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Comment on "Deformation of compliant fault zones induced by nearby earthquakes: Theoretical investigations in two dimensions" by Benchun Duan et al.

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1. Introduction

[1] *Duan et al.* [2011] recently presented analysis of deformation caused by dynamic and static stress changes on fault zones that have reduced strength and effective elastic moduli relative to the ambient rocks. Low-rigidity fault zones were previously proposed to explain anomalous geodetic signals around major crustal faults in the vicinity of large earthquakes [e.g., *Fialko et al.*, 2002; *Fialko*, 2004; *Hamiel and Fialko*, 2007; *Barbot et al.*, 2009]. *Duan et al.* [2011] claimed that "some deficiencies may exist" in the previously published results (in particular, those presented by *Fialko et al.* [2002]), and called for a reexamination of existing observations. Unfortunately, claims made by *Duan et al.* [2011] appear to stem from their misunderstanding of the published data and theory. Here I refute claims made by *Duan et al.* [2011], and explain why their arguments are flawed.

[2] Inferences of low-rigidity zones surrounding major crustal faults have been made based on a number of seismic [e.g., *Li et al.*, 1994; *Ben-Zion et al.*, 2003; *Spudich and Olsen*, 2001; *Cochran et al.*, 2009], and geodetic [e.g., *Lisowski et al.*, 1991; *Chen and Freymueller*, 2002; *Fialko et al.*, 2002] observations. Such zones most likely result from extensive damage associated with slip on faults, in agreement with geologic evidence [*Faulkner et al.*, 2003; *Oskin and Iriondo*, 2004; *Chester et al.*, 2005; *Dor et al.*, 2006].

[3] Compliant fault zones are of considerable interest as they encapsulate a long-term record of time-dependent damage and healing associated with the earthquake cycle, likely affect the earthquake rupture dynamics, bear on the issue of strain localization in the brittle upper crust, and may even hold clues about the magnitude of stress at seismogenic depths [e.g., *Hearn and Fialko*, 2009]. Thus more studies of compliant fault zones are certainly warranted, from both the observational and theoretical perspectives.

[4] *Duan et al.* [2011] (hereafter, DKL11) explored the effects of plastic yielding of fault zones due to dynamic stress changes from passing seismic waves, and compared predictions of their elastoplastic simulations to those of the elastic inhomogeneity model like that previously invoked to explain InSAR observations of small-scale strain anomalies on a number of faults in the Eastern California Shear Zone [*Fialko et al.*, 2002; *Fialko*, 2004]. In the framework of the elastic inhomogeneity model, the observed strain anomalies represent elastic response of massive compliant fault zones to static stress changes from a nearby earthquake.

2. Yielding Due to Dynamic Shaking Versus Elastic Response to Static Stress Changes

[5] DKL11 conclude, based on results of their numerical experiments, that "the elastic inhomogeneity hypothesis generally works well in explaining localized displacements across preexisting faults, if the response of a compliant fault zone to a nearby rupture is elastic" (DKL11, p. 10). This conclusion is accompanied by two caveats, most explicitly stated on page 15 of their paper:

[6] 1. "The hypothesis is not valid along portions of fault zones that experience inelastic deformation."

[7] 2. "Furthermore, even if fault zones respond to a nearby rupture elastically along their entire lengths …, our theoretical models demonstrate that there may be some deficiencies in previous InSAR studies in applying the hypothesis to infer the fault zone structure (i.e., width and depth) and properties (e.g., reduction in rigidity)."

