Effects of fault geometry on stressing rates and off-fault seismicity on the southern San Andreas and San Jacinto faults

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Investigators: Michele Cooke (UMass)

I. Project Overview

A. Abstract

In the box below, describe the project objectives, methodology, and results obtained and their significance. If this work is a continuation of a multi-year SCEC-funded project, please include major research findings for all previous years in the abstract. (Maximum 250 words.)

Two crustal deformation models examine the short term stressing of the crust between earthquakes and the longer-term off-fault residual stresses over multiple earthquake cycles. In regions of fault complexity, such as the San Gorgonio Pass Special Fault Study Area, not all stresses are relieved by slip along faults. These residual off-fault stresses can produce permanent deformation including microseismicity. The spatial correlation of patterns of stresses from focal mechanism inversions with off-fault stresses over multiple earthquake cycles suggests that the microseismicity of the San Gorgonio Pass region may be recording permanent off-fault deformation that is distinctly different from the long-term strike-slip loading of the San Andreas fault. This suggests that our current seismic catalog under-samples strike-slip events along the San Andreas Fault. Consequently, the stress inversions from the catalog provide inaccurate information about the loading of the major faults and instead reveal permanent distributed off-fault deformation.

The mean normal compressive stress from the multi-cycle model shows high spatial correlation (location and depth) with regions of anomalously high stress drop from the focal mechanism inversions in the San Gorgonio Pass region. This spatial correlation suggests that small slip surfaces off of the major faults are strengthened due to localized clamping. In addition to local variations in explicit fault strength, heterogeneous stress fields can also produce spatial variations in stress drop. The anomalously high stress drop within the San Gorgonio Pass may reflect localized compression rather than high static fault strength.

B. SCEC Annual Science Highlights

Each year, the Science Planning Committee reviews and summarizes SCEC research accomplishments, and presents the results to the SCEC community and funding agencies. Rank (in order of preference) the sections in which you would like your project results to appear. Choose up to 3 working groups from below and re-order them according to your preference ranking.

Stress and Deformation Through Time (SDOT)
Southern San Andreas Fault Evaluation (SoSAFE)
ault and Rupture Mechanics (FARM)

C. Exemplary Figure

Select one figure from your project report that best exemplifies the significance of the results. The figure may be used in the SCEC Annual Science Highlights and chosen for the cover of the Annual Meeting Proceedings Volume. In the box below, enter the figure number from the project report, figure caption and figure credits.

Figure 3: Mean normal stressing rate from (A) interseismic and (B) off-fault models compared to (C) the focal mechanism inversions of Yang et al., [2012]. The green lines outline areas of greater relative tension (warmer colors) in the focal mechanism inversion. Within the San Gorgonio Pass region, the stress pattern from the focal mechanism inversions has better match to the off-fault stressing rate (correlation coefficient, r = 0.41) than to the interseismic stressing rate (r = 0.007). This correlation suggests that the seismic catalog in the SGP region under-samples strike-slip events that would reveal interseismic loading of the San Andreas fault and instead these earthquakes record permanent deformation off of the major faults. The stress inversions from focal mechanisms may not accurately inform the stress patterns that drive seismic hazards in southern California.

D. SCEC Science Priorities

In the box below, please list (in rank order) the SCEC priorities this project has achieved. See *https://www.scec.org/research/priorities* for list of SCEC research priorities. *For example: 6a, 6b, 6c*

4d, 4a, 4b

E. Intellectual Merit

How does the project contribute to the overall intellectual merit of SCEC? *For example: How does the research contribute to advancing knowledge and understanding in the field and, more specifically, SCEC research objectives? To what extent has the activity developed creative and original concepts?*

The project provides a new approach for analyzing microseismicity that could greatly impact how we interpret stresses from focal mechanism inversions. Within the San Gorgonio Pass, the pattern of stresses from the focal mechanism inversion better match models of residual off-fault deformation than models of intersiesmic loading of the San Andreas fault system. This suggests that the past few decades of microseismicity of the San Gorgonio Pass region may primarily record permanent off-fault deformation that is distinctly different from the long term loading of the San Andreas fault. Because our current seismic catalog under-samples strike-slip events along the San Andreas, the catalog may not represent the loading on all parts of the San Andreas fault system. The complex fault geometry in the San Gorgonio Pass special fault study area may promote local off-fault deformation so that stress inversions are less reliable here than other regions of southern California. The results of this study can guide efforts of the Community Stress Model to characterize the crustal stresses within southern California.

