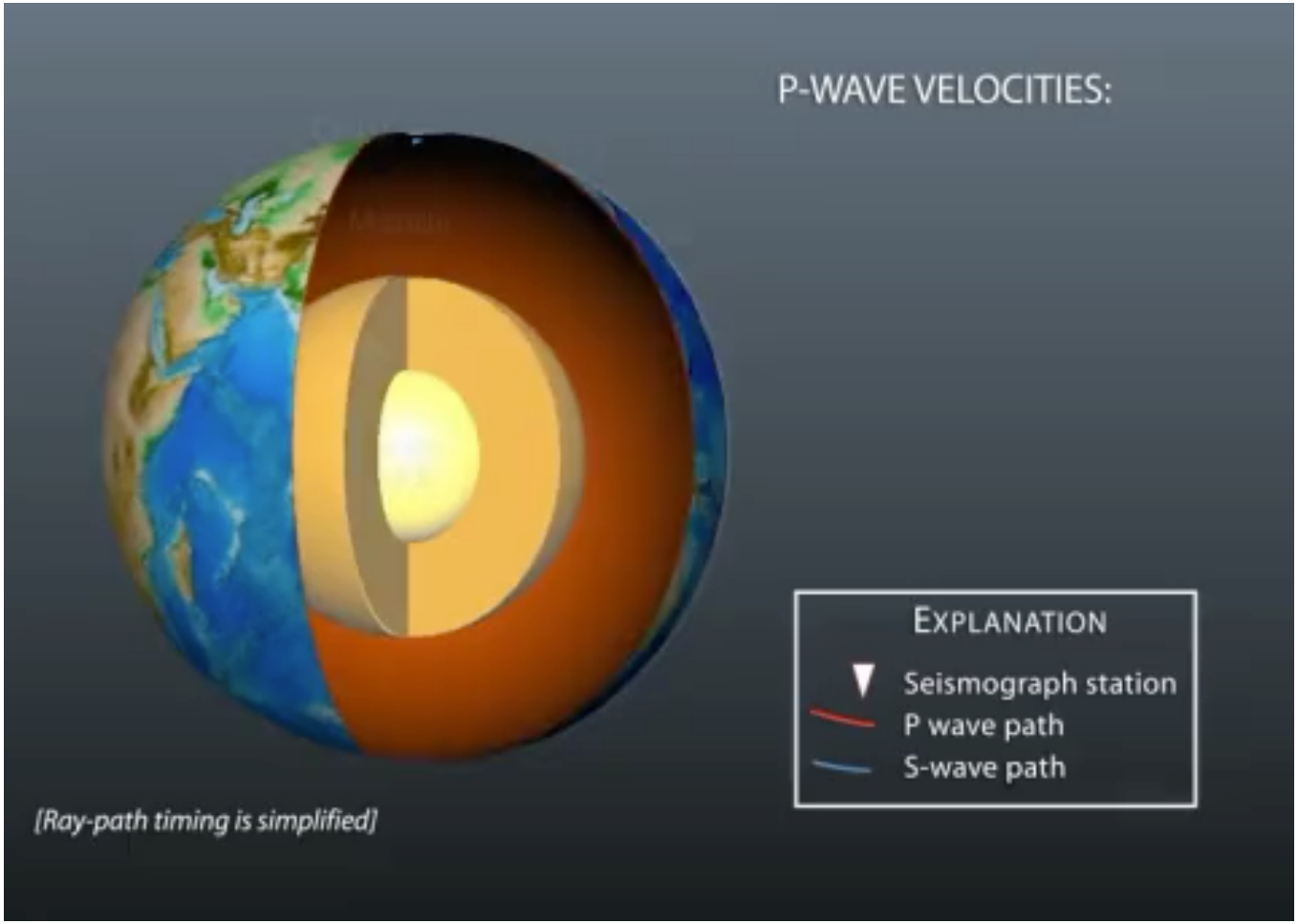
$$\delta(t) \simeq v_0 t_r \ln\left(1 + \frac{t}{t_{as}}\right)$$

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

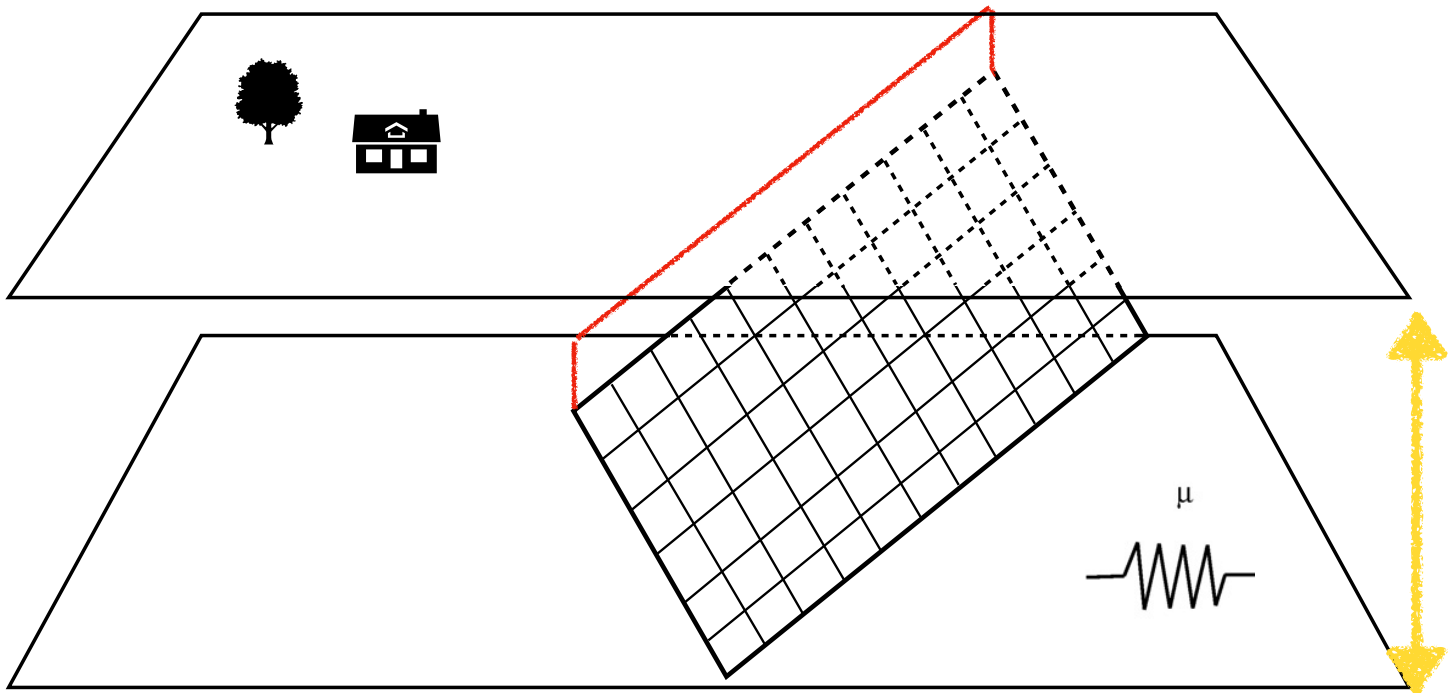
$$t_{as} = \frac{v_0 t_r}{v_i} \exp\left(-\frac{\Delta\tau}{(a-b)\sigma_n}\right)$$

