2014 SCEC Project Summary

Contributions to the SCEC CSM: A finite-element model of the southern California lithosphere

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Abstract

I am developing a finite element (FE) deformation model of the southern California lithosphere to estimate stresses and stressing rates for the SCEC Community Stress Model. Other modeling objectives include reconciling geological and geodetic slip rates, and better understanding how strain is accommodated away from known, major faults. Though the model mesh is largely complete, initial calculations have made it clear that plasticity and an alternative to the "split node" technique for modeling stress-driven slip along faults are required. These features have been implemented, and are being evaluated with test models. Models with plasticity produce higher and more uniform slip rates along discontinuous faults, and plasticity can profoundly influence modeled stresses. For elastic models, modified "slippery" nodes (with specified shear tractions) give surface velocities, stress rates and slip rates identical to those for conventional, traction-free "slippery" nodes, but absolute stresses are different for the two cases. Hence, using modified "slippery" nodes, stress tensor data (e.g. Yang and Hauksson, 2013) might be inverted for fault tractions and (given modeled or measured slip rates) shear zone properties.

Technical Report

Last year, I proposed to develop a finite-element deformation model of the southern California lithosphere, and to supply SCEC with estimates of stresses below the elastic upper crust (as well as stressing rates throughout the lithosphere) by the end of the funding period. The first-cut model mesh is complete, and as proposed, it incorporates all of the UCERF3 block model-bounding faults. Though lithosphere stresses have been forward-modeled throughout the region, they do not converge to a steady-state solution, so I have not uploaded them to the SCEC Community Stress Model (CSM).

The main issue, flagged by Thorsten Becker during the October 2014 CSM workshop, relates to numerical instability and inaccurate stresses along model faults with stress-driven creep implemented using the “split node” technique (Melosh and Raefsky, 1980). Though the “split node” method works well for earthquake-cycle models and for fairly straight faults that completely cut the mesh, model faults with sharp kinks or discontinuities give rise to spurious local stresses that build up over time. Simple ruses such as enforcing slip speed limits, inserting low-viscosity elements or not specifying the slip vector orientation at trouble spots are ineffective at suppressing this behavior (Figure 1).

Plasticity. During the funding period, I addressed the problem in two ways. First, I implemented plasticity in my finite-element code. My reasoning was that since extreme stress buildup is muffled in plastic deformation models, numerical instabilities are bounded and inaccurate stresses should be restricted to the neighborhood of the fault kink or tip. Furthermore, actual fault bends and kinks are surrounded by regions of intense damage in the upper crust, and linear elasticity does not adequately represent the rheology in such locations.

I implemented plasticity using the predictor-corrector method, which is suitable for static long-term deformation problems. A Drucker-Prager rheology is assumed, though by eliminating dependence of the rheology on volumetric strain, I can model Von Mises plasticity as well. Plasticity parameters from Li et al. (2009) are adopted ($\mu = 0.4$ and cohesion = 50 MPa, so plasticity parameters α and k are 0.17 and 61 MPa, respectively). Simple tests with uniform strain throughout the modeled domain reproduce analytical stress solutions, but models in which a restraining bend is present give stresses that increase steadily with time. This is because increasingly compressive mean normal stresses prevent the plasticity yield condition from being met. I solve this problem using a “cap” function (e.g., Sandler and Rubin, 1979), in which an elliptical function closes the yield envelope at mean normal stresses exceeding 100 MPa, allowing plastic strain to occur in elements undergoing compression. The choice of cap function and its implementation details will require more justification and refinement because in regions undergoing compression (e.g. the Big Bend) they may exert a strong influence on modeled stresses. (Li et al. [2009] use a cap function in their California deformation models, but details are not provided.)

Figures 2a and 2b show modeled surface velocities, fault slip rates and stresses for a uniform elastic volume (E = 75 GPa, Poisson’s ratio = 0.25) cut by a left-lateral strike-slip fault with a large, extensional stepover. Relative motion across the 250-km-square domain is 45 mm/yr. The fault is modeled with conventional “slippery” nodes and the model time (which matters for continuously accruing elastic stresses) is 20,000 years. Figure 2c shows the difference in velocities and slip rates when plasticity is added to this model. When the residual slip rates (Figure 2c) are added to those in Figure 2a, the rate is near uniform at 44 mm/yr. Hence, plasticity has a first-order influence on geologic slip rates, and when it is accounted for, higher and less variable slip rates result. Hence, fault bends and discontinuities may exert less influence on long-term slip rates than has been suggested based on purely elastic models with disconnected faults (Herbert et al., 2014). Stresses for the plastic model are shown on Figure 2d. Maximum shear stresses are of the order of 60 MPa, as expected given the plasticity model parameters.

