REALISTIC MODELS OF FAULT FRICTION AND CRUSTAL STRESS IN THE LOS ANGELES AREA

Award:	01HQGR0064
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Program Element:	Southern California

Research supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number 01HQGR0064. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

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ABSTRACT

The project focuses on constructing a three-dimensional dynamic model of the Earth's crust in a portion of the Los Angeles region. The overall goal is to develop a friction model that captures the behavior of the dynamic stresses during sliding on fault surfaces. A wide variety of seismological and geodetic observations provide constraints on the friction model. Additionally, the friction model should be consistent with the stress field that includes the effects of the variations in gravitational body forces due to sedimentary basins and topography. The friction model and stress in the crust will be used in future work to simulate earthquakes using dynamic ruptures.

The majority of the effort in this project centers on enhancing the simulation software and generating the 3-D finite-element model. Modeling rupture behavior in the complex tectonic environment of the Los Angeles region requires including the complex fault geometry. By localizing the fault orientation information, a limitation in the simulation software of using only a single, planar fault surface was removed. This allows the use of multiple, arbitrarily-oriented, nonplanar fault surfaces. With the goal of a self-consistent model we also added the ability to estimate the stresses present in the Earth's crust resulting from tectonic loading and the variations in the gravitational body forces associated with sedimentary basins and topography. Such calculations required adding a static solver and the appropriate boundary conditions to the simulation software.

The finite-element model is centered on the western portion of the Los Angeles area. It incorporates a region 110 km long, 100 km wide, and 40 km deep. The model includes the variations in the material properties as designated by the Southern California Earthquake Center (SCEC) Community Velocity Model and six of the major faults. In this first phase we idealize the fault surfaces defined by the California Geological Survey to planar surfaces. Additionally, this model does not include topography (the top of the model is flat with an elevation equal to sea level); a model with topography is being constructed, which will allow us to study what influence topography may have on the stress field. Using tetrahedral finite elements the volume is discretized to accurately capture wave propagation down to periods of 2.0 s.

We estimate the shear stresses generated by the presence of the lateral variations in the mass density by computing the perturbation in the stress field from the lithostatic stress state associated with a flat, laterally homogeneous (but depth dependent) Earth structure. The perturbations in the displacement field from the lithostatic stress state create upward bulges in the sedimentary basins and downward sinks in the areas with exposed bedrock. These deformations associated with the deepest portion of the Los Angeles basin create shear stresses approaching 10 MPa on dipping planes in the center of the basins and favor reverse faulting. This implies motion on the thrust faults in the central portion of the basin are aided by the gravitational body forces.

NON-TECHNICAL SUMMARY

The project focuses on constructing a three-dimensional model of a portion of the Los Angeles region. The overall goal is to develop a model of friction on faults that captures the behavior of the sliding during earthquakes. A wide variety of observations provide constraints on the friction model. The friction model will be used in future earthquake simulations. Modeling earthquake ruptures in the complicated tectonic environment of the Los Angeles region requires including the complex fault geometry. By localizing the fault orientation information, we extend the software's capabilities to include multiple, arbitrarily-oriented, nonplanar fault surfaces. The finite-element model is centered on the western portion of the Los Angeles area. It incorporates a region 110 km long, 100 km wide, and 40 km deep. The model includes the variations in the material properties, such as the soft sediments of the Los Angeles and San Fernando basins. As part of determining the stress state in the Earth, which is an initial condition in the model, we estimate the shear stresses generated by the presence of the lateral variations in the mass density. We find that the motion on the blind thrust faults underneath the Los Angeles basin, such as the Elysian Park fault, are aided by the lateral variation of the gravitational body forces associated with the deep sedimentary basin.

SIMULATION SOFTWARE ENHANCEMENTS

In previous work the simulation software used uniform normal and tangential directions to define the orientation of the fault surface. By localizing these directions to each finite-element node on the fault surface, the orientation of the dislocations along the fault surface may change arbitrarily. This also permits the existence of multiple fault surfaces. The fault surfaces must still be present in the model geometry in order to prevent elements from straddling the fault. Whereas the methodology does not limit the curvature of the fault surface, the curvature is limited by the discretization size in much the same fashion as the minimum period of the propagating waves.

