Slab Stress and Strain Rate as Constraints on Global Mantle Flow

Laura Alisic (alisic@gps.caltech.edu), Michael Gurnis (Seismological Laboratory, Caltech)
Georg Stadler, Carsten Burstedde, Lucas C. Wilcox, Omar Ghattas (ICES and Jackson School of Geosciences, University of Texas at Austin)

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Key Points

- **We use the new-generation adaptive mesh mantle convection code Rhea to compute dynamically consistent instantaneous models of global convection with plates.**
- **The models have a local resolution of 1 km and a composite nonlinear rheology that includes yielding.**
- **The regions containing the Mw 8.3 Bolivia and Mw 7.6 Tonga 1994 events are considered in detail. Modeled stress orientations match stress patterns from earthquake focal mechanisms.**
- **A yield stress of at least 100 MPa is required to fit plate motions and matches the minimum stress requirement obtained from the stress drop for the Bolivia 1994 deep focus event.**
- **The minimum strain rate determined from seismic moment release in the Tonga slab provides an upper limit of ~200 MPa on the strength in the slab.**

Method

We use the adaptive mesh mantle convection code Rhea *(Burstedde et al, 2008)* to model convection in the mantle with plates in both regional and global domains. Rhea is a new generation parallel finite element mantle convection code designed to scale to hundreds of thousands of compute cores. It uses forest-of-octree-based adaptive meshes via the p4est library. With Rhea's adaptive capabilities we can create local resolution down to ~1 km around plate boundaries, while keeping the mesh at a much coarser resolution away from small features. The global models in this study have approximately 160 million elements, a reduction of ~2000x compared to a uniform mesh of the same high resolution. The equations solved in Rhea are the conservation of mass, momentum and energy:

$$\nabla \cdot \mathbf{u} = \mathbf{0},$$

$$\nabla \mathbf{p} - \nabla \cdot \left[\eta(T,\mathbf{u})\left(\nabla \mathbf{u} + \nabla \mathbf{u}^{\mathsf{T}}\right)\right] = \mathrm{Ra}\, T\, \mathbf{e}_r$$

$$\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T - \nabla^2 T = \gamma,$$

A composite formulation of Newtonian (diffusion creep) and non-Newtonian (dislocation creep) rheology along with yielding is implemented *(Billen and Hirth, 2007)*. Nonlinearity comes in through the second invariant of the strain rate, $\dot{\epsilon}_{II}$. Plate boundaries are modeled as very narrow weak zones with a defined viscosity reduction of several orders of magnitude.

$$\eta = \left(\frac{d^p}{A\, {C_{OH}}^r}\right)^{\frac{1}{n}} \dot{\epsilon}_{II}^{\frac{1-n}{n}} \exp\left(\frac{E_a + pV_a}{nRT}\right) \qquad \eta_{comp} = \frac{\eta_{df}\,\eta_{ds}}{\eta_{df} + \eta_{ds}}$$

$$\sigma_y = \min\left(\sigma_0 + \frac{\delta\sigma}{\delta z} z\,,\ \sigma_{y_{\max}}\right) \quad \longrightarrow \quad \eta_{eff} = \min\left(\frac{\sigma_y}{\dot{\epsilon}_{II}}\,,\ \eta_{comp}\right)$$

The global models are constructed with detailed maps of the age of the plates *(Müller et al, 2008)* and a thermal model of the seismicity-defined slabs which grades into the more diffuse buoyancy resolved with tomography *(Li et al, 2008)*. They are tested by assessing the plateness of the surface velocity field, and its misfit with measured surface velocities.

