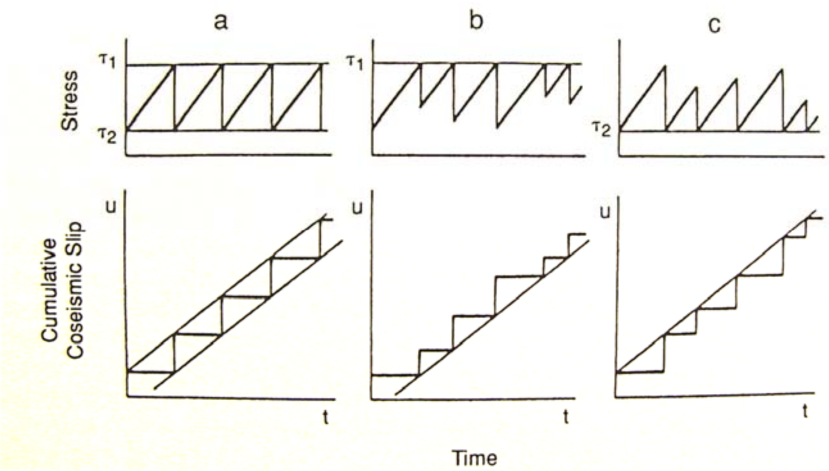
Earthquake Prediction and Forecasting

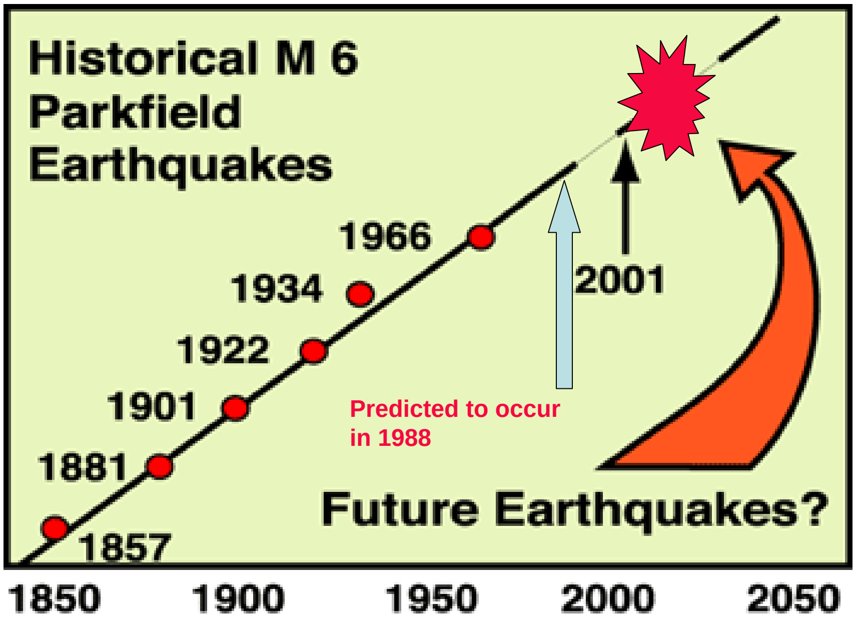
- Pre-Event Mitigation
  - Prediction
    - Presently not viable
  - Forecasting
    - Causative faults
    - Recurrence rates
    - Empirical and/or deterministic assessments of earthquake effects
    - Probabilistic hazard estimate
- Post-Event Mitigation
  - Early warning
    - Issued before arrival of damaging ground motions or tsunami
  - Near-realtime
    - Strong shaking information to help direct emergency response
  - Basic research
    - Improved forecasts, better constrained ground motion estimates, updated building code and practice

Earthquake Prediction

- Must be testable by means of <u>specific</u> statements regarding:
  - Location
  - Size
  - Time
  - Issued in a testable time frame (ideally one that could allow authorities to act)
- Short term
  - Hours to several weeks
  - Goals: evacuation orders, protect critical facilities
  - Needs: precursory phenomena, physics
  - Outlook: not good
- Intermediate term
  - Weeks to a few years
  - Goals evacuation orders, protect critical facilities, planning
  - Needs: precursory phenomena, recurrence rates, physics
  - Outlook: better
- Long term
  - Years to decades
  - Goals: probabilistic statements (forecasts), urban planning
  - Needs: geologic and seismologic investigations, recurrence rates, physics
  - Outlook: good

Models of Earthquake Occurrence





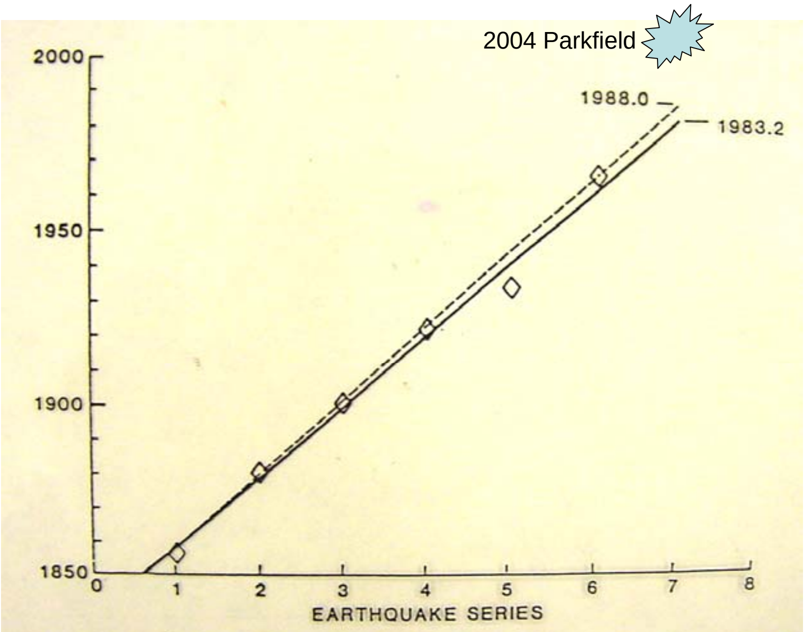


Fig. 5.16 History of Parkfield earthquakes. Dashed line is a linear fit without the 1934 earthquake, solid line includes it. (From Bakun and McEvilly, 1984.)

Dilatancy Model

Based on laboratory observations of rock fracture

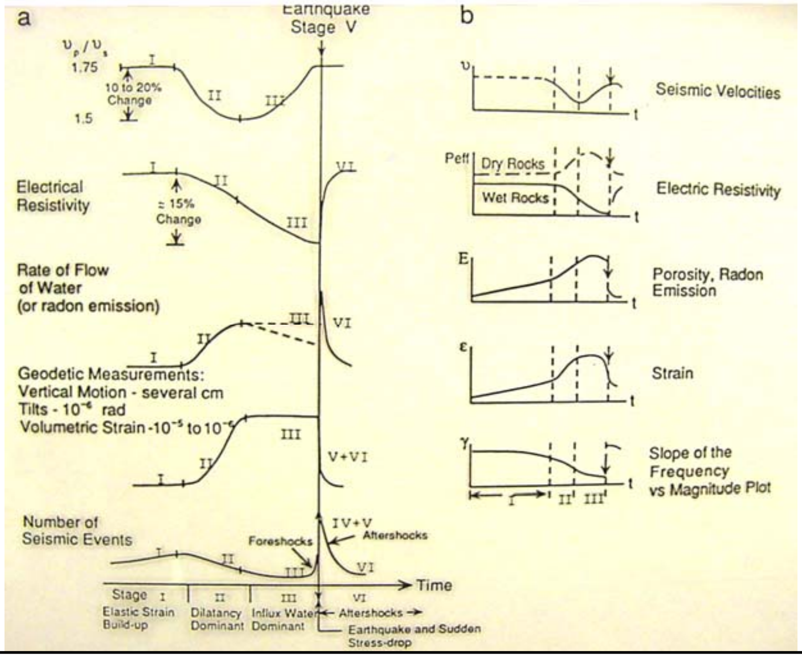
Increasing strain

- Stage I – elastic strain build up
- Stage II - development of micro-cracks
- Stage III - influx of H_2O (minimally hydrostatic)
- Stage IV - micro-cracks close & H_2O is expelled (local super-lithostatic)

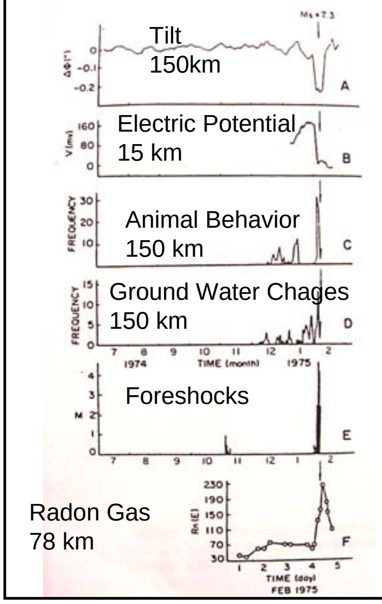
Predicts a clear progression of geophysical observables that might be used for earthquake prediction.

