Simulations of the 1906 San Francisco Earthquake (M7.8+) using High Performance Computing

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Simulated Ground Shaking from the 1906 Earthquake

At 5:12 am on the morning of April 18, 1906, a 480 km segment of the San Andreas fault broke between San Juan Bautista to Cape Mendocino. The magnitude of this earthquake has been estimated to be between 7.7 – 8.3, with modern studies placing the size between 7.8-8.0 on the Ricker scale. The number of people killed due to this disaster, which occurred in what was then a relatively sparsely populated region of California, is believed to be between 700 and 3000. This event marked the birth of modern earthquake science and seismic hazard studies.

The epicenter of the 1906 event was centered offshore near Daly City. The rupture front propagated 150 km south to San Juan Bautista and 330 km north to Cape Mendocino. The slip along the San Andreas fault averaged 3.0 m, and was especially large in Marin County. Surprisingly, the close proximity of the epicenter to the Bay Area actually minimized ground shaking in the immediate vicinity of San Francisco.

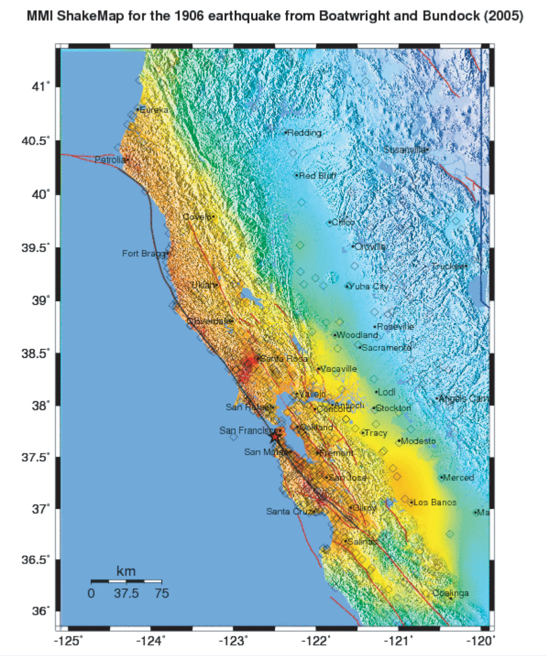
This is a collaborative effort between the U.S. Geological Survey, Stanford University, URS Corporation, the University of California at Berkeley, and LLNL. The objectives of this study are: 1) to better understand the 1906 earthquake by simulating ground motions from the 1906 event and comparing these data with observed measurements of ground shaking; 2) contrast these motions with an alternate and potentially more severe rupture scenarios along the San Andreas and other faults within the San Francisco Bay Area; 3) utilize these measurements to better understand the impact to buildings and others structures (e.g., levee reliability in the Sacramento Delta Region).

This study utilizes a 3-D geologic model of northern California recently developed at the U.S. Geologic Survey. The source term (slip and rupture mechanism along the San Andreas fault) is constrained by regional measurements of ground shaking, as well as geodetic and teleseismic data. This information is used as input into seismic wave propagation codes. In this case, we used E3D and CODE3 (a new community-based wave propagation code developed at a number of institutions). The effects of surface topography, attenuation, and water are incorporated into the model. Seismic frequencies up to 1 hz are well modeled.

This effort was not funded by the Laboratory (nights and weekends). However, we thank Livermore Computing and the Japanese government for graciously providing computer time to perform the simulations.

