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Building the SCEC 3D Community Fault Model: Onshore Western Transverse Ranges and Ventura Basin

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PROJECT DESCRIPTION

The purpose of this project was to provide digital 3D structural representations of active faults in selected areas for input into the SCEC high-resolution 3D Community Fault Model (CFM-B). The initial areas selected included the onshore western Transverse Ranges and Ventura basin. The faults we were most concerned with include the onshore Oak Ridge, Red Mountain-Pitas Point, San Cayetano, Santa Ynez and Arroyo Parida-Mission Ridge faults. This work ties into and complements similar studies to define active 3D fault structure offshore in the Santa Barbara Channel and Santa Monica Bay [e.g., *Kamerling and Nicholson,* 1995; *Kamerling et al.,* 2001; *Sorlien et al.,* 2001].

For several years now, we have been attempting to develop a 3D database of subsurface structure for the Santa Barbara-Ventura region [*Nicholson et al.,* 1997]. The idea was to use this database as a prototype for how accurate and reliable 3D fault models could be developed in southern California. This region was chosen because it includes a complicated system of active high-angle and low-angle faults and fault-related fold structures (**Fig.1**). Many of these structures exhibit recent seismicity (**Fig.2**). In addition, owing to the region's hydrocarbon potential and to the fact that half the area is underwater (and thus accessible using deep-penetration multi-channel seismic data), a wealth of subsurface information is available that can be used to identify important subsurface structure in 3D, and to test and evaluate the reliability of using various models and techniques to infer deep fault structure from surface or near-surface data. So far, our results indicate that the most reliable method to determine such subsurface fault structure is still by the most direct means. This includes using such evidence as measured offset, missing or repeated section, and changes in resistivity and dipmeter in deep wells [*Kamerling and Nicholson,* 1995]; fault plane reflections, diffractions, offsets and changes in reflection character from MCS data [*Kamerling et al.,* 2001]; and correlations and alignments of relocated earthquake hypocenters in space and time with fault plane solutions from earthquake focal mechanisms (e.g., **Fig.3**) [*Nicholson and Kamerling,* 1998].

As part of this on-going program, we acquired a unique 3D dataset for the Ventura basin provided by the Ventura Basin Study Group (VBSG). The VBSG study consists of 17 structure contour maps and 84 interlocking cross section data panels (**Fig.4**) based on nearly 1200 correlated deep-penetration wells. The wells vary in depth from 1 to 5 km. Many of these wells drill active fault and fold structures associated with major fault systems, including the San Cayetano, Oak Ridge, Red Mountain, and Santa Susana faults. This integrated 3D study is based on wire-line logs, mud logs, paleontological reports, core analyses, and surface maps. Each data panel typically ties in 4 directions to define the sides of a 3D data volume or cell. The result is a 3D presentation of an enormous quantity of high-quality subsurface data that have been reconciled into a coherent geological interpretation. Any 2D or 3D structural model of the basin and its associated fault and fold geometry, as well as any valid estimate of the seismic hazard, must incorporate these well data if it is to be successful. The VBSG structure contour maps and cross sections are now available from our ICS website at http://www.crustal.ucsb.edu/projects/hopps .

The original VBSG maps and cross sections were analyzed primarily for the purpose of hydrocarbon exploration and not in terms of deep basement fault structure or the compatibility of displacement with the observed fault and fold geometry. Nevertheless, these data can provide information on 3D reference stratigraphic (time) horizons, in addition to 3D fault surfaces. **Figure 1** shows two such reference horizons (green and yellow) as they extend onshore into the Ventura Basin, as well as the onshore Oak Ridge (blue) and segments of the Red Mountain, North Channel and Pitas Points faults (purple). The geometry of these multiple 3D reference horizons and the 3D fault surfaces can provide important clues on the timing and distribution of finite strain, as well as additional constraints on the geometry and slip orientation of buried or blind faults [e.g., *Gratier et al.,* 1997; *Thibaut et al.,* 1996].

