2021 SCEC Report

Project #21146

Alternative White Wolf Fault Geometry, Kern County

Scott Condon

AECOM, Los Angeles

February 29, 2024

1. Introduction

The Community Fault Model (CFM; Plesch et al., 2007) is a three-dimensional fault model for southern California which is widely used as input for physics-based simulations and probabilistic seismic hazard analysis (PSHA). The model itself includes more than 150 active faults that are capable of producing moderate to large earthquakes (Plesch et al., 2007). The current version, CFM6.1, incorporates 492 fully documented fault objects and introduces separate sub-models (Marshall et al., 2023). Alternative fault representations are included in the CFM and provide important insight into the variability of, and epistemic uncertainty associated with, plausible fault geometries. For this reason, the development of alternative models is important, as differences in fault geometry can have significant effects on physics-based simulations and PSHA. In this project we focus our attention on the White Wolf Fault, situated north of the San Andreas Garlock junction.

In July 1952, the White Wolf Fault (Figure 1) produced one of the largest earthquakes to strike southern California. Since then, a number of important source studies have been published attempting to characterize the **M** 7.2–7.4 event. Despite these efforts however, source representations of this event have fundamentally different rupture geometries and slip directions. These differences, which arise from data limitations and uncertainties associated with the structure of the White Wolf Fault system, highlight the need for alternative models, to better recognize the epistemic uncertainties associated with this fault system.

The aim of this study was originally to apply the Riesner et al. (2017) methodology to the White Wolf Fault, to provide a new and objective 3D representation of the fault. The Riesner et al. (2017) method relies on a variety of data sources, including earthquake hypocenters, seismic and well data, 3D fault traces, and focal mechanisms. During this study, we found that access to the geocad software, which was used by Riesner et al. (2017), would have incurred a license fee of $20,000, and that no open-source software alternatives were available (Andreas Plesch, personal communication). Upon learning this, we aimed to develop an open-source software package that would apply the three stages of the Riesner et al. (2017) approach and test it with the White Wolf Fault. This software package could also be applied to future CFM updates of other faults. However, we encountered unexpected challenges related to the creation and implementation of this software package, as described further below. As a result, the software package is incomplete at this stage.

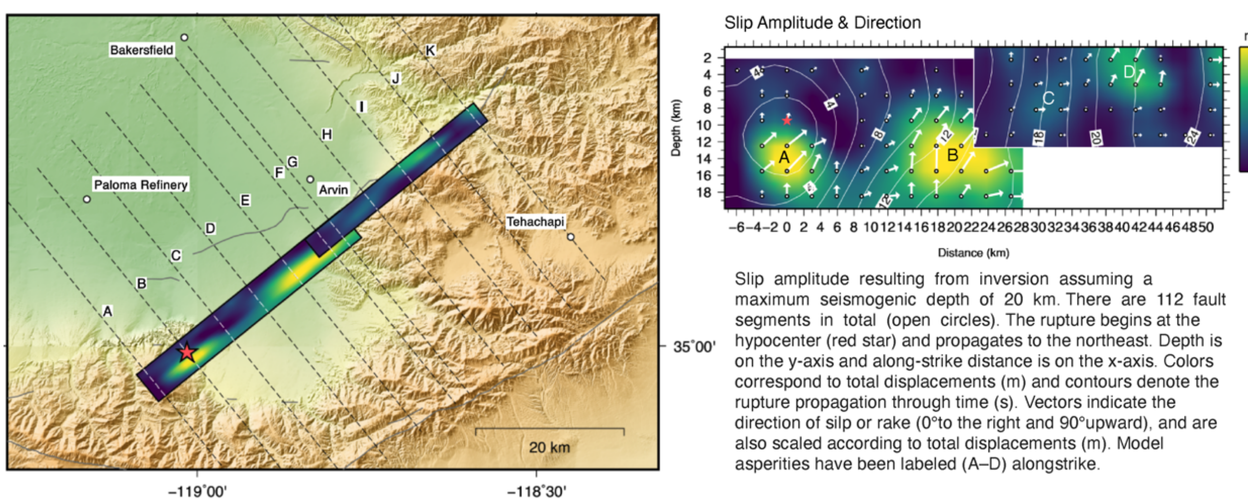

Figure 1. Rupture Model of the 1952 Kern County Earthquake adapted from Condon (2020).