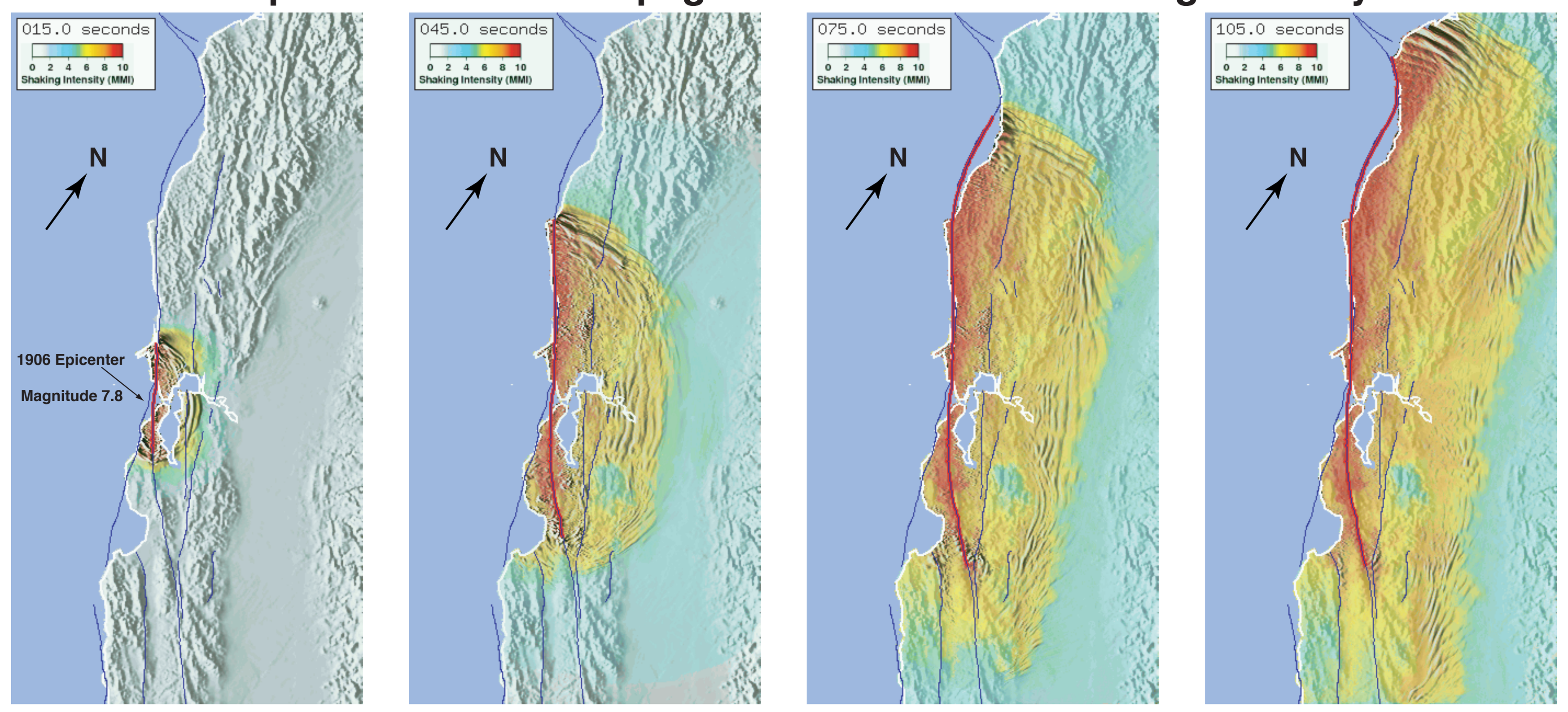
Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

Observed Ground Shaking and Intensity Pattern from 1906 Earthquake



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Snapshots of Wave Propagation and Ground Shaking Intensity

