II. Technical Report

1. Summary of Major Findings

The goal of this research has been to develop a forward model of stress state in the Cajon Pass region based on existing models of individual geodynamic processes, and to investigate the length scales over which driving stress in the region is heterogeneous. Four primary findings have resulted from SCEC Award #18150, and form the basis of several avenues of future research:

- We model the *in situ* stress field in Cajon Pass as the superposition of stress from three tectonic processes: the accumulation of stress on locked faults over variable loading times [*Smith-Konter and Sandwell*, 2009; *Tong et al*., 2013; *Burkhard et al*., 2018], the load of topography [*Luttrell and Smith-Konter*, 2017], and the far field geodynamic driving stress. We allow the magnitude and orientation of geodynamic driving stress to be free parameters, as well as the effective loading times of locked fault segments, and compare the orientations of the resulting 3-D stress field with available observations of stress state in the Cajon Pass region [*Yang and Hauksson*, 2013; *Zoback and Healey*, 1992].

- We find that along each individual fault segment, the best fitting models exhibit a tradeoff between fault segment loading time and geodynamic driving stress orientation, with more clockwise driving stress orientations requiring longer loading times to match observations. When we compare the optimal model parameters from each segment, we find that a single geodynamic driving stress with compression oriented at 16ºEofN does the best job reproducing the observed orientations, but only for very long loading times, in some cases an order of magnitude more than paleoseismic estimates of last rupture.

- We also find that the ability of the best-fitting synthesis models to reproduce observed stress orientations varies considerably along fault segments. While some segments are well fit by the best-fitting forward model (e.g., the Clark and Mojave segments), others have high misfits (e.g., the San Bernardino and Claremont segments). This persistent spatial heterogeneity even in the best-fitting model, along with the unphysically high best-fitting estimates of loading time, indicate the deficiency of the simple model presented here. It is more likely, instead, that driving stresses vary in orientation or magnitude across the region, or that a distinct source of stress not considered is contributing to the observed orientations.

- Our results indicate that major features of the *in situ* stress field orientation indicated by earthquake focal mechanism can only be reproduced with a heterogeneous plate driving stress: variations from topography and fault loading are insufficient to account for the observed stress rotations.

These findings directly support the objectives of the Community Models (CXM) and Stress and Deformation over Time (SDOT) interdisciplinary working groups to answer the basic earthquake science question of "How are faults loaded across temporal and spatial scales?" by constraining how absolute stress and stressing rate vary laterally and with depth on faults (SCEC Research Priority 1c), as well as quantifying stress heterogeneity of faults at different spatial scales (SCEC Research Priority 1d) and evaluating the time dependence of stress transfer on faults (SCEC Research Priority 1e). This project has also provided training and experience for a Graduate Student Research Assistant, LSU MS student Elliott Helgans, who worked to develop the models and synthesize the observations under the direct supervision of Luttrell.

2. DEVELOPMENT AND ANALYSIS OF SYNTHESIS MODELS OF STRESS STATE

The Cajon Pass region lies within a restraining bend of the San Andreas fault at its junction with the San Jacinto fault [e.g., *Saucier et al.,* 1992]. Long-term paleoseismic records and numerical models of dynamic rupture and faulting scenarios have led to suggestions that Cajon Pass operates as an "earthquake gate", exerting control over the propagation or arrest of large ruptures [e.g., *Lozos et al*., 2015; *Onderdonk* et al., 2015; *Onderdonk* et al., 2013; *Scharer et al*., 2010; *Lozos*, 2016]. However, these model predictions are particularly sensitive to the representation of the initial conditions of the background stress field, influencing stress drop, final rupture length, and strength of ground motions [e.g., *Lozos et al*., 2015; *Lozos*, 2016]. It is thus of primary importance to quantitatively characterize the stress field in the Cajon Pass region, including its orientation, magnitude, and dominant spatial scales of heterogeneity.