An important question though is how these active fault and fold structures defined in the shallow crust from seismic reflection and well data connect with—and are related to—deeper faults at seismogenic depths. Combining the VBSG and other datasets with seismicity has proven particularly effective in developing an improved understanding of what this relation might be. For example, examination of the seismicity of the Ventura basin, and especially the 1996 M4.1 Ojai sequence (**Fig.3**), reveals a number of faults in the hanging-wall of the Red Mountain fault. This includes the south-dipping Arroyo Parida and Santa Ynez faults, as well as a curviplanar fault not previously identified in either the VBSG dataset or other published 2D models [*e.g., Huftile and Yeats,* 1996]. In addition, our mapping of active fault structures offshore with seismicity (**Fig.2**), indicates that the Ventura Avenue Anticline and uplifted portions of the coast are fundamentally related to a south-verging fault system at depth (**Fig.3**). This also differs from previously published 2D models for these structures [*e.g., Yeats et al.*, 1988; *Namson and Davis,* 1991].

Project Results

Several digital 3D structure contour maps of active fault surfaces were produced for input into the SCEC high-resolution Community Fault Model (CFM-B), and preliminary versions of the mapped fault surfaces have been incorporated into CFM-A 1.0 beta [*Plesch et al.*, 2002]. These include the Oak Ridge (onshore and offshore), Red Mountain (onshore and offshore), North Channel and Ventura-Pitas Point faults (e.g., **Figs1&2**). Down-dip projections based on seismicity were determined for the Pitas Point, Red Mountain, Arroyo Parida-Mission Ridge, Santa Ynez, Ancestral Santa Ynez and Oak Ridge faults (e.g., **Fig.3**). Additional digital structure contour maps of the San Cayetano (**Fig.5**), Santa Susana, and Arroyo Parida-Mission Ridge faults are in progress. Fault surfaces are defined in 3D based on integrating seismic reflection, seismicity, topography, surface mapping, and well data. Variations in possible interpretations of 3D fault surfaces are also being documented. For example, there are currently 5 published interpretations for the shallow (upper 3 km) geometry of the San Cayetano fault alone (e.g., **Fig.5**) [*Hester and Truex,* 1977; *Çemen,* 1989; *Namson and Davis,* 1991; *Hopps et al.*, 1992, *Huftile and Yeats,* 1996].

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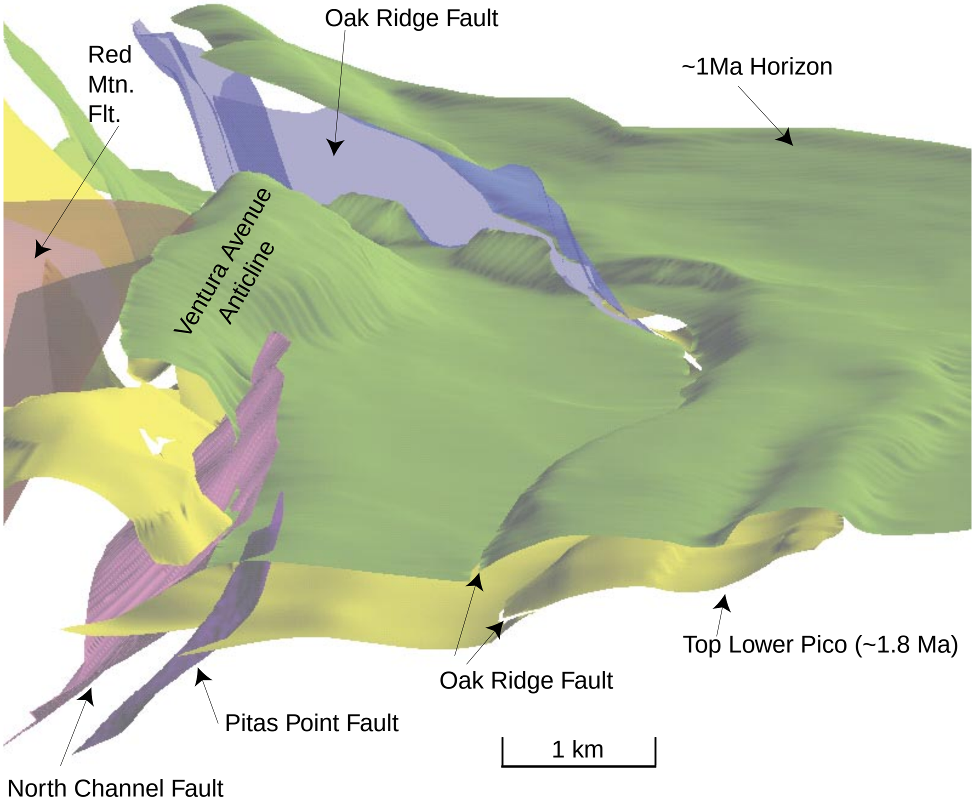

