2012 SCEC ANNUAL REPORT

Evaluating 3D Fault Geometry in Special Fault Study Areas and Improving the SCEC Community Fault Model (CFM)

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Summary

This project is part of an on-going, multi-year effort within SCEC to systematically upgrade and improve the Community Fault Model (CFM). In 2012 and working in close cooperation with Andreas Plesch, John Shaw, and Egill Hauksson, we continued to make steady and significant improvements to the CFM and its associated fault database [*Nicholson et al.,* 2012]. These improvements include more detailed and complex 3D representations of major active fault systems (**Fig.1**), additional detailed fault surface trace data, and finalization of our new naming and numbering scheme for CFM that allows for closer links to the USGS/CGS Quaternary fault database (Qfaults). A systematic revision of CFM fault models was triggered by unexpected discrepancies between previous CFM-v.3 fault representations and the newer Qfaults surface traces, as well as by the availability of extensive relocated earthquake catalogs to better define the complex subsurface geometry of active faults. A draft version of CFM-v.4 was sent out for review and comment; however, this upgrade to CFM-v.4 is not yet complete. Many fault models in CFM-v.3 still need to be re-registered to the more detailed Qfault surface traces and, together with recent relocated hypocenters, require newer, more complex and more realistic 3D fault models for CFM. This includes major faults within designated, past, or soon-to-be designated Special Fault Study Areas (SFSA). In 2012, this project was able to develop improved CFM 3D models for a number of these areas including Parkfield, San Gorgonio Pass, Laguna Salada-Sierra Cucapah and San Fernando-Northridge.

