2017 SCEC Proposal FINAL REPORT
Analysis of earthquake source parameters and rupture simulation along southern San Andreas Fault through the San Gorgonio Pass

Jeff McGuire, Woods Hole Oceanographic Institution and Yajing Liu, McGill University.

Proposal Category B: Integration and Theory.
SCEC Research Priorities: 1d, 3a, FARM, EG
Disciplinary Area: Seismology, FARM

The San Gorgonio Pass (SGP) region of the San Andreas Fault consists of a complex set of strike-slip and thrust-slip fault structures, as part of the restraining bend along the San Andreas Fault in southern California. Between the San Bernardino segment to the north and the Coachella Valley segment to the south, the dominant active structure within the SGP region is the San Gorgonio Thrust and the Garnet Hill Fault, a dextral-reverse fault system that dips moderately northward (Fig. 1). Despite frequent occurrences of small earthquakes, the SGP region of the San Andreas Fault has experienced very few M6+ large earthquakes in the historical record. The 1857 M8 Fort Tejon earthquake is inferred to have terminated in Cajon Pass [*Sieh*, 1978], and the 1986 M6 North Palm Springs earthquake rupture stopped on the northern end of the Coachella Valley segment of the Banning fault [*Jones et al*., 1986]. Therefore it remains unclear whether a large earthquake rupture can nucleate or propagation onto the SGP segment, which is an issue critical for seismic hazard assessment given its proximity to densely populated areas near Los Angeles.

Hypotheses that have been proposed to explain the rupture termination at the SGP often involve the geometrical complexity of San Gorgonio Thrust-Garnet Hill Fault system. Within the ~ 20-km wide contractional stepover between the San Bernardino and Coachella Valley segments, an east-west belt of active structures consists of a variety of geological features: folds, dextral-reverse and dextral-normal faults. The geometrical complexity is likely to play a leading role in affecting earthquake rupture propagations, as clearly illustrated in other fault systems [e.g., *Poliakov et al., 2002; Kame et al., 2003; Bhat et al., 2004; Rice et al., 2005; Dunham and Archuleta, 2005*]. Dynamic rupture can continue on the main fault or divert onto a branching fault, depending on principle stress orientation, the angle between the main falt and the branching fault as well as the rupture speed as it encounters the branch [*Bhat et al*., 2004]. For propagation along a discontinuous fault, the gap between adjacent segments can also limit the total rupture length [*Harris et al.,* 1991; *Harris and Day*, 1993; *Fliss et al.,* 2005]. The uncertainty of the SGP deeper fault structure also contributes to the geometrical complexity. In a microseismicity hypocenter relocation study, *Magistrale and Sanders* [1996] found no evidence of a continuous fault at the seismogenic depth connecting San Bernardino Strand and Coachella Valley segment, and further inferred that large earthquakes would be inhibited from propagating through SGP due to the lack of a deep fault structure. However, a recent study by *Share and Ben-Zion* [2016] using fault zone head waves indicates the presence of two large-scale bi-material interfaces with opposite senses of velocity contrasts in the north and south from the SGP, implying that fault sections are probably continuous at depth.

Through synthesizing the results from seismicity relocation [*Magistrale and Sanders*, 1996] and geological mapping of active faults and folds, *Yule and Sieh* [2003] proposed that a three-dimensional, transpressional stepover model, in which the San Bernardino and Coachelle Valley strike-slip segments of the SAF transfer slip via thrust faulting in the SGP region. A 3D structural contour map of the primary fault systems in SGP was also constructed and supported by more recent active-source imaging studies in this area [*Nicholson et al.,* 2015]. Numerical modeling of the geological uplift and strike-slip rates also found the model incorporating a non-vertical, north-dipping fault structure for the San Gorgonio Thrust-Garnet Hill Fault segment provide better agreements to the observations of such rates [*Dair and Cooke*, 2009].

Finally, the recently revealed bi-material velocity structure [*Share and Ben-Zion*, 2016] further suggests that sub-shear ruptures propagating from either direction toward the SGP would be inhibited because of the unfavorable conditions dictated by the opposite velocity contrast in the north and south of the region. A large SGP earthquake would only be possible if it is nucleated in the middle, in which case bi-lateral rupture propagation is permissible. The goal of this proposal is to incorporate the three-dimensional complexities in the fault geometry and heterogeneities in the fault-bounding materials, as discussed above, into a numerical model for earthquake sequences to investigate various rupture scenarios and seismic/aseismic slip budget across the San Gorgonio Pass.

