Effect of the crust-mantle boundary on the geometry of ductile shear zones

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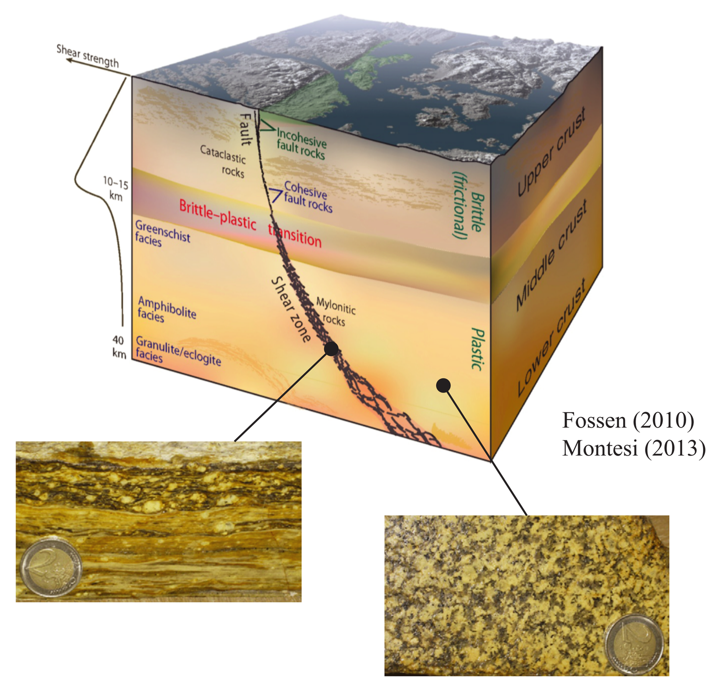
Introduction

Ductile shear zones act as the continuation of faults into the lower crust, and their structure depends in part on their rheology and in part on the faults' frictional properties in the brittle-ductile transition (BDT) region. We explore how fault and ductile shear zone structure are coupled in a 2D steady-state model of a continental strike-slip fault zone. The model considers brittle deformation in the upper crust, characterized by localized slip on a fault, and distributed viscous flow in the lower crust and upper mantle. Two viscous deformation mechanisms are considered: grain-size sensitive diffusion creep and grain-size insensitive dislocation creep. Grain size is determined using a piezometer (Twiss, 1977) and depends on stress.