Observations of crustal stress in the Cajon Pass area are limited, with only a few direct observations from scientific boreholes [e.g., *Zoback et al*., 2010; *Zoback and Healey*, 1992]. Stress orientation has been estimated by the inversion of a catalog of earthquake focal mechanisms (FMs) [*Yang et al*., 2012; *Yang and Hauksson,* 2013], and indicates strong heterogeneity, with rotations of 30º – 60º between the Mojave, San Bernardino, and Claremont fault segments and variations in faulting regime from normal to strike-slip to thrust. The source of this heterogeneity is unclear, but could be related to patterns of stress accumulation on locked faults, or to spatial variations in the load of topography, or potentially to other factors such as heterogeneity in the geodynamic plate driving stress within the region. Identifying the nature and underlying causes of the observed stress rotations is an important step toward understanding which processes have governed stress state in the Cajon Pass during past ruptures, and which can be expected to be of primary importance during future ruptures.

We model the *in situ* stress field in Cajon Pass as the superposition of stress from three tectonic processes (Figure 1): the accumulation of stress on locked faults over variable loading times [*Smith-Konter and Sandwell*, 2009; *Tong et al*., 2013; *Burkhard et al*., 2018], the load of topography [*Luttrell and Smith-Konter*, 2017], and the far field geodynamic driving stress. We allow the magnitude and orientation of geodynamic driving stress ($\Delta\sigma_G$ and θ_G) to be free parameters, as well as the effective loading times (t_{load}) of locked fault segments (which ideally should approximate the time since last rupture if previous earthquakes achieved complete stress release). We calculate the stress field as a forward model, exploring parameter space with ~10,000 model runs. We compare the orientation of each resulting cumulative stress field with that indicated by earthquake focal mechanisms (σ_{total}) [*Yang and Hauksson*, 2013], and the loading times on each segment with paleoseismic estimates of last rupture [e.g., *McGill et al*., 2002; *Onderdonk* et al., 2013; *Onderdonk* et al., 2015; *Scharer et al*., 2010].

