2017 SCEC ANNUAL TECHNICAL REPORT - SCEC Award 17066
Refine 3D Fault & Deformed Surface Geometry to Update & Expand the SCEC Community Fault Model

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Summary

During SCEC4 and through 2017, I and my colleagues Andreas Plesch, Chris Sorlien, John Shaw and Egill Hauksson continued to make steady and significant improvements to the SCEC Community Fault Model (CFM), culminating in the recent release of CFM-v5.2 [*Nicholson et al.,* 2017]. This systematic and on-going update to CFM represents a substantial improvement of 3D fault models for southern California. The CFM-v3 fault set 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 (**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 faults 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, Coast Ranges, offshore Borderland, and updated faults within Special Fault Study or Earthquake Gate Areas [*Nicholson et al.,* 2012, 2013, 2014, 2015, 2016, 2017; *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 alignments and, where possible, subsurface imaging of fault geometry with seismic reflection data. In 2015-2017, 150 new updated 3D fault objects were added to CFM-v5.2 since the initial release of v5.0.

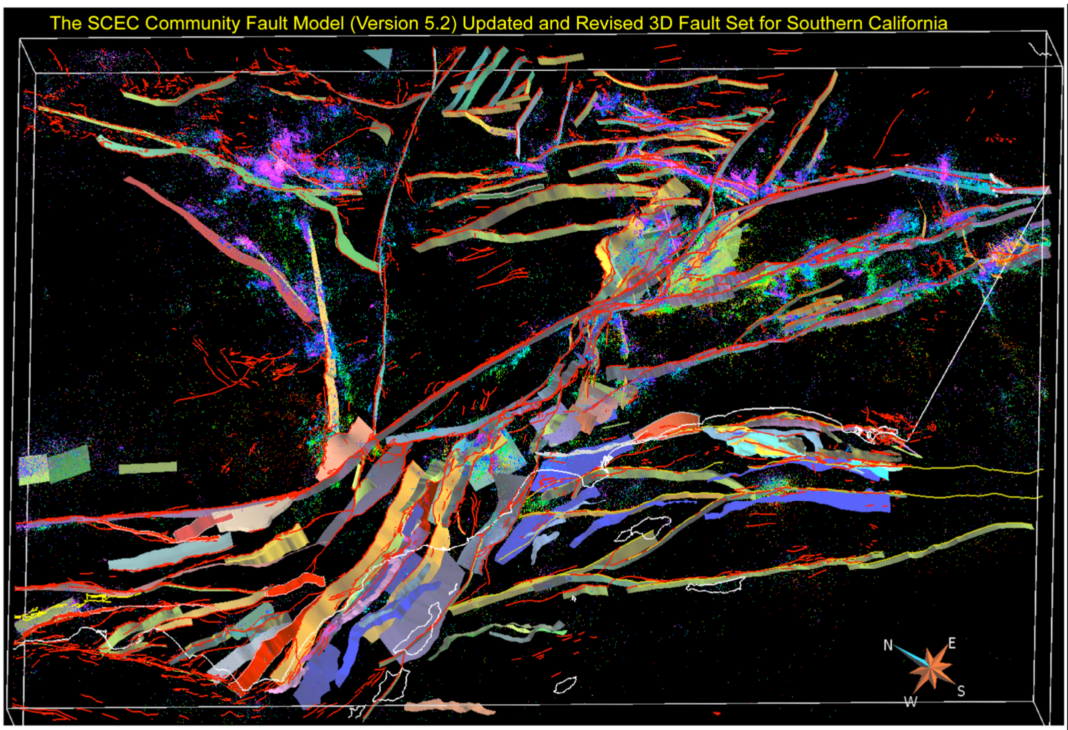

Figure 1. Oblique 3D view looking NE of CFM-v5.2 fault models, plus Qfault surface traces (red lines), and relocated seismicity [*Nicholson et al.,* 2017]. For 2017 alone, updates to CFM include 30 new or updated fault models located in the Borderland, Coast Ranges and Western Transverse Ranges, including Ventura Special Fault Study Area and Cajon Pass Earthquake Gate Area. Relocated hypocenters (1981-2016) from *Hauksson et al.* [2012 + recent updates].

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), as well as 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 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, 2016; *Nicholson et al.,* 2015, 2016, 2017; *Shaw et al.,* 2015]. Such efforts to update and improve 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, dynamic rupture, 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 CFM (**Fig.1**), resulting in fault representations that are more precise and often more complex, segmented, curviplanar and multi-stranded than in previous CFM model versions.