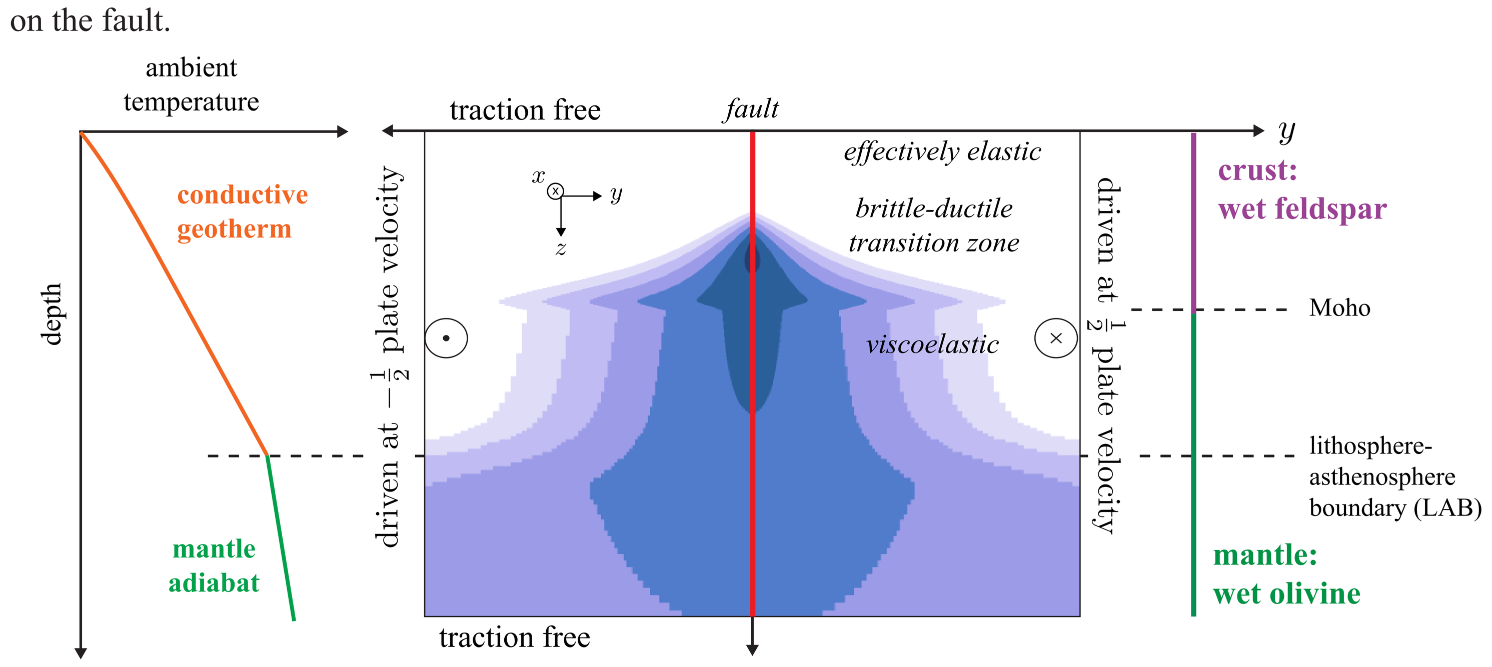
This model makes it possible to self-consistently simulate: strain rate, grain size, dominant deformation mechanism, and stress, in the vicinity of a strike-slip fault and its deep extension in the lower crust.



Model

To investigate interactions between a shallow seismogenic zone, deeper aseismic fault creep, and off-fault viscous flow, we have developed a finite-difference code for simulating rate-and-state friction and power-law viscoelasticity coupled to a grain size evolution equation. The method is extended from Erickson and Dunham (2014) and Allison and Dunham (2017).

We model system behavior using a steady-state approximation, in which the fault slips steadily (no earthquakes), and the slip velocity and viscous strain rates are determined as part of the steady-state solution. The transition in deformation style from frictional sliding to viscous flow is not imposed a priori but determined as part of the solution. In the results shown here, we use uniformly velocity-weakening rate-and-state properties on the fault.

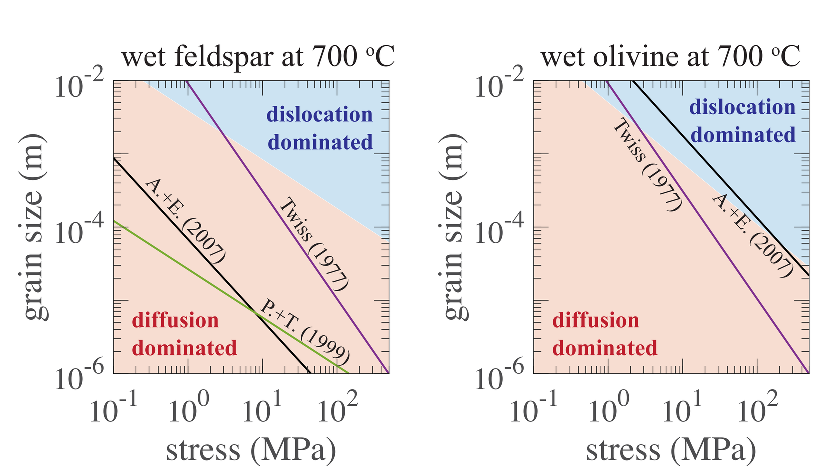


We consider two crystal-plastic creep deformation mechanisms: grain size insensitive dislocation creep and grain size sensitive diffusion creep. These two mechanisms act in parallel

$$\begin{aligned}\dot{\epsilon}_{\mathrm{tot}} &= \dot{\epsilon}_{\mathrm{disl}} + \dot{\epsilon}_{\mathrm{diff}} \\ &= A_{\mathrm{disl}} e^{-Q_{\mathrm{disl}}/RT} \sigma^{n_{\mathrm{disl}}} + A_{\mathrm{diff}} e^{-Q_{\mathrm{diff}}/RT} \sigma^{n_{\mathrm{diff}}} d^{-m}\end{aligned}$$

