The Next Bay Area Earthquake

How Strong? How Long? More than One?

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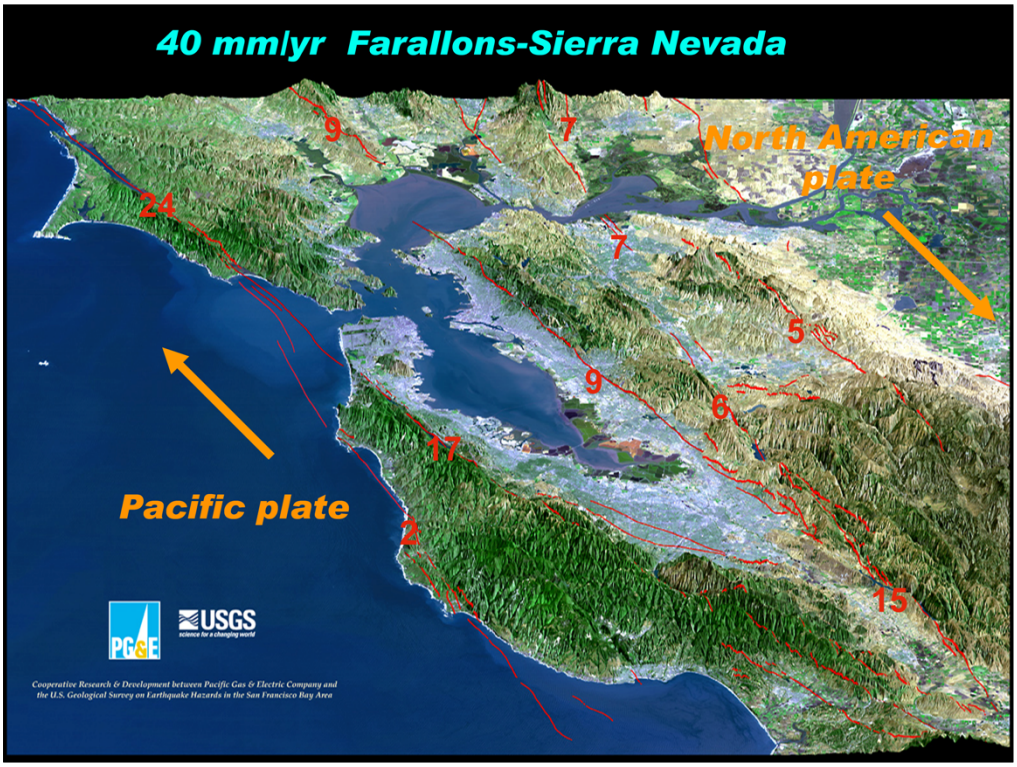
This morning I would like to describe some of the lessons we've learned about ground motion in the last ten years, and more recently about anticipating large and great earthquakes.

What have we learned from the large & great earthquakes in the last 10 years?

- The large earthquakes in California, Taiwan, China, Turkey, and Alaska have significantly improved our understanding of ground motion (PEER-NGA ground motion equations)

- The great earthquake in Tohoku, Japan should convince us that incorporating uncertainty is critical. Earthquakes routinely violate the models that we build for them.

My talk will be divided into two parts. First, what have we learned about the strong ground motions radiated by large earthquakes? In the last twelve years, we have obtained important strong motion data from the 1999 Izmit and Duzce earthquakes in Turkey, the 1999 Chi-chi earthquake in Taiwan, the 1999 Hector Mine earthquake in Southern California, the 2002 Denali Fault earthquake in Alaska, and the 2008 Sichuan earthquake in China. These records have greatly improved our models of earthquake ground motion in large and great earthquakes. Second, what does the recent M9 Tohoku earthquake tell us about anticipating large and great earthquakes? Is it a mistake to try to anticipate these earthquakes?

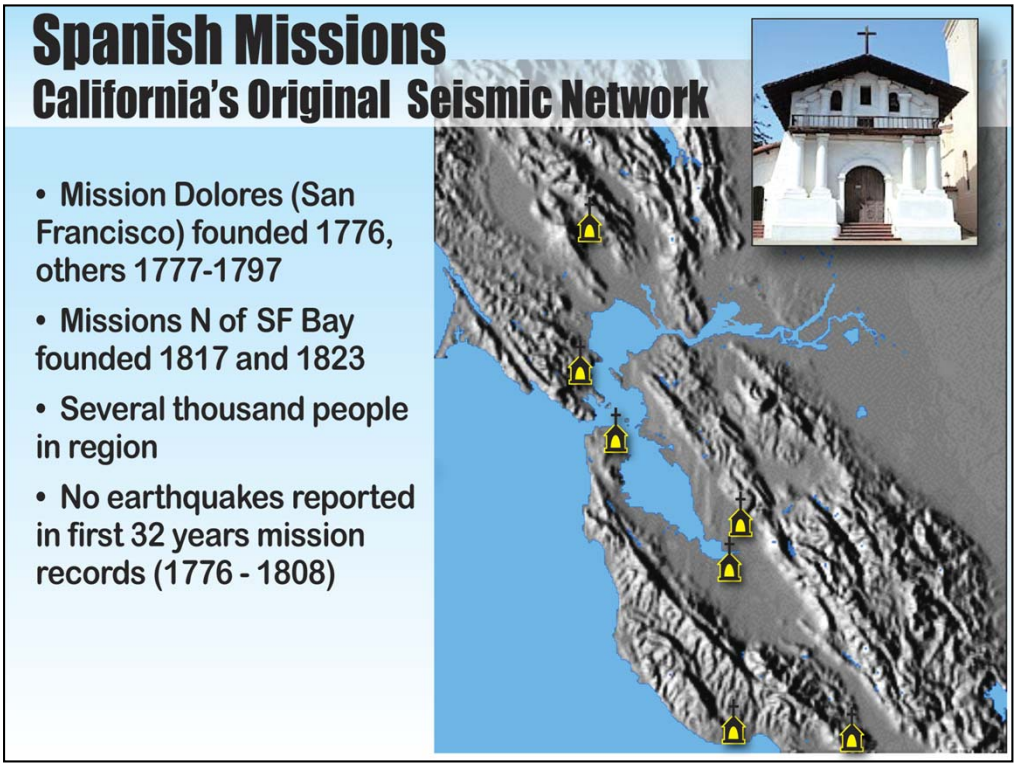


But I would like to start by summarizing what we know about large earthquakes in the Bay Area. The Bay Area is underlain by a complex web of faults. This means that the 40 mm/yr motion of the Pacific Plate past the North American Plate is spread across many faults. The San Andreas has half of the motion in the north Bay and only a third of the motion along the Peninsula. The seismic hazard does not simply lie along the San Andreas fault, but spreads across the entire Bay Area as far east as Livermore and Fairfield.

