Tsunami hazard from the Ventura Pitas-Point fault system

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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.)

Offshore faulting in the Continental Borderland poses a potential local tsunami hazard in Southern California. Recent studies have shown the recurrence times for major earthquakes on the Ventura-Pitas Point system to be on the order of several hundred to several thousand years, well within the range of engineering interest. While the recurrence model (magnitude distribution and return periods) is not clearly established yet, we have estimated the tsunami impact of several scenarios of major earthquakes on the Southern California coastline.

As expected, large events on this system cause significant amounts of inundation along the coast in Ventura and, to a lesser degree, Santa Barbara counties. While local bathymetry of the Continental Borderlands causes energy focusing and reverberations with the Santa Barbara Channel, the tsunami waves outside of the Santa Barbara Channel attenuate rapidly, and therefore the tsunami hazard diminishes to the south and east. Details in the fault geometry and slip distribution are important for the tsunami simulations, and we will explore different models as well as events on the nearby Oak Ridge fault.

We present these results in the context of the existing and upcoming (draft) tsunami hazard modeling and maps from the California Geological Survey as well as the tsunami evacuation zone used by the counties. Our results suggest that the hazard from the largest scenarios (M > 7.7) on the Ventura-Pitas Point structure in Ventura county is of the same order of magnitude as both the existing tsunami hazard and evacuation maps and the upcoming 2500 year draft maps. A better understanding of the recurrence model for this source is therefore essential in determining whether these fault systems will significantly add to the existing tsunami hazard models. Outside of Ventura County, the tsunami hazard from the Ventura-Pitas Point system is very limited and is unlikely to contribute much to the tsunami hazard maps of those areas

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.

Earthquake Geology
Unified Structural Representation (USR)
Fault and Rupture Mechanics (FARM)

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.

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*

Structure and evolution of fault zones and systems: relation to earthquake physics **4a.** Detailed geologic, seismic, geodetic, and hydrologic investigations of fault complexities at Special Fault Study Areas and other important regions.

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?*

The research has given us insight in the tsunami hazard posed by the Ventura-Pitas Point and Oak Ridge systems and puts the hazard into context relative to other tsunami sources.

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?*

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.

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.)

A. Introduction

1. The Ventura-Pitas Point complex

The Ventura-Pitas point complex has recently received significant attention (Shaw et al., 2015) due to the studies by Hubbard et al (2015) and Ryan et al (2015). The former postulated the occurrence of very large earthquakes along the Ventura-Pitas point complex based on 5-10 m of co-seismic uplift of marine terraces in the Ventura area. In a simple faulting environment, such uplift would require large amounts of slip on the fault that require a much larger magnitude than can be sustained on the Ventura–Pitas Point complex itself, and would therefore require co-seismic slip on east or westward extension such as the San Cayetano and Red Mountain faults. Ryan et al. (2015) presented a dynamic rupture model of an earthquake that is consistent with the uplift given in Hubbard et al. (2014), although much simplified compared to the published geologic models. Their results show significant inundation in the Ventura and Oxnard regions.

Nicholson et al. (2015) have argued that the large uplift of the marine terraces are only a local manifestation due to complexities in the fault geometry, and do not reflect the overall deformation on the Ventura-Pitas Point system, which they estimate to be significantly smaller. Furthermore, Sorlien and Nicholson (2015) argue that the source model used for the tsunami simulations of Ryan et al (2015) are inconsistent with the observed crustal structure under the seafloor, most notably they find that there is no evidence that the fault rupture extends to the surface, which means that the Ryan et al. (2015) study overestimated the seafloor uplift and therefore the size of the tsunami.

Source	Max slip	Return period
Ventura-Pitas Point	6.2	500-1500
Ventura-Pitas Point	10.0	800-2250
Ventura-Pitas Point	10.8	900-2500
Oak Ridge	8	> 5000

Table 1 Sources modeled (After Hubbard et al., 2014).

For this study we modeled the earthquakes on the Ventura-Pitas Point complex using geologically consistent geometries, but with maximum uplift of about 6m, which is at the low end of the Hubbard et al. (2014) numbers. The average slip for the three scenarios, corresponding to the three largest events (“most likely smallest”, “most likely largest”, “largest”) in Hubbard et al (2014) are shown in Table 1.

