2019 SCEC ANNUAL TECHNICAL REPORT - SCEC Award 19031
Evaluate & Refine 3D Fault and Deformed Surface Geometry to Update & Improve the SCEC Community Fault Model

Craig Nicholson
Marine Science Institute, University of California, Santa Barbara, CA 93106-6150

Summary

Since SCEC3, I and my colleagues Andreas Plesch, Chris Sorlien, John Shaw, Egill Hauksson, and now Scott Marshall continue to make steady and significant improvements to the SCEC Community Fault Model (CFM), culminating in the release of CFM-v5.3 [*Nicholson et al.,* 2019]. This on-going systematic update represents a substantial improvement of 3D fault models for southern California. The CFM-v3 fault set was expanded from 170 faults to over 860 fault objects and alternative representations in CFM-v5.3 that define nearly 400 faults organized into 106 complex fault systems (**Fig.1**). Most of these updated 3D fault models were developed by UCSB, or to which UCSB made significant contributions. This includes all the major fault models of major fault systems (*e.g.,* San Andreas, San Jacinto, Elsinore-Laguna Salada, Newport-Inglewood, Imperial, Garlock, *etc.*), and most major faults in the Mojave, Eastern & Western Transverse Ranges, offshore Borderland, and updated faults within designated Special Fault Study or Earthquake Gate Areas (**Fig.1**) [*Nicholson et al.,* 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019; *Sorlien et al,* 2012, 2014, 2015, 2016; *Sorlien and Nicholson,* 2015]. These new models allow for more realistic, curviplanar, complex 3D fault geometry, including changes in dip and dip direction along strike and down dip, based on the changing patterns of earthquake hypocenter and nodal plane alignments and, where possible, imaging subsurface fault geometry with industry seismic reflection data. The major purpose of this particular project component was to continue our on-going evaluation of active 3D fault geometry and the development of new, updated 3D fault models for the CFM.

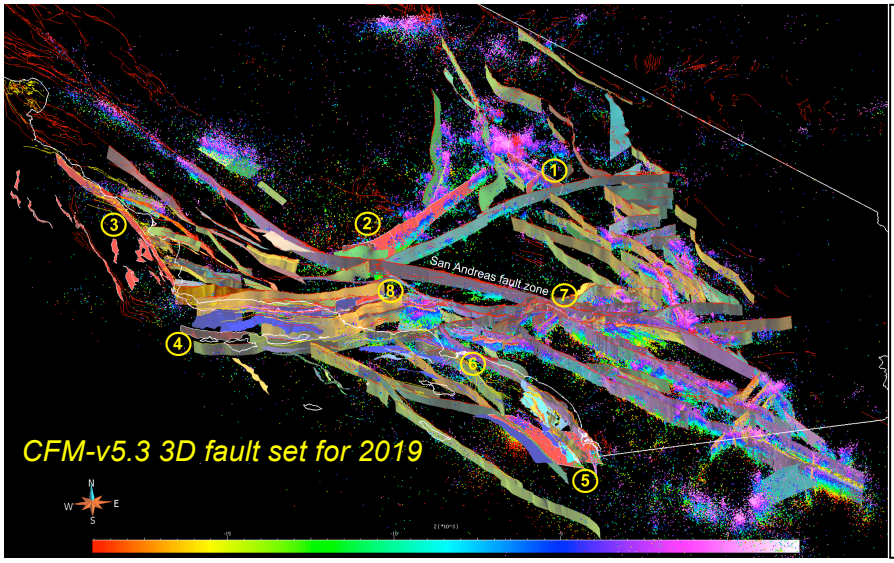

Figure 1. Oblique 3D view of 2019 CFM-v5.3 fault models, plus Qfault surface & mapped offshore seafloor fault traces, and relocated seismicity (color-coded by depth) [*Nicholson et al.,* 2019]. Updates to CFM-v5.3 (red surfaces) include 32 new 3D fault objects that help define 18 new, alternative, or updated fault models in 8 fault areas (yellow numbered circles). Relocated seismicity (1981-2018) from *Hauksson et al.* [2012 + updates]; mapped seafloor traces from *Walton et al.* [2019] and *Legg et al.* [2015]; updated Qfault surface traces from *USGS/CGS* [2018].

Technical Report

Under the SCEC research organization, many aspects of earthquake forecasting (EFP) and seismic hazard evaluation (UCERF3), including developing credible earthquake rupture scenarios (Cybershake) and simulations (CISM), predicting strong ground motion (GM), understanding the mechanical behavior of faults (FARM), and modeling stress, crustal deformation (SDOT), or geodetic and geologic fault slip rates (SAFS) over time, as well as the successful development of related community models (CXM), are all strongly dependent on accurately resolving the 3D geometry of active faults at seismogenic depths. For this reason, a considerable effort within SCEC has been focused on developing, updating and improving the CFM, and its associated Unified Structural Representation of the crust and upper mantle for southern California [*e.g., Plesch et al.,* 2007, 2016, 2018; *Nicholson et al.,* 2015, 2016, 2017, 2018, 2019; *Shaw et al.,* 2015]. Such efforts to update and improve the CFM are fundamental to SCEC's primary research

objectives if we are to better understand the geometry of the San Andreas system as a complex network of faults, and other aspects of fault kinematics, rupture dynamics, strain accumulation, and stress evolution. Because of this need, during SCEC4 and continuing into SCEC5, hundreds of new, updated or alternative 3D fault models for major active faults and fault systems were added to the CFM (**Fig.1**), resulting in fault representations in versions CFM-v4.0 through CFM-v5.3 that are more precise, realistic, and often more complex, segmented and multi-stranded than in previous CFM model versions.

As part of our on-going group efforts to update and improve the CFM and expand its user access, in 2019, access to the CFM and its associated fault database were enhanced through the CFM webpage (*https://www.scec.org/research/cfm*) and a new, interactive, web-based CFM viewer interface [*Su et al.,* 2019]. In addition, we continued to update, expand and improve the CFM 3D fault set, as well as the underlying datasets used for model evaluation, development, and refinement. This included expanding the 3D digital elevation models used to define onshore and offshore topography, updating mapped fault surface and seafloor trace files [*e.g., Walton et al.,* 2019] (**Fig.2**), and incorporating both a more complete dataset of linked relocated hypocenter and focal mechanism catalogs (1981–2018) [*Hauksson et al.,* 2012 + updates] and the more extensive QTM catalog [*Ross et al.,* 2019] (**Fig.2**). In the offshore Santa Maria basin, an integrated dataset of industry marine seismic reflection data and offshore well data was also used to help develop new fault models and refine existing fault geometry [*e.g., Sorlien et al.,* 2015].