As part of our on-going group efforts to update, expand and improve CFM, this project added many new, updated or revised 3D fault models to CFM in the Inner Borderland and Coast Ranges, and in the Western Transverse Ranges associated with the Ventura Special Fault Study Area (SFSA) or Cajon Pass Earthquake Gate Area (EGA). The Borderland fault updates to CFM included an updated and improved Newport-Inglewood fault, and extending the active Thirtymile Bank and Coronado Bank detachments imaged at shallow depth using seismic reflection data to seismogenic depths based on correlations to relocated seismicity and focal mechanism nodal planes provided by *Hauksson et al.* [2012] and *Yang et al.* [2012](**Fig.2**). These new down-dip extensions have significant implications for how high- and low-angle faults may interact and intersect, the down-dip extent of high-angle strike-slip faults, and the prospect for potential larger complex, multi-fault ruptures in the offshore Borderland [*Legg et al.,* 2018], similar to the recent, complex 2016 M7.8 Kaikoura, NZ event [*e.g., Hamling et al.,* 2017].

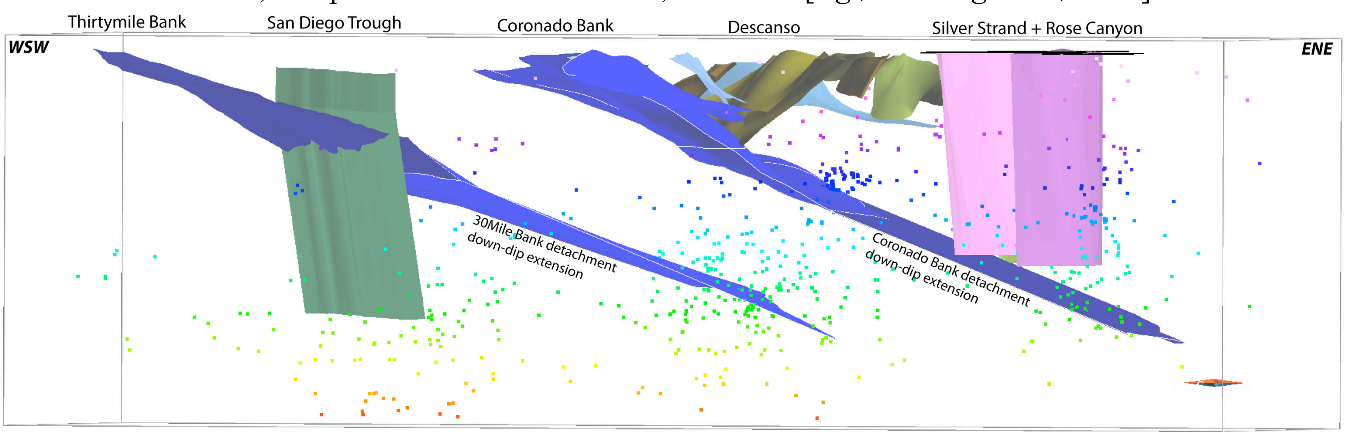

Figure 2. Cross sectional view looking WNW of CFM-v.5.2 3D fault surfaces with updated relocated seismicity (1981-2016) from [*Hauksson et al.,* 2012 + updates] color coded by focal depth. Alignments of hypocenters and nodal planes along the downdip projection of the E-dipping Thirtymile Bank and Coronado Bank detachment faults indicate that these stacked low-angle detachments are likely seismically active [*Legg et al.,* 2018].

New or revised CFM fault surfaces in the Coast Ranges and Sierra Nevada fault areas developed in collaboration with Andreas Plesch include the Airport Lake, Big Springs, Little Pine, Oceanic plus West Huasna, San Juan and Santa Ynez River faults (**Fig.3**)[*Nicholson et al.,* 2017]. These faults expand the 3D fault set previously developed under SCEC4, and provide an alternative explanation for the observed patterns of local geodetic uplift previously attributed to a ramp geometry and faults south of the Santa Ynez Range [*Marshall et al.,* 2017] that did not otherwise account for these newly added CFM faults.

