2018 SCEC Annual Technical Report

SCEC Award #17027

Developing a Technical Activity Group (TAG) for the Community Fault Model (CFM) to support SCEC science, community model development, and hazard assessment

Principal Investigators:
John H. Shaw
Professor of Structural & Economic Geology
Andreas Plesch
Senior Research Scientist
Harvard University
Dept. of Earth & Planetary Sciences
20 Oxford St., Cambridge, MA 02138
shaw@eps.harvard.edu // (617) 495-8008

Craig Nicholson
Marine Science Institute
University of California
Santa Barbara, CA 93106-6150
craig.nicholson@ucsb.edu // (805) 893-8384

Proposal Categories: A: Data gathering and products
Science Objectives: P1a, P3a, P4a

Summary

This research project supported continued development of the Community Fault Model (CFM) (Plesch et al., 2007, 2016; Nicholson et al., 2017), with a specific emphasis on facilitating use of the CFM in new community modeling efforts (e.g., Community Rheologic Model), fault systems studies, earthquake simulators, and hazard assessment. The CFM is one of the most mature modeling efforts within SCEC, and has seen widespread use in many aspects of our science, including block modeling, wave propagation simulations, and probabilistic seismic hazards assessment (e.g., UCERF3). Nevertheless, it remains critical that the CFM continues to be updated, expanded, improved, assessed, and validated – and that it effectively supports a wider range of community modeling activities targeted by SCEC5. To help facilitate these efforts, this past year we:

1) Released a new version of the SCEC CFM (5.2), which includes a series of refinements and improvements to faults represented in the model based on the latest earthquake and focal mechanism catalogs and surface trace maps.
2) Completed a metadata spreadsheet for the latest model version implementing a new fault system hierarchy and providing supporting information about the fault representations.
3) Continued working with SCEC CME to improve and implement a database and web-based graphical interface that can be used to access the model and supporting information. This included development of a dedicated CFM webpage at: https://www.scec.org/research/cfm.
4) Developed regular gridded representations of the latest CFM model version and establish linkages between CFM fault geometry and UCERF3 slip rate information. These efforts are designed to help support use of the CFM in earthquake simulators;
5) Coordinated activities with other community modeling projects in SCEC that will benefit from CFM representations, including the Geologic Framework and the Community Rheologic Model.

This project represents a collaborative effort between the lead development teams for the CFM at Harvard University and the University of California, Santa Barbara.

2017-2018 Results

At the 2017 Annual Meeting, we released a new version of the SCEC Community Fault Model (CFM-v5.2) for southern California (**Figure 1**, Nicholson et al., 2017). This model represents a substantially enhanced version of the southern California fault representations, which were systematically updated and improved using detailed fault traces from the USGS Quaternary Fault & Fold database, precisely relocated earthquake hypocenters, and new focal mechanism catalogs (Lin et al., 2007; Yang et al., 2012; Hauksson et al., 2012 + updates). This resulted in fault representations that are more precise, and often more highly segmented than in previous model versions. For 2017, new faults were added or existing representations updated in the Coast Ranges, Ventura basin, offshore Continental Borderland, Sierra Nevada region, and within the newly designated Cajon Pass Earthquake Gate Area. The CFM 5.2 release also included comprehensive database metadata tables that provide unique identifiers (name and number) for each level (that includes fault area, fault system, fault section, fault name & fault strand) of the fault hierarchy within which a fault segment occurs. This hierarchical naming and numbering scheme thus allows for grouping of individual faults as part of geometrically or kinematically linked fault systems, and enables model users to access and assess the context and full richness of fault systems, 3D fault models, and alternative 3D fault representations in CFM. Additionally, the expanded CFM database now includes densely populated fields for alternate and CFM version number, source, descriptor, references, USGS Quaternary fault (Qfault) ID, and fault attributes of average strike, average dip, fault area, and faulting style. Finally, the new model release also included remeshed versions of the preferred CFM 3D fault set (original CFM surface meshes are irregular, reflecting the availability of local data constraints). The remeshing of these faults is intended to facilitate their use in fault system models, earthquake simulators, and a variety of other numerical modeling efforts that require more regularly gridded or meshed fault representations.

