Fault Dynamics and Tsunamis in the Ventura Basin

Report for SCEC Award # 15160
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I. Project Overview

A. Abstract

In the box below, describe the project objectives, methodology, and results obtained and their significance. If this work is a continuation of a multi-year SCEC-funded project, please include major research findings for all previous years in the abstract. (Maximum 250 words.)

The Ventura basin in southern California includes coastal dip-slip faults that can likely produce earthquakes of magnitude 7 or greater, and significant local tsunamis. We have constructed a 3D dynamic rupture model of an earthquake on the Pitas Point and Lower Red Mountain faults to model low-frequency ground motion and the resulting tsunami, with a goal of elucidating the seismic and tsunami hazard in this area. Our model results in an average stress drop of 6 megapascals, an average fault slip of 7.6 meters, and a moment magnitude of 7.7, consistent with regional paleoseismic data. Our corresponding tsunami modeling uses final seafloor displacement from the rupture models as initial conditions to compute local propagation and inundation, resulting in large peak tsunami amplitudes northward and eastward due to site and path effects. Modeled inundation in the Ventura area is significantly greater than that indicated by state of California's current reference inundation line. A modeled earthquake that is otherwise identical, but does not propagate all the way to the free surface, produces similar inundation, implying that the somewhat unconstrained surface penetration of the fault system may not matter tremendously for tsunami generation.

B. SCEC Annual Science Highlights

Each year, the Science Planning Committee reviews and summarizes SCEC research accomplishments, and presents the results to the SCEC community and funding agencies. Rank (in order of preference) the sections in which you would like your project results to appear. Choose up to 3 working groups from below and re-order them according to your preference ranking.

Fault and Rupture Mechanics (FARM)
Seismology
Computational Science

C. Exemplary Figure

Select one figure from your project report that best exemplifies the significance of the results. The figure may be used in the SCEC Annual Science Highlights and chosen for the cover of the Annual Meeting Proceedings Volume. In the box below, enter the figure number from the project report, figure caption and figure credits.

Figure 3. Map (red box shown in figure 1) 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 sold 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 estimate. From *Ryan et al.* [2015].

D. SCEC Science Priorities

In the box below, please list (in rank order) the SCEC priorities this project has achieved. See *https://www.scec.org/research/priorities* for list of SCEC research priorities. *For example: 6a, 6b, 6c*

6b, 4a, 3e

E. Intellectual Merit

How does the project contribute to the overall intellectual merit of SCEC? *For example: How does the research contribute to advancing knowledge and understanding in the field and, more specifically, SCEC research objectives? To what extent has the activity developed creative and original concepts?*

Through 3D dynamic rupture modeling, we find that a plausible but severe earthquake on the combined Pitas Point/Lower Red Mountain fault system could produce an earthquake of up to M 7.7. Our tsunami modeling implies that such an earthquake in turn could produce inundation in Ventura and Oxnard that in places exceeds the tsunami inundation previously estimated by the State of California. Whether the earthquake is blind or surface-rupturing does not change the resulting inundation pattern very significantly. These results emphasize the risk that coastal California may experience from local tsunamigenic earthquakes, in contrast to the well-known risk of tsunamis from Japan and Alaska. The probability of such an event in a given time frame is low compared to smaller earthquake events. Nonetheless, it is crucial to investigate the possible effects from such rare but plausible earthquake and tsunami scenarios so that a full hazard assessment can be made. While the details of an actual future event are likely to be more complex, our model likely captures many important aspects for the purposes of tsunami generation.

F. Broader Impacts

How does the project contribute to the broader impacts of SCEC as a whole? *For example: How well has the activity promoted or supported teaching, training, and learning at your institution or across SCEC? If your project included a SCEC intern, what was his/her contribution? How has your project broadened the participation of underrepresented groups? To what extent has the project enhanced the infrastructure for research and education (e.g., facilities, instrumentation, networks, and partnerships)? What are some possible benefits of the activity to society?*

Results from these modeling efforts can help reveal potential regions of high tsunami hazard in Southern California. Additionally, further development of this methodology in tsunamigenic regions worldwide can contribute to hazard assessments. This project has supported the training of a graduate student in both dynamic rupture and tsunami modeling—a combination that is not well represented but could be of crucial use in the future to SCEC. This project has also fostered long-term collaborations between earthquake and tsunami scientists.

