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Tsunamis Within the Eastern Santa Barbara Channel

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Abstract. Several locally generated tsunamis have been reported in Southern California during the past 200 years, yet the hazard from locally generated tsunamis has received considerably little attention. We consider here tsunamis generated by coseismic displacements on the Channel Islands Thrust (CIT) system, as well as waves generated by slope failures along the walls of the Santa Barbara Channel. We find that purely tectonic sources could generate regional tsunamis with $\approx 2m$ runup, whereas combinations of tectonic sources and submarine mass movements could generate local runup as large as $\approx 15m$.

Introduction

Until the identification of the Cascadia subduction zone, the mitigation of locally generated tsunami hazards had received little attention, even for densely populated coastlines in the continental United States. Although historically tsunamis have caused enormous losses farfield, their long travel times allow for early warning. In contrast, locally generated tsunamis may have travel times as short as a few minutes. Furthermore, nearshore tsunamis may be enhanced by coseismic submarine mass failures. For example, the tsunami generated by the $M_w \approx 8.0$ Manzanillo, Mexico earthquake of 1995, hit the coast within $15min$ of the earthquake [*Borrero et al.*, 1995]; photos can be found at http://www.usc.edu/dept/tsunamis. Typical maximum runup values ranged from $2-4m$ – roughly as expected for the induced seafloor deformation. In contrast, the tsunami generated after the 1998 $M_w \approx 7.0$ Papua New Guinea earthquake produced runup in excess of $12m$ and caused major loss of life. *Kawata et al.,* [1999]. The cause of the extreme runup has been attributed to a large ($4km^3$) slump along the continental margin of Papua New Guinea [*Synolakis* in review].

These two and another ten tsunamis in the past decade struck nearby coastlines, but had little impact farfield, leading us to reassess the paradigm for tsunami hazards in southern California. McCulloch (1985) had earlier described the local hazard as 'moderate' with the potential for $2-4m$ runup heights. Following the 1992 Cape Mendocino earthquake, McCarthy et al. (1993) reassessed the risk to southern California from locally generated tsunamis as moderate to high. As Synolakis et al. (1997a) noted, these investigations were obtained without hydrodynamic modeling, using only earthquake magnitude–to–tsunami height relationships developed for Japan, which may not be appropriate for other tectonic settings. The region offshore Southern California has numerous possible tsunamigenic hazards, including submarine faults and mass failures on unstable basin slopes [*McCulloch*, 1985; *Vedder et al.*, 1986; *McCulloch et al.*, 1989]. Computational tools now exist *Synolakis et al.,* [1997b] to allow quantitative modeling of the inundation potential from locally generated events. We present here results from modeling tsunamis that could be triggered from faulting and submarine mass movements within the Santa Barbara Channel.

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Regional Geologic Setting

Southern California lies astride a major transition between two tectonic provinces. The region to the south is dominated by northwest–trending, right–lateral strike-slip faults. The area to the north is characterized by west-trending mountain ranges–the Transverse Ranges–that have developed above west-trending reverse faults. Understanding of the thrust faults of the Transverse Ranges has increased dramatically over the past several decades, revealing the presence of several major reverse fault systems e.g. *Davis et al.,* [1989]; *Shaw and Suppe* [1994]; *Dolan et al.,* [1995].

The E–W Santa Barbara Channel forms the submerged western end of the Ventura basin *Vedder, et al.* [1969]. It is $\approx 130km$ long, extending from Point Conception in the west to the eastern end of Anacapa Island. The SB channel reaches a maximum depth of over $600m$ (fig. 1).

Several major active thrust fault systems, including the Channel Islands Thrust (CIT) of Shaw and Suppe (1994) lie offshore, beneath the Santa Barbara Channel. Potential coseismic deformation associated with this fault system represent a significant potential source for tsunami generation. Furthermore, the walls of the basin forming the channel are susceptible to submarine slope failures. At least two slope failures have been mapped in the central Santa Barbara Channel, one believed to have been seismically induced *Vedder et al.* [1986]; *McCulloch et al.* [1989]; *Edwards et al.,* [1993]. Recent studies reveal details of these two slope failures, additional failures along the northern wall of the channel, and several other possibly unstable regions *Greene and Maher,* [2000].