Finding a realistic model of the dynamic sliding friction within a self-consistent model of crustal stress requires an estimation of the background stress field. If we assume the background stress field can be broken into relatively independent components, then we can construct an estimation of the stress field by determining each of the components and superimposing the solutions. Three of these components are the stresses due to gravitational body forces, the stresses due to deformation of the boundaries, which are associated with tectonic motion, and the stresses due to static dislocations on fault surfaces. All three can be computed by solving the static elasticity equation,

$$\tau_{ij,j} - \rho g \delta_{i3} = 0$$
$$\tau_{ij} = \lambda \varepsilon_{kk} \delta_{ij} + 2\mu \varepsilon_{ij},$$

where τ is the stress tensor, ρ is the mass density, g is the acceleration due to gravity, ε is the strain tensor, and λ and μ are Lame's constants. The finite-element method converts this differential equation into a simple matrix equation,

$$[K]\{u\} = \{f\}, \tag{1}$$

where $[K]$ is the stiffness matrix, $\{u\}$ is the vector of global displacements, and $\{f\}$ is the vector of global externally applied forces. Solving the matrix equation efficiently with parallel processing generally requires an iterative method. We employ the preconditioned conjugate gradient method using the inverse of the diagonal of the stiffness matrix as the preconditioner. Any combination of the displacement components of the lateral sides and bottom of the domain can be used as boundary conditions.

CONSTRUCTION OF FINITE-ELEMENT MODEL

The domain encompasses a large portion of the Los Angeles region as shown in figure 1. The domain runs from just north of the San Andreas fault to the tip of the Palos Verdes Peninsula and from Simi Valley to Diamond Bar. The geologic features of this domain include the the San Gabriel Mountains, the San Fernando basin, and the deeper portions of the Los Angeles basin. The major faults that fall within the boundaries and which we include in the model are the San Andreas fault, the Santa Monica fault, the Hollywood fault, the Raymond fault, the Sierra Madre fault, the Elysian Park fault, the Newport-Inglewood fault, and the Northridge thrust fault (Pico fault). With only small variations in strike along the Santa Monica, Hollywood, and Raymond faults, we approximate the fault surfaces with a single planar fault.

Maintaining accuracy in the solution across the entire domain while minimizing the number of degrees of freedom in the problem requires varying the size of the tetrahedral finite elements with the shear-wave speed. With the complex geologic structure of our domain this is not a trivial task. Because the mesh generation software we use (I-DEAS) only allows control of the element size using the geometry in the solid model (geometric description of the domain), we imported shear-wave speed isosurfaces extracted from the SCEC Community Velocity Model into the mesh generation software. In order for the mesh to honor the fault surfaces, we also incorporated the geometry of the planar fault surfaces. With these features in place (see figure 2), I-DEAS produces the finite-element mesh shown in figure 3.

