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Poroelastic Coupling Between the 1992 Landers and Big Bear Earthquakes

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Abstract. A three-dimensional finite element model was constructed to investigate the significance of poroelastic coupling between the 1992 Landers and Big Bear earthquakes in southern California. The homogeneous poroelastic model predicted a maximum increase in left lateral slip potential (change in shear stress less the change in effective fault normal stress scaled by a coefficient of friction) along the southwest part of the Big Bear fault, consistent with the epicentral location. In contrast, slip potential calculated for a weak fault zone in a state of isotropic stress for drained conditions, indicated a maximum increase along the northeast part of the Big Bear fault.

Introduction

Rupture associated with the June 28, 1992 Landers, California earthquake (M_w=7.3) occurred along five major and several minor fault segments in a region known as the Eastern California Shear Zone. The dislocation was primarily right lateral strike-slip, with up to six meters of offset observed along the 85-kilometer surface trace of the rupture. The Landers earthquake was followed three hours later by the M_w=6.1 Big Bear earthquake (Figure 1). The purpose of this study is to investigate the hypothesis that the temporal relationship is due to poroelastic coupling. The change in slip potential is compared for the assumptions of a homogeneous poroelastic fault region versus a weak one in which the state of isotropic stress exists. *Simpson and Reasenberg* [1994] classified three sets of model assumptions, all based on the Coulomb failure criteria. These are (1) homogeneous poroelastic fault zone, (2) undrained weak fault zone, and (3) drained weak fault zone.

Quasi-Static Slip Potential

Frictional slip occurs along a fault when shear stress overcomes frictional strength. The change in quasi-static slip potential quantifies the change in the tendency for frictional slip to occur along a fault due to an applied stress field with respect to some reference state. For this study, the reference state occurs an instant before the Landers rupture.

Homogeneous Poroelastic Formulation

Poroelastic theory allows us to calculate the quasi-static change in slip potential when pore pressure effects are present. The change in slip potential based on a Coulomb failure relationship is given by

$$\Delta S = \Delta\sigma_S + f(\Delta\sigma_n + \Delta P) \tag{1}$$

where S is the slip potential, σ_S is the shear stress aligned with a given slip vector, σ_n is fault normal stress (compression is negative), P is pore pressure, and f is the coefficient of friction. The coefficient of friction ranges between 0.6 and 0.85 [*Byerlee*, 1978]. Equation 1 is a precisely defined relationship among poroelastic state variables and coefficient of friction, and generally valid for transient fluid flow conditions.

For undrained conditions, changes in pore pressure are proportional to changes in mean normal stress

$$\Delta P = -B(\Delta\overline{\sigma}) \tag{2}$$

where $\overline{\sigma}$ is the mean normal stress and B is the pore pressure buildup coefficient, also known as Skempton's coefficient [*Wang*, 1993]. Therefore, another expression for change in slip potential combining Equations 1 and 2 is

$$\Delta S = \Delta\sigma_S + f\left[\Delta\sigma_n - B(\Delta\overline{\sigma})\right] \tag{3}$$

This expression is only valid for undrained conditions, such as immediately following an earthquake.

Undrained Weak Fault Formulation

A modification of Equation 3, termed the "Rice Model" by *Simpson and Reasenberg* [1994], was based on an heuristic model developed to account for the apparent frictional weakness of the San Andreas Fault zone within which stress is isotropic. In that case, fault normal stress is equal to the mean normal stress ($\sigma_n = \overline{\sigma}$) [*Rice*, 1992]. Slip potential can then be expressed in terms of shear stress and fault normal stress scaled by an apparent coefficient of friction (f').

$$\Delta S = \Delta\sigma_S + f'(\Delta\sigma_n) \tag{4}$$

where $f' = f\ (\ 1 - B\ )$. This model requires three assumptions. First of all, undrained conditions are implied. Secondly, the existence of a weak fault zone with no shear strength such that strain is restricted to simple shear (no volumetric strain) is required. Finally, either plastic deformation of the fault zone is instantaneous or a loading time dependence exists such that either the loading rate is slow or the time since a loading event is long while maintaining undrained conditions.

