Inferring the effective rheology of the Earth's lithosphere using geodetic observations of earthquake sequences

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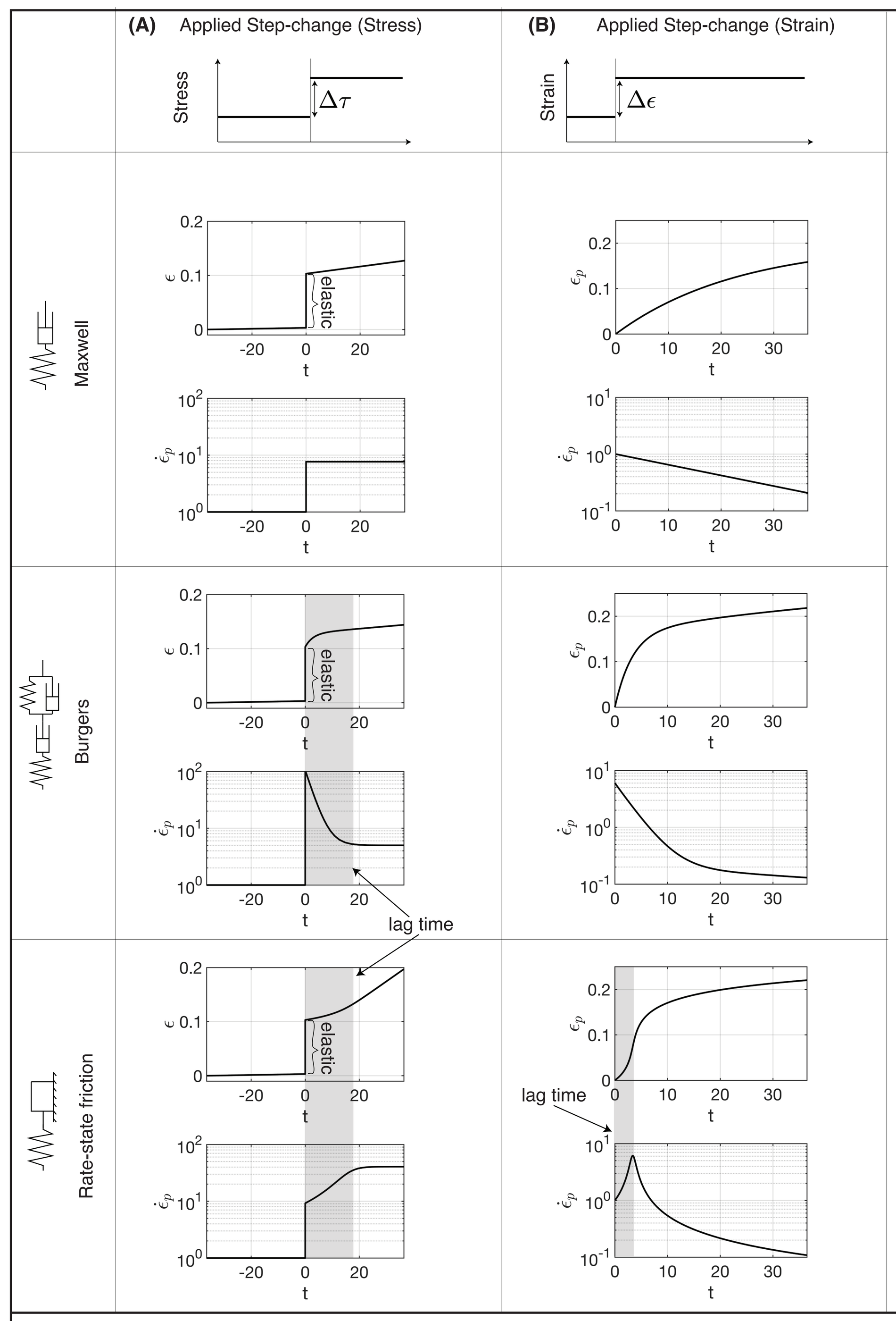
Main Points

