Continuing to Evaluate & Update Active 3D Fault Geometry in Special Fault Study Areas and to Improve the SCEC Community Fault Model

2015 Annual Report for SCEC Award #15154
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I. Project Overview

A. Abstract

In the box below, describe the project objectives, methodology, and results obtained and their significance. If this work is a continuation of a multi-year SCEC-funded project, please include major research findings for all previous years in the abstract. (Maximum 250 words.)

This project is part of an on-going, multi-year effort to systematically update and improve the SCEC Community Fault Model (CFM). Since 2011 and working in close cooperation with Andreas Plesch, Chris Sorlien, John Shaw and Egill Hauksson, we continue to make steady and significant improvements to CFM [*Nicholson et al.,* 2015a; *Plesch et al.,* 2015]. These improvements include a substantial set of new, more detailed and complex 3D fault representations for CFM, updated digital surface trace data, and a new hierarchical naming and numbering scheme for the CFM fault database. In 2014 and 2015, in addition to continuing to update, evaluate and improve older CFM fault models, many new faults were added to CFM-v5 that were not represented in any previous model versions. This included faults in the onshore Santa Maria basin, Eastern & Western Transverse Ranges, Mojave, offshore Borderland, and faults within the designated San Gorgonio Pass & Ventura Special Fault Study Areas. Recent highlights include recognition that the anomalous uplift events at Pitas Point near Ventura may be controlled by the S-dipping Padre Juan fault [*Nicholson et al.,* 2015b], and confirmation that the Banning and Garnet Hill strands of the through-going San Andreas fault in San Gorgonio Pass are steeply dipping and subparallel in the northern Coachella Valley. The net result is that CFM-v5 now contains 90 distinct fault zones or fault systems defined by over 300 individually named faults, with over 360 new, updated or revised 3D fault models or alternative representations added to CFM since CFM-v3.

B. SCEC Annual Science Highlights

Rank (in order of preference) the sections in which you would like your project results to appear.

Unified Structural Representation (USR)
Seismology
Southern San Andreas Fault Evaluation (SoSAFE)

C. Exemplary Figure

Select one figure from your project report that best exemplifies the significance of the results. In the box below, enter the figure number from the project report, figure caption and figure credits.

Figure 1 is a comprehensive 3D image showing the preferred updated and new fault models (yellow and orange surfaces) added to CFM-v5 and the remaining older fault models (green) since CFM-v3. However, a more interesting figure that exemplifies the significance of our updates to CFM may be Figure 4. It compares the 3D models in CFM-v5 with the recent imaging results from SSIP Line 6 in the northern Coachella Valley. Its figure caption is:

Figure 4. Section looking NW along Banning & Garnet Hill faults in the northern Coachella Valley [*Nicholson et al.,* 2014]. In CFM-v5, these faults remain steeply dipping and subparallel to depths >10 km (model 1), they can splay down-dip (model 2), or do both to merge and interact with faults involved in the 1986 North Palm Springs sequence (model 3) [*Nicholson et al.,* 2010, 2012]. (*overlay*) Bright green lines are line segments of steeply-dipping reflectors imaged by SSIP Line 6 [*Fuis et al.,* 2014]; red dashed lines are possible alternate interpretations of the Garnet Hill & Banning faults as suggested by *Fuis et al.* [2015]; white dashed lines correspond to the Pinto Mountain fault (far right), and possibly the Dillon shear zone (middle) or other previously unrecognized secondary faults. The high degree of correlation between CFM fault models and fault plane reflections as imaged by Line 6 confirm that the Banning & Garnet Hill strands of the San Andreas fault are indeed steeply dipping & subparallel through San Gorgonio Pass.

D. SCEC Science Priorities

In the box below, please list (in rank order) the SCEC priorities this project has achieved. See *https://www.scec.org/research/priorities* for list of SCEC research priorities. *For example: 6a, 6b, 6c*

4c, 4a, 4b

E. Intellectual Merit

How does the project contribute to the overall intellectual merit of SCEC? *For example: How does the research contribute to advancing knowledge and understanding in the field and, more specifically, SCEC research objectives? To what extent has the activity developed creative and original concepts?*