Global Model

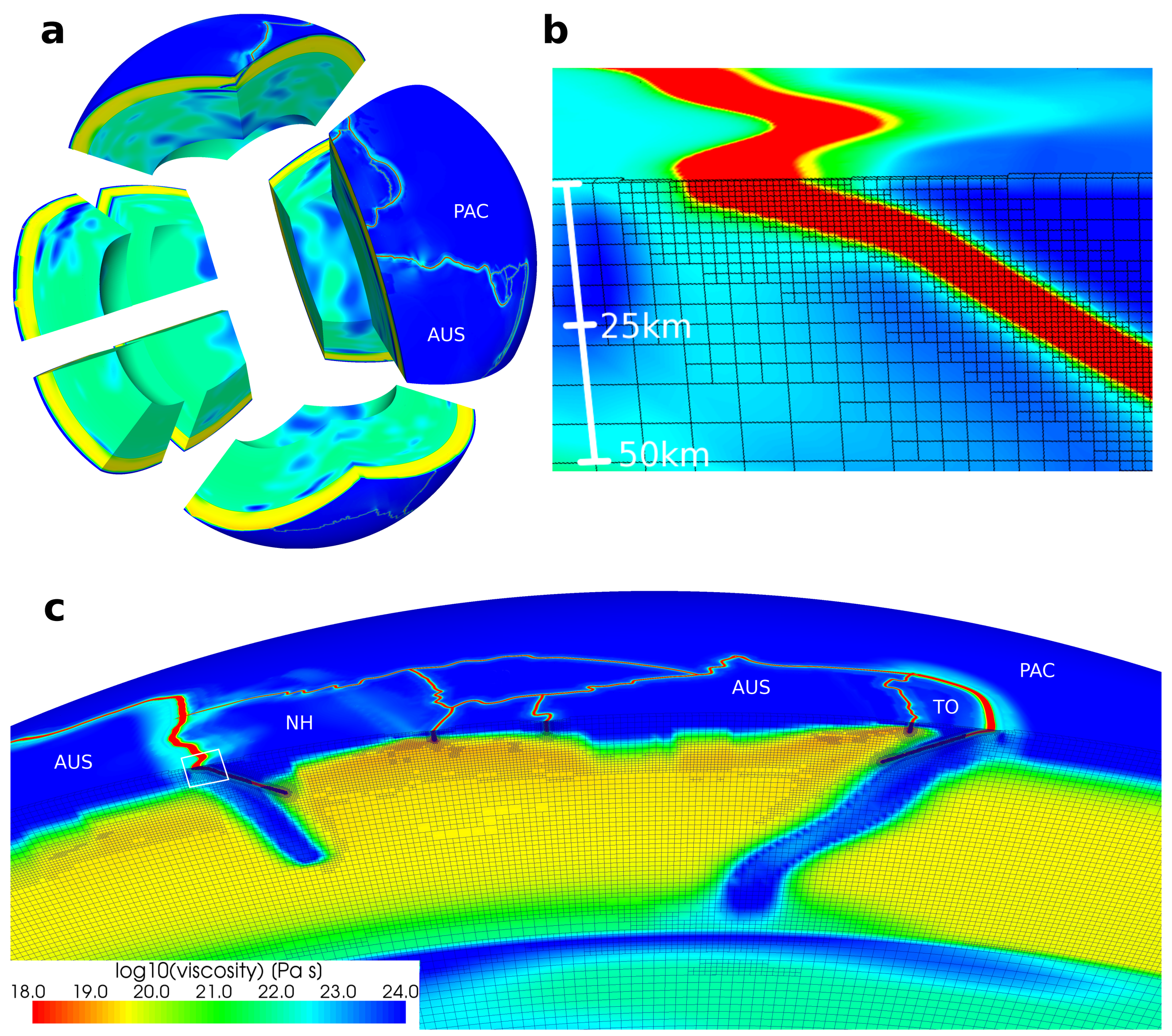

Figure 1: (a) Splitting of earth's mantle into 24 warped cubes. Each cube is identified with an adaptively subdivided octree whose octants are the mesh elements. The effective viscosity field is shown; the narrow low-viscosity zones corresponding to plate boundaries are seen as red lines on earth's surface. Slabs in the upper mantle are defined by seismicity; the structure in the lower mantle is derived from the S20RTS tomography model *(Ritsema et al, 2004)*. **(b)** Zoom into the hinge zone of the Australian plate (as indicated by the box in (c)) showing the adaptively refined mesh with a finest resolution of about 1 km. **(c)** Cross-section showing the refinement that occurs both around plate boundaries and dynamically in response to the nonlinear viscosity, with plastic failure in the region from the New Hebrides to Tonga in the SW Pacific. Plates labeled: Australian (AUS), New Hebrides (NH), Tonga (TO), and Pacific (PAC).