Historical Tsunamis and Earthquakes offshore Southern California

December 21, 1812 Santa Barbara. This one of the first reported large earthquakes in California appears to have generated a moderate-sized tsunami. The wave reportedly affected over $60km$ of the Santa Barbara coast *Toppozada et al.,* [1981]; *Lander et al.,* [1993]. This $M_w \approx 7.2$ earthquake caused extensive damage to the Spanish missions in the area. Historical sources report unusual ocean activity and high waves following the 12/21/1812 tremor *McCulloch* [1985]. Runup from this event is believed to have been as much as $4m$ at El Refugio, $40km$ west of Santa Barbara, and $\approx 2m$ in Santa Barbara and Ventura. Contemporary eyewitness accounts report that "the sea receded and rose like a high mountain", and "...it has been necessary for us to withdraw for now, more than half a league inland" *Toppozada et al.,* [1981]. Other accounts from survivors describe

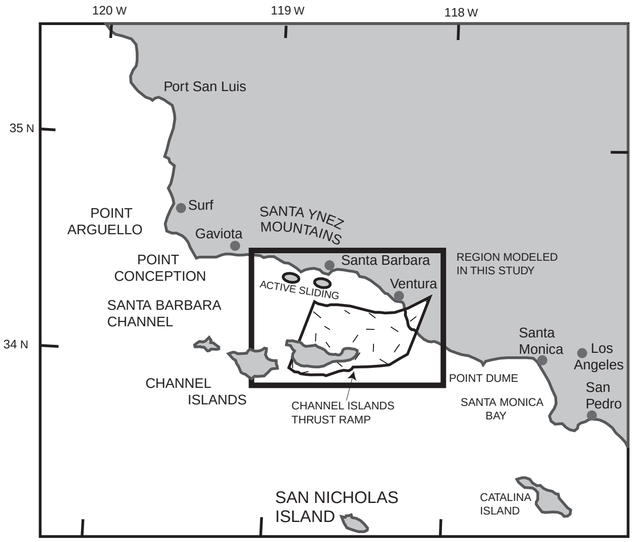

Figure 1. The southern California coast and locations mentioned in the text. The area within the box was the region used in numerical models. The hatchured area is the shape of the Channel Islands Thrust ramp as described by Shaw and Suppe (1994).

residents along the coast relocating their settlements further inland after being flooded by unusual waves. Lander et al. (1993) also report that this tsunami may have produced $4m$ runup in Kona, Hawaii.

November 4, 1927 Point Arguello-Lompoc. Even though outside our study region, the largest and best–observed locally generated tsunami on the entire west coast was triggered by the $M_s \approx 7.0$ November 4, 1927 Point Arguello-Lompoc earthquake northwest of Point Conception *Byerly* [1930]. The causative fault and exact location of this earthquake have been much debated, but the event is now believed to have occurred on an offshore thrust or oblique–reverse fault oriented parallel to the coast west of Point conception *Helmberger et al.,* [1992]. The tsunami generated by this event was observed in several locations along central California coast, and even reached Hawaii. A $2m$ wave was observed in Surf just north of Point Arguello, while at Port San Luis, a reported $2m$ recession was followed by a similar rise *Byerly* [1930]; *Lander et al.,* [1993]. Newspaper accounts from San Pedro, California south of Los Angeles describe an "exceptionally high tide" $1hr$ after the event but "no damage". Simulations of this tsunami match contemporary observations and helped relocate the source *Satake and Somerville* [1992].

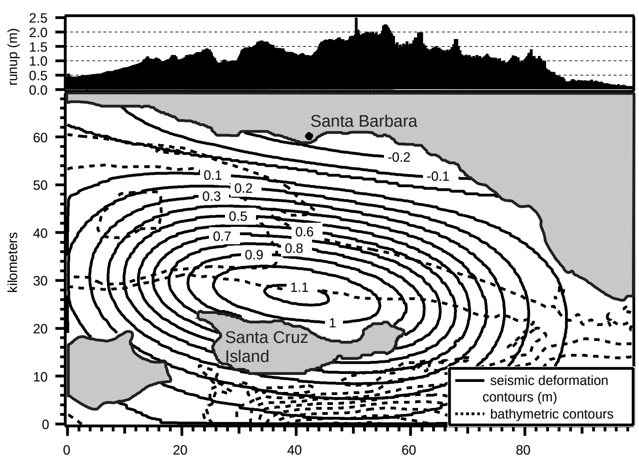

Figure 2. Co-seismic deformation contours (solid lines) in meters from a complete rupture of the Channel Islands Thrust Fault. The computed tsunami is represented as the vertical black bars above the map.