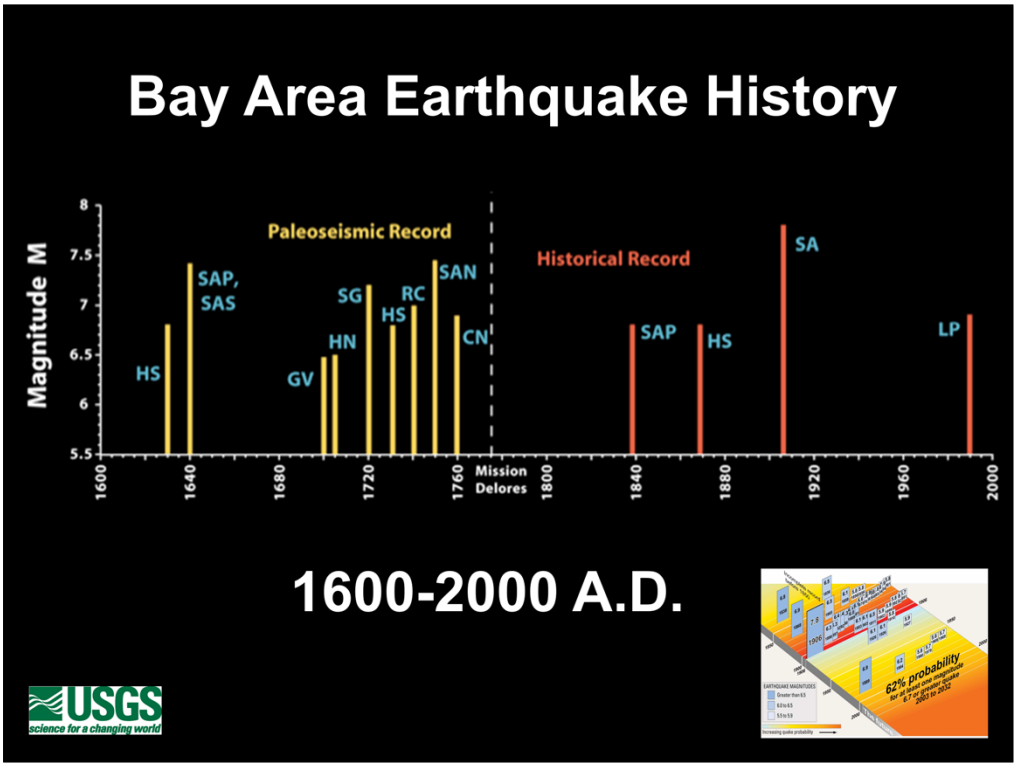
What is the History of Large Earthquakes in the Bay Area?

- 1989 Loma Prieta (M6.9)
- 1906 San Francisco (M7.8)
- 1868 Hayward (M6.8)
- 1838 Peninsula (M7?)
- 7 Paleoseismic Earthquakes (1680-1776) identified by trenching

The historic record of earthquakes in the Bay Area consists of 4 large events in 230 years. The paleoseismic record of earthquakes contains 7 large events in the century preceding the Spanish exploration and settlement.



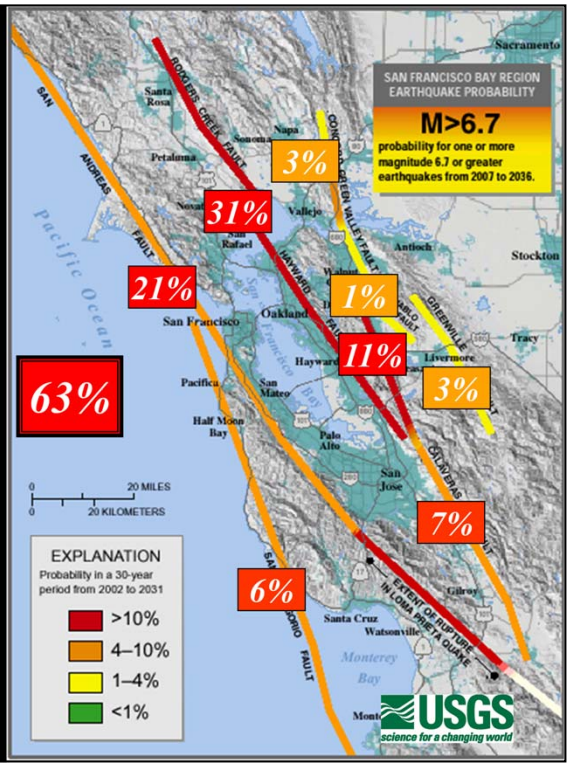
Written history in the Bay Area dates back to the founding of Mission Dolores in San Francisco, which occurred about 10 days before the Declaration of Independence was signed. Remarkably, there were no large earthquakes noted in the first 32 years of mission records.



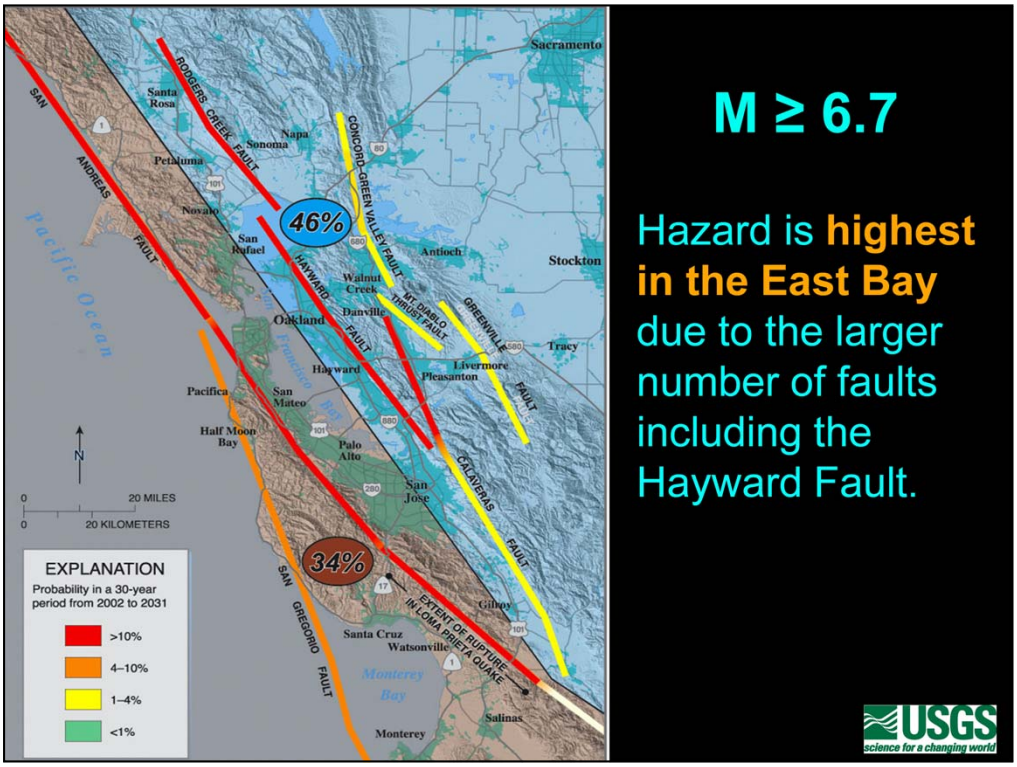
Four large earthquakes have occurred in the historic record: the 1838, 1868, 1906, and 1989. But before the Spanish arrived in Baja California, there was a century of large earthquakes that geologists have found by trenching the active faults in the Bay Area. These paleo-earthquakes are indicated by the yellow lines. Note that this is a temporally bunched but spatially diffused release of stress. The east Bay was extremely active, with an event on the Green Valley fault, an event on the northern Calaveras fault, and events on the northern and southern Hayward fault.

