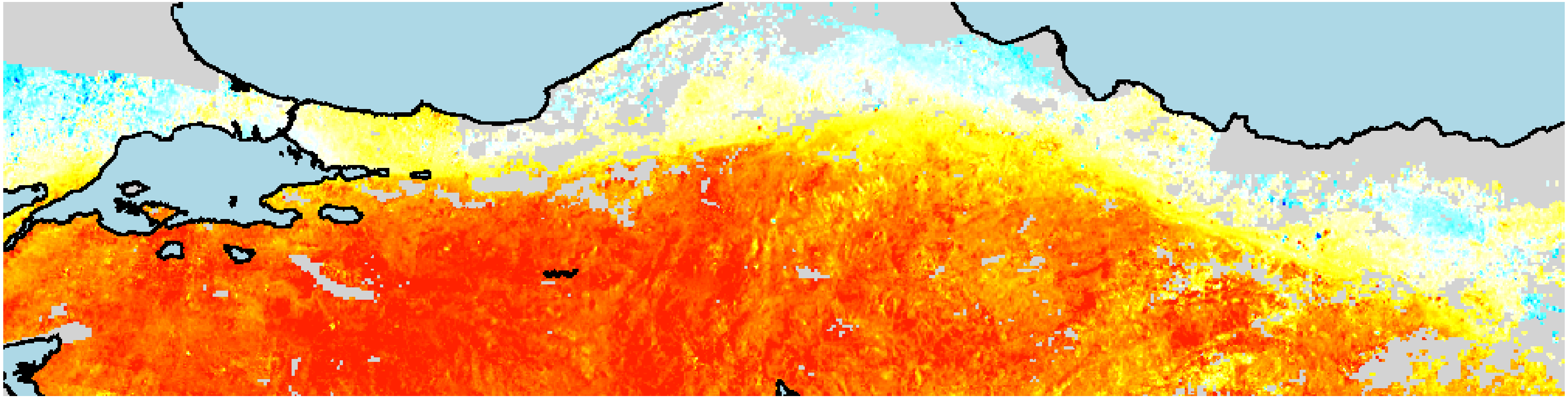
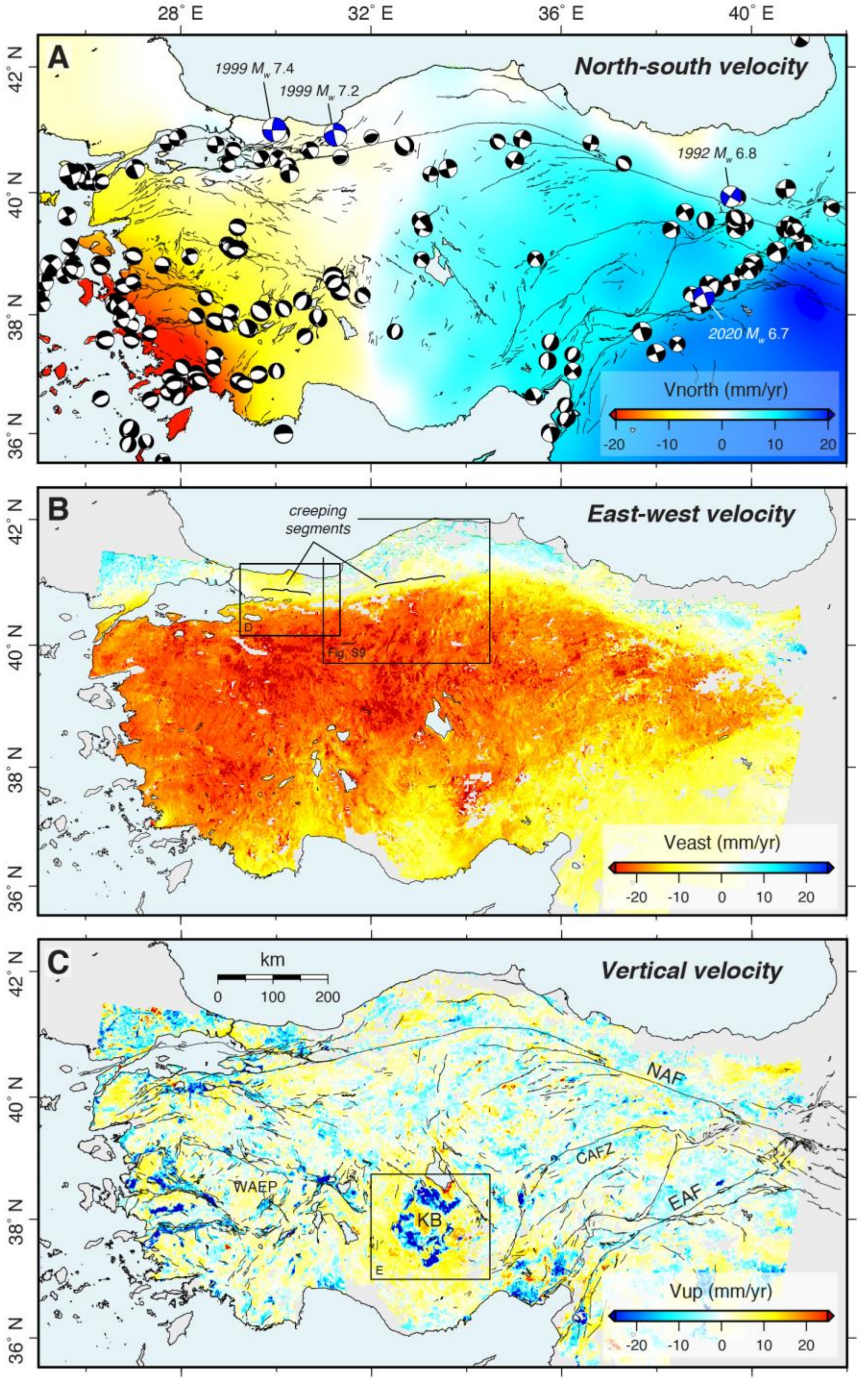
Constraints on the rheology of the mid- to lower-crust from geodetic studies of the earthquake deformation cycle



Tim J Wright[1], Tom Ingleby[2], Ekbal Hussain[3]

[1]COMET, University of Leeds, UK; [2]SatSense Ltd, Leeds, UK; [3]British Geological Survey, UK

@timwright_leeds
@NERC_COMET



Weiss et al., preprint: https://eartharxiv.org/8xa7j/

Take Home Messages:

- Observations of earthquake deformation cycle from satellite geodesy are increasing in quality and quantity.
- Interseismic and postseismic deformation provide powerful constraints on the rheology of the mid- to lower- crust.
- Interseismic strain is focused around major faults: this requires a relaxation time ≥ earthquake repeat time (i.e. a relatively strong material).
- Postseismic deformation transients are rapid and follow a Omori Law decay ($V \sim t^{-1}$): this requires afterslip or power-law creep in a narrow shear zone.
- Combining these processes can explain the whole earthquake cycle for a major fault like the North Anatolian Fault.
- Inferences from geodetic data are not unique, but they can be combined with understanding from field and lab studies of rock rheology to test hypotheses.

Key Papers:

Ingleby and Wright, *Geophys. Res. Lett.* 2017
Hussain et al., Nat. Comms. 2018

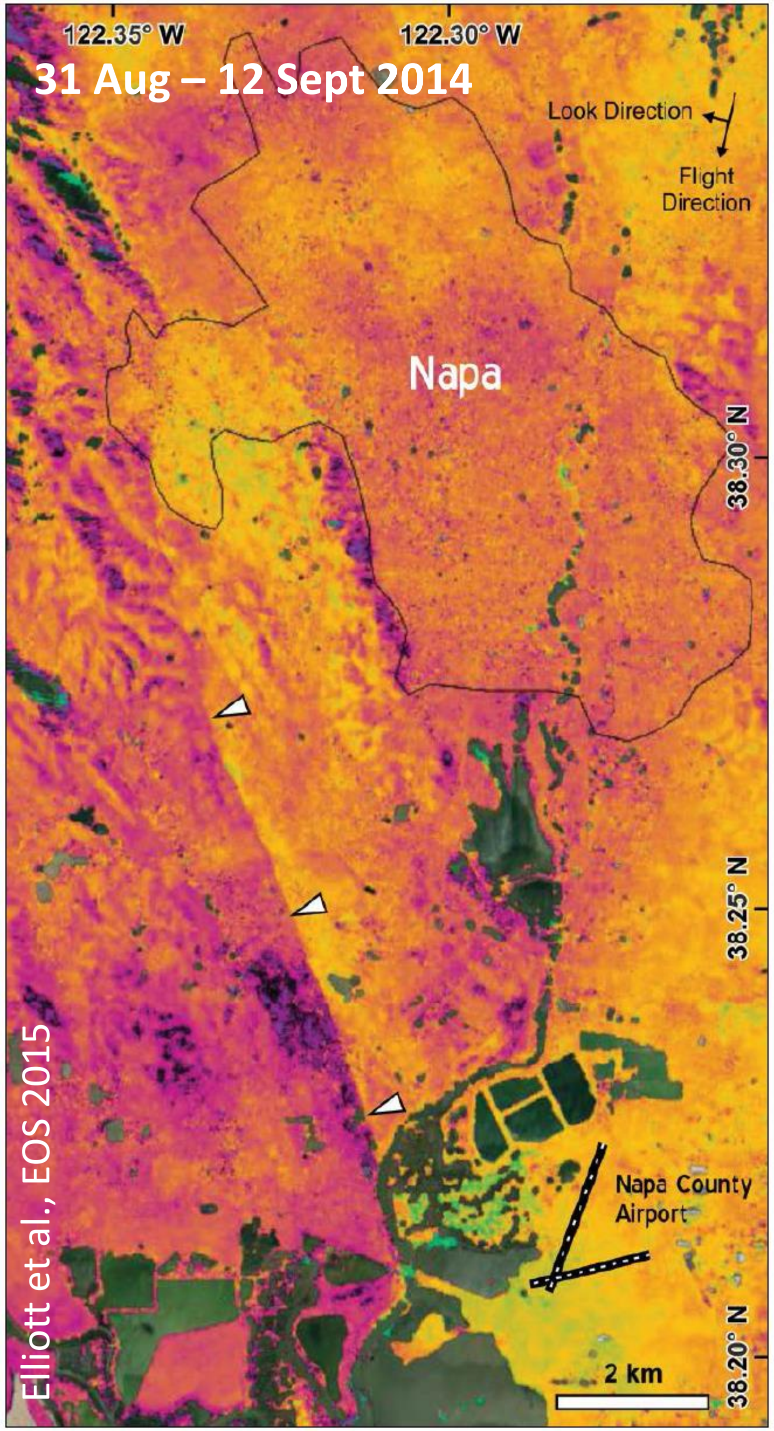
Part 1: Postseismic Deformation

2014 Napa earthquake: August to December afterslip

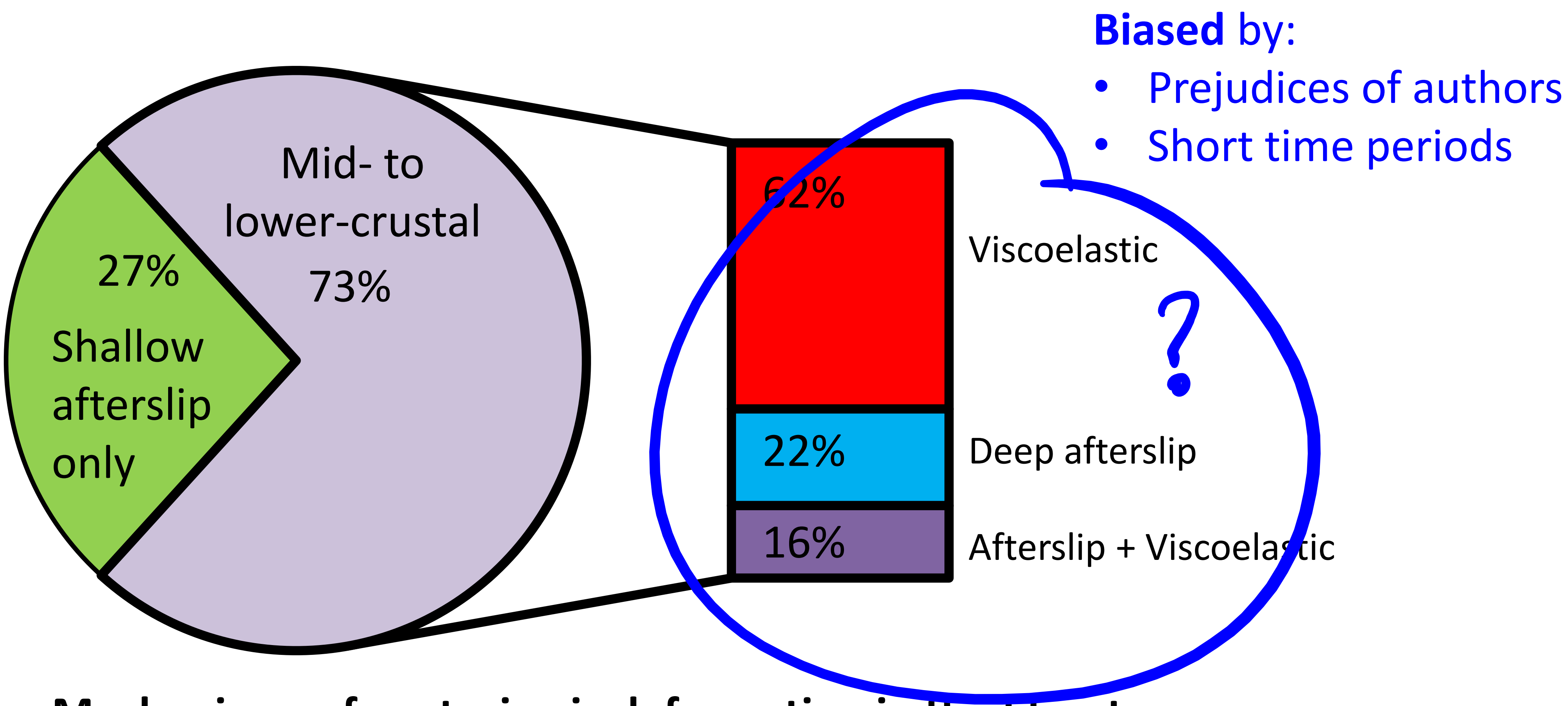
From: Stephane Baize blog

Leaning Oak Road - Napa

http://stephaneonblogger.blogspot.co.uk/2015/11/those-faults-that-move-without-quaking.html



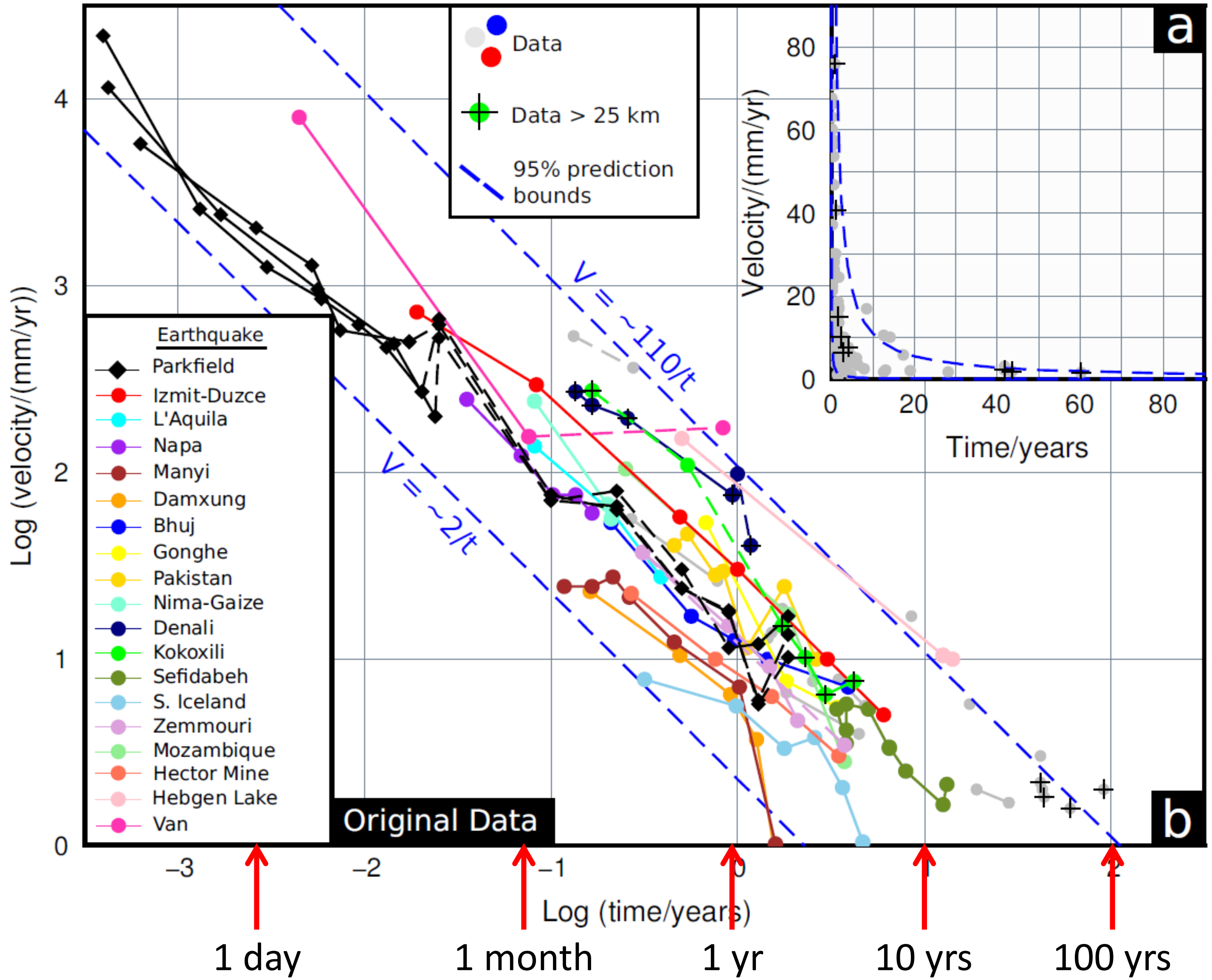
Part 1: Postseismic Deformation



Mechanisms of postseismic deformation in the literature

Wright et al., Tectonophysics 2013:
49 postseismic studies of 23 earthquakes

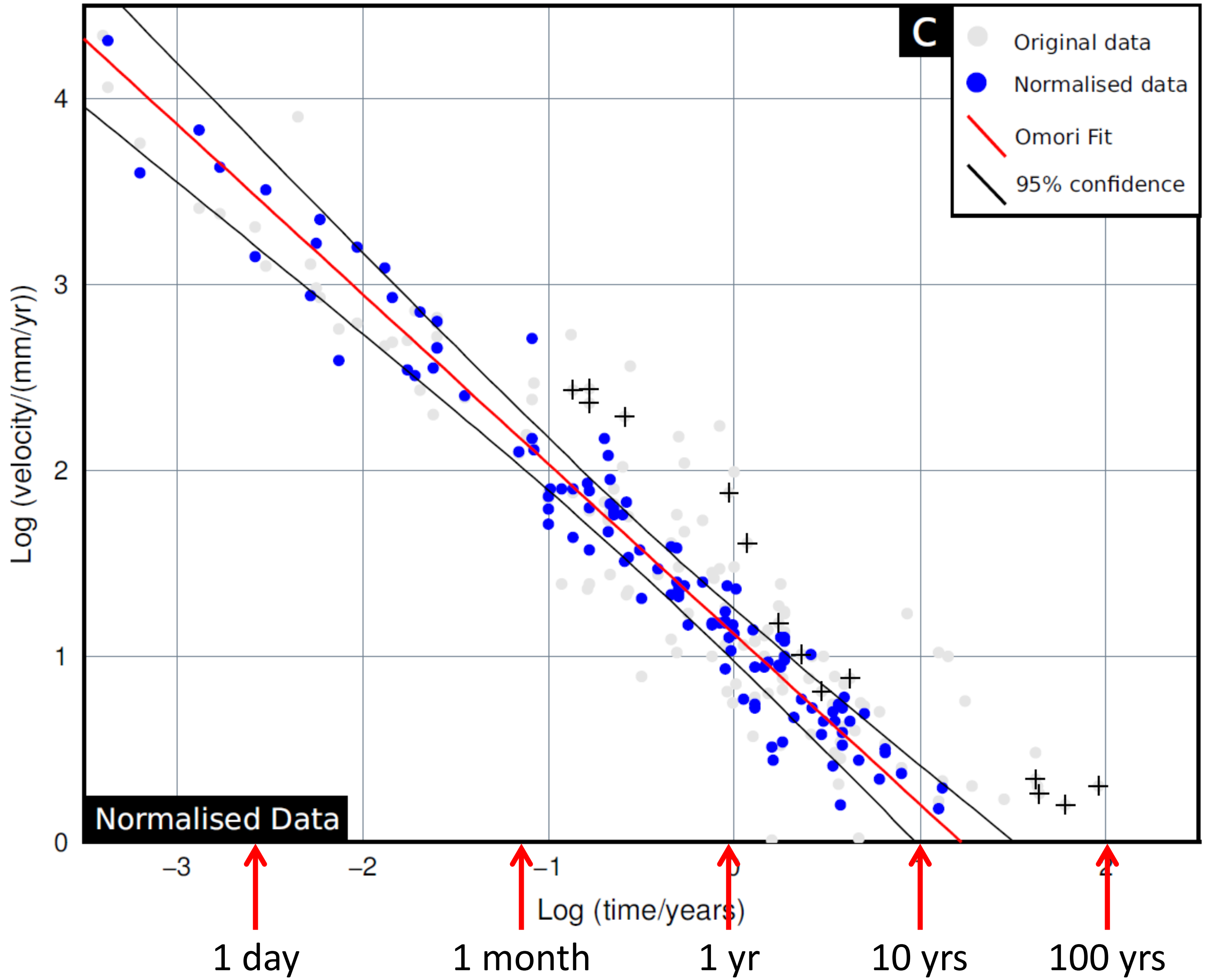
Part 1: Postseismic Deformation



- Compiled observations from the literature of maximum postseismic velocity as a function of time for 34 moderate to large continental earthquakes.
- Shows rapid decay for most earthquakes.
- Temporal behaviour is more diagnostic in log-log space.
- Maximum velocities decay as ~1/t

