Modeling the Interaction Between Fault Slip and Viscoelastic Deformation

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- Greatly simplify and speed up modeling of distributed deformation
- Develop models of earthquake cycles in the lithosphere-asthenosphere system
- Investigate the effects of local rheology on long-term fault behavior

An autonomous institute of
Nanyang Technological University

Overview

1) Deep Deformation

- Classical view of the seismogenic zone
- Transition from localized to distributed deformation

2) Kinematics of Distributed Deformation

- Quasi-static solutions for finite strain volumes

3) Numerical modeling of earthquake cycles

- Earthquake cycles in the lithosphere-asthenosphere system
- Evolution of fault zone rheology

How to define the seismogenic zone?

Classic seismogenic zone defined by the depth extent of **microseismicity** and/or the **fault locking depth**

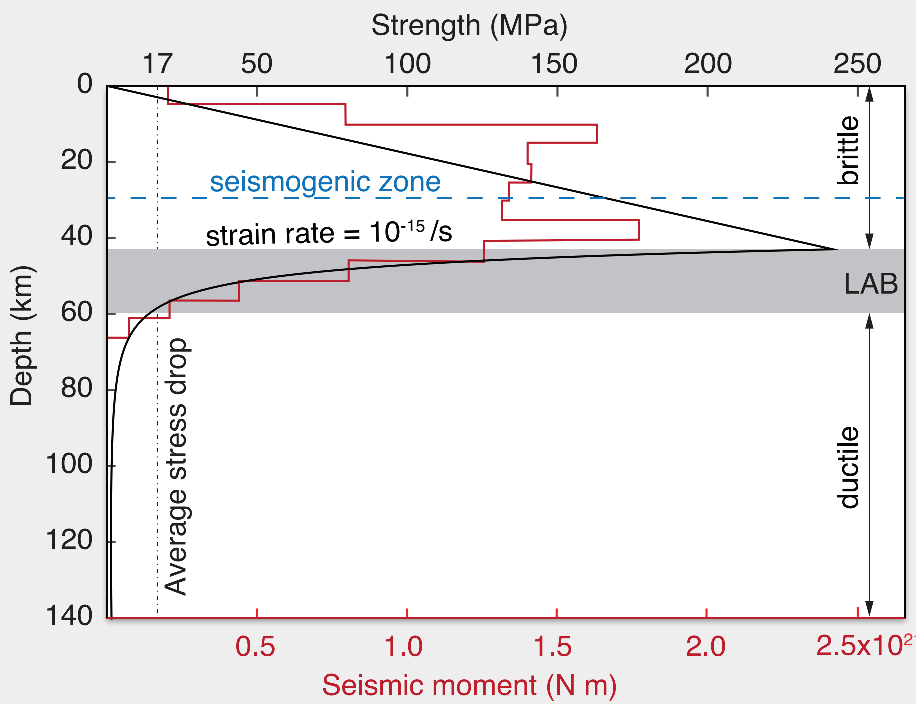
Likely corresponds to transition in **thermal**, **frictional**, **hydraulic** and **structural** properties

Recent observations show that the width of the seismogenic zone may vary along a fault section over long-time scales:

- Tsunami earthquakes which rupture further up-dip (*Hubbard et al., 2015*)
- Through-lithospheric ruptures (e.g. 2012 Mw 8.6 Wharton Basin earthquake (*Wei et al., 2013*))

2012 Mw 8.6 Wharton Basin earthquake

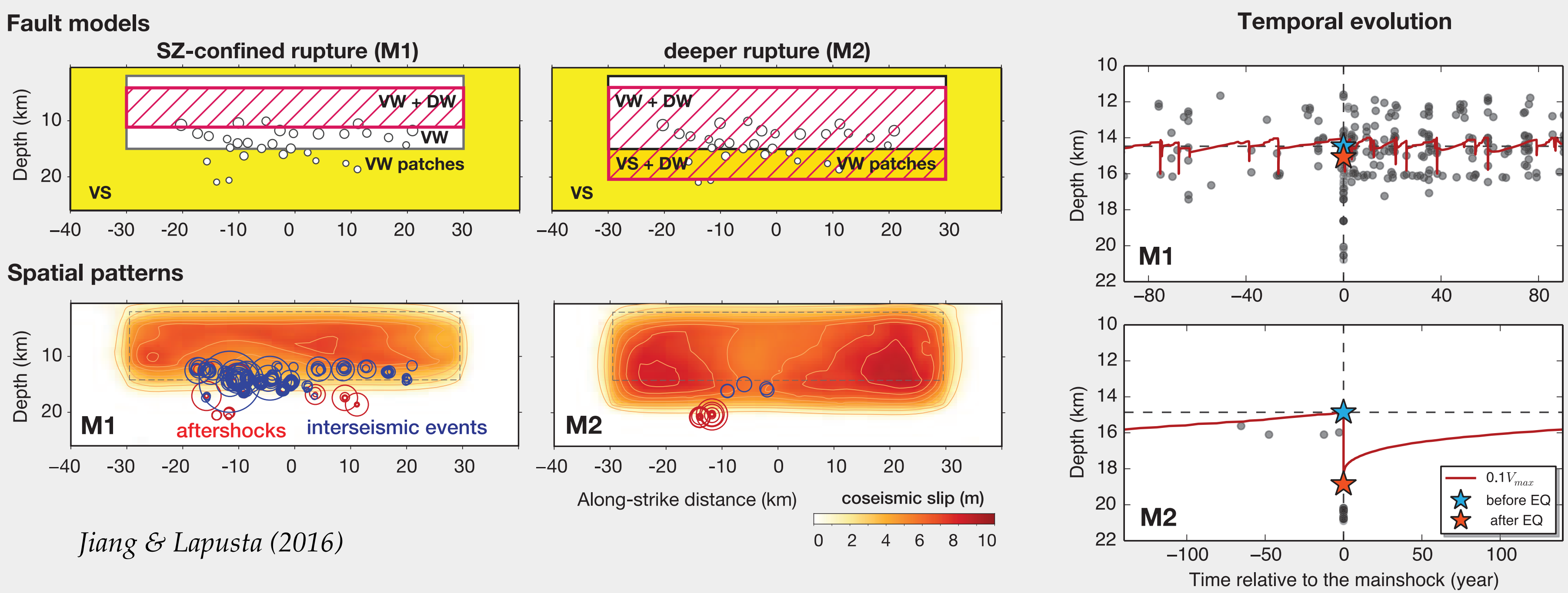
The depth distribution of the **seismic moment** (Wei et al., 2013) and the average **stress drop** of 17 MPa (Hill et al., 2015) suggests a **thick lithosphere.**



Deep Slip and Locking Depth

Deep slip from large earthquakes can extend the boundary between creeping and locked regions.

- Enhanced coseismic weakening can extend ruptures to regions that are considered frictionally stable



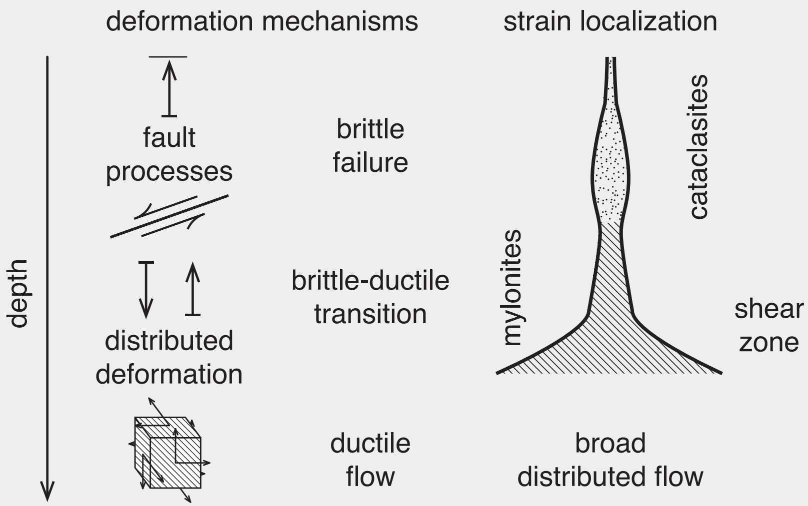
Jiang & Lapusta (2016)