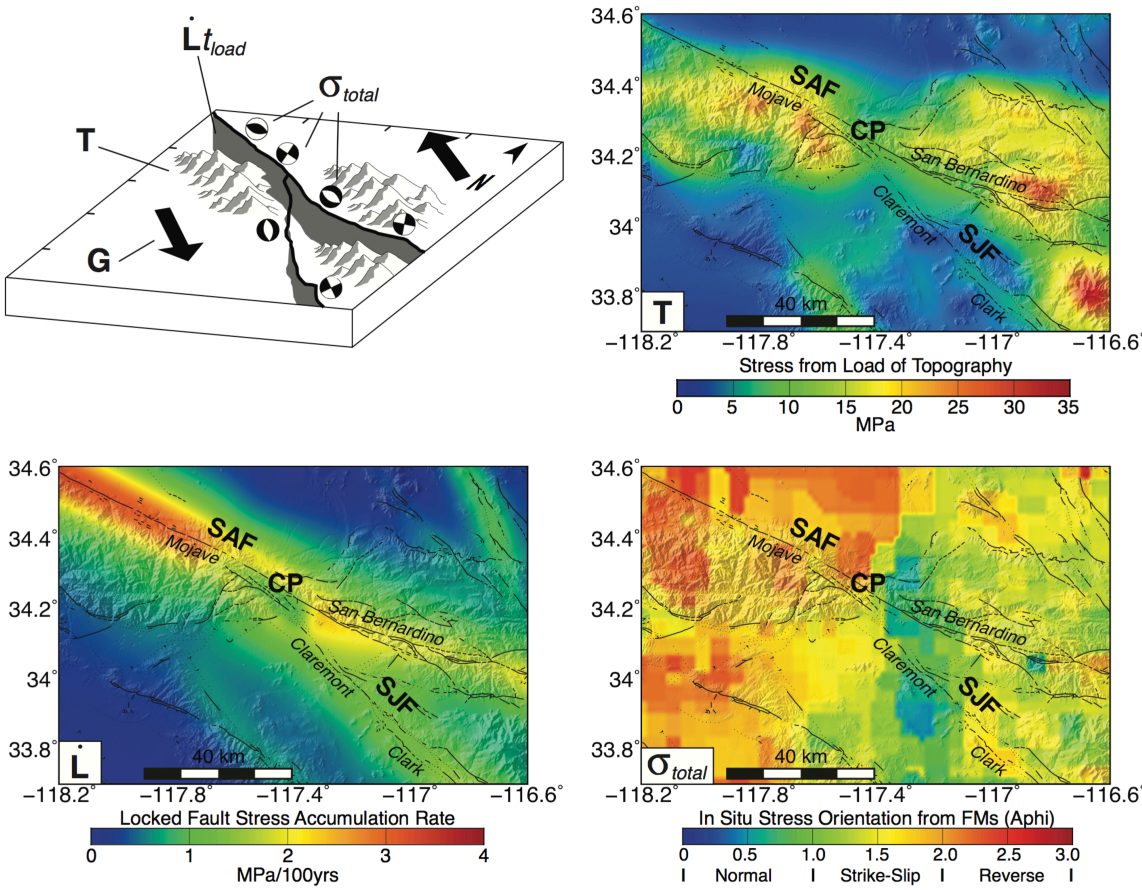

Figure 1: Components of stress considered in this study: a) schematic of stress components in the Cajon Pass region. (b) magnitude of stress from topography [*Luttrell and Smith-Konter*, 2017]. (c) stress accumulation rate due to loading of locked fault segments [*Tong et al*., 2013; Smith-Konter and Sandwell, 2009]. d) Aphi orientation of the stress field observed from earthquake focal mechanisms [*Yang and Hauksson*, 2013].

3. Synthesis Model Results: Stress Heterogeneity Goes Beyond Faults

We find that along each individual fault segment, the best fitting models exhibit a tradeoff between fault segment loading time and geodynamic driving stress orientation (Figure 2a). We then compare the best fitting model parameters for each segment to determine if any single homogeneous driving stress applied across the Cajon Pass region is capable of producing optimal fit at all segments simultaneously, given the corresponding best-fitting loading times (Figure 2b – 2h). While overall misfits to FM orientation improve with increased magnitude of geodynamic driving stress up to ~30 MPa, a lower differential stress of ~10 MPa results in the most reasonable fault loading time estimates. When we compare the optimal model parameters from each segment, we find that a single geodynamic driving stress with compression oriented at 16ºEofN does the best job reproducing the observed orientations, but only for very long loading times, in some cases an order of magnitude more than paleoseismic estimates of last rupture.

We also find that the ability of the best-fitting synthesis models to reproduce observed stress orientations varies considerably along fault segments (Figure 3). The numerically best fitting model (Figure 3a), with a homogenous driving stress with differential magnitude 30 MPa and SHmax orientation 16ºEofN, along with corresponding best-predicted loading times (Figure 2h), is compared to the orientation indicated by earthquake focal mechanisms [*Yang and Hauksson*, 2013] (Figure 3b). Misfit is quantified using a scalar metric calculated as one minus the normalized 3D tensor dot product between the two fields, such that 0 indicates perfect 3-D alignment and 1 represents arbitrary misalignment. While some segments are well fit by the "best-fitting forward model" (e.g., the Clark and Mojave segments), others have high misfits of ≥ 0.5 (e.g., the San Bernardino and Claremont segments). This persistent spatial heterogeneity even in the best-fitting model, along with the unphysically high best-fitting estimates of loading time, indicate the deficiency of the simple model presented here. It is more likely, instead, that driving stresses vary in orientation or magnitude across the region, or that a distinct source of stress not considered is contributing to the observed orientations.

