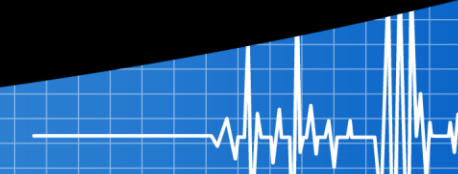




Worldwide Seismic Activity and Recent Oklahoma Earthquakes

July 23rd, 2014

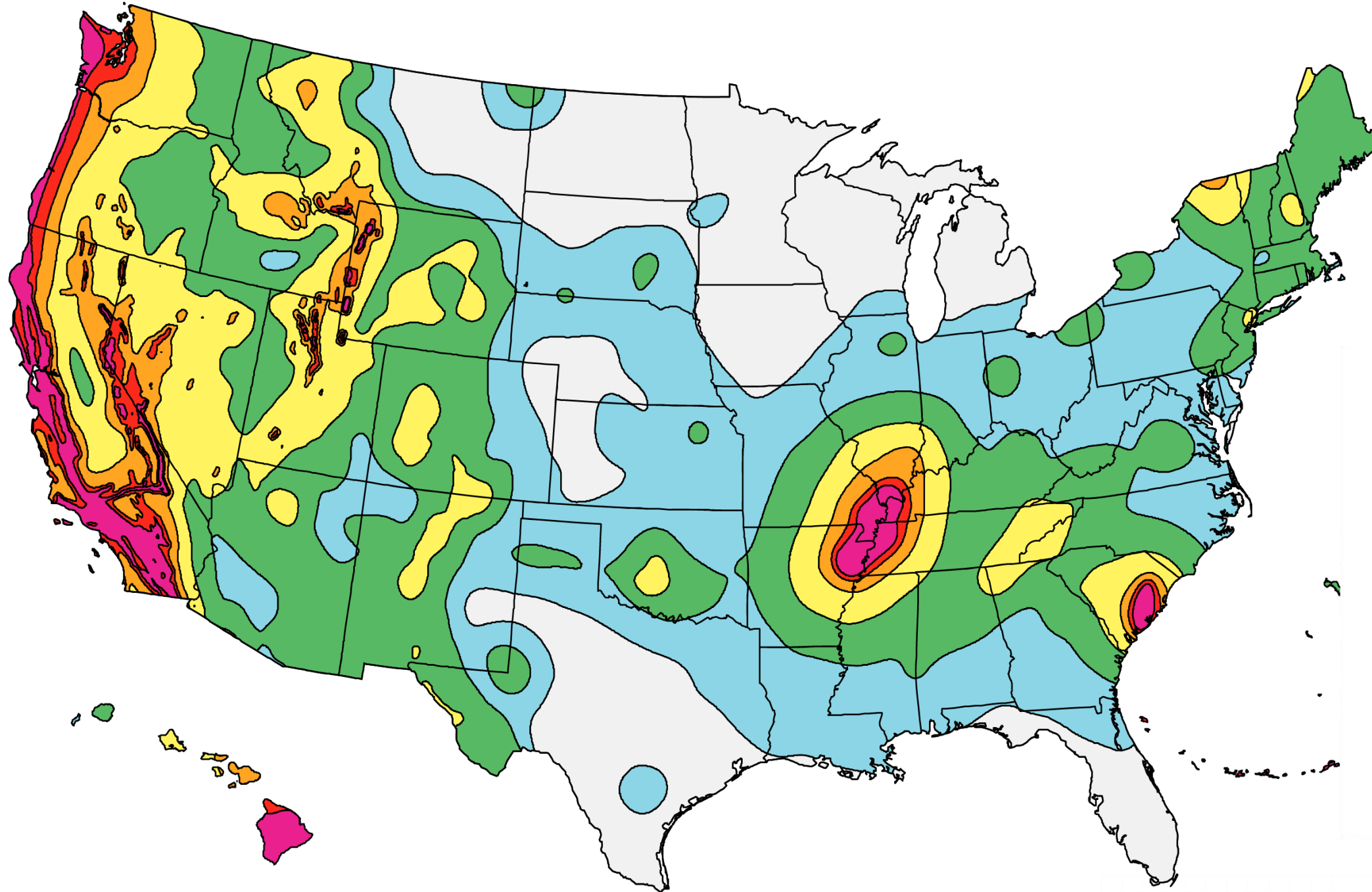
Oklahoma seismic activity uptick in last 5 years is not unprecedented. During the 50's another active earthquake period occurred in Oklahoma but was poorly measured as compared to today. From a global perspective both earthquake prone periods in Oklahoma history were each coincident with 50% of the largest Worldwide quakes over 8.8 Richter Scale from 1900 to 2014. Oklahoma activity may be related to these large quakes despite being away from actual plate boundaries. Earthquake locations in Oklahoma are inversely related to horizontal drilling, stimulation and/or salt water disposal. Unusual earthquake activity is also observed during the last 5 years in Virginia, South Carolina, Alaska, Mexico and the Gulf of California in areas where no oil and gas activity is present.



