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Reply to comment by Y. Fialko on "Deformation of compliant fault zones induced by nearby earthquakes: Theoretical investigations in two dimensions"

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1. Introduction

[1] Fault zone structure and properties may contain important information about past earthquake rupture and subsequent healing processes. Damaged fault zones are observed geologically in the field [e.g., *Chester and Chester*, 1998; *Ben-Zion and Sammis*, 2003]. Seismic studies have revealed the existence of low-velocity fault zones around active faults [e.g., *Li et al.*, 1998; *Ben-Zion et al.*, 2003]. Compliant fault zones are inferred from InSAR observations of the displacement field of recent earthquakes [e.g., *Fialko et al.*, 2002; *Fialko*, 2004]. However, the width and depth extent of fault zones are still under debate in the community.

[2] *Duan et al.* [2011] conduct detailed theoretical investigations of the response of compliant fault zones to nearby earthquakes using spontaneous rupture models with off-fault elastoplastic rheology in a 2-D plane-strain framework, built upon an earlier study by *Duan* [2010]. They call for a reexamination of existing observations, based on possible constraints on the in situ stress state by the inelastic response of compliant fault zones revealed by their theoretical studies, and possible deficiencies in previous studies in deducing the structure and properties of compliant fault zones. *Fialko* [2011] (hereafter referred to as Fialko11) provides a comment to *Duan et al.* [2011] and refutes the call. Although primarily defending the previous studies [*Fialko et al.*, 2002; *Fialko*, 2004] which considered only the elastic response of compliant fault zones to static stress changes, Fialko11 also downplays significance of the possible inelastic response of compliant fault zones to dynamic stress changes. I will first discuss significance of both the previous studies on elastic response to static stress changes and the recent studies on inelastic response to nearby ruptures. Then I will reply in some details to the comments made by Fialko11.

2. Significance of the Response of Compliant Fault Zones to Nearby Earthquakes

[3] It was significant to recognize that the localized deformation in the InSAR images around the preexisting faults in the Mojave Desert after the 1999 Hector Mine earthquake represents the response of the compliant fault zones to the event [*Fialko et al.*, 2002]. The elastic inhomogeneity model [*Fialko et al.*, 2002] better explains retrograde horizontal motion (i.e., opposite to the long-term slip direction) and vertical displacements across some portions of the faults, compared with other hypotheses such as triggered slip. Furthermore, the model builds a foundation for InSAR images to be used to constrain the structure and properties of fault zones.

[4] Compliant, low-velocity, damaged fault zones are likely weaker than host rocks and are thus more responsive to stress changes induced by nearby earthquakes. The elastic inhomogeneity model only considers the linearly elastic response of fault zones to static stress changes. However, an observation that the healing process of the Johnson Valley Fault (JVF) was interrupted by the 1999 Hector Mine earthquake strongly suggests the response of compliant fault zones may be well beyond linear elasticity and dynamic stress changes may play an important role [*Vidale and Li*, 2003]. *Duan* [2010] and *Duan et al.* [2011] are motivated by this observation. From a theoretical point of view, they explore conditions and consequences of the inelastic response of compliant fault zones using dynamic rupture models with off-fault elastoplastic rheology. They find that when the preevent stress state of a fault zone is close to the strength of the fault zone, inelastic response to a nearby rupture (e.g., ~10 km away) can occur along portions of the fault zone that experience dilatational stress changes, while the rest of the fault zone may still respond to the rupture elastically. Furthermore, in a roughly parallel strike-slip fault system, inelastic response results in sympathetic motion (i.e., consistent with the long-term slip direction) across the fault zone, while elastic response gives rise to retrograde motion. These findings do not invalidate the elastic inhomogeneity model, which explains retrograde motion very well. Instead, the findings from the recent theoretical studies complement the elastic inhomogeneity model. In particular, the condition for inelastic response to occur may allow us to constrain the in situ stress in the crust, as the fault zone rock strength may be measured in the lab. The compliant fault zone model should include both elastic and inelastic response of fault zones.

[5] Fialko11 argues in section 1 that *Duan et al.* [2011] compared effects of plastic yielding of fault zones to predictions of the elastic inhomogeneity model. This is not the

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case. As discussed in detail by *Duan* [2010] and *Duan et al.* [2011], elastic and inelastic response can be concurrent along a compliant fault zone, but on different segments along strike. *Duan et al.* [2011] did not attempt to make that comparison, though they pointed out that the elastic inhomogeneity model does not apply to the portions of fault zones that experience inelastic strain, which appears self-evident.