Seismic Tsunami Sources

Channel Islands Thrust (CIT). The Channel Islands Thrust is an N–dipping blind thrust fault that is responsible for uplift of the Channel Islands S. of the Santa Barbara coast (fault plane shown as the stippled region on fig. 1) *Shaw and Suppe* [1994]. These islands represent the crest of the predominantly submarine, southernmost Transverse Ranges. Shaw and Suppe's (1994) balanced cross–section models indicate that the CIT dips gently (23°) N. from a depth of about $7km$ beneath the S. edge of Santa Cruz island, to a depth of $\approx 17km$ beneath the Santa Barbara coast. The main thrust ramp that they modeled extends along strike for $40km$ from east of Santa Cruz Island to its west end, with a total fault plane area of $1900km^2$. Shaw and Suppe (1994) used these fault parameters to estimate a maximum surface–wave magnitude $M_s \approx 7.2 - 7.3$ and slip estimates of comparable earthquakes to estimate $\approx 2m$ of average coseismic displacement, for a complete rupture. Regressions by Wells and Coppersmith (1994) relating fault plane area, eq. magnitude, and average slip yield similar values of $M_w \approx 7.3$ and average slip of $\approx 2.8m$. Regressions in which only southern California earthquakes are considered *Dolan et al.,* [1995] yield larger estimates of maximum magnitude of $M_w \approx 7.4$, and average slip/event $3.5 - 4m$.

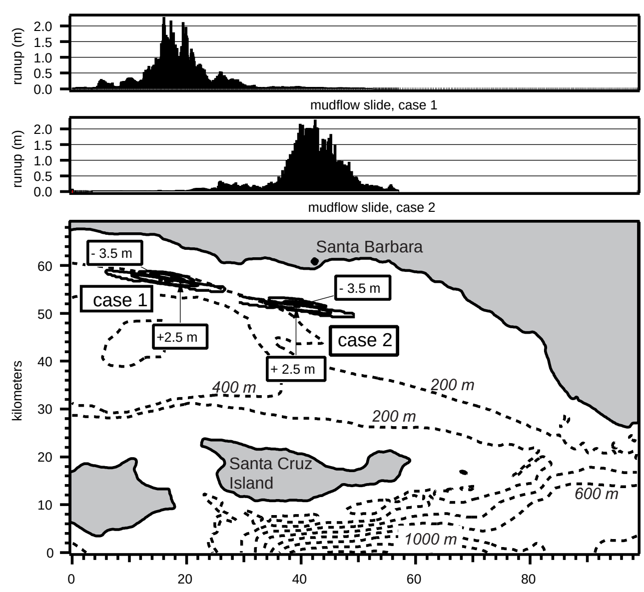

Figure 3. Tsunami runup producced by slide 1, modeled after seismically induced mudflow described by Edwards and Lee (1993). Two cases are shown with the initial condition placed in different locations off of the coast. Note how the runup pattern stays basically the same, and is shifted along the coast.

Although the main N–dipping CIT ramp does not reach the seafloor, its large size and the possibility of large slip per event suggests that it has the potential to produce $\approx 2m$ vertical uplift of the seafloor.

The CIT is the master thrust fault of a system of blind and surficial thrust faults that extend along the Santa Barbara coast. Several of these active faults, including the Pitas Point Thrust and the North Channel Slope fault, they could also generate significant vertical uplift of the seafloor, but they are not modeled in this study.

Other Tsunami Sources

In recent decades, tsunami research has focused on waves directly generated by coseismic uplift of the seafloor induced by fault slip. Motivated by the 1998 Papua New Guinea *Kawata et al.,* [1999] and 1999 Vanuatu [*Synolakis,* in prep]. tsunamis enhanced by underwater mass movements, we model three hypothetical offshore slides to assess their possible impact. We note however that detailed marine geologic investigations of offshore slope stability and evidence of past submarine slope failures are urgently needed to determine the true tsunamigenic potential of offshore slides in Southern California.