In the next 30 years, there is a **63%** probability, nearly a 2/3rds chance, of an **M6.7** or larger earthquake in the greater Bay Area. Hazard is **highest in the East Bay** due to the larger number of faults there, including the Hayward fault. (UCERF2 Report, 2007)

2007-2036



The USGS started making Probability Reports after the 1989 Loma Prieta earthquake. This figure shows the result for the third iteration for the Bay Area, which was published in 2007. These probabilities are derived from the slip rate and the recurrence interval on each fault segment.



Remarkably, there is more hazard in the east Bay than in the west Bay along the San Andreas, even though the total slip is larger in the west Bay.

Why do we think that the strong ground shaking will be weaker?

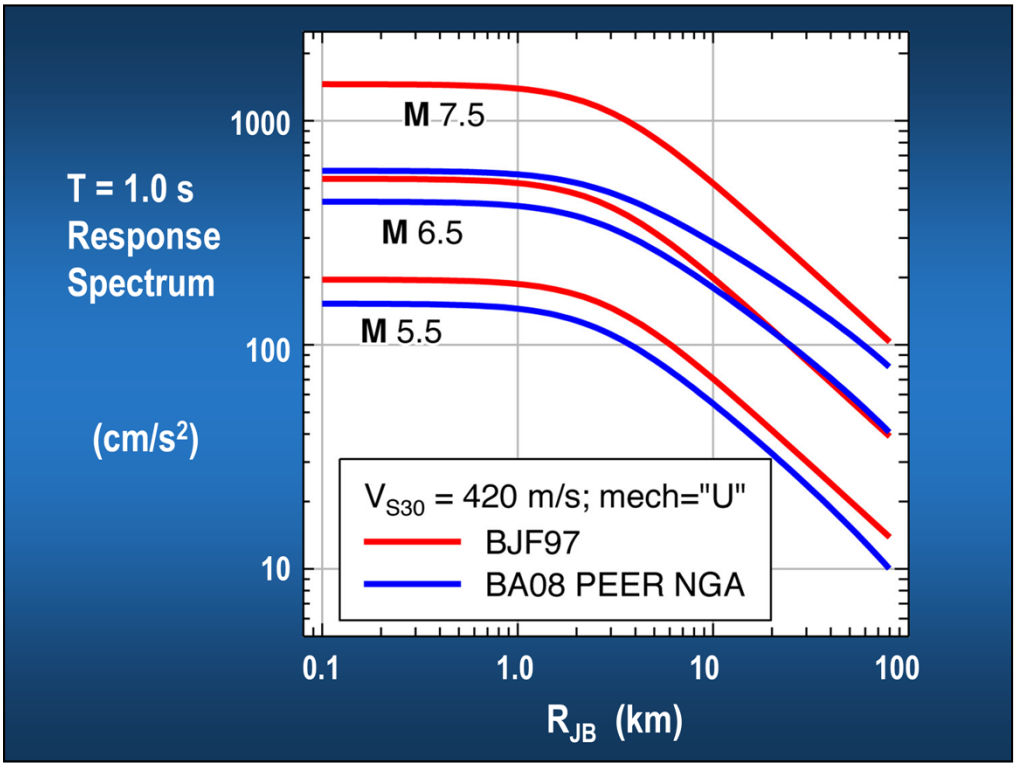
The PEER-NGA Project collected a comprehensive ground motion database

Invited 5 "Developer Teams" to regress for ground motion prediction equations

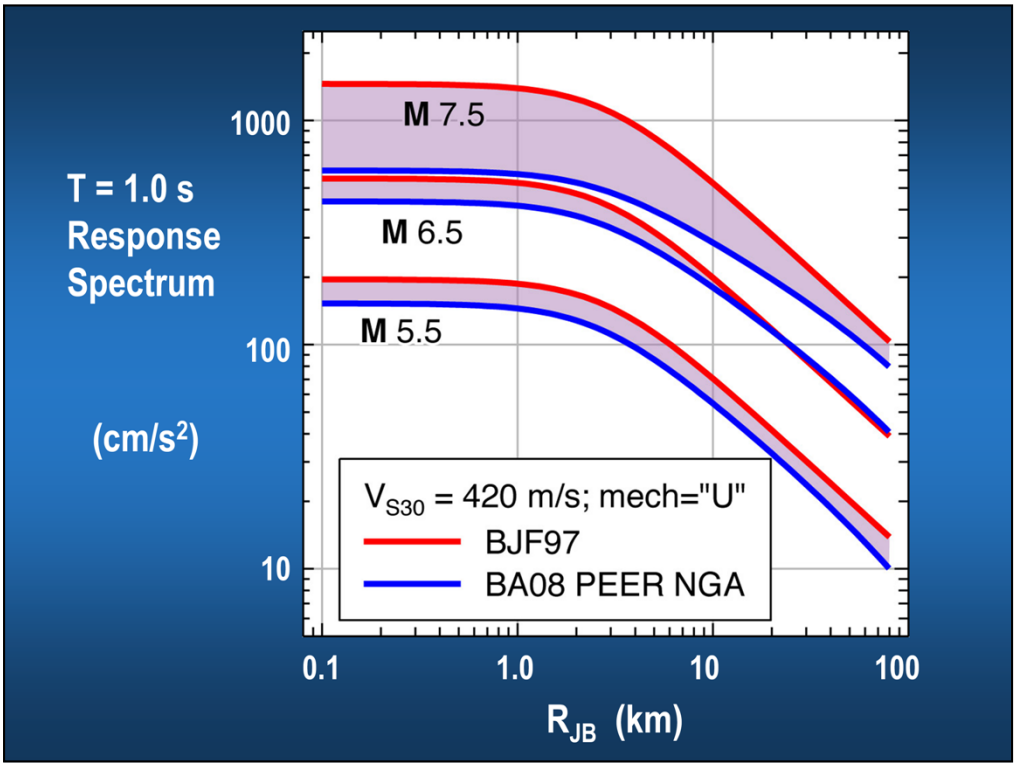
Critical Advances-

- **Data for M > 7 earthquakes**
- **Data at distances up to 200 km**
- **Saturation of ground motion for large earthquakes**

