Collaborative Research: Relating fault-slip gradients to distributed deformation in the Eastern California Shear Zone

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Proposal Category: A Data Gathering

Science Objectives:  
1: Stress transfer from plate motion to crustal faults: long-term fault slip rates

4b: Investigations of along-strike variations in fault roughness and complexity as well as the degree of localization and damage perpendicular to the fault.

4c: Improvements to the CFM using better mapping, including lidar, and precise earthquake relocations. We will also extend the CFM to include spatial uncertainties and stochastic descriptions of fault heterogeneity.

4e: Use of earthquake simulators and other modeling tools, together with the CFM and CSM, to quantify how large-scale fault system complexities govern the probabilities of large earthquakes and rupture sequences.
Abstract

Using a combined modeling and observational approach, we have investigated the amount and style off-fault deformation from a very well exposed, active set of strike-slip faults in the central Mojave Desert portion of the Eastern California shear zone (ECSZ). Our investigations have been three-pronged: quantifying the role of disconnected faults in promoting off-fault deformation within the Mojave ECSZ, geologic and geomorphic assessment of off-fault deformation around the northern tip of the Gravel Hills fault, and understanding the role of thrust faults in accommodation deformation within the central Mojave Desert. Our new geologic observations and synthesis of prior mapping illuminates several mechanisms of active distributed deformation: (1) fault propagation, led by a zone of distributed active faulting and folding, and expressed as gradients in fault slip-rate (2) transpressional deformation between strike slip faults, and (3) long-wavelength warping and folding. Each of these processes provides information for validation of our Boundary Element Method modeling results. The BEM model results show that disconnected faults of the Mojave ECSZ produce fault slip rates that better match geologic data and produce off-fault deformation that could account for part of the observed discrepancy between geologic and geodetically-derived slip rates across the shear zone. The inclusion of the mapped thrust faults within the models produces uplift patterns that match well many regions of active uplift. These results confirm that details of fault connectivity have a significant impact on partitioning of deformation and the details of fault geometry should be considered for accurate assessment of seismic hazards.

1. Introduction

Because the Earth’s crust is not purely elastic, it can accrue permanent, distributed deformation during and between earthquakes. This permanent off-fault deformation may be expressed in damaged, folded and uplifted rocks between active faults in southern California. By not accounting for off-fault deformation, most geodetic inversions for fault slip rates (see Bird, 2009 for an exception), may over-estimate seismic hazard if this deformation accrues aseismically. Hazard may also be under-estimated away from known fault traces if some off-fault strain energy is released by rare, seismogenic slip events on unrecognized secondary structures.

The problem of off-fault deformation is especially relevant to understanding strain release at ends of earthquake ruptures, where coseismic slip must gradually diminish to avoid unrealistically high strains. Enforcement of uniform slip rate along faults leads to persistent slip deficits toward rupture tips. These deficits may be realistic for very long, straight and mature faults, such as the central San Andreas, where overlapping earthquake ruptures can fill in the gaps left from previous events (e.g. Biasi and Weldon, 2009). However, it is unrealistic to expect such fill-in events at the ends of faults that may rupture end-to-end, and instead permanent off-fault deformation may accrue to accommodate gradients in fault slip. Even the San Andreas fault may lose significant slip to permanent off-fault deformation in areas of structural complexity, such as the San Gorgonio Pass (Cooke and Dair, 2011; McGill et al., 2012).

For the 2012-2014 SCEC funding cycles, we proposed to quantify and model the amount and style off-fault deformation from a very well exposed, active set of strike-slip faults in the central Mojave Desert portion of the Eastern California shear zone (Lenwood, Camp Rock, and Calico faults in the south, to the Blackwater and Gravel Hills faults in the north). We hypothesized that these faults do not connect as depicted in elastic block models and the CFM, and as a result, model slip rates were overestimated. Furthermore, we demonstrate that the consideration of thrust faults impacts estimates of strain partitioning within the region.
2. Summary of Results

Using a combined modeling and observational approach, we have investigated the amount and style of off-fault deformation from a very well exposed, active set of strike-slip faults in the central Mojave Desert portion of the Eastern California shear zone (Lenwood, Camp Rock, and Calico faults in the south, to the Blackwater and Gravel Hills faults in the north). In 2013-2014 we have made several important advances in understanding how distributed deformation is accommodated across this system:

1. Based on existing geologic maps we produced a revised model of the fault system and analyzed this model using the boundary element method (BEM) technique to reassess the slip distribution. We found that slip rates are indeed strongly affected by the connectivity of faults, and that a more geologically accurate and disconnected fault system in the Mojave produces slip rates in closer agreement to geological observations. (Herbert et al., 2014 Geology).

2. Using the BEM model with the revised fault geometry, we estimate that as much as 40% of the regional deformation may be accommodated as off-fault deformation within the central Mojave. This suggests that geodetic estimates of slip in the region that do not account for off-fault deformation may significantly overestimate strike-slip rates (Herbert et al., 2014 Geology).

