2020 SCEC ANNUAL TECHNICAL REPORT - SCEC Award 20047
Continuing to Evaluate & Refine 3D Fault Geometry to Update & Improve the SCEC Community Fault Model

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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, 2020; *Plesch et al*., 2020]. 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 900 fault objects and alternative representations in CFM-v5.3 that define nearly 440 faults organized into 107 complex fault systems (**Fig.1**). Many if not most of these new, updated 3D fault models were developed at UCSB. 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 faults within designated Special Fault Study or Earthquake Gate Areas (**Fig.1**)[*Nicholson et al.,* 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020; *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 and an expanded fault database for the CFM.

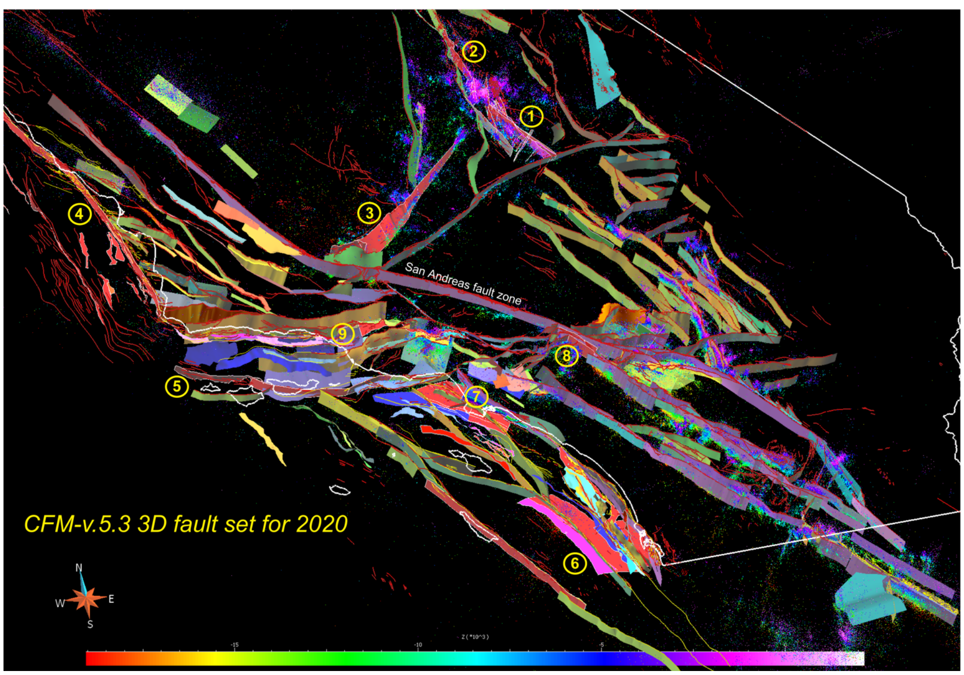

Figure 1. Oblique 3D view of 2020 CFM-v5.3 fault models, plus Qfault surface & mapped offshore seafloor fault traces, and relocated seismicity (color-coded by depth) [*Nicholson et al.,* 2020]. Since CFM-v5.2, updates to CFM-v5.3 (red/ magenta) for 2019 & 2020 include 94 new 3D fault objects that define 79 new, updated or revised fault models in 9 fault areas (yellow numbered circles). Relocated seismicity (1981-2018) from *Hauksson et al.* [2012 + updates]; updated Qfault surface and seafloor fault traces from *USGS/ CGS* [2018] and *Walton et al.* [2019].

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, 2020; *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 and 2020, access to the CFM and its associated fault database were further enhanced through the CFM webpage (*https://www.scec.org/research/cfm*) and the new, interactive, web-based CFM viewer interface—now with both 2D and 3D viewer capability [*Su et al.,* 2019; *Plesch et al.*, 2020]. 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 [*Walton et al.,* 2019], and incorporating both a more complete dataset of linked relocated hypocenter and focal mechanism catalogs (1981–2019) [*Hauksson et al.,* 2012 + updates] and the more extensive QTM catalog [*Ross et al.,* 2019]. In the offshore Santa Maria basin, Ventura basin and Inner Continental Borderland, integrated datasets of industry marine seismic reflection, multibeam bathymetry, and offshore well data were also used to help develop new fault models and refine existing fault geometry [*Sorlien et al.,* 2013, 2015; *Nicholson et al.,* 2017, 2019, 2020].

