2016 SCEC Annual Report

4D Stress Evolution Models of the San Andreas Fault System Using Improved Geodetic and Paleoseismic Constraints

1. Abstract

Major earthquakes of the San Andreas Fault System (SAFS) are thought to occur when accumulated fault stress in the upper locked portion of the crust exceeds some threshold value. 4D simulations of stress evolution provide rare insight into earthquake cycle crustal stress variations at seismogenic depths where earthquake ruptures nucleate, however we emphasize two important details: 1) modeled stress accumulation through time is largely prescribed by the assumed slip history, and thus these results highlight the need for continual improvements to and utilization of contemporary paleoseismic chronologies; 2) improved resolution and accuracy of the near-fault velocity field using new, integrated GPS and InSAR data is critical for improving strain and stress rate models of the SAFS, particularly in areas where the GPS array spacing is inadequate for resolving small variations in locking depth. Utilizing new SCEC community paleoseismic and geodetic data, our refined 4D stress models are used to explore the temporally and spatially varying stress rates and threshold conditions, and the sensitivity of these results on fault locking depth, for major segments of the SAFS. Our new estimates of stress accumulation rate in Southern California are most significant along the Imperial (2.8 MPa/100yr) and Coachella (1.2 MPa/100yr) faults, consistent with an 11-17% change in stress rate due to locking depth and geologic slip rate parameter updates over the last 5 years. Revised estimates of present-day earthquake cycle stress accumulation in Southern California are most significant along the Imperial (2.25 MPa), Coachella (2.9 MPa), and Carrizo (3.2 MPa) segments, consistent with a 15-29% decrease in stress due to locking depth, geologic slip rate parameter updates, and postseismic relaxation from the El Mayor-Cucapah earthquake.

2. TECHNICAL REPORT FOR 2016 SCEC PROPOSAL 16177

FUNDED PROPOSALS RELATED TO THIS PROJECT:

NSF EarthScope ($224,597) 8/01/16 - 7/31/19; Imaging Vertical Earthquake Cycle Crustal Deformation of the San Andreas Fault System Utilizing the GAGE Facility.

PUBLICATIONS AND ABSTRACTS RELATED TO THIS PROJECT:
*Underline denotes student authorship

In preparation:
Solis, T., and B. Smith-Konter (2017), Estimating variations in locking depth for the Mojave segment of the San Andreas fault over the past 1500 years from paleoseismic stress drop, *to be submitted to BSSA*.

Luttrell, K. and B. Smith-Konter (2017), Regional-scale models of crustal stress in southern California with implications for heterogeneous tectonic loading and in situ stress magnitude, *to be submitted to J. Geophys. Res*.

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Luttrell, K. and B. Smith-Konter (2017), Limits on crustal differential stress in southern California from topography and earthquake focal mechanisms, submitted to *Geophys. J. Int.*, GJI-17-0126, in revision.

Howell, S., B. Smith-Konter, N. Frazer, X. Tong, and D.T. Sandwell (2016), The vertical fingerprint of earthquake-cycle loading in Southern California, *Nature Geosciences*, doi: 10.1093/2015-03-04591.

Luttrell, K., and B. Smith-Konter (2016), Regional-scale models of crustal stress in Southern California, with implications for heterogeneous tectonic loading and in situ stress magnitude, *SSA Annual Meeting*, Abstract 16-698.

Luttrell, K. and B. Smith-Konter (2016), Regional-scale models of crustal stress along the Pacific-North American plate boundary, with implications for heterogeneous tectonic loading and in situ stress magnitude, 2016 *GSA South-Central Section Meeting,* Abstract #273845*,* Baton Rouge, LA.

Luttrell, K. and B. Smith-Konter (2016), How stressed are we really? Harnessing community models to characterize the crustal stress field in Southern California, 2016 *SCEC Annual Meeting*, Plenary Talk Presentation, Palm Springs, CA.

Smith-Konter, B., K. Luttrell, X. Tong, and D.T. Sandwell (2016), 4D stress evolution models of the San Andreas Fault System using improved geodetic and paleoseismic constraints, *2016 SCEC Annual Meeting*, Abstract 010, Palm Springs, CA.