The project also demonstrates that apparent spatial variations in stress drop within the San Gorgonio Pass region can arise from heterogeneous stresses due to complex fault geometry rather than explicit fault strength variations. This result highlights the need for investigation of fault geometry within focused studies such as the Special Fault Study Areas of SCEC4.

F. Broader Impacts

How does the project contribute to the broader impacts of SCEC as a whole? *For example: How well has the activity promoted or supported teaching, training, and learning at your institution or across SCEC? If your project included a SCEC intern, what was his/her contribution? How has your project broadened the participation of underrepresented groups? To what extent has the project enhanced the infrastructure for research and education (e.g., facilities, instrumentation, networks, and partnerships)? What are some possible benefits of the activity to society?*

By integrating results of crustal deformation models and the stress inversions from focal mechanisms, this project crosses disciplines within SCEC. This project supported a female graduate student at UMass and a female PI with a hearing impairment.

G. Project Publications

All publications and presentations of the work funded must be entered in the SCEC Publications database. Log in at *http://www.scec.org/user/login* and select the Publications button to enter the SCEC Pubications System. Please either (a) update a publication record you previously submitted or (b) add new publication record(s) as needed. If you have any problems, please email *web@scec.org* for assistance.

II. Technical Report

A. Introduction

Permanent off-fault deformation that accumulates between earthquake events can accommodate a significant portion of the deformation budget across irregular fault networks. While slip rates along planar faults may match the overall plate velocity, non-planar fault systems accrue off-fault deformation near fault irregularities with corresponding reduction in slip rate along the faults [e.g. *Cooke et al.,* 2013]. An example of this reduction in slip rate within southern California is the decrease of strike-slip rates along the San Bernardino strand of the San Andreas with proximity to the fault's bend at the San Gorgonio Pass [e.g. *McGill et al.,* 2013].

Forward mechanical models of deformation that permit both fault slip and accumulation of strain between faults reveal that 28-33% of the total velocity across southern California may be accommodated off of major faults [*Bird*, 2009; *Johnson*, 2013]. The local degree of off-fault deformation depends on fault geometry. Within the highly disconnected fault network of the Eastern California Shear Zone, 40% of the deformation across the zone may be accumulated off of faults [*Herbert et al.,* 2014a]. These findings challenge our assumption that the sum of slip rates along major faults should equal the velocity across the plate. Consequently, our efforts to evaluate seismic hazards in southern California may incur uncertainties that arise from insufficient characterization of fault complexity and associated off-fault deformation.

Direct measurements of off-fault deformation are hard to come by. Within the geologic record, deformation adjacent to faults records that 10-20% of the strain of fault slip can be accommodated within a few kilometers of the fault trace [*Shelef & Oskin*, 2010; *Titus et al*., 2011]. Microseismicity also provides a record of off-fault deformation [e.g. *Goebel et al.,* 2014]. Small earthquakes often do not occur along major faults but within the crust between these faults. The double-couple recorded for these events show that these are slip events but the slip may be occurring within folds adjacent to faults, along small faults, along distributed planes of weakness (e.g. foliation) etc. We can conceptualize these small slip events as records of permanent deformation within the rock surrounding major faults. Unlike elastic strain stored in the host rock, the strain accommodated by on-going off-fault microseismicity will not likely be released in the next large earthquake as this would require that all the accumulated microseismicity since the last large earthquake slips in the exact reverse manner as the original double-couples. The unlikeliness of such loading requires that off-fault microseismicity contribute to permanent deformation during the interseismic period. Thus, the seismic catalog provides a multidecadal record of off-fault deformation in regions that can be compared to forward model predictions of off-fault deformation.