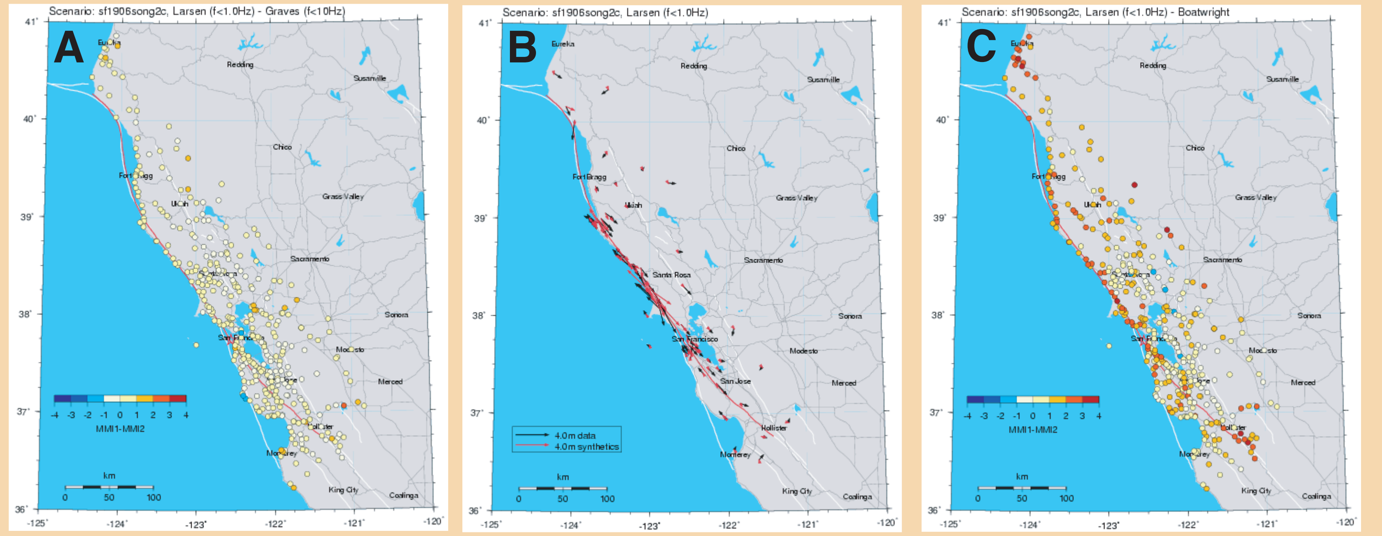


Validation

The simulations are validated by comparing results obtained by different modeling teams, and by comparing the simulated displacement and ground shaking data with that observed for the 1906 event.

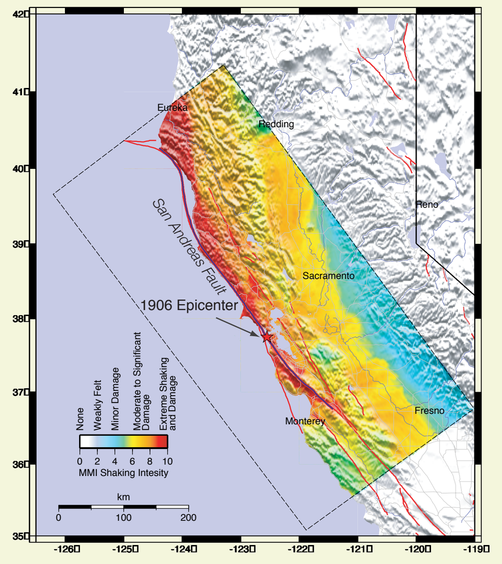
A) Result Comparison Between Modeling Teams
B) Observed vs Simulated Geodetic Displacement
C) Observed vs Simulated Shaking Intensity

Excellent agreement is observed when comparing results between modeling teams (A). In this case, a comparison is made between the ground shaking intensities obtained here and those obtained by Robert Graves at URS Corporation who incorporates high frequency data. Good agreement is obtained between the simulated and observed geodetic displacements (B). Discrepancies may be caused by a number of factors, including non-seismic strain, measurement error, and model error. Good agreement is obtained between simulated and observed ground intensity (C), although some differences are observed close to the fault rupture. Discrepancies may be caused by poorly modeled rupture parameters, near surface geologic conditions, and poorly constrained mappings between observed intensity and computed ground motion.



Scenario Earthquakes on the San Andreas, Rogers Creek, And Hayward Faults

San Francisco 1906 Magnitude 7.8



The capabilities used to simulate the 1906 San Francisco earthquake can be used to estimate ground motions for scenario earthquakes in northern California and the San Francisco Bay Area. This is important due of the high probability of a large earthquake occurring sometime during the next 30 years.

Earthquake Probabilities 2003-2032 (M >= 6.7 event) WG02

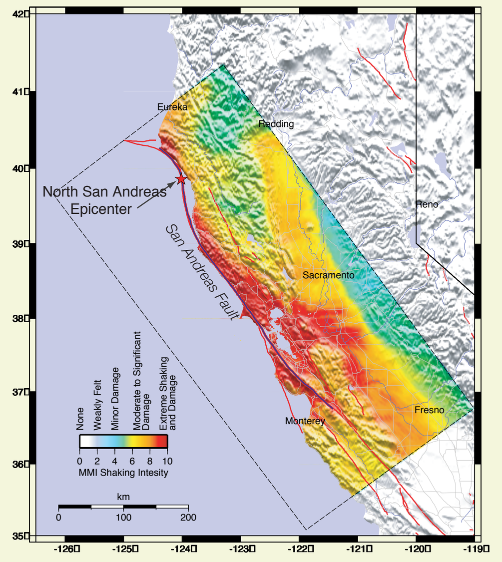
San Francisco Bay Area	62%
Hayward / Rogers Creek	27%
San Andreas	21%
Calaveras	11%

To date, we have performed over 20 simulations of scenario earthquakes on the Hayward, Rogers Creek, San Andreas, and other faults in the Bay Area. For each fault, we run multiple scenario simulations to investigate the impact that different fault rupture mechanisms have on ground shaking.