Perfettini and Avouac, 2004a, *JGR*

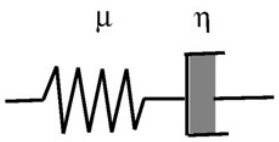
Viscoelastic Mantle



Viscoelastic Mantle



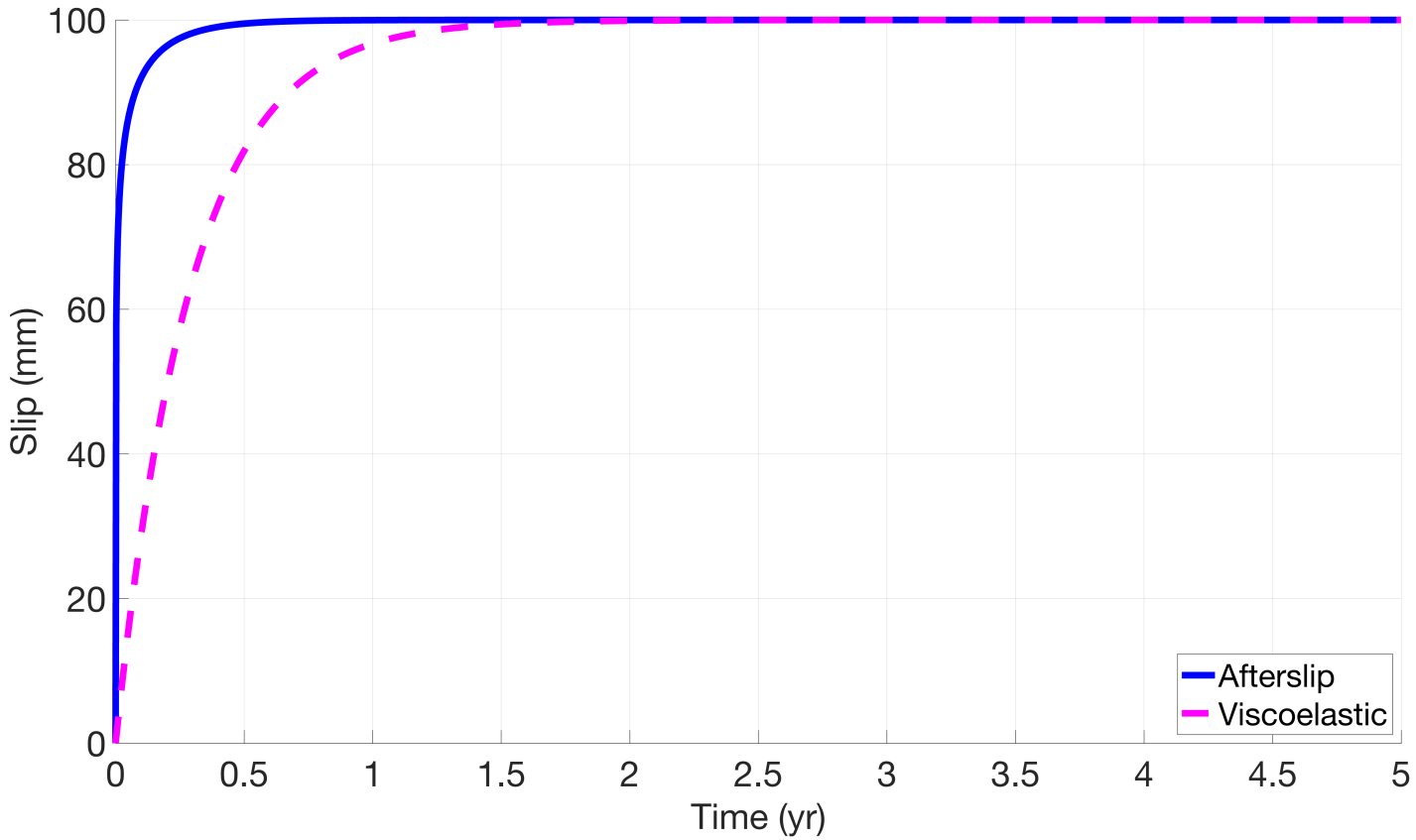
crust



mantle

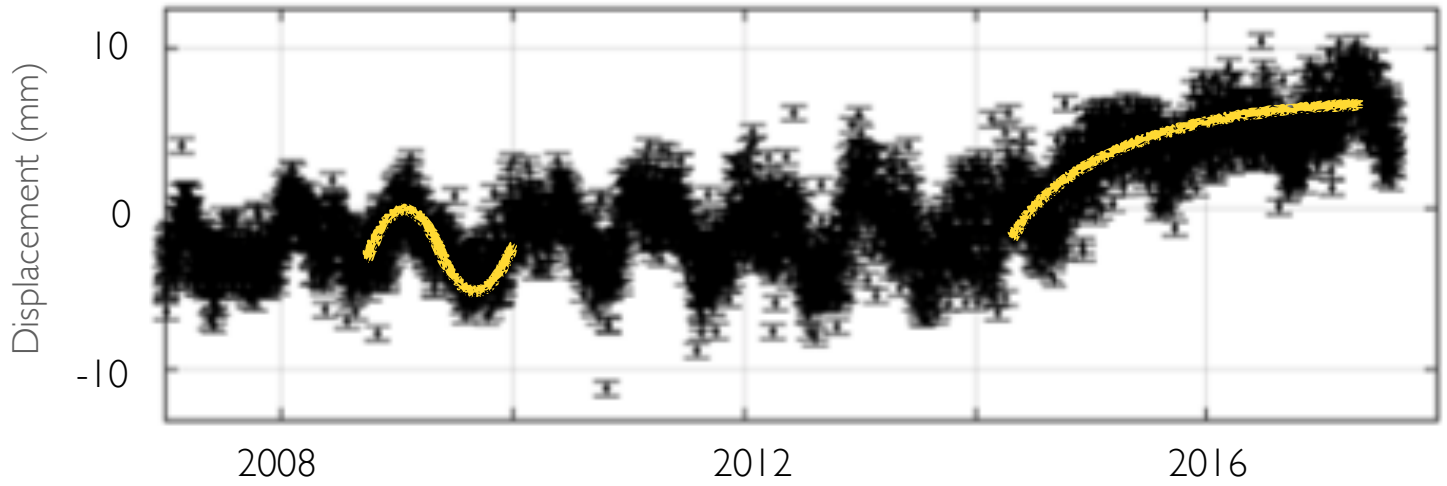
$$\delta(t) = v_0 t + \frac{\Delta\tau}{k}\left[1 - \exp\left(-\frac{k}{\eta}t\right)\right]$$

Afterslip vs Viscoelastic Relaxation



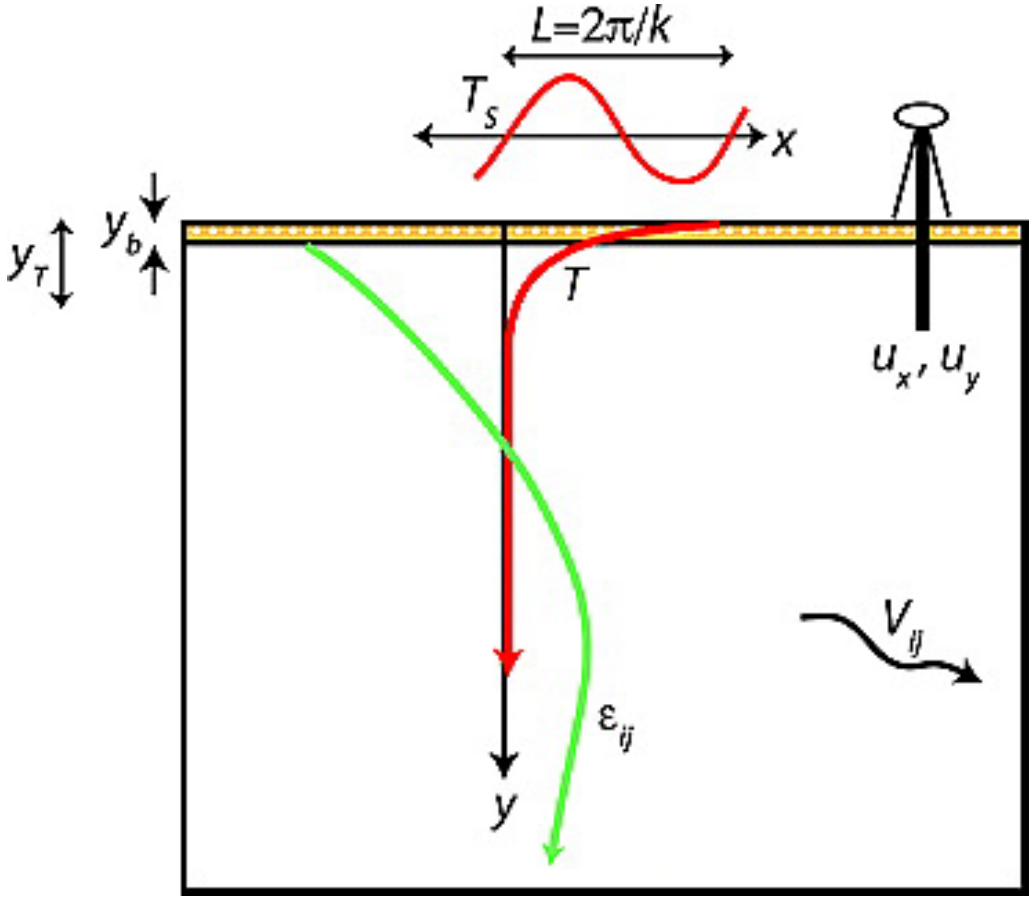
Daily GNSS Position Time Series

What can generate oscillations ?



