Ventura Special Fault Study Area Workshop

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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.)

With the Ventura SFSA winding down in the next year, the time has come to bring together the most up-to-date and significant results and attempt to form a consensus view of the Ventura fault system and its associated hazards. To this end, we hosted a 1-day workshop on the Saturday before the annual SCEC meeting (9/10) in Palm Springs, CA. Workshop presentations focused on recent findings for the Ventura SFSA in the areas of near-surface and offshore geophysics, crustal structure, geodesy, fault modeling, paleoseismology, tectonic geomorphology, seismology, and dynamic rupture and tsunami modeling. Each topical session consisted of invited oral presentations followed by significant time for constructive discussions.

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.

1) Unified Structural Representation (USR)
2) Earthquake Geology
3) Tectonic Geodesy

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.

N/A

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*

4a, 4b, 4e.

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?*

As the SCEC Ventura SFSA project winds down, it is time to attempt to form a consensus view on the Ventura-Pitas Point fault and its associated hazards. The recent recognition of ~M8 earthquakes in the geologic record was inconsistent with seismic hazard estimates at the time, but after several years of the Ventura SFSA project, we now have new constraints on this hazardous fault system. This project has been an excellent example of the strengths of SCEC in that geologists, geodesists, and seismologists have all been working together to better understand this fault system.

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?*

This work has fostered collaborations between numerous existing SCEC researchers at various institutions, including significant contributions from graduate and undergraduate students. For example, SFSA funds partially supported geodetic research by an undergraduate student at Appalachian State University and graduate students at SDSU and UCR. Two graduate students gave talks at the workshop on their SFSA work.

Societal benefits will include the increased awareness of the seismic potential in the western Transverse Ranges, and specifically in the heavily urbanized coastal zone in Santa Barbara and Ventura Counties, which lie immediately over the Pitas Point-Ventura fault system. Knowledge transfer will be through published reports as well as direct interaction with City and County geologists, reviewers and planners.

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 Publications 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

A. Project Objectives

The SCEC Ventura Special Fault Study Area (SFSA) was established to promote interdisciplinary science investigating the prospects for large, multi-segment thrust fault earthquakes in the western Transverse Ranges of southern California, and to address the hazards posed by these potentially devastating events. Several recent earthquakes (e.g., 1999 M7.6 Chi-Chi, Taiwan; 2005 M7.6 Kashmir, Pakistan; and 2008 M7.8 Wenchuan, China) demonstrate the capacity of thrust fault ruptures to breach lateral segment boundaries and involve multiple, stacked fault splays. These large, multi-segment events are generally not considered in regional seismic hazard assessments, but often pose great risks due to the intensity, duration, and extent of their strong ground shaking.

The Ventura SFSA is centered on the Ventura-Pitas Point fault and the overlying Ventura Avenue anticline [*Rockwell et al.*, 1988], which occupy a unique position, located at the juncture of several of the largest and fastest slipping faults in the Transverse Ranges (e.g., San Cayetano and Red Mountain faults). Based on detailed analysis of seismic reflection and industry well data combined with structural modeling, the Ventura-Pitas Point fault has an estimated reverse slip rate of 4.4-6.9 mm/yr. [*Hubbard et al.*, 2014]. Holocene terraces on the anticline suggest that it deforms in discrete 5-10 m uplift events, with the latest event occurring ~800 to 1000 years ago [*Rockwell et al.*, 1988; *McAuliffe et al.*, 2015; *Rockwell et al.*, 2016]. The magnitude of these uplift events (7-9 m at Punta Gorda) implies that the Ventura fault ruptures in conjunction with adjacent faults, yielding large (M7.5 to 8), multi-segment earthquakes [*McAuliffe et al.*, 2015; *Rockwell et al.*, 2016]. The SFSA was established to document and assess the hazards posed by these events through integrated research in geology, paleoseismology, exploration geophysics, seismology, tectonic geodesy, rupture dynamics, strong ground motion simulations, and tsunami studies.

The previous workshop for the Ventura SFSA was held in August of 2013. Since then, we have seen the collection of new data and modeling efforts that attempt to better understand the seismic hazards of the greater Ventura region. With the current SFSA winding down this year, the time had come to bring together the most up to date and significant results and attempt to form a consensus view of the fault system and its associated hazards. To this end, we held a one-day workshop before the 2016 SCEC Annual Meeting in Palm Springs, CA. The workshop consisted of 13 invited oral presentations by researchers that have contributed to the SFSA, and ~50 total workshop attendees. The workshop focused on recent findings for the SFSA in five thematic sessions:

Session 1: Crustal Structure, Near Surface Geophysics, Seismology
Session 2: Geology, Paleoseismology, Tectonic Geomorphology
Session 3: Geodesy and Fault Modeling
Session 4: Dynamic Rupture and Tsunamis
Session 5: What's Next? Future Research Directions

The workshop itinerary is currently posted at *https://www.scec.org/workshops/2016/ventura*. Each topical session consisted of several invited oral presentations followed by significant time for constructive discussions. We found the discussions to be lively and useful to the progress of the SFSA goals. Below, we briefly summarize salient points from each thematic session along with some recommendations for future research directions.

