Bay Area Earthquakes, Faults, and Earthquake Probabilities

David P. Schwartz
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USGS, Menlo Park, CA
Anxiety of the week

Terrorism

Threat Condition Orange

Avian Flu

WMD

Anthrax

SARS

West Nile

North Korea
“We need to correct our style of architecture … to work a savings of untold sums of money in the future”

- San Jose Mercury News

October 29, 1868
San Francisco  May 1900

Photo courtesy Carol Prentice, USGS
San Francisco  April 1906

Photo courtesy Carol Prentice, USGS
Loma Prieta
1989
Bay Area Earthquakes, Faults, and Earth Probabilities

Plate Boundary

Faults

Faults and Earthquakes/Creep/Structure

Earthquake Cycle
  historical record/historical events
  paleoseismic record

Probabilities/Future Earthquakes: Putting it all together
THE PLATE BOUNDARY
Repeated earthquake cycles and fault interactions at a regional scale
40 mm/yr Farallon Islands-Sierra Nevada

North American Plate

Pacific Plate

Cooperative Research & Development between Pacific Gas & Electric Company and the U.S. Geological Survey on Earthquake Hazards in the San Francisco Bay Area
A network of faults slip in response to 40mm per year of plate tectonic motion.
San Francisco Bay Area Faults

Summed slip rates constrained to 36-43 mm/yr
Geodesy

Systematic strain accumulation across San Andreas system consistent with plate tectonic rates

Velocity = 40 mm/yr ± 1.5 mm/yr
(1.6 inches/year)

Motion of Farallon Islands relative to Columbia, CA
Four measures of SFBR rates

- Short-term Release (Historic Earthquakes)
- Long-term Release (Geology)
- Short-term Accumulation (Geodetic arrays)
- Long-term Accumulation (Plate motions)
The Plate Boundary

A Balance of Rates

- Plate tectonics provides the stress
  - Stressing rate is slow and steady
- Faults slip in earthquakes to relieve the stress
  - Earthquake slip is fast and unsteady(!)
- In the long term, the rates balance:
  - Rate of stressing matches rate of stress release

What Goes in...Must Come Out
FAULTS
M≥7.8 Continental Earthquakes Since 1900

1905 M8
Bulnay, Mongolia
350 km, 11m

1906 M7.9
San Andreas
470 km, 9m

1920 M7.9
Haiyuan, China
240 km, 10m

1939 M7.9
N. Anatolia, Turkey
350 km, 7.5m

1957 M7.8
Gobi Altay, Mongolia
250 km, 8m

2001 M7.8
Kunlun, Tibet
410 km, 7.6m
Denali Fault Surface Rupture

Km 123
Canwell Glacier

November 2002
Denali Fault Surface Rupture
Slate Creek
Km 140

July 2004
Denali Fault Surface Rupture

Km 184

8.1 m
Denali Fault Surface Rupture

Km 184
Tok Cutoff Hwy
Totschunda Fault Surface Rupture
“When, therefore, I was awakened in Berkeley on the eighteenth of April last by a tumult of motions and noises, it was with unalloyed pleasure that I became aware that a vigorous earthquake was in progress.”

---

G. K. Gilbert
at U.C. Berkeley
studying the effects of hydraulic mining during his stay at the U.C. Faculty Club.
San Bruno
San Francisco Peninsula, near Skyline Road

Annotated photo from Carol Prentice (USGS)

- Established movement on the fault as strike-slip
Road SW from Point Reyes Station
Fault trace 50-60 feet wide, Total offset ~20 feet

"As the embankment of the road for that distance was broken into several pieces, it was not possible to make certain that the dissevered remnants of the road had originally been in exact alinement."

--- G.K. Gilbert
Inferred earthquake recurrence from evidence of similar past movements

- “The surface changes associated with the earthquake, within this belt, tended to increase the differentiation of the land into ridges and valleys”
  
  G. K. Gilbert

- “The successive movements which in the past have given rise to the peculiar geomorphic features …..have with little question been attended in every case by an earthquake of greater or less violence.”
  
