Seismic strain accumulation and release in the Apennines

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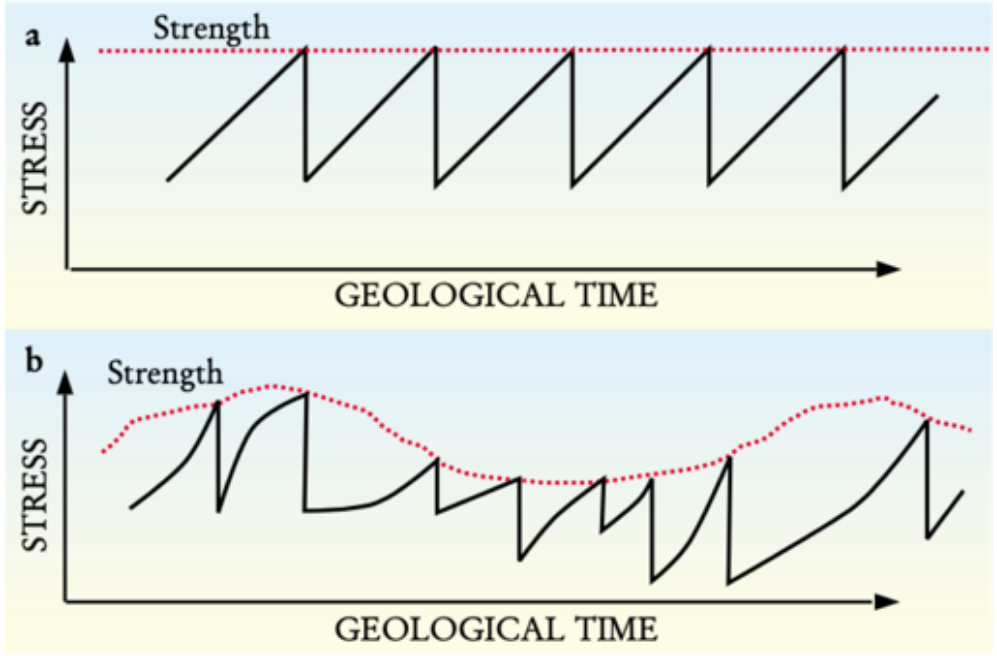
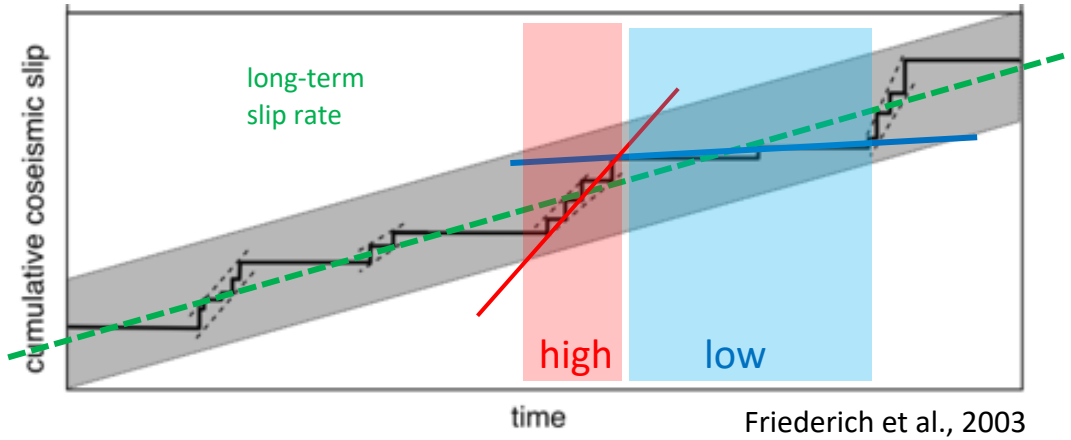
Earthquake release is intrinsically episodic



Kanamori & Brodsky, 2002



Friederich et al., 2003

Elastic rebound theory [*Reid*, 1910] linked the rate of tectonic loading to the intermittent earthquake release

Successful application of quasi-periodic, deterministic models of recurrence has been challenging

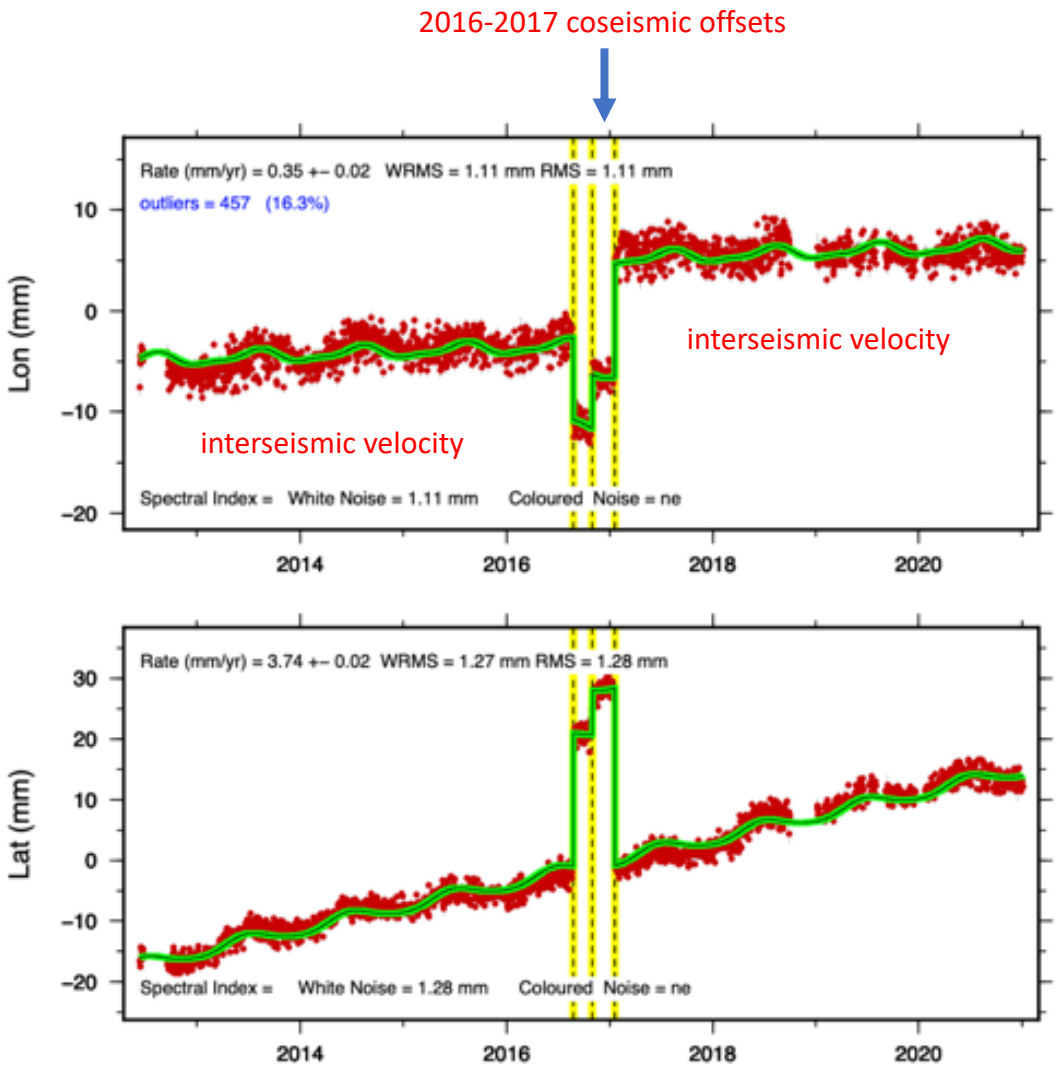
Seismic release is characterized by clustering of events (supercyles)

A budget between strain accumulation and seismic release ?