1.1 Condon (2020)

Condon (2020) combined reported geodetic observations with a collection of previously unused, local seismic recordings, in series of inversions to constrain a slip model for the 1952 Kern County earthquake. Results suggest that the 1952 event initiated on a low-angle fault plane with dominant strike-slip motion (strike=49±3°; dip=35±1°; and rake=11±5°) then triggered an abnormally energetic rupture on a high-angle fault plane (strike=51°, dip=75°), 2 s later (Figure 1). This energetic rupture, contained within a 9–6 km patch near the hypocenter, accumulated 6–7 m of slip and had a high average static stress-drop (larger than 50 MPa). The final rupture broke a 60 km section of the White Wolf Fault, with a cumulative moment of 7.61×10^{19} Nm, or **M** 7.18, and duration of 23–26 s. An important finding of this research is that most of the moment-release occurred in the southwest portion of the White Wolf Fault and that the corresponding weighted-average rake-angle over this region (47–57°) falls between previous models based on individual seismic or geodetic data sets.

1.2 Community Fault Model Versions

White Wolf Fault geometry in the original CFM (version 1) is represented as a simple planar fault surface, extrapolated to depth at a fixed dip angle of 75° (Figure 2). This fault representation also includes the assumed fault trace of the White Wolf Fault (Jennings & Bryant, 2010) and is bounded by topographic surfaces and a regional base of seismicity (Plesch et al., 2007).

The basis for this 75° dipping interpretation comes from the rupture model proposed by Bawden (2001) for the 1952 Kern County earthquake, a two-decade old source study based on triangulation and leveling observations. This estimation resulted from an iterative process of refining an overparameterizing rectangular fault surface, modeling the geodetic data assuming a uniform slip, defining model resolution, and examining aftershock locations. Bawden (2001) found that a rectangular fault plane dipping 65–85° could explain geodetic observations equally well. His preferred fault geometry has two rectangular segments, one larger to the southwest and one smaller to the northwest (Figure 3). The southwest segment has a strike of 51°, dip of 75°, and slip at 6.0–27 km depths. The northwest segment has the same strike and dip but is offset to the southeast and has slip at 1.0–12.5 km depths. Bawden importantly notes that none of the models tested can completely replicate the observed geodetic measurements fully and therefore the preferred model may be “an oversimplified approximation of the true fault geometry” (Bawden, 2001).

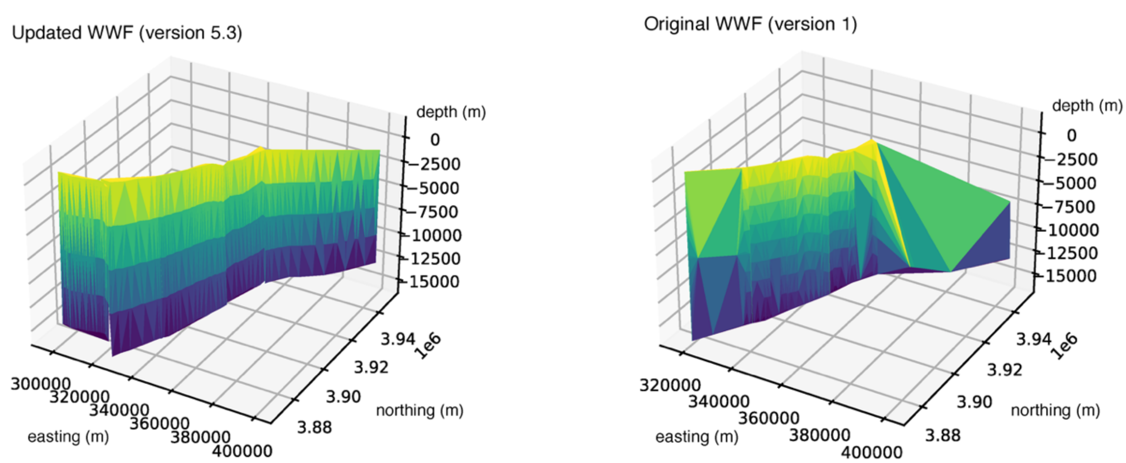

Figure 2. Comparison between White Wolf Fault (WWF) geometries in the original (version 1) and updated (version 5.3) CFM. Fault geometries are plotted in the UTM Zone 11, NAD 27 coordinate system.