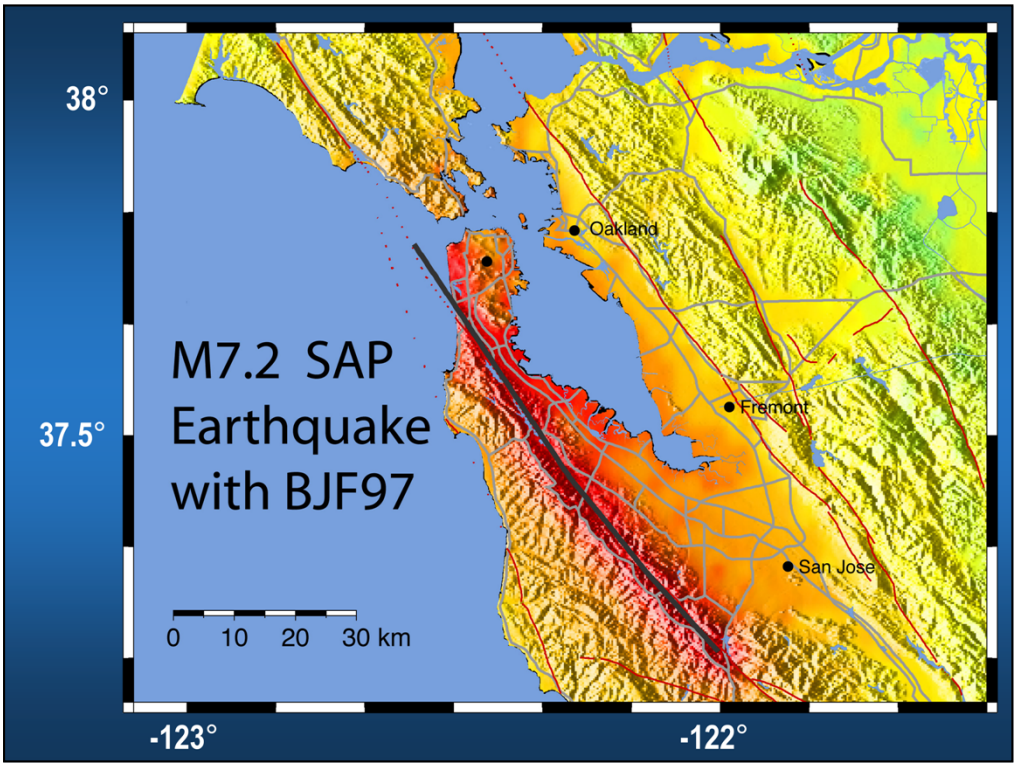
The PEER-NGA Project was begun in 2003 to try to systematize the process of regressing ground motion estimates to predict strong ground motion from large earthquakes. The first part of the project was to build a comprehensive database of recordings and earthquake models. Then five different Developer Teams regressed this data to update their ground motion prediction equations. The Developer Teams had to describe why they excluded earthquakes or recordings in the dataset from their regressions. The critical advance was derived from the inclusion of so many records from M > 7 earthquakes. The Developers were able to "see" the effect of saturation, that is, that is, as the magnitude of the earthquake increases, the ground motion near the fault increases more and more slowly.



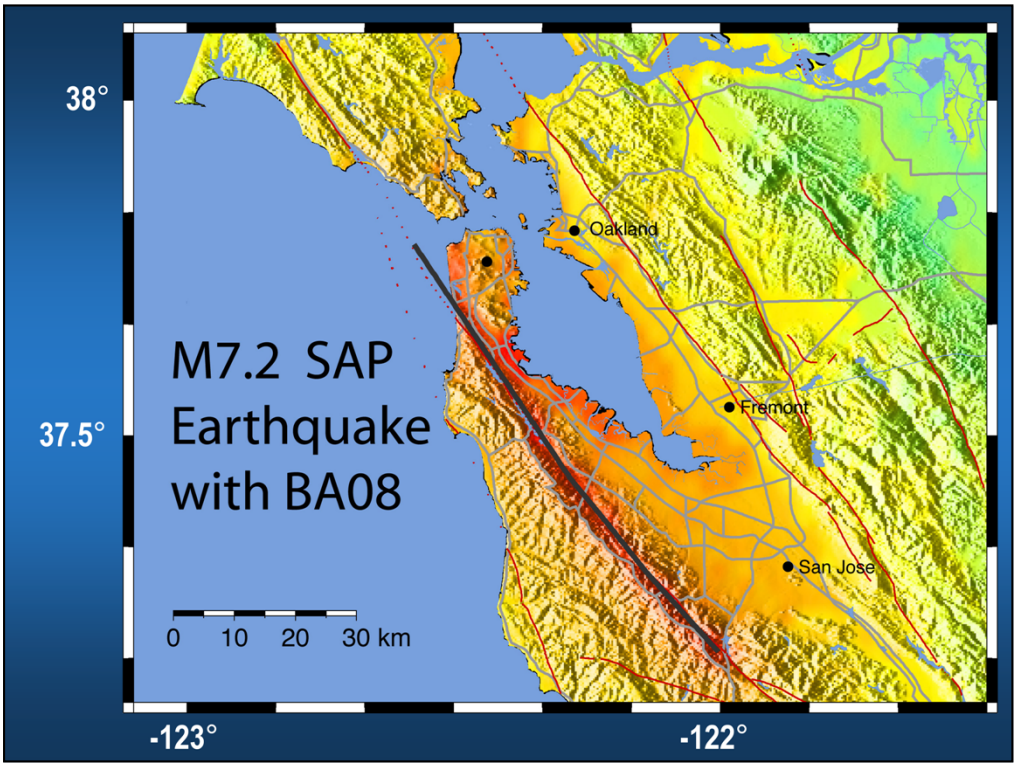
This plot shows the difference between the Boore, Joyner, and Fumal (1997) ground motion predictions (red lines) and the Boore and Atkinson (2008) predictions (blue lines) for 1 s response spectra. Note that the difference for an M 7.5 earthquake is a factor of 2.5.



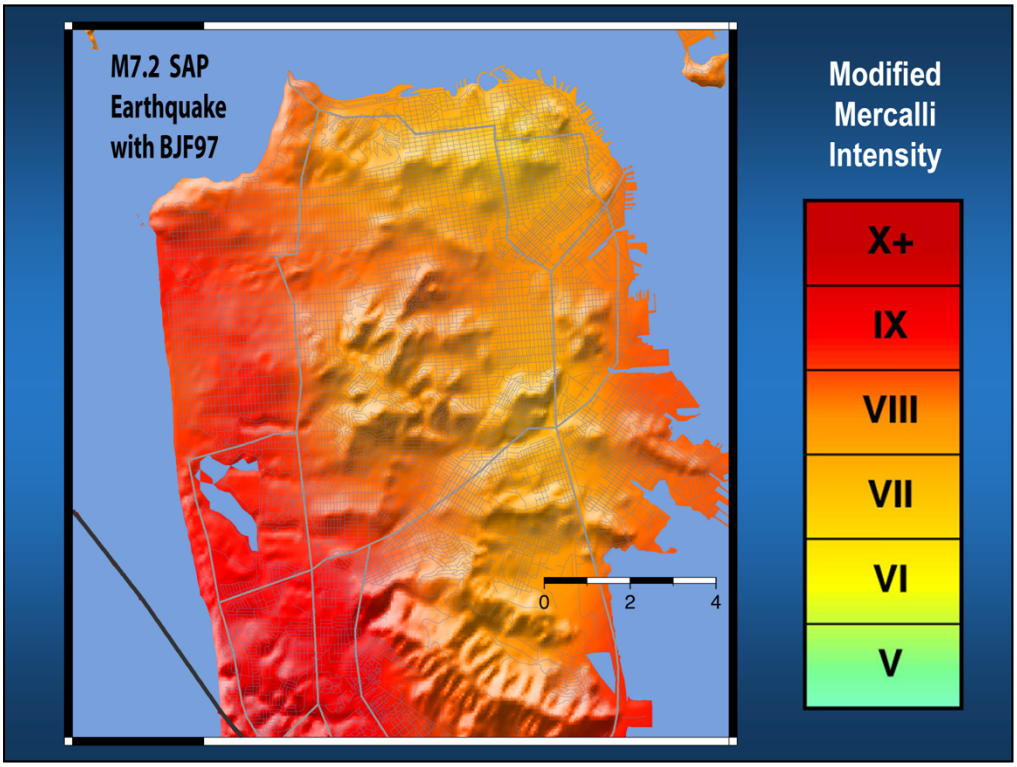
This plot just highlights the difference described earlier. It is greatest for the largest earthquake.