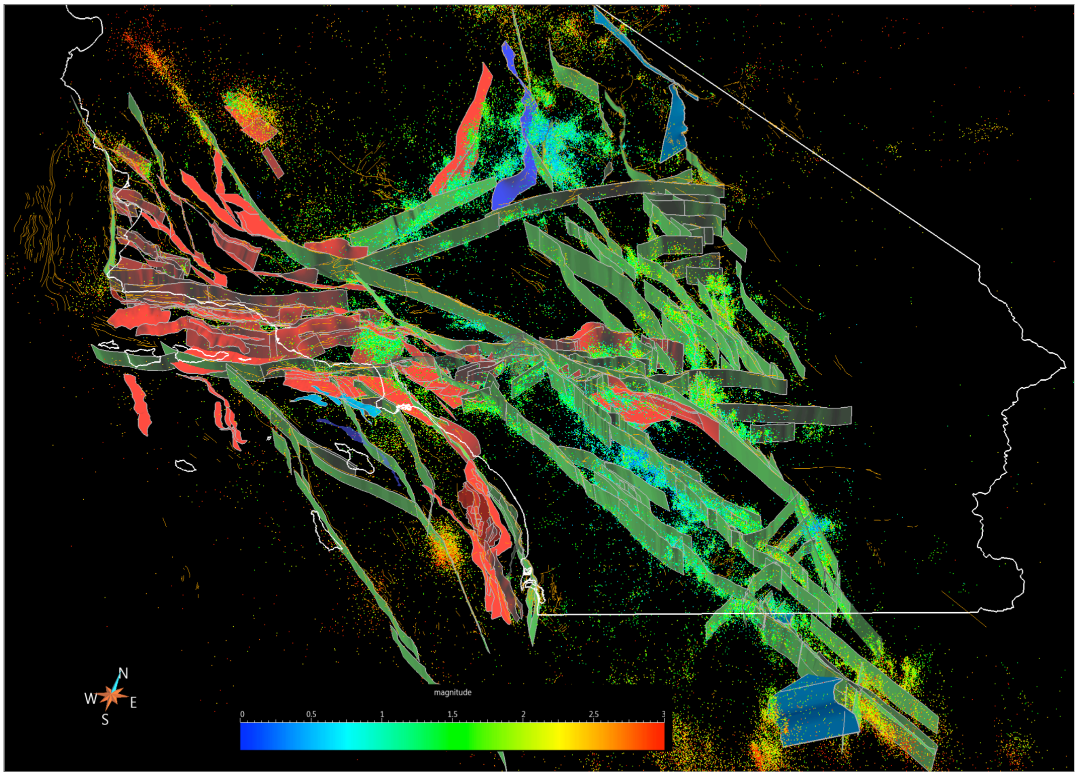

Figure 1: Perspective view of primary representations for each of the nearly 400 fault and fault sections in CFM 5.2. Fault color-coding refers to faulting style from primarily normal (blue) to primarily strike-slip (green) to primarily reverse-slip (red). Relocated 1981-2016 hypocenters by Egill Hauksson (dots) are color-coded by magnitude.

CFM Database Organization, Maintenance and Accessibility

During SCEC4 and into 2017, steady and significant improvements to the CFM were made, culminating in the release of CFM 5.2 (Nicholson et al., 2017). As a result, the CFM 3.0 fault set (Plesch et al., 2007) was expanded from ~170 faults to over 850 3D fault objects and alternative representations that define nearly 400 faults organized into 105 complex fault systems (**Figure 1**). In fact, it is largely because the CFM and its associated database has become so large and complex, that this effort to maintain and develop the CFM database, to enhance its accessibility, and to coordinate its integration with other CXM modeling initiatives, has been broken out into its own separate TAG initiative.