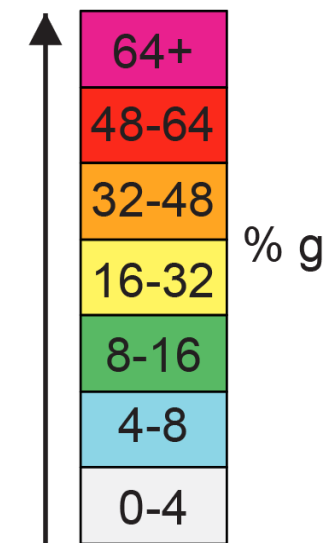
2008 U.S. Event Hazards Rating Map



“Before this all started...”



Highest hazard



Lowest hazard

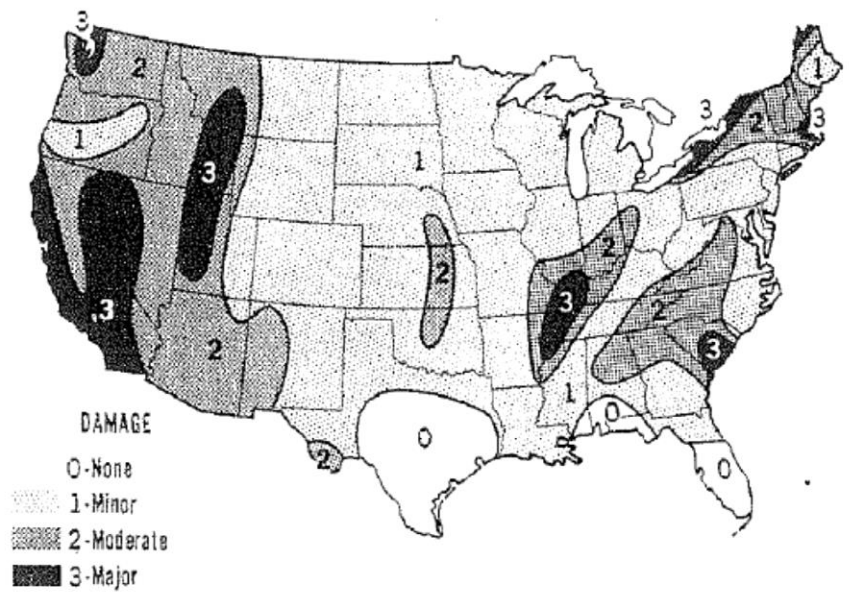
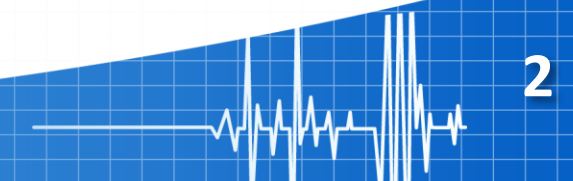


FIGURE 1
Seismic risk map for conterminous United States.
AS RESOLVED IN 1970 BY THE U.S.G.S.

