Progress and Pitfalls in Earthquake Prediction and Forecasting

Presentation to the APS MASPG
by Dr. Michael L. Blanpied
Associate Coordinator
USGS Earthquake Hazards Program

USGS
science for a changing world

Earthquake Hazards and Impacts

- Strong shaking
- Ground fracture
- Landslides
- Liquefaction
- Damage to structures
- Severing of roads, bridges, pipelines, sewers, communication networks
- Levee breaks, floods
- Hazmat spills
- Fires ignited
- Tsunami waves


Demons escape from crack in California freeway!
WEEKLY WORLD NEWS
Exclusive photo!
L.A. QUAKE OPENS GATES OF HELL!
President puts National Guard on red alert!

USGS
science for a changing world

Can Earthquakes Be Predicted?

USGS
science for a changing world

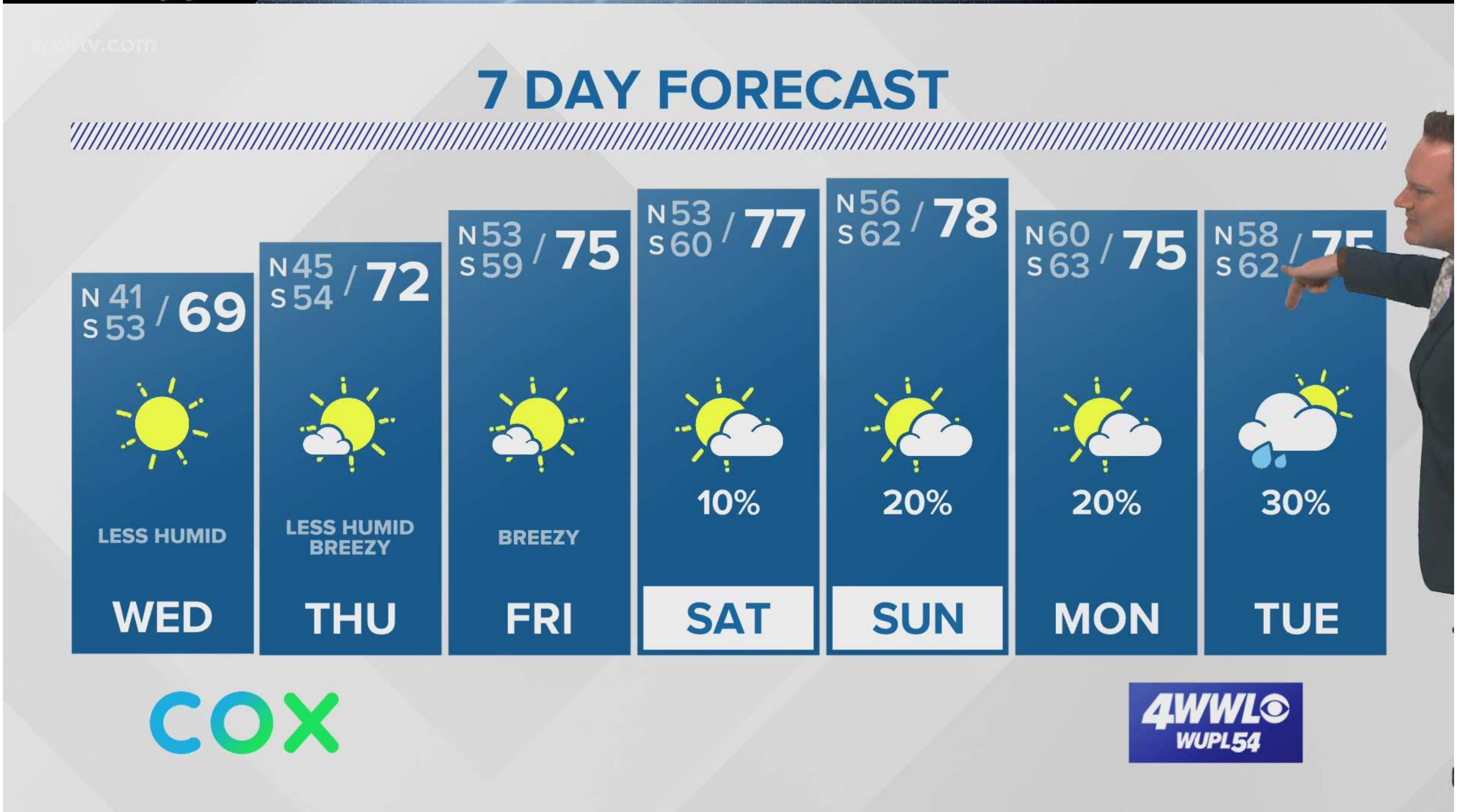
Basilica of Saint Benedict in Norcia, Italy, built in the 14th century.

Collapsed in the M 6.5 earthquake of October 30, 2016.

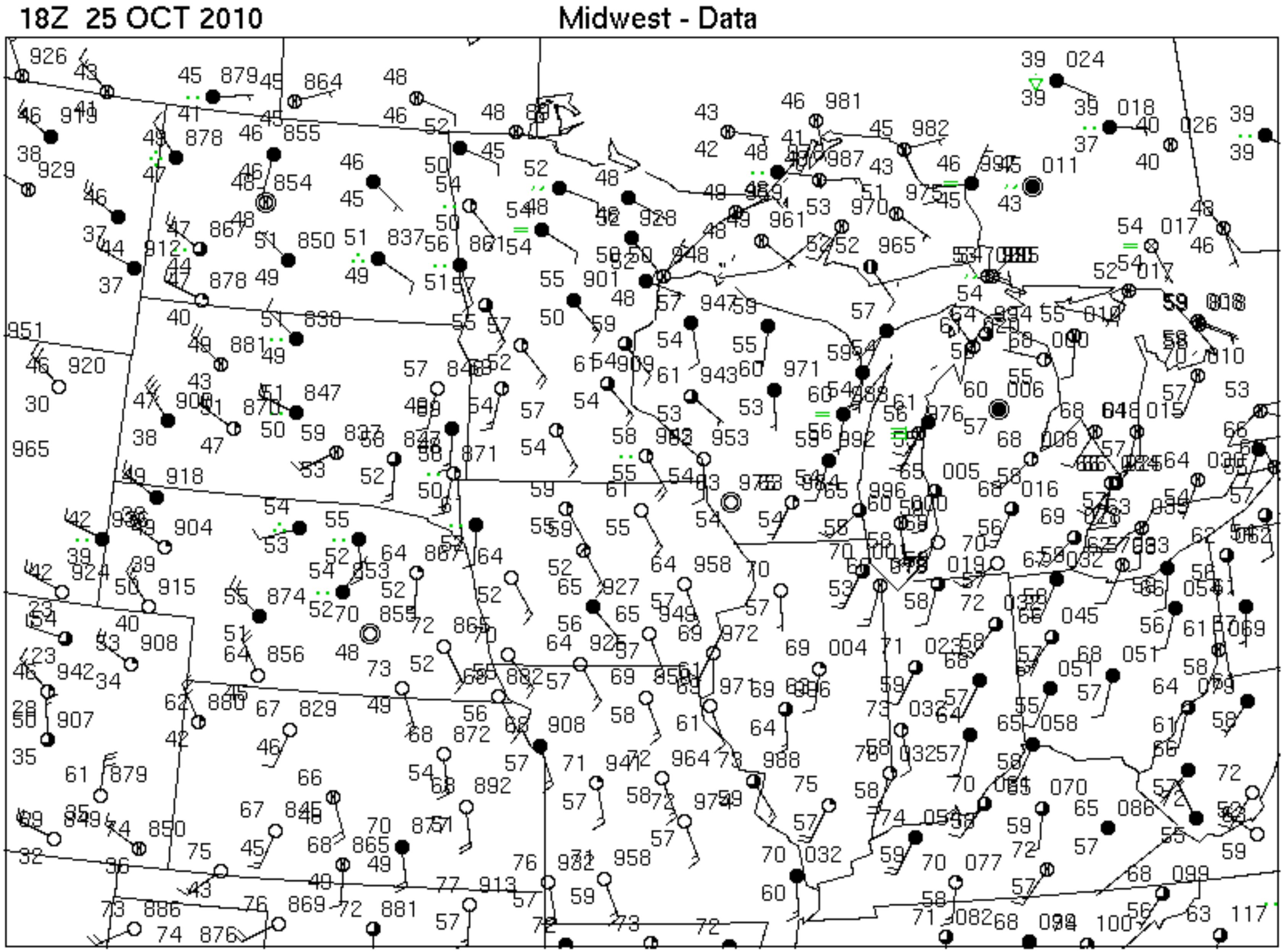
USGS
science for a changing world

Amatrice, central Italian Apennines.

Devastation from M 6.2 earthquake of August 24, 2016.

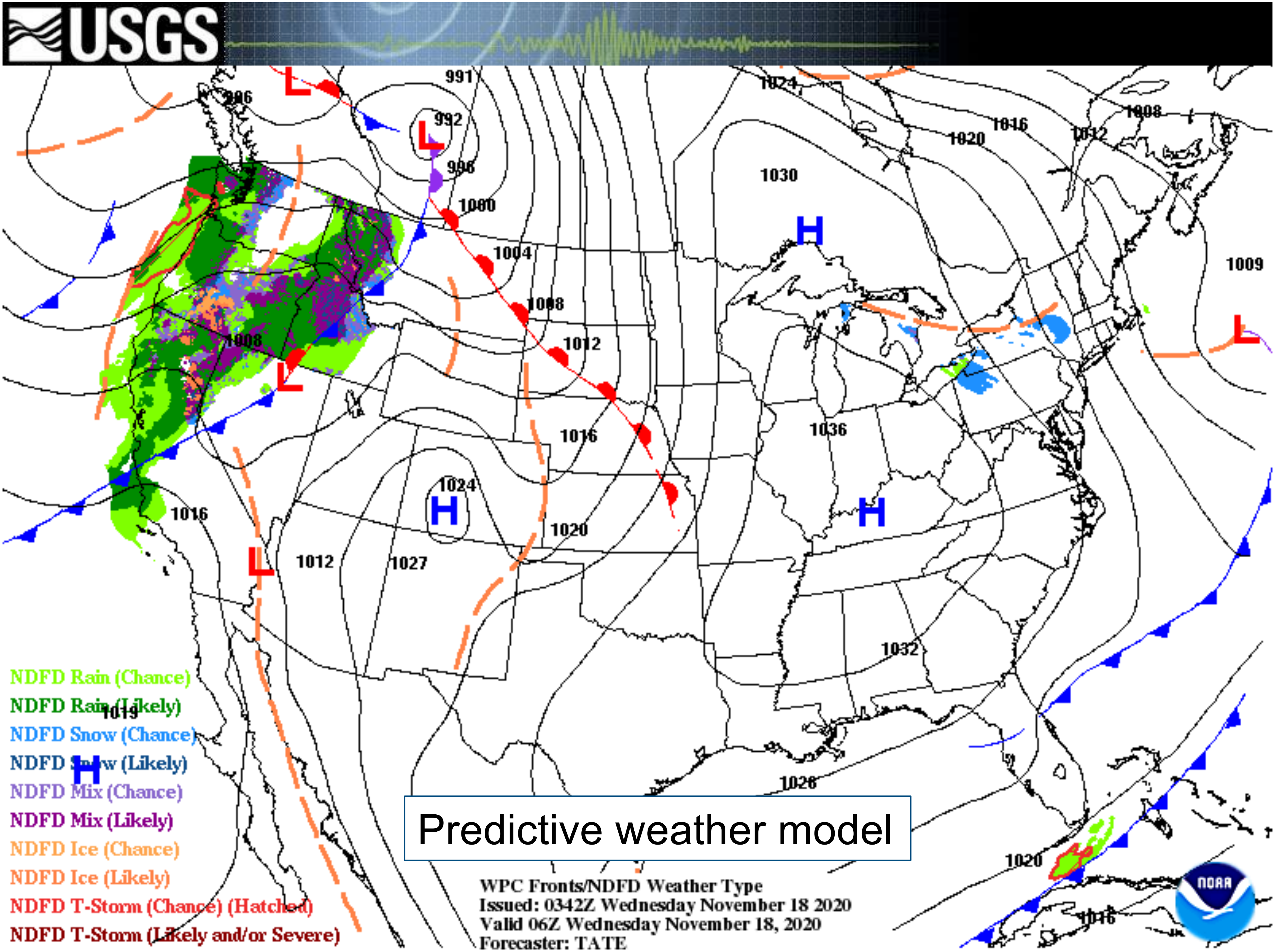


Weather forecast of temperature, cloud cover, precipitation, wind, with onset time of conditions, and probability of rainfall.



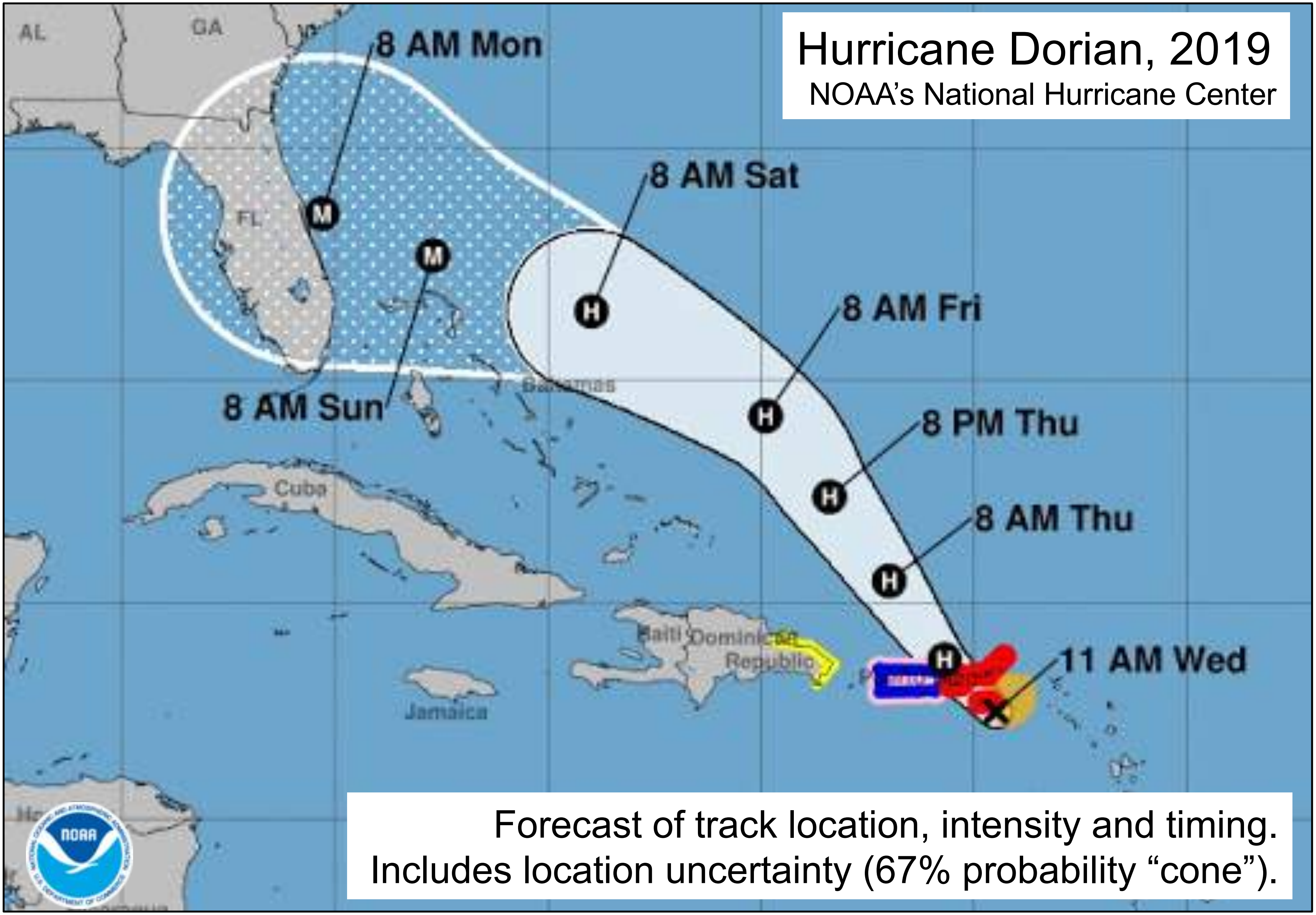
Data: temperature, wind velocity, barometric pressure, etc.

Predictive weather model



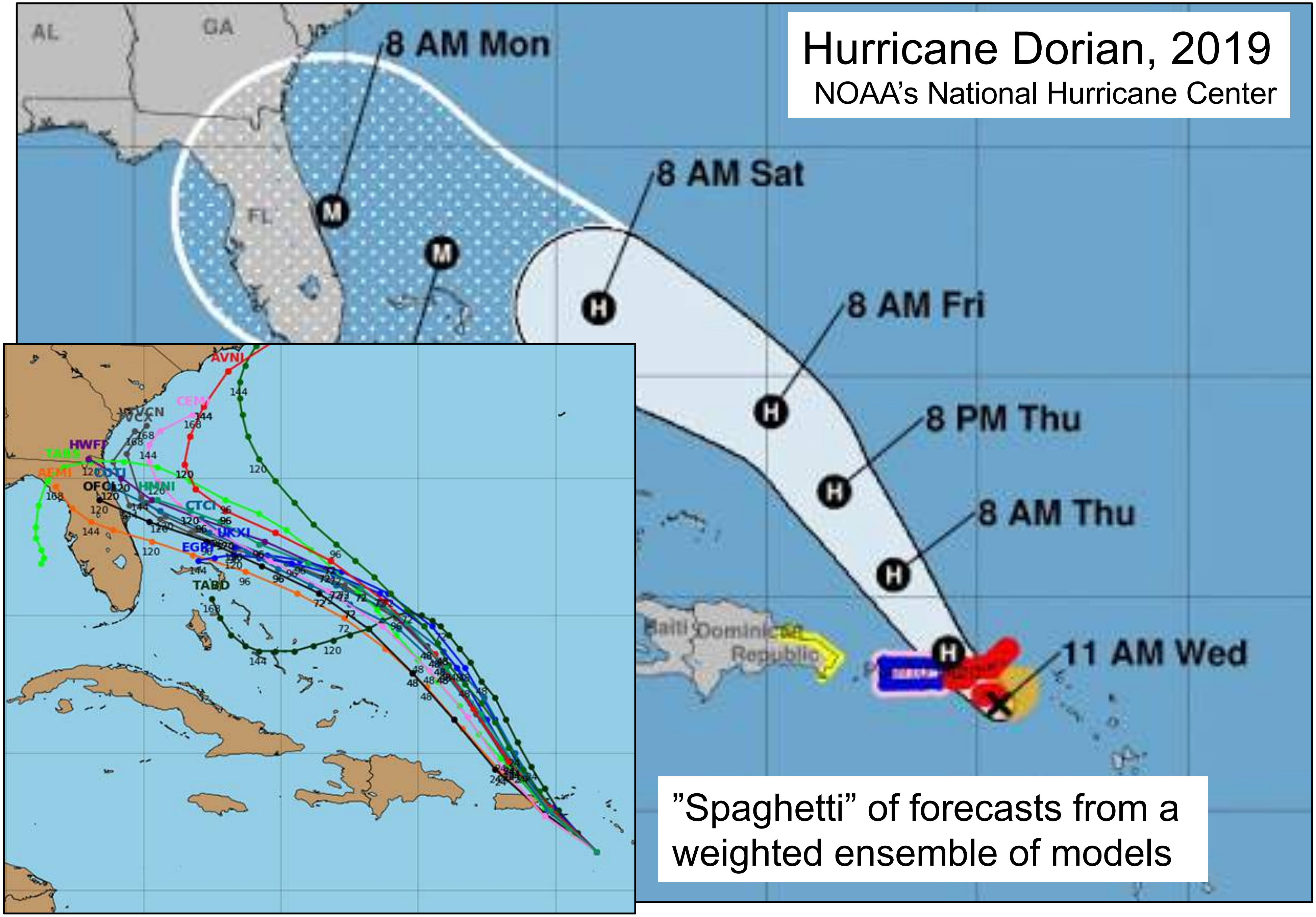
USGS
science for a changing world

Hurricane Dorian, 2019
NOAA's National Hurricane Center



Forecast of track location, intensity and timing.
Includes location uncertainty (67% probability "cone").