Many aspects of seismic hazard evaluation, including understanding earthquake rupture and developing credible earthquake rupture scenarios, modeling geodetic and geologic fault slip, or predicting strong ground motion, are all strongly dependent on accurately resolving the 3D geometry of active faults at seismogenic depths. A considerable effort within SCEC has thus been focused on developing, updating and improving the SCEC 3D Community Fault Model (CFM). Such efforts to improve CFM are fundamental to SCEC's primary research objectives if we are to better understand aspects of fault kinematics and accurately characterize the seismic behavior, subsurface geometry and stress evolution of major fault systems. Having accurate and realistic 3D models of subsurface fault geometry is also important when investigating the likelihood of multi-segment or multi-fault ruptures on major southern California faults. The primary purpose and intellectual merit of this on-going, multi-year effort is thus to provide just such improved, more detailed and realistic 3D fault models for CFM based on the distribution of improved fault surface trace data, relocated hypocenters, focal mechanisms, seismic reflection and well data, to accurately define the 3D geometry of active faults. These updated 3D fault surfaces have already proven useful in developing dynamic earthquake rupture models along the San Andreas fault, as well as providing a better match to the observed patterns of uplift, topography, and fault slip rates along and across these active structures. In addition to providing alternative fault models and interpretations of complex fault geometry, this work has been also able to more accurately identify and characterize the degree of spatial interaction between adjacent, closely-spaced sub-parallel fault systems, and the influence of multiple high- and low-angle fault sets, fault splays, secondary faults and detachments.

F. Broader Impacts

How does the project contribute to the broader impacts of SCEC as a whole? *For example: How well has the activity promoted or supported teaching, training, and learning at your institution or across SCEC? To what extent has the project enhanced the infrastructure for research and education (e.g., facilities, instrumentation, networks, and partnerships)? What are some possible benefits of the activity to society?*

Project personnel actively participate in a number of outreach and educational activities related to informing the public, students and various stakeholders of the earthquake and tsunami hazards of coastal and Southern California. This includes contributions to and participation in various workshops organized by local Emergency Response Teams and the County Office of Emergency Services in preparation for or associated with the annual California Earthquake ShakeOut drill. Inn 2015, this included active participation as an invited speaker in the UCSB Emergency Operations Center Earthquake Exercise providing up-to-date information on earthquake, tsunami and secondary effect hazards. All these activities help instruct people on how to better prepare for, respond, or mitigate the risks from potential natural or induced earthquakes, or from more regional earthquake and tsunami hazards. As part of these outreach efforts, this project helped generate a composite regional geologic cross section across the Western Transverse Ranges, and together with various CFM products of active faults in southern California, helped develop additional digital classroom and outreach visual aids. This project also helped support and maintain various state-of-the-art interactive 3D visualization, analysis and modeling programs for use by students and researchers at UCSB for the interpretation, mapping, analysis, and modeling of subsurface 3D fault structure, seismicity, and related syntectonic stratigraphy.

G. Project Publications

All publications and presentations of the work funded must be entered in the SCEC Publications database. Log in at *http://www.scec.org/user/login* and select the Publications button to enter the SCEC Publications System. Please either (a) update a publication record you previously submitted or (b) add new publication record(s) as needed. If you have any problems, please email *web@scec.org* for assistance.

Project publications and presentations were entered in the SCEC Publications database as requested. Recent additions for 2015 are replicated below.

SCEC Project Reports, Publications, and Related Presentations for 2015:

DeHoogh, G.L., C. Nicholson, C.C. Sorlien, and R.D. Francis, Structure and Evolution of the Eastern Boundary of the California Outer Continental Borderland, *Seismological Research Letters*, **86**, n.2B, p.735 (2015).

Hauksson, E., J. Andrews, J.H. Shaw, A.Plesch, D. Shelly and C. Nicholson, The 2015 Earthquake Swarm Near Fillmore, California: Evidence for a Dehydration Event Near the Bottom of the Over-Pressurized Ventura Basin, *2015 SCEC Annual Meeting Proceedings & Abstracts*, **XXV**, poster 167, p.152-153 (2015).

Nicholson, C., Updating Active 3D Fault Geometry in Special Fault Study Areas and Improving the SCEC Community Fault Model (CFM), *2014 SCEC Annual Report*, n.14015, 8 pp (2015).

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., 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).

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).

Shaw, J.H., A. Plesch, C. Tape. M.P. Suess, T.H. Jordan 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., et al., The Ventura Special Fault Study Area: Assessing the potential for large, multisegment thrust fault earthquakes and their hazard implications, *2015 SCEC Annual Meeting Proceedings & Abstracts*, **XXV**, Plenary Talk, p.112 (2015).