2017 Accomplishments

Stress Drop Database: McGuire, Haoran Meng, and Yehuda Ben-Zion have been developing a database of earthquake source parameter estimates using the second moment technique. Additionally, we have developed an approach for mapping the second moment estimates of rupture area into estimates of static stress drop that would be consistent with the results of dynamic crack model [*McGuire and Kaneko*, 2018], similar to the traditional Madariaga formulas for circular cracks [*Madariaga*, 1976]. Figure 1 shows a map with the locations and stress drops determined so far using the second moment method for earthquakes in the San Gorgonio Pass area.

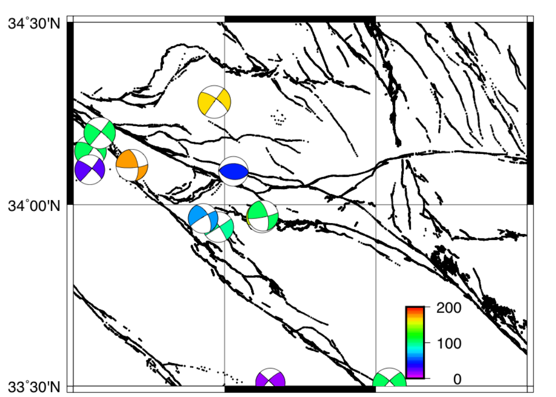

Figure 1. Earthquake stress drop estimates derived from the second moment estimates of Meng et al. [SSA poster, 2018] assuming a 2:1 aspect ratio and the crack model following McGuire and Kaneko [2018]. Colors give stress drops in MPa.

Model Setup: Liu and her PhD Student Ge Li have recently developed the ability to simulate rupture propagation through complicated stepovers using the SPECFEM3D model. This work was initially motivated by their recent studies of the Leech River fault on Vancouver Island [Li et al., 2018]. They are in the process of modifying this approach for the San Gorgonio region. To develop a reasonable mesh in Cubit they have developed an initial model that takes the CFM (Figure 2) and removes the Mission Creek Strand since that may be inactive. The simplified mesh is shown in Figure 3. Li is currently modifying the mesh to remove problems. He will then incorporate the stress drop results from Figure 1 to specify the friction parameters and begin simulations of ruptures propagating through the San Gorgonio Pass. We expect to present initial results at the 2018 SCEC Annual Meeting.

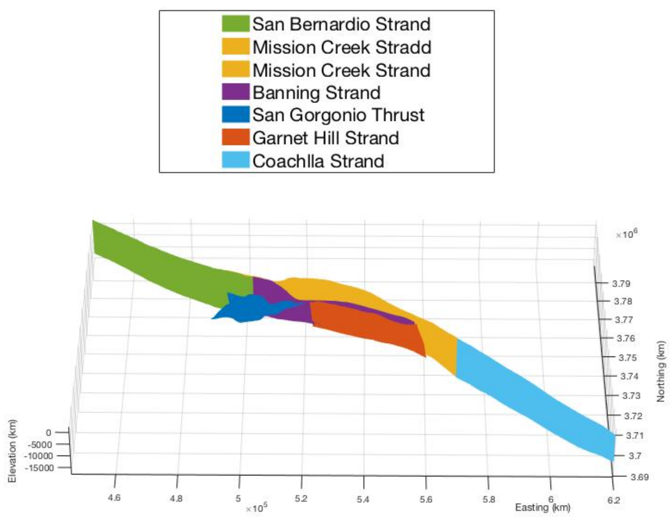

Figure 2. SCEC CFM of the fault systems in the CFM.