2. The Oak Ridge blind thrust

This structure is located under the Santa Barbara channel, several kilometers south of the Ventura-Pitas point complex, and consists of a south dipping blind thrust fault. It is not clear whether this structure has been active in the Holocene, but its location poses a potential tsunami hazard for the Ventura-Oxnard region. We modeled a single scenario earthquake on this fault

B. Methodology

1. Tsunami Model

The simulations of tsunami propagation and inundation were conducted with the GeoClaw model. The GeoClaw tsunami model is a branch of the open source software package – Clawpack (Conservation LAWs PACKage). This model implements high-resolution finite volume methods to solve the two-dimensional nonlinear shallow water equations, a depth-averaged system of partial differential equations. The GeoClaw model has undergone extensive verification and validation tests (LeVeque and George, 2007; González et al, 2011; LeVeque, et al, 2011) and has been approved as a validated model by the

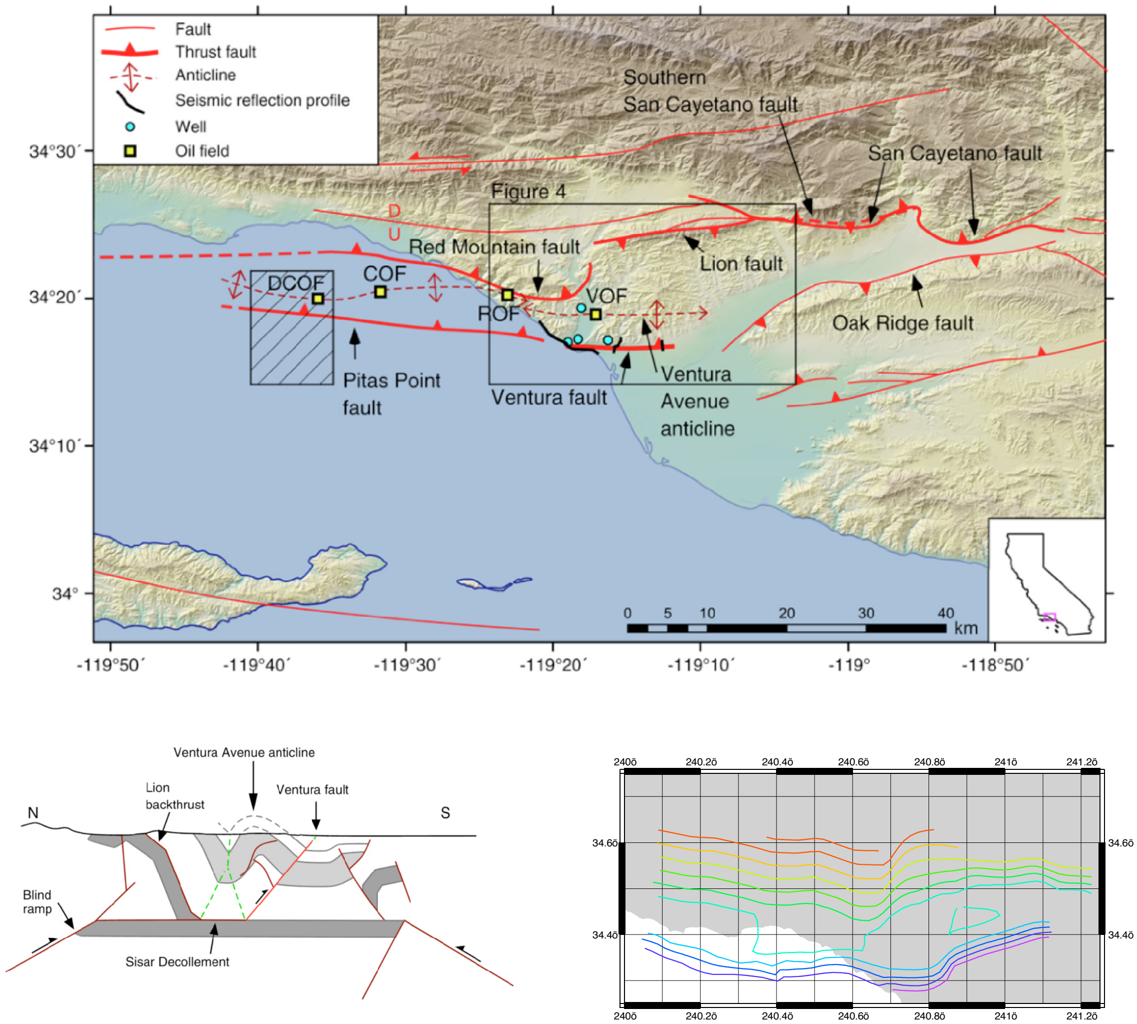

Figure 1. a - Ventura-Pitas fault and fold system (top figure) has recently been shown to be a fault-propagation fold system capable of earthquakes in the M 7.7-8.1 range with return times in the 100-2500 yr range. Our preliminary model for the tsunami analysis consists of three fault sections, a blind thrust to the north, the Sisar decollement at approximately 10 km depth and the Ventura-Pitas fault to the south which reaches the surface in the Santa Barbara Channel and inland south of the Ventura Avenue anticline (bottom left) (figures from Hubbard et al., 2014). The bottom right panel shows the depth contours of the fault system.

U.S. National Tsunami Hazard Mitigation Program (NTHMP) as a result of successful completion of the benchmark problems (NTHMP, 2012).

2. Digital Elevation Model

We used the ETOPO1 global data set at 1 arcmin resolution, US Coastal Relief Model at 3 arcsec resolution and Southern California coast regional grids with resolution of 1/3 arcsec, available online at the NOAA/NGDC website. In total we used 5 levels of refinement ranging from a coarse grid with 2 arcmin resolution covering much of the Ocean on Level 1 to the finest Level 5 with resolution of 1/3 arcsec (~10 m) in the regions of interest.