CFM Organization and Expanded 3D Fault Set: For version 5.2, a primary focus was thus expanding and improving the database and metadata component of CFM that is critical for the internal consistency and maintainability of the model. This CFM hierarchical name and numbering system provides an organizational structure for the increasing variety and complexity of multi-stranded principal slip surfaces, adjacent secondary faults, and alternative fault models that have been or will be developed for CFM, while facilitating improved correspondence and compatibility with the USGS Quaternary fault (Qfault) nomenclature and naming conventions. Care was taken to insure that the CFM database is synchronized with the latest catalog of individual, t-surf CFM fault representations. Through this process, various fault models or components were identified that needed to be added or improved. These models were updated either by developing new alternative 3D fault models or by better regularization of their 3D fault surface meshes. In addition, the database fault name entries were updated to reflect any changes in the underlying fault geometry, revised fault linkages, or if more suitable locations in the hierarchical naming system were found. For example, the Earthquake Valley, Agua Caliente, Hot Springs, and San Felipe faults are now separated out into their own fault systems, and re-assigned to their respective Agua Tibia-Earthquake Valley and Hot Springs-San Felipe fault zones (e.g., Gordon et al., 2015).

In close collaboration with a related companion project, many new or updated 3D fault representations were added to CFM based on updated USGS/CGS Qfault mapped surface traces, improved relocated seismicity catalogs, or revised interpretations of 3D fault geometry from surface geologic mapping and subsurface well correlations (Nicholson et al., 2017; Nicholson, 2018). For 5.2, new or revised fault models were added in the Sierra Nevada (Airport Lake) and Coast Ranges fault areas (San Juan, Big Spring, Little Pine, Oceanic, West Huasna), an updated, split Newport-Inglewood fault was developed along with down-dip extensions for the Thirtymile Bank and Coronado Bank detachments, a revised low-angle Southern San Cayetano fault was created for the Ventura Special Fault Study Area, and new updated rupture models for the 1812 and 1857 earthquakes and adjacent Transverse Ranges faults related to the Cajon Pass Earthquake Gate Area (Lozos et al., 2017) were developed. These new 3D fault models included a revised Cucamonga fault and Sierra Madre-Cucamonga connector, and new San Antonio Canyon, Stoddard Canyon, South Fork-Stoddard Canyon, Icehouse Canyon, Weber, and Red Hill faults.

<u>*CFM Database and Metadata Table Expansion*</u>: Faults in the CFM are represented in a hierarchical structure including *Fault Area, Fault Zone or System, Fault Section, Fault Name, Splay, and Alternative* designations. Where faults are present in both the CFM and Qfault datasets, the *Fault Zone, Fault Section, and Fault Name* designations are synchronized, which ensures that users can properly relate fault information between the CFM and Qfault databases, such as geometry and slip rate, respectively. Each of these fault representations also includes interpolated and extrapolated fault patches, reflecting the degree of local data coverage used to control fault geometry. For cases where fundamentally different interpretations persist, these faults may include two or more alternative representations. Finally, there are a series of attributes associated with each fault, including average strike, average dip, fault area, faulting style, CFM version number, associated Qfault ID, a quality factor average, references, and a fault authorship or source identifier. The quality factor is defined by the formal CFM community review process, which was last conducted in 2016 for CFM 4.0 and Statewide CFM 3.0 [Plesch et al., 2016].

Currently, all of these fault components and attributes are organized into a master spreadsheet, which is provided for download along with digital 3D fault surfaces (Tsurfs) bundled into preferred and alternative model groupings. While this approach effectively organizes and archives model components, it does not allow users to effectively search the model database and assemble components into potential user-preferred linked fault systems. To improve these capabilities, we have the goal of developing a new relational database structure and web interface that will allow users to identify, assemble, and download selected model components. Specifically, these new tools will enable users to search the database by fault name, geographic region, attributes (e.g., fault type), and other criteria. Users will be able to visualize and evaluate assembled model components, and download the specific content that they need.