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, 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, M.-H. Cormier, C. Nicholson, M.R. Legg, R.J. Behl and L. Seeber, Moderately-dipping California strike-slip faults with bends in map view and cross-section, *Eos (Transactions of AGU)*, **96** (52), Abstract T23C-2957 (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).

2015 SCEC ANNUAL REPORT - SCEC Award 15154
Continuing to Evaluate & Update Active 3D Fault Geometry in Special Fault Study Areas and to Improve the SCEC Community Fault Model

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Summary

This project is part of an on-going, multi-year effort to systematically update and improve the SCEC Community Fault Model (CFM). In 2015 and working in close cooperation with Andreas Plesch, Chris Sorlien, John Shaw and Egill Hauksson, we continued to make steady and significant improvements to CFM-v5 [*Nicholson et al.,* 2015; *Plesch et al.,* 2015]. These improvements include new, more detailed and complex 3D fault representations for CFM (**Fig.1**), and continued expansion of our new hierarchical naming and numbering scheme for CFM that allows for closer links to the USGS Quaternary fault (Qfault) database. However, many older fault models from CFM-v3 still needed to be re-registered to the more detailed Qfault surface traces and together with recent relocated hypocenters, required newer, more complex and realistic 3D fault models for CFM. Thus, in 2014 and 2015, in addition to continuing to update and improve older CFM fault models, many new faults were added to CFM that were not represented in any previous model versions. This included faults in the onshore Santa Maria basin, Eastern & Western Transverse Ranges, Mojave, offshore Borderland, and faults within the designated San Gorgonio Pass & Ventura Special Fault Study Areas. The net result is that CFM-v5 now contains 90 distinct fault zones or fault systems defined by over 300 individually named faults, with over 360 new, updated or revised 3D fault models or alternative representations added to CFM since CFM-v3 (**Fig.1**).

Figure 1. Oblique view looking NE of 2015 CFM-v5 fault models, plus Qfault surface traces (red lines), and relocated seismicity (blue dots) [*Nicholson et al.,* 2015; *Plesch et al.,* 2015]. CFM-v5 improvements include 210 new or updated 3D fault models added to CFM since the release of CFM-v4, or a total of over 360 new or updated faults (orange to yellow surfaces) or alternative representations added to CFM since version 3.0, and to the remaining CFM-v3 fault models (green surfaces). Seismicity (1981-2012) from *Hauksson et al*. [2012].

Technical Report

Many aspects of seismic hazard evaluation, including developing credible earthquake rupture scenarios, predicting strong ground motion, modeling geodetic and geologic fault slip rates, or the mechanical behavior of faults, all strongly depend on accurately resolving the 3D geometry of active faults at seismogenic depths [*e.g., Marshall et al.,* 2013, 2014; *Oglesby et al.,* 2014; *Shi and Day,* 2014, 2015; *Cooke et al.,* 2015; *Barall and Tullis,* 2015; *Bruhat and Dunham,* 2015; *Johnson,* 2015]. For this reason, a considerable effort within SCEC has been focused on developing, updating and improving the SCEC 3D Community Fault Model (CFM) and its associated Unified Structural Representation of the crust and upper mantle for southern California [*e.g., Plesch et al.,* 2007, 2014; *Nicholson et al.,* 2011, 2015; *Shaw et al.,* 2015]. Such efforts to improve CFM are fundamental to SCEC's primary research objectives if we are to better understand aspects of fault kinematics, and accurately characterize the seismic behavior, dynamic rupture, strain accumulation and stress evolution of major mapped fault systems. Having accurate and realistic 3D models of subsurface fault geometry is also particularly important when investigating the likelihood of multi-fault ruptures in southern California, and helping to resolve the influence of fault roughness and fault complexity.

Thus, as part of our on-going group efforts to expand, update and improve CFM, many new or revised 3D fault models for major active faults were added to CFM. In 2015, this included completion of an updated and expanded fault set for active faults in the Mojave, additional detailed faults in the offshore Borderland (**Fig.1**), and initial development and evaluation of alternative models and an expanded fault set involved in the complex 3D pattern of fault and fold deformation for the Ventura Special Fault Study Area (SFSA)(**Fig.2**)[*Nicholson et al,* 2015; *Sorlien et al,* 2015; *Plesch et al,* 2015].