Michel et al., 2019a, *PAGEOPH*

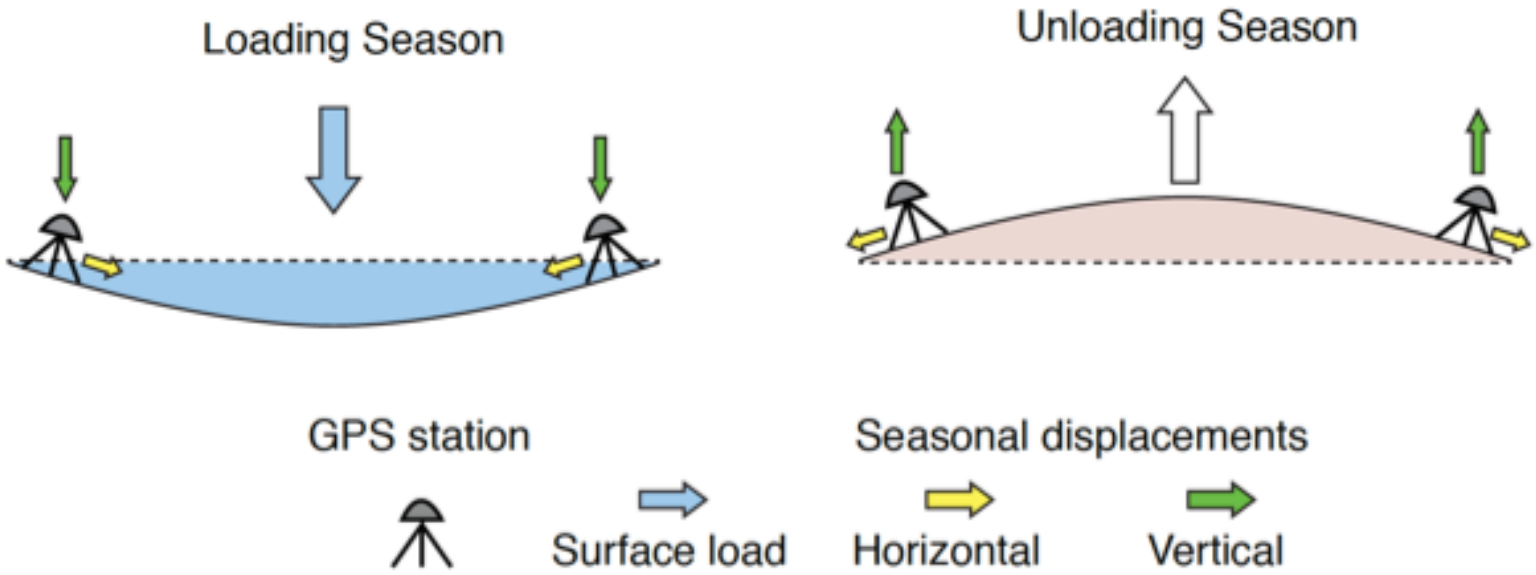
Thermal Dilation



competent layer

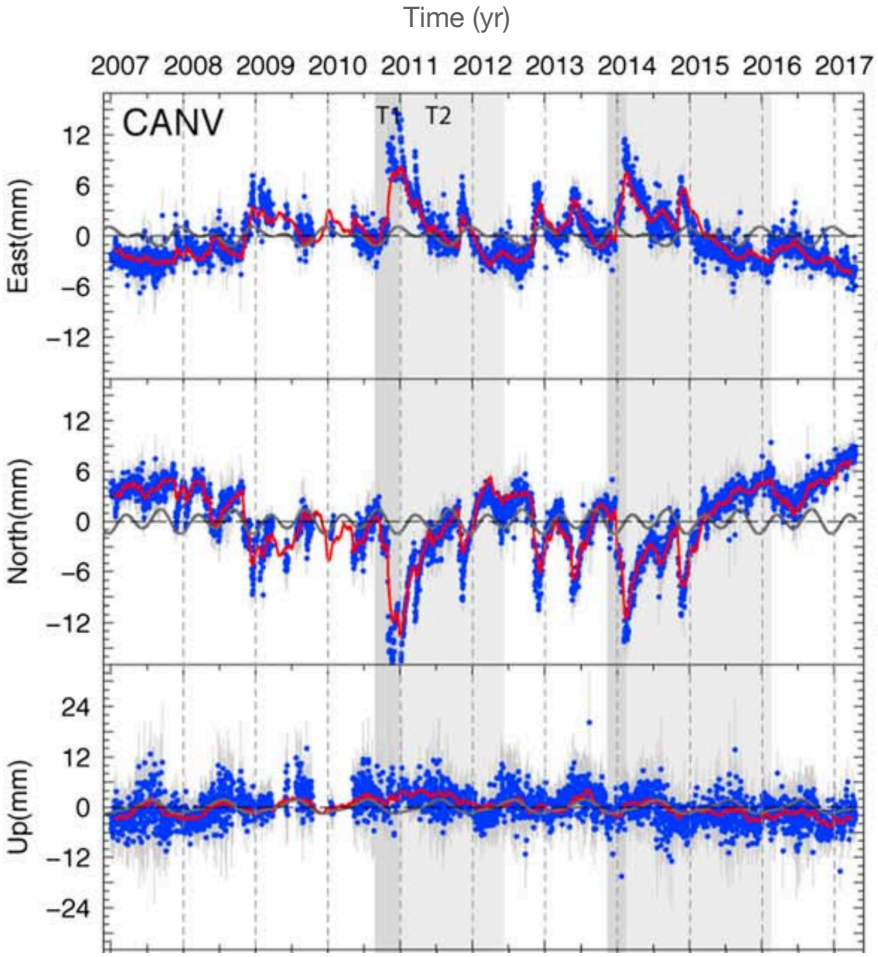
Tsai, 2011, *JGR*

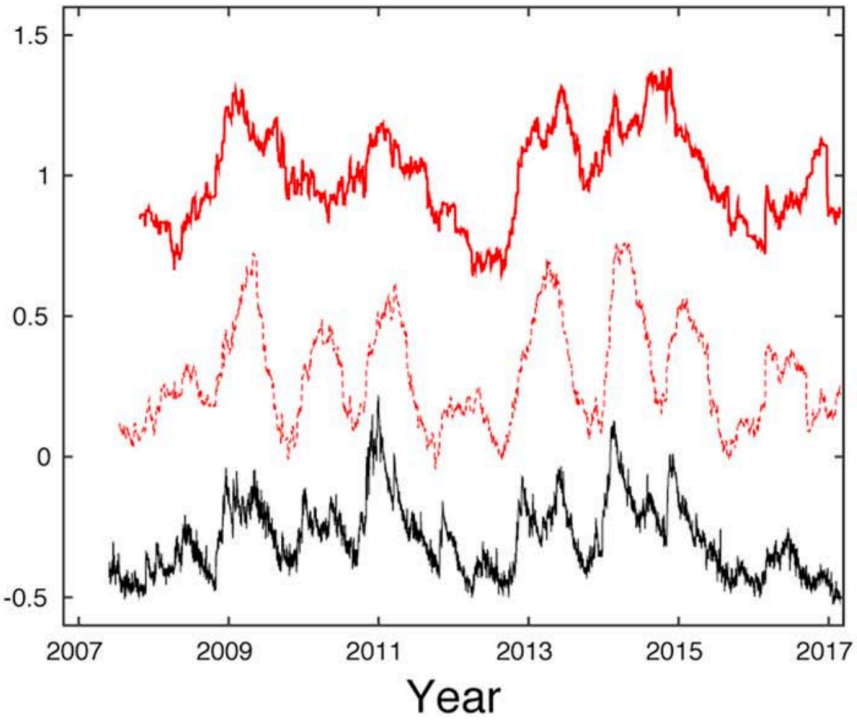
Hydrological Load



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

