

*Final Report*

*Submitted by Ruth Harris to SCEC  
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**A Collaborative Project:  
Rupture Dynamics, Validation of the Numerical Simulation Method  
(SCEC Project 16056)**

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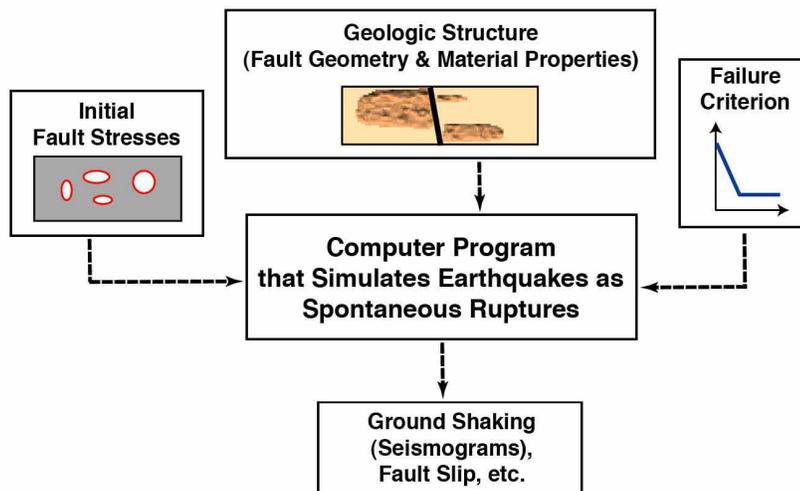
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**\* these co-PI's did not request or receive SCEC funds for this project**

## INTRODUCTION

This is the final report for the 2016-funded collaborative multi-investigator Southern California Earthquake Center (SCEC) project 16056. The project was completed on March 1, 2017. The related 2016-funded, March 1, 2017 Harris and Archuleta SCEC workshop, project 16184, has its own final report that has been submitted separately to SCEC.

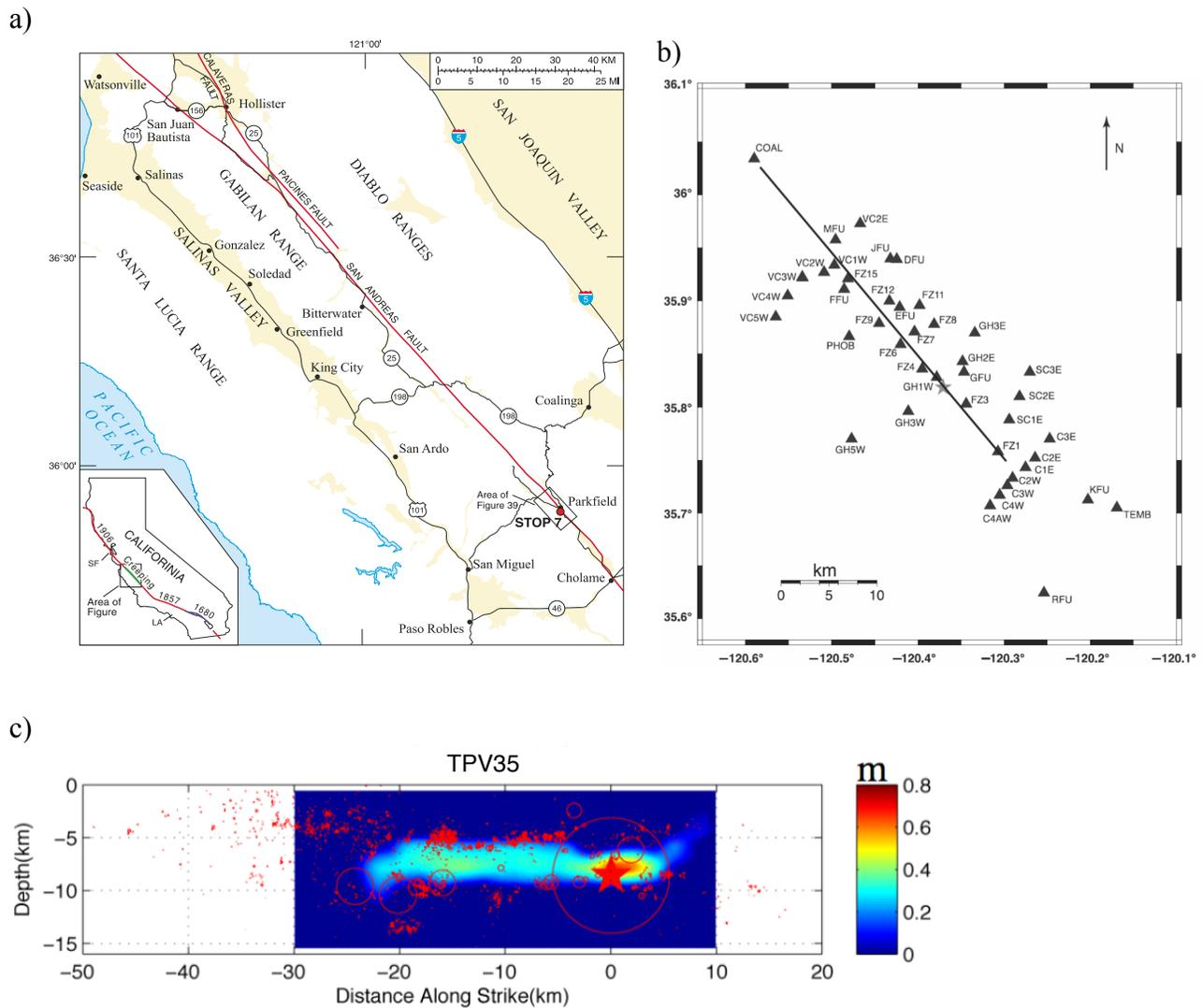
This multi-co-PI collaborative project (16056) included SCEC investigators (senior PIs, post-docs, and students) from multiple countries who participated in the winter 2016-2017 spontaneous earthquake rupture code-comparison exercise and related scientific discussions. These code comparisons are conducted so as to test the spontaneous rupture computer codes used by SCEC and USGS scientists to computationally simulate dynamic earthquake rupture. Over the past decades, a variety of numerical methods have been used to examine or simulate earthquakes and their rupture processes. These mathematical approaches have ranged from simple analytical solutions, all of the way to complex numerical solutions that incorporate the Earth's intricate physical processes, such as friction and inertia. Spontaneous, dynamic earthquake rupture codes are among these more-complex numerical methods, and there are no mathematical solutions that can easily be used to test if these codes are working as expected. To remedy this problem, we compare the results produced by each spontaneous rupture code with the results produced by other spontaneous rupture codes. If when using the same assumptions about fault-friction, initial stress conditions, fault geometry, and material properties, the codes all produce the same results (e.g., rupture-front patterns and synthetic seismograms), then we are more confident that the codes are operating as intended. Please see **Figure 1**, and Harris [2004] for more explanation about what spontaneous rupture codes do, and Harris et al. [2009, 2011], and our group's website <http://www.sceccdata.edu/cvws> for more information about our collaborative scientific project.