We first consider a hypothetical tsunami generated by a small, $0.2km^3$ mudflow *Watts,* pers. comm., 1998, as per marine geophysical data offshore of Gaviota, W. of Santa Barbara *Edwards et al.,* [1993]. We then consider a hypothetical tsunami generated by a much larger $4km^3$ slide, where we use the offshore slide believed to be responsible for generating the 1998 PNG tsunami, as per [*Synolakis* in review]. These two initial conditions are used in order to provide a possible range of runup values that could be expected from a submarine mass movement within the Santa Barbara Channel, with the mudflow case and the PNG case (slide2) as plausible lower and upper bounds, respectively.

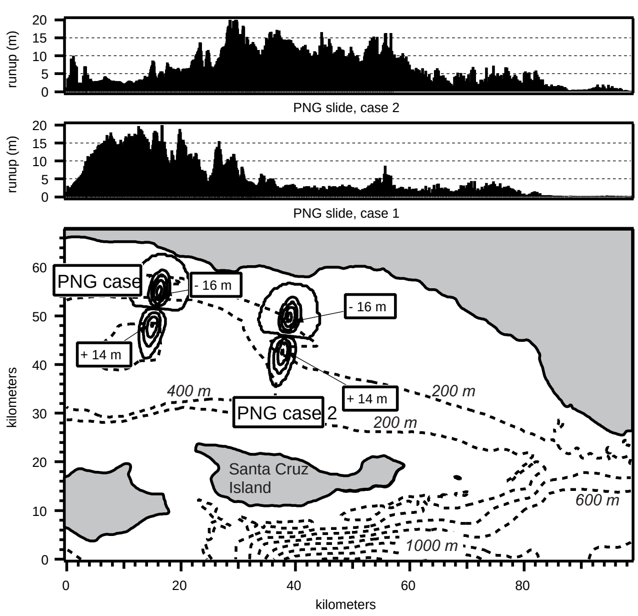

Figure 4. Tsunami runup produced by slide 2, modeled after a larger, thicker mass faliure, simmilar to the one believed to have caused the 1998 Papua New Guinea Tsunami. Again, two location scenarios are shown.

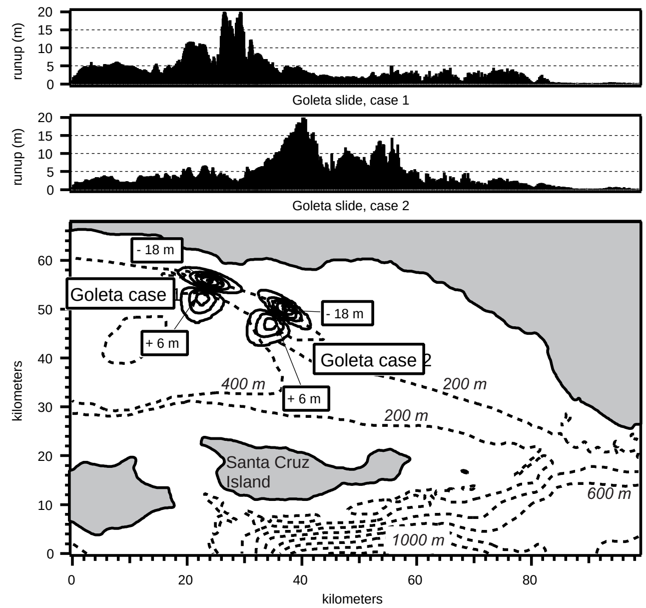

Figure 5. Tsunami runup produced by slide 3, modeled after a slide identified offshore of Goleta, California by Greene and Maher 2000. Again, two location scenarios are shown.