Hurricane Dorian, 2019
NOAA's National Hurricane Center

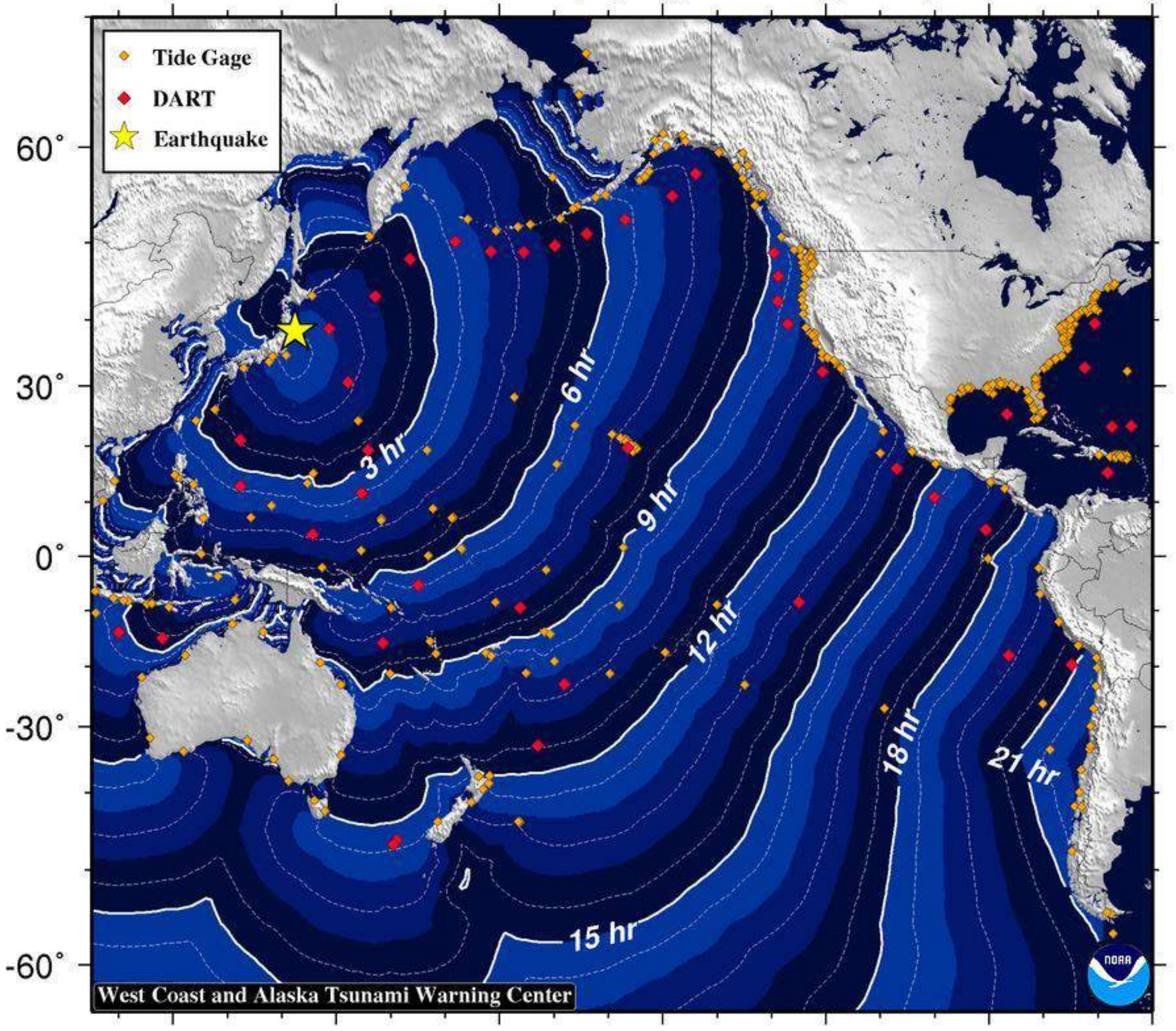


"Spaghetti" of forecasts from a weighted ensemble of models

USGS
science for a changing world

Tsunami Travel Times

Tsunami travel time contours in hours, beginning from the earthquake origin time.



Modeled tsunami following M9.0 Tohoku-Oki, Japan earthquake of March 11, 2011.

NOAA Tsunami Warning Center model forecasts wave height and arrival time.

Wave propagation is modeled from water depth, constrained by data from tide gages and DART buoys.

Earthquake Early Warning system

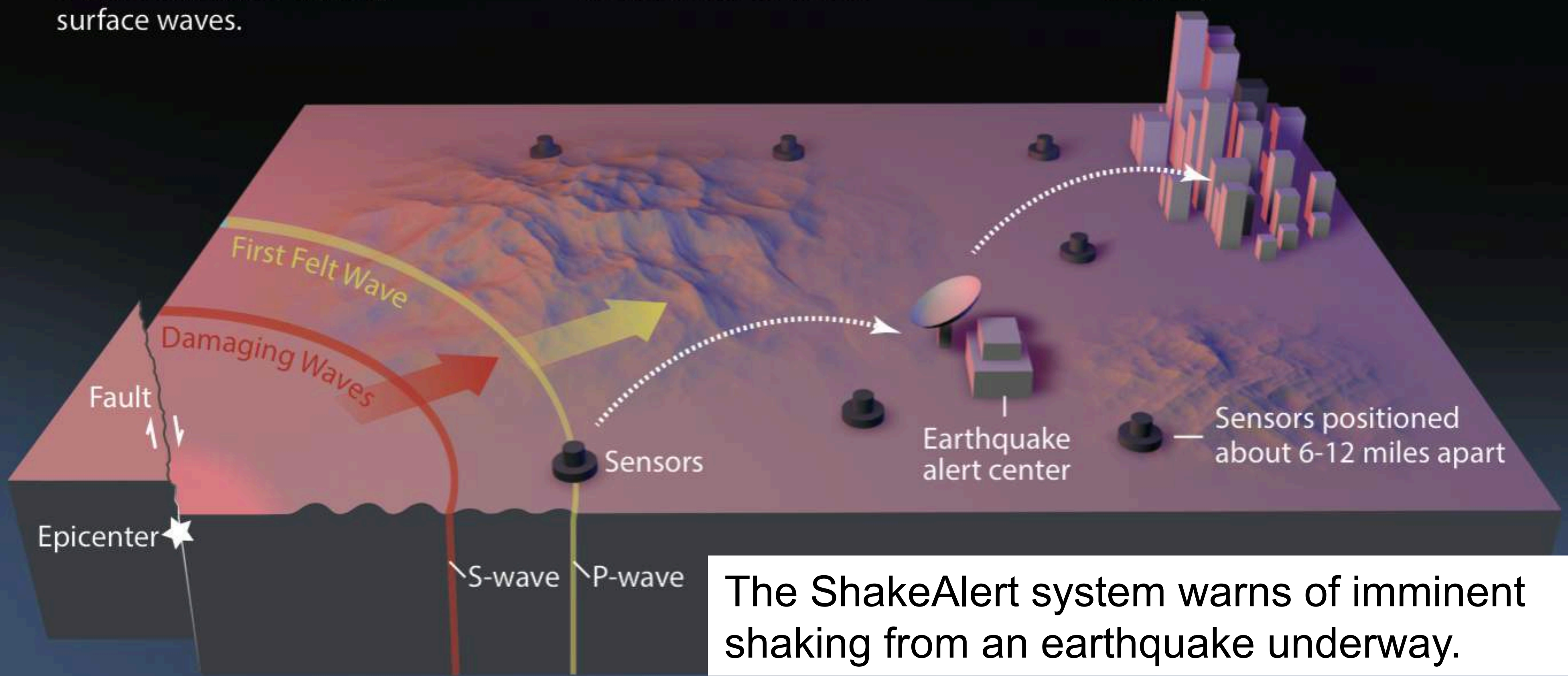
ShakeAlert

An Earthquake Early Warning System for the US West Coast

1 In an earthquake, a rupturing fault sends out different types of waves. The fast-moving P-wave is first to arrive, but damage is caused by the slower S-waves and later-arriving surface waves.

2 Sensors detect the P-wave and immediately transmit data to an earthquake alert center where the location and size of the quake are determined and updated as more data become available.

3 A message from the alert center is immediately transmitted to your computer or mobile phone, which calculates the expected intensity and arrival time of shaking at your location.



The ShakeAlert system warns of imminent shaking from an earthquake underway.

Can Earthquakes Be Predicted?

- Depends on what you mean by "predicted"
- Location
  - Hypocenter
  - Fault
  - Rupture extent
  - Energy centroid
- Magnitude
- Time
- Earthquake rate
- Impacts

"Is it possible to predict the magnitude, location and time of an earthquake?"

Can Earthquakes Be Predicted?

- Depends on what you mean by "predicted"
- Location
  - Hypocenter
  - Fault
  - Rupture extent
  - Energy centroid
- Magnitude
- Time
- Earthquake rate
- Impacts

"Is it ^currently or theoretically^ possible to predict the magnitude, location and time of an important earthquake a short time in advance, with confidence and accuracy sufficient to warrant special actions?"

Approaches to Earthquake Prediction

- Based on periodic recurrence of similar earthquakes
- Based on seismicity patterns
- Based on predisposing conditions
- Based on observed precursors
  - Relating to the earthquake nucleation process
  - Relating to fault or regional readiness

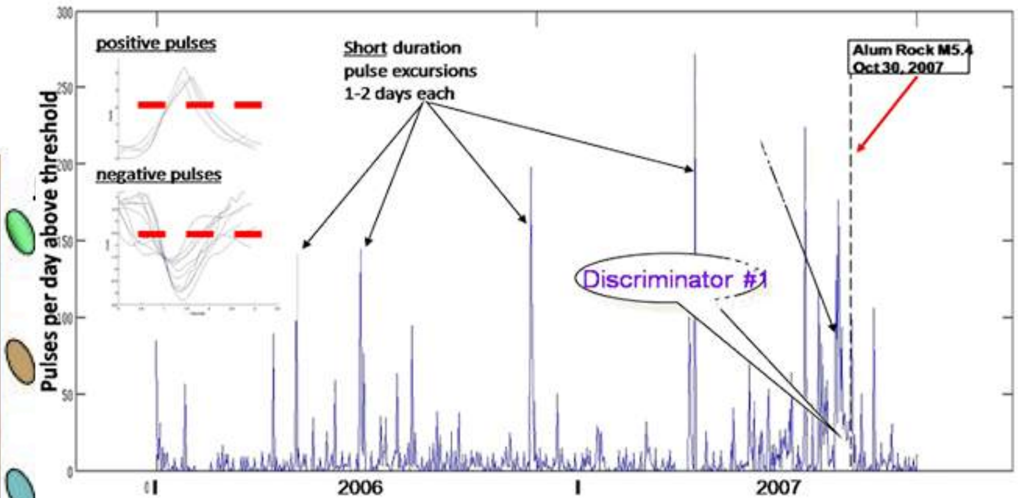
Precursor-based prediction

- Foreshocks
- Seismicity rate change
- Change in eq statistics
- Surface strain
- Borehole strain
- Fault creep
- Surface cracking
- Well water levels
- Accelerating moment release
- Water chemistry
- Gaseous emissions
- EM signals
- Ionospheric disturbance
- Surface or air heating
- Cloud patterns
- Animal behavior
- Planetary motions
- Earthquake sensitives

There is an enormous literature on scientific exploration of these and other potential earthquake precursors.

And an equally large history of non-scientific trials and claims.

This non-profit venture attempted to use observations of low-frequency magnetic signals for earthquake prediction.



- 3 axis mag.
- GPS
- GlobalStar
- Air Conduct.
- Geophone

Berkeley

Future Sites

Stanford (2005)

QF-1005 (2005)

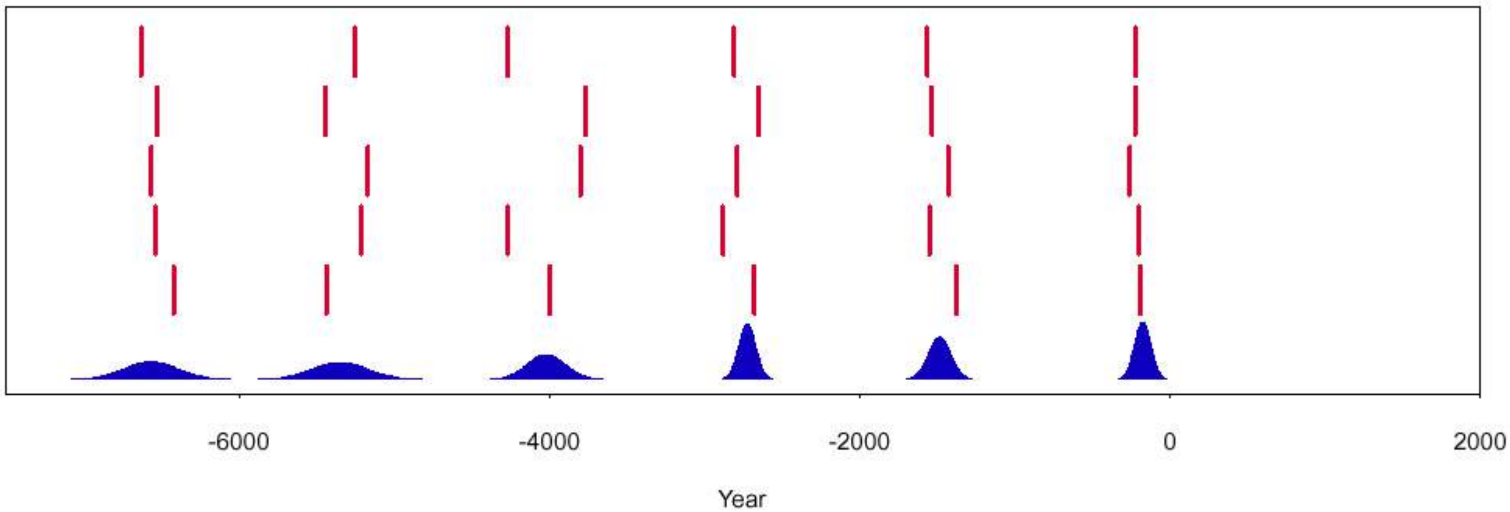
USGS
science for a changing world

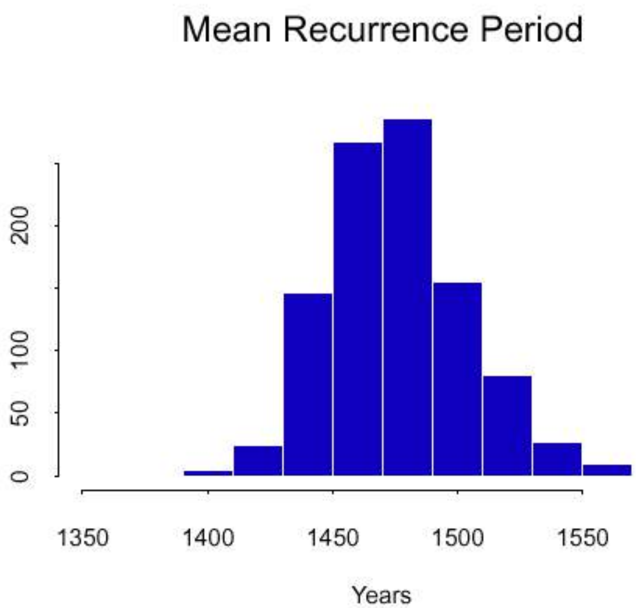
Richter on Predictors

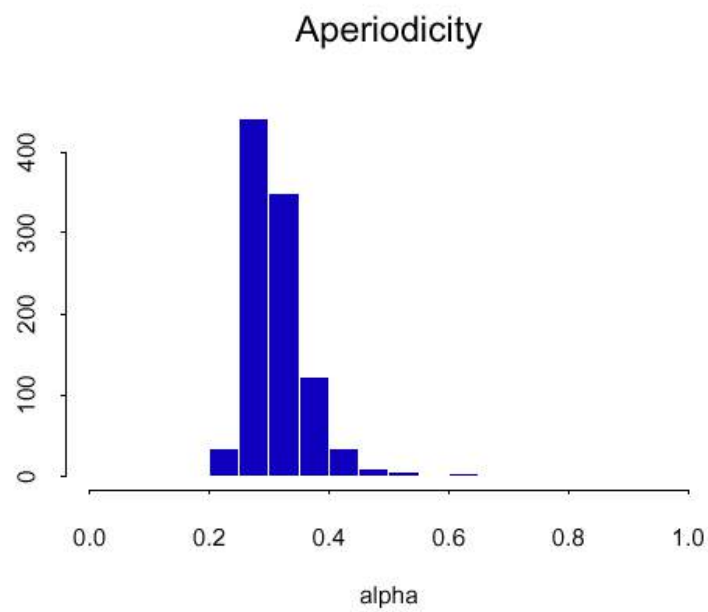
"Since my first attachment to seismology, I have had a horror of predictions and of predictors. Journalists and the general public rush to any suggestion of earthquake prediction like hogs toward a full trough.... [Prediction] provides a happy hunting ground for amateurs, cranks, and outright publicity-seeking fakers. The vaporings of such people are from time to time seized upon by the news media, who then encroach on the time of men who are occupied in serious research."