Modified Slippery Nodes. My other approach was to modify the "slippery node" technique to allow (specified) non-zero shear tractions along the fault. This is analogous to modeling stress-driven creep, though with a spatially varying viscous or plastic rheology enforcing a specified, constant shear stress along the fault. Such models produce more "well-behaved" slip distributions, and the computations are very rapid (for elastic Earth models, no time stepping is needed). Though this approach makes sense for steady-state deformation models, it remains inappropriate for earthquake-cycle modeling because it does not allow for cyclic buildup and release of stresses at fault tips (and the time-dependent fault creep rates that result).

In my revised "slippery node" method, I allow a non-zero shear stress along the fault surface (i.e., on a plane tangent to the fault surface, acting in the direction opposing fault slip). This is accomplished by adding a term to the force vector in the along-slip degree-of-freedom direction (in rotated coordinates). For elastic models, the resulting slip rate distribution and surface velocities are essentially identical to those obtained with the (zero-traction) slippery node technique (i.e., Figure 2a), as long as a uniform traction value is specified. Residual shear stresses (Figure 2e) are time-invariant and clearly display a residual shear traction of 6 MPa along the modeled fault, acting in a sense that opposes left-lateral slip. This implementation may offer a way to directly invert absolute stress tensor data for fault tractions, though it is meant as a tool to indirectly model stress-driven fault creep. In the latter case, shear traction and slip rate would be used to infer rheological parameters such as friction coefficient or viscosity per unit width of the shear zone.

Monte-Carlo inversion for slip rates based on GPS misfit and strain energy minimization. I have re-implemented Monte Carlo (MC) sampling of fault slip rates and have my first kinematic model results for the southern California model (special case with uniform elastic plate, just the SAF segments switched on and fully unlocked). In this model, slippery nodes are placed between segments for which slip rates are sampled in the MC routine, in an effort to reduce the effects of sudden jumps in slip rates on the summed strain energy (for strain energy minimization, this can matter more than the segment slip rates themselves). The results are too preliminary to present here. I am currently attending seminar on Bayesian inference at the USGS and am planning to employ this technique in the near future. This work is funded by NEHRP but is connected to my SCEC activities: for example, stress rate estimates for the CSM will be informed by slip rates from my best kinematic model.

References

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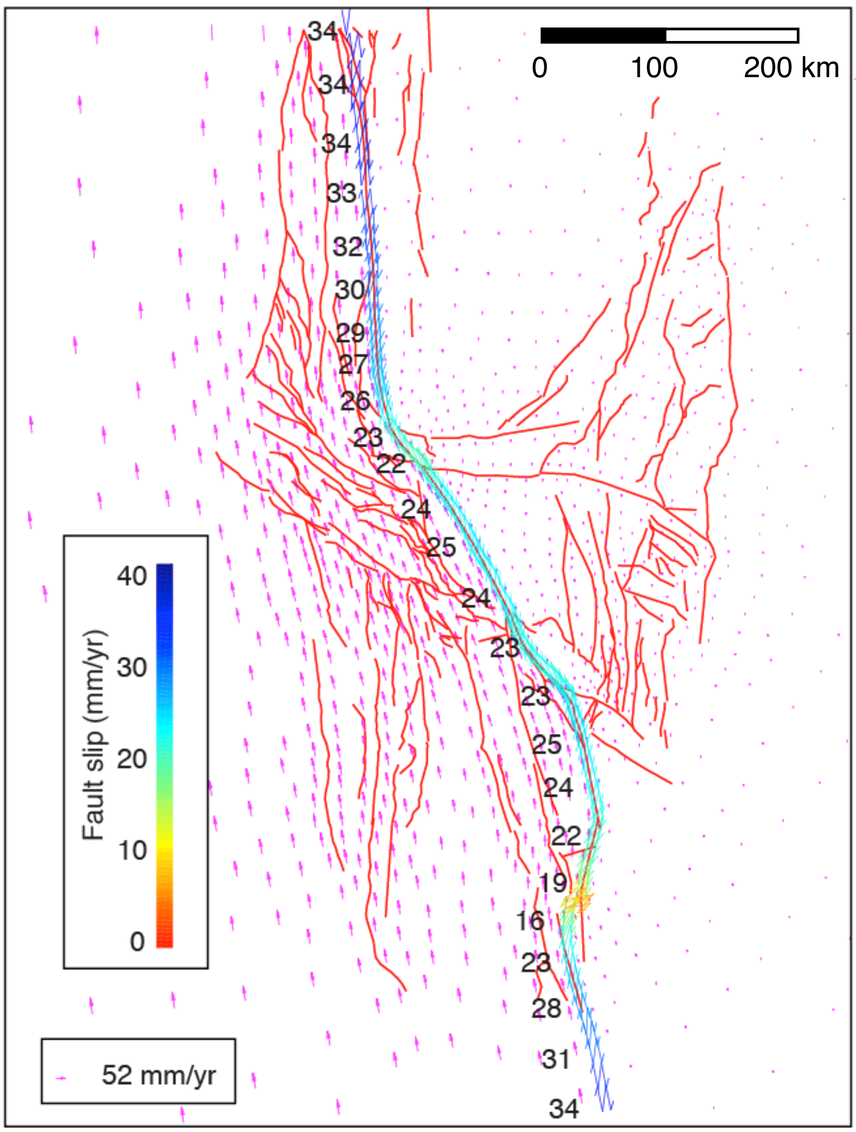
Exemplary Figure and caption for general audience