Fault Surface Mesh Regularization for Simulators and Other Applications: Triangulated-surfaces (Tsurfs) were chosen as the native format for CFM faults because they provide for more accurate representations of complex, curviplanar 3D surfaces that vary their geometry in depth or along strike. However, many earthquake simulators and other fault system models have used rectangular dislocations (e.g. Okada, 1992) to represent the surface elements. Approximating curviplanar faults from the tsurf representations with a collection of rectangles means that the rectangles do not join together at their edges and the fault geometry is not described accurately. Recently, solutions for triangle dislocations have been developed (Gimbutas et. al, 2012) that overcome the problems of singularities that arise at certain locations in earlier treatments (e.g., Jeyakumaran et al., 1992; Kuriyama and Mizuta, 1993; Thomas, 1993; Meade, 2007). Thus, tsurfs comprised of generally equilateral triangles at appropriate resolutions can be used by some earthquake simulators. Native tsurfs in the CFM, however, generally do not satisfy these criteria as triangles are not equilateral and the mesh density varies considerably as a function of data coverage or constraints. Thus, in cooperation with various SCEC investigators we have developed a set of regularly meshed tsurfs based on CFM 4.0 and the preferred fault set for CFM 5.2 for use in earthquake simulators and other applications (**Figure 2**). Experience has shown that some applications can use these surface meshes directly, while others require further refinement to avoid numerical instabilities.

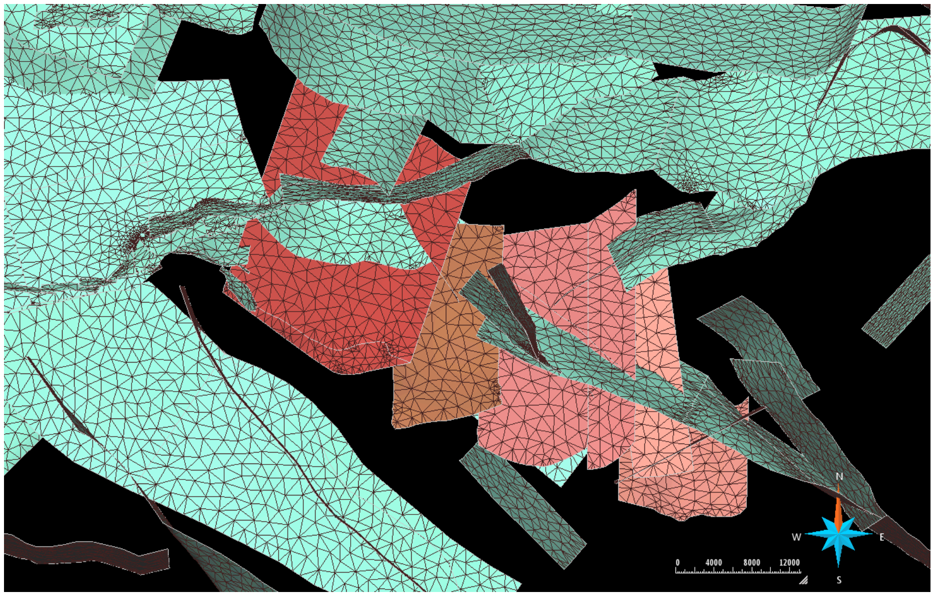

Figure 2: Map view of regular surface meshes developed for the SCEC CFM in the LA basin (Puente Hills thrust is shown in red, pink and brown patches).

CFM 5.2 Release and Access: We continue to receive requests for access to the CFM from a wide variety of parties on a regular basis. For example, we responded to such requests by a utility, a research project at the Geology and Geological Engineering Department at SDMT, and a variety of SCEC affiliated institutions. These responses often included pointers to a preliminary web page. While a fully relational on-line CFM database is in development, in conjunction with Scott Marshall (CFM Coordinator), CFM 5.2 is now accessible from the new SCEC CFM website (https://www.scec.org/research/cfm)(**Figure 3**). This website includes links to download CFM 5.2 gzip files of tsurfs plus supporting metadata tables and documentation, along with similar links to the previously released and reviewed CFM 3.0 and CFM 4.0. Links are also provided to other CXM webpages, as well as a set of useful community created tools to analyze, view and manipulate CFM fault objects. The packaged gzip file for CFM 5.2 includes directories with the complete CFM 5.2 tsurfs, plus additional directories for the preferred CFM fault representations in native and regularized 500-m & 100-m fault meshes for facilitating use by other modeling activities. Supporting documentation includes the metadata spreadsheet of CFM hierarchical names & numbers and associated fault attributes and characteristics as previously described.