Drained Weak Fault Formulation

Because the model presented by *Rice* [1992] was not developed for quasi-static slip potential, the above assumptions are not generally applicable to poroelastic coupling between earthquakes [*Cocco and Rice*, 1999; *Masterlark*, 2000]. However, overlooking the limitations of Equation 4 leads to an expression for the change in slip potential in terms of an apparent coefficient of friction and state variables calculated with drained elastic constants, where $f' = f\ (\ 1 - B'\ )$. The

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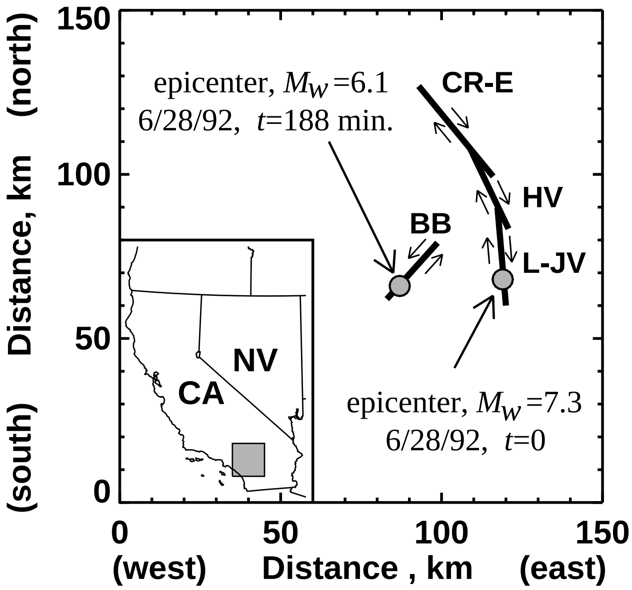

Figure 1. Site Location, 1992 Landers, California Earthquake. The fault trace of the rupture was simplified to include three fault segments designated Camp Rock-Emerson (CR-E), Homestead Valley (HV), and Landers-Johnson Valley (L-JV). The dislocation was primarily right-lateral strike-slip, with up to six meters of offset observed along the 85-kilometer surface trace of the rupture. Left-lateral rupture along the Big Bear (BB) fault occurred 188 minutes later. Although several slip distribution models have been proposed for the Big Bear event, we assume a single 23-kilometer fault striking northeast with an epicenter located seven kilometers from the southwest end.

parameter B' is some phenomenological combination of material properties and transient flow conditions; however this formulation is truly drained only when $B' = 0$. Despite its ambiguities, the drained weak fault formulation has become commonplace in slip potential analyses [*Harris*, 1998].

Landers Model

A finite element model constructed with *ABAQUS* was used to investigate the change in quasi-static slip potential along the Big Bear fault due to the stress field caused by the Landers rupture. *ABAQUS* is capable of solving the fully coupled, transient poroelastic governing equations [*Biot*, 1941]. Spatial dependence of slip potential was determined for each of the three formulations.

The finite element model consisted of two 15-kilometer thick layers in which a fully-coupled poroelastic upper crust overlies a viscoelastic lower crust layer. The upper mantle was implicitly modeled via the boundary conditions as an infinitely thick viscoelastic layer decoupled from the overlying lower crust [*Kohlstedt et al.*, 1995]. The model configuration is shown in Figure 2. The problem domain was discretized into three-dimensional isotropic brick elements. Poroelastic and drained elastic material properties for Westerly Granite (B=0.85) [*Rice and Cleary*, 1976] were used in the upper crust and lower crust layers respectively. The lower crust viscosity was $5{\times}10^{18}$ Pa·s and the hydraulic diffusivity was 10^{-2} m^2·s^{-1} in the poroelastic layer [*Masterlark*, 2000].

The model domain in a horizontal plane was separated into three regions. The fault trace was bounded for 200 meters on either side by fault zone elements [*Johnson et al.*, 1997]. The near-field region surrounding the fault zone consisted of elements measuring one kilometer per side. This region measured 80 kilometers (east-west) and 100 kilometers (north-south). The far-field region extended the horizontal problem domain to 600 kilometers per side. Elements in this zone gradually increased in size by a factor of 1.2 with distance from the near-field region. A third region bounded the far-field region with infinite elements. These elements simulate an exponential decay to zero displacement at infinity.

Specified displacements were applied to fault element nodes to simulate the 1992 Landers coseismic slip distribution [*Wald and Heaton*, 1994]. The upper surface was an elastic free surface with zero–excess fluid pressure, while lateral boundaries were zero–displacement with zero–excess fluid pressure. The bottom of the poroelastic layer was a no fluid flow boundary. The bottom of the lower crust was given a vertical stiffness based on the material properties of the upper mantle [*Turcotte and Schubert*, 1982]. Solutions for the change in slip potential for a depth of 6.25 kilometers [*Wald and Heaton*, 1994] along the Big Bear fault were determined after a time step of 188 minutes following the Landers coseismic displacement. Because this time step is relatively short compared to the lower crust viscosity and