Hydrological Load





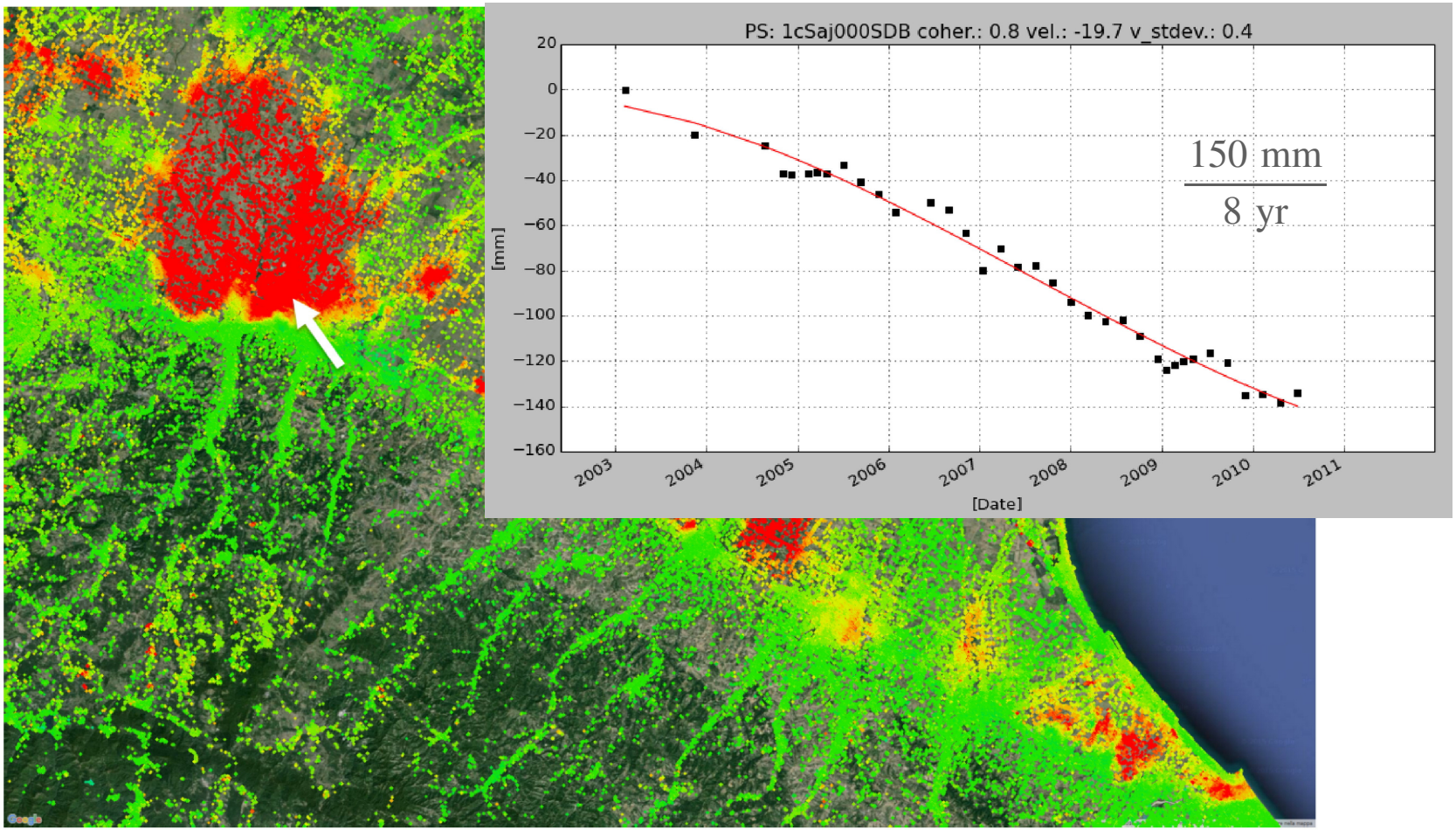
precipitation

precipitation – evapo-transpiration

cumulative precipitation

Serpelloni et al., 2018, *JGR*

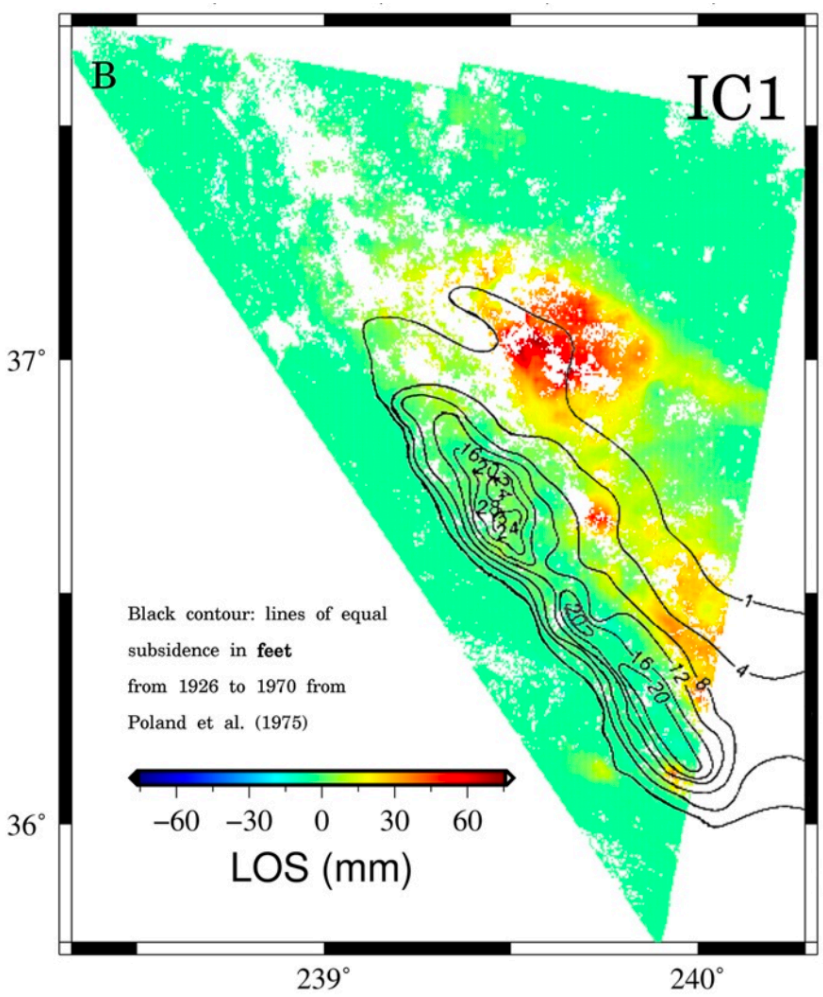
Aquifer Depletion

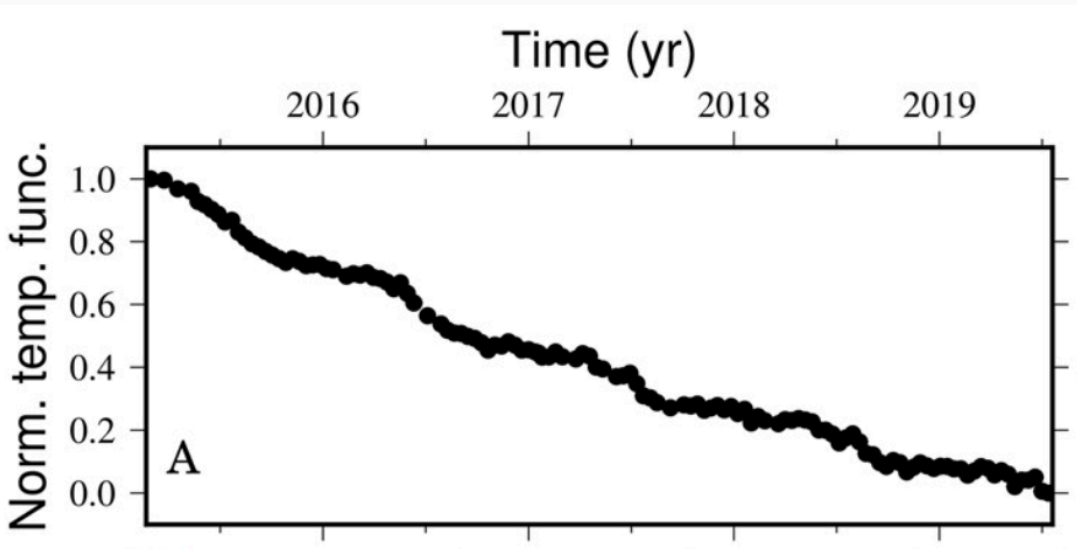


Envisat descending (2003-2010)