B. Session 1 Summary: Crustal Structure, Near Surface Geophysics, and Seismology

The first talk by Yuval Levy argued that the Ventura-Pitas Point fault is part of a large regional scale north-dipping fold and thrust belt that has propagated south with time. As the system propagated southward, older faults to the north rotate and steepen in dip. Based on geologic mapping, there are numerous regional-scale folds with fold axes approaching 140 km in length. The simplest explanation for this is that the faults that make these folds must also be ~140 km in length. The second and third talks focused on the deep geometry of the Ventura-Pitas Point fault. Industry seismic data only image faults to about 6 km depth, so below this, fault geometry is very loosely constrained. Craig Nicholson's talk, argued that the CFM geometry of the Ventura-Pitas Point fault is incorrect and the fault must have a relatively steep dip down to 10km

depth based on earthquake locations and industry seismic data. Furthermore, he argued that the south-dipping Padre Juan fault is a major structure which is not included in the CFM. John Shaw's subsequent talk laid out evidence for the Ventura-Pitas Point fault shallowing into a mid-crustal detachment which centers on the presence of major synclines in the region. John argued that classic fault bend fold models explain the presence of synclines with bends in the causative fault at depth. Craig Nicholson explains these synclines with south dipping faults. The discussion was vigorous and it was pointed out that because the Santa Ynez Mountains are to the north and the Santa Barbara channel is to the south that north-dipping faults must be dominant over long timescales, but all agreed that south dipping backthrusts are important and not well-understood. Using seismicity to define the deep portions of the Ventura-Pitas Point fault may be problematic because earthquake locations are diffuse and not well constrained due to the large sedimentary basin.

C. Session 2 Summary: Geology, Paleoseismology, and Tectonic Geomorphology

Session 2 focused on research involving the paleoearthquake record on the Ventura-Pitas Point fault. Tom Rockwell presented evidence based on uplifted marine and fluvial terraces of at least four events with 8-11 meters of uplift in the past 6,670 yrs. To get this much uplift, the earthquakes must have been large (~M8). James Dolan presented evidence for only two events in suburban Ventura based on detailed seismic reflection and stratigraphic data. There are several explanations for this discrepancy, but Dolan's preferred explanation is that some of the paleo earthquakes dated at Pitas Point by Rockwell and others likely propagate onto backthrusts in the onshore region. Dylan Rood presented additional evidence for the existence of the South San Cayetano fault which is not included in current hazard assessments but was proposed to exist by *Hubbard et al.* [2014]. The Southern San Cayetano fault is of significant importance, because if it connects to the Ventura-Pitas Point fault to the west, the effective length and hazard of the Ventura fault system increases. Dylan's slip rate estimates for the Southern San Cayetano fault are in the 2-3 mm/yr range. The last talk of the session was given by Thomas Goebel and focused on analyses of stress drops in the Ventura and San Gorgonio regions. Thomas suggests that b-values in Ventura are similar to San Gorgonio, but Ventura has less distributed hypocenter locations compared to San Gorgonio. Also, Ventura tends to have low stress drops (~1 MPa) with p-axes that indicate mostly N/S directed convergence, which is consistent with GPS measurements [*Marshall et al.*, 2013].