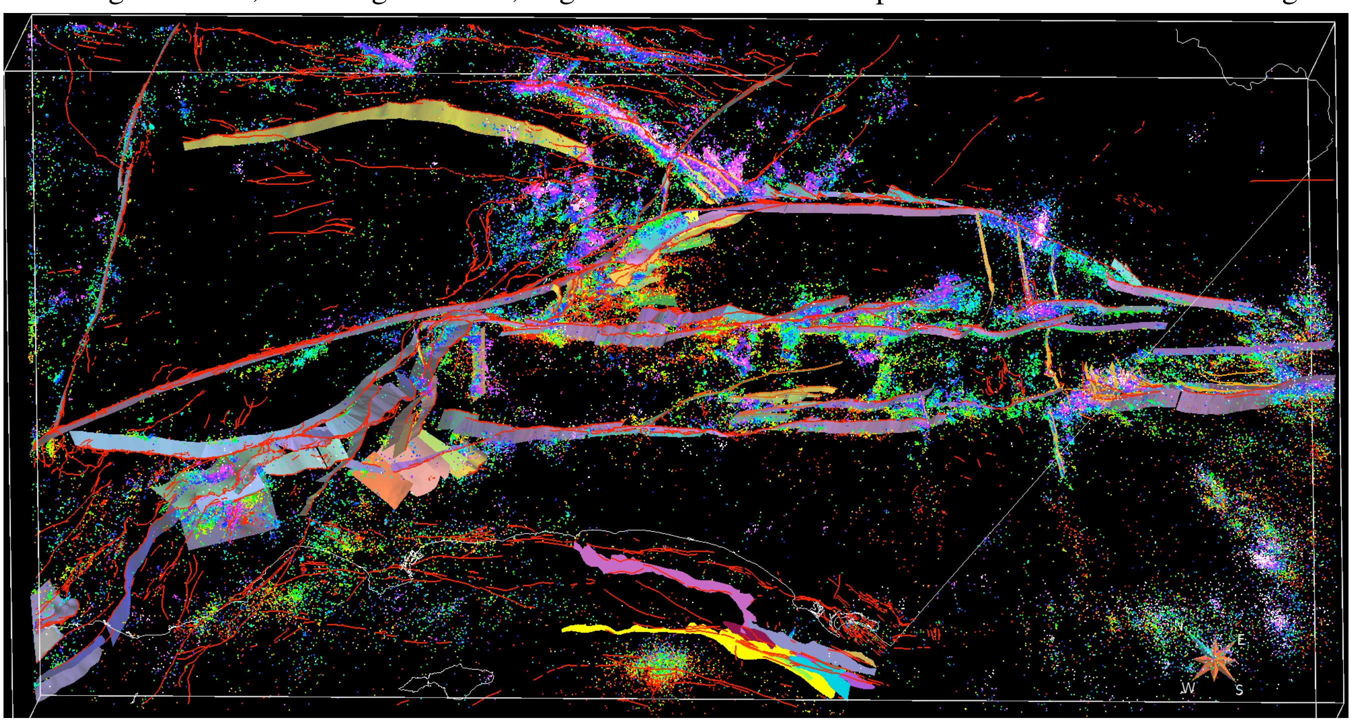


Figure 1. Oblique 3D view looking NE of new, revised CFM-v.4 fault representations developed in 2011 and 2012, plus Qfault surface traces (red lines), and relocated seismicity (dots color-coded by depth) [*Nicholson et al.,* 2011; 2012]. New CFM 3D faults are now registered to the Qfault surface traces and major strike-slip faults are no longer assumed to be vertical, but change dip and dip direction along strike and with depth to better correlate with the relocated hypocenters. Seismicity from *Hauksson et al*. [2012]. Offshore models for Carlsbad, Coronado Bank, and Descanso faults recently provided by Chris Sorlien [*Bennett et al.,* 2012].

Technical Report

The purpose of this collaborative project was to continue our on-going evaluation of active 3D fault structure and the development of new digital 3D fault representations for CFM. In addition to updating 3D fault representations for CFM, Andreas and I, together with John, Egill, Tom Rockwell and Jerry Treiman have nearly completed a new CFM fault database hierarchical naming and numbering scheme. This allows CFM to properly organize, name and number the increasing variety and complexity of modeled, multi-stranded principal slip surfaces and associated secondary faults, while maintaining more consistency with fault nomenclature from the USGS/CGS Fault Activity database. This work is being conducted in coordination with CGS (Chris Wills, Jerry Treiman) and USGS (Kathy Haller) fault database personnel, and it too needs continued updating and review as new fault models are developed.

Thus, as part of our on-going group efforts to expand and improve CFM, a major upgrade to CFM and its associated fault database was initiated [*Plesch et al.,* 2010; *Nicholson et al.,* 2011, 2012]. This upgrade involves four major elements: 1) addition of a new surface trace layer that allows subsurface 3D fault models in CFM to be registered to the more detailed, mapped fault traces from Qfaults and other digital map sources; 2) incorporation of new 3D fault representations that allow for more non-planar 3D fault geometry, as suggested by the relocated microseismicity (**Fig.1**); 3) implementation of a new fault hierarchical naming and numbering scheme for individual 3D fault models that allows for more flexible database searches and easier identification of fault components, alternative representations and possible system-level associations of the 3D fault elements that comprise CFM; and 4) availability of CFM fault representations and other CFM objects referenced to the modern WGS84 datum. The problem is that, although major components of this upgrade to CFM-v.4 have been successfully completed and a draft version has been sent out for review and comment, this revision of CFM still needs more work owing to the large number of faults that still need to be remodeled in 3D and re-registered to Qfaults.

Project Activities

1) In 2012, substantial progress was made on implementing newly revised 3D models for several major fault zones, including the San Andreas from Parkfield to Cajon Pass, Garlock, Imperial-Brawley, Landers-Joshua Tree ruptures, Laguna Salada-Sierra Cucapah, San Gabriel, Oak Ridge-Northridge and the San Fernando/Sierra Madre faults, as well as for several major intervening cross faults (**Fig.1**) [*Nicholson et al.,* 2012]. These new models expand the lexicon of revised 3D fault models previously developed for CFM-v.4 that include the San Andreas (SAF) from San Gorgonio Pass to the Salton Sea, the adjacent sub-parallel Mecca Hills-Hidden Springs, the San Jacinto, the Elsinore, and Agua Tibia-Earthquake Valley fault systems [*Nicholson et al.,* 2011]. The new models allow for more non-planar, multi-stranded 3D fault geometry, including changes in dip and dip direction along strike and down dip, based on the changing patterns of earthquake hypocentral and focal-mechanism nodal plane alignments, rather than projecting faults to depth assuming a constant (often vertical) dip and dip direction, as is the case for many of the previous preliminary fault models in CFM.

