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

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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 ~ 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:

Hussain et al., *Nat. Comms.* 2018

Weiss et al., preprint: https://eartharxiv.org/8xa7j/
Part 1: Postseismic Deformation

2014 Napa earthquake: August to December afterslip

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

Elliott et al., EOS 2015
31 Aug – 12 Sept 2014
Part 1: Postseismic Deformation

Mechanisms of postseismic deformation in the literature

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

Biased by:
• Prejudices of authors
• Short time periods

- Mid- to lower-crustal: 73%
- Shallow afterslip only: 27%
- Deep afterslip: 22%
- Afterslip + Viscoelastic: 16%

Viscoelastic
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 $\sim 1/t$. 

Ingleby and Wright, GRL 2017
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- Shows rapid decay for most earthquakes.
- Temporal behaviour is more diagnostic in log-log space.
- Maximum velocities decay as $\sim 1/t$
- Normalised data shows a remarkably simple pattern.
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• 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 $p = 1$].

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

Barka et al., 1997

Distance (km)
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

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
• Project east-west velocity field and GNSS onto fault-perpendicular profiles of fault parallel velocity.

• Solve* for slip rate and locking depth (Screw dislocation)

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

(*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 = \( \frac{\text{Slip Rate}}{\pi \text{(Locking Depth)}} \)

- 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

- Derived from post-1999 GNSS (Ergintav et al., 2009)
- Derived from InSAR & GNSS velocity field
- Derived from pre-1999 GNSS (McCluskey et al., 2000)

Hussain et al., Nat. Comm. 2018
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 \( \tau_0 \)

\[
\tau_0 = \frac{\tau_m}{\Delta T}
\]

Maxwell relaxation time, \( \frac{\eta}{\mu} \)
Inter-event time

- All else equal:
  Low \( \tau_0 \) implies low viscosity
  High \( \tau_0 \) implies high viscosity

Hussain et al., Nat. Comm. 2018
Part 3: Implications for the rheology of the mid/lower crust?

- Low viscosity required to match early high postseismic strains (but cannot match temporal evolution)
- Relaxation time $\geq$ inter-event time ($\tau_0 \geq ~10^{20}$ Pa s) required to give near constant strain many years after an earthquake
- Maxwell relaxation cannot explain postseismic relaxation

Hussain et al., Nat. Comm. 2018
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 $\eta \sim 10^{20}$ 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.

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