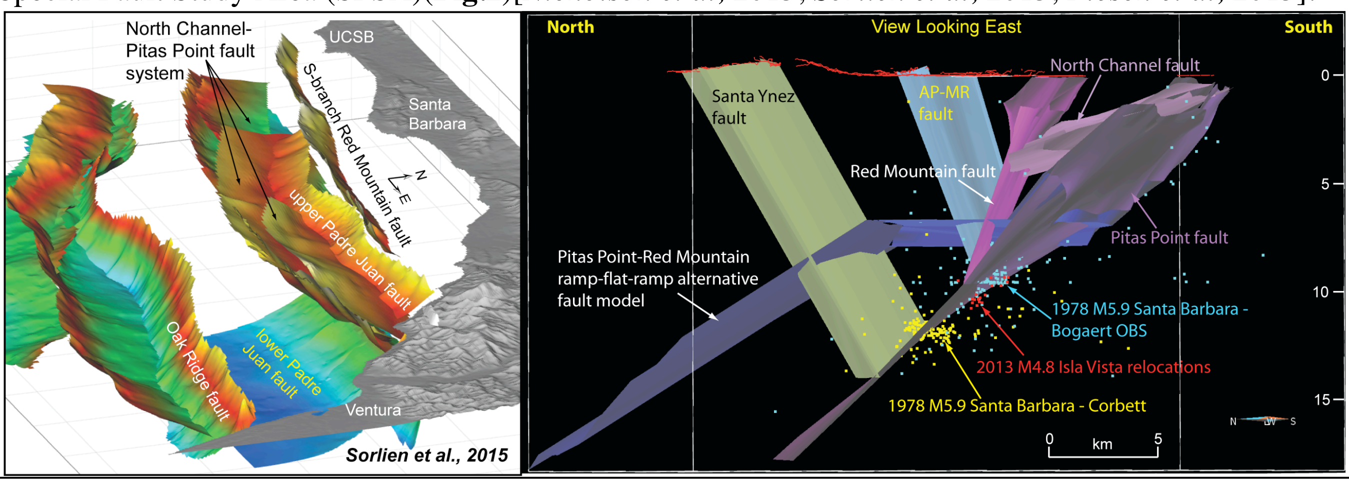


Figure 2. (*left*) Oblique 3D view looking NW of new 3D fault models mapped using industry multi-channel seismic reflection data [*Sorlien et al.,* 2015]. North Channel-Pitas Point fault system now extends from Ventura west to Pt. Conception, a distance of over 140 km. Newly mapped upper and lower S-dipping, listric Padre Juan fault is also shown. (*right*) Oblique 3D view looking East of North Channel-Pitas Point-Red Mountain fault system (red-purple faults) [*Nicholson et al.,* 2014] and alternative ramp-flat Pitas Point-Red Mountain fault model (dark blue)[*Hubbard et al.,* 2014]. Independent datasets of relocated hypocenters from the 1978 M5.9 Santa Barbara and 2013 M4.8 Isla Vista earthquakes (not included in either original model construction) indicate that recent slip is more consistent with the steeply dipping fault model, rather than the proposed alternative ramp-flat model [*Nicholson et al.,* 2015].

Many of these efforts to improve CFM, however, are not yet complete. For example, the revised, expanded fault set in the Mojave area still needs community review prior to formal release. The updated fault models in the offshore Borderland were based on imaging with industry multi-channel seismic (MCS) data to depths of ~5-6 km [*e.g., Rivero and Shaw,* 2011; *Sorlien et al.,* 2015]. Several of these faults mapped at shallow crustal levels still need to be extended deeper using the available relocated seismicity [*e.g., Astiz and Shearer,* 2000; *Hauksson et al.,* 2012]. This is particularly important for major active faults along the coast like the Newport-Inglewood-Rose Canyon fault system.

These issues of fault model completion also pertain to preliminary updated fault models developed for the North Channel-Pitas Point-Red Mountain fault system (**Fig.2**) as part of the Ventura SFSA. This system includes the N-dipping Pitas Point-Ventura fault (PPVF) believed to be responsible for the large vertical uplift events found at Pitas Point [*Rockwell et al.,* 2014]. Alternatively, the anomalous uplift events at Pitas Point and the unusual fold geometry of the San Miguelito anticline—that lies directly beneath—may be controlled by slip on the newly mapped S-dipping Padre Juan fault (**Fig.3**), either as a backthrust off the PPVF, or as a separate, interacting out-of-syncline thrust fault [*Nicholson et al.,* 2015]. Regardless, the preliminary shallow crustal fault models mapped in two-way travel time (twtt) using MCS data (*e.g.,* **Fig.2,** *left*; **Fig.3**, *right*) need to be properly depth converted with appropriate velocity models and extended deeper with the available seismicity [*e.g., Nicholson and Kamerling,* 1998; *Kamerling et al.,* 2003; *Hauksson et al.,* 2012], and important S-dipping faults like the Padre Juan fault—that have not yet been incorporated into existing fault-related fold models [*c.f., Hubbard et al.,* 2014]—need to be properly mapped and extended onshore in 3D using an integrated dataset of offshore MCS and onshore-offshore well data (*e.g.,* **Fig.3**)[*Nicholson et al.,* 2015].