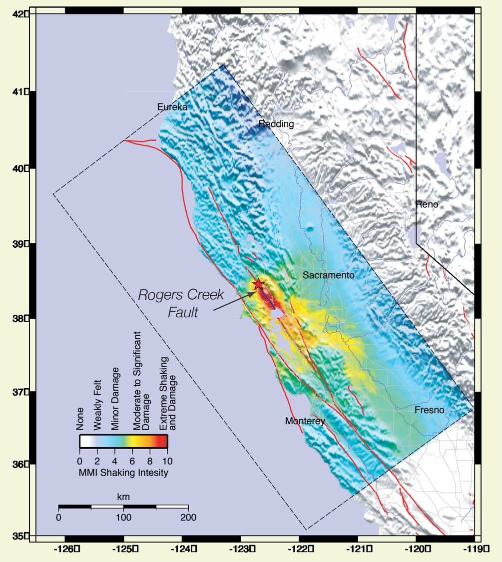
Simulations of scenario earthquakes on the Hayward (M=7.1) and Rogers Creek (M=6.8) faults illustrate that although the ground shaking distribution would not be as widespread as that for the 1906 event, the amplitudes close to the faults can be very large. In fact, the simulations suggest that the amplitude of ground shaking in the San Francisco East Bay for a large earthquake on the Hayward fault would be larger than the shaking that occurred in 1906. In addition, large ground motions can occur well out into the Central Valley and within the Sacramento Delta Region.

The 30-year probability of a magnitude 7.8 earthquake on the San Andreas fault is less than 5%. However, if such an event did occur, simulations revel that the ground motions in the San Francisco Bay Area would strongly depended on the epicentral location. For example, ground motions in the Bay Area from a M=7.8 event initiating on the northern part of the San Andreas fault would be more severe than those that occurred in 1906. The simulations suggest that extreme shaking could occur well out into the Central Valley, including the Sacramento Delta Region.