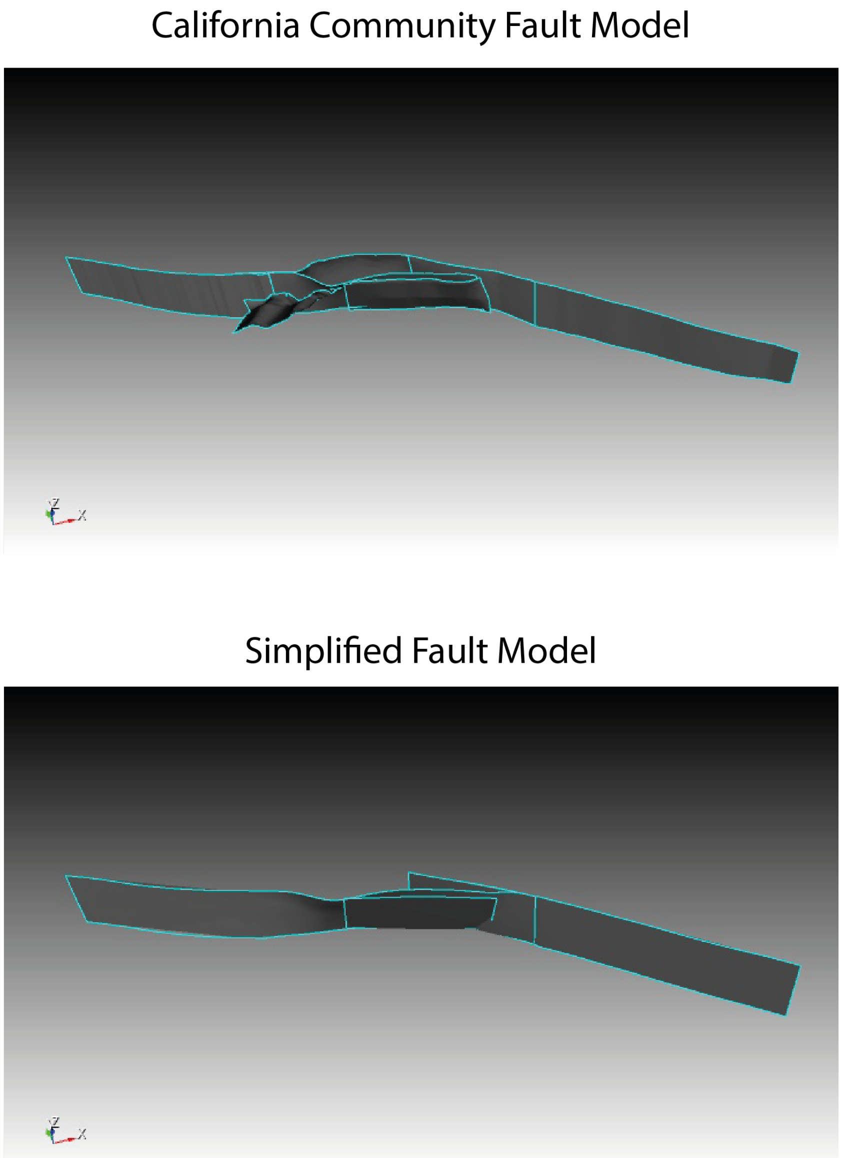

Figure 3. Cubit Mesh of the model setup for SPECFEM3D runs. The top is the SCEC community fault model for the San Gorgonio Pass region. The bottom is the initial geometry that Ge and Liu are running simulations on. The lower model has had the Mission Creek strand removed for simplicity.

References:

Behr, W. M., Rood, D.H., Fletcher, K.E., Guzman, N., Finkel, R., Hanks, T.C., Hudnut, K.W., Kendrick, K.J., Platt, J.P., Sharp, W.D., Weldon, R.J., Yule, J.D. (2010), Uncertainties in slip-rate estimates for the Mission Creek strand of thesouthern San Andreas fault at Biskra Palms Oasis, southern California, Geological Society of America Bulletin, v. 122; no. 9/10; p. 1360–1377; doi: 10.1130/B30020.1.

Bhat, H. S., Dmowska, R., Rice, J. R., & Kame, N. (2004). Dynamic slip transfer from the Denali to Totschunda faults, Alaska: Testing theory for fault branching. *Bulletin of the Seismological Society of America*, *94*(6B), S202-S213.

Blanpied, M. L., C. J. Marone, D. A. Lockner, J. D. Byerlee, and D. P. King (1998), Quantitative measure of the variation in fault rheology due to fluid-rock interactions, J. Geophys. Res., 103, 9691–9712.

Bonner, J. L., Blackwell, D. D., Herrin, E. T. (2003), Thermal constraints on earthquake depths in California, *Bulletin of the Seismological Society of America*, v93, n6, pp. 2333-2354.

Dair and Cooke (2016), San Andreas fault geometry through the San Gorgonio Pass, California, Geology, v. 37; no. 2; p. 119-122, doi:10.1130/G25101A.

Dunham, E. M., and R. J. Archuleta (2005), Near-source ground motion from steady state dynamic rupture pulses, Geophys. Res. Lett., 32, L03302, doi:10.1029/2004GL021793.

Fliss, S., H. S. Bhat, R. Dmowska, and J. R. Rice (2005), Fault branching and rupture directivity, J. Geophys. Res., 110, B06312, doi:10.1029/2004JB003368.

Harris, R. A., R. J. Archuleta, and S. M. Day (1991), Fault steps and the dynamic rupture process: 2-D numerical simulations of a spontaneously propagating shear fracture, Geophys. Res. Lett., 18, 893–896.

Harris, R. A., and S. M. Day (1993), Dynamics of fault interaction: Parallel strike-slip faults, J. Geophys. Res., 98, 4461– 4472.