Figure 1. Cut-away oblique 3D view looking east of two stratigraphic horizons (green and yellow) and selected segments of 3D fault surfaces (purple and blue)[Kamerling and Sorlien, 2000]. Fault surfaces, as well as their down-dip projection based on relocated seismicity (lower left), have been incorporated into the SCEC 3D Community Fault Model. Such 3D visualization and analysis with programs like gOcad allows better understanding of the spatial relationships betwen faulting, folding, and basin subsidence. 3D map restoration of multiple stratigraphic (time) horizons allows the fintite strain field with time, as well as the timing, location, and evolution of fault slip, folding, regional uplift and subsidence to be determined.

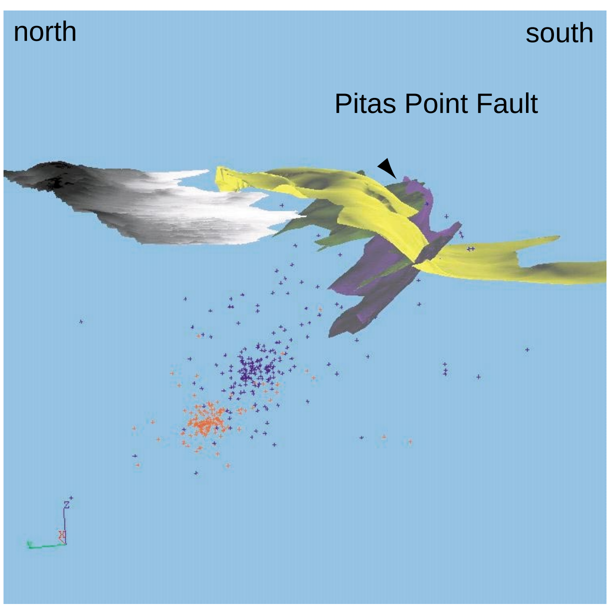

Figure 2. Cut-away oblique 3D view looking east along the northern Santa Barbara Channel [Kamerling et al., 2001]. Top Lower Pico horizon (yellow, ~1.8 Ma) and segments of Pitas Point-North Channel fault system (purple) mapped using seismic reflection and subsurface well data are shown along with aftershock hypocenters of the 1978 M5.9 Santa Barbara earthquake before (blue) and after (red) relocation.