D. Session 3 Summary: Geodesy and Fault Modeling

Session 3 focused on geodetic and fault modeling research that attempts to determine the contemporary geometry and slip rates of faults in the western Transverse Ranges region. The first talk, by Scott Marshall, reiterated a conclusion of *Marshall et al.* [2013]: the highly localized contraction at the Ventura basin is difficult to reconcile with existing fault models because these fault models produce significant uplift that is not observed in GPS data. Marshall compared results using mechanical models of the two proposed geometries for the Ventura-Pitas Point fault. In the end, both models produce slip rates that match geologic data reasonably well, but only the Ventura fault model with the mid-crustal detachment fits the vertical GPS data. The constant dip Ventura fault model produces uplift too far south compared to the GPS data. Furthermore, Marshall showed that the latest CFM5.0 model seems to be a significant improvement over CFM4.0. Bill Hammond presented work that involves merging GPS, InSAR, leveling, and tide gauge data to produce a vertical geodetic velocity map of the region. He showed that the vertical geodetic data are often contaminated by non-tectonic sources and that GPS imaging can effectively see through the noise. During the discussion session many questions were raised about which geodetic measurements were being affected by inelastic basin-related processes. This is still very much an important topic that requires further investigation. Kaj Johnson presented work on modeling the geodetic data using non-block inverse models. This work, while using very different assumptions compared to Marshall's work, yields similar slip rate predictions. Kaj Johnson also showed that uplift due to water mass removal in the central valley cannot explain the uplift across the Transverse Ranges region.

E. Session 4 Summary: Tsunamis and Dynamic Rupture Modeling

This session focused on geologic evidence for tsunamis and dynamic rupture and tsunami models of the Ventura Pitas Point fault system. Alex Simms presented a detailed study of sediment/stratigraphy from numerous estuaries and lakes in the near coast region along the extent of the Ventura Pitas Point fault. He finds evidence for several storm events, but no clear evidence of tsunamis at any of his sites. In the discussion session Alex stated that a > 2-3 meter tsunami would probably be required to leave evidence behind that his work could see. Kenny Ryan presented dynamic rupture models of hypothetical earthquakes on the Ventura-Pitas Point fault. He finds that while a non-planar (curved) fault geometry generally decreases coseismic slip, the curved fault produces a larger tsunami because slip tends to be shallower. He also showed that the local bathymetry causes large tsunami heights in the Ventura/Oxnard coastline region. Hong Kie Thio also presented dynamic tsunami models with similar implications, but he showed that he is unable to create any earthquakes as large as M8 with the current fault geometry.

F. Points of General Consensus

The final discussion section was focused on attempting to determine what aspects have majority consensus and what additional research should focus on. While many aspects of the Ventura-Pitas Point fault system are still topics of much debate, as a group, we came up with a list of general points of consensus (in no particular order).

- The seismic hazard of the Ventura-Pitas Point fault system is higher than previously thought and the fault is likely connected to various other structures that may rupture together.
- Multiple large uplift events (~5-10 m) have been documented at different locations along the Ventura-Pitas Point fault using independent methods. These uplifts imply significantly large earthquakes, but the large uplifts observed at Pitas Point may represent maximum values compared to the rest of the fault.
- North-dipping reverse faults must be dominant over long timescales, but south-dipping back thrusts are likely involved and warrant further study. The CFM geometries, especially in the Santa Barbara channel likely require revision to incorporate the key backthrusts and other structures.
- Geodetic data does detect interseismic deformation associated with the Ventura-Pitas Point fault. Deformation is consistent with the Ventura-Pitas Point fault having a mid-crustal ramp because interseismic uplift is observed far north of the fault trace (as is expected); however, geodetic measurements are likely contaminated by basin-related processes in locations near the Ventura basin.
- Geodetic data are sparse/noisy where we need them the most (in the Santa Ynez Mountains). New continuous GPS stations in the Santa Ynez Mountains would be greatly helpful. New InSAR mission will improve data coverage, but mountainous terrain is still problematic for InSAR.
- There is currently no convincing evidence for past tsunamis in the geologic records at numerous sites along the Ventura and Santa Barbara coastlines; however, if the Ventura-Pitas Point fault were to rupture in a ~M8 event, a tsunami would likely be produced and significant run-up would occur in the Ventura/Oxnard coastal areas.

G. Recommendations for Future Research

Moving forward, we recognize that, while we have greatly increased our understanding of this complex fault system, many aspects are still poorly constrained or understood. Therefore, while the SCEC Ventura SFSA will officially end on February 1, 2017, we recommend that SCEC should continue to fund research related to better understanding the greater Ventura-Pitas Point fault system. Considerable discussion was given to the idea of proposing a special journal issue dedicated to the SFSA work, but due to the often slow process of getting a special issue published, the consensus was that the community would be best served with each group publishing their work wherever is most appropriate to expedite the process of getting our

results all published. In this vein, we recommend that SCEC create an SFSA project website where we can post links to the Ventura SFSA-related publications as they come to press along with other relevant data. This way researchers that are interested in the greater Ventura region, can have a single place where they can find the latest SFSA-related publications. This is helpful given the interdisciplinary nature of the SFSA where many key papers may be published in journals that are out of an individual author's typical reading list. We are currently working with the SCEC IT personnel to make this website a reality and expect a version to be up and running by January of 2017.

References

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