1. We developed a numerical method to solve for the evolution of stress, strain rate and surface displacements in response to periodic and aperiodic earthquake sequences for popular linear and non-linear viscoelastic rheologies.
2. Homogeneous linear Maxwell materials are incompatible with typical interseismic and postseismic geodetic observations, while heterogeneous linear Maxwell, homogeneous linear Burgers and power-law materials are nearly indistinguishable for periodic cycles.
3. Earthquake sequence deformation (coseismic events spanning an order of magnitude) may be used to discriminate between linear and power-law rheologies, even with current uncertainties in geodetic observations.
4. Surface deformation kinematics may appear similar for different rheologies, but the details of regional stress transfer and rates of creep migration may change dramatically.



Earthquake cycles and rheological models (elasticity + ?)

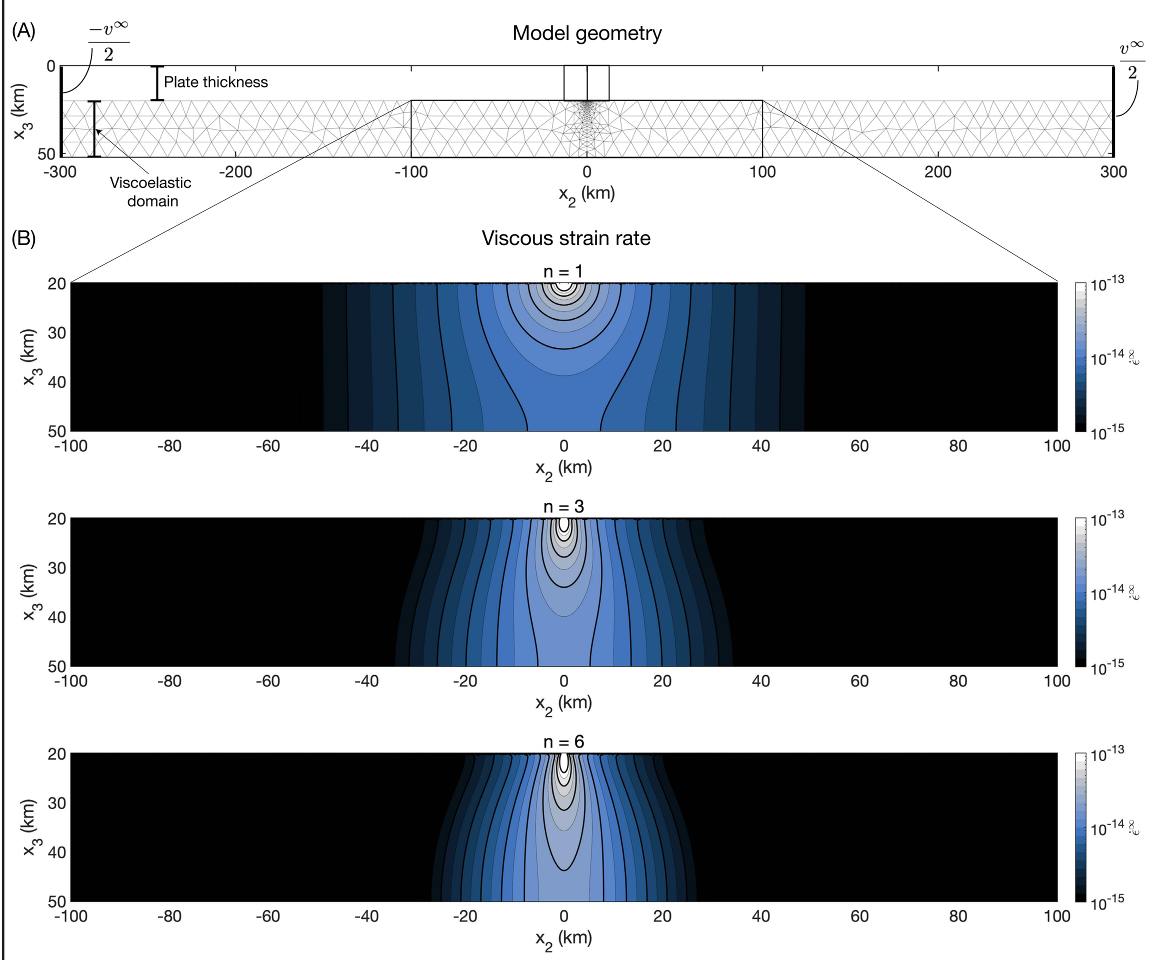
The solid Earth behaves as a brittle-elastic material over short timescales (1 second - 1 day). At longer timescales, the viscous properties of the lithosphere-asthenosphere system control the mode of deformation. Together, the elastic and non-elastic (friction/viscous) properties of the solid Earth control the amplitude and timescales of stress transfer within the entire medium.