Costantini et al., 2017, *Remote Sensing of Environment*

Aquifer Depletion

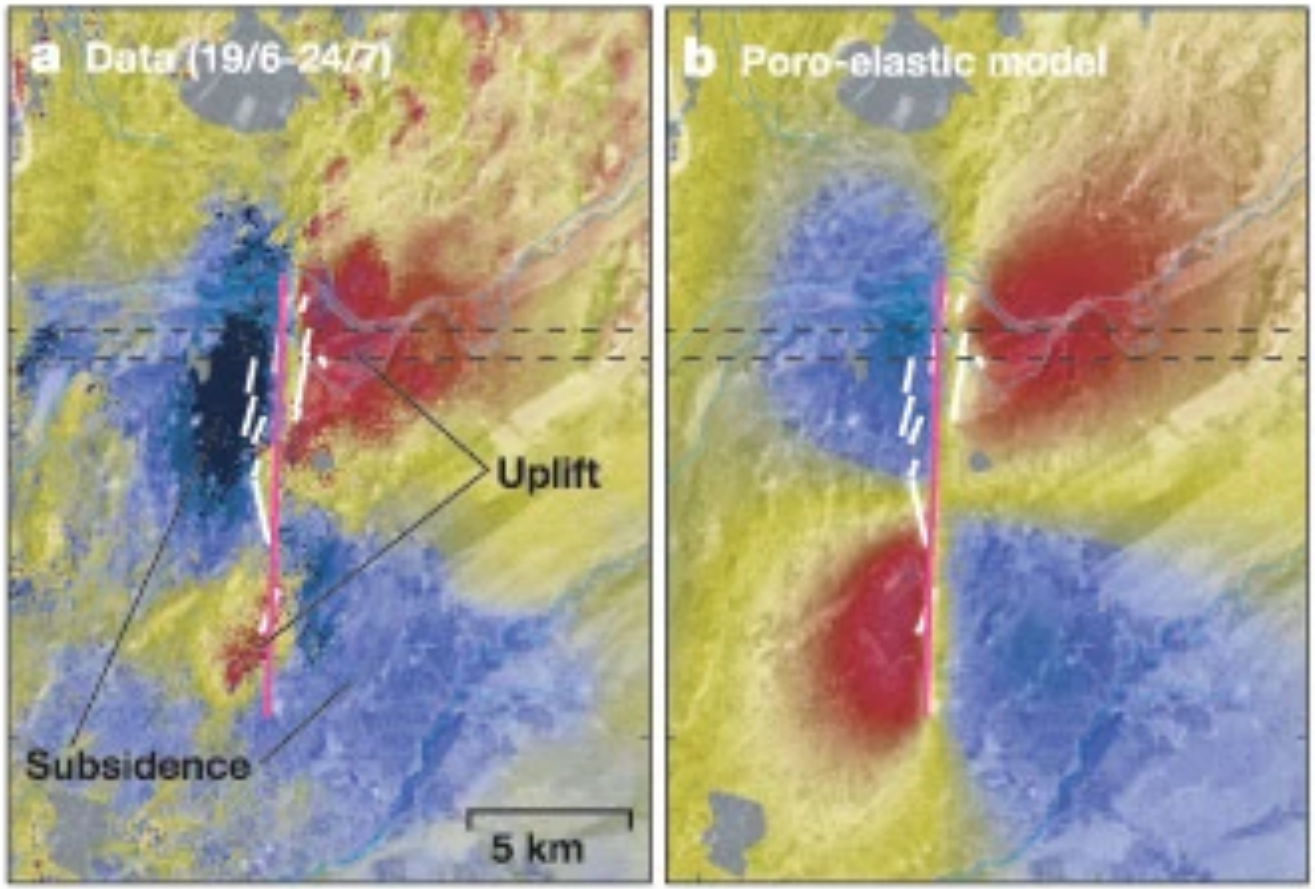




$$\frac{60\ \text{mm}}{4\ \text{yr}}$$

Gualandi and Liu, 2021, *JGR*

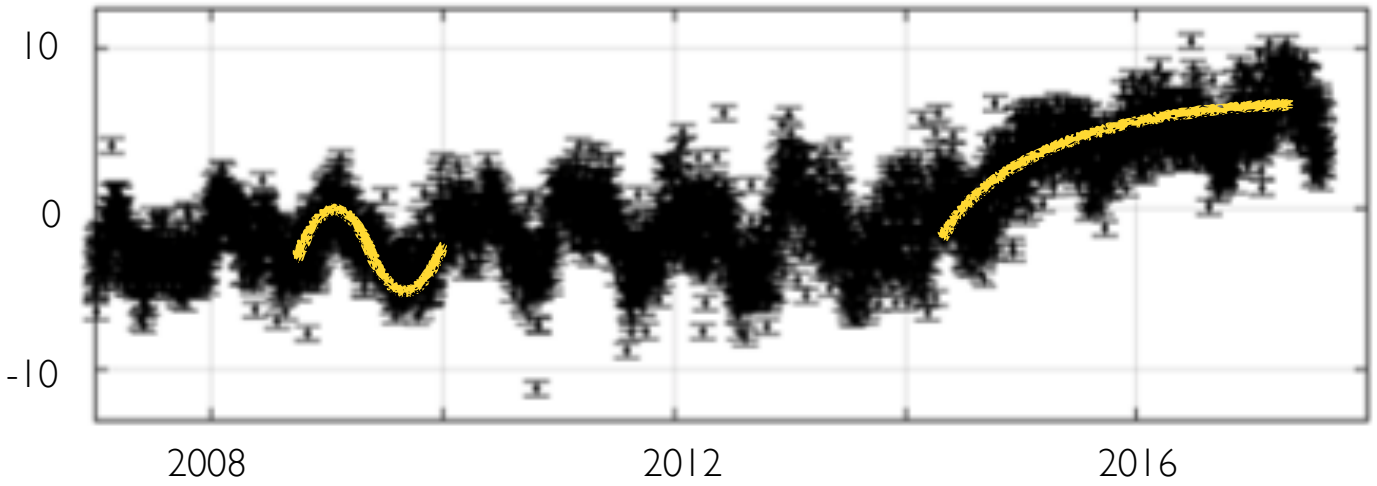
Pore Pressure Variations



Jónsson et al., 2003, *Nature*

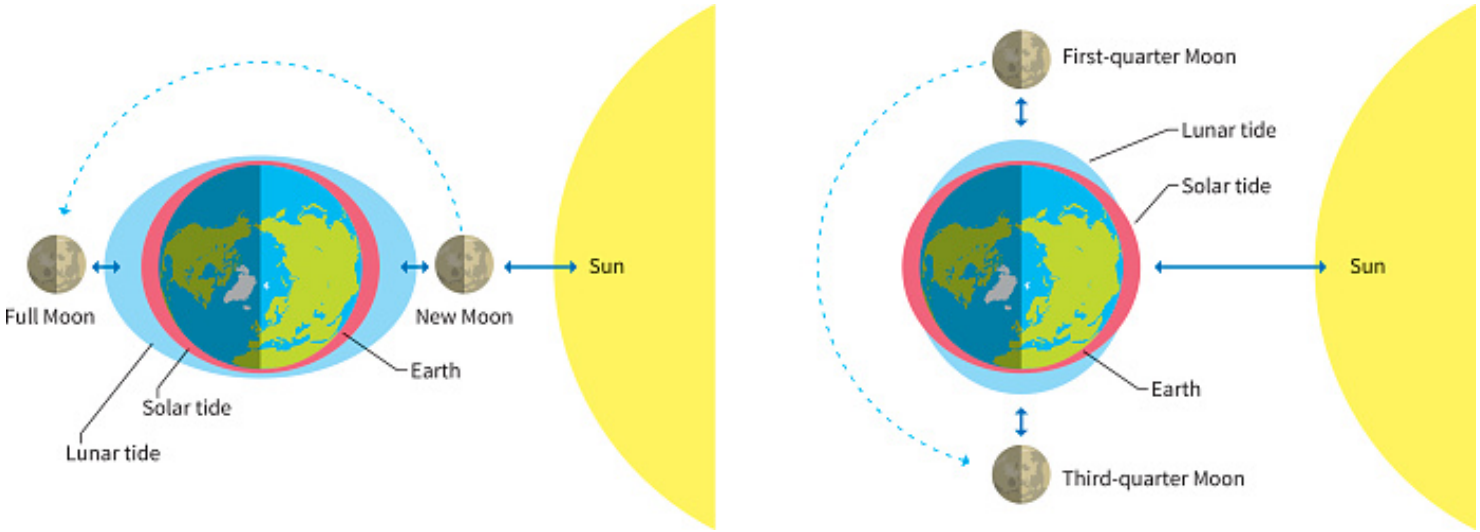
Daily GNSS Position Time Series

What other signals can affect our measurements ?