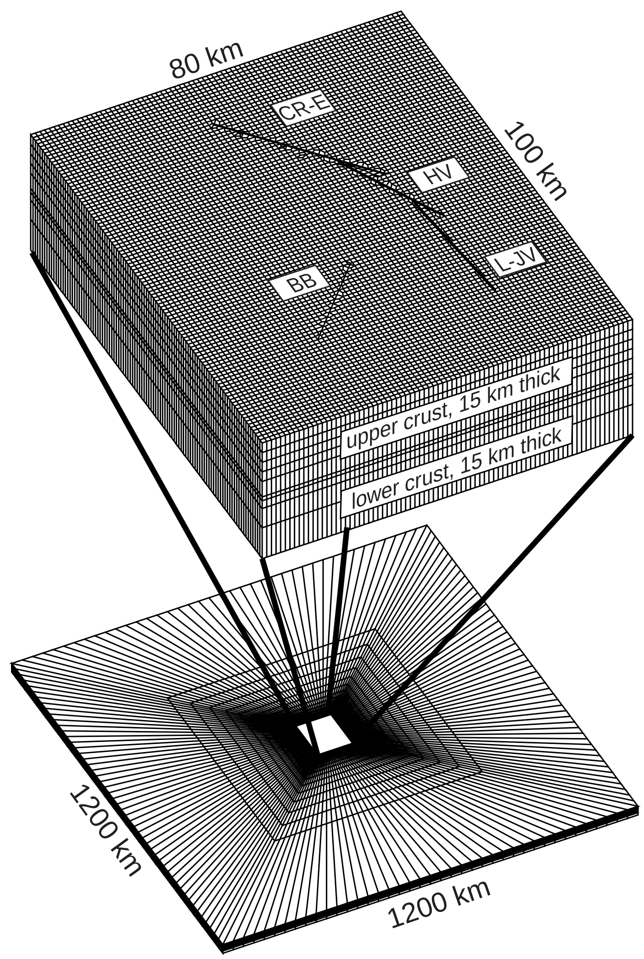

Figure 2. Finite Element Model. The three-dimensional problem domain consists of 109,135 first order elements separated into six layers of poroelastic upper crust elements overlying three layers of viscoelastic lower crust layers.

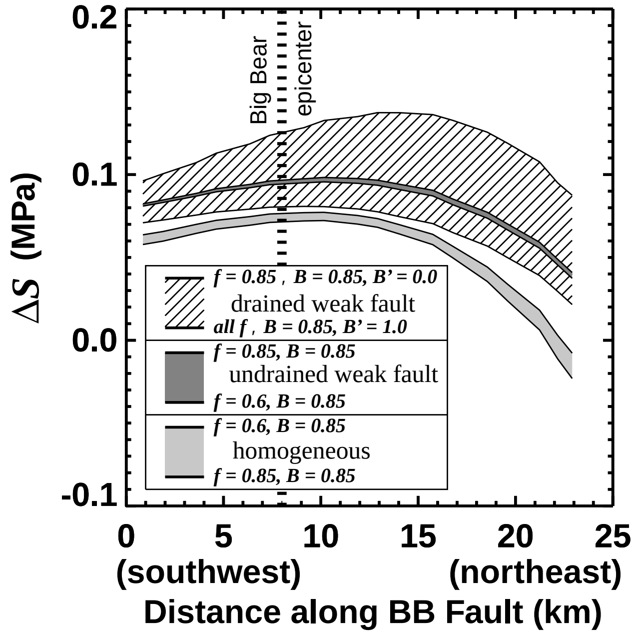

Figure 3. Range of Solutions. Results for each solution method were determined over the frictional range $0.6 \leq f \leq 0.85$. The maximum homogeneous poroelastic solution is most consistent with the location of the epicenter. The weak fault zone solutions do not overlap the homogeneous poroelastic solution. The wide range of possible drained weak fault zone solutions is due to the ambiguity of the parameter B'.

upper crust hydraulic diffusivity time constants, the homogeneous poroelastic transient results closely approximated undrained conditions.

Results

The numerical model generally predicts an increase in slip potential ($\Delta S > 0$) along the entire Big Bear fault zone for the homogeneous poroelastic and both weak fault solutions. Solutions were determined over the frictional range $0.6 \leq f \leq 0.85$ and the parameter B' was allowed to vary between 0.0 and 1.0 as discussed in the drained weak fault zone formulation. A comparison of results is shown in Figure 3.

The model predicts a maximum change in homogeneous poroelastic slip potential in the southwest half of the fault segment. This is consistent with the location of the epicenter (Figures 1 and 3). The weak fault zone slip potential solution maxima are generally less consistent with the epicentral location than the homogeneous poroelastic solution. Furthermore, the drained weak fault zone slip potential solutions are greatest in the northeast half of the fault segment. Thus, the homogenous solution provides better agreement with the observed epicentral location. Both the homogeneous poroelastic and undrained weak fault zone model solutions are much more precise, based on their much narrower ranges, than that of the drained weak fault solution. The wide range of possible drained weak fault solutions can be attributed to the ambiguity associated with the parameter B'.