Tong, X., A. Gonzalez-Ortega, B. Smith-Konter, and D.T. Sandwell (2016), Postseismic deformation and viscosity of the Mexicali region following the El-Mayor Cucapah earthquake inferred from GPS observations, *2016 SCEC Annual Meeting*, Abstract 156, Palm Springs, CA.

Gonzalez-Huizar, H., S. Hardy, and B. Smith-Konter (2016), Investigating tremor sources along the San Andreas Fault using integrated static and dynamic stress models, *2016 SCEC Annual Meeting*, Abstract 179, Palm Springs, CA.

PROJECT SUMMARY

The primary objective of this project was to investigate plate boundary stress evolution of the San Andreas Fault System (SAFS). Our continually developing stress simulations carry important implications for seismic hazard analyses, however we emphasize two important details: 1) modeled stress accumulation through time (Figure 1) is largely prescribed by the assumed slip history, and thus these results highlight the need for continual improvements to and utilization of contemporary paleoseismic chronologies; 2) improved resolution and accuracy of the near-fault velocity field using new, integrated GPS and InSAR data is critical for improving strain and stress rate models of the SAFS (Figure 2), particularly in areas where the GPS array spacing is inadequate for resolving small variations in locking depth. Hence, for this project we performed a new analysis of earthquake cycle stress evolution using contemporary geologic and paleoseismic data (slip rates, rupture dates, slip estimates, and uncertainties in these data), observations of surface deformation from the Community Geodetic Model (CDM), and a refined 4D earthquake cycle model of the SAFS. Moreover, to accurately investigate plate boundary stress evolution and the spatial/temporal occurrence of major earthquakes of the SAFS, we focused our investigation on the following scientific tasks:

• *Task 1: Refine 4D stress rate and stress accumulation models constrained by new CGPS & InSAR data.*

• *Task 2: Integrate recently published paleoseismic chronologies into new stress models.*

• *Task 3: Investigate time- and depth-dependent stress thresholds for major segments of the SAFS.*

We are pleased to report that we have made significant progress on these tasks in a reasonable time frame and have presented our results at several meetings and the 2016 SCEC Annual Meeting. Four primary activities and findings have resulted from this work, described in further detail in the following pages:

1) Using SCEC/EarthScope GPS and ALOS InSAR data, in addition to UCERF3 fault database modifications, we have tuned model locking depths and slip rates to best fit these data, and have run new earthquake cycle stress simulations to reflect changes in these critical faulting parameters.

2) Revised estimates of stress accumulation rate in Southern California are most significant along the Imperial (2.8 MPa/100yr) and Coachella (1.2 MPa/100yr) faults, consistent with an 11-17% change in stress rate due to locking depth and geologic slip rate parameter updates. (Figure 2)

3) Revised estimates of earthquake cycle stress accumulation in Southern California are most significant along the Imperial (2.25 MPa), Coachella (2.9 MPa), and Carrizo (3.2 MPa) segments, consistent with a 15-29% decrease in stress due to

locking depth, geologic slip rate parameter updates, and postseismic relaxation from the El Mayor-Cucapah earthquake. (Figure 3)

4) In conjunction with SCEC Award #16090, using 3-D stress from topography and earthquake cycle loading, we found best-fitting fault segment loading threshold times and found these to be low on the SAF and SJF, and high on the Elsinore and ECSZ, consistent with expected earthquake recurrence interval on each fault. We were also able to identify absolute lower bounds on the regional stress magnitude of 30 MPa NNE principal compression and 10 MPa ESE principal tension (*Luttrell and Smith-Konter*, 2017).

For this project, our goal was to utilize high-accuracy CDM/UNAVCO PBO GPS measurements to estimate the 3D strain and stress fields at length scales greater than the typical GPS spacing of ~10 km. Contributions from ALOS L-band radar interferograms were used to estimate the strain field at shorter length scales. Using methods and results from *Wei et al*. (2010) and *Tong et al*. (2014), these two types of measurements were combined using our 4D deformation model as the interpolating function. Also included were SCEC CFM fault locations and adopted slip rate constraints from the UCERF3 modeling community (*Field et al*., 2015) and recently published studies (i.e., *Tong et al.,* 2014). We extended our dislocation model spatial domain to encompass fault segments of the Gulf of California to reflect new dense campaign GPS data across the Cerro Prieto and Imperial faults in collaboration with scientists at CICESE, Ensenada, Mexico. As this data archive is continually evolving, we will continue to refine our analyses to incorporate the most accurate representation of model fault parameter into our stress simulations.