[6] In section 2, Fialko11 defends the elastic inhomogeneity model by downplaying inelastic response of compliant fault zones. As discussed above, our view is that the elastic inhomogeneity model proposed by *Fialko et al.* [2002] and the inelastic response revealed by *Duan* [2010] and *Duan et al.* [2011] are two complementary aspects of a more complete version of the compliant fault zone model. Although the preevent stress state and the fault zone strength are poorly constrained, the observation by *Vidale and Li* [2003] strongly suggests that the response of the JVF zone to the 1999 Hector Mine earthquake is well beyond linear elasticity and may be characterized as inelastic. Some of other portions of the Landers fault zone may still respond to the 1999 Hector Mine event elastically, resulting in left-lateral motion on right-lateral faults, which can be well explained by the elastic inhomogeneity model. With this more complete view of the response of compliant fault zones to nearby ruptures, reexamination of the InSAR observations from the 1999 Hector Mine and 1992 Landers earthquakes may provide us with new insights into the structure, properties, and even the preevent stress state of the fault zones.

3. Concerns and Possible Deficiencies in Previous InSAR Studies

[7] *Duan et al.* [2011] discussed some concerns and possible deficiencies in previous InSAR studies. Fialko11 refutes them point by point. Before I reply to these comments, I emphasize that the discussion of these concerns and possible deficiencies does not intend to reduce significance of the previous InSAR studies. Rather, it intends to make future estimations of the structure and properties of compliant fault zones from InSAR observations more accurate.

[8] The first point is a concern about the scheme in estimating the width of fault zones by the width of anomalous displacements in the previous InSAR studies. The concern is a logical outcome of the match between the width of anomalous displacements and the prescribed width of fault zones in the 2-D models of *Duan et al.* [2011], because the 2-D models assume the depth extent of a fault zone is infinite, while in reality (3-D) it is finite. Fialko11 points out that the width of anomalous horizontal displacements derived from two look directions by *Fialko et al.* [2002] is a good proxy for the width of a fault zone. This may be valid for a compliant fault zone with a uniform width along depth. However, it is not clear how this scheme applies to a fault zone with varying widths along depth, as proposed by *Cochran et al.* [2009]. Furthermore, this scheme will depend on the resolution of InSAR images, which was not reported in the previous InSAR studies [*Fialko et al.*, 2002; *Fialko*, 2004]. Although the finite element models of *Fialko et al.* [2002] included 3-D effects, these models make an assumption of a constant perturbing stress. In addition, "although the finite element model is fully three-dimensional, the solution is essentially a superposition of the plane strain deformation that depends only on the fault-normal stress, and the antiplane strain deformation that depends only on the shear stress" (from *Fialko* [2004]).

[9] The second point is about usage of fault-normal displacements and possible overestimations of the reduction in the fault zone rigidity. Fialko11 argues that "*Fialko et al.* [2002] did not neglect fault-normal motion in their analysis, and in fact concluded that such motion was significant." *Duan et al.* [2011] noticed that *Fialko et al.* [2002] stated that "… the InSAR data (Figure 2) likely represent both left-lateral motion and collapse within kilometer wide shear zones…" after a qualitative analysis. However, in a subsequent quantitative analysis of rigidity reduction, they assumed that the fault-normal contraction is negligible to get the upper bound of the shear displacement, D < 4 to 8 cm. With their equation 3, they obtained the ratio of rigidity between a fault zone and host rocks ≥ 0.43 to 0.60. Then they concluded "the inferred retrograde motion on the Calico and Rodman faults requires a reduction in the effective shear modulus by about a factor of two within 2 km wide fault zones...." This conclusion did essentially ignore the fault-normal motion. Otherwise, the reduction of "a factor of two" should not be required. Rather, the reduction is upper bounded by a factor of two. It could be much smaller if the fault-normal motion is significant (actually the fault-normal motion can be significant as shown by *Duan et al.* [2011]). Notice that the ratio ≥ 0.43 to 0.60 does not mean the ratio is about 0.5 (thus "a factor of two"). Logically, it may mean the ratio is 1 and thus no reduction at all.

[10] The third point is about ignorance of some components of the stress tensor in previous InSAR studies. Fialko11 acknowledges that *Fialko et al.* [2002] and *Fialko* [2004] ignored changes in the fault-parallel stress (normal) component. However, Fialko11 claims that "the effect of fault-parallel stress on fault-normal displacements is small" and "…the contribution of fault-normal displacements to the observed LOS displacements is also small, the effect is negligible overall." Without arguing how small is the "small," the seemly "small" effect of the fault-parallel stress component on the fault-normal motion, shown by *Duan et al.* [2011, Figure 13b], comes from the Poisson effect: the fault-normal stress component is dominant in the fault-normal deformation, while the effect of the fault-parallel stress component on the fault-normal deformation is reduced by the Poisson ratio (i.e., 0.25 for the Poisson solid). However, when we examine the vertical motion of the fault zone, the Poison effect is equally applied to both the fault-parallel and fault-normal stress components, and the effect of the fault-parallel component can be as important as the fault-normal component. Thus, the above claim of "the effect is negligible overall" by Fialko11 does not hold. Fialko11 also mentions that *Cochran et al.* [2009] took into account all stress components and states that "the overall agreement between the fault zone properties inferred by *Cochran et al.* [2009] and previous studies [*Fialko et al.*, 2002; *Fialko*, 2004] demonstrates that the assumptions made in the early studies were indeed justified." However, the fault zone structure and properties inferred from *Cochran et al.* [2009] are obviously different from those by *Fialko et al.* [2002] and *Fialko* [2004], though *Cochran et al.* [2009] claimed they are consistent. *Cochran et al.* [2009] stated in the first

