# TSUNAMI INUNDATION MAPPING FOR THE STATE OF CALIFORNIA

EGU 2010

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State of California Seismic Safety Commission

OES California
Governor's Office of Emergency Services

# Milestones in Understanding Tsunami Hazards in California from the "academic" point of view.

1970s - Houston and Garcia assessment of tsunamis from Alaska and Chile - estimates every 5 miles of coastline at 500m offshore depth.

1992 - McCarthy, Legg & Bernard assessment of risk in the aftermath of the Cape Mendocino event.

1995 - First simulation  of local tsunami in Southern California - presentation to SSC in 1996. SSC->FEMA->USC&LLNL&SLC local offshore faults.

1997 - Synolakis, Titov & McCarthy re-assessment of Houston & Garcia estimates - factor of 5 difference in inundation distances.

1998 Papua New Guinea tsunami focuces attention to offshore landslides. Funding from NOAA->OES->USC for first modern inundation maps.

2001 McCarthy et al simulations in NATO ARW on California. Eisner et al in ITS.

2002 Analysis of Skagway tsunami.

2005 Refocusing of thinking on distant sources in the aftermath of Sumatra.

2006 Damage to Crescent City underscores the impact of  "marginal" events.

2009 Completion of "most" MOST maps, dissemination under way.

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# California has been affected from both farfield and nearfield tsunamis.

Exposure - not just the population on the 1200km coastline, but also
California has 11 cargo seaports and 27 small craft harbors
with > 500,000 jobs statewide and US$30 Billion -> to the California economy.

(Pacific Merchant Shipping Association)

TRC-California

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3 major ports and harbors including Los Angeles/Long Beach , San Diego harbor and San Francisco Bay

# The 2001 OES/USC maps

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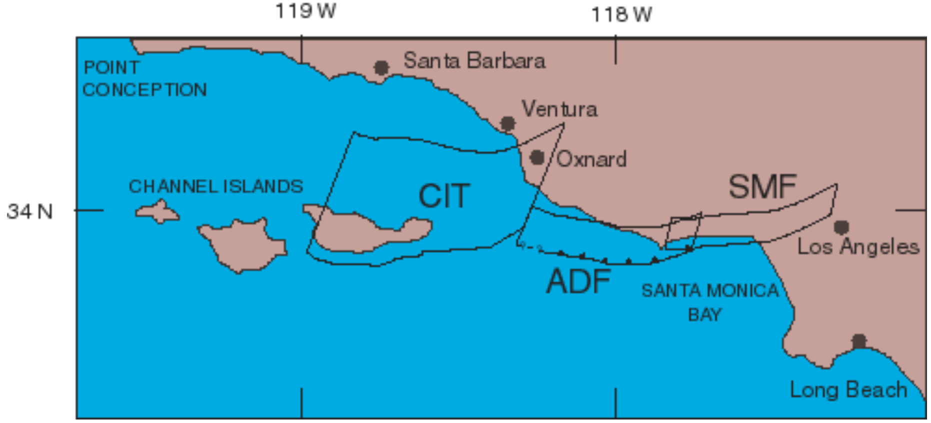
# Emphasis in the period 1998-2004 was on local sources.

All known offshore faults were considered. As an example, the CIT, ADF and SMF were considered potentially tsunamigenic in the Santa Barbara Channel.



CIT - Channel Islands Thrust
ADF - Anacapa-Dume Fault
SMF - Santa Monica Fault

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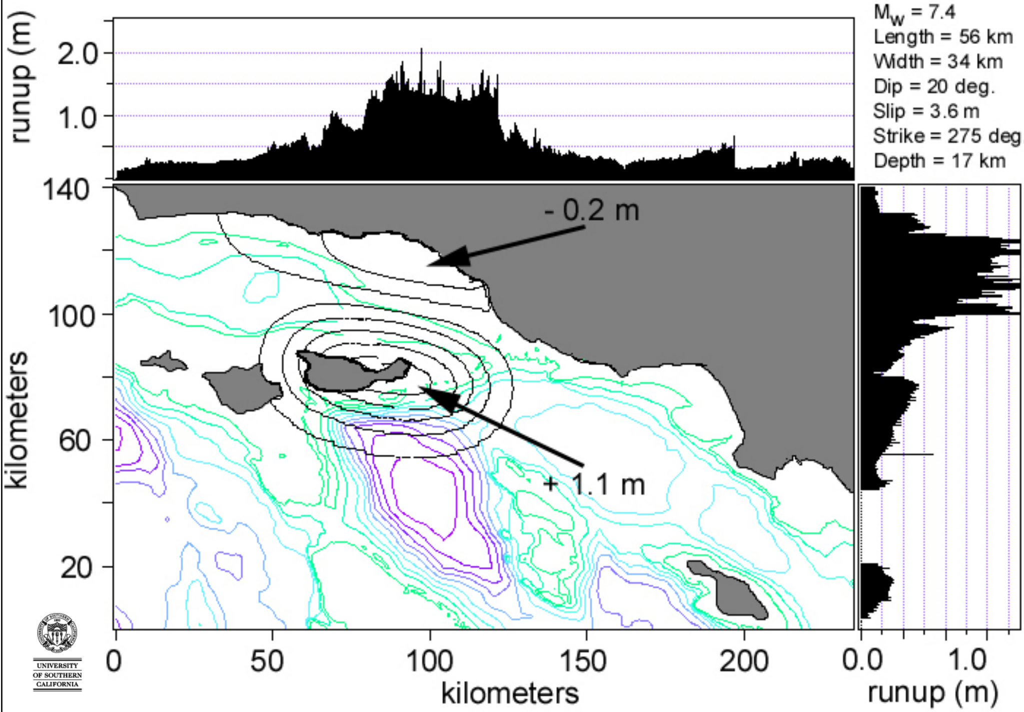
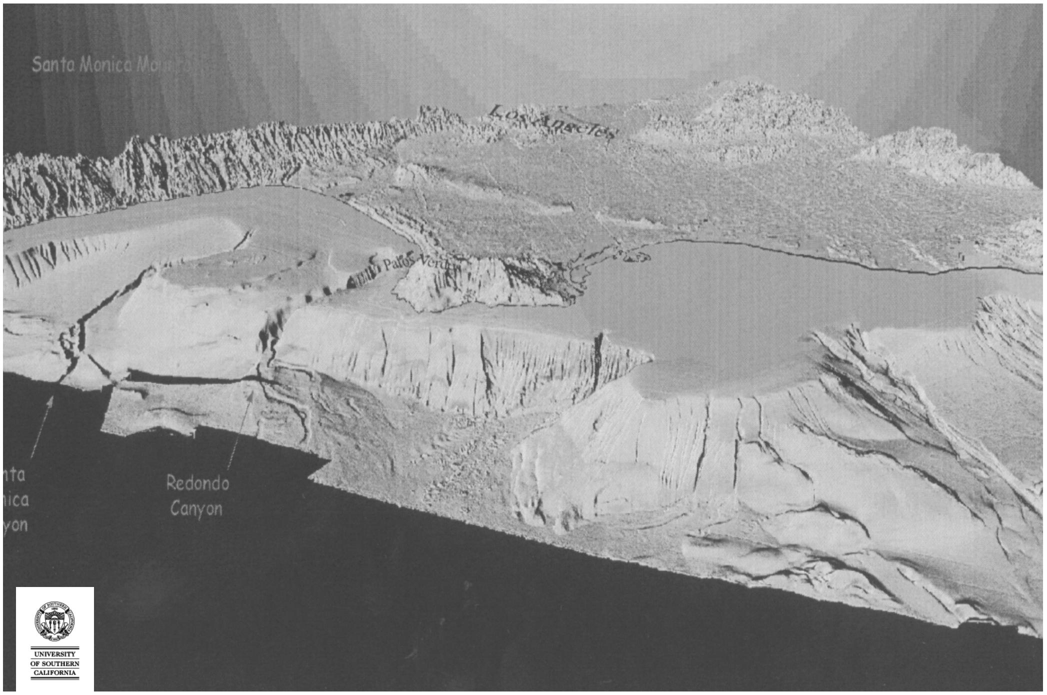
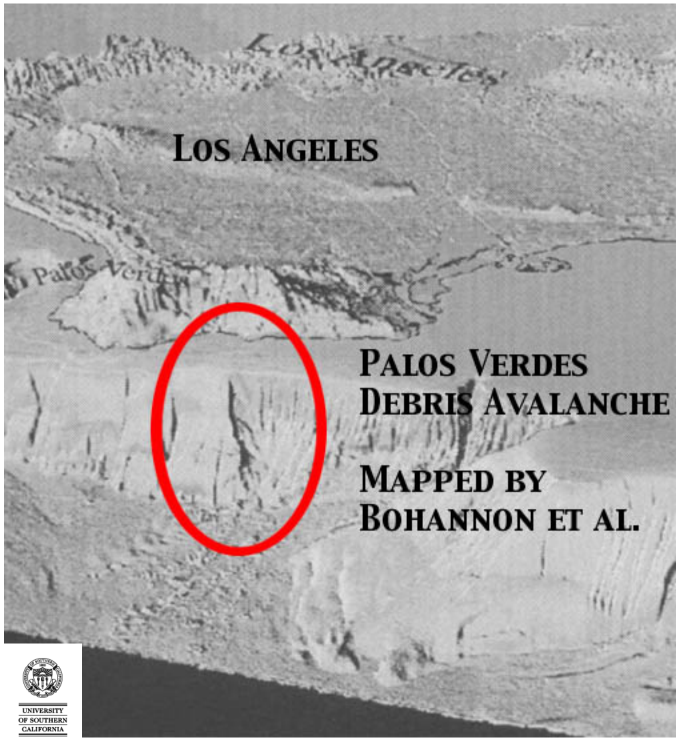
# Channel Islands Thrust



$M_w$ = 7.4
Length = 56 km
Width = 34 km
Dip = 20 deg.
Slip = 3.6 m
Strike = 275 deg.
Depth = 17 km