Main problem is that not all geophysical changes are universally observed.

Dilatancy Model

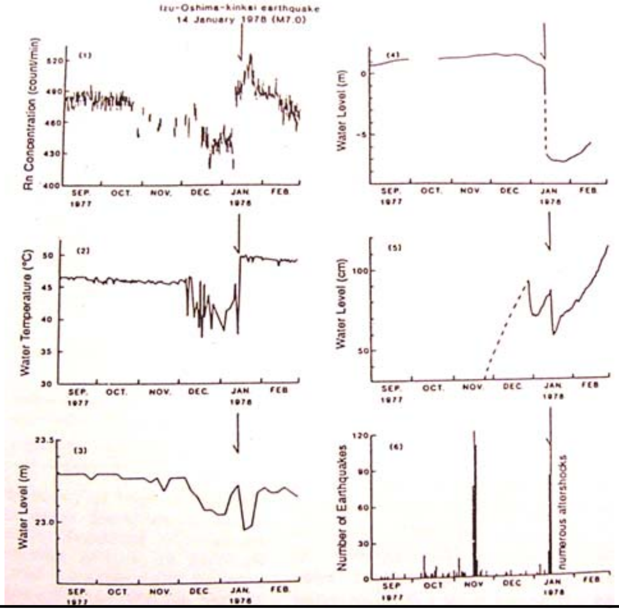


Haicheng and Tangshan

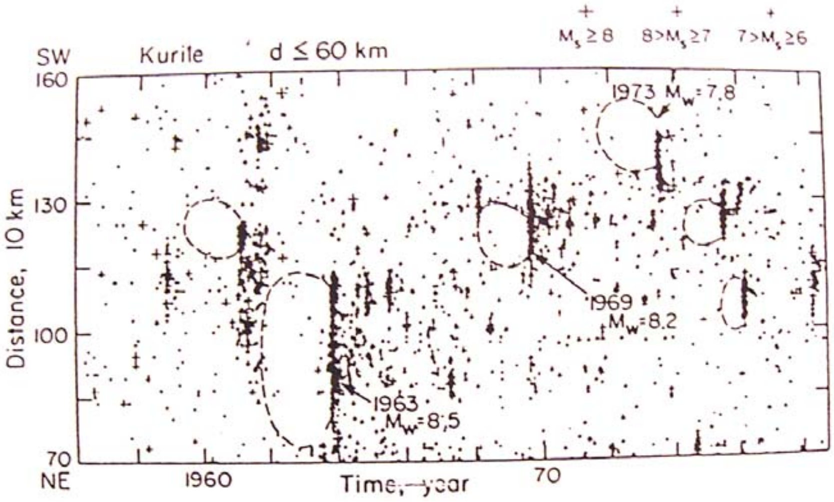


- Haicheng, 1975
  - Ms7.3
  - Precursors led to Chinese authorities issuing EQ warning with evacuation order
  - Considerable destruction but loss of life was greatly reduced
- Tangshan, 1976
  - Ms7.6
  - 200 km from Haicheng
  - One year later
  - No precursors
  - No warning (prediction)
  - > 250,000 killed

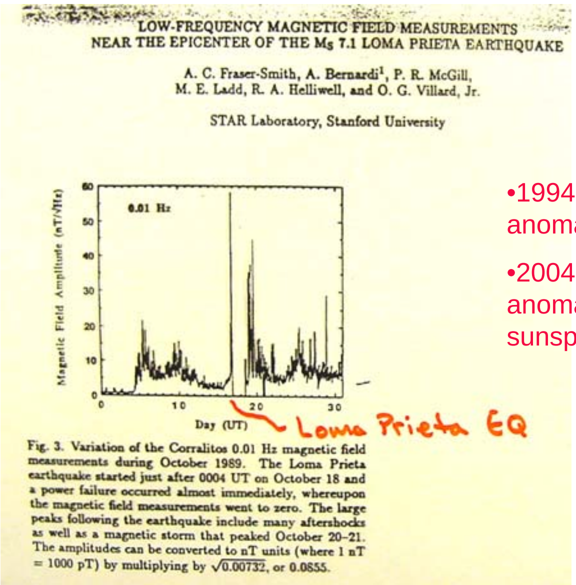
Japanese Precursors



Pre-Event Quiescence



EM Precursors?



LOW-FREQUENCY MAGNETIC FIELD MEASUREMENTS
NEAR THE EPICENTER OF THE M_S 7.1 LOMA PRIETA EARTHQUAKE

A. C. Fraser-Smith, A. Bernardi[1], P. R. McGill,
M. E. Ladd, R. A. Helliwell, and O. G. Villard, Jr.

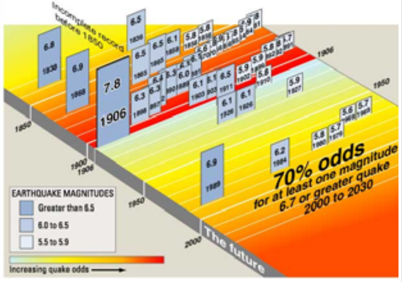
STAR Laboratory, Stanford University

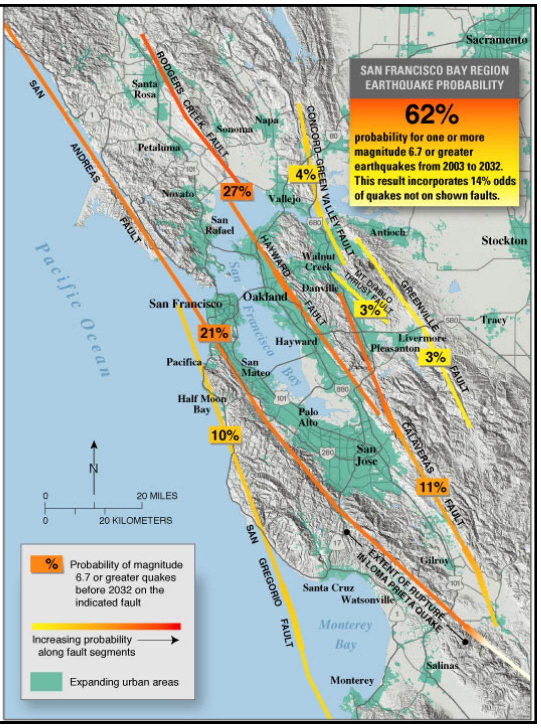
Loma Prieta EQ

Fig. 3. Variation of the Corralitos 0.01 Hz magnetic field measurements during October 1989. The Loma Prieta earthquake started just after 0004 UT on October 18 and a power failure occurred almost immediately, whereupon the magnetic field measurements went to zero. The large peaks following the earthquake include many aftershocks as well as a magnetic storm that peaked October 20–21. The amplitudes can be converted to nT units (where 1 nT = 1000 pT) by multiplying by $\sqrt{0.00732}$, or 0.0855.

- 1994 Northridge – no detectable anomalies at 80 km distance
- 2004 Parkfield – no detectable anomalies above back ground sunspot and seasonal signals

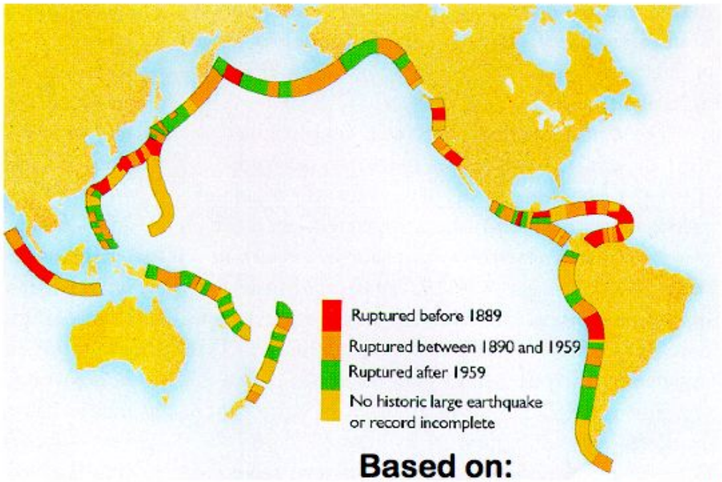
Earthquake





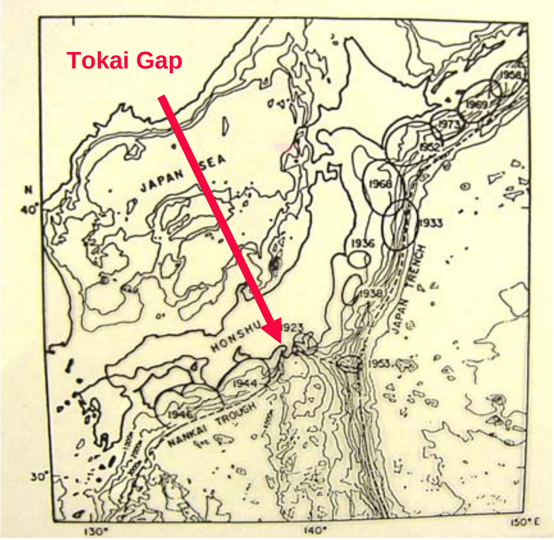
- •Where are the faults?
- •What is the fault segmentation?
- •What is the earthquake history on each f (recurrence rate) ?
- •What is the influence from other nearby earthquakes?