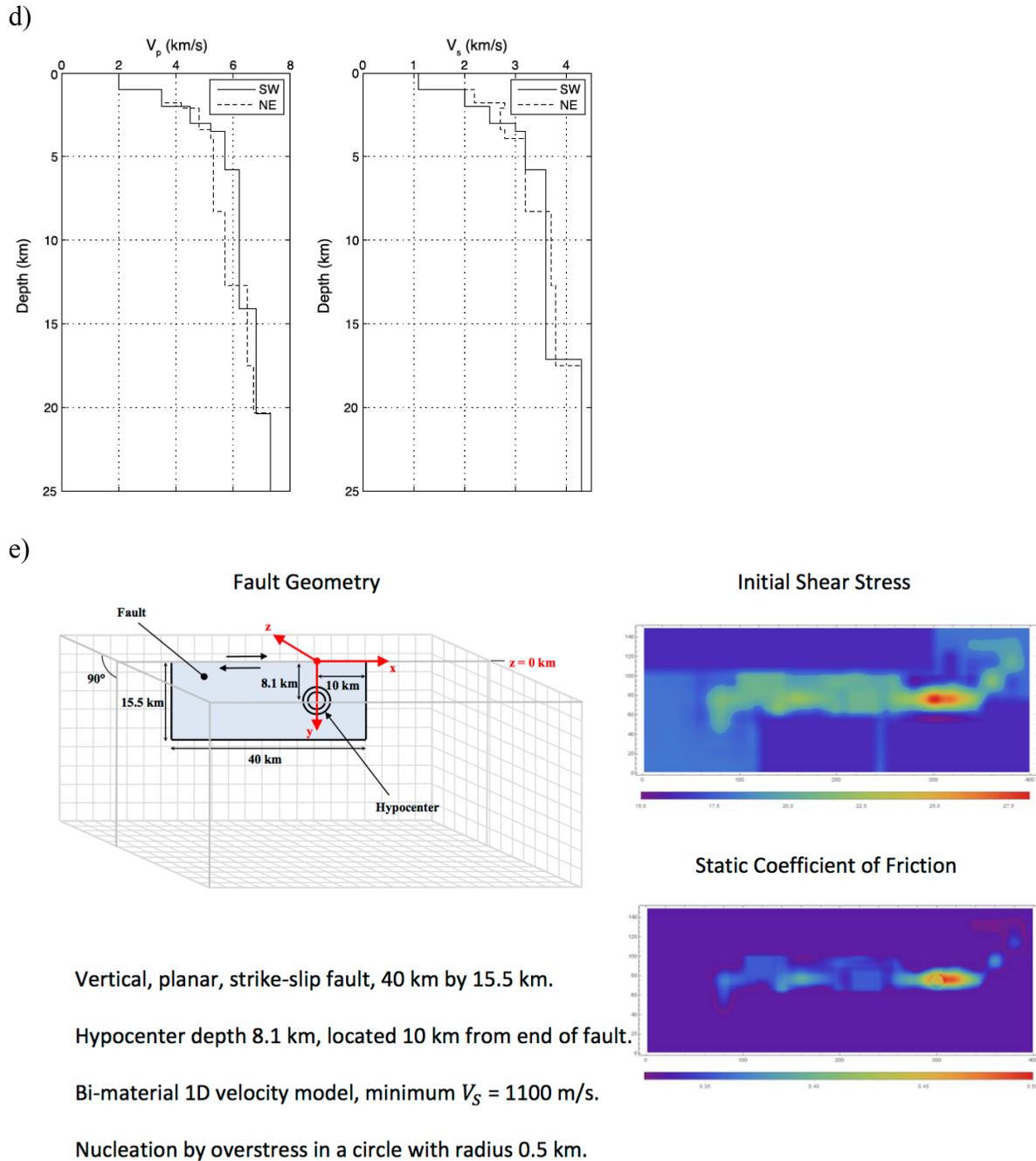


**Figure 1.** Ingredients necessary for a spontaneous rupture simulation. Spontaneous earthquake rupture simulations need assumptions about the initial stresses on the fault (and off the fault also, if the medium is not elastic), the fault geometry, the off-fault materials, and a failure criterion, which describes how fault friction works. These physics-based computer simulations can be used to produce many different types of results, including patterns of fault slip, ground and sub-surface shaking, heat generation, etc. Please see Harris [2004] for more details.

## WINTER 2016-2017: AIMING FOR CODE-VALIDATION BENCHMARK EXERCISE TPV35

In the winter of 2016-2017, our group designed then tackled a code-comparison benchmark exercise, which was designed not only to be an inter-code comparison, but to also be compared with recorded seismogram data. The Problem Version (TPV)35 (**Figure 2**) is the case of the M6.0 2004 Parkfield, California, earthquake. The TPV35 benchmark exercise assumed the initial conditions adopted in the preferred spontaneous rupture by Ma et al. [2008], which has a single planar vertical strike-slip fault, slip-weakening friction, and a 3D velocity structure that consists of two 1D velocity structures glued together at the fault plane. Please see the Benchmark Descriptions page of our website, <http://scecddata.usc.edu/cvws> for more details about TPV35. Our website also contains our previous code-comparison benchmark exercises, and links to our group papers. Please see our group papers [Harris et al., SRL, 2009 and Harris et al., SRL, 2011] for more general information about our group's science goals.





**Figure 2.** The Problem Version (TPV)35. a) Setting for the Parkfield region (stop 7 on this figure from Rymer et al., 2006). b) Seismic stations that recorded the 2004 Parkfield earthquake. Figure from Ma et al., 2008. c) The final slip produced in the favored spontaneous rupture model for TPV35, Figure from Ma, March 1, 2017 SCEC workshop presentation, based on Figure 9 of Ma et al. [2008]. d) the velocity structure used for the benchmark used two 1D velocity structures that were attached along the fault rupture plane. Figure from Ma et al., 2008. e) fault geometry and initial shear stress and friction conditions. Figure from Barall, March 1, 2017 SCEC workshop presentation, based on the Ma et al. [2008] Parkfield model. A complete benchmark description is available at <http://sceccdata.usc.edu/cvws/tpv35docs.html>.

## Code-Comparison Benchmark Exercise TPV35

TPV35 was designed to mimic the M6.0 2004 Parkfield earthquake spontaneous rupture model B constructed by Ma et al. [2008]. TPV35 used the observed seismic time-series data collected and processed by Ma et al. [2008], along with data from the NGA-West2 database [Ancheta et al., 2013]. Co-PI Ma's March 1, 2017 SCEC workshop presentation shows many details of the TPV35 benchmark description. Co-PI Barall's March 1, 2017 SCEC workshop presentation shows results produced by the 9 codes that participated in the TPV35 benchmark exercise, along with code simulation results for synthetic seismic stations on the fault, and comparisons between synthetic and real seismic data for seismic stations off the fault.