I use well-validated 3D Boundary Element Method (BEM) models that are adept at simulating deformation associated with irregular fault geometry. For this study, I compare the off-fault stressing rates within BEM models of the San Gorgonio Pass to stress patterns interpreted from the seismic catalog in this region [*Yang et al*. 2012; *Goebel et al.,* 2015]. The San Gorgonio Pass has served as a successful Special Fault Study area in SCEC 4 and this study has benefited from the multi-disciplinary nature of the co-laboratory. Through this comparison, the proposed study will characterize the influence of fault configuration on the permanent off-fault deformation as well as interseismic stressing rates. If we know how much of the interseismic stressing rate is portioned into permanent deformation, such as recorded by microseismicity, then we can estimate how much interseismic deformation is stored elastically to be released in the next earthquake as fault slip.

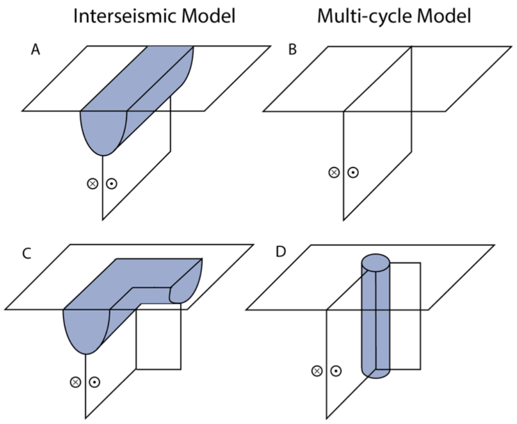

Figure 1: A&C) Interseismic models are loaded with slip rates below the locking depth. B) For straight faults, the multi- earthquake cycle model doesn't produce off-fault deformation. D) With irregular fault geometry local off-fault stresses are not relieved in slip events and could be recorded in microseismicity.

B. Methods

Faults surfaces based on the SCEC Community Fault Model v. 4 are discretized into triangles and loaded by tectonic velocities at the edges of the model. Faults of the CFM are extended to 35 km depth where they merge with a horizontal crack. This crack provides distributed deformation below the seismogenic crust. Uncertainty of the tectonic loading of 5 mm/yr and 5˚ orientation are incorporated in the models by assessing several different models with applied right lateral shear orientated at 320˚ and 325˚ and with velocities of 50 and 55 mm/yr [e.g. Herbert and Cooke, 2012]. These velocities are applied to the outer edges of the deep horizontal crack. The shear traction-free faults in the model and the center of the deep horizontal crack slip in response to this loading and interaction with each other [e.g. Fattaruso et al., 2015].

To investigate stressing off of faults, I have developed two stressing rate models that simulate different time periods (Fig. 1). Within the multi-cycle model, all portions of the fault surfaces slip in order to simulate the impact of multiple earthquake cycles. For planar faults, no stresses accumulate within the host rock (Fig. 1B) but the model produces high stresses around geometric irregularities along the fault (Fig. 1D). These residual stresses in the surrounding host rock reveal the stresses not released by fault slip that are responsible for permanent off-fault deformation. The second model (Fig. 1A and C) simulates the interseismic stressing rates between earthquakes using a back slip approach with slipping faults below the locking depth [e.g. *Marshall et al.,* 2009]. The deep fault slip rates for the interseismic model are determined from the multi-cycle model. If our catalog of microseismicity within the San Gorgonio Pass spanning the past few decades represents the interseismic stressing due to deep slip on the San Andreas fault, then the stresses from the microseismicity focal mechanisms should resemble the stressing rate pattern from the interseismic model. If instead, the microseismicity reflects permanent off-fault deformation, then the stresses from the focal mechanisms will resemble the residual stresses within the multi-cycle model.