G. Project Publications

All publications and presentations of the work funded must be entered in the SCEC Publications database. Log in at *http://www.scec.org/user/login* and select the Publications button to enter the SCEC Pubications System. Please either (a) update a publication record you previously submitted or (b) add new publication record(s) as needed. If you have any problems, please email *web@scec.org* for assistance.

Ryan, K. J., E. L. Geist, M. Barall, and D. D. Oglesby (2015), Dynamic models of an earthquake and tsunami offshore Ventura, California, *Geophysical Research Letters*, *42*, doi:10.1002/2015GL064507.

II. Technical Report

The technical report should describe the project objectives, methodology, and results obtained and their significance. If this work is a continuation of a multi-year SCEC-funded project, please include major research findings for all previous years in the report. (Maximum 5 pages, 1-3 figures with captions, references and publications do not count against limit.)

Introduction

Although the hazard from earthquake-generated tsunamis offshore southern California has received relatively little attention, there have been reports of several significant local tsunamis in the past 200 years [*Borrero et al.*, 2001; *Lander et al.*, 1993; *Townley and Allen*, 1939; *Ulrich*, 1942]. *Lander et al. [1993]* explain that both locally generated tsunamis (e.g., tsunamis generated from the 1812 and 1854 Santa Barbara earthquakes and possible submarine landslides) as well as far-field generated tsunamis (e.g., the tsunami generated from the 1946 Aleutian earthquake) have impacted the California coast. Dynamic earthquake rupture models are a useful way of providing realistic earthquake scenarios on geometrically complex faults; such models are physics-based and do not assume a fault slip distribution or ground motion *a priori;* rather, slip distribution and ground motion are calculated results of the models based on estimates of fault stress, geometry, and material properties. The use of such methods in tsunami modeling is quite new; to date, only *Wendt et al.* [2009] and *Ryan et al.* [2015] have used dynamic rupture modeling to estimate tsunami generation from geometrically complex faults. Furthermore, there have been few tsunami modeling studies offshore Ventura, California (see figure 1). *Borrero et al. [2001]* perform hydrodynamic analysis from a locally generated tsunami offshore southern California on the Channel Islands Thrust system, a south-dipping fault that is located approximately 50 km south of Santa Barbara. However, they do not incorporate any geometrical complexity or spatially-heterogeneous slip in their earthquake models, nor do they investigate potential tsunamis from other offshore reverse faults in the region, including the Red Mountain and Pitas Point faults, which are closer to some populated regions. The Pitas Point and Red Mountain faults are north-dipping and generally trend east-west. *Hubbard et al.* [2014] used several available datasets, including industry seismic profiles as well as their own seismic profiles to improve the subsurface fault model for this fault system. Their model suggests a complex, segmented fault system that extends to seismogenic depth (~20 km). *Rockwell* [2011] used aerial photography to identify marine terraces in the Ventura region along the coast of southern California, suggesting discrete movements in the past with 5-10 m of uplift, with the last event occurring approximately 800 years ago. Therefore, a proper tsunami hazard analysis should incorporate modeled earthquakes that produce deformation consistent with such events.

Method

We use a 3-D finite element method (FEM) [*Barall*, 2009] to model earthquake rupture on a connected, non-planar Pitas Point and Lower Red Mountain fault geometry with spatially constant initial traction and a homogeneous linear elastic Earth structure. The output consists of the rupture pattern on the fault as well as the full seismic wave field and surface deformation. A key input is the fault system geometry. *Plesch et al.* [2007] developed a new 3-D community fault model for southern California that consists of major fault systems defined by geologic and seismic evidence (e.g., surface traces and seismicity). *Hubbard et al.* [2014] further improved upon fault geometries both on and offshore Ventura County by utilizing additional datasets, including seismic reflection profiles and drill-hole data. Therefore, we use a fault system geometry consistent with *Hubbard et al.* [2014] to dynamically model earthquake rupture on the Pitas Point and Lower Red Mountain faults offshore Ventura. In particular, we utilize a fault geometry that connects the Pitas Point fault at depth to the deeper Lower Red Mountain fault via a more horizontal section of fault. We employ a relatively curved fault geometry (e.g., the transition from the Lower Red Mountain fault to the Pitas Point fault is curved) that can result in a relatively smoother rupture transition along dip and slightly smoother ground deformation when compared to the kinked fault geometry in *Hubbard et al.* [2014] with analogous fault rupture. The resultant tsunami is not likely to be sensitive to these small spatial and temporal wavelength features.