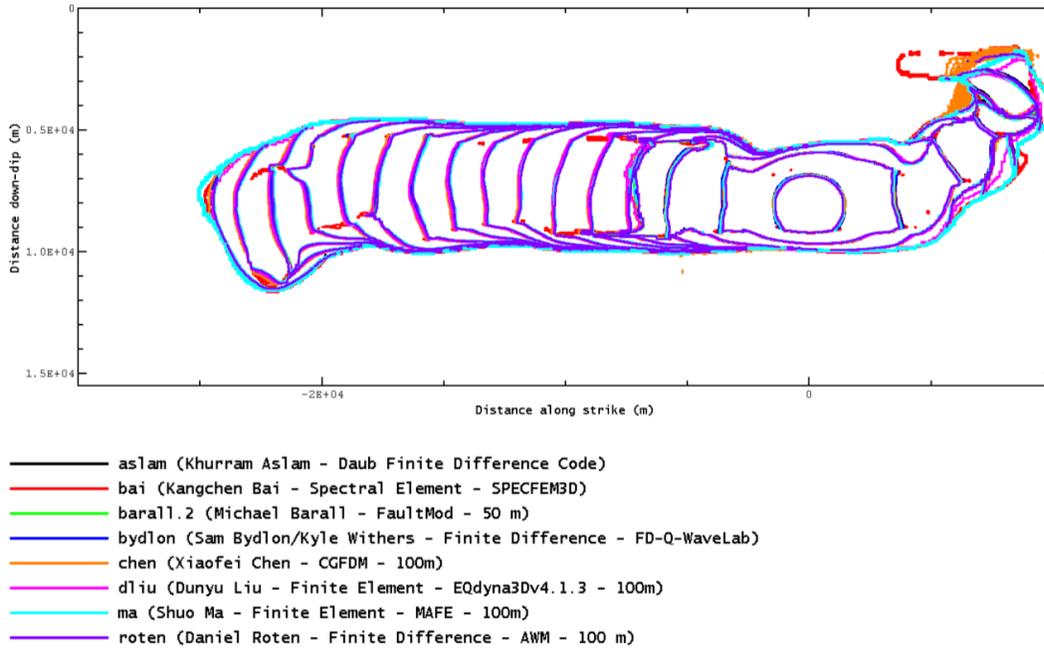
The inter-code comparisons using the benchmark exercise TPV35 worked well, with the dynamic rupture modelers' results for on-fault source behavior and on-fault seismic stations providing excellent agreement among themselves. **Figure 3** shows the rupture-front contour plots (progress of the rupture in time, on the fault surface), from eight of the nine different codes that participated in the TPV35 code-comparison benchmark exercise. Both qualitative and quantitative metrics [Barall and Harris, 2015] generated for the TPV35 rupture-front contour results are presented in **Figure 3**. Both types of metrics demonstrate excellent agreement among eight of the nine-codes' results for the progress of the earthquake rupture on the fault plane. The ninth code produced some slow meandering of the rupture into some fault regions where the other eight codes did not propagate. The ninth code was therefore not included in the rupture-front quantitative metrics calculations, because the metrics formulation isn't able to distinguish this type of behavior from behavior on the main, more important parts of the fault.

As part of the TPV35 benchmark exercise, the codes were tasked with computing seismograms at synthetic on-fault stations at depth and for real off-fault stations at the Earth's surface. The on-fault stations were primarily used for inter-code comparisons (because no on-fault stations exist at these depths near Parkfield) and the off-fault stations were used for both inter-code comparisons, and comparisons with data at these off-fault stations (**Figure 2b**) that recorded the 2004 Parkfield earthquake. At each of the synthetic on-fault seismic stations, each of the nine codes produced stress, slip, and slip-rate seismograms that matched well among the codes. **Figure 4a** shows an example of a qualitative comparison of the simulated time-series generated by the nine codes at one of the on-fault synthetic seismic stations. The matches are good, as expected based on the agreement among the codes of the rupture's progress on the fault plane (**Figure 3b**). **Figure 4b** shows the quantitative metrics for inter-code comparisons at all of the off-fault seismic stations. There is good agreement among the codes at most of the off-fault seismic stations.

The comparisons of the spontaneous rupture codes' results with the seismograms recorded during the 2004 Parkfield earthquake are another story. **Figure 5** shows codes' results versus data comparisons for two of the off-fault seismic stations that recorded the 2004 Parkfield earthquake. For some of the seismograms, the matches might be acceptable, if one focuses on a particular aspect of the seismograms, but for many of the time series simulations there is a clear mismatch between simulations and the observed (filtered) data. This presents a challenge for our code validation efforts in the future, and helps us realize that it is not realistic to attempt to predict earthquakes' time-series data. Instead, as done by the SCEC broadband platform kinematic rupture

modelers [Goulet et al., 2014], one needs to find other aspects of the data to match and predict. The conversation about how best to do this will continue in 2017.