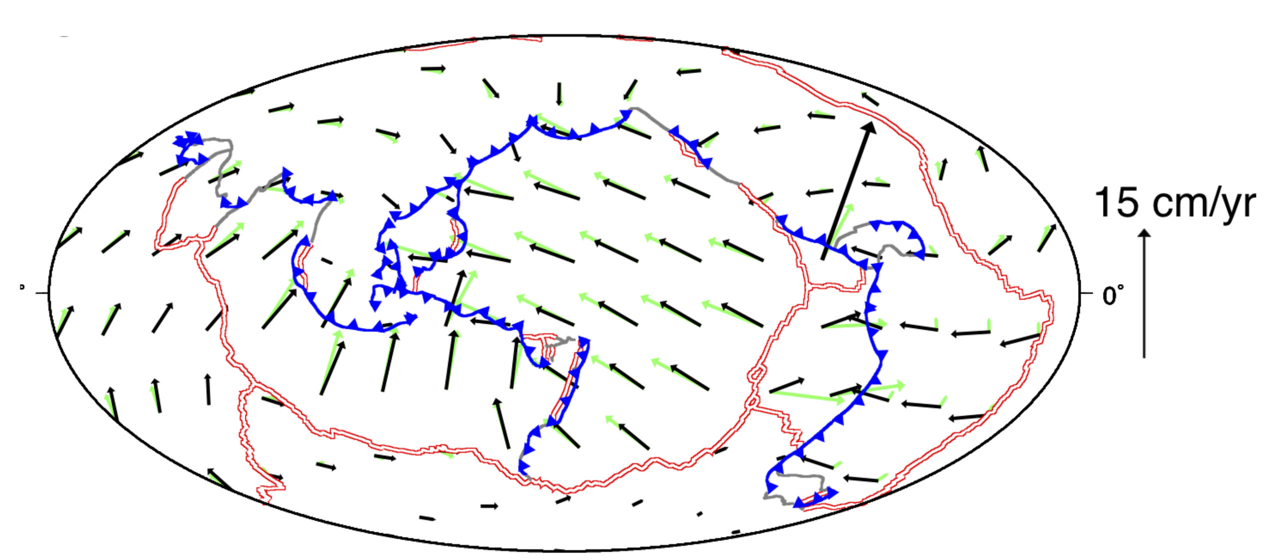

Figure 2: Plate motions in a no-net-rotation frame (NNR) *(Argus and Gordon, 1991)* as green arrows and predicted velocities as black arrows. Maximum yield stress: 100 MPa. Stress exponent: 3.0.