3. Static Deformation

The static displacements were computed using a frequency-wave-number integration technique (FK) using a simple layered crustal model (Wang et al., 2003; 2006). The advantage of using this technique over the traditional Okada, analytical, approach is that we can use realistic layered elastic crustal structures

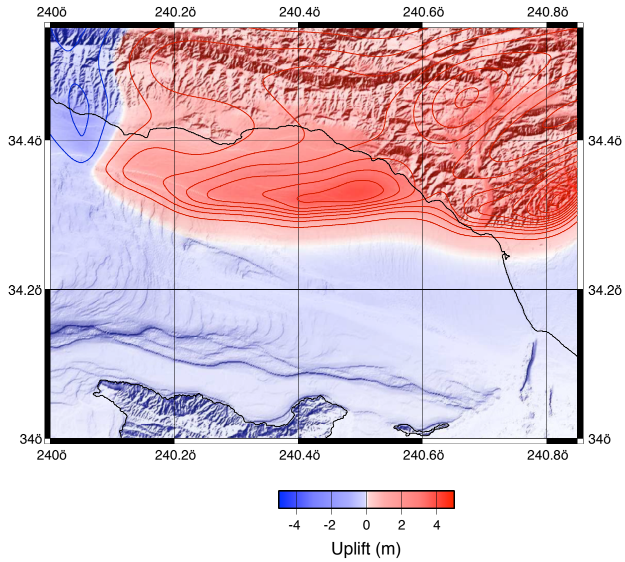

Figure 2. The surface uplift and subsidence caused by movement on the Ventura-Pitas point fault system were computed using a wavenumber integration technique for distributed slip on the subfaults. The slip is not uniform in depth, but instead has 1.5 the average slip on the deeper ramp, and approximately 0.75 the average slip on the decollement and Ventura-Pitas thrust.

rather than half-space models, which can make a significant difference in the surface deformation due to slip at depth.

C. Results

1. Regional impact

In this section we present the results of our modeling efforts. The regional propagation characteristics are summarized in Figure 3, which shows the maximum waveheights from a large event on the Ventura-Pitas Point system throughout the Continental Borderlands. It is clear that the large amplitudes are confined to the Santa Barbara Channel, and that the northern Channel Islands (San Miguel to Anacapa) and associated seafloor topography are effective barriers to tsunami propagation outside the Channel. In the rest of this section, we shall only discuss the local impact in and around the Santa Barbara Channel.

2. Ventura-Pitas Point Scenarios

We considered three scenarios from the Hubbert et al. (2014) study. In Figures 4 we present the inundation maps for the Ventura and Oxnard areas for the largest of these scenarios. Although there is some inundation seen in some of the outer regions, the largest impact is clearly in the Ventura and Oxnard areas, which span the footwall of the Ventura-Pitas Point system.