### TPV35 Rupture Contours — Results from 8 of 9 Modelers

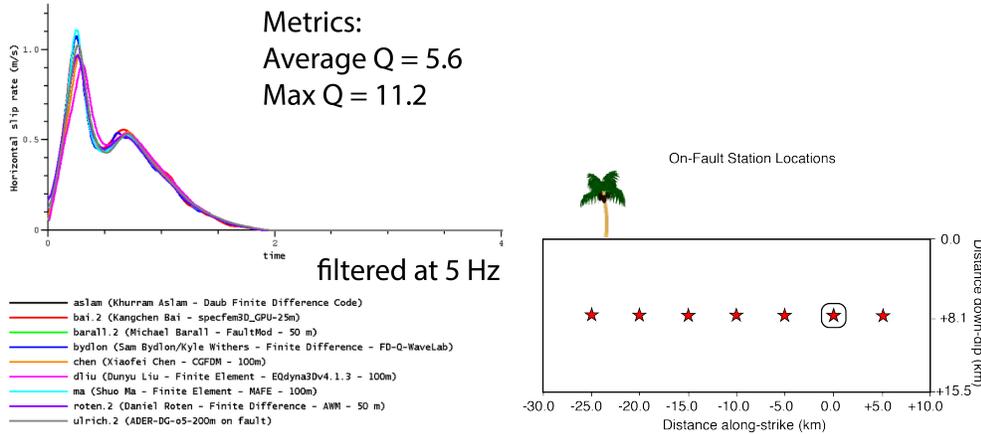


### TPV35 Rupture Contours — Metrics (RMS Difference in Rupture Time)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(1) aslam		45.4	30.3	5.8	24.5	25.1	36.4	30.1
(2) bai	45.4		54.6	45.3	49.0	48.3	50.6	54.3
(3) barall.2	30.3	54.6		28.1	42.9	33.9	17.1	23.0
(4) bydlon	5.8	45.3	28.1		25.1	24.8	34.3	28.3
(5) chen	24.5	49.0	42.9	25.1		19.1	51.0	40.4
(6) dliu	25.1	48.3	33.9	24.8	19.1		41.5	30.0
(7) ma	36.4	50.6	17.1	34.3	51.0	41.5		21.9
(8) roten	30.1	54.3	23.0	28.3	40.4	30.0	21.9	

**Figure 3.** TPV35 Results. Top) Rupture-front contours on the fault plane, generated by 8 different (colored lines) spontaneous rupture codes, show excellent agreement. Contours are at 0.5 second intervals and indicate where the fault slip rate first exceeds 1 mm/s. The rupture is artificially nucleated in the circular nucleation zone, then propagates outward on the fault plane, then spontaneously stops before it reaches any of the fault’s edges including the Earth’s surface. Bottom) Quantitative metrics [Barall and Harris, 2015] also show good agreement among the rupture-front contours produced by each of 8 spontaneous rupture codes, with just over 50 milliseconds maximum difference in rupture times. Figures from Barall SCEC workshop presentation March 1, 2017.

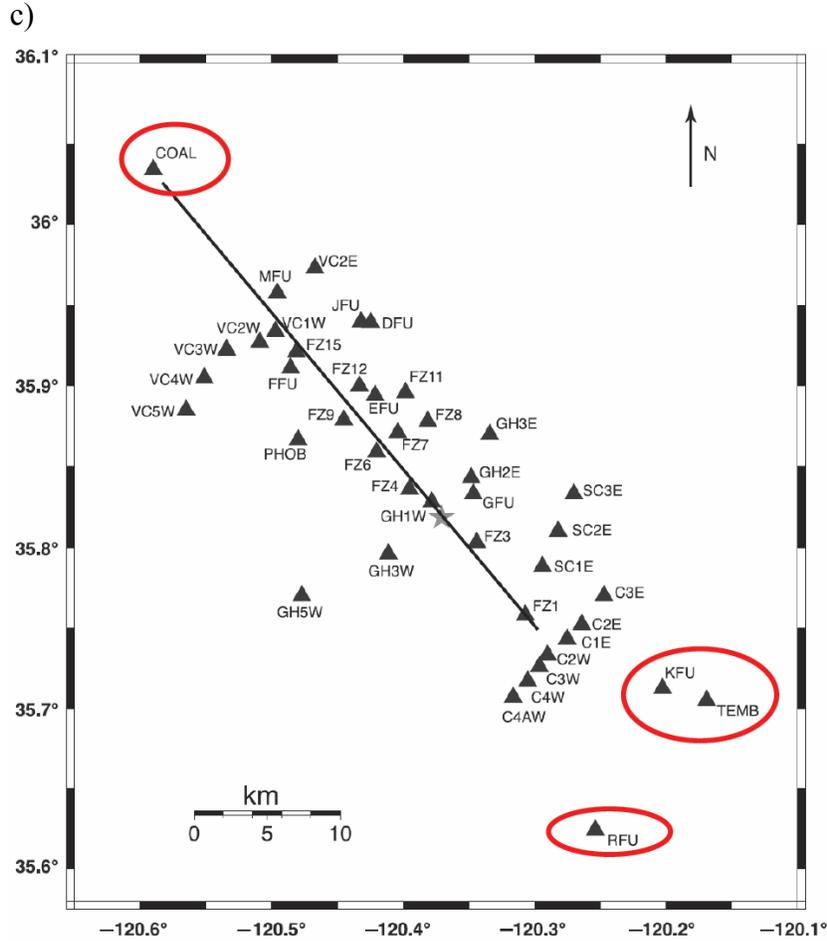
a)



b)

