Communicating Earthquake Hazards: Lessons from Earthquake Alerting

ELIZABETH S. COCHRAN

EARTHQUAKE SCIENCE CENTER, USGS

USGS
science for a changing world

April 2020 RISC Meeting

NATURAL HAZARDS

How low should we go when warning for earthquakes?

Social responses to alerts are critical but understudied

By **Elizabeth S. Cochran**[1] *and* **Allen L. Husker**[2]

A DISCUSSION OF EARTHQUAKE EARLY WARNING

→ Detour
USGS research and products

USGS CORE ACTIVITIES

Fundamental Research

Information Products

INDUCED SEISMICITY RESEARCH

Objectives:

- *Understand and mitigate the hazards associated with earthquakes that are induced by human activities.*
- *Better understand the physics of earthquake failure.*

Basic earthquake science

- Conditions and stress changes that lead to fault slip
- What causes ruptures to start and stop
- Role of fluids in triggering slip
- Ground motion variability

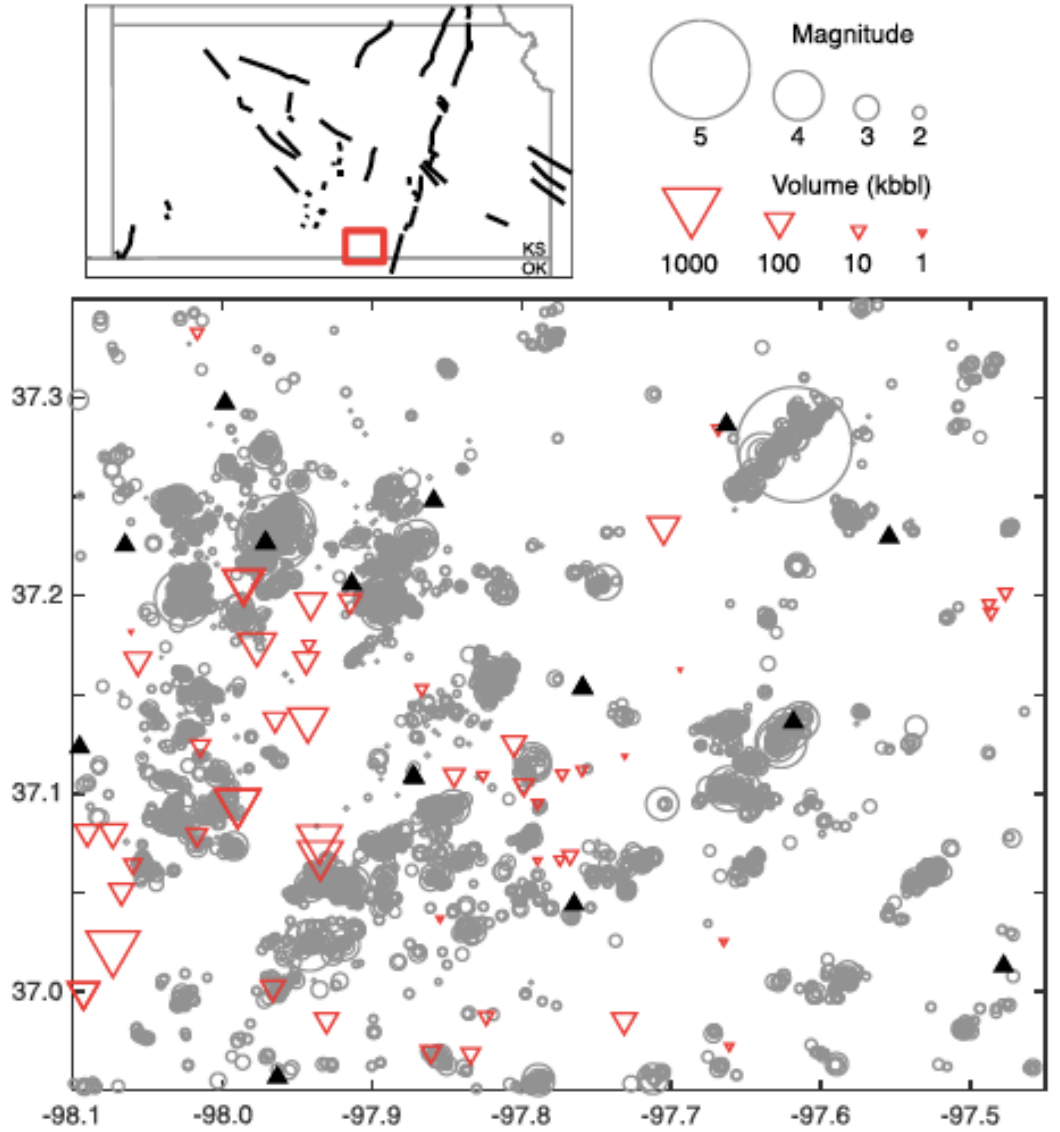
Direct application of science to reduce hazard

- Identification of risk factors for IS
- Inform regulations
- Short-term hazard forecasts
- Injection protocols
- Risks of sudden shut-in versus flowback

Temporary Seismic Networks

Example - Kansas:

- 2014-2019
- 15 stations
- Real-time data sent to NEIC, archived at IRIS
- Automated catalog complete to M1.3, catalog published in ComCat

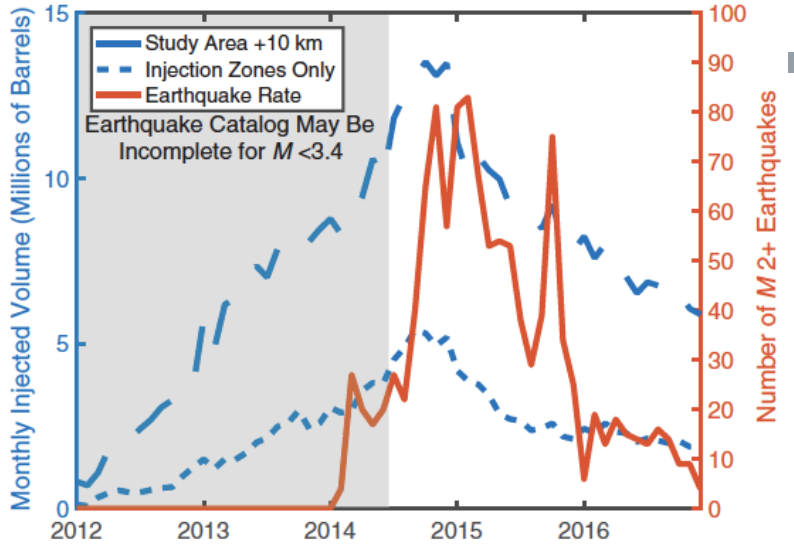


Rubinstein et al. (2018); Cochran et al. (2019)

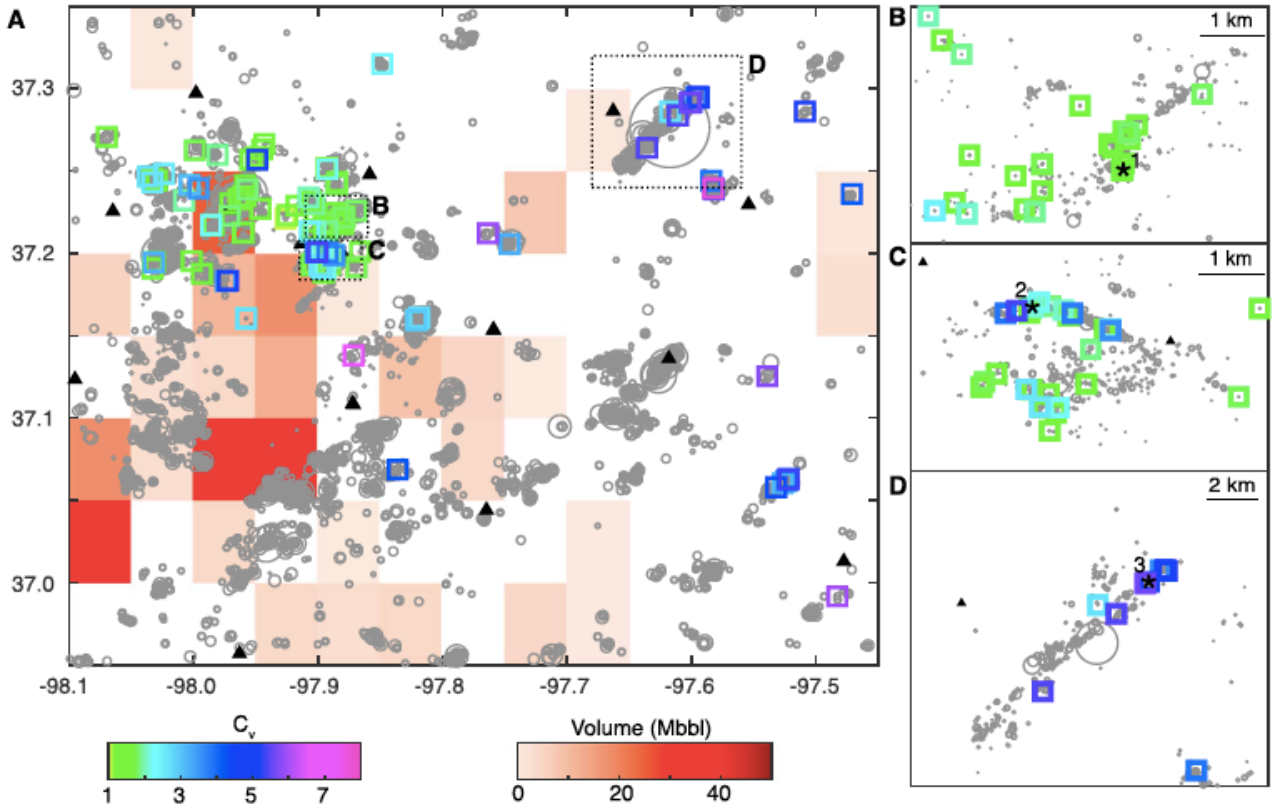
Kansas Findings

- Small stresses are enough to induce earthquakes (15-20 kPa)
- Events close to injectors occur at regular rates over long time periods (not clustered)
- 1-3 km halos of scant seismicity surrounding injection wells
  - Local geology is likely controlling occurrence of seismicity

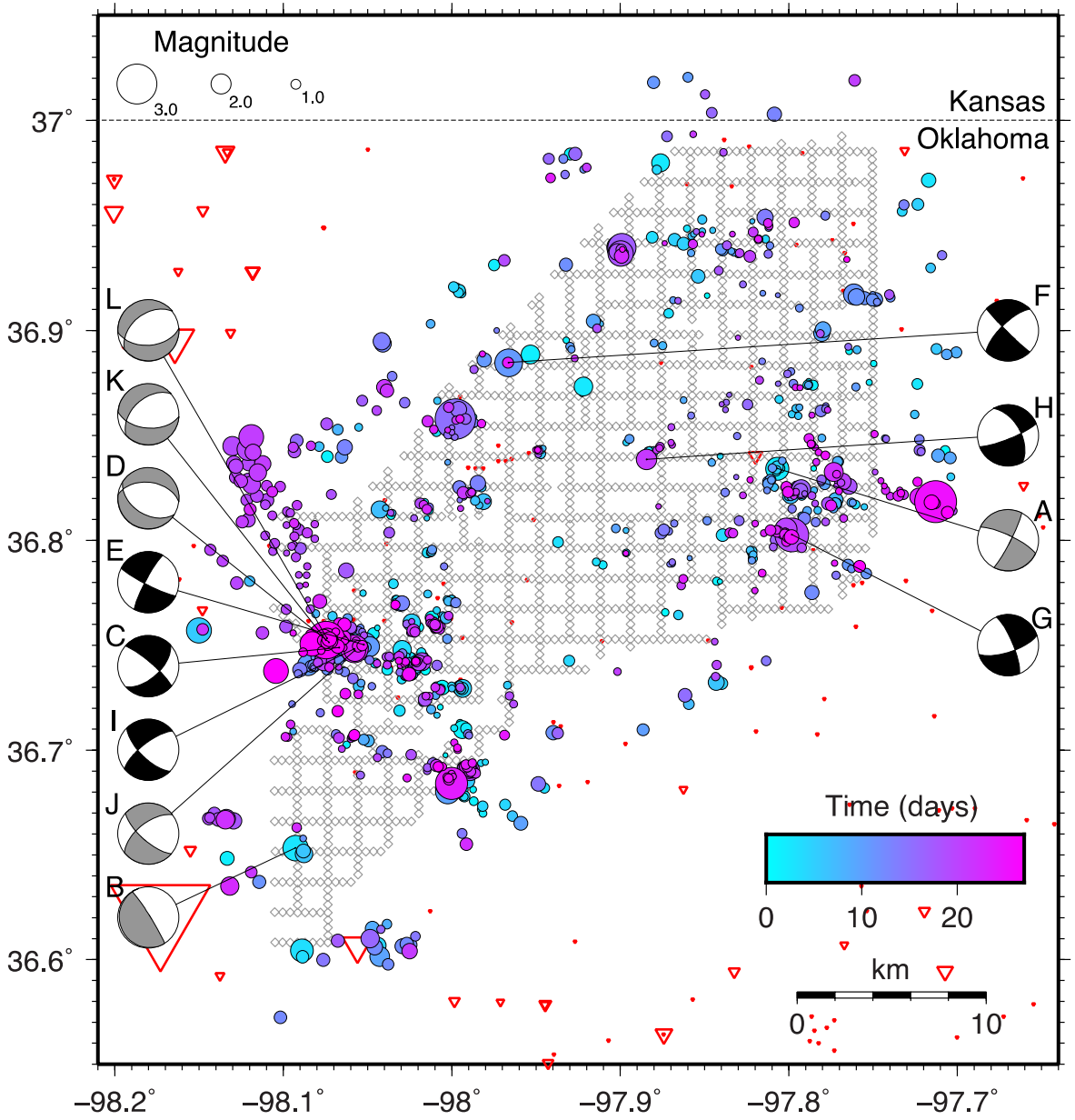
2020 deployment starting in southern New Mexico to examine seismicity in Permian Basin

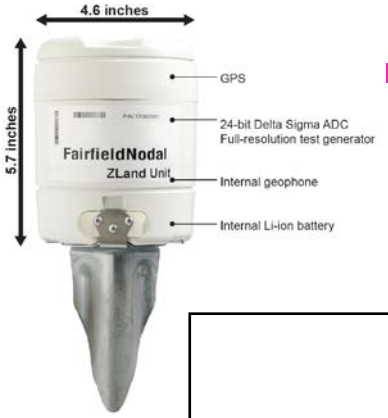


Rubinstein et al. (2018)
Cochran et al. (2019)



NODAL DEPLOYMENTS



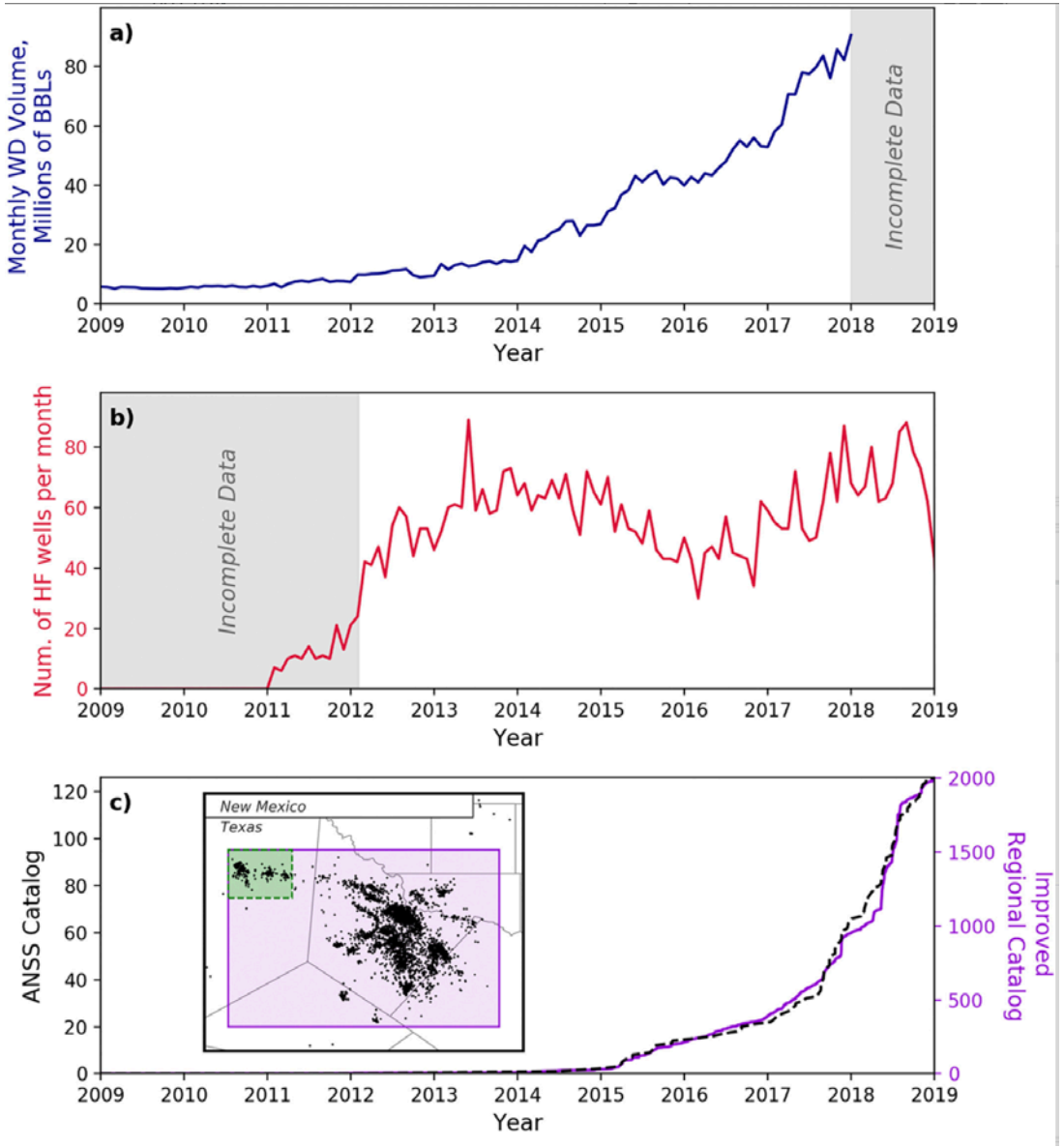


2016 Grant County, Oklahoma

Dougherty et al. (2019); Cochran et al. (in press)