We model grain size evolution following the piezometer proposed by Twiss (1977), in which grain size is a nonlinear function of stress. Rheological parameters in the lower crust are for wet feldspar (Dresen et al. 1996; Rybacki et al, 2006) and in the mantle are for wet olivine (Karato et al. 1980, van der Wal, 1993; Hirth and Kohlstedt, 2003). The transition between the feldspar in the lower crust and olivine is gradual, occuring over a width of 3 km centered at 30 km depth.

In the lower crust, under typical conditions, diffusion creep is expected to be the dominant deformation mechanism.



Shear Zone Definitions

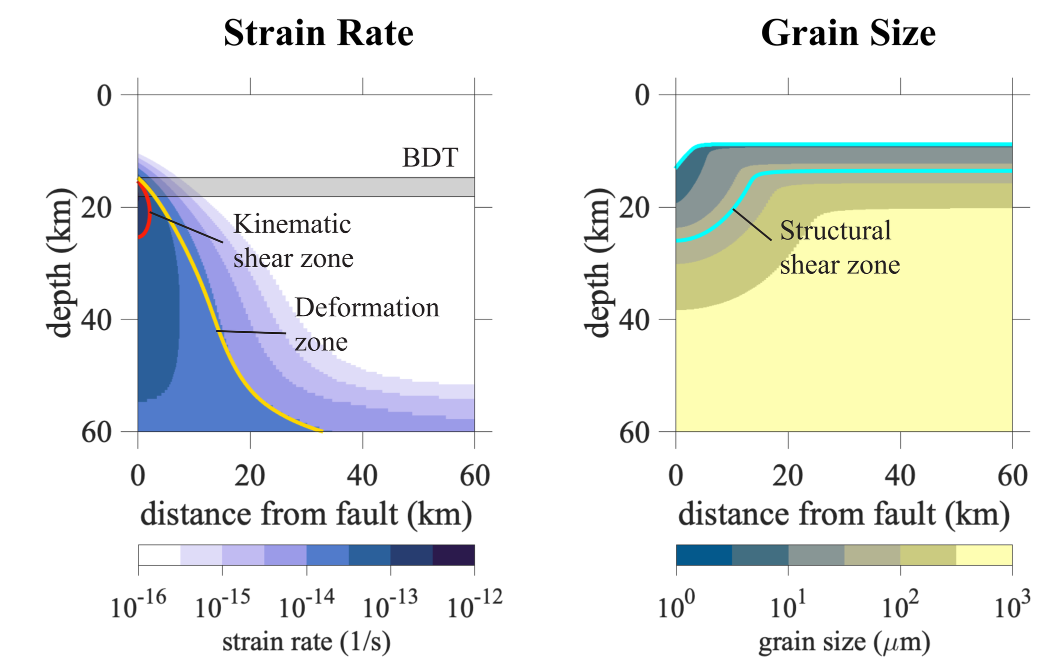
To facilitate comparison between simulation results and different types of observations, we introduce 4 definitions:

Kinematic Shear Zone:
- the region in which viscous strain rate is significantly elevated
- may be observable through surface geodesy
- defined as region in which the viscous strain rate is >100x the background strain rate (>10^{-13} s^{-1})

Deformation Zone:
- measures the degree of the localization of deformation
- region in which 90% of total deformation occurs (both fault slip and integrated viscous strain)

Structural Shear Zone :
- the region in which mylonites might form
- defined as the region in which grain size is reduced to <50 μm, and stresses do not exceed the Mohr-Coulomb failure envelope

Brittle-Ductile Transition (BDT):
- the region in which appreciable fault slip and viscous flow both occur
- depth range over which the fault transitions from accommodating 90% to 10% of the background tectonic loading