Ingleby and Wright, GRL 2017

Part 1: Postseismic Deformation

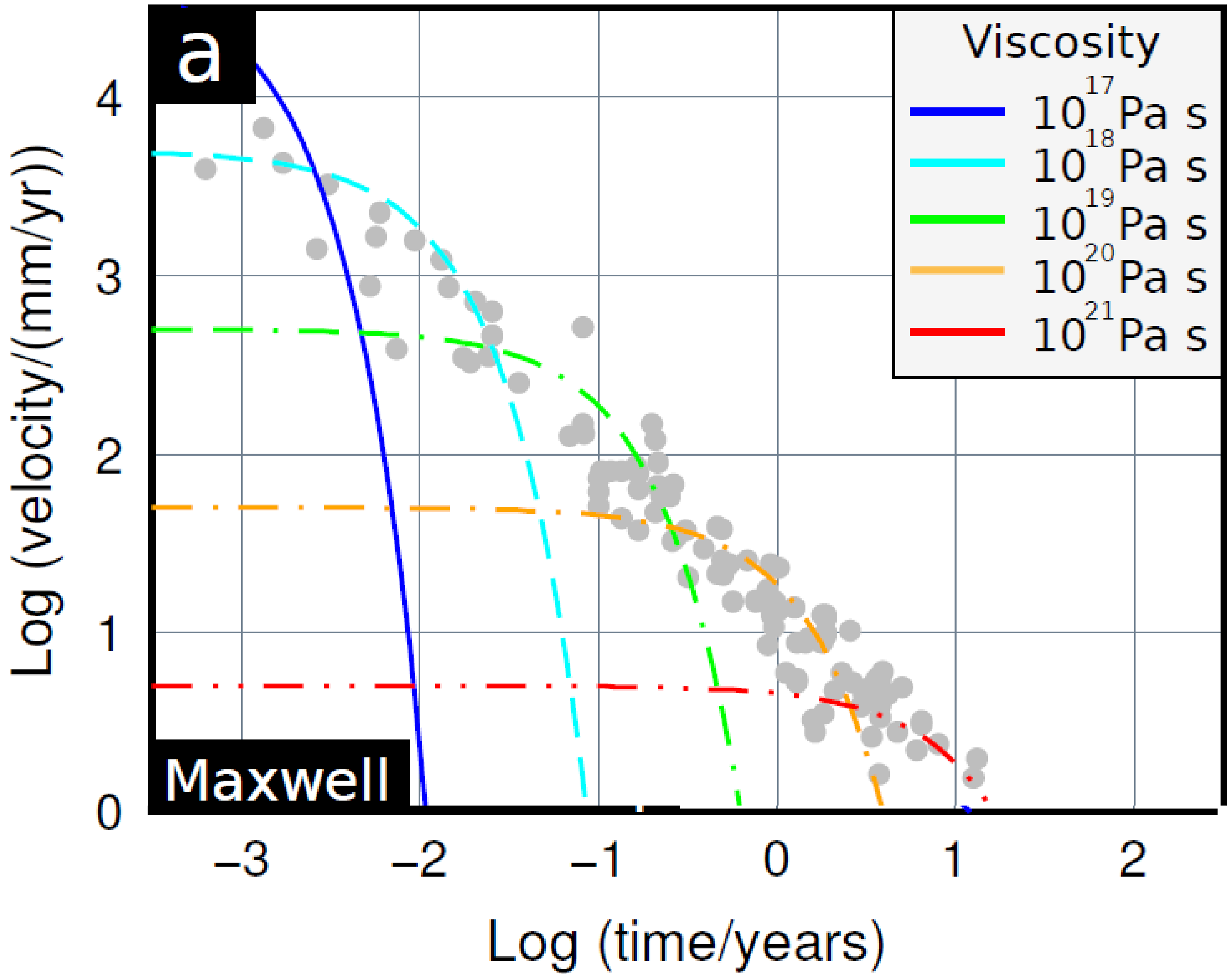


- Compiled observations from the literature of maximum postseismic velocity as a function of time for 34 moderate to large continental earthquakes.
- Shows rapid decay for most earthquakes.
- Temporal behaviour is more diagnostic in log-log space.
- Maximum velocities decay as ~1/t
- Normalised data shows a remarkably simple pattern.

Ingleby and Wright, GRL 2017

Part 1: Postseismic Deformation

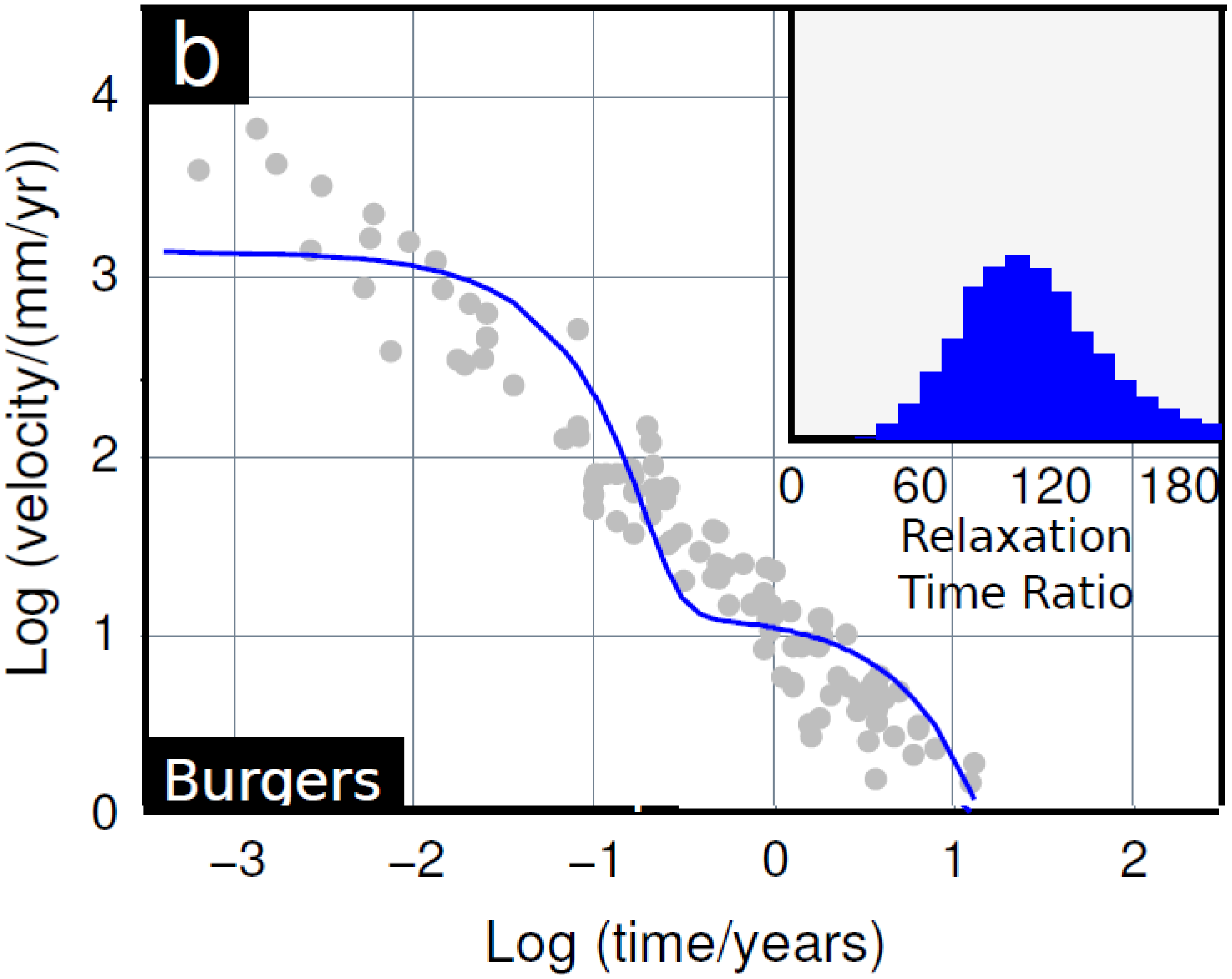
- Observations are incompatible with uniform linear Maxwell rheology (effective viscosity increases with time)



Ingleby and Wright, GRL 2017

Part 1: Postseismic Deformation

- Observations are incompatible with uniform linear Maxwell rheology (effective viscosity increases with time).
- Burgers rheology can match spread of data but does not give ~1/t decay observed.



Ingleby and Wright, GRL 2017

Part 1: Postseismic Deformation

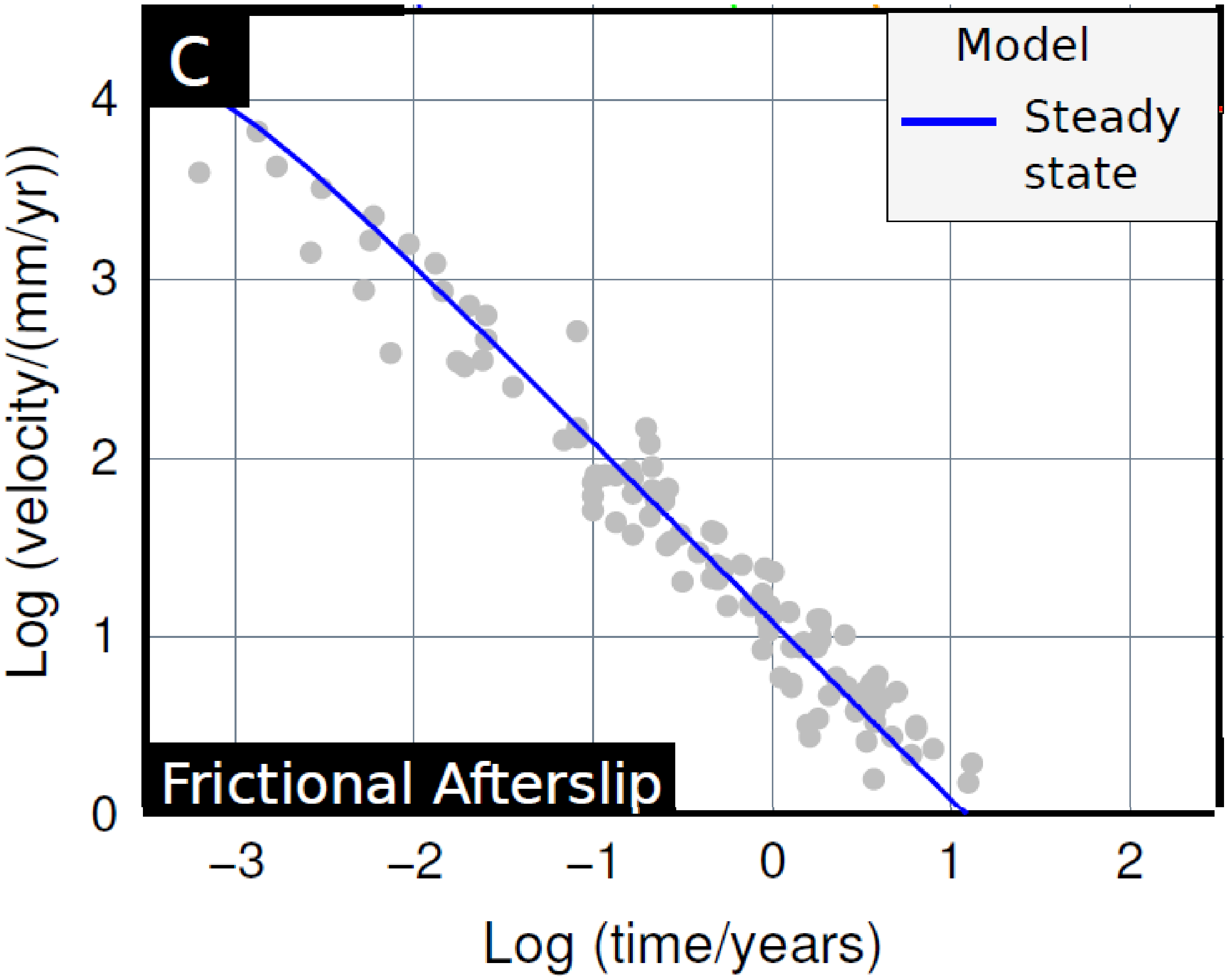
- Observations are incompatible with uniform linear Maxwell rheology (effective viscosity increases with time).
- Burgers rheology can match spread of data but does not give ~1/t decay observed.
- Rate and state frictional afterslip (steady state) predicts observed temporal decay:

$$V(t) = \frac{V_0}{1 + \frac{t}{\tau}}$$

- Note this is of identical form to Omori's Law for aftershock decay:

$$n(t) = \frac{K}{(t + c)^p}$$

[if $v(t) = n(t),\ c = \tau,\ K = V_0\tau$, and $p = 1$].