IMPROVED DETECTION METHODS

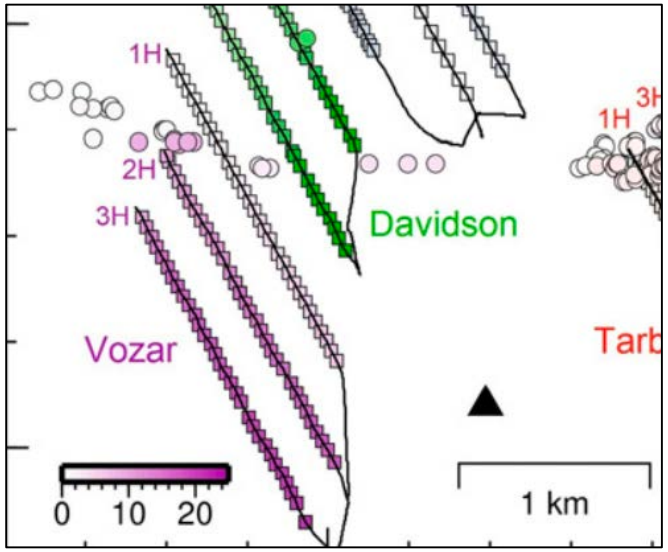
- Correlation detections
  - 10x increase in detections
  - Identified a productive foreshock sequence prior to the Pawnee EQ
  - Identified that hydraulic fracturing induced EQs are common in Oklahoma.
  - Earthquake occurrence in the Permian Basin, TX.

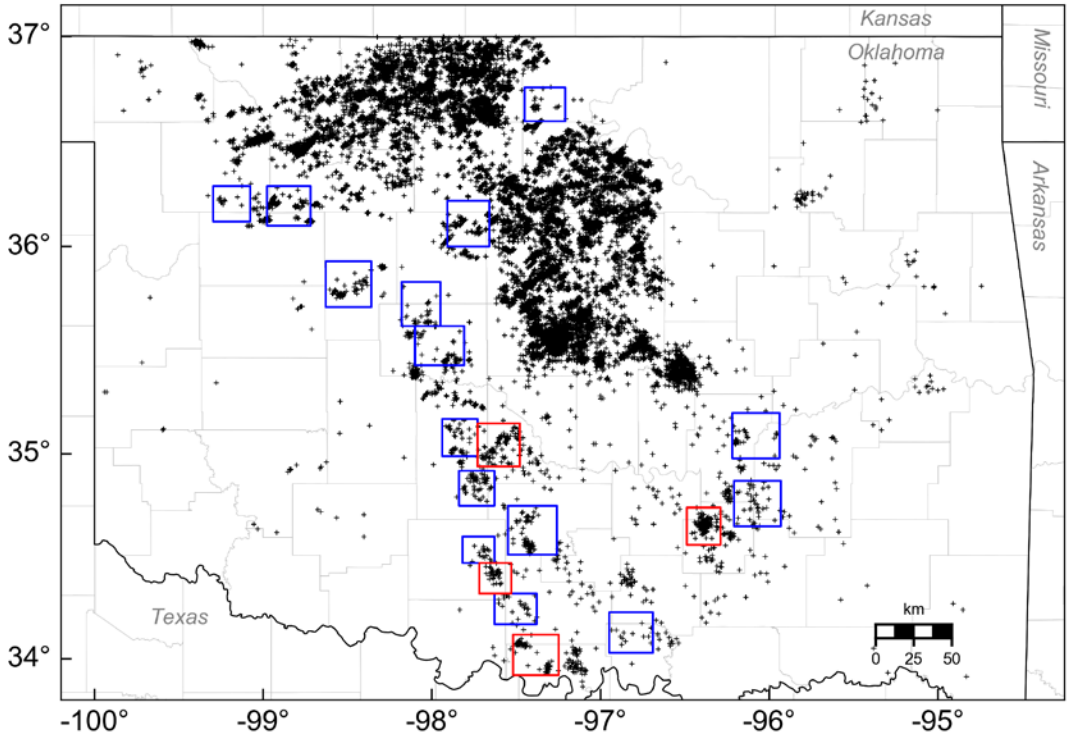


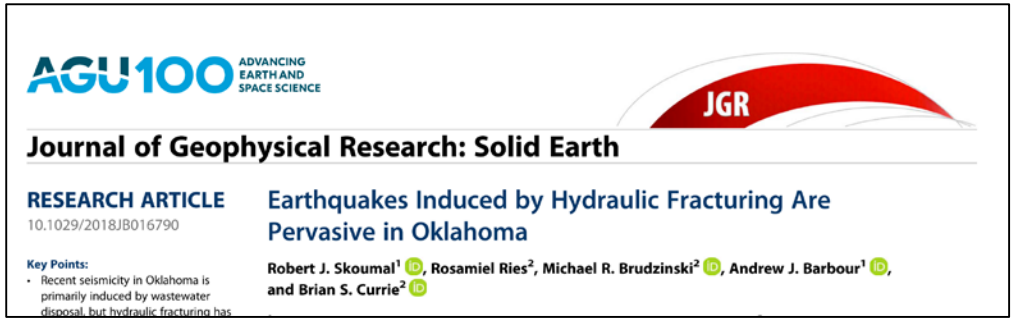
Skoumal et al. (2019)

Hydraulic Fracturing and Earthquakes

- ~3% of seismicity in OK
- Short-lived
- Small magnitude
- Evidence of larger EQs elsewhere






AGU100 ADVANCING EARTH AND SPACE SCIENCE

JGR

Journal of Geophysical Research: Solid Earth

RESEARCH ARTICLE

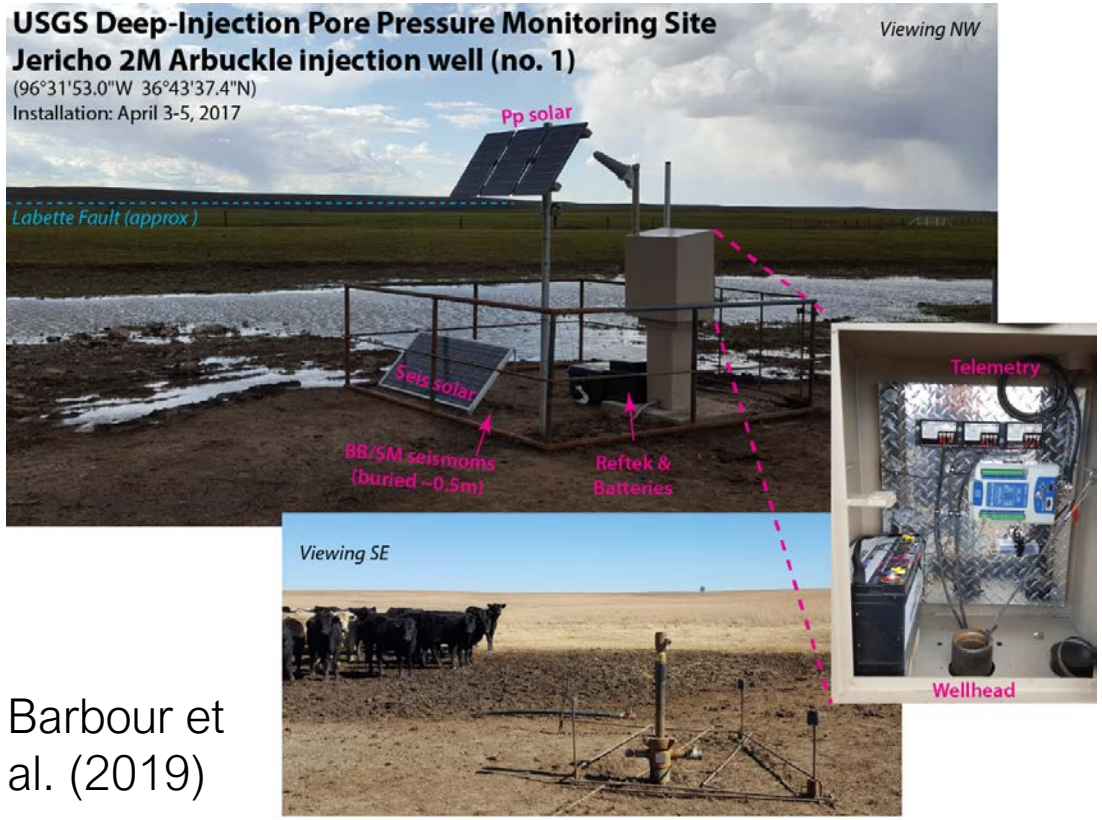
10.1029/2018JB016790

Earthquakes Induced by Hydraulic Fracturing Are Pervasive in Oklahoma

Key Points:
- Recent seismicity in Oklahoma is primarily induced by wastewater disposal, but hydraulic fracturing has

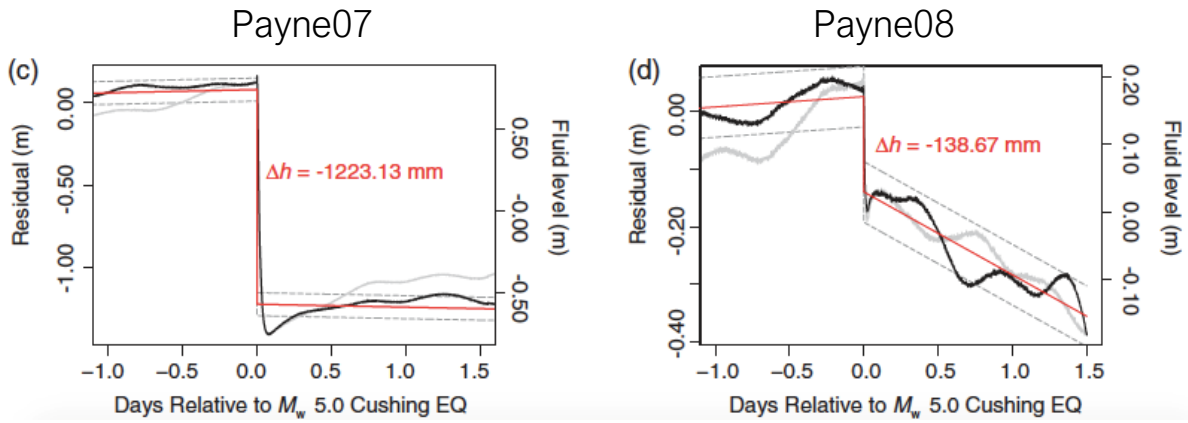
Robert J. Skoumal[1], Rosamiel Ries[2], Michael R. Brudzinski[2], Andrew J. Barbour[1], and Brian S. Currie[2]

Skoumal et al. (2018)



Barbour et al. (2019)

Static water level change in Arbuckle due to M5.0 Cushing



Kroll et al. (2017)

DOWNHOLE PORE PRESSURE MONITORING

- Evidence of fluid migration from the Arbuckle into basement. Slow consistent pressure increase in Arbuckle. (
  - 1 USGS station in Osage County with co-located seismometer (2 additional sensor packages available)
- Static fluid level changes in response to nearby earthquakes
  - OGS network

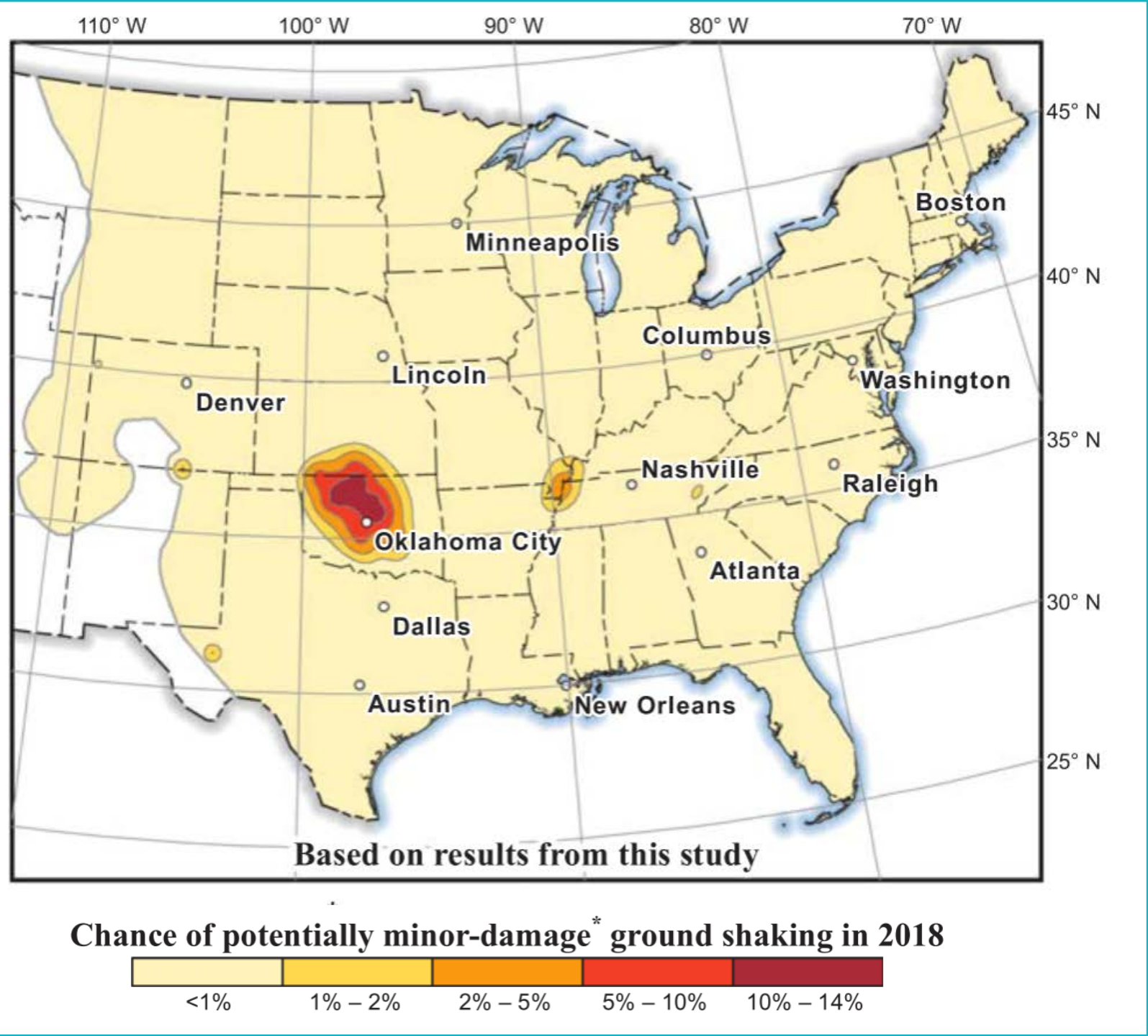
HAZARD FORECASTING

1-Year Hazard Maps

- Induced + natural hazard
- Releases for 2016, 2017, 2018
- No release for 2019
- 10x increase in hazard

Purely Statistical Methodology

Petersen et al. (2015, 2016, 2017, 2018)