C.F. Richter (1977)

Earthquake cycle on the Wasatch



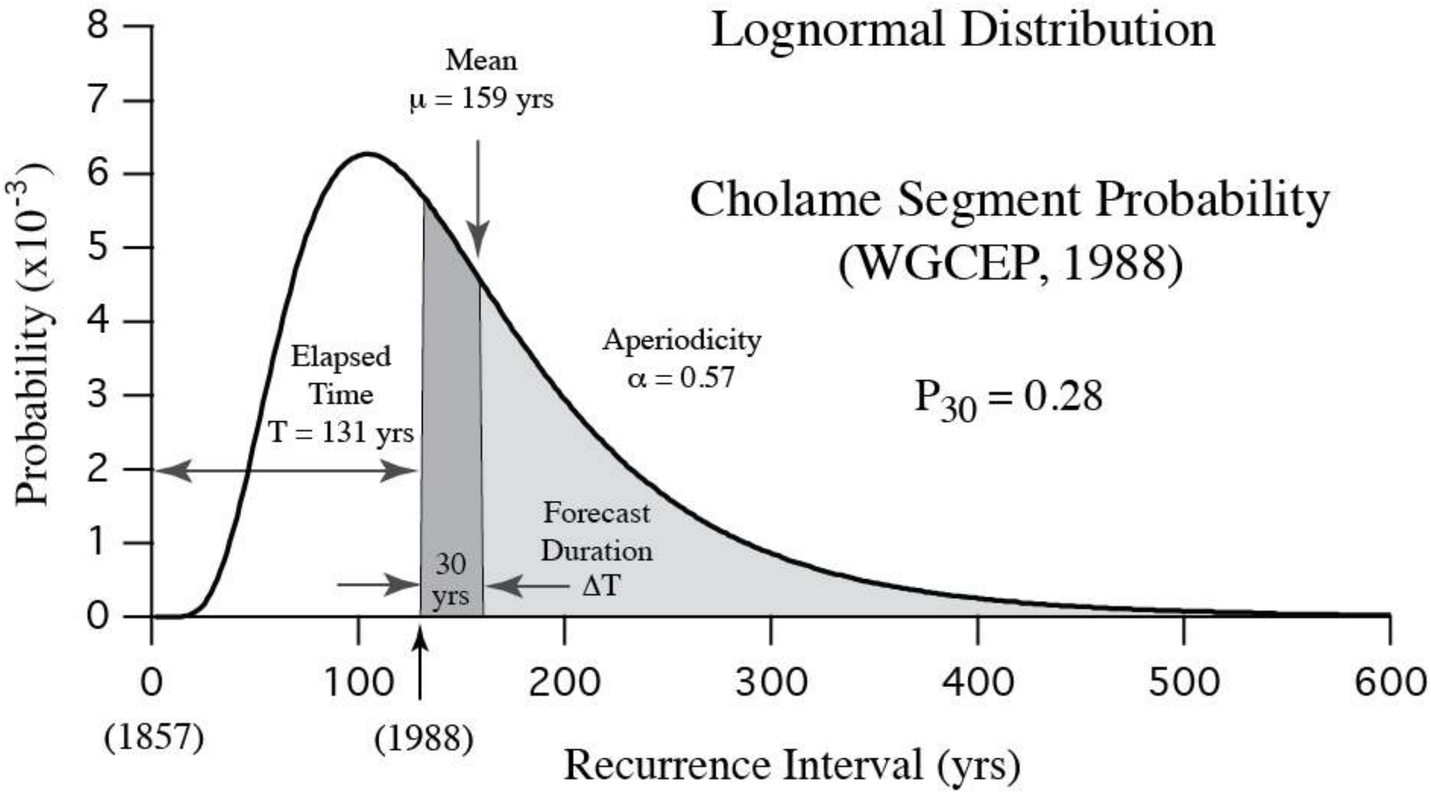




Renewal Model for Earthquake Recurrence

$$f(t)$$

Distribution (PDF) of recurrence intervals (RIs)



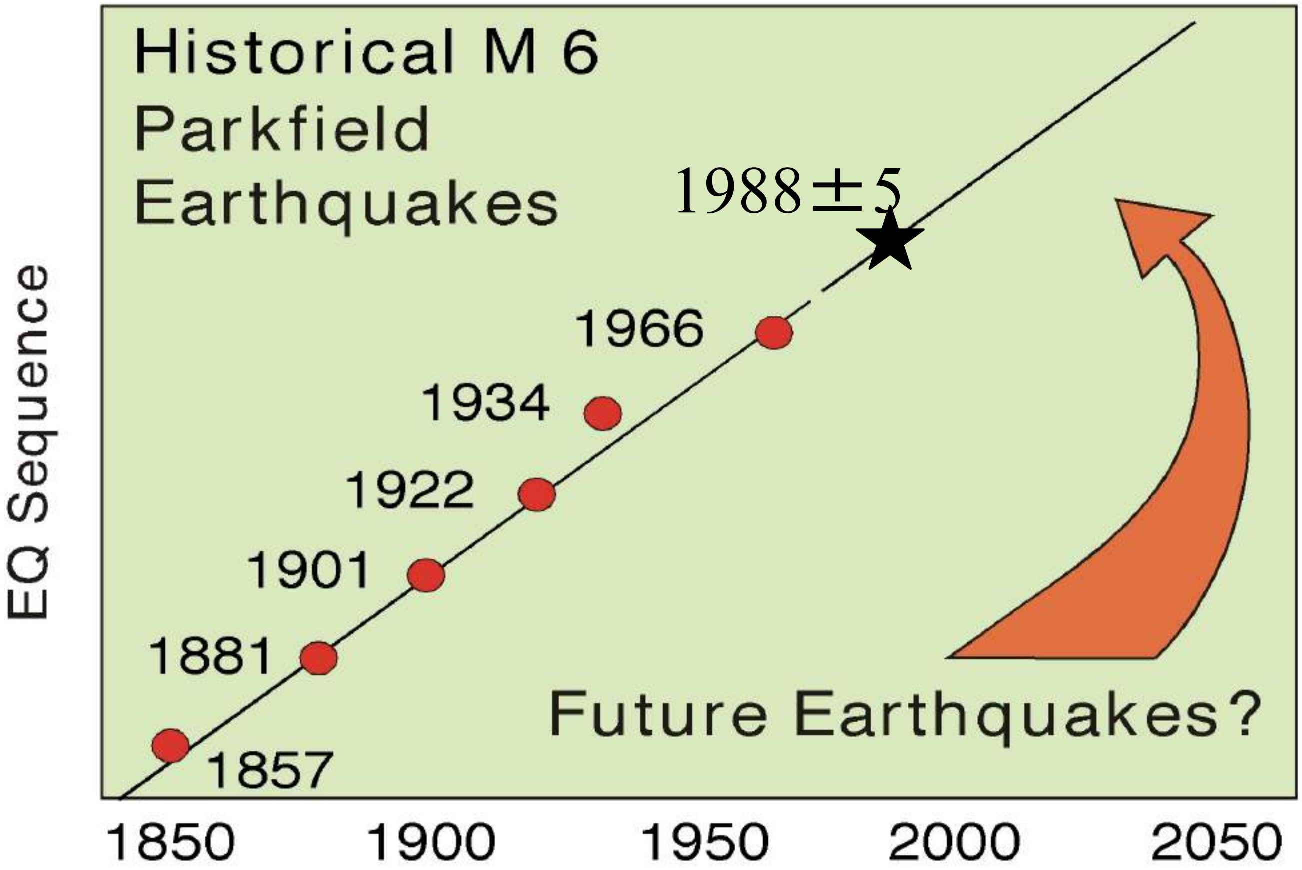
Conditional probability of occurrence during interval ΔT, given that it has not yet occurred:

Time Since Last Event

Forecast Duration

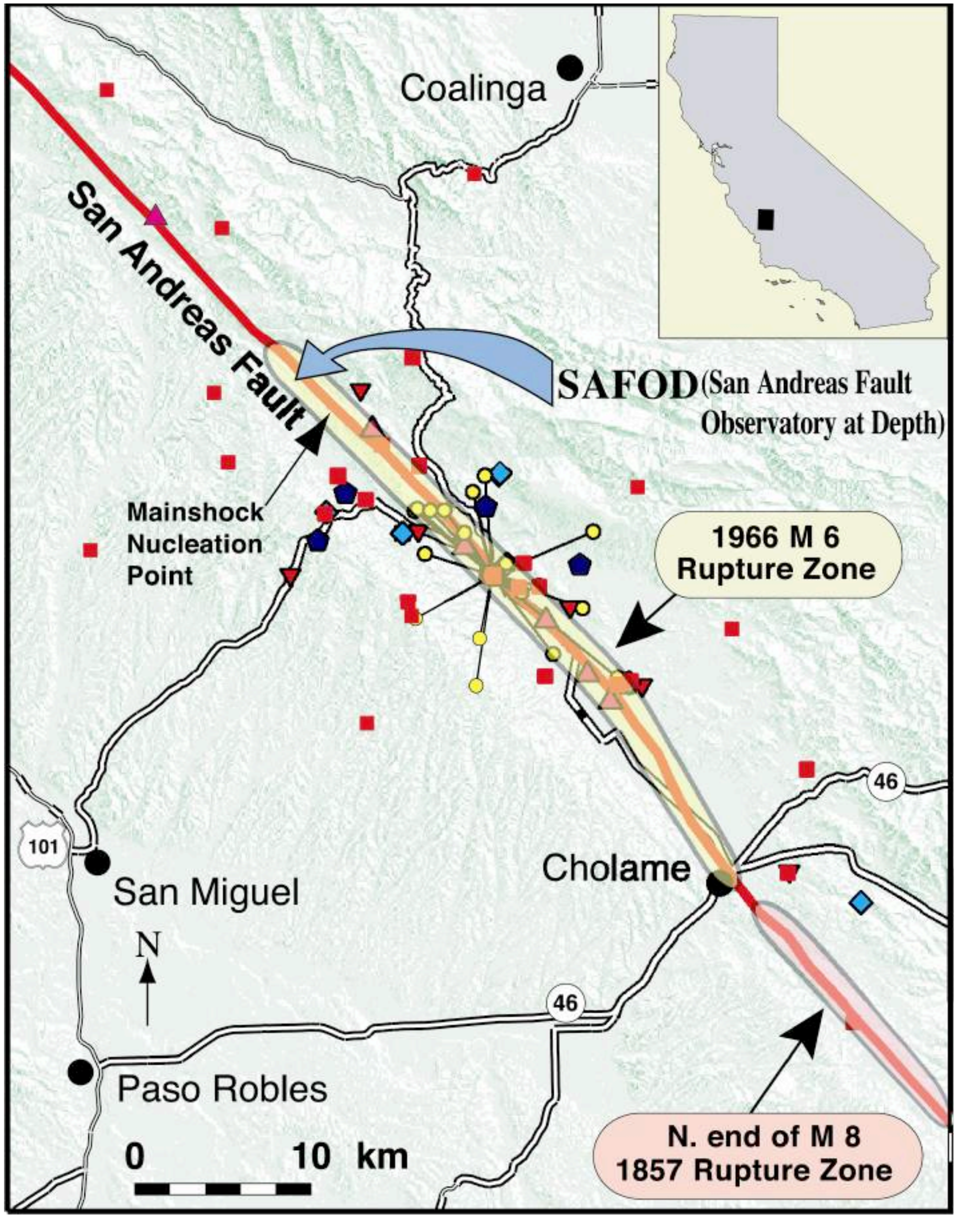
$$P(T \leq t \leq T + \Delta T | t > T) = \frac{\int_T^{T+\Delta T} f(t)dt}{\int_T^{\infty} f(t)dt}$$

Parkfield Earthquake Experiment



- Based on observed recurrence and similarity of previous M~6 earthquakes, “characteristic earthquake” with R.I. = 22 years.
- In 1985 USGS predicted next event to occur before 1993.
- NEPEC endorsed prediction & its assigned probability of 95%.

USGS science for a changing world

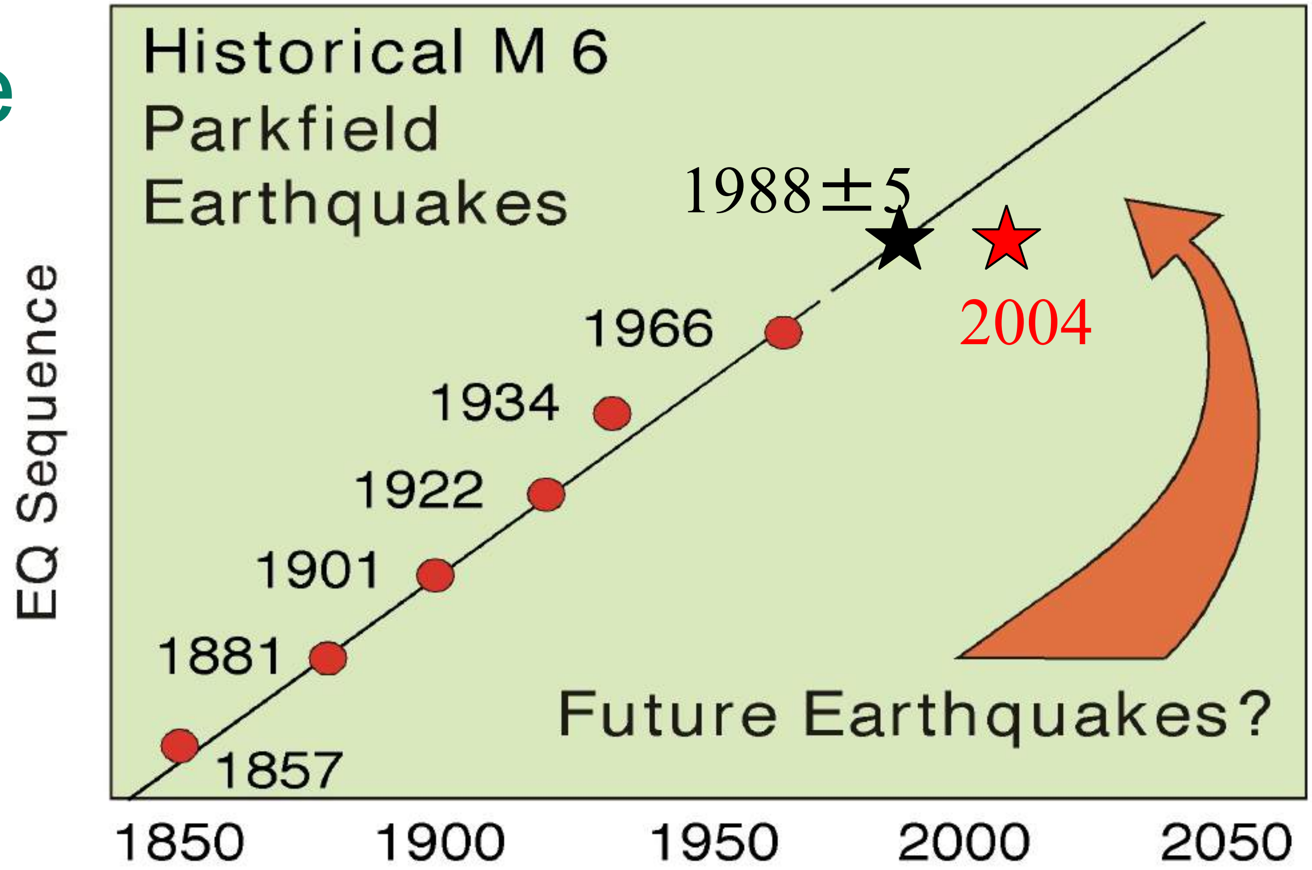


Surface Monitoring Instrumentation

Goals of the Parkfield Experiment

- Test the feasibility of short-term earthquake prediction, based on recurrence model, and on observed precursors.
- Communication of warnings.
- Observe the build-up and release of stresses on the San Andreas Fault through multiple earthquake cycles.
- Measure near-fault ground motion and the amplification of shaking by different soil types, for improving building codes and engineering designs.

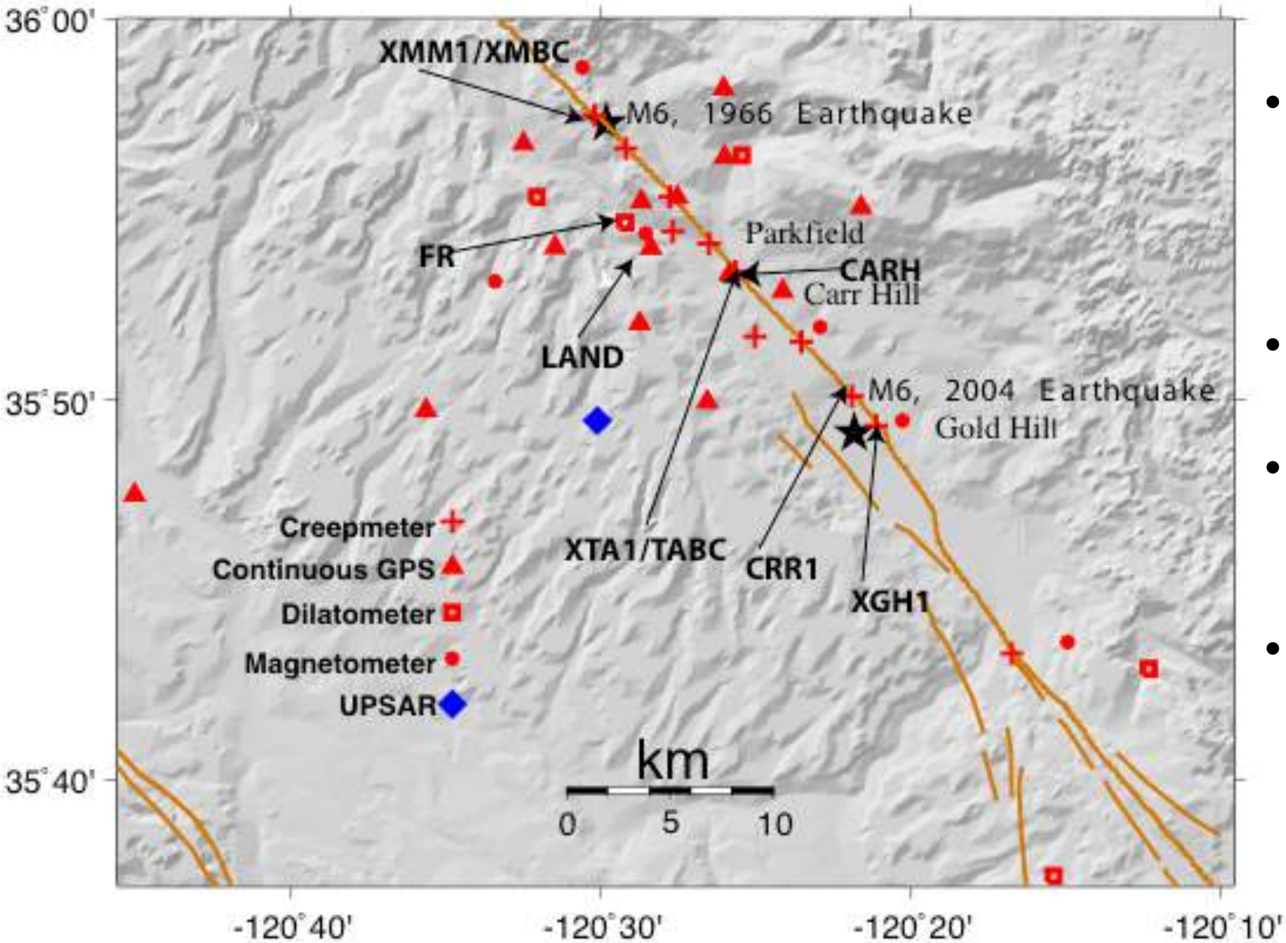
Results of the Parkfield Earthquake Experiment



- Earthquake did not occur within predicted interval.
- In 1994 NEPEC recommended that observations be continued.
- Widely agreed that 95% probability had been incorrect.
- M6.0 earthquake occurred in September 2004.