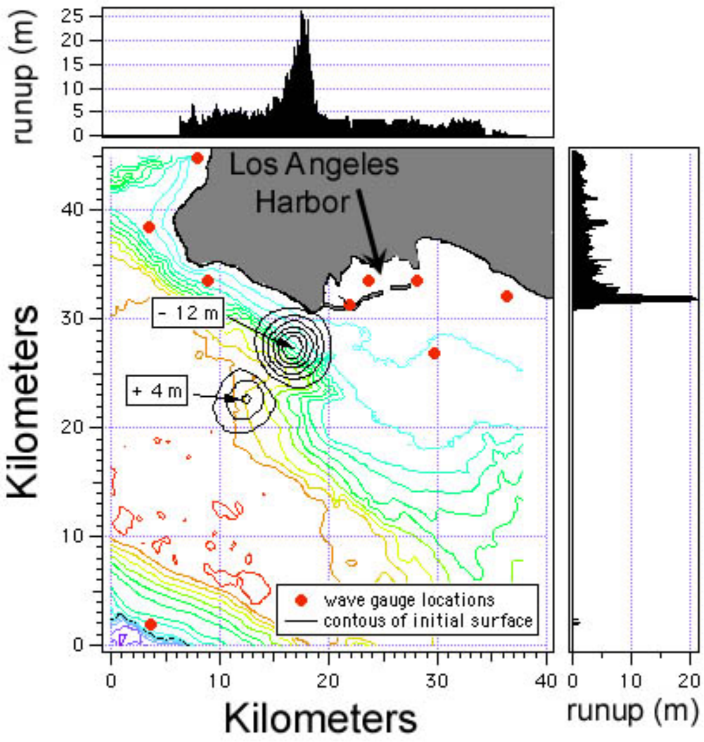
# Landslide sources -> another potential tsunami source:





Palos Verdes
debris avalanche
(believed to have occurred a
few thousand years ago)

- 2km wide
- 4.6km long
- 60m thick
- volume .35 to .72 km$^3$
- depth -100m to -800m



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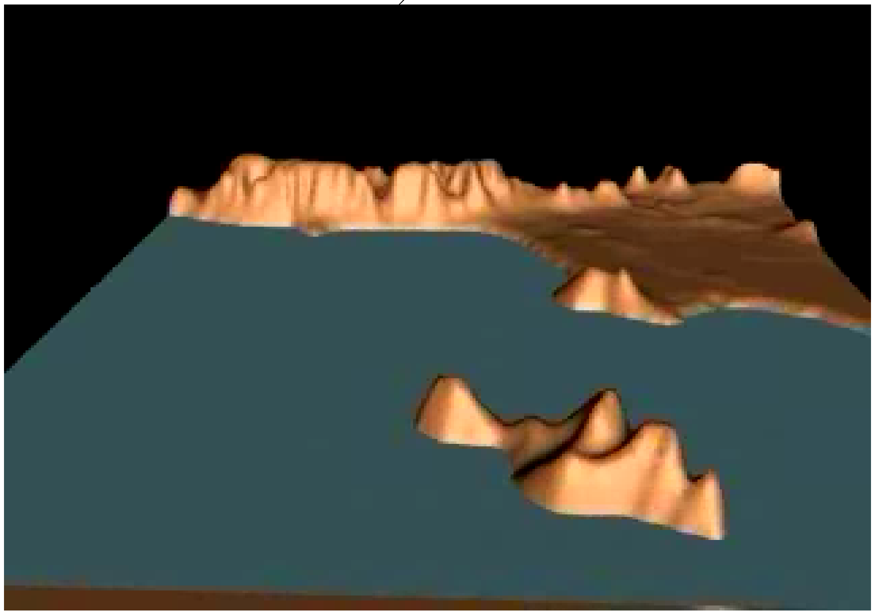
# An animation of the PV slide.



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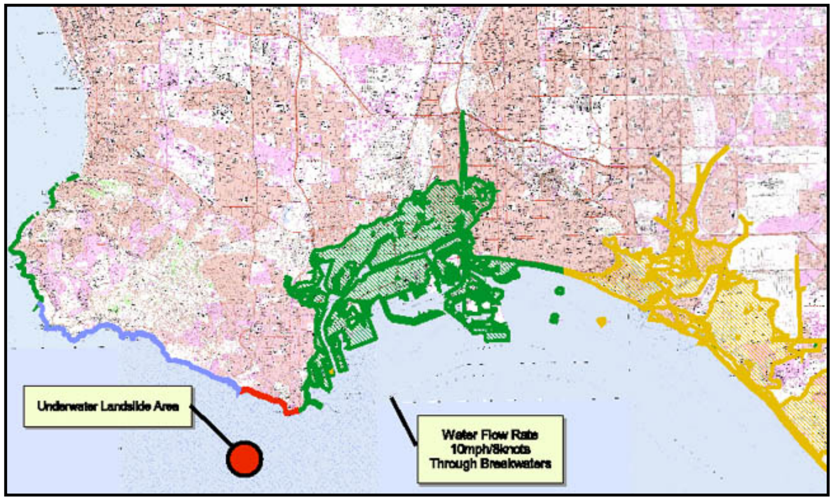
# PALOS VERDES TSUNAMI INUNDATION



**TSUNAMI EXPOSURE:**
74,600 PEOPLE
4.5 BILLION DOLLARS
(4.5 x $10^{15}$ TURKISH LIRA!)

**DAM BREAK FLOOD:**
15,200 PEOPLE
1 BILLION DOLLARS
(~5 TIMES LESS THAN TSUNAMI)

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# Could It Happen Here?

The catastrophic tsunami that struck southern Asia on December 26, 2004, underscored the extraordinary social and economic havoc that such an event can wreak. Could it happen here in the United States—in particular, off the coast of Southern California? The disturbing answer is that, yes, it could. Although the National Oceanic and Atmospheric Administration's National Ocean Service has 13 continuously operating tide stations in the state of California that are capable of producing real-time data for tsunami warnings, there is no way to prevent a strike. Recent developments in the modeling of tsunami waves and the analysis of their economic consequences, combined with data from recent offshore mappings of the Santa Barbara Channel and other locations, suggest the mechanism and economic effect of an undersea landslide in the vicinity of Los Angeles that would spawn a tsunami. **By Jose Borrero, Ph.D., Sungbin Cho, James E. Moore II, Ph.D., Harry W. Richardson, and Costas Synolakis, Ph.D.**

The seismic sensitivity of the Los Angeles metropolitan region is well recognized, although the densely populated regions of coastal Southern California have been relatively free of severely damaging earthquakes during the past 200 years (see figure 1). However, several recent moderate earthquakes—the Northridge earthquake, which occurred in California in 1994 and had a seismic moment ($M_w$) of 6.7, and the $M_w$ 6.0 Whittier Narrows earthquake, which occurred in 1987—have brought to light the hazards associated with thrust and reverse faulting beneath Southern California. There have been several smaller, less damaging thrust and reverse earthquakes near the shore that illustrate the possibility of a larger earthquake offshore. The shaking from an earthquake of magnitude 7 or greater on an offshore thrust or reverse fault would undoubtedly be damaging to coastal communities, and its effect could be greatly magnified if it were to generate a tsunami.

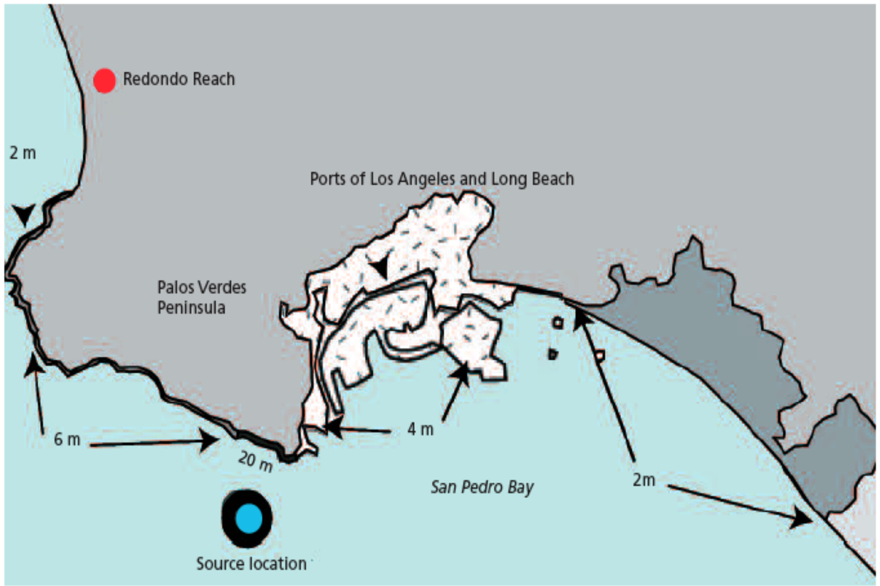
The hazard to metropolitan Southern California posed by locally generated tsunamis has received considerably less study than the hazards posed by onshore earthquakes. This is likely to change. The mechanisms that generate tsunamis have received considerable study following the unusually large waves associated with the tsunami that struck Papua New Guinea on July 17, 1998. As a result of this increasing scientific scrutiny, Southern California's susceptibility to tsunami damage is becoming better understood.

Several locally generated tsunamis have been recorded in the region over the past 200 years. There will be others, and the research outlined in this article focuses on the likelihood and the potential economic effect of a large tsunami. One of the first large earthquakes to be recorded in Southern California—the temblor that struck Santa Barbara on December 21, 1812—appears to have generated a moderate tsunami that affected more than 60 km of the Santa Barbara coast. Table 1 summarizes the details of several nearshore earthquakes, some of which generated tsunamis.