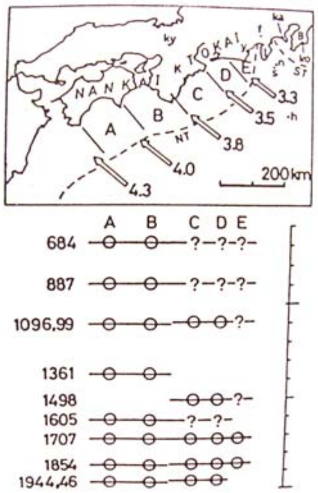
Seismic Gaps Hypothesis

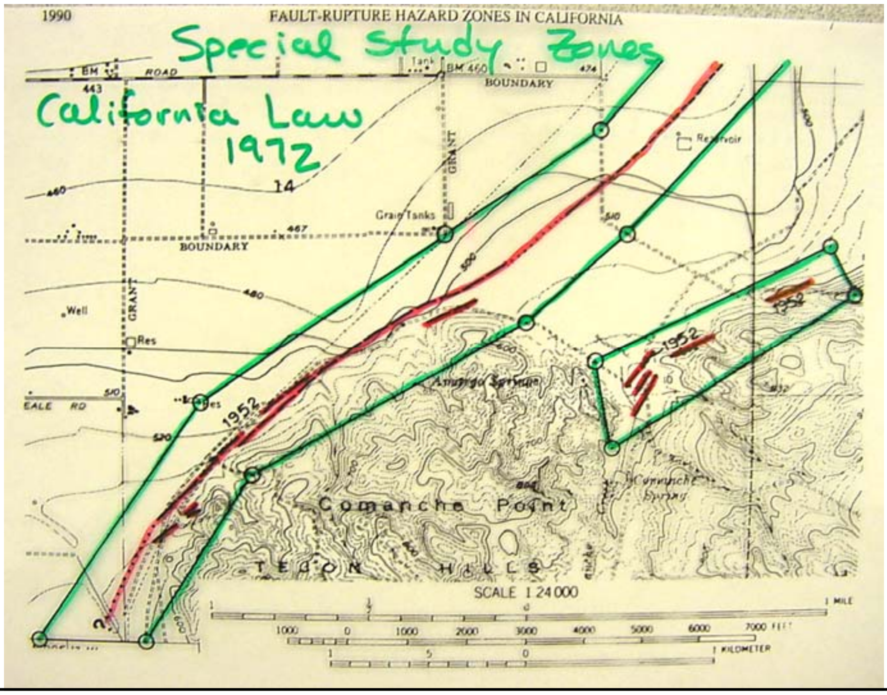


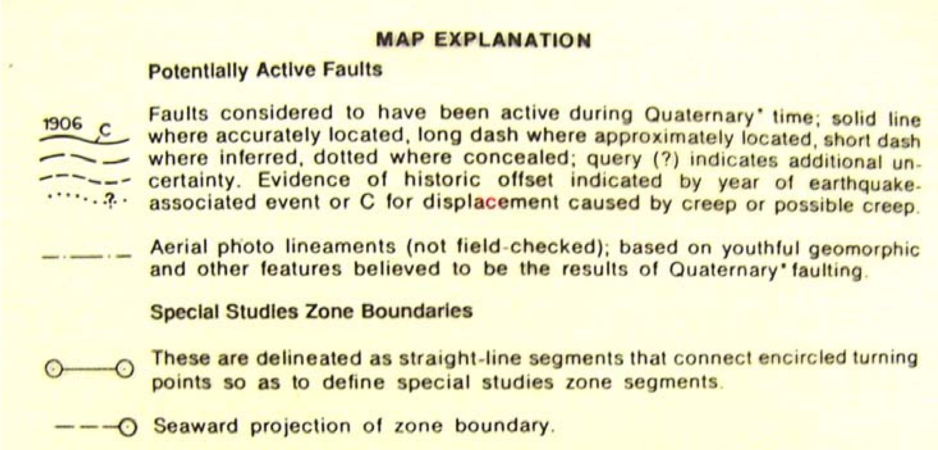
Based on:
- **Frequency of small quakes**
- **Time since last large event**

Seismic Gaps in Japan









MAP EXPLANATION

Potentially Active Faults

Faults considered to have been active during Quaternary* time; solid line where accurately located, long dash where approximately located, short dash where inferred, dotted where concealed; query (?) indicates additional uncertainty. Evidence of historic offset indicated by year of earthquake-associated event or C for displacement caused by creep or possible creep.

Aerial photo lineaments (not field-checked); based on youthful geomorphic and other features believed to be the results of Quaternary* faulting.

Special Studies Zone Boundaries

These are delineated as straight-line segments that connect encircled turning points so as to define special studies zone segments.

Seaward projection of zone boundary.

Forecasting earthquakes using Gutenberg-Richter

- Assumptions
  - Seismicity occurs randomly in time
  - Average rates of seismicity can be quantified
  - No inter-dependency between previous, nearby earthquakes
- Model
  - Poisson distribution
  - Δt forecast interval – usually 30 years
  - λ is the # of events of a given magnitude in a year

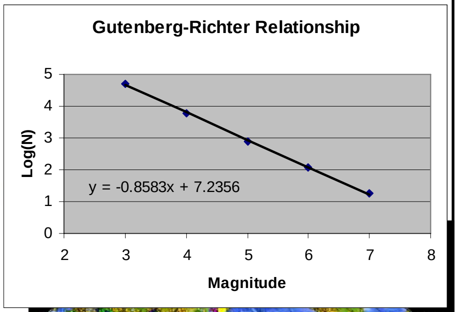
$$P(\lambda, \Delta t) = 1 – e^{-\lambda \cdot \Delta t}$$

Size - Frequency Relationship

Frequency of Occurrence of Earthquakes Based on Observations since 1900

Great	**> 8**		**higher**	**1/year**
Major	**7**	**-**	**7.9**	**18**
Strong	**6**	**-**	**6.9**	**120**
Moderate	**5**	**-**	**5.9**	**800**
Light	**4**	**-**	**4.9**	**~6,200**
Minor	**3**	**-**	**3.9**	**~49,000**
Micro	**1**	**-**	**3**	**~9000/day**

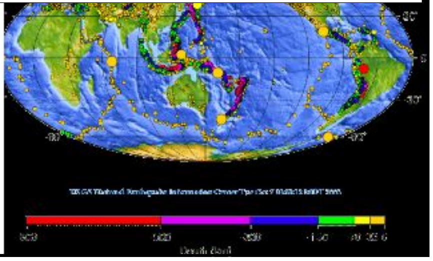
From neic.usgs.gov/neis/bulletin/mag7.html#1999



Gutenburg-Richter Relationship:

Log (number) = a + b*(magnitude)

Log (N) = a + b*M



Example

There are 800 magnitude to 5-5.9 events globally per year.