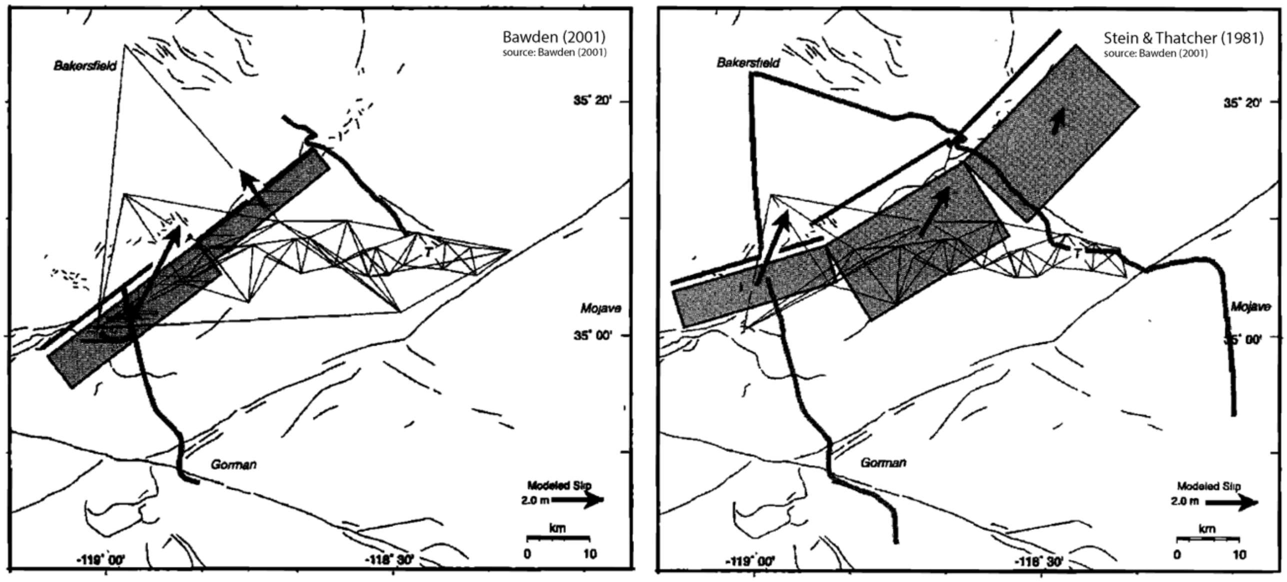

Figure 3. Comparison between the WWF geometries of Bawden (2001) and Stein & Thatcher (1981). Fault planes are represented by grey rectangles. Modeled slip is represented by arrows.

The CFM v5.3 (Nicholson et al., 2020) added much needed complexity to the White Wolf Fault (Figure 2; Figure 4). The current CFM, v6.1 (Marshall et al., 2023), shown in Figure 4, did not update the WWF from v5.3. The v5.3 interpretation is based loosely on previous works (Bawden, 2001; Goodman & Malin, 1992) and constrained with fault surface traces (Jennings & Bryant, 2010) and extensive seismic data from the Southern California Seismic Network (SCSN) (Hauksson et al., 2012; Ross et al., 2019; Yang et al., 2012). The updated White Wolf Fault is significantly larger than the previous model, includes additional segments, and has variable dip along strike and at increasing depths. This recent, significant change in the White Wolf fault geometry from the previous original CFM version, illustrates the importance of improving models to better constrain the range of epistemic uncertainty in the fault geometry.

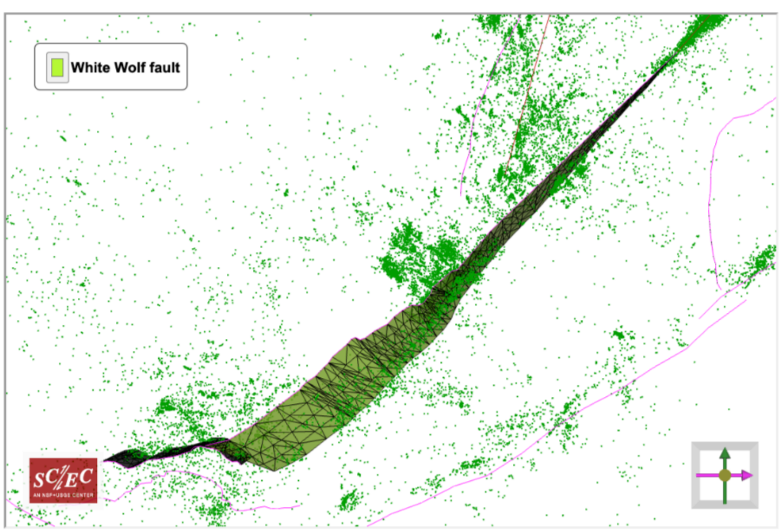

Figure 4. The CFM v6.1 White Wolf Fault surface with relocated seismicity from Hauksson et al. (2012).