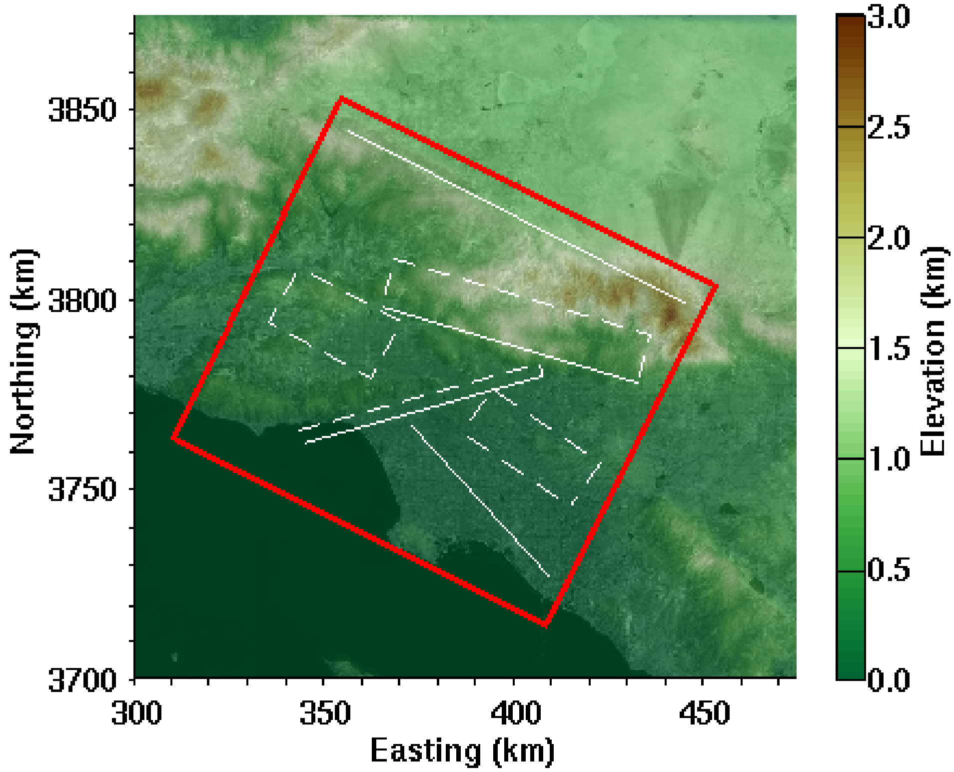

Figure 1: Location of model domain. The domain stretches from Simi Valley to Diamond Bar and from the Palos Verdes Peninsula to ten kilometers north of the San Andreas fault. The model includes six of the major faults in the region: the San Andreas fault, the Sierra Madre fault, the Newport-Inglewood fault, the Elysian Park fault, the Pico fault, and the Santa Monica, Hollywood, and Raymond faults modeled as a single fault.