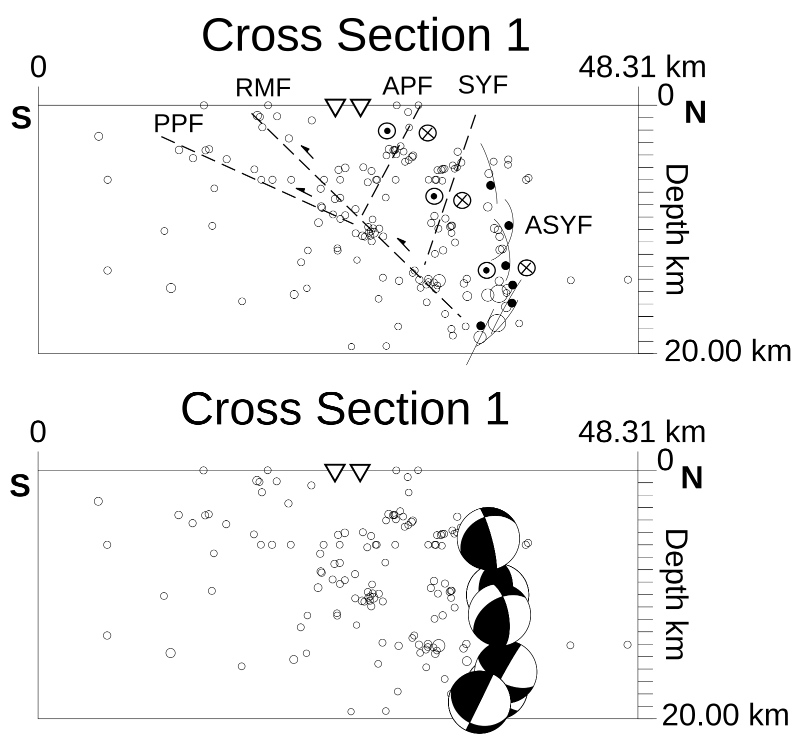

Figure 3. Vertical cross sections looking west of relocated seismicity (1994-1996) and the 1996 M4.6 Ojai sequence. Front hemisphere projection focal mechanisms of the Ojai events and interpretations of active subsurface faults are shown. Earthquakes define south-dipping Pitas Point (PPF) and Red Mountain (RMF) faults, as well as three major faults in the hanging-wall of the Red Mountain fault – Arroyo Parida fault (APF); Santa Ynez fault (SYF); and a curviplanar fault whose surface trace projection would also correspond with the SYF. We call this the ancestral Santa Ynez fault (ASYF), and it may be responsible for the observed change in dip of the SYF from south-dipping to north-dipping along strike.