Map source: <http://earthquake.usgs.gov/hazards/products/>



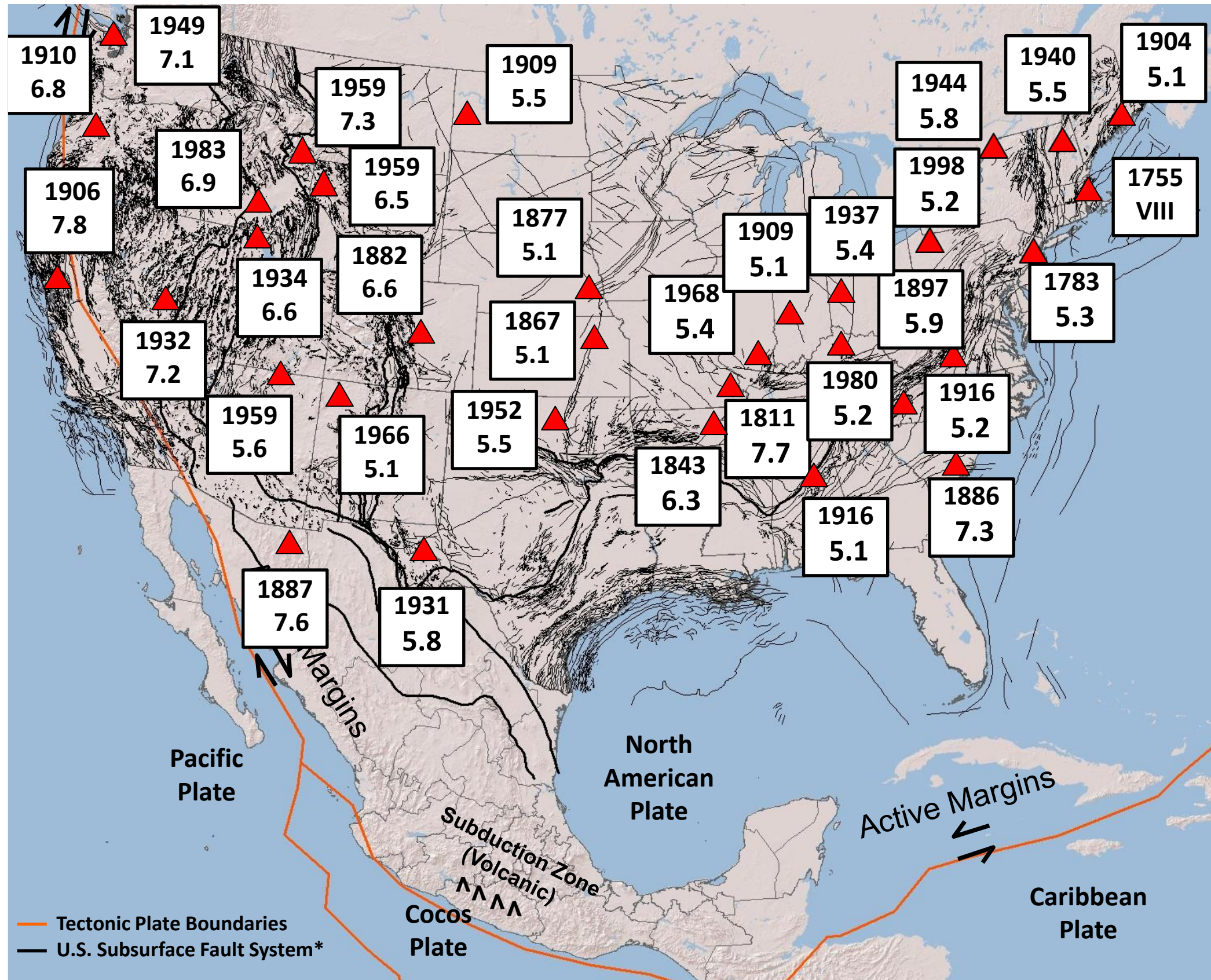
U.S. Tectonic Map with largest Earthquake events prior to 2000

In the lower 48:

46 states have documented earthquakes
96%

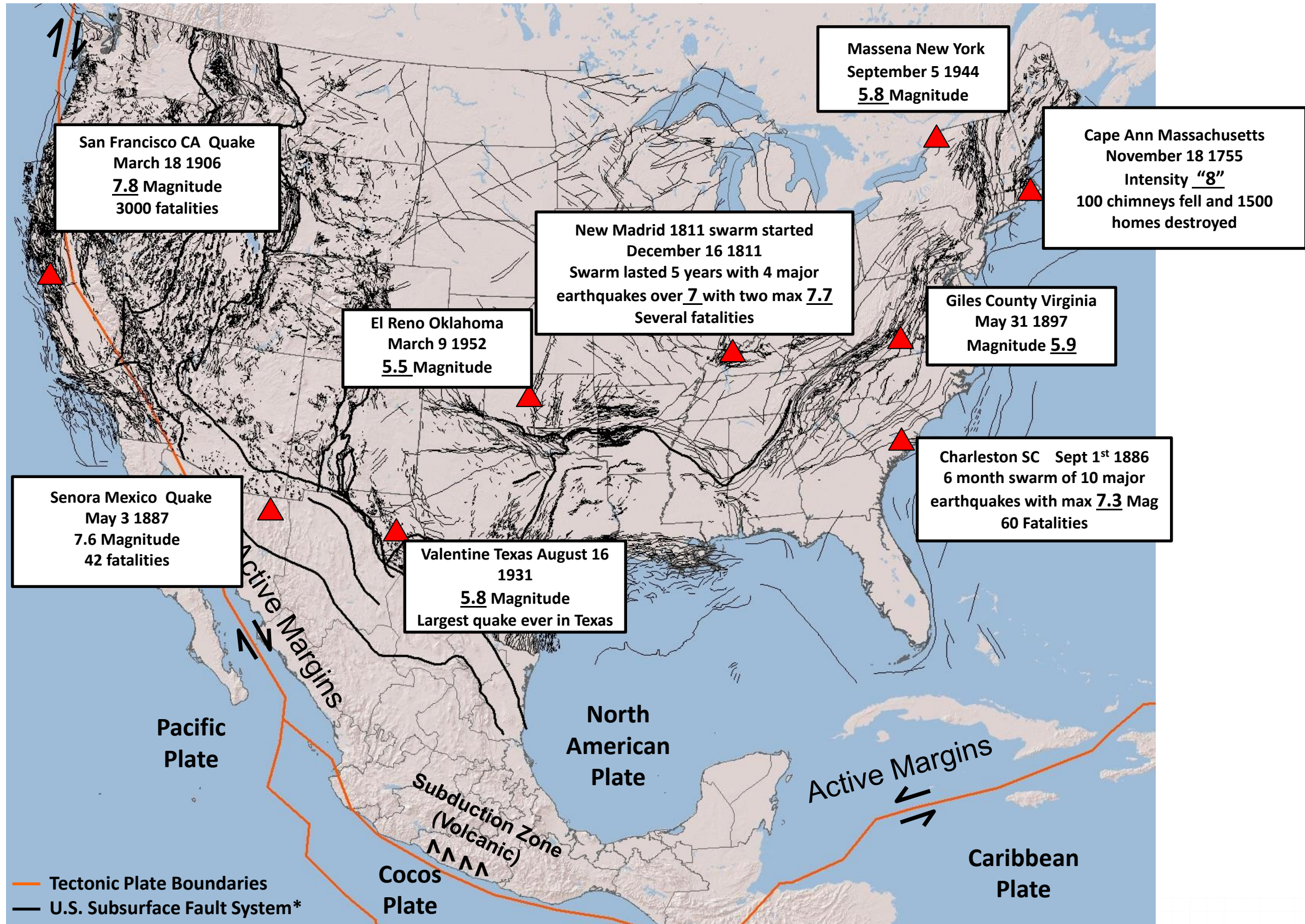
32 states have magnitude greater than 5
66%