$\lambda = 800$

The probability of at least one event in this magnitude range in a given month is;

$$P(800, {}^{1}\!/_{12}) = 1 - e^{-67} = 1$$

The probability of at least 1 event in a given day is;

$$P(800, {}^{1}\!/_{365}) = 1 - e^{-2.2} = 0.89$$

And in a given hour;

$$P(800, {}^{1}\!/_{(365 \cdot 24)}) = 1 - e^{-0.09} = 0.09$$

Northern California Seismicity Rates

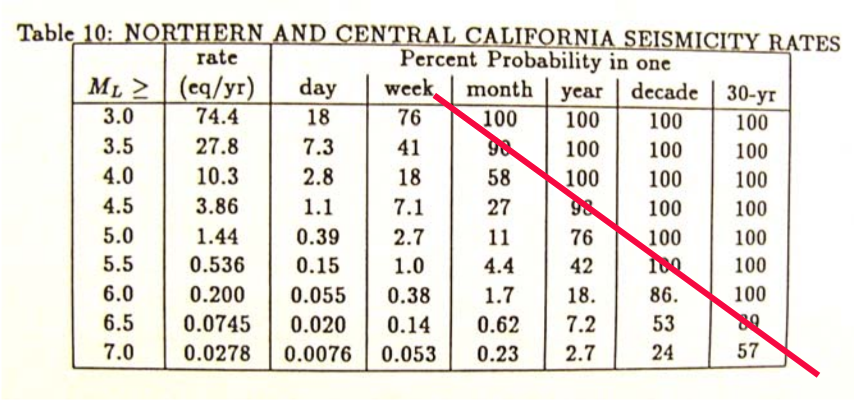
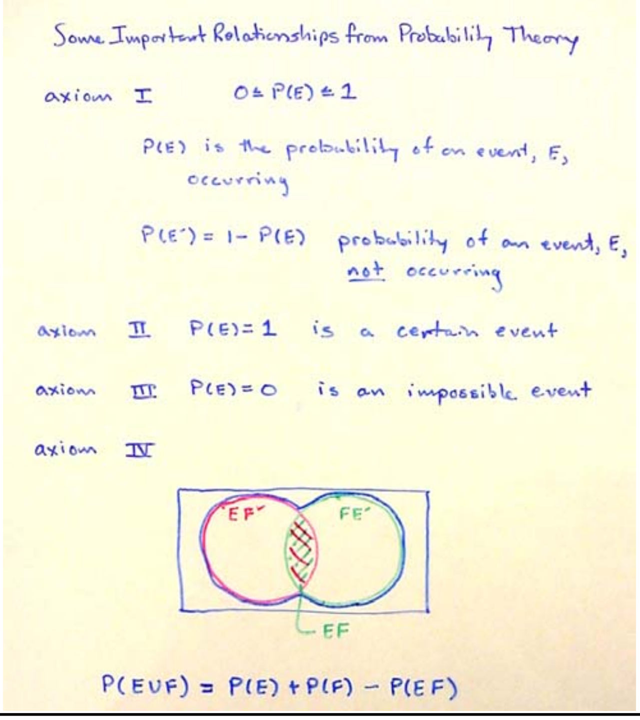


Table 10: NORTHERN AND CENTRAL CALIFORNIA SEISMICITY RATES

$M_L \geq$	rate (eq/yr)	Percent Probability in one day	week	month	year	decade	30-yr
3.0	74.4	18	76	100	100	100	100
3.5	27.8	7.3	41	90	100	100	100
4.0	10.3	2.8	18	58	100	100	100
4.5	3.86	1.1	7.1	27	98	100	100
5.0	1.44	0.39	2.7	11	76	100	100
5.5	0.536	0.15	1.0	4.4	42	100	100
6.0	0.200	0.055	0.38	1.7	18.	86.	100
6.5	0.0745	0.020	0.14	0.62	7.2	53	89
7.0	0.0278	0.0076	0.053	0.23	2.7	24	57



Some Important Relationships from Probability Theory

axiom I $0 \leq P(E) \leq 1$

$P(E)$ is the probability of an event, E, occurring

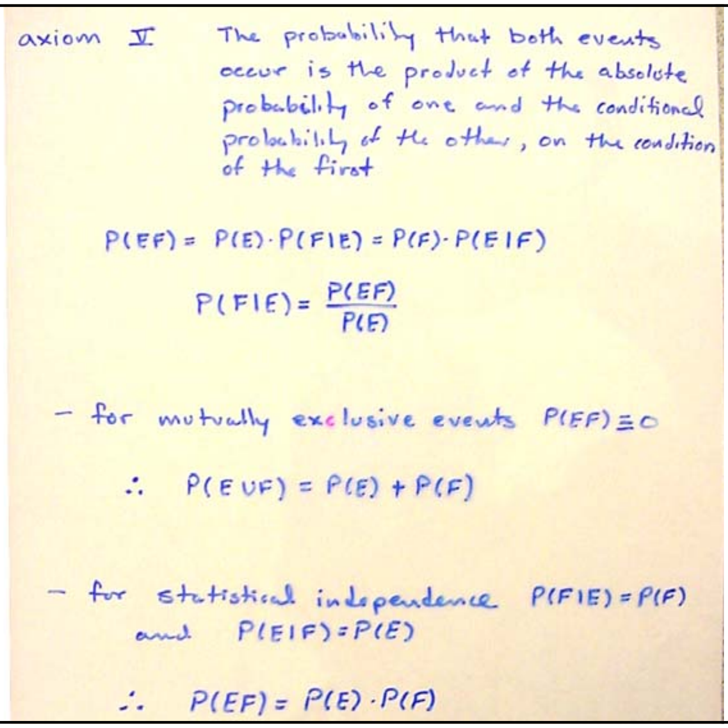
$P(E') = 1 - P(E)$ probability of an event, E, <u>not</u> occurring

axiom II $P(E) = 1$ is a certain event

axiom III $P(E) = 0$ is an impossible event

axiom IV

$P(E \cup F) = P(E) + P(F) - P(EF)$



axiom V The probability that both events occur is the product of the absolute probability of one and the conditional probability of the other, on the condition of the first

$$P(EF) = P(E) \cdot P(F|E) = P(F) \cdot P(E|F)$$

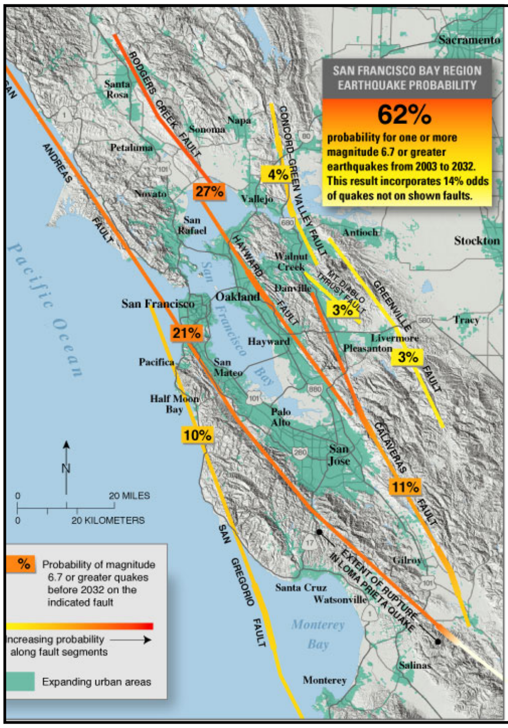
$$P(F|E) = \frac{P(EF)}{P(E)}$$

- for mutually exclusive events $P(EF) \equiv 0$

$$\therefore \quad P(E \cup F) = P(E) + P(F)$$

- for statistical independence $P(F|E) = P(F)$ and $P(E|F) = P(E)$

$$\therefore \quad P(EF) = P(E) \cdot P(F)$$

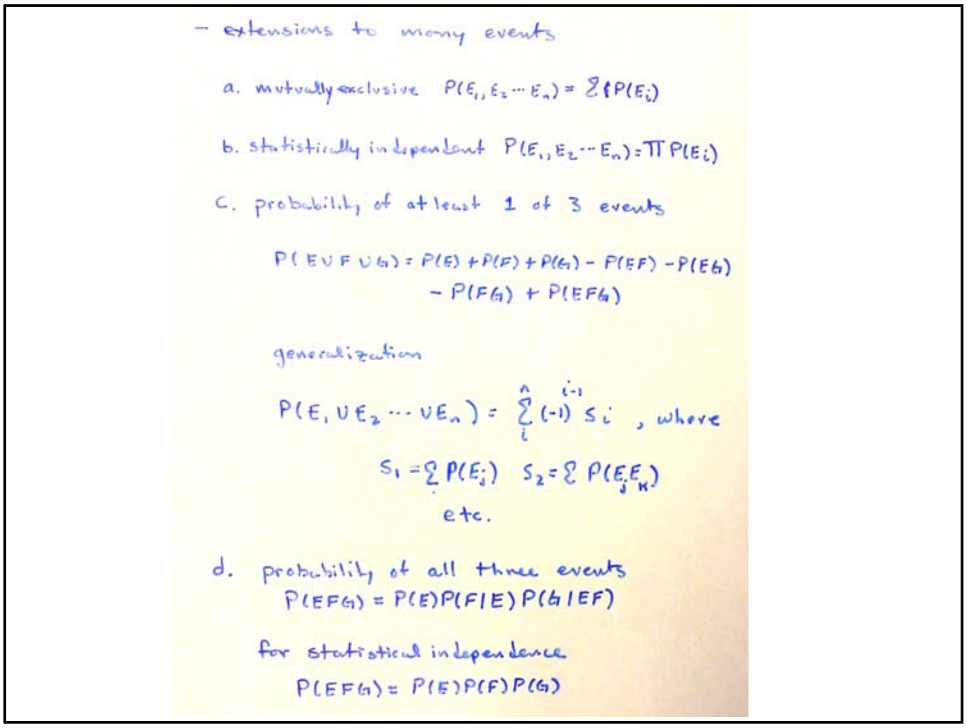


SAN FRANCISCO BAY REGION EARTHQUAKE PROBABILITY

62%

probability for one or more magnitude 6.7 or greater earthquakes from 2003 to 2032. This result incorporates 14% odds of quakes not on shown faults.