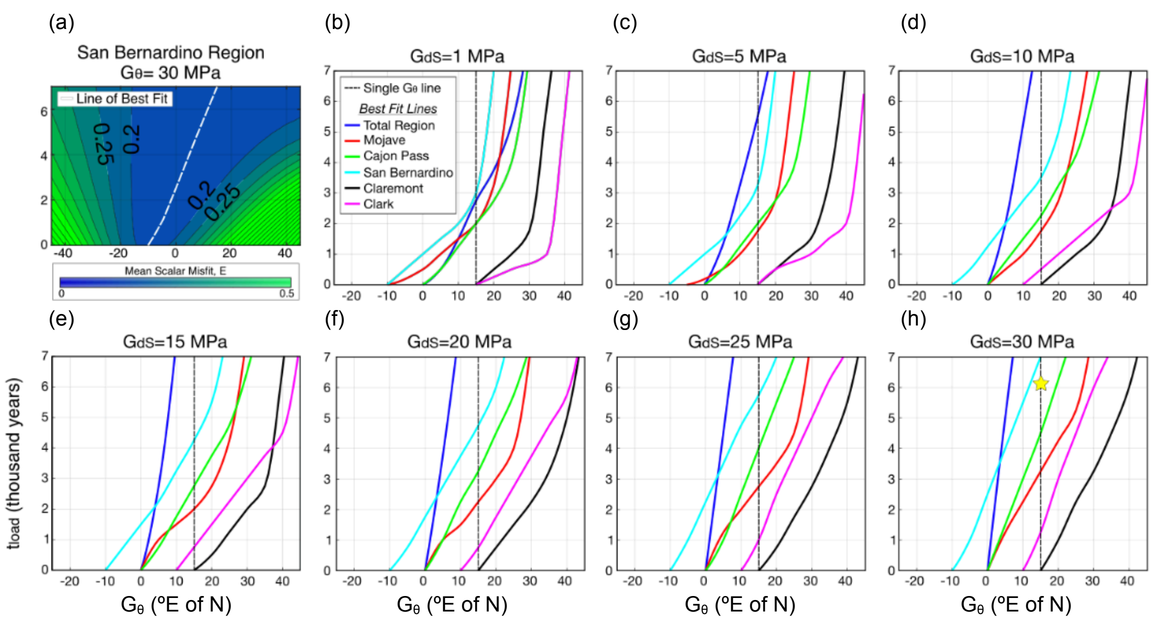

Figure 2: Best-fitting model parameters assuming a uniform geodynamic driving stress: (a) model misfit in parameter space for a single fault segment (San Bernardino). Minimum misfit (dashed white line) involves a tradeoff between driving stress orientation (G_θ) and locked fault loading time (t_{load}). (b-h) lines of best fitting parameter space for each of 6 considered fault segment subregions. Dashed line indicates the best-fitting driving stress orientation, i.e. the orientation across model space. Yellow star in (h) indicates the parameters that are used to construct the best fitting model shown in Figure 3a.

4. Toward Quantifying Synthesis Model Uncertainty and Sensitivity

The results of these investigations, thus far, are intriguing and informative. One might expect that the presence of high topography and major locked faults in the Cajon Pass region should dominate the pattern of observed stress, but the counter-observation that another source of variation is required raises interesting questions about the sensitivity of this fault system to spatio-temporal variations in plate-driving stresses. However, before such implications can be fully explored, it is crucial to quantify the uniqueness of the model results. In particular, it is important to describe: (1) the sensitivity of these stress estimates to various model parameters, (2) the degree to which the limited available observations of stress control best-fitting model solutions, and (3) the degree to which these model results are consistent with the predictions of other community models in the area. The issues of model validation and uncertainty have been a key concern to the SCEC Community Models, especially for the Community Stress Model for which direct observations are so rare. The next steps of this research will be to quantify the non-uniqueness of the synthesis stress models in the Cajon Pass region, with the goal of improving the utility of this modeled stress contribution for the potential user community, including as a potential background stress state and initial conditions for future dynamic rupture simulations in the region.