[8] The mechanism of fault zone deformation imaged by InSAR studies (elastic vs inelastic) is not completely understood, and even a formal distinction between elastic and inelastic deformation in this case may not be straightforward. As mentioned above, permanent reductions in the effective elastic moduli imaged by seismic and geodetic observations most likely result from past damage, i.e. are of origin that is fundamentally inelastic. Some formulations of damage mechanics express damage (plastic yielding) in terms of reductions in the effective elastic moduli [e.g., *Lyakhovsky et al.*, 2001; *Turcotte et al.*, 2003]. Time-dependent variations in seismic velocities within compliant fault zones [e.g., *Vidale and Li*, 2003] are evidence that damage and healing do perturb the effective elastic moduli of the fault zone rocks. These induced perturbations however are small compared to the permanent reductions in seismic velocities and elastic moduli within fault zones [e.g., *Vidale and Li*, 2003; *Cochran et al.*, 2009]. The elastic compliant fault zone model

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is a useful approximation because it has a predictive power. For example, a model that was used to interpret deformatin of fault zones due to the 1999 Hector Mine earthquake [*Fialko et al.*, 2002] successfully explained deformatin of the same fault zones due to the 1992 Landers earthquake [*Fialko*, 2004].

[9] A relevant question is whether the underlying assumptions of the elastic heterogeneity model are correct. DKL11 do not address this question. They argued that some inelastic deformation may occur due to dynamic stressing if a target fault zone is already near the yield limit. Because both the preexisting stress in the crust and the in situ strength properties (in particular, cohesive strength) of faults zones are poorly constrained, this argument neither proves nor disproves the assumption of the essentially elastic response of fault zones to static stress changes. DKL11 use a 2-D model which is not capable of predicting surface displacements that could be compared to the available data. Indeed, their study does not involve any data. The compliant fault zone model was introduced to explain left-lateral shear on the right-lateral Calico and Rodman faults, as well as vertical displacements on the Pinto Mountain fault [*Fialko et al.*, 2002]. Such deformation patterns cannot be explained by plastic yielding. The Pinto Mountain fault zone is a particularly instructive example because it experienced changes in normal stress of an opposite sign due to the Landers and Hector Mine earthquakes, and responded in a good agreement with predictions of a linear elastic model [*Fialko*, 2004].

[10] While some inelastic yielding may well occur within fault zones due to dynamic shaking, the magnitude and extent of such yielding is yet to be determined. Major unresolved issues include: (1) relationships between reductions (both permanent and transient) in the effective elastic moduli and the rock strength and (2) distributed versus localized nature of yielding.

[11] The main purpose of this Comment is to demonstrate that the arguments made in our previous studies (in particular, *Fialko et al.* [2002]) are robust and "deficiencies" pointed out by DKL11 reflect their inadequate understanding of the previously published data and theory.

3. Observed and Predicted Response of Compliant Fault Zones to Static Stress Changes

[12] DKL11 (pp. 15–19) raised several criticisms in their paper, which I quote and address in their original order.

[13] "First, validity of using the width of the high gradient in the satellite LOS displacement [e.g., *Fialko et al.*, 2002] as the width of a compliant fault zone has not been confirmed theoretically. As shown in Figures 3 and 12, this is valid in a 2-D strike-slip fault system. However, as discussed earlier, this theoretical confirmation in the 2-D models actually raises a concern of its validity in 3-D because the depth extent is finite in 3-D cases. This concern should be addressed by 3-D theoretical modeling."

[14] *Fialko et al.* [2002, Figures 2d–2f] combined line-of-sight (LOS) displacements from two look directions (corresponding to the ascending and descending orbits) to isolate a signal that depends only on horizontal displacements and does not depend on a vertical component of the displacement field. Gradients in horizontal displacements are a good proxy for the width of a compliant zone, regardless of the fault zone depth (unlike vertical displacements that can be broader than the low-rigidity area). DKL11 fail to notice that finite element simulations presented by *Fialko et al.* [2002] in fact do explicitly consider 3-D effects (in particular, variations in the fault zone depth). A model presented by DKL11 is 2-D and therefore incapable of investigating this effect. I strongly support DKL11 in their wish to address their concern by performing 3-D modeling.