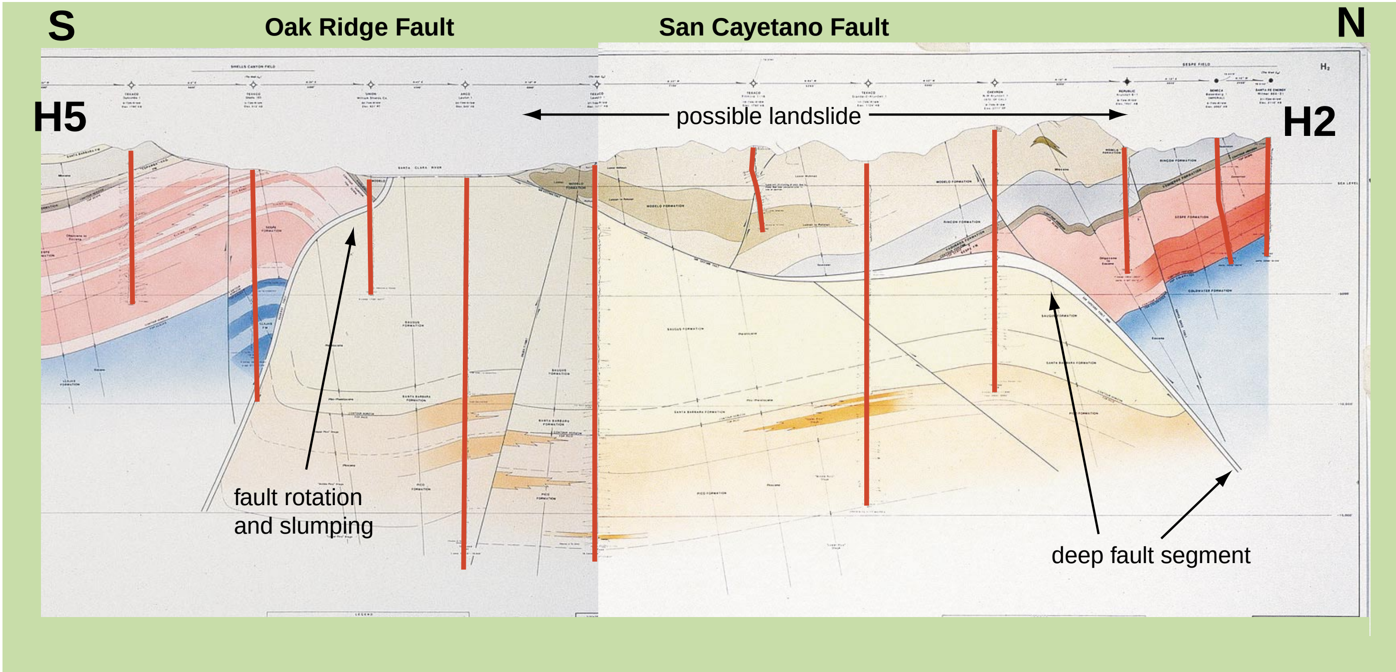

Figure 4. Vertical cross section (H2-H5) across Ventura basin, and Oak Ridge and San Cayetano faults (Hopps et al., 1992). Red lines show well control. This shows how oblique-reverse faults thrust early-Cenozoic and older rocks over mostly Plio-Pleistocene and younger sediments. Note the rotated and non-planar geometry of both faults. Possible landslide responsible for the thrust-nappe 3D geometry of San Cayetano fault is shown. If this shallow part is the result of a mega-landslide, it occupies over 60 cubic km. Red - Sespe (~30 Ma); Yellow - Saugus (~0.5 Ma); Gray - Rincon shale (possible slide surface).

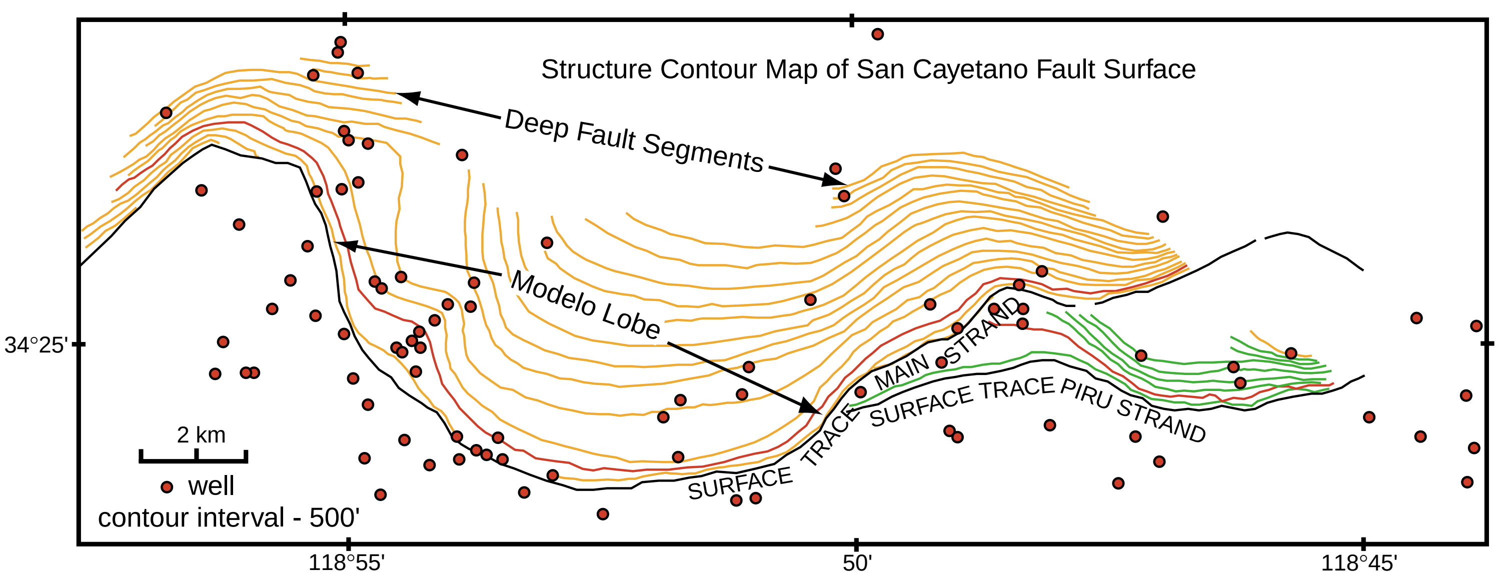

Figure 5. Structure contour map of the San Cayetano fault surface (after Cemen, 1989). Note the lobate shape, and shallow dip of the Modelo Lobe segment of the fault that extends out in front of the deep fault segment by over 4 km.