For example, **Figure 2** shows a map view of some of the new CFM 3D fault representations along the southern San Andreas fault through San Gorgonio Pass [*Nicholson et al*., 2012]. San Gorgonio Pass and its surrounding region are currently designated a Special Fault Study Area [*Yule et al.,* 2012]. Knowing the subsurface geometry of active faults here is critical for properly extrapolating near-surface observations to depth, and is particularly important in such complex areas where principal slip surfaces can be multi-stranded, exhibit significant non-planar subsurface fault geometry, and/or intersect other adjacent major faults. The recent 2010 M7.2 El Mayor-Cucapah earthquake demonstrated that major earthquakes can be quite complex [*Hudnut et al.,* 2010] and can occur on adjacent sub-parallel faults in close proximity to previous large earthquake ruptures on major mapped faults (e.g., 1892 M7 Laguna Salada). Along the San Andreas fault proper, there is no place more complex, enigmatic, or more important to properly understand (particularly in 3D) than San Gorgonio Pass [*Yule,* 2009] and its extension to Cajon Pass where the major San Andreas and San Jacinto fault zones intersect (**Figs. 1&2**).

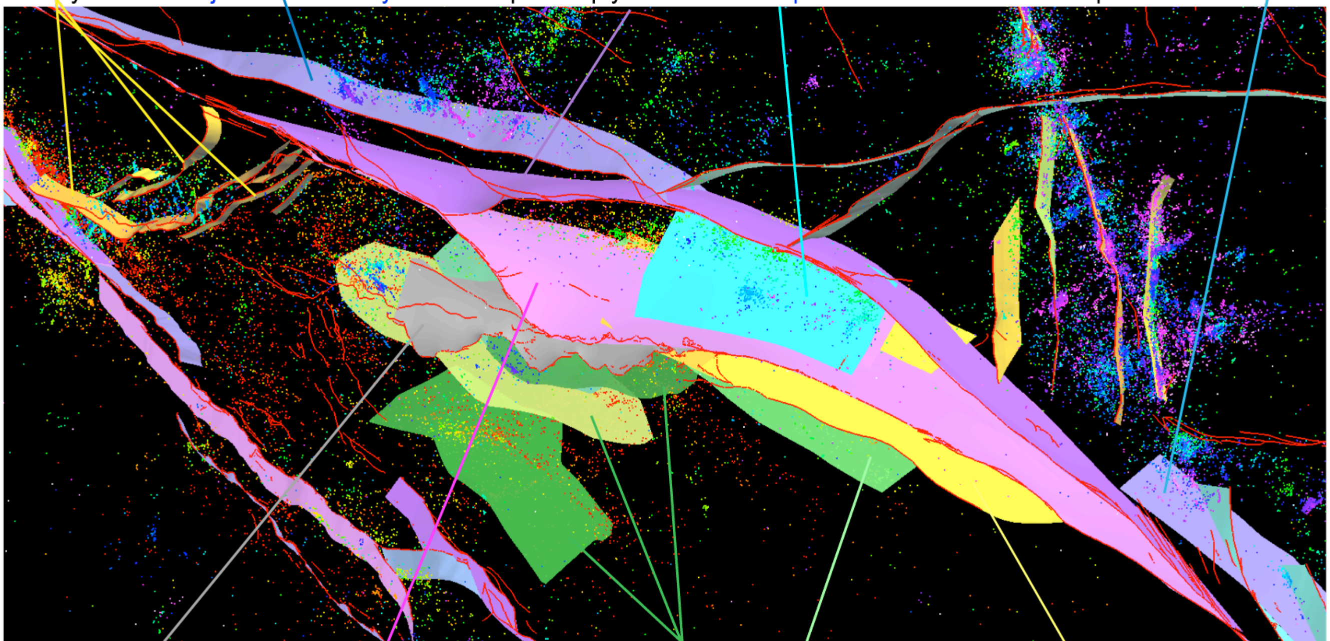


Figure 2. New CFM-v.4 fault models for the San Andreas fault system through San Gorgonio Pass [*Nicholson et al.,* 2012]. Three distinctly separate fault strands (Mission Creek, Banning, and Garnet Hill) are now defined in the northern Coachella Valley, and are typically steeply dipping and sub-parallel to depths of 8–10 km. The presence of the principal through-going Banning strand at depth increases the possibility of dynamic rupture through the pass [*Shi et al.,* 2012], while the Crafton Hills complex affects SAF slip rates [*Herbert*, 2012].