Figures for the year 1994 indicate that the annual economic output of metropolitan Los Angeles is $746 billion. Such natural disasters as earthquakes, fires, floods, and landslides have serious economic ramifications. Quantifying the economic effects of natural disasters has long been of theoretical interest to economists, social scientists, and engineers, but progress has been slowest within the social sciences. The physical science of earthquakes and tsunamis is challenging, but it may be far less difficult than assesing the social consequences of disasters. Consequently, it is not surprising that only limited attention has been focused on the socioeconomic effects of

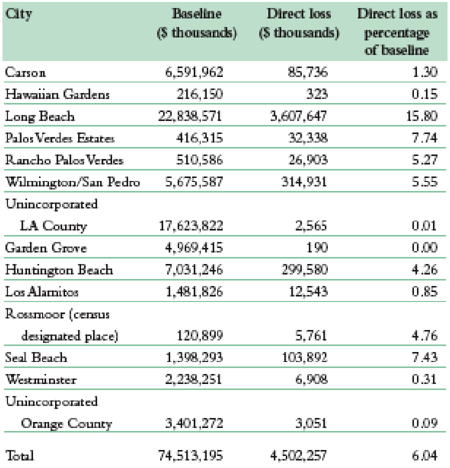
Figure 1

# Deterministic (worst case) scenario map for the Ports of LA/LB

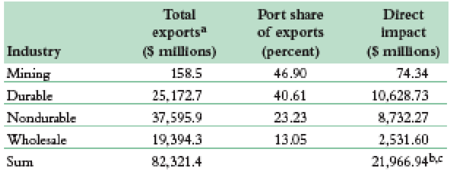


*Borerro et al, Civil Engineering, 2005*

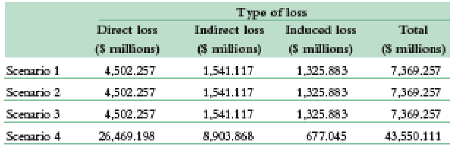
# Regional economic losses from landslide tsunami in POLA/LB.



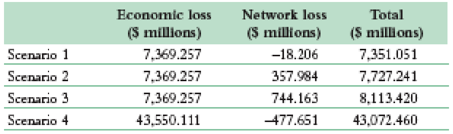
| City | Baseline ($ thousands) | Direct loss ($ thousands) | Direct loss as percentage of baseline |
|---|---|---|---|
| Carson | 6,591,962 | 85,736 | 1.30 |
| Hawaiian Gardens | 216,150 | 323 | 0.15 |
| Long Beach | 22,838,571 | 3,607,647 | 15.80 |
| Palos Verdes Estates | 416,315 | 32,338 | 7.74 |
| Rancho Palos Verdes | 510,586 | 26,903 | 5.27 |
| Wilmington/San Pedro | 5,675,587 | 314,931 | 5.55 |
| Unincorporated LA County | 17,623,822 | 2,565 | 0.01 |
| Garden Grove | 4,969,415 | 190 | 0.00 |
| Huntington Beach | 7,031,246 | 299,580 | 4.26 |
| Los Alamitos | 1,481,826 | 12,543 | 0.85 |
| Rossmoor (census designated place) | 120,899 | 5,761 | 4.76 |
| Seal Beach | 1,398,293 | 103,892 | 7.43 |
| Westminster | 2,238,251 | 6,908 | 0.31 |
| Unincorporated Orange County | 3,401,272 | 3,051 | 0.09 |
| Total | 74,513,195 | 4,502,257 | 6.04 |



| Industry | Total exports[a] ($ millions) | Port share of exports (percent) | Direct impact ($ millions) |
|---|---|---|---|
| Mining | 158.5 | 46.90 | 74.34 |
| Durable | 25,172.7 | 40.61 | 10,628.73 |
| Nondurable | 37,595.9 | 23.23 | 8,732.27 |
| Wholesale | 19,394.3 | 13.05 | 2,531.60 |
| Sum | 82,321.4 |  | 21,966.94[b,c] |



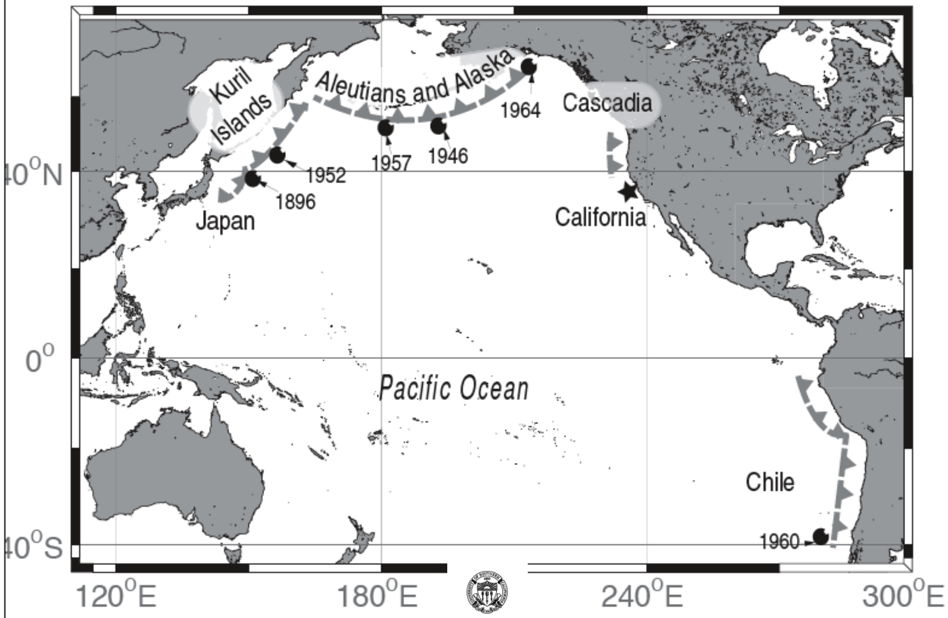
|  | Type of loss |  |  |  |
|---|---|---|---|---|
|  | Direct loss ($ millions) | Indirect loss ($ millions) | Induced loss ($ millions) | Total ($ millions) |
| Scenario 1 | 4,502.257 | 1,541.117 | 1,325.883 | 7,369.257 |
| Scenario 2 | 4,502.257 | 1,541.117 | 1,325.883 | 7,369.257 |
| Scenario 3 | 4,502.257 | 1,541.117 | 1,325.883 | 7,369.257 |
| Scenario 4 | 26,469.198 | 8,903.868 | 677.045 | 43,550.111 |



|  | Economic loss ($ millions) | Network loss ($ millions) | Total ($ millions) |
|---|---|---|---|
| Scenario 1 | 7,369.257 | –18.206 | 7,351.051 |
| Scenario 2 | 7,369.257 | 357.984 | 7,727.241 |
| Scenario 3 | 7,369.257 | 744.163 | 8,113.420 |
| Scenario 4 | 43,550.111 | –477.651 | 43,072.460 |

# *Post the 2004 Indian Ocean tsunami,*
# *emphasis returned to far field events*

## Seismic sources with known historic tsunamis affecting California



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# The USC Tsunami Research Center
# www.usc.edu/dept/tsunamis

- Field surveys of current and past events - 22 total from 1992 Nicaragua to Solomon Islands and Chile 2010
- Numerical and Analytical Modeling
- Hazard Assessment and Planning
- Public Education
- Research in tsunami hydrodynamics

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# Numerical modeling of tsunami propagation and inundation

We use MOST (Method of Splitting Tsunami)

A finite difference model based on the nonlinear shallow water equations - benchmarked with the NOAA/ Nuclear Regulatory Commission standards and guidelines for tsunami models.

$$h_t + (uh)_x + (vh)_y = 0$$

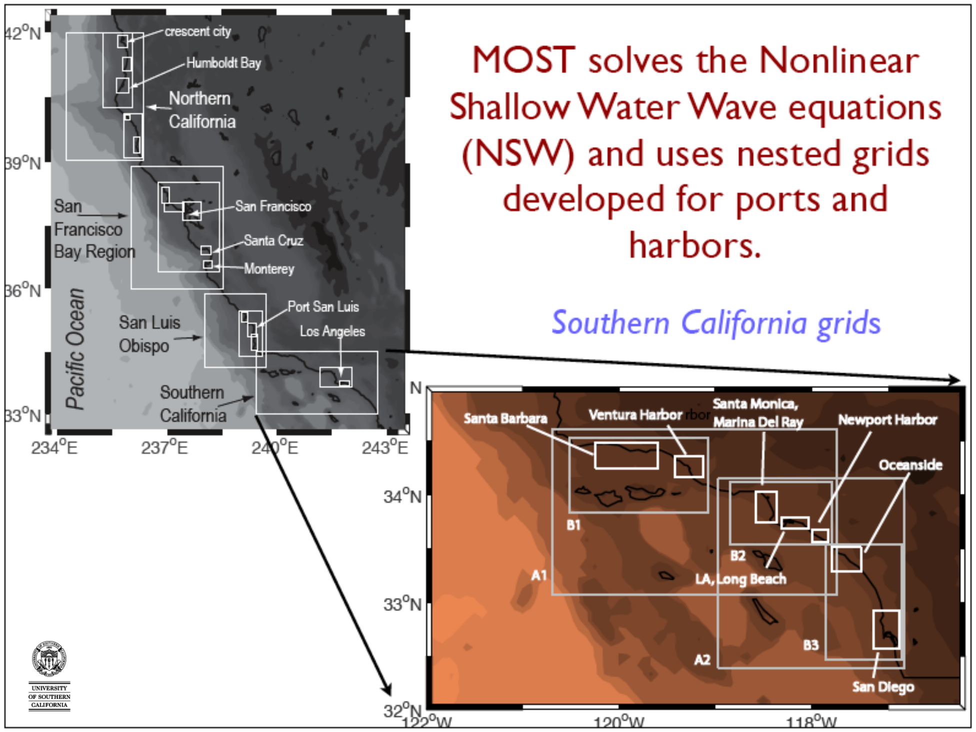
$$u_t = uu_x + vu_y + gh_x = gd_x$$

$$v_t + uv_x + vv_y + gh_y = gd_y$$

where $h = \eta(x, y, t) + d(x, y, t)$; $\eta(x, y, t)$ = wave amplitude; $d(x, y, t)$ = undisturbed water depth; $u(x, y, t)$ and $v(x, y, t)$ = depth-averaged velocities in the onshore $x$ and long-shore $y$ directions, respectively; and $g$ = acceleration of gravity.