8 States have magnitude greater than 4
16%



*Source: Geologic Data Systems

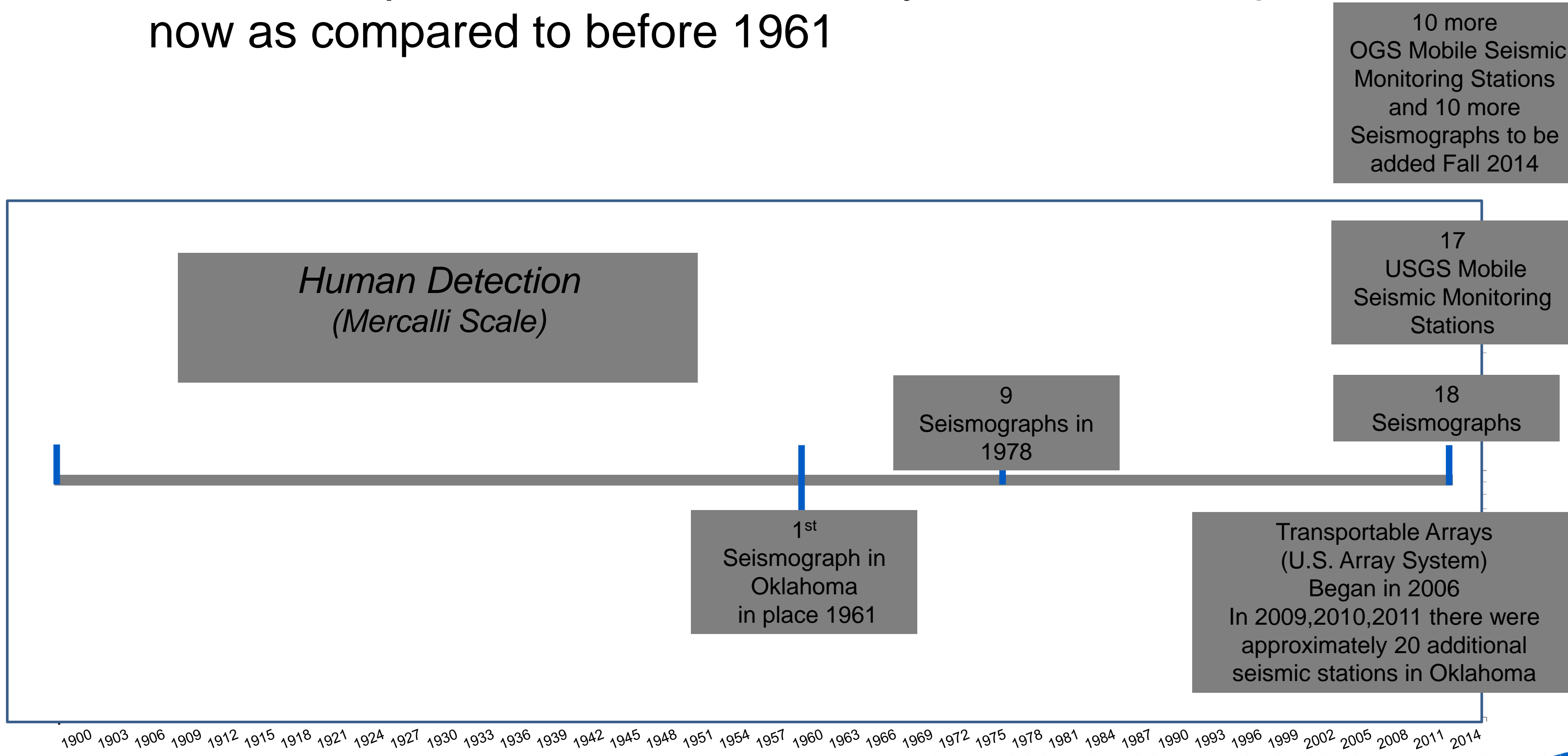
U.S. Tectonic Map with historic Earthquake events



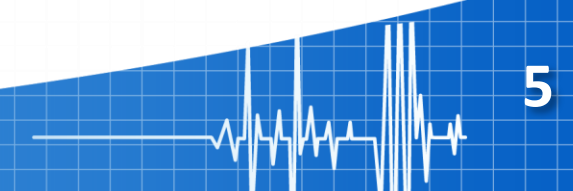
*Source: Geologic Data Systems

Oklahoma detection of earthquakes has evolved

What is “*unprecedented*” is our ability to detect earthquakes now as compared to before 1961