In developing these new 3D fault representations for CFM, care was taken that fault models were first smoothed to reduce artifacts of model construction, and if the fault extended to surface outcrop, the fault was registered to both DEM and the Qfaults surface trace. In this way, 3D models for active strands and down-dip splays of Banning, Garnet Hill, Mission Creek, Mill Creek, San Gorgonio Pass, North Palm Springs, and southern San Andreas faults (SSAF) were developed, in addition to the sub-parallel Mecca Hills–Hidden Springs fault adjacent to the SSAF (**Figs.1-2**). In 2012, faults in the Crafton Hills complex and blind faults like Palm Springs and other secondary faults beneath San Gorgonio Pass were also added. The advantage of these new models is that they allow for more variability in dip along strike and with depth, are more consistent with alignments of relocated hypocenters and focal mechanism nodal planes, and have a higher concentration of hypocenters within close proximity (±1 km) of the modeled 3D slip surface [*Hauksson*, 2012] than previous CFM fault models. The new 3D fault models also help characterize a more complex pattern of fault interactions at depth between various fault sets and linked fault systems, while providing more continuous rupture surfaces through San Gorgonio Pass.

These revised 3D models for the principal slip surfaces through San Gorgonio Pass and into the Coachella Valley, including the Mecca Hills-Hidden Springs fault, have already proven useful to modeling dynamic earthquake rupture along the San Andreas fault [*Shi et al.,* 2012; *Tarnowski and Oglesby*, 2012], as well as providing a better match to the observed uplift patterns and topography in the Coachella Valley [*Fattaruso and Cooke*, 2012]. Furthermore, **Figure 2** shows that additional active secondary faults, such as the faults in the Crafton Hills complex and blind faults at depth below San Gorgonio Pass (like the Palm Springs fault) are also present. These additional secondary faults are also important as they can strongly influence modeled slip rates along the San Andreas fault itself [*Herbert and Cooke*, 2012]. Although we have made progress on evaluating the active structures at depth in San Gorgonio Pass, many of these models are still preliminary, and need to be further tested and reviewed.

2) Besides developing new fault models along major mapped surface traces (*e.g.,* **Fig.1**), substantial effort was also made to develop preliminary 3D fault models for several major recent earthquake ruptures. This included fault models for the 1971 San Fernando, 1979 Imperial Valley, 1986 North Palm Springs, 1987 Elmore Ranch-Superstition Hills, 1992 Landers-Joshua Tree, 1994 Northridge, and 2010 El Mayor-Cucapah earthquakes and their associated aftershocks. For example, **Figure 3** shows an oblique view of new 3D models we developed for the 2010 Laguna Salada-Sierra Cucapah sequence based on relocated aftershocks provided by Egill Hauksson [*Hauksson et al.,* 2011; 2012], and near-surface geologic mapping and InSAR studies of fault surface traces provided by Ken Hudnut, John Fletcher, Mike Oskin and Jerry Treiman [*e.g., Fletcher et al.,* 2010*; Oskin et al.,* 2011, 2012*; Teran et al.,* 2011*; Treiman et al.,* 2010]. Several of these CFM models were revised in 2012 following comment and review of preliminary ones presented at the 2011 meeting. The new CFM 3D models include fault representations for the Borrego, Pescadores, Paso Superior, Paso Inferior, Sierra Cucapah, and Indiviso faults, as well as several adjacent dipping strands of the Laguna Salada fault and associated cross faults like Panted Gorge Wash, Shell Beds, Yuha, Yuha Well, Devil's Canyon, and El Mayor-Cucapah faults.

