2014 SCEC Annual Report

Fault Dynamics and Tsunamis in the Ventura Basin

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Proposal Category C: Special Fault Study Areas

Research Priorities: 6b, 4a, 3e

Introduction: The Ventura Basin in southern California is an area that is increasingly recognized to present a significant seismic hazard. It is underlain by a network of dip-slip faults (Figure 1) that appear to connect at depth, raising the possibility that they may rupture in a large multisegment earthquake with magnitude potentially above 7.5 [*Hubbard*, 2011]. In addition, at least two large thrust faults (the Ventura/Pitas Point and Red Mountain) extend offshore, and may thus produce a significant local tsunami whether they rupture separately or in tandem. To help elucidate the earthquake and tsunami hazards in this region, the Oglesby lab at UC Riverside has been performing 3D dynamic rupture models for potential earthquakes in the Ventura Basin and offshore, and using the ground motion output from these models to produce scenario tsunami models. This project was funded by SCEC for 2013 and 2014. As will be detailed below, we have had some very promising success with our early models. This proposal is part of a coordinated approach to examine the hazard associated with the Ventura Area Special Focus Study Area (SFSA). We are using fault structural information obtained by other groups in this SFSA, and tuning our models to reproduce inferred historical earthquakes, with the idea that they may represent possible future events. The results of these modeling efforts can then be used to pinpoint areas in which more data (such as structural and material properties) are needed to better constrain source properties. This "closing of the loop" is a key advantage of the SFSA approach.

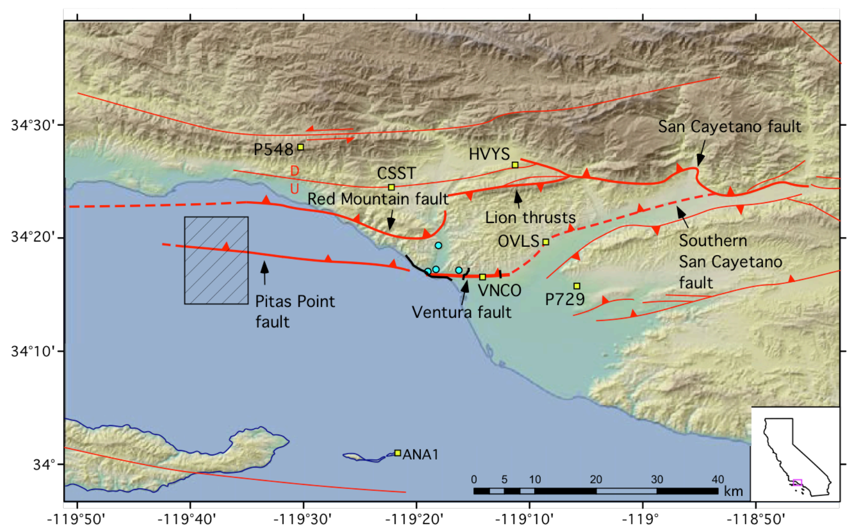

Figure 1. Faults in the Ventura Basin. From Hubbard [2011]

Faults and Fault Dynamics: The Ventura Basin is a very rapidly deforming region that is cut by several large thrust/reverse faults (some of which may have a small left-lateral component), including the Ventura, Pitas Point, Red Mountain, and San Cayetano [*Hubbard*, 2011; *Perry and Bryant*, 2002; *Sarna-Wojeicki et al.*, 1976]. Recent work by Hubbard [2011] has indicated that there exist additional dip-slip faults, including the Lion backthrust and the Southern San Cayetano. Her 3D fault representation (which we implement in simplified form in our models) is shown in Figure 2. Seismic and GPS data, as well as well logs, indicate that all these faults may converge and/or merge between 5 km and 10 km depth in a detachment known as the Sisar Décollement, which in turn connects to a deeper blind thrust fault that spans the entire fault system. Connections between these faults raise the specter of multi-fault rupture, which has been observed in southern California in the 1992 Landers and 1999 Hector Mine earthquakes, and in Alaska on the 2002 Denali Fault earthquake. Hubbard [2011] and her coworkers estimate that the Ventura fault alone could produce an earthquake of magnitude 6.2, while if all the fault segments were to rupture in a single event, the magnitude could be as high as 7.6. Uplifted marine terraces [*Rockwell*, 2011] indicate single-event uplifts of 5-10 m, with fault slip even larger. Many of these faults outcrop in populated areas (such as metropolitan Ventura), so the risk of extreme ground motion from such a compound earthquake is quite high. Furthermore, many of these faults have slip rates between 5 and 10 mm per year [*Hubbard*, 2011], which implies high levels of seismic activity. For these reasons, it is imperative to examine the size, slip distributions, and ground motion from potential earthquakes in this region.