- Earthquakes are not mutually exclusive
  - e.g. in a given time window there are probabilities for occurrence of an NHF and RC events. If in this time period the RC fault slips it is <u>not</u> true that the NHF event cannot occur.
- They are statistically independent



- extensions to many events

a. mutually exclusive $P(E_1, E_2 \cdots E_n) = \sum P(E_i)$

b. statistically independent $P(E_1, E_2 \cdots E_n) = \prod P(E_i)$

c. probability of at least 1 of 3 events

$$P(E \cup F \cup G) = P(E) + P(F) + P(G) - P(EF) - P(EG) - P(FG) + P(EFG)$$

generalization

$$P(E_1 \cup E_2 \cdots \cup E_n) = \sum_{i}^{n} (-1)^{i-1} S_i \text{ , where}$$

$$S_1 = \sum P(E_j) \quad S_2 = \sum P(E_j E_k)$$

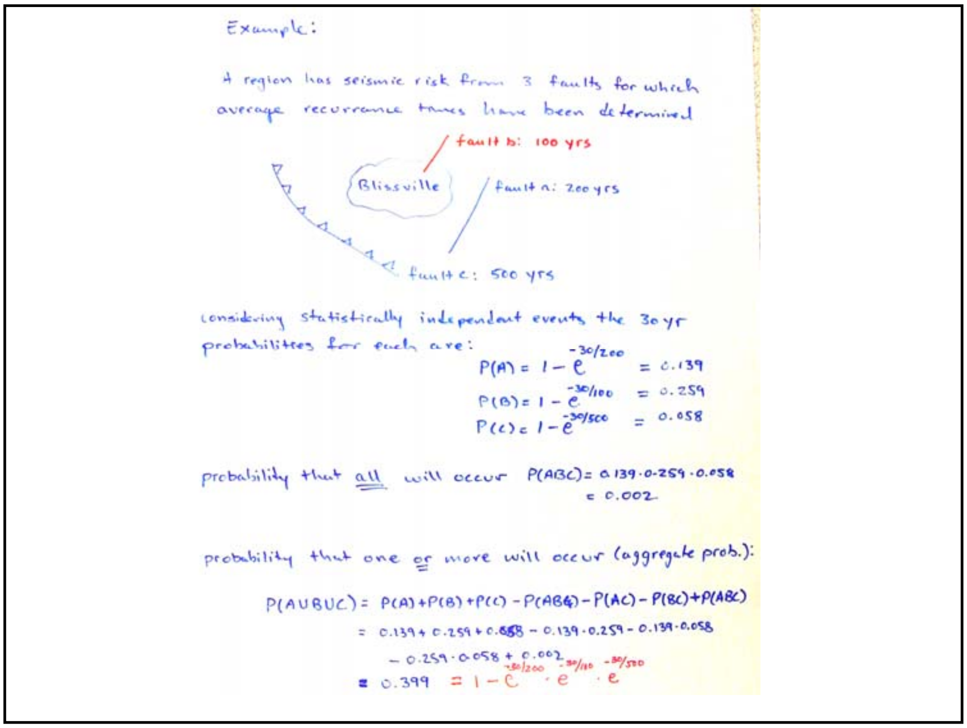
etc.

d. probability of all three events

$$P(EFG) = P(E)P(F|E)P(G|EF)$$

for statistical independence

$$P(EFG) = P(E)P(F)P(G)$$



Example:

A region has seismic risk from 3 faults for which average recurrance times have been determined

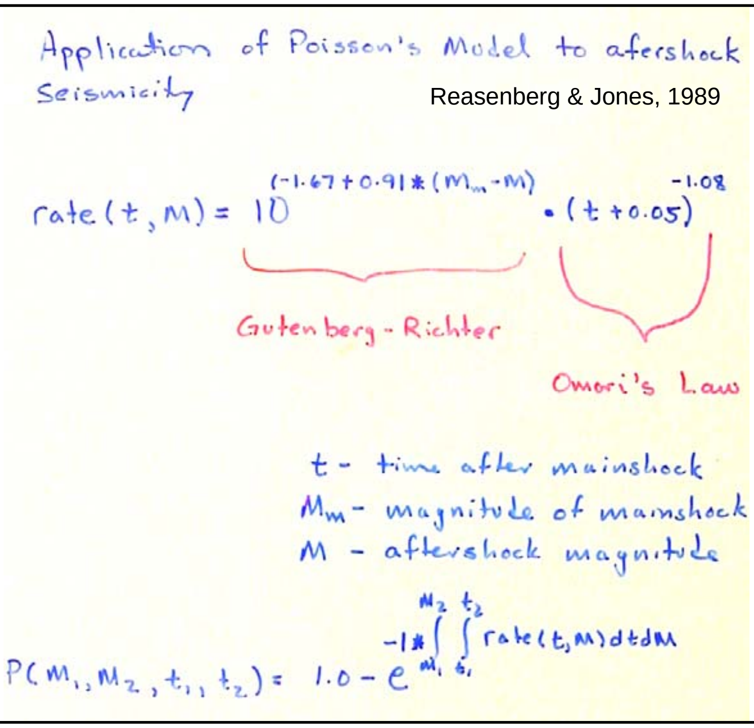
considering statistically independent events the 30 yr probabilitees for each are:

$$P(A) = 1 - e^{-30/200} = 0.139$$
$$P(B) = 1 - e^{-30/100} = 0.259$$
$$P(C) = 1 - e^{-30/500} = 0.058$$

probability that <u>all</u> will occur $P(ABC) = 0.139 \cdot 0.259 \cdot 0.058 = 0.002$

probability that one <u>or</u> more will occur (aggregate prob.):

$$P(A \cup B \cup C) = P(A) + P(B) + P(C) - P(ABC) - P(AC) - P(BC) + P(ABC)$$
$$= 0.139 + 0.259 + 0.058 - 0.139 \cdot 0.259 - 0.139 \cdot 0.058 - 0.259 \cdot 0.058 + 0.002$$
$$= 0.399 = 1 - e^{-30/200} \cdot e^{-30/100} \cdot e^{-30/500}$$



Application of Poisson's Model to aftershock seismicity

Reasenberg & Jones, 1989

$$\text{rate}(t, M) = \underbrace{10^{(-1.67+0.91*(M_m - M))}}_{\text{Gutenberg-Richter}} \cdot \underbrace{(t+0.05)^{-1.08}}_{\text{Omori's Law}}$$