C. Results

The results thus far of this on-going project 1) highlight regions of potential off-fault deformation within the San Gorgonio Pass, 2) illuminate the differences between multi-cycle and interseismic stressing rates 3) demonstrate that multi-cycle off-fault stressing rates better match the stresses associated with microseismicity and 4) show correlation of high compression with regions of high stress drop.

1. Where is the off-fault deformation in the San Gorgonio Pass?

Boundary Element Method models of multi-earthquake cycle deformation demonstrate the partitioning of deformation as along fault slip and off-fault strain. The resulting velocity along the Earth's surface projected into the 145˚ (fault parallel) orientation reveals that while most of the deformation within the San Gorgonio Pass is taken up as strike-slip along faults (vertical risers on Fig. 1), some fault parallel strain is accommodated within the San Bernardino Mountains as distributed off-fault deformation (warped surface on Fig. 2 under the text of San Bernardino Mountains). A variety of deformation mechanisms may accommodate fault-parallel shear within the San Bernardino Mountains including slip on

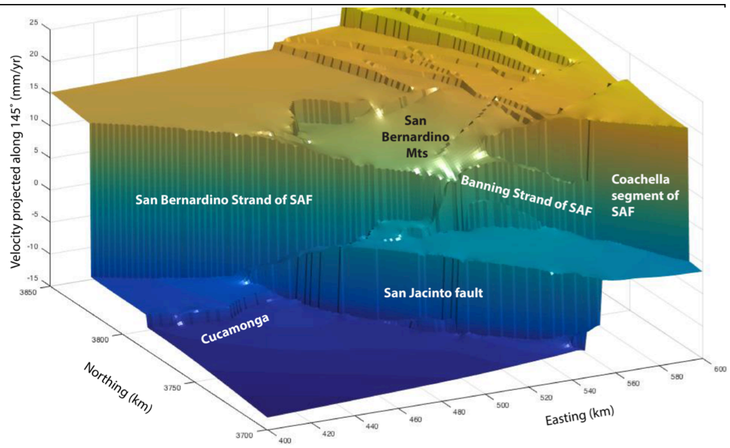

Figure 2: Fault parallel (145˚) velocities. Vertical risers indicate fault parallel velocities taken up as slip rates along faults and warped surfaces indicate strain within the host rock. Fault slip rates decrease within the SGP. Because off-fault deformation within the San Bernardino Mts. accounts for a portion of the strain, the fault slip rates do not sum to the plate rate.

surfaces that yields microseismicity.

2. How are the multi-cycle stressing rates different from the interseismic stressing rates?

The interseismic and off-fault crustal deformation models show distinct stressing rate patterns. The interseismic model with deep slip along faults below the locking depth produces a predominantly strike-slip stress regime consistent with the deep slip along the San Andreas fault. In contrast, the multi-cycle model has a spatially heterogeneous stress regime with some areas favoring strike-slip faulting whereas other areas favor thrust and normal faulting. Within the multi-cycle model, the predominant strike-slip stresses are relieved by fault slip, and the residual stresses that develop around fault irregularities do not necessarily reflect the overall strike-slip stress regime of the transform plate margin. The stress inversions from focal mechanisms of the San Gorgonio Pass region display a range of stress regimes [*Yang et al.,* 2012; *Goebel et al.,* 2015].