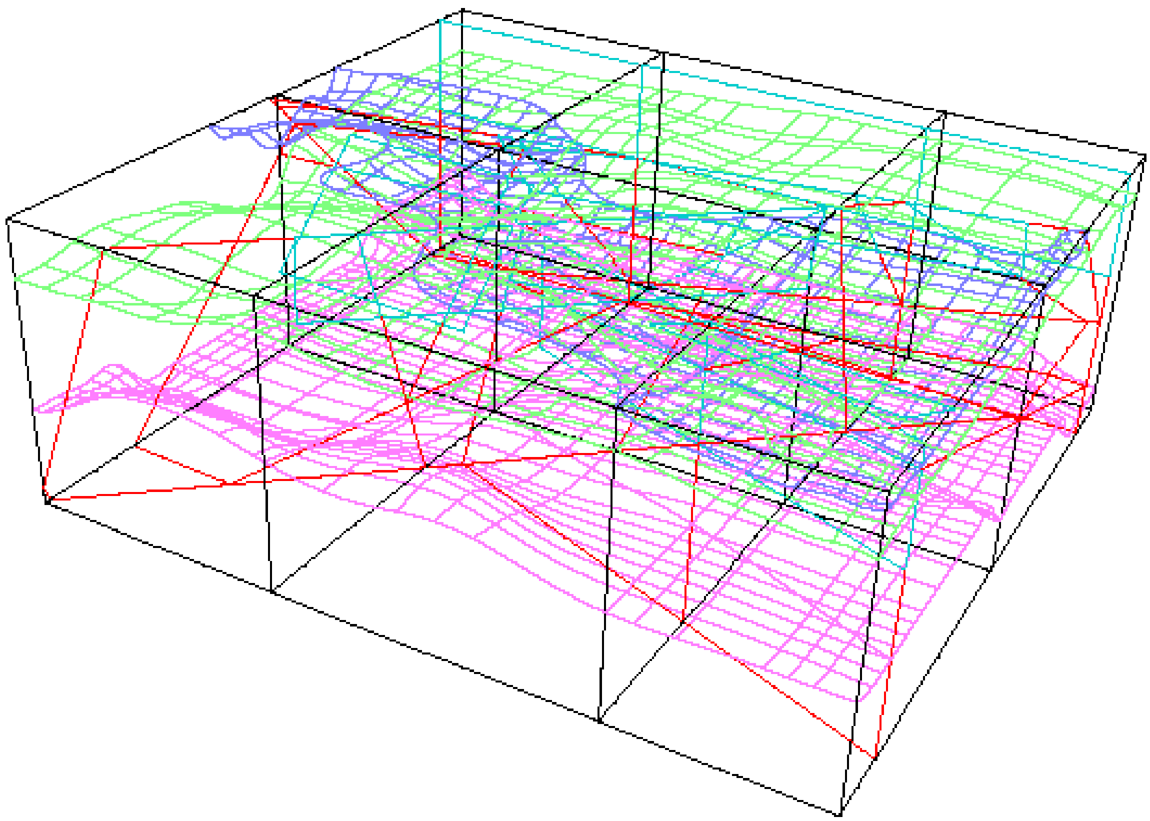

Figure 2: Perspective view from the southeast of the solid model geometry of the finite-element domain. The geometry includes four shear-wave speed isosurfaces (magenta, green, and blue surfaces) extracted from the Southern California Earthquake Center (SCEC) Community Velocity Model and the six fault planes (light blue) along with their extensions (red).

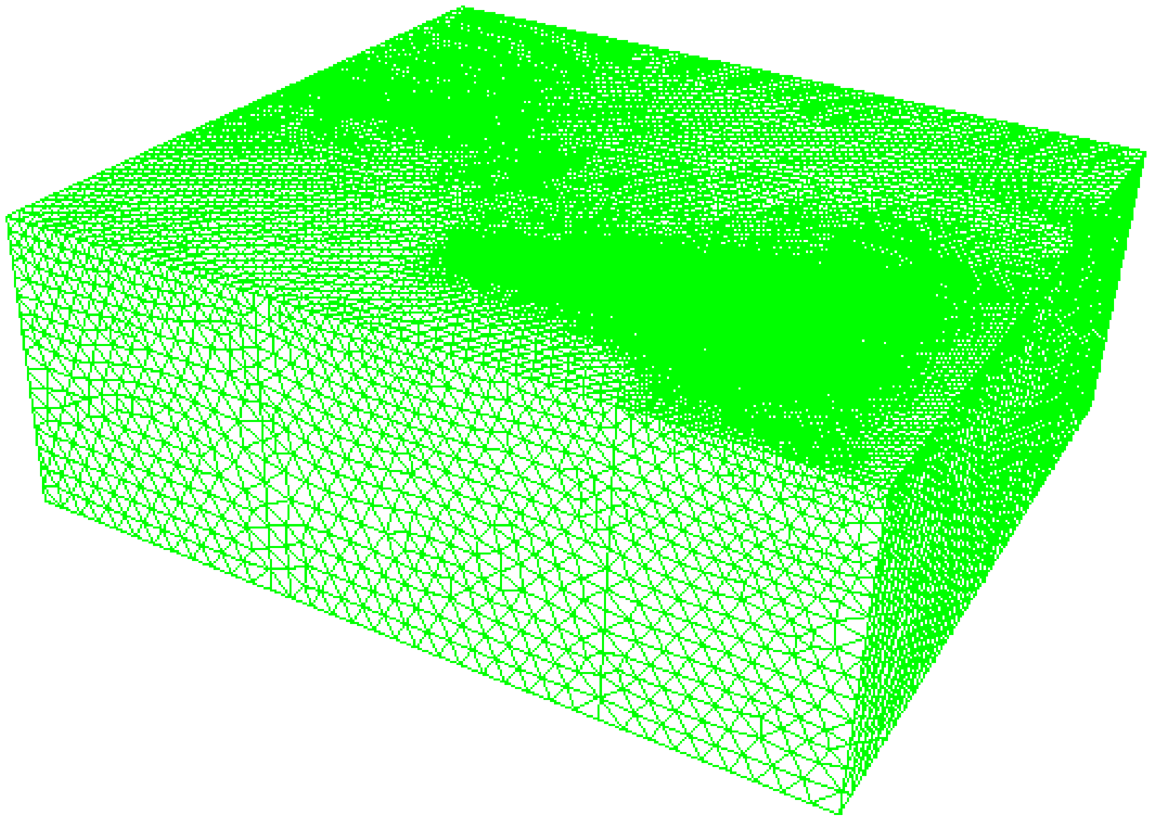

Figure 3: Perspective view from the southeast of the finite-element model at a coarse resolution. The full resolution model uses a node spacing that is one fourth that of the model shown. The node spacing and element size vary according to the shear-wave speed.