*Source: OGS/USGS, 2014

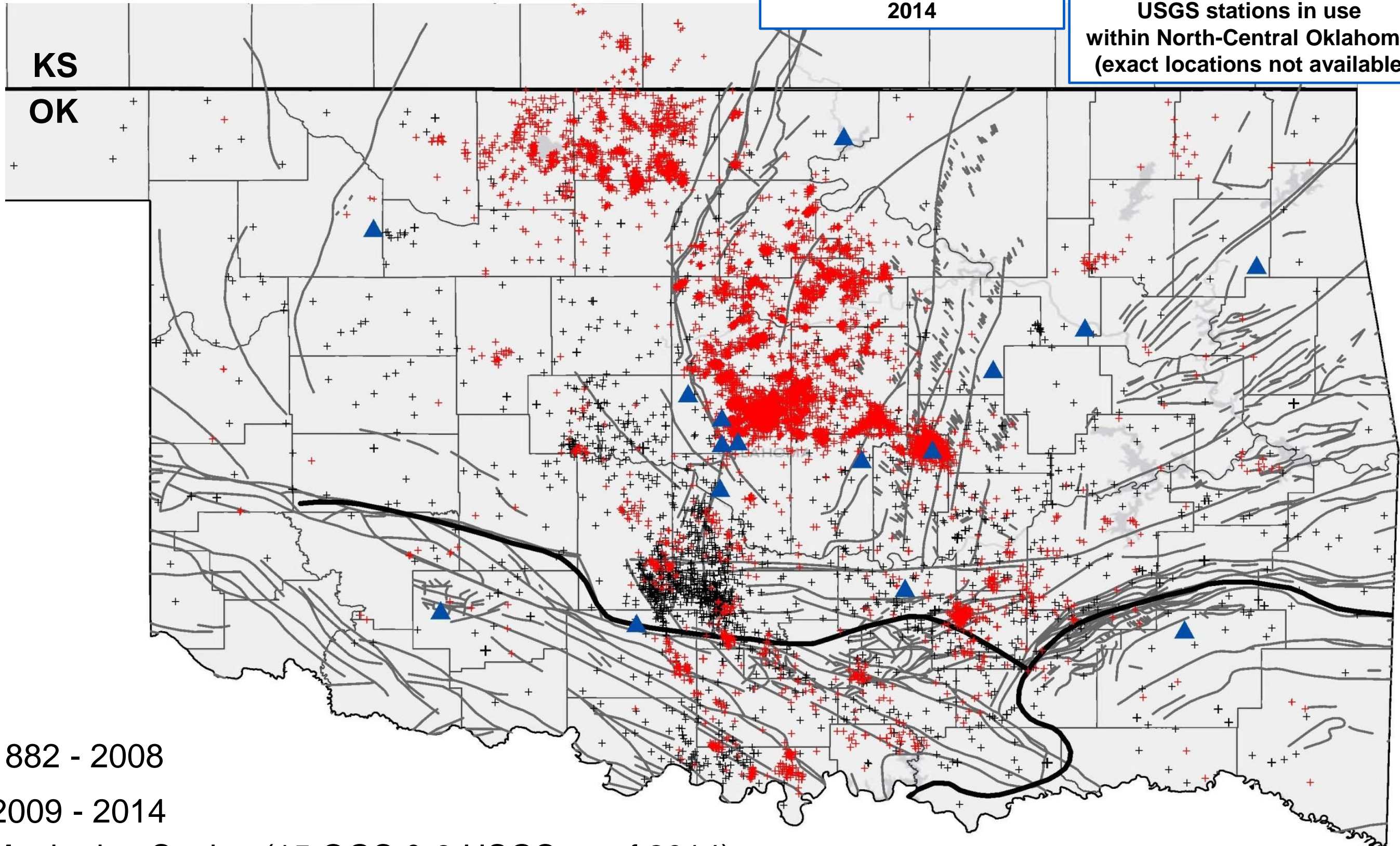


Oklahoma Earthquakes

Installing 10 new
Seismographs fall 2014

55 total stations in late
2014

27 additional mobile/temp
USGS stations in use
within North-Central Oklahoma
(exact locations not available)