Figure 1. Modeled surface velocities (pink arrows) and long-term San Andreas Fault slip rates in southern California (numerals and colored symbols), from a simplified computational model. Relative motion of the Pacific and North American plates is prescribed at the boundaries of the model (which is much larger than the area shown). The relative plate motion is almost parallel to the sides of the figure, so where the San Andreas fault bends, its slip rate decreases as shown. After we add more faults and other model refinements, fitting the pink vectors to measured (GPS) surface velocities allows us to estimate long-term slip rates, which go into rupture forecasts.



Intellectual merit

Although several deformation modeling studies have targeted the southern California lithosphere, surprisingly few provide depth-dependent estimates of stresses, and address the dynamics of deformation throughout southern California. Given detailed GPS surface deformation data and compilations of fault geometries and slip rates, as well as new EarthScope constraints on the structure and properties of the lithosphere and asthenosphere, a comprehensive and detailed dynamic model of the region is overdue. I am developing a finite-element model to bridge the gap between this vision and the available, mostly fault-free dynamic models of the region. My phased approach involves developing both kinematic and dynamic models. Objectives include estimating stresses and stressing rates in the southern California lithosphere for the active tectonics and seismic hazard communities, reconciling geological and geodetic slip rates, and better understanding the mechanics of regional deformation and how much strain is accommodated away from known faults.

Broader Impacts

Absolute stresses in the lithosphere are used in earthquake forecasts, and are also key to understanding likely maximum rupture depths in large earthquakes, which may be pertinent to scaling relationships and moment balancing. Stressing rates on known faults and estimates of off-fault stress accumulation are both required for earthquake forecasts such as UCERF3, which lead to improved building codes and zoning, reducing casualties and economic losses. Modeled stresses and stressing rates will be shared by way of the SCEC Community Stress Model website (https://sceczero.usc.edu/projects/CSM), from which they may be downloaded by anyone.

Publications

No peer-reviewed SCEC publications during 2014.