Because neither weak fault zone solution overlaps with the homogeneous poroelastic solution, the weak fault zone solutions are unable to accurately predict the undrained results for a homogeneous poroelastic model. The reason for this can be seen if the state variable components from each solution method are separated (Figure 4). The shear stress change increase ($\Delta\sigma_S$) is greatest along the southwest portion of the Big Bear fault. The normal stress change ($\Delta\sigma_n$) is less compressive over the entire fault, and it

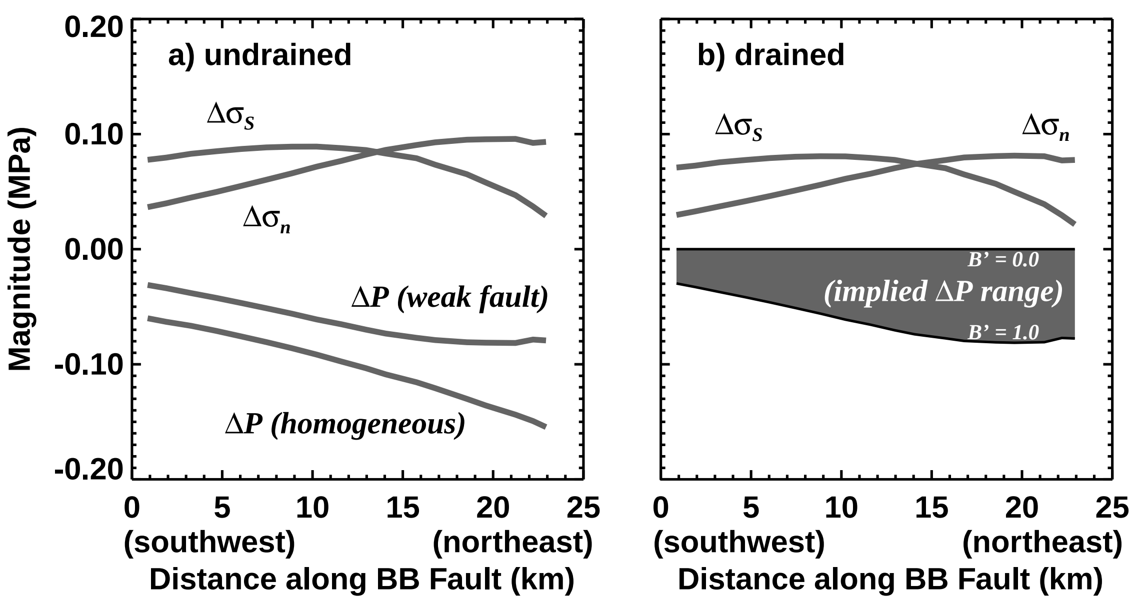

Figure 4. Stress and Pore Pressure Profiles Along the Big Bear Fault. (a) The homogeneous poroelastic and undrained weak fault zone solutions share the same state of stress. However, the magnitude of the homogeneous poroelastic pore pressure decrease is greater than the fault normal stress, therefore the slip potential is significantly smaller compared to the undrained weak fault zone solution. (b) The homogeneous poroelastic pore pressure lies outside of the range implicitly assumed by the drained weak fault zone formulation. For both weak fault zone formulations, the apparent coefficient of friction would have to be less than zero, a nonphysical result.

is increasingly less compressive from the southwest to the northeast. Because $\Delta P = -B(\Delta\sigma_n)$ for the undrained weak fault, the pore pressure change is negative. The undrained pore pressure change for the homogeneous case is significantly more negative, although it shows the same decreasing southwest to northeast trend. For the drained, weak fault assumptions (Equation 4), the implied pore pressure change is $\Delta P = -B'\Delta\sigma_n$, which is shown in Figure 4(b) for the range $0 \leq B' \leq 1$. The magnitude of the weak fault pore pressure change is limited by the fault normal stress. In order to match the homogeneous poroelastic pore pressure changes, the value of the apparent friction coefficient f' must be negative, a nonphysical implication.

Conclusions

A homogeneous poroelastic model of the 1992 Landers dislocation and slip potential based on the Coulomb friction criterion predicted the epicenter of the Big Bear earthquake. For the same dislocation model, slip potentials computed under a weak fault zone assumption for both undrained and drained cases give spatial results that are generally less consistent with the Big Bear earthquake epicenter. Because frictional strength may be sensitive to changes in slip potential as small as 0.1 MPa, our results suggest that differences between the homogeneous poroelastic model and the weak fault models are significant.

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