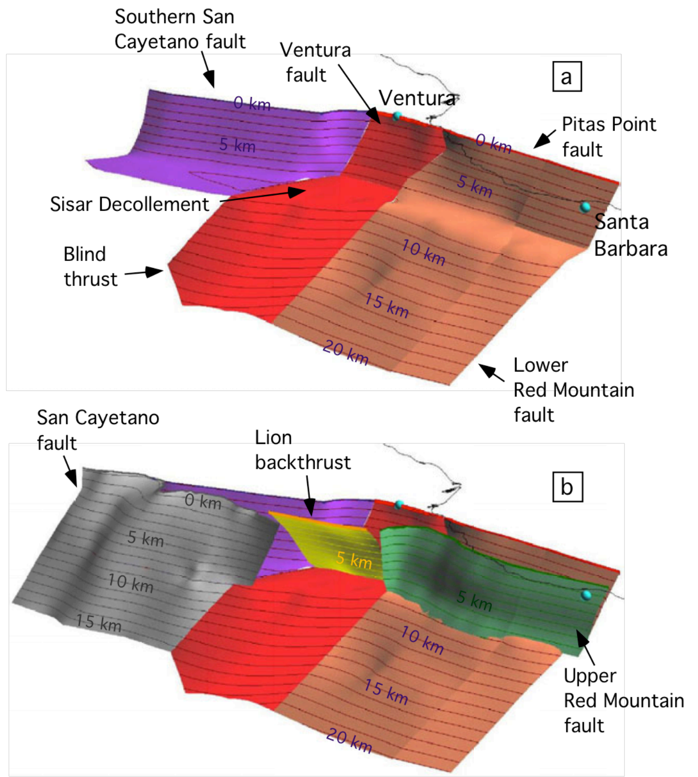

Figure 2. 3D representation of faults in the Ventura Basin. From Hubbard [2011]

Without extensive paleoseismological data (especially offshore), most current estimates for the size of potential earthquakes in this region [e.g., *Cramer et al.*, 1996; *Hubbard*, 2011] use regression analyses such as Wells and Coppersmith [1994] to relate the faulting area to earthquake magnitude. However, such studies do not answer the question of whether it is likely that multiple fault segments will rupture in a single event, leading to a large magnitude quake. To answer this question, we turn to dynamic earthquake modeling. Dynamic models start from an assumed fault geometry, material structure, and frictional parameterization, and allow researchers to simulate the evolution of rupture, slip, and near-source ground motion from a fault system. In particular, dynamic models can be used to examine whether earthquakes may propagate through geometrical heterogeneities such as stepovers, bends, and branches [e.g, *Aochi et al.*, 2000; *Bouchon and Streiff*, 1997; *Duan and Oglesby*, 2005; *Harris et al.*, 1991; *Harris and Day*, 1999; *Kame et al.*, 2003; *Lozos et al.*, 2011; *Oglesby*, 2005] and to forecast the rupture path, slip pattern, and potential earthquake size for scenario earthquakes [*Anderson et al.*, 2003; *Andrews and Hanks*, 2007; *Oglesby et al.*, 2008]. In the Ventura basin, the complex fault system lends itself to this type of analysis. For example, the close proximity of the Ventura/Pitas Point and Red Mountain faults, as well as the potentially linking Sisar Décollement, bring up the question of the circumstances under which rupture might propagate across the entire system. The state of stress in this region is quite uncertain, so dynamic modeling will need to include suites of models with different assumptions about the stress, including (for example) constant traction, a regional stress field inferred from local earthquakes, and a stochastic stress field constrained by the regional stress field. While not part of our current results, such models are the subject of our proposed work for 2015.