3. Is the seismic catalog revealing interseismic stressing patterns or off-fault deformation in the SGP?

Correlation of stressing rates from both the interseismic and multicycle models to stress inversions from southern California focal mechanisms by *Yang et al*. [2012] show that the residual off-fault stressing rate pattern of the multi-cycle model better matches the pattern from the stress inversions (Fig. 3). The focal mechanism inversions show relatively tensile mean normal stress between the San Jacinto and SAF and also within the eastern portion of the SGP (Fig. 3B). Between the San Jacinto and San Andreas faults, this dilation owes to right-lateral slip along the San Jacinto fault, which brings the region into relative tension. The normal stress in eastern portion of the SGP may arise from the increased right lateral slip from the Banning strand to the Coachella segment of the SAF. These regions of relatively high mean normal stress are not evident in the interseismic stress rate pattern, which is dominated by strike-slip along the SAF (Fig. 3A). The correlation coefficient between the focal mechanism stress inversion and the interseismic stressing pattern is low (r = 0.007). The residual off-fault stressing rates of the multi-cycle model produce relatively high mean normal stress in the same locations as the focal mechanism inversions (outlined in grant on Figure 3C). The correlation coefficient between the focal mechanism stress inversions and the off-fault stressing rate pattern is much higher than between the stress inversions and the interseismic stressing rates (r = 0.041 >> 0.007).

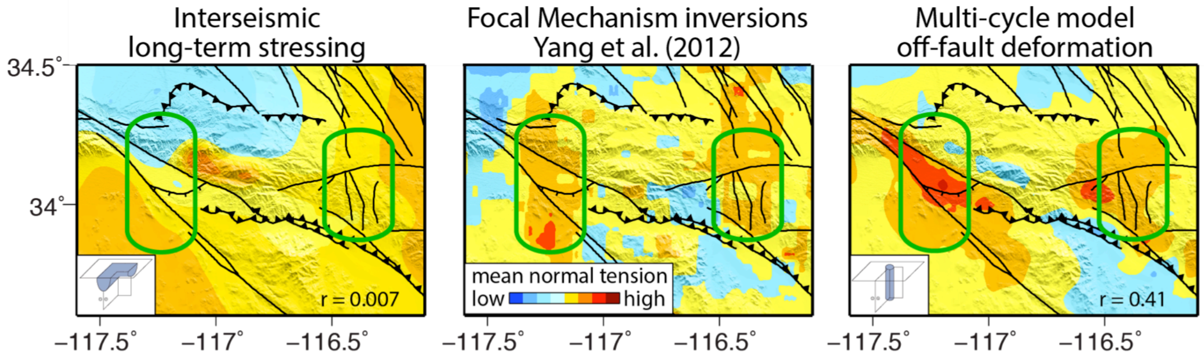

Figure 3: Mean normal stressing rate from (A) interseismic and (B) off-fault models compared to (C) the focal mechanism inversions of Yang et al., [2012]. The green lines outline areas of greater relative tension (warmer colors) in the focal mechanism inversion. Within the San Gorgonio Pass region the stress pattern from the focal mechanism inversions have better match to the off-fault stressing rate (correlation coefficient, r = 0.41) than to the interseismic stressing rate (r = 0.007). This correlation suggests that the seismic catalog in the SGP region undersamples strike-slip events that would reveal interseismic loading of the San Andreas fault and instead these earthquakes record permanent deformation off of the major faults.