Following significant additions to the Southern California paleoseismic database in recent years (i.e., *Blisniuk et al*., 2012; *McGill et al*., 2013; *Blisniuk et al*., 2013; *Scharer et al*., 2014; *Owen et al*., 2014; *Rockwell et al*., 2015; and many others), we have also made a first-order attempt to integrate new estimates of paleoseismic faulting histories into our 4D model to refine hindcast simulations of stress accumulation, dating as far back as 2000 years. Completion of this task requires further scrutiny from the paleoseismic community, which we hope to carry out over the next year. These data provide appreciable improvements of paleoseismic rupture dates and lengths for many regions of the southern SAFS, however confidently characterizing the extent of ruptures in context with our existing fault representation requires additional work.

Our refined stress model simulations have generated a variety of updates to our former stress rate and stress accumulation quantities (last release 2012) for several segments of the San Andreas Fault System. This work is ongoing, in conjunction with a new NSF grant recently funded, and here we report on new findings for some example segments in Southern California (Imperial, Coachella, Mojave, and Carrizo) (Figure 2). Revised slip rates (slightly decreased) for the Mojave and Coachella segments (adopted primarily from *Field et al*., 2015 and *Tong et al.,* 2014) resulted in decreases in stress rate. In 2012 we modeled these rates at 1.56 MPa/100 years (Coachella) and 1.59 MPa/100 years (Mojave), but our 2017 model estimates reduce these rates to 1.25 MPa/100 years and

1.35 MPa/100 years, respectively. The Imperial stress rate increased from our 2012 estimate (2.7 MPa/100 years) to 2.85 MPa/100years due to a combined decrease in locking depth (5.0 km) and a slightly increased slip rate. Estimates for the Carrizo segment remain largely the same between past and present model runs. For illustrative purposes, we have also provided a comparison of the stress rates (Figure 2) for different observation depths, as well as the uncertainties in stress rate as reflected by our uncertainties in locking depth for each segment. Future work will include the incorporation of slip rate uncertainty into these stress rate estimates.

Accumulation of stress over the earthquake cycle is another important quantity to assess. Our revised stress model simulations (Figure 3) suggest some significant changes to the estimated stress accumulation budget, largely in part to the modified fault parameters described above, and also due to some minor modifications to the paleoseismic slip history and postseismic relaxation from the El Mayor-Cucapah earthquake. Revised estimates of earthquake cycle stress accumulation in Southern California are most significant along the Imperial (2.25 MPa, a decrease of 0.65 MPa), Coachella (2.9 MPa, a decrease of 1.15 MPa), and Carrizo (3.2 MPa, a decrease of 0.55 MPa) segments. For illustrative purposes, we have also provided a comparison of accumulation of stress (Figure 3) for different observation depths, as well as the uncertainties in stress accumulation as reflected by our uncertainties in locking depth for each segment. These variations of stress with depth are also reflected in the 4D simulations of Figure 1, where accumulated stress below a fault locking depth results in a distinct drop to near-zero values. Future work will include the incorporation of slip rate uncertainty into these stress accumulation estimates. Continuing on from this work, UH student L. Burkhard is finalizing a new release of our 4D SAFS stress evolution visualization, which we hope to have ready for the 2017 SCEC Annual Meeting.

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3. Exemplary Figure and Supporting Figures

