Physics of the Brittle Ductile Transition*  
(and other thoughts on simulators)  
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context: predicting seismicity patterns at the level of detail relevant for earthquake simulators (but this can be high level of detail, given possibility of utilizing RSQSim coseismic ruptures for ground motion)  

Ways that BDT processes might influence simulator results:  
• limit rupture depth (and influence moment-length scaling)  
• influence loading of seismogenic zone (and hence recurrence interval, slip distribution, rupture history)  
• 3D fault/shear zone geometry in viscous region might be different than in seismogenic zone, influencing stress transfer and loading  

*caveat: my own experience on BDT processes is limited to 2D antiplane shear strike-slip models
What limits rupture depth? (key for hazard because it controls moment-length scaling)

Transition from velocity-weakening to velocity-strengthening friction or frictional sliding to viscous flow (i.e., BDT)?

Mitchell et al. (2016) show VW friction for granite gouge up to 600 °C

Most SEAS (sequences of earthquakes and aseismic slip) simulations are in elastic solids, with coseismic rupture depth determined by frictional velocity-weakening to velocity-strengthening transition [Mavko, ~1983; Tse and Rice, 1986]. But:

- friction might remain VW to BDT
- viscous flow of lower crust and upper mantle is evident in geodetic data (and consistent with lab experiments on high T rock deformation)

However, is it necessary to identify depth-limiting process, given that depth can be constrained from seismicity and geodesy, then taken as input to simulator with back-slip loading?

Figure 7. The (a – b) versus temperature, Westerly granite. Open symbols denote results from previous studies. Filled symbols denote results from this study. Error bars on symbols representing velocity-stepping tests correspond to 2 standard deviations. Error bars on symbols representing model fits to the time series correspond to the variation in (a – b) that triples the minimum misfit at a given temperature. Same test numbers as in Figure 5.
Viscoelastic sequence simulations: strike-slip fault, loading by steady displacement of side boundaries.

red = 1 s
blue = 10 yr

not many changes (similar EQ nucleation depth, rupture depth, recurrence interval, slip/event) as compared to elastic case – probably due to ~5 km region of aseismic slip

change in recurrence interval and slip/event indicates change in how seismogenic zone is loaded

heating and weakening of lower crust effectively eliminates deep aseismic fault creep, raising BDT so that it limits rupture depth

LAB 50 km, $\lambda = 0.37$, $w = 1$ m

Allison, 2018 PhD thesis
Sensitivity to geotherm, flow law, pore pressure

geotherms

shear stress on fault and its deep extension

figure from Kali Allison, based on results from Allison and Dunham [2018]
Pore pressure and effective normal stress

increasing pore pressure reduces thermal anomaly and deepens BDT

Allison, 2018 PhD thesis
Pore pressure, effective stress, and stress drop – processes at the base of the seismogenic zone

fixed effective stress

variable effective stress from upward fluid transport and permeability evolution

SEAS simulations with “fault valving”

(Zhu, Allison, Dunham, work in progress, 2019)
Pore pressure, effective stress, and stress drop – processes at the base of the seismogenic zone

The main point is that there are likely processes, other than elastic stress transfer, that can substantially alter stresses on faults during interseismic period – but there are very few constraints on these processes...

SEAS simulations with "fault valving"

(Zhu, Allison, Dunham, work in progress, 2019)
Should simulators account for these process?

• Fluid effects are very poorly constrained, understanding nowhere close to mature enough to include in simulators.
• If there is an aseismically slipping zone ~5 km below seismogenic zone, then effects of deeper viscous flow are almost identical to those from localized slip at depth (à backslip dislocation model is probably fine).
• However, if viscous transition limits rupture depth, then loading is evidently quite different, with pronounced differences in recurrence interval and slip/event (but no validation yet with data, so unclear if these simulations should be trusted).
Loading of geometrically complex faults?

1992 Landers earthquake

Yann Klinger, IPGP

details of fault geometry relevant for rupture propagation cannot be resolved in even most complex block models (and geodetic data do not have resolution to constrain details of loading)
Loading of geometrically complex faults?

Plate motion transfers stresses through lithosphere, causing aseismic slip or viscous flow in ductile shear zone, which loads seismogenic layer

(or relatively young faults might not have developed ductile shear zones?)

Map view

Fault segments in seismogenic upper crust

Ductile shear zone beneath each segment?

(back-slip fairly well justified)

Map view

Fault segments in seismogenic upper crust

Through-going ductile shear zone?

(back-slip not well justified)
Multisegment ruptures: Navigating bends and branches

1. Sustained propagation controlled by resolved prestress, independent of inertial effects

2. Navigating through bend/branch controlled by leading terms in expansion of stress around propagating rupture

\[
\sigma_{ij} = \sigma_{ij}^0 + \Delta \sigma_{ij} = \frac{K_p}{\sqrt{2\pi r}} F_{ij}(\theta, v_r) + \begin{bmatrix} \sigma_{xx}^0 & \tau_r \\ \tau_r & \sigma_{yy}^0 \end{bmatrix} + O(\sqrt{r}).
\]

(Poliakov et al., 2002)

...but failed ruptures through bend/branch would leave (near-)singlar static stress perturbation that would enter here in singular term:

\[
\frac{K_{static}}{\sqrt{2\pi r}} F_{ij}(\theta, v_r = 0)
\]

in local coordinate system for each segment would get terms like this for each rupture, approaching junction from different directions

(Kame et al., 2003)