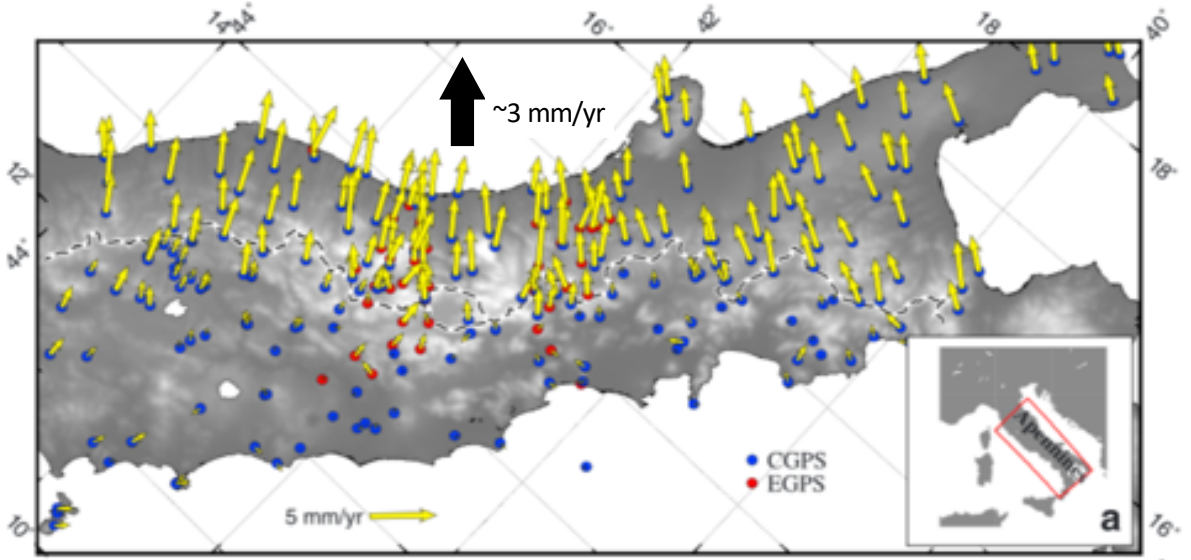
What time scale for stationary seismic release ?

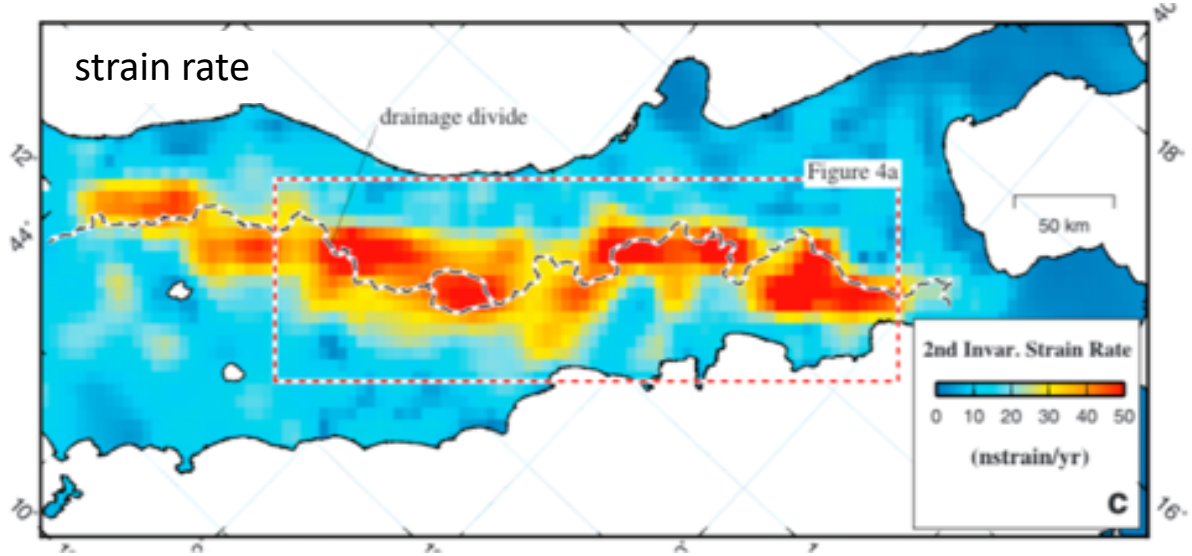
Geodesy shows **stable** strain accumulation across deformation zones

Amatrice GPS station:



Interseismic velocity field:





Objectives

- Estimate rates of **seismic release** (from historical seismicity) and **strain accumulation** (from geodesy)
- What is their balance ?
- Time scale at which they are comparable ?

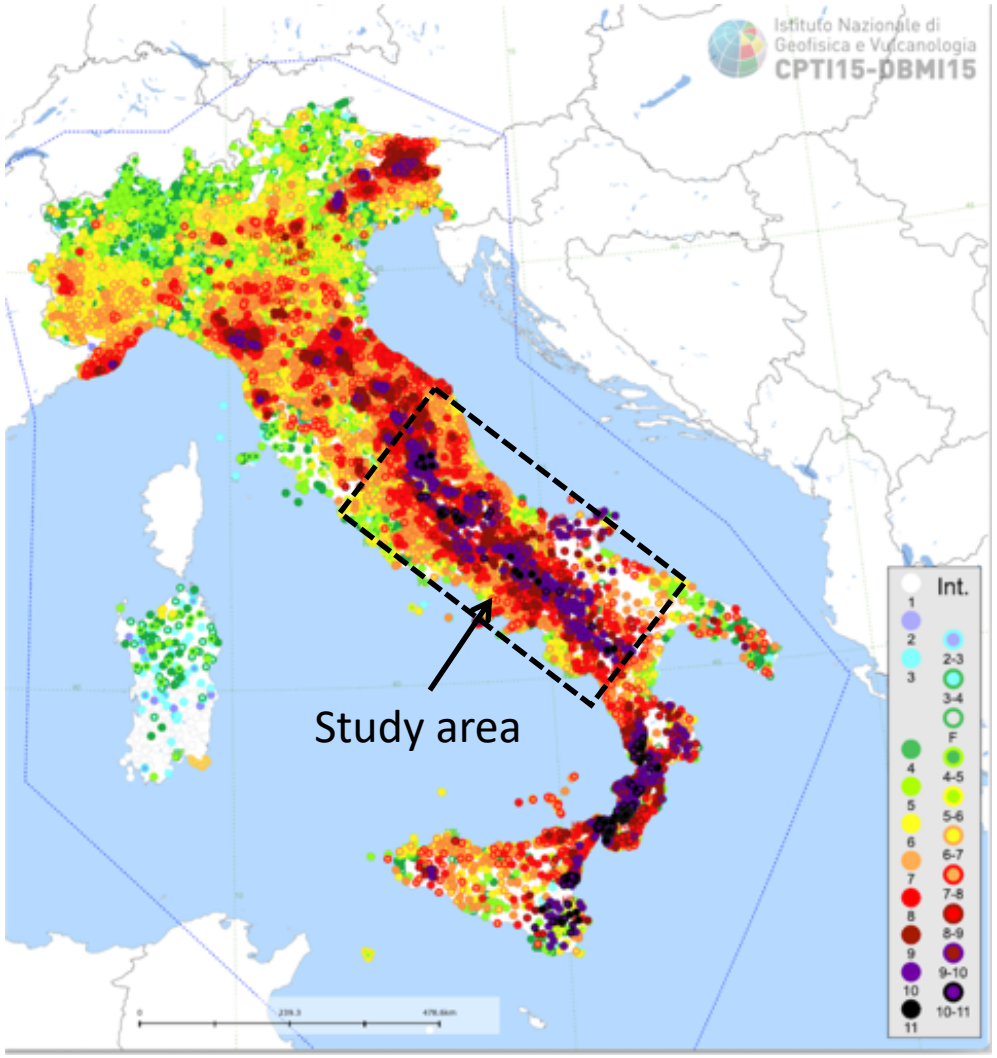
Implications

- Independent assessment of seismicity rate
- Independent geodetic contribution to seismic hazard
- Aseismic deformation (creep, postseismic)

