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Earthquake Nucleation on Nonplanar Fault Systems with Heterogeneous Frictional Properties

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In the past year we have produced two different types of results in our research on earthquake nucleation on faults with complex geometry and heterogeneous initial stresses. In the first class of results, we analyze earthquake nucleation on dip-slip faults with heterogeneous initial shear stress. For these models, we use the simple slip-dependent friction law and Varational Boundary Integral Method of Zhang et al. (Zhang *et al.*, 2004; Zhang *et al.*, 2006). A cartoon of the 2-D plane-strain fault geometry is shown in Figure 1. We apply a steady loading velocity to the base of the fault, and allow unstable slip to take place at a calculated time and location down-dip. Our previous research (Xu and Ortiz, 1993; Xu, 2000; Xu and Zhang, 2003; Zhang *et al.*, 2004; Zhang *et al.*, 2006) has shown that fault geometry and depth-dependent frictional properties (i.e., variations in the critical slip-weakening parameter and the frictional coefficiant) can both have an important effect on the nucleation process on dip-slip faults. Depth-dependent properties can moderate the effects of fault geometry, and thus remove some fo the differences between thrust and normal faulting and between faults of different dip. The next step was to simulate dip-slip earthquake nucleation on faults with (arbitrary) heterogeneous initial shear

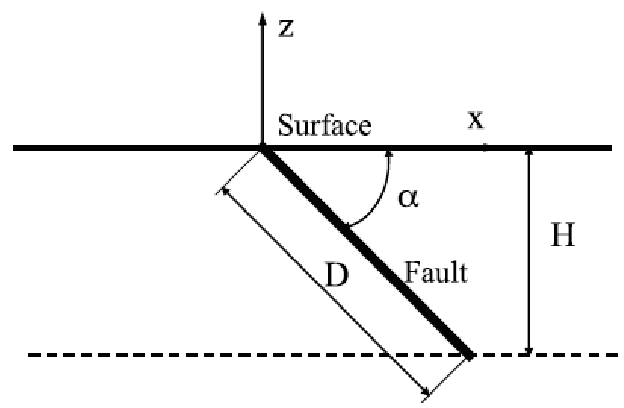

Figure 1. Cartoon of dip-slip fault geometry

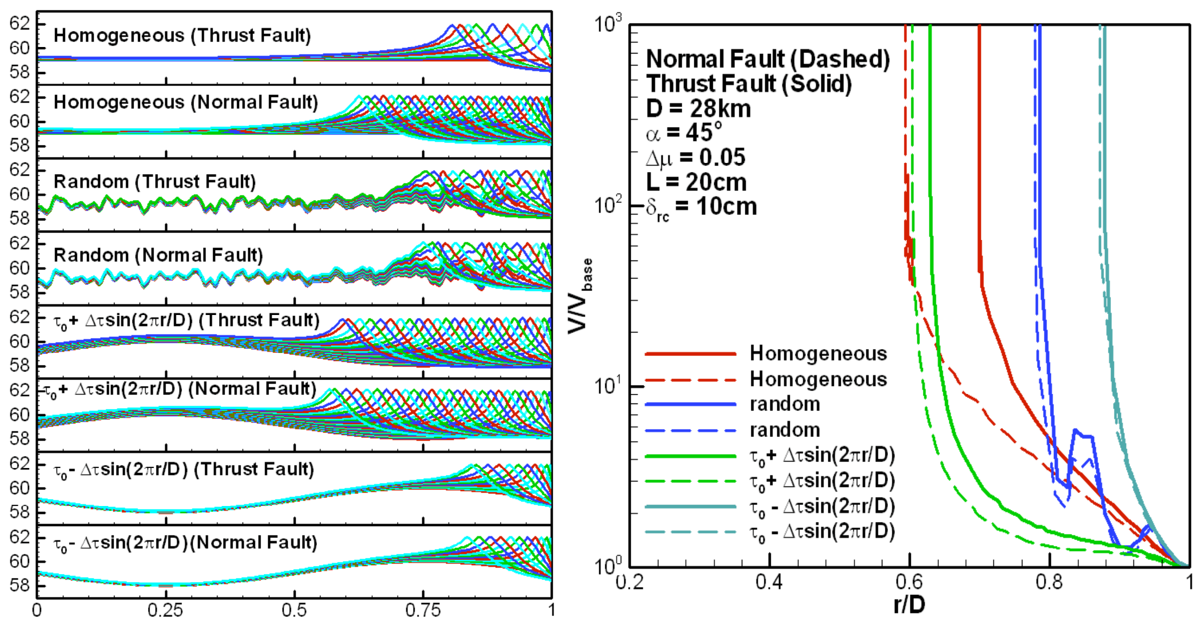

Figure 2. Left panel: sequential snapshots of shear stress on various dip-slip faults culminating with the time of earthquake nucleation. Right panel: Maximum slip velocity as a function of down-dip distance; the location of earthquake nucleation corresponds to the down-dip location of the divergent slip velocity. Homogeneous stresses produce quite different behavior for the thrust and normal faults, but heterogeneous stresses produce very similar behavior for both thrust and normal faults.