SHEAR STRESSES GENERATED BY 3-D GEOLOGIC STRUCTURE

We estimate the magnitude and orientation of the stresses present from the variations in the gravitational body forces associated with the lateral variations in mass density by computing the perturbation in the stress field from the lithostatic stress state associated with a flat, laterally homogeneous (but depth dependent) Earth structure. This means that we assume gravitational body forces only generate shear stresses in regions with lateral variations in the mass density. In regions where the mass density matches the 1-D (depth dependent) average, the shear stresses are zero and the the axial stresses are equal to the overburden (lithostatic) pressure. In Cartesian coordinates the reference stress field is given by

$$\tau_{xx} = \tau_{yy} = \tau_{zz} = \int_0^z \rho(s) g \, ds$$
$$\tau_{xy} = \tau_{yz} = \tau_{xz} = 0.$$

The elastic perturbation follows

$$\tau_{ij,j} - (\rho(x,y,z) - \rho(z)) g \delta_{i3} = 0$$
$$\tau_{ij} = \lambda \varepsilon_{kk} \delta_{ij} + 2\mu \varepsilon_{ij},$$

where $\rho(z)$ is the horizontal average of the mass density.

The perturbations in the displacement field, which are displayed in figure 4, create upward bulges in the sedimentary basins (lighter than average material) and sinks in the areas with exposed bedrock (heavier than average material). Relative to the 1-D average, the overburden pressure is less in areas that bulge upwards and more in areas that sink downwards. These bulges and sinks generate shear stresses. Figure 5 shows the magnitude and orientation of the conjugate planes of the maximum shear stresses. The largest shear stresses occur underneath the central portion of the Los Angeles basin and are compatible with thrust motion. A profile across the basin from the Los Angeles Harbor to Pearblossom (figure 6) illustrates these trends. This suggests that the motion on the blind thrust faults underneath the Los Angeles basin, such as the Elysian Park fault, are aided by the lateral variation of the gravitational body forces associated with the deep sedimentary basin.

PUBLICATIONS

Aagaard, B. T. and T. H. Heaton (2002a, September). A fault friction driven model of crustal stress in the Los Angeles region. In *Annual Meeting Abstracts*, Oxnard, California. Southern California Earthquake Center.

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Aagaard, B. T., T. H. Heaton, and J. F. Hall (2001, September). A fault friction driven model of crustal stress in the Los Angeles region. In *Annual Meeting Abstracts*, Oxnard, California. Southern California Earthquake Center.