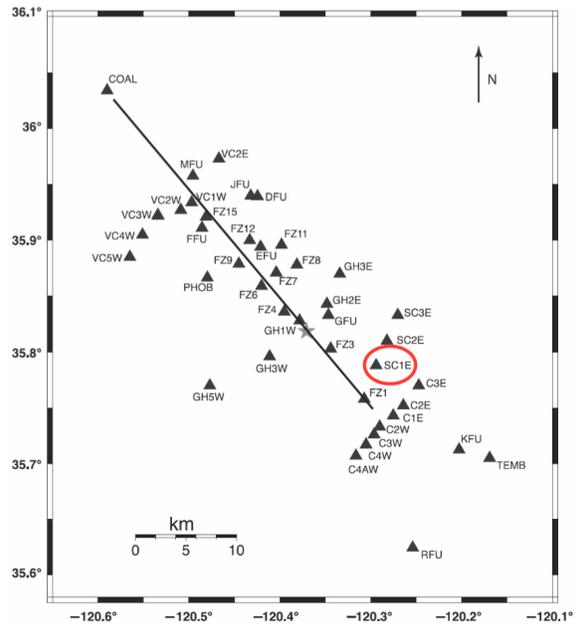
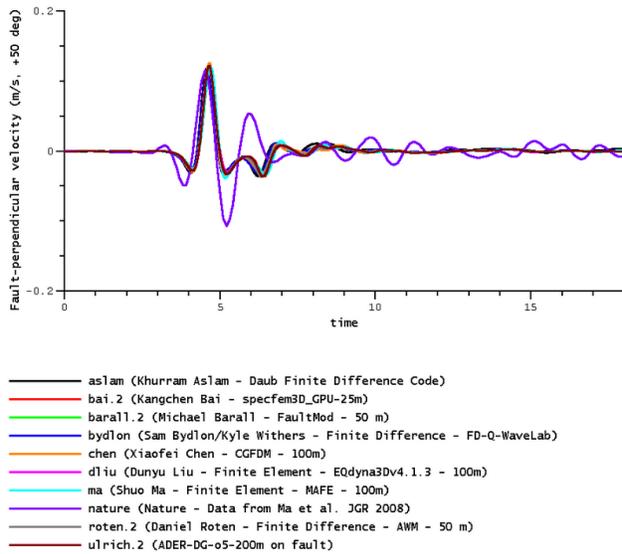
Average metric values across all 9 modeling codes (no data),  
for each of the 43 stations.

	3d-disp	3d-vel	t-shift		3d-disp	3d-vel	t-shift
DFU	11.9	11.0	0.038	FZ8	7.0	11.1	0.032
EFU	11.2	9.9	0.032	FZ9	14.7	11.1	0.048
FFU	15.5	9.5	0.051	FZ11	8.5	12.3	0.035
GFU	9.3	11.1	0.031	FZ12	12.6	9.4	0.037
KFU	24.8	21.8	0.064	FZ15	16.9	9.4	0.044
MFU	12.0	10.4	0.045	GH1W	19.4	14.4	0.036
MFU	16.5	9.6	0.051	GH2E	7.7	10.9	0.033
RFU	26.2	33.3	0.096	GH3E	7.0	9.5	0.036
VFU	14.9	12.4	0.054	GH3W	8.6	10.0	0.048
COAL	26.5	23.5	0.100	GH5W	13.7	13.6	0.064
C1E	18.6	12.8	0.031	SC1E	14.6	13.2	0.036
C2E	17.8	13.5	0.041	SC2E	11.7	12.1	0.033
C2W	20.3	15.9	0.048	SC3E	11.7	10.0	0.034
C3E	16.0	15.2	0.037	TEMB	26.9	26.3	0.058
C3W	17.9	14.0	0.051	VC1W	17.3	10.2	0.053
C4W	16.8	14.9	0.050	VC2E	14.6	11.4	0.043
C4AW	16.4	17.2	0.053	VC2W	15.9	9.9	0.056
FZ1	18.2	11.3	0.035	VC3W	15.8	13.3	0.056
FZ3	21.2	12.4	0.029	VC4W	15.6	13.8	0.055
FZ4	14.8	11.9	0.047	VC5W	17.9	16.2	0.061
FZ6	13.7	10.1	0.043	PHOB	10.4	13.2	0.053
FZ7	10.2	9.2	0.032				