Bolivia

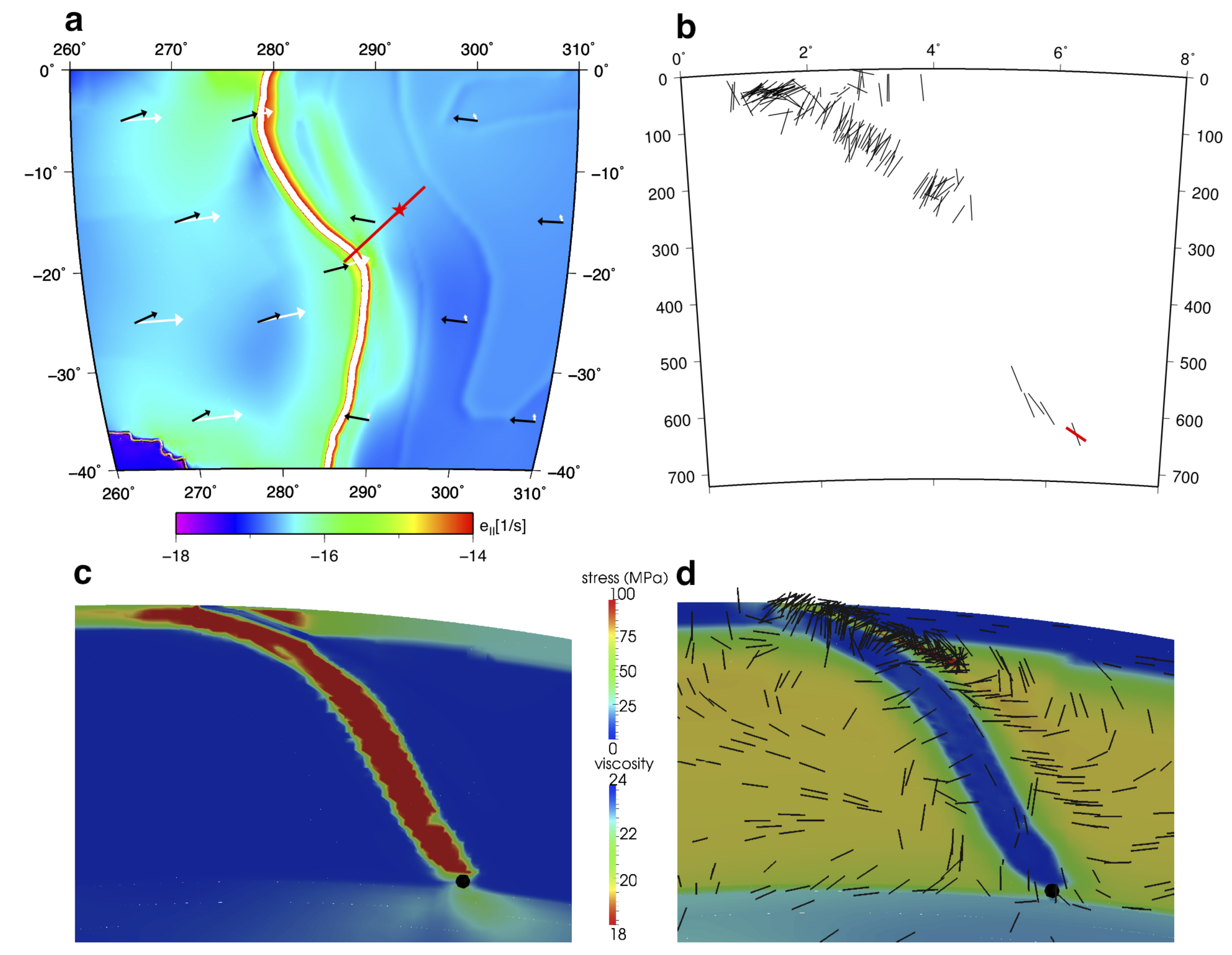

Figure 4: (a) Map with plate motions. Black arrows: Rhea model prediction; white arrows: Nuvel1-NNR plate motion model by *Argus and Gordon (1991)*. Background color: second invariant of the strain rate. Red star: Bolivia 1994 earthquake. Red line: cross-section. **(b)** Cross-section with compressional axes from focal mechanisms of earthquakes with magnitude larger than 5.0 and within 100 km of the cross-section. Red axis: Bolivia 1994 event. **(c)** Cross-section of stress magnitude. Black sphere: location of Bolivia 1994 event. **(d)** Cross-section of viscosity with compressional axes plotted with unit length.