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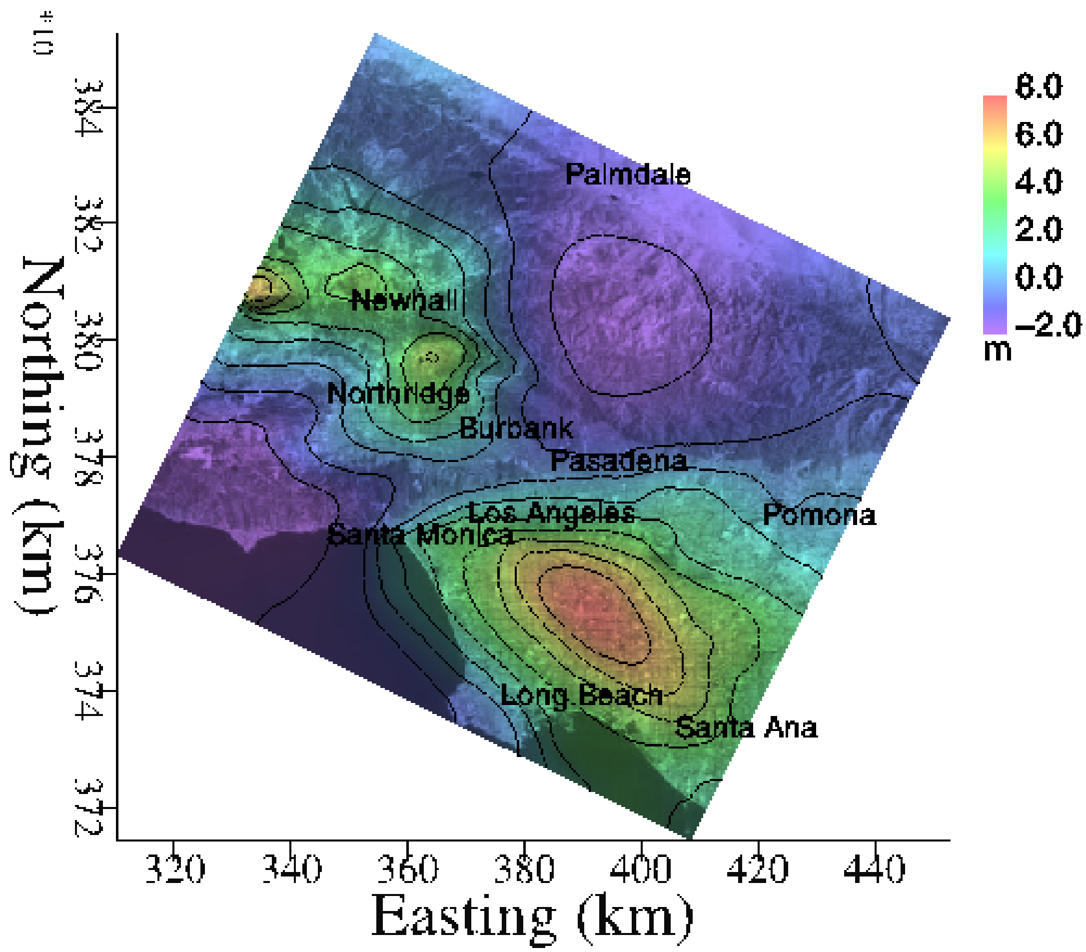

Figure 4: Perturbations in the displacement field from the 1-D model in a lithostatic stress state create upward bulges in the sedimentary basins (lighter than average material) and sinks in the areas with exposed bedrock (heavier than average material). The color scale and contours show the vertical component of the displacement perturbations. The contour interval is 1 m.