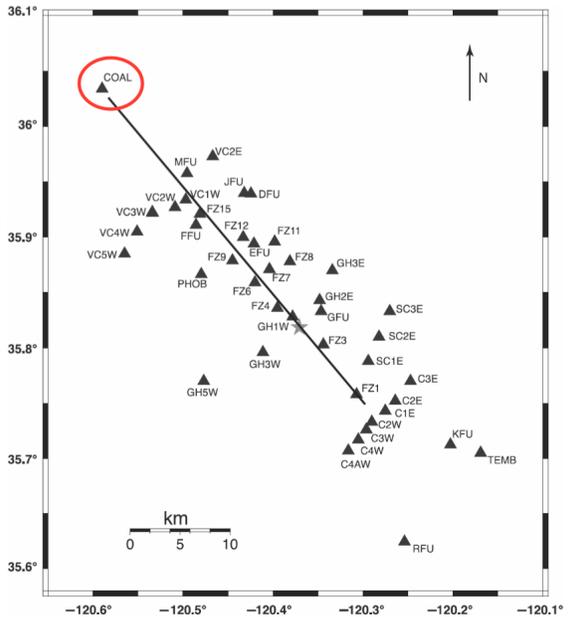
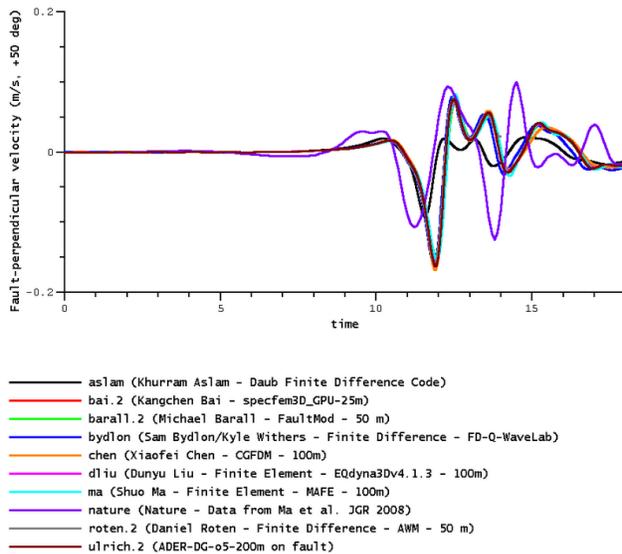


**Figure 4.** TPV35 Results. Comparisons among codes (no data). a) Time-series seismograms generated by 9 different (colored lines) spontaneous rupture codes, show excellent agreement at a synthetic on-fault station at the hypocenter (circled star). b) Quantitative metrics show the code comparisons for each of the 43 off-fault stations. c) The red-circled off-fault stations have slightly worse matches, although all are quite good. See Barall and Harris [2015] for metrics definitions.

a)



b)



**Figure 5.** TPV35 Results. Qualitative comparisons between 9 codes (multiple colors) and data (purple). Whereas the codes' results agree well with each other (**Figure 4**), there are differences between the codes' results and the time-series data. This is a known challenge for earthquake rupture modeling and is due to unknown Earth parameters, including how earthquake sources themselves work (initial fault stress conditions, frictional behavior, etc.), and details of wave propagation paths from sources to the seismic stations ( $v_p$ ,  $v_s$ , density, site conditions, etc.). The data are from Ma et al. [2008] who bandpass filtered between 0.16Hz and 1.0 Hz. The codes' results are filtered at 1.0 Hz. a) comparison of fault-perpendicular velocity versus time for 9 codes and data at station Stone Corral 1E. The code results themselves agree with each other (as shown in Figure 4), but the code results do not match the time-series data well. b) comparison of fault-perpendicular velocity versus time for 9 codes and data at station Slack Canyon.

## FUTURE PLANS:

We have started on our path of code validation, whereby we develop methods for using spontaneous rupture code results to predict observations from well-recorded earthquakes. Our first, baby steps, were to make sure that we could first succeed at producing similar results among the codes, for a real earthquake, which we have accomplished this year. Next, we need to figure out how to take the bigger steps, to start with random initial conditions then attempt to match some observed aspects of recorded data, perhaps via comparison with GMPE's. The overall question is what we should be validating and what our best strategies are for accomplishing this multi-year goal. Our March 1, 2017 workshop (see the accompanying workshop report for SCEC Project 16184) produced interesting discussion points that we need to consider for our validation efforts in 2017 and beyond, including that it appears to be very difficult, if not impossible, to use simulated results to satisfactorily match time-series data (e.g., seismograms) from actual large earthquakes. This is the case even for kinematic rupture models, that have the flexibility of not needing to produce physically self-consistent earthquake source models, so for the spontaneous rupture simulations that our group produces, there appear to be many challenges. As we move forward in 2017 we will discuss among our group members and consult additional experts about favored pathways to code validation. On another research front, starting in late 2017, some members of our group plan to multi-task and initiate work that addresses how best to combine multi-cycle earthquake models with dynamic rupture simulations.