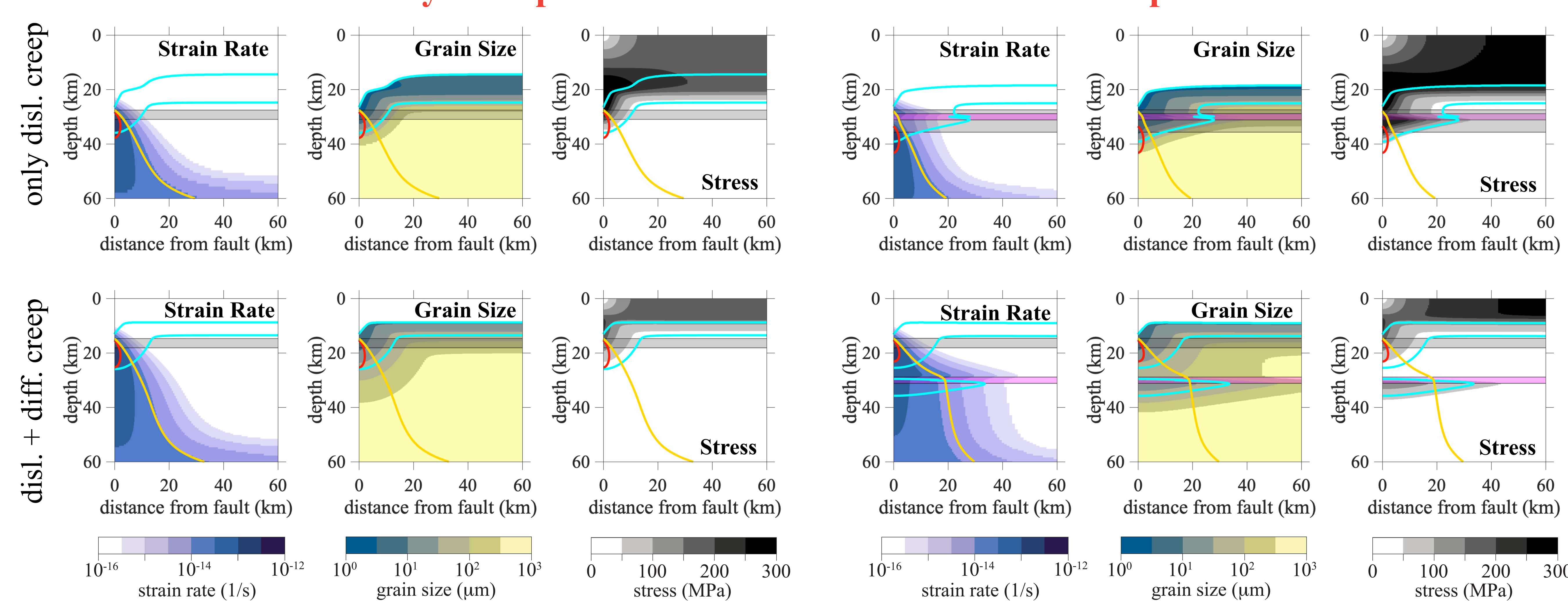


In simulations with only feldspar, the highest strain rates and smallest grain sizes occur near the fault tip at depth, where the shear stress is also highest.

The structural and kinematic shear zones are not coincident. Here, the structural shear zone is much deeper and broader.

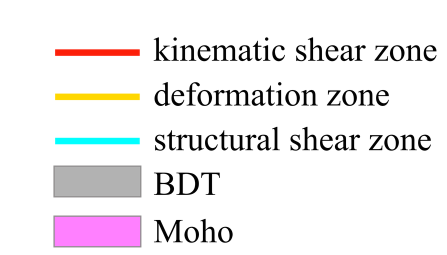
Effect of Layered Model

Only Feldspar **Feldspar over Olivine**



While grain size reduction and grain size sensitive flow do have a moderate localizing effect, the effect may not be powerful enough to produce a highly localized shear zone. In this case, grain size reduction would be a consequence of localization, but not its cause.