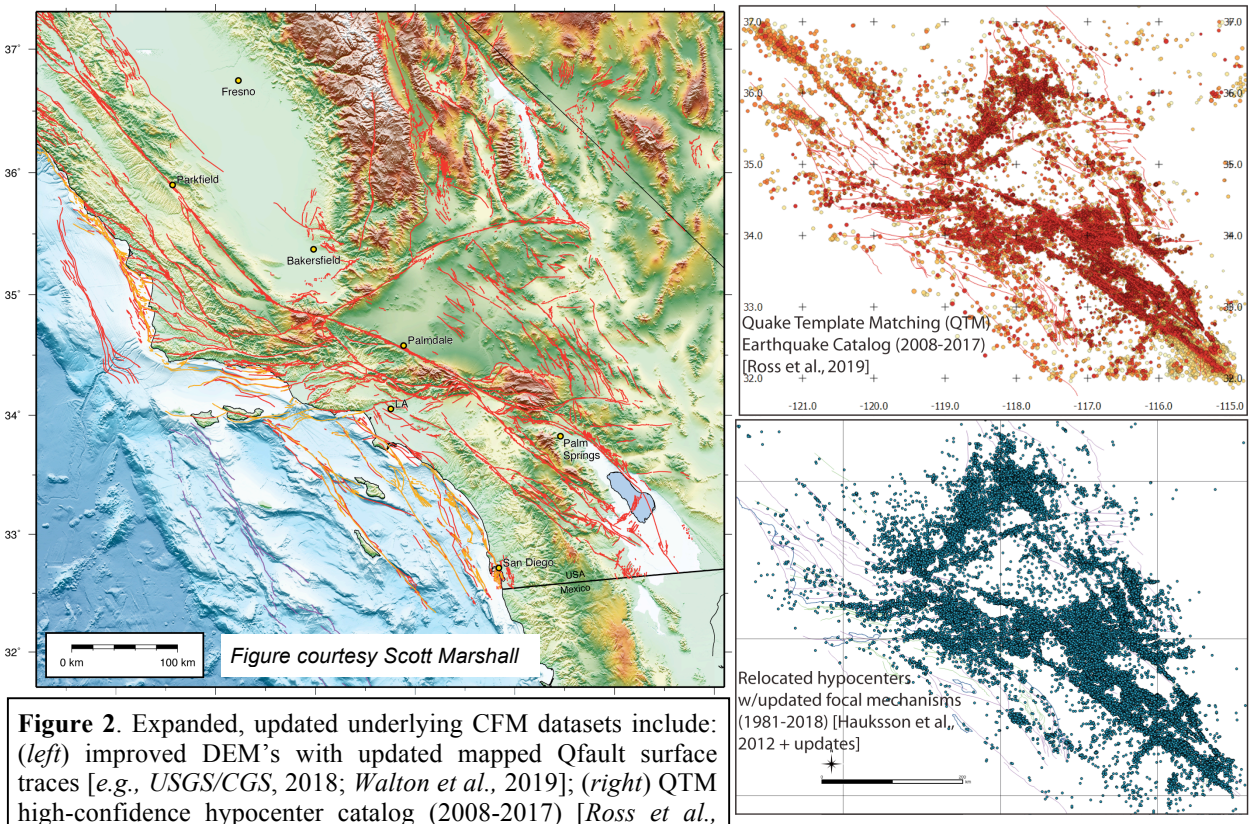

Figure 2. Expanded, updated underlying CFM datasets include: (*left*) improved DEM's with updated mapped Qfault surface traces [*e.g., USGS/CGS*, 2018; *Walton et al.,* 2019]; (*right*) QTM high-confidence hypocenter catalog (2008-2017) [*Ross et al.,* 2019] and relocated hypocenters (1981-2018) with updated focal mechanisms [*e.g., Hauksson et al.,* 2012 + updates].

With these expanded, updated, underlying datasets, new or updated 3D fault representations were added to CFM-v5.3 in the Offshore Central California fault area (Hosgri-San Simeon, Lompoc, Purisima, Santa Lucia Bank, Santa Maria Basin thrust, Sur and West Basin faults), in the Great Valley fault area (White Wolf fault and Scodie Lineament)(**Fig.3**), and in the Inner Continental Borderland (including down-dip extensions of the Thirtymile Bank and Coronado Bank detachments)[*Nicholson et al.,* 2019]. In addition, an updated Lytle Creek fault was added in the Cajon Pass Earthquake Gate Area and a new Western Santa Cruz Island fault was added in the Santa Barbara Channel (**Figs.1, 3 & 4**). The expanded CFM-v5.3 fault set also now includes an alternative, low-dip southern San Cayetano fault in the Ventura

SFSA [*Hughes et al.,* 2018, 2020], a new Wilmington Blind Thrust fault in the offshore Borderland [*Wolfe et al.*, 2019] and, in response to the 2019 Ridgecrest events, 3D representations of the Eastern Little Lake and Southern Little Lake faults in the Sierra Nevada fault area [*Plesch et al.,* 2019].

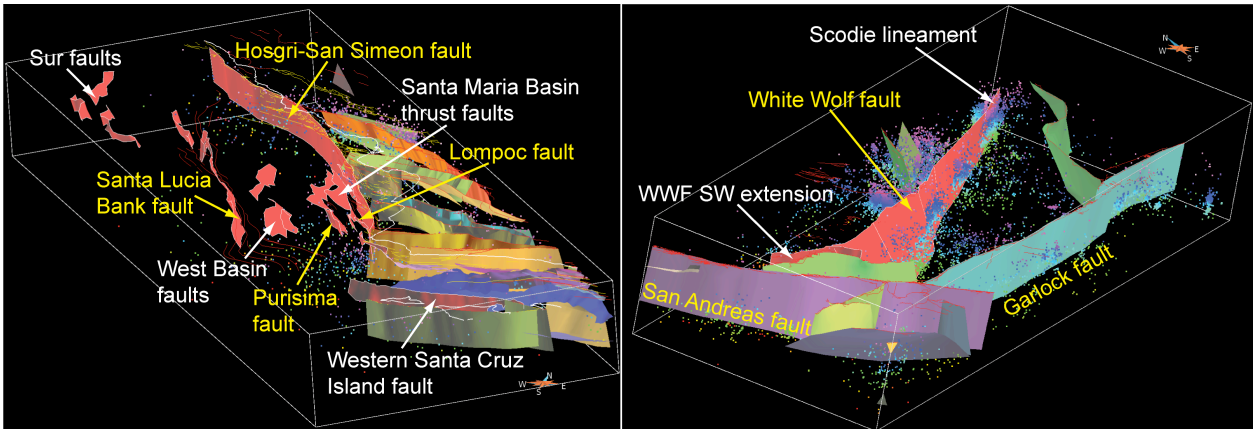

Figure 3. Oblique 3D views of (*left*) revised Hosgri-San Simeon fault and new Lompoc, Purisima, Sur, Santa Lucia Bank, Santa Maria Basin thrust and West Basin faults in the offshore Santa Maria basin, and (*right*) alternative White Wolf fault and Scodie linement in the San Joaquin Valley (red surfaces) based on industry seismic reflection and well data [*e.g., Goodman and Malin*, 1992; *Willingham et al.,* 2013; *Sorlien et al.,* 2015] and updated (1981-2018) relocated seismicity catalogs (e.g., **Fig.2**) [*Nicholson et al.,* 2019].