Ingleby and Wright, GRL 2017

Part 1: Postseismic Deformation

- Observations are incompatible with uniform linear Maxwell rheology (effective viscosity increases with time).
- Burgers rheology can match spread of data but does not give ~1/t decay observed.
- Rate and state frictional afterslip (steady state) predicts observed temporal decay:

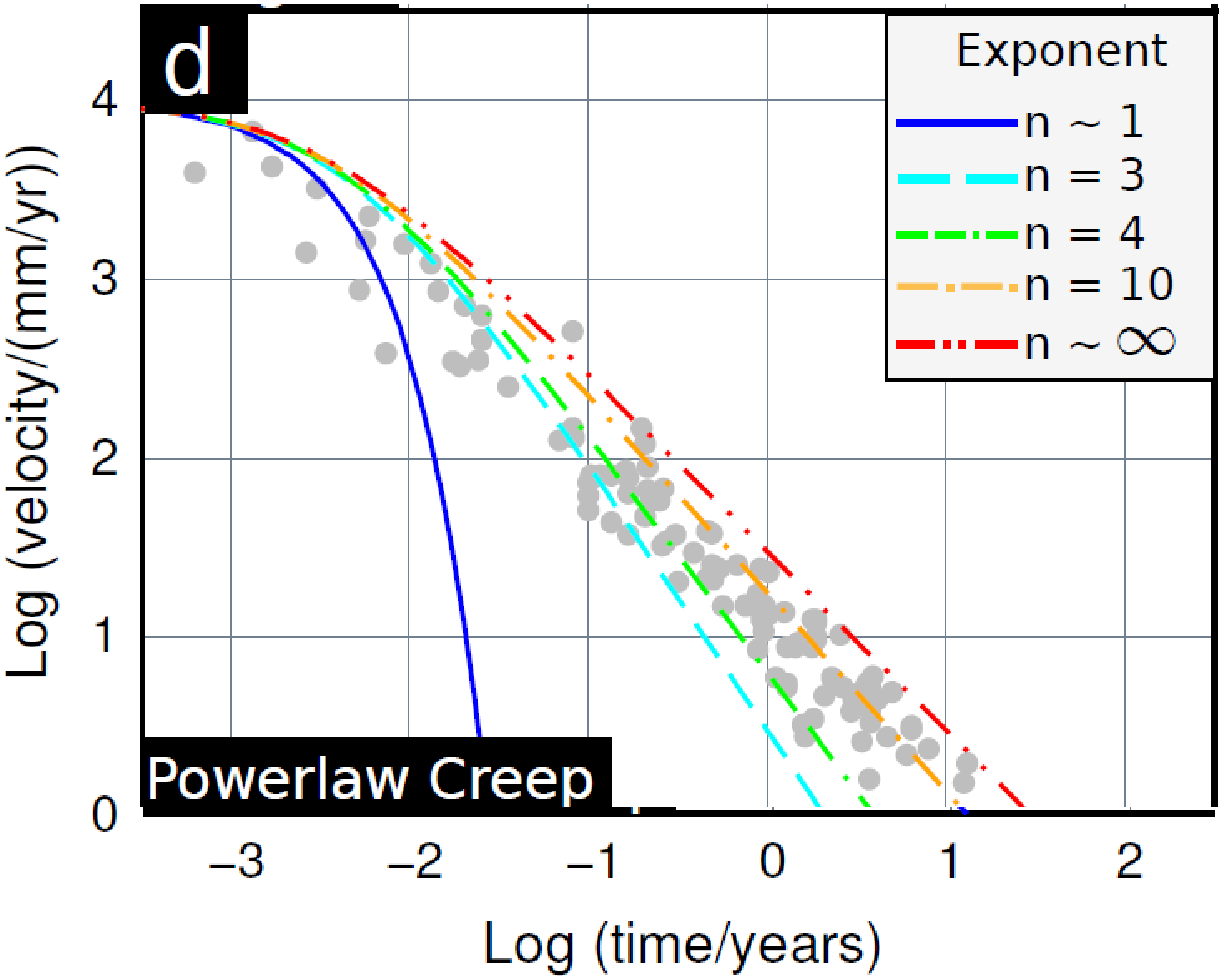
$$V(t) = \frac{V_0}{1 + \frac{t}{\tau}}$$

- Note this is of identical form to Omori's Law for aftershock decay:

$$n(t) = \frac{K}{(t + c)^p}$$

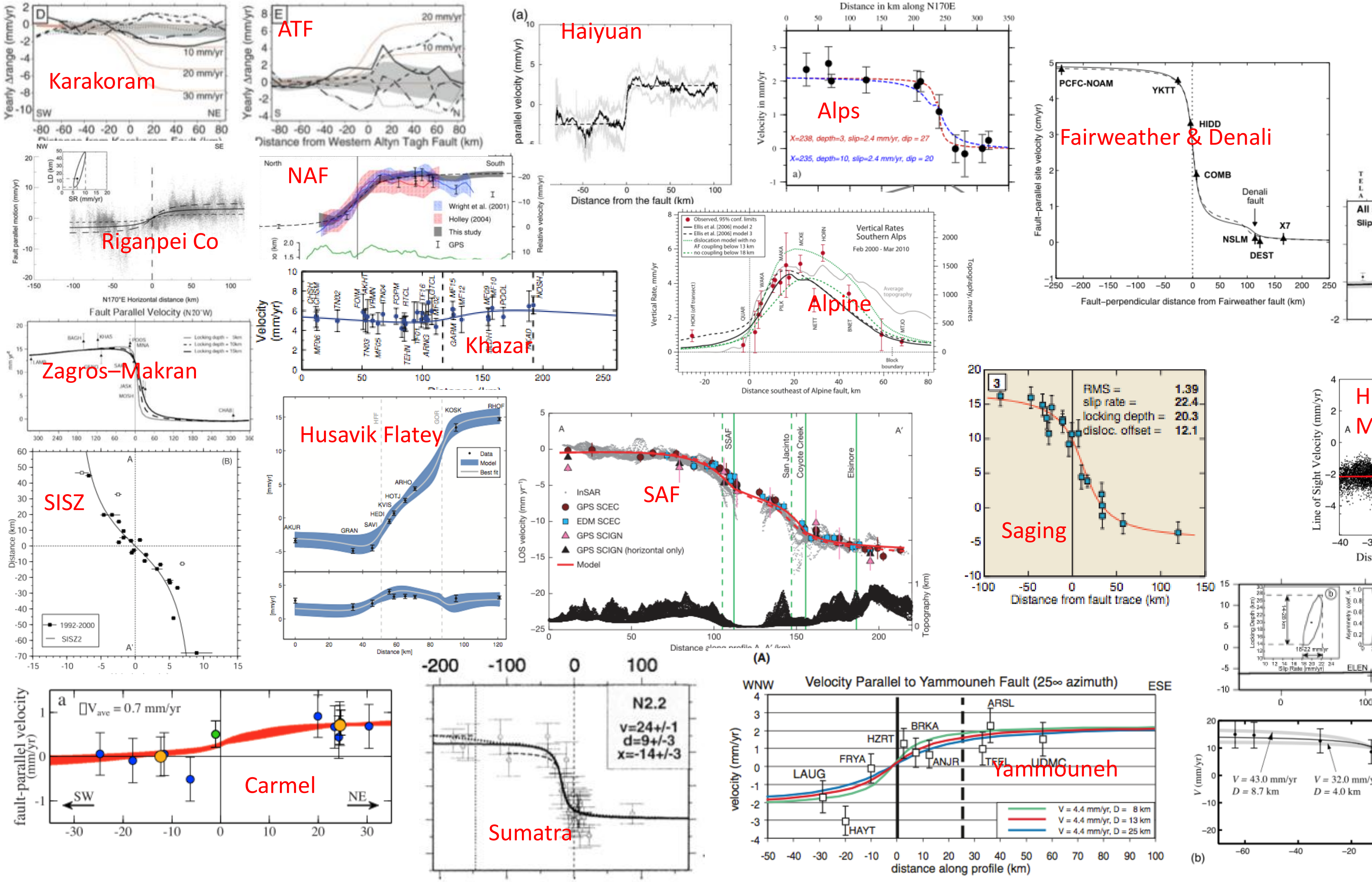
[if $v(t) = n(t),\ c = \tau,\ K = V_0\tau$, and $p = 1$].

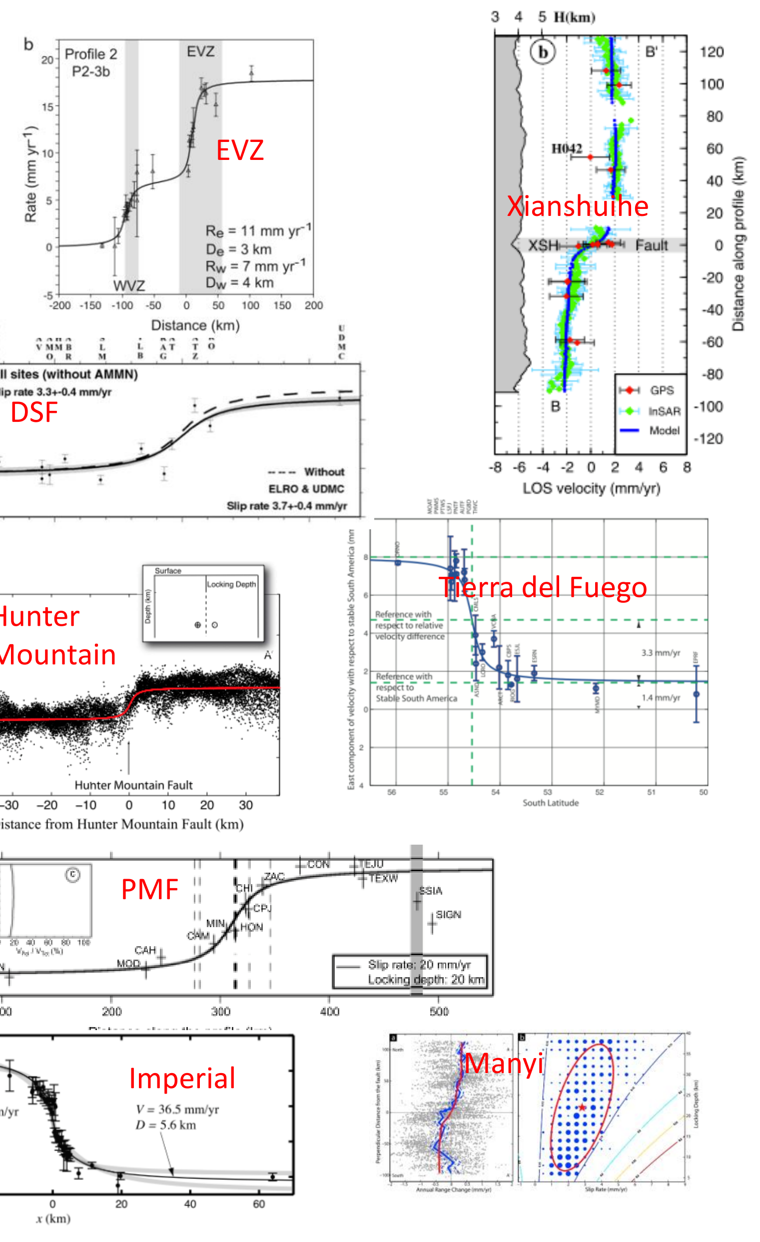
- Power-law creep in a shear zone can only match observations if *n* is higher than usual range of experimentally-determined values.