In addition to expanding the 3D CFM fault set for southern California and related issues of fault model completion and extending faults deeper with relocated seismicity, there are also issues regarding fault model *evaluation,* model *validation,* and how to properly discriminate between various competing alternative representations. For example, in the Ventura SFSA, there is still a persistent, major on-going controversy regarding the faults responsible for the large vertical uplift events found at Pitas Point [*Rockwell et al.,* 2014, 2016]. One model postulates that these uplift events are driven exclusively by slip on the N-dipping Pitas Point-Ventura fault (PPVF), that the size of the uplift events is characteristic of the average slip over the fault during rupture, and that the PPVF exhibits a distinctive ramp-flat-ramp geometry, with a flat detachment at 7 km depth [*e.g., Hubbard et al.,* 2014; *Rockwell et al.,* 2016]. The alternative model considers the uplift events at Pitas Point to be anomalous and localized, and therefore not representative of the average slip at depth further along strike during rupture; to consider the PPVF—and the Red Mountain fault with which it merges—to be relatively steeply dipping to depths of 18-20 km without a flat detachment, and that the uplift at Pitas Point is primarily driven by slip on the S-dipping Padre Juan fault that forms the San Miguelito anticline, its interaction with the PPVF, and/or the result of a localized restraining bend or possible tear fault in the PPVF [*Nicholson et al.,* 2015; 2016].

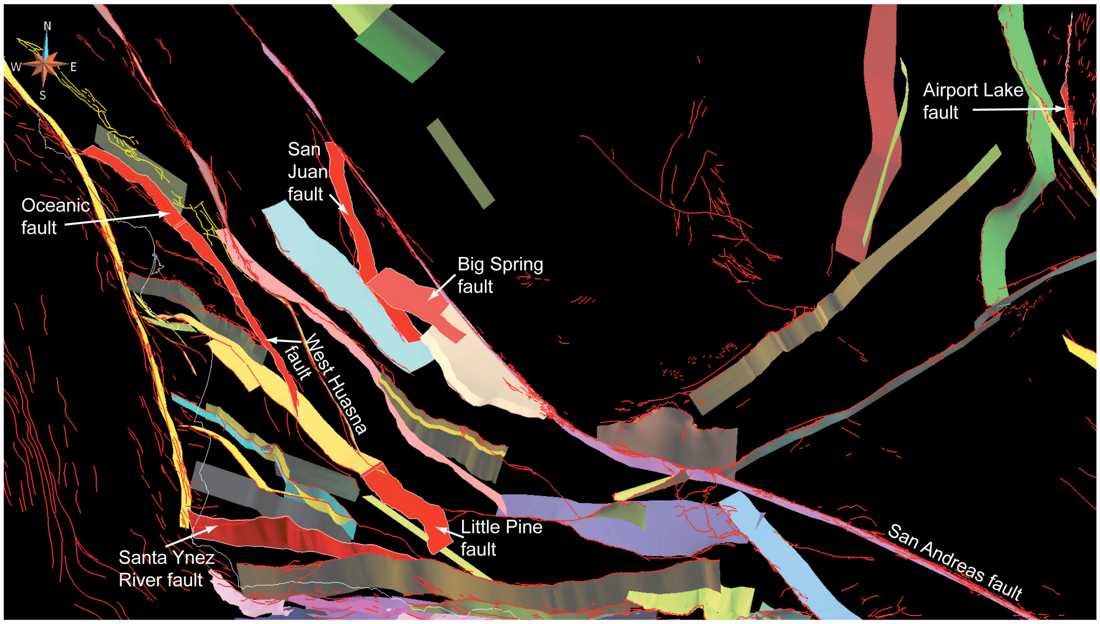

Figure 3. Oblique 3D map view of CFM fault models in the Coast Ranges, Great Valley & Sierra Nevada fault areas [*Nicholson et al.,* 2017]. Some of the updated 3D models for v5.2 include the Airport Lake, Big Spring, Little Pine, Oceanic, San Juan, Santa Ynez River, and West Huasna faults (red surfaces with white outlines).

Given the absence of seafloor deformation or Holocene fault offset west of Pitas Point on the PPVF, an additional postulate to account for the possible occurrence of proposed, multiple ~M8 earthquakes is that the PPVF is linked farther east to the San Cayetano fault [*Hubbard et al.,* 2014]. The proposed linking structure was called the Southern San Cayetano fault (SSCF), but as no data were provided to confirm its existence or orientation, the proposed SSCF could dip either north or south [*Hubbard et al.,* 2014]. If the SSCF did dip north, similar to the Ventura fault with which it was intended to connect, then it was presumed to dip at 45°-50° and was located in the middle of the Santa Clara River Valley.