Tonga

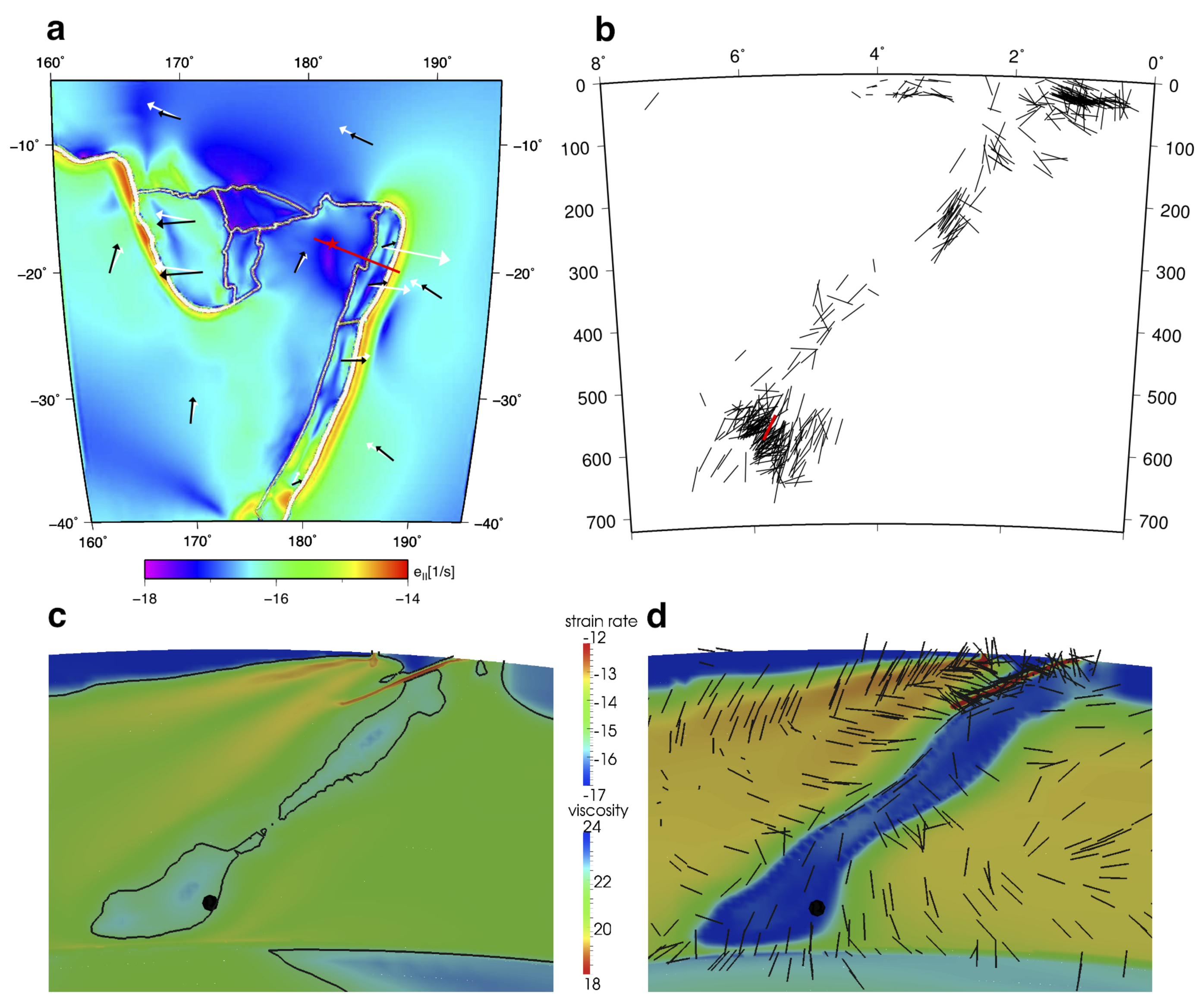

Figure 5: Same annotations as for Figure 4. **(a)** Map with plate motions. **(b)** Cross-section with compressional axes from focal mechanisms of earthquakes with magnitude larger than 5.0 and within 50 km of the cross-section. Red axis: Tonga 1994 event. **(c)** Cross-section of the second invariant of the strain rate. Black contour: value of 5×10^{-16} s^{-1}. **(d)** Cross-section of viscosity with compressional axes plotted with unit length.