Seismic strain release in the Apennines

Historical seismicity

www.emidius.mi.ingv.it/CPTI

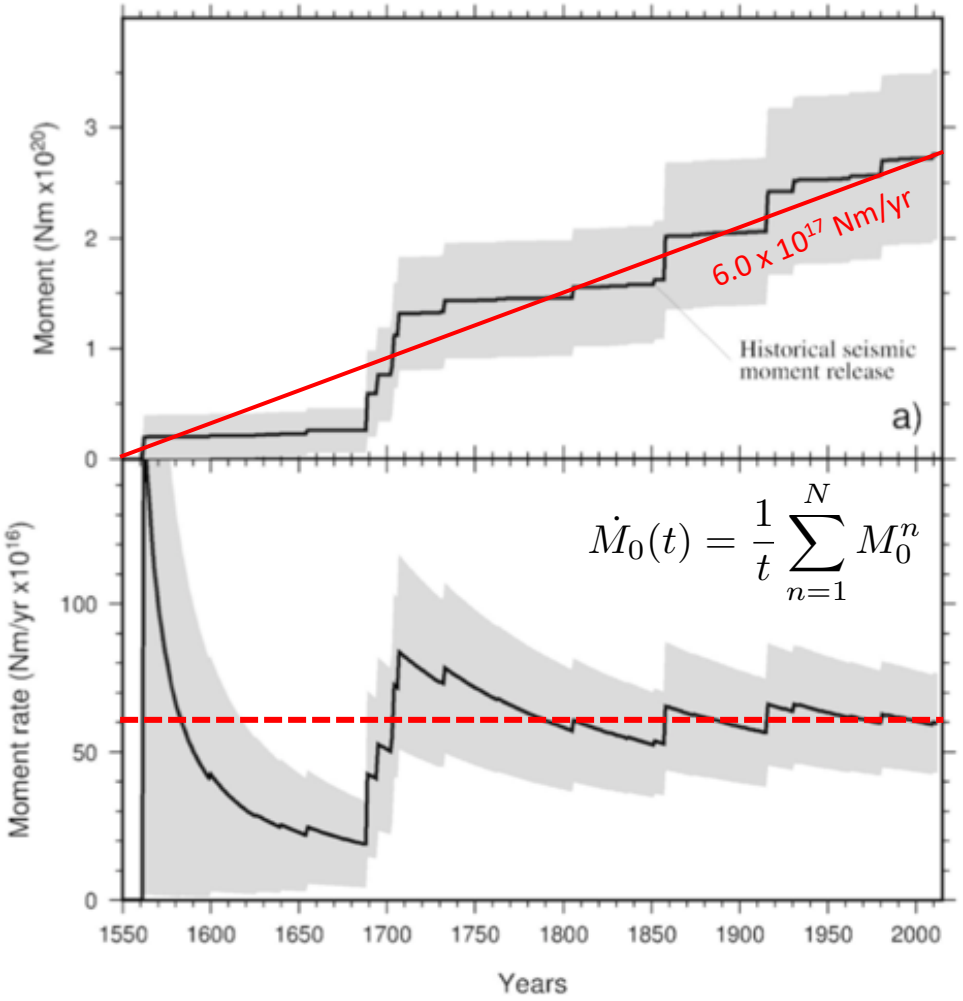


- CPTI15 the most recent realization of the Italian historical catalogue
- Moment magnitudes M_w for pre-instrumental events estimated from intensity distribution and regressions coefficient calibrated with instrumentally-recorded eqs
- Considered complete for M > 6 in the last ~500 yrs
- Seismic moment of each historical event given by:

$$M_0 = 10^{1.5M_w+9.05}$$

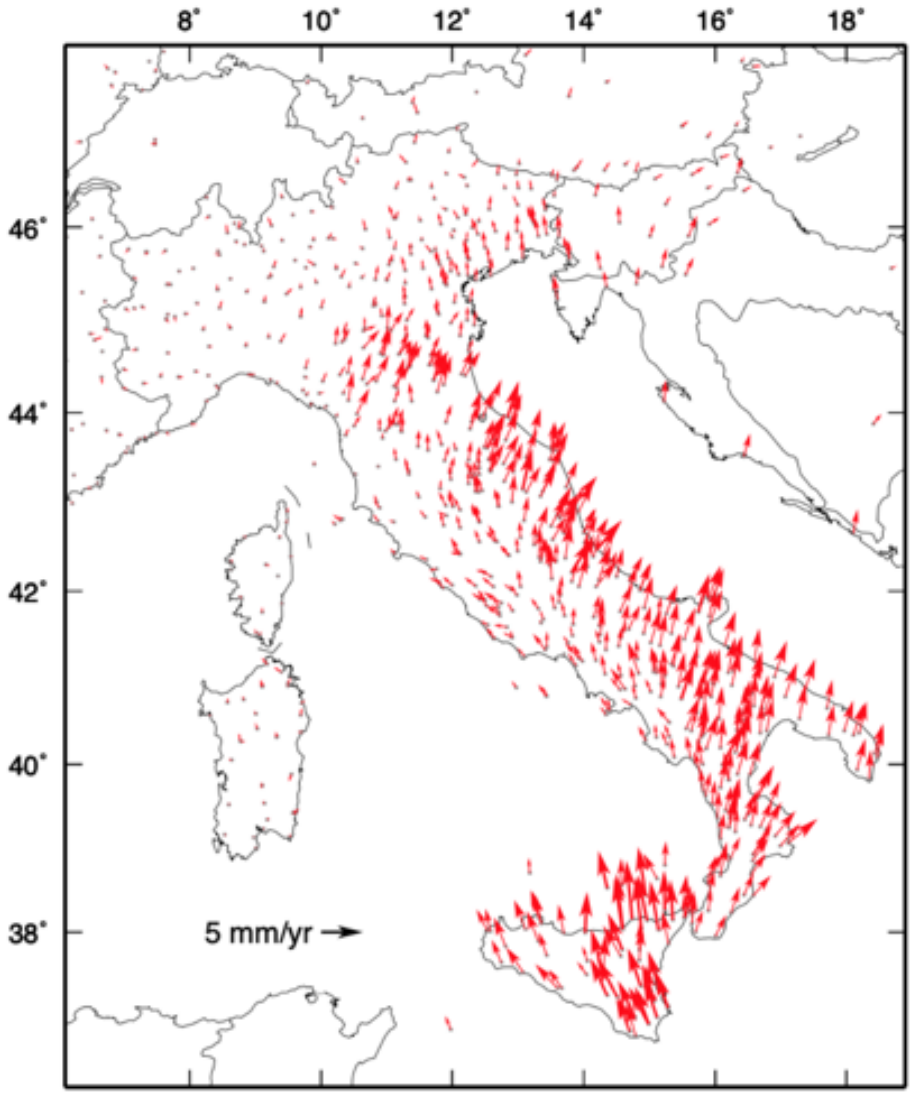
Seismic strain release in the Apennines

Historical seismicity (1550-2015)



- Average ~500 yrs seismic moment release = 6.0 x 10^{17} Nm/yr
  1 Mw 5.8 event/year
- Periods of clustered events
- 2016-2017 seismic moment release
  (Mw 5.9, 6.0, 6.5) = 0.08 x 10^{20} Nm
- Asymptotic approach to stationary value

Strain accumulation in the Apennines



Devoti et al., 2017

Private and public (scientific and cadastral) continuous GPS/GNSS networks

RING INGV largest scientific network in Europe (> 200 stations)