# MOST solves the Nonlinear Shallow Water Wave equations (NSW) and uses nested grids developed for ports and harbors.

*Southern California grids*



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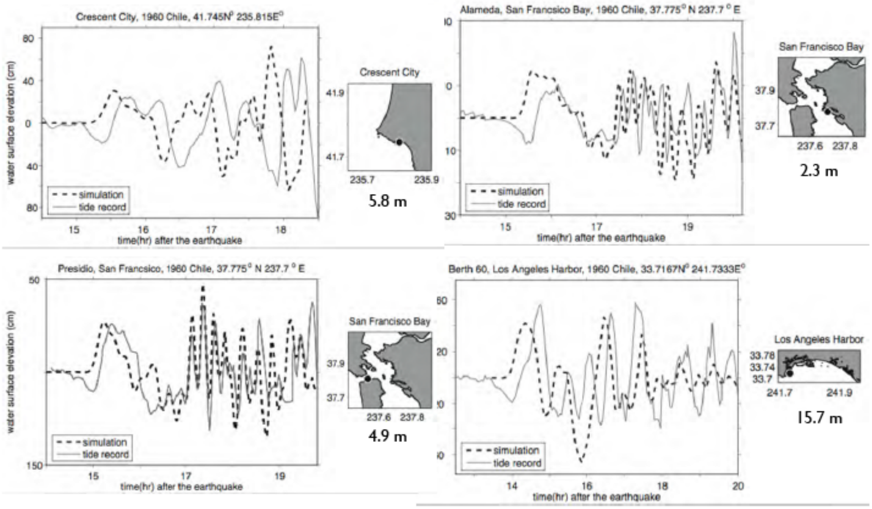
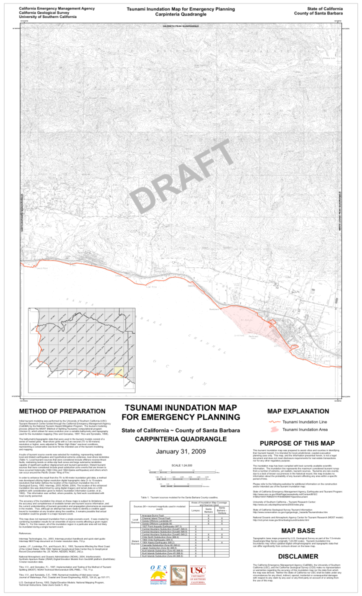
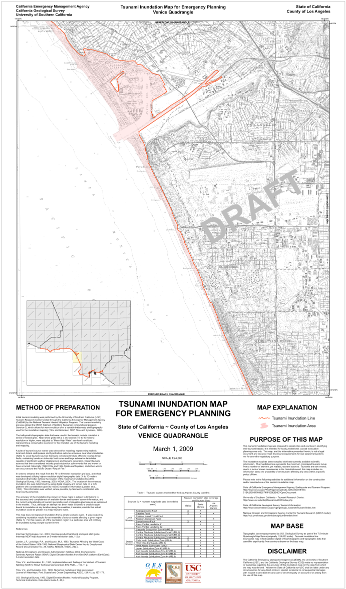
# Comparison of tide gage records of 1960 event with MOST predictions based on combinations of 20 farfield unit sources.



# Examples of two inundation maps for Carpinteria and Venice





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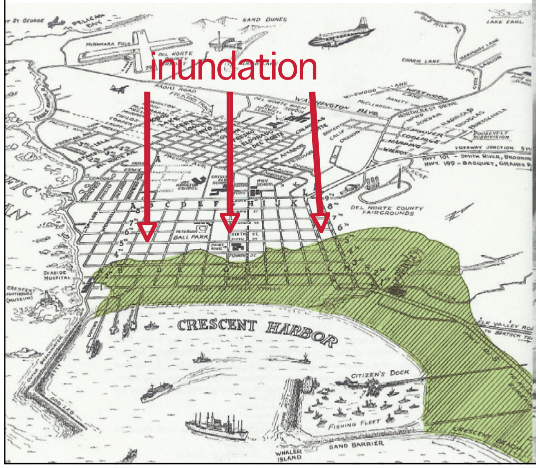
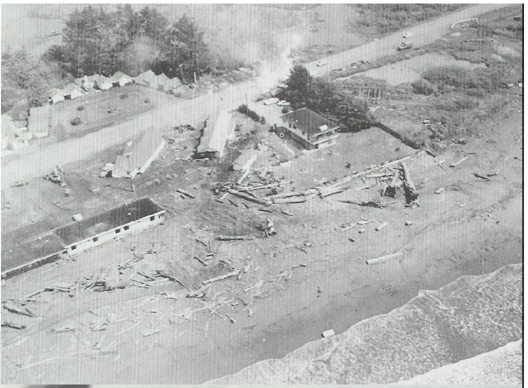
Damage in Crescent City from 1964 Alaska earthquake.

Pictures and diagrams from Wallace Griffin (1984).





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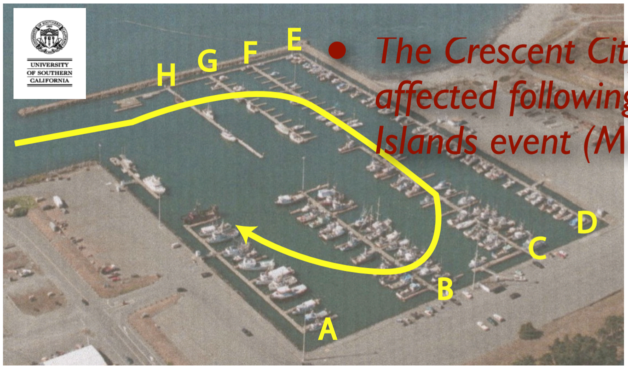
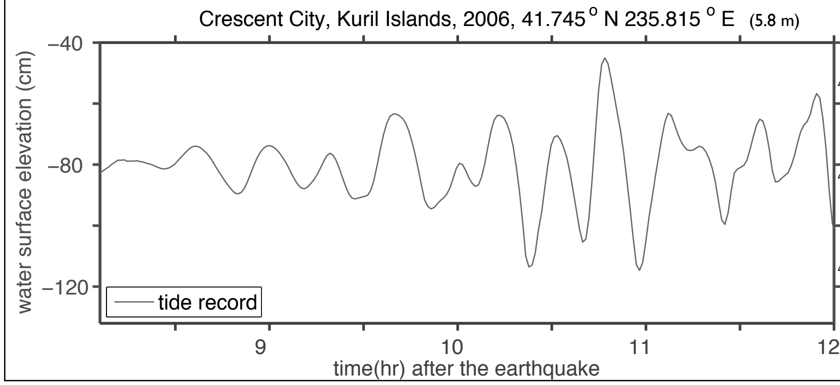
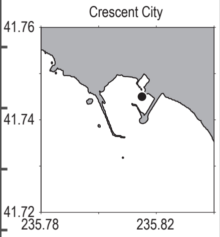
- *The Crescent City marina was severely affected following the 15 Nov 2006 Kuril Islands event ($M_w$~8.3)*

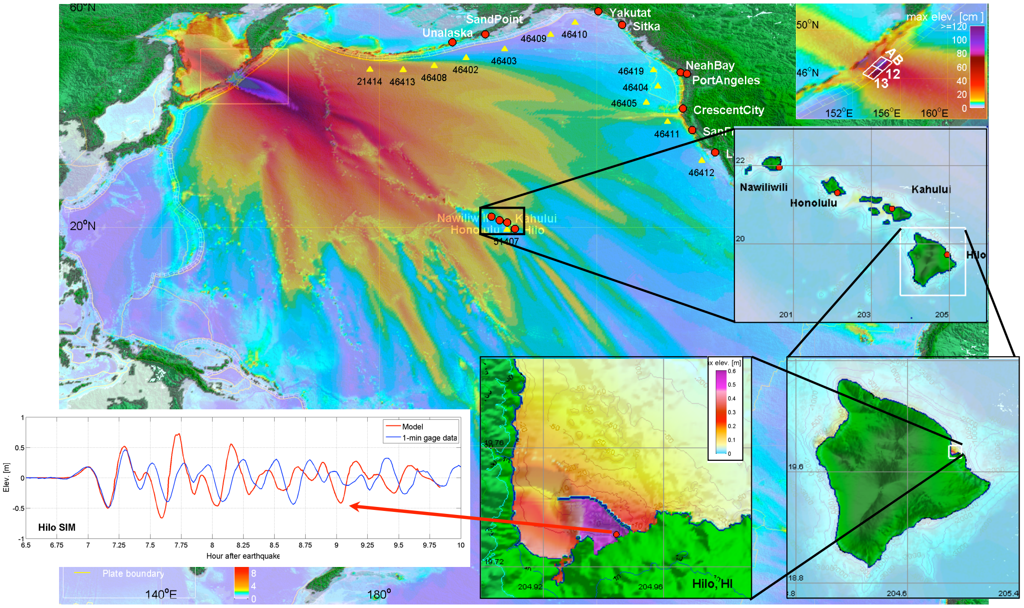


Dock H failed initially. Boats carried pieces of Dock H and crashed into Dock G and F.