stress to determine how important this factor was in comparison to fault geometry. A summary of the results is shown in Figure 2. We experiment with faults of different slip direction (thrust and normal faults), as well as faults with different assumptions for the spatial variation of initial shear stress. The variation includes homogeneous stress, random stress variations, and sinusoidal stress variation of two different signs. As seen in Figure 2, heterogeneous initial stress can have a controlling effect on the location of earthquake nucleation on a dip-slip fault, overwhelming the combined effects of fault geometry and slip direction. In the homogeneous case, there is a clear difference between the nucleation location of the otherwise equivalent thrust and normal faults (Zhang *et al.*, 2004). However, adding around 2% of variability in the initial shear stress overwhelms the effect of the fault geometry; for the random cases and the two sinusoidal cases, nucleation for both thrust and normal faults takes place at a location on the fault with relatively high initial stress, and is quite similar for both the thrust and normal faults. These results imply that in the presence of even a small amount of stress heterogeneity has a larger effect than the dip angle on the nucleation process on dip-slip faults. This is somewhat bad news for predicting nucleation on such faults, because while fault geometry may be somewhat knowable ahead of an earthquake, the initial stress pattern is usually unknowable.

In the past year we have also made important advancements in our modeling methods, and now have completed some preliminary models of earthquake nucleation on nonplanar faults using rate-and-state friction. An example model is shown in Figure 3. It consists of a 2D plane-strain strike-slip system with a stepover that is spanned by a shorter linking strike-slip fault.

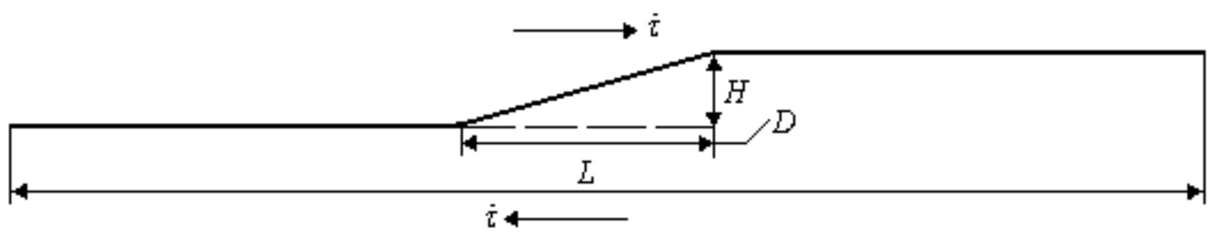

Figure 3. Stepover fault geometry for nucleation calculations with rate-and-state friction

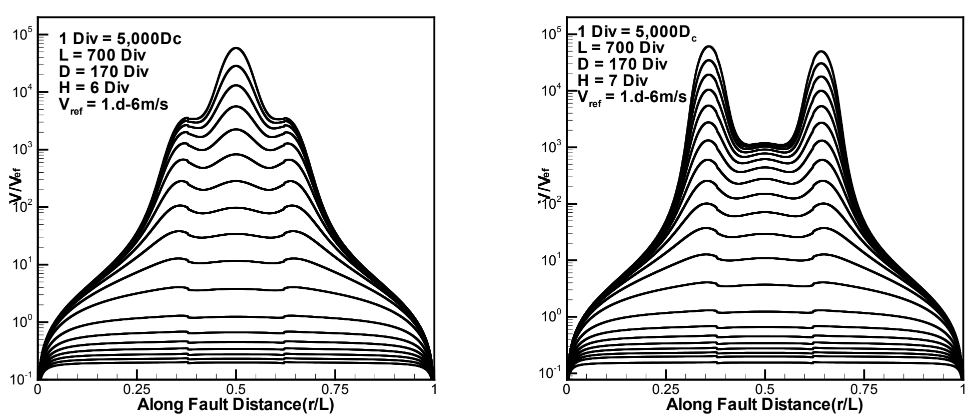

Figure 4. Snapshots of accelerating slip rate on stepover fault system for case of small stepover width H (left panel) and slightly larger H (right panel). Note that the nucleation location changes dramatically between the two cases.

Loading in the right-lateral direction will cause the shear stress on the fault to change due to the evolution of the slip rate and state variable as well as the change in normal stress. This interaction leads to interesting geometrical effects, as shown in Figure 4. This figure shows snapshots of fault slip rate over time for two cases: with a smaller stepover width perpendicular to strike (H) on the left, and with a larger stepover width perpendicular to strike (H) on the right. Note that both cases start out quite similarly, but in the small stepover length case, accelerating slip is concentrated in the middle of the linking fault segment, whereas in the case of the slightly larger stepover distance, accelerating slip is concentrated at the bends in the fault system. This result shows that small changes in fault geometry can have crucial effects on where an earthquake's hypocenter will be. In the future, we plan to couple this model with heterogeneous initial stresses, as well as examine a wider range of geometrical configurations, in hopes of learning some general "rules of thumb" for earthquake nucleation on geometrically complex faults. We also plan to incorporate a rate-and-state friction law (Linker and Dieterich, 1992) that explicitly includes the effect of time-dependent normal stress on the evolution of the state variable. Finally, we will eventually merge these models with dynamic models of the coseismic rupture process in order to perform multi-cycle earthquake simulations with realistic nucleation and dynamic rupture.

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