> 500 stations currently active in the Italian territory

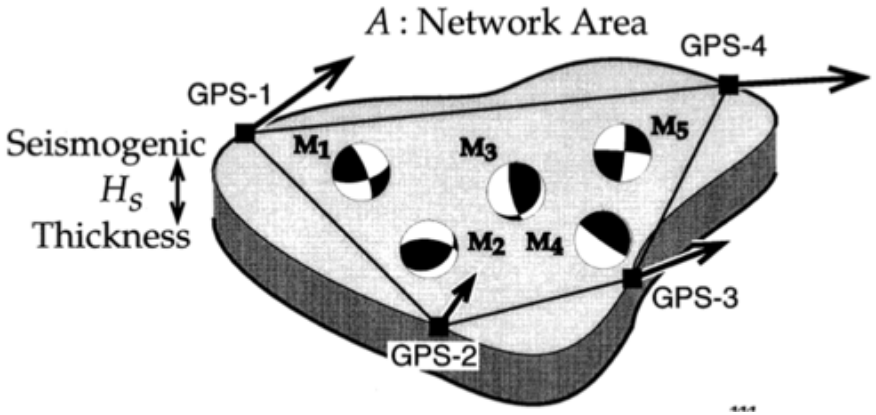
Coverage not homogeneous

Accuracy 1 mm horizontal, 3-4 mm vertical

Stable velocities achieved after 3-4 years

Theoretical framework for comparing strain accumulation and seismic release - 1

Kostrov(1974)



$$\bar{\epsilon}_{ij} = \frac{1}{2\mu A H_s} \sum_{n=1}^{N} M_{ij}^{n}$$

average strain of the volume = sum of the moment tensors of all the earthquakes within it

$$\dot{M}_{ij}^{g} = 2\mu A H_s \dot{\epsilon}_{ij}$$

A_f	Area
H_s	seismogenic thickness
$\dot{\epsilon}_{ij}$	strain rate tensor
μ	rigidity

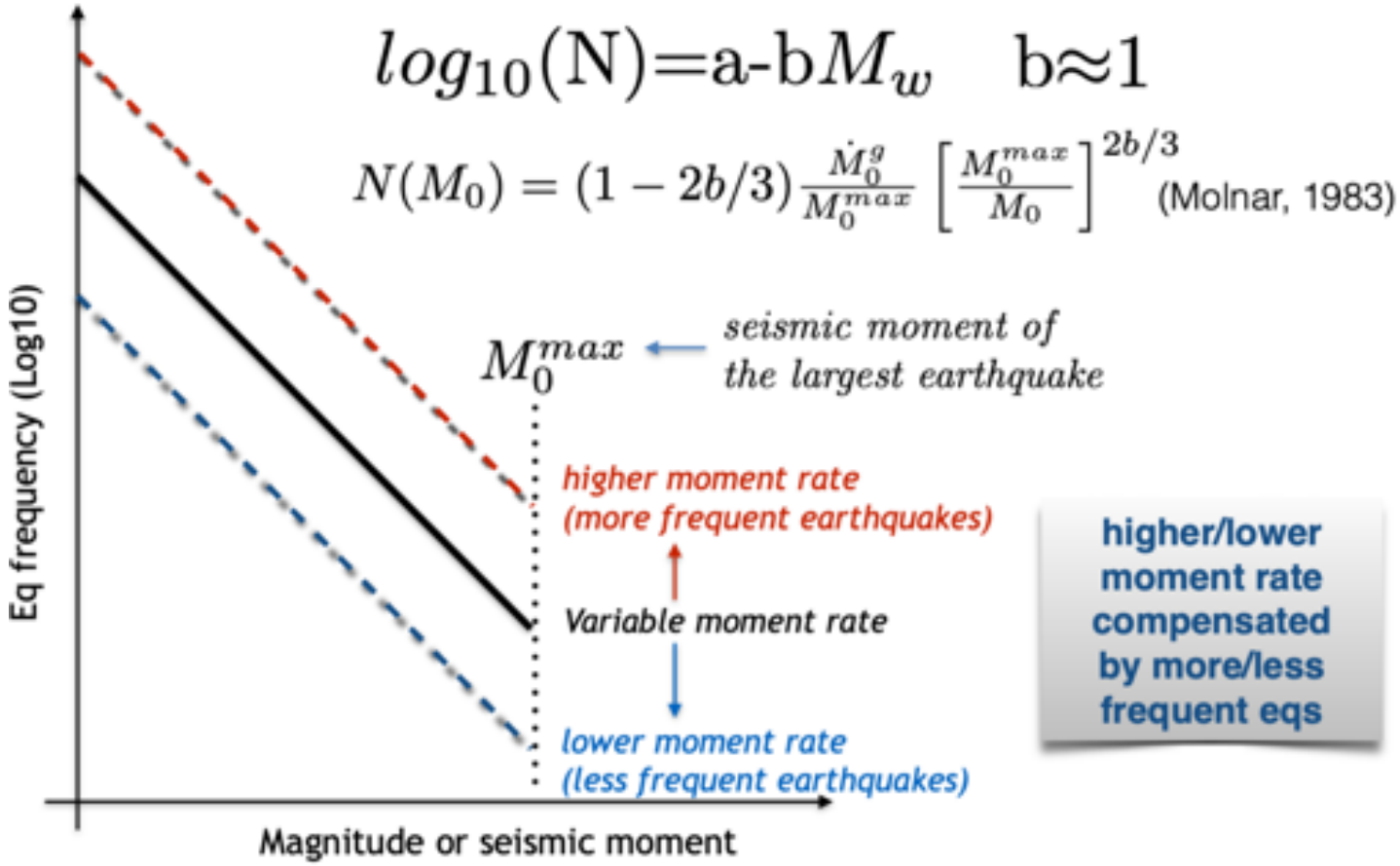
budget of seismic moment available to be released in future eqs