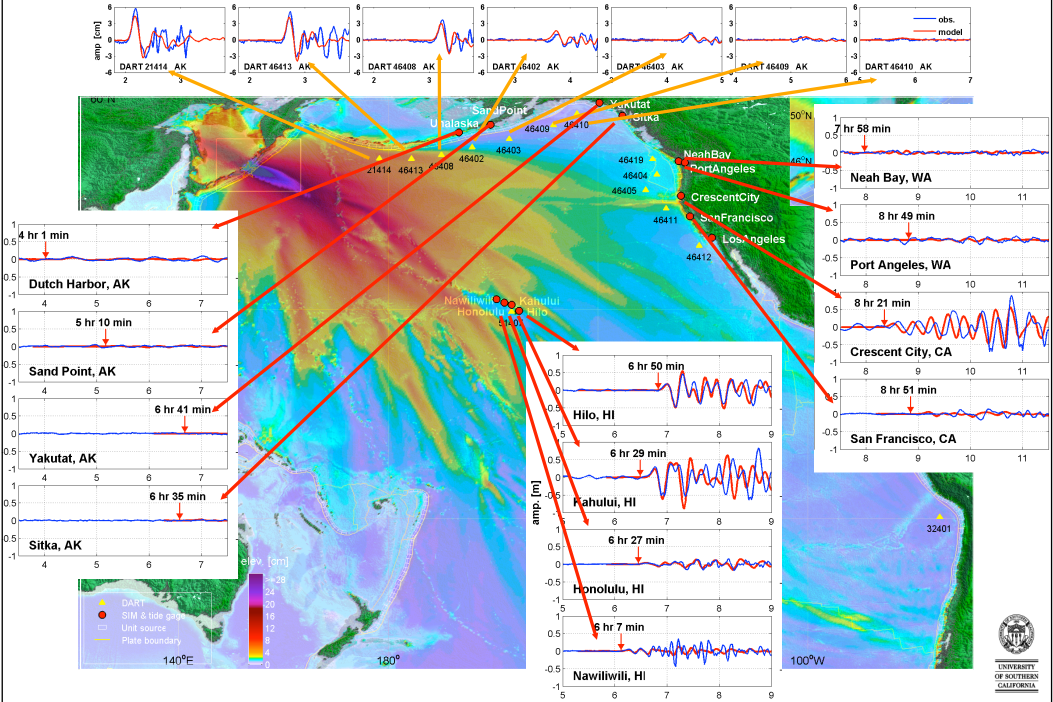




# The 15 Nov 2006 Central Kuril Tsunami



# The Nov. 15, 2006 Kuril Is. Tsunami -- forecast modeling



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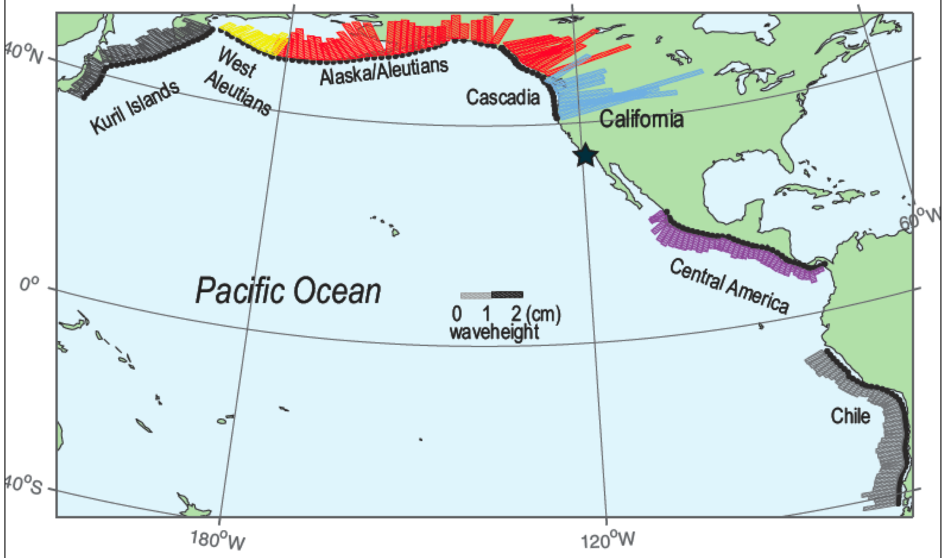

Which source produces the highest tsunami wave off San Francisco ?

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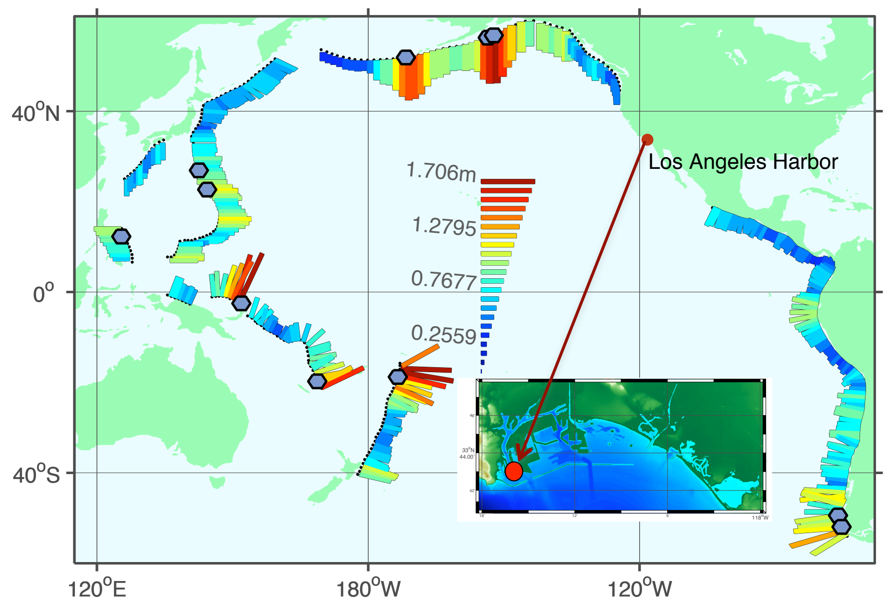
322 tsunami scenarios are computed at the tide gauge in Los Angeles Harbor from Mw 9.3 earthquakes with 1000km x 100km and 30m slip on Pacific Rim Subduction zones *(Alaska-Aleutians*, *Kuril Islands*, *Chile* and *Central America).*



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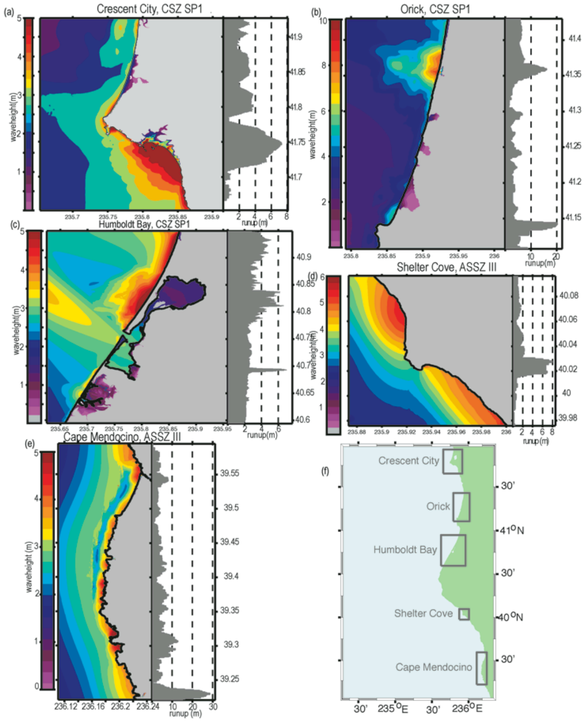
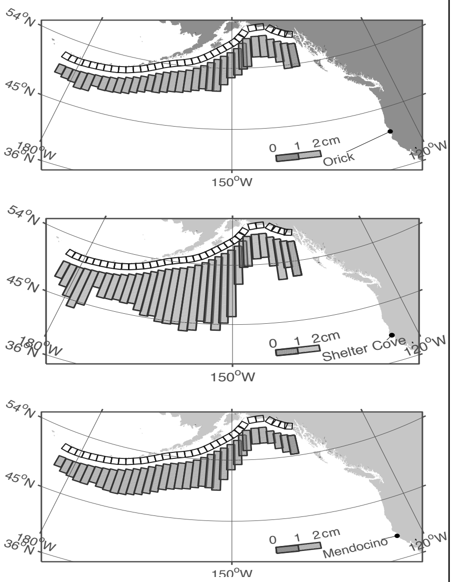
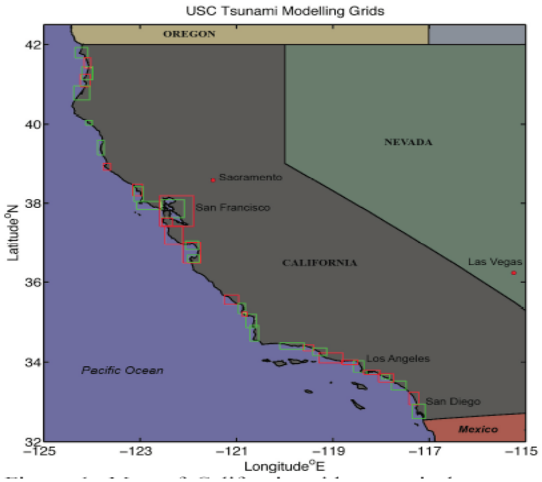

(a)
Crescent City, CSZ SP1
waveheight(m)
runup (m)
(b)
Orick, CSZ SP1
waveheight(m)
runup(m)
(c)
Humboldt Bay, CSZ SP1
waveheight(m)
runup(m)
(d)
Shelter Cove, ASSZ III
waveheight(m)
runup(m)
(e)
Cape Mendocino, ASSZ III
waveheight (m)
runup (m)
(f)
Crescent City
Orick
Humboldt Bay
Shelter Cove
Cape Mendocino
30'
41°N
30'
40°N
30'
30'
235°E
30'
236°E


54°N
45°N
36°N
180°W
150°W
120°W
0 1 2 cm
Orick
Shelter Cove
Mendocino

# Distribution of inundation grids across California

- 35 numerical grids used
- 20 counties covered
- 90 and 30 m resolution used
- 12 distant sources used
- 23 Local Sources
- 16 Local earthquake sources
- 7 landslide sources
- 130 maps produced (USGS quadrangle format)