The updated catalogs also allow us to better characterize the active subsurface 3D fault geometry in complex fault regions. For example, in the Cajon Pass Earthquake Gate Area (EGA) focal mechanisms with nodal planes parallel or nearly parallel to the major San Andreas and San Jacinto faults exhibit predominantly strike-slip motion on steeply dipping faults (**Fig.4**), while additional events farther east provide further evidence for a through-going, steeply dipping San Andreas fault (San Bernardino-Banning strand) through San Gorgonio Pass (**Fig.5**). These refinements and improvements to the 3D fault models continue as more relevant data become available, are evaluated, and are integrated into the CFM.

The Method

Optimally, the basic method we employ to develop updated 3D fault surfaces for the CFM incorporates diverse datasets of surface and subsurface observations. For example, in the offshore Santa Maria Basin (**Fig.3**, *left*), the integrated dataset used to develop the Hosgri-San Simeon and related fault models included: grids of 2D and 3D multichannel seismic (MCS) reflection data, industry well data, relocated seismicity and revised focal mechanism catalogs, digital bathymetry data, and where available, sets of well-dated stratigraphic reference horizons [*e.g., Willingham et al.,* 2013; *Sorlien et al.,* 2015; *Behl et al.,* 2016; *Nicholson et al.,* 2019]. Similarly, industry MCS and well data were used to help define the White Wolf fault in map and cross section [*e.g., Goodman and Malin,* 1992]. These shallow fault surfaces mapped onshore and offshore in the upper 6-7 km were then extended to seismogenic depths based on available relocated seismicity [*Nicholson et al.,* 2019]. This typically involves rotating the reference frame to look down-dip of the upper fault to identify alignments of hypocenters and focal mechanism nodal planes that correlate with the geometry and plane of slip of the upper fault (or mapped fault surface trace) to define a consistent lower fault extension.

This process of looking down-dip—in the plane of slip—of the fault with seismicity can be extremely useful in terms of independently evaluating subsurface fault geometry, and the validity of proposed fault models, especially for those that may not otherwise have any subsurface constraints on fault geometry at seismogenic depths. Looking down-dip of the recently updated Lytle Creek fault in the Cajon Pass EGA (**Fig.4**) with the expanded, updated catalog of relocated hypocenters and focal mechanisms (**Fig.2**, *right*) demonstrates several important characteristics. First, events with nodal planes parallel or sub-parallel to the San Andreas and San Jacinto faults exhibit predominantly strike-slip motion on steeply dipping planes. Second, there is no significant evidence of major fault strands merging at depth, rather the seismicity tends to define a sub-vertical zone of distributed right-lateral shear through the Pass. And third,

aligned hypocenters and nodal planes suggest the Glen Helen fault strand may extend in the subsurface farther to the NW than it has been mapped at the surface (purple-dashed line, upper-left corner, **Fig.4**).

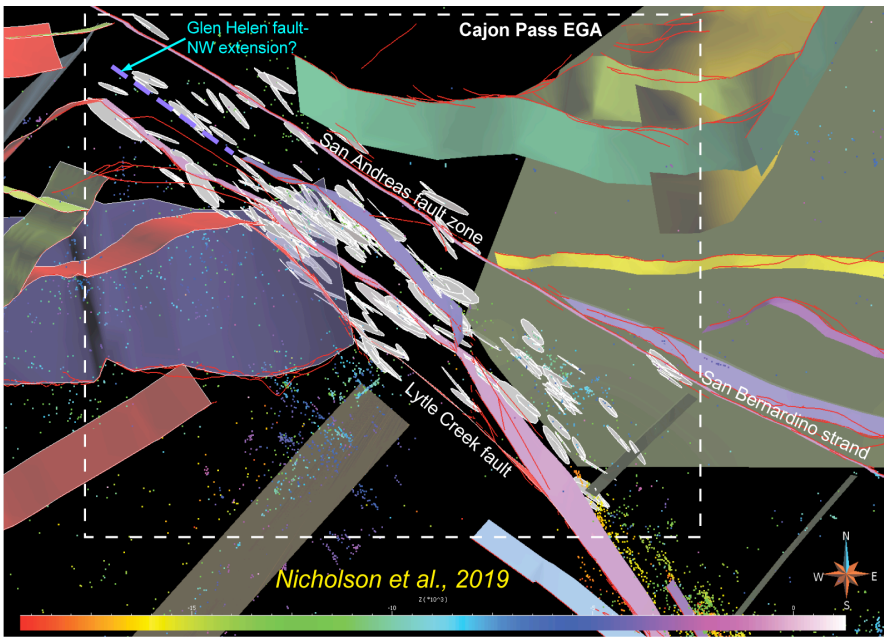

Figure 4. Oblique 3D view looking down-dip of updated Lytle Creek fault in the Cajon Pass EGA. Nodal planes (disks) parallel or sub-parallel to San Andreas and San Jacinto faults are steeply dipping (80°–90°) and define a sub-vertical zone of distributed right-lateral shear through the Pass. In the upper left corner, nodal planes appear to define a NW extension of the Glen Helen fault (purple-dashed line) in the subsurface as compared to its mapped surface trace.

Continued CFM Evaluation and Validation

In terms of regional seismic hazard, it is critically important to resolve the depth extent of faults, what linkages may exist at depth between major fault systems, and whether major faults may be detached at some shallow, mid-crustal, or deeper structural level. There is also the issue of fault model *evaluation, validation,* and how to properly discriminate between various competing alternative fault representations. For example, **Figure 5** shows some of the various CFM 3D fault sets through San Gorgonio Pass previously mapped and defined by seismicity [*Nicholson et al.,* 2013]. These CFM 3D fault models have significant predictive value. Many of the subsequent high-amplitude seismic reflectors from SSIP Line 6 [*Fuis et al.,* 2014] independently imaged important aspects of this previously determined fault geometry [*Nicholson,* 2016; *Plesch et al.,* 2015; *Nicholson et al.,* 2018], including intersecting sets of high-angle strike-slip and moderately dipping oblique-reverse faults. In addition, more recent updated relocated hypocenters and revised focal mechanism nodal planes (not previously used in CFM model construction), including the 2018 M4.5 Cabazon sequence, continue to reaffirm and validate this inferred subsurface fault geometry. This includes a steeply dipping, nearly planar, through-going San Andreas fault (San Bernardino-Banning strand) in San Gorgonio Pass that extends to depths >18 km (**Fig.5**). Other proposed San Andreas fault (SAF) representations (*e.g.,* red-dashed lines, **Fig.5**, *right*)[*Fuis et al.,* 2012; 2015] are inconsistent with these observations of a more planar steeply dipping, continuous SAF at deeper depths.