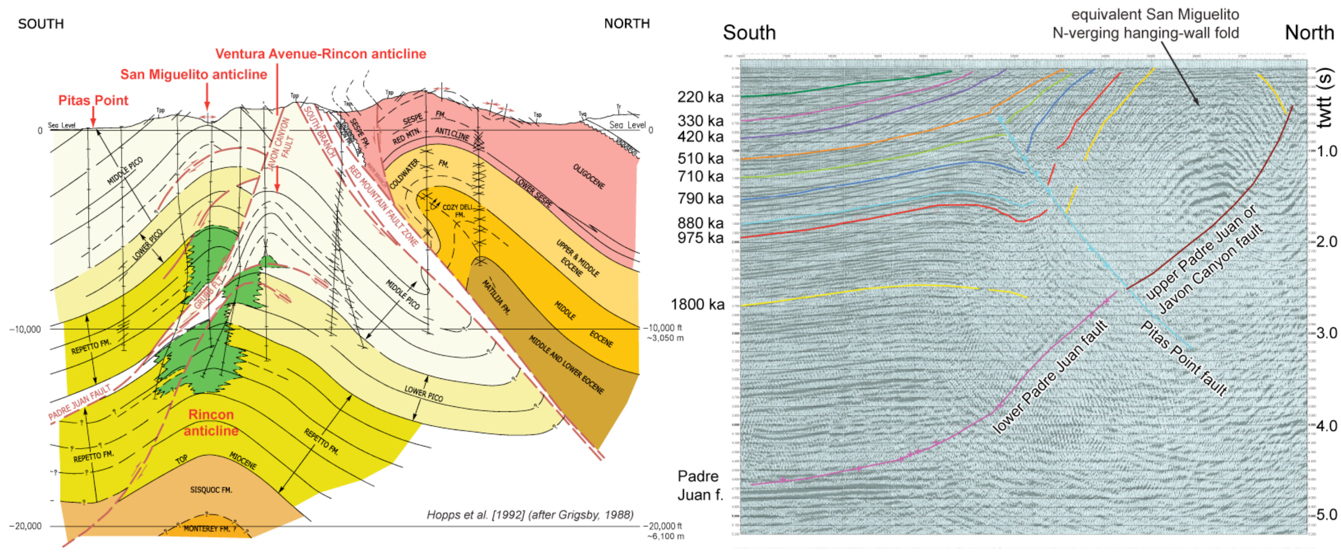


Figure 3. (*left*) Vertical cross section looking west through Pitas Point based on industry well data [*Grigsby,* 1988; *Hopps et al.,* 1992; *Nicholson et al.,* 2015]. Note the S-dipping listric Padre Juan-Javon Canyon fault that thrusts the asymmetric N-verging San Miguelito anticline above the more symmetric Ventura Avenue-Rincon anticline located in its footwall. (*right*) Example of deep-penetration industry MCS line showing mapped dated reference horizons (colored lines) used to assess rates of deformation and the S-dipping Padre Juan fault imaged in the footwall (purple) and hangingwall (dark red) of the N-dipping Pitas Point fault (light blue). Lower Padre Juan is imaged near the coast (**Fig.2,** *left*), and projects to merge with the upper fault farther east onshore.