Improving estimates of these parameters has important implications for understanding fundamental issues such as the existence of plate-like tectonics, as well as more applied challenges in regional seismic hazard and risk.

- Observations that constrain the non-elastic properties of the Earth's lithosphere are limited.
- Postseismic relaxation of the lithosphere following large earthquakes allow us to use surface observations to constrain the non-elastic properties of the lithosphere-asthenosphere system.
- The postseismic relaxation problem is mathematically similar to a strain-step IVP (stress relaxation - ***Figure 1B***). This makes it difficult to distinguish between various lab-derived rheological models (linear Maxwell, power-law, linear/power-law Burgers, rate-state friction) using surface deformation observations (***Figure 1***).
- We want to know - to what degree do current observations allow us to constrain an average unique rheological model of the lithosphere (and relevant parameters)?

Figure 1. Comparison of the response of three popular rheological descriptions (Maxwell, Burgers and rate-state friction) to a step-change in (A) stress and (B) strain. ε - total strain, ε_p - non-elastic strain.
The stress-step experiments allow visual discrimination between the various rheologies, while strain-step experiments mostly appear as relaxation curves with monotonically decaying rates (except for rate-state friction).

Numerical Model (Viscoelastic earthquake sequence simulations)



- Boundary integral representation (using eigen strain formulation) of quastatic equilibrium equations for a faulted elastic layer over a viscoelastic channel.
- Viscous strain rate is split into a long-term (Moore and Parsons, 2015) and earthquake-cycle modulated component.
- 2 sets of numerical experiments -
  1. Homogeneous parameters for a given rheology to investigate how well each model class can explain typical geodetic features (periodic events) - ***Figure 2 A-B***.
  2. Bulk non-elastic deformation is collapsed onto a fault and we want to know how well can each model approximate kinematics from other model classes (periodic events and sequences)? - ***Figure 2 C***

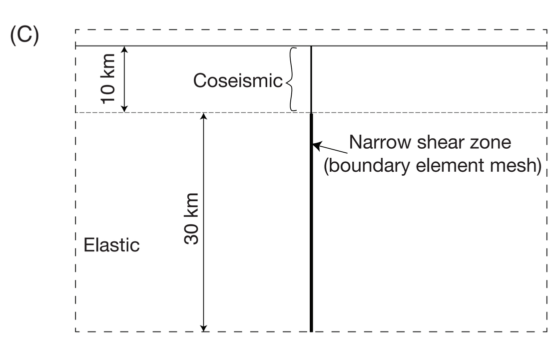


Figure 2. (A) Geometry of the first set of numerical experiments. (B) Long-term viscous strain rate as a function of n. (C) Model geometry for the second set of numerical experiments