[15] "Second, the assumption that the fault-normal horizontal motion is negligible [e.g., *Fialko et al.*, 2002] may result in a significant overestimation in rigidity reduction in the fault zone (Figure 14). As shown in our models, the fault-normal horizontal motion can be comparable in amplitude to the fault-parallel horizontal motion along portions of fault zones that experience large changes in the normal components of the stress tensor (Figures 12 and 13). Along these portions, we need to take into account both fault-parallel and fault-normal horizontal motions in inferring the fault zone structure and properties by the elastic inhomogeneity hypothesis."

[16] *Fialko et al.* [2002] did not neglect fault-normal motion in their analysis, and in fact concluded that such motion was significant. As stated in their study, "… the InSAR data (Figure 2) likely represent both left-lateral motion and collapse within kilometer wide shear zones centered on the preexisting faults" [*Fialko et al.*, 2002, p. 1860 and reference 16]. Finite element calculations presented by *Fialko et al.* [2002] and *Fialko* [2004] took into account changes in both shear and normal stress across the fault zones, and the modeled LOS displacements (as well as inferences of the fault zone properties) included dependence on fault-normal motion.

[17] "Third, only the fault-shear and fault-normal stress changes are considered in previous InSAR studies [*Fialko et al.*, 2002; *Fialko*, 2004; *Cochran et al.*, 2009]. However, in predicting the fault-normal horizontal motion by the elastic inhomogeneity hypothesis, we find that both the fault-normal stress component $\Delta\sigma_{yy}$ and the normal component parallel to the fault $\Delta\sigma_{xx}$ are needed to match the observed fault-normal motion from the models (Figure 13b)."

[18] *Fialko et al.* [2002] and *Fialko* [2004] did not consider changes in the fault-parallel stress component because the effect of fault-parallel stress on fault-normal displacements is small, as corroborated by DKL11 (their Figure 13b). Given that the contribution of fault-normal displacements to the observed LOS displacements is also small, the effect is negligible overall. Results presented by *Cochran et al.* [2009] were obtained using a 3-D model that fully accounted for spatial variations in coseismic stress field, without any simplifying assumptions, contrary to the claim made by DKL11 (see *Barbot et al.* [2009] for the modeling details). Note 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.

[19] "This should also apply to vertical motion in 3-D cases. In previous InSAR studies, the vertical motion of a compliant fault zone is considered to be caused solely by the fault-normal stress change with a formula based on the

elastic inhomogeneity hypothesis as [*Fialko et al.*, 2002, equation (4)],

$$U = w\Delta\sigma_n\left(\frac{\nu'}{E'} - \frac{\nu}{E}\right), \tag{10}$$

where $\Delta\sigma_n$ corresponds to $\Delta\sigma_{yy}$ in our models, U is the vertical motion of the fault zone, w is the width of the fault zone, and other variables are given earlier. However, assuming that $\Delta\sigma_{zz}$, $\Delta\sigma_{yz}$ and $\Delta\sigma_{zx}$ are negligible for a strike-slip fault system, we obtain the vertical motion of a fault zone by the elastic inhomogeneity hypothesis as (see Appendix B),

$$U = -d\left(\Delta\sigma_{xx} + \Delta\sigma_{yy}\right)\left(\frac{\nu'}{E'} - \frac{\nu}{E}\right), \tag{11}$$

where d is the depth extent of the fault zone and the negative sign is needed to make sign convention self-consistent (i.e., dilatational changes in stress and extensions in deformation as positive, which implies that uplift in the vertical motion is positive). Thus, equation (10) not only ignores the other equally important normal component of the stress tensor (e.g., Figure 13d), it also has an error in using the width rather than the depth extent in predicting the vertical motion. Accordingly, there may be deficiencies in the estimation of the rigidity contrast from the vertical motion by equation (10), which was used as an independent estimate to corroborate that inferred from the fault-parallel horizontal motion. The rigidity ratio from equation (11) with an assumption of $\nu' = \nu$ should be

$$\frac{G'}{G} = \frac{1}{2\frac{1+\nu}{\nu}\frac{-UG}{d\left(\Delta\sigma_{xx}+\Delta\sigma_{yy}\right)} + 1}. \tag{12}$$

and should not be [*Fialko et al.*, 2002, equation (5)]

$$\frac{G'}{G} = \frac{1}{2\frac{1+\nu}{\nu}\frac{UG}{w\Delta\sigma_n} + 1}. \tag{13}$$

Therefore, the vertical motion (uplift/subsidence) of a fault zone should provide information of the depth extent of the fault zone, which is an important part of the fault zone structure."