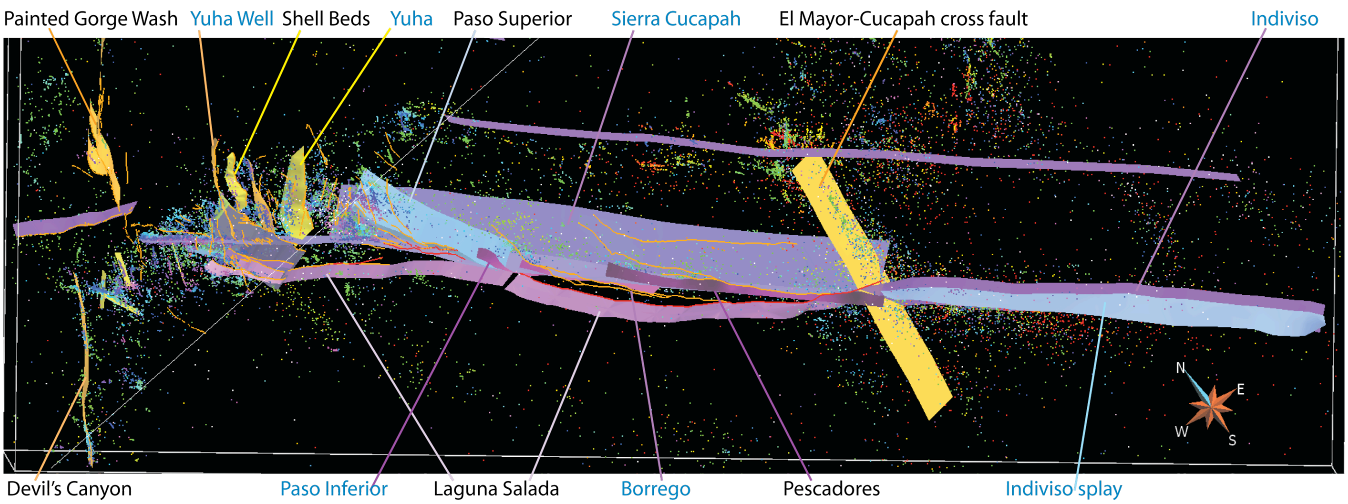
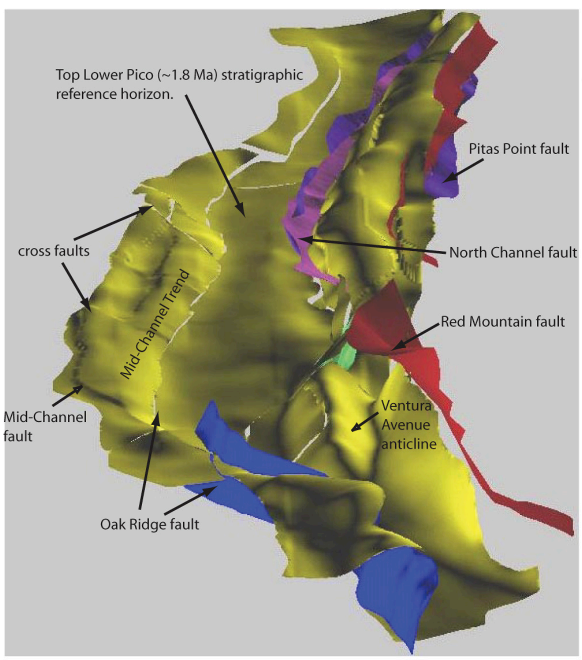


Figure 3. Oblique 3D view looking East across various preliminary CFM 3D fault representations for the 2010 M7.2 El Mayor-Cucapah rupture and its associated aftershocks [*Nicholson et al.,* 2012]. Relocated aftershock hypocenters from Egill Hauksson, mapped fault surface trace data from Ken Hudnut, John Fletcher and Jerry Treiman. CFM 3D fault models were developed for the steep to east-dipping Pescadores, Borrego, Paso Superior, Paso Inferior, deep Sierra Cucapah and east Laguna Salada faults, for the steep to west-dipping Indiviso and west Laguna Salada faults, and for a number of curved to planar cross faults, including the Panted Gorge Wash, Shell Beds, Yuha, Yuha Well, Devil's Canyon and various other El Mayor-Cucapah cross faults.

3) In collaboration with Andreas Plesch, the reorganization of the CFM fault database was nearly completed, and a draft version was sent out for review and comment. This reorganization involves a new hierarchical naming and numbering scheme to allow 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. The new fault database naming scheme provides unique identifiers (number, name, abbreviation) for each level of the fault hierarchy under which a particular fault segment is classified. Levels of hierarchy include Fault Area, Fault Zone or System, Fault Section, Fault Name, Fault Strand or Model, and Fault Component. These additional hierarchical levels allow for more flexible database searches and easier identification of fault components and possible system-level associations of individual 3D fault elements that comprise CFM. This scheme also allows for grouping related individual faults under a higher level fault system (*e.g.*, Southern Frontal Fault System for the Raymond, Hollywood, Santa Monica, and Malibu Coast faults) to help facilitate identification of

potentially larger earthquake ruptures between such kinematically linked, and geometrically similar multiple fault segments. This fault database reorganization also needs further work to incorporate feedback review comments by the USGS, CGS and other SCEC colleagues.