Hydromechanical Induced EQ Forecasts

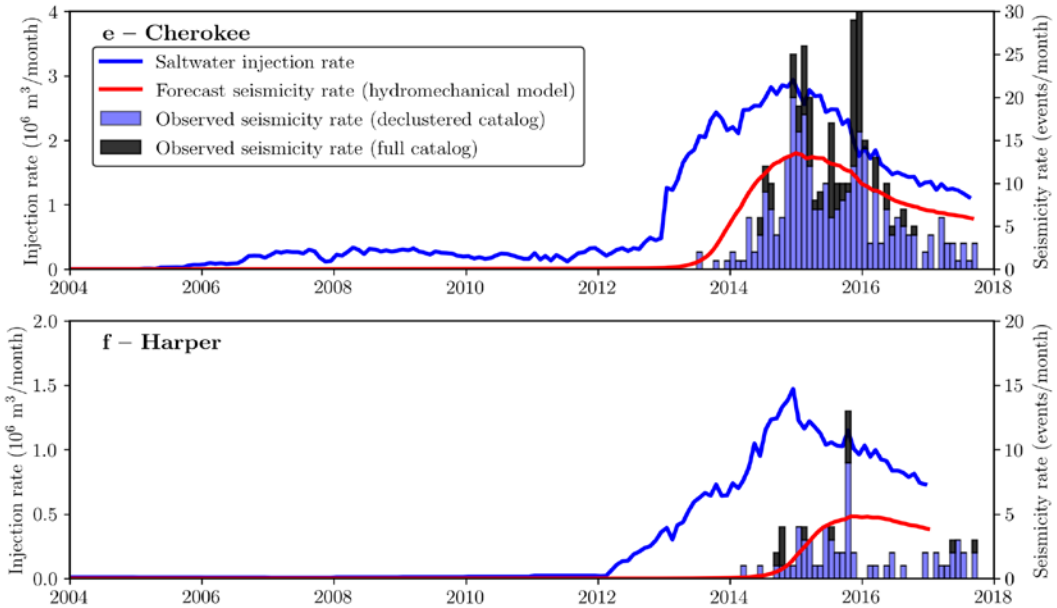
- Reservoir model to capture first-order effects
- Pressure changes are dominated by compressibility effect

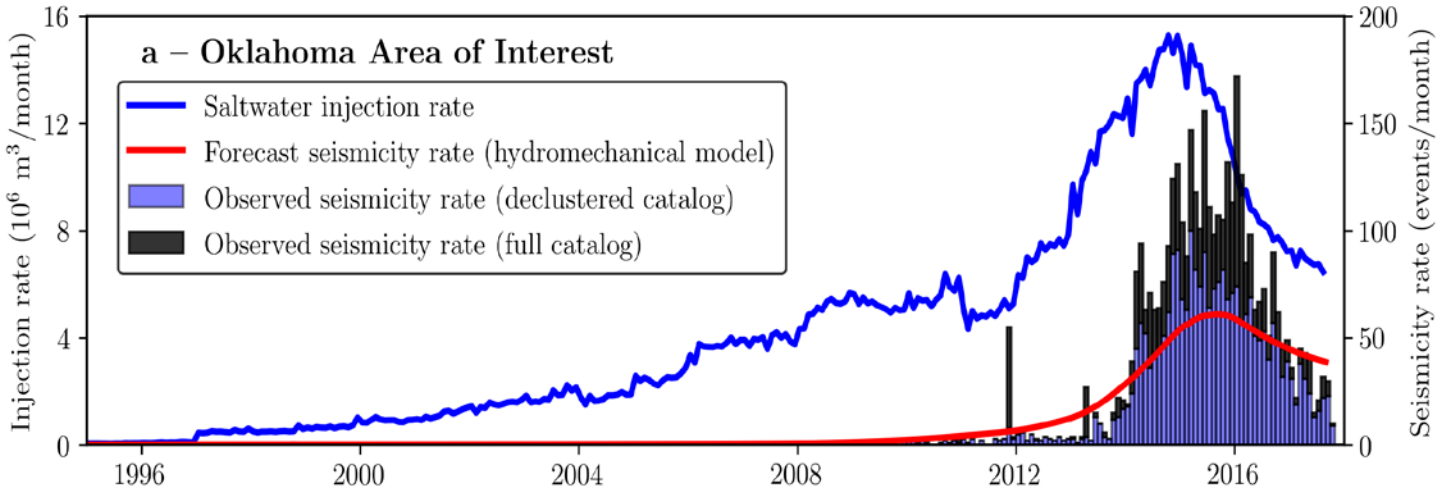
$$\dot{p} = \frac{q}{V\phi\beta}$$

- Forecast earthquake rates w/ Rate and State (Dieterich '94)

$$\frac{dR}{dt} = \frac{R}{t_{c0}}\left(\frac{\dot{s}}{\dot{s}_0} - R\right)$$

Norbeck and Rubinstein (2018)





Other Induced Topics

- Geothermal and EGS
- CCS
- Reservoir impoundment
- Other

On-going research:

Microseismicity and hazard associated with CO2 sequestration

Ambient noise tomography to (perhaps) detect CO2 plume

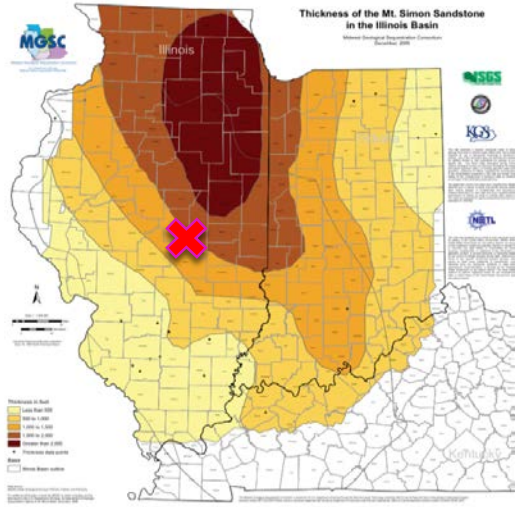
Deformation observations and modeling in geothermal fields

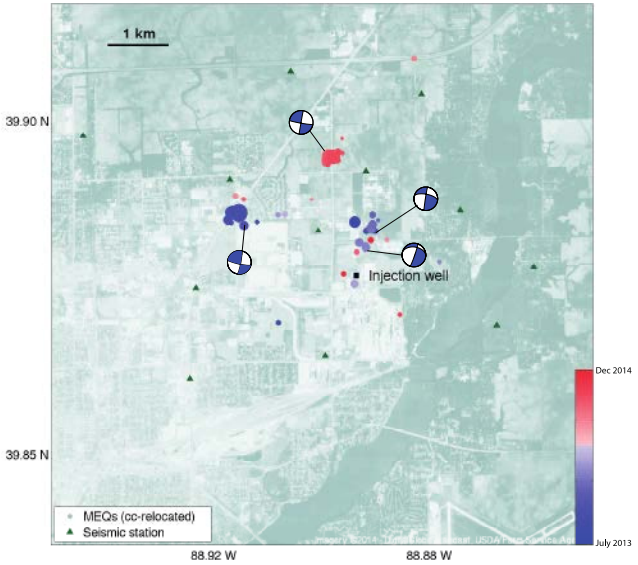
Pressure evolution in reservoirs

Monitoring using fiber-optic DAS

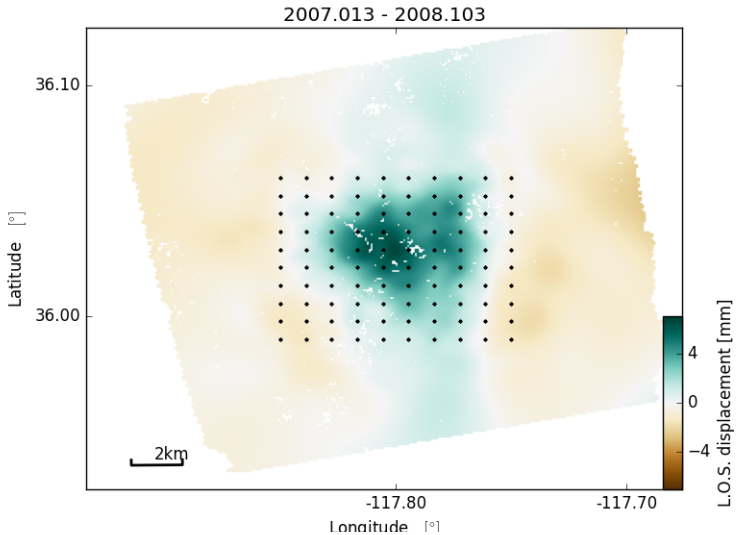
Kaven, Barbour, McGarr, etc.

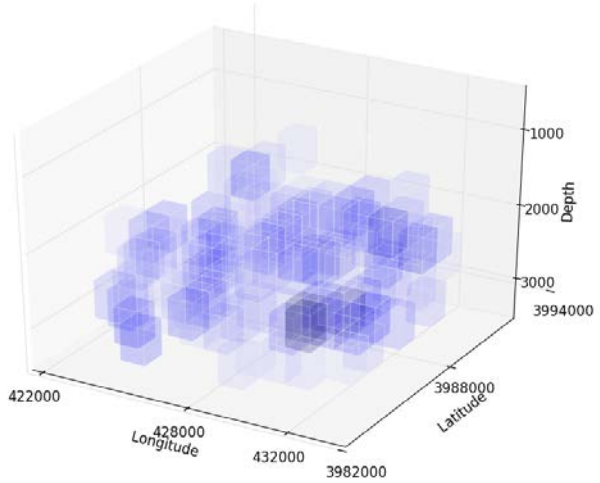
CCS Seismic Monitoring - Decatur





Long-term Geothermal Field Deformation and Modeling





Coso Geothermal Field

USGS CORE ACTIVITIES

Fundamental Research

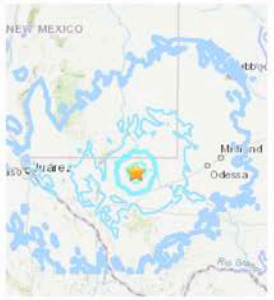
Information Products

USGS POST-QUAKE INFORMATION PRODUCTS

M 5.0 - 41km W of Mentone, Texas

2020-03-26 15:16:27 (UTC) | 31.708°N 104.039°W | 6.6 km depth

Interactive Map



Contributed by US [2]

Regional Information

Contributed by US [2]

Felt Report - Tell Us!

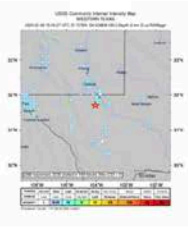
0 0 2 0 3 0

Responses

Contribute to citizen science. Please tell us about your experience.

Citizen Scientist Contributions

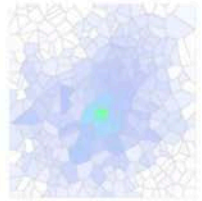
Did You Feel It? V



Community Internet Intensity Map

Contributed by US [2]

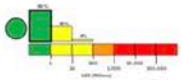
ShakeMap VI



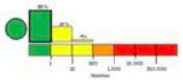
Estimated Intensity Map

Contributed by US [2]

PAGER GREEN



Estimated Economic Losses



Estimated Fatalities

Contributed by US [2]

Ground Failure

Landslide Estimate

Little or no area affected

Little or no population exposed

Liquefaction Estimate

Little or no area affected

Little or no population exposed

Contributed by US [2]

Origin

Review Status
REVIEWED

Magnitude
5.0 mww

Depth
6.6 km

Time
2020-03-26 15:16:27 UTC

Contributed by US [2]

Moment Tensor

Fault Plane Solution

Contributed by US [2]

Aftershock Forecast

Be ready for more earthquakes.

Our model of the expected numbers and odds of future earthquakes.

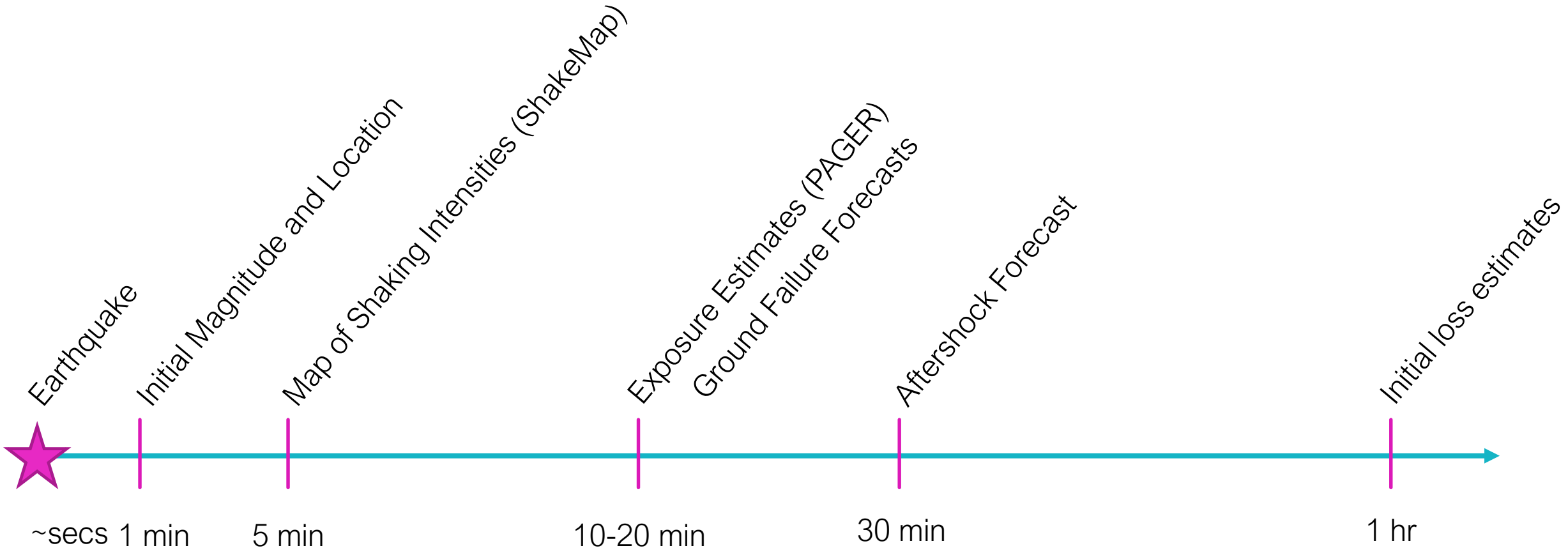
Contributed by US [2]