Theoretical framework for comparing strain accumulation and seismic release - 2

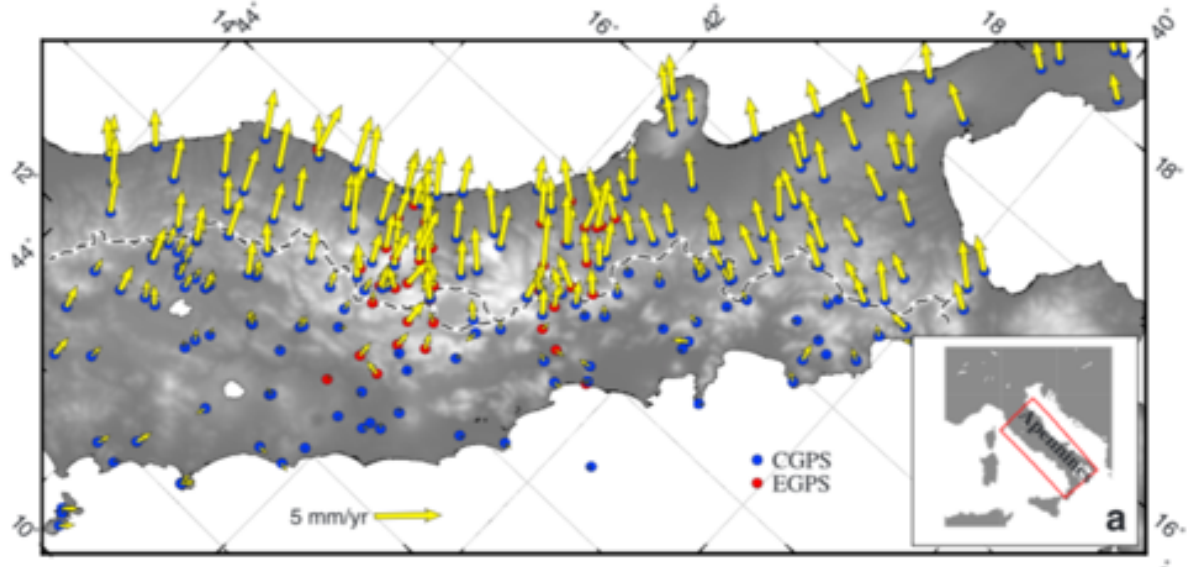
Gutenberg-Richter relationship

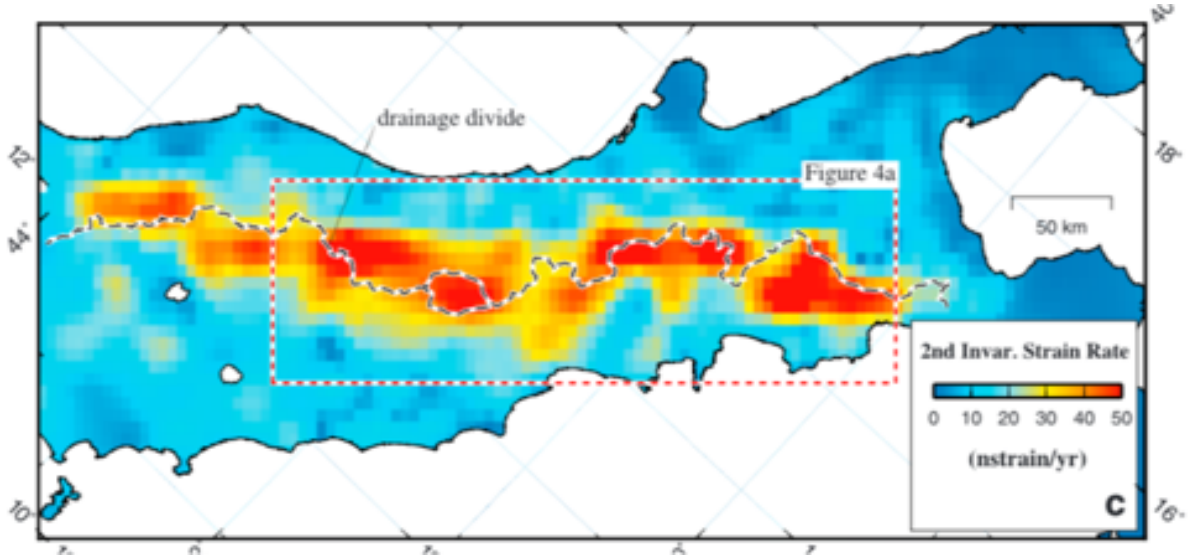
$$log_{10}(\mathrm{N}) = \mathrm{a\text{-}b}M_w \quad \mathrm{b} \approx 1$$

$$N(M_0) = (1 - 2b/3)\frac{\dot{M}_0^g}{M_0^{max}}\left[\frac{M_0^{max}}{M_0}\right]^{2b/3}$$ (Molnar, 1983)



GPS strain accumulation





Strain rate field from interpolation and spatial derivation of the velocity field

$$\epsilon_{ij} = \frac{1}{2}\left(\frac{\partial v_x}{\partial y} + \frac{\partial v_y}{\partial x}\right)$$

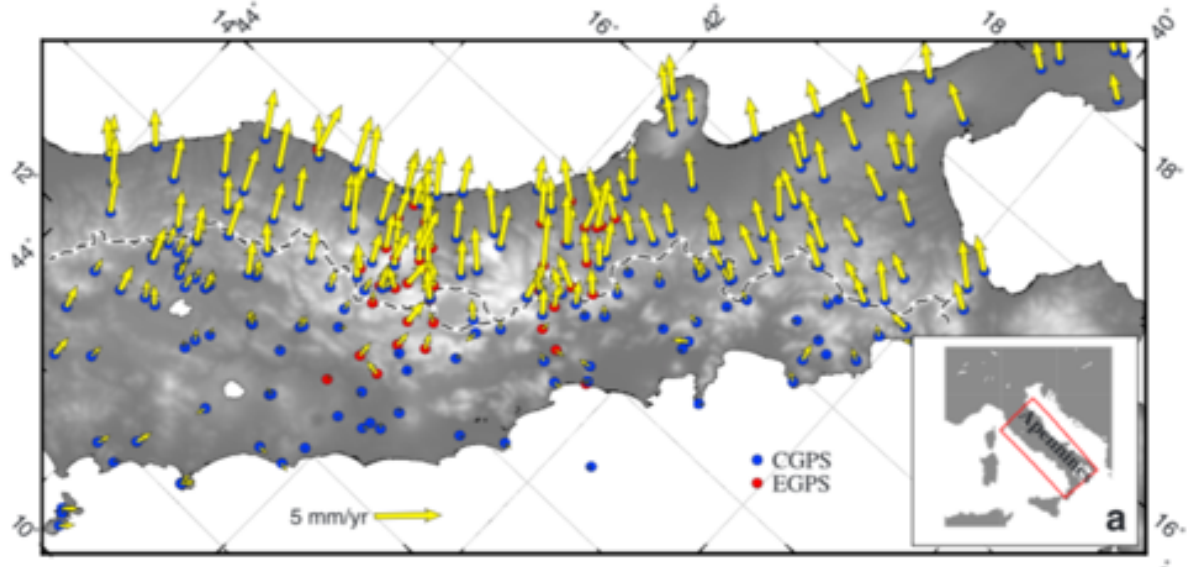
Total rate of moment accumulation by spatial integration of the strain rate field

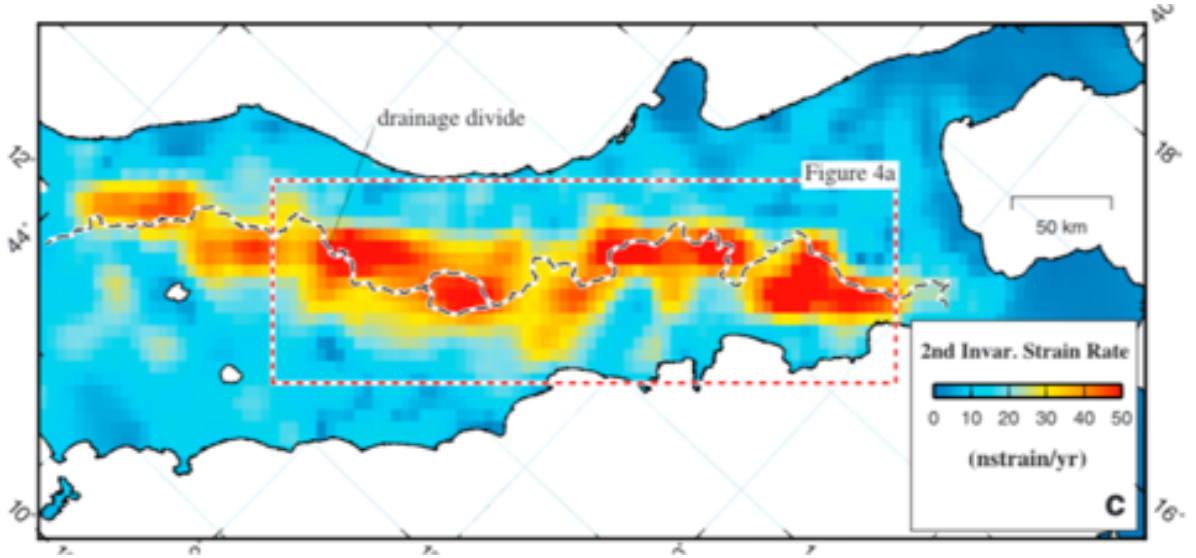
$$\dot{M}_0^g = 2\mu A H_s \dot{\epsilon}_{max}$$

$H_s = 10 \pm 2.5km$ seismogenic thickness

$$\dot{M}_0^{geod} = 76.9 \pm 15.6 \times 10^{16} Nm/yr$$

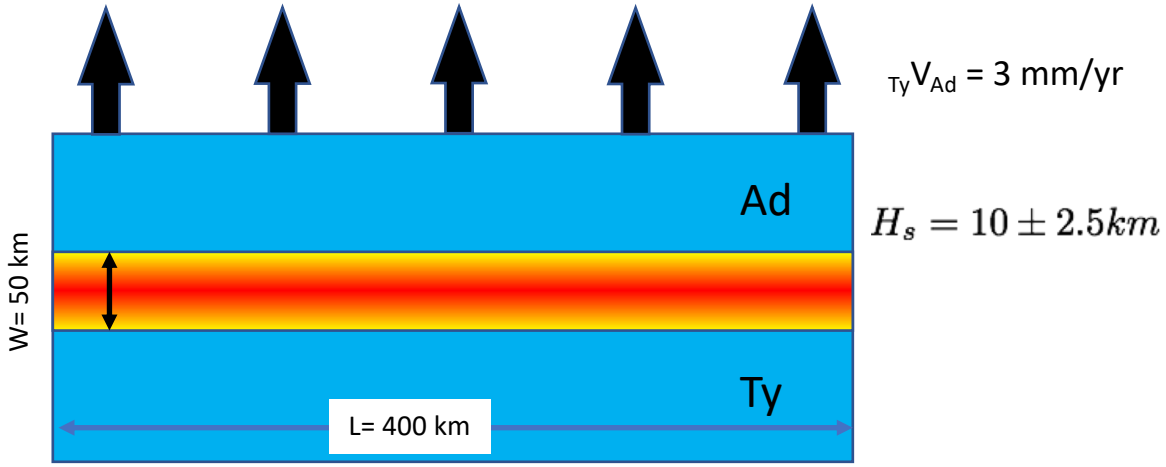
GPS strain accumulation





Does the rate of seismic moment accumulation reflect mainly the deformation to accomodate the relative motion between Ad and Ty ?