Explaining interseismic & postseismic geodetic features for periodic cycles

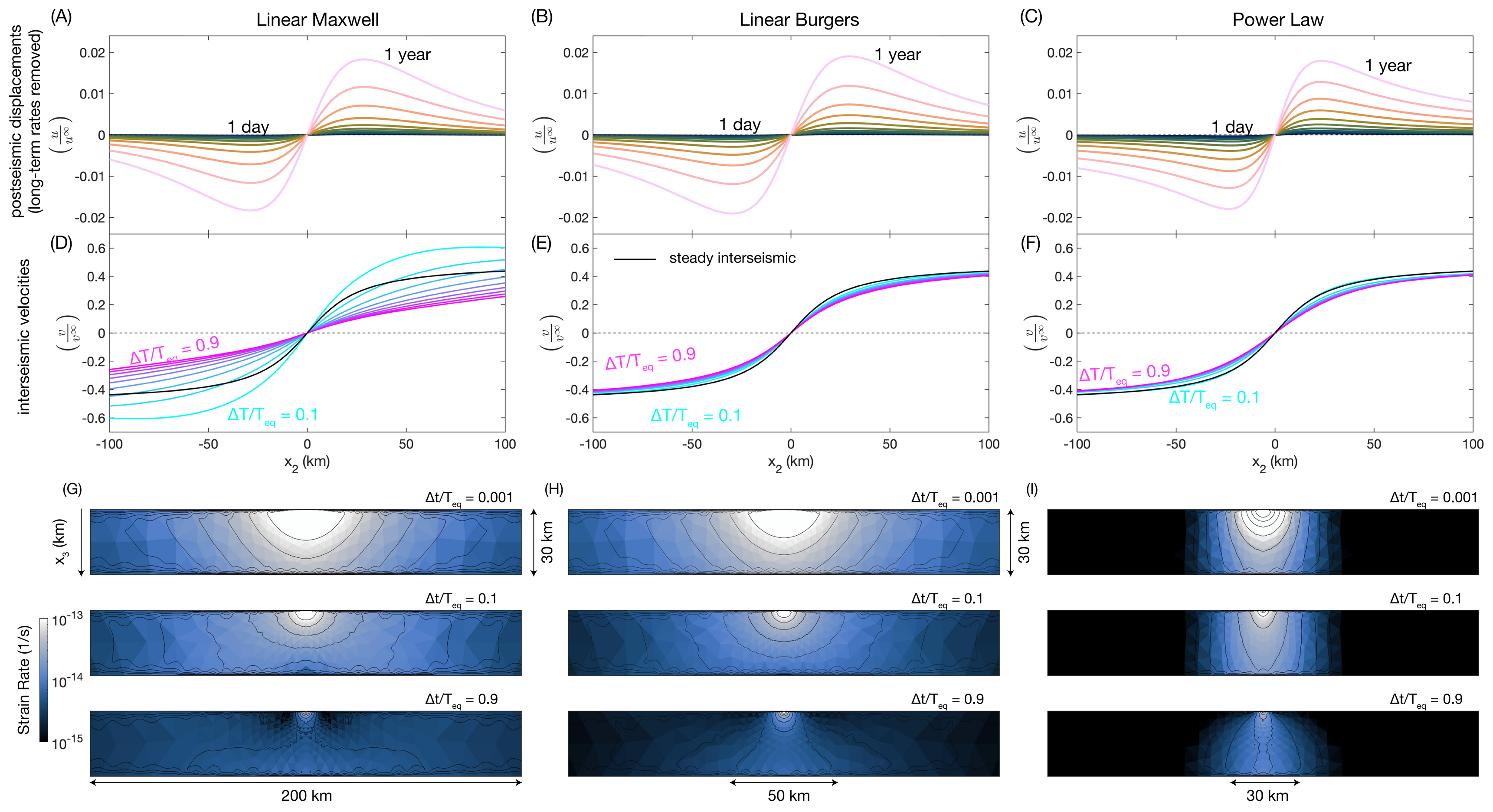
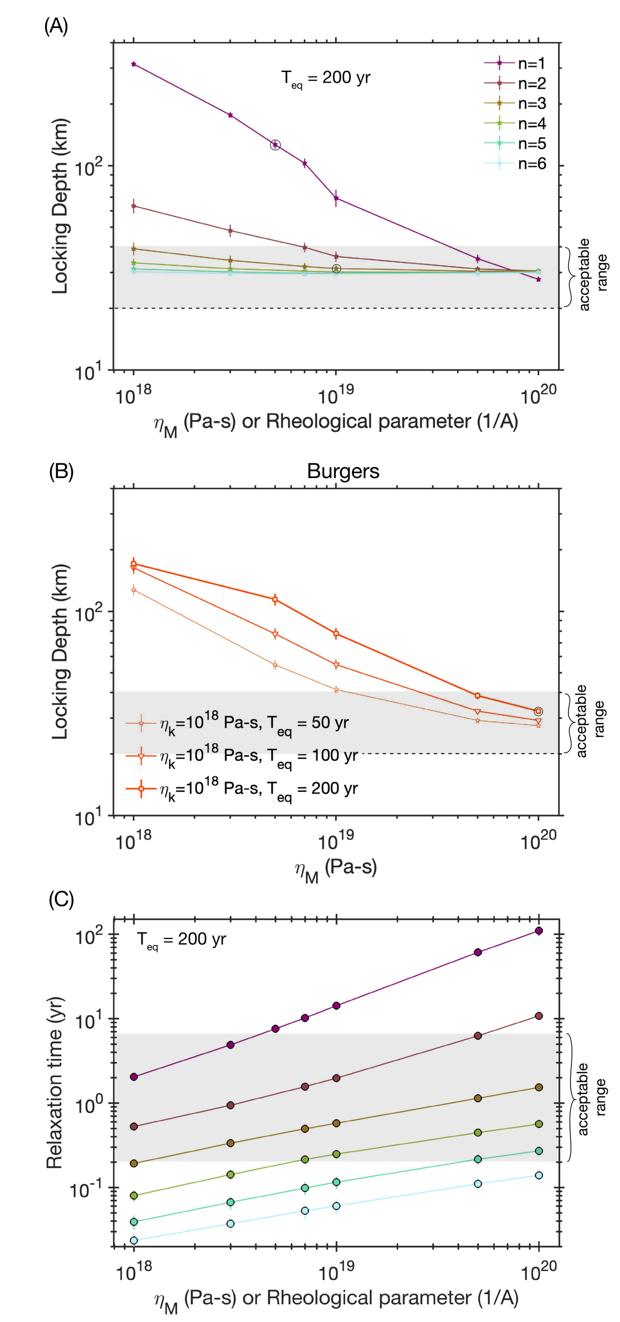