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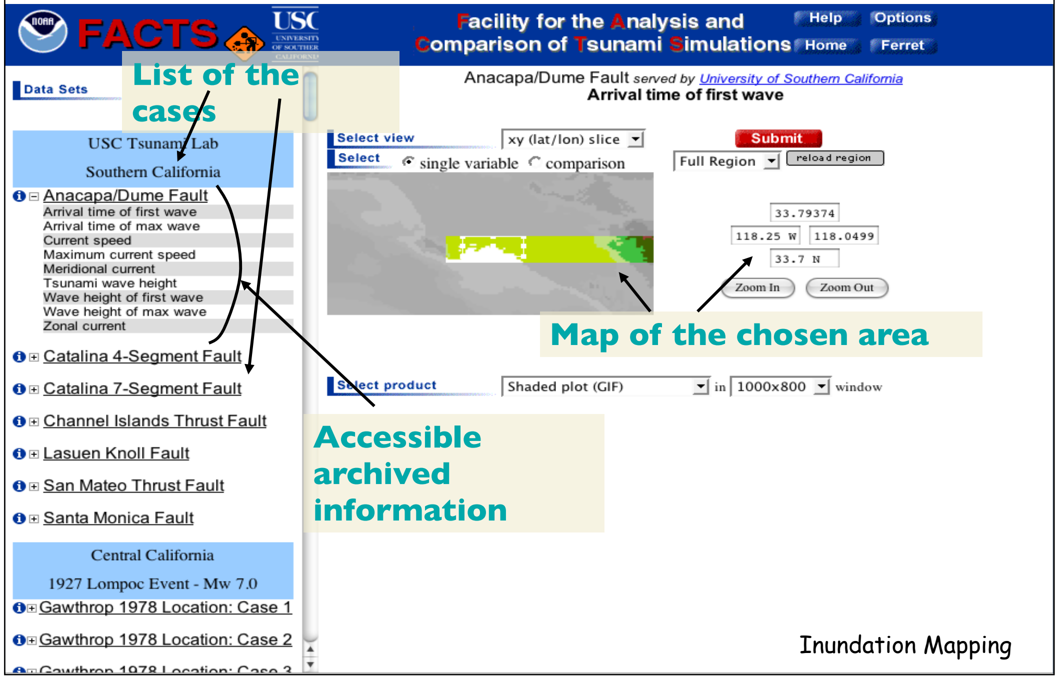
Several grids have been developed for the various ports, harbors and locations of interest and earthquake scenarios. The numerical grids are derived from 3-second (90m) combined topographic/bathymetric data. In later slides we show results that demonstrate results of various simulations of scenario earthquake generated tsunamis.

# Results archived in USC-FACTS Server



Facility for the Analysis and Comparison of Tsunami Simulations

Anacapa/Dume Fault *served by* University of Southern California

**Arrival time of first wave**

Select view: xy (lat/lon) slice

Select: ● single variable ○ comparison

Full Region

33.79374
118.25 W
118.0499
33.7 N

Select product: Shaded plot (GIF) in 1000x800 window

USC Tsunami Lab

Southern California

- Anacapa/Dume Fault
  - Arrival time of first wave
  - Arrival time of max wave
  - Current speed
  - Maximum current speed
  - Meridional current
  - Tsunami wave height
  - Wave height of first wave
  - Wave height of max wave
  - Zonal current
- Catalina 4-Segment Fault
- Catalina 7-Segment Fault
- Channel Islands Thrust Fault
- Lasuen Knoll Fault
- San Mateo Thrust Fault
- Santa Monica Fault

Central California

1927 Lompoc Event - Mw 7.0

- Gawthrop 1978 Location: Case 1
- Gawthrop 1978 Location: Case 2

**List of the cases**

**Map of the chosen area**

**Accessible archived information**

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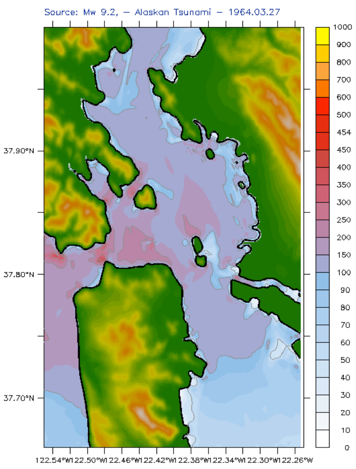
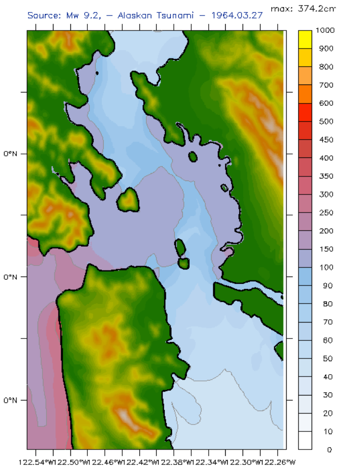
# Example of archiving The 1964 Alaska Tsunami in the USC-FACTS server

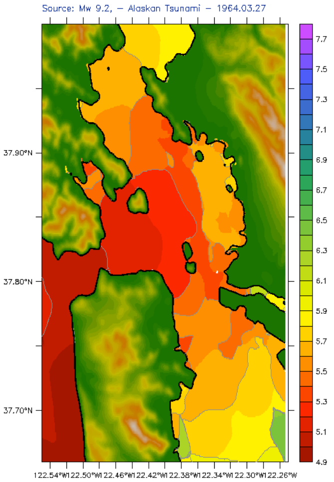
Maximum current speed (cm/s)


Source: Mw 9.2, – Alaskan Tsunami – 1964.03.27

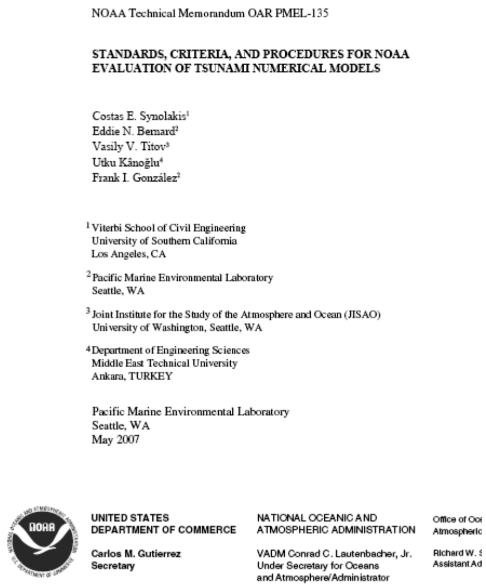
Maximum wave height (cm)


Source: Mw 9.2, – Alaskan Tsunami – 1964.03.27
max: 374.2cm

Tsunami arrival time (hr)


Source: Mw 9.2, – Alaskan Tsunami – 1964.03.27

# *Tsunami modeling is not just one of your everyday holiday games.*



NOAA Technical Memorandum OAR PMEL-135

**STANDARDS, CRITERIA, AND PROCEDURES FOR NOAA EVALUATION OF TSUNAMI NUMERICAL MODELS**

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May 2007

**UNITED STATES DEPARTMENT OF COMMERCE**

**Carlos M. Gutierrez**
**Secretary**

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

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**Pure and Applied Geophysics**

## Validation and Verification of Tsunami Numerical Models

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*Abstract*—In the aftermath of the 26 December, 2004 tsunami, several quantitative predictions of inundation for historic events were presented at international meetings differing substantially from the corresponding well-established paleotsunami measurements. These significant differences attracted press attention, reducing the credibility of all inundation modeling efforts. Without exception, the predictions were made using models that had not been benchmarked. Since an increasing number of nations are now developing tsunami mitigation plans, it is essential that all numerical models used in emergency planning be subjected to validation—the process of ensuring that the model accurately solves the parent equations of motion—and verification—the process of ensuring that the model represents geophysical reality. Here, we discuss analytical, laboratory, and field benchmark tests with which tsunami numerical models can be validated and verified. This is a continuous process; even *proven* models must be subjected to additional testing as new knowledge and data are acquired. To date, only a few existing numerical models have met current standards, and these models remain the only choice for use for real-world forecasts, whether short-term or long-term. Short-term forecasts involve data assimilation to improve forecast system robustness and this requires additional benchmarks, also discussed here. This painstaking process may appear onerous, but it is the only defensible methodology when human lives are at stake. Model standards and procedures as described here have been adopted for implementation in the U.S. tsunami forecasting system under development by the National Oceanic and Atmospheric Administration, they are being adopted by the Nuclear Regulatory Commission of the U.S. and by the appropriate subcommittees of the Intergovernmental Oceanographic Commission of UNESCO.

**Key words:** Tsunami, benchmarked tsunami numerical models, validated and verified tsunami numerical models.

### *1. Introduction*

Following the Indian Ocean tsunami of 26 December, 2004, there has been substantial interest in developing tsunami mitigation plans for tsunami prone regions worldwide (Synolakis and Bernard, 2006). While UNESCO has been attempting to coordinate capacity building in tsunami hazards reduction around the world, several national agencies have been making exceptional progress towards being tsunami-ready.

