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Geological Assessment of Continuum Off-Fault Deformation and its Implications for Damage Rheology of the Crust

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Introduction

Displacement across fault zones may be significantly underestimated due to unrecognized off fault deformation (OFD). Insights into the mechanism of OFD will improve understanding of fault zone structure and fault evolution. We conducted measurements of OFD indicators, adjacent to 10^1-10^2 km-long strike slip faults in the Mojave Desert section of eastern California shear zone to trace the magnitude and mechanism of OFD. We compared these results to InSAR images of compliant zones (zones of reduced shear rigidity) along these same faults (Fialko et al. 2002). Our results suggest that displacement via OFD is an active process accommodated by faulting and block rotation within 400-700m of main fault strands, and that OFD accounts for up to 23% of the total displacement across fault zones. Most of this displacement is focused within 100m of the main fault trace. Detailed mapping indicates along strike variations of OFD patterns that may be attributed to structural or lithologic heterogeneities. Comparison of mapped OFD markers to elastic compliant zones next to faults imaged via InSAR suggests that displacement and damage are closely related and that surficial lithology does not significantly affect rigidity variation in the damage zone next to faults.

Background

Off-fault deformation (OFD) is distributed anelastic strain next to faults that may extend tens of kilometers away from the main fault trace (Scholz, 1990). In the upper crust, OFD probably occurs as distributed brittle failure via microcracks, joints, secondary faults, rigid-body rotation and folding (Katz et al, 2003, Thatcher, 1995, Jones and Nelson, 1987). The fractal nature of fault networks (Bonnet et al, 2001, Darcel et al, 2003) suggests that OFD scales with fault dimension. OFD may occur prior, during, and after fault initiation and growth. Prefaulting OFD is assumed to be quasi-uniformly distributed and reflects the stress and strain fields prior to fault inception (Katz et al, 2003, Lyachovsky et al, 1997). Fault-growth related OFD probably occurs next to fault tips due to stress concentration at the fault-tip zone (Chinnery, 1966, Vermilye and Scholz, 1998). Slip-related OFD takes place next to mature, active faults and is attributed to wear affected by fault roughness, causing a continuously widening OFD zone caused by repeated earthquakes (Scholz, 1990).

Displacement via OFD may occur in many configurations ranging from continuous flexure of planar and linear features (usually termed fault drag) to complex patterns of faulting and block rotation (Jones and Nelson, 1987). Damage via OFD, reflected by microcrack density, increases exponentially towards faults (Faulkner et al, 2006, Vermilye and Scholz, 1998). This damage may induce a zone of reduced rigidity within few to tens of meters next to faults due to the inverse relation between damage and rigidity (Lyachovsky et al, 2005, Faulkner et al, 2006). Although displacement via OFD can account for up to 60% of the total displacement across shear zones (Kimorah et al, 2004, Jones and Nelson, 1987), it is often ignored because of it is difficult to observe and quantify. Displacement via OFD, if active, may increase slip rate estimates across active shear zones and thus affect comparisons between geologic and geodetic slip rates (Salyards et al, 1992, Gold et al, 2006, Thatcher and Lisowski, 1987).

Overview of Investigations

We isolated the dependency of OFD on variables like structural complexity, lithology, and fault displacement, by pairing study sites that differed by only one variable. We measured OFD by mapping of planar and linear features (dikes, secondary faults, mylonitic lineation) next to faults of known total horizontal displacement, and from paleomagnetic analysis of dated volcanic units, at 10 different locations across the Mojave section of eastern California shear zone. Deflected dikes, secondary faults and were mapped in 3 locations along the Calico fault, and paleomagnetic samples were taken in one site. Next to the Harper Lake fault, we conducted a detailed survey of mylonite lineations and mapped secondary faults over an area of ~25 km^2 (Fig. 1). We used high-resolution air photos to map and analyze secondary fault arrays in lava flows of different ages next to the Pisgah fault. Along the Lenwood fault we sampled tuffs for paleomagnetic analysis to trace vertical axis rotation and analyzed LiDAR topography for spatial distribution of secondary active faults. Along the Blackwater fault, we sampled basalts and rhyolites at 3 different locations for paleomagnetic analysis to define vertical axis rotation and conducted mapping to determine offsets along secondary faults.

Summary of Results

Magnitude of OFD: Displacement via OFD can account for up to 23% of the total displacement across faults of the Mojave portion of the Eastern California shear zone. This relatively high value of displacement via OFD suggest that displacement estimates based on narrow aperture of piercing points should be carefully examined for the existence of OFD.