Parkfield precursors?

Monitoring sites



Observations prior to Sept. 28, 2004 Earthquake:

- **No foreshocks M > 0**
- **Absence of clear premonitory deformation on strainmeters.**
- **No water level changes.**
- **No precursory fault slip detected on creepmeters.**
- **Difference in total magnetic field between instruments varied by less than 1 nT – No Precursory Signals.**

Lessons from 2004 Parkfield Earthquake

- Earthquake magnitude and location were predicted
  - …but hypocenter and rupture direction were not
- Earthquake sequence is periodic
  - …but with a variability far greater than earlier assumed.
  - The 2004 quake did occur within 95% uncertainty interval, if calculated with aperiodicity of ~45% of mean recurrence time.
- No observable precursors
  - Strain, creep, water level, EM, ground cracks, or foreshocks
- Conclusion 1: Nucleation patch or volume is very small
- Conclusion 2: Slip and energy release are highly variable

- *Positive:* Invaluable data were collected both before and during the earthquake.

USGS
science for a changing world

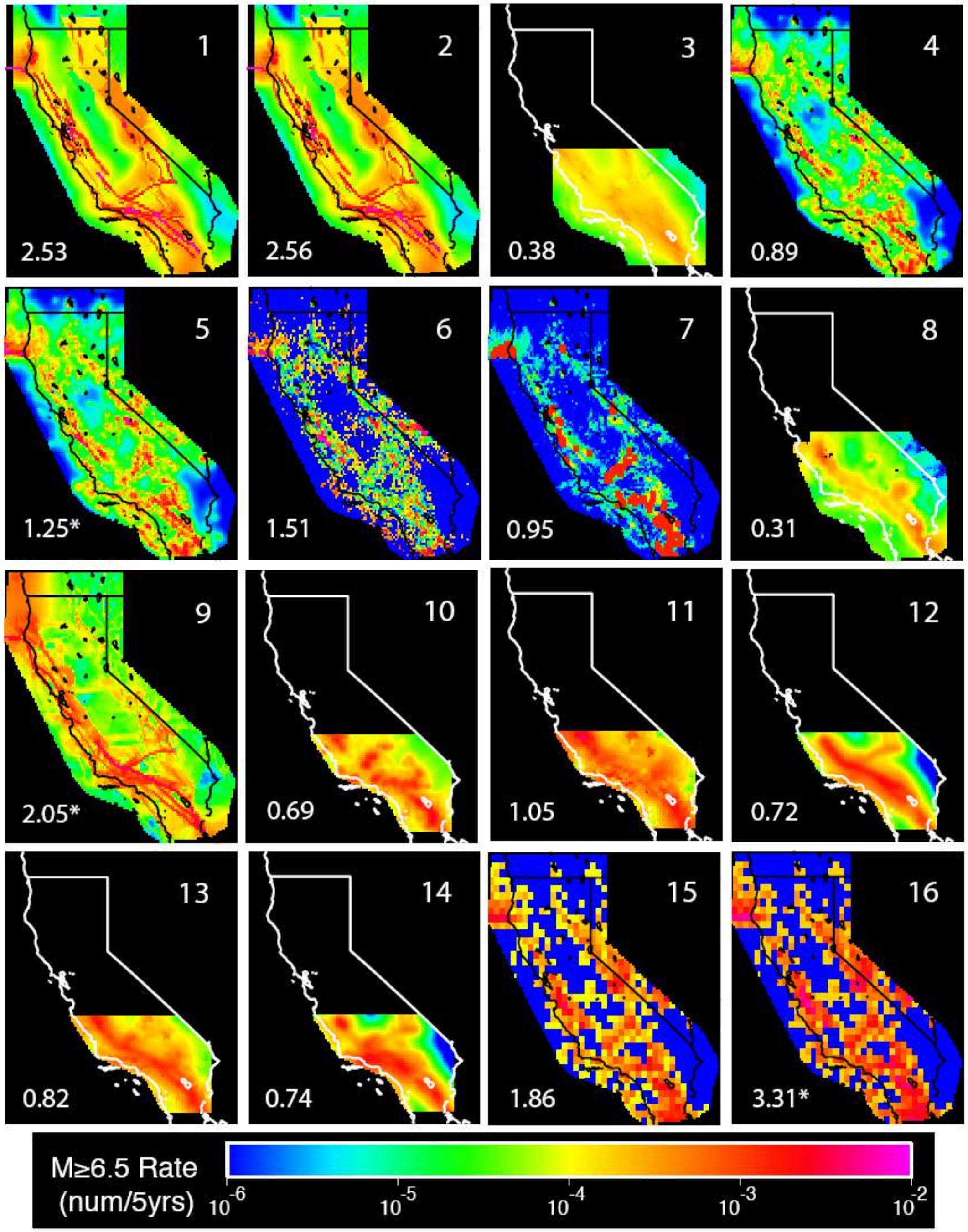
Earthquake Prediction Is Hard (or impossible?)

- No pre-seismic process has been observed.
- Sobering hypothesis 1: An observable pre-seismic process exists, but it is small and its location cannot be predicted.
- Sobering hypothesis 2: There is a pre-seismic process, but it is the same for both large and small earthquakes.
- Sobering hypothesis 3: There is no pre-seismic process that produces observable or distinguishable signals.

So…what can we do to usefully predict or forecast earthquakes?

Research continues…

- Increased appreciation for the fact that earthquake prediction research requires rigor, patience, diligence and dispassion.
- Promising research paths:
  - Human-induced seismicity
  - Borehole observations
  - Mining observations
  - Repeating micro-earthquakes
  - Non-volcanic tremor
  - Creep events
  - Region- and system-level modeling
  - Prospective, global tests
  - Big, new data streams
  - Machine-learning approaches



Rigorous testing of prediction hypotheses

Regional Earthquake Likelihood Models (RELM) experiment.

Five-year forecasts for M ≥ 6.5.

Head-to-head comparisons and exacting statistical tests revealed differences in skill.

Collaboratory for the Study of Earthquake Predictability
CSEPtesting.org

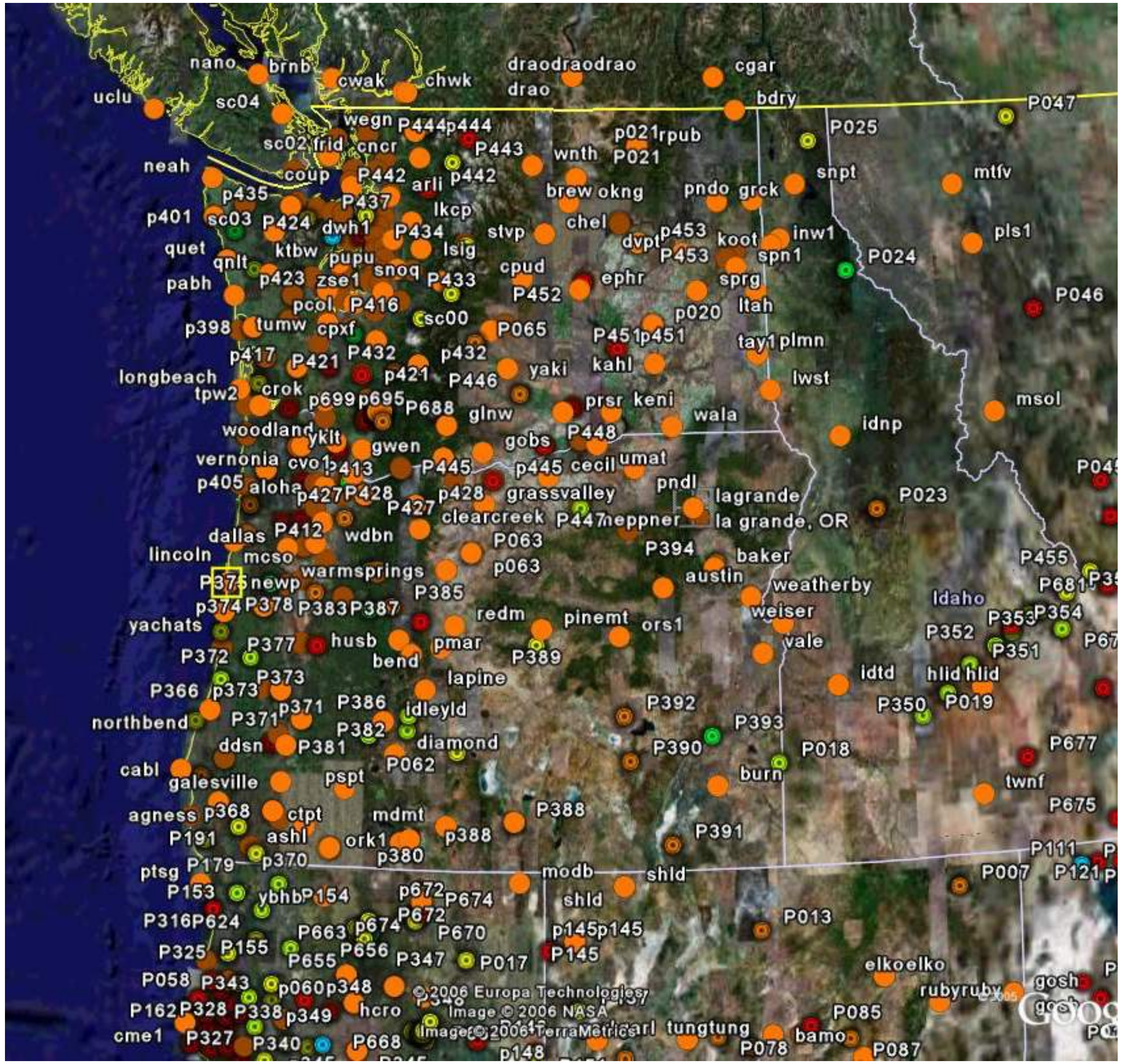
USGS
science for a changing world

GPS strain monitoring in Cascadia

GPS/GNSS stations and borehole strainmeters.

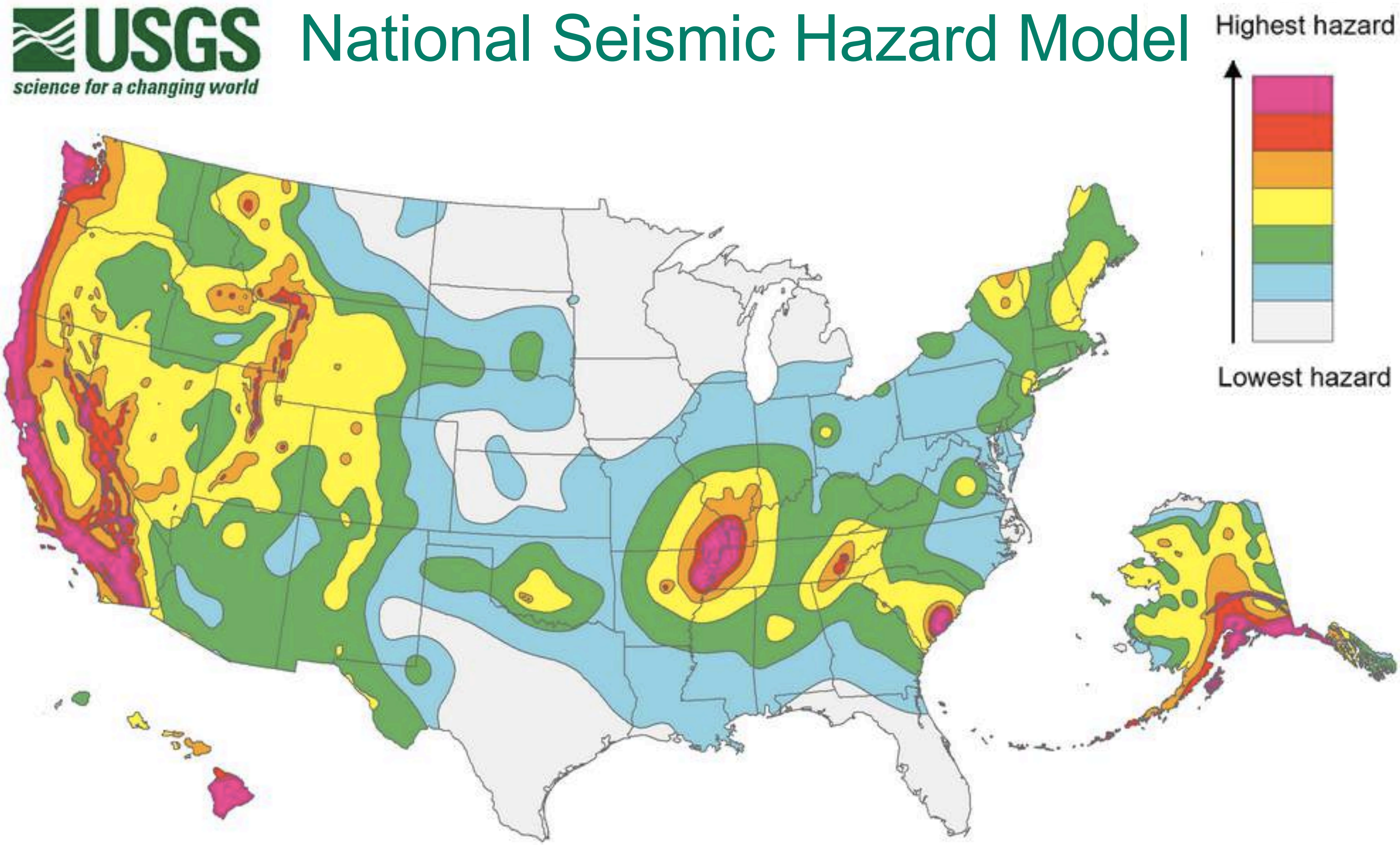
Now adding offshore GPS.

Recording tectonic strain related to cycles of crustal and subduction zone earthquakes.



Slide from Tim Melbourne

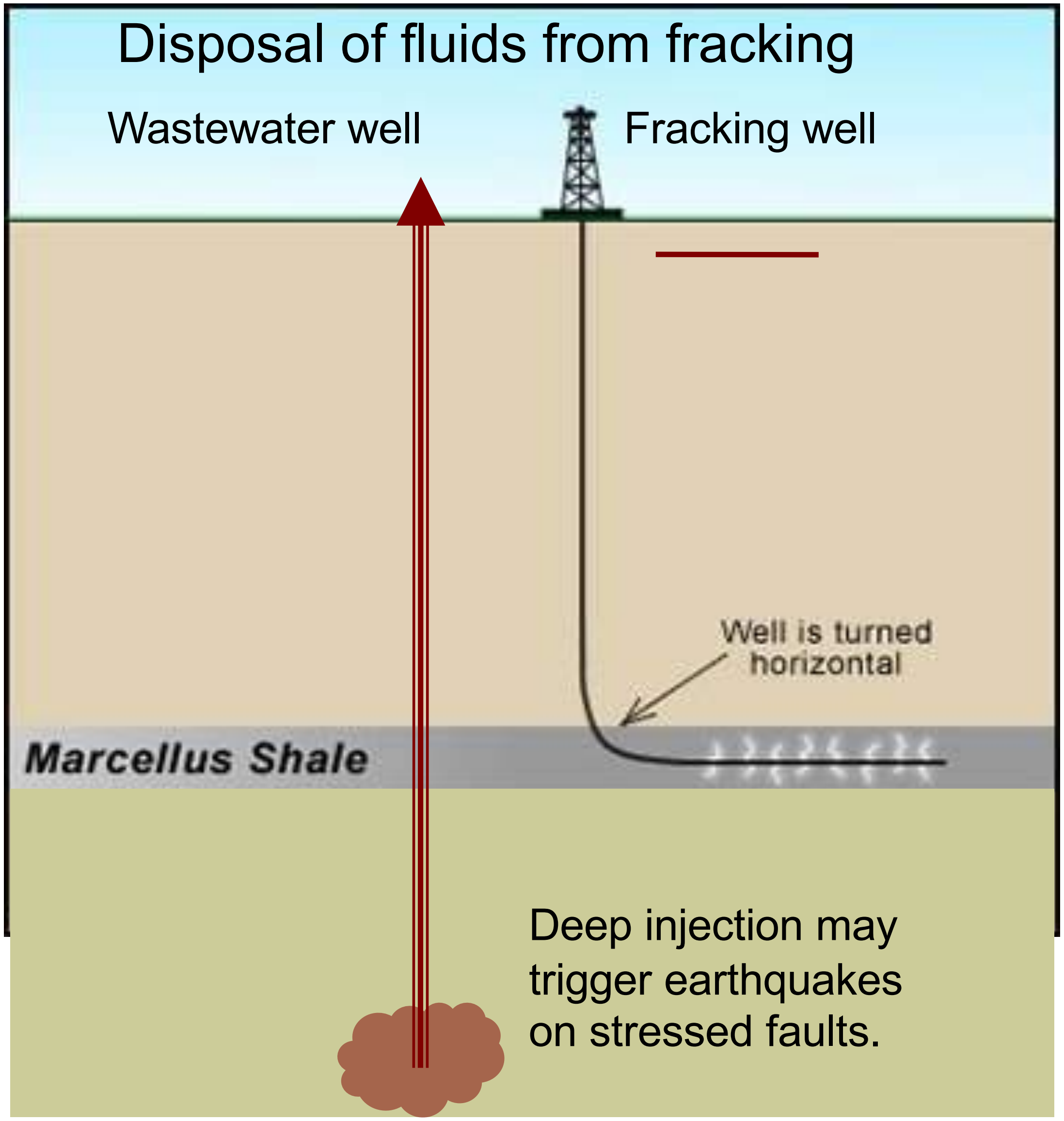
National Seismic Hazard Model



Time-independent model of seismic hazard (probability of ground motion).
Combines models of earthquake likelihood and shaking attenuation.
Inputs include observed and historic earthquakes, faults, strain rates, etc.