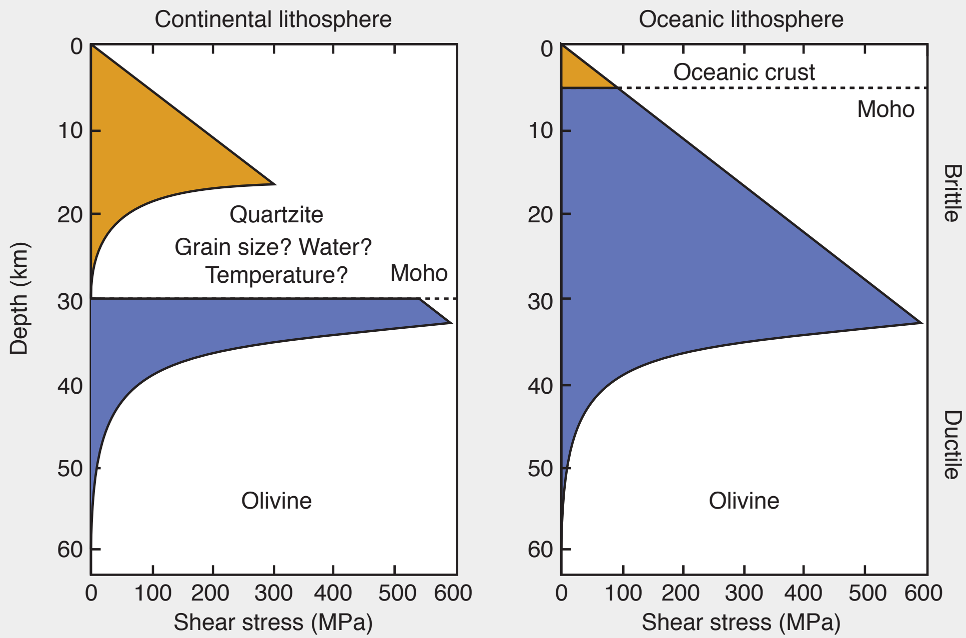
Transition in Fault Zone Structure

With increasing depth we expect,

- Transition to more stable, rate-strengthening behavior
- Delocalization of deformation

Fault zone structure and localization of shear is critical for shear heating efficiency and enhanced coseismic weakening





Motivating Questions

How deep can earthquakes rupture?

What controls variability in rupture depth?

Can they penetrate into deeper, more stable areas?

How would this affect the occurrence of future events?

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Goals:

Examine the competition between fault slip and distributed deformation near the deeper extension of the fault zone.

- Simulate earthquake cycles incorporating both mechanisms within the lithosphere-asthenosphere system

Examine how the evolution of local rheology can modulate the extent of the seismogenic zone and long-term slip behavior.

Quasi-static Solutions for Distributed Deformation

We seek to solve **complex friction, viscoelastic, thermoelastic,** or **poroelastic** problems **analytically** in closed form.

We assume that the elastic and inelastic strains add up

$$\epsilon = \epsilon^e + \epsilon^i$$

With stress/strain relationship

$$\sigma = C : \epsilon^e$$

Conservation of momentum leads to the equivalent body force

$$f = -\nabla \cdot (C : \epsilon^i)$$

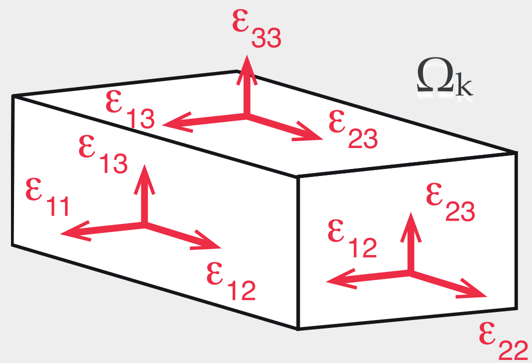
The displacement field is obtained using the Green's functions

$$u(x) = \int_\Omega G(x,y) \cdot f(y) dy$$

The solution can be approximated by a finite series:

$$u(x) \approx \sum_k \int_{\Omega_k} G(x,y) \cdot f_k(y) dy$$

Where the domain is a finite cuboid volume.

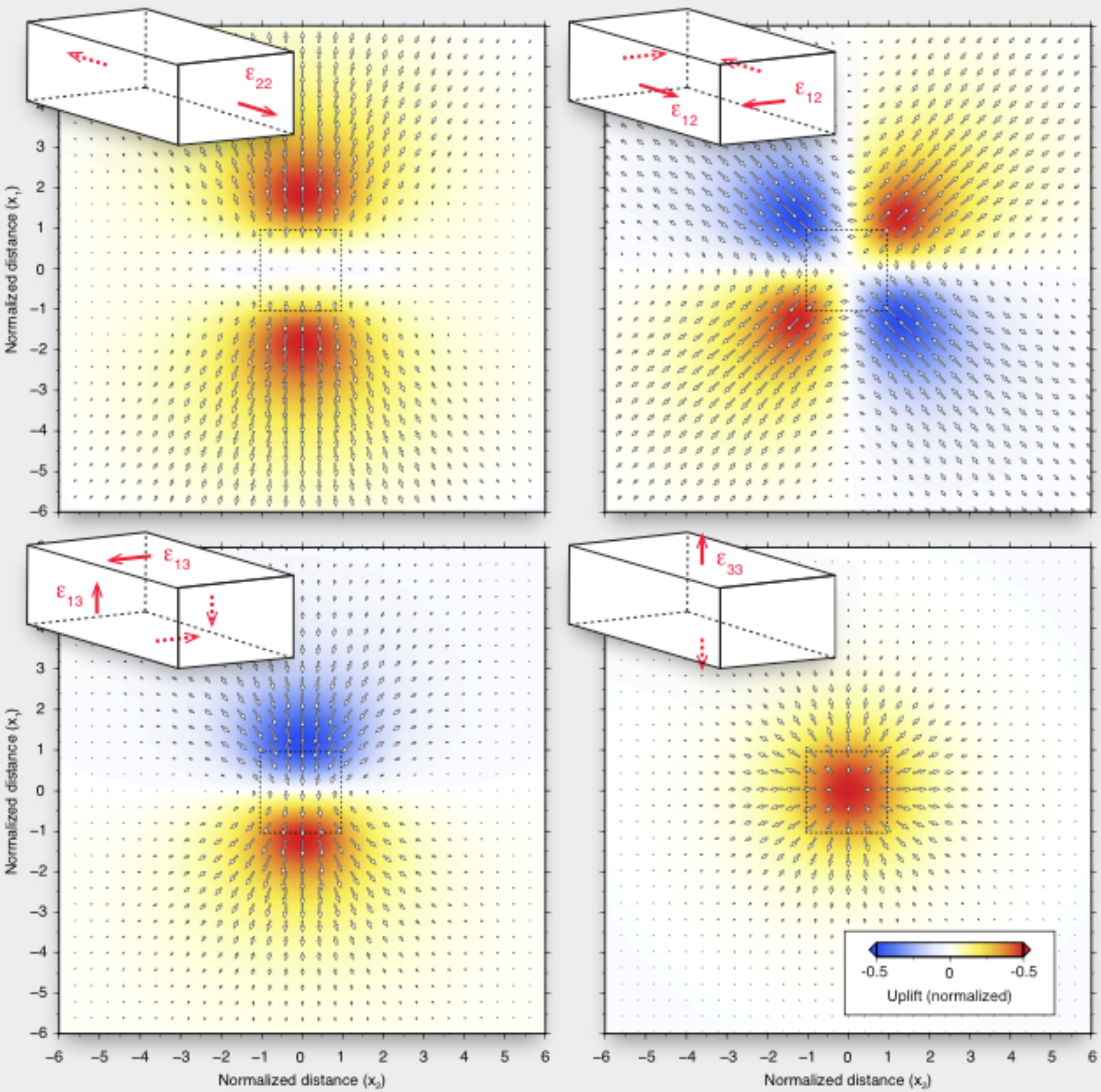


The kernels

$$u_k(x) = \int_{\Omega_k} G(x,y) \cdot f_k(y) dy$$

Represent a unified expression for quasi-static deformation throughout the earthquake cycle

