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

Principal Investigators:

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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.
1.1 Abstract

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. Our study examines the rates of slip along faults in the Mojave Desert portion of the Eastern California Shear zone from both geologic and numerical modeling approaches. In this final year of this project we have (1) completed defining new fault geometries that include previously unrecognized active thrust faults and reconfigured connections between strike-slip faults, (2) developed a boundary element method model that incorporates these new fault geometries and yields a distributed uplift signal very similar to that observed, and (3) determined five new fault slip that quantify gradients in fault displacement rate and help to test our model. One paper published in 2014 on our initial modeling efforts was lead authored by PhD student Justin Herbert who completed his thesis in June 2014. Also, one Ph.D. student, Jacob Selander, completed his thesis in February 2015. We anticipate publishing three chapters from this thesis, along with additional modeling results that incorporate the improved geologic information.

1.2 Intellectual Merit

Quantifying off-fault deformation is needed to improve our understanding strain release at ends of earthquake ruptures, where coseismic slip must gradually diminish to avoid unrealistically high stresses. Similar processes may act at geometric irregularities along faults. Enforcement of uniform slip rate along faults leads to persistent slip deficits in these regions. 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. 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 must accrue to accommodate gradients in fault slip. This study examines the distributed network of strike-slip and reverse faults present in the central Mojave Desert portion of the eastern California shear zone. According to our modeling and existing slip rate data, this fault network displays an unusually high proportion of off-fault deformation. This may explain geologic versus geodetic rate discrepancies in this area.

1.3 Broader Impacts

By not accounting for permanent off-fault deformation, most geodetic inversions for fault slip rates 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. 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. If significant off-fault deformation occurs aseismically, as our preliminary results suggest, this lowers the expected seismic moment accumulation rate across California, especially in areas away from the principal strike-slip faults.
Technical Report

Using a combined modeling and observational approach combined, 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 2012-2014 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 re-assess 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 over-estimate 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 completed a lidar database for the entire strike-slip fault system under study, including a new data set for the Gravel Hills fault. Using these data we have delineated new slip-rate sites and alluvial fan surfaces deformed one the more significant fault-cored folds. We also discovered distributed faulting and warping at the northern termination of the Gravel Hills fault that transition from discrete coseismic fault slip to volumetric deformation of rocks surrounding this fault tip. A manuscript on the northward propagation of the Gravel Hills fault is in preparation (Selander and Oskin, in prep).

5. To complete our slip rate and uplift rate data set we completed 10Be exposure age-dates and determined slip rates from five localities along the Calico fault (2), the uplifted hanging wall of the Mud Hills thrust (1), and the Harper Lake-Gravel Hills fault (2).

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 the addition of these thrust faults, off-fault deformation is ~36% of the regional deformation.

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 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.
2. Geologic Data Collection  (UC Davis lead)

Geologic data collection focussed on three tasks: (1) quantifying distributed deformation at the northwest tip of the Gravel Hills fault; (2) obtaining new slip-rate data to test predicted slip-rate gradients and quantifying uplift rates in the hangingwalls of active reverse faults; (3) 3D modeling the geometry of intersecting strike-slip and reverse faults in the central Mojave Desert using serial cross-sections and 3D Move software. All three of these tasks have been completed and have been published in thesis form (Selander, 2015). We plan to submit three manuscripts for publication from this work. In the following sections we highlight some of the results of our geologic data collection. The effects of revised fault geometry on deformation modeling is considered separately in the following section.

The northwest termination of the Gravel Hills fault ends far (>20 km) from other active faults. This isolated fault tip and the slow rate of landscape evolution in this desert area provide a natural laboratory for understanding how distributed deformation is accumulated as a strike-slip fault propagates. We find that long-wavelength subsidence and uplift surrounding the fault is consistent with an elastic model of strain surrounding a tapered, partially blind strike slip fault. Our modeling is reproduces the pattern of uplift of the Gravel Hills, subsidence of the Cuddeback lake basin, and fault slip tapering from 4 km to 0 km along a 70° to 80° NE dipping fault plane. Analysis of syn-tectonically deposited strata shows that a depocenter formed ahead of the propagating fault tip, and that the locus of subsidence migrated northwest with propagation. Overall we define a spatio-temporal sequence of fault-tip deformation: (1) Long-wavelength (5-10 km) gentle warping of the crust surrounding the fault tip. (2) Development of short-wavelength (0.25-1 km) folds associated with the leading edge of surface faulting. (3) Surface faulting initiates as en-echelon reverse faults, evolving to dextral slip with accumulated displacement. Ahead and surrounding the propagating fault, strain is accumulated elasto-plastically within a surrounding crustal volume that scales with the seismogenic zone. Based on the lack of seismicity in this area, and generally in areas surrounding fault tips, we tentatively conclude that much of this deformation occurs aseismically and as aftershocks from major earthquakes along the primary fault.