View Nearby Seismicity

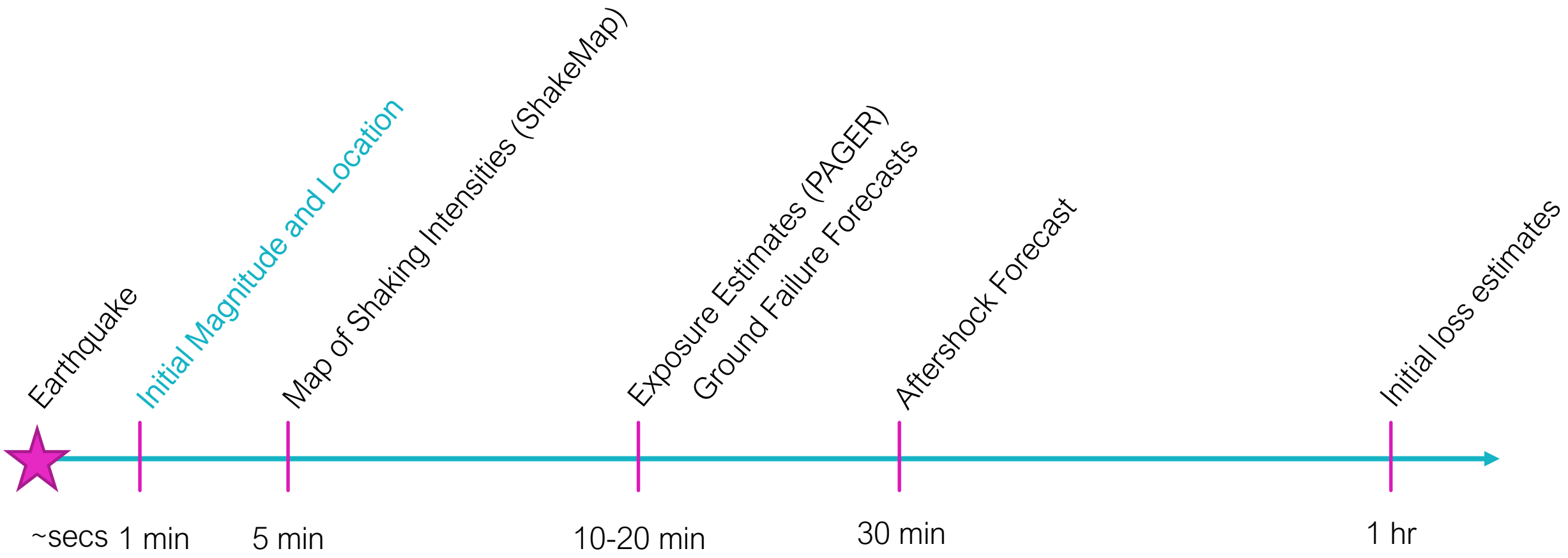
Time Range

± Three Weeks

Search Radius



Information products are updated as new data become available



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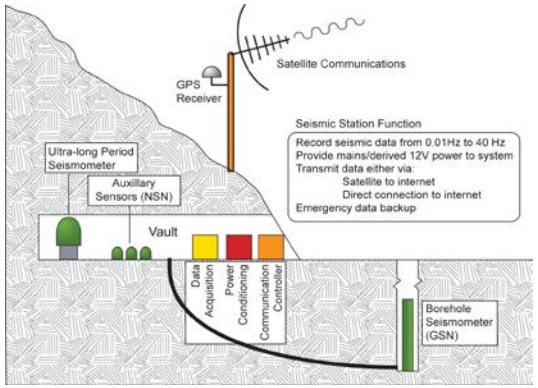
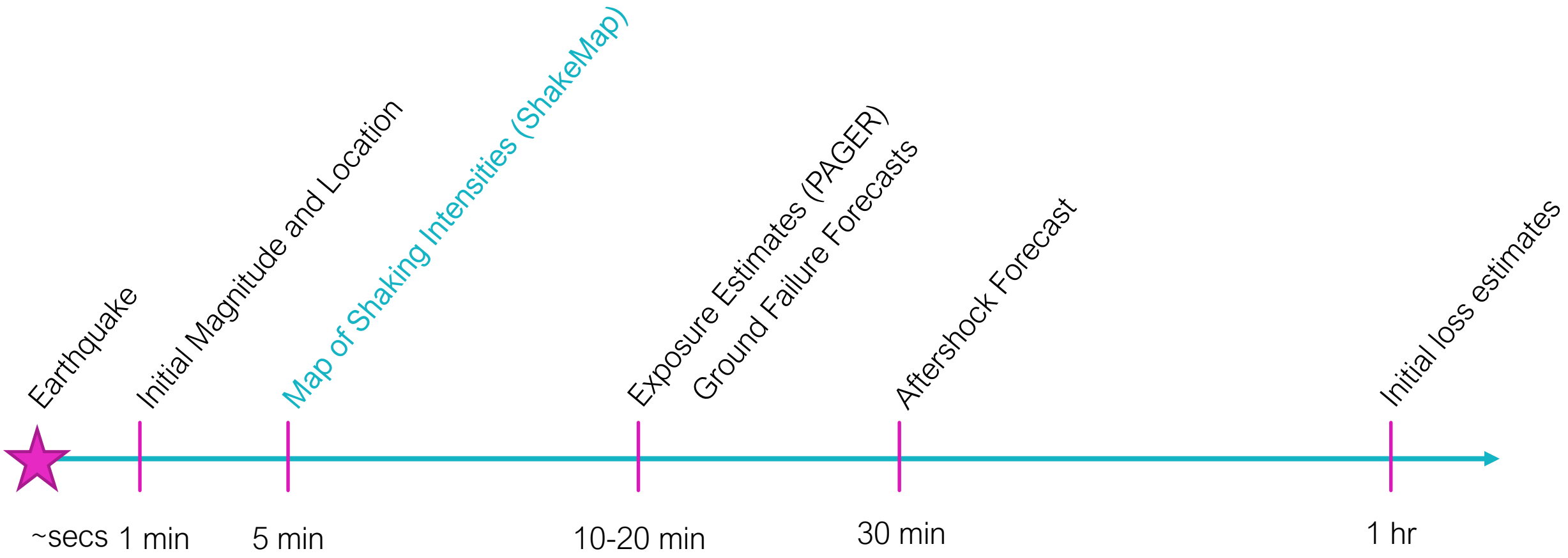
SEISMIC MONITORING

- Advanced National Seismic System
  - Backbone network
  - Regional and partner networks
- Monitoring of small to moderate earthquakes depends on sufficient near-source station coverage





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Seismic Station Data + Did You Feel It? = ShakeMap

NMP02 New Mexico Permian - Site# 02

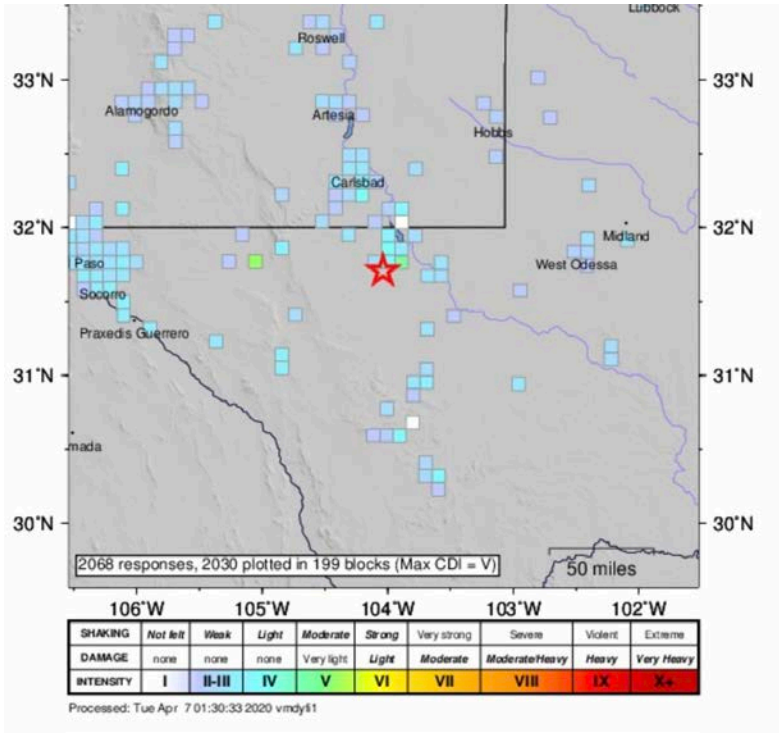
IV mmi	0.58 %g pga	0.34 cm/s pgv	43.84 km dist

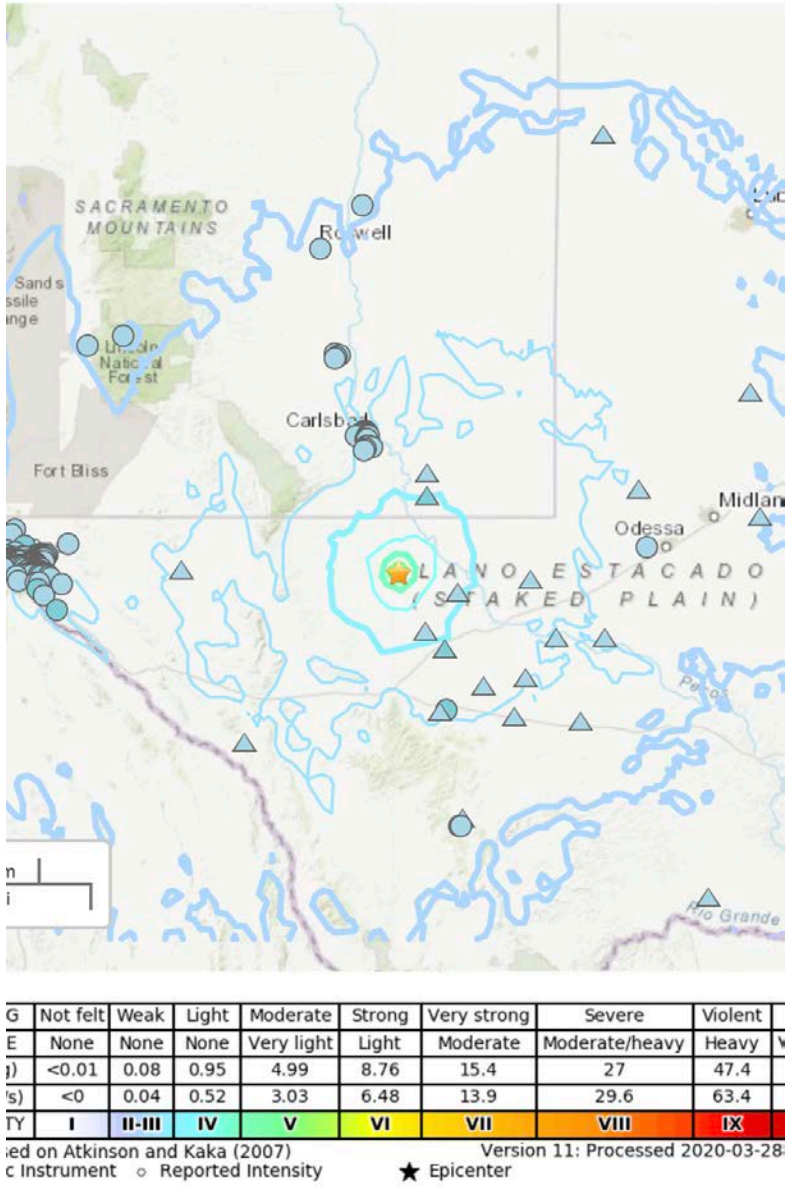
Details

Network	GM
Location	32.089°N 103.861°W
Source	GM
Intensity	3.7

Channels

Name	PGA	PGV	PSA(03)	PSA(10)	PSA(30)
HNE	0.51 %g	0.22 cm/s	1.11 %g	0.28 %g	0.03 %g
HNN	0.53 %g	0.34 cm/s	1.36 %g	0.34 %g	0.04 %g
HNZ	0.30 %g	0.15 cm/s	0.59 %g	0.23 %g	0.03 %g
--.HNE	0.50 %g	0.22 cm/s	0.73 %g	0.27 %g	0.02 %g
--.HNN	0.58 %g	0.34 cm/s	0.81 %g	0.33 %g	0.04 %g

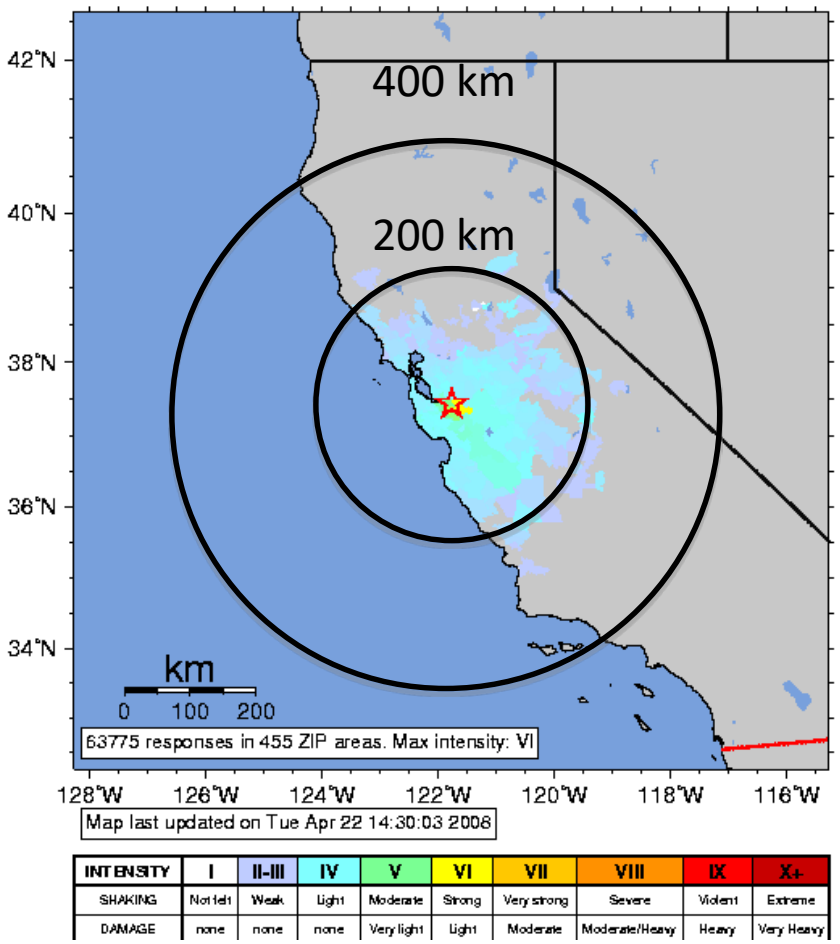




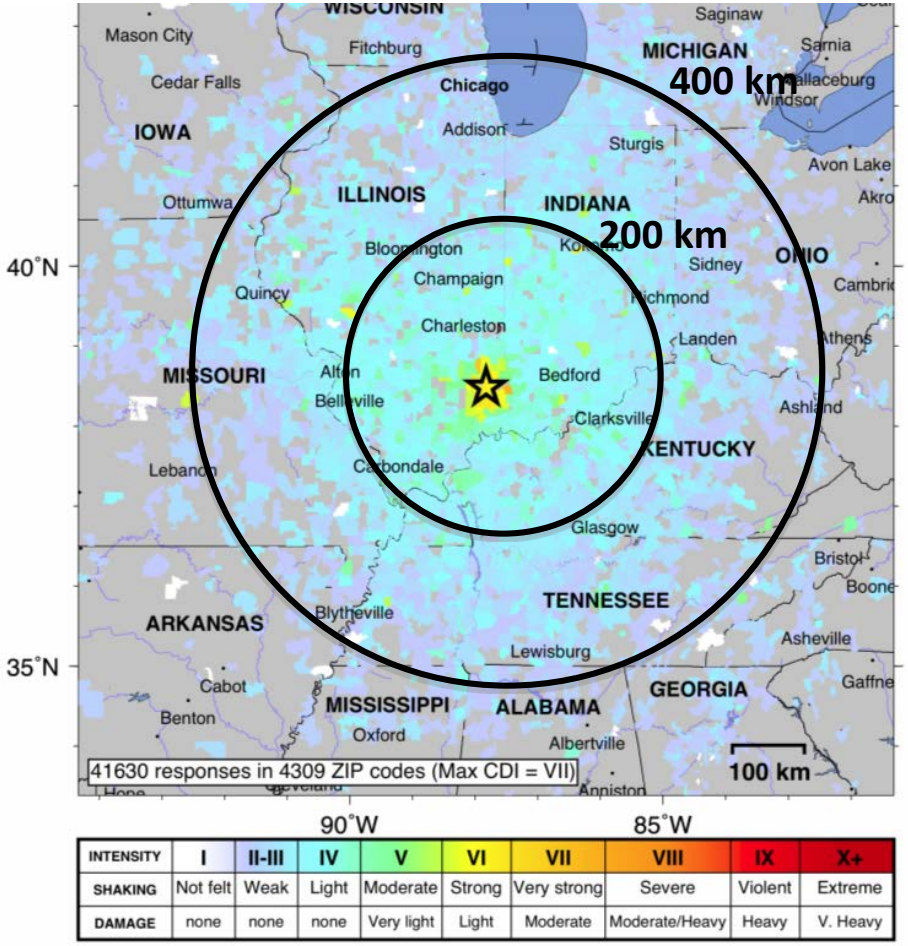
SHAKEMAP

CENTRAL AND EASTERN US EARTHQUAKES ARE WIDELY FELT

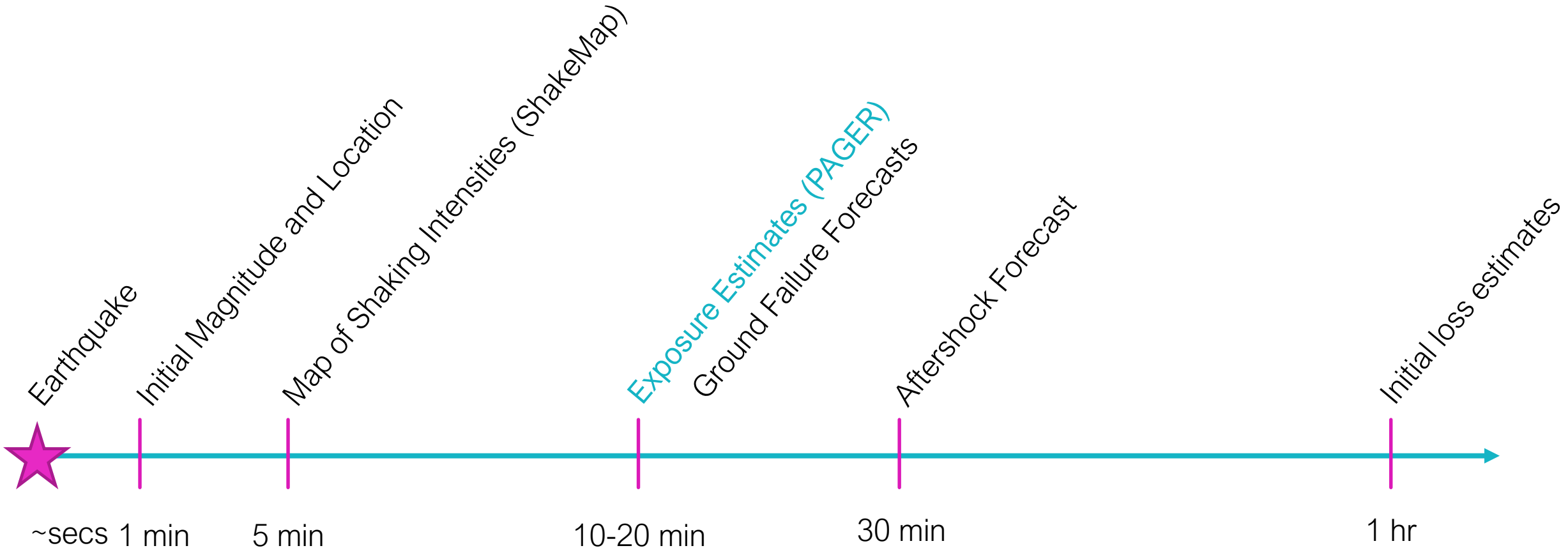
2007 M5.6 California



2008 M5.4 Illinois



Comparison of public reports of shaking to USGS's Did You Feel It?