CFM Database Enhancement

Besides developing new, updated 3D fault sets for the CFM (*e.g.,* **Figs.1,3,4**), evaluating alternative representations (**Fig.5**), and updating the underlying CFM datasets used for fault model evaluation and development (**Fig.2**), as part of our on-going Harvard-UCSB CFM collaboration, Andreas and I continue to develop, expand and improve the associated fault database & metadata component of the CFM, which is critical to the internal consistency and maintainability of the model. An important contribution to SCEC's studies of fault system science was the implementation within the CFM of a hierarchical fault name and numbering scheme that allows for grouping of individual faults as part of larger, geometrically or kinematically linked fault systems [*Nicholson et al.,* 2012; *Plesch et al.,* 2014]. This enhanced CFM database organization enables model users to access and assess the full richness of the various modeled fault systems and alternative 3D models in the CFM, and allows for the increasing variety and complexity of multi-stranded principal slip surfaces, adjacent secondary faults, and alternative fault representations that have been or will be developed for CFM to be properly integrated, catalogued and registered.

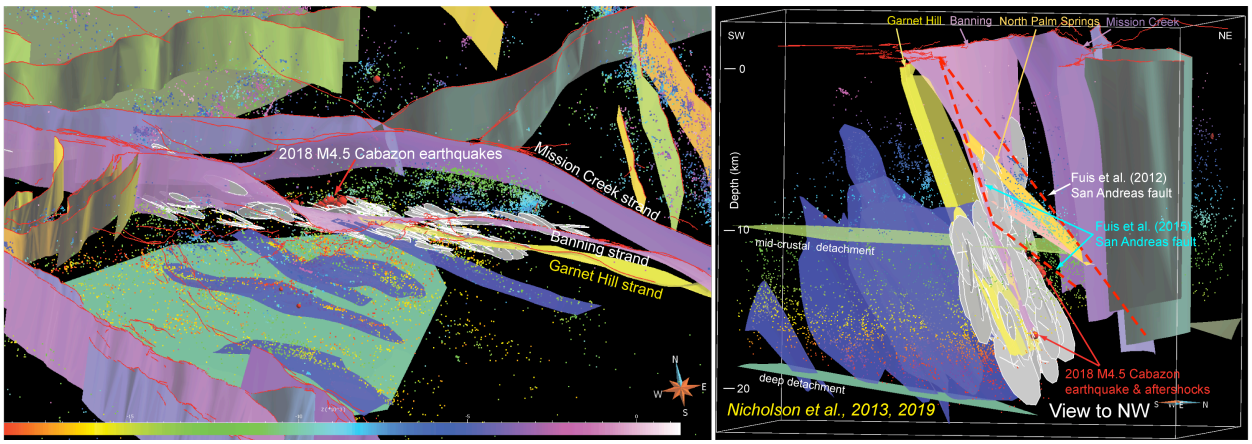

Figure 5. (*left)* Oblique 3D view looking down-dip of the Banning strand through San Gorgonio Pass of CFM 3D faults, relocated hypocenters (dots) and relocated 2018 M4.5 Cabazon hypocenters (red spheres). Circular gray disks are focal mechanism nodal planes that parallel the strike of the San Andreas fault zone. These nodal planes align along and *validate* active, through-going, steeply dipping (70°-80°) CFM Banning (purple) and Garnet Hill (yellow) fault strands through the Pass. (*right*) Oblique cross-section view looking NW through San Gorgonio Pass. Nodal planes (circular disks) and 2018 M4.5 Cabazon relocated hypocenters (red spheres) again align along steeply dipping, through-going CFM Banning (purple) and Garnet Hill (yellow) fault models to depths >18 km, *i.e.,* well below both proposed SAF models of *Fuis et al*. [2012, 2015](red-dash lines).

Starting with CFM-v5.1 and continuing into CFM-v5.3 [*Plesch et al.,* 2016; *Nicholson et al.,* 2017, 2019], the CFM fault database spreadsheet was further expanded and improved. Thus, in addition to hierarchical levels of fault area, system, section and name for each CFM 3D object, the expanded CFM database now includes fields for alternate and CFM version number, source, descriptor, references, USGS Quaternary fault (Qfault) ID, and fault property attributes of average strike, dip, area, and faulting style. In 2019, 32 new 3D fault objects that help define 18 new, alternative, or updated fault models in 8 fault areas were added to CFM-v5.3 (**Fig.1**), requiring an update and corresponding population of the associated fault database elements.

Intellectual Merit and Broader Impacts

This project supported continued development and enhancement of the CFM to facilitate its use in new community modeling efforts, fault systems studies, and probabilistic hazard assessments. As widely acknowledged, the CFM and its associated fault database are crucial components of SCEC, and are critical to many on-going SCEC activities, research objectives, program elements, and science initiatives. Having accurate and realistic 3D models of subsurface fault geometry is also important when investigating the likelihood of multi-segment or multi-fault ruptures. The main purpose and intellectual merit of this particular on-going, multi-year project component was to continue to expand, update and improve the CFM 3D fault set and its associated underlying datasets and fault database (*e.g.,* **Figs.1-3**). The project also helped, in conjunction with Andreas, John, Scott and SCEC IT, to enhance the availability and accessibility of the SCEC CFM and, as a consequence, the broader impacts of the CFM to a wider range of earthquake science initiatives, community modeling efforts, and related student research activities. Development of the dedicated SCEC CFM webpage and new, interactive web-based CFM viewer interface [*e.g., Nicholson et al.,* 2018; *Shaw et al.,* 2019; *Su et al.,* 2019] provides easier user access to the digital CFM 3D fault set of complex fault representations, allowing for comparative studies of such complex fault systems on a more global basis. In addition, at UCSB and Harvard, this project and its related collaborative component continued to support and encourage the use of state-of-the-art interactive facilities and software for the 3D visualization, analysis, interpretation and modeling of complex fault representations and underlying datasets -- facilities and software that help promote research, education and student instruction in complex earth system science and earthquake investigations with the ultimate goal of improved earthquake hazard assessment and risk mitigation.

Recent SCEC Project Reports, Publications and Related Presentations:

Behl, R.J., C. Nicholson, C.C. Sorlien, J.P. Kennett, C. Marshall, S.H. Decesari and D.E. Escobedo. Chrono-stratigraphy of the Quaternary Santa Barbara Basin: An integrated geophysical, sedimentologic and paleoceanographic approach, *2016 AAPG Pacific-Rocky Mountain Joint Meeting Program*, p.39, Las Vegas, NV (2016).

DeHoogh, G.L., C.C. Sorlien, C. Nicholson, C.S. Schindler and R.D. Francis, Structure, Evolution and Tectonic Significance of the Eastern Boundary of the Outer Continental Borderland, *SEPM Special Publication*, **110,** doi: 10.2110/sepmsp.110.08, 14 pp (2017).