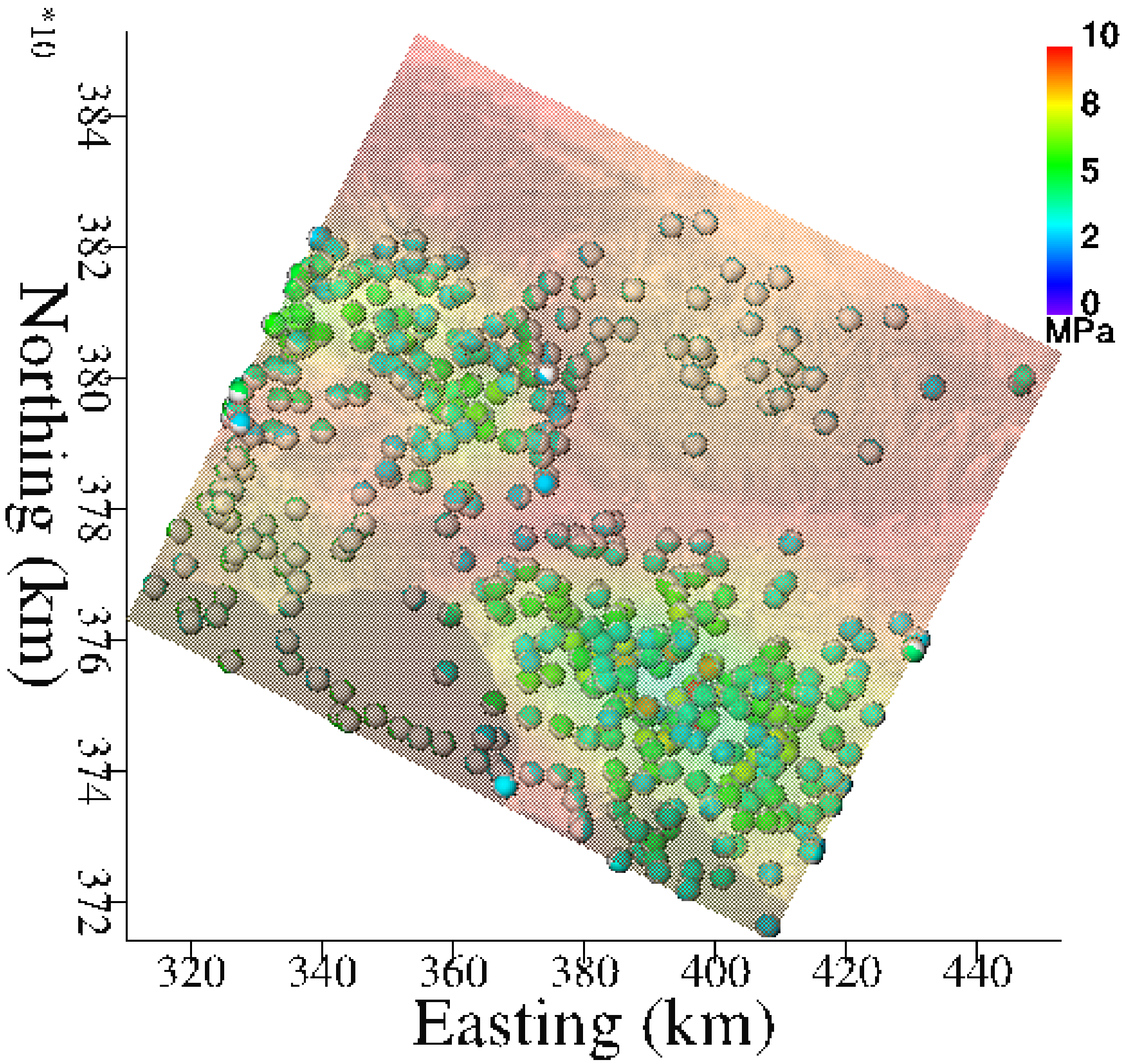

Figure 5: Maximum shear stresses above 3 MPa plotted as focal spheres. The color scale shows the magnitude and the orientation gives the planes on which the maximum shear stress occurs. The lateral variations in the gravitational body forces create shear stresses of around 10 MPa aiding thrust motion in the Los Angeles basin.

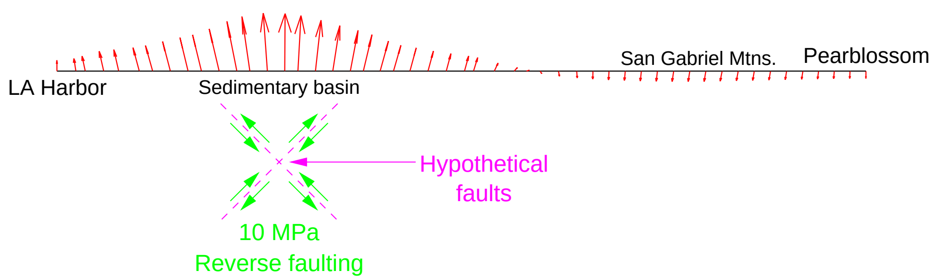

Figure 6: Displacement perturbation (top) and shear stresses on hypothetical faults (bottom) on a profile through the model from the Los Angeles Harbor to Pearblossom. These deformations create shear stresses approaching 10 MPa on dipping planes in the middle of the basin and favor reverse faulting. On the other hand, the deformations generate shear stresses of less than about 3 MPa on dipping planes below the San Gabriel Mountains and favor normal faulting. Because the mountains are not present in this model, we anticipate we will find significantly larger normal faulting shear stresses when we create the finite-element model that includes topography.