Transient deformation (postseismic, hydrology) ?

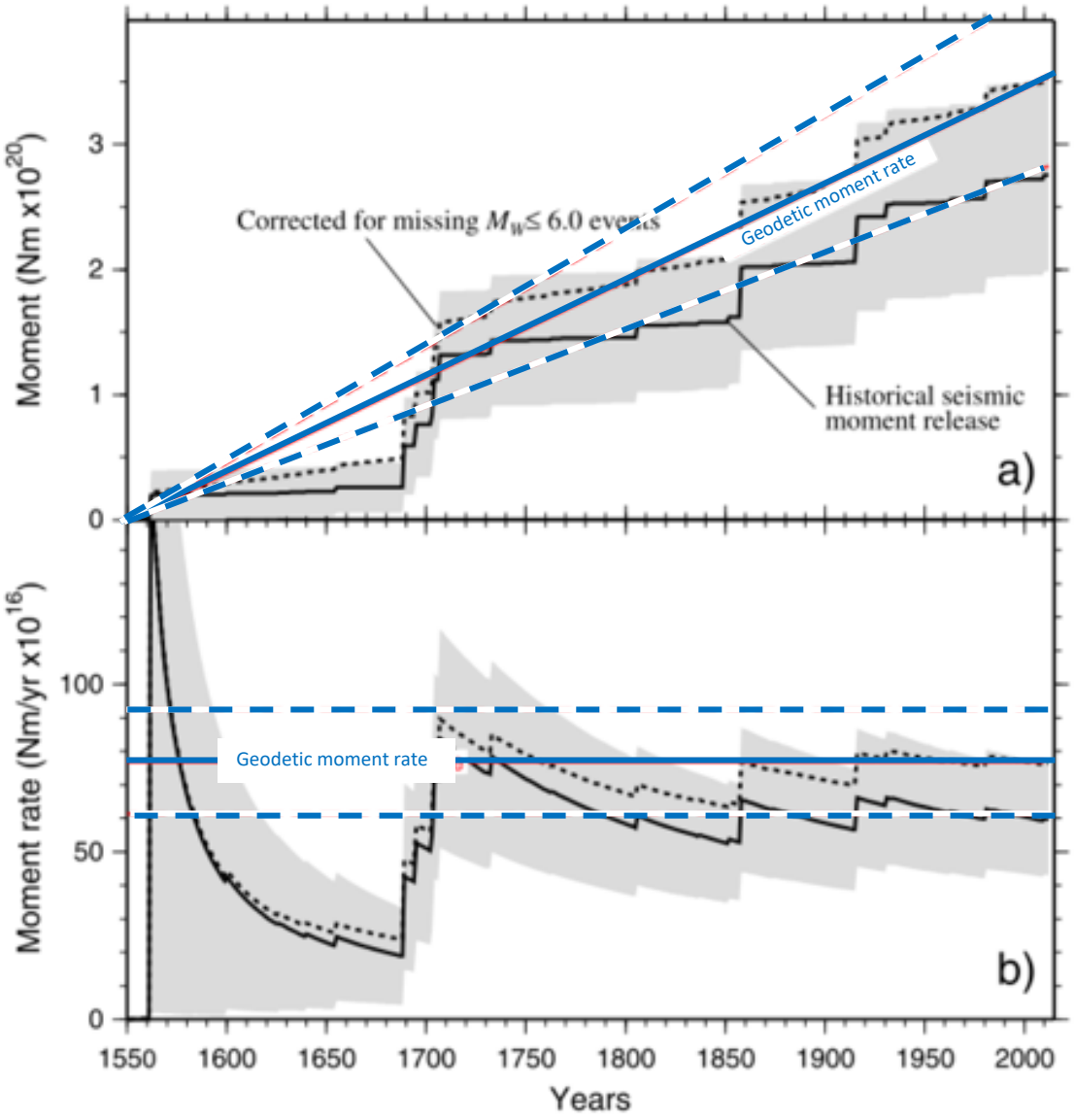


$$\dot{M}_0^{geod} = 2\mu A H_s \dot{\epsilon}_{max} = 2\mu \times W \times L \times H_s \times \frac{V}{W}$$

$$\dot{M}_0^{geod} = 72.0 \pm 18.0 \times 10^{16} Nm/yr \quad \text{calculated}$$

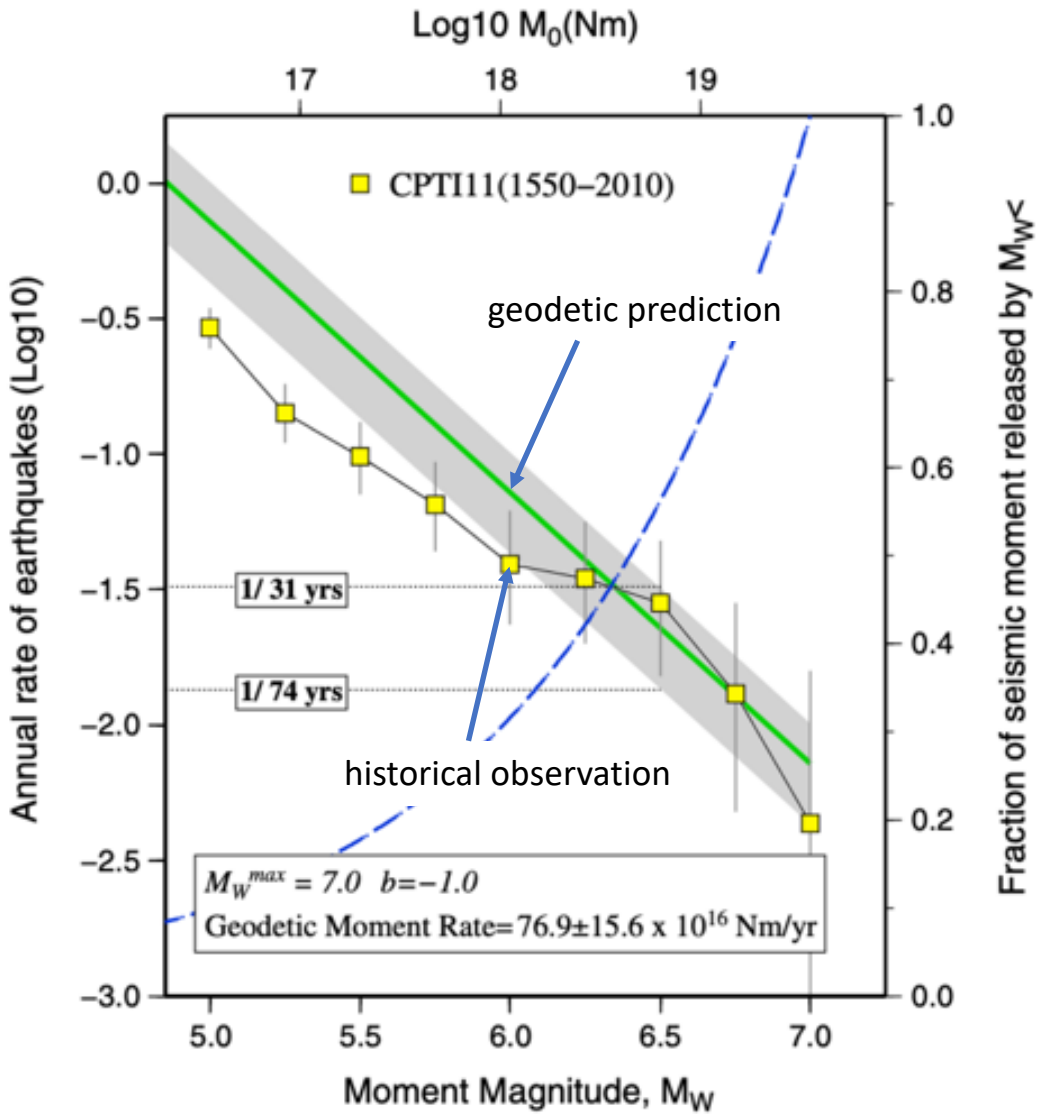
$$\dot{M}_0^{geod} = 76.9 \pm 15.6 \times 10^{16} Nm/yr \quad \text{observed}$$