The Cornell Multi-grid Coupled Tsunami (COMCOT) Model solves the discretized, nonlinear shallow-water wave equations, using an explicit leap-frog finite-difference algorithm. The nonlinear convection term in the momentum equation is discretized using an upwind scheme. Attenuation from shear stress along the sea floor is included using Manning's formulation, where a constant Manning's coefficient of 0.013 is used. Runup and inundation over initially dry cells are also included through the implementation of moving boundary conditions. The merged bathymetric and topographic digital elevation models (DEMs) used for the tsunami model are from 1 and 3 arc-second resolution Southern California Coastal Relief Model version 2 from the National Geophysical Data Center. The reference elevation for both DEMs is mean sea level (MSL). A mean high water (MHW) vertical datum is used for the calculations by adjusting the DEMs according to the MHW-MSL difference listed at the Santa Barbara tide gauge station. The duration of the simulation is 160 min., sufficient for the maximum amplitude to be recorded in the model domain. Because the phase speed of tsunami waves is much slower than either the velocity of the rupture front or the slip rate, particularly in the shallow ocean above the Pitas Point fault, the time-varying effects of tsunami generation are small [cf. Geist et al., 2007]. Therefore, the instantaneous initial condition for tsunami generation is thought to be an adequate approximation.

Results and Conclusions

Figure 2 shows vertical surface (i.e., seafloor) displacement and total slip resulting from the earthquake model. The largest vertical displacement, over 6 m, occurs on the hanging wall (north) side of the fault, consistent with observations of the Ventura fault – the onshore fault that is likely connected to the Pitas Point fault [e.g., *Hubbard et al.*, 2014; *Rockwell*, 2011]. The largest slip on the fault occurs updip from the nucleation zone (> -12 km depth), with somewhat reduced slip on the most updip section due to rate-strengthening friction. These results indicate that unclamping of normal stress induced by the updip-propagating rupture allows rupture to penetrate a rate-strengthening region near the surface [*Kozdon and Dunham*, 2013; *Ryan*, 2012]. Additionally, the curved fault geometry and constant traction result in an energetic rupture that produces significant slip within the surficial rate-strengthening zone, similar to that inferred in the 2011 Tohoku, Japan Earthquake [*Yamazaki et al.*, 2011].

Figure 3 shows localized peak tsunami amplitude around Ventura and Oxnard, CA. The solid black line indicates the coastline, and the solid red line is the statewide tsunami inundation border used by the California Emergency Management Agency [*http://www.conservation.ca.gov/cgs/geologic_hazards/tsunami/inundation_maps/*]. Letters indicate key geographic locations, including Santa Barbara, Ventura Harbor, the Santa Clara River Mouth, McGrath State Beach, and the Channel Islands Harbor Entrance. Our modeled tsunami inundation exceeds the state estimate in multiple locations. We have also run a faulting model with the rupture constrained not to continue to depths shallower than 1 km; we find that the peak seafloor uplift is reduced from over 7 m to less than 6 m, but the overall inundation map is qualitatively similar to that of the surface-rupturing case.