Hughes, A., D.H. Rood, A. Whittaker, *et al.,* Geomorphic evidence for the geometry and slip rate of a young, low-angle thrust fault: Implications for hazard assessment and fault interaction in complex tectonic environments, *Earth and Planetary Science Letters,* **504**, doi:10.1016/j.epsl.2018.10.003, p.198–210 (2018).

Hughes, A., D.H. Rood, A. Whittaker, *et al.,* Geomorphic evidence for the geometry and slip rate of the Southern San Cayetano fault: Implications for hazard assessment and fault interaction in complex tectonic environments, *2018 SCEC Annual Meeting Proceedings & Abstracts*, **XXVIII**, poster 253, p.152 (2018).

Hughes, A., R.E. Bell et al., Three-dimensional structure, ground rupture hazards, and static stress models for complex non-planar thrust faults in the Ventura basin, southern California, *Journal of Geophysical Research: Solid Earth*, submitted and in final review, 2020.

Legg M, Sorlien C, Nicholson C, Kamerling M and Kuhn G., Potential for large complex multi-fault earthquakes offshore southern California. *Proceedings of the 11th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Los Angeles, CA, 11 pp. (2018).

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

Nicholson, C., Continuing to evaluate & update active 3D fault geometry in Special Fault Study Areas and to improve the SCEC Community Fault Model, *2015 SCEC Annual Report*, n.15154, 9 pp (2016).

Nicholson, C., Continuing to evaluate 3D fault geometry in Special Fault Study Areas and to update & improve the SCEC Community Fault Model, *2016 SCEC Annual Report*, n.16065, 8 pp (2017).

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., What Does Fault Geometry Look Like? Observations from the Field--Community Fault Model (CFM), *SCEC Dynamic Rupture Group Ingredients Workshop on Fault Geometry*, Pomona, CA, 30 Nov (2018).

Nicholson, C. and J.C. Lozos, Cajon Pass: A key QuakeGate in Southern California, *SCEC Earthquake Gate Incubator Workshop*, Pomona, CA, March 10 (2017).

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).

Nicholson, C., A. Plesch, J.H. Shaw and S.T. Marshall, Enhancements, Updates, and Improved Access to the Community Fault Model, *2018 SCEC Annual Meeting Proceedings & Abstracts*, **XXVIII**, p.173-174 (2018).

Nicholson, C., A. Plesch, C.C. Sorlien, J.H. Shaw, S. Marshall and E. Hauksson, Continued Updates, Expansion and Improvements to the Community Fault Model (CFM version 5.3), *2019 SCEC Annual Meeting Proceedings & Abstracts*, **XXIX**, poster 323, p.203-204 (2019).

Nicholson, C., C.C Sorlien and T.E. Hopps, Anomalous Uplift at Pitas Point: Implications from Onshore & Offshore 3D Fault & Fold Geometry and Observed Fault Slip, *2016 SCEC Annual Meeting Proceedings & Abstracts*, **XXVI**, poster 006, p.216-217 (2016).

Nicholson, C., C.C Sorlien, T.E. Hopps and M.J. Kamerling, Anomalous Uplift at Pitas Point: Localized Phenomena or Indicator of Tsunamigenic M8 Earthquakes Along Coastal California?, *Eos (Transactions of AGU)*, **97** (52), Abstract OS21A-1935 (2016).

Nicholson, C., C.C Sorlien, M.J. Kamerling and T.E. Hopps, An Integrated Onshore-Offshore Re-Evaluation of 3D Fault and Fold Geometry, *USGS Final Technical Report,* Award G16AP00100, 24 pp. (2017).

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, SCFM Working Group and C. Nicholson, SCFM 3.1: Updates, maps and modeling support, *2018 SCEC Annual Meeting Proceedings & Abstracts*, **XXVIII**, poster 144, p.178 (2018).

Shaw, J.H., A. Plesch, et al., Unified Structural Representation of the southern California crust and upper mantle, *Earth & Planetary Science Letters,* **415**, doi:10.1016/201501016 (2015).

Shaw, J.H., A. Plesch and C. Nicholson, Developing a Technical Activity Group for the CFM to support SCEC science, community model development, and hazard assessment, *2017 SCEC Annual Report 17027*, 7 pp (2018).

Shaw, J.H., A. Plesch and C. Nicholson, Collaborative Proposal (Harvard and UCSB): Enhancing the Community Fault Model (CFM) to support SCEC science, community model development, and hazard assessment, *2018 SCEC Annual Report 18032*, 8 pp (2019).

Sorlien, C.C., J.T. Bennett, M.-H. Cormier, B.A. Campbell, C. Nicholson and R.L. Bauer, Late Miocene-Quaternary fault evolution and interaction in the Southern California Inner Continental Borderland, *Geosphere*, **v.11**, n.4, doi:10.1130/GES01118.1 (2015).

Sorlien, C.C. and C. Nicholson, Post-1 Ma deformation history of the Pitas Point-North Channel-Red Mountain fault system and associated folds in Santa Barbara Channel, California, *USGS Final Technical Report,* Award G14AP00012, 24 pp. (2015).

Sorlien, C.C, C. Nicholson, R.J. Behl and M.J. Kamerling, Displacement direction and 3D geometry for the south-directed North Channel–Pitas Point fault system and north-directed ramps, decollements, and other faults beneath Santa Barbara Channel, *2016 SCEC Annual Meeting Proceedings & Abstracts*, **XXVI**, poster 007, p.238-239 (2016).

Su, M-H., P. Maechling, S. Marshall, E. Hearn, C. Nicholson, A. Plesch, J. Shaw and E. Pauk, Developing a Web-based Interface to the SCEC Community Fault Model (CFM), *Seismological Research Letters***, v.90**, n.2B, p.934 (2019).

Su, M-H., P. Maechling, S. Marshall, C. Nicholson, A. Plesch, J. Shaw, E. Pauk, T. Huynh and E. Hearn, A Queryable Map-Based Web Interface to the SCEC Community Fault Model, *2019 SCEC Annual Meeting Proceedings & Abstracts*, **XXIX**, poster 322, p.224 (2019).

Additional References and Related Bibliography:

Brune, J., *SCEC Precarious Rock and Related Archive*, Santa Ynez Range, 2009.

Bryant, W. A. (compiler) et al., 2005, Digital Database of Quaternary and Younger Faults from the Fault Activity Map of California, version 2.0: Latest CGS release accessed June, 2017 at: http://www.conservation.ca.gov/cgs/rghm/ap/Pages/official_release.aspx. (2017).

Cooke, M.L., D.D. Ogelsby and J.D. Yule, San Gorgonio Pass Special Fault Study Area, *2015 SCEC Annual Meeting Proceedings & Abstracts*, **XXV**, invited talk, p.141-142 (2015).