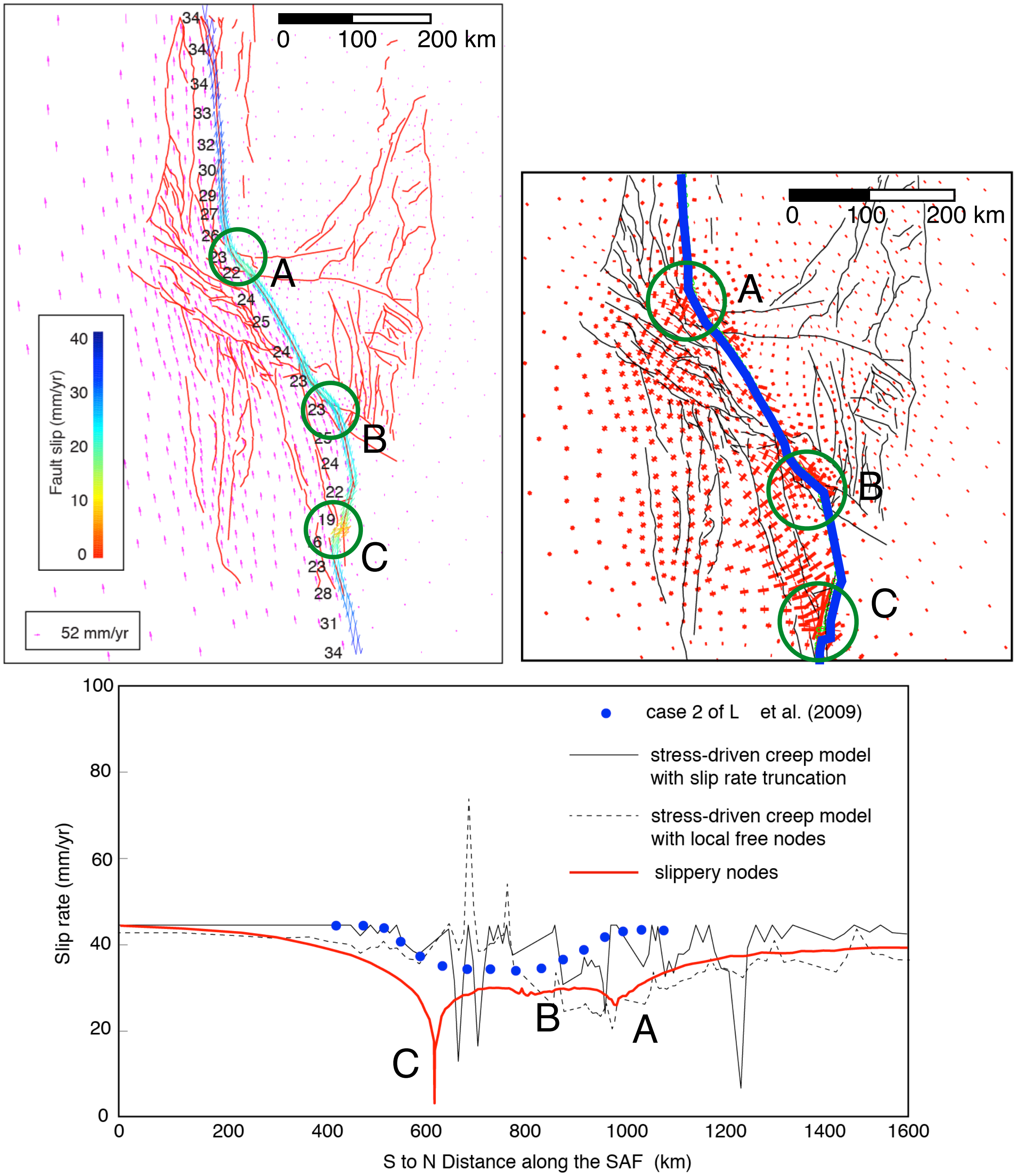
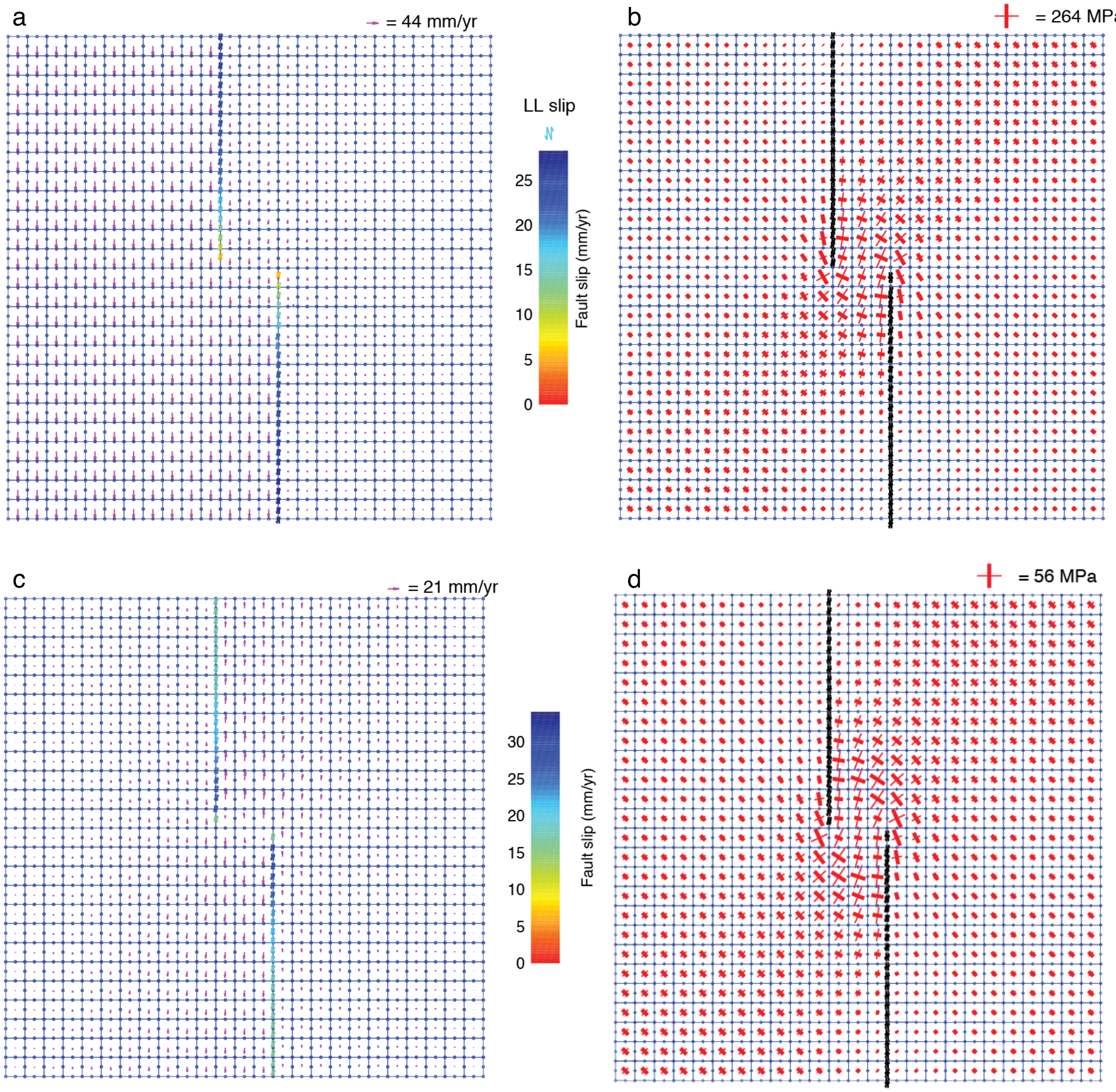