The slide parameters that most affect tsunami generation are not yet well established, and the prediction of waves generated by future mass movements remains a formidable undertaking *Synolakis et al.,* [1997b]. Although the $4km^3$ Papua New Guinea slump is larger than any slides that have thus far been observed offshore southern California, its mean initiation depth at $\approx 1200m$ is much deeper than the shallower water depths $100-500m$ in the Santa Barbara Channel, implying much more efficient wave generation, and compensating for the smaller volumes. We checked this conjecture by modeling the recently identified Goleta slide of *Greene and Maher,* [2000], per their preliminary parameters provided in http://www.mbari.org. Other slope failures have been identified offshore southern California *McCulloch* [1985]; *Edwards et al.,* [1993], and detailed surveys to identify other failure features are currently underway *Greene and Maher,* [2000].

Discussion

Given a fault solution, the prevailing paradigm in tsunami inundation modeling uses elastic dislocation theory to estimate the seafloor deformation, which is assumed to be instantaneous so as to allow use of the shallow water (SW) wave equations without forcing terms. Here, we used VTCS–3 (a.k.a. MOST), one of the two existing $2+1$ nonlinear SW codes, validated with laboratory and field data *Yeh et al.,* [1996]. MOST predicts wave evolution over irregular bathymetries by utilizing a variable grid that allows a consistent number of grid nodes per wavelength. Inundation is calculated without using artificial viscosity or friction terms *Titov and Synolakis* [1998].

We used a variety of maps and sources to develop a $250m$ computational grid. Onshore topography was verified with field surveys in selected locales along the Santa Barbara coast. Whereas the location of the seismic sources are constrained by geology, the location of a potential landslide is more variable. We therefore performed multiple runs in different suspicious locales off the coast.

As shown in figs. 2 and 3, the CIT and mudflow slide, both have the potential to generate $2m$ runup along the coast. For the CIT, the maximum runup appears near the center of the source and remains fairly constant until it drops off outside of the deformed region. The mudflow slide could potentially augment the runup of a seismic source *see Geist* [2000]; if the slide occurs within the zone of tectonic uplift, maximum runup would be approximately the sum of the tectonic–and slide–induced waves. If , as in fig. 2, the slide lies outside of the region of tectonic uplift or occurs a significant time after the earthquake induced wave, it is manifested as a narrow runup peak.

The simulation of the PNG–style slide in fig. 4 generates runup in excess of $15m$, similar to the simulations and observed values in Papua New Guinea. We observe an area of runup greater than $10m$ over a $20km$ stretch of coast, with maximum runup of nearly $20m$. This zone is superimposed on a much broader, $\approx 100km$–long area of $2-4m$ runup. Figure 5 shows the runup values for a wave generated by the Goleta slide, *Greene and Maher,* [2000]. The distribution is different, but extreme values in excess of $15m$ are similar with the PNG–style slide. Extreme runup of this size anywhere along populated shores would be devastating. However, uncertainties in the calculations of slide evolution, directivity and localization suggest using the runup distributions' more representative values of $10-15m$ as a guide for emergency planning.

These are the first quantitative hydrodynamic calculations of locally generated tsunamis offshore southern California. This type of analysis is important for realistic tsunami hazard assessment along the densely populated coastlines, and has been the basis for generating tsunami hazard maps throughout the western United States. Future studies of locally generated tsunamis in Southern California depend on more accurate mapping and dating of submarine slope failures, better combined bathymetry and topography data, and improved hydrodynamic models of wave generation from landslides and seismic sources.

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References

Borrero J.C., M. Ortiz, V.V. Titov, and C.E. Synolakis, Field survey of Mexican tsunami produces new data, unusual photos, *Eos Trans. AGU, 78, # 8,* 85, 87-88, 1995.

Byerly, P.,The California Earthquake of November 4, 1927, *Bull. Seismol. Soc. Am., 20,* 53-66, 1930.

Davis, T., J., Namson, and R. Yerkes, A Cross Section of the LA Area: Seismically Active Fold and Thrust Belt, *J. Geophys. Res., 94,* No. B7 9644 –9664, 1989.

Dolan, J. F. et al., Prospects for larger or more frequent earthquakes in the Los Angeles Metropolitan region, *Science 267,* 199–205, 1995.

Edwards, B.D., H.J. Lee, and M.F. Field, Seismically induced mudflow in Santa Barbara Basin, in *USGS Bull., 2002,* 167–175, 1993.

Geist, E., Origin of 17 July 1998 Papua New Guinea Tsunami: Earthquake or Landslide? *Seismological Review Letters 71 #3,* 344 - 351, 2000.