Information products are updated as new data become available

PAGER –
PROMPT ASSESSMENT OF GLOBAL EARTHQUAKES FOR RESPONSE

- Estimates exposure based on population and shaking levels
- Available for M5.5 earthquakes globally
- Initial product within 20-30 mins

USGS science for a changing world

Earthquake Shaking — Yellow Alert

USAID FROM THE AMERICAN PEOPLE

GSN ANSS

PAGER Version 6

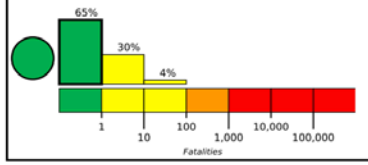
Created: 12 hours, 43 minutes after earthquake

M 7.1, 17km NNE of Ridgecrest, CA

Origin Time: 2019-07-06 03:19:52 UTC (Fri 20:19:52 local)

Location: 35.7665° N 117.6048° W Depth: 17.0 km

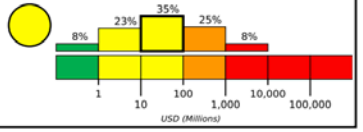
Estimated Fatalities



Yellow alert for economic losses. Some damage is possible and the impact should be relatively localized. Estimated economic losses are less than 1% of GDP of the United States. Past events with this alert level have required a local or regional level response.

Green alert for shaking-related fatalities. There is a low likelihood of casualties.

Estimated Economic Losses

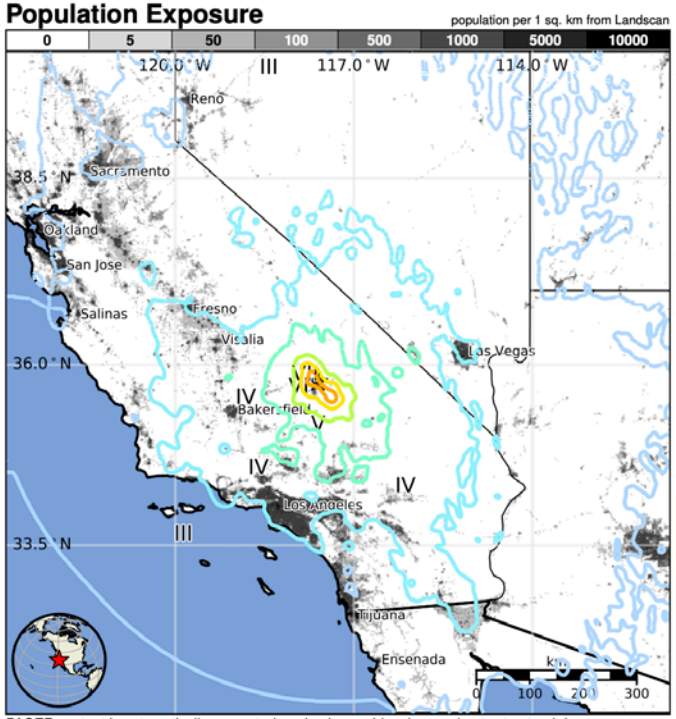


Estimated Population Exposed to Earthquake Shaking

ESTIMATED POPULATION EXPOSURE (k=x1000)		–*	28,545k*	21,546k	602k	2k	45k	0	0	0
ESTIMATED MODIFIED MERCALLI INTENSITY		I	II-III	IV	V	VI	VII	VIII	IX	X+
PERCEIVED SHAKING		Not felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	Resistant Structures	None	None	None	V. Light	Light	Moderate	Mod./Heavy	Heavy	V. Heavy
	Vulnerable Structures	None	None	None	Light	Moderate	Mod./Heavy	Heavy	V. Heavy	V. Heavy

*Estimated exposure only includes population within the map area.

Population Exposure



Structures

Overall, the population in this region resides in structures that are highly resistant to earthquake shaking, though some vulnerable structures exist. The predominant vulnerable building types are unreinforced brick masonry and reinforced masonry construction.

Historical Earthquakes

Date (UTC)	Dist. (km)	Mag.	Max MMI(#)	Shaking Deaths
1991-06-28	174	5.6	VI(1,267k)	1
1992-06-28	201	7.3	VIII(23k)	1
1971-02-09	167	6.6	IX(21k)	65

Recent earthquakes in this area have caused secondary hazards such as tsunamis, landslides and liquefaction that might have contributed to losses.

Selected City Exposure

from GeoNames.org

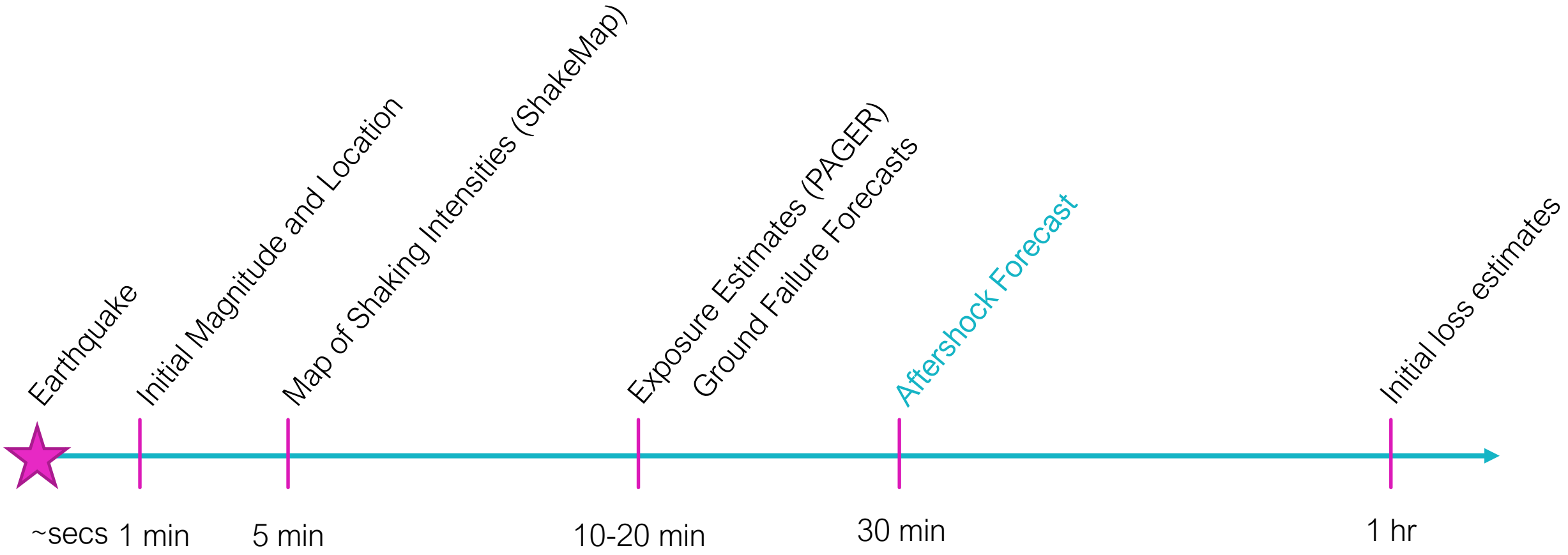
MMI	City	Population
VII	Ridgecrest	28k
VII	China Lake Acres	2k
VII	Inyokern	1k
VI	Searles Valley	2k
V	Adelanto	32k
V	Weldon	3k
IV	**Los Angeles**	**3,793k**
III	Mexicali	597k
III	Carson City	55k
III	**Sacramento**	**466k**
II	Phoenix	1,446k

bold cities appear on map. (k=x1000)

PAGER content is automatically generated, and only considers losses due to structural damage. Limitations of input data, shaking estimates, and loss models may add uncertainty.

https://earthquake.usgs.gov/earthquakes/eventpage/ci38457511#pager

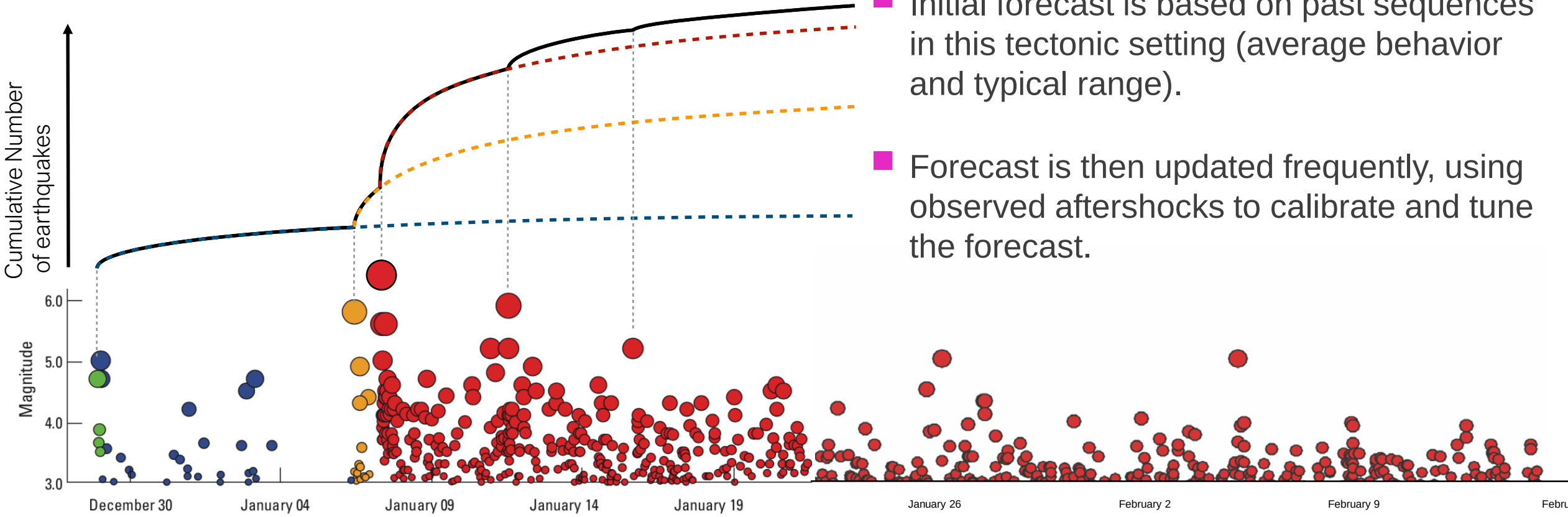
Event ID: ci38457511



Information products are updated as new data become available

FORECAST MODELS

- Aftershocks are “random” but follow well-established statistical patterns.
- an Aftershock Forecast is a statistical projection of behavior seen in past aftershock sequences, calibrated to the current sequence.



- USGS issues aftershock forecasts after all M5.0 and larger earthquakes in the US.
- First forecast delivered after 30 minutes.
- Initial forecast is based on past sequences in this tectonic setting (average behavior and typical range).
- Forecast is then updated frequently, using observed aftershocks to calibrate and tune the forecast.

FORECAST MODELS

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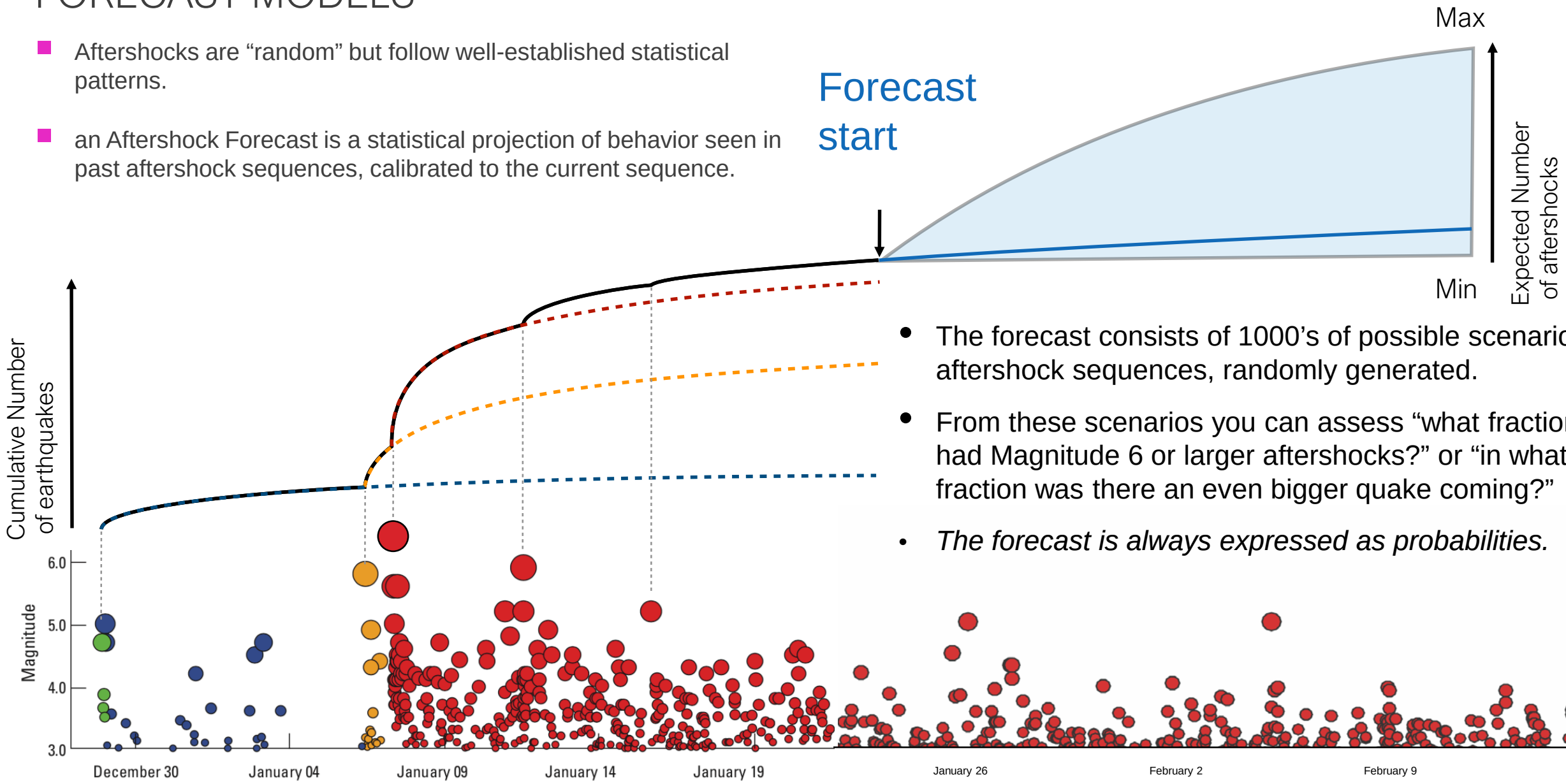
- an Aftershock Forecast is a statistical projection of behavior seen in past aftershock sequences, calibrated to the current sequence.



- The forecast consists of 1000’s of possible scenario aftershock sequences, randomly generated.
- From these scenarios you can assess “what fraction had Magnitude 6 or larger aftershocks?” or “in what fraction was there an even bigger quake coming?”
- *The forecast is always expressed as probabilities.*

Automatic USGS forecast

Aftershock Forecast

Contributed by US [5] last updated 2020-02-25 23:49:36 (UTC)

✓ The data below are the most preferred data available
✓ The data below have 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 Month there is a 3 % chance of one or more aftershocks that are larger than magnitude 6.4. It is likely that there will be smaller earthquakes over the next 1 Month, with 25 to 200 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.