  A. C. Lawson
OTHER
FAULTS
Pakistan Earthquake
October, 2005

Photo: Takashi Nakata
Thrust and Reverse Faults
Folds and Thrust Faults--East Bay
Swarm of Small Quakes Is Fraying the Nerves of Californians

By DEAN E. MURPHY

SAN RAMON, Calif., Nov. 30 — The ground started shaking last Sunday morning beneath this bedroom community about 35 miles east of San Francisco, but there was little concern. The quake measured 3.9 on the Richter scale, and left barely a picture on the wall askew. People in California tend to save their worry for the Big One — something catastrophic, like the quake that destroyed much of San Francisco in 1906.

But when another small quake struck here Sunday night, and another Monday morning, and another and another and another — by Friday, the United States Geological Survey had registered what it called a “swarm” of more than 120 quakes — nervousness set in.

“Earthquakes are primal-fear things,” said Stephanie J. Hanna, the Geological Survey’s communications chief for the Western region. “They don’t kill as many people as you think, but when people aren’t sure what’s going on, it scares people down to the deepest level.”

Technically, the San Ramon earthquakes are regarded as “background seismicity” because they did not occur on a main fault. But San Ramon is not far from the Calaveras fault, one of three major faults in the San Francisco Bay Area that scientists consider most likely to produce a big earthquake.

More significantly, the San Ramon quakes have happened on a small, previously unknown fault that crosses the Calaveras seven miles beneath the surface, potentially triggering quakes on the Calaveras, too.

“I grew up in San Ramon, and normally you have an earthquake and it passes,” said Parshav Vaziri, the outreach director at the Pacific Earthquake Engineering Research Center in Berkeley. “To have it be repetitive for so many days has people thinking. There is a fear that this is leading to something bigger.”

Seismologists say quakes like San Ramon’s are not uncommon, but when they strike in heavily populated places known for seismic volatility, they can create unusual anxiety.

The last significant swarm near San Ramon occurred several miles to the north in Alamo, Calif., in 1990, when there were 350 quakes over six weeks. In nearby Danville in 1970, there were 353 quakes in a month.

David P. Schwartz, chief of the Geological Survey’s San Francisco Bay Area Earthquake Hazards Project, said the previous swarms did not set off any major earthquakes. But he and other earthquake experts do not know whether this swarm will be harmless.

A study in 1989 by scientists at the United States Geological Survey and elsewhere concluded that there was a 70 percent probability of at least one quake of magnitude 6.7 or greater in the Bay Area before 2030. The Calaveras was among the faults with the highest probability.

“The reason we have concern is that we have seen other places where earthquakes on one fault trigger earthquakes on another fault,” Mr. Schwartz said. “Our experience with this is just very short. More likely than not, the swarm will dissipate and we will have the San Ramon swarm to talk about. But we are just trying to be a little cautious, and fundamentally watch the zone, develop and watch for any changes.”

Fear that a whole lot of shaking means a bigger jolt is coming.

He said the last big quake on the Calaveras fault was more than 300 years ago, making it ripe for activity. The San Ramon near San Ramon has been quiet for 40 years, he said.

“Whenever you have a section of a fault that has been quiet, and suddenly you have activity on or near it, that raises a flag: What does this mean?” Mr. Schwartz said.

The San Ramon shaking has been minor, no loss of life, no injuries and no reports of property damage, according to the Police Department.

Dorin Dickey, a city councilwoman, said that most of the quakes had been so small she could not tell if the shaking was from the ground, her grandchildren or the family dog. But she said the amount of shaking was less relevant than its source: a previously unknown fault beneath a city that had nearly doubled in population in two decades. As San Francisco’s suburbs spread east, the thousands of unknown faults that scientists suspect exist in the Bay Area carry potentially greater consequences for life and property.

For all the attention on the swarm in San Ramon, Mr. Schwartz said that a recent earthquake in Alaska also carried great significance for Californians. On Nov. 3, a magnitude 7.9 quake, centered about 90 miles south of Fairbanks, damaged supports on the Trans-Alaska Pipeline and cracked highways and roads.