3. Newly generated maps and balanced cross-sections reveal a set of east-west striking blind thrust faults and fault-related folds that act to transfer slip between strike-slip faults. All five of the strike-slip faults we studied terminate within this thrust system, which is located where our revised BEM model results predict a large amount of off-fault strain.

4. We have mapped and modeled deformation within the active damage zone at the northwest tip of the Gravel Hills fault. We estimate that approximately 2 km of dextral-oblique slip is absorbed over a distance of 10 km. This deformation manifests as secondary faulting and folding within the damage zone, as well as long-wavelength flexure of the surrounding crust. A manuscript on the northward propagation of the Gravel Hills fault is nearly ready for submission (Selander and Oskin, in prep).

5. We have sampled three slip-rate sites on the Gravel Hills fault and one site along the Calico fault. Sample processing is to be completed this summer, and results will be reported at the SCEC annual meeting. The new slip rate data will test the hypothesis that fault slip rate declines toward the tips of these faults.

6. We have incorporated the fault network constrained from the results of #3 into the 3D model of the central Mojave Desert fault system. The model with thrust faults shows good correlation of uplift pattern and strike-slip rates with some areas of discrepancy.

With general applications in mind, we aim to quantify how slip-gradients at the ends of faults are accommodated by deformation in the surrounding volume of crust. We have already tested many aspects of our two related hypotheses for the role and mechanisms of off-fault deformation, using a combined modeling and observational approach:

Hypothesis 1: Lack of connectivity between faults promotes off-fault deformation that is accommodated permanently, in a distributed manner, within the surrounding crust.

Hypothesis 2: A component of permanent off-fault deformation is accommodated through long-wavelength subsidence and uplift without obvious secondary faulting.
3. **Geologic Data Collection and Analysis**

Fieldwork and structural interpretations target a suite of active dextral faults crossing the central and northern Mojave Desert, as well as a set of previously undocumented active thrust faults and fault-related folding comprise an important component of distributed deformation in this region (Figure 1). Structural interpretation, field mapping, and interpretation of lidar data sets have yielded the following new discoveries:

1. Most, if not all, active dextral faults in this area appear to terminate in a zone of transpressional deformation and folding in the central Mojave Desert. South-vergent blind thrust faults and related folding transfer slip from the ends of the Gravel Hills, Calico, and Blackwater faults. An opposing north-vergent system is growing at the northern termination of the Lenwood, and Camp Rock faults.

2. The northernmost Calico fault appears to have been deactivated in the Late Quaternary, transferring its slip to shortening within the Mud Hills and Waterman Hills, and dextral slip on the Tin Can Alley fault east of the Calico Mountains.

3. New slip rate sites have been documented along the Gravel Hills fault and the Calico fault. These sites will be important for testing our boundary element method models, described below. Sampling of alluvial fan surfaces for cosmogenic $^{10}$Be surface exposure age-dating was completed in early 2014. Sample analysis will be performed over the coming summer.

4. Detailed mapping of the northernmost Gravel Hills fault using new airborne lidar and field observations reveals a complex zone of faulting as this structure propagates northwestward. This area captures a rare glimpse of the propagation of a major seismogenic strike-slip fault into a largely undeformed region. Several offset geomorphic and stratigraphic units in this area document a progression of faulting and strain localization within an evolving damage zone. Long-wavelength deformation surrounding this damage zone is consistent with a model of repeated elastic deformation accrued at the tip of coseismic ruptures on the Gravel Hills fault (Figure 2). We hypothesize that the stresses driving this fault-tip deformation may be relieved aseismically during the interseismic period.

In summary, our new geologic observations and synthesis of prior mapping illuminates several mechanisms of active distributed deformation: (1) fault propagation, led by a zone of distributed active faulting and folding, and expressed as gradients in fault slip-rate (2) transpressional deformation between strike slip faults, and (3) long-wavelength warping and folding. Each of these processes provides information for validation of our boundary element method modeling results.

4. **Effect of fault geometry revisions on deformation**

We use the Boundary Element Method (BEM) code Poly3D to simulate three-dimensional deformation of the ECSZ. Our model incorporates 52 active faults extracted from the SCEC CFM within and around the ECSZ. Within the mechanical model, we extend the faults to a depth of 35 km where they join into a horizontal dislocation that simulates distributed deformation beneath the seismogenic crust. Where faults extend to the model boundaries we prescribe known geologic slip rates to avoid zero slip at the lateral fault tips. We apply geodetically determined plate velocities (e.g. DeMets et al., 2010) to the outer edge of the basal dislocation. The faults freely slip in response to this loading and their interactions with nearby faults. Similar three-dimensional BEM models have been used recently to investigate active faulting in southern California [e.g., Marshall et al., 2009; Cooke and Dair, 2011; Herbert and Cooke, 2012].
Within the first phase of model revision, we implement several changes to the CFM geometry to better reflect mapping of Jennings and Bryant (2010).

1. Revise the inactive northern portion of the Calico fault (north of interstate 15)
2. Remove the non-existent fault connecting the Camp Rock and Gravel Hills faults
3. Inactive segments of the Helendale, Lockhart and Lenwood fault are removed to better represent their segmented nature.
4. Add the Tin Can Alley fault and the Mt General fault

The revisions to the geometry of the Calico, Gravel Hills, Camp Rock, Lockhart, Lenwood and Helendale faults within Herbert et al. (2014) better replicate the mapped active traces from the Fault Activity Map of California (Jennings and Bryant, 2010) and better match the available strike-slip rates of (Oskin, et al., 2007; Oskin, et al., 2008).