These results emphasize the risk that coastal California may experience from local tsunamigenic earthquakes, in contrast to the well-known risk of tsunamis from Japan and Alaska. It is worth noting that the hypothetical earthquake scenario in this study would be among the top three or four largest magnitude earthquakes ever recorded in California, dating back to the mid eighteenth century [*http://earthquake.usgs.gov/earthquakes/eqarchives/*]. The probability of such an event in a given time frame is low compared to smaller earthquake events. Nonetheless, it is crucial to investigate the possible effects from such rare but plausible earthquake and tsunami scenarios so that a full hazard assessment can be made. While the details of an actual future event are likely to be more complex, our model likely captures many important aspects for the purposes of tsunami generation. Results from these modeling efforts can help reveal potential regions of high tsunami hazard. Additionally, further development of this methodology in tsunamigenic regions worldwide can contribute to hazard assessments.

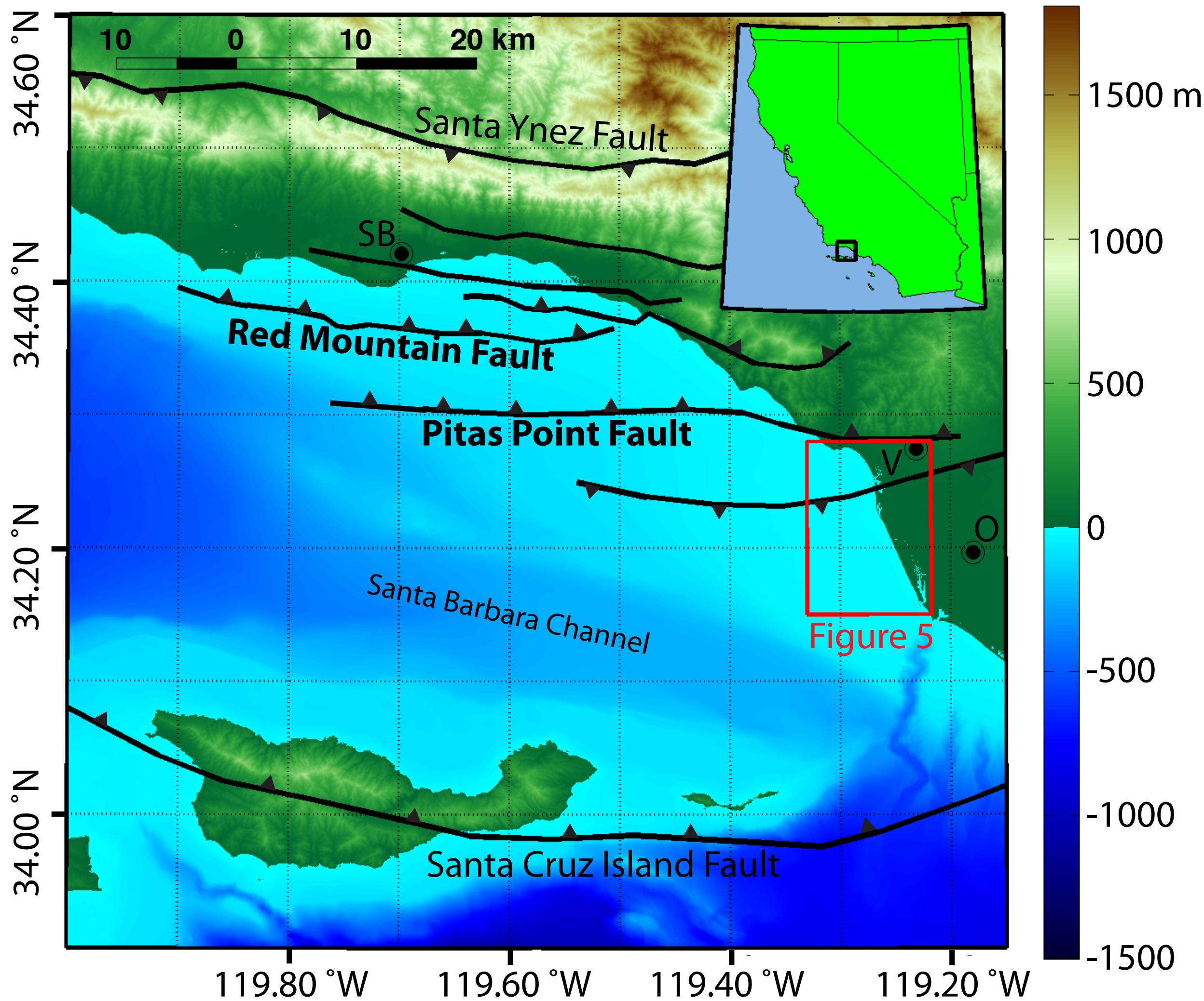

Figure 1. Topographic/bathymetric map of onshore/offshore southern California, with height and depth in meters. The Red Mountain and Pitas Point faults are considered in this study. Triangles indicate direction of dip; faults without triangles are considered strike-slip. Letters show approximate (central) city locations: SB = Santa Barbara; V = Ventura; O = Oxnard. The rectangle outlined in red contains the geographic region for figure 5. Inset shows the map boundary in black. From *Ryan et al.* [2015].