Integration into CXM ecosystem and model development

SCEC5's CXM effort of community earth models can be considered an evolving ecosystem where constituents may increasingly weave together data and models to form a consistent and robust platform for earthquake science. As a developing building block, CFM fully supports the CXM project.

<u>Support of CXM:</u> Success of the CFM and its counterpart velocity models (CVM), as well as the emergent need of SCEC science, have led to a proliferation of community modeling efforts in SCEC5. These include the Community Stress Model (CSM), Community Rheologic Model (CRM), Community Thermal Model (CTM), and 3-D Geological Framework. Several of these models benefit from incorporating 3D fault representations – for example, lithologic and thus rheologic boundaries in the crust often correspond to faults. Thus, we have initiated a general effort through this CFM TAG to coordinate and support efforts in these other CXM modeling activities. As demonstrated by provisioning regularized surface meshes for CFM 5.2, this effort will often involve providing fault representations and model components in formats that are desired by these groups, and working with them to ensure that fault representations are accurately incorporated in their analysis. In another example, we have worked directly with CRM to establish fault bounded crustal blocks which are defined by CFM fault surfaces. To

facilitate coordination and communication with one of the primary CFM user groups, the lead development teams from Harvard and UCSB attended the 2017 Earthquake Simulator workshop. Several useful and desired enhancements to CFM were identified. As a result, many of these CFM enhancements and refinements are already targeted and under development with the follow-on 2018 joint Harvard-UCSB CFM database project.