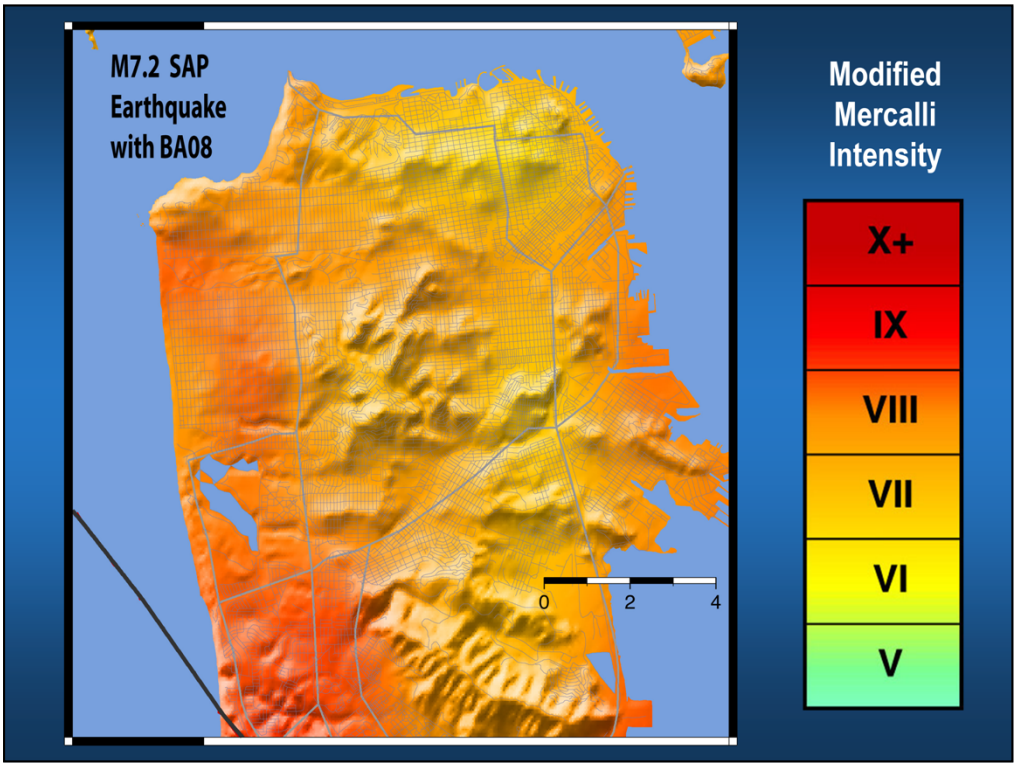
So let's see what happens when we use the new GMPE. This maps shows the ground shaking for an M7.2 scenario earthquake on the Peninsula section of the San Andreas fault. The ground motions were estimated using the Boore, Joyner, and Fumal (1997) GMPE. The scenario maps published in the ShakeMap archive are all generated using this small ground motion prediction equation and soil map.



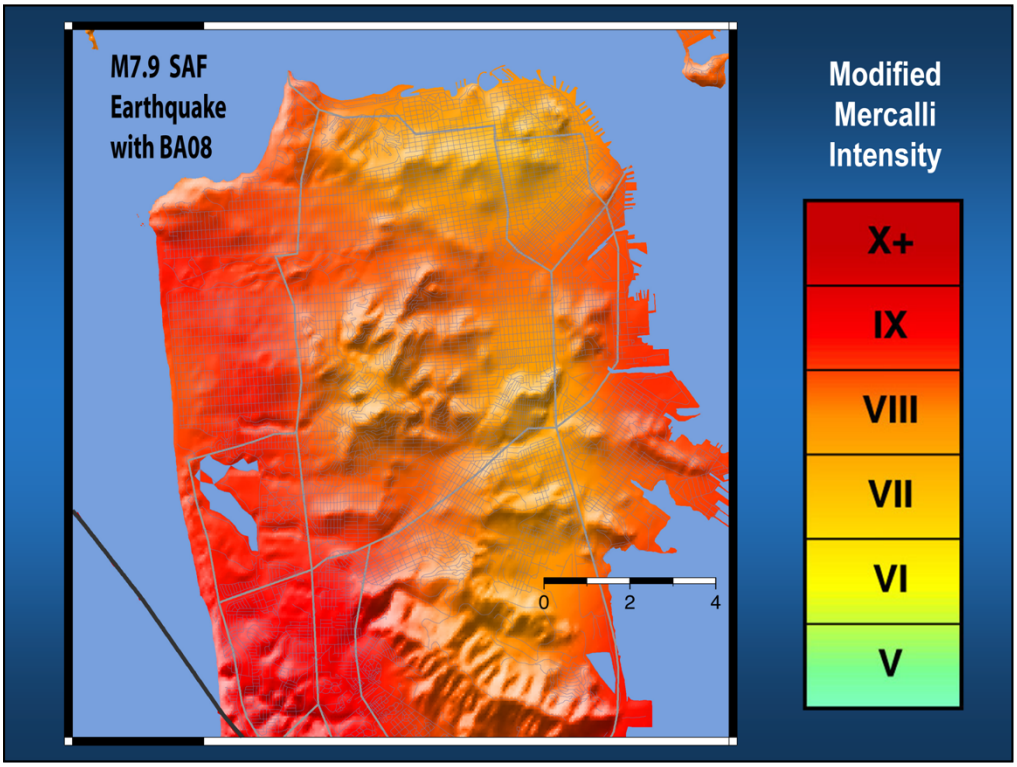
This maps shows the ground shaking for an M7.2 scenario earthquake on the Peninsula section of the San Andreas fault. These ground motions were estimated using the Boore and Atkinson (2008) GMPE, that was the update of BJF97 GMPE in the PEER-NGA Project. You can see that the shaking predicted along the fault is much less severe for the BA08 GMPE.