We report new slip-rate determinations from five locations (Figure 1). This work confirms that the northern Calico fault is inactive (no displacement of recently developed landforms across the fault), and that the Mud Hills thrust is active with uplift >0.6 mm/yr, transferring slip from the Calico fault to the Blackwater fault and Harper lake fault. The new rates also confirm northward diminishing slip-rate along the Harper Lake-Gravel Hills fault, from 1.1 ± 0.4 mm/yr at its south end, near Barstow, to 0.20 ± 0.07 mm/yr near its northwest termination. The asymmetry in these rates is consistent with strain transfer from the Calico fault to the Harper Lake fault in the south, and propagation and distributed deformation surrounding the fault tip in the north. Overall these new slip rates confirm the results of elastic modeling by Herbert et al. (2014) for slip-rate gradients in the central Mojave Desert, except for the southern Calico fault, which is slower in the geology than our model predictions.

3. Effect of fault geometry revisions on deformation (UMass lead)

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 SSEC 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; Herbert et al., 2014].

**Figure 1.** A. Compilation of existing and new slip-rate data from the central Mojave portion of the eastern California shear zone. B. Comparison of geologic slip rates with model rates from Herbert et al. (2014) for the (1) the Gravel Hills-Harper Lake fault and (2) Calico fault. Abrupt northward slip taper of both faults matches geologic rates. However southward increase in Calico fault slip rate is not confirmed from new slip rate data point. C. Comparison of slip rate on the Calico fault to the combined slip rates on the Harper Lake and Blackwater faults shows how these systems are linked across the central Mojave desert via shortening across the active Mud Hills thrust and blind Yermo thrust. D. Compilation of slip rates from the southern Mojave Desert sums to ≤6.2 ± 1.9 mm/yr (Oskin et al., 2008). Similar compilation for faulting across the northwestern Mojave desert sums to only 2.6 ± 0.5 mm/yr. Deformation in the NE Mojave Desert likely absorbs the remaining ~3 mm/yr or more of dextral shear.
The 3D BEM model results reveal how much fault slip and off-fault deformation each contributes to the total velocity across the fault zone. The ratio of off-fault contribution to total velocity increases from the south to north in the region of investigation (Herbert et al., 2014). Across the Mojave region, between UTM northing 3820 km and 3890 km, off-fault deformation accounts for 3.1 ± 1.8 mm/yr of plate-parallel velocity and the average contribution of off-fault deformation across the ECSZ is 40 ± 23% of the total plate velocity. 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.

The incorporation of our revised fault geometry and newly defined 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 of Herbert et al. (2014) at this stage of the model include:

1. Mud Hills thrust added
2. Harper Lake thrust added
3. NE Dipping Calico fault replaces vertical segment
4. SW dipping Lenwood fault replaced vertical segment
5. Connection of Lenwood fault with northern tip of Camp Rock via a blind thrust fault
6. NE dipping Gravel Hills fault replaced vertical segment

Figure 2: Uplift patterns within the Mojave change with the addition of thrust faults and revision of dip along other faults. Uplift rates increase within the hanging walls of dipping faults as these faults accommodate convergence via dip slip. The region of subsidence along the footwall of the Gravel Hills fault is generally consistent with local areas of deposition.

Strike slip rates along the Helendale and Lenwood faults continue to match the geologic estimates with the revisions to the fault model. The increased length of the Calico increases strike-slip rates along this fault so that the modeled strike slip rates increased above the geologically measured rates.

The inclusion of reverse faults and dipping strike-slip faults has significant impact on uplift pattern (Figure 2). The uplift pattern is adjusted for isostacy and normalized by the average uplift within the study area. The dipping faults of the model accommodate convergence within the central Mojave resulting in greater uplift within the hanging walls and greater down drop within footwalls of faults. Uplift patterns from the model with thrust faults and dipping segments of the ECSZ faults match well many of the regions of active uplift including the Mud Hills anticline as well as subsidence, such as the Harper Lake basin southwest of the Gravel Hills fault, and the Manix basin along I-40 east of Barstow.
The inclusion of the dipping faults slightly reduces the strain energy density within the central Mojave (Figure 3) from that predicted by model of Herbert et al. (2014), which did not include thrust faults. The SED is reduced at the location A east of Barstow but remains high to the north of location A within the hangingwall of the thrusts. Inelastic processes not explicitly simulated with the model, such as flexural slip within with hanging wall anticlines, may accommodate off-fault deformation and account for the remaining high SED in the hanging walls of the blind thrusts. The average ratio of off-fault deformation to the total 320° oriented right-lateral velocity across the region of investigation is 36% (Figure 3B), which is 4% lower than the model without the thrust and dipping faults.

Herbert et al (2014) demonstrated that off-fault deformation accumulation within the central Mojave may account for a portion of the discrepancy between geologic and geodetic estimates for fault slip rates. The geodetic estimates, which do not consider permanent off-fault deformation may erroneously attribute this deformation to slip along faults. Our recent contribution in mapping and adding thrust faults to the model, shows that these dipping structures can accommodate about 4% of the overall right-lateral shear across the region leaving significant strain partitioned as permanent off-fault deformation, such as flexural slip.

**Figure 3.** A) The strain energy density at 3km depth from the revised model that includes thrust faults and dipping fault segments. We smooth the SED results with an 8 km filter to remove discretization artifacts. The inclusion of thrust faults significantly reduces the strain energy density at location A. Off fault deformation increases to the north of A within the hanging walls of the thrusts where uplift rates are also high. B) Ratio of off-fault deformation to total velocity across the region plotted in A). The off-fault deformation is still higher in the northern portion of the region of investigation but the average ratio has dropped with the addition of thrust faults to 36%.
References
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