Figure 1. Top: Modeled slip rates and surface velocities (left), and principal stress axes at 5 km depth (right). Only the San Andreas Fault is slipping in this model, and it is treated as a viscous shear zone with a viscosity per unit width of 10^{15} Pa s /m (black dotted line on the bottom panel). Bottom: comparison of modeled slip rates using a variety of techniques. Local problems at A-C arise from fault kinks and discontinuities. Stress-driven slip models (black) require multiple iterations and slip rates do not converge. Slippery node slip rates (red) require just one computational step. These rates are somewhat lower than those of Li et al. (2009; blue dots) who use a simpler fault geometry and employ elastic-plastic rheologies for the SAF and its surroundings.



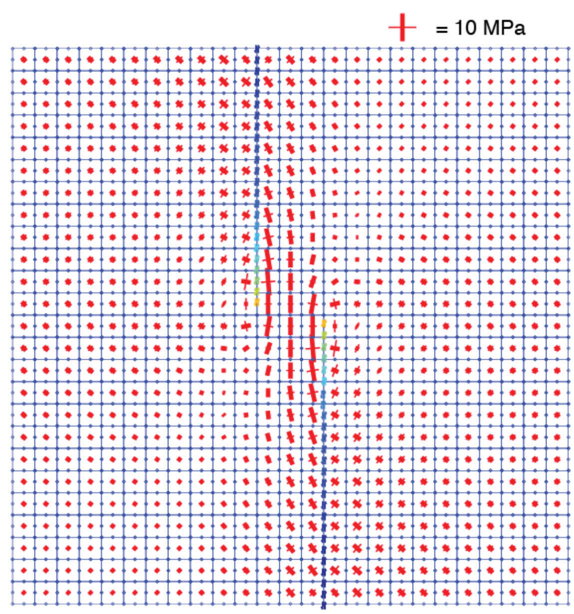


Figure 2. (a) Slip rates and surface velocities for slippery node faults in a uniform, linearly elastic Poissonian plate, with 45 mm/yr offset across the model. (b) Stresses for this model, at 20,000 model years. (c) Surface velocity and slip rate difference: plastic model minus elastic model. Slip rate near the fault tips tapers much less when plasticity is employed, so the difference is clearest in these locations. (d) Stresses for plastic model. These reach a steady state. (e) Stresses from elastic model with modified slippery nodes minus those from model with conventional slippery nodes. A shear traction of 6 MPa (rather than 0 MPa) is enforced along the fault. Model time is irrelevant (for e).