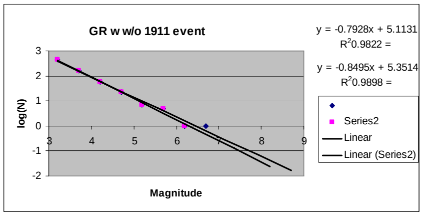
t - time after mainshock

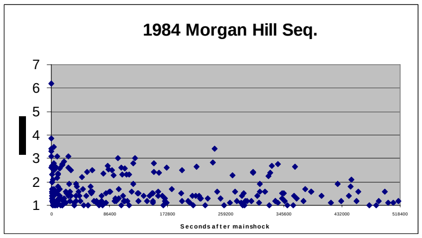
M_m - magnitude of mainshock

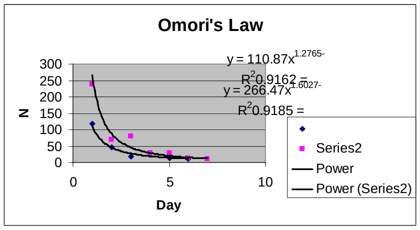
M - aftershock magnitude

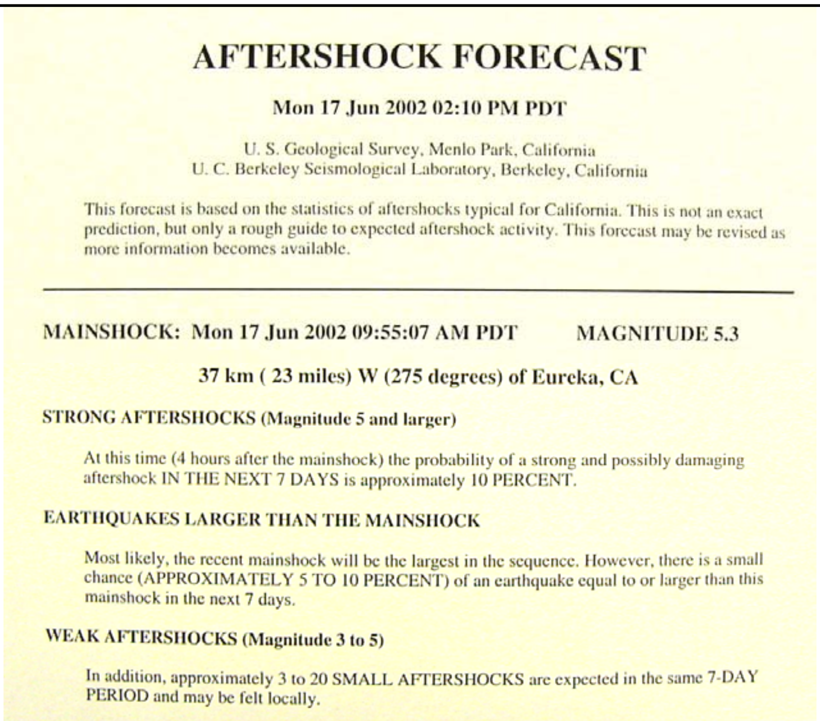
$$P(M_1, M_2, t_1, t_2) = 1.0 - e^{-1*\int_{M_1}^{M_2}\int_{t_1}^{t_2} \text{rate}(t,M)\,dt\,dM}$$

From our Homework









AFTERSHOCK FORECAST

Mon 17 Jun 2002 02:10 PM PDT

U. S. Geological Survey, Menlo Park, California
U. C. Berkeley Seismological Laboratory, Berkeley, California

This forecast is based on the statistics of aftershocks typical for California. This is not an exact prediction, but only a rough guide to expected aftershock activity. This forecast may be revised as more information becomes available.

MAINSHOCK: Mon 17 Jun 2002 09:55:07 AM PDT MAGNITUDE 5.3

37 km (23 miles) W (275 degrees) of Eureka, CA

STRONG AFTERSHOCKS (Magnitude 5 and larger)

At this time (4 hours after the mainshock) the probability of a strong and possibly damaging aftershock IN THE NEXT 7 DAYS is approximately 10 PERCENT.

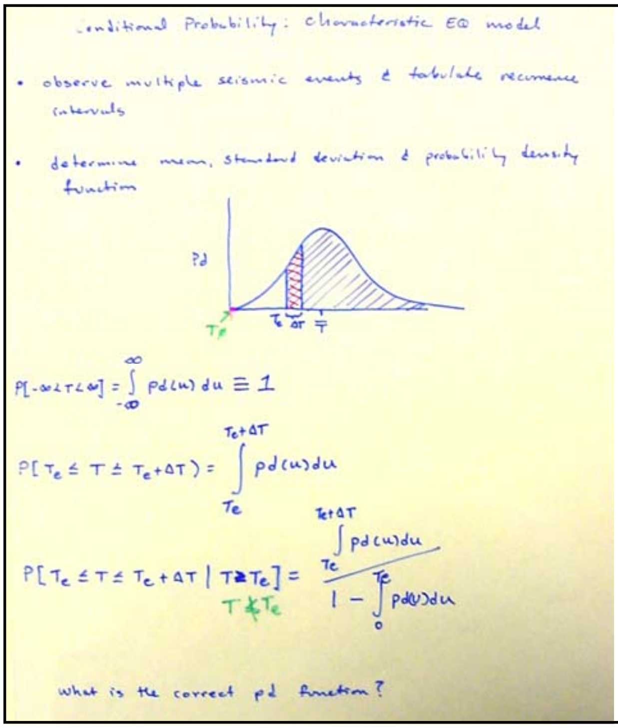
EARTHQUAKES LARGER THAN THE MAINSHOCK

Most likely, the recent mainshock will be the largest in the sequence. However, there is a small chance (APPROXIMATELY 5 TO 10 PERCENT) of an earthquake equal to or larger than this mainshock in the next 7 days.

WEAK AFTERSHOCKS (Magnitude 3 to 5)

In addition, approximately 3 to 20 SMALL AFTERSHOCKS are expected in the same 7-DAY PERIOD and may be felt locally.

- Poisson Model
  - Assumes random occurrence
  - Probability of occurrence does not change with time
  - Can be applied to seismicity catalogs
- Time Dependent Model
  - Assumes quasi-periodicity of characteristic seismicity (takes into account rate and time of previous event)
  - Probability of occurrence accumulates with passing time
  - Applied to fault-specific cases



Conditional Probability: characteristic EQ model

- observe multiple seismic events & tabulate recurrence intervals
- determine mean, standard deviation & probability density function

$$P[-\infty < T < \infty] = \int_{-\infty}^{\infty} pd(u)\,du \equiv 1$$

$$P[T_e \le T \le T_e + \Delta T) = \int_{T_e}^{T_e+\Delta T} pd(u)du$$

$$P[T_e \le T \le T_e + \Delta T \mid T \ge T_e] = \frac{\int_{T_e}^{T_e+\Delta T} pd(u)du}{1 - \int_{0}^{T_e} pd(u)du}$$

$T \nleq T_e$

what is the correct pd function?

Pallet Creek Recurrence

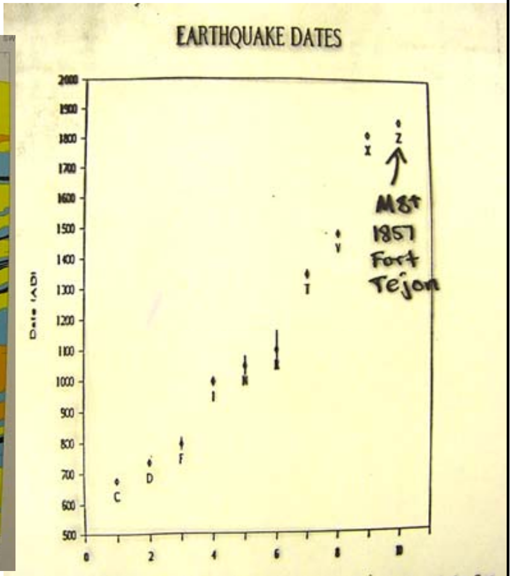
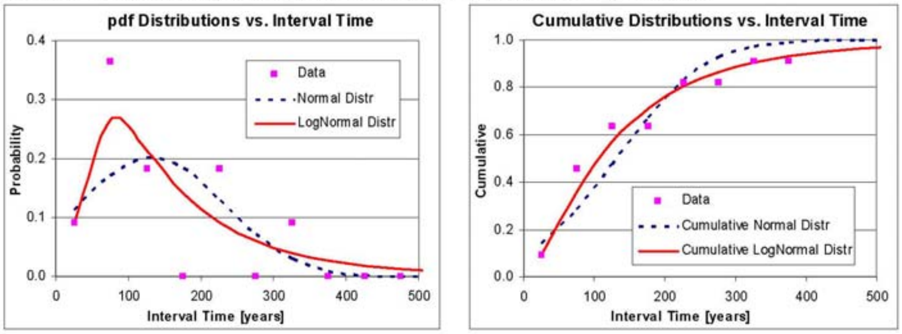
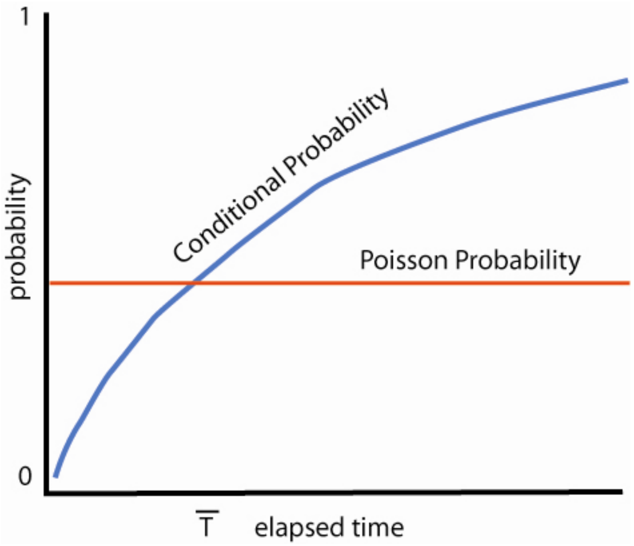


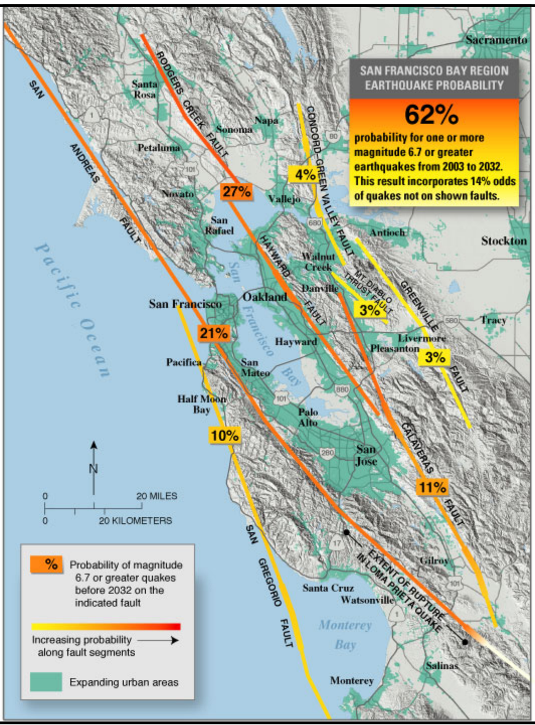
Fig. 5.33 Dates of the last 10 earthquakes to have ruptured the San Andreas fault at Pallet Creek, obtained from trenching studies. Error bars indicate uncertainties in the radiocarbon dates. (From Sieh, Stuiver, and Brillinger, 1989.)