Besides issues of fault refinement using the more detailed 3D fault surfaces mapped with MCS and well data (**Figs.2&3**), or extending faults deeper with available relocated seismicity, there is also the issue of fault model *evaluation* and how to properly discriminate between various competing alternative representations. For example, **Figure 2** (*right*) shows two alternative fault models in CFM-v5 for the offshore Pitas Point-Red Mountain fault. The dark-blue, ramp-flat-ramp model is based on limited well data in the onshore Ventura basin and a 2D fault-related fold model that has been projected offshore [*Hubbard et al,* 2014]. The purple, more steeply dipping model is based mostly on previous offshore mapping with industry MCS data, and combining this with relocated seismicity & well data in the Santa Barbara Channel [*Nicholson and Kamerling,* 1998; *Kamerling et al.,* 2003; *Nicholson et al,* 2014]. If we compare these alternative fault models with independent datasets of relocated hypocenters of the 1978 M5.9 Santa Barbara and 2013 M4.8 Isla Vista earthquakes (the two largest reasonably recorded events and ones not previously included in either original model construction), this indicates that the steeply dipping fault model, rather than the alternative ramp-flat model, is more consistent with this recent slip.

For the Ventura SFSA, we thus have made substantial progress in documenting, mapping and modeling the fault geometry and behavior of the North Channel-Pitas Point-Red Mountain fault system (which includes the PPVF), as well as its potential interactions with secondary S-dipping structures [*e.g., Nicholson et al.,* 2014, 2015; *Sorlien et al.,* 2014, 2015]. Based on integrating MCS, well and seismicity data, together with onshore geologic mapping and offshore bathymetry, several key characteristics of this important fault system can be readily identified: (1) The fault system is complex (**Fig.2**, *left*), it exhibits elements of strain partitioning, it can be mapped from Ventura west to Pt. Conception (a distance of over 140 km), and it extends to depths of 20 km; (2) The PPVF strand is mostly blind (**Fig.3**, *right*) with little-to-no offset of the Last Glacial Maximum unconformity (dated at ~11-12 ka for this area) offshore; (3) The PPVF tends to merge with the Red Mountain fault at a depth of ~10 km (**Fig.2**, *right*); (4) Slip on the PPVF diminishes up dip and is largely absorbed by hangingwall folding; (5) Uplift at Pitas Point is mainly driven by folding of the San Miguelito anticline situated above the S-dipping Padre Juan fault (**Fig.3**, *left*) and possibly by continued uplift associated with the distinctly separate, deeper Ventura Avenue anticline located below the Padre Juan fault; (6) Although offset by the PPVF farther west, the upper and lower Padre Juan faults tend to merge eastward (**Fig.3**, *right*) and may thus become an independent out-of-syncline thrust that drives uplift and emplacement of the N-verging San Miguelito anticline [*Grisby,* 1988; *Yeats et al.,* 1988; *Hopps et al.,* 1992; *Nicholson et al.,* 2015]. These characteristics exhibited by the N-dipping and S-dipping faults are all important properties that need to be fully incorporated into CFM, into any further 2D or 3D fault-related fold model development, and into any seismic or tsunami-generating dynamic rupture models and regional hazard assessments.

In the San Gorgonio Pass SFSA, we continued our evaluation of and development of various fault models and alternative representations for the San Andreas fault system and adjacent secondary faults, based on the seismicity [*Nicholson et al.,* 2012, 2014, 2015] and on recent results from the Salton Sea Imaging Project (SSIP)[*Fuis et al.,* 2014]. It is very reassuring that—to date, a number of the important characteristics of the 3D fault models in CFM have now been independently verified by the SSIP results. **Figure 4** shows an overlay of steeply dipping line segments (green lines) imaged by SSIP Line 6 [*Fuis et al.,* 2014] on top of a cross section of CFM-v5 faults in the northern Coachella Valley [*Nicholson et al.,* 2014]. The SSIP results confirm that the Banning (light purple) and Garnet Hill (yellow) fault strands remain steeply dipping and sub-parallel to depths of ~10 km (model 1), where they begin to merge with a set of more moderately dipping secondary faults (model 2), including the fault(s) responsible for the 1986 North Palm Springs sequence (model 3)[*Nicholson et al.,* 2010, 2012]. The implication is that there is indeed one or more active, steeply dipping, through-going strands of the San Andreas fault through San Gorgonio Pass that can accommodate dynamic rupture, in addition to more moderately dipping secondary faults that help accommodate crustal shortening—and not just a single, moderate-to-low-angle dipping San Andreas fault, as was originally proposed by *Fuis et al*. [2012].