Recent geologic mapping, in combination with industry well data document the presence of a young, active, low-angle fault along the north side of the basin that would seem to connect the Ventura fault to the San Cayetano fault [*Rood,* 2016; *Hughes et al.,* 2018]. At its eastern end, this revised, updated proposed SSCF matches the location and dip of the previously identified Pagenkopp fault based on correlating industry subsurface well data [*Çemen,* 1989; *Hopps et al.,* 1992]. The primary difference between this new, low-angle SSCF and the older proposed version is that it dips north at ~20° and is located along the range-front rather than out in the middle of the basin. **Figure 4** shows oblique CFM 3D views for this new SSCF (green, Alex-20°) in relation to the older Hubbard SSCF model (orange)(**Fig.4,** *left*), and the disparity in dip between the new, low-angle SSCF (green) in relation to the more steeply N-dipping Ventura fault (VF, purple) and San Cayetano fault (SCF)(*right*). Although in oblique map view (**Fig.4**, *right*), the new, low-angle SSCF does connect the Ventura and San Cayetano faults at the surface, the disparity in their dips suggests, however, that there may not be an adequate link at seismogenic depths to allow slip to propagate between these two fault systems during dynamic rupture, as many people had originally believed if there was indeed an active, connecting SSCF present. Thus, it is unclear what the seismic hazard potential is for this newly identified, low-angle SSCF, as it currently exhibits relatively small cumulative displacement, it is confined to the shallow crust and it is unclear if it can rupture independently of the SCF or link ruptures between the VF & SCF.

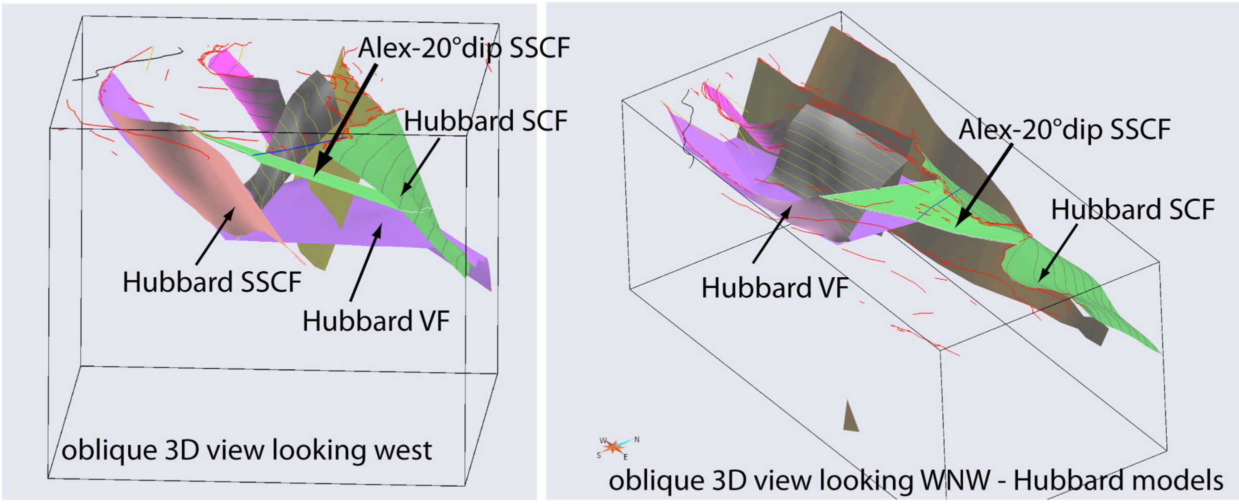

Figure 4. (*left*) Oblique view looking west of CFM surfaces for old, steeply N-dipping proposed Southern San Cayetano fault (SSCF) (orange) [*Hubbard et al.,* 2014] versus the newly identified, alternative, active low-angle SSCF (green, Alex-20°)[*Hughes et al.,* 2018]. (right) Oblique view looking down to the WNW with the older SSCF now missing. This view shows how the low-angle, range-front SSCF connects the Ventura (VF) and San Cayetano faults (SCF) at the surface, but not at seismogenic depths where most earthquakes tend to propagate.