Potential Tsunamis: The extension of the Ventura/Pitas Point and Red Mountain faults westward underneath the Santa Barbara Channel brings up the question of whether these faults, rupturing either individually or in concert with other faults in the region, could generate a strong enough tsunami to be hazardous to the nearby coast. Indeed, there is some evidence of past tsunamis due to faulting in this region, including 1812, in which a tsunami from a M 7.2 earthquake caused a tsunami with runups of up to 4 m near Santa Barbara [*Toppozada et al.*, 1981]. Borrero et al. [2001] have estimated that an M 7.3 earthquake on the Channel Islands Thrust system could produce local tsunamis with runups as high as 2 m. Such runups are large enough to damage harbors and cause significant monetary loss. More recently, Reynolds et al. [2013] have found sedimentological evidence of paleotsunami deposits in a salt marsh in Carpenteria. Most tsunami models assume simple kinematic (dislocation) sources, often with constant slip over the entire fault. However, it has been shown [*Geist*, 1998; 2002; *Geist and Dmowska*, 1999] that the slip distribution on a fault can have a significant effect on local tsunami runup. Dynamic modeling is one of the only ways to estimate large-scale slip patterns for scenario earthquakes, based on the fault geometry and regional stressing, and interactions with neighboring faults. Furthermore, the height and areal extent of the tsunami is very sensitive to both the size and rupture path of an earthquake. In the first published work combining dynamic rupture modeling with tsunami modeling, Wendt *et al.* [2009] showed that in a subduction zone system, a barrier on the plate boundary thrust can cause rupture to propagate to a steeper splay fault, leading to greater vertical seafloor displacement and therefore a much higher tsunami hitting the nearby shore. If multiple faults participate in an earthquake (for example, the Ventura/Pitas Point and Red Mountain), the resultant tsunami could be much more complex than what would be anticipated based on standard modeling techniques. Unlike typical kinematic dislocation models, dynamic models can help answer the question of which fault segments are most likely to rupture together, and the partitioning of slip between fault segments. For these reasons, we propose that dynamic models can underpin tsunami models in much the same way that they can underpin ground motion models on-shore.

Method: We use the 3D finite element code FaultMod [*Barall*, 2009] to model the dynamics of earthquakes in the Ventura Basin fault system. FaultMod has been validated by the SCEC/USGS dynamic earthquake rupture code verification exercise [*Harris et al.*, 2009] and can be used to model dynamic rupture on geometrically complex fault systems with heterogeneous material properties. For the Ventura Basin, we are using a somewhat geometrically simplified version of the faults parameterized by Hubbard [2011] as well as the SCEC community velocity model (CVM) to simulate the dynamics of potential earthquakes on this fault system. The output from the 3D dynamic models are then used as a time-dependent boundary condition for the deformation of the water column in a hydrodynamic flow code. We are currently using COMCOT [*Liu and Cho*, 1994] for the tsunami propagation and runup calculations. This code allows for the calculation of frequency dispersion and turbulent dissipation of energy, and has been validated against experimental and observational data [e.g., *Liu et al.*, 1995]. Our models use accurate, high-resolution bathymetry from the NOAA/NGDC DEM [*Carignan et al.*, 2009]. We are conducting the tsunami modeling with help and guidance from Eric Geist at USGS Menlo Park, who will not draw any funding from SCEC.

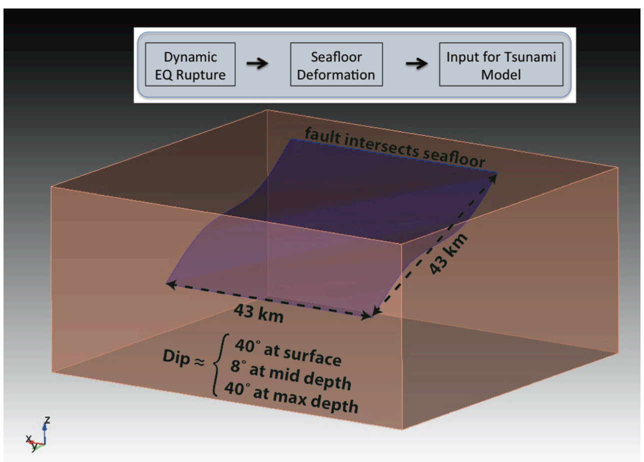

Figure 3. Fault geometry and method flowchart for Preliminary results

Results: We have incorporated the Pitas Point- Sisar Décollement-Lower Red Mountain fault system into a 3D dynamic model of potential earthquakes in the Ventura Basin, and taken the final surface deformation from these models as an initial condition for tsunami calculations as described above. Our fault geometry is shown in Figure 3, along with the basic flowchart of our method. We use rate-state friction with constant initial tractions on the fault and a rate-strengthening zone near the surface, leading to an average stress drop of 6 MPa. Figure 4 shows the fault slip and surface deformation from this