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Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

## REFERENCES:

### General Articles about Spontaneous Rupture Propagation and our Code Comparison Exercise:

- Barall, M., and R.A. Harris (2015), Metrics for comparing dynamic earthquake rupture simulations, *Seism. Res. Lett.*, 86(1), 223-235, doi:10.1785/0220140122.
- Harris, R.A. (2004), Numerical simulations of large earthquakes: dynamic rupture propagation on heterogeneous faults, *Pure and Applied Geophysics*, 161(11/12), 2171-2181, doi:10.1007/s00024-004-2556-8.
- Harris, R.A., M. Barall, R. Archuleta, E. Dunham, B. Aagaard, J.P. Ampuero, H. Bhat, V. Cruz-Atienza, L. Dalguer, P. Dawson, S. Day, B. Duan, G. Ely, Y. Kaneko, Y. Kase, N. Lapusta, Y. Liu, S. Ma, D. Oglesby, K. Olsen, A. Pitarka, S. Song, E. Templeton (2009), The SCEC/USGS Dynamic Earthquake Rupture Code Verification Exercise, *Seism. Res. Lett.*, 80(1), 119-126, doi:10.1785/gssrl.80.1.119.
- Harris, R.A., M. Barall, D.J. Andrews, B. Duan, E.M. Dunham, S. Ma, A.-A. Gabriel, Y. Kaneko, Y. Kase, B. Aagaard, D. Oglesby, J.-P. Ampuero, T.C. Hanks, N. Abrahamson (2011), Verifying a computational method for predicting extreme ground motion, *Seism. Res. Lett.*, 82(5), 638-644, doi:10.1785/gssrl.82.5.638.

### SCEC workshop presentations discussing the TPV35 benchmark:

- Ma, S. (2017), Dynamic modeling of the 2004 Mw6.0 Parkfield earthquake, March 1, 2017 SCEC workshop presentation, [http://scecddata.usc.edu/cvws/download/mar1\\_2017/Ma\\_parkfield.pdf](http://scecddata.usc.edu/cvws/download/mar1_2017/Ma_parkfield.pdf)
- Barall, M. (2017), TPV35-Parkfield 2004 M6 earthquake, March 1, 2017 SCEC workshop presentation, [http://scecddata.usc.edu/cvws/download/mar1\\_2017/Barall\\_TPV35\\_Results\\_v11.pdf](http://scecddata.usc.edu/cvws/download/mar1_2017/Barall_TPV35_Results_v11.pdf)

### Publication about the M6.0 2004 Parkfield earthquake dynamic rupture model used for TPV35:

- Ma, S., S. Custodio, R. J. Archuleta, and P. Liu (2008), Dynamic modeling of the 2004 Mw 6.0 Parkfield, California, earthquake, *J. Geophys. Res.*, 113, B02301, doi:10.1029/2007JB005216.

### Publication about a field guide to the creeping section of the San Andreas fault:

- Rymer, M.J., S.H. Hickman, and P.W. Stoffer (2006), A field guide to the central, creeping section of the San Andreas fault and the San Andreas Fault Observatory at Depth, in Prentice, C.S., Scotchmoor, J.G., Moores, E.M., and Kiland, J.P., eds., 1906 San Francisco Earthquake Centennial Field Guides: Field trips associated with the 100th Anniversary Conference, 18–23 April 2006, San Francisco, California: Geological Society of America Field Guide 7, p. 237–272, doi:10.1130/2006.1906SF(16).

### Publication about the NGA-West2 Data:

- Ancheta, T. D., et al. (2013), PEER NGA-West2 Database PEER Report 2013/03, May 2013, updated July 2013, 172 pp.

### Publication about the Broadband Platform:

- Goulet, C.A., N.A. Abrahamson, P.G. Somerville, and K.E. Wooddell (2015), The SCEC Broadband Platform validation exercise: Methodology for code validation in the context of seismic-hazard analyses, *Seism. Res. Lett.*, 86(1), 17-26, doi: 10.1785/0220140104.

*Thank you to our Winter 2016-2017*



**GOLD-STAR DYNAMIC RUPTURE MODELERS**



(who simulated the Winter 2016-2017 benchmark exercises)

**Kangchen Bai**

**Michael Barall**

**Sam Bydlon / Kyle Withers**

**Khurram Aslan / Eric Daub**

**Dunyu Liu**

**Shuo Ma**

**Daniel Roten**

**Thomas Ulrich**

**Zhenguo Zhang**