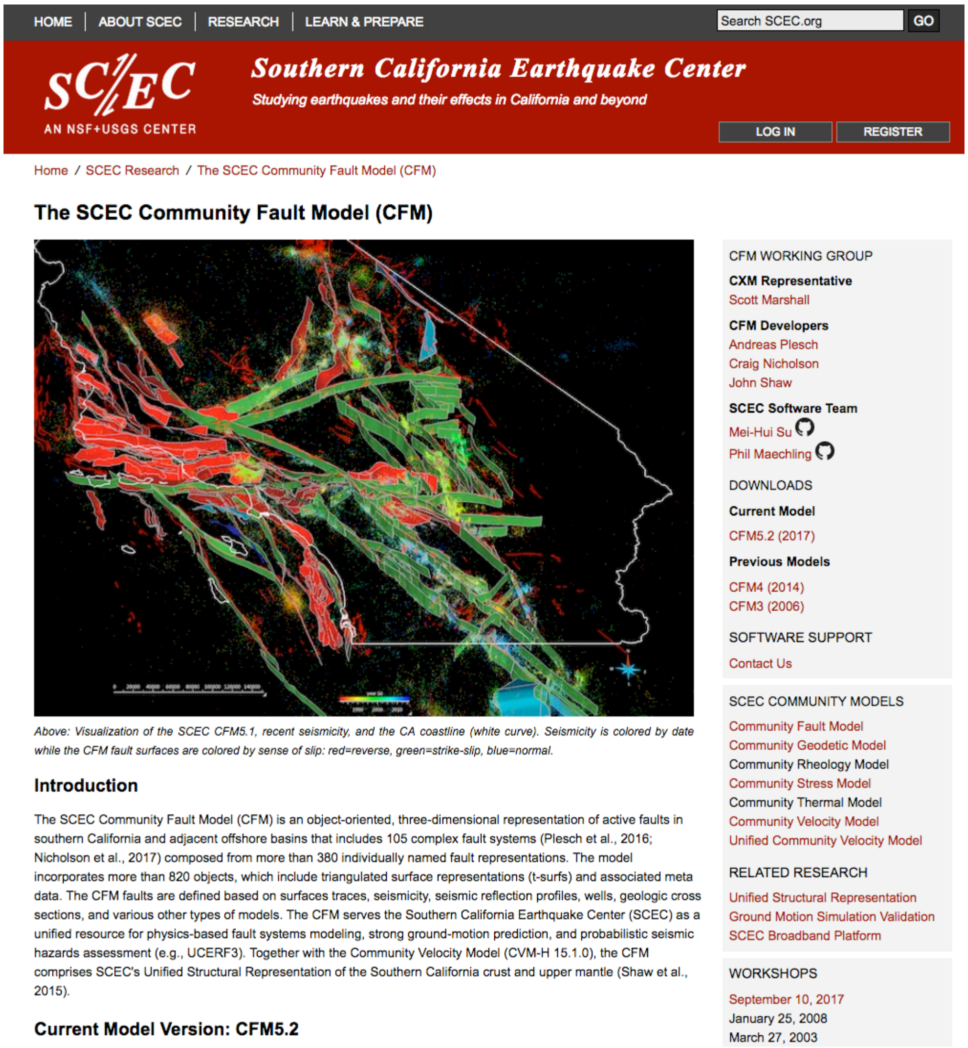

Figure 3: New, dedicated SCEC CFM webpage at: https://www.scec.org/research/cfm.

Accommodating further development of and updates to the CFM 3D fault set: CFM requires continued refinement to improve and expand the existing CFM fault set for southern California. This includes developing new 3D fault models for CFM and incorporating other geologic, lithologic or rheological surfaces, material interfaces, and/or dated reference horizons that are compatible with the faults in CFM, and which are critically important to CVM, CRM, CSM and modeling deformation over time (e.g., SDOT). Some of this additional, related on-going effort to further update and improve CFM 3D fault representations is often provided by a companion CFM science project at UCSB, and it is anticipated that additional 3D models will be contributed to CFM by other SCEC investigators and projects. CFM already includes a number of new, mostly blind or buried faults that are not included yet in the USGS Quaternary Fault & Fold database that is mostly tied to fault surface traces. Thus, an important continuing role for this CFM TAG will be to interface and coordinate with these various groups, as well as with other CXM modeling efforts, to plan, implement and incorporate these model upgrades, and improve consistency with developers of these related products in the organization and naming of these new fault models.

References

Brocher, T.M., R.C. Jachens, R. W. Graymer, C. W. Wentworth, B. Aagaard, and R. W. Simpson, 2005, A new community 3D seismic velocity model for the San Francisco bay Area: USGS Bay Area Velocity Model 05.00, SCEC Annual Meeting, Proceedings and Abstracts, Volume XV, p. 110.

Comninou, M., and J. Dunders (1975). Angular dislocation in a half space, J. Elast. 5, 203–216.

Field, E.H., G. P. Biasi, P. Bird, T. E. Dawson, K. R. Felzer, D. D. Jackson, K. M. Johnson, T. H. Jordan, C. Madden, A. J. Michael, K. R. Milner, M. T. Page, T. Parsons, P. M. Powers, B. E. Shaw, W. R. Thatcher, R. J. Weldon, II, and Y. Zeng, (2013), Uniform California Earthquake Rupture Forecast, Version 3 (UCERF3)—The Time-Independent Model, USGS Open-File Report 2013–1165, CGS Special Report 228, and Southern California Earthquake Center Publication 1792.

Gordon, E.M., T.K. Rockwell, G.H. Girty and C. Goetz, Geomorphic analysis of late Quaternary activity of the Earthquake Valley and Hot Springs–San Felipe fault zones, and their role in slip transfer between the northern Elsinore and southern San Jacinto faults, in: Geology of the Coyote Mountains, southern California (R. Wagner, ed.), San Diego Association of Geologists, Sunbelt Publications, p. 95-108 (2015).

Hauksson, E., W. Yang, and P. M. Shearer (2012), Waveform relocated earthquake catalog for southern california (1981 to june 2011), Bull. Seismol. Soc. Am., 102(5), 2239–2244.

Jeyakumaran, M., J. W. Rudnicki, and L. M. Keer (1992). Modeling slip zones with triangular dislocation elements, Bull. Seismol. Soc. Am. 82, 2153–2169.

Kuriyama, K., and Y. Mizuta (1993). Three-dimensional elastic analysis by the displacement discontinuity method with boundary division into triangular leaf elements, Int. J. Rock Mech. Min. Sci. & Geomech. Abstr. 30, 111–123.

Lin, G., P. M. Shearer, and E. Hauksson, 2007, Applying a three-dimensional velocity model, waveform crosscorrelation, and cluster analysis to locate southern California seismicity from 1981 to 2005, J. Geophys. Res., v.112, n.B12, 14 pp, B12309, doi:10.1029/2007JB004986.