Greene, G., and N. Maher, Slope Instability and the Potential for Tsunami Generating Landslides, NSF Workshop on the Prediction of Underwater Landslide and Slump Occurrence of Southern California, Los Angeles, CA, 2000.

Helmberger, D.V., P.G. Somerville, and E. Garnero, The location and source parameters of the Lompoc, California Earthquake of 4 November 1927. *Bull. Seismol. Soc. Am., 82, # 4,* 1678-1709, 1992.

Kawata, Y., B. Benson, J.C. Borrero, J.L. Borrero, H.L. Davies, W.P. deLange, F. Imamura, H. Letz, J. Nott, and C.E. Synolakis, Tsunami in Papua New Guinea was as Intense as First Thought, *Eos Trans. AGU, 80, # 9,* 101, 104-105, 1999.

Lander, J., P.Lockridge, and M. Kozuch (Eds.), *Tsunamis Affecting the West Coast of the United States,* 242 pp., U.S. Department of Commerce, NOAA, 1993.

McCarthy, R.J., Bernard, E.N., and Legg, M.R., Cape Mendocino Earthquake: A wake Local Tsunami Wakeup Call?, paper presented at the Symposium on Coastal and Ocean Management, New Orleans, LA, July 19-23 1993.

McCulloch, D., Evaluating tsunami potential, in *USGS Prof. Paper 1360* pp. 375–414, 1985.

McCulloch, D.S., Geologic map of the south-central California continental margin (Map No. 4A, Scale 1:250,000), CDMG, 1989.

Satake, K. and P. Somerville, Location and Size of the 1927 Lompoc, California Earthquake from Tsunami Data, *Bull. Seismol. Soc. Am., 82* 1710-1725, 1992.

Shaw, J. and J. Suppe, Active faulting and growth folding in the eastern Santa Barbara Channel, California, *Geol. Soci. of Am. 106,* 607-626, 1994.

Synolakis, C.E., Liu, P.L.-F, Carrier, G., Yeh, H.H., Tsunamigenic Seafloor Deformations *Science 278,* 598-600, 1997.

Synolakis, C.E., D. McCarthy, V. Titov, J. Borrero, Evaluating the Tsunami Risk in Southern California, paper presented at the California and the World Oceans '97 conference, San Diego, CA 3/24-27/97.

Synolakis, C.E., Bardet, J-P., Borrero, J.C., Davies, H., Grilli, S., Okal, E., Silver, E., Sweet, S., Tappin, D., Watts, P., The Slump origin of the 1998 Papua New Guinea Tsunami, *in review*, 2001.

Synolakis, C.E., Moore, A., Kanoglu, U., Ruscher, C., Field Survey of 1999 Vanuatu Tsunami, *in preparation*.

Titov, V. and C., Synolakis, Numerical modeling of tidal wave runup, *Journal of Waterway, Port, Coastal and Ocean Engineering 124,* 157-171, 1998.

Toppozada, T., C. Real, and D. Parke, Preparation of isoseismal maps and summaries of of pre– 1900 California Eqs., *CDMG # 81-11SAC,* p. 34, 136–140, 1981.

Vedder, J.G., H.C. Wagner, J.E. Schoellhamer, Geologic Framework of the Santa Barbara Channel Region, in *USGS Prof. Paper 679–D*, pp. 1–11, 1969.

Vedder, J.G., Greene, H.G., Clark, S.H., and Kennedy, M.P., Geologic map of the mid–S. California continental margin (Map No. 2A Scale 1:250,000), CDMG, 1986.

Watts, P., Wavemaker curves for tsunami generated by underwater landslides, *J. Waterway, Port, Coastal and Ocean Engineering 124 # ,3,* 127–137, 1998.

Watts, P., Personal Communications, 1998.

Wells, D. and K., Coppersmith, New empirical relationship among magnitude,rupture length, rupture width, rupture area and surface displacement, *Bull. Seismol. Soc. Am., 84 # ,4,* 974–1002, 1994.

Yeh, H., P. Liu, and C.E. Synolakis (Eds.), *Long Wave Runup Models,* 403 pp., World Scientific, New Jersey, 1996.

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