4. Could off-fault deformation account for anomalously high stress drops in the SGP?

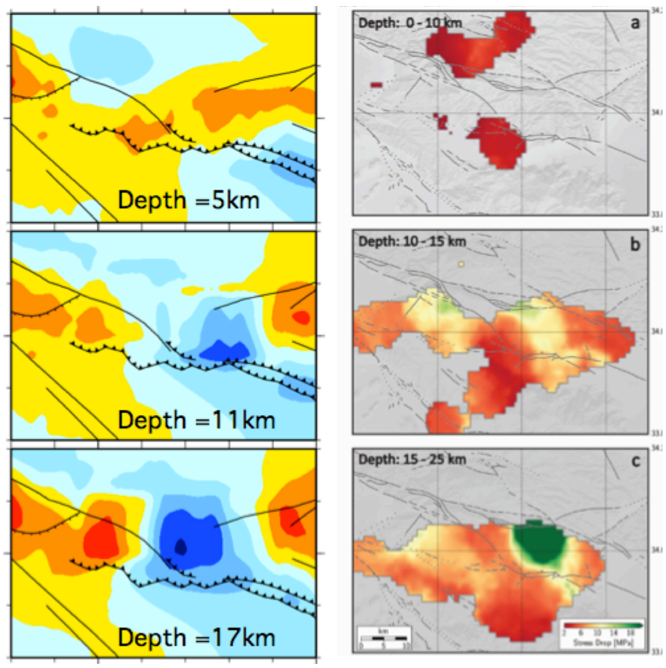

Figure 4: left column) Mean normal stressing rate from different depths of the multi-cycle off-fault deformation model. Right column) Focal mechanism stress drop at different depths from Goebel et al. (2015). The location of high stress drop coincides with high potential off-fault clamping (negative mean normal stress).

The multi-earthquake cycle models with residual off-fault stressing show spatially variable mean normal stress that correlate with spatial variations in stress drop analyzed by *Goebel et al*. [2015] (Fig. 4). The SGP hosts a region of >18 MPa stress drop, larger than observed elsewhere in southern California [*Goebel et al.,* 2015]. These anomalously high stress drops occur at 15-25 km depth within the foot wall of the San Gorgonio Pass thrust. The location and depth of these high stress drops closely correlates to locations of negative first stress invariant, high mean compression (blue on Fig. 4), in the off-fault stressing rates. This suggests that localized compression around the restraining bend may account for the anomalously high stress drops. The small micro-faults off of the primary fault structures are clamped by this high compression so that they behave as stronger faults and produce larger stress drops. Locally high stress drops could be attributed to local increases in fault static frictional strength [Goebel et al., 2015]. However, heterogeneous fault strength is not required if the normal compressive stress is high within the region of high stress drop.

D. Conclusions

The correlation of stress patterns from focal mechanism inversions with patterns of off-fault stressing rate over multiple earthquake cycles suggests that the microseismicity of the San Gorgonio Pass region may be recording permanent off-fault deformation that is distinctly different from the long term loading of the San Andreas fault. The stressing rate models within the SCEC Community Fault Model produce a strike-slip stress regime within the San Gorgonio Pass [*Hardebeck*, 2014] in disagreement with focal mechanism stress inversions. This suggests that our current seismic catalog under-samples large strike-slip events along the SAF. Instead, the stress inversions from the seismic catalog provide more information about permanent distributed off-fault deformation than loading of the faults.

The spatial correlation of mean normal compressive stress with regions of high stress drop from the focal mechanism inversions suggests that small faults here effectively strengthened due to localized clamping. High fault strength is consistent with long recurrence times of ruptures though the San Gorgonio Pass [*Yule et al.,* 2014]. The multi-cycle model assumes uniform fault strength so the variation in mean normal stress is entirely due to the influence of fault geometry. This study suggests that spatial variation in stress drop does not require higher explicit fault strength but the heterogeneous stress state can alter apparent fault strength.

E. References

Bird, P., 2009, Long-term fault slip rates, distributed deformation rates, and forecast of seismicity in the western United States from joint fitting of community geologic, geodetic, and stress direction data sets: *Journal of Geophysical Research Solid Earth,* v. 114.

Blisniuk, K., K. M. Scharer, W. D. Sharp, R. Burgmann, M. J. Rymer, and P. L. Williams (2013), New slip rate estimates for the Mission Creek strand of the San Andreas fault zone, paper presented at AGU Fall Meeting, American Geophysical Union, San Francisco, CA

Cooke, M.L., and Marshall, S.T., 2006, Fault slip rates from three-dimensional models of the Los Angeles metropolitan area, California: *Geophysical Research Letters* 33.21.

Cooke, Michele L., Mariel T. Schottenfeld and Steven W. Buchanan, 2013. Evolution of Fault Efficiency at Restraining Bends within Wet Kaolin*, Journal of Structural Geology,* doi:10.1016/j.jsg.2013.01.010.

Cooke, M.L., and Dair, L.C., 2011, Simulating the recent evolution of the southern big bend of the San Andreas fault, Southern California: *Journal of Geophysical Research* 116, B04405, doi:10.1029/2010JB007835.