Development of Building Codes

Induced seismicity



Adapted from geology.com

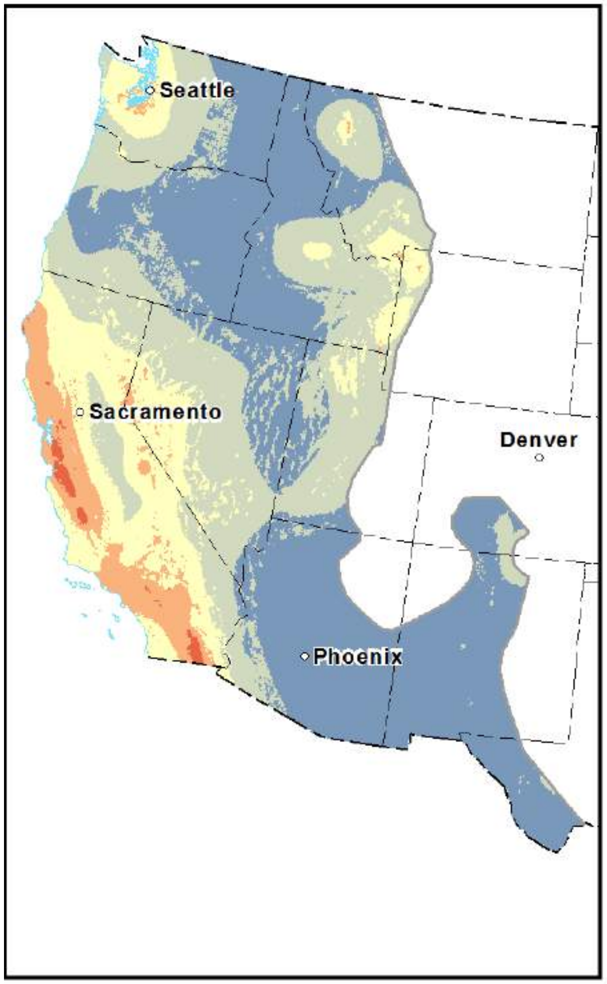
Deeply injected of wastewater (brine) can migrate into basement rocks containing naturally stressed faults capable of generating earthquakes.

Primary cause of large upswing in central U.S. earthquake rates since 2008.

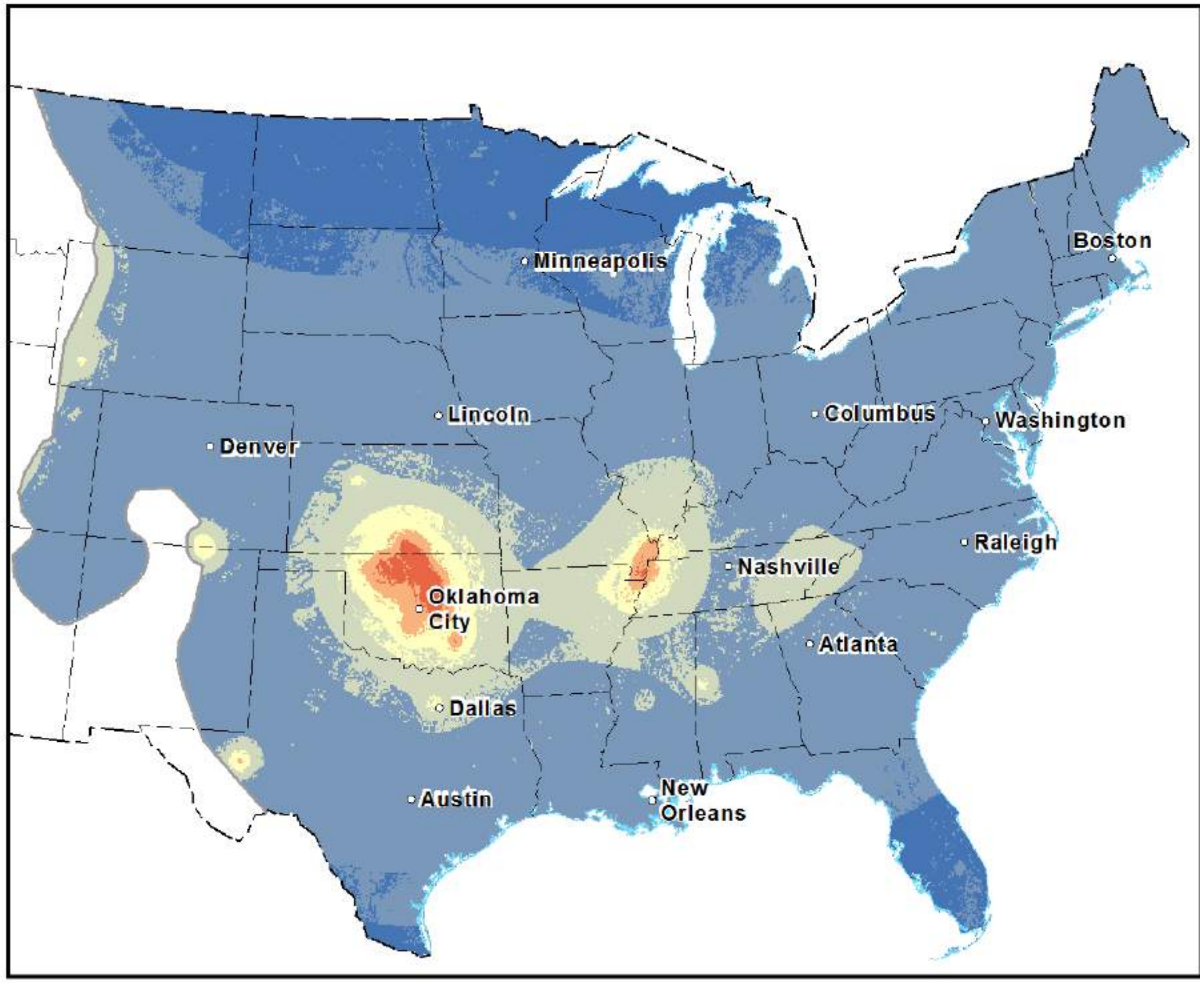
USGS
science for a changing world

One-year seismic hazard model

Shaking Intensity with 1% probability of being exceeded in 2016



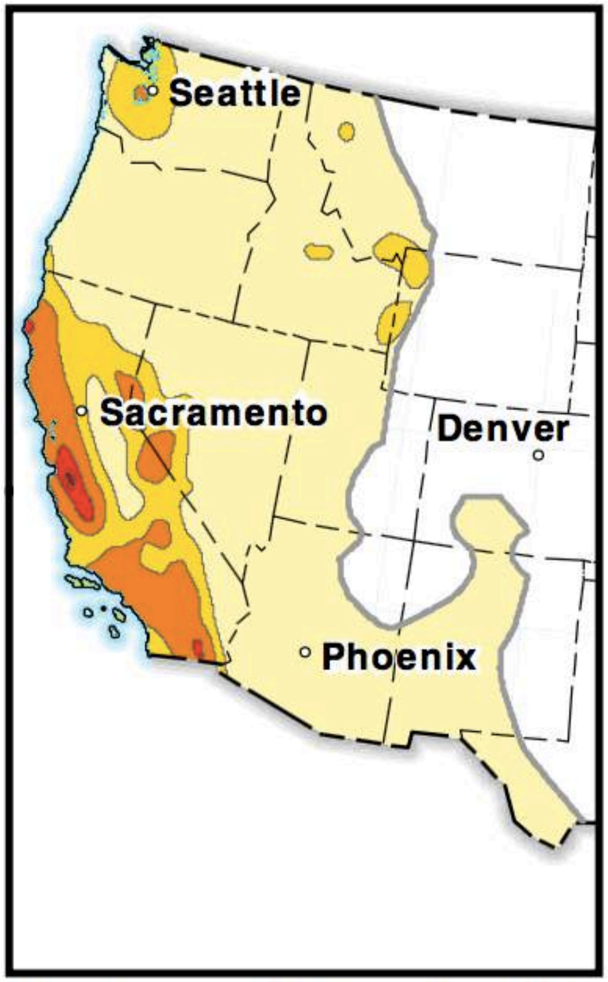
Based on results from the 2014 National Seismic Hazard Model



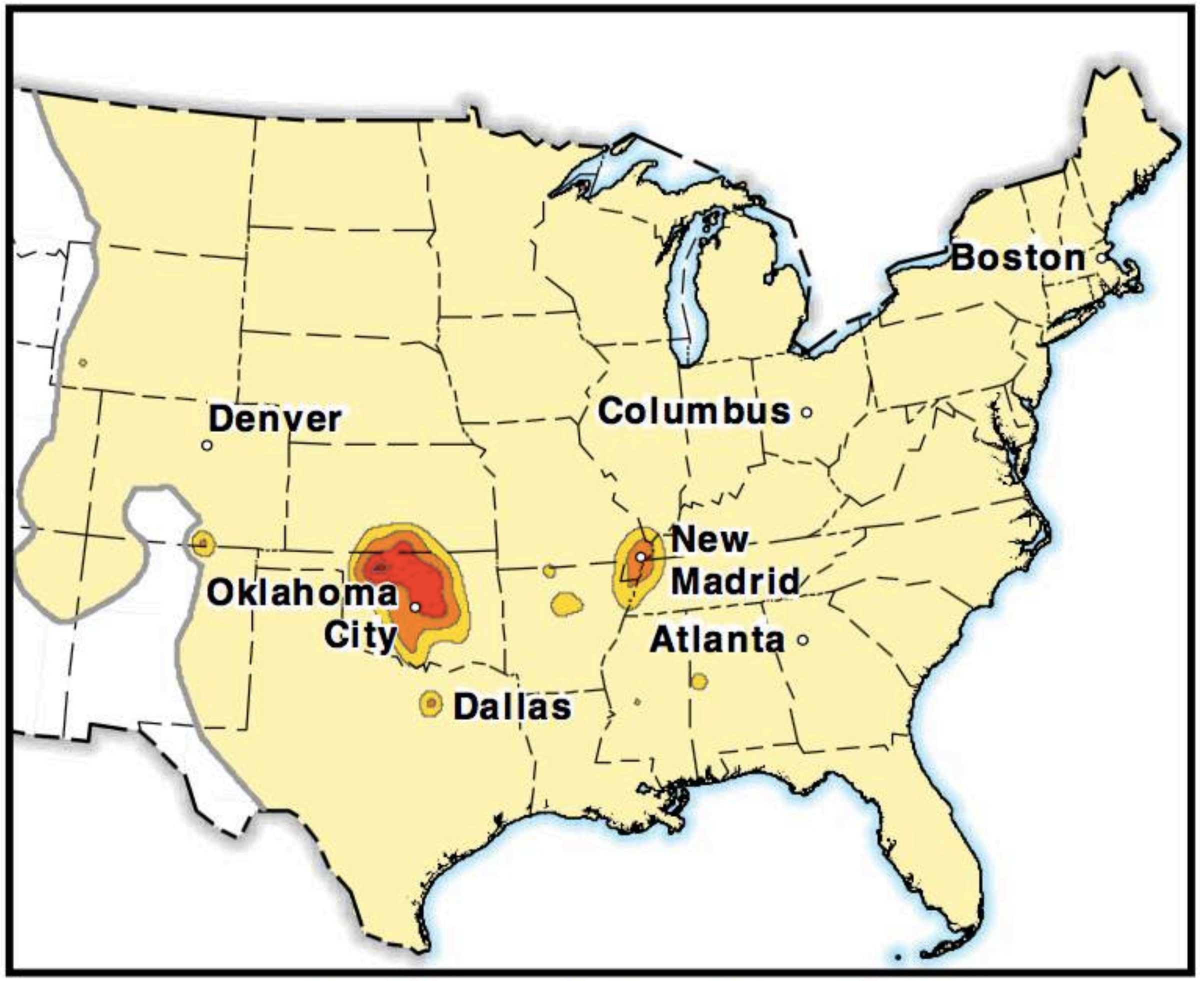
Based on results from this study

Modified Mercalli Intensity (MMI)

Probability of damaging ground motions in 2016



Based on results from the 2014 National Seismic Hazard Model



Based on results from this study

Probability of exceeding MMI VI

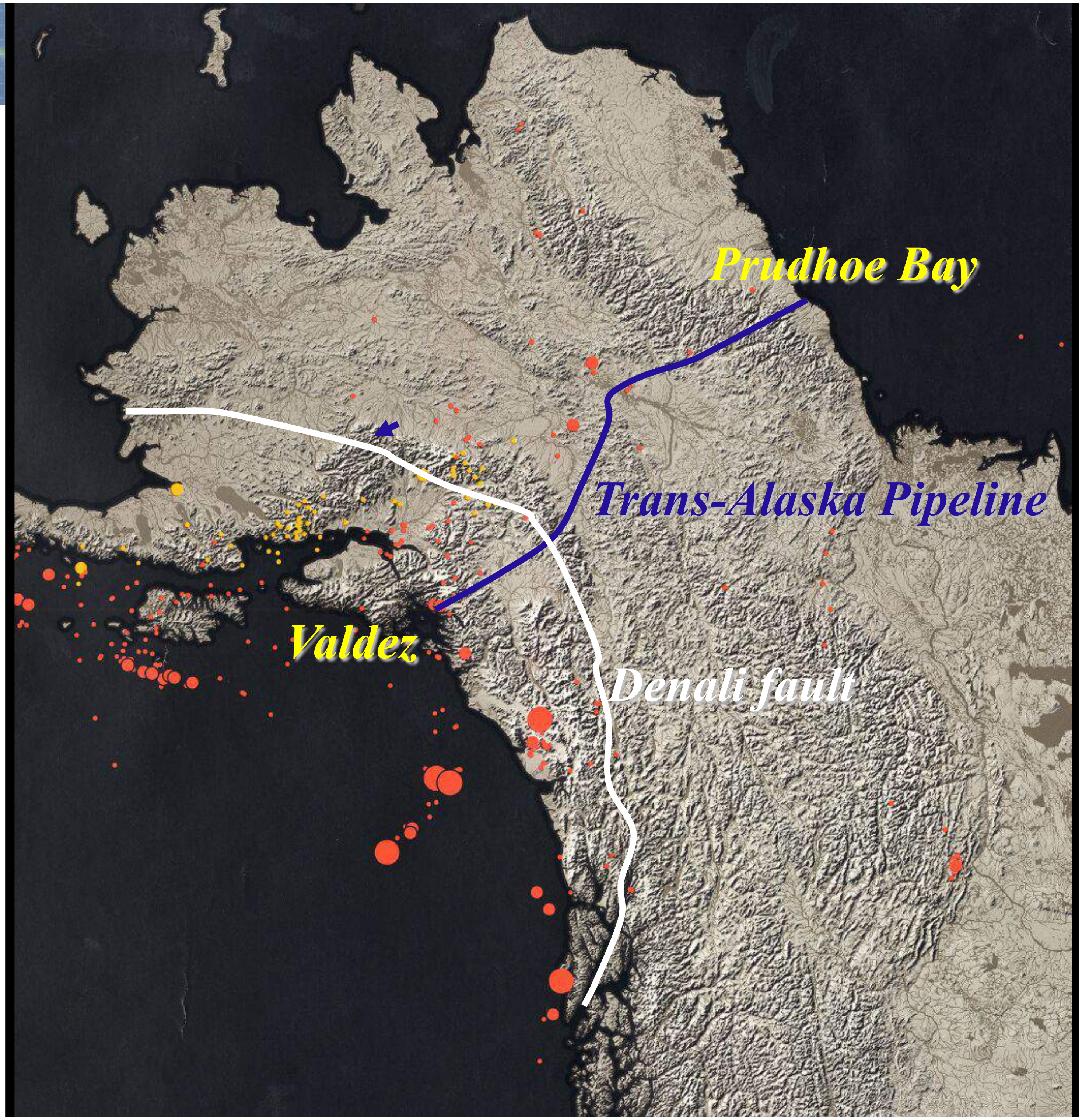
Trans-Alaska Oil Pipeline

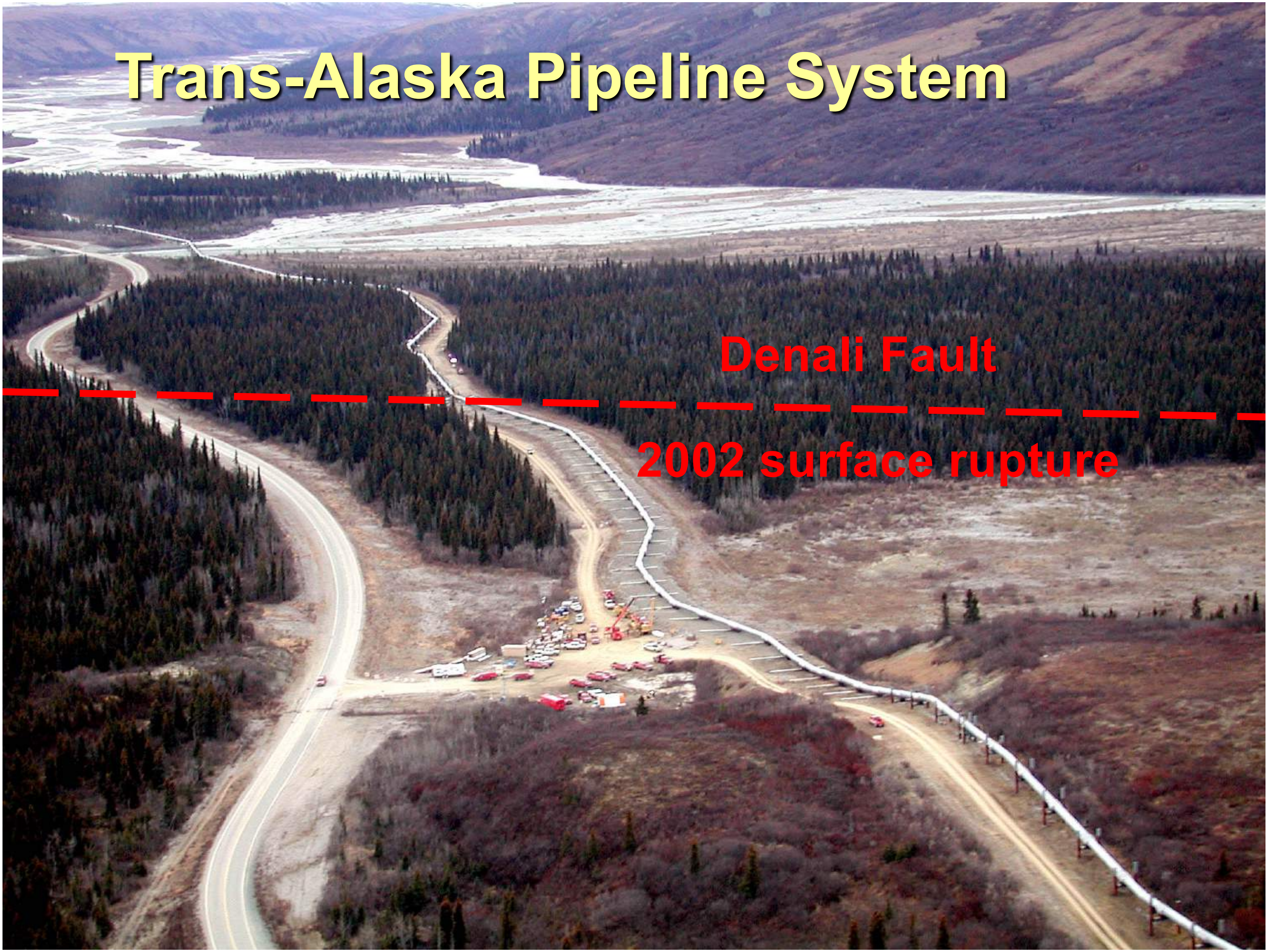
48” pipeline carrying 1 to 2 million barrels per day