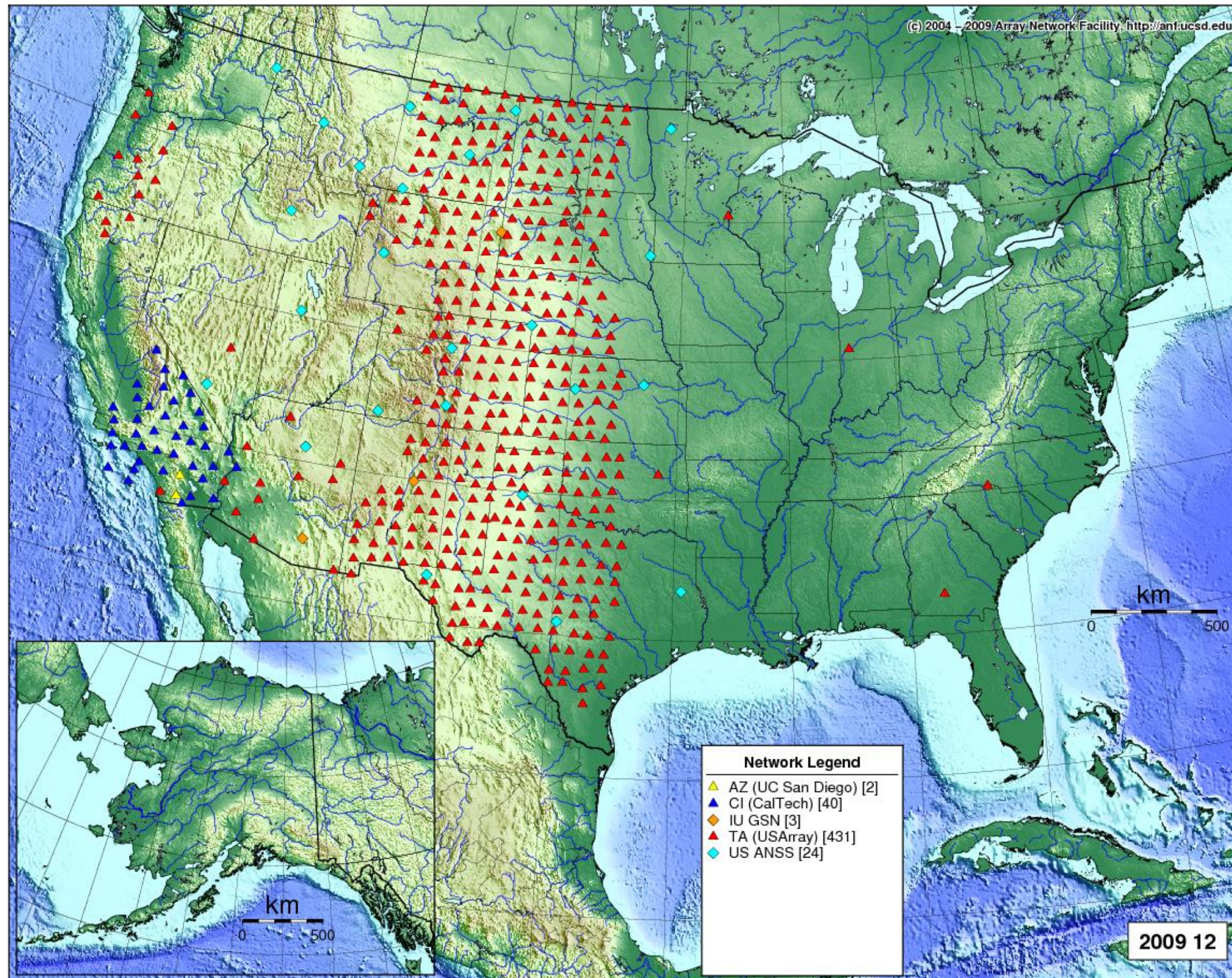
✚ 1882 - 2008

✚ 2009 - 2014

▲ Monitoring Station (15 OGS & 3 USGS as of 2014)