Kinematics of Distributed Deformation

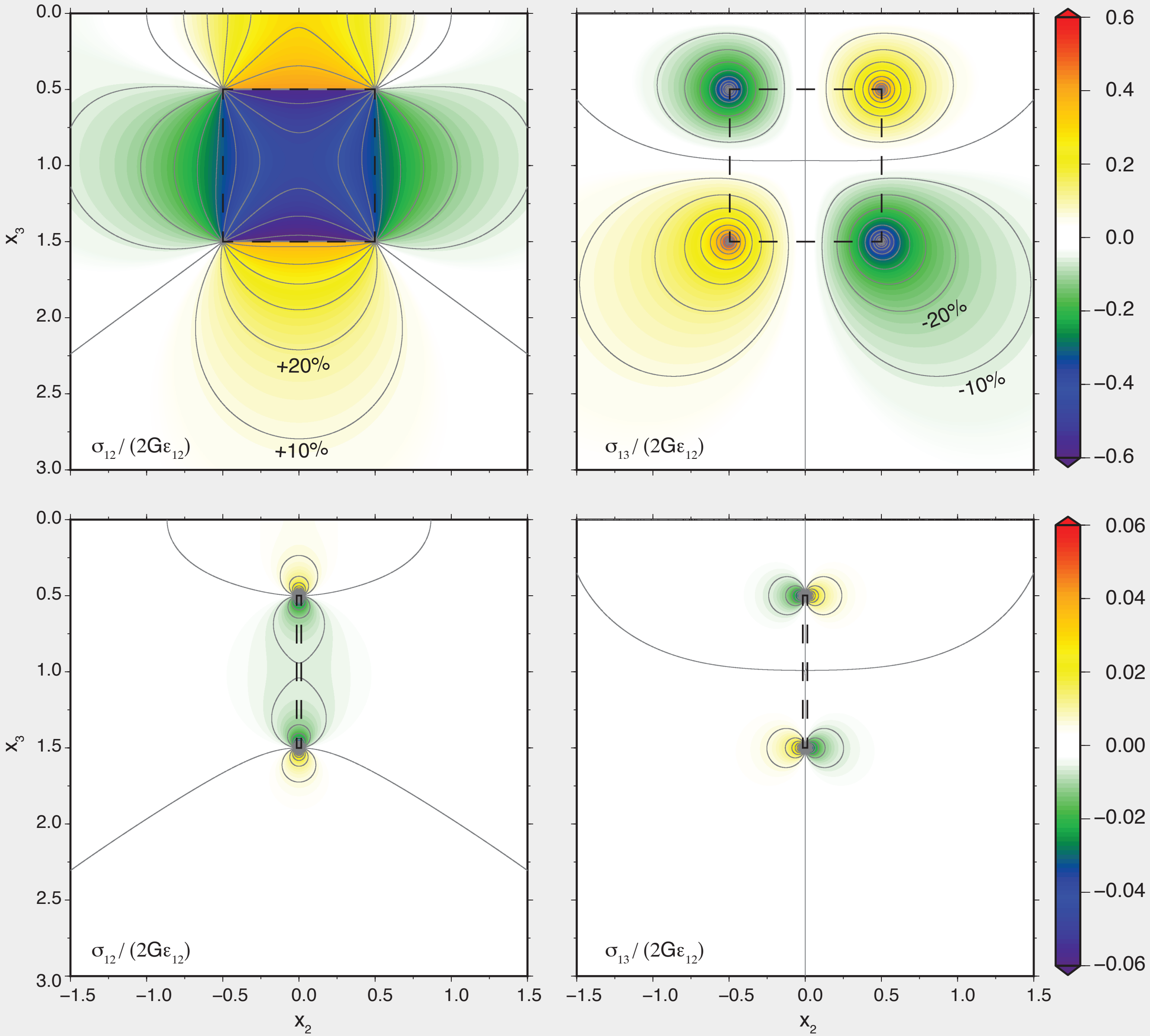


A suite of solutions for the **displacements, strains** and **stresses** due to **distributed inelastic deformation** of finite shear zones in a half-space for cuboid sources.

Any distribution of inelastic strain can be associated with **surface displacements**, allowing **linear kinematic inversion** of deformation data.

Barbot, S., Moore, J., and V. Lambert (2017). Displacement and Stress Associated with Distributed Anelastic Deformation in a Half-Space. Bull. of the Seism. Soc. of America, 107, 2, 821-855.

Geometric Convergence of Deformation



Solutions for distributed strain converge to those for a dislocation along with geometry.

Barbot, Moore & Lambert (2017)

Viscoelastic Deformation

Viscoelastic deformation in the mantle asthenosphere and continental lower-crust is accommodated by **diffusion** and **dislocation** creep mechanisms,

$$\dot{\epsilon}^{i} = \dot{\epsilon}^{\text{diffusion}} + \dot{\epsilon}^{\text{dislocation}}$$

Which are dependent on pressure, temperature, and hydration conditions.

Dislocation creep : movement of dislocations through crystal lattice (highly stress dependent)

$$\dot{\epsilon}^{\text{dislocation}} = A\tau^{n}\left(C_{OH}\right)^{r}\exp(\alpha\phi)\exp\left(-\frac{Q+pV}{RT}\right)$$

Diffusion creep: diffusion of vacancies along grain boundaries (grain-size dependent)

$$\dot{\epsilon}^{\text{diffusion}} = A\tau d^{-m}\left(C_{OH}\right)^{r}\exp(\alpha\phi)\exp\left(-\frac{Q+pV}{RT}\right)$$

Grain-size is a controlling factor in the dominant deformation mechanism

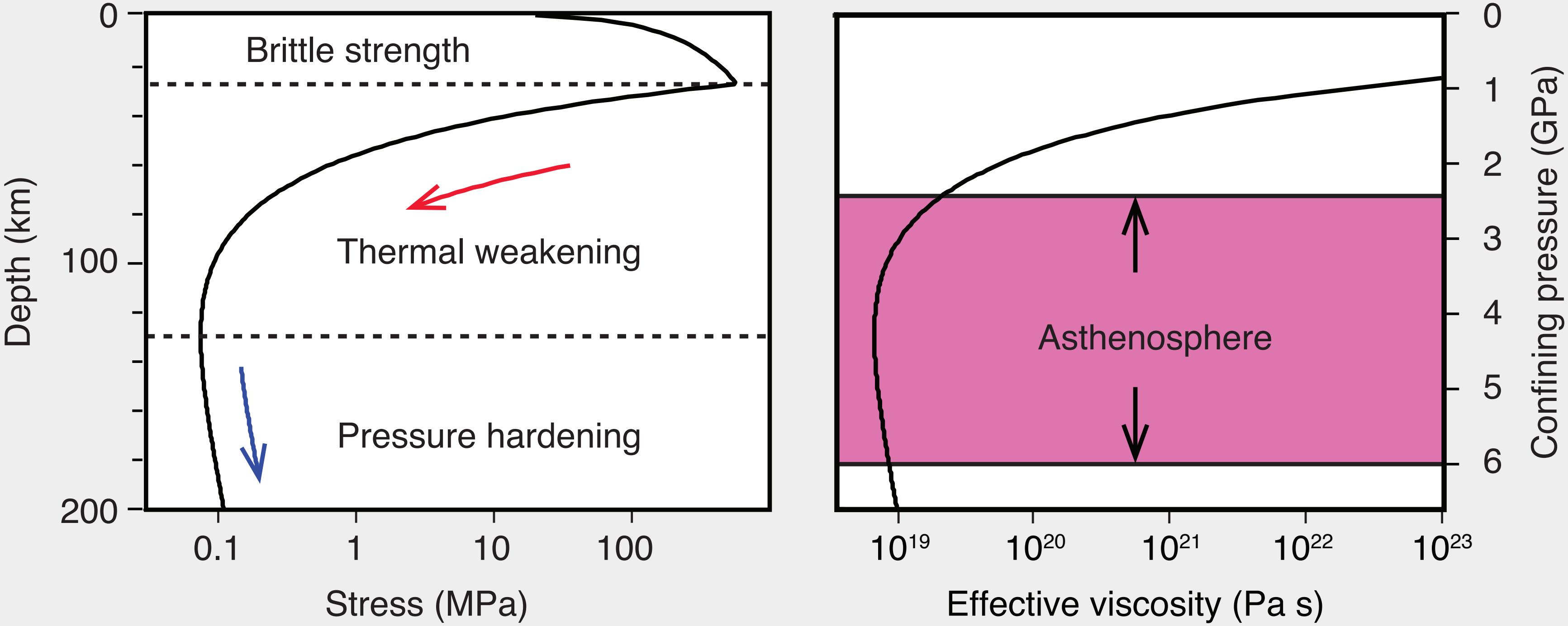
Depth-Dependent Viscosity

Depth-dependent steady-state rheology is defined by a competition of **thermal activation** and **pressure inhibition**.

pressure hardening

$$\dot{\epsilon}^{\text{dislocation}} = A\tau^n \left(C_{OH}\right)^r \exp(\alpha\phi) \exp\left(-\frac{Q+pV}{RT}\right)$$