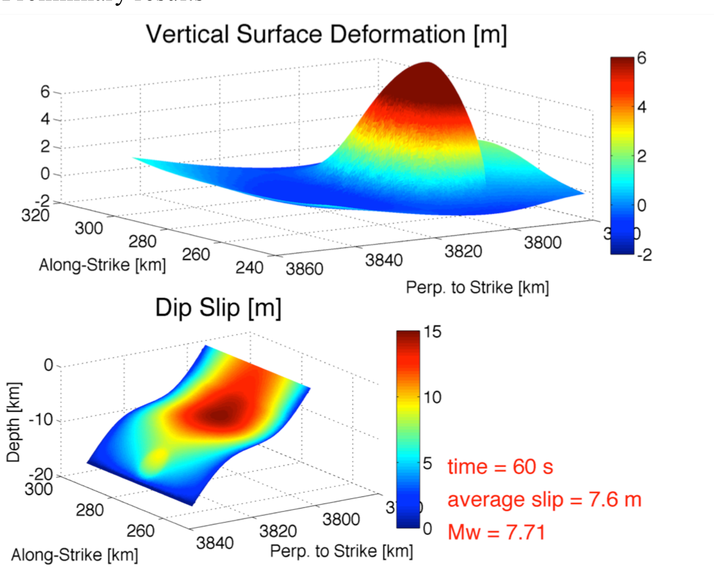

Figure 4. Fault slip and vertical seafloor deformation

model. Peak surface slip values and surface uplift are in line with that estimated by Rockwell [2011]; thus, our model is plausible and not a worst-case scenario. As would be expected, the northward-directed tsunami generated by this earthquake produces significant inundation in the Santa Barbara area. However, the southward-directed wave is strongly refracted by bathymetry such that it is redirected almost entirely to the east, directly toward the low-lying and highly populated Ventura/Oxnard region. Figure **Error! Reference source not found.** shows that tsunami inundation in this region significantly exceeds the state-estimated inundation line (red curve), and produces extensive flooding, especially in