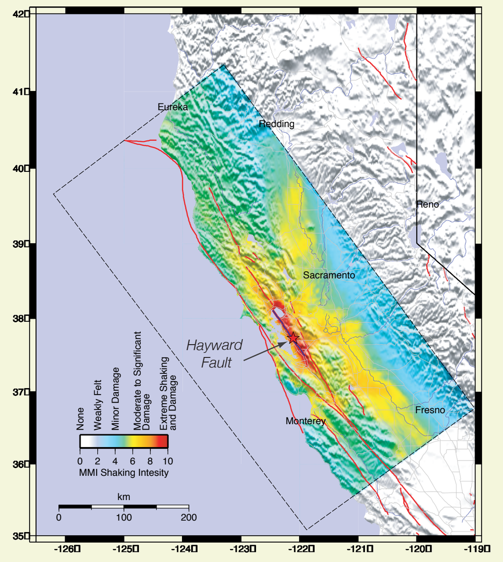
San Andreas Fault (North) Magnitude 7.8



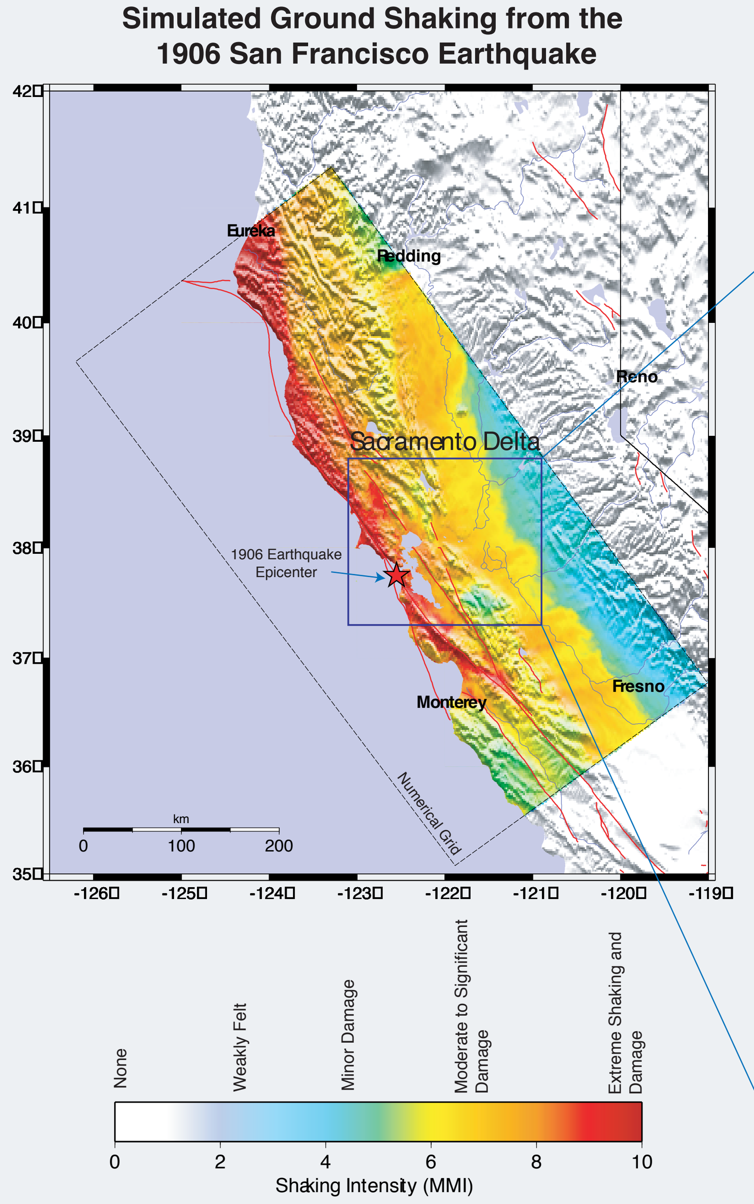
Rogers Creek Fault Magnitude 6.8



Hayward Fault Magnitude 7.1

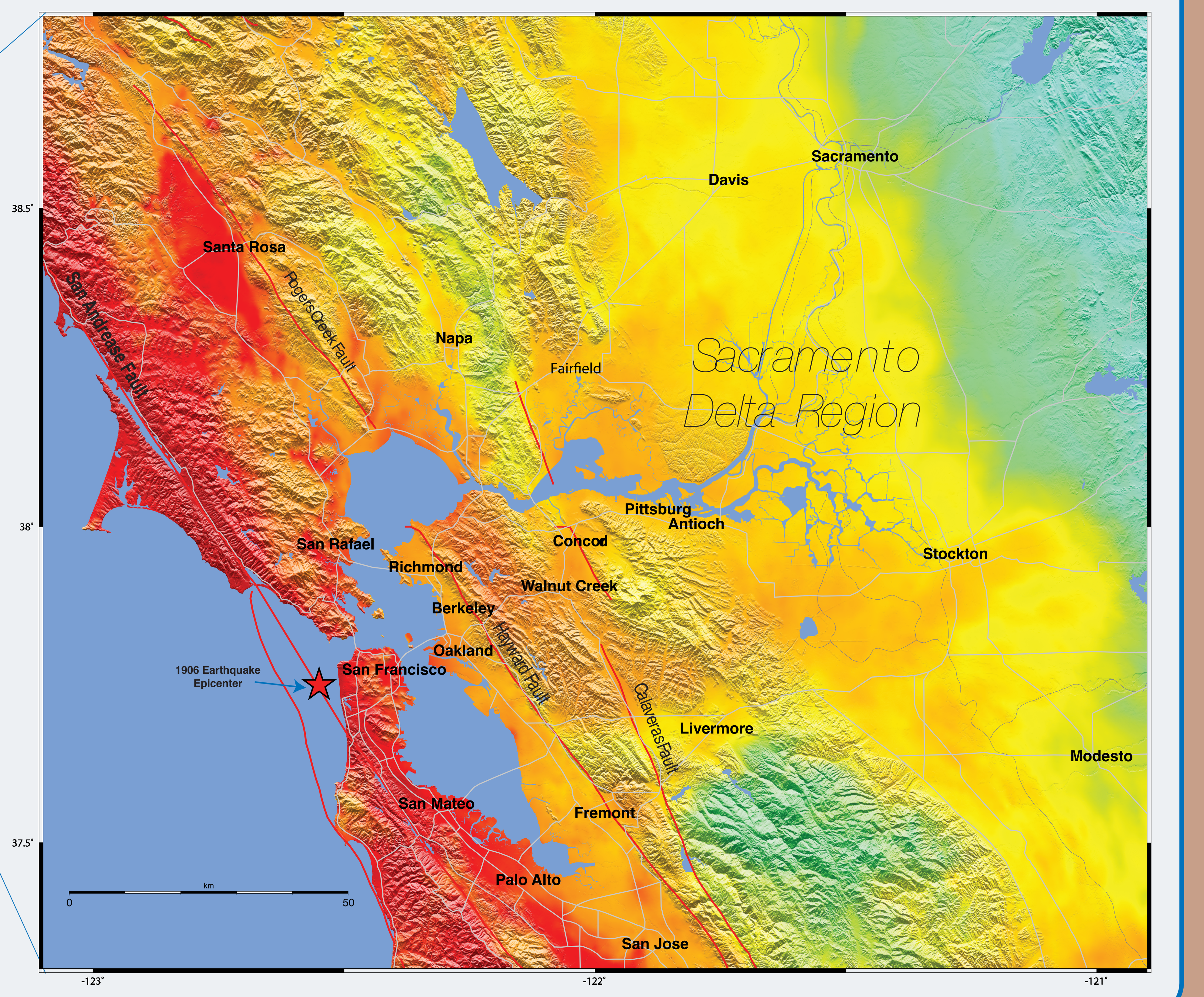


Ground Shaking Intensity in the Sacramento Delta Region



These figures show the intensity of seismic ground shaking computed from a simulation of the 1906 San Francisco Earthquake (Magnitude 7.8). Shown is the intensity of ground shaking in northern California, and specifically in the Sacramentio Delta Region. Although the Delta Region is approximately 100 km (60 miles) from the San Andreas fault and the epicenter of the 1906 event, shaking is still significant (moderate damage to well-built structures; significant damage in poorly built structures). Extreme shaking is shown to have occurred at locations within 25-50 km (15-30 miles) of the San Andreas rupture.

We are currently working with hydrologists and engineers to address levee reliability in the Sacramentio Delta Region



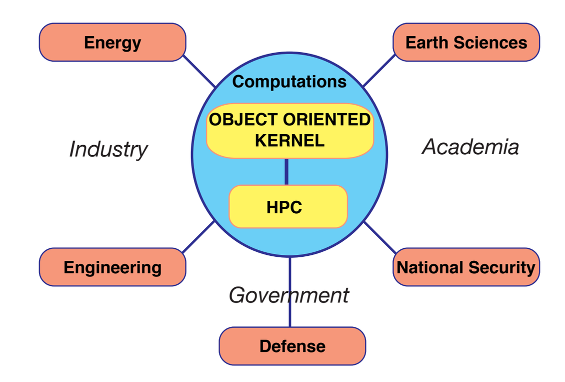
CODE3: Community-Based Open-Source Wave Propagation Package

The simulations presented here were performed with **E3D** and **CODE3 (beta)**. **CODE3** is a community-based wave propagation package available in the public domain. This tool is the result of a 4-5 year effort involving faculty, staff, students, and technical personnel at several organizations (Tokyo University, the Massachusetts Institute of Technology, Applied Data Solutions, the University of Texas, Adaptive Technology, the Univerity of