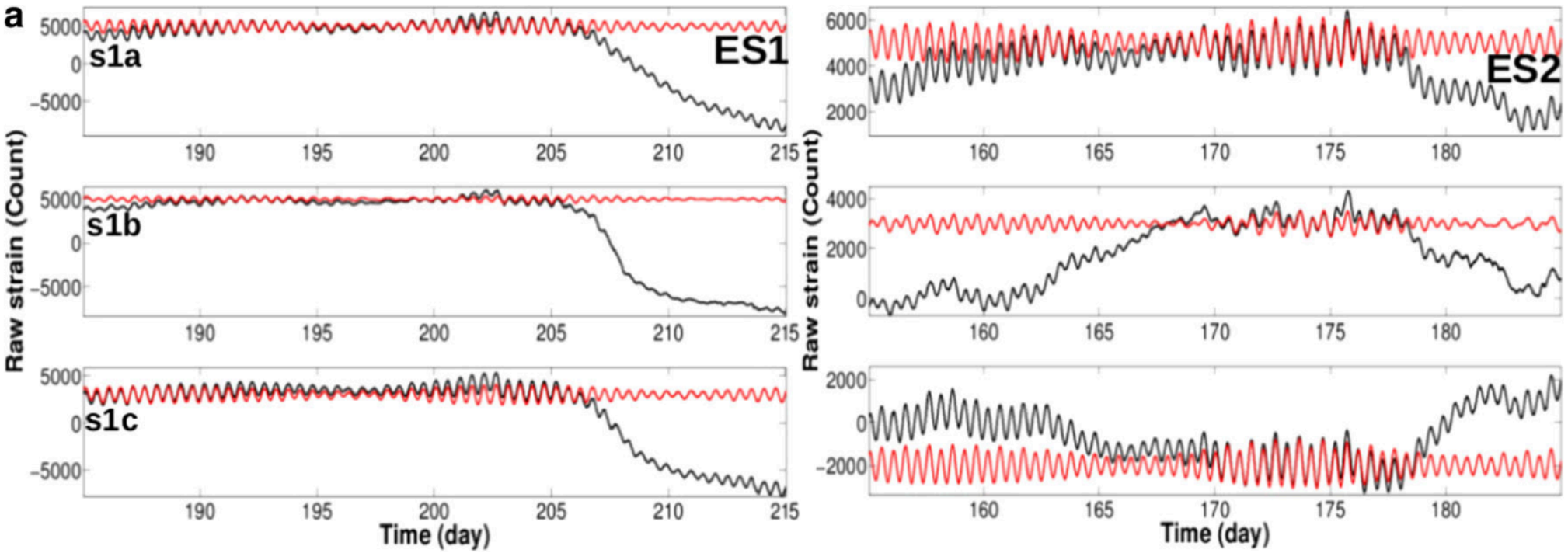
Michel et al., 2019a, *PAGEOPH*

Tides



Rubenstein et al., 2008, *Science*
Hawthorne and Rubin, 2010, *JGR*

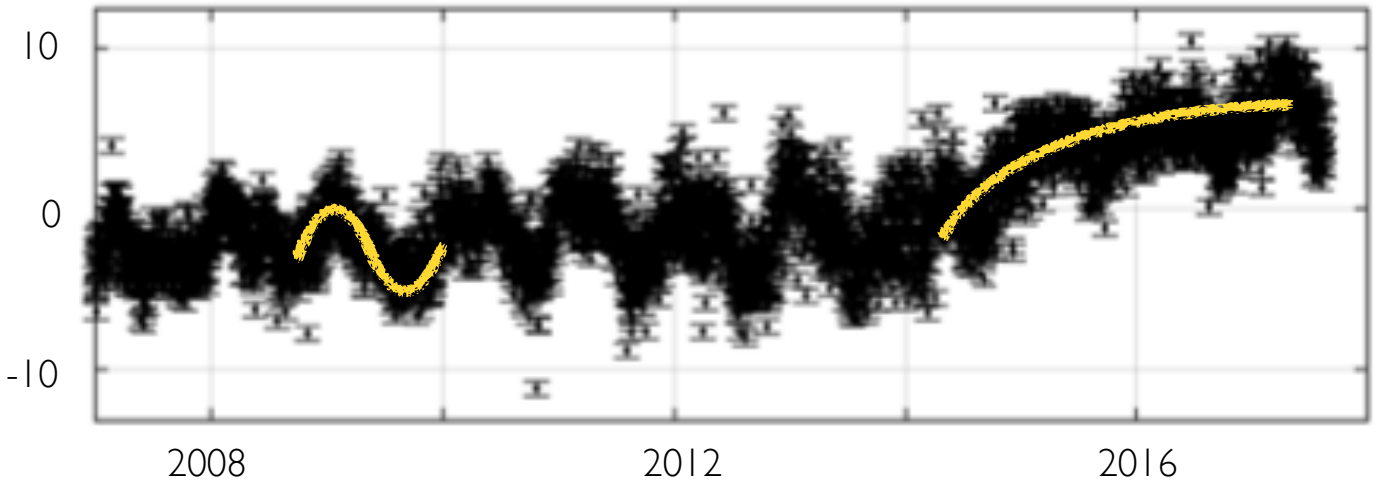
Strainmeter Calibration



Canitano et al., 2018, *JGR*