That quake offered a preview of what seismologists expect on the San Andreas fault in Southern California, he said. A recent report released by the Bulletin of the Seismological Society of America said the southern section of that fault “is primed for an earthquake” of magnitude 7.6 to 7.8.

“The kind of ground rupture we saw in Alaska, about 200 miles, is the kind of ground rupture that could occur on the southern San Andreas, the part that runs past Palm Springs to San Bernardino,” he said. “Had that earthquake occurred in Southern California, we would still be picking up the pieces.”
San Ramon swarm

Nov. 24-28, 2002
132 events
M 3.9
2006
Quaternary Fault Map
Bay Area

http://pubs.usgs.gov/sim/2006/2919
FAULTS
AND
EARTHQUAKES
Bay Area Seismicity

Locked vs. Creeping
QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.
Bay Area is world creep capitol!

Hayward
Calaveras
Concord
Sargent
Maacama
Bartlett Springs

Concord
Maacama in Willits
Reduces effective fault area/earthquake magnitude
3D Geologic “fault and block” model

Bob Jachens, Russ Graymer, Bob Simpson, and Carl Wentworth
2006
Geologic Map
Bay Area

http://pubs.usgs.gov/sim/2006/2918
Graymer et al., 2005, Three-dimensional geologic map of the Hayward fault, northern California: Correlation of rock units with variations in seismicity, creep rate, and fault dip: Geology.

Figure 1. Location of study area and simple geologic map of Hayward fault zone within outline of three-dimensional geologic model (from Blake et al., 2002; Graymer, 2000; Graymer et al., 1996, 2002a; Wentworth et al., 1998; thick lines represent faults, dotted where concealed or inferred; Hayward fault in red).
Figure 2. Oblique view of three-dimensional geologic map of Hayward fault zone (water and surficial deposits removed) split open to show fault faces (units as in Fig. 1; numeric scale on right is kilometers measured from Point Pinole).
Surface vs. Depth

Hayward-Calaveras Faults

DD Eqs 0-12km

Fault Surfaces
EARTHQUAKE CYCLE
62% probability for at least one magnitude 6.7 or greater quake 2003 to 2032
Bay Area Earthquake History

Magnitude M

1600-2000 A.D.

Historical Record

SAP

SA

HS

LP
LONG TIME SERIES + SLIP / EVENT AT MULTIPLE SITES
Bay Area Paleoearthquake History

Date

A.D.

B.C.

SG  SAS  SAP  SAN  HS  HN  RC  CN  C  GV  G

2000

1600

2 events

2 - 4 events
RADIOCARBON: critical, not straight forward
IN PURSUIT OF A LONG EARTHQUAKE HISTORY ON THE SOUTHERN HAYWARD FAULT

GEOSLICER

A Cooperative Study with the Geological Survey of Japan and Hiroshima Univ.

Allows sampling below the water table
Southern Hayward fault--Tyson’s Lagoon
Fremont, CA

From Lienkaemper et al., 2002 and in prep
Bay Area Earthquake History

1600-2000 A.D.

Magnitude M

Historical Record

1600 1640 1680 1720 1760 1800 1840 1880 1920 1960 2000

HS SAP HS SA LP

Mission Delores
Northern Hayward
Mira Vista golf course
Northern Hayward fault
Mira Vista site

1635-1776
Downtown San Francisco from Rodgers Creek Fault
Rodgers Creek Fault

Offset drainage
From Hecker et al, 2004
Paleoearthquake chronologies to evaluate possible rupture scenarios: Hayward-Rodgers Creek Fault Zone

- Rodgers Creek
- North Hayward
- South Hayward

AD 1200 1400 1600 1800 2000

RC 7.0 7.0 7.1
NH 6.5 6.9 6.8
SH 6.8 6.8 7.3
SAN ANDREAS FAULT

V 1680-1790
D 1720-1776
F 1568-1655
GF 1600-1670
AF 1620-1680

Central Trench South Wall

Cooperative Research & Development between Pacific Gas & Electric Company and the U.S. Geological Survey on Earthquake Hazards in the San Francisco Bay Area
SAN ANDREAS FAULT
SAN ANDREAS
Vedanta Marsh

1680-1790

Figure 0. Evidences of the last three earthquake events in Trench T3 south wall. A log took on 09-14-2002.