3. Oak Ridge Scenario

The Oak Ridge blind thrust, which is located several kilometers south of the Ventura-Pitas Point structure is also considered to be a potential tsunami source. Since its area of impact will be similar to the Ventura-Pitas Point sources, we also studied the effect of a large earthquake on this structure. In Figures 4 we present inundation maps for an Oak Ridge event with 8m of buried slip, the top of the seismogenic zone 1 km below the surface. Compared to the largest Ventura-Pitas Point scenario, the Oak Ridge scenario produces higher waves on the south facing shoreline of the Santa Barbara Channel. This is due to both the more favorable orientation of the Oak Ridge structure relative to this region, as well as the fact that, at least in the Ventura area, the south facing shoreline is in the hanging wall of the Ventura-Pitas Point scenario, and thus uplifted during the earthquake.

D. Comparison to other tsunami hazard studies

To put the importance of the Ventura-Pitas Point system in perspective, we will briefly list other tsunamigenic sources that are relevant for the hazard in the Ventura-Oxnard region.

Local sources

- Goleta landslide complex: an area along the continental rise off Santa Barbara that has shows evidence for repeated submarine landslides

Distant:

- Alaska-Aleutian subduction zone: the source area for the 1964 Alaska earthquake (among many others), which historically has had the strongest tsunami impact in central and southern California
- Other sources such as the Chile subduction zone and the Kuril-Kamchatka system have had moderate impact in southern California

A comparison with results for some of these structures is shown in Figures 5.

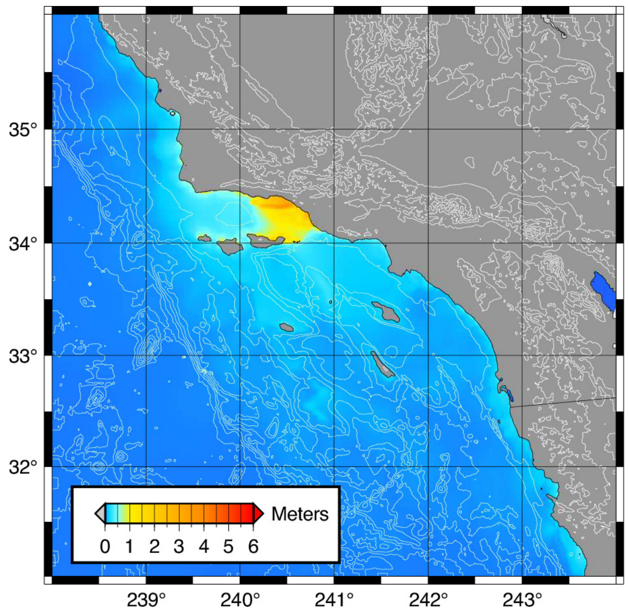

Figure 3. Regional model of tsunami amplitudes from a large earthquake on the Ventura-Pitas Point system.

1. Goleta landslide complex

Recurrence rates for the local sources in particular are currently poorly constrained. For the Goleta complex, the Lee et al. dated several slide events with 30,000 to 50,000 yr intervals, the last one dated 5,500 years ago. Green et al (2006) modeled the tsunami effects of such a landslide, and found runups as high as 10m in the Goleta area, the area that would be worst affected. Submarine landslides tend to have a very strong directional effect, and since Ventura is located away from the direction of maximum waveheights, we expect the effect of a Goleta submarine landslide to be much less.

2. SAFRR scenario

In 2013, the USGS carried out a multi-disciplinary study of the impact of a hypothetical large (Tohoku-like) tsunami scenario originating in Alaska on the coast of California (Ross et al., 2013). Generally, this scenario caused little inundation around the Santa Barbara Channel and the biggest hazard came from the increased current in ports and harbors. This scenario, is thought to represent a 400-500 yr event .

3. State emergency response maps

The State of California has published tsunami inundation maps for emergency response purposes. These are based on a set of local and distant scenarios, which in the case of the Santa Barbara Channel includes the aforementioned Goleta slide as well as distant subduction zone events.

4. Probabilistic results

Several probabilistic tsunami hazard analyses (PTHA) have included the site area. Thio et al. (2010) carried out a probabilistic analysis of the tsunami hazard in California. This analysis was based on distant large earthquake sources around the Pacific Rim, using a comprehensive recurrence model for the sources as well as aleatory variability and epistemic uncertainties. They produced inundation maps at 30 m horizontal resolution for return periods of 72, 475, 975 and 2500 years.
More recently, inundation zones for 2500 yr return period were developed by ASCE for inclusion in the ASCE 7-16 chapter on tsunami loads and effects. The resolution of these maps is 60 m, and it is therefore likely that some of the smaller scale barrier to inundation, such as levees and narrow rows of dunes are not represented in these grids, or incomplete, which can result in more extensive inundation.