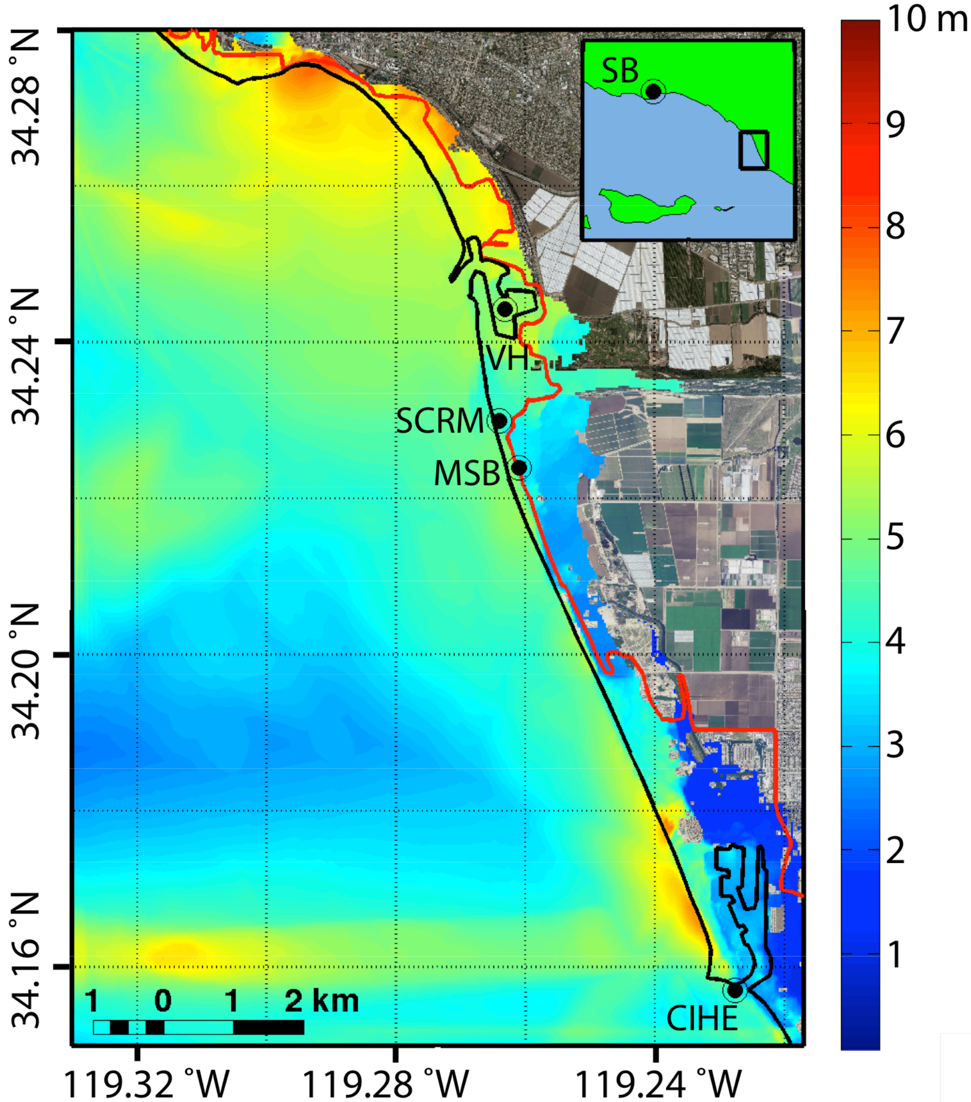

Figure **Error! Reference source not found.**. Map of localized peak tsunami amplitude, in meters (around Ventura, CA), resulting from slip on the Pitas Point and Lower Red Mountain fault system. The solid black line indicates the coastline. The solid red line is the statewide tsunami inundation map coordinated by the California Emergency Management Agency. Letters indicate example locations (approximate): SB = Santa Barbara; VH = Ventura Harbor; SCRM = Santa Clara River Mouth; MSB = McGrath State Beach; CIHE = Channel Islands Harbor Entrance. Inset shows the map boundary in black. Note that inundation from the model is significantly greater in many places than the statewide

harbor areas. We emphasize that this modeled earthquake is not the worst-case scenario for this region; if rupture were to propagate to nearby faults such as the on-shore Ventura fault or the Upper Red Mountain fault, peak slip and fault area could increase as well. This sobering result strongly argues for more research to determine the likelihood of such an event, and to apply more realistic stress fields and fault geometries.

Significance of the project: This work will have important significance for ground motion and seismic hazard estimates in the Ventura Basin. In particular, the resultant slip models can be used as the basis for broadband ground motion models. The results should also shed light on the likelihood of multi-fault rupture in this region, and thus on the maximum earthquake size. The resultant tsunami models will help to characterize the tsunami hazard in southern California; because they will be based on slip models that are themselves physically based, the tsunami models should provide physically plausible estimates of local runup. In the future, this type of analysis could be applied in multiple locations in California and elsewhere. This proposed work is part of the coordinated effort to investigate the proposed Ventura Anticline and Thrust System SFSA; dynamic rupture modeling and tsunami modeling of the type proposed herein are both cornerstones of this larger project. As such, we are using structural and stressing rate information gathered by other SFSA researchers as soon as they are available. In turn, our source models can be used by other SFSA researchers to help pinpoint the best places for future work to further constrain faulting behavior. Thus, the relationship between modeling and structural determination is a two-way street. This work is related to SCEC Research Objectives 6b (Modeling of ruptures that includes realistic dynamic weakening mechanisms, off-fault plastic deformation, and is constrained by source inversions), 4a (Detailed geologic, seismic, geodetic, and hydrologic investigations of fault complexities at Special Fault Study Areas and other important regions), and 3e (Construction of computational simulations of dynamic earthquake ruptures to help constrain stress levels along major faults, to help explain the heat-flow paradox, and to help us understand extreme slip localization, the dynamics of self-healing ruptures, and the potential for repeated slip on faults during earthquakes).

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