From Niemi and Fumal, in prep
Bay Area Earthquake History

1600-2000 A.D.
Bay Area Earthquake History

1600-2000 A.D.

Historical Record

SAN

Mission Delores

SAP

HS

SA

LP
Bay Area Earthquake History

Magnitude

1600-2000 A.D.
CALAVERAS FAULT
Leyden Creek site

1670-1830

From Kelson et al, 1996
SAN GREGORIO FAULT
Pillar Pt. Marsh/Seal Cove

1640-1776

Seal Cove
1270/1400-1776
5m

From Simpson et al, 1998; Lettis et al, in prep
Spanish Missions
California’s Original Seismic Network

• Mission Dolores (San Francisco) founded 1776, others 1777-1797
• Missions N of SF Bay founded 1817 and 1823
• Several thousand people in region
• No earthquakes reported in first 32 years mission records (1776 - 1808)
Bay Area Earthquake History

Paleoseismic Record

Historical Record

Magnitude M

1600-2000 A.D.
Bay Area Earthquake History

1600-2000 A.D.

The next 30 years?
Between 1600 and 1906 the San Andreas fault failed in series of large ruptures rather than as a multi-segment 1906-type rupture.

A regional series of large events occurred between 1670-1776, and likely during a shorter interval in the 18th century.

Moment release during the cluster (irrespective of the order of events) was comparable to moment release in 1906.

The cluster was followed by a regional quiescence of large (surface faulting) earthquakes, with only two (1838, 1868) until 1906.
EARTHQUAKE PROBABILITIES
Plate motions continually load strain onto faults.

Fault slip occurs during earthquakes, releasing strain.
“Thank God! A panel of experts!”
Plus contributions from dozens of other earth scientists in government, academia, and the private sector.

Working Group 2002
Oversight Committee and Participants

Michael Blanpied, USGS (co-chair)
David Schwartz, USGS (co-chair)
Norm Abrahamsen, PG&E
William Bakun, USGS
William Ellsworth, USGS
William Foxall, L. Livermore Labs
Thomas Hanks, USGS
Kathryn Hansen, Geomatrix
William Lettis, Lettis & Assoc.
James Lienkaemper, USGS
Mark Petersen, USGS
Paul Reasenberg, USGS
Michael Reichle, CGS
Working Group 2002 study

- We constructed a long-term model for large-earthquake production in the SFBR
  - balances slip rates and plate tectonic rates
  - accounts for overlapping ruptures, fault creep, earthquake interactions, and other complexities
  - provides magnitudes and rates of earthquakes

- We then calculated short-term earthquake probability forecasts
  - gives probabilities for faults, fault segments, and the Bay region
  - for a range of time intervals and earthquake magnitudes

- Results are applicable to hazard and loss calculations, and scenario planning
Sam Francisco Bay Area Earthquake Model

What goes in...must come out

AVERAGE long-term earthquake recurrence

- Plate Motions
- GPS rates
- Paleoseismology
- Historical Seismicity
- Fault Interactions
- Expert Opinion
Segmentation Modeling Of Bay Area Faults for WG99/02 Probability Study

- Average recurrence interval
- Expected magnitude
- Time of most recent event
Logic Tree for the Seismic Area of a Fault

Fault Area = L x W x R

81 weighted branch tips
1. Calculation Sequence for SFBR Earthquake Model

- Calculating segment lengths, $L$
- Calculating seismogenic areas, $A = LW_R$
- Calculating segment moment rates, $\mu A v$
- Calculating mean magnitudes of rupture sources, $M = f(A)$
- Calculating mean earthquake moments
- Long-term slip rates, $v$
- Fault rupture model (relative rupture source rates)
- Seismogenic width, $W$ (base of seismogenic zone)
- Seismogenic scaling factor, $R$
- Regional slip-rate constraint