Dolan, J.F., J.H. Shaw and T.K. Rockwell, The Ventura Region Special Fault Study Area: Towards an understanding of the potential for large, multi-segment thrust ruptures in the Transverse Ranges, *2012 SCEC Annual Meeting Proc. & Abstracts*, **XXII**, p.99-100 (2012).

Ehlig, P.L., Geologic structure near the Cajon Pass scientific drill 839 hole, *Geophysical Research Letters*, **v.15**, p. 943-946 (1988).

Faure Walker, J.P., F. Visini, G. Roberts, C. Galasso, K. McCaffrey and Z. Mildon, Variable fault geometry suggests detailed fault-slip-rate profiles and geometries are needed for fault-based probabilistic seismic hazard assessment (PSHA), *Bulletin of the Seismological Society of America*, **108**, doi: 10.1785/0120180137 (2018).

Forand, D., J.P. Evans, S. Janecke and J. Jacobs, Insights into fault processes and the geometry of the San Andreas fault system: Analysis of core from the deep drill hole at Cajon Pass, California, *Geological Society of America Bulletin*, **130**(1-2), doi:10.1130/B3168.1, p.64-92 (2017).

Fuis, G.S., D. Scheirer, V. Langenheim and M. Kohler, A new perspective on the geometry of the San Andreas fault in southern California and its relationship to lithospheric structure, *Bull. Seismol. Soc. Am.*, **102**, n.1, pp.236-251, doi: 10.1785/0120110041 (2012).

Fuis, G.S., K. Bauer, et al., Geometry of the San Andreas fault and sedimentary basin in the northern Salton Trough, *2014 SCEC Annual Meeting Proc. & Abstracts*, **XXIV**, poster 092, p.141 (2014).

Fuis, G.S, K. Bauer, et al., Active flower structure along the San Andreas fault zone in Coachella Valley, California: Results from the Salton Seismic Imaging Project, *2015 SCEC Annual Meeting Proceedings & Abstracts*, **XXV**, poster 223, p.146-147 (2015).

Fuis, G.S, K. Bauer, M.R. Goldman, et al., Subsurface geometry of the San Andreas fault in Southern California: Results from the Salton Seismic Imaging Project (SSIP) and strong ground motion expectations *Bull. Seismol. Soc. Am.,* **107**, n.4, pp. 1642–1662, doi: 10.1785/0120160309 (2017)

Goodman, E.D. and P.E. Malin, Evolution of the southern San Joaqin basin and Mid-Tertiary "transitional" tectonics, central California, *Tectonics,* **v.11**, n.3, p.478-498 (1992).

Grant-Ludwig, L., J.N. Brune, A. Anooshehpoor, M.D. Purvance, R.J. Brune and J.C. lozos (2015). Reconciling Precariously Balanced Rocks (PBRs) with large earthquakes on the San Andreas fault system, *Seism. Res. Lett.* **v.86**, n.5, doi: 10.1785/0220140239, 9 pp.

Harris, R. and M. Barall, The 2018 SCEC Dynamic Rupture TAG Ingredients Workshop – Fault Geometry, *2018 SCEC Annual Report 18217*, 10 pp (2019).

Hart, P. E., and J. R. Childs (2005), National archive of marine seismic surveys (NAMSS): Status report on U.S. Geological Survey program providing access to proprietary data, *Eos Trans. AGU*, **86**, Abstract S41A-10.

Hauksson, E., Understanding seismicity in the context of complex fault systems and crustal geophysics, *2012 SCEC Annual Meeting Proc. & Abstracts*, **XXII**, p.108 (2012).

Hauksson, E., W. Yang and P. Shearer, Waveform relocated earthquake catalog for Southern California (1981 to June 2011), *Bull. Seismol. Soc. Am.,* **v.102,** n.4, p.2239-2238, doi:10.1785/0120110241, 2012.

Hopps, T.E., H.E. Stark, and R.J. Hindle, *Subsurface geology of Ventura Basin, California, Ventura Basin Study Group Report*, 45 pp., 17 structure contour maps and 84 structure cross section panels (http://projects.eri.ucsb.edu/hopps/), Rancho Energy Consultants, Inc., Santa Paula, CA, 1992.

Hubbard, J., J.H. Shaw, J.F. Dolan, T.L. Pratt, L. McAuliffe and T. Rockwell, Structure and seismic hazard of the Ventura Avenue anticline and Ventura fault, California: Prospect for large, multisegment ruptures in the Western Transverse Ranges, *Bull. Seismol. Soc. Am.*, **104**, n.3, doi:10.1785/0120130125 (2014).

Hudnut, K.W., L. Seeber and J. Pacheco, Cross-fault triggering in the November 1987 Superstition Hills earthquakes sequence, Southern California, *Geophys. Res. Lett*., **16**, n.2, p. 199–202 (1989).

Jennings, C.W., and Bryant, W.A., 2010, Fault activity map of California, *California Geological Survey Geologic Data Map No. 6*, map scale 1:750,000.

Johnson, K.M., Growth of fault-propagation folds by flexural slip folding: implications for earthquakes, *2015 SCEC Annual Meeting Proc. & Abstracts*, **XXV**, poster 226, p.158 (2015).

Johnson, S.Y., P. Dartnell, et al., California State Waters Map Series -- Offshore Ventura and Carpenteria, California, *USGS Scientific Investigations Maps 3254 & 3261*, http://pubs.usgs.gov/sim/3254/, 2013.

Kamerling, M.J., C.C. Sorlien, and C. Nicholson (1998), Subsurface faulting and folding onshore and offshore of Ventura basin: 3D map restoration across the Oak Ridge fault, *SCEC 1998 Annual Meeting Report,* p.68-69.

Kamerling, M.J., C.C. Sorlien and C. Nicholson (2003), 3D development of an active oblique fault system, northern Santa Barbara Channel, California, *Seismol. Res. Lett.*, v. **74**, n.2, p. 248.

Legg, M.R., M.D. Kohler, N. Shintaku and D.S. Weeraratne (2015), High-resolution mapping of two large-scale transpressional fault zones in the California Continental Borderland: Santa Cruz-Catalina Ridge and Ferrelo faults, *J. Geophys. Res.,* **120**, p. 915–942, doi:10.1002/2014JF003322.

Levy, Y. and T.K. Rockwell, Structural Architecture of the Western Transverse Ranges and Potential for Large Earthquakes, *Eos (Transactions of AGU)*, **96** (52), Abstract T41A-2856 (2015).

Lindsey, E.O, V.J. Sahakian, Y. Fialko, Y. Bock and T.K. Rockwell, Space geodetic investigation of interseismic deformation along the San Jacinto fault: Effects of heterogeneous elastic structure and fault geometry, *Seismological Research Letters*, **v.83**, n.2, p. 434, 2012.

Lozos, J.C., A case for historic joint rupture of the San Andreas and San Jacinto faults, *Science Advances,* **2**, e150061, pp. 1-7 (2016).