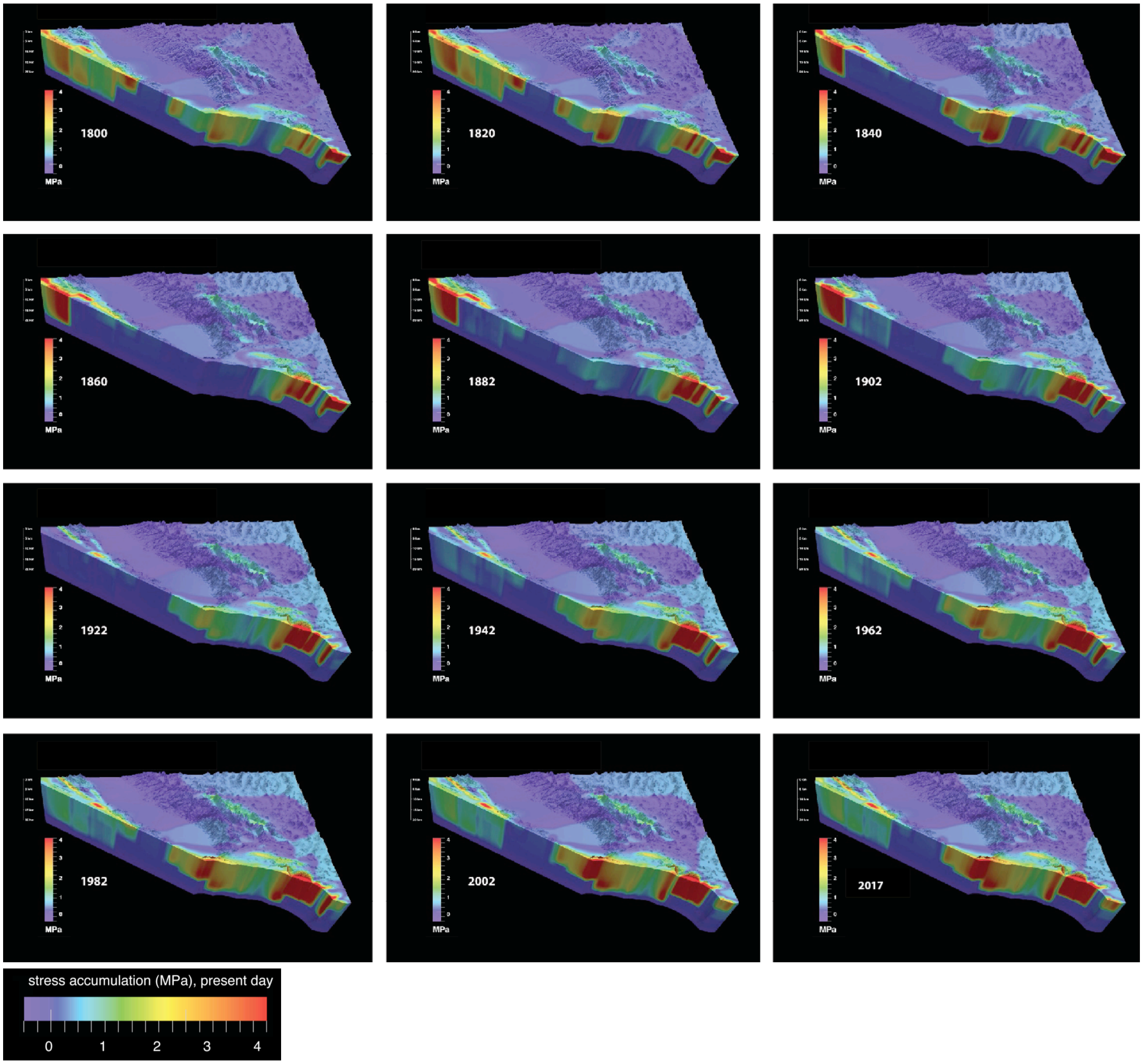

Figure 1. Sliced view of present-day (2017) Coulomb stress accumulation model of the San Andreas Fault System based on interseismic stress accumulation rates and stress changes from 112 historical and prehistorical earthquake ruptures. Stress variations with depth are due to transitions in along-strike locking depth.