17% of US crude oil

80% of Alaska’s revenue

1977 to 2003,
14 billion barrels




Trans-Alaska Pipeline System
Denali Fault
2002 surface rupture

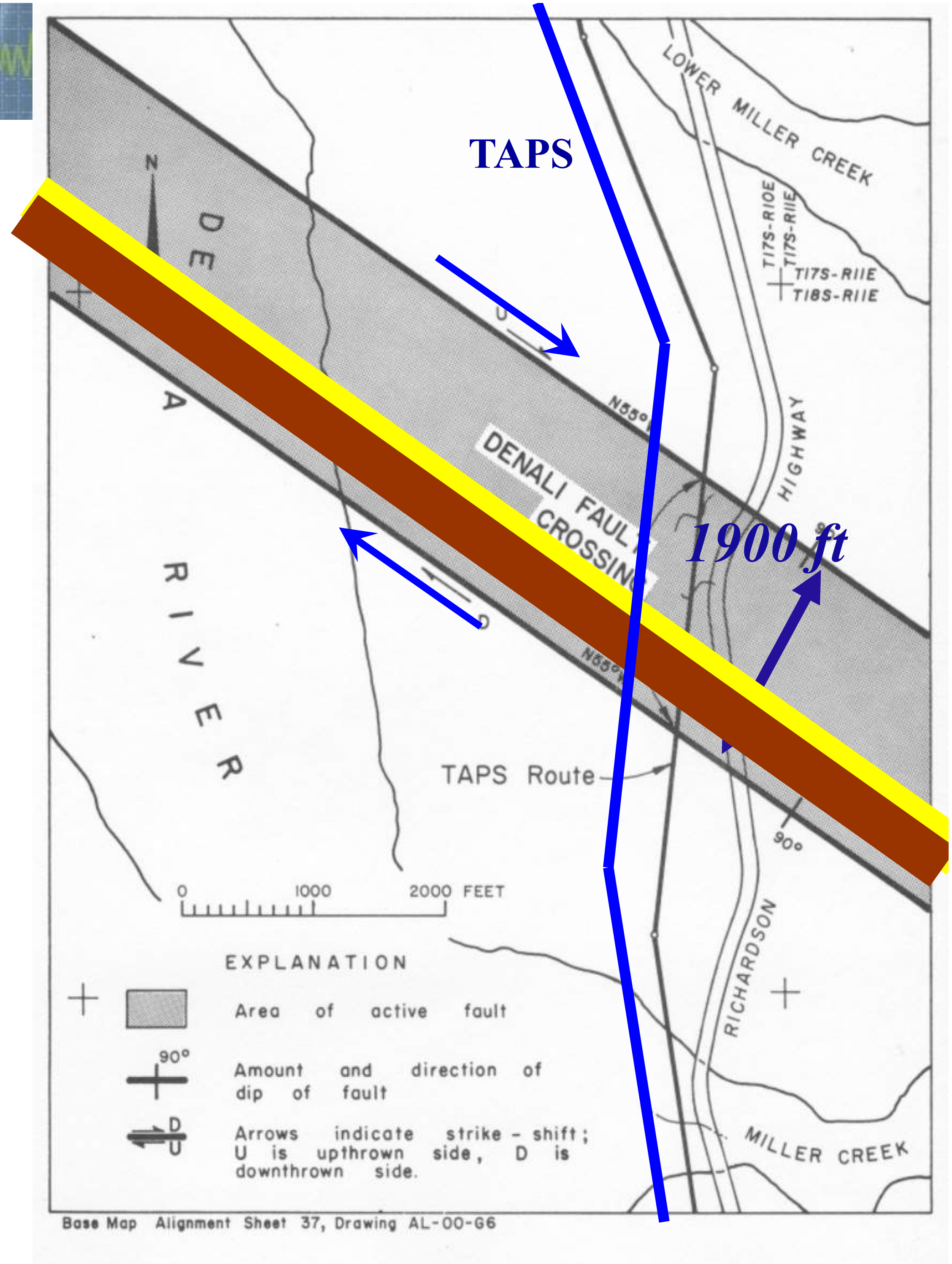
Denali fault-crossing design

Design assumptions:

Earthquake Magnitude 8.0
Horizontal, 20 feet
Vertical, 5 feet
Minor compression

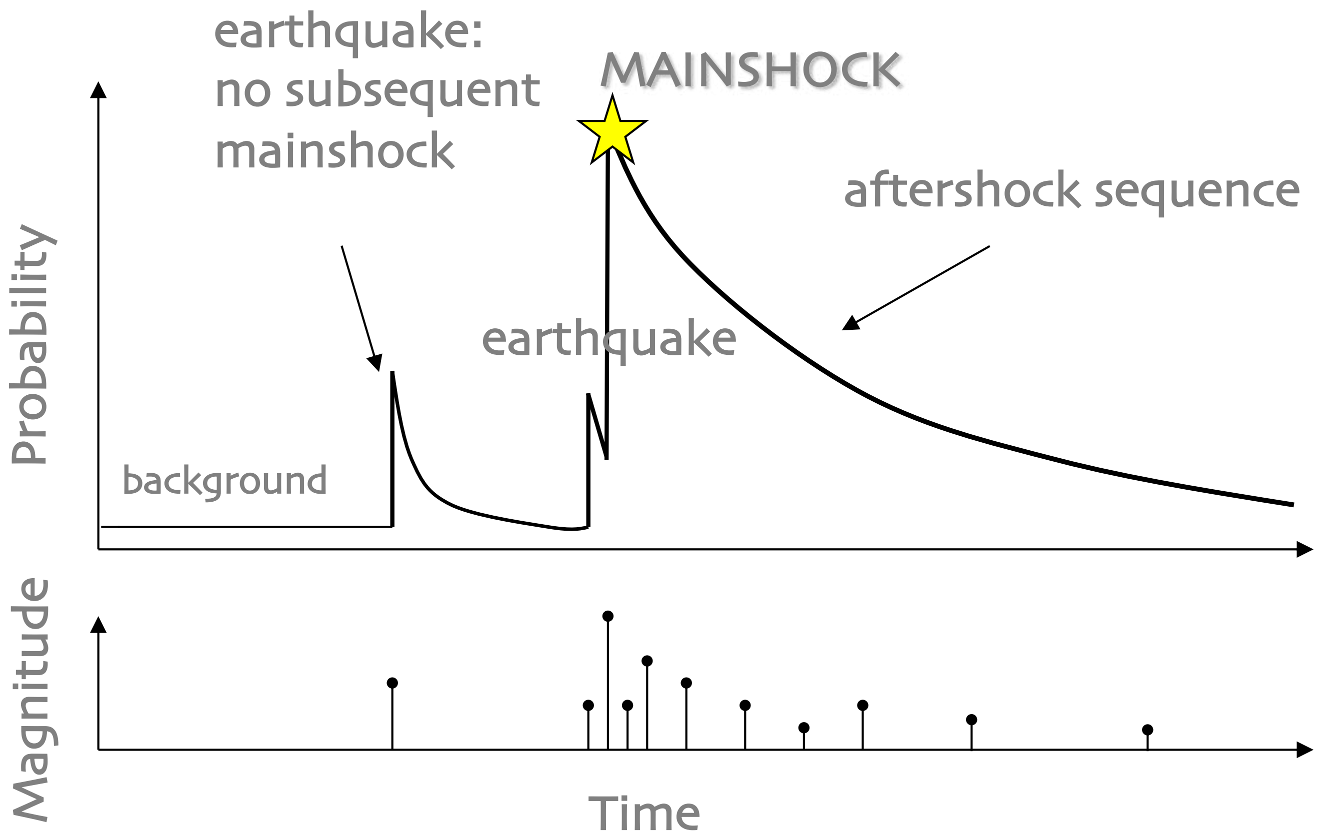
Nov. 3, 2002 rupture:

Earthquake Magnitude 7.9
Horizontal, 18 feet
Vertical, 2.5 feet
Minor compression



Denali Fault Crossing (Before and After)

Earthquake Clustering



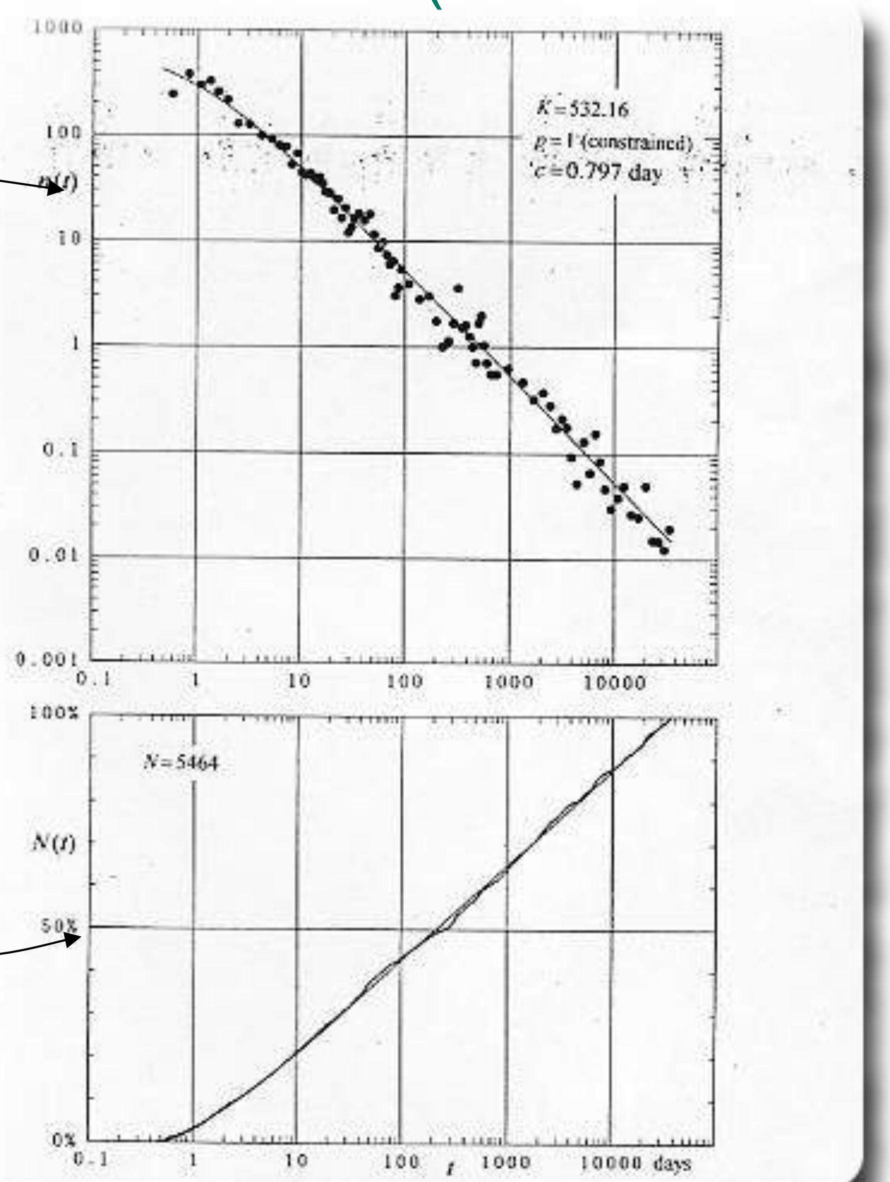
Aftershocks/Foreshocks > 50% of all events in California

"Omori's Law" (Fusakichi Omori, 1868-1923)

Aftershock occurrence rate (t^{-1} decay)

Number of felt aftershocks (N = 5,464)

Number of Aftershocks

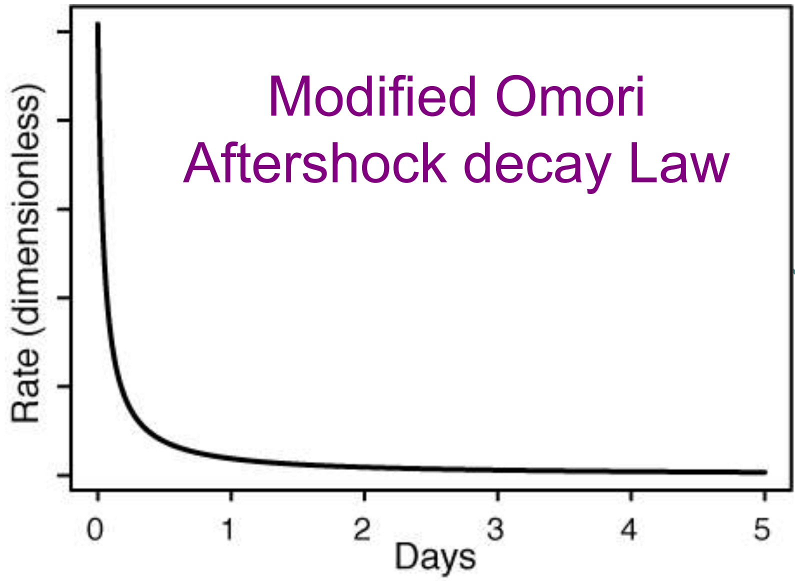


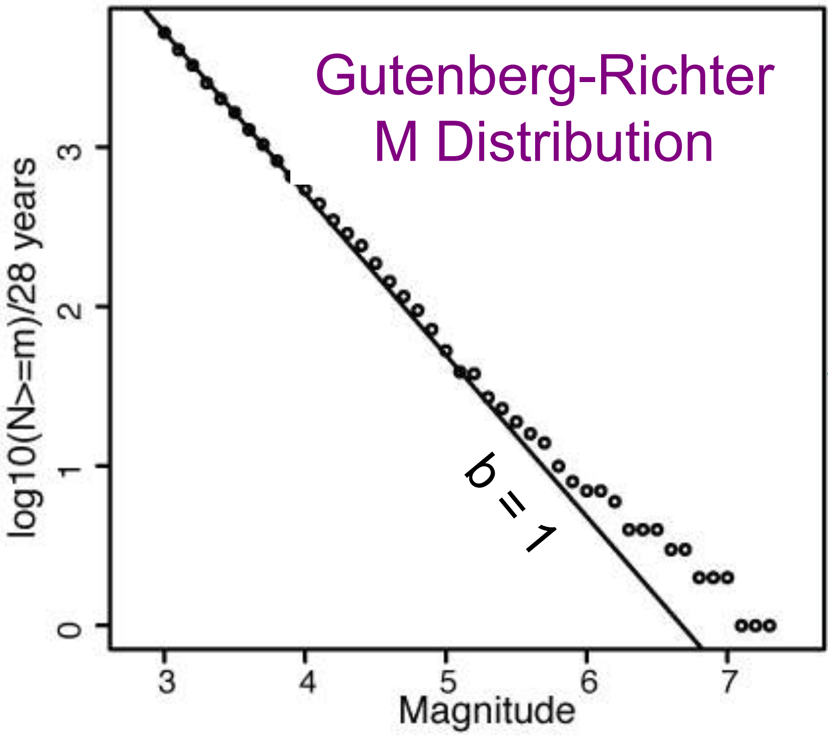
time since main shock

Imperial University of Tokyo

Nobi, Japan earthquake, 1891. 100 years of aftershocks!

Aftershock systematics enable forecasting





Probability of earthquakes during an aftershock sequence as a function of time and magnitude.

Reasenberg and Jones Science, 1989

Reasenberg and Jones (Science, 1989) method

$$\lambda(t, M) = 10^{bM_m} 10^{a-bM} (t+c)^{-p}$$

Rate of aftershocks ≥M at time t.

Utsu law of aftershock productivity for M_m mainshock.

Gutenberg-Richter magnitude frequency distribution.

Modified Omori law aftershock decay.

a (productivity of the sequence) ≈ -1.5 to -3.5
b (magnitude rate scaling within the sequence) ≈ 1
c (time offset) ≈ 0 **p** (temporal decay rate) ≈ 1

Reasenberg & Jones estimated values of a, b, c, and p from a set of California aftershock sequences. These are used as "generic" *(a priori)* parameter values.