Figure 3. Surface predictions of postseismic displacements and interseismic velocities for different rheological models for a periodic earthquake cycle. The rheological parameters are chosen such that the cumulative postseismic after 1 year is nearly identical for all three models. (A)-(C) Cumulative postseismic displacements normalized by the coseismic slip amount $u\infty = v\infty T_{eq}$ for times varying from 1 day to 1 year. (D)-(F) Interseismic velocities compared to the steady interseismic expectation (black line). (G-I) Snapshots of internal viscous strain rates at different times during the earthquake cycle for each rheological model.



- Late interseismic localization of strain (arc-tangent shaped velocity field) is a characteristic observation for mature strike-slip fault settings globally.
- Linear homogenous Maxwell rheology - unable to capture this behaviour (***Figure 4 A***) since strain rate is diffusive (***Figure 3 A,D,G***).
- Linear Burgers and power-law rheologies predict late interseismic strain rate localization (***Figure 3 H,I, 4***).
- Postseismic relaxation timescales estimated using regression with the functional form $\beta_1\exp(-t/\beta_2)$ (over a 2 year period) shows all 3 rheologies can be made consistent with typical observations (***Figure 4C***).
- By combining observations from two different strain rate regimes (late interseismic - ***Figure 4 A-B***; postseismic - ***Figure 5***), we can rule out a class of rheological model choices for the lithosphere.
- Postseismic observations for coseismic events of different magnitudes are key to distinguishing between linear and power-law rheologies - for a given set of rheological parameters, the normalized cumulative postseismic deformation over a given time window is larger and occurs at a faster rate as the coseismic event magnitude increases (***Figure 5***).