2. Methodology: Building Objective 3D Fault Representations

The Riesner et al. (2017) method to determine objective 3D fault geometries involves three stages and relies on a combination of surface fault traces, focal mechanism orientations, earthquake hypocenters, and geologic information (Riesner et al., 2017). The three stages, described below, are (1) selecting an initial fault surface, (2) iteratively refining that surface based on data, and (3) validation. A key difference in the Riesner et al. (2017) method is that the iterations are objectively based on the data, as opposed to the classical methods which are subjective because they rely on manual selection and interpretation of the data.

Stage 1: Initial Fault Surface

The first step in this workflow is critical for the determination of an alternative White Wolf Fault geometry as it uses the surface trace of the fault and associated focal mechanisms to determine an initial fault surface. This is important because there is ambiguity associated with both the fault surface trace and the focal mechanism orientation of the largest event to occur on the White Wolf Fault, the 1952 Kern County earthquake (Condon, 2020). Uncertainties in either the assumed fault trace or associated focal mechanisms may significantly alter the resulting fault geometry. Therefore, to test the stability of the updated geometry of the White Wolf Fault (CFM), we chose the geodetic fault model proposed by Stein & Thatcher (1981) as the basis for developing an alternative White Wolf Fault Geometry (Figure 3). This fault model differs significantly from the model proposed by Bawden (2001) in assumed fault geometry and rupture style, despite having similar methodologies and data constraints.

The model proposed by Stein & Thatcher (1981) consists of three rectangular segments, all of which have variable strike, dip, and depth ranges (Figure 3). This interpretation of the 1952 rupture is based on seismically derived aftershock locations, surface geology, and the same triangulation and leveling observations used by Bawden (2001). The first segment in this model, to the southwest, has a strike of 73°, dip of 75°, and depth range 5.0–27 km. The central segment has a strike of 58°, dip of 35°, and depth range 3.5–15 km. The northeast segment has a strike of 43°, dip of 20°, and depth range 2.0–10 km. The most striking difference between this model and the model proposed by Bawden (2001) is the size and shape of the proposed fault geometry (Figure 3). Stein and Thatcher argue that the curved representation of the White Wolf Fault is necessary to satisfy the geodetic observations.

Stage 2: Fault Geometry Refinement

The second stage is an iterative step where at first hypocenters within a certain distance (e.g., 10 km) of the initial planar surface are selected and used as constraints for a new fault surface, then the process is repeated with successively using smaller distances from the fault plane. Histograms of the events within the chosen distance from the planar surface are examined with each iteration to guide further model refinement, following Riesner et al., (2017).

The Hauksson-Yang-Shearer (HYS) catalog contains events recorded by the Southern California Seismic Network (SCSN) from 1981–2019 (Hauksson et al., 2012). This catalog contains relocated events which range from **M** 0.0 to **M** 7.3 and is supplemented with focal mechanisms from Yang et al. (2012).

Ross et al., (2019) apply a template-matching waveform technique to analyze 10 years of data from the original Southern California Seismic Network (SCSN); this is called the Quake Template Matching (QTM) seismicity catalog for southern California. The QTM catalog has 10 times the number of events compared to the original and is able to completely detect magnitudes greater than **M** 0.3. Relocated event hypocenters are comparable to SCSN's highest quality catalogs.

We have created python modules which include functions to fetch the earthquake catalogues from a given URL (HYS or QTM) and transform them into a GeoDataFrames object, which is a geospatial data file from the open-source GeoPandas python project. GeoPandas enables a user to easily do operations in python that would otherwise require a spatial database. These modules also read the fault model (Stein & Thatcher, 1981, or Bawden, 2001), convert geodetic bounds to east-north-up (ENU) cartesian coordinates, and create a bounding box of coordinates based on the fault model and earthquake catalogue.

The code implementation of the next step, involving iterations for an improved fault models using the earthquake data, was not completed. We found that access to the geocad software, which was used by Riesner et al. (2017), would have incurred a license fee of $20,000. We attempted instead to use LoopStructural, an open-source 3D geological modeling library for Python. LoopStructural can provide interpolation algorithms within a geological model to characterize a fault surface geometry. The source code for LoopStructural is available on GitHub (github.com/Loop3D/LoopStructural). This approach has the potential to tie into the proposed open-source software package, but we were unable to implement it successfully, and as a result were not able to perform the tetrahedral mesh interpolation for the new fault surface.