[20] In their analysis, DKL11 assume that vertical displacements of a fault zone due to a change in the fault-normal stress are given by expressions for uniaxial deformation (as described in their Appendix B). This assumption is wrong. Vertical displacements would scale with the depth d of the fault zone if the boundaries between the fault zone and host rocks were free of shear stress. Because both normal and shear displacements are continuous between the fault zone and the host rocks, vertical strain in a thin fault zone is appreciably different from that in the host rocks only near the free surface. The length scale that defines the proximity to the free surface is the width of the fault zone w, as indicated in the order-of-magnitude estimate of *Fialko et al.* [2002, equation (5)] and verified by their finite element simulations. I encourage Duan et al. to perform experiments (numerical or physical) to verify that vertical displacements due to a thin compliant layer embedded in a rigid host do not scale with the depth of the layer d provided the latter is much greater than the layer width w.

[21] "Fourth, our theoretical modeling results show that the amplitude of the fault-parallel and fault-normal horizontal motions varies along strike of a fault zone even there is no change in the fault zone structure and properties (Figures 12 and 13). These variations in the across-fault zone motion along strike seems to be ignored in previous InSAR studies as they generally worked on one profile along a compliant fault zone to infer its structure and properties."

[22] Deformation induced by an earthquake on a nearby compliant zone is obviously expected to vary along strike, due to spatial variations in coseismic stress changes, as well as possible changes in the fault zone properties. The stress variability was taken into account by computing stress changes at the locations of interest (e.g., where InSAR data revealed anomalous strain), and using the inferred stress changes to drive finite element models of compliant fault zones, assuming a locally homogeneous stress [*Fialko et al.*, 2002; *Fialko*, 2004; *Hamiel and Fialko*, 2007]. The assumption of a locally homogeneous stress was relaxed in subsequent studies [e.g., *Cochran et al.*, 2009; *Barbot et al.*, 2009], which arrived to essentially the same results.

[23] DKL11 (pp. 14) go on to claim

[24] "Although a recent study [*Cochran et al.*, 2009] attempted to reconcile the discrepancy in the width of compliant fault zones, the 1.5 km width across the Calico fault is primarily required by fitting the InSAR data, while the seismic trapped waves can be fitted by a much narrower zone with a significant reduction in seismic velocities."

[25] The Calico fault seismic tomography experiment [*Cochran et al.*, 2009] was specifically designed to test the hypothesis of a massive compliant zone suggested by the previous InSAR studies [*Fialko et al.*, 2002; *Fialko*, 2004]. The experiment revealed a low-velocity zone having the size and rigidity reduction that were remarkably similar to those estimated by *Fialko et al.* [2002] and *Fialko* [2004] from the analysis of space geodetic data. Such an agreement provides strong evidence in support of the compliant zone model, as reduced seismic velocities are directly related to reduced elastic moduli. The fault zone parameters reported by *Cochran et al.* [2009] were determined from fitting seismic data only; static deformation model was used to demonstrate that the velocity structure imaged by the seismic experiment is consistent with the InSAR data. One of the coauthors of the DKL11 study was also a coauthor on the *Cochran et al.* [2009] study, so the assertion that "the seismic trapped waves can be fitted by a much narrower zone" is puzzling because it clearly contradicts the conclusions of *Cochran et al.* [2009]. To date I am not aware of any published results that would support such a claim. Should such results be presented, a reexamination of the compliant fault zone model proposed for the Calico fault would be certainly warranted.

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