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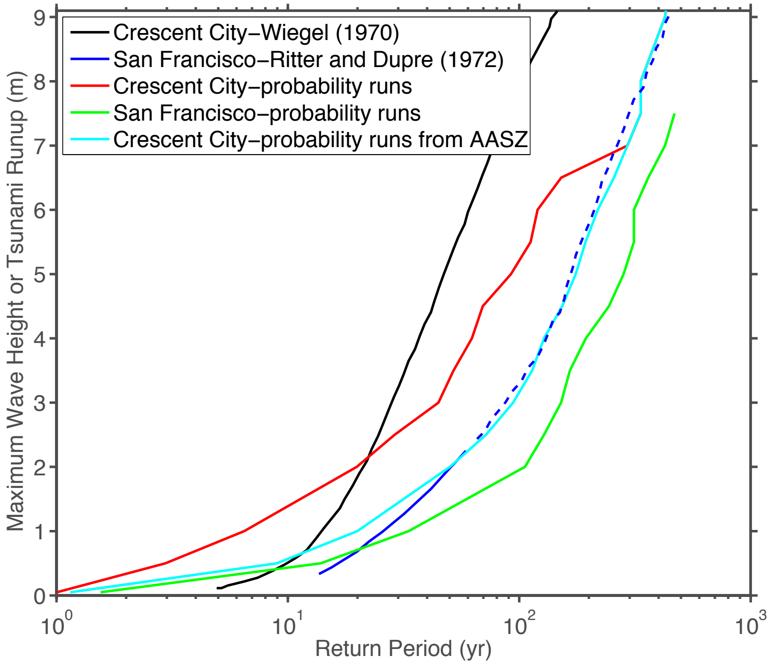
*NOAA Standards now adopted by the NRC and soon to be adopted internationally.*

# Probabilistic Tsunami Studies for California

- Probabilistic hazard analysis involves superposition of probabilities of exceedance of different wave heights from specific sources.
- Two methods exist for estimating probabilities - time-dependent and time-independent.
- An example of a time-independent event is rolling dice. The probability of rolling 6 is 1/6, every time.
- An example of a time-dependent event is drawing a card. The probability of drawing a spade is 1/4, only the first time. The following draw will depend on the initial draw (Stein, 2003).

# The end result compared to Wiegel's pioneering work



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# Soloviev and Go, 1969

They introduced a probabilistic frequency tsunami distribution *n (i),*

$$n(i) = \alpha \cdot 10^{-\beta i},$$

where *n* gives the frequency of a tsunami with an intensity *i,*

$$i = \log\left(\sqrt{2}H_{\mathrm{avg}}\right)$$

Soloviev and Go (1969) were motivated by a Gutenberg and Richter-type relationship,

$$\log N = \alpha - \beta M,$$

where *M* is an earthquake magnitude and *N* the number of earthquakes magnitude M.

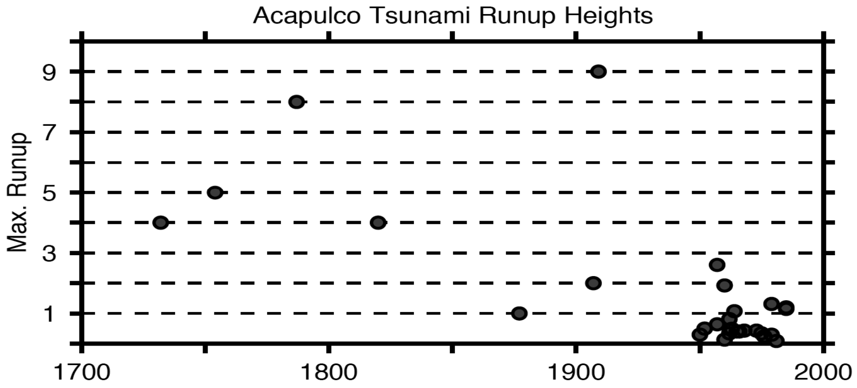
# Houston and Garcia, 1974 and Houston, 1980

They derived an exponential frequency distribution, $n(i) = \alpha e^{-\beta i}$, where $\alpha$, $\beta$ are not necessarily the same as before.

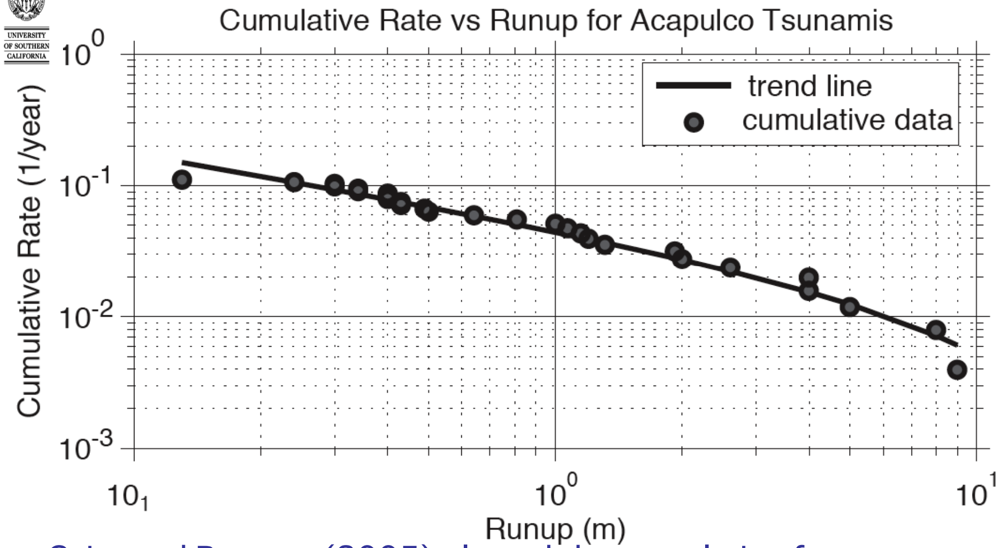
Soloviev (1970) assumed b=0.31 for all subduction zones and calculated intensity as $n(i) = \alpha 10^{-0.31i}$; whereas, Houston (1980), solution for ChSZ was $n(i) = 0.07410^{-0.63i}$ and AASZ was $n(i) = 0.113 \cdot 10^{-0.63i}$.

# Review of most recent probabilistic hazard studies.

## Acapulco, Mexico from Geist and Parsons (2005)



To get cumulative frequency-size distribution graphs, they plotted tsunami runup height data as in figure above. Runup data from 1732 to 1950 depend on visual estimates and data later than 1950 are from tide gauge records by assuming the maximum crest-though height equal to runup.



Geist and Parsons (2005) plotted the cumulative frequency-size distribution with respect to runup. *n(h)* was obtained by least square regression,

$$n_T(h) = 0.056(h^{-0.52} - 20^{-0.52}).$$

# Seaside Oregon Study cases

| source number | location | $M_w$ | $L(km)$ | $W(km)$ | disp $(m)$ | return period $(yr)$ |
|---|---|---|---|---|---|---|
| 1 | AASZ | 9.2 | 1000 | 100 | 17.7 | 1,313 |
| 2 | AASZ | 9.2 | 1100 | 100 | 18.1 | 750 |
| 3 | AASZ | 9.2 | 600 | 100 | – | 750 |
| 4 | AASZ | 9.2 | 1200 | 100 | 16.3 | 1,133 |
| 5 | AASZ | 9.2 | 1200 | 100 | 14.8 | 750 |
| 6 | AASZ | 8.2 | 300 | 100 | 2.1 | 875 |
| 7 | AASZ | 8.2 | 300 | 100 | 2.1 | 661 |
| 8 | KSZ | 8.2 | 300 | 100 | 2.1 | 661 |
| 9 | KSZ | 8.8 | 500 | 100 | 9.8 | 100 |
| 10 | KSZ | 8.8 | 600 | 100 | 9.8 | 100 |
| 11 | KSZ | 8.5 | 300 | 100 | 5.8 | 500 |
| 12 | KSZ | 8.5 | 300 | 100 | 5.8 | 500 |
| 13 | KSZ | 8.5 | 1000 | 100 | 5.8 | 500 |
| 14 | SASZ | 9.5 | 800 | 100 | 40.0 | 300 |
| 15–26 | CSZ | 9.1 | N/A | N/A | N/A | 300 |

Table 3.1: Earthquake scenarios used in the Gonzalez et al. (2006) study.

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# We use the NOAA database of unit sources to produce scenarios per Uslu (2007).

# Scenario earthquakes for probabilistic models

| case | $L(km)$ | $W(km)$ | disp $(m)$ | $mo(Nm)$ | $M_w$ |
|---|---|---|---|---|---|
| a | 100 | 100 | 1 | 3E+20 | 7.65 |
| b | 200 | 100 | 1 | 6E+20 | 7.85 |
| c | 300 | 100 | 1 | 9E+20 | 7.97 |
| d | 400 | 100 | 1 | 1.2E+21 | 8.05 |
| e | 300 | 100 | 2 | 1.8E+21 | 8.17 |
| f | 400 | 100 | 2 | 2.4E+21 | 8.25 |
| g | 500 | 100 | 2 | 3E+21 | 8.32 |
| h | 500 | 100 | 3 | 4.5E+21 | 8.44 |
| I | 600 | 100 | 4 | 7.2E+21 | 8.57 |
| j | 600 | 100 | 5 | 9E+21 | 8.64 |
| k | 700 | 100 | 6 | 1.26E+22 | 8.73 |
| l | 700 | 100 | 7 | 1.47E+22 | 8.78 |
| m | 800 | 100 | 8 | 1.92E+22 | 8.86 |
| n | 800 | 100 | 9 | 2.16E+22 | 8.89 |
| o | 800 | 100 | 10 | 2.4E+22 | 8.92 |
| p | 800 | 100 | 12 | 2.88E+22 | 8.97 |
| q | 800 | 100 | 15 | 3.6E+22 | 9.04 |
| r | 800 | 100 | 20 | 4.8E+22 | 9.12 |
| s | 1000 | 100 | 20 | 6E+22 | 9.19 |
| t | 1000 | 100 | 30 | 9E+22 | 9.30 |