Jones, L., L. Hutton, D. Given, and C. Allen, The North Palm Springs, California, earthquake sequence of July 1986, Bull. Seismol. Soc. Am., 76, 1830– 1837, 1986.

Kame, N., J. R. Rice, and R. Dmowska (2003), Effects of pre-stress state and rupture velocity on dynamic fault branching, J. Geophys. Res., 108(B5), 2265, doi:10.1029/2002JB002189.

Li, D., and Y. Liu, Spatiotemporal evolution of slow slip events in a non-planar fault model for northern Cascadia subduction zone, J. Geophys. Res., doi:10.1002/2016JB012857, 2016.

Li, G., Y. Liu, C. Regalla, K. D. Morell, Seismicity Relocation and Fault Structure Near the Leech River Fault Zone, Southern Vancouver Island, (2018), J. Geophys. Res., doi:10.1002/2017JB015021.

Liu, Y., J. J. McGuire, and M. Behn, Frictional behavior of oceanic transform faults and its influence on earthquake characteristics (2012), J. Geophys. Res., 117, doi:10.1029/2011JB009025.

Madariaga, R. (1976). Dynamics of an expanding circular fault. *Bulletin of the Seismological Society of America*, *66*(3), 639–666.

Magistrale, H., and C. Sanders (1996), Evidence from precise earthquake hypocenters for segmentation of the San Andreas Fault in San Gorgonio Pass, J. Geophys. Res., 101, 3031–3041, doi:10.1029/95JB03447.

McGill, S., Weldon, R.J., II, Kendrick, K., and Owen, L. (2006), Late Pleistocene slip rate of the San Bernardino strand of the San Andreas fault in Highland: Possible confi rmation of the low rate suggested by geodetic data: Seismological Research Letters, v. 77, no. 2, p. 279.

McGuire, J., and Y. Ben-Zion (2005), High-resolution imaging of the Bear Valley section of the San Andreas Fault at seismogenic depths with fault-zone head waves and relocated seismicity, Geophys. J. Int., 163, 152–164. McGuire, J. J. (2004), Estimating finite source properties of small earthquake ruptures, *Bull. Seismol. Soc. Amer.*, *94*(2), 377-393.

McGuire, J. J. (2016). A MATLAB Toolbox for Estimating the Second Moments of Earthquake Ruptures, in review at *Sesimological Research Letters.*

.

McGuire, J. J. and Y. Kaneko (2018), Directly estimating earthquake rupture area using second moments to reduce the uncertainty in stress drop, *Geophys. J. Intl*., in press.

Nicholson, C., Plesch, A., Sorlien, C., Shaw, J., Hauksson, E. (2015), Continuing to map the 3D geometry of active faults in southern California, U.S. Geological Survey Final Technical Report.

Poliakov, A. N. B., R. Dmowska, and J. R. Rice (2002), Dynamic shear rupture interactions with fault bends and off-axis secondary faulting, J. Geophys. Res., 107(B11), 2295, doi:10.1029/2001JB000572.

Rice, J. R., C. G. Sammis, and R. Parsons (2005), Off-fault secondary failure induced by a dynamic slip-pulse, Bull. Seismol. Soc. Am., 95(1), 109134, doi:10.1785/0120030166.

Share, P.-E., and Y. Ben-Zion (2016), Bimaterial interfaces in the south San Andreas Fault with opposite velocity contrasts NW and SE from San Gorgonio Pass, Geophys. Res. Lett., 43, doi:10.1002/2016GL070774.

Shi, Z., and Y. Ben-Zion (2006), Dynamic rupture on a bimaterial interface governed by slip-weakening friction, Geophys. J. Int., 165, 469–484.

Sieh, K., Slip along the San Andreas fault associated with the great 1857 earthquake, Seismol. Soc. Am. Bull., 68, 1421– 1428, 1978.

Wei, M., Y. Kaneko, Y. Liu, and J. J. McGuire (2013), Episodic fault creep events in California controlled by shallow frictional heterogeneity, Nature Geoscience, 6, 566-570.

Wei, M. Y. Liu, Y. Kaneko, J. J. McGuire, and R. Bilham (2015), Dynamic triggering of creep events in the Salton Trough, Southern California by regional M>5.4 earthquakes constrained by geodetic observations and numerical simulations, EPSL, 427, 1-10.

Yule, D., and K. Sieh (2003), Complexities of the San Andreas Fault near San Gorgonio Pass: Implications for large earthquakes, J. Geophys. Res., 108(B11), 2548, doi:10.1029/2001JB000451.