Scenario 1 – Most Likely (~80%)

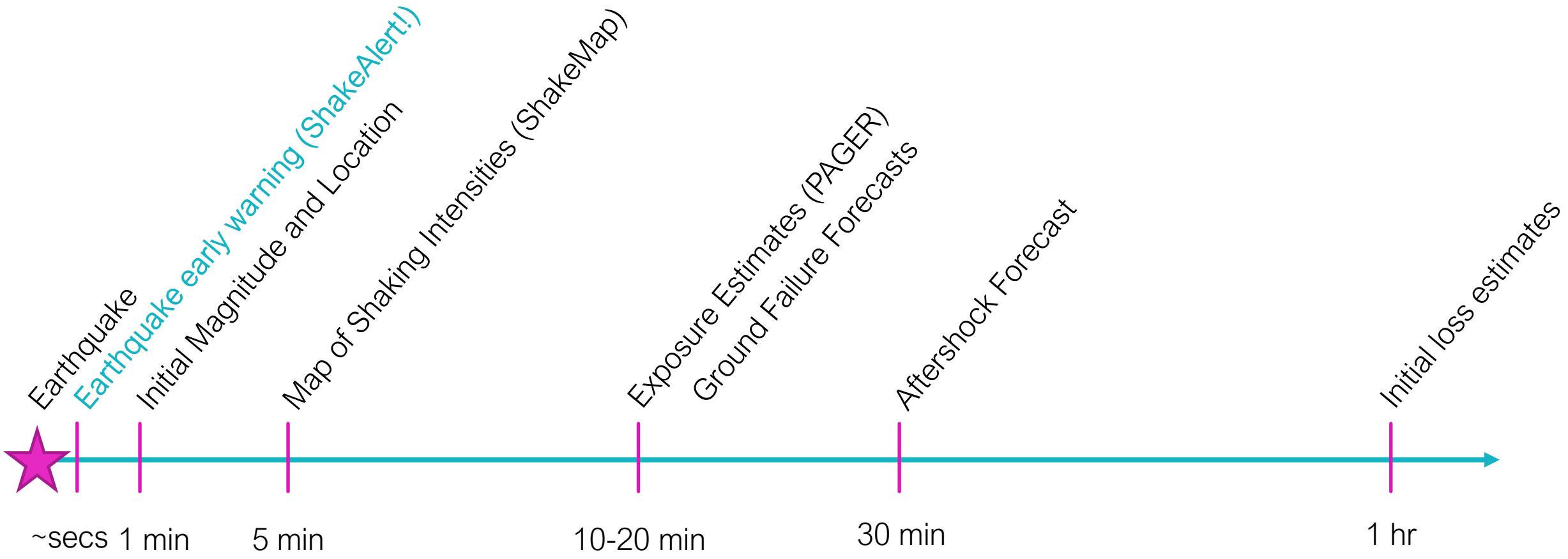
Aftershocks continue, but the worst is over.

Scenario 2 – Less Likely (~15%)

An aftershock large enough to do additional damage (~M6+)

Scenario 3 – Least Likely (~5%)

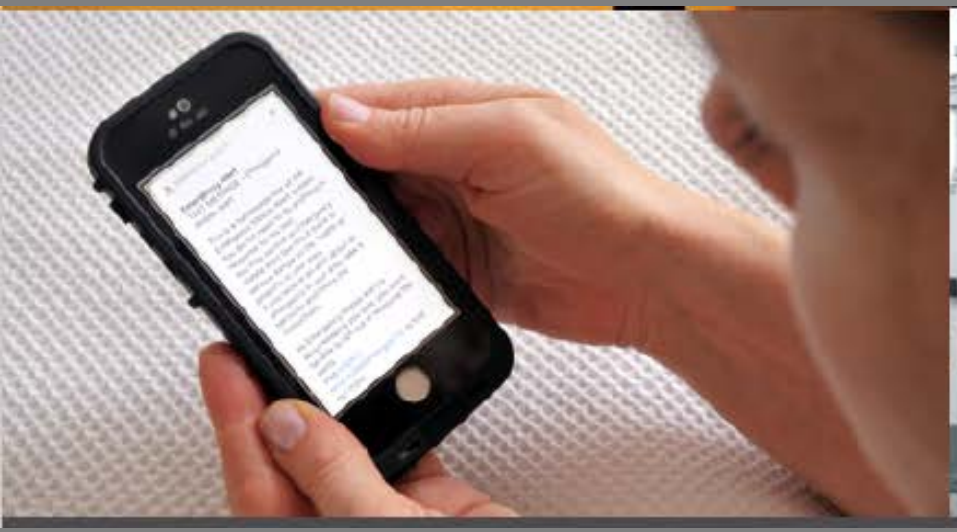
Something bigger than the mainshock. (Mainshock is just a foreshock.)



Information products are updated as new data become available

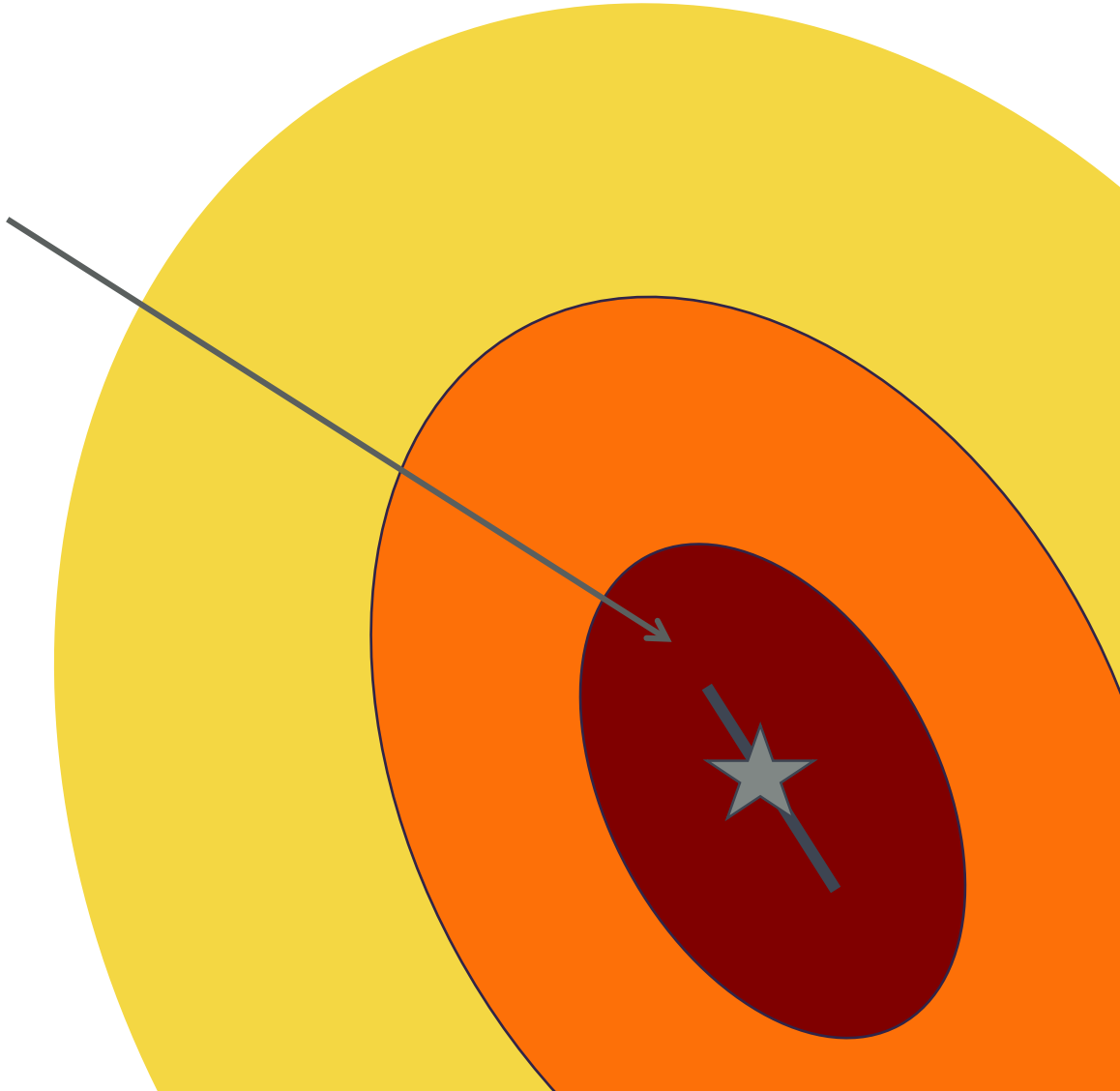
What is Earthquake Early Warning?

Goal: Provide advanced warning of potentially damaging ground shaking so people and machines can take protective actions



Goldilocks Sweet Spot:

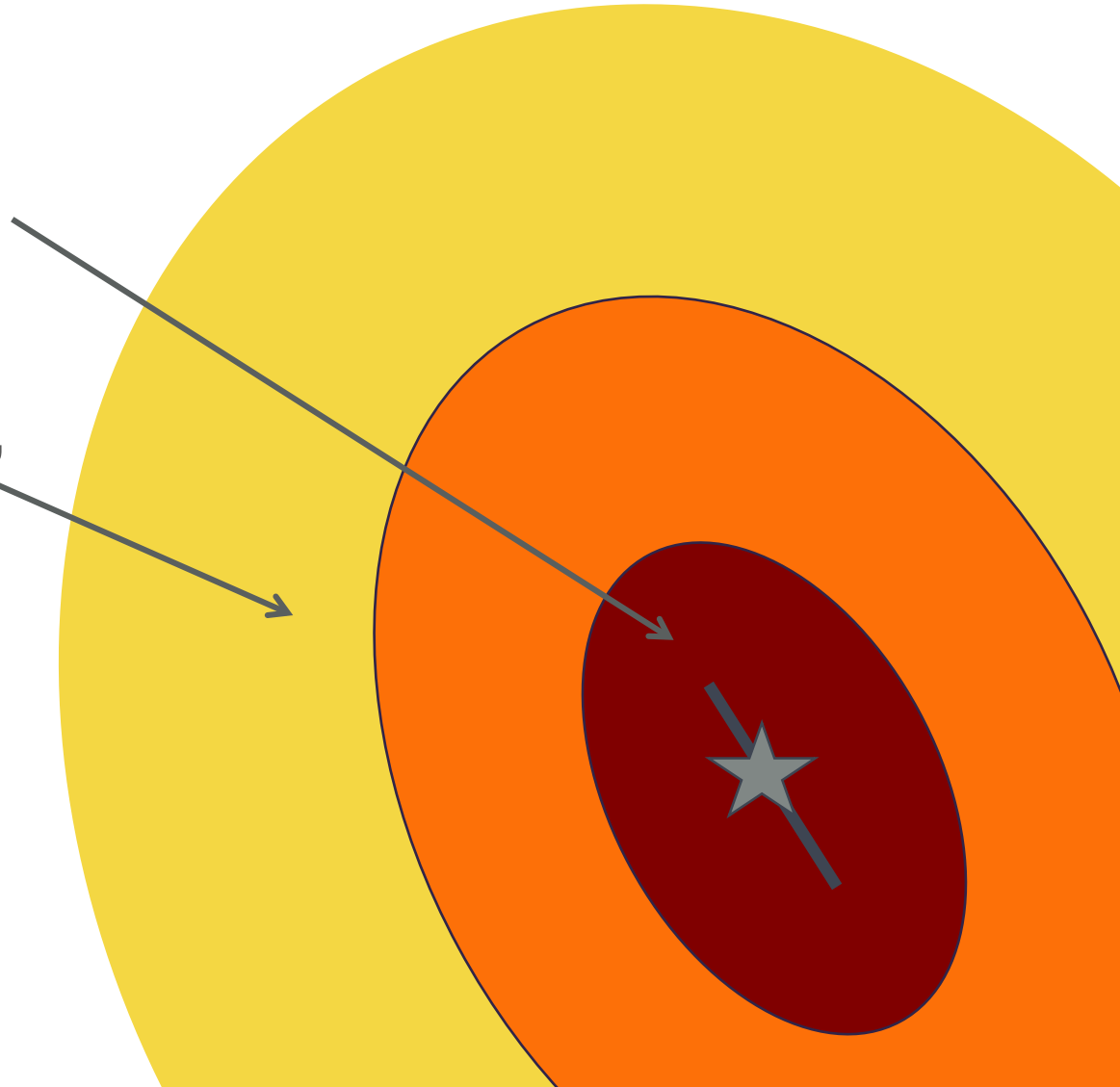
- **Too close** = strong shaking, but little to no warning



Minson et al. [2018; 2019]

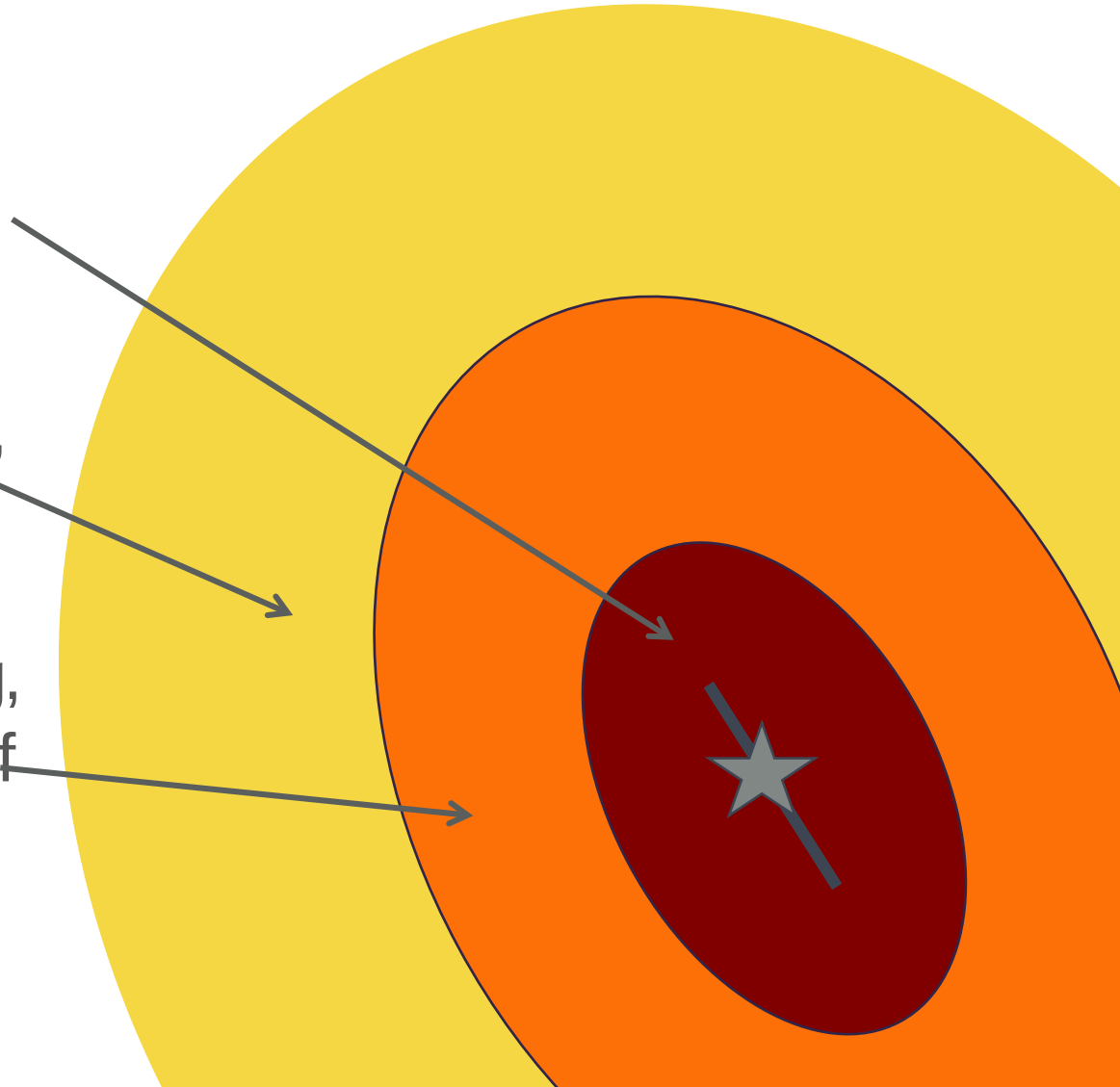
Goldilocks Sweet Spot:

- **Too close** = strong shaking, but little to no warning
- **Too far** = longer warning times possible, but weak shaking



Goldilocks Sweet Spot:

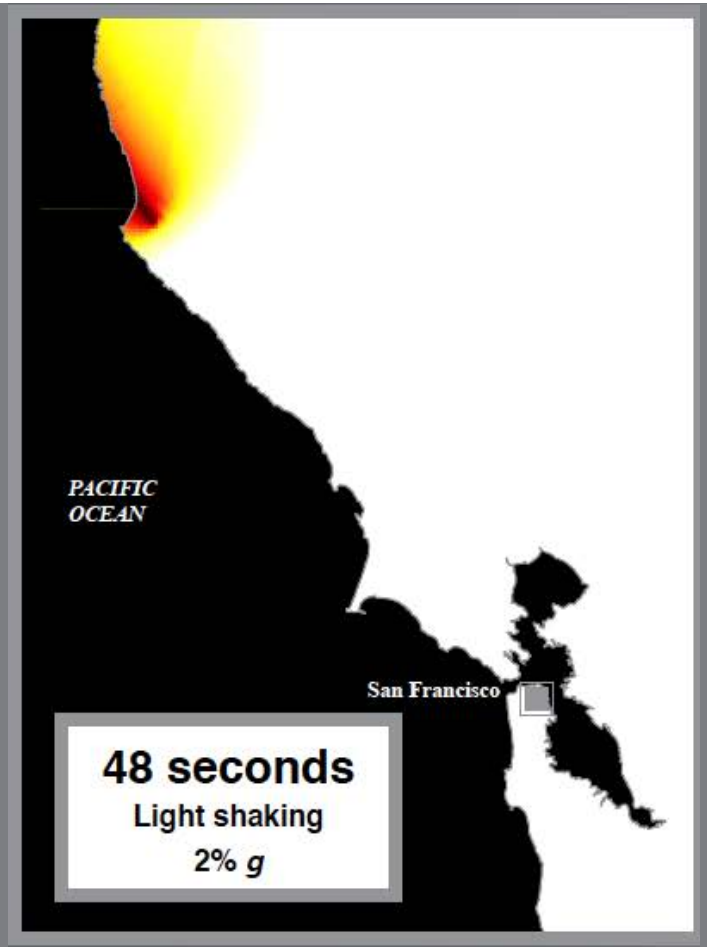
- **Too close** = strong shaking, but little to no warning
- **Too far** = longer warning times possible, but weak shaking
- **Just right** = moderate to strong shaking, and non-zero warning times (up to 10s of seconds)



Goldilocks Sweet Spot #2 (Alerting levels):

- **<u>Too soon</u>** = little chance of strong shaking, potentially long warning times

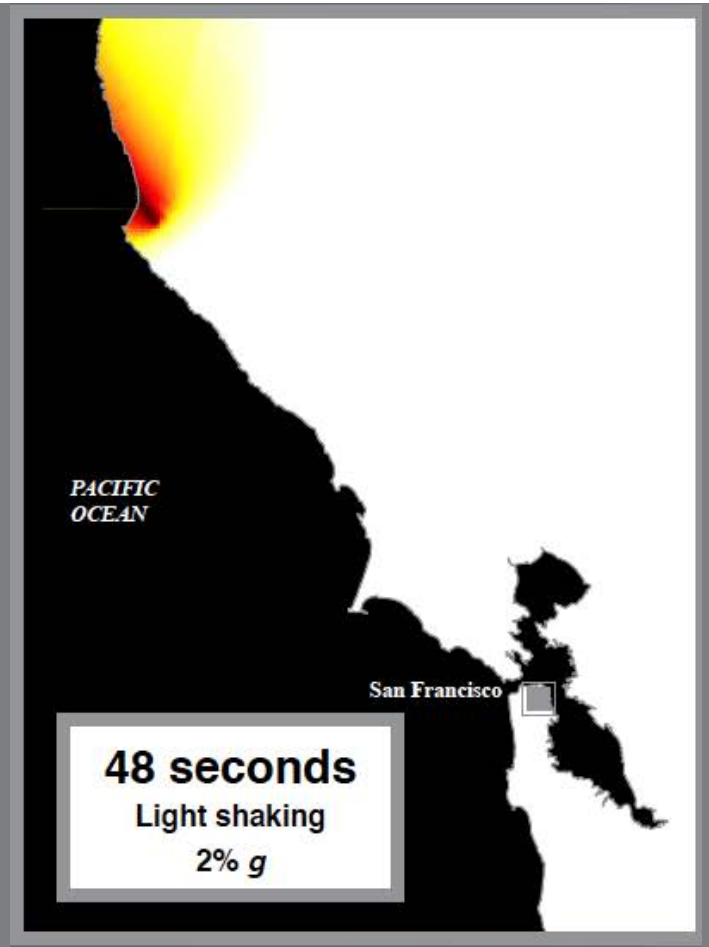
Minson et al. [2018; 2019]

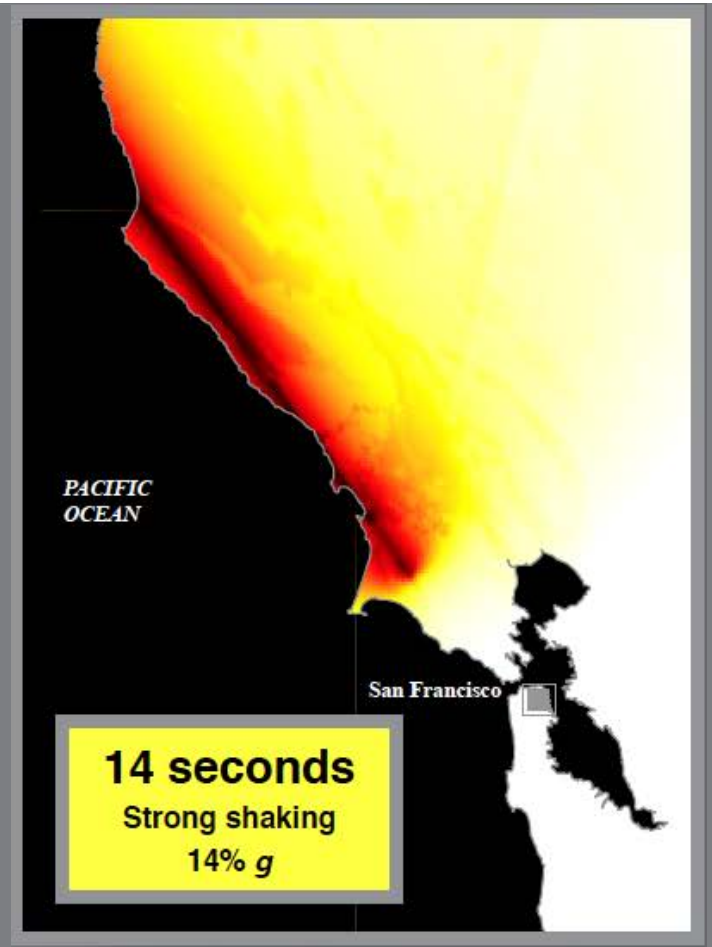


Goldilocks Sweet Spot #2 (Alerting levels):

- **Too soon** = little chance of strong shaking, potentially long warning times
- **Too late** = damaging shaking expected, short/no warning times

Minson et al. [2018; 2019]

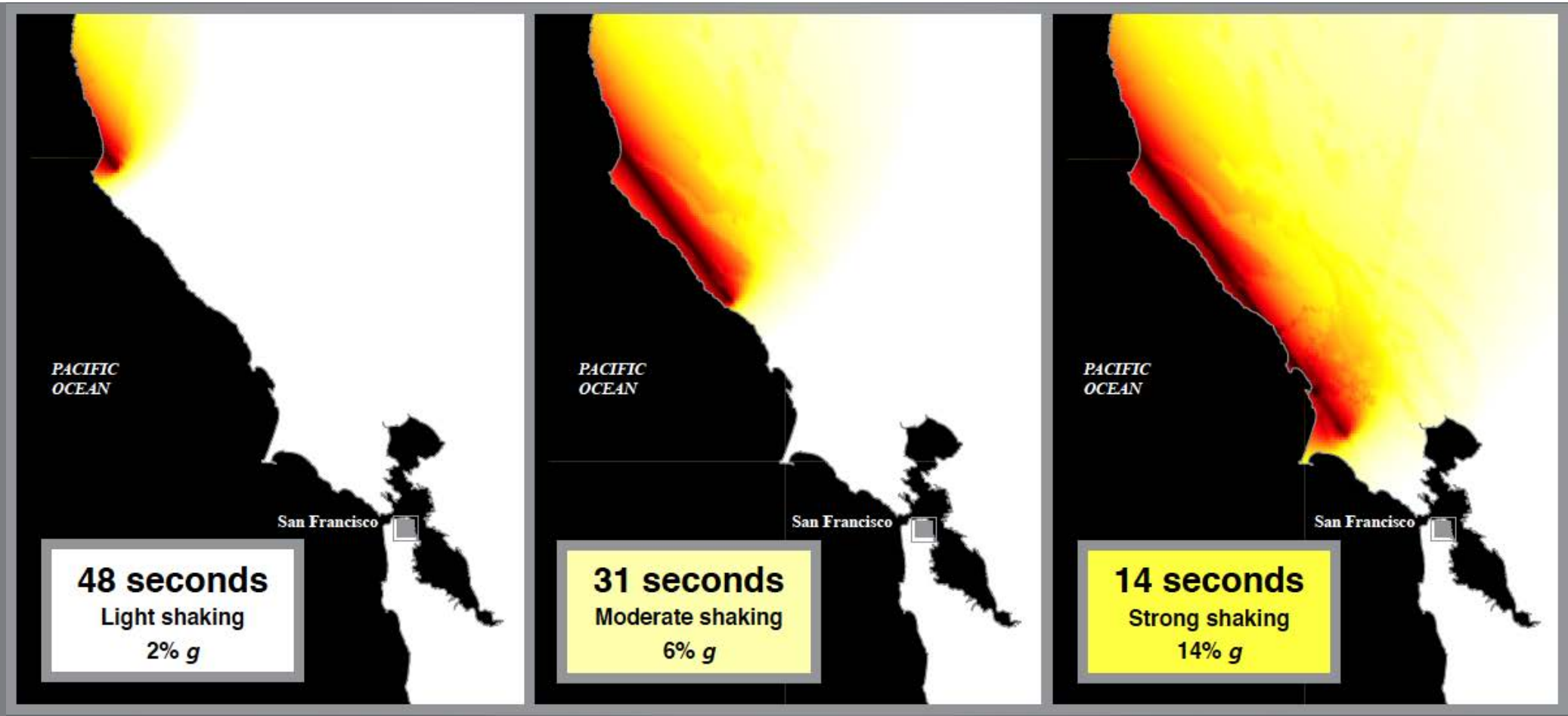




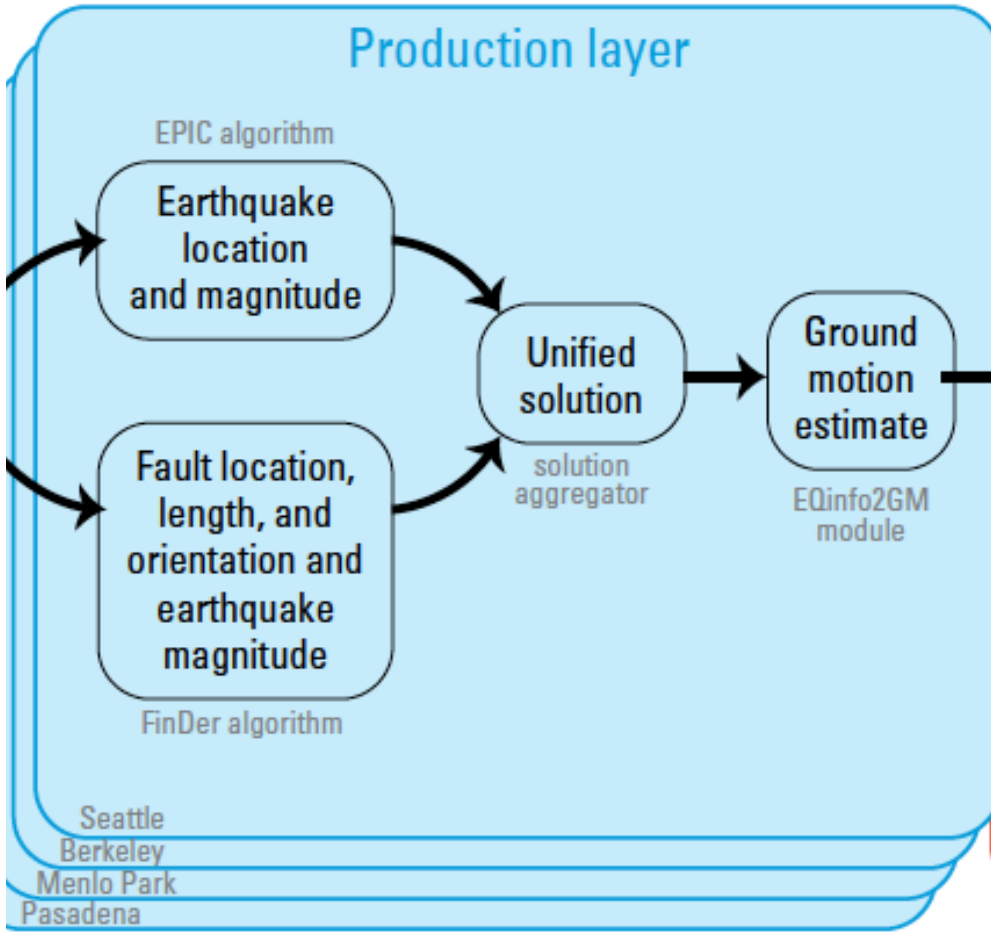
Goldilocks Sweet Spot #2 (Alerting levels):

- **Too soon** = little chance of strong shaking, potentially long warning times
- **Too late** = damaging shaking expected, short/no warning times
- **Just right** = moderate chance of damaging ground motions, moderate warning times possible

Minson et al. [2018; 2019]



ShakeAlert™

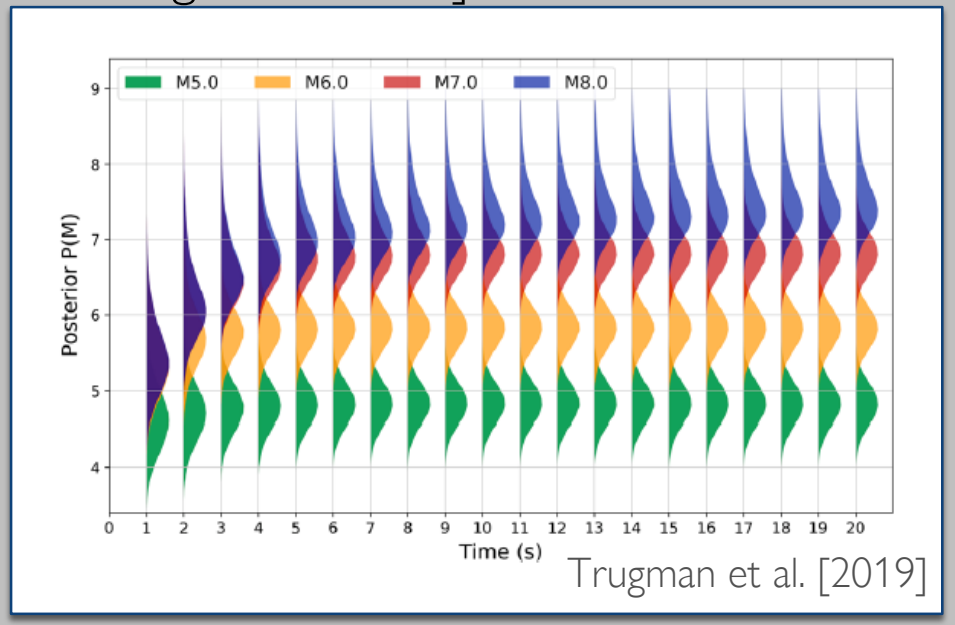


Given et al. [2018]

EPIC

Earthquake Point-source Integrated Code

- Estimates point-source location and magnitude
- Peak displacement measured in first 4 seconds (saturates at M~6.5)
- Combination of two methods: Onsite [e.g. Kanamori, 2005; Bose et al., 2009] and ElarmS [e.g. Kuyuk et al., 2014; Chung et al., 2019]