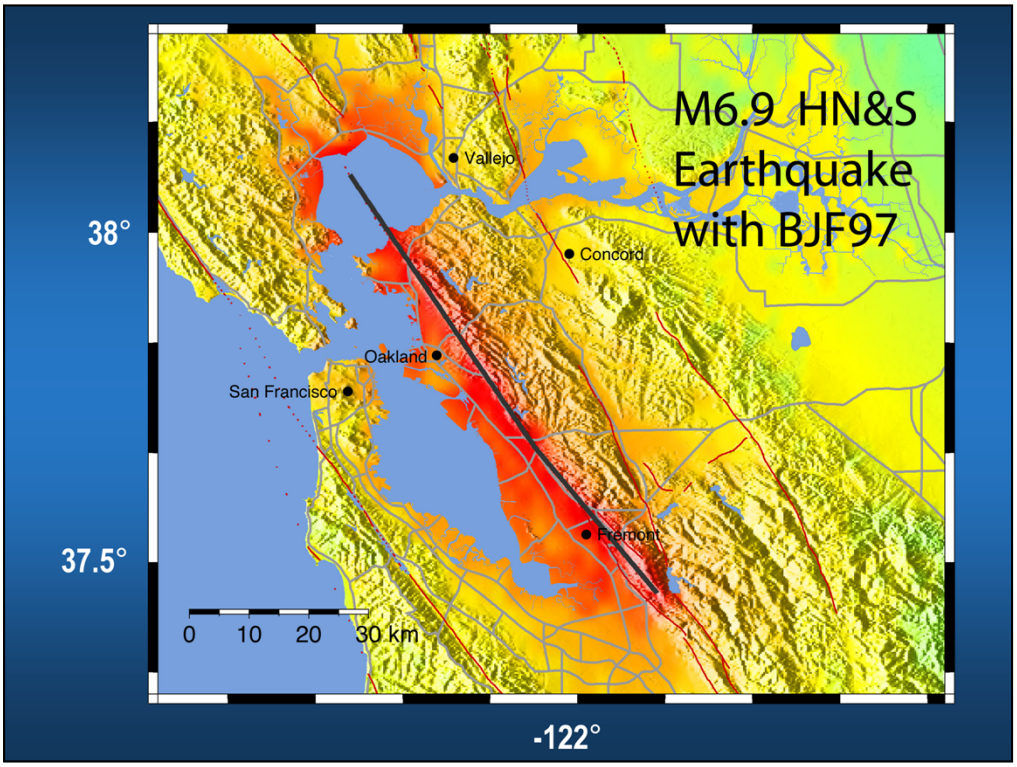
Perhaps it is easier to look in closer detail, as the ABAG maps allow. The San Andreas fault is drawn as a shaded line running offshore across the lower left of the plot. The BJF97 predicted intensities in San Francisco range from MMI 8-9 near the fault to MMI 6-7 on Pacific Heights and Russian Hill. The map shows that western San Francisco, specifically the Sunset and Lake Merced Districts, would suffer the strongest shaking from the earthquake. Buildings on soft material (that is "made land") at the edge of the San Francisco Bay would also be strongly shaken.



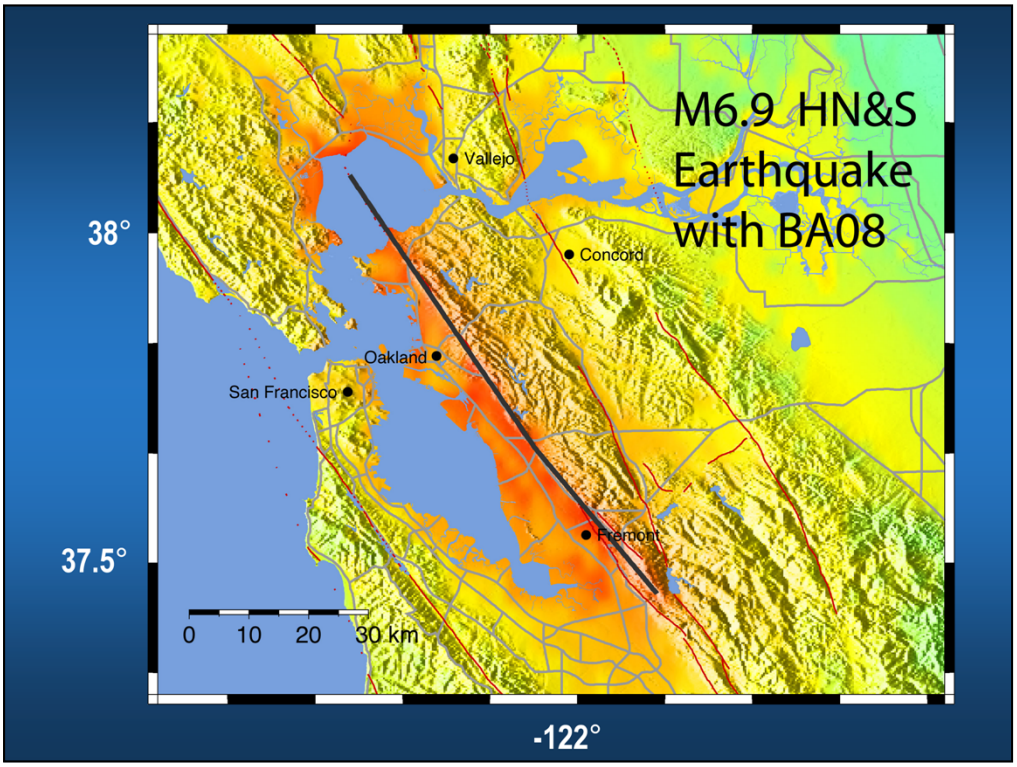
When we recalculate the ShakeMap for this M7.2 earthquake using the Boore and Atkinson (2008) ground motion prediction equations, however, we obtain a significant decrease in the estimated intensity. The Boore and Atkinson (2008) GMPE predicts intensities that are approximately an intensity unit less than the intensities predicted by the Boore et al. (1997) GMPE. Although it is difficult to gauge the continuous color ShakeMaps in this intensity range, the intensity on the stiff sediments in the Richmond and Sunset Districts appears to decrease from MMI 8 to MMI 7.



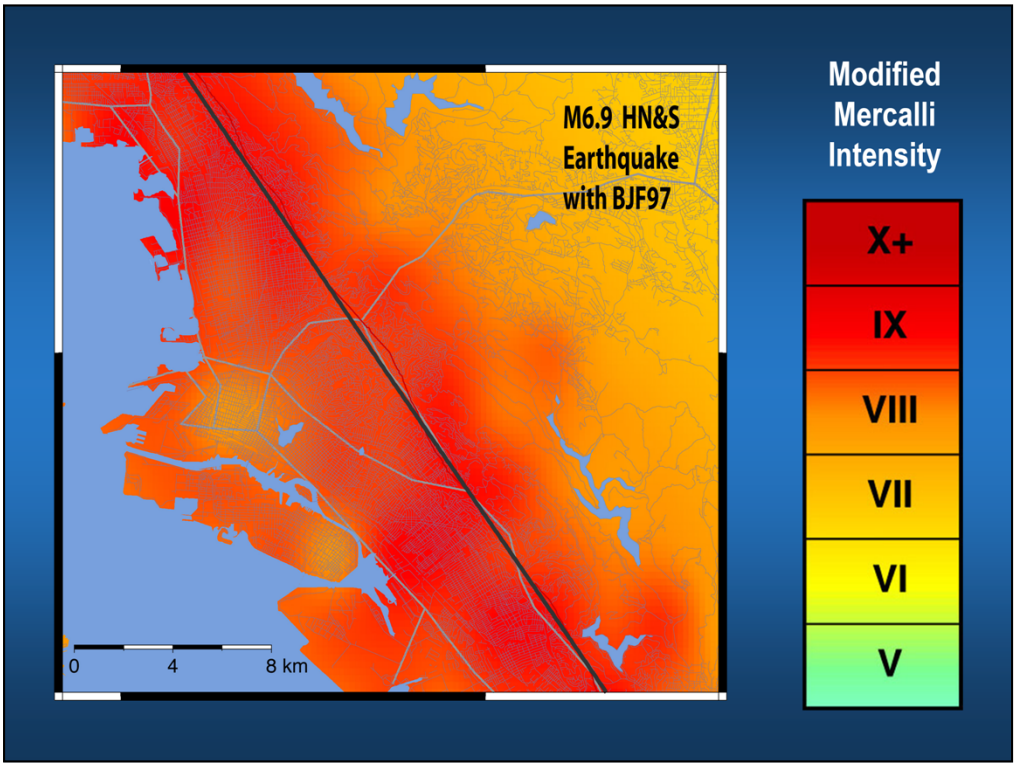
When we compute the ground motions for a repeat of the 1906 earthquake using the Boore and Atkinson (2008) GMPE, we obtain the plot above. At first glance, these intensities appear very similar to the intensities obtained for the M7.2 earthquake using the Boore et al. (1997) GMPE: the intensity on the western side of the city is the MMI 8-9 while the intensity on the eastern hills in the city is MMI 6-7. Closer scrutiny shows that the M7.9 1906 intensities obtained using the BA GMPE appear very slightly larger in Mission Bay and along the northern shore of the city than the M7.2 intensities obtained using the BJF GMPE.