Ingleby and Wright, GRL 2017

Part 2: Interseismic Deformation





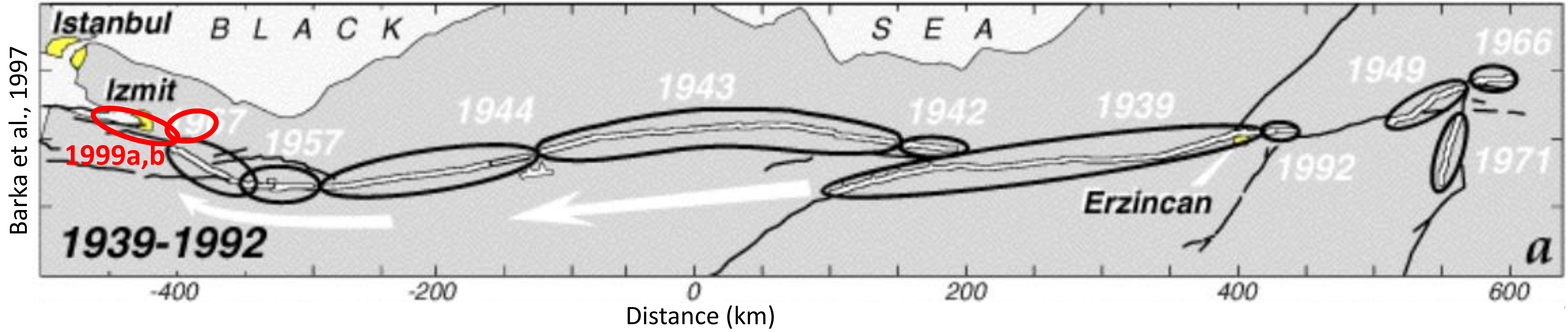
Interseismic deformation (in most cases) is focused around faults (and can be modelled with a screw dislocation)

We found 187 examples of this in Wright et al., Tectonophysics 2013

Part 2: Interseismic Deformation

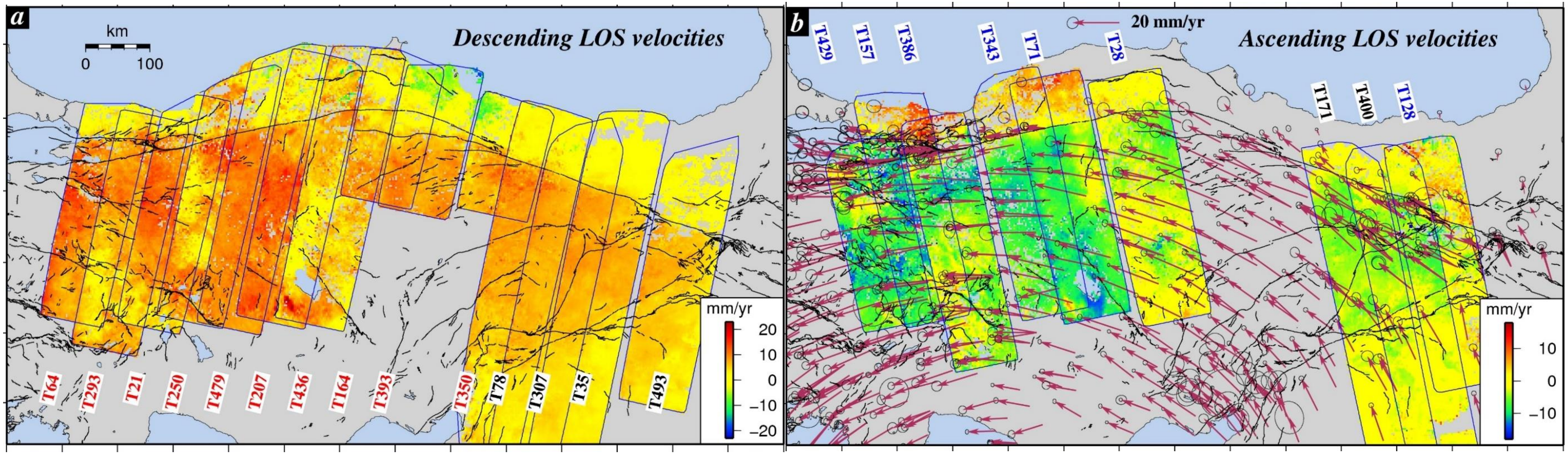
Question: Do strain rates vary throughout the seismic cycle?

- To test this, we use strain data from the North Anatolian Fault in Turkey, where the fault has failed at different times.
- Assuming that the system is similar along strike, present-day strain data from different locations give us observations at different times in the cycle.



Part 2: Interseismic Deformation

Measuring strain rates along the entire North Anatolian Fault

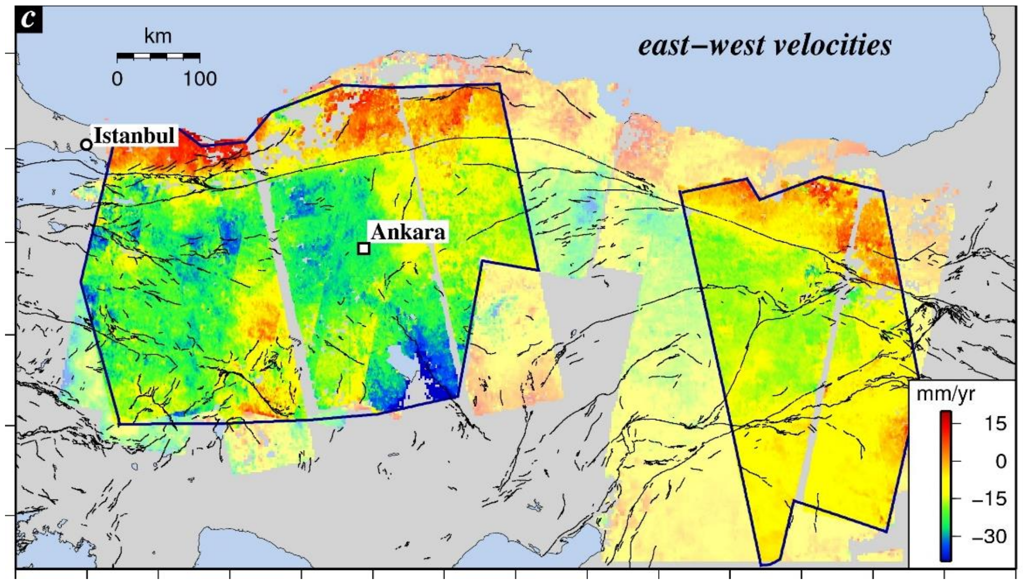


Input data sets

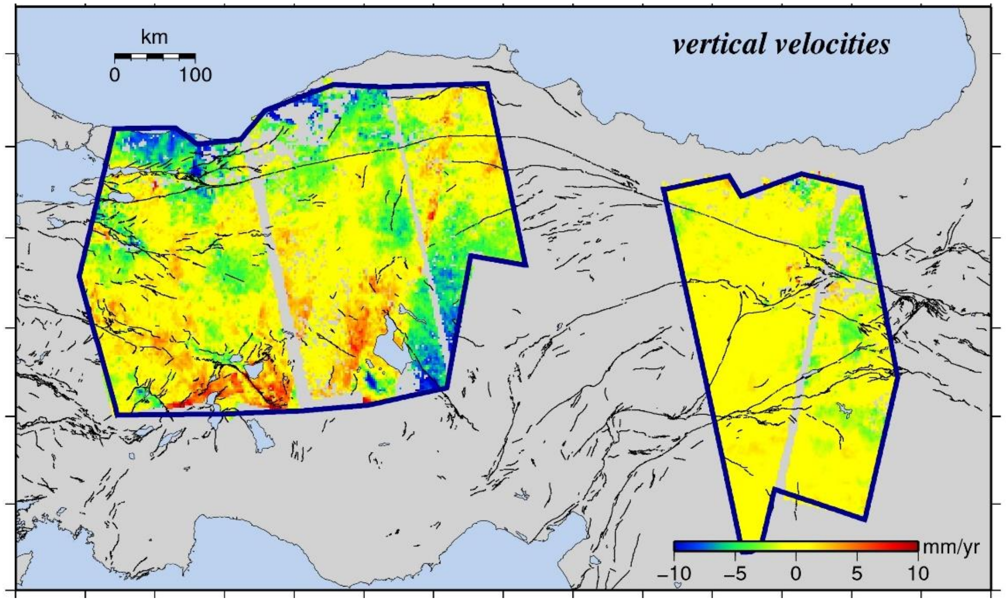
- Determine average line of sight velocities for period 2003 to 2010 using 14 Descending and 9 Ascending Envisat tracks.
- Process each line-of-sight velocity map using a small baselines approach in StaMPS
- Use iterative unwrapping as outlined in Hussain et al. (JGR 2016).
- Uncertainties (from overlaps) ~ 2-5 mm/yr for most tracks.
- GNSS compilation from GSRM. Used to tie InSAR to Eurasian reference frame and to constrain N-S in 3D inversion.

Hussain et al., Nat. Comm. 2018

Part 2: Interseismic Deformation



East-West velocity field



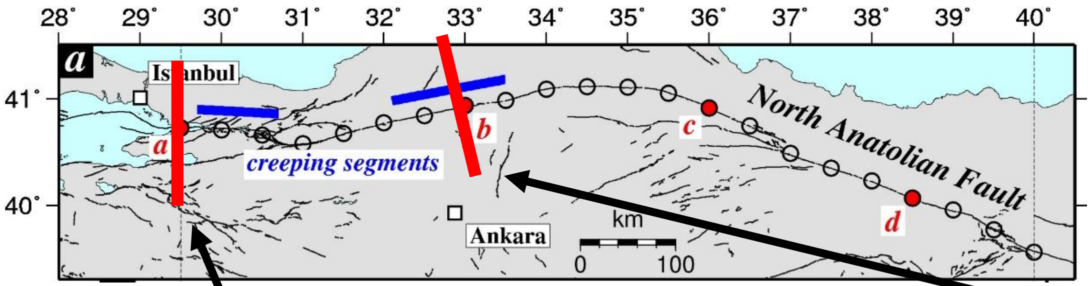
Vertical velocity field

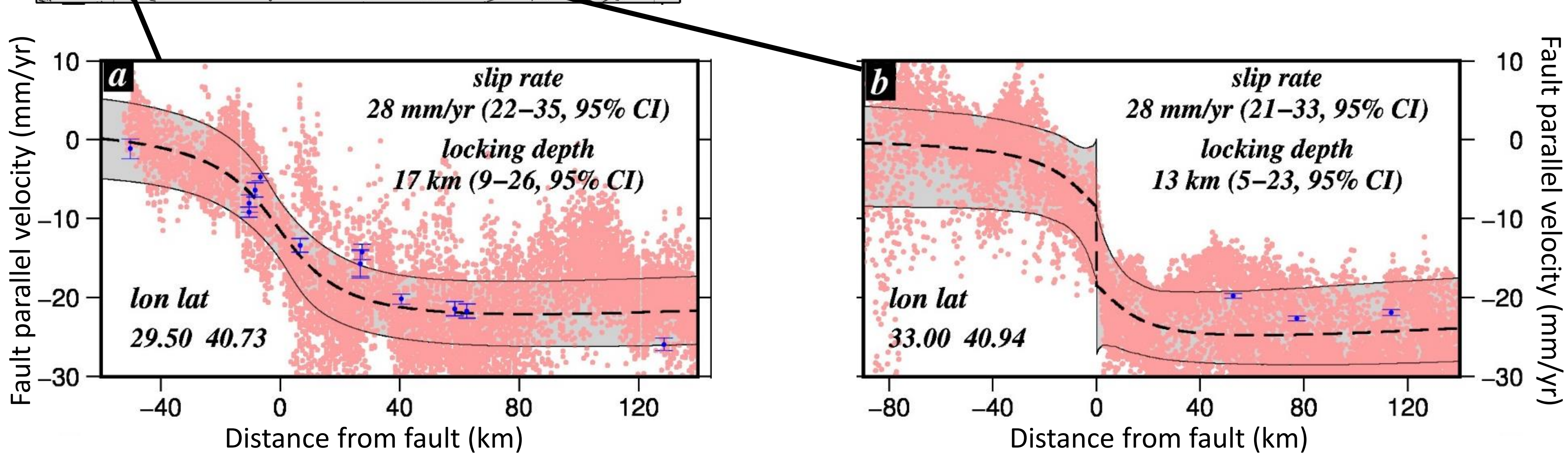
Combine data in 3D velocity field (at InSAR resolution)

- East-west velocities show the westward motion of Anatolia with respect to Eurasia, and strain accumulation across the North Anatolian Fault Zone
- Vertical motions are not systematic. Mostly within 5 mm/yr of zero.