Width of deforming zone: Significant OFD extends outward 400 m to 1000 m from the main fault trace. Most of the distributed displacement occurs within a high-strain zone located within ~100 m from the main fault. This finding is similar to a recent study of distributed coseismic surface deformation resulting from the 1992 Landers earthquake (Michel and Avouac, 2006). The high displacement values next to faults as well as the form of the deflected markers suggests that displacement via OFD as function of distance from the main fault follows a power or an exponential law as suggested by Nelson and Jones (1987) and Kimorah et al (2004).

Activity of OFD: Several observations suggest that displacement via OFD is an active process. (1) Comparison between displacement via OFD along the Calico fault and Harper Lake fault shows that displacement via OFD increases with fault offset. (2) Structural relationships between the Pisgah fault and the deformed lava flows of different ages indicate that secondary faulting within 400m from faults coexisted with a well developed main fault trace. (3) Displaced alluvial deposits indicate active secondary faulting within 1.5 km from the main traces of the Harper Lake fault and Lenwood fault. (4) OFD is widely reported in studies of surface deformation following major earthquakes in the Mojave Desert (Mcgill and Rubin, 1999, Michel and Avouac, 2006) and elsewhere (Lawson et al, 1908, Rockwell et al, 2002, Rymer et al, 2004), and seems to be concentrated within 100m from faults. (5) InSAR measurements show good agreement between the width of the OFD zone and the width of compliant zones around active faults, supporting that repeated coseismic damage of these zones.