Figure 4. Compilation of late interseismic locking depths for various rheological choices. Locking Depth for (A) Linear Maxwell and power-law materials with n varying from 1 to 6 for T_{eq} = 200 years. (B) Locking depths for a linear Burgers rheology for a constant η_k and varying η_M and T_{eq}. Late interseismic locking depths show no dependence on η_k. (C) Postseismic relaxation times estimated over a 2-year period following the earthquake.

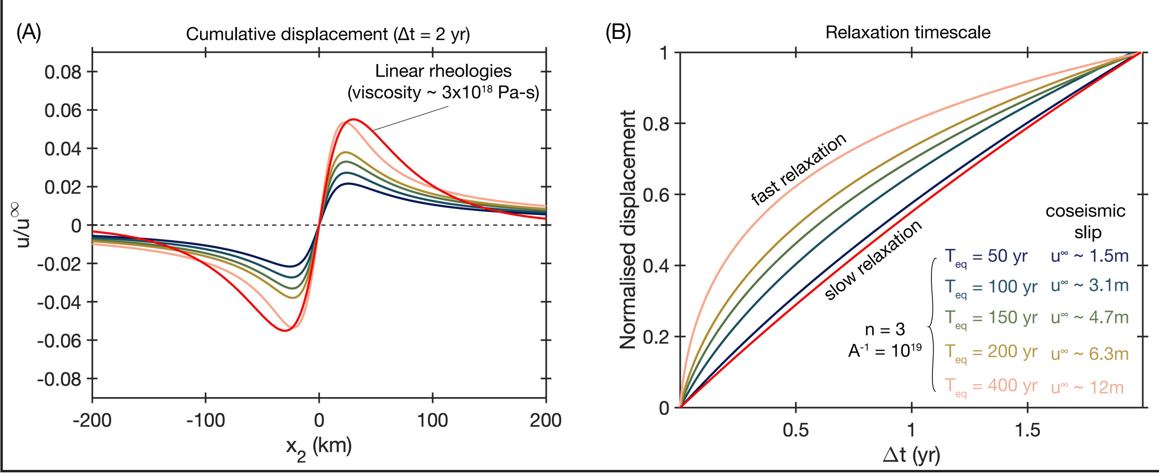
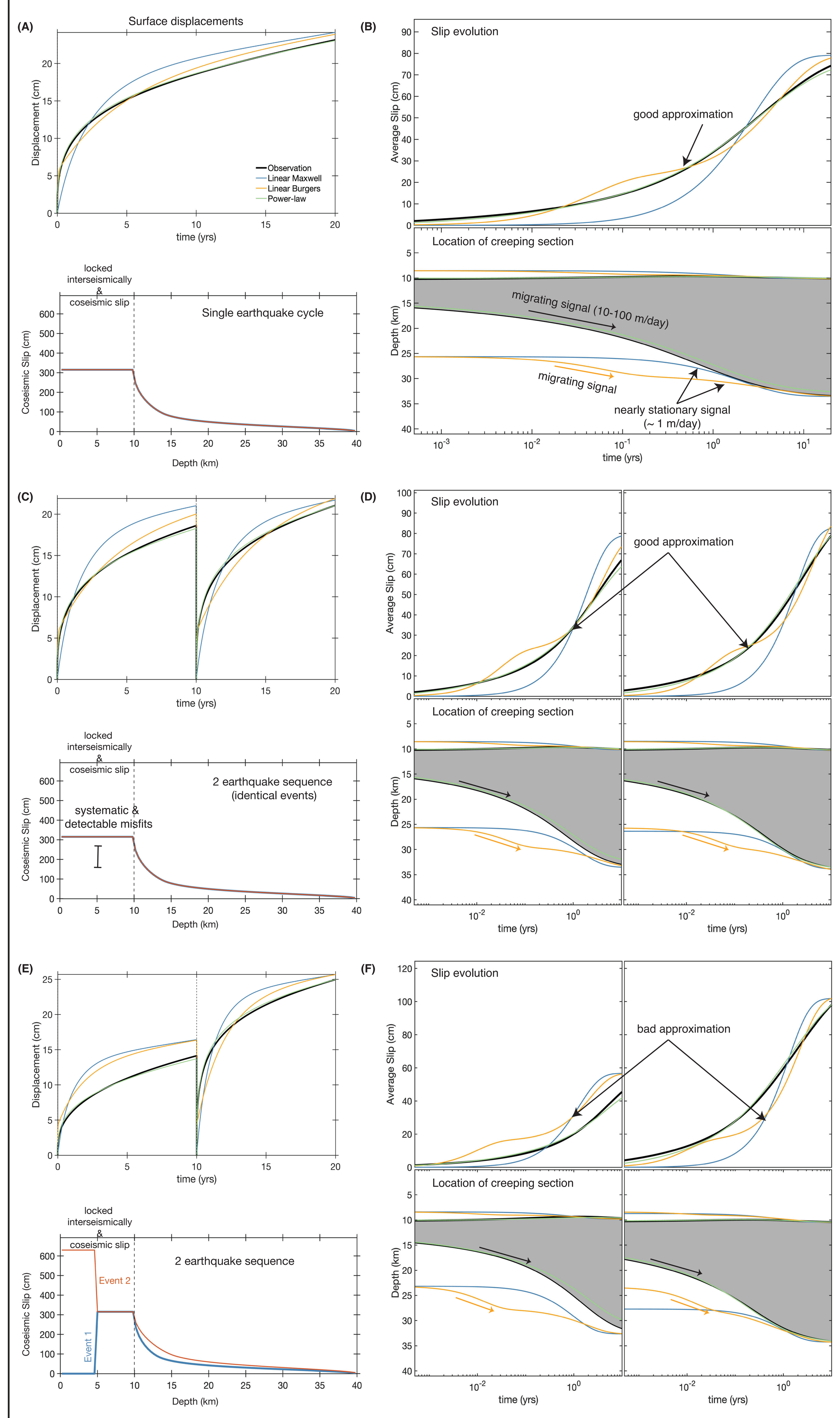