Olivine is stronger than feldspar, leading to a strength contrast between the lower crust and upper mantle. This complicates the architecture of the shear zone, and can even lead to multiple discontinuous shear zones.



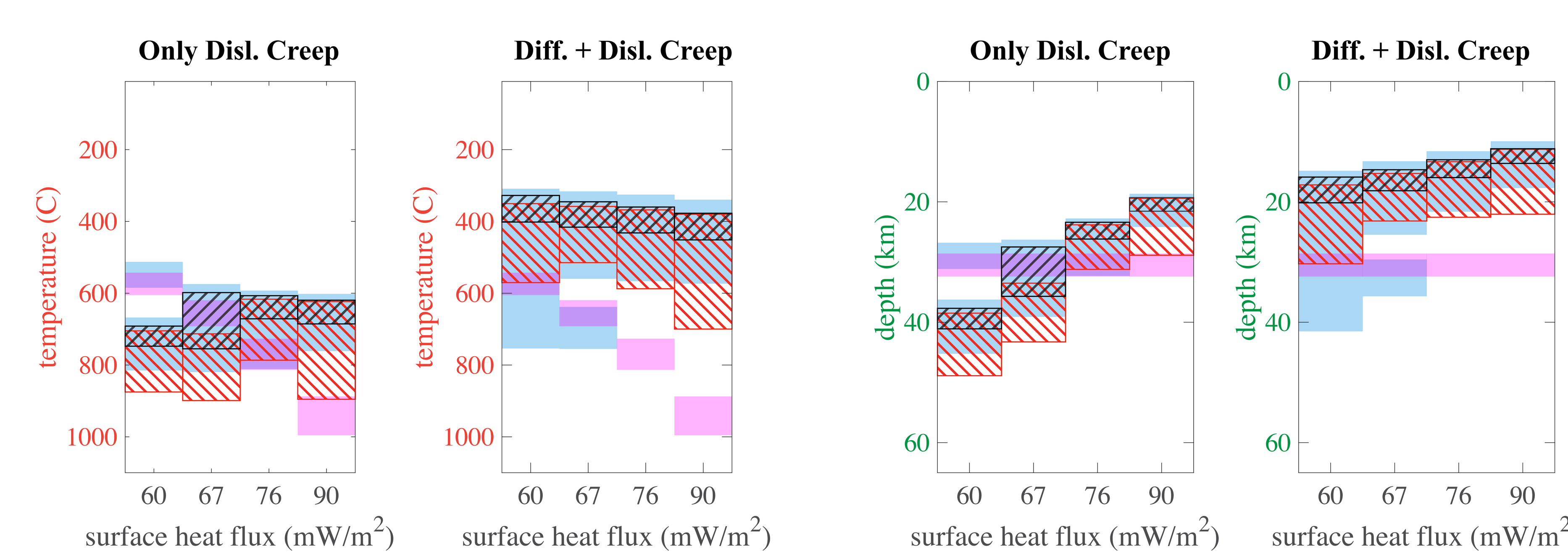
Results shown for uniformly velocity-weakening rate-and-state fault parameters, and a geotherm that produces 66 mW/m² surface heat flux.

Effect of Background Geotherm

We consider the effect of varying background geotherm on the range of the BDT, the kinematic shear zone, and the structural shear zone along the fault and its ductile root.

These simulations are for a hypothetical strike-slip fault. We could use the developing CTM and CGM to model faults like the San Andreas and San Jacinto, and compare predictions with observed depths of microseismicity and large earthquakes in southern California.

Temperature Range **Depth Range**



- The BDT and lower limit of the structural shear zone both occur at a roughly constant temperature.

- In feldspar, the effect of diffusion dominance, as opposed to dislocation dominance, is to shallow the BDT by ~250 °C. This moves the BDT from the mantle into the lower crust in all simulations.

- The maximum depth of microseismicity may correspond with the lower limit of the BDT.

- Large earthquakes would be limited either by the VW-VS transition (not modeled here) or by the lower limit of the BDT, whichever is shallower.