With these expanded, updated, underlying datasets, in 2019 and 2020, 94 new 3D fault objects that define 79 new, updated or revised 3D fault representations were added to CFM-v5.3 in the recently active (1) Ridgecrest and (2) Coso-Owens Valley fault areas [*Plesch et al.,* 2019, 2020], in the (3) Great Valley, (4) Offshore Central California, (5) Western Transverse Ranges and (6) Offshore Continental Borderland fault areas [*Sorlien et al.,* 2015; *Legg et al.,* 2018; *Nicholson et al.,* 2019, 2020], and in the (7) Coastal Los Angeles, (8) Cajon Pass Earthquake Gate, and (9) Ventura Special Fault Study areas (SFSA)(**Fig.1**) [*Nicholson et al.,* 2020]. These refinements, updates 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 incorporates a diverse dataset of surface and subsurface observations. For example, in the Ventura SFSA, this integrated dataset included: grids of 2D and 3D marine multichannel seismic reflection data, onshore/offshore industry well data, industry correlation structure contour maps and cross sections, relocated seismicity and revised focal mechanism catalogs, digital onshore topography and offshore bathymetry data, onshore/offshore geologic maps, and where available, sets of well-dated stratigraphic reference horizons [*e.g., Sorlien et al.,* 2015; *Sorlien and Nicholson,* 2015; *Behl et al.,* 2016; *Nicholson et al.,* 2017]. The multichannel seismic (MCS) reflection data were used to map fault surfaces and dated reference horizons in 3D [*Sorlien et al.*, 2015; *Sorlien and Nicholson,* 2015]. These shallow fault surfaces mapped in the upper 6-7 km were then extended to seismogenic depths based on available relocated seismicity (*e.g.,* **Fig.4**)[*Nicholson et al.,* 2017]. 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, the validity of proposed fault models, or distinguishing between alternative fault representations. Looking down-dip of the recently updated Lytle Creek fault in the Cajon Pass EGA (**Fig.2**) with the expanded, updated catalog of relocated hypocenters and focal mechanisms demonstrates several important characteristics [*Nicholson et al.,* 2020]. 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 nodal planes—together with mapped surface geology [*Forand et al.,* 2017]—tend to define a wide, sub-vertical viscoelastic zone of coupling and 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 and to the SE than it has been previously mapped at the surface (**Fig.2,** *right, red surfaces*), allowing the Glen Helen fault representation to be updated and expanded for CFM-v5.3 [*Nicholson et al.,* 2020].