4) As part of our on-going investigations of active offshore faulting and plate boundary deformation, we have continued to identify, map and model a number of stratigraphic reference horizons in the Santa Barbara Channel (*e.g.,* **Fig.4**, left) and offshore Continental Borderland [*Kamerling et al*., 1998, 2003; *Nicholson et al.,* 2008, 2011; *DeHoogh et al.,* 2009; *Marshall et al.,* 2010; *Sorlien et al.,* 2012]. These dated reference horizons document the cumulative finite strain accommodated by folding, faulting and rotation since deposition, and as such are important, useful strain markers to help quantify long-term fault slip rates and the evolution in space and time of crustal motions important to SCEC's Vertical Motion Map and the geodynamic modeling of lithospheric deformation. In the Santa Barbara Channel, we have now mapped and modeled nine reference horizons ranging in age from ~120 ka to ~1.8 Ma [*Kamerling et al.,* 2003; *Marshall et al.,* 2010; *Sorlein et al.,* 2012] and about 5 reference horizons of various ages in the offshore Outer Continental Borderland [*DeHoogh et al.,* 2009; *Nicholson et al.,* 2011]. This mapping includes major portions of the North Channel-Pitas Point-Red Mountain oblique thrust fault system (**Fig.4**) and its associated fault-related folding that controls the onshore and offshore deformation extending along the coast from the Ventura Avenue anticline to Gaviota, a distance of over 70 km [*Kamerling et al.,* 2003]. Understanding the potential for large earthquakes and unusually large slip events in this area [*Rockwell*, 2011; *Hubbard*, 2011] will necessarily require a better understanding and improved 3D models of these active faults for CFM, and which are internally consistent not only with the earthquake distributions at depth, but also with the surface and near-surface observations of fault and fold geometry from surface mapping and well data [*e.g., Hubbard, 2011; Dolan et al.,* 2012].



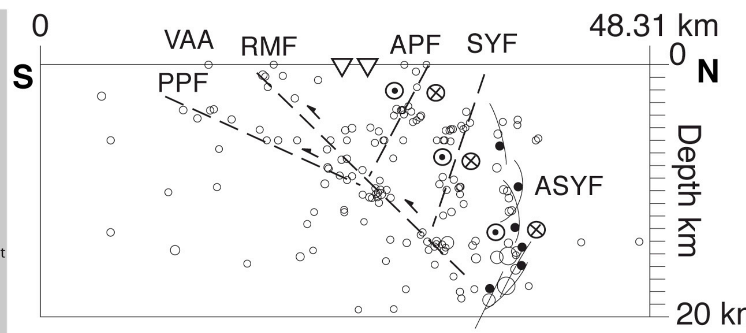


Figure 4. (left) Oblique 3D view looking WNW of 3D faults controlling the onshore and offshore deformation of the Ventura Avenue anticline (VAA), Oak Ridge, the Mid-Channel trend, the Santa Barbara-Ventura coastline and a mapped ~1.8 Ma reference horizon (yellow) [*Kamerling et al*., 2003]. (right) Cross section of relocated seismicity that define the principal N-dipping Pitas Point (PPF) and Red Mountain faults (RMF), and the S-dipping Arroyo Parida (APF), Santa Ynez (SYF) and ancestral Santa Ynez faults [*Nicholson & Kamerling*, 1998]. Together, these kinds of data can help define fault slip rates and 3D fault geometry to 20 km depth.

5) Outreach activities associated with this project include several presentations to various local civic groups on earthquake and tsunami hazards in the Santa Barbara and Ventura areas, as well as invited talks and collaboration with various Emergency Response Teams and the Santa Barbara County Office of Emergency Services involved with organizing activities and workshops associated with, or in preparation for the California State-wide 2012 ShakeOut drill [*e.g., Nicholson*, 2012].

Recent SCEC Project Reports, Related Publications and Outreach Presentations

Nicholson, C., Evaluating active 3D fault structure through San Gorgonio Pass – A focused natural laboratory for complex fault behavior, *2010 SCEC Annual Report*, n.10125, 6 pp (2011).

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