Similarly, farther south, the results of SSIP Line 4 are also encouraging. **Figure 5** shows a map and cross section across the nearly-vertical Southern San Andreas fault (red-purple, SSAF) and NE-dipping Mecca Hills-Hidden Springs fault system (dark purple) with its more steeply dipping, shallow fault splays (turquoise). CFM fault models are based on distinctly separate groups of hypocenters (orange and yellow spheres), aligned nodal planes (gray disks), and mapped Qfault surface traces (red lines). Results from SSIP Line 4 (bright green line segments) image the NE-dipping Mecca Hills-Hidden Springs fault and a number of the steeply dipping hangingwall splays (red dashed lines are from *Fuis et al.,* 2015). The most remarkable aspect of these results is that, at Line 4, they suggest the NE-dipping Mecca Hills fault would project to crop out west of the SSAF surface trace. In addition, on both SSIP Line 4 (**Fig.5**) and Line 6 (**Fig.4**), the steeply dipping faults with the largest cumulative displacement (i.e., SSAF on Line 4 and Mission Creek fault on Line 6), and thus presumably with the largest impedance contrasts, are not imaged by the SSIP reflected refractions at either shallow or deep crustal levels. This limitation of SSIP capabilities strongly indicates that care must be taken when interpreting these SSIP images.

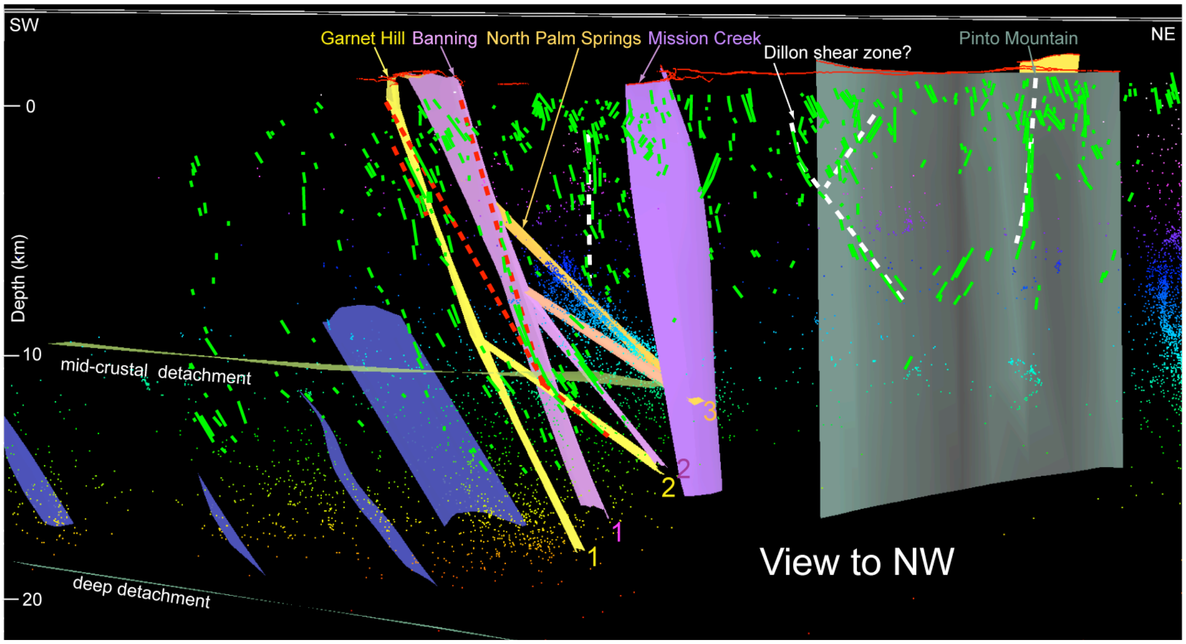
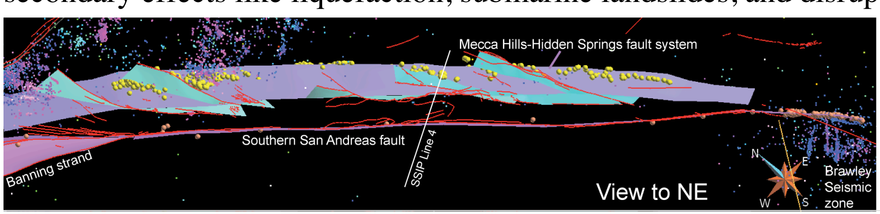


Figure 4. Section looking NW along Banning & Garnet Hill faults in the northern Coachella Valley [*Nicholson et al.,* 2014]. In CFM-v5, these faults remain steeply dipping and sub-parallel to depths >10 km (model 1), they can splay down-dip (model 2), or do both to merge and interact with faults involved in the 1986 North Palm Spings sequence (model 3) [*Nicholson et al.,* 2010, 2012]. (*overlay*) Bright green lines are line segments of steeply-dipping reflectors imaged by SSIP Line 6 [*Fuis et al.,* 2014]; red dashed lines are possible alternate interpretations of the Garnet Hill & Banning faults as suggested by *Fuis et al*. [2015]; white dashed lines correspond to the Pinto Mountain fault (far right), and possibly the Dillon shear zone (middle) or other previously unrecognized secondary faults.