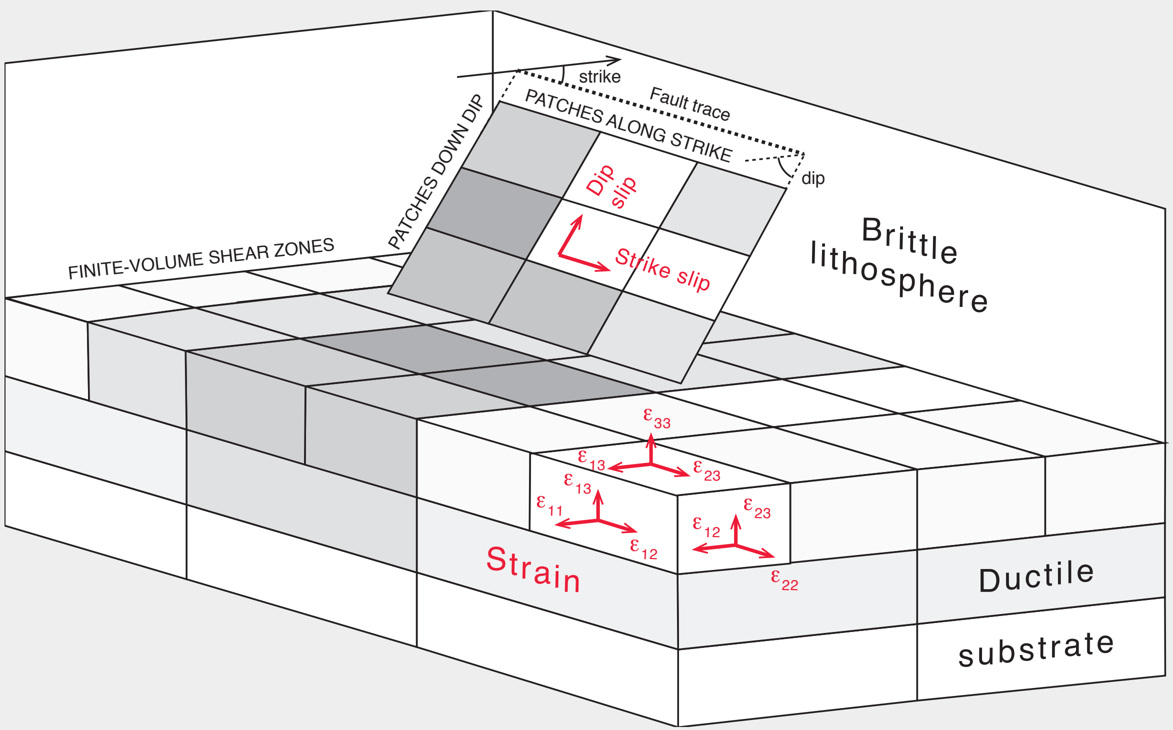
thermal weakening



Coupling Fault Slip and Off-fault Deformation

We build unified models of earthquake cycles coupling the evolution of fault slip and distributed strain using the **integral method**.

- Account for stress interactions with Green's functions for **slip along fault patches** and **distributed strain in finite volumes**



- Using the analytic solutions for stress interactions, the integral method is several orders of magnitude faster than finite elements.

- Can now quickly and easily couple multiple physical processes in earthquake simulations.

Rate and State Friction

Model fault slip evolution using Dieterich-Ruina rate and state friction with the aging law

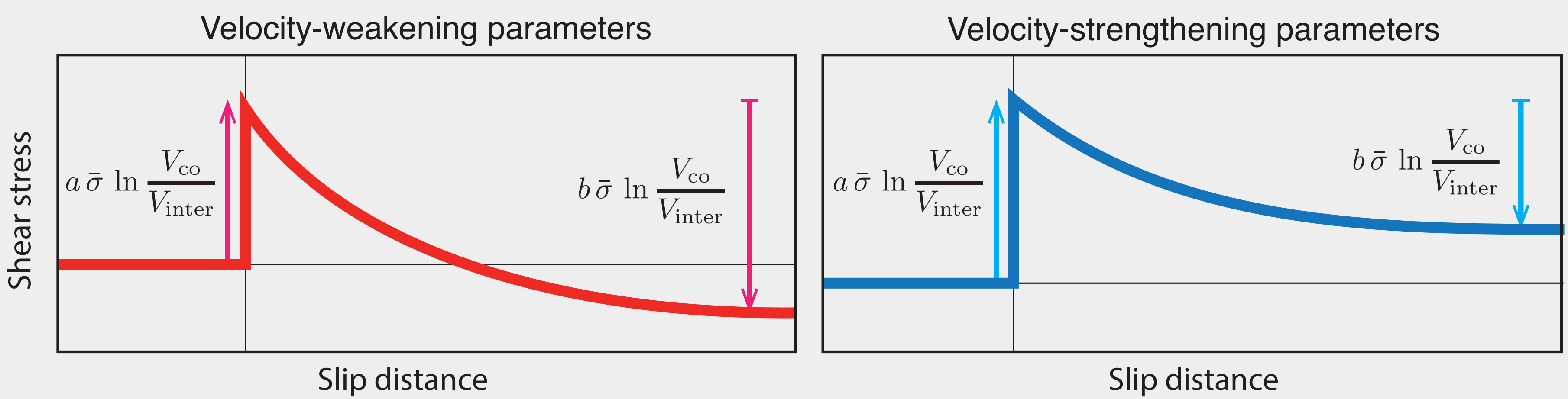
shear stress on fault

slip rate

$$\tau = \bar{\sigma}\left[\mu_0 + a\ln\frac{\dot{s}}{\dot{s}_0} + b\psi\right] \quad \text{where} \quad \psi = \ln\frac{\theta\dot{s}_0}{L}$$

state parameter

$$\dot{\theta} = 1 - \frac{\theta\dot{s}_0}{L}$$



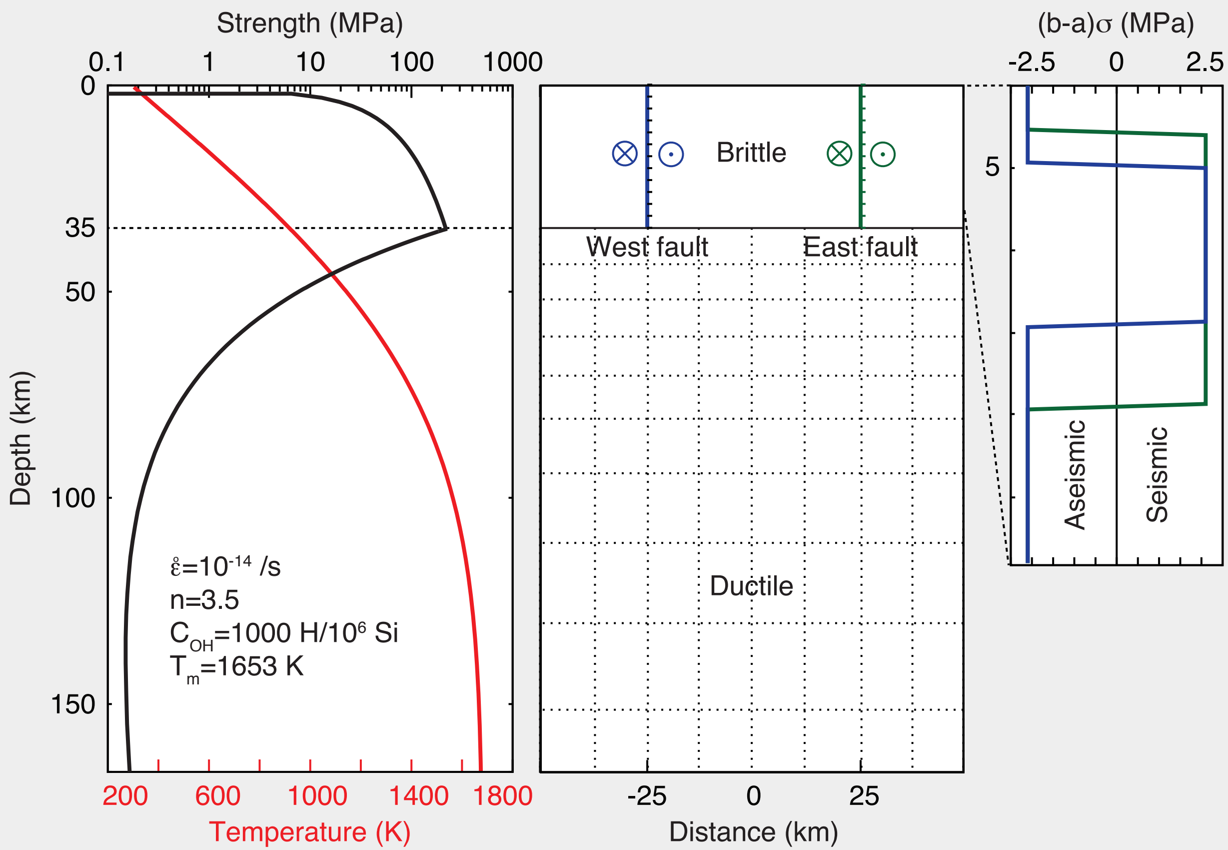
Earthquake Cycles in the Lithosphere-Asthenosphere System

Perform quasi-dynamic modeling incorporating the interactions of fault slip and viscoelastic deformation using the integral method

Fault slip:
Rate-and-state friction

Viscoelastic flow:
Power law dislocation creep

$$\dot{y} = f(y,t) \qquad y = \begin{bmatrix} s \\ \tau \\ \psi \\ \cdots \\ \sigma_{12} \\ \sigma_{13} \\ \epsilon_{12} \\ \epsilon_{13} \\ \cdots \end{bmatrix}$$



Lambert & Barbot (2016), GRL

2D Antiplane Model Schematic

Fault Slip:

Rate-and-state friction

Depth-dependent frictional properties

Radiation damping

Loaded with driving plate rate

Stress transfer using Green's functions for fault slip and strain within finite volumes

Viscoelastic Deformation:

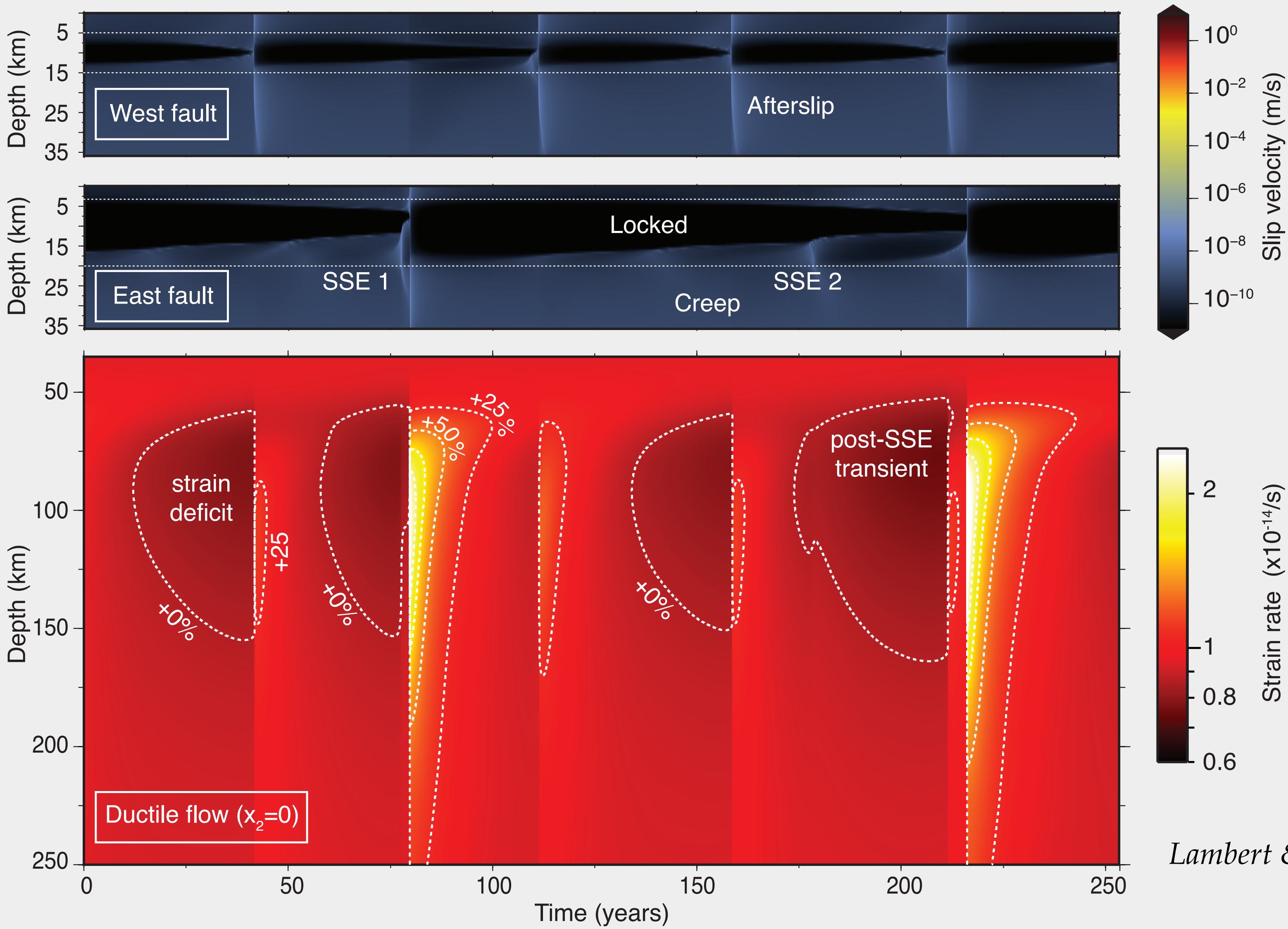
Power-law dislocation creep

Depth-dependent thermal and pressure profiles

Loaded with reference strain rate

Earthquake Cycles in the Lithosphere-Asthenosphere System

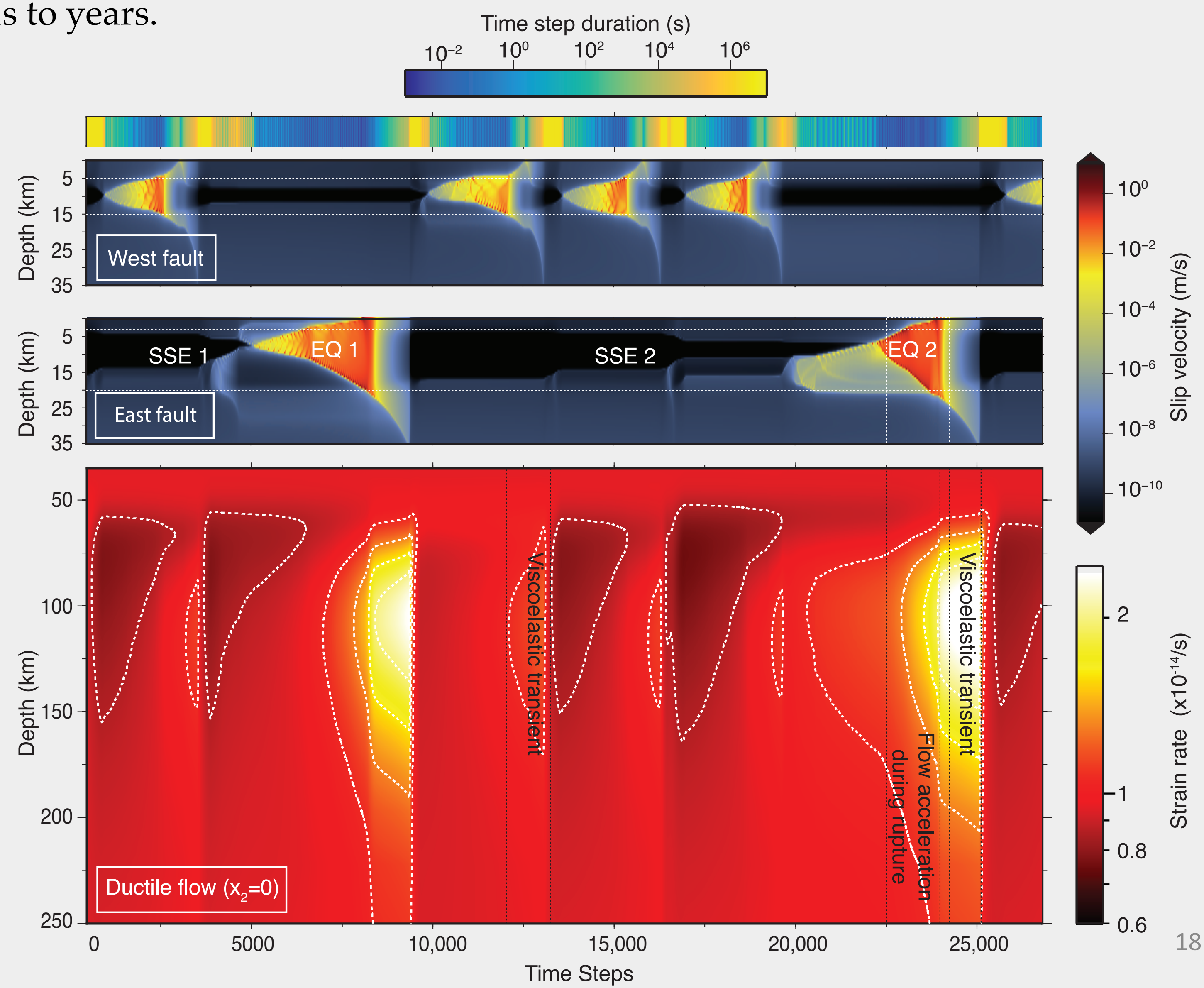
Periods of strain acceleration and deficit associated with earthquakes and slow-slip events



Lambert & Barbot (2016)