Dair, L., and Cooke, M.L., 2009, San Andreas Fault geometry through the San Gorgonio Pass, California. *Geology* [Boulder] 37, p. 119–122.

Goebel, T. H. W., Becker, T. W., Sammis, C. G., Dresen, G., & Schorlemmer, D., 2014. Off-fault damage and acoustic emission distributions during the evolution of structurally complex faults over series of stick-slip events. *Geophysical Journal International*, *197*(3), 1705-1718.

Goebel, T. H. W., et al., 2015, Stress-drop heterogeneity within tectonically complex regions: a case study of San Gorgonio Pass, southern California: *Geophysical Journal International*, v. 202.1, p. 514-528.

Gold, P.O., et al., 2015, Holocene geologic slip rate for the Banning strand of the southern San Andreas Fault, southern California: *Journal of Geophysical Research Solid Earth*, v. 120.8, p. 5639-5663.

Hardebeck, J., 2014. Current status of the CSM, at SCEC Community Stress Model Workshop October 27, 2014.

Hauksson, E. 2014. Average Stress Drops of Southern California Earthquakes in the Context of Crustal Geophysics: Implications for Fault Zone Healing. *Pure and Applied Geophysics*, 1-12.

Herbert, J.W., and Cooke, M.L., 2012, Sensitivity of the Southern San Andreas Fault System to Tectonic Boundary Conditions and Fault Configurations: *Bulletin of the Seismological Society of America* 102, p. 2046–2062.

Herbert, J.W., Cooke, M.L., Oskin, M., and Difo, O., 2014a, How much can off-fault deformation contribute to the slip rate discepency within the Eastern California shear zone?: *Geology* [Boulder] 42(1). P. 71-75. doi:10.1130/G34738.1.

Herbert, Justin W., Michele L. Cooke and Scott T. Marshall, 2014b. Influence of fault connectivity on slip rates in southern California: Potential impact on discrepancies between geodetic derived and geologic slip rates, *Journal of Geophysical Research Solid Earth*, doi:10.1002/2013JB010472K.J.

Kendrick, K.J., Matti, J.C., Mahan, S.A., (2015), Late Quaternary slip history of the Mill Creek strand of the San Andreas fault in San Gorgonio Pass, southern California: The role of subsidiary left-lateral fault in strand switching: *GSA Bulletin*, v. 127, no. 5/6, p. 825-849

Johnson, K. M., 2013, Slip rates and off-fault deformation in Southern California inferred from GPS data and models: *Journal of Geophysical Research Solid Earth*, v. 118.10, p. 5643-5664.

Loveless, J.P., and Meade, B.J. , 2011, Stress modulation on the San Andreas fault by interseismic fault system interactions: *Geology*, 39.

Marshall, S.T., Cooke, M.L., and Owen, S.E., 2008, Effects of Nonplanar Fault Topology and Mechanical Interaction on Fault-Slip Distributions in the Ventura Basin, California: *Bulletin of the Seismological Society of America* 98, p. 1113–1127.

Marshall, Scott T, Michele L. Cooke and Susan E. Owen, 2009. Interseismic Deformation Associated with Three-Dimensional Faults in the Greater Los Angeles Region, California, *Journal of Geophysical Research,* v, 114, B12403, doi:10.1029/2009JB006439.

Matti, J.C., Morton, D.M., and Cox, B.F., 1992, The San Andreas fault system in the vicinity of the central Transverse Ranges province, Southern California (No. 0196-1497). U. S. Geological Survey : Reston, VA, United States, United States.

McGill, S. F., Owen, L. A., Weldon, R. J., & Kendrick, K. J. (2013). Latest Pleistocene and Holocene slip rate for the San Bernardino strand of the San Andreas fault, Plunge Creek, Southern California: Implications for strain partitioning within the southern San Andreas fault system for the last~ 35 ky.*Geological Society of America Bulletin*, *125*(1-2), 48-72.