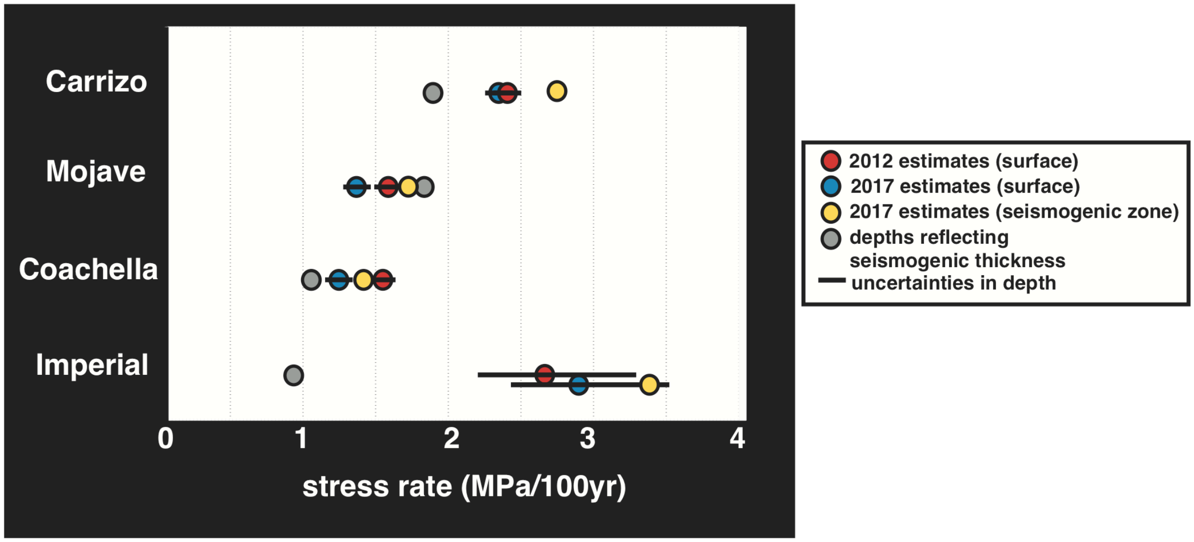

Figure 2. Inferred stress rates for the Imperial, Coachella, Mojave, and Carrizo segments resulting from variations in model fault parameters. Red dots reflect previous near-surface (0.1 km depth) stress rate results from a 2012 study (adopting parameters from *Smith and Sandwell* (2009)). Blue dots reflect results from this investigation (also near-surface (0.1 km depth)) using revised slip rates and locking depths. Yellow dots reflect stress rates from the same model as that represented by the blue dots, but now showing stress rates at depths within the seismogenic zone (or at half the locking depth for each fault segment). Gray dots reflect stress rates observed at the bottom of the seismogenic thickness, as defined by microseismicity. Uncertainties for both our past and present stress rate results are also provided, defined by the uncertainty in locking depth for each segment.