For operational aftershock forecasting:

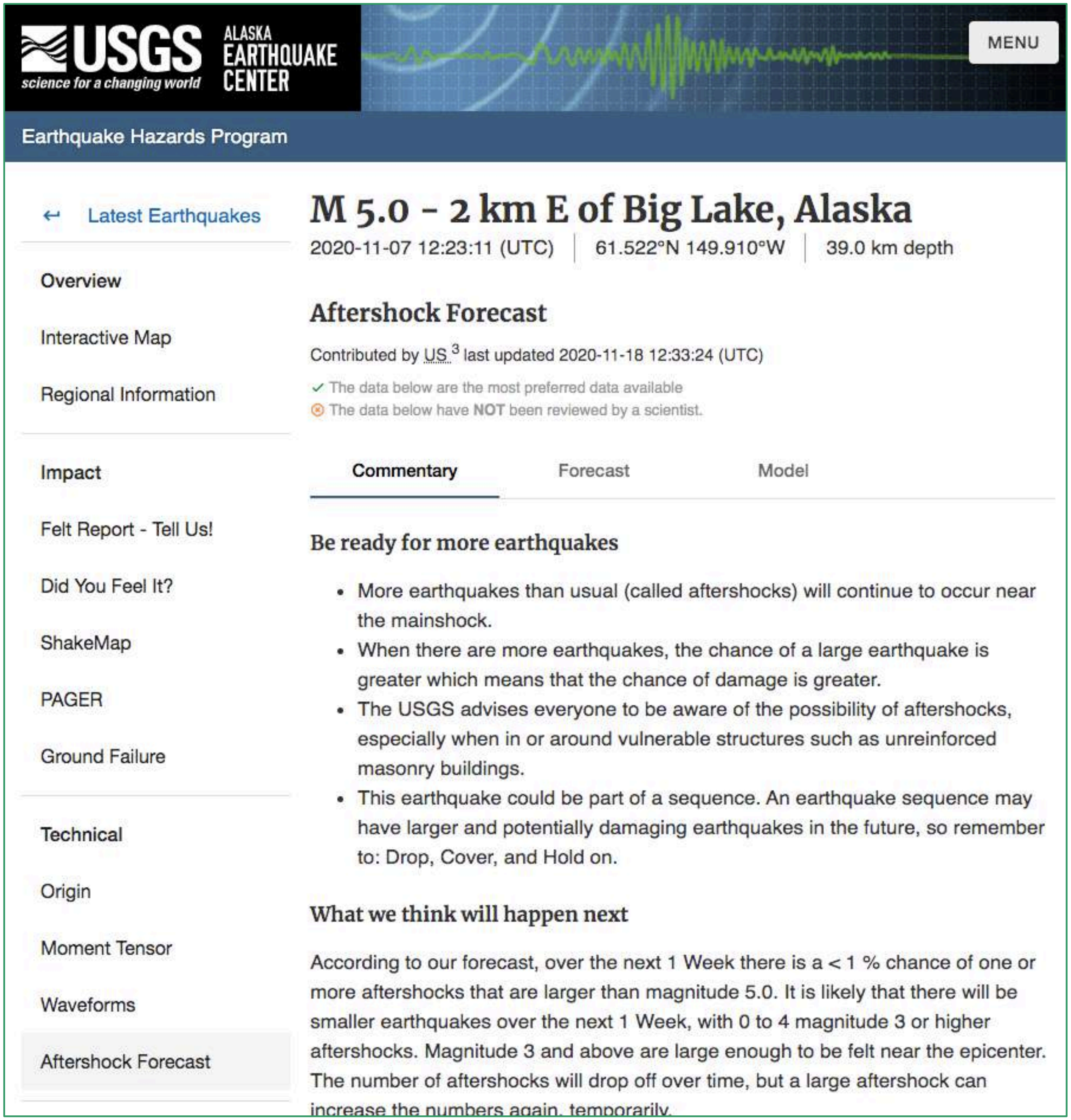
- Initial forecasts use the *generic* parameter values.
- Later in the sequence, can substitute *sequence-specific* parameter values.

Forecast following a Magnitude 7 mainshock

Aftershock Forecast for the First Week

Minimum Magnitude	Expected Number	Probability of 1 or more events
3	670	>99%
4	67	>99%
5	6.7	99%
6	0.67	50%
7	**0.067**	**6.5%**
8	0.0067	0.66%

Operational aftershock forecast


USGS ALASKA EARTHQUAKE CENTER
science for a changing world
MENU

Earthquake Hazards Program

↩ Latest Earthquakes

Overview
Interactive Map
Regional Information

Impact
Felt Report - Tell Us!
Did You Feel It?
ShakeMap
PAGER
Ground Failure

Technical
Origin
Moment Tensor
Waveforms
Aftershock Forecast

M 5.0 - 2 km E of Big Lake, Alaska

2020-11-07 12:23:11 (UTC) | 61.522°N 149.910°W | 39.0 km depth

Aftershock Forecast

Contributed by US [3] last updated 2020-11-18 12:33:24 (UTC)

✓ The data below are the most preferred data available
⊗ The data below have **NOT** been reviewed by a scientist.

Commentary | Forecast | Model

Be ready for more earthquakes

- More earthquakes than usual (called aftershocks) will continue to occur near the mainshock.
- When there are more earthquakes, the chance of a large earthquake is greater which means that the chance of damage is greater.
- The USGS advises everyone to be aware of the possibility of aftershocks, especially when in or around vulnerable structures such as unreinforced masonry buildings.
- This earthquake could be part of a sequence. An earthquake sequence may have larger and potentially damaging earthquakes in the future, so remember to: Drop, Cover, and Hold on.

What we think will happen next

According to our forecast, over the next 1 Week there is a < 1 % chance of one or more aftershocks that are larger than magnitude 5.0. It is likely that there will be smaller earthquakes over the next 1 Week, with 0 to 4 magnitude 3 or higher aftershocks. Magnitude 3 and above are large enough to be felt near the epicenter. The number of aftershocks will drop off over time, but a large aftershock can increase the numbers again, temporarily.

USGS issues aftershock forecasts after all M5.0 and larger earthquakes in the US.

First forecast delivered after 30 minutes.

Initial forecast parameters based on past sequences in this tectonic setting.

Forecast is updated frequently, with sequence-specific parameters.

Aftershock Forecast

Contributed by US[3] last updated 2020-11-18 12:33:24 (UTC)

✓ The data below are the most preferred data available

⊗ The data below have **NOT** been reviewed by a scientist.

Commentary | **Forecast** | Model

Note: The expected rate of earthquakes continues to decline throughout the time windows. The probabilities in the longer time windows are higher only because the rates are being summed over a longer time period. These longer periods may be useful when planning recovery and rebuliding projects.

The probability of at least one aftershock of at least magnitude M within the given time frame. Forecast starting 2020-11-18 13:00:00 (UTC)

	1 Day	1 Week	1 Month
M ≥ 3	12 %	49 %	79 %
M ≥ 4	1 %	7 %	20 %
M ≥ 5	< 1 %	< 1 %	2 %
M ≥ 6	< 1 %	< 1 %	< 1 %
M ≥ 7	< 1 %	< 1 %	< 1 %

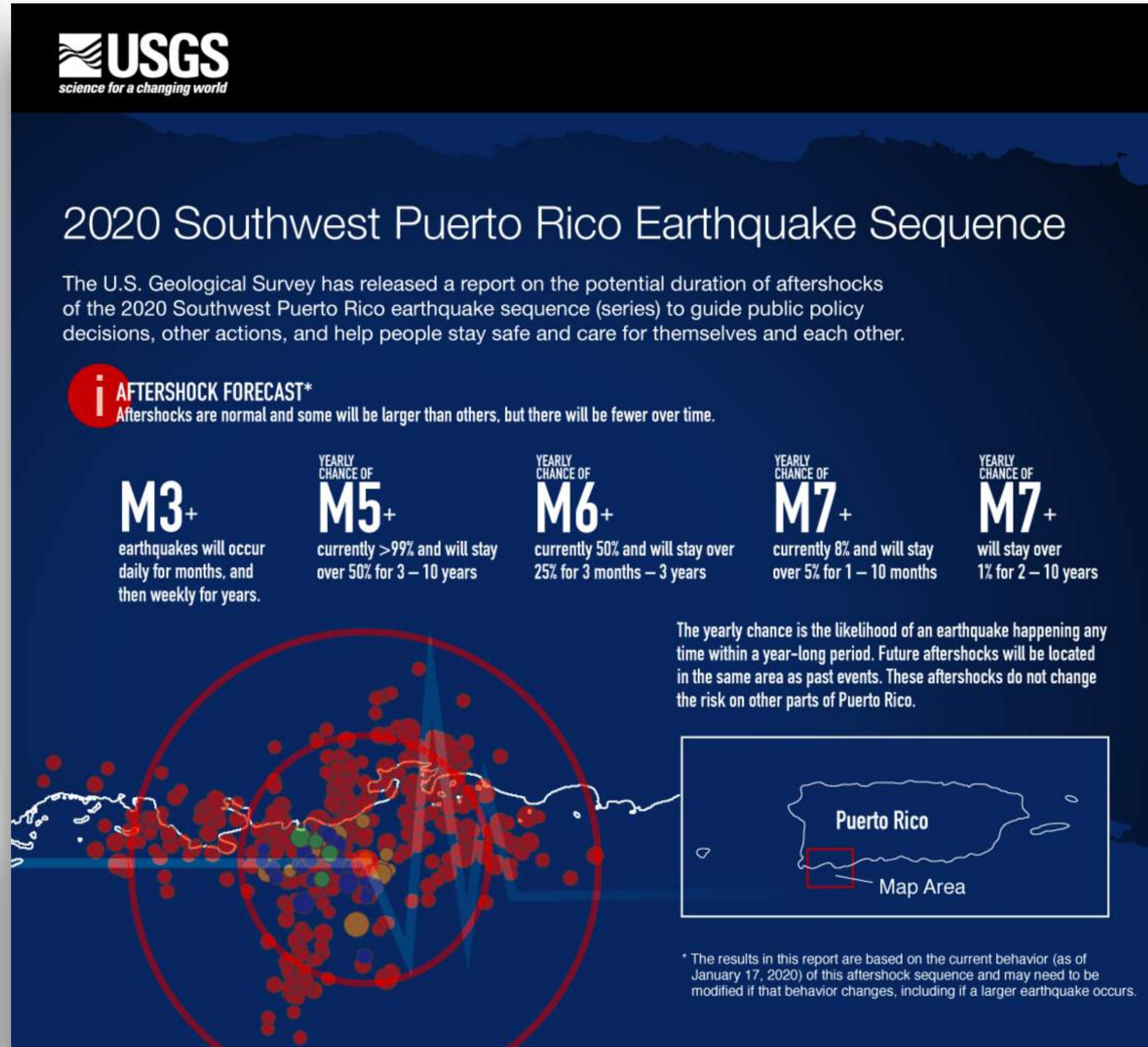
Operational aftershock forecast

Forecast includes plain-language summary, and tables summarizing the probability and expected numbers of aftershocks of various magnitudes in the coming day, week, month and year.

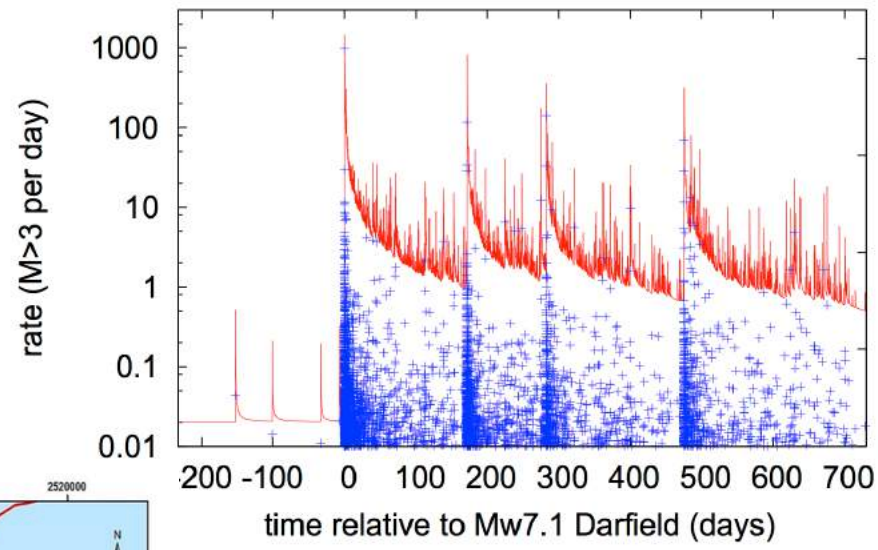
Custom products incl. duration estimates for FEMA

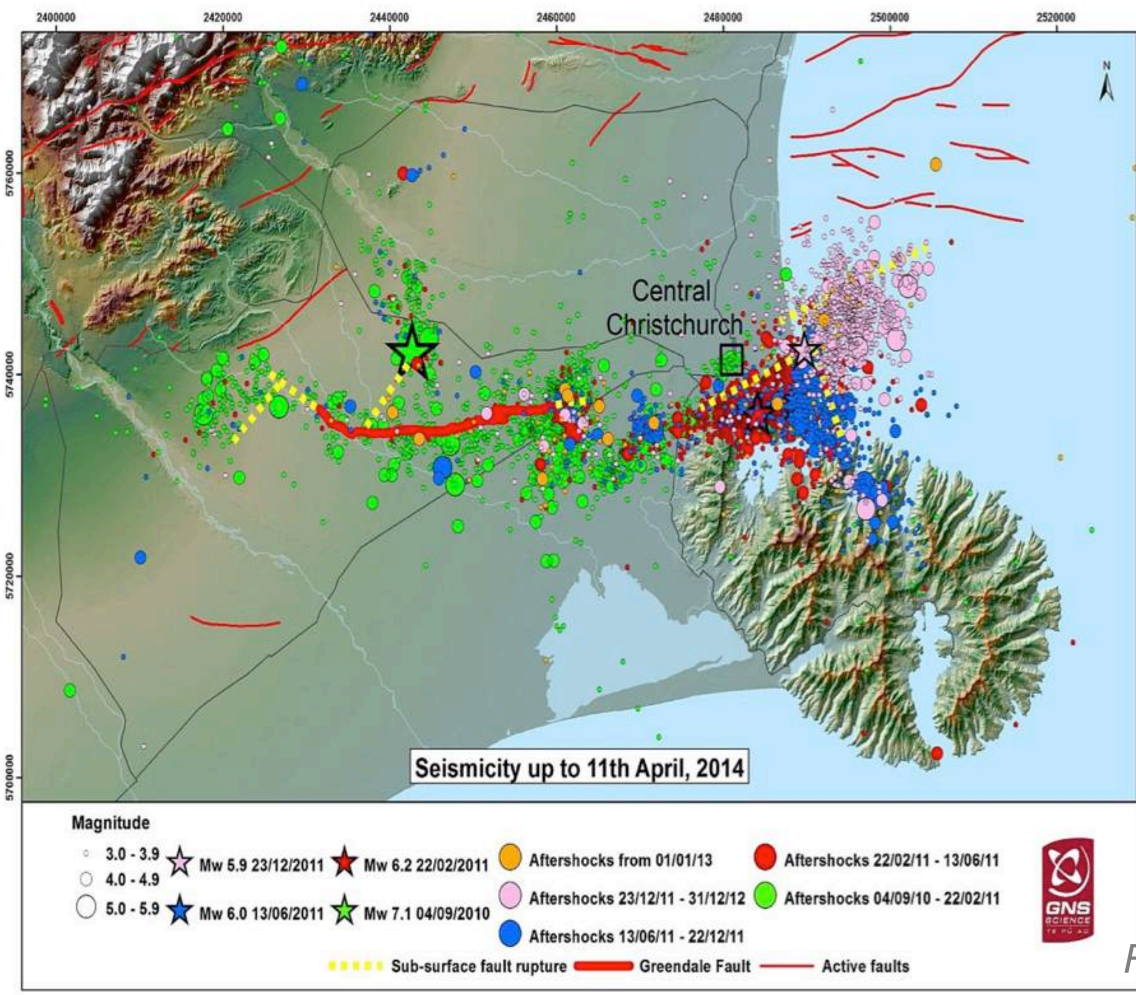
Table 2. Expected duration for earthquakes occurring on a regular basis[1] after January 17, 2020[2].

Frequency of earthquakes	Magnitude 3 or greater	Magnitude 4 or greater
Daily	2–6 months	5–13 days
Weekly	1.5–10 years	4–16 months
Monthly	10 or more years	1.5–10 years



Canterbury, NZ earthquake sequence (began 2010)

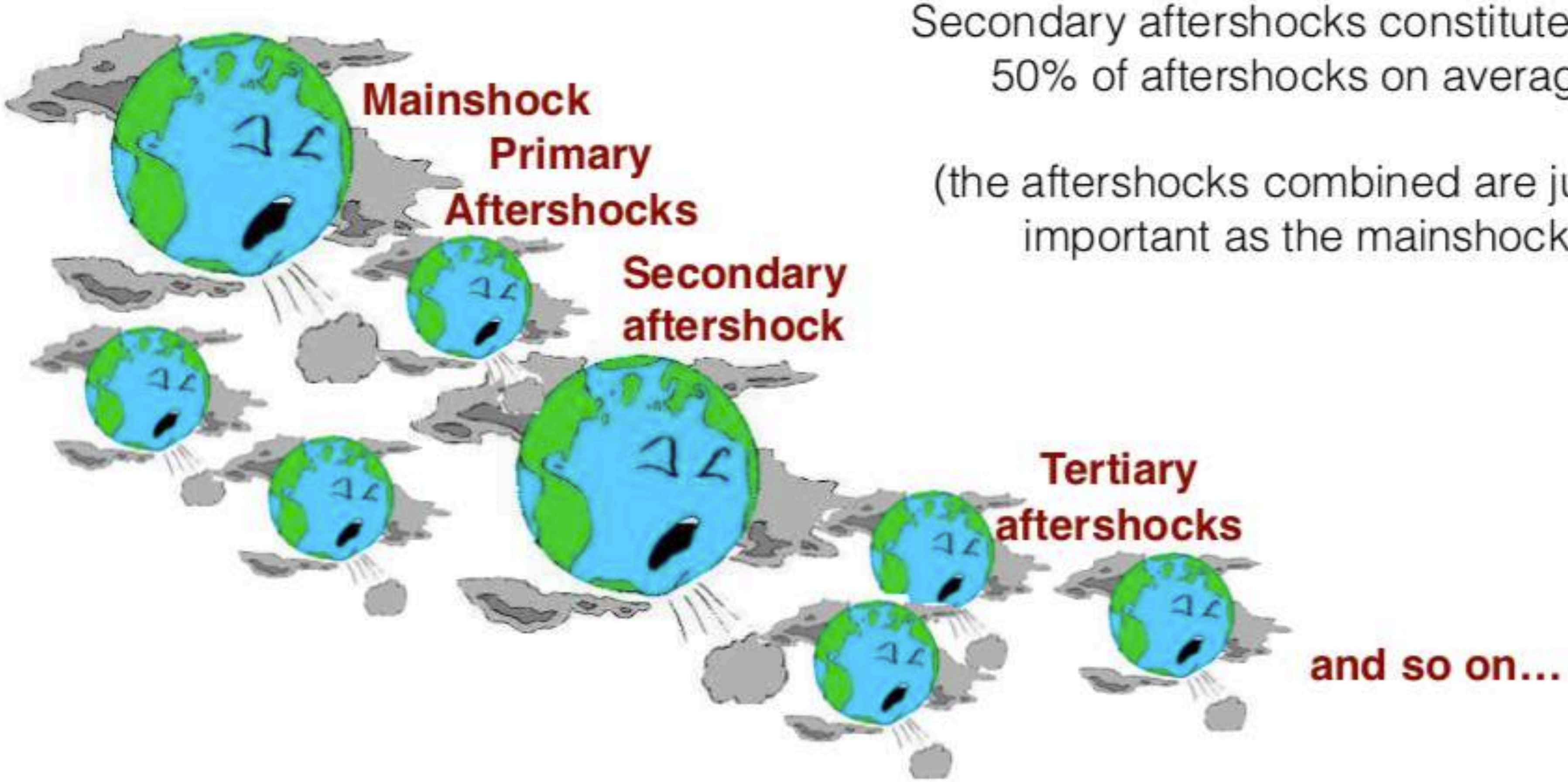




Getty Images

From: Christophersen et al., GNS Science, 2013.