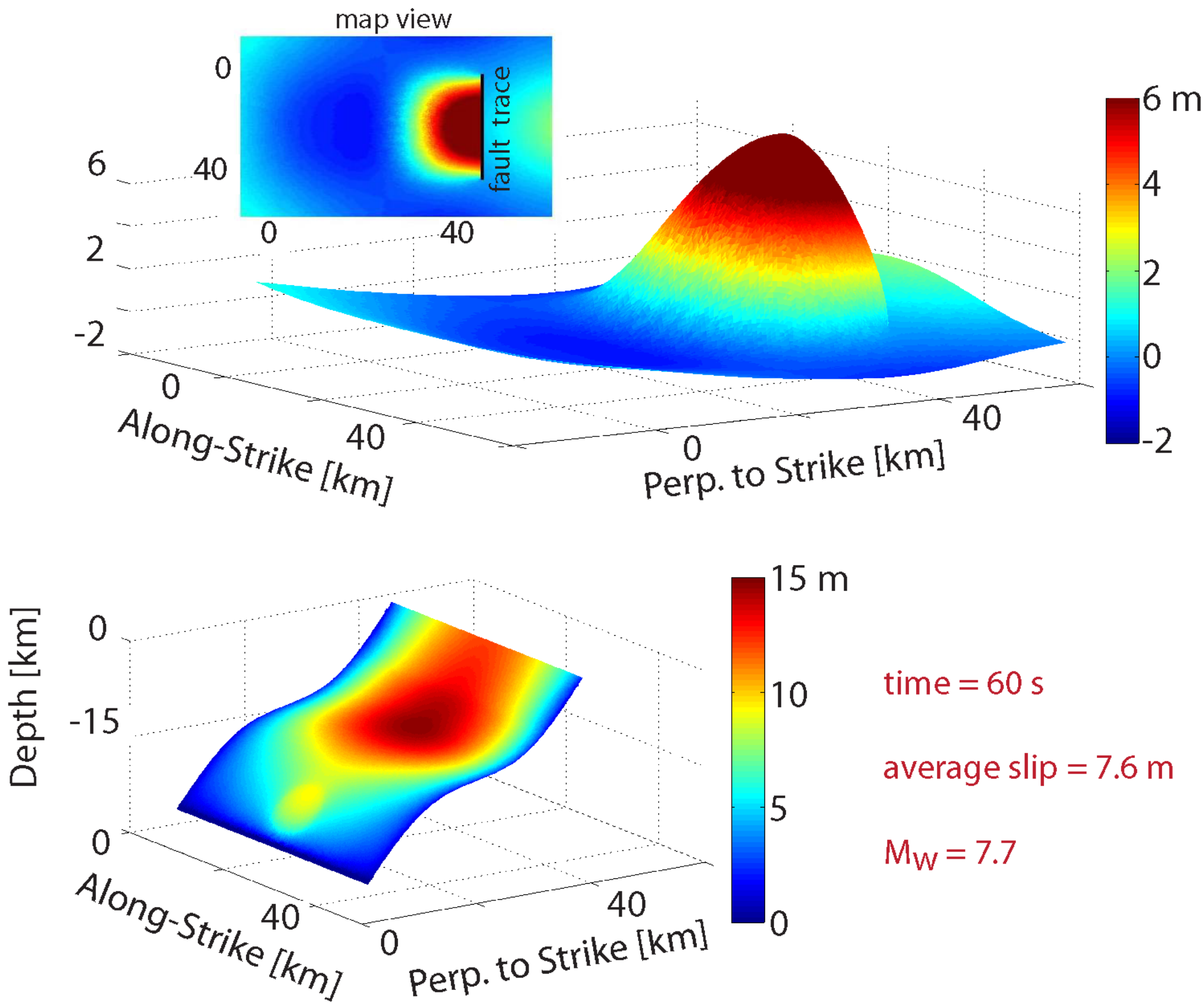

Figure 2. Vertical free surface deformation and total slip. Top: Vertical surface (i.e., seafloor) deformation resulting from slip on the fault system, with a maximum vertical displacement of over +6 m. The map view inset shows the same vertical deformation and indicates the fault trace by a solid black line. Bottom: Amplitude of slip on the fault system, with an average of 7.6 meters. Note that the final deformation and slip are shown at 60 seconds after nucleation. The Mw for the earthquake is 7.7. From *Ryan et al.* [2015].