5. Other Ventura-Pitas Point models

Ryan et al. (2015) modeled tsunami waves from dynamic rupture scenarios on the Ventura-Pitas Point structure. Overall, the Ryan et al. (2015) are very similar to the existing and draft probabilistic CGS maps.

E. Conclusion

It is clear that the tsunamis generated by either the Ventura-Pitas point and Oak Ridge faults can significantly contribute to the overall tsunami hazard in the eastern Santa Barbara Channel. It is therefore crucial to understand the recurrence behaviour of earthquakes along both these structures. Because of the significant influence of uplift and subsidence on the inundation extent, understanding the details of these ruptures (geometry and slip distribution) are likewise of great importance.
Compared to the proposed draft 2500 yr tsunami inundation map, the Ventura-Pitas Point scenarios seem to be quite comparable in impact on the Ventura-Oxnard, but even the largest scenario does not

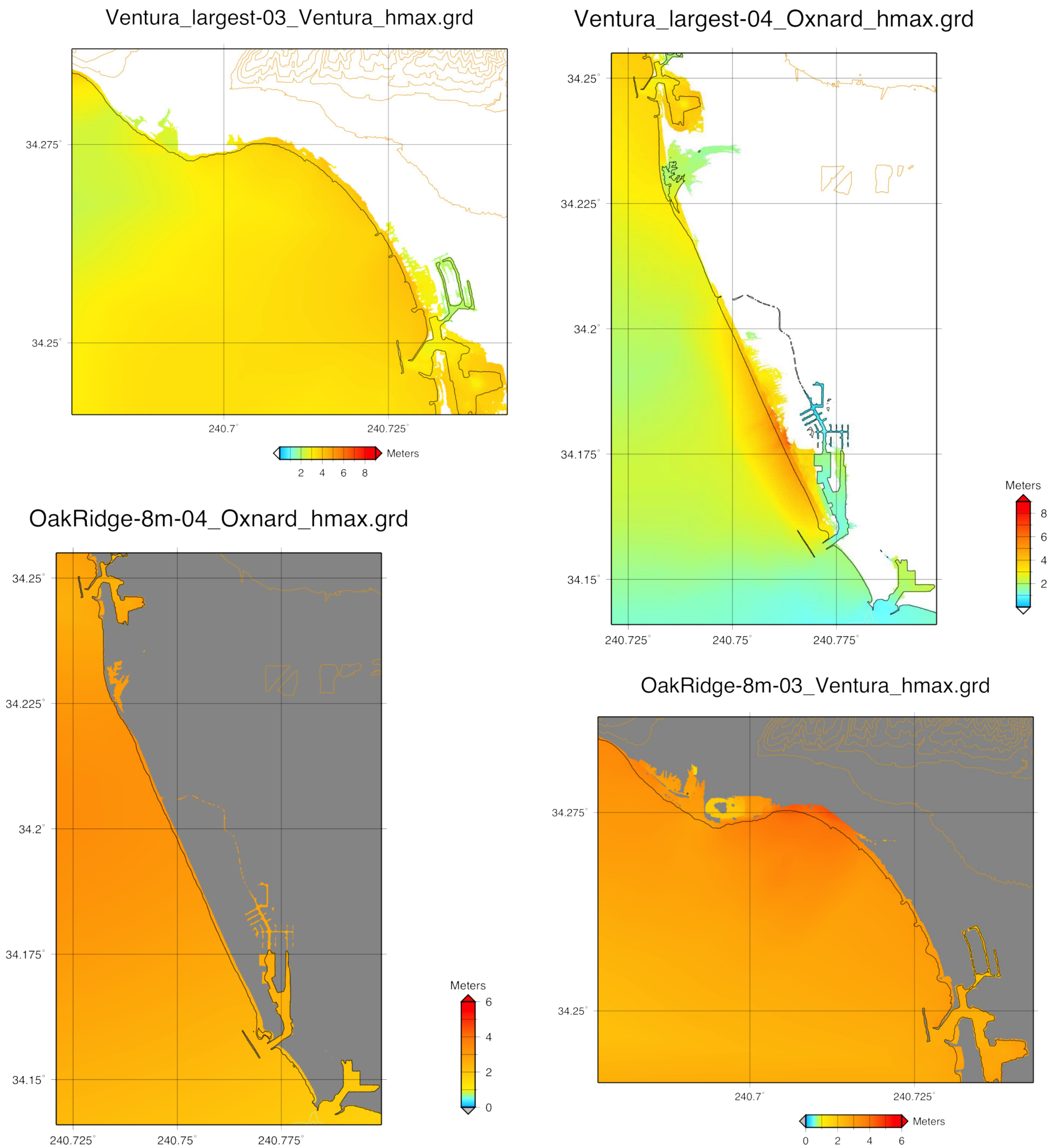

Figure 4. Inundation maps for the largest Ventura scenario (top) and Oak Ridge scenario (bottom) for the Ventura and Oxnard areas.