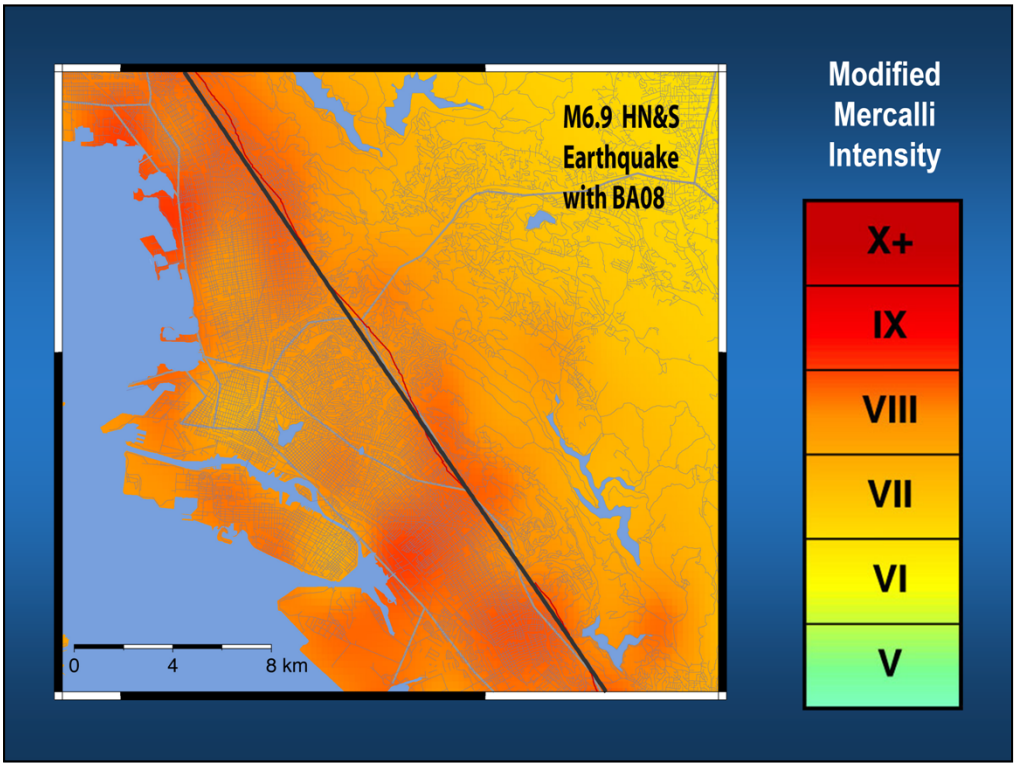
We see a similar decrease of predicted ground motion for a scenario earthquake on the northern and southern Hayward fault. This figure shows the scenario earthquake comptued using the BJF96 ground motion prediction equations.



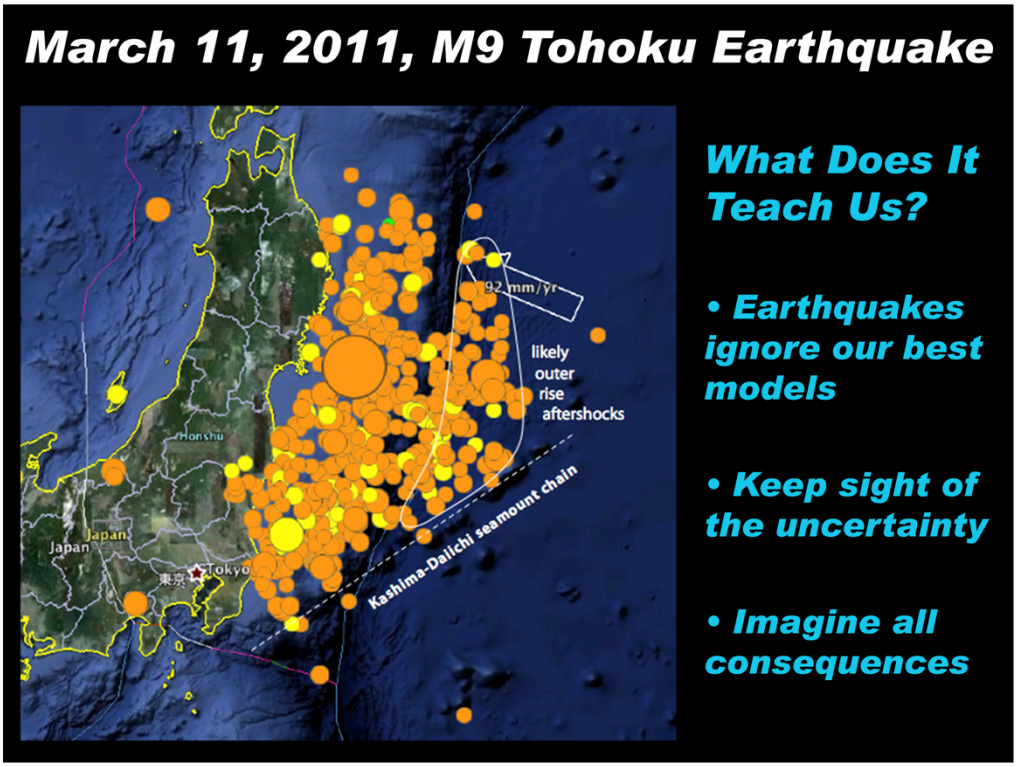
While this map shows the new BA08 ground motions. Again, the shaking along the fault is strongly reduced.