Hussain et al., Nat. Comm. 2018

Assessing slip rates, locking depths and strain rates





- Project east-west velocity field and GNSS onto fault-perpendicular profiles of fault parallel velocity.
- Solve* for slip rate and locking depth (Screw dislocation)

$$v_{par}(x) = \frac{S}{\pi}\arctan\left(\frac{x}{d_1}\right) + x\theta_{rot} + a$$

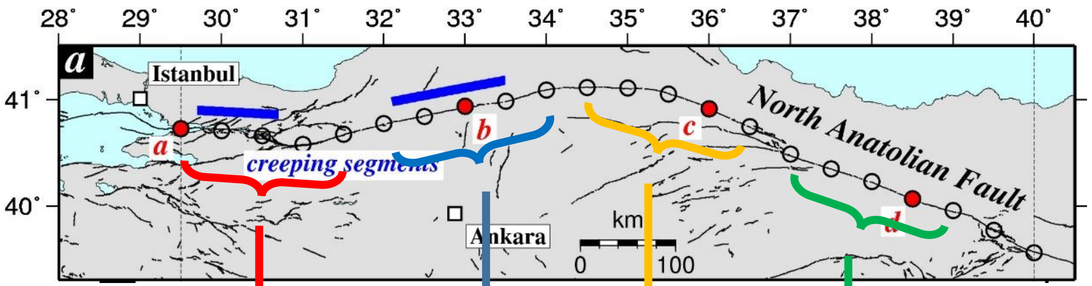
Rotation of Anatolia

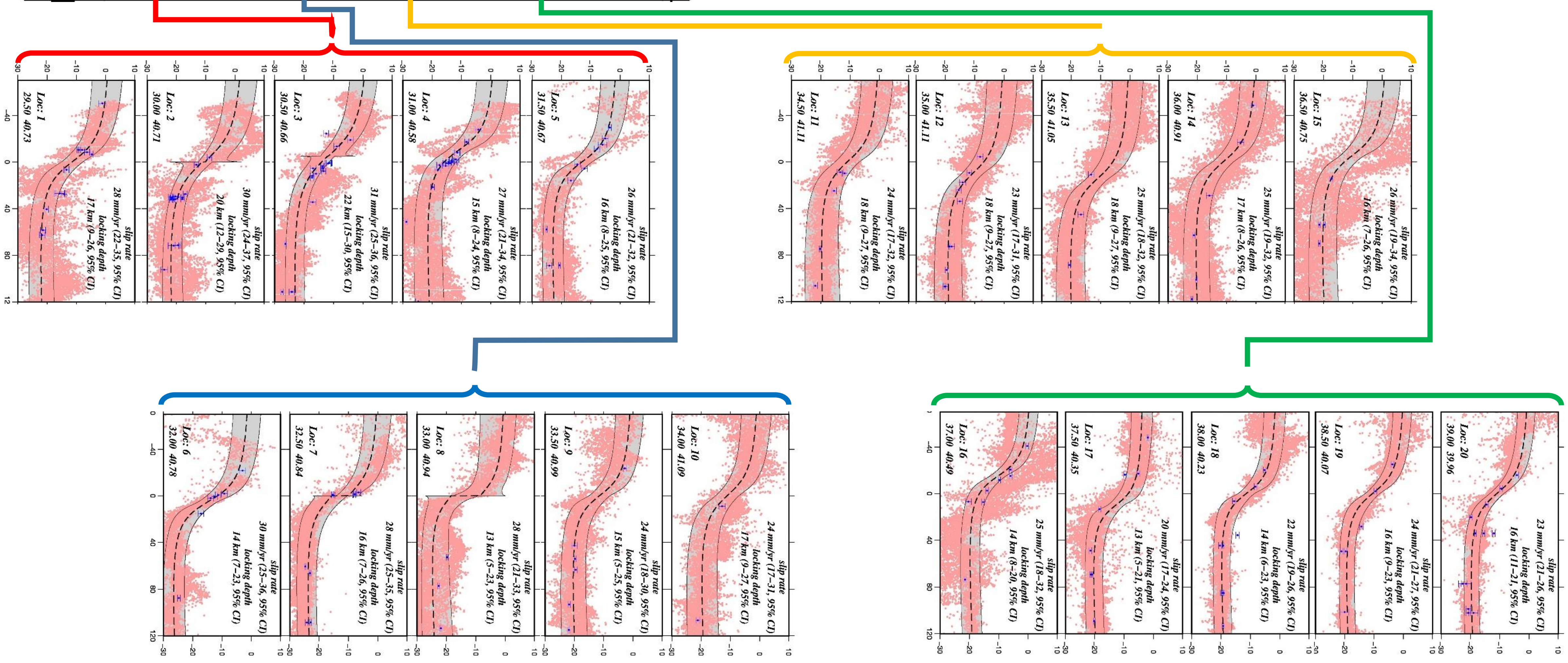
- Where there is creep, also solve for creep rate and depth

$$v_{par}(x) = \frac{S}{\pi}\arctan\left(\frac{x}{d_1}\right) + C\left[\frac{1}{\pi}\arctan\left(\frac{x}{d_2}\right) - \mathcal{H}(x)\right] + x\theta_{rot} + a$$

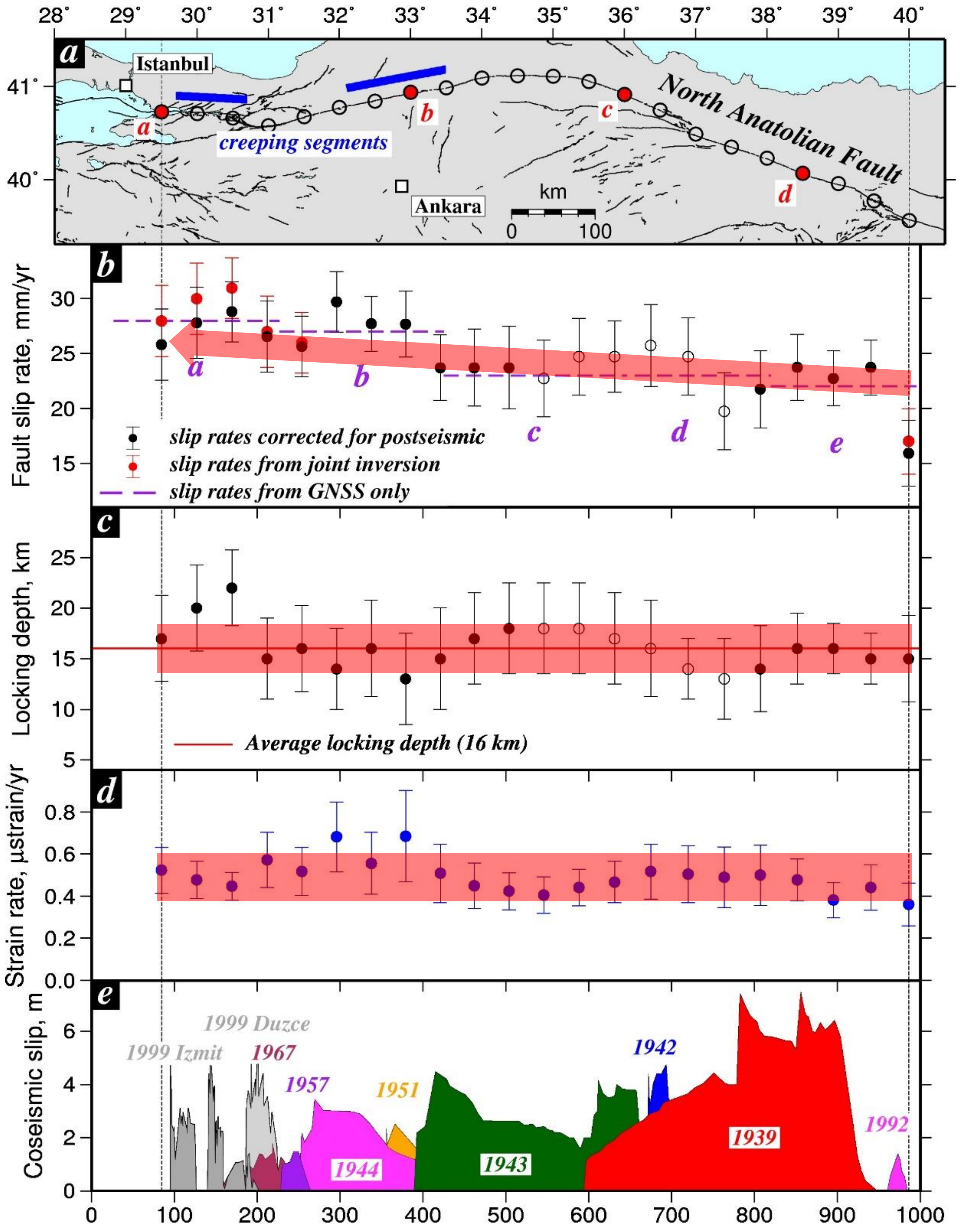
(*Bayesian Markov Chain Monte Carlo sampler)

Assessing slip rates, locking depths and strain rates





Hussain et al., Nat. Comm. 2018

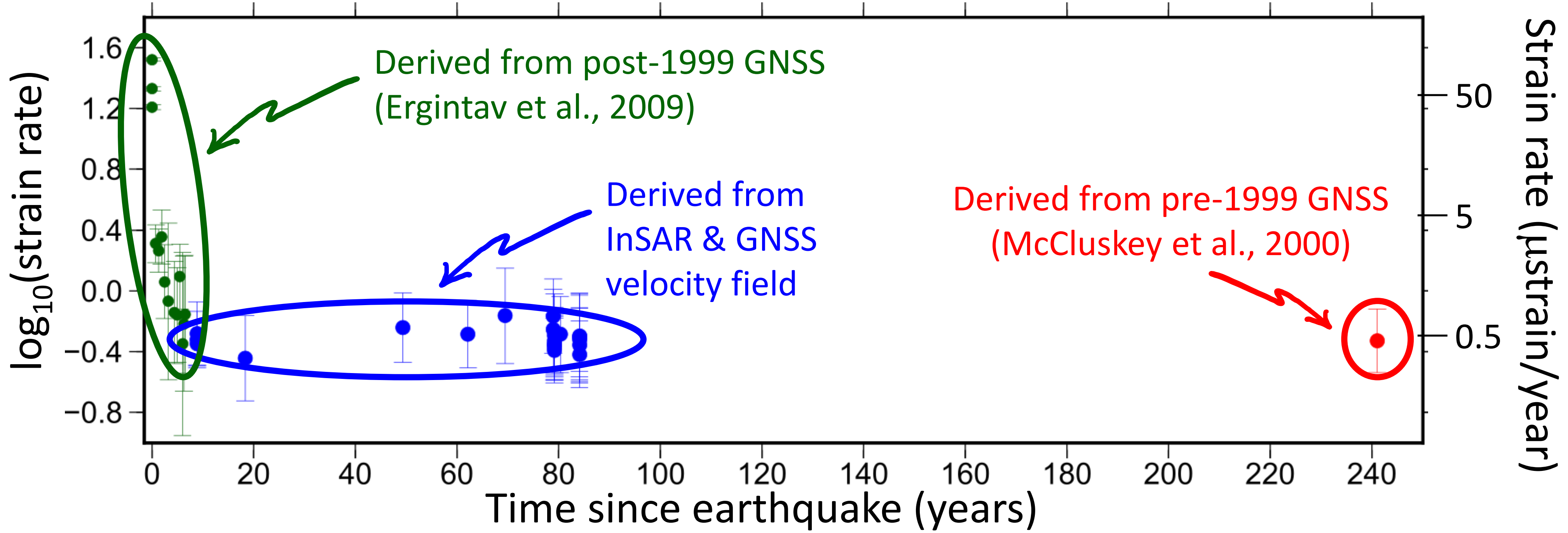


Assessing slip rates, locking depths and strain rates

- Slip rate shows a gradual increase from ~22 mm/yr in East to ~26 mm/yr in West.
- Locking depth is ~constant at 16 ± 2 km
- Strain rate at fault = $\frac{Slip\ Rate}{\pi(Locking\ Depth)}$
- Strain rate approximately constant along fault at 0.5 ± 0.1 µstrain/year.
- Slip, Locking Depth, and Strain rate show no clear relationship to time since most recent earthquake.