exceed them. However, in a probabilistic analysis, these will contribute to the overall hazard and, given the return periods proposed by Hubbard et al (2014) (Table 1), will likely to a modest increase to the local tsunami hazard.

F. References

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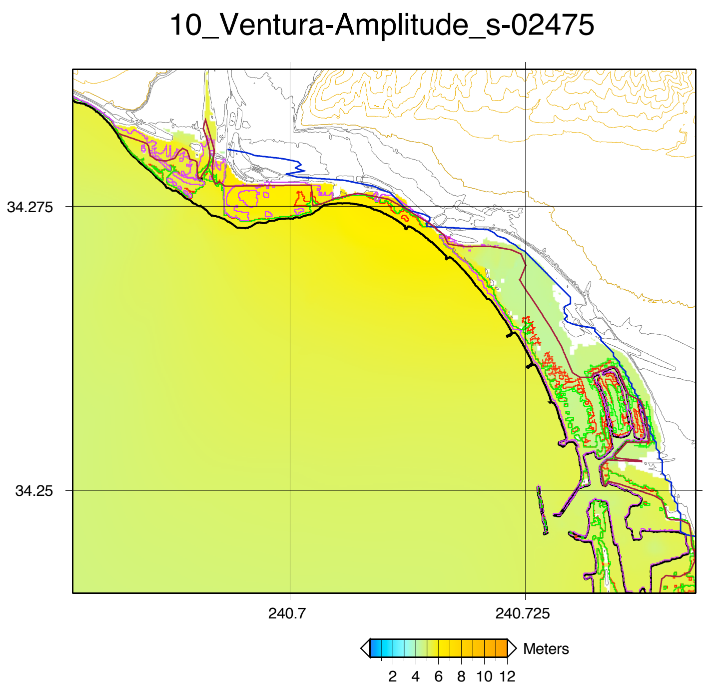

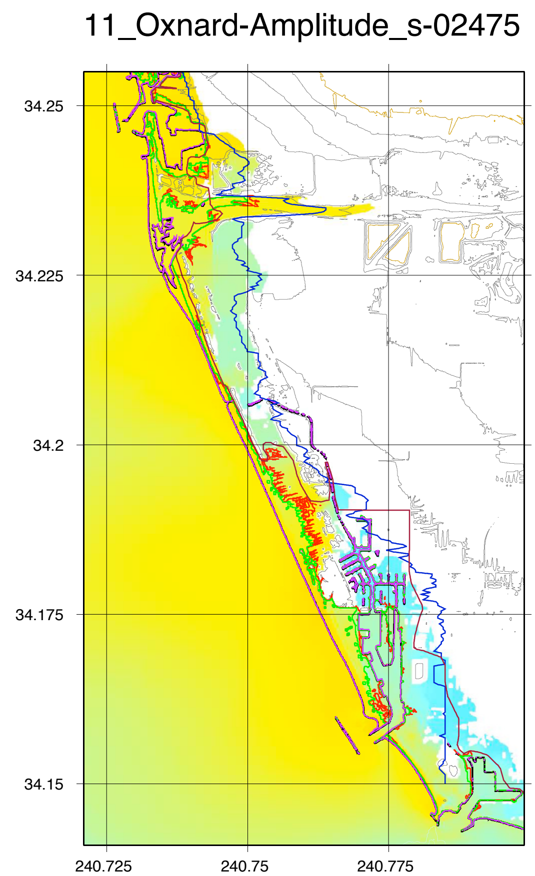

Figure 5. In the above figures, we compare the results of our models shown in the center (red and green for the Ventura-Pitas point scenarios, purple for the Oak Ridge fault), the Ryan et al. inundation line (maroon), the existing CGS tsunami inundation maps (blue) overlain on the preliminary draft probabilistic tsunami hazard maps (2500 yr ARP) developed by CGS and AECOM.

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