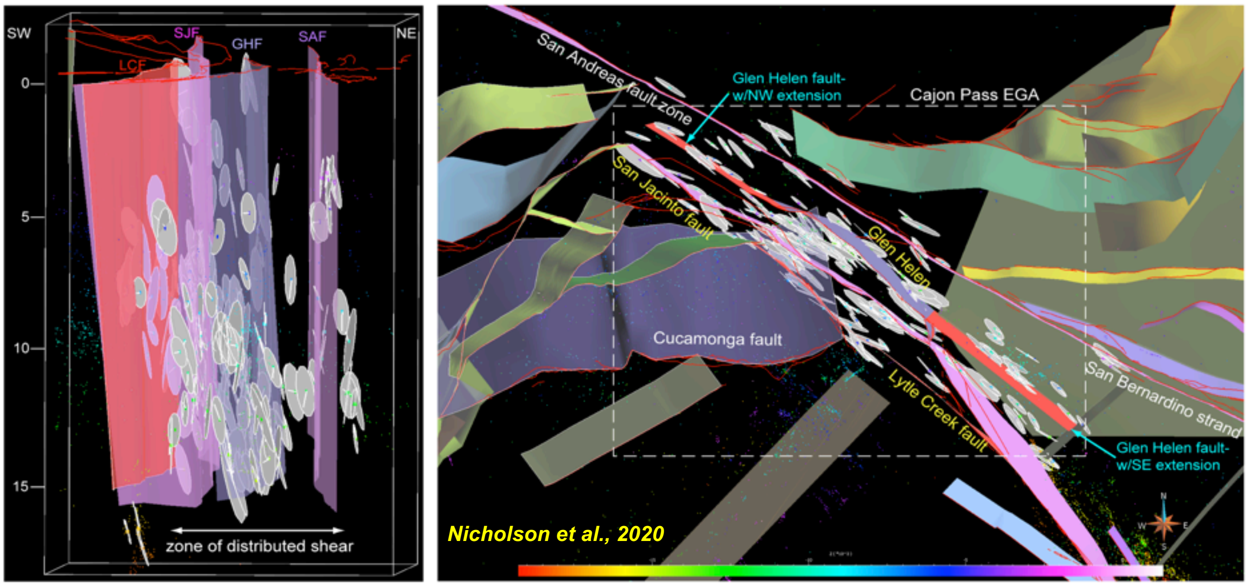

Figure 2. (*left*) Oblique 3D cross section view looking along San Andreas fault in the Cajon Pass EGA. Nodal planes (disks) parallel or sub-parallel to San Andreas (SAF) and San Jacinto (SJF) faults are steeply dipping and define a wide, sub-vertical zone of distributed right-lateral shear through the Pass. (*right*) Oblique 3D map view looking down-dip of updated Lytle Creek fault (LCF). In addition to the wide sub-vertical zone of coupling, nodal planes help define steeply dipping, NW and SE CFM extensions (red surfaces) to the Glen Helen fault (GHF)[*Nicholson et al.,* 2020].

The integrated, underlying datasets were also used to expand the CFM 3D fault set and geologic surface library for coastal Los Angeles and San Pedro basin [*Sorlien et al*., 2013; *Nicholson et al.,* 2020]. The Palos Verdes Anticlinorium is a large, regional active fold structure that is best defined in the subsurface by the near-base Repetto-top Miocene reference horizon (**Fig.3**, *left*). It is produced by slip on an underlying detachment that daylights offshore with the Santa Monica Bay detachment and San Pedro Escarpment faults, and that connects with the blind Compton thrust fault beneath Los Angeles (**Fig.3**, *cross section inset*)[*Sorlien et al.,* 2013]. New faults and geologic surfaces added to CFM-v5.3 for 2020 include the active Wilmington blind faults [*Wolfe et al.,* 2019], the San Pedro Escarpment faults [*Sorlien et al.,* 2013] and the near-base Repetto and top Miocene horizons (mapped in 3D with industry seismic and well data) that help define the Palos Verdes Anticlinorium (PVA), as well as the new underlying detachment (**Fig.3**, *right*) that connects these faults and faults in Santa Monica Bay with the blind Compton thrust [*Nicholson et al.,* 2020].

In terms of regional seismic hazard, it is thus 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 (*e.g.,* **Fig.3**). Including dated geologic surfaces related to the PVA in the CFM not only helps us to better define the regional extent of this active fold structure and thus the mapped extent and subsurface geometry of the underlying detachment that links these important faults at depth, but also provides controls to better evaluate rates and components of fault slip, uplift, subsidence, non-elastic finite strain due to folding, and other aspects of crustal deformation over time, as demonstrated with other dated reference horizons in other fault areas [*e.g., Gratier et al.,* 1999; *Sorlien and Kamerling*, 2000; *Nicholson et al.,* 2007; *Don et al.,* 2020; *Johnson et al.,* 2020].