Besides continuing to evaluate and help discriminate between alternative fault representations (like the Hubbard SSCF versus low-angle SSCF), a considerable effort of this project, in conjunction with my colleagues Julian Lozos and Nate Onderdonk, was focused on developing and promoting the Cajon Pass Earthquake Gate Area Initiative [*Nicholson and Lozos,* 2017; *Lozos et al.,* 2017] and subsequent Cajon Pass EGA Science Plan, as well as updating and expanding the preliminary CFM 3D fault set associated with the recently designated Cajon Pass EGA (**Fig.5**)[*Nicholson et al.,* 2017]. Updated 3D fault surfaces for CFM-v5.2 included the Cucamonga fault and Sierra Madre-Cucamonga connector, and newly added secondary San Antonio Canyon, Stoddard Canyon, South Fork-Stoddard Canyon, Icehouse Canyon, Weber and Red Hill faults. These CFM updates also included new updated rupture models for the 1812 [*Grant-Ludwig et al.,* 2015; *Lozos,* 2016](*e.g.,* **Fig.5**, red segments) and 1857 earthquakes.

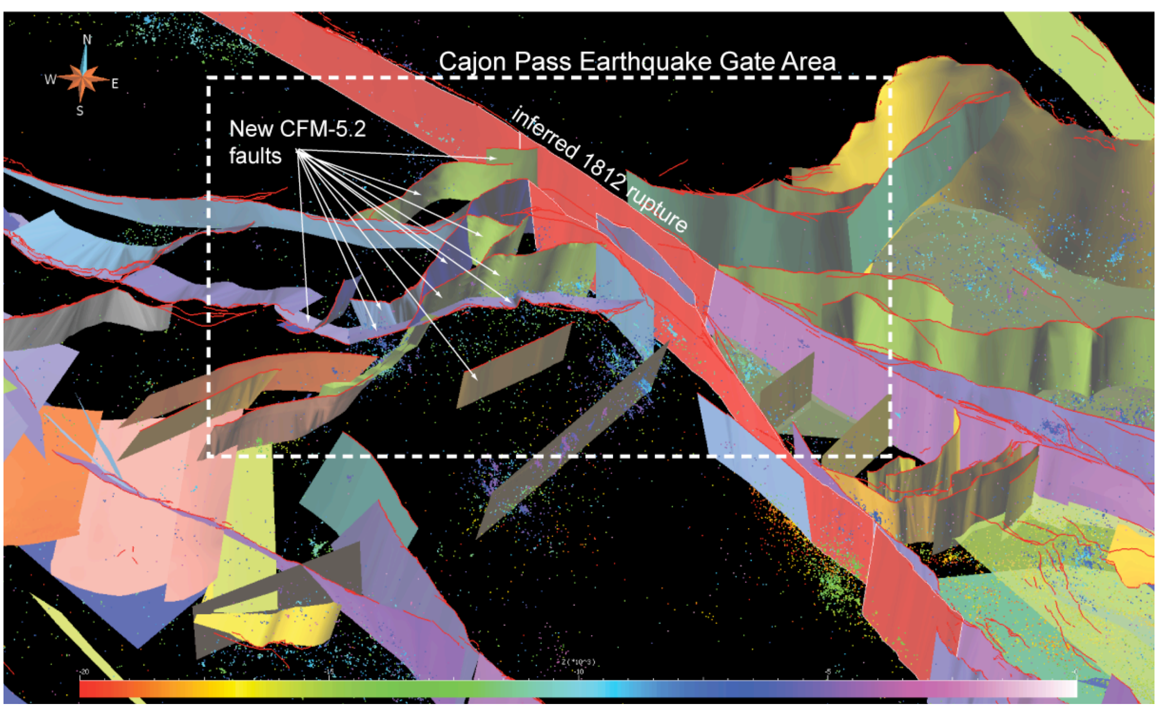

Figure 5. Oblique 3D map view looking North of CFM fault models in the Cajon Pass EGA. Updated 3D models for CFM-v5.2 include the Cucamonga fault and Sierra Madre-Cucamonga connector, and new secondary San Antonio Canyon, South Fork, Stoddard Canyon, Icehouse Canyon, Red Hill and Weber faults. Red colored sections of the San Andreas & San Jacinto faults represent the updated rupture model for the 1812 M7.5 earthquake [*Lozos,* 2016].