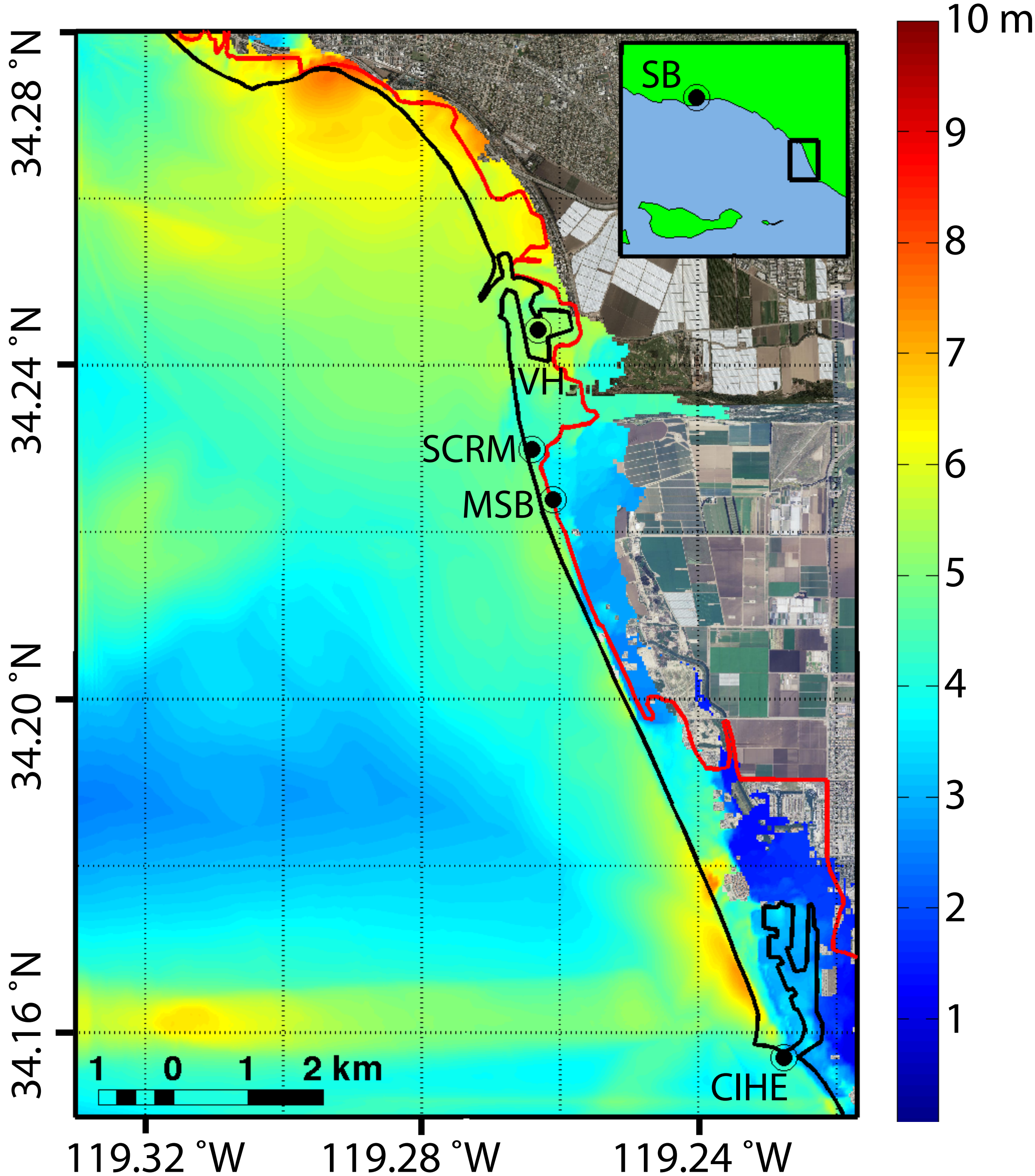

Figure 3. Map (red box shown in figure 1) of localized peak tsunami amplitude, in meters (around Ventura, CA), resulting from slip on the Pitas Point and Lower Red Mountain fault system. The solid black line indicates the coastline. The sold red line is the statewide tsunami inundation map coordinated 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 estimate. From *Ryan et al.* [2015].

References

Barall, M. (2009), A grid-doubling technique for calculating dynamic three-dimensional spontaneous rupture on an earthquake fault, *Geophysical Journal International*, *178*, 845-859.
Borrero, J. C., J. F. Dolan, and C. E. Synolakis (2001), Tsunamis within the Eastern Santa Barbara Channel, *Geophysical Research Letters*, *28*(4), 643-646.
Hubbard, J., J. H. Shaw, J. Dolan, T. L. Pratt, L. McAulife, and T. K. Rockwell (2014), Structure and seismic hazard of the Ventura Avenue Anticline and Ventura Fault, California: Prospect for large, multisegment ruptures in the Western Transverse Ranges, *Bulletin of the Seismological Society of America*, *106*(1), doi: 10.1785/0120130125.
Kozdon, J. E., and E. M. Dunham (2013), Rupture to the trench: dynamic rupture simulations of the 11 march 2011 Tohoku Earthquake, *Bulletin of the Seismological Society of America*, *103*(2B), 1275-1289.
Lander, J. F., P. A. Lockridge, and M. J. Kozuch (1993), *Tsunamis Affecting the West Coast of the United States 1806-1992*, United States Department of Commerce, National Oceanic and Atmospheric Administration.