Part 2: Interseismic Deformation

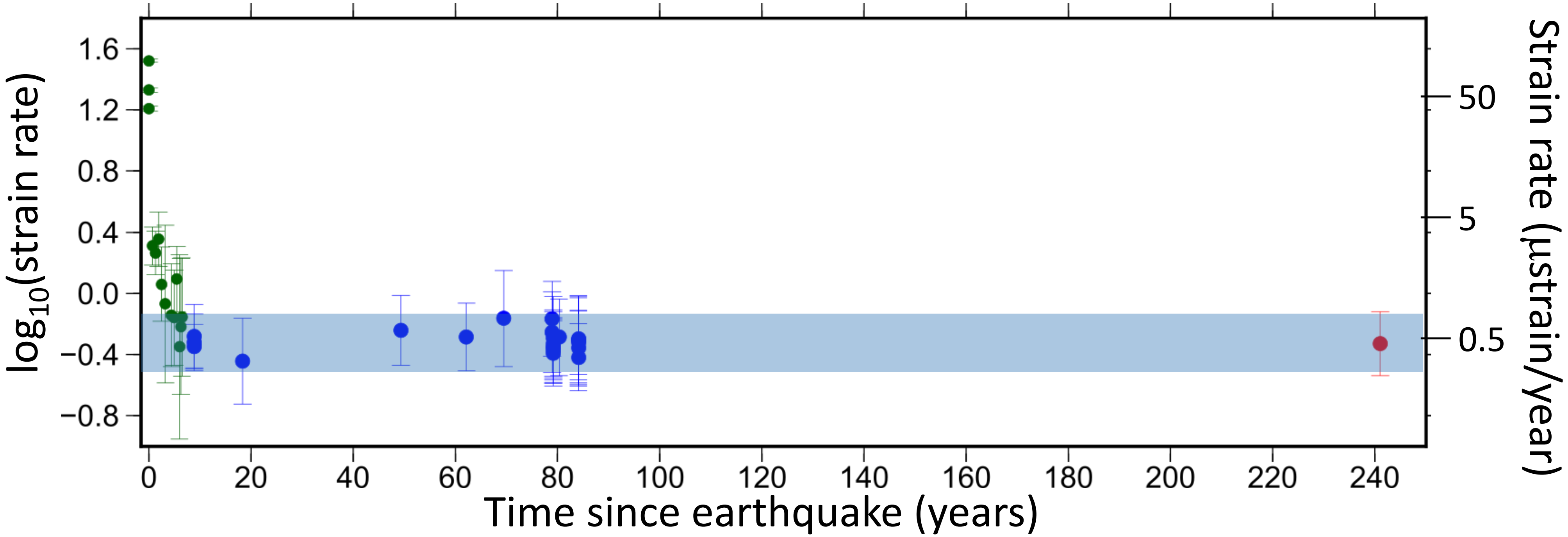
A 250 year strain rate history the North Anatolian Fault



Hussain et al., Nat. Comm. 2018

Part 2: Interseismic Deformation

A 250 year strain rate history the North Anatolian Fault

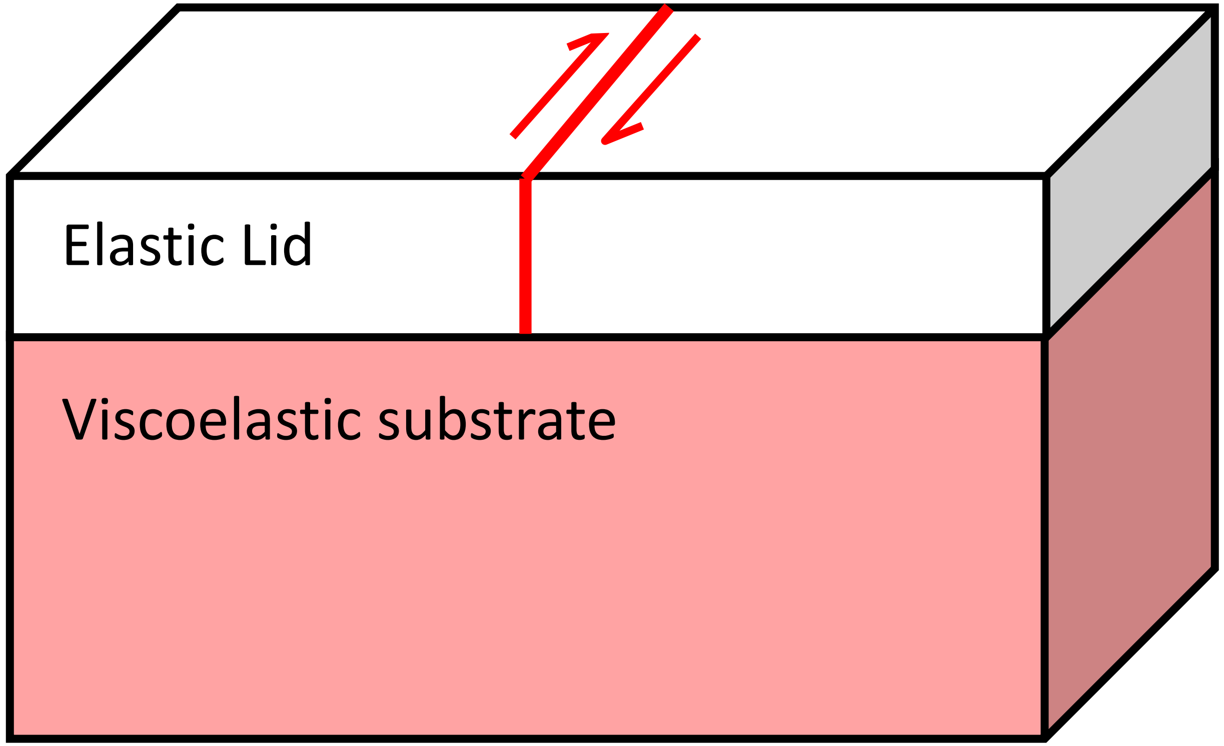


Result: Strain rate along the entire North Anatolian Fault is independent of time since the last earthquake, except in decade following a major earthquake.

Hussain et al., Nat. Comm. 2018

Part 3: Implications for the rheology of the mid/lower crust?

Viscoelastic Coupling Model,
Savage & Prescott 1978; Savage 2000



- Repeating earthquakes in upper layer
- Surface deformation controlled by parameter τ_0

$$\tau_0 = \frac{t_m}{\Delta T}$$

Maxwell relaxation time, $\frac{\eta}{\mu}$

Inter-event time

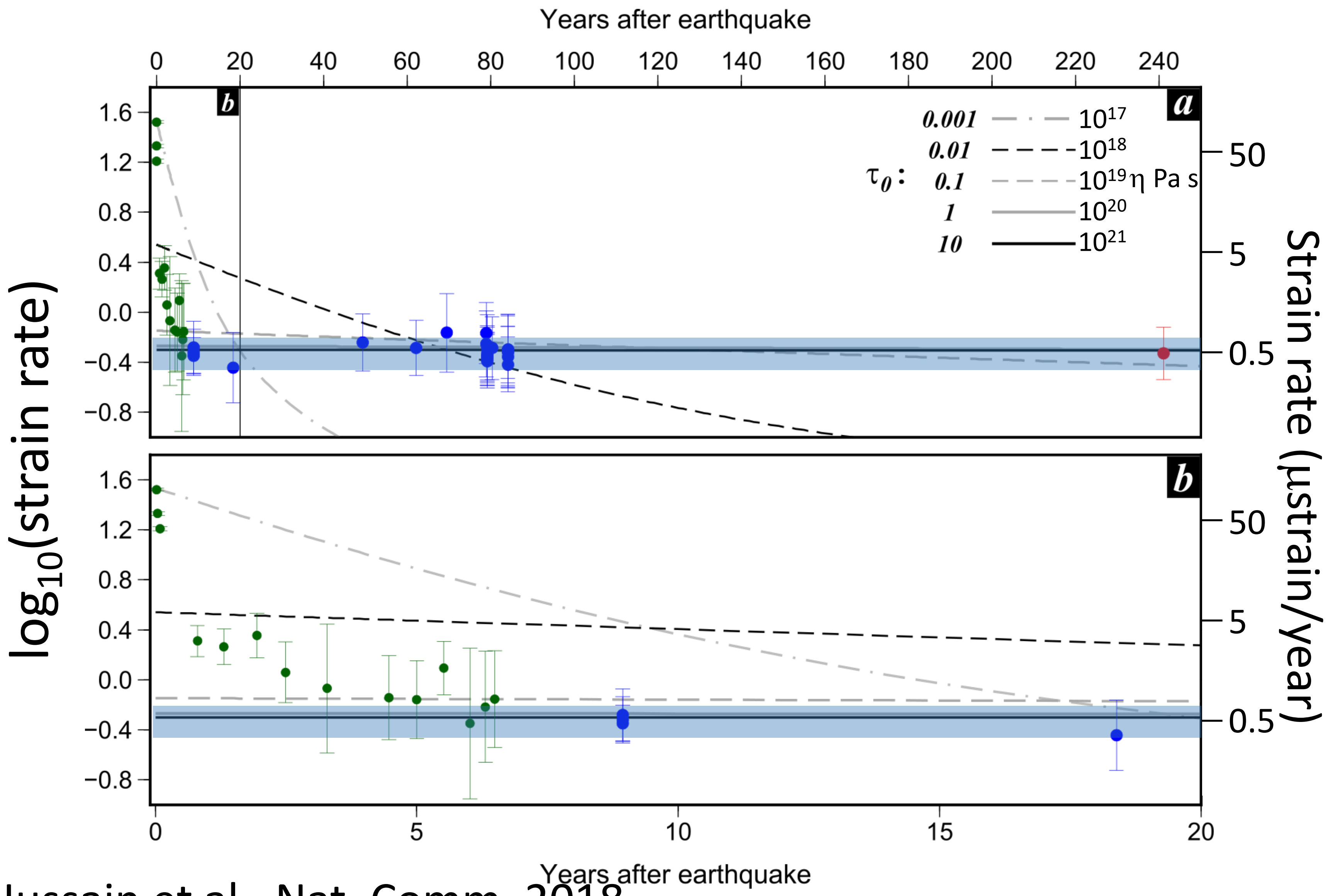
- All else equal:

  Low τ_0 implies low viscosity

  High τ_0 implies high viscosity

Hussain et al., Nat. Comm. 2018

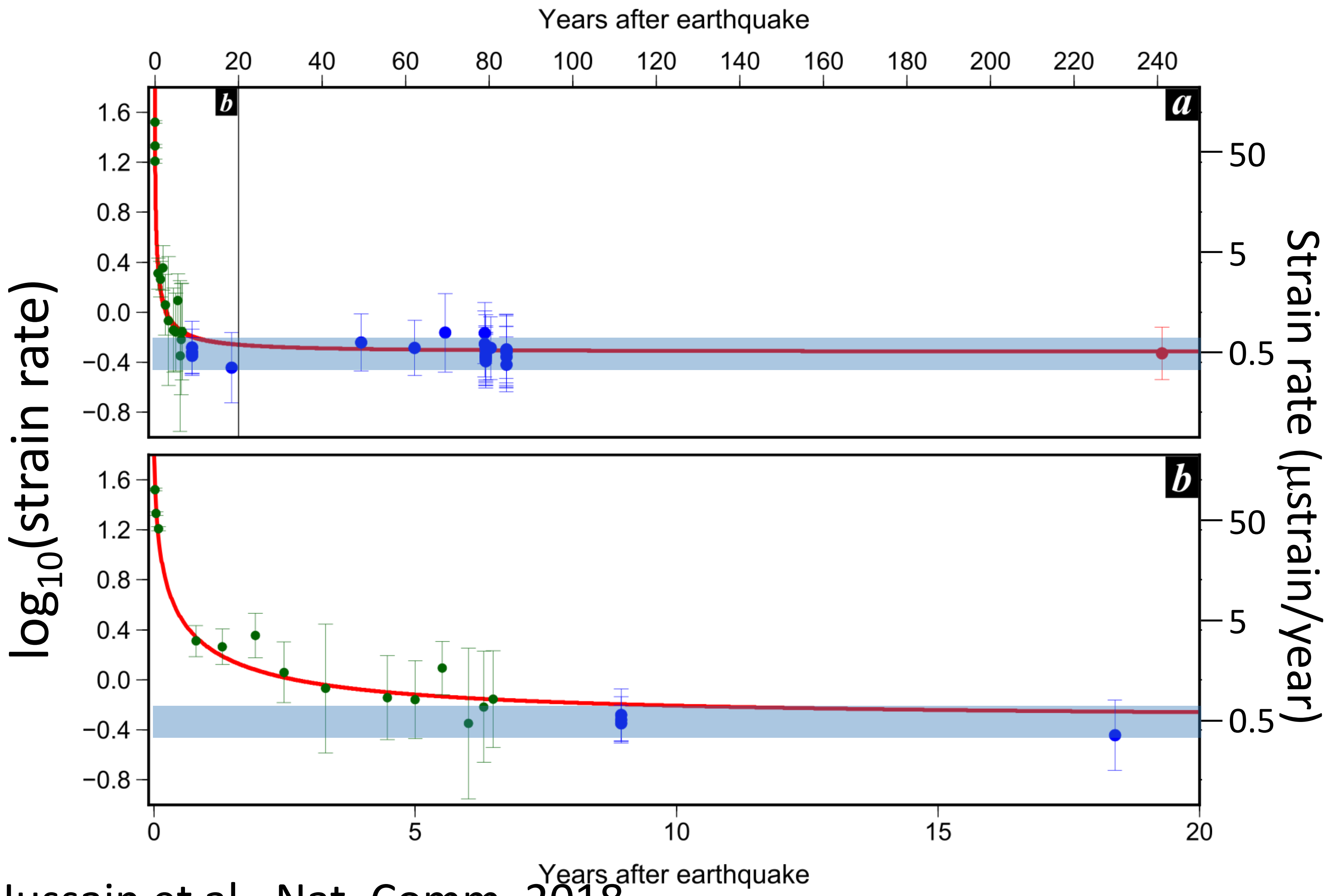
Part 3: Implications for the rheology of the mid/lower crust?



Hussain et al., Nat. Comm. 2018

- Low viscosity required to match early high postseismic strains (but cannot match temporal evolution)
- Relaxation time ≥ inter-event time (η ≥ ~10^{20} Pa s) required to give near constant strain many years after an earthquake
- Maxwell relaxation cannot explain postseismic relaxation

Part 3: Implications for the rheology of the mid/lower crust?



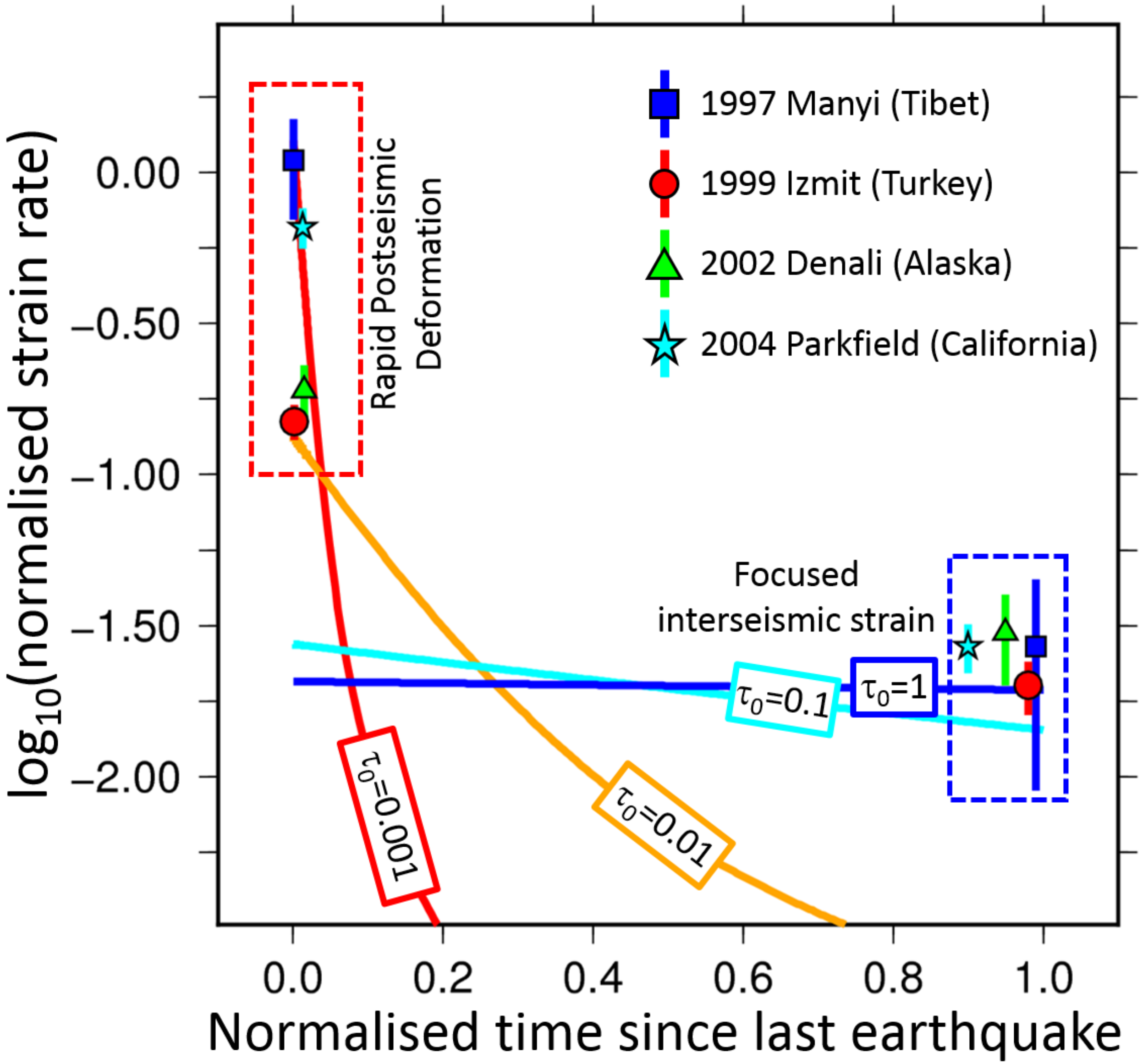
- Can match entire inter-event strain history if postseismic deformation rates are controlled by near-fault processes (i.e. follow Omori's Law)

and

- Background substrate has η >~ 10^{20} Pa s.

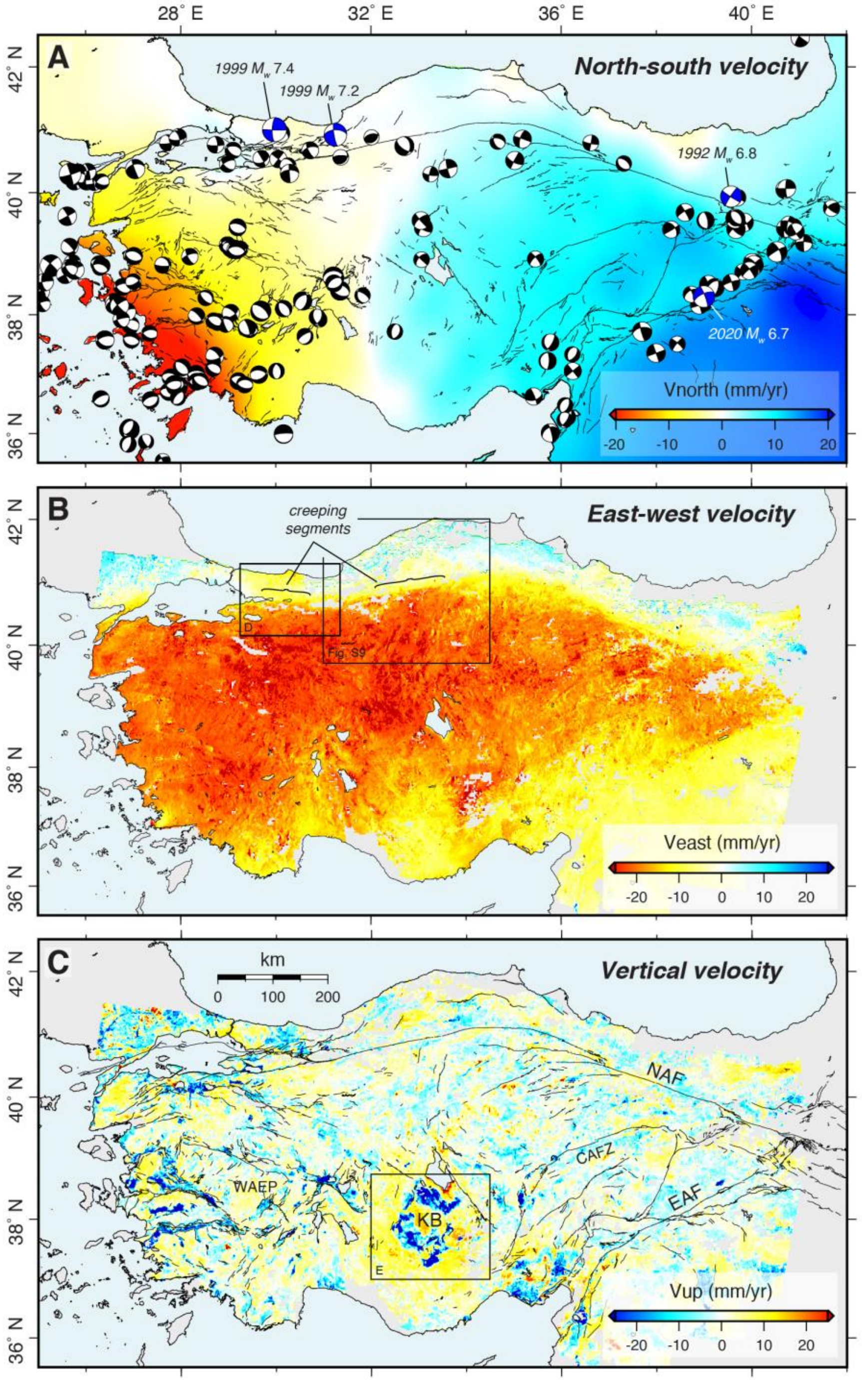
Hussain et al., Nat. Comm. 2018

Part 3: Implications for the rheology of the mid/lower crust?



- Consistent picture for all major strike slip faults where strain rate at the fault has been measured early and late in the seismic cycle.

Elliott et al., Nat. Comm. 2016



Weiss et al., preprint: https://eartharxiv.org/8xa7j/

Take Home Messages:

- Observations of earthquake deformation cycle from satellite geodesy are increasing in quality and quantity.
- Interseismic and postseismic deformation provide powerful constraints on the rheology of the mid- to lower- crust.
- Interseismic strain is focused around major faults: this requires a relaxation time ≥ earthquake repeat time (i.e. a relatively strong material).
- Postseismic deformation transients are rapid and follow a Omori Law decay ($V \sim t^{-1}$): this requires afterslip or power-law creep in a narrow shear zone.
- Combining these processes can explain the whole earthquake cycle for a major fault like the North Anatolian Fault.
- Inferences from geodetic data are not unique, but they can be combined with understanding from field and lab studies of rock rheology to test hypotheses.

Key Papers:

Ingleby and Wright, *Geophys. Res. Lett.* 2017

Hussain et al., Nat. Comms. 2018