It should be noted that these preliminary CFM fault models for the Cajon Pass EGA are not yet complete. Many still need to be properly evaluated and validated, and even for the major through-going strike-slip faults, like the San Andreas and San Jacinto, it is still not clear the extent to which these major faults do or do not physically merge at depth. Currently in CFM, neither the San Jacinto and San Andreas faults actually intersect at depth, nor do the Cucamonga and San Andreas faults.

One of the enhancements to CFM that we had hoped to introduce with SCEC5 is the incorporation of more geological, lithologic or rheological surfaces into CFM besides faults. CFM already includes important boundaries like top-basement, base seismicity, and various local detachment surfaces. Expansion of the CFM digital surface library to include other useful surfaces and material interfaces, like the dated, deformed stratigraphic reference horizons mapped offshore in the Santa Barbara Channel (**Fig.6**)[*Sorlien et al,* 2016] and onshore in the Ventura basin [*Hopps et al.,* 1992] can provide a geologic framework for quantifying finite strain, modeling rates of off-fault and fault-related fold deformation, and helping to provide a foundation for other CXM initiatives, like the Community Rheological Model. Unfortunately, delays in funding for 2017, an expanded focus on the Cajon Pass EGA Initiative, and a lack of support in 2018 from SCEC and the CRM for these types of expanded research components for CFM has led to a substantial delay in implementation of these proposed CFM improvements.

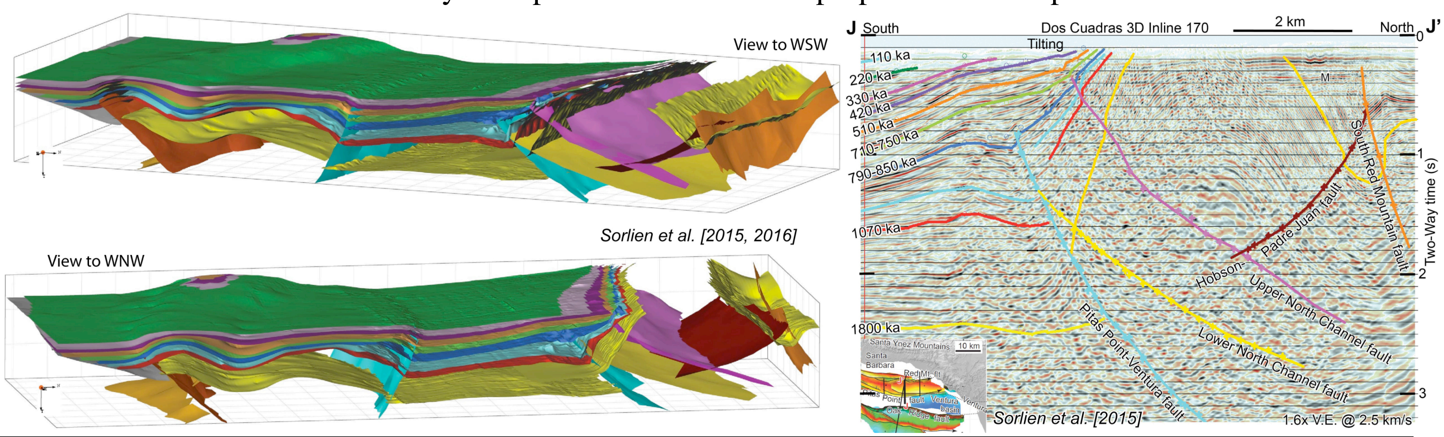

Figure 6. (*left*) Oblique 3D views in Santa Barbara Channel looking WNW & WSW of faults and dated stratigraphic reference horizons mapped in 3D with industry MCS data. (*right*) Example of MCS data from Dos Cuadras 3D survey used to map faults and dated reference horizons that can help model finite strain and better define the CRM.

Besides developing new, updated 3D fault sets for CFM and evaluating alternative representations (**Figs.1-5**), as part of an on-going companion CFM TAG project, Andreas and I continue to develop, expand and improve the associated database & metadata component of CFM, which is critical for the internal consistency and maintainability of the model. This enhanced database organization enables model users to access and assess the full richness of the various modeled fault systems and alternative 3D models in 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 catalogued, registered and coordinated. Outreach activities associated with this project include on-going presentations to various local civic groups and Emergency Response Teams on the hazards associated with earthquakes, tsunamis and landslides, and specific presentations to the South Coast Geological Society and to UC Riverside on CFM, its properties and capabilities to enhance research and earthquake hazard assessment, and on the complexities of major fault systems.

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