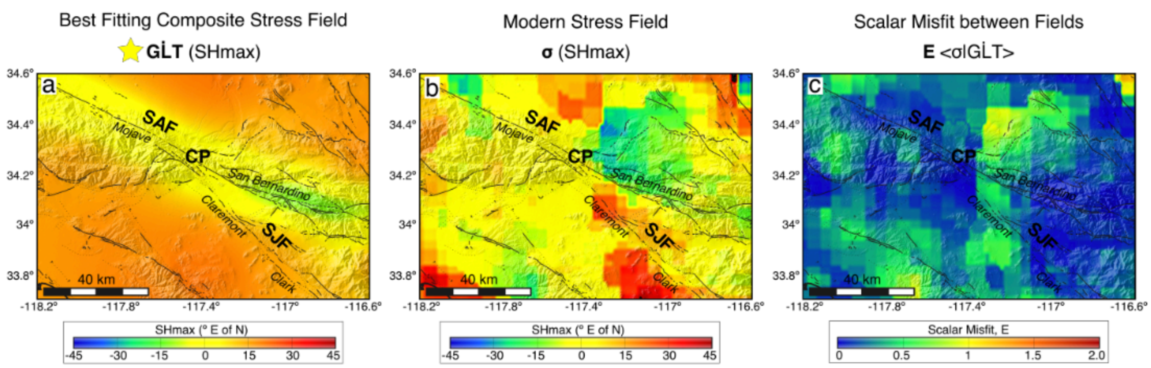

Figure 3: Comparison of best-fitting forward model using a uniform geodynamic driving stress with observed stress field orientation: (a) SHmax orientation of the best-fitting forward model from this study using a uniform geodynamic driving stress with parameters indicated by yellow star in Figure 2. (b) SHmax orientation of the stress field observed from earthquake focal mechanisms [*Yang and Hauksson*, 2013]. (c) map of scalar misfit between best-fitting forward model and observed stress orientations (0 indicates perfect 3-D alignment, 2 indicates perfect 3-D misalignment, and 1 indicates arbitrary misalignment).

Funding from this award was used to support 1.4 semesters of work by LSU graduate student Elliott Helgans to develop and analyze models of in situ stress state in the Cajon Pass area. This ongoing work was presented at the 2018 SCEC Annual Meeting [*Helgans et al*., 2018a], the 2018 Fall AGU meeting [*Helgans et al*., 2018b], in an invited seminar [*Luttrell*, 2018], and at the 2019 SCEC CSM Workshop [*Luttrell*, 2019], and continues to mature toward the publication of a peer-reviewed journal article.

REFERENCES CITED

Burkhard, L., B. Smith-Konter, L. Ward, K. Scharer, and D. Sandwell (2018) Earthquake cycle stress accumulation disparities of the Cajon Pass region, SCEC Annual Meeting poster 262.

Helgans, E., K. Luttrell, and B. Smith-Konter (2018), Multicomponent Model of Crustal Stress at Cajon Pass with Stress Field Heterogeneity Implications, SCEC Annual Meeting poster 259.

Helgans, E., K. Luttrell, and B. Smith-Konter (2018), Multicomponent Model of Crustal Stress at Cajon Pass with Implications for Stress Field Heterogeneity, EOS Trans. AGU, Fall Meeting Suppl., Abstract.

Lozos, J. C. , D. D. Oglesby, J. N. Brune, and K. B. Olsen (2015) Rupture and ground-motion models on the northern San Jacinto fault, incorporating realistic complexity. *Bull. Seismol. Soc. Am.105,* 1, 387-399, doi:10.1785/0120140114.

Lozos, J.C., (2016) A case for historic joint rupture of the San Andreas and San Jacinto faults, *Sci. Adv.,* **2**(3), doi:10.1126/sciadv.1500621.