Lozos, J.C., C. Nicholson and N.W. Onderdonk, Introducing the Cajon Pass Earthquake Gate Area, 2017 SCEC Annual Meeting Proceedings & Abstracts, XXVII, Tues.talk, p.133 (2017).

Meade, B. J. and B. H. Hager (2004), Slip rates, scaling laws and a moment balance in Southern California, SCEC Annual Meeting, Oxnard, California.

Meade, B. J. (2007). Algorithms for the calculation of exact displacements, strains, and stresses for triangular dislocation elements in a uniform elastic half space, Comput. Geosci. 33, 1064–1075.

Nicholson, C., Refine 3D fault & deformed surface geometry to update & expand the SCEC Community Fault Model, 2017 SCEC Annual Report, n.17066, 8 pp (2018).

Nicholson, C., A. Plesch, C.C. Sorlien, J.H. Shaw and E. Hauksson, The SCEC Community Fault Model Version 5.0: An updated and expanded 3D fault set for southern California, 2015 Pacific Section AAPG Joint Meeting Program, p.77, Oxnard, CA (2015).

Nicholson, C, A. Plesch, and J.H. Shaw, Community Fault Model Version 5.2: Updating & expanding the CFM 3D fault set and its associated fault database, 2017 SCEC Annual Meeting Proceedings & Abstracts, XXVII, poster 234, p.142-143 (2017).

Okada, Y. (1992). Internal deformation due to shear and tensile faults in a half-space, Bull. Seismol. Soc. Am 82, 1018–1040.

Pacific Gas and Electric Company (PG&E) (2015). Central Coastal CA Seismic Imaging Project Report, downloaded 11/2015 at http://www.pge.com/en/safety/systemworks/dcpp/seismicsafety/report.page.

Plesch, A., C. Nicholson, C. Sorlien, J.H. Shaw and E. Hauksson, CFM Version 5.1: New and revised 3D fault representations and an improved database, 2016 SCEC Annual Meeting Proceedings & Abstracts, XXVI, poster 003, p.222-223 (2016).

Plesch, A., J. H. Shaw, C. Benson, W. A. Bryant, S. Carena, M. Cooke, J. Dolan, G. Fuis, E. Gath, L. Grant, E. Hauksson, T. Jordan, M. Kamerling, M. Legg, S. Lindvall, H. Magistrale, C. Nicholson, N.

Niemi, M. Oskin, S. Perry, G. Planansky, T. Rockwell, P. Shearer, C. Sorlien, M. P. Süss, J. Suppe, J. Treiman, and R. Yeats, (2007), Community Fault Model (CFM) for Southern California, Bulletin of the Seismological Society of America, Vol. 97, No. 6, doi: 10.1785/012005021

Ryan, H.F., Parsons, T., and Sliter, R.W. (2008). Vertical tectonic deformation associated with the San Andreas fault zone offshore of San Francisco, California. doi: 10.1016/j.tecto.2008.06.011

Stozek, B. (2012). Geophysical evidence for quaternary deformation within the offshore San Andreas Fault System, Northern California, M.Sc. Thesis, San Francisco State University, 129 pp.

Thomas, A. (1993). POLY3D: A three-dimensional, polygonal element, displacement discontinuity boundary element computer program with applications to fractures, faults, and cavities in the Earths crust, Master's Thesis, Stanford University, Stanford, California.

Watt, J.T., Dartnell, P., Golden, N.E., Greene, H.G., Erdey, M.D., Cochrane, G.R., Johnson, S.Y., Hartwell, S.R., Kvitek, R.G., Manson, M.W., Endris, C.A., Dieter, B.E., Sliter, R.W., Krigsman, L.M., Lowe, E.N., and Chin, J.L. (J.T. Watt and S.A. Cochran, eds.), 2015, California State Waters Map Series — Drakes Bay and Vicinity, California: U.S. Geological Survey Open File Report 2015 – 1041, pamphlet 36 p., 10 sheets, scale 1:24,000, doi: 10.3133/ofr20151041

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. BSSA, 102(3), 1179-1194.