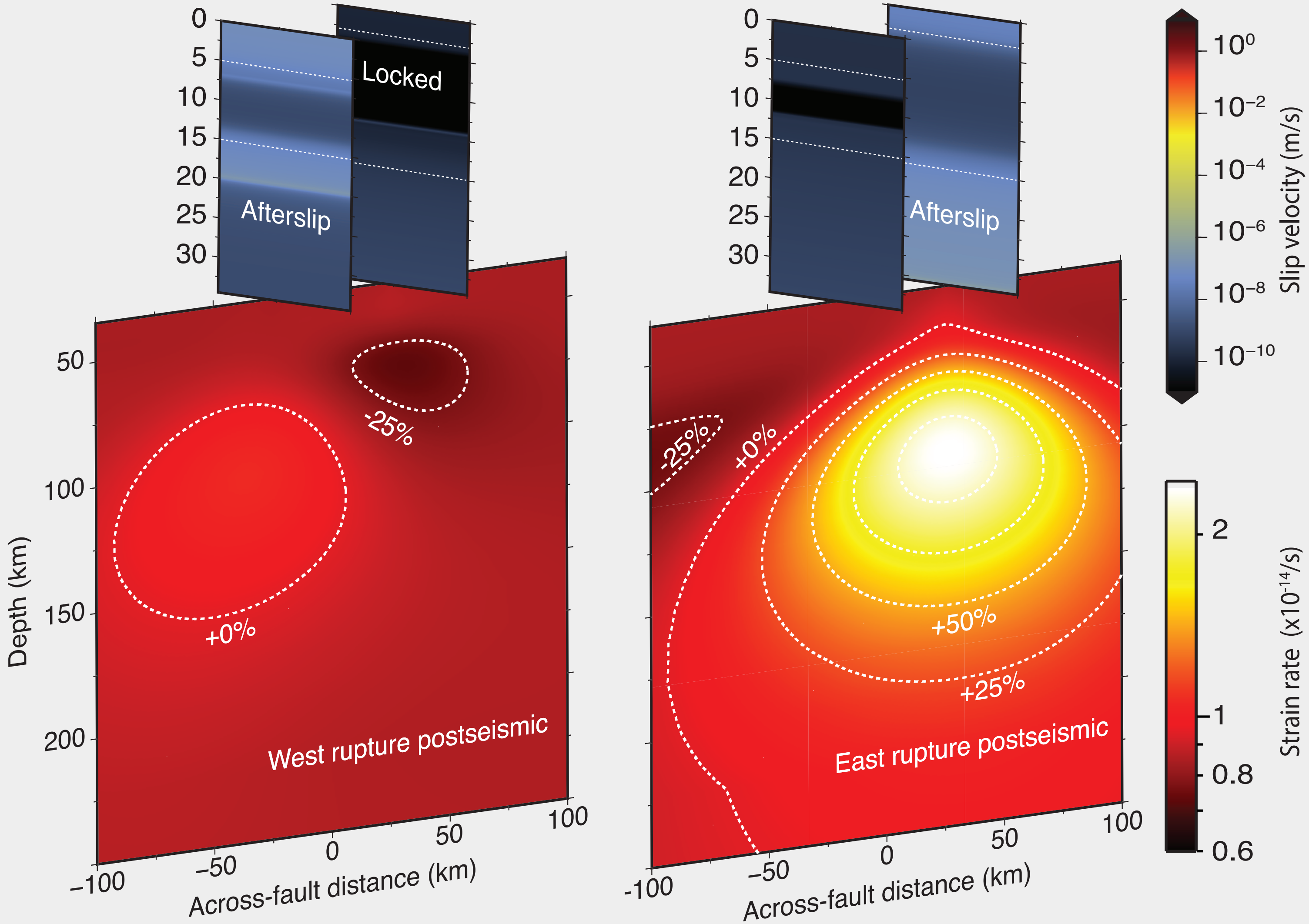
Earthquake Cycles in the Lithosphere-Asthenosphere System

Use adaptive time steps to optimize calculations over a wide temporal range from milliiseconds to years.



Lambert & Barbot (2016)

Spatial Distribution of Deformation



Lambert & Barbot (2016)

Evolution of Fault Zone Rheology

So far we have considered spatial variations in viscosity

- Want to consider temporal variability of rheological properties

hydration

partial melt

$$\dot{\epsilon}^{\text{dislocation}} = A\tau^{n} \left(C_{\text{OH}}\right)^{r} \exp\left(\alpha\phi\right) \exp\left(-\frac{Q+pV}{RT}\right)$$

temperature

$$\dot{\epsilon}^{\text{diffusion}} = A\tau d^{-p} \left(C_{\text{OH}}\right)^{r} \exp\left(\alpha\phi\right) \exp\left(-\frac{Q+pV}{RT}\right)$$

grain size

Balancing of creep mechanisms controlled by grain-size evolution,

Grain growth, healing

$$\dot{d} = \left(\frac{d_0}{d}\right)^{p-1} - d\dot{\epsilon}^{\text{dislocation}}$$

Grain size reduction

Barbot et al. (in prep.)

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The Role of Thermally-Activated Deformation

How deep can earthquakes rupture?

What controls variability in rupture depth?

Can they penetrate into deeper, more stable areas?

Competition between thermal strengthening and weakening mechanisms

✧ Fault slip is,

- ➢ Enhanced by **coseismic thermal weakening mechanisms**
- ➢ Mitigated by off-fault **thermally-activated viscous strain**

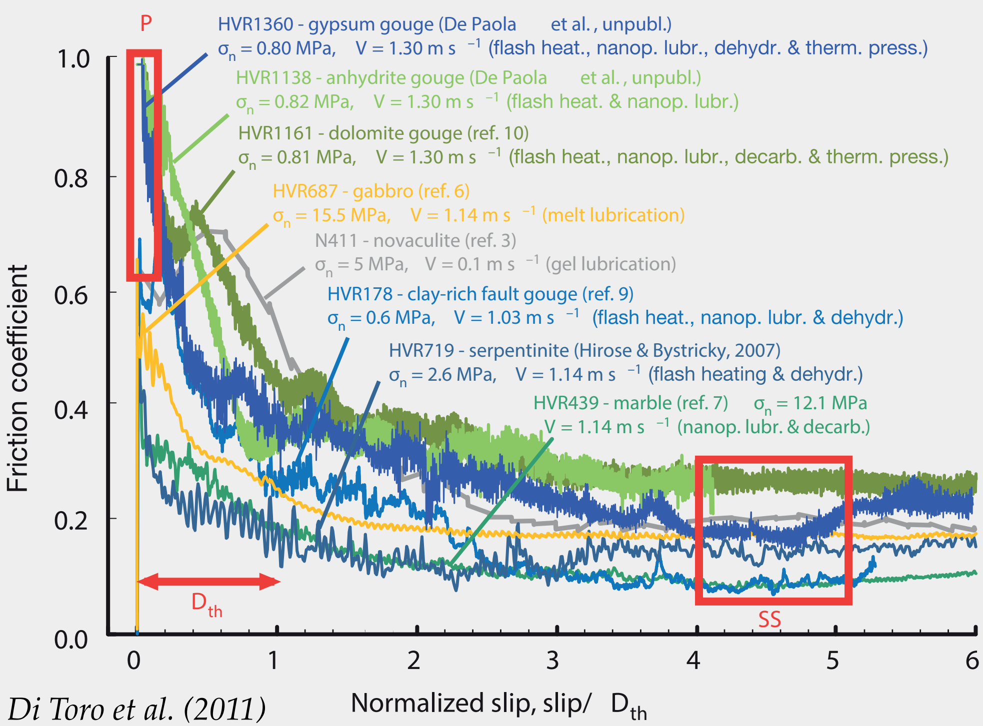
How would this affect the occurrence of future events?

✧ Explore the how the local rheology can be influenced by deep slip and potentially modulate subsequent loading

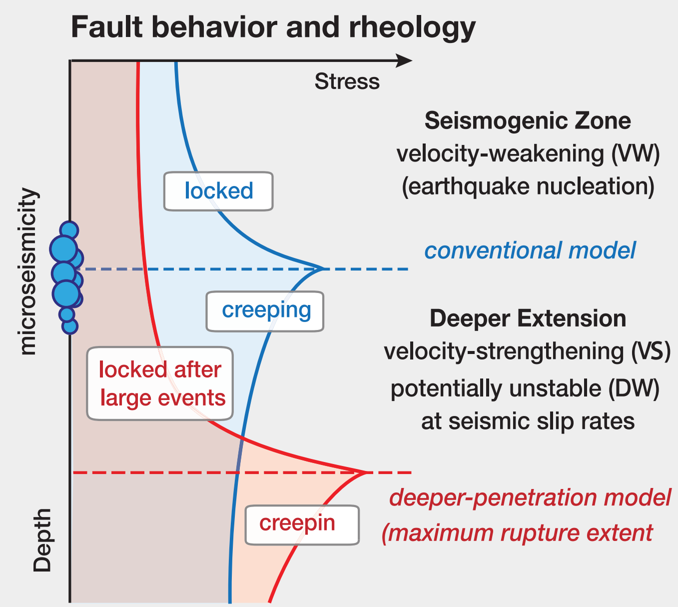
Enhanced Dynamic Weakening

Laboratory experiments show a dramatic reduction in the coefficient of friction at high slip rates (> 0.1 m/s).