Luttrell, K (2018), How stressed are we really? Insights into the crustal stress field in southern California, Departmental Seminar, Department of Geology and Geophysics, Louisiana State University, September 2018.

Luttrell, K. (2019), Using local topography to constrain absolute stress, SCEC Community Stress Model workshop, January 2019, Pomona, CA.

Luttrell, K., and B. Smith-Konter (2017), Limits on crustal differential stress in southern California from topography and earthquake focal mechanisms, *Geophys. J. Int., 211*, 472-482, doi:10.1093/gji/ggx301.

McGill, S., S. Dergham, K. Barton, T. Berney-Ficklin, D. Grant, C. Hartling, K. Hobart. R. Minnich, M. Rodriguez, E. Runnerstrom, J. Russell, K. Schmaker, M. Stomfall, J. Townsend, and J. Williams (2002) Paleoseismology of the San Andreas Fault at Plunge Creek, near San Bernardino, Southern California, *Bull. Seismol. Soc. Am., 92,* (7), 2903-2840, doi:10.1785/0120000607.

Onderdonk, N. W., S. F. McGill, T. K. Rockwell (2015) Short-term variations in slip rate and size of prehistoric earthquakes during the past 2000 years on the northern San Jacinto fault zone, a major plate-boundary structure in southern California, *Lithosphere, 7,* (3) 211 – 234, doi:13.1130/L393.1.

Onderdonk, N. W., T. K. Rockwell, S. F. McGill, and G. I. Marliyani, (2013) Evidence for seven surface ruptures in the past 1600 years on the Claremont fault at Mystic Lake, northern San Jacinto fault zone, California, *Bull. Seismol. Soc. Am. 103*, 519–541, doi:10.1785/0120120060.

Saucier, F., E. Humphreys, and R. Weldon (1992) Stress Near Geometrically Complex Strike-Slip Faults: Application to the San Andreas Fault at Cajon Pass, Southern California, *J. Geophys. Res., 97*, (84) 5081-5094.

Scharer, K. M., G. P. Biasi, R. J. Weldon, and T. E. Fumal (2010) Quasi-periodic recurrence of large earthquakes on the southern San Andreas fault, *Geology*, *38*, (6), 555-558, doi:10.1130/G30746.1.

Smith-Konter, B. and D.T. Sandwell (2009), Stress evolution of the San Andreas Fault System: Recurrence interval versus locking depth, *Geophys. Res. Lett.*, 36, doi:10.1029/2009GL037235.

Tong, X., D. T. Sandwell, and B. Smith-Konter (2013), High-resolution interseismic velocity data along then San Andreas Fault from GPS and InSAR, *J. Geophys. Res. Solid Earth*, *118*, 369-389, doi:10.1029/2012JB009442.

Yang, W., and E. Hauksson (2013), The tectonic crustal stress field and style of faulting along the Pacific North America Plate boundary in Southern California, *Geophys. J. Int.*, 194, doi:10.1093/gji/ggt113.

Yang, W., E. Hauksson, and P. M. Shearer (2012), Computing a Large Refined Catalog of Focal Mechanisms for Southern California (1981-2010): Temporal Stability of the Style of Faulting, *Bull. Seismol. Soc Am.*, *102*(3), 1179-1194, doi:10.1785/0120110311.

Zoback, M. D., and J. H. Healy (1992), In situ stress measurements to 3.5 km depth in the Cajon Pass Scientific Research Borehole: Implications for the mechanics of crustal faulting, *J. Geophys. Res.*, *97*(B4), 5039, doi:10.1029/91jb02175.

Zoback, M. D., S. Hickman, and W. Ellsworth (2010), Scientific Drilling Into the San Andreas Fault Zone, *Eos Trans. AGU*, *91*(22), 197-199, doi:10.1029/2010EO220001.