Lozos, J.C. and D.D. Oglesby, Seemingly minor details of fault geometry may strongly affect rupture propagation, *Seismol. Res. Lett.,* **83**, n.2, p.370 (2012).

Lozos, J., K.B. Olsen, D.D. Oglesby and J.N. Brune, Rupture and ground motion models on the Claremont-Casa Loma stepover of the San Jacinto fault: incorporating complex fault geometry, stresses, and velocity structure, *2013 SCEC Annual Meeting Proceedings & Abstracts*, **XXIII**, poster 149, p.127 (2013).

Marshall, S.T., G.J. Funning and S.E. Owen, Fault slip rates and interseismic deformation in the western Transverse Ranges, California, *J. Geophys. Res,* **v.118**, p.4511-4534, doi:10.1002/jgrb.50312 (2013).

McAuliffe, L.J., J.F. Dolan, E.J. Rhodes, J. Hubbard, J.H. Shaw and T.L. Pratt, Paleoseismologic evidence for large-magnitude (Mw7.5–8.0) earthquakes on the Ventura blind thrust fault: Implications for multifault ruptures in the Transverse Ranges of southern California, *Geosphere*, **11**, no. 5, 1629–1650. (2015).

Meisling, K.E., and Weldon, R.J. II, Late Cenozoic tectonics of the northwestern San Bernardino Mountains, southern California, *Geological Society of America Bulletin*, **v.101**, p. 106-128 (1989).

Morton, D.M., and Miller, F.K., Geology of the San Andreas Fault north of San Bernardino between Cajon Canyon and Santa Ana Wash, *in* Crowell, J. C., ed., *San Andreas Fault in southern California, California Division of Mines and Geology, Special Report* **118**, p. 136-146 (1975).

Nicholson, C., Seismic behavior of the San Andreas fault in the Northern Coachella Valley, California: Comparison of the 1948 and 1986 earthquake sequences, *Bulletin of the Seismological Society of America,* **v.86**, n. 5, p. 1331-1349 (1996).

Nicholson, C., E. Hauksson, and A. Plesch, Revised 3D fault models for the Southern San Andreas fault system extending from San Gorgonio Pass to the Salton Sea, *Pacific Section AAPG-GSA Cordilleran Joint Meeting Abstracts w/Program*, **v.42**, n.4, Abstract 21-8, p.69, Anaheim, CA (2010).

Nicholson, C., E. Hauksson and A. Plesch, Active fault geometry and crustal deformation along the San Andreas fault system through San Gorgonio Pass, California: The view in 3D from seismicity, *Eos (Transactions of AGU)*, **93** (52), Abstract T22C-03 (2012).

Nicholson, C. and M.J. Kamerling, Reliability of 2D kinematic fold models to infer deep fault structure in the western Transverse Ranges, California, *Proceedings of the NEHRP Conference and Workshop on the Northridge, California Earthquake of January 17, 1994*, v. **II**, p. 299–306 (1998).

Nicholson, C., M.J. Kamerling, C.C. Sorlien, T.E. Hopps and J.-P. Gratier, Subsidence, compaction and gravity-sliding: Implications for 3D geometry, dynamic rupture and seismic hazard of active basin-bounding faults in southern California, *Bulletin of the Seismological Society of America,* **97**, n.5, p.1607-1620 (2007).

Nicholson, C., A. Plesch, J.H. Shaw and E. Hauksson, Upgrades and improvements to the SCEC Community Fault Model: Increasing 3D fault complexity and compliance with surface and subsurface data, *2012 SCEC Annual Meeting Proceedings & Abstracts*, **XXII**, p.125-126 (2012).

Nicholson, C., A. Plesch, C. Sorlien, J.H. Shaw and E. Hauksson, Updating the 3D fault set for the SCEC Community Fault Model (CFM-v4) and revising its associated fault database, *2013 SCEC Annual Meeting Proceedings & Abstracts*, **XXIII**, poster 123, p.134 (2013).

Nicholson, C., A. Plesch, C. Sorlien, J.H. Shaw and E. Hauksson, The SCEC 3D Community Fault Model (CFM-v5): An updated and expanded fault set of oblique crustal deformation and complex fault interaction for southern California, *Eos (Transactions of AGU)*, **95** (52), Abstract T31B-4584 (2014).

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., L. Seeber, P. Williams and L.R. Sykes, Seismic evidence for conjugate slip and block rotation within the San Andreas fault system, southern California, *Tectonics,* **5,** p. 629-648 (1986).

Nicholson, C., C.C Sorlien, T.E. Hopps and A.G. Sylvester, Anomalous Uplift at Pitas Point, California: Whose fault is it anyway?, *2015 SCEC Annual Meeting Proceedings & Abstracts*, **XXV**, poster 221, p.171 (2015).

Oglesby, D.D, G.J. Funning and C. Kyriakopoulos, Dynamic models of the 2010 Sierra El Mayor-Cucapah earthquake, *2014 SCEC Annual Meeting Proceedings & Abstracts*, **XXIV**, poster 148, p.168 (2014).

Plesch, A., C. Nicholson, J.H. Shaw, E. Hauksson and P.M. Shearer, New developments for the SCEC Community Fault Model and its associated fault database, *2010 SCEC Annual Meeting Proceedings & Abstracts*, **XX**, p.261-262 (2010).

Plesch, A., J.H. Shaw, C. Nicholson, C.C Sorlien, and SCFM Workshop Participants, Release & Evaluation of the Statewide Community Fault Model (SCFM) Version 3.0 and Continued Updates to the SCEC CFM 5.0, *2015 SCEC Annual Meeting Proceedings & Abstracts*, **XXV**, poster 217, p.175 (2015).

Plesch, A., J.H. Shaw, C. Benson, W.A. Bryant, S. Carena, *et al.*, Community Fault Model (CFM) for Southern California, *Bulletin of the Seismological Society of America*, **97**, n.6, p.1793-1802 (2007).

Plesch, A., J.H. Shaw, Z. Ross and E. Hauksson, Detailed 3D source fault representations for the 2019 Ridgecrest earthquake sequence, *2019 SCEC Annual Meeting Proceedings & Abstracts*, **XXIX**, poster 278, p.209-210 (2019).

Redin, T., J. Forman and M.J. Kamerling, 2005, Santa Barbara Channel structure and correlation sections, Pacific Section AAPG Cross Sections CS-32 through CS-42, Bakersfield, CA.

Rockwell, T., K. Wilson, L. Gamble, M. Oskin, and E. Haaker, Great earthquakes in the western Transverse Rages of southern California on the Pitas Point-Ventura thrust system, *5th International INQUA Meeting on Paleoseismology, Active Tectonics and Archeoseismology (PATA)*, Busan, Korea (2014).

Rockwell, T.K., K. Clark, L. Gamble, M.E. Oskin, E.C. Haaker and G.L. Kennedy, Large Transverse Range earthquakes cause coastal upheaval near Ventura, Southern California, *Bulletin of the Seismological Society of America*, **v.106**, n.6, doi: 10.1785/0120150378, 14 pp (2016).