Houston, IFP, the Univerity of Oregon, and others). **CODE3** provides the academic, government, and industrial communities with open-source capabilities utilizing state-of-the-art technology to address problems in earthquake hazard, oil exploration, defense applications, intelligence, environmental management, hydroacoustics, engineering, and fundamental research. **CODE3** is currently being used in a beta state by researchers at several universities and government organizations, and by scientists in the petroleum industry. **CODE3** utilizes an object oriented paradigm to provide plug-and-play modeling components.

Major Features

Full Parallelizaton and Optimization
Adaptive Gridding
Model Suite (e.g., elastic, inelastic, linear, nonlinear, EM)
Boundary Conditions (surface, reflective, Cerjan, paraxial, PML, DN, attenuative)
Topographic Boundaries
Hybridization (embedded boundaries)
Multi-model coupling (e.g., couple non-linear FE with linear FD)
Run-time Visualization

Multidiscipline-Multiorganization Utilization



High Performance Computing Simulations

The 1906 San Francisco earthquake simulations presented here utilized massively parallel computing systems at Livermore and in Japan

	Memory	Speed*	Speed**
LLNL MCR Linux Cluster (2304 CPU)	4.6 TB	11.1 TF	18%
LLNL Thunder Linux Cluster (4096 CPU)	8.2 TB	22.9 TF	23%
Japanese Earth Simulator (5129 CPU)	10.0 TB	40.0 TF	34%

*peak speed
**observed speed with E3D or CODE3 (percentage of peak for given processor set)

Blue Gene/L (131,072 CPU)	32 TB	360 TF	not used

Largest Problem Size: 21 Billion Nodes