Plesch, A., et al. (2007), Community Fault Model (CFM) for Southern California, *Bulletin of the Seismological Society of America*, *97*(6), 1793-1802.
Rockwell, T. K. (2011), Large co-seismic uplift of coastal terraces across the Ventura anticline: Implications for the size of earthquakes and the potential for tsunami generation, paper presented at Southern California Earthquake Center Annual Meeting, Palm Springs, CA.
Ryan, K. J. (2012), Dynamic Models of Earthquake Rupture on Fault Stepovers and Dip-Slip Faults Using Various Friction Formulations, Master's Thesis thesis, 114 pp, University of California, Riverside, Riverside, CA.
Ryan, K. J., E. L. Geist, M. Barall, and D. D. Oglesby (2015), Dynamic models of an earthquake and tsunami offshore Ventura, California, *Geophysical Research Letters*, *42*, doi:10.1002/2015GL064507.
Townley, S. D., and M. W. Allen (1939), Descriptive catalog of earthquakes of the Pacific coast of the United States 1769 to 1928, *Bulletin of the Seismological Society of America*, *29*(1), 1-297.
Ulrich, F. P. (1942), *Progress report of the seismological work*.
Wendt, J., D. D. Oglesby, and E. L. Geist (2009), Tsunamis and splay fault dynamics, *Geophysical Research Letters*, *36*, L15303, doi:15310.11029/12009GL038295.
Yamazaki, Y., T. Lay, K. F. Cheung, H. Yue, and H. Kanamori (2011), Modeling near-field tsunami observations to improve finite-fault slip
models for the 11 March 2011 Tohoku earthquake *Geophysical Research Letters*, *38*, L00G15, doi:10.1029/2011GL049130.