<u>Stage 3: Validation</u>

Because Stage 2 was not completed, Stage 3 could not be carried out. Our plans for Stage 3 were to refine the new fault geometry by examining it in detail to assess its consistency with the original fault traces, source model, earthquake catalog, and another applicable geologic information. At this stage any outliers would be removed. If for example, an event with known association with an adjacent fault is included in the refined fault geometry, then this event will be removed. Additionally, during this stage we can compare the resulting geometry to independent datasets such as the well data from Goodman & Malin (1992) and other observations made by Stein & Thatcher (1981).

3. Future Steps

To complete the open-source software package applying the three stages of the Reisner et al. (2017) methodology, and to provide an objective 3D fault representation of the White Wolf fault, the modules for modeling the fault surface (3D-mesh) need to be incorporated. The open-source python library LoopStructural holds promise for this application. Once this component is completed, the iteration and validations stages of the Reisner et al. (2017) methodology can be performed.

References

Bawden, G. W. (2001). Source parameters for the 1952 Kern County earthquake, California: A joint inversion of leveling and triangulation observations. Journal of Geophysical Research: Solid Earth, 106(B1), 771–785. https://doi.org/10.1029/2000jb900315

Caumon, G., Collon-Drouaillet, P., Le Carlier De Veslud, C., Viseur, S., & Sausse, J. (2009). Surface-based 3D modeling of geological structures. Mathematical Geosciences, 41(8), 927–945. https://doi.org/10.1007/s11004-009-9244-2

Condon, S. J. (2020). Joint Study of the 1952 Kern County , California Earthquake. UC Santa Barbara UC Santa Barbara Electronic Theses and Dissertations. https://escholarship.org/uc/item/9xz225z2

Goodman, E. D., & Malin, P. E. (1992). Evolution of the Southern San Joaquin Basin and Mid-Tertiary “Transitional” Tectonics, Central California. Tectonics, 11(3), 478–498.

Hauksson, E., Yang, W., & Shearer, P. M. (2012). Waveform relocated earthquake catalog for Southern California (1981 to June 2011). Bulletin of the Seismological Society of America, 102(5), 2239–2244. https://doi.org/10.1785/0120120010

Jennings, C. W., & Bryant, W. A. (2010). Fault Activity Map of California: California Geologic Survey Geologic Data Map. California Geologic Survey.

Marshall, S., Plesch, A., & Shaw, J. (2023). SCEC Community Fault Model (CFM) (6.1) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.8327463

Nicholson, C., Plesch, A., Sorlien, C., Shaw, J. H., & Hauksson, E. (2020). Updates, Evaluation and Improvments to the Community Fault Model (CFM version 5.3). Poster Presentation at 2020 SCEC Annual Meeting.

Plesch, A., Shaw, J. H., Benson, C., Bryant, W. A., Carena, S., Cooke, M., Dolan, J., Fuis, G., Gath, E., Grant, L., Hauksson, E., Jordan, T., Kamerling, M., Legg, M., Lindvall, S., Magistrale, H., Nicholson, C., Niemi, N., Oskin, M., … Yeats, R. (2007). Community Fault Model (CFM) for southern California. Bulletin of the Seismological Society of America, 97(6), 1793–1802. https://doi.org/10.1785/0120050211

Riesner, M., Durand-Riard, P., Hubbard, J., Plesch, A., & Shaw, J. H. (2017). Building objective 3D fault representations in active tectonic settings. Seismological Research Letters, 88(3), 831–839. https://doi.org/10.1785/0220160192

Ross, Z. E., Trugman, D. T., Hauksson, E., & Shearer, P. M. (2019). Searching for hidden earthquakes in Southern California. Science, 771(May), 2–5. https://doi.org/10.1126/science.aaw6888

Stein, R. S., & Thatcher, W. (1981). Seismic and aseismic deformation associated with the 1952 Kern County, California, earthquake and relationship to the Quaternary history of the White Wolf Fault. Journal of Geophysical Research, 86(B6), 4913–4928. https://doi.org/10.1029/JB086iB06p04913

Yang, W., Hauksson, E., & Shearer, P. M. (2012). Computing a large refined catalog of focal mechanisms for southern California (1981-2010): Temporal stability of the style of faulting. Bulletin of the Seismological Society of America, 102(3), 1179–1194. https://doi.org/10.1785/0120110311