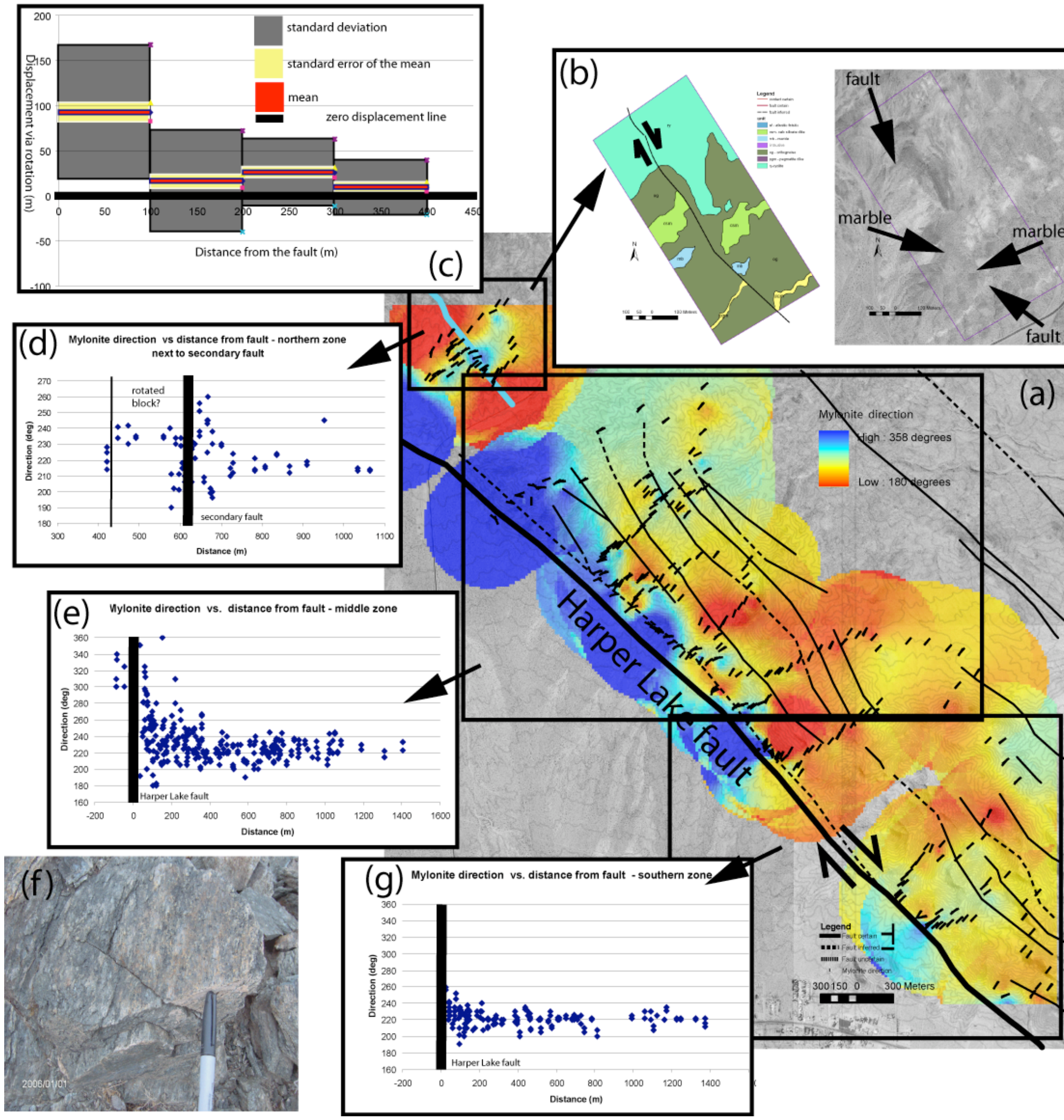

Figure 1. Example measurements of OFD, Mitchell Range, Mojave Desert, California. Early Miocene mylonitic lineations, originally oriented ~220°, are used as markers of distributed brittle shear adjacent to cross-cutting dextral Harper Lake fault. Figures described counterclockwise from right. A. Map of mylonitic lineations. Colors represent smoothed map of mylonite trends, with blue colors representing clockwise deflection of these trends next to the fault. Deformation mechanism seems to trade off along the strike of the Harper Lake fault. B. Geologic map and air photo of active secondary fault ~650 m east of and sub-parallel to the Harper Lake fault, with 200±47m offset of bedrock units. C. Graph shows values of displacement via distributed rotation in 100m bins next to the central area of the Harper Lake Fault (data graphed in e). Note that standard deviation values also increase with proximity to the fault. D. Mylonitic lineation directions graphed vs. distance in the northern map area, next to a secondary fault (in light blue on A). Vectors west of the fault are clockwise rotated by ~15° with respect to the vectors east of the fault, suggesting clockwise rotation of west block. E. Measurements of mylonitic lineations as function of distance from the Harper Lake fault in the central map area indicate a ~400 m wide zone of distributed deformation. Average distributed dextral displacement here is calculated as 143±27 m. This is ~9 ± 3% of the 3 to 4 km of total displacement across the Harper Lake fault, assuming symmetry of distributed deformation across the fault. F. Field photograph of typical outcrop of mylonite with lineation direction illustrated by pen. G. Measurements of mylonitic lineation as function of distance from the Harper Lake fault in southern map area. Insignificant variation of mylonitic lineation directions in this area indicates that distributed displacement in this zone is either small or occurs mostly by shear along secondary faults without block rotation.

Preliminary Conclusions

Based on our observations, we suggest that OFD is not unique to fault initiation processes but rather coexists with an active, developed, master fault. The similarity between coseismic displacement patterns and our observations suggest that at some, if not all displacement via OFD occurs coseismically or immediately thereafter. Slip-rate estimates based on narrow aperture piercing points, such as offset channels and offset strata within trenches, should be carefully examined for the existence of an OFD component and should take into account the significant error that this component may introduce.

Displacement via OFD occurs via a complex pattern of block rotation and simple-shear displacement along secondary faults. The significance of these mechanisms vary along fault strike and may also vary with lithology. Rotation of mylonite lineation trends next to the Harper Lake fault increases towards the fault. In some cases secondary faults are bound areas of differential rotation (Fig. 1). Changes in mylonitic lineation directions within few km along strike of the Harper Lake fault may be a result of variations in the amount of OFD, or tradeoff between rotation and slip along sub-parallel secondary faults. Increasing variance of these directions with proximity to the Harper Lake fault suggests an increasing number of blocks with diminishing average size approaching the master fault. These blocks appear to undergo varying amounts of rotation to accommodate OFD (cf. Lamb, 1987). Segments of a once-continuous dike next to the Calico fault are observed to be separated by discrete secondary faults with dextral or sinistral sense of motion. The faults define block dimensions that also systematically decrease from ~80m to ~30m with increasing proximity to the master Calico fault.

Paleomagnetic investigations thus far have failed to recover clockwise rotation of blocks adjacent to the Blackwater and Lenwood faults. We suggest that in these settings, where thick sedimentary cover is cut by the active master fault, secondary faults accommodate OFD via simple shear without rotation of intra-fault blocks. Further studies are pending of deformed dike segments adjacent to the Calico fault to test for rotation in a setting where conjugate secondary dextral and sinistral faults are observed.

Similarity between width of the OFD zone and width compliant zones imaged via InSAR, suggests that these features are related via damage accrual through coseismic displacements. Because post seismic healing is a relatively fast process (Lyachovsky et al, 2005, Yong et al, 2006, Vidale and Li, 2003) we would predict that inactive faults should not be surrounded by compliant zones. Significant damage increase within ~100 m of faults is reported by seismic and mapping studies of other fault zones (Yong et al, 2006, Vidale and Li, 2003, Dor et al, 2006), though it has been suggested that this damage is not associated with shear (Wilson et al. 2005, Dor et al, 2006). We also find ~100m-wide zones of more intense deformation, but we add that this is in fact associated with significant shear. These observations may be reconciled if this shear is localized along discrete faults, rather than at the grain scale observed by Wilson et al. (2005).

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