These distributions can be plotted together with the data to see how well they fit the data.

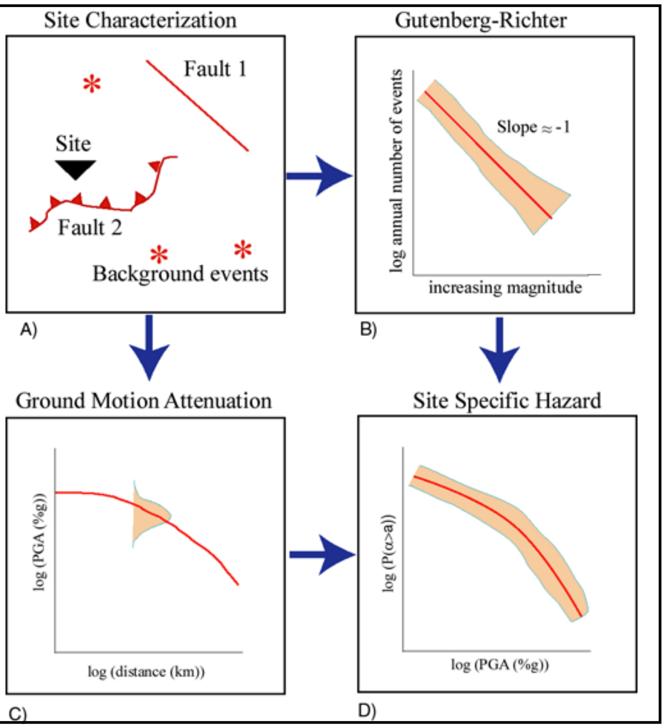


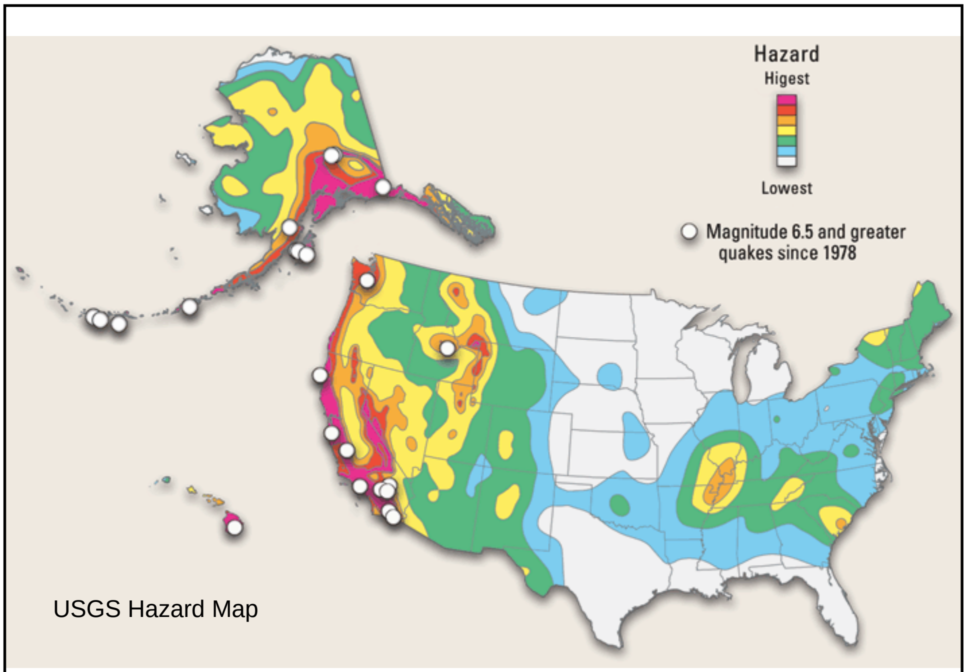
Poisson vs. Conditional Probability





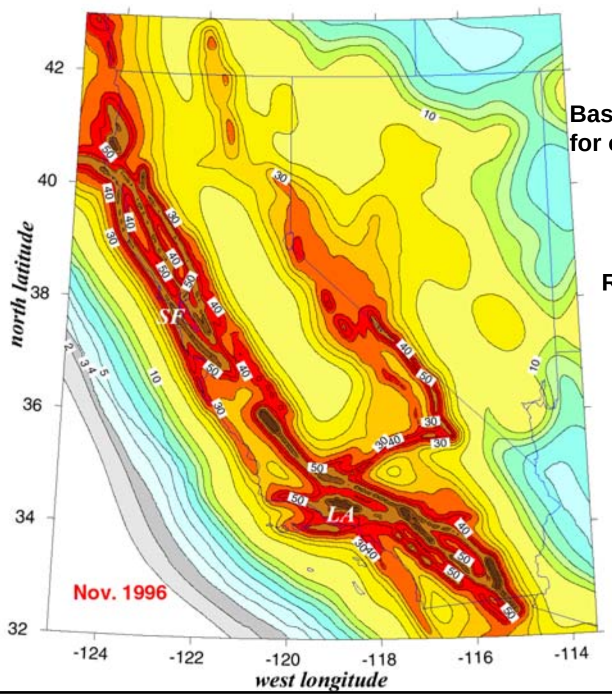
Putting it all together





USGS Hazard Map

Peak Acceleration (%g) with 10% Probability of Exceedance in 50 Years



Based on Poisson Probability for one or more events

$$P(\lambda, \Delta t) = 1 - e^{-\lambda \cdot \Delta t}$$

Rewrite for λ

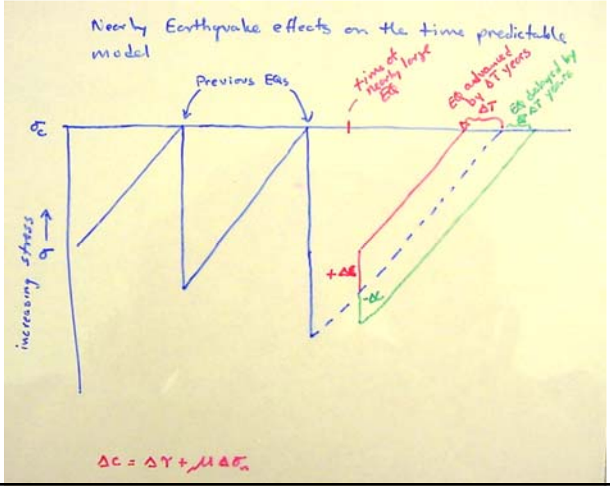
$$\lambda = \frac{-\ln(1-P)}{\Delta t}$$

10% probability of exceedance in 50 years gives a return period of

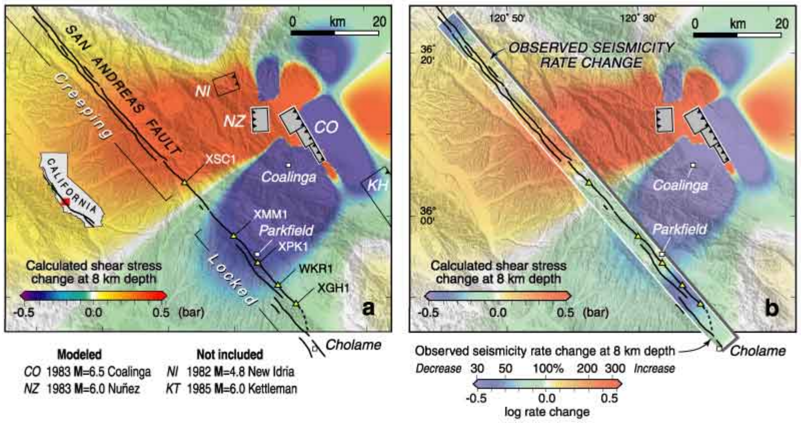
1/λ=475 years

We have so far assumed no fault interaction

How can nearby earthquakes affect forecasts?