Strain accumulation vs release - 1



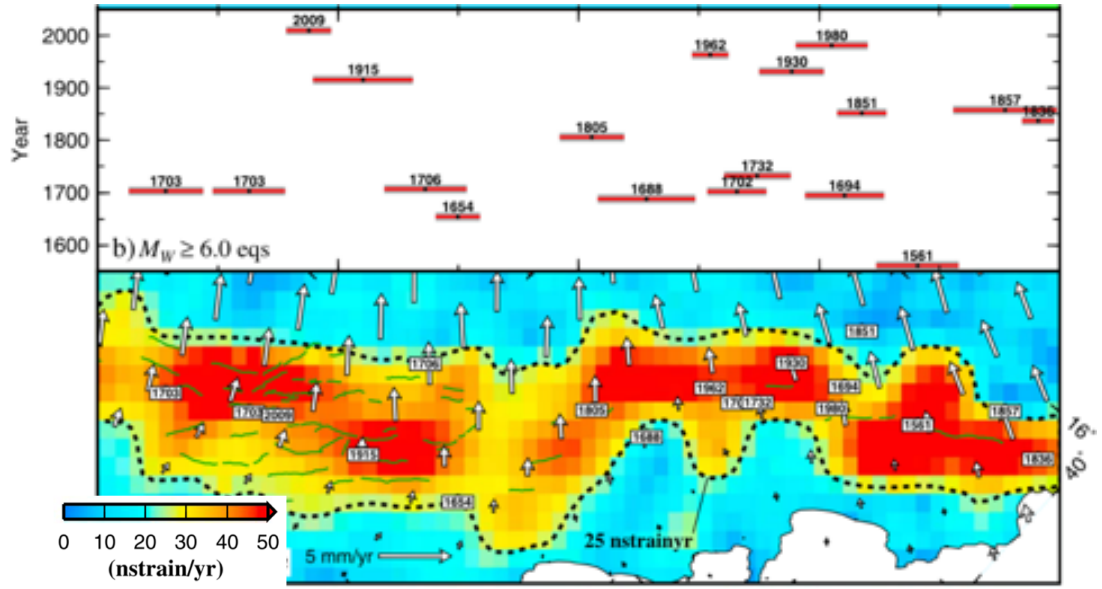
- Assume that GPS strain accumulation operated in the last 500 yrs
- geodetic strain accumulation **76.9 ± 15.6 x 10^{16}** Nm/yr
  seismic strain release **60.1 ± 17.0 x 10^{16}** Nm/yr
- Geodetic strain accumulation ≈ seismic release (within errors) on a 500 yrs timescale
- Clustering (or seismic quiescence) must occur on timescales << 500 years

Strain accumulation vs release - 2



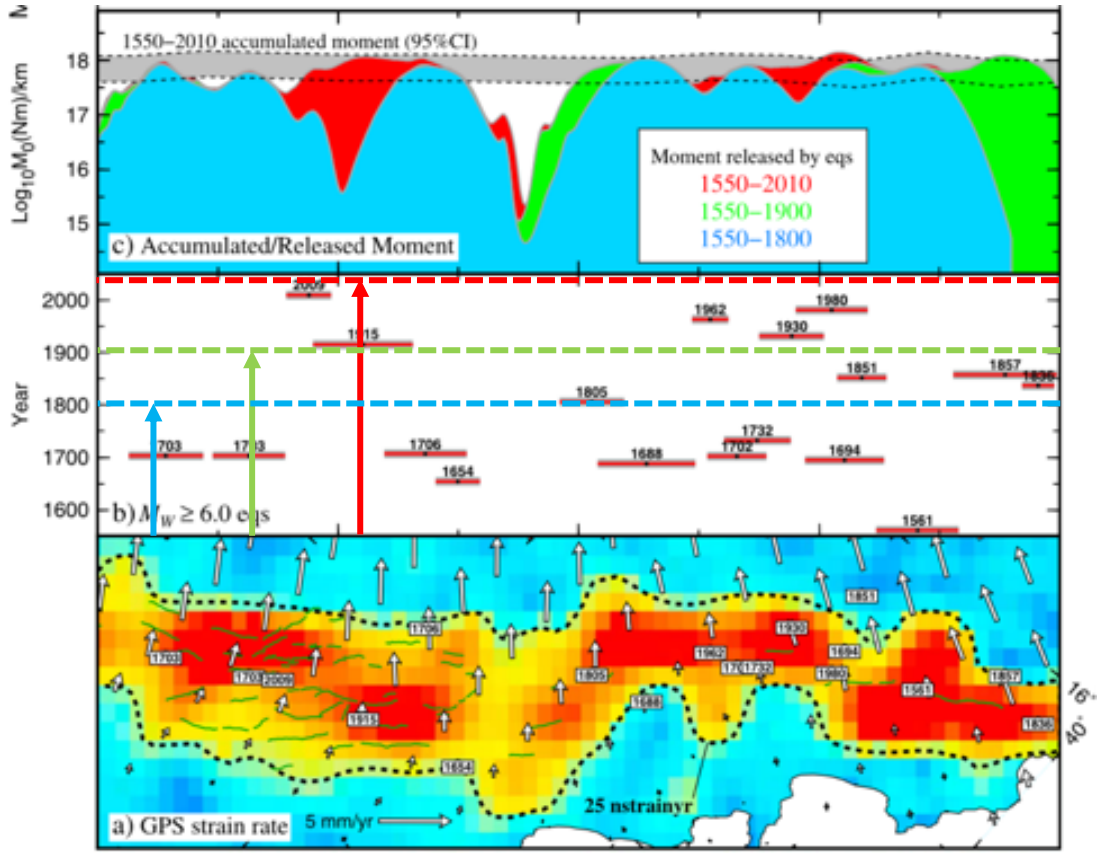
- Earthquake frequency predicted by GPS compatible with historical frequency distribution ?
- Use geodetic moment accumulation to predict frequency distribution using Kostrov(1974) and GR b= 1, M_{max} = 7
- Discrepancy Mw < 6 (uncomplete catalogue)
  Agreement Mw > 6 (complete catalogue)
- To balance geodetic rate no need of M_{max} > 7
- Mw ≥ 6.5 every 31-75 years

Time/Space distribution of strain accumulation/release (1500-2010)



Space/time distribution of M > 6 events
(fault length from scaling relations)