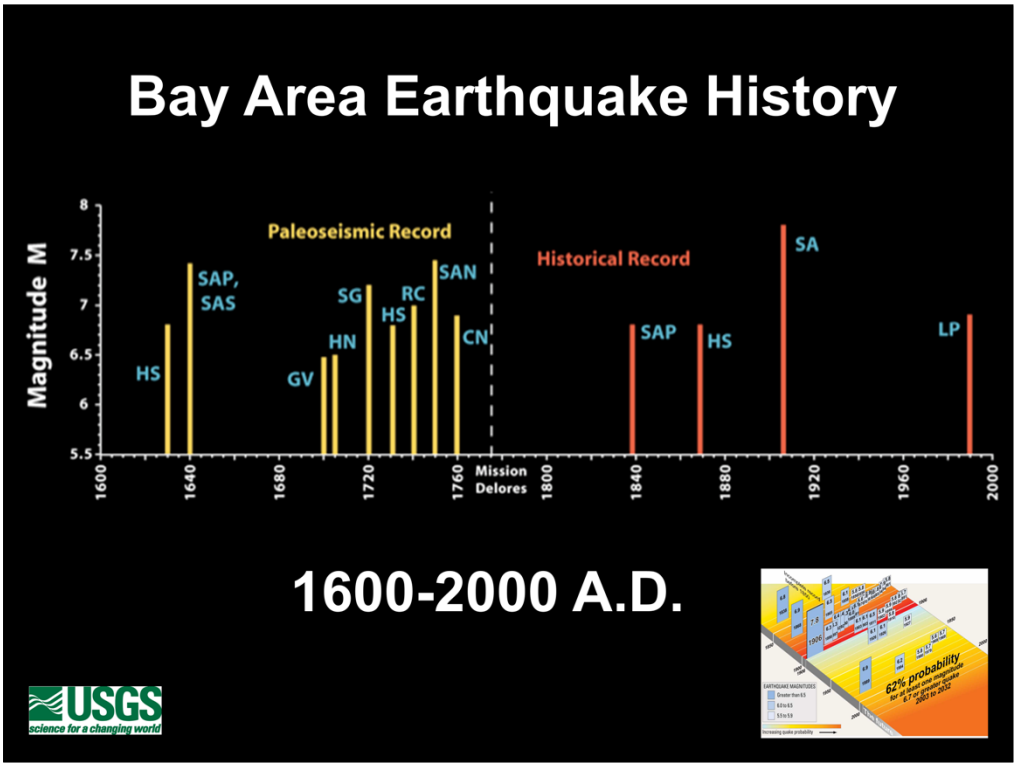
Again, it is easier to look in closer detail, as the ABAG maps allow. The Hayward fault is drawn as a shaded line running diagonally across the plot. The BJF97 predicted intensities in the east Bay range from MMI 8-9 near the fault to MMI 6-7 in the east Bay hills.



The shaking predicted by the BA08 GMPE is reduced by about an intensity unit within 10 km of the fault. Further away from the fault, the difference is much smaller.



Now I'd like to switch gears and talk about how we should anticipate large and great earthquakes. The M9 Tohoku earthquake greatly surprised the Japanese seismologists, and devastated the coast of Sendai, as well as producing a nuclear crisis that will have enormous ramifications in all of our lifetimes. The Japanese had 2000 years of tsunami records on this coast, why did they fail to anticipate such a large earthquake? Well, there was only a single instance of an M > 8 earthquake in that entire record, in the 9th century, and the Japanese assumed there was little uncertainty in their prediction, and they failed to imagine the consequences of a much greater earthquake.



What does this say about Bay Area earthquakes? Clearly, using this set of M~7 earthquakes to predict our future earthquakes doesn't mean that the anticipated earthquakes will all be M~7 or smaller. In fact, it would be extremely surprising if they were. But as I have just showed you, we have been building stronger ground motions in our models. What we need to do is predict a mean + one standard deviation ground motion, rather than simply a mean ground motion. And there is another thing that this paleo-history tells us. We need to consider that earthquakes tend to cluster together, that is, when one large earthquake occurs, it is much more likely that another large earthquake will follow.

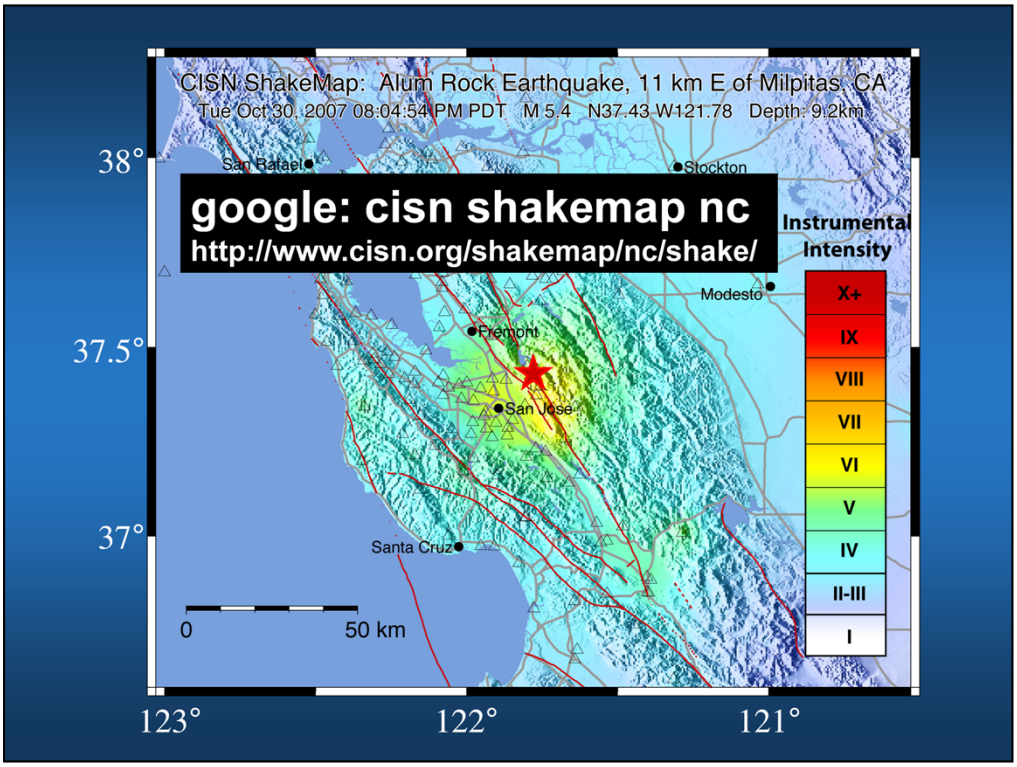
This model implies that we should expect these M~7 earthquakes to occur in bunches, and that the Bay Area will probably suffer more than one of these earthquakes in a short period of time. This is very bad news if we expect to drive economic recovery from the wider Bay Area.

Summary

- Our scenario models are being revised to predict smaller ground motion
- Uncertainty should dominate our models of earthquake shaking
- The next large Bay Area earthquake might only be the first of a cluster

So, in summary, it's good news and bad news. Our scenario models are being revised to predict smaller ground motions, and therefore, less damage when one of these earthquakes occurs.

But uncertainty should dominate our models of earthquake shaking and our ideas about anticipating earthquakes. Finally, the next large Bay Area earthquake might only be the first of a cluster of large earthquakes.



Within 10 minutes of a M > 3.5 earthquake anywhere in northern California, we post a ShakeMap that shows the recorded ground motions, plotted as intensities.

Yellow is MMI 6, the threshold for damage. Orange is MMI7, which can damage chimneys and masonry. Orange-red is MMI 8, which can damage wood-frame buildings.

Google “cisn shakemap nc” & bookmark it!

One of the most vulnerable building type is soft-story buildings. The weight of these buildings is greater than the strength of the (open) first story. The building shown in the upper-right is criminal, if it is in a seismically active area.

This is an “action” photo from the heart of the Marina district, following the 1989 earthquake. In the foreground, you can see the wreckage of two soft story buildings, 2090 Beach, from which Sherra Cox was rescued, and 3701 Divisadero, in which there were two fatalities and where the Marina fire started.

We were lucky in 1989: there was no wind to drive the fire through the Marina. I live on the flank of Russian Hill, just to the left of this picture. It was really eerie watching the fire and all that night smelling the bay water that had been used to put it out.