Subject offered for a contract starting October 2019

SUBJECT TITTLE:

Towards micromechanics-based brittle rheologies in long-term tectonic models.

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Over the last 40 years, long-term tectonic models (LTTMs) have become a method of choice to gain insight into the evolution of tectonic plate boundaries on time scales of ~10^5 to 10^8 yrs. These numerical models typically solve for conservation of mass, momentum (Stokes equations) and energy in a continuum where stress and strain are related through experimentally-determined flow laws. Brittle faulting is a key component of LTTMs, as the faulting sequence and patterns of off-fault deformation strongly impact the model outputs that are most directly comparable with observations: topography and tectonic structure.

LTTMs typically index the localization of new faults to reaching a threshold in deviatoric stress, mimicking the experimentally-determined criterion for failure of rock samples [e.g., *Byerlee*, 1978]. This is often formulated as a Mohr-Coulomb or Drucker-Prager plasticity criterion, which states that the shear stress necessary to break intact rock is proportional to the mean normal stress. In practice, these criteria are implemented by treating the upper crust as a visco-(elasto)-plastic medium [e.g., *Gerya*, 2010] using an effective plastic viscosity that caps deviatoric stresses at the plastic yield stress (η_{PLAS} = plastic yield stress divided by the local strain rate). Areas of strain localization are characterized by high strain rates which induce low plastic viscosities in narrow viscous "faults" (shear bands). By contrast, areas of distributed deformation between major faults have low strain rates, resulting in high plastic viscosities and long Maxwell times. This means they can behave elastically, visco-elastically, or viscously over the typical time span of LTTMs.

Whether these effective rheologies are appropriate for the upper crust remains unknown, mainly because of a lack of systematic observations. In addition, because both distributed and localized deformation are typically modeled as plastic flows, there is no objective criterion to trigger a transition from the former to the latter. Instead, localization is promoted by softening the yield stress (i.e., dropping material cohesion and friction) with accumulated plastic strain, which happens rapidly in proto-shear bands [e.g., *Lavier et al.*, 2000]. This makes standard LTTMs very sensitive to small heterogeneities in strain rate, initial conditions, and most-critically: to poorly-constrained empirical parameters (e.g., strain weakening rate).

Fortunately, the last 30 years have seen spectacular developments in our understanding of the grain-scale processes that lead to brittle strain localization after a phase of distributed deformation [see review by *Paterson & Wong*, 2005]. It is now understood that these mechanisms consist of the nucleation and growth of small cracks (broadly referred to as "brittle damage") from grain-scale flaws, which macroscopically manifest as distributed deformation. [e.g., *Brantut et al.*, 2012]. As these cracks lengthen and become more closely-spaced, they begin to interact, which weakens the effective elastic moduli of the sample and induces a strain-rate dependence (effective viscosity) to the deformation. When a certain fracture density threshold is reached, cracks coalesce catastrophically into a fault.

The goal of this PhD project is to incorporate micromechanical models of brittle deformation that capture the processes described above into the LTTM *SiStER* [*Olive et al.*, 2016; https://github.com/jaolive/SiStER], to better simulate the initiation and growth of major fault systems. First, a novel theoretical framework for damage build-up and subsequent localization under slow tectonic loading will be designed and implemented in a numerical setup that mimics a triaxial press test. This will allow direct comparisons between the damage-based model [e.g., *Ashby & Sammis*, 1990; *Bhat et al.*, 2012] and rock deformation experiments (e.g., comparing stress-strain curves, patterns of acoustic emissions, time to brittle failure, etc.). Once the model is validated at the sample scale, it will be upscaled to simulate long-term deformation of the continental upper crust. The models will then be evaluated on their ability to reproduce characteristic tectonic features of extensional plate boundaries, which offer relatively straightforward benchmarks such as: the geometry of flexed rift shoulders, the life span of major normal faults (detachment faults vs. short-lived half-grabens), or the distribution of brittle damage near the axis of a rift.

If successful, the outcome of this PhD project will be a new generation of LTTMs where brittle deformation is described in a physics-based manner, and allows direct comparison with geological observations spanning tens of km to a fraction of a mm. These will be applicable to a wide range of plate boundary evolution problems.

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