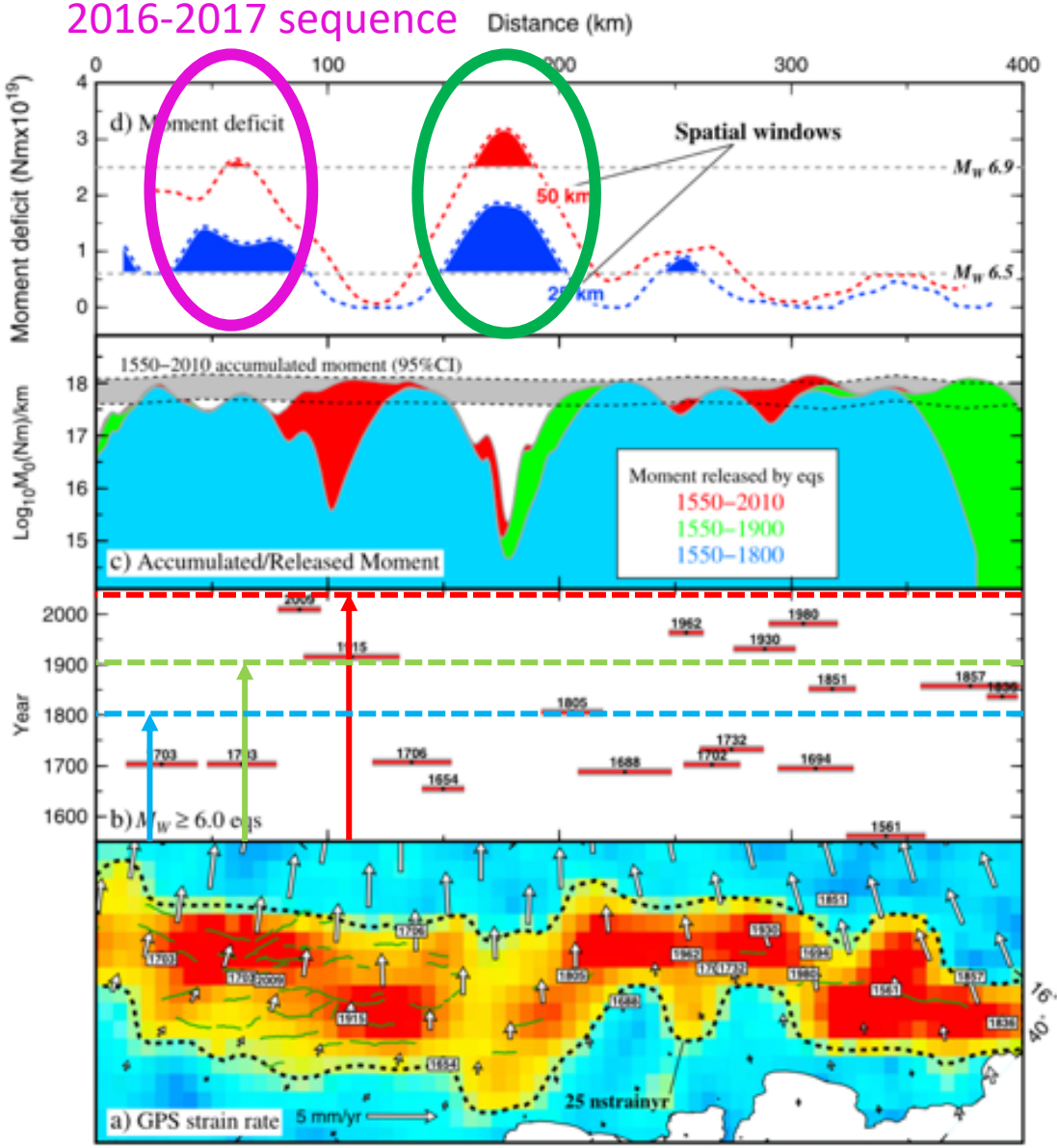
Time/Space distribution of strain accumulation/release (1500-2010)



Intermediate snapshots of seismic release

Space/time distribution of M > 6 events
(fault length from scaling relations)

Time/Space distribution of strain accumulation/release (1500-2010)



Space distribution of unreleased seismic moment

Moment deficit (minimum estimates) at two different length scales (25, 50 km)

Intermediate snapshots of seismic release

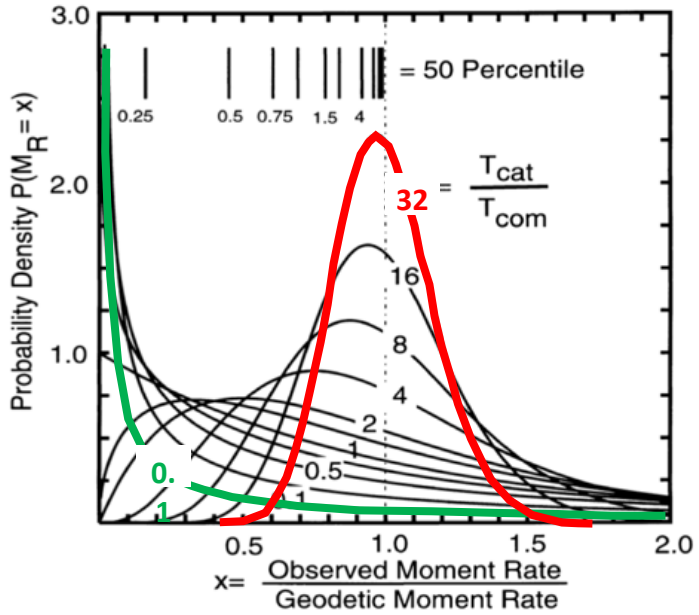
Space/time distribution of M > 6 events (fault length from scaling relations)

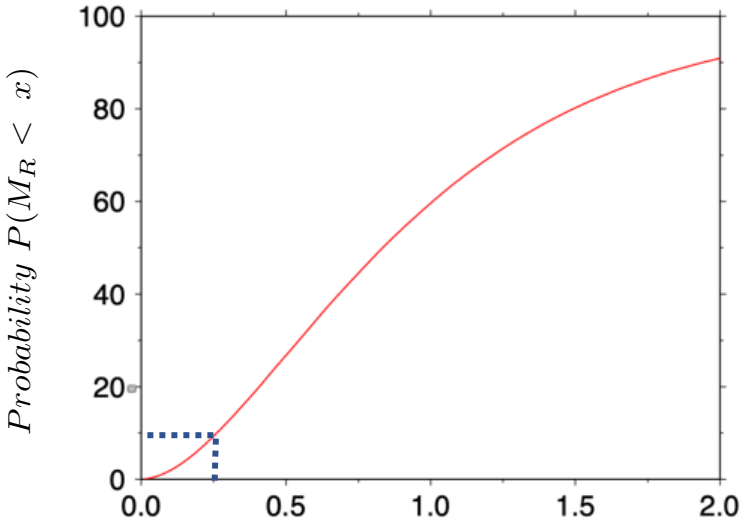
Two areas of significant **unreleased** strain:

1) Umbria-Marche **(drained by the 2016-2017 sequence)**

2) S.Lazio-Molise (seismic/geodetic < 0.25)

Probability of observing unreleased strain ?





Overall in the Apennines seismic/geodetic ≈ 1 (if observed long enough)

But locally ? What is the probability of observing a given amount of unreleased strain ?

Ward(1998): probability of seismic/geodetic ratio as a gamma distribution controlled by the T_{cat}/T_{com} ratio

T_{cat} = catalogue length

T_{com} = characteristic time

$$T_{com} = \frac{\Delta\epsilon}{\dot{\epsilon}} = \frac{coseismic\ strain\ drop}{regional\ strain\ rate}$$

Low T_{cat}/T_{com} = high probability to observe x << 1

High T_{cat}/T_{com} = high probability to observe x ~1

S. Lazio-Molise

T_{com} = 0.75 x 10^{-5} / 30 x 10^{-9} yr^{-1} = 250 years

T_{cat} = 500 years

Tcat/Tcom = 2

Probability of seismic/geodetic < 0.25 ≈ 10%

Conclusions

- Most of the tectonic deformation in the Apennines is accomodated seismically
- 500 yrs seem enough to estimate long-term seismicity rate
- Independent estimate of M_{max} (M_w 7)
- Clustered events (or quiet intervals) on time scales << 500 yrs
- Regions of high unreleased strain can be the target for prevenctive, specific actions aimed at reduction of seismic risk