Was Parkfield in a Stress Shadow?

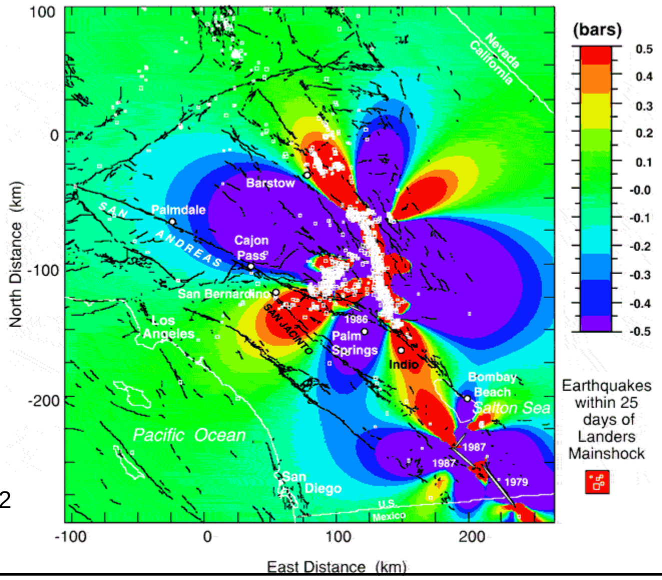


Toda and Stein, 2001

http://quake.wr.usgs.gov/research/deformation/modeling/people/ross.html

Fig. 1

Lead up to Landers



Stein et al., 1992

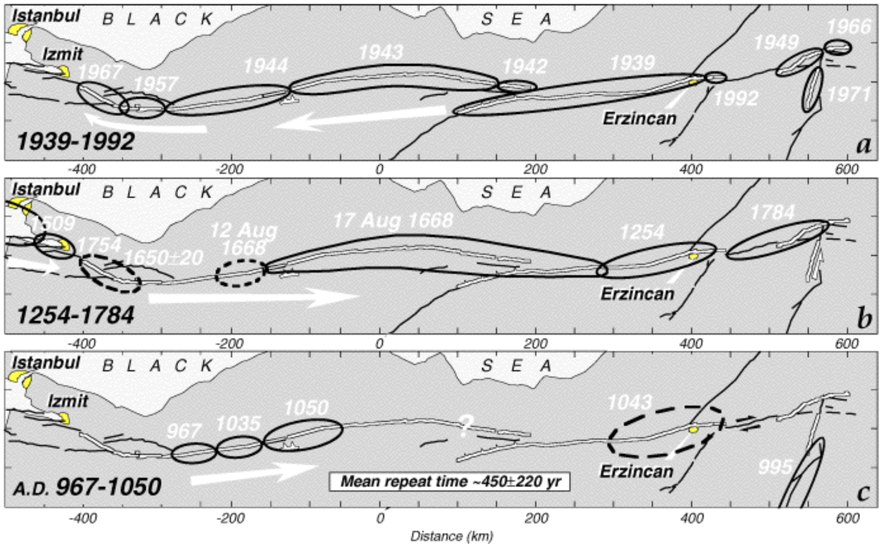


Fig. 7 *17 Oct 96* ***Stein et al.***

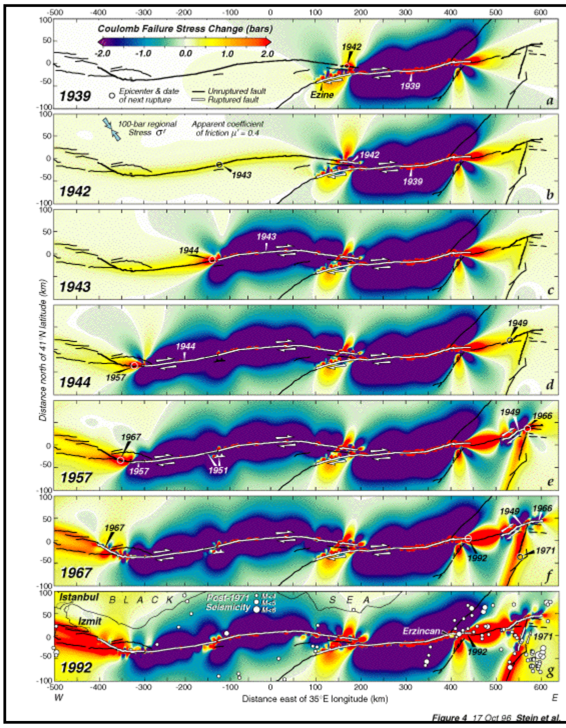
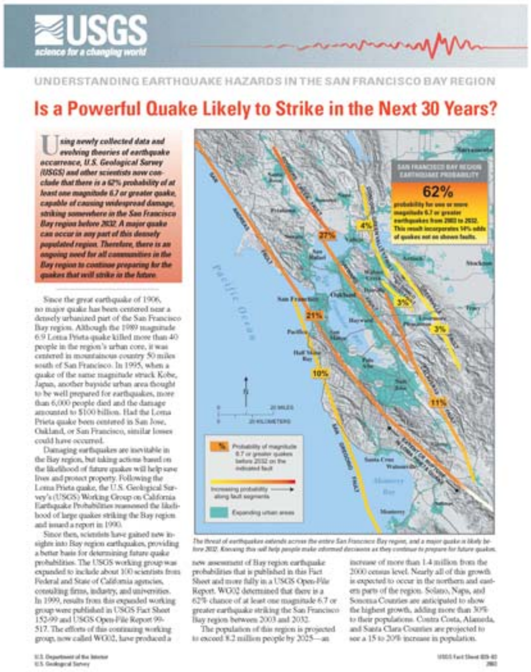


Figure 4 17 Oct 96 Stein et al.

Lead up to Izmit

http://pubs.usgs.gov/fs/2003/fs039-03/fs039-03.pdf



UNDERSTANDING EARTHQUAKE HAZARDS IN THE SAN FRANCISCO BAY REGION

Is a Powerful Quake Likely to Strike in the Next 30 Years?

Using newly collected data and evolving theories of earthquake occurrence, U.S. Geological Survey (USGS) and other scientists now conclude that there is a 62% probability of at least one magnitude 6.7 or greater quake, capable of causing widespread damage, striking somewhere in the San Francisco Bay region before 2032. A major quake can occur in any part of this densely populated region. Therefore, there is an ongoing need for all communities in the Bay region to continue preparing for the quakes that will strike in the future.

Since the great earthquake of 1906, no major quake has been centered near a densely urbanized part of the San Francisco Bay region. Although the 1989 magnitude 6.9 Loma Prieta quake killed more than 40 people in the region's urban core, it was centered in mountainous country 50 miles south of San Francisco. In 1995, when a quake of the same magnitude struck Kobe, Japan, another bayside urban area thought to be well prepared for earthquakes, more than 6,000 people died and the damage amounted to $100 billion. Had the Loma Prieta quake been centered in San Jose, Oakland, or San Francisco, similar losses could have occurred.

Damaging earthquakes are inevitable in the Bay region, but taking actions based on the likelihood of future quakes will help save lives and protect property. Following the Loma Prieta quake, the U.S. Geological Survey's (USGS) Working Group on California Earthquake Probabilities reassessed the likelihood of large quakes striking the Bay region and issued a report in 1990.

Since then, scientists have gained new insights into Bay region earthquakes, providing a better basis for determining future quake probabilities. The USGS working group was expanded to include about 100 scientists from Federal and State of California agencies, consulting firms, industry, and universities. In 1999, results from this expanded working group were published in USGS Fact Sheet 152-99 and USGS Open-File Report 99-517. The efforts of this continuing working group, now called WG02, have produced a new assessment of Bay region earthquake probabilities that is published in this Fact Sheet and more fully in a USGS Open-File Report. WG02 determined that there is a 62% chance of at least one magnitude 6.7 or greater earthquake striking the San Francisco Bay region between 2003 and 2032.

The population of this region is projected to exceed 8.2 million people by 2025—an increase of more than 1.4 million from the 2000 census level. Nearly all of this growth is expected to occur in the northern and eastern parts of the region. Solano, Napa, and Sonoma Counties are anticipated to show the highest growth, adding more than 30% to their populations. Contra Costa, Alameda, and Santa Clara Counties are projected to see a 15 to 20% increase in population.

The threat of earthquakes extends across the entire San Francisco Bay region, and a major quake is likely before 2032. Knowing this will help people make informed decisions as they continue to prepare for future quakes.

U.S. Department of the Interior
U.S. Geological Survey

USGS Fact Sheet 039-03
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