Rodriguez-Padilla, A.M., M. Oskin, T. Rockwell, I. Delusina and D. Singleton, Paleoseismic investigation and mechanical modeling of rupture behavior through Cajon Pass, *2019 SCEC Annual Meeting Proceedings & Abstracts*, **XXIX**, poster 142, p.212-213 (2019).

Ross, Z.E., D.T. Trugman, E. Hauksson and P.M. Shearer, Searching for hidden earthquakes in Southern California, *Science*, **364**, 10.1126/science.aaw6888, p.767–771 (2019).

Ross, Z.E., B. Idini, Z. Jia, *et al.,* Hierarchical interlocked orthogonal faulting in the 2019 Ridgecrest earthquake sequence, *Science*, **366**, doi:10.1126/science.aaz0109, p. 346–351 (2019).

Ryan, K.J., E.L. Geist, M. Barall and D.D. Oglesby, Dynamic models of earthquakes and tsunamis from rupture on the Pitas Point and lower Red Mountain faults offshore Ventura, California, *Seismological Research Letters,* **86**, n.2b, p.666 (2015).

Shi, Z., S. Ma, S. Day and G.P. Ely, Dynamic rupture along the San Gorgonio Pass section of the San Andreas fault, *Seismological Research Letters*, **v.83**, n.2, p. 423 (2012).

Shi, Z. and S.M. Day, Implications of observed fault geometry and stress field on rupture dynamics along the SGP Section of the San Andreas fault, *2015 SCEC Annual Meeting Proceedings & Abstr.*, **XXV**, p.184 (2015).

Sliter, R.W., Triezenberg, P.J., Hart, P.E., *et al.*, High-resolution chirp and mini-sparker seismic reflection data from the southern California continental shelf—Gaviota to Mugu Canyon: U.S. Geological Survey Open-File Report 2008–1246, available at http://pubs.usgs.gov/of/2008/1246/ (2008).

Sorlien, C.C. and M.J. Kamerling, Fault displacement and fold contraction estimated from unfolding of Quaternary strata onshore and offshore Ventura basin, California. *U.S. Geological Survey NEHRP Final Technical Report 97-GR-03085*, 16 pp., digital map scale 1/100,000 (1998).

Sorlien, C.C. and M.J. Kamerling, Fault displacement and fold contraction estimated by unfolding of Quaternary strata, onshore and offshore Ventura basin, California, *Final Technical Report to U.S. Geological Survey NEHRP*, contract 99HQGR0080 (2000).

Sorlien, C.C, M.J. Kamerling, L. Seeber, K.G. Broderick, Restraining segments and reactivation of the Santa Monica-Dume-Malibu Coast fault system, offshore Los Angeles, California, *Journal of Geophysical Research*, **v.111**, n.B11402, 22 pp., doi:10.1029/2005JB003632 (2006).

Sorlien, C.C, C. Nicholson, M.J. Kamerling and R.J. Behl, Strike-slip displacement on gently-dipping parts of the Hosgri fault and fold-related relief growth patterns above the blind oblique-slip North Channel-Pitas Point-Red Mountain fault system, *2015 SCEC Annual Meeting Proceedings & Abstracts*, **XXV**, poster 220, p.185 (2015).

Sorlien, C.C, C.J. Marshall, C. Nicholson et al., Post-1 Ma deformation history of the anticline forelimb above the Pitas Point-North Channel fault in Santa Barbara Channel, California, *2012 SCEC Annual Meeting Proceedings & Abstracts*, **XXII**, p.139-140 (2012).

Sorlien, C.C., L. Seeber, K.G. Broderick, B.P. Luyendyk, M.A. Fisher, R.W. Sliter and W.R. Normark, 2013, The Palos Verdes anticlinorium along the Los Angeles, California coast: Implications for underlying thrust faulting. *Geochemistry, Geophysics, Geosystems*, vol. **14**, no. 6, p. 1866–1890, doi: 10.1002/ggge.20112.

Tarnowski, J.M. and D.D. Oglesby, Dynamic models of potential earthquakes in the San Gorgonio Pass, CA, *Eos (Transactions of AGU)*, **93** (52), Abstract S21B-2519 (2012).

U.S. Geological Survey and California Geological Survey, 2018, Quaternary fault and fold database for the United States, accessed July 2019 from USGS web site: http://earthquake.usgs.gov/hazards/qfaults/.

Walton, M.A.L., A. Papesh, S.Y. Johnson, J.E. Conrad and D.S. Brothers, Quaternary Faults Offshore of California, *U.S. Geological Survey Data Release*, GIS digital shapefile (2019).

Weldon, R.J. (1986), The late Cenozoic geology of Cajon Pass: Implications for tectonics and sedimentation along the San Andreas fault, *Ph.D. Dissertation*, California Institute of Technology, Pasadena, CA, 400 p.

Weldon,, R.J., II, and K.E. Sieh, Holocene rate of slip and tentative recurrence interval for large earthquakes on the San Andreas fault, Cajon Pass, southern California, *Geol. Soc. Am. Bull.* **96**, 793–812 (1985).

Weldon, R.J. II, and Springer, J.E., Active faulting near the Cajon Pass well, southern California: Implications for the stress orientation near the San Andreas fault, *Geophysical Research Letters*, **v. 15**, p. 993-996 (1988).

Willingham, C.R., J.D. Rietman, R.G. Heck and W.R. Lettis, Characterization of the Hosgri Fault Zone and adjacent structures in the offshore Santa Maria Basin, south-central California, *Chap. CC of Evolution of Sedimentary Basins/Onshore Oil and Gas Investigations—Santa Maria Province*, M.A. Keller, ed., *U.S. Geological Survey Bulletin 1995-CC*, 105 pp. plus 7 plates (2013).

Wolfe, F.D., J.H. Shaw, A. Plesch, D.J. Ponti, J.F. Dolan and M.R. Legg, The Wilmington Blind-Thrust fault: An active concealed earthquake source beneath Los Angeles, California, *Bulletin of the Seismological Society of America*, **109**, n. 5, pp. 1890–1906, doi: 10.1785/0120180335 (2019).

Yang, W., E. Hauksson and P. Shearer, Computing a large refined catalog of focal mechanisms for Southern California (1981–2010): Temporal stability of the style of faulting, *Bull. Seismol. Soc. Am.,* **v.102,** n.3, p.1179-1194, doi:10.1785/0120110311, 2012.

Yeats, R. S., Huftile, G. J., and Grigsby, F. B., 1988, Oak Ridge fault, Ventura fold belt, and the Sisar decollement, Ventura basin, California, *Geology*, **v. 16**, p. 1112-1116.

Yule, D., Research Focus: The enigmatic San Gorgonio Pass, *Geology*, **37**, n.2, p.191-192 (2009).