paragraph of their results section that the "lateral velocity profile across the fault is approximated as a Hanning taper, and the velocity reduction tapers linearly to zero between 0 and 12 km depth." The ~1.5 km width of the fault zone appears to include the entire Hanning taper. While the Calico fault zone inferred by *Fialko et al.* [2002] and *Fialko* [2004] appears to be a boxcar in shape along both the horizontal and vertical directions and the 2 km wide zone has a uniform rigidity reduction. If these two results are still considered to be in good agreement, then uncertainties associated with either or both must be very large. I also notice that the fit to the Landers-induced LOS displacement across the Calico fault [*Cochran et al.*, 2009, Figure 4b] is not good, which may further suggest the two results are not in good agreement.

[11] Related to the above third point is the dependence of the vertical residual displacement of a compliant fault zone on stress changes and structure/properties of the fault zone. As discussed above, the fault-parallel normal stress change plays an equally important role as the fault-normal stress change in determining the vertical residual displacement. However, this stress component was ignored in equation (5) of *Fialko et al.* [2002]. If the change in this stress component were taken into account, the estimation of the ratio of shear modulus could be larger than that (0.55) given by *Fialko et al.* [2002]. Fialko11 points out that equation (11) of *Duan et al.* [2011] is for uniaxial deformation with an assumption of free shear stress at the boundary between the fault zone and host rocks. I agree with this insightful comment, and thus the equation should be considered as an approximation for the vertical displacement under the uniaxial deformation condition, though it includes both stress components. Fialko11 further argues that the vertical residual displacement depends on the width of the fault zone as in equation (5) of *Fialko et al.* [2002], not the depth extent as in equation (11) of *Duan et al.* [2011]. This argument is based on continuity of displacements at the boundary between the fault zone and host rocks. However, this statement may be only valid when the host rock is rigid. In reality, the host rock is not rigid. Our ongoing preliminary 3-D modeling results suggest that both deformability of host rocks and presence of the shear stress at the boundary play roles in the vertical displacement field, and neither equation (5) of *Fialko et al.* [2002] nor equation (11) of *Duan et al.* [2011] is accurate. Systematic numerical experiments are needed to accurately determine dependence of vertical displacements on depth and width of compliant fault zones.

[12] The fourth point is about variability of across-fault motions along strike. This point was raised by noticing that generally only one profile across a fault zone was examined to infer the structure and properties of a fault zone in previous InSAR studies [*Fialko et al.*, 2002; *Fialko*, 2004] and homogeneous stresses are assumed. Although the homogeneous stress assumption was relaxed in subsequent studies [*Cochran et al.*, 2009; *Barbot et al.*, 2009], these later studies still chose only one or two profile(s) across a fault zone in inferring fault zone structure and properties. We suggest to perform full 3-D analyses so that variations in both residual displacements and the structure and properties of fault zones along strike can be included.

[13] The final point is about the structure and properties of the Calico fault zone and reconciliation between seismic studies and geodetic studies. As discussed above, the fault zone given by *Cochran et al.* [2009] and *Fialko et al.* [2002] is obviously different, though it might look like in good agreement to some of those involved in both studies. The statement that seismic data can be fitted by a narrower zone with larger reduction in seismic velocities is from the fact that there is a trade-off between the width and the rigidity reduction. This fact needs to be recognized by the scientific community. However, I acknowledge that the structure and properties of the Calico fault zone reported by *Cochran et al.* [2009] may be a good model with available data, despite the existence of the trade-off.

4. Conclusions

[14] The compliant fault zone model of anomalous displacements around preexisting faults induced by nearby earthquakes is significant in advancing our understanding of small-scale deformation signals, which may contain important information of past earthquake ruptures and subsequent healing processes. The elastic inhomogeneity model proposed in the previous InSAR studies [*Fialko et al.*, 2002; *Fialko*, 2004] works well when the response of compliant fault zones is linearly elastic. The findings from the more recent theoretical studies [*Duan*, 2010; *Duan et al.*, 2011], motivated by an important observation on JVF by *Vidale and Li* [2003], add new contributions to the compliant fault zone model. The compliant fault zone model should not be considered to be equivalent to the elastic inhomogeneity model. Rather, it should include new findings in recent and future studies, including *Duan* [2010] and *Duan et al.* [2011]. The observation by *Vidale and Li* [2003] and the findings on conditions and consequences of the inelastic response of compliant fault zones by *Duan* [2010] and *Duan et al.* [2011] warrant a reexamination of InSAR observations in the Mojave Desert from the 1992 Landers and 1999 Hector Mine earthquakes, to improve estimates of the structure and properties of the fault zones, and even to place some constraints on the preevent stress state in the crust.

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