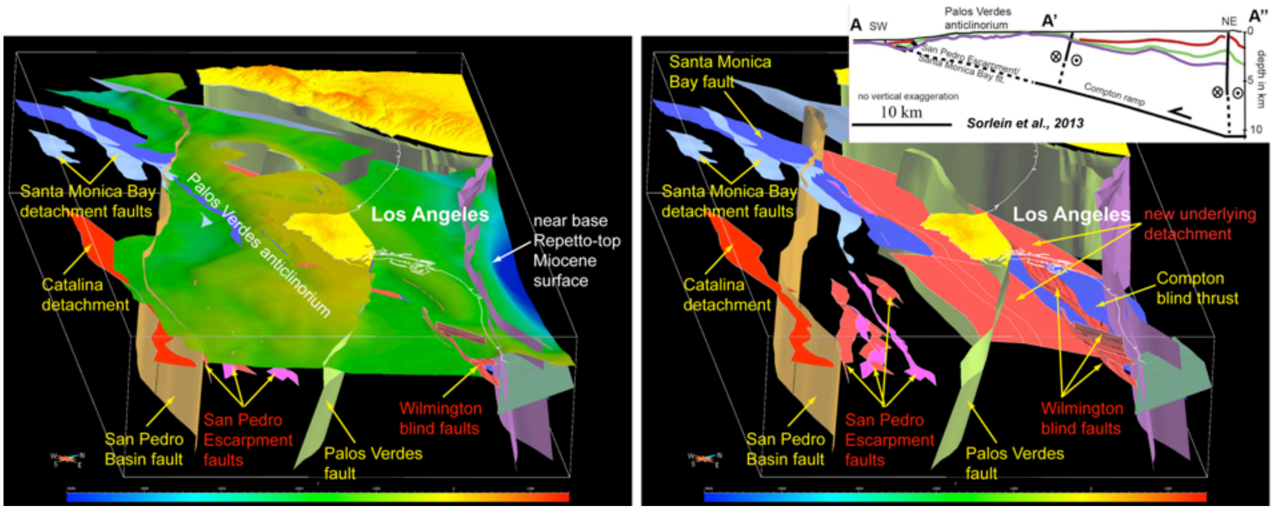

Figure 3. (*left*) Oblique 3D view looking NNW across the near-base Repetto surface, Palos Verdes Anticlinorium, and underlying CFM-v5.3 faults. Shaded near-base Repetto-top Miocene surface from *Sorlien et al.* [2013]. (*right*) Same as left, but with base Repetto surface removed. New faults added to CFM-v5.3 include San Pedro Escarpment faults [*Sorlien et al.,* 2013], Wilmington blind faults [*Wolfe et al.,* 2019], and the new underlying detachment (red) that connects these faults and faults in Santa Monica Bay with the blind Compton thrust [*Nicholson et al.,* 2020].

Continued CFM Evaluation and Validation

There is also the issue of continued fault model *evaluation, validation,* and how to properly discriminate between various competing alternative fault representations. For example, in 2019, over 70 events occurred within 2 days near the Ventura River at Pitas Point (**Fig.4**). Initial double-difference relocated hypocenters are located in the footwall of the Ventura fault and at or above the S-dipping, listric Padre Juan fault (PJF)[*Nicholson et al.,* 2017]. Focal mechanism nodal planes are consistent with either slip on a high-angle NNW-striking tear fault or on the low-angle, S-dipping PJF (**Fig.4**)[*Nicholson et al.,* 2020]. This suggests that the PJF is still independently Holocene active. If true, the large uplift events found at Pitas Point [*Rockwell et al.,* 2016] may not be necessarily or solely related to slip on the Ventura fault, as has often been previously proposed, but may be instead related to slip on the S-dipping PJF.