Epidemic-Type Aftershock Sequence
(ETAS model)



Secondary aftershocks constitute about 50% of aftershocks on average.

(the aftershocks combined are just as important as the mainshock)

USGS
science for a changing world

Epidemic Type Aftershock Sequence (ETAS)

Ogata, J. Am. Stat. Assoc., 1988
Triggering comes from all prior events.

$$\lambda(t) = \mu + \sum_{\{i:t_i<t\}} \frac{K e^{\alpha(M_i - M_c)}}{(t - t_i + c)^p}$$

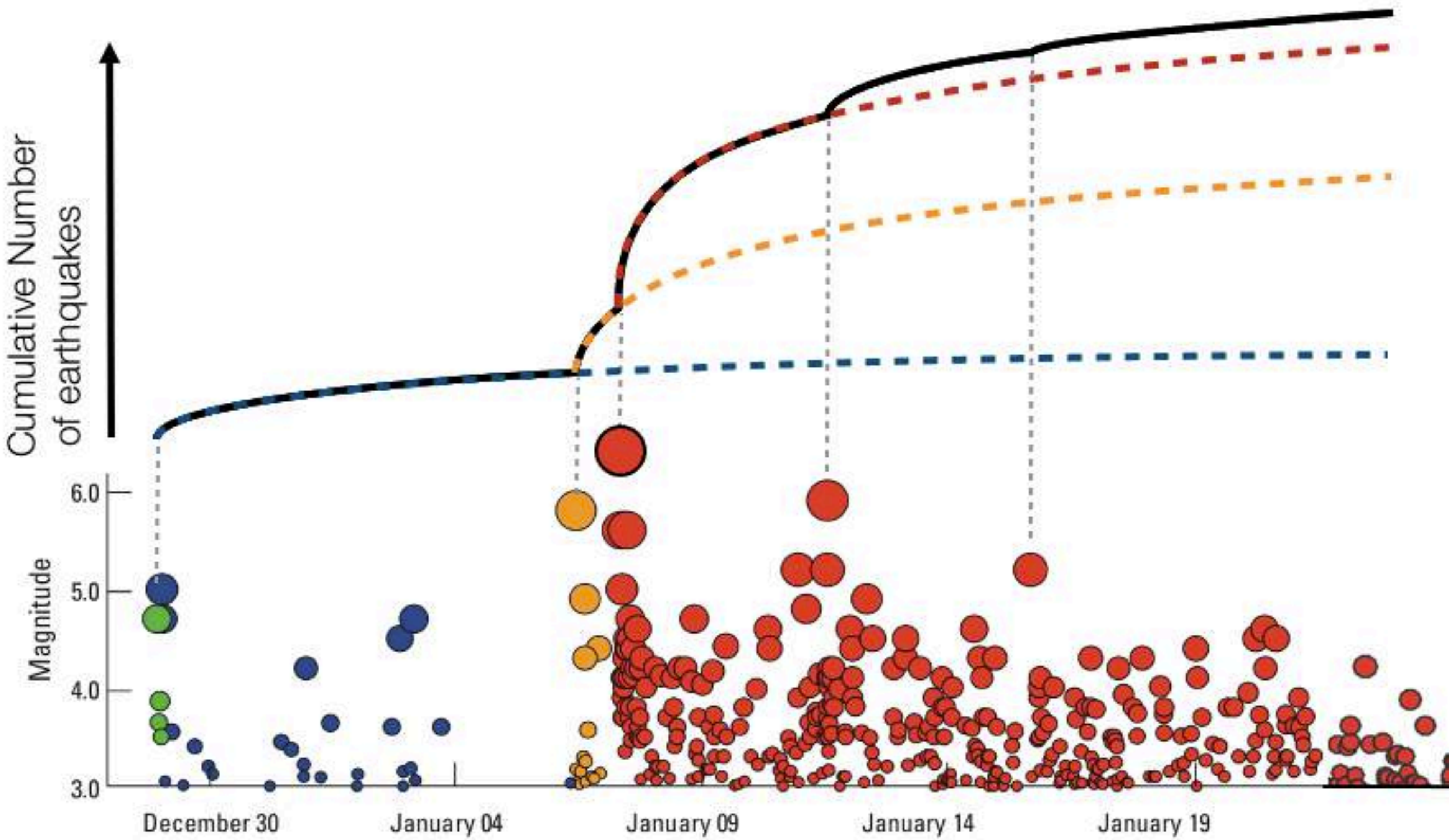
Total rate as a function of time

Background rate

Aftershock rate from all prior earthquakes

ETAS Forecast Model

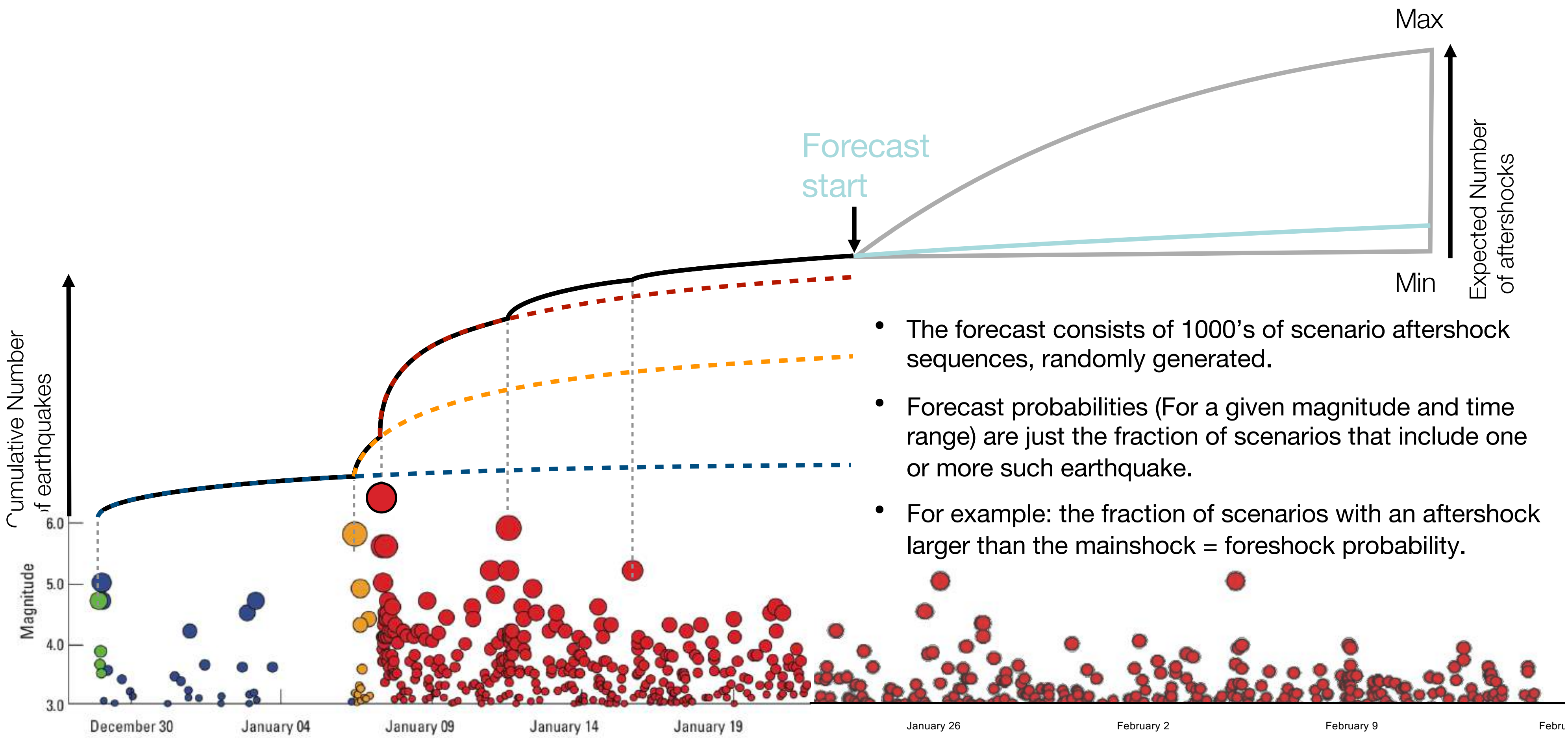
Step 1: Forecast model parameters are estimated from observed sequence.



ETAS Forecast Model

Step 2: A large suite of scenario earthquake catalogs are calculated.

Step 3: Forecast probabilities are generated from that ensemble.



- The forecast consists of 1000's of scenario aftershock sequences, randomly generated.
- Forecast probabilities (For a given magnitude and time range) are just the fraction of scenarios that include one or more such earthquake.
- For example: the fraction of scenarios with an aftershock larger than the mainshock = foreshock probability.

Spatial ETAS Forecast Model

$$\lambda(t, \mathbf{x}) = \mu + \sum_{\{i:t_i<t\}} \frac{K e^{\alpha(M_i - M_c)}}{(t - t_i + c)^p} \mathrm{D}(\mathbf{x}, \mathbf{x}_i)$$

Total rate as function of time and space

Background rate

Aftershock rate from all prior earthquakes

Spatial kernel

Spatial ETAS Forecast Model

Map-based forecasts can support a wide variety of decision-making during an earthquake sequence.

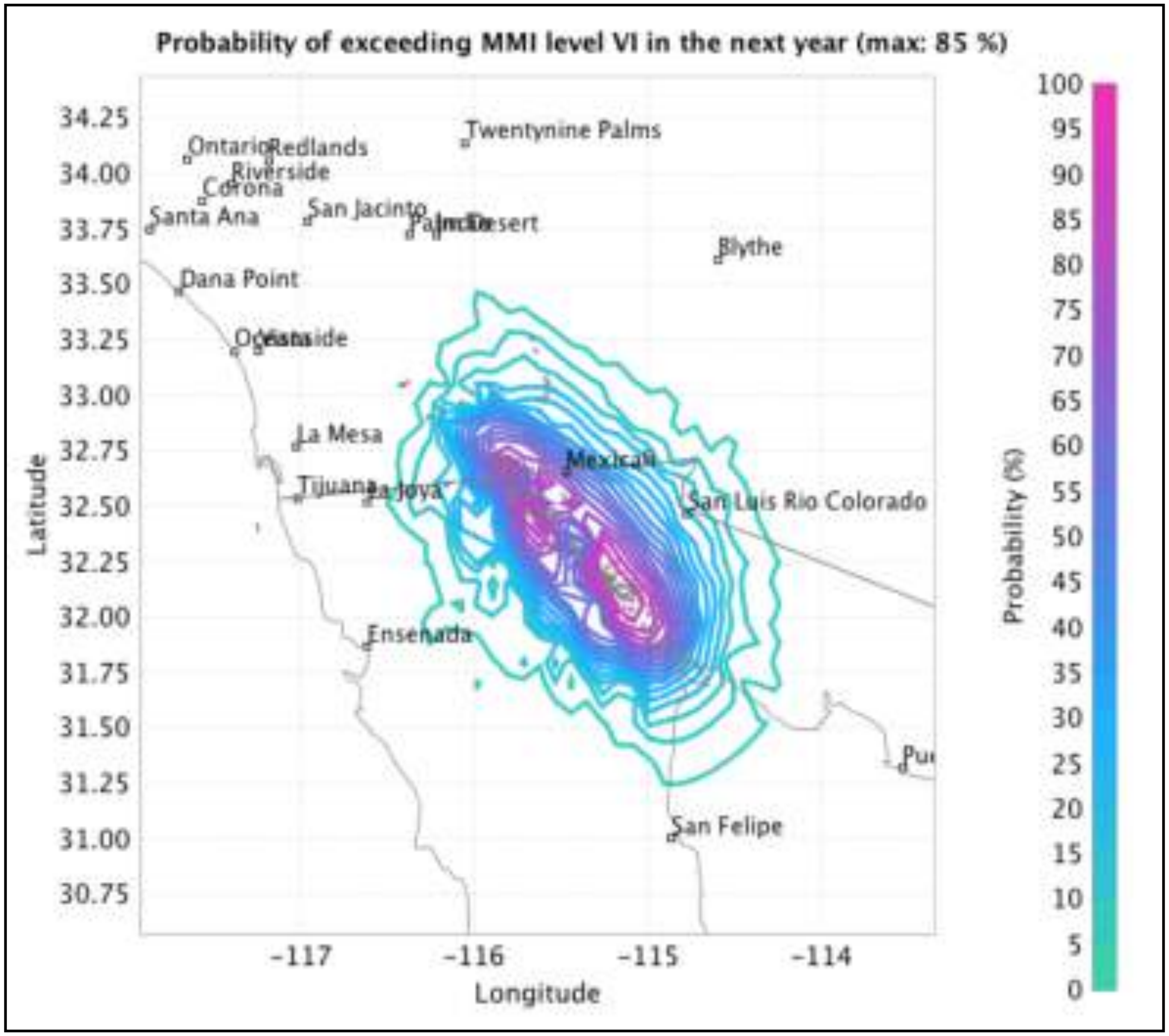
"Where are aftershocks most likely?"

"What's the chance that my city will experience damaging ground motions?"

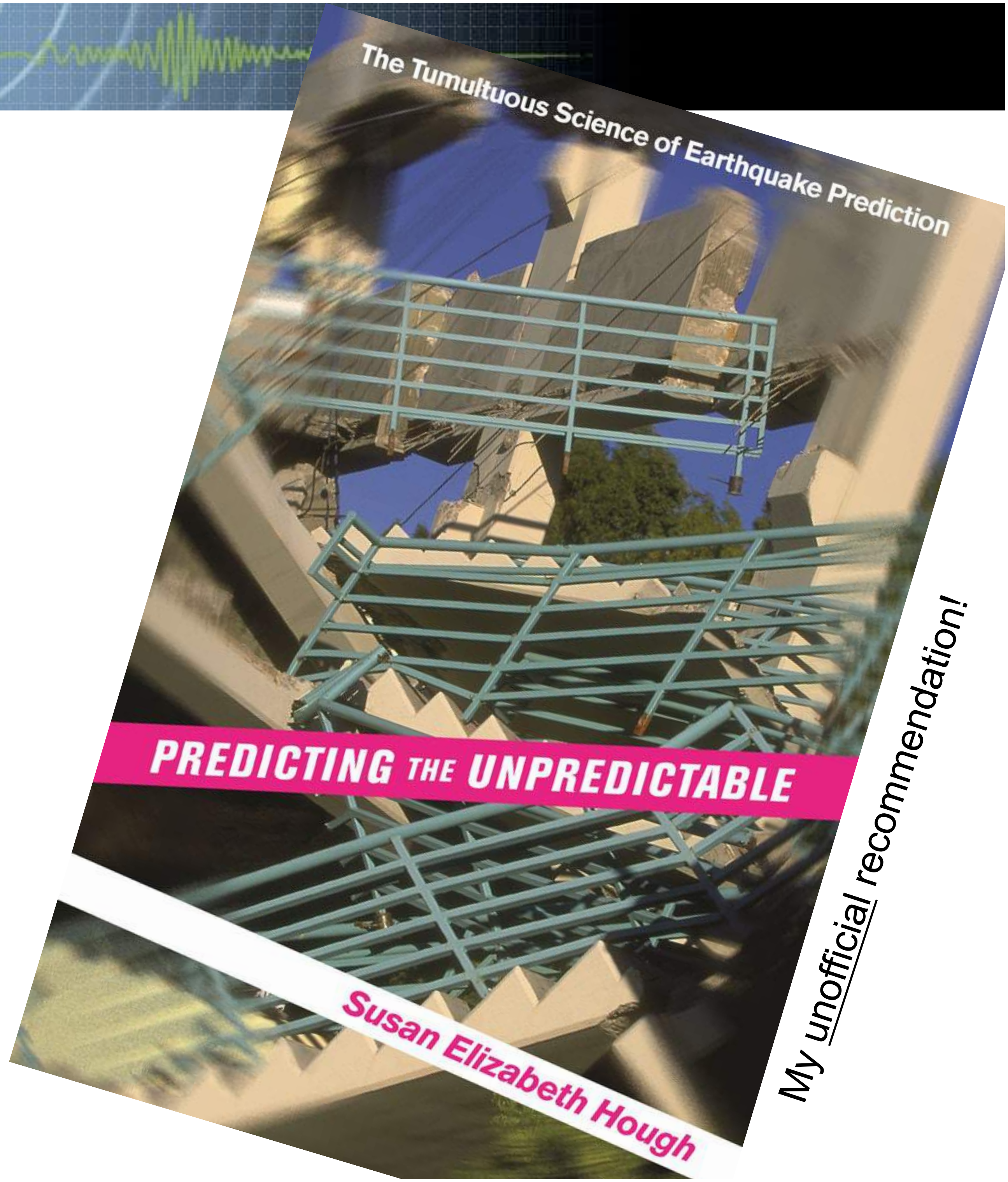
"What is the chance we'll have to do this repair twice?"

"Where should we situate the fuel depot?"

"What's the probability that building X will take damage with SAR team inside?"



For more on the interesting and “tumultuous” science and history of earthquake prediction, read *Predicting the Unpredictable* by Susan Hough (Wiley 2010)



My <u>unofficial</u> recommendation!

Thank you!

http:earthquake.usgs.gov

mblanpied@usgs.gov