We investigate the pattern of off-fault deformation in the ECSZ using strain energy density, which shows the mechanical work of deformation in the rock surrounding the faults. The elastic properties of the BEM model do not explicitly consider inelastic processes but the loci of high strain energy density highlight where inelastic processes should be prevalent. The strain energy density is greatest near fault tips and bends along faults of the ECSZ (Fig. 3). For example, several faults terminate or bend near point A in Figure 3a to produce a large lobe of high strain energy density at the same location where we are mapping active thrust faults.

The model results reveal how much fault slip and off-fault deformation each contribute to the total velocity across the fault zone. Across the Mojave region, between UTM northing 3820 km and 3890 km, off-fault deformation accounts for $3.1 \pm 1.8$ mm/yr of plate-parallel velocity and the average contribution of off-fault deformation across the ECSZ is $40 \pm 23\%$ of the total plate velocity (Herbert et al., 2014). This is consistent with the findings of Shelef and Oskin (2010) that show up to 25% off-fault deformation within 2 km adjacent to faults in the ECSZ.

In the second phase of the modeling we explore the role of thrust in deformation within the Mojave. The incorporation of our recently mapped active thrust faults into the 3D BEM model, permits us to investigate the role of these thrusts in accommodating off-fault deformation. Revisions to the model as of March 2014 include:

1. Mud Hills and Harper Lake thrusts added
2. NE Dipping Calico blind thrust replace vertical segment (still in progress)
3. Blind thrust under Lenwood anticline added
4. NE dipping Gravel Hills replaced vertical segment
5. Mt General fault extended

The inclusion of these thrust faults reduces the strain energy density in the central Mojave (Figures 3c and d) and produces nearby warping of the crust (Figures 3a and b). uplift patterns from the model with thrust faults and dipping segments of the ECSZ faults match well many of the regions of active uplift. One remaining discrepancies include insufficient uplift of the Mud Hills anticline, which will be explored by varying the geometry of the northern Calico fault.

3. Broader Impacts

An important indirect outcome of this work is to quantify deformation away from major faults. This contributes to hazard assessment in understanding rare earthquakes on slow-sliping faults and, potentially, quantifying a contribution of aseismic deformation to the strain budget. The project has supported the training of two PhD students, Justin Herbert at the University of Massachusetts, Amherst and Jacob Selander at the University of California, Davis. The project has also supported UMass undergraduate, Karl Grette in his honors thesis. One of the PIs is a member of two underrepresented groups, as a woman with a hearing impairment.
6. Bibliography of Publications
Herbert, J W., M. L. Cooke, M. E. Oskin and O. Difo, 2014. How much can off-fault deformation contribute to the slip rate discrepancy within the Eastern California Shear Zone?, Geology. doi:10.1130/G34738.1
Selandar, J. and M. E. Oskin, in preparation, Distributed deformation at an actively propagating dextral fault tip revealed in high-resolution topography.

Figure 1. Overview of mapping results as of March, 2014, showing revised fault geometry for the central Mojave Desert based on map and cross-sectional interpretations and recent field work. Stars note locations of slip-rate sites where \(^{10}\)Be depth profiles have been sampled for exposure-age dating.

Figure 2. Topography of the northern Mojave Desert surrounding the propagating tip of the Gravel Hills fault. (B) Modeled long-wavelength deformation field surrounding the northern Gravel Hills fault due to termination of earthquake ruptures. Fault model (shown in A) dips 80 degrees NE, with slip tapering from 2 to 0 km over 10 km strike-distance. <1 km slip on the Blackwater fault is also included in the model.
Figure 3. Uplift and Strain Energy Density patterns within the Mojave change with the inclusion of mapped thrust faults. (A) The model with only vertical faults does not show mapped uplift between the Gravel Hills and Blackwater faults nor at the Lenwood Anticline. (B) With the inclusion of thrust fault segments, many regions of model uplift are consistent with regions of active uplift. (C) Strain energy density at 3 km depth reveals the pattern of off-fault deformation. Location A shows abundant off-fault deformation where thrust faults are mapped. (D) The inclusion of thrust faults reduces but does not eliminate the strain energy density at location A.
References


Cochran, E. S., Li, Y., Shearer, P. M., Barbot, S., Fialko, Y., and Vidale, J. E. (2009), Seismic and geodetic evidence for extensive, long-lived fault damage zones, Geology, v. 37, n. 4, p. 315-318.


Jennings, C., and Bryant, W., 2010, Fault activity map of California: California Geological Survey, Geologic Data Map No. 6, map scale 1:750,000.


Herbert, J. W., M. L. Cooke, M. E. Oskin and O. Difo, 2014. How much can off-fault deformation contribute to the slip rate discrepancy within the Eastern California Shear Zone?, Geology. doi:10.1130/G34738.1