Figure 5. Magnitude dependent postseismic motions for power law bodies. (A) Cumulative postseismic displacement normalized by the coseismic slip amount ($u\infty = v\infty T_{eq}$) over 2 years for the same rheology. Only power law materials show increasing cumulative deformation with increase in the recurrence interval. (B) As the cumulative deformation increases, the relaxation timescale decreases i.e., the postseismic deformation becomes faster and larger.

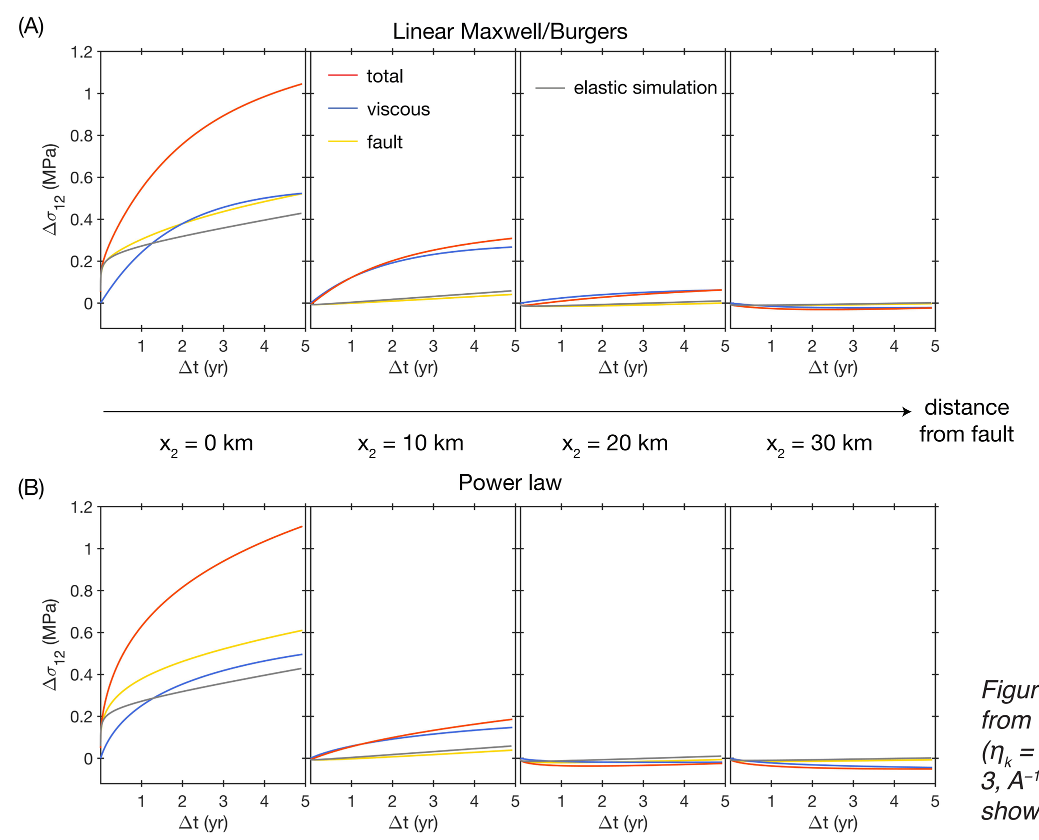
Observations from earthquake sequences can constrain the average rheological model of the lithosphere uniquely



- For periodic cycles, the kinematics of heterogeneous linear Maxwell, homogeneous linear Burgers and power-law models are indistinguishable at the level of geodetic position uncertainty ~ 1 cm (***Figure 6 A***).
- Similar kinematics but dramatically different dynamics - location of peak creep rate and stress (***Figure 6 B***).
- Migrating stress front may drive aftershock activity (***Figure 6 B***). Could be an additional way to constrain parameters for a given rheology.
- Earthquake sequences where the coseismic events are of similar magnitudes (perturbation of pre-seismic conditions) may be insufficient to distinguish between linear Burgers and power-law rheologies (***Figure 6 C,D***).
- Events that vary by an order of magnitude allow clear distinction between various rheologies (***Figure 6 E,F***).

Figure 6. Comparison between the surface predictions from a visco-elasto-frictional earthquake sequence simulation and various approximate rheological models over a 20-year time window.
We explore 3 earthquake sequence scenarios - (1) periodic cycles, (2) 2-event sequence of identical magnitudes 10 years apart, (3) 2-event sequence of different magnitudes 10 years apart. (A,C,E) Surface displacement timeseries at 25 km from the fault trace. (B,D,F) Domain averaged slip timeseries (top panel) and depth of a uniform slip crack representation of each model (bottom panel).

Implications for time-dependent regional stress transfer



- The stress evolution within the medium over the first 5 years (function of effective relaxation time) following an earthquake is dominated by the viscoelastic response (***Figure 7***).
- Stress transfer from viscous creep permeates farther away from the fault and can lead to long-range stress interactions between faults.
- Due to the mechanical coupling between deep fault slip and viscous shear, stress transfer from fault slip evolution in the viscoelastic simulations is significantly different from the elastic simulations.

Figure 7. Stress change and decomposition into contributions from fault slip and viscous shear for (A) linear Burgers rheology ($\eta_k = 3\times10^{18}, \eta_M = 10^{20}$ Pa-s), and (B) power law rheology with n = 3, $A^{-1} = 10^{19}$. Total stress evolution from an elastic model is also shown (gray).