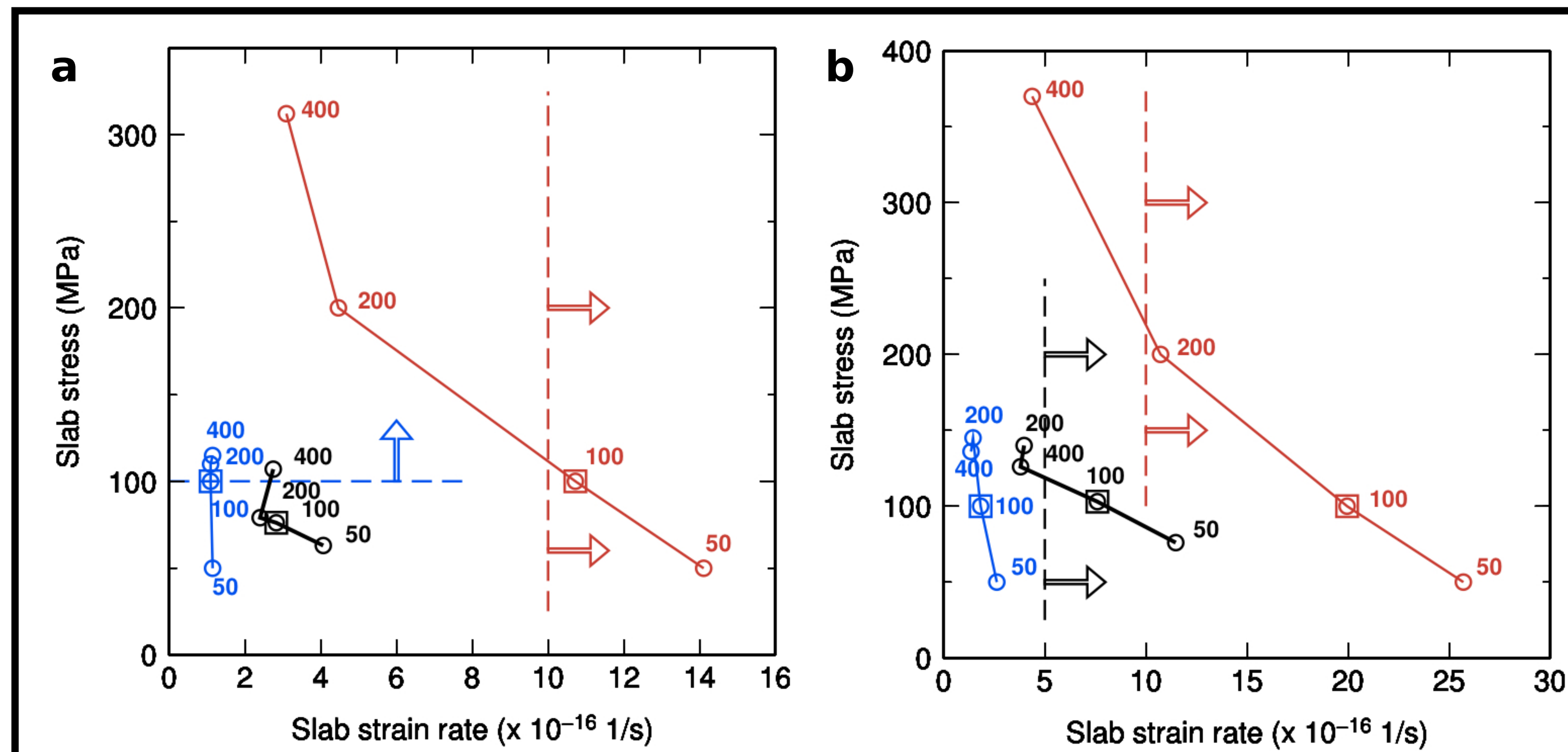

Figure 6: (a) Strain rate and stress in the Bolivia slab. Square: nominal model. The numbers next to the data points refer to the global maximum yield stress used. **(b)** Strain rate and stress in the Tonga slab.

Increasing yield stress results in higher stress and lower strain rate. Hence, a minimum strain rate from seismicity limits the maximum stress to 100-200 MPa (black and red dashed lines). A minimum stress of 100 MPa for Bolivia is given by the stress drop (blue dashed line).