% moment in characteristic earthquakes $F_{char}$

Recurrence rates $r = F_{char} \frac{M_o}{M}$

To Probability calculations
inputs, models ±
natural variability
San Francisco Bay Region Earthquake Probabilities

Probability for one or more M6.7 or greater earthquakes from 2002 to 2031

USGS Open-File Report 03-214
30-year Probabilities at Different Magnitude Thresholds

< M6.7  80%-96%
≥ M6.7  62%
≥ M7   35%
≥ M7.5 10%
Probabilities for Other Exposure Times

Table 6.2. Probability of $M \geq 6.7$ earthquakes in the SFBR in various exposure times

<table>
<thead>
<tr>
<th>Exposure Time (years from 2002)</th>
<th>Weighted Models</th>
<th>Poisson Model (Time-independent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.04 [0.02 - 0.08]</td>
<td>0.03 [0.02 - 0.04]</td>
</tr>
<tr>
<td>5</td>
<td>0.16 [0.07 - 0.32]</td>
<td>0.14 [0.11 - 0.18]</td>
</tr>
<tr>
<td>10</td>
<td>0.29 [0.14 - 0.49]</td>
<td>0.26 [0.21 - 0.33]</td>
</tr>
<tr>
<td>20</td>
<td>0.49 [0.27 - 0.74]</td>
<td>0.46 [0.37 - 0.55]</td>
</tr>
<tr>
<td>30</td>
<td>0.62 [0.38 - 0.85]</td>
<td>0.60 [0.51 - 0.70]</td>
</tr>
<tr>
<td>100</td>
<td>_</td>
<td>0.96¹ [0.92 - 0.99]</td>
</tr>
</tbody>
</table>

1. Equivalently, the number of $M \geq 6.7$ earthquakes expected in the SFBR in 100 years is 3.1 [2.4 – 4.1]
M ≥ 6.7
Five models for short-term earthquake probability

**Alternative Probability Models**

- Poisson
- Empirical
- BPT
- BPT-Step
- Time-predictable

**Earthquake occurrence rate**
Recurrence model pdf's
Mean=1, Aperiodicty=0.5
Probability of the Next Quake

Time of the last quake: historical/paleoseismic

Time interval of interest: 30 yr

Probability density function for time of the next quake

Probability model, recurrence interval, variability (cov)
Moment Accumulation in the SF Bay Region

- 1868 M6.8
- 1906 M7.8
- 1989 M6.9

Cumulative M0, dyne-cm

Stress Shadow
Models vs. Historical Data

Annual Number of $M \geq 6.7$ Events

Catalog $M \geq 5.5$

Empirical Model Extrapolations

Weighted Mean of Extrapolations

WG99 BPT
WG99 Poisson
Bakun catalog
CNSS catalog
Empirical Model

30-year Probability
Time-predictable model

Shimazaki and Nakata, 1980

\[ T_{\text{next}} - T_{\text{last}} = \frac{\text{Slip}_{\text{last}}}{\text{Slip rate}} \]

San Andreas fault only

Thatcher, 1997 slip model
30-year Probability of Rupture, M>6.7

**Red**: Any 30 year interval (on average)

**Green**: The next 30 years (2002-2031)
Conclusions from Working Group 2002

- Damaging earthquakes are likely in the coming years and decades
- 62% chance of a Northridge-sized event in 30 years
- Moderate-sized (M>6) quakes very likely (80–90+%)
- M>7.5 earthquakes less likely but possible (10%)
- Shaking hazard is high throughout the region
- Potential shaking is strongest along the Bay margins
Earthquake Threat Condition

SEVERE
You can run,
but you can't hide.
Surface faulting
Strong shaking
Liquefaction
Lateral Spreading
Landslides
Trans-Alaska Pipeline at the Denali Fault
Bay Area Bridges

Benicia
Carquinez
Richmond
San Mateo

Eastern Bay Bridge Construction: June 2004
Will BART keep the Bay Area moving after the next big quake?

On November 2, 2004, you will decide whether to authorize funding the BART Earthquake Safety Program.
Bay Area Water Systems

Fault crossings
Lateral spreading
Enough Time?