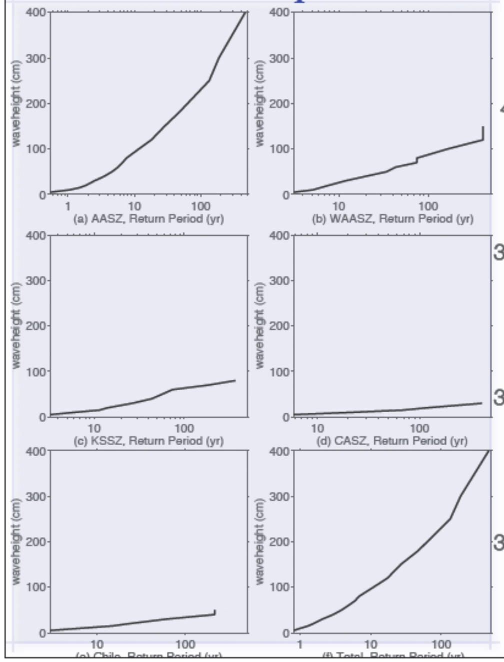
| Location | year | lat | lon | convergence rates (mm/yr) | plates |
|---|---|---|---|---|---|
| South Chile | 1960 | -39.5 | -74.5 | 70 | NZ-SA |
| Central Chile | 1922 | -28.5 | -70 | 70 | NZ-SA |
| North Chile | 1877 | -20 | -70.5 | 68 | NZ-AP |
| South Peru | 1868 | -18.3 | -70.6 | 67 | NZ-AP |
| North Peru | 1940 | -10.5 | -77 | 63 | NZ-SA |
| Ecuador-Colombia | 1906 | 1 | -81.5 | 55 | NZ-ND |
| Central America | 1992 | 11.2 | -87.8 | 73 | CO-NA |
| Mexico | 1932 | 19.5 | -104.25 | 30 | RI-NA |
| Cascadia | 1700 | 48 | -125 | 42 | JF-NA |
| Alaska | 1964 | 61.04 | -147.73 | 54 | PA-NA |
| East Aleutian | 1946 | 53.31 | -162.88 | 64 | PA-NA |
| West Aleutian | 1965 | 51.1 | 178.4 | 73 | PA-NA |
| Kamchatka | 1952 | 52.75 | 159.5 | 78 | PA-OK |
| Kuril Islands | 1963 | 44.8 | 149.5 | 81 | PA-OK |
| Northeast Japan | 1968 | 40.84 | 143.22 | 83 | PA-OK |
| Nankai | 1707 | 33.2 | 136.5 | 57 | PS-AM |
| Ryukyu | 1920 | 30.47 | 131.29 | 65 | PS-ON |
| Izu | 1947 | 32.54 | 141.64 | 45 | PA-PH |
| Marianas | 1929 | 24.27 | 142.66 | 27 | PA-MA |
| Loyalty-Vanuatu | 1950 | -18.25 | 167.5 | 103 | AU-NH |
| Tonga | 1865 | -20 | -173.5 | 185 | NH-CR |
| Kermadec | 1917 | -29 | -177 | 63 | AU-KE |
| New Zealand | 1931 | -39.5 | 177 | 43 | AU-KE |
| Java | 1994 | -10.5 | 112.8 | 64 | AU-SU |
| South Sumatra | 1833 | -3 | 100 | 51 | AU-SU |
| North Sumatra | 2004 | 3.3 | 95.78 | 33 | IN-BU |
| Makran | 1945 | 24.5 | 63 | 28 | AR-EU |
| Lesser Antilles | 1974 | 16.7 | -61.4 | 20 | SA-CA |

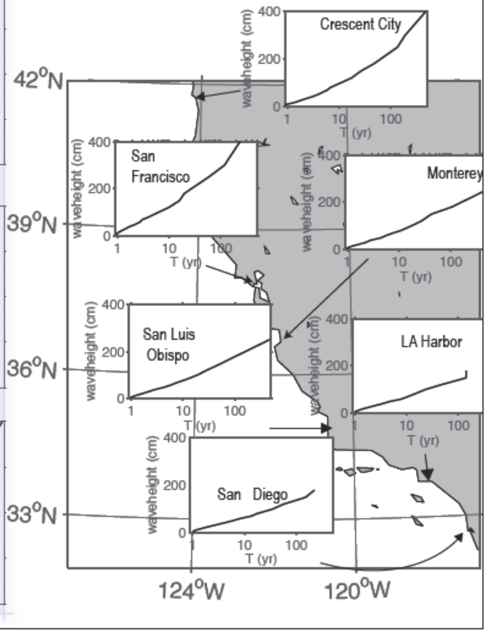
# Summary of parameters for probabilistic analysis

| subduction zones | segments | runs |
|---|---|---|
| KSZ | 31 | 519 |
| WASZ | 10 | 99 |
| AASZ | 45 | 559 |
| CASZ | 36 | 619 |
| SASZ | 45 | 799 |

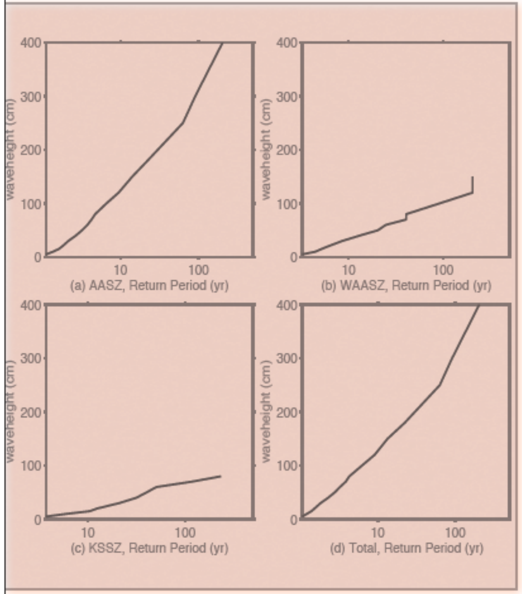
| location | Longitude | Latitude | depth |
|---|---|---|---|
| Crescent City | 234.95 | 42.02 | 422 |
| Pt. Reyes | 236.55 | 38.35 | 344 |
| San Francisco | 237.33 | 37.72 | 31 |
| Monterey | 237.02 | 37.72 | 57 |
| San Luis Obispo | 238.95 | 35.14 | 448 |
| Los Angeles | 241.88 | 33.61 | 52 |
| San Diego | 242.68 | 32.713 | 83 |

# Time Independent Probability Estimates





# Time Dependent Probability Estimates

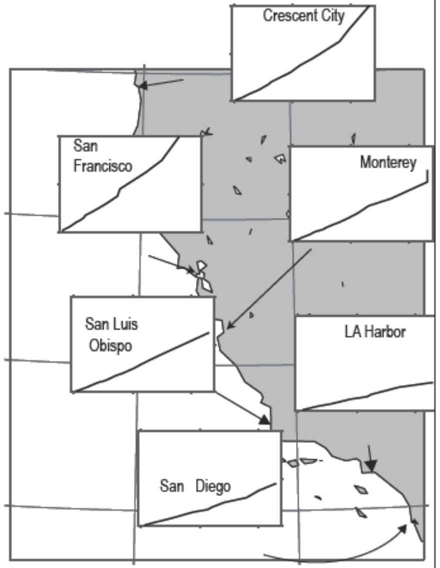


(a) AASZ, Return Period (yr)

(b) WAASZ, Return Period (yr)

(c) KSSZ, Return Period (yr)

(d) Total, Return Period (yr)



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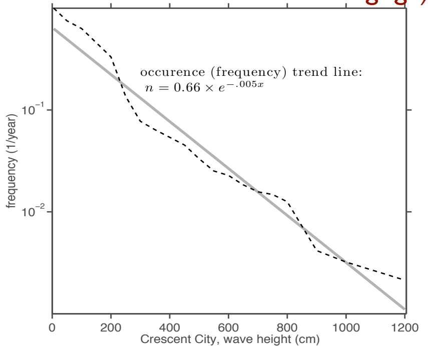
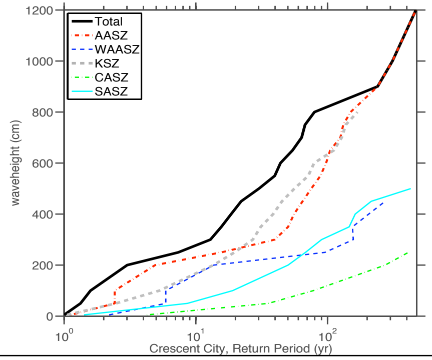
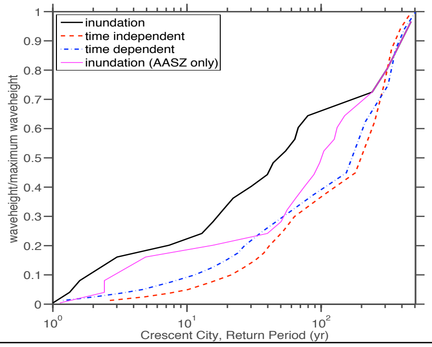
# *The future of Crescent City, California ?*

## *(Inundation estimates at the CC tide gage)*

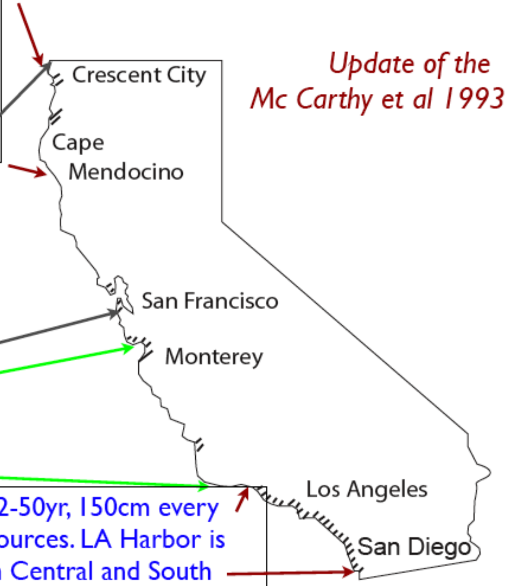






# Conclusions ?

*Update of the*
*Mc Carthy et al 1993 Map*



High risk of Tsunami inundation from CSZ sources north of Cape Mendocino and Shelter Cove (8m runup every 500 year)

High risk, frequent tsunamis (100cm every 4-10yr, 400 cm every 100-500yr) mostly from AASZ

Moderate risk, (100cm every 6-18yr, 250 cm every 60-500yr)

Low risk, (100cm every 22-50yr, 150cm every 100-150yr) from farfield sources. LA Harbor is vulnerable to waves from Central and South America. Landslide waves can result in 4-6m runup.