In addition, Andreas and I continue to develop and expand the associated CFM fault database to accommodate 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. Outreach activities associated with this project include on-going presentations to various local civic groups on earthquake and tsunami hazards in the Santa Barbara and Ventura areas; various radio, TV, and newspaper interviews as requested, as well as invited talks organized by local Emergency Response Teams. In 2015, this included participation in the UCSB Emergency Operations Center Earthquake Exercise as an invited speaker on the hazards associated with earthquakes, tsunamis, and possible secondary effects like liquefaction, submarine landslides, and disruption of critical utility lines.



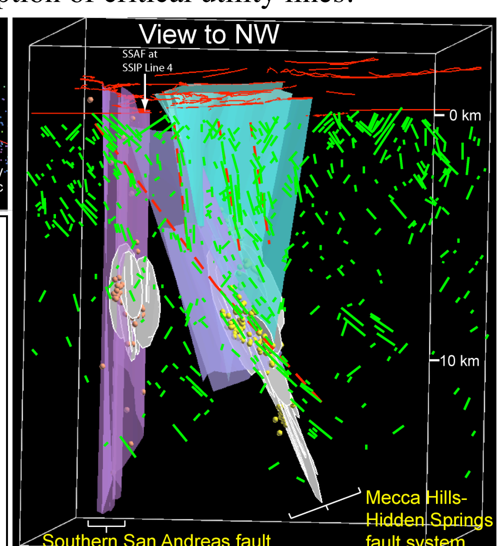


Figure 5. (*top*) Map view looking NE of the near-vertical Southern San Andreas and adjacent subparallel NE-dipping Mecca Hills-Hidden Springs fault systems. Earthquakes associated with each separate fault system are highlighted as orange and yellow spheres, respectively. (*right*) Cross section view looking NW along these two separate near-vertical and NE-dipping fault systems [*Nicholson et al*., 2014]. The separate groups of hypocenter and nodal plane alignments are consistent with two distinct adjacent fault systems. (*overlay*) Bright green lines are line segments of steeply-dipping reflectors imaged by SSIP Line 4 [*Fuis et al.,* 2014]; red dashed lines are fault interpretations from *Fuis et al*. [2015].

Recent SCEC Project Reports, Publications, and Related Presentations:

DeHoogh, G.L., C. Nicholson, C.C. Sorlien, and R.D. Francis, Structure and Evolution of the Eastern Boundary of the California Outer Continental Borderland, *Seismological Research Letters*, **86**, n.2B, p.735 (2015).

Hauksson, E., C. Nicholson, J.H. Shaw, A. Plesch, P.M. Shearer, D.T. Sandwell and W. Yang, Refined views of strike-slip fault zones, seismicity, and state of stress associated with the Pacific-North America plate boundary in Southern California, *Eos (Transactions of AGU)*, **94** (52), Abstract T21E-05 (2013).

Hauksson, E., J. Andrews, J.H. Shaw, A.Plesch, D. Shelly and C. Nicholson, The 2015 Earthquake Swarm Near Fillmore, California: Evidence for a Dehydration Event Near the Bottom of the Over-Pressurized Ventura Basin, *2015 SCEC Annual Meeting Proceedings & Abstracts*, **XXV**, poster 167, p.152-153 (2015).

Nicholson, C., Earthquake hazard associated with deep well injection in California, *Invited Ojai Chautauqua Panel Discussion Talk*, Ojai, California, November, 9, 2014.

Nicholson, C., Updating Active 3D Fault Geometry in Special Fault Study Areas and Improving the SCEC Community Fault Model (CFM), *2014 SCEC Annual Report*, n.14015, 8 pp (2015).

Nicholson, C., A. Plesch and E. Hauksson, Active 3D fault geometry along the San Andreas fault system through San Gorgonia Pass inferred from seismicity and other data, SCEC San Gorgonio Pass Special Fault Study Area Workshop, *2014 SCEC Annual Meeting Proceedings & Abstracts*, **XXIV**, p.102 (2014).

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).

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