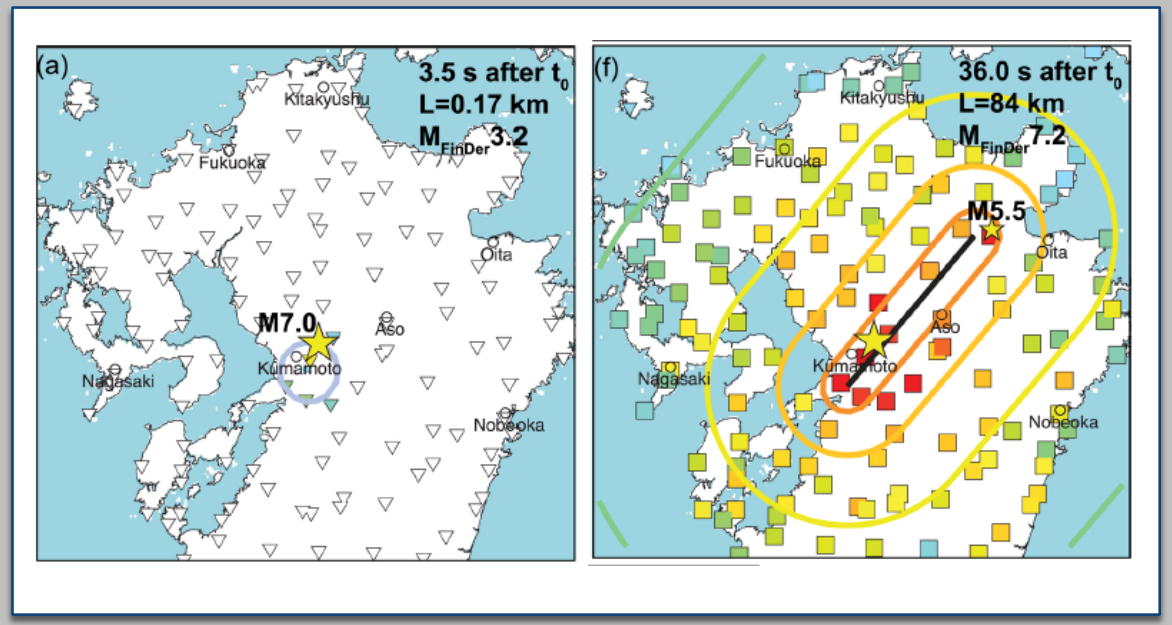


Trugman et al. [2019]

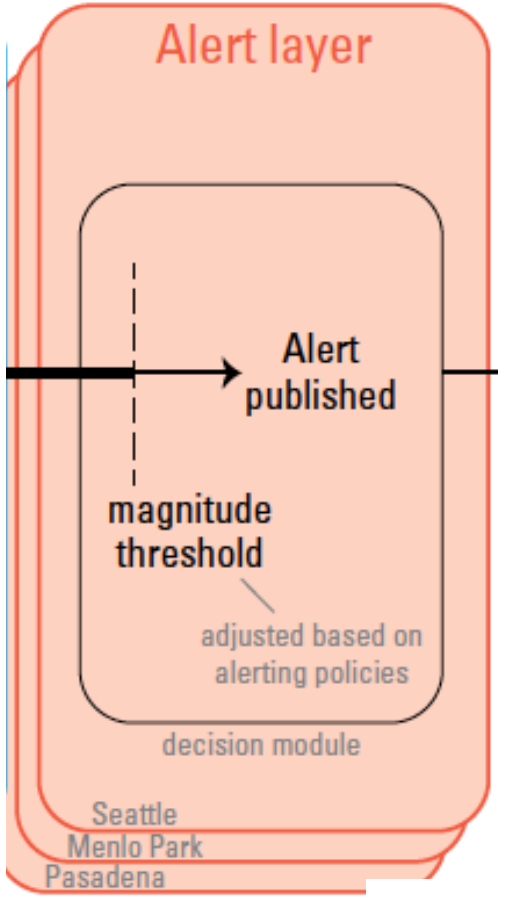
FinDer

Finite-fault rupture Detector

- Estimates a line source from peak acceleration measurements [Bose et al., 2012; 2017]
- Performs best for earthquakes with M>~6



ShakeAlert™



Given et al. [2018]

1) Event Message

- Earthquake Source
  - Point: location, magnitude & uncertainty
  - "Finite fault" (If M6.0+)

2) Contour Message

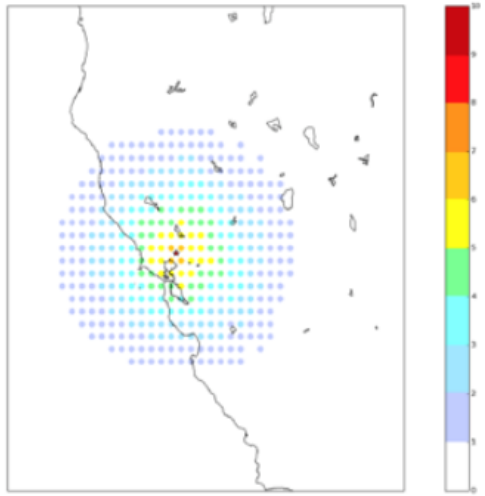
- **Event Message** + MMI contours
  - nested 8-pt polygons enclosing areas by MMI, PGA, PGV

3) Map Grid Message

- **Event Message** + MMI grid
  - grid map of MMI, PGA, PGV
  - ~20km spacing

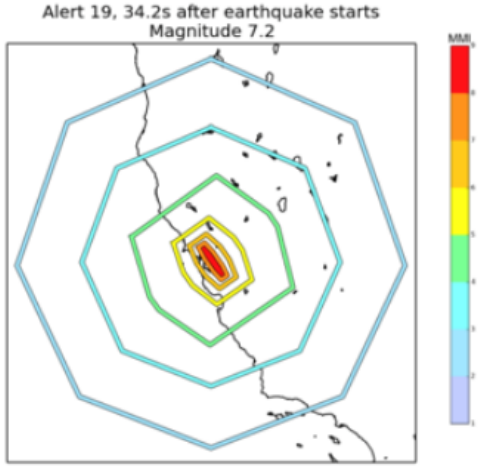
Also special messages like CAP for IPAWS/WEA

1) Event Info



3) Grid Map

Hayward M7.0 Simulation



2) Contour Map

Alert updates as event grows

USGS science for a changing world

ShakeAlert

Given et al. [2018]

ShakeAlert™

Ridgecrest Sequence

July 4 – July 9
M4.0+ Earthquakes/Alerts:

	SA	EPIC	FinDer
Reported	70	43	49
Matched	65	42	44
Missed	31	53	50
False	1	0	3
Duplicates	4	1	1

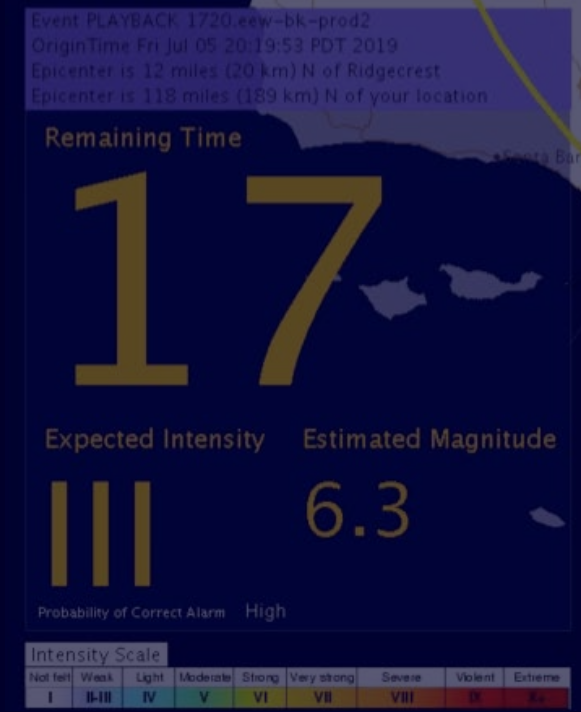
Weak Shaking Expected

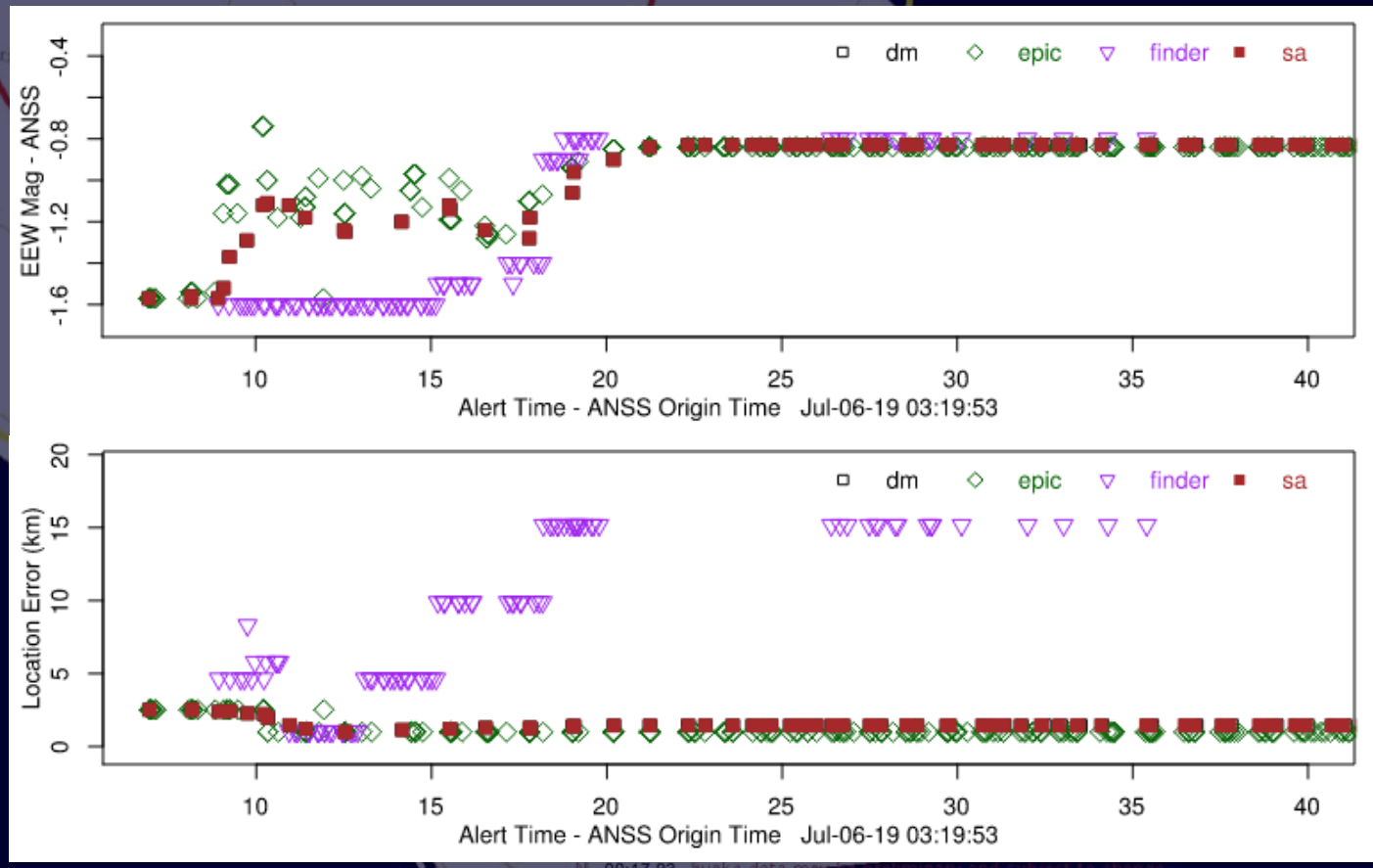
M7.1 Mainshock

First alert: +6.8 sec M5.5

Last alert: +46.5 sec M6.3

Data latencies limited final magnitude estimates

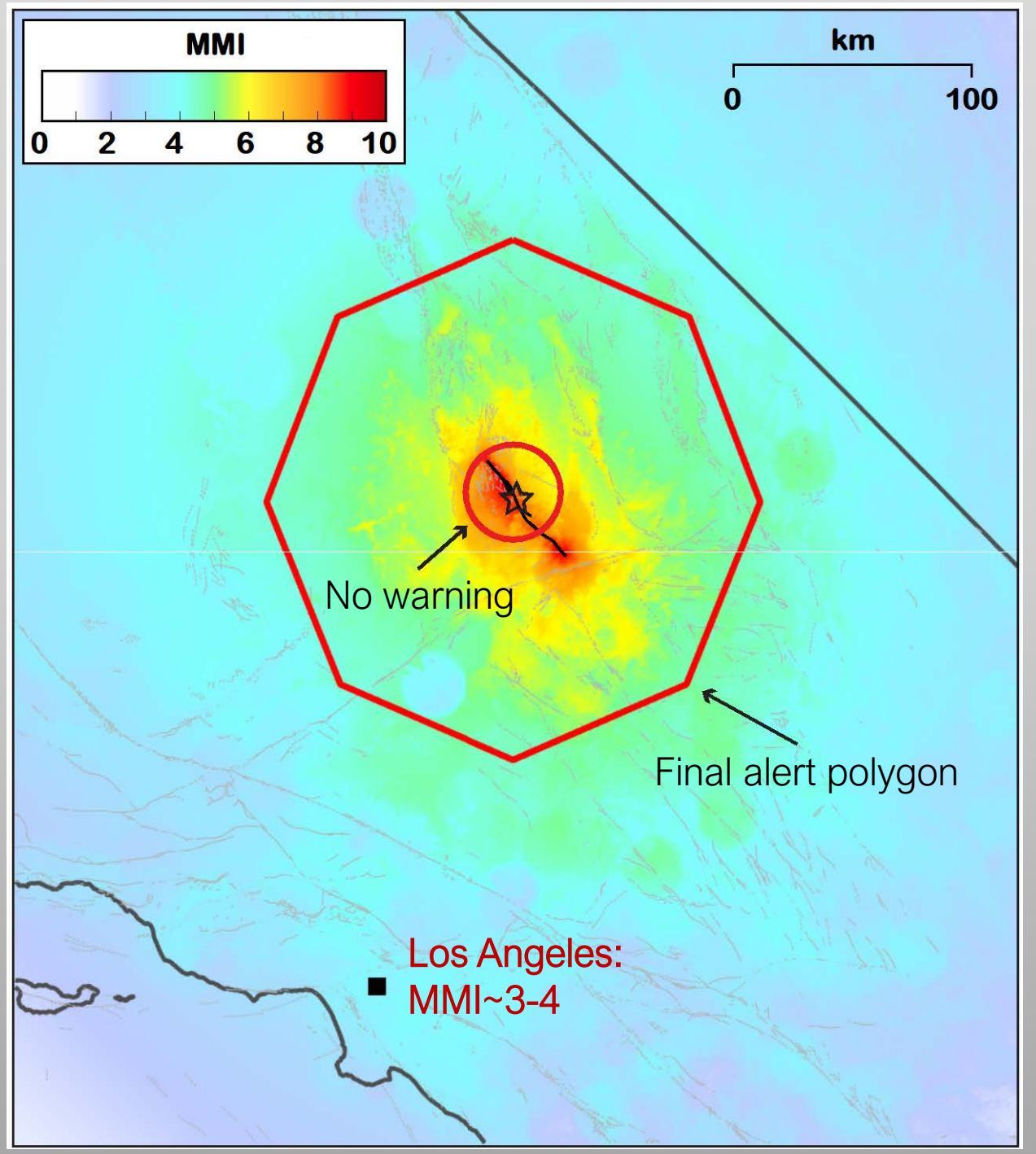




ShakeAlertLA

Should Los Angeles have received an alert?

- Goal: Timely alert for damaging ground motion (MMI 6.0+)
- Alerts issued when M5.0+, MMI 4.0+
- Some parts of LA had MMI 4.0+ ground motion, no alert because of underestimate of magnitude



LOS ANGELES RESIDENTS WERE UNHAPPY THEY DIDN'T RECEIVE A WARNING

Should the alert threshold

Individual actions (Drop, Cover, Hold On) are generally expected to be low-cost:

- OK to alert for ground motions that are lower than those expected to be damaging
- Precautionary alerts allow for training on appropriate responses

Reasons not to go too low:

- Very difficult to predict low-levels of ground motion (MMI 2-3)
- For MMI of 4 or lower many people may not recognize shaking as an earthquake

Caution! In response to an alert in Mexico City 1 person injured after jumping from the 2nd story of a building and two heart attack deaths (http://aristeguinoticias.com/2309/mexico/sismo-en-cdmx-2-muertas-por-infarto-y-un-lesionado-por-lanzarse-de-un-segundo-piso/)

SUMMARY

- USGS primer
  - Research on various types of induced seismicity
  - Suite of post-event products available online
  - Input from users/stakeholders always welcome – what do you wish we did?

- Earthquake early warning
  - Live in California, coming soon to Pacific Northwest
  - Warnings are most useful to users who can act at lower thresholds
  - Setting (public) alert thresholds requires careful consideration
    - Need to know current expectations
    - Communicating expectations is key (and complex)

Communicating Earthquake Hazards: Lessons from Earthquake Alerting

Questions?

ELIZABETH S. COCHRAN

ECOCHRAN@USGS.GOV