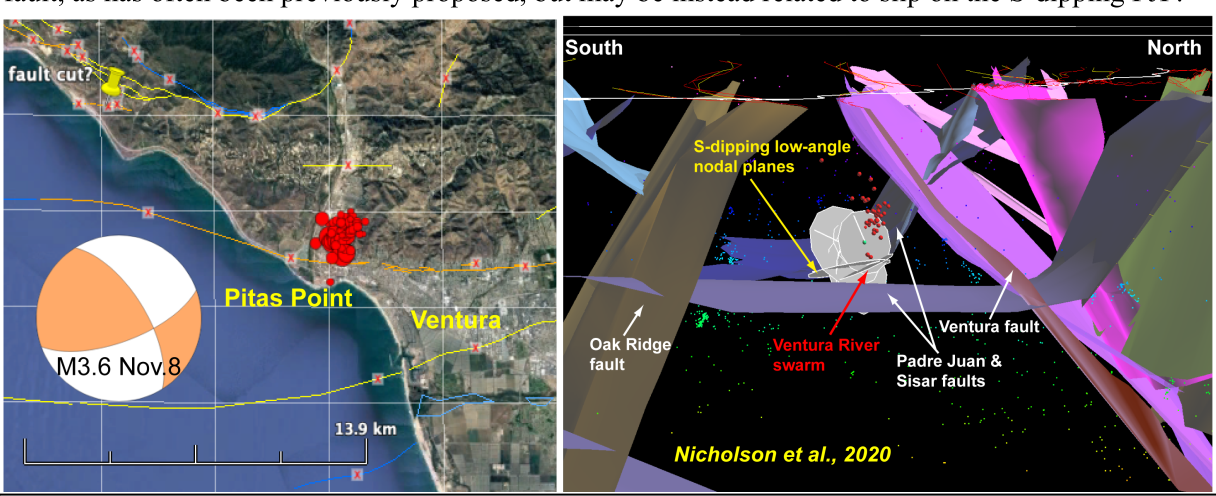

Figure 4. Relocated double-difference hypocenters (red spheres) of 2019 Ventura River earthquake swarm shown in map (*left*) and cross section (*right*). Locations from E. Hauksson; 3D fault surfaces from CFM-v5.3 [Nicholson et al., 2019]. Map inset shows focal mechanism of largest swarm event and reflects right-slip on a NW-striking nodal plane consistent with the right-step between the onshore Ventura fault and offshore Pitas Point fault. (*right*) Cross section view looking West of relocated 2019 swarm hypocenters (red spheres) and preferred focal mechanism nodal planes (gray disks) of seven largest swarm events that suggest seismic slip on a steeply dipping NW-striking tear fault and the S-dipping, low-angle Padre Juan fault [*Nicholson et al.,* 2020].

CFM Database Enhancement

Besides developing new, updated 3D fault sets for the CFM (*e.g.,* **Figs.1, 2, 3**), validating existing 3D representations (**Fig.4**), and updating the underlying CFM datasets used for fault model evaluation and development, as part of our on-going Harvard-UCSB CFM collaboration, Andreas and I continue to develop, expand and improve the associated fault database and 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.

Starting with CFM-v5.1 and continuing into CFM-v5.3 [*Plesch et al.,* 2016, 2018, 2020; *Nicholson et al.,* 2017, 2019, 2020], the CFM fault database 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 fault attribute table now provides fields for sequence and CFM version number, source, author, generation method, USGS fault ID (when available), references, and fault property attributes of average strike, dip, area, and faulting style or slip sense. In 2020 alone, references were provided for over 800 named CFM fault objects derived from a compiled list of nearly 200 CFM, data source, and fault geometry/mapped trace citations and web-based hyperlinks. Since the release of CFM-v5.2 in 2017, 94 new 3D fault surfaces that help define 79 new, alternative, or updated fault models in 9 fault areas were added to CFM-v5.3 (**Fig.1**). To accommodate this expanded CFM fault population, several pre-existing CFM faults were renamed, and the corresponding additional CFM faults and associated fault database elements were organized into 7 newly named fault systems.

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 through the development of the dedicated SCEC CFM webpage and interactive web-based CFM viewer interface [*e.g., Nicholson et al.,* 2018; *Shaw et al.,* 2019; *Su et al.,* 2019; *Plesch et al.,* 2020]. These web-based tools provide easier user access to and visualization (now in both 2D and 3D) of the digital CFM 3D fault set, 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.

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