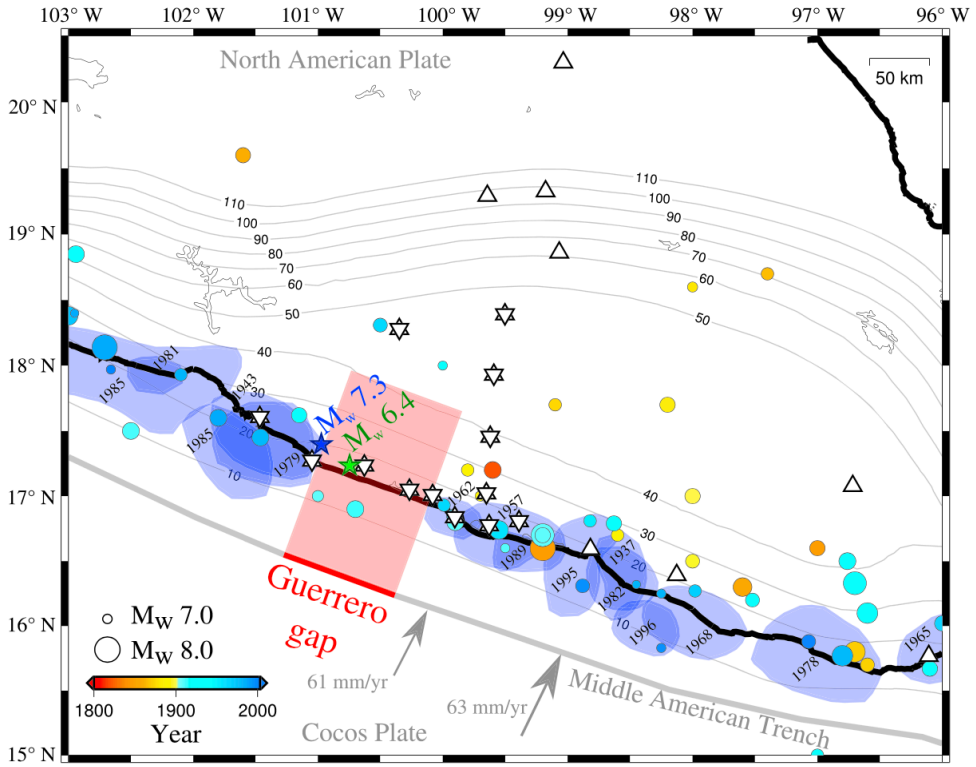
Daily GNSS Position Time Series

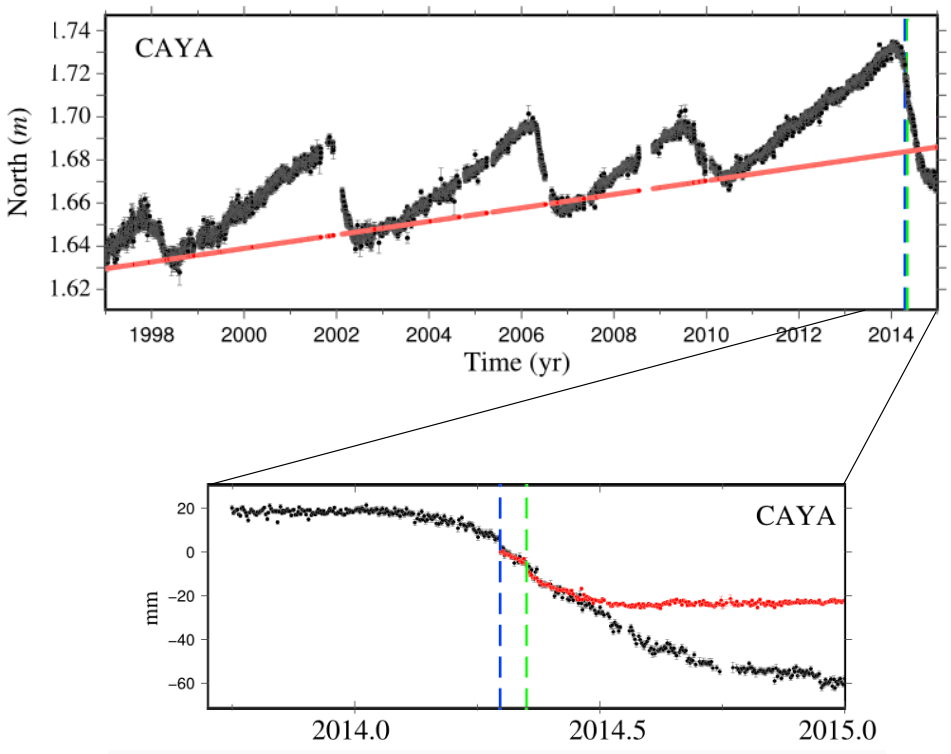
Any other ?



Michel et al., 2019a, *PAGEOPH*

Slow Slip Events



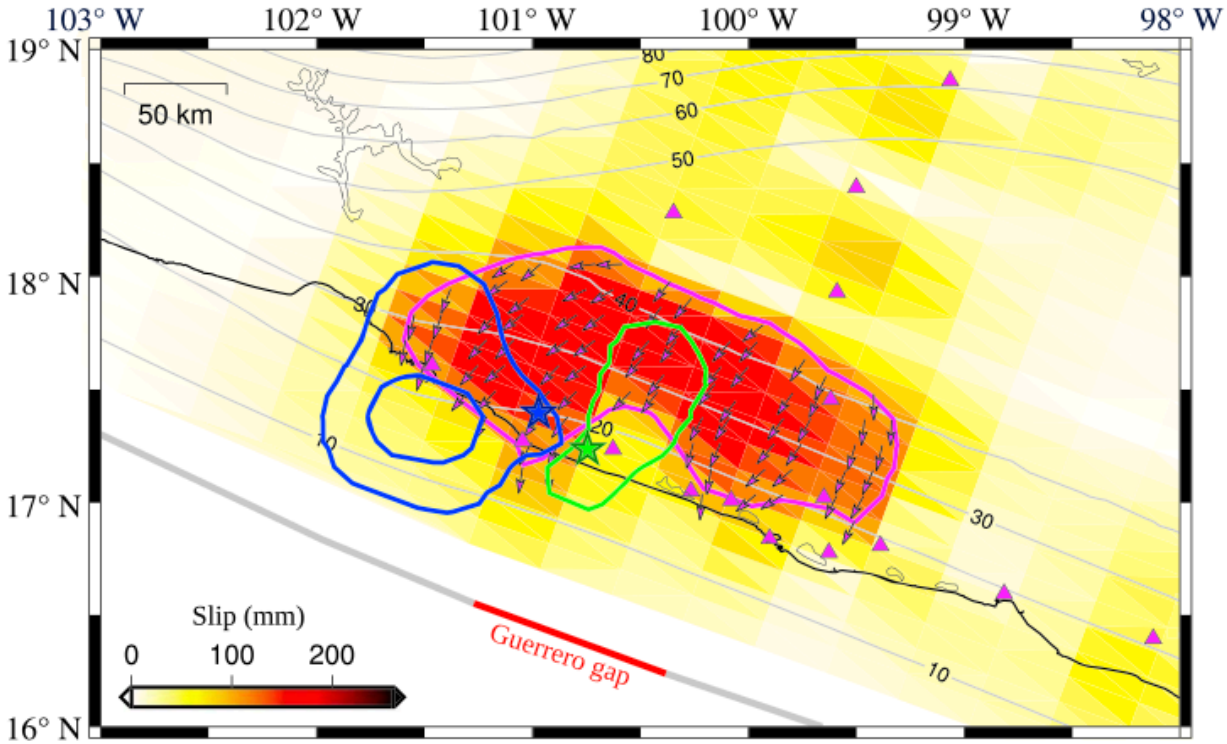


★ Mainshock ($M_w = 7.3$)

★ Largest aftershock ($M_w = 6.4$)