- ➢ **Flash heating** – large frictional heating induced at seismic speeds on very localized contacts
- ➢ **Thermal pressurization** – rapid decrease in effective confining pressure (thermal expansion of pore fluids)
- ➢ **Highly localized viscous strain** - dramatic viscosity reduction
- ✧ The efficiency of thermal weakening mechanisms is **highly dependent on fault zone structure and properties**



Di Toro et al. (2011)



Jiang & Lapusta (2016)

Thermally-Driven Rheology

- **Evolving rheology** – temperature and stress as state variables

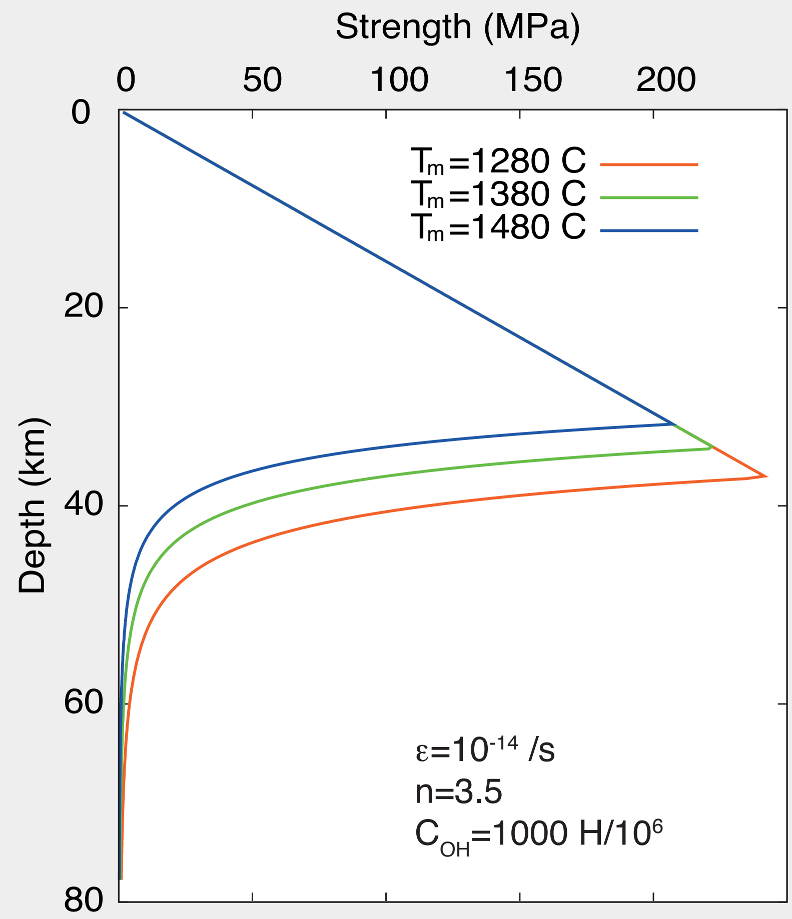
$$\dot{\epsilon} = A\tau^{n} \left(C_{OH}\right)^{r} \exp\left(\alpha\phi\right) \exp\left(-\frac{Q+pV}{RT}\right)$$

- Temperature is increased by **shear heating** and moderated by **thermal diffusion**.

$$\dot{T} = k\nabla^{2}T + \frac{1}{\rho_m C_p}\left[\dot{\epsilon}\tau + \dot{s}\tau_F\Omega(\bar{x})\right]$$

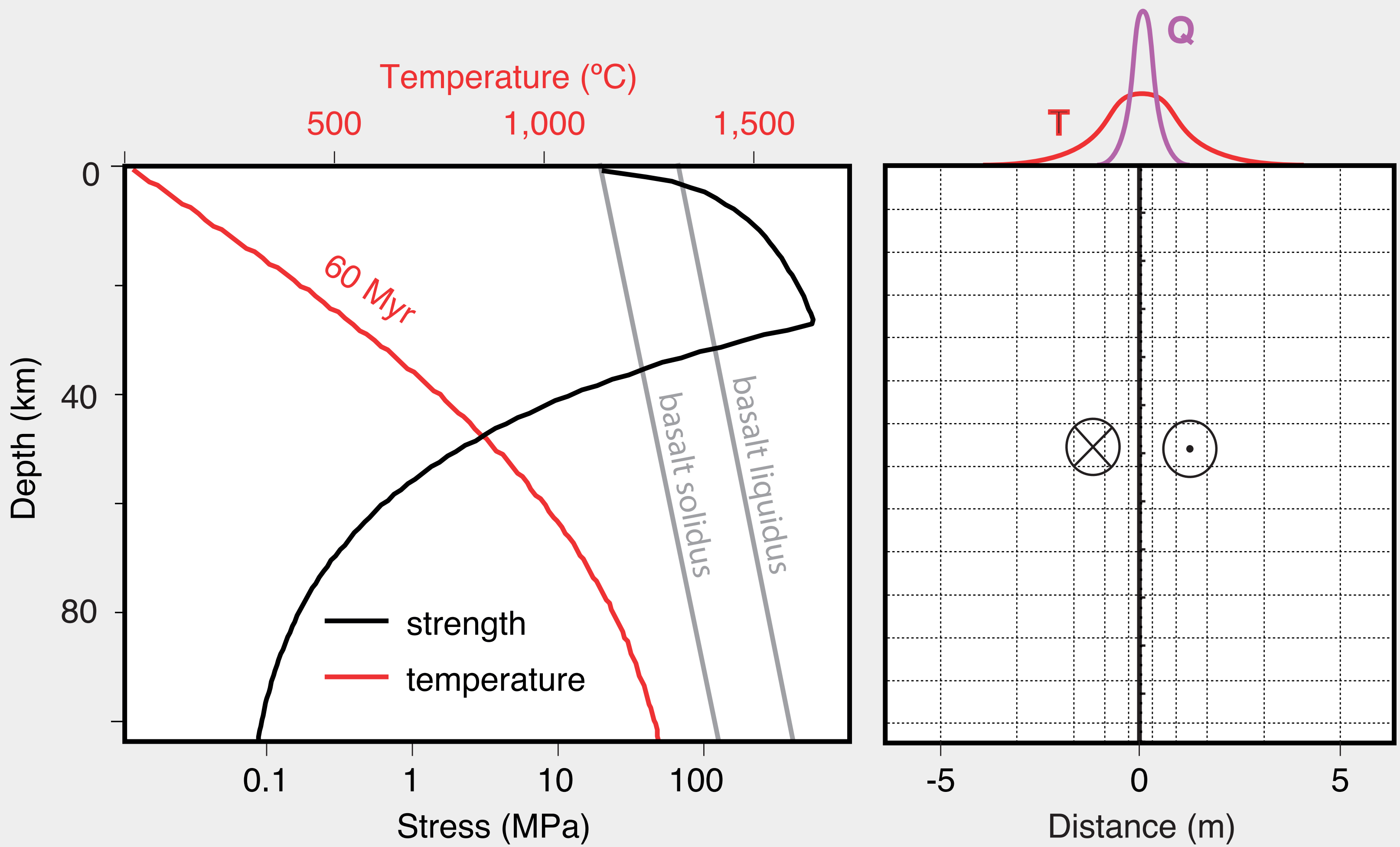
Thermal diffusion **Shear heating**

- The **viscosity** of the off-fault material **responds to heat production** from deformation



Competition between Styles of Deformation

Extend the discretization of the bulk to allow competition between slip and viscoelastic deformation



Model Schematic

Fault Slip:

Rate-and-state friction

Depth-dependent frictional properties

Enhanced dynamic weakening

Loaded with driving plate rate

Stress transfer using Green's functions for fault slip and strain within finite volumes

Thermal Evolution:

Shear heating

Diffusion throughout bulk

Viscoelastic Deformation:

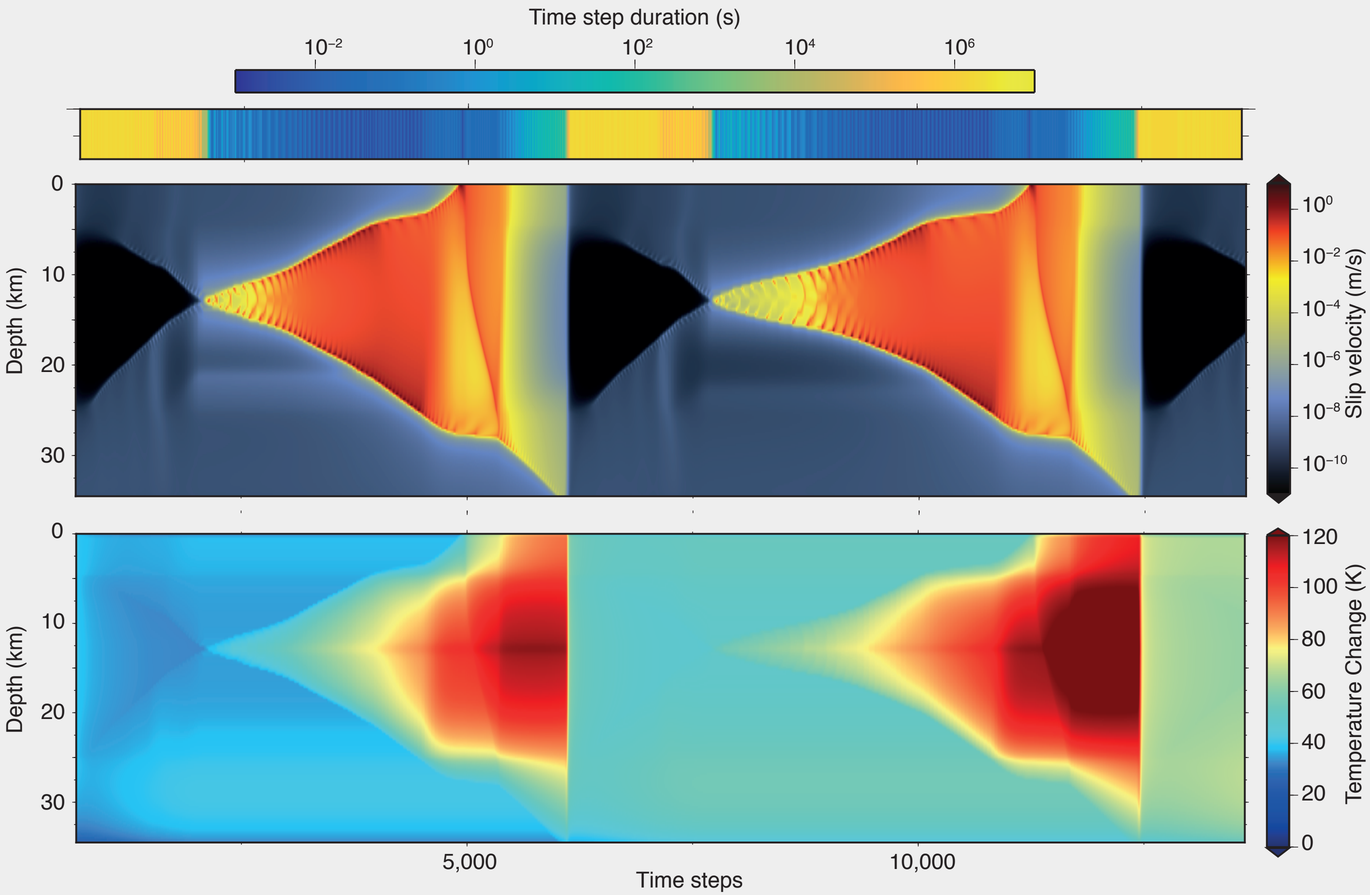
Thermally-activated Power-law dislocation creep

Depth-dependent thermal and pressure profiles

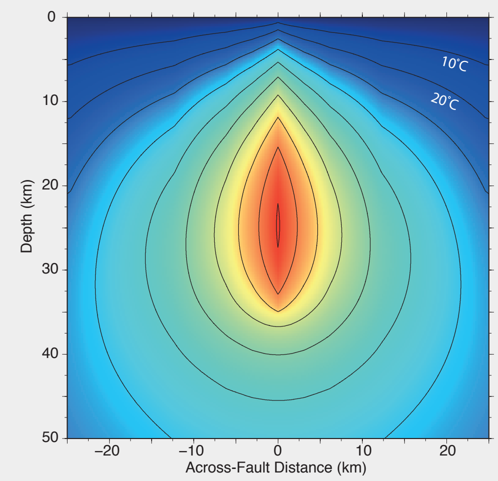
Loaded with reference strain rate

Shear Heating Throughout Seismic Events

Examine heat production over many seismic events and consider the evolution of local viscosities surrounding the fault

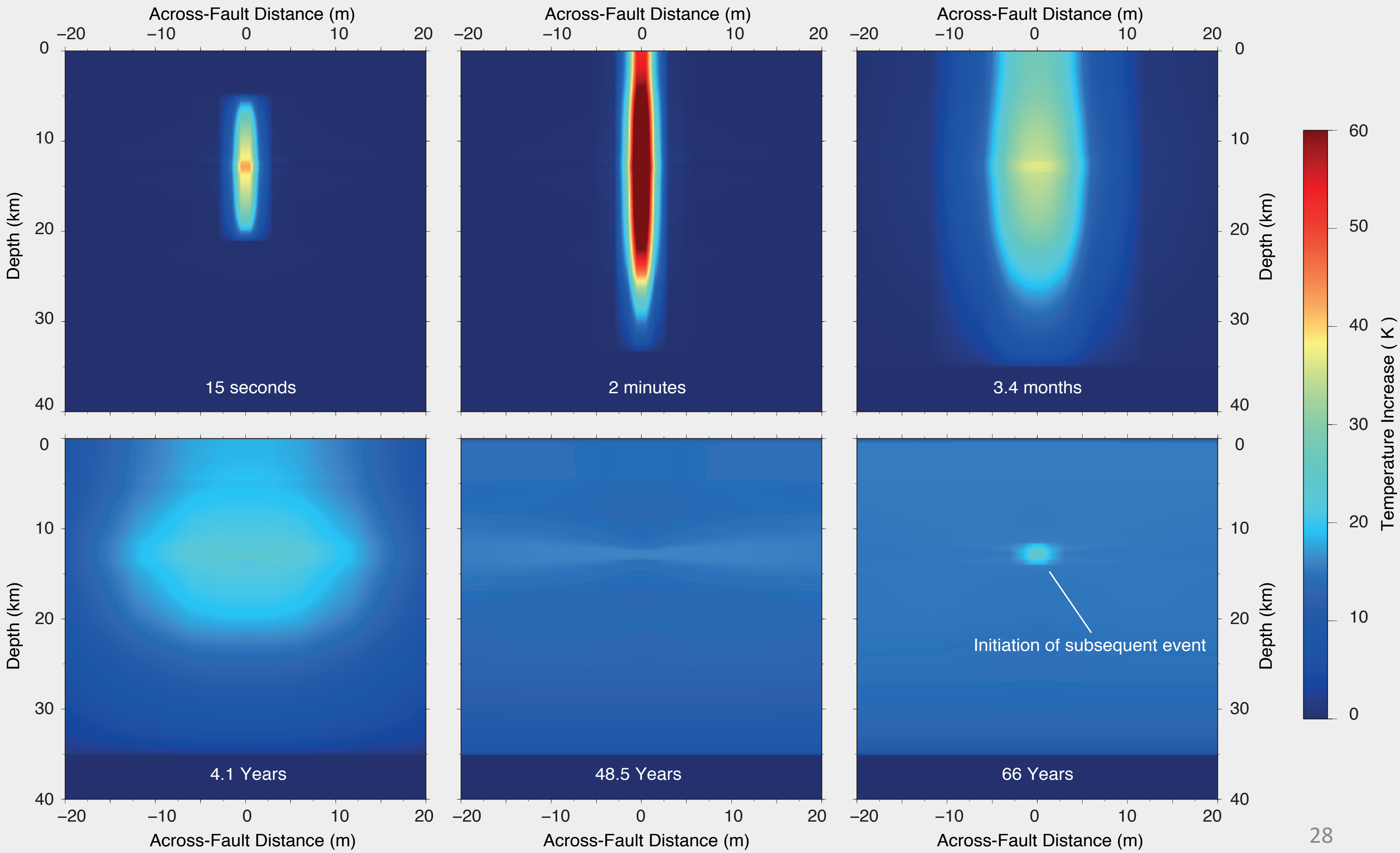


Long-term thermal profile surrounding fault (geothermal gradient removed)



Thermal Evolution within the Bulk

Evolution of temperature within the bulk over varying timescales



Modeling Outlook

Framework for combining multiple styles of deformation in quasi-dynamic earthquake cycles of the lithosphere-asthenosphere system.

- Can incorporate:
  - Nonlinear rheologies
  - New physical processes (e.g. poroelasticity, thermoelasticity)
  - More variables of state (temperature, grain size, water content, etc.)

- Very efficient modeling of quasi-static deformation

Limited in consideration of inertial effects

- Looking to couple with fully dynamic rupture sequences

Concluding Thoughts

<u>Considerations for long-term fault behavior</u>

What conditions would be necessary to propagate ruptures to various depths?

- ➢ Efficient enhanced dynamic weakening mechanisms

How might the evolution of fault zone rheology alter the loading rate and strength of faults over various time-scales?

- ➢ Viscous flow enhances far-field stress transfer

How might this affect the potential size and recurrence of earthquakes?

How would this play into regional studies of fault networks?

Code available at: https://bitbucket.org/sbarbot/unicycle

Lambert, V., and S. Barbot (2016), Contribution of viscoelastic flow in earthquake cycles within the lithosphere-asthenosphere system, Geophys. Res. Lett., 43, 10,142–10,154, doi:10.1002/2016GL070345.