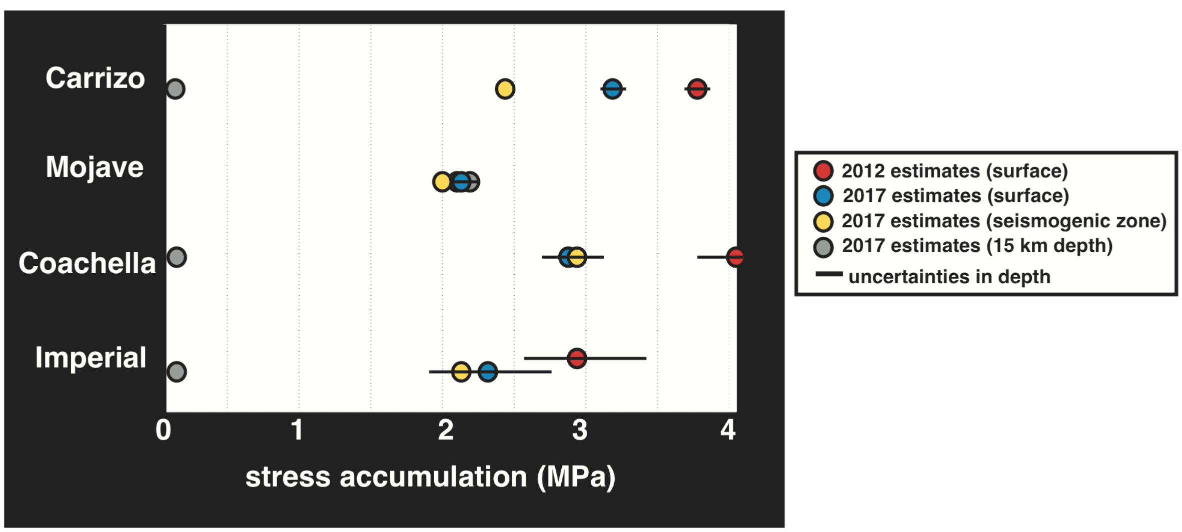

Figure 3. Inferred stress accumulation (spanning the last several earthquake cycles) for the Imperial, Coachella, Mojave, and Carrizo segments resulting from variations in model fault parameters. Red dots reflect previous near-surface (0.1 km depth) stress accumulation results from a 2012 study (adopting parameters from *Smith and Sandwell* (2009)). Blue dots reflect results from this investigation (also near-surface (0.1 km depth)) using revised slip rates and locking depths. Yellow dots reflect stress accumulation from the same model as that represented by the blue dots, but now showing stress at depths within the seismogenic zone (or at half the locking depth for each fault segment). Gray dots reflect deep stress accumulation at 15 km depth. Uncertainties both our past and present stress results are also provided, defined by the uncertainty in locking depth for each segment.

4. INTELLECTUAL MERIT AND BROADER IMPACTS

A fundamental objective of SCEC4, and in particular, of the Stress and Deformation Over Time (SDOT) focus group, has been to develop a Community Stress Model (CSM), a large-scale effort to deliver a set of spatio-temporal (4D) representations of the stress tensor in Southern California. Complex earthquake cycle modeling of the full range of temporal and spatial scales using nonlinear rheology with realistic spatial variations requires computationally intensive 4-D finite element models that are currently being developed within the SDOT group. Simpler semi-analytic models, using computationally fast algorithms, however, can be used to assess the importance of basic stress model components and the first-order consistency of paleoseismic data and time-dependent earthquake cycle stress calculations. Using the later, this project has focused on the development of 4D simulations of stress evolution that provide rare insight into earthquake cycle crustal stress variations at seismogenic depths where earthquake ruptures nucleate. As these models develop, several critical science questions have emerged that are helping to advance the body of knowledge of earthquake cycle crustal dynamics: Is stress accumulation consistent over multiple earthquake cycles? Can improved earthquake cycle stress models be reconciled with paleoseismic data to determine a characteristic stress threshold for major fault segments of the SAFS? How do long-term (1000-yr) variations in stress accumulation influence the spatial and temporal pattern of earthquake occurrence? Utilizing new SCEC community paleoseismic and geodetic data, our refined 4D stress models suggest a high degree of sensitivity to fault locking depth along the San Andreas Fault System, a quantity best estimated by spatially dense geodetic observations. The findings of this work promote further investigations into the relationship between fault stress accumulation rate and earthquake occurrence, guided by the SCEC Community Geodetic Model.

A component of this SCEC4 funded project emphasized Earth Science education and communication of pertinent and accessible earthquake information to the general public. Directly aimed at disseminating geoscience educational material to our local community, we worked closely with the Earth Science on Volcanic Islands summer REU program, hosted by UH's Department of Geology and Geophysics, to develop visualization content for a visiting student from the University of South Carolina (J. Burnstein). We have been actively sharing relevant interactive visualization products with teachers and colleagues in Honolulu. Manao Elementary School and Waialae Public Charter School have benefited greatly from interactive educational products provided by our team, in conjunction with the research activities supported by this award. We have also utilized the UH Hawaiian Institute of Geophysics visualization center many times over the year to display San Andreas visualizations for classroom and public education activities. Two undergraduate UH students contributed to the body of this work (A. Lee and L. Burkhard), and coursework lectures and visualization exposure of these datasets was provided to 18 UH undergraduate students enrolled in GG451 Earthquakes and Crustal Deformation.

Results from these tasks were presented at the 2016 SCEC Annual Meeting in 3 poster presentations and 1 invited plenary presentation. Results were also presented at the 2016 AGU, GSA, and SSA meetings. One manuscript submitted to GJI (*Luttrell and Smith-*

Konter, 2017) is currently undergoing minor revision, and two additional mature manuscripts are in preparation to be submitted to BSSA and JGR. We also welcome future collaborative activities with the SCEC Community Stress Model, of which we will eagerly share and distribute these results.

5. PUBLICATIONS SUPPORTED BY SCEC FUNDS

In preparation:

Solis, T., and B. Smith-Konter (2017), Estimating variations in locking depth for the Mojave segment of the San Andreas fault over the past 1500 years from paleoseismic stress drop, *in preparation to be submitted to BSSA*.

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