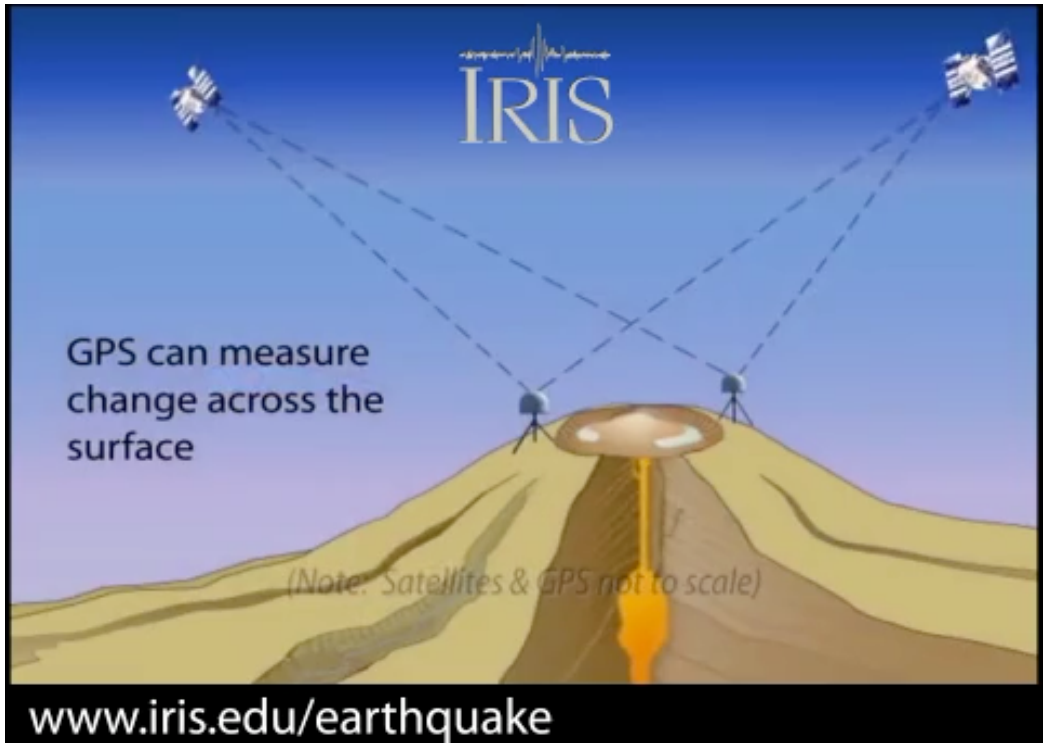
Gualandi et al., 2017b, *GRL*

Slow Slip Events

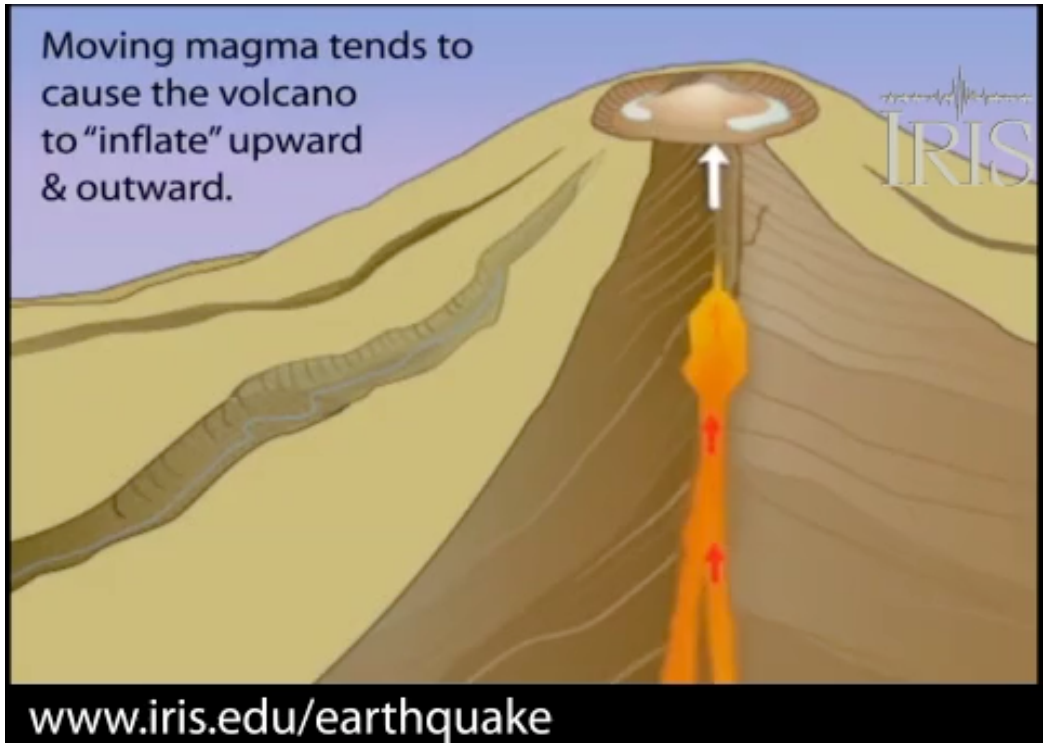


Gualandi et al., 2017b, *GRL*

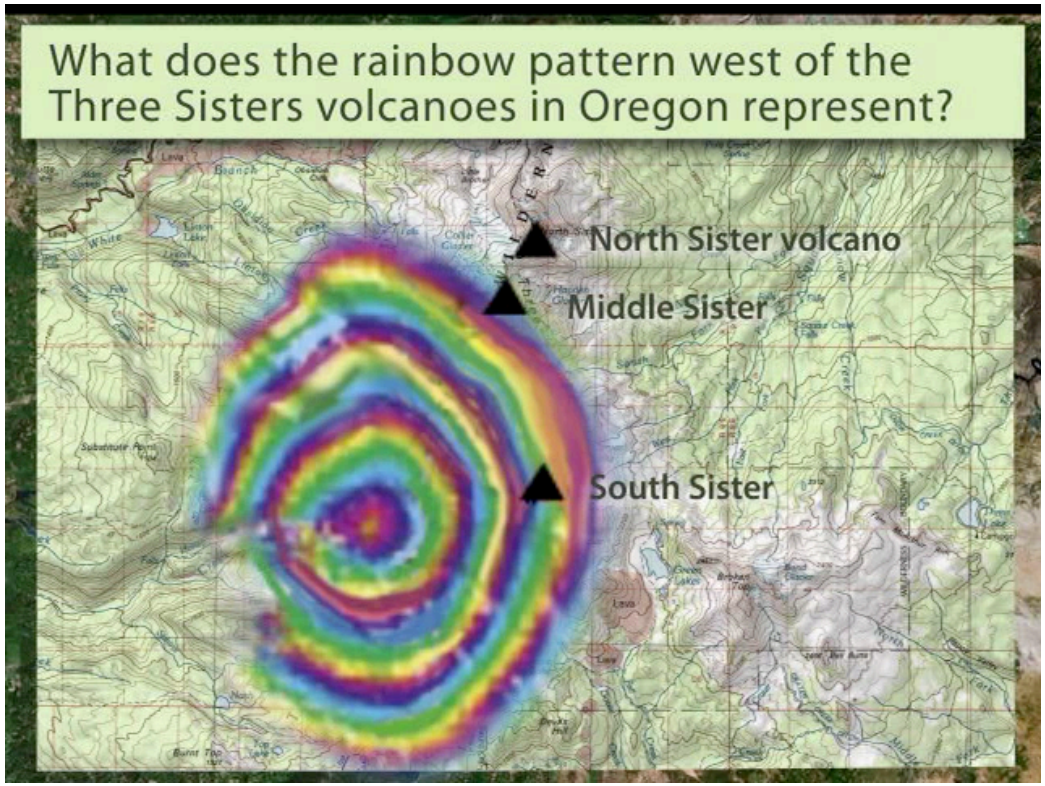
Volcanic Deformation: GNSS



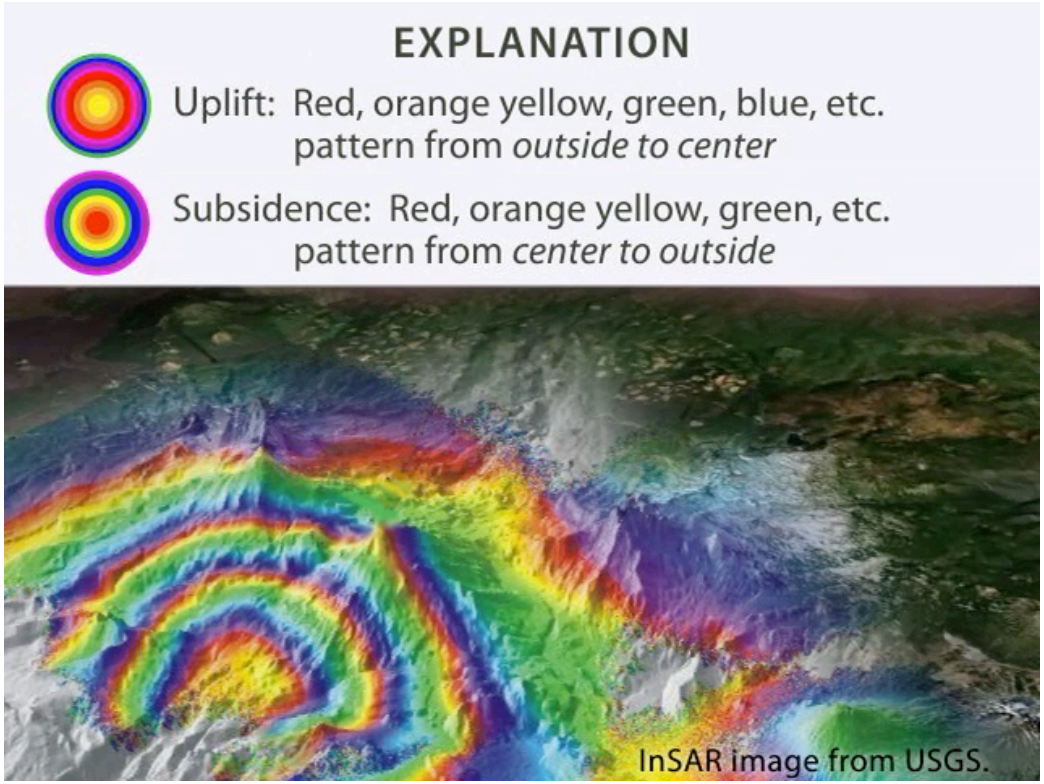
Volcanic Deformation: Tiltmeters



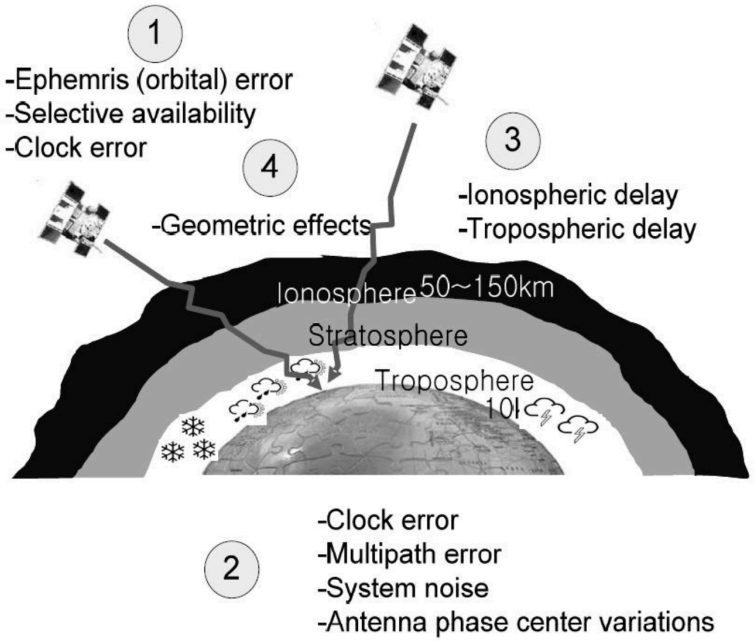
Volcanic Deformation: InSAR



Volcanic Deformation: InSAR



Errors



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

Conclusions

Geodetic observations are very useful to study the seismic cycle…

and much more !