Meigs, A.J., Cooke, M.L., and Marshall, S.T., 2008, Using vertical rock uplift patterns to constrain the three-dimensional fault configuration in the Los Angeles Basin: *Bulletin of the Seismological Society of America* 98, p. 106–123.

Morelan, Alexander, Michael Oskin, Judith Chester, and Daniel Elizondo, 2014 Active slip on the Mill Creek fault rhough the San Gorognio Pass, paper presented at *Southern California Earthquake Center Annual Meeting*, Palm Springs, CA.

Oskin, Michael E., Alex E. Morelan, Daniel Elizondo, and Judith S. Chester, 2015. Assessing fault structure and recent activity of the Mill Creek fault across Yucaipa Ridge and Upper Raywood Flat, San Gorgonio Pass Region, paper presented at *Southern California Earthquake Center Annual Meeting*, Palm Springs, CA.

Scharer, K. M., K. Blisniuk, W. Sharp, P. Williams, and K. Johnson (2014), Vertical deformation along the Indio Hills, San Andreas Fault, California, paper presented at *Southern California Earthquake Center Annual Meeting*, Palm Springs, CA..

Plesch, A., Shaw, J.H., Benson, C., Bryant, W.A., Carena, S., Cooke, M.L., Dolan, J., Fuis, G.S., Gath, E., Grant, L., Hauksson, E., Jordan, T., Kamerling, M., Legg, M., Lindvall, S., Magistrale, H., Nicholson, C., Niemi, N., Oskin, M., Perry, S., Planansky, G., Rockwell, T., Shearer, P., Sorlien, C., Suess, M.P., Suppe, J., Treiman, J., and Yeats, R., 2007, Community fault model (CFM) for Southern California. *Bulletin of the Seismological Society of America* 97, p. 1793–1802.

Shelef, E., and Oskin, M., 2010, Deformation processes adjacent to active faults: Examples from eastern California: *Journal of Geophysical Research*, v. 115, B05308, p. 1–24, doi:10.1029 /2009JB006289.

Thomas, A.L., 1993, POLY3D: A three-dimensional, polygonal element, displacement discontinuity boundary element computer program with applications to fractures, faults, and cavities in the Earth's crust. Stanford University, Stanford, California.

Titus, S.J., Dyson, M., DeMets, C., Tikoff, B., Rolandone, F., and Burgmann, R., 2011, Geologic versus geodetic deformation adjacent to the San Andreas fault, central California: Geological Society of America Bulletin, v. 123, p. 794– 820, doi:10.1130/B30150.1.

Wersan, Louis, 2015. Reinvestigating the Mission Creek fault: Holocene slip rates in the northern Coachella Valley and implications for southern California earthquake hazard assessment. Paper presented at the *Geological Society of America annual meeting*.

Working Group on California Earthquake Probabilities, 2008, The Uniform California Earthquake Rupture Forecast, Version 2 (UCERF 2): U.S. Geological Survey Open-File Report 2007-1437 and *California Geological Survey Special Report 203* [http://pubs.usgs.gov/of/2007/1437/].

Yang, W., E. Hauksson and P. M. Shearer, Computing a large refined catalog of focal mechanisms for southern California (1981 - 2010): Temporal Stability of the Style of Faulting, *Bull. Seismol. Soc. Am.*, June 2012, v. 102, p. 1179-1194, doi:10.1785/0120110311, 2012.

Yule, D., and Sieh, K., 2003, Complexities of the San Andreas Fault near San Gorgonio Pass; implications for large earthquakes: *Journal of Geophysical Research* 108.

Yule, D., R. Heermance, I. Desjarlais, and K. Sieh (2014), Late Pleistocene and Holocene Rates of Slip and Size of Prehistoric Earthquakes on the San Andreas Fault System in San Gorgonio Pass, in *Southern California Earthquake Center Annual Meeting*, edited, Palm Springs, CA.