**Source: OGS, USGS, GDS, September 2014

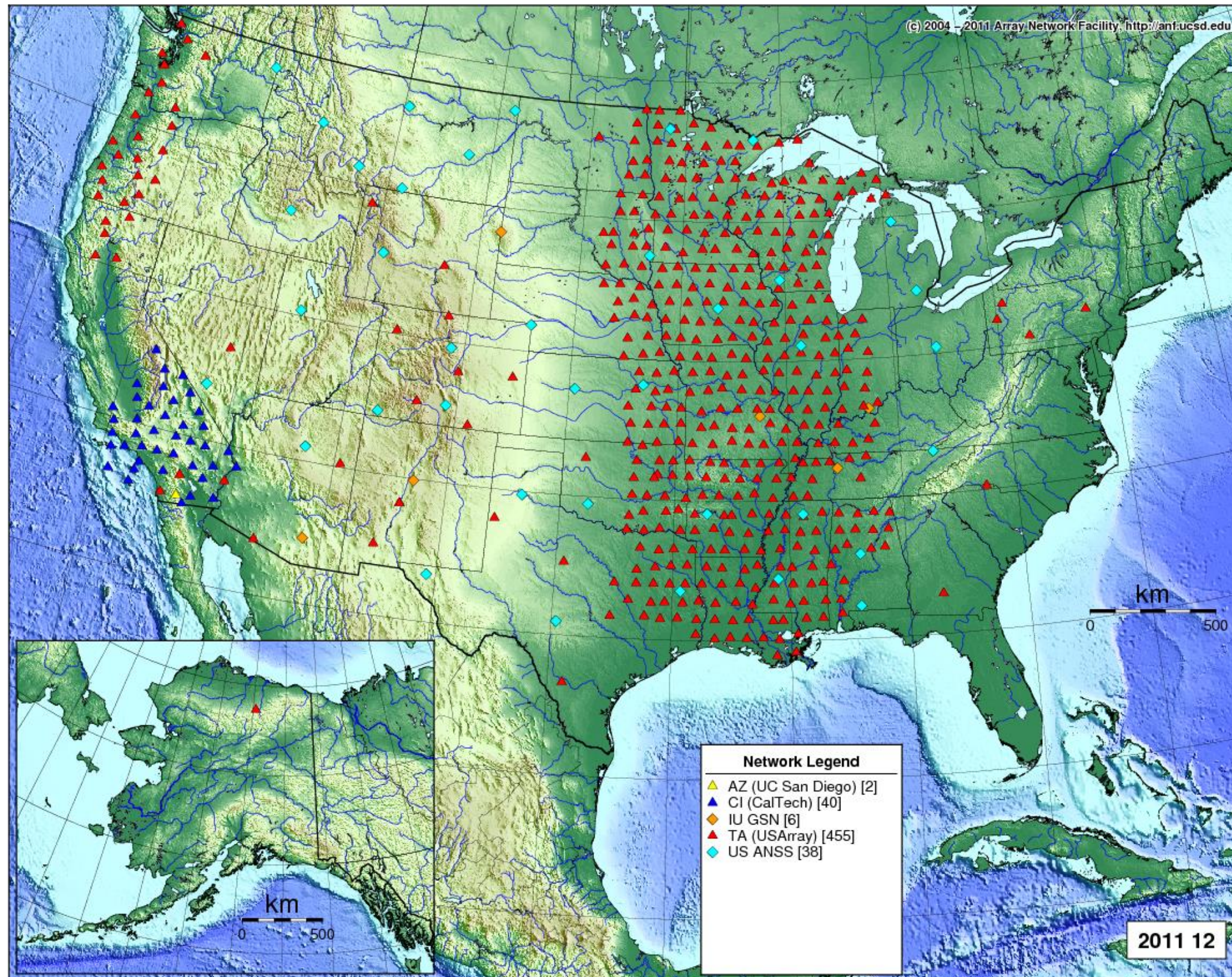
In 2009 the NSF EarthScope U.S. Array program deployed stations at 70-km spacing across Oklahoma.



In 2010 the NSF EarthScope U.S. Array program deployed stations at 70-km spacing across Oklahoma.



In 2011 the NSF EarthScope U.S. Array program deployed stations at 70-km spacing across Oklahoma.



IRIS DMS Combined Ground Motion Visualization

GULF OF CALIFORNIA 2007 - 2013

- M 6.1 event of 2007-09-01 19:14:26
- M 5.9 event of 2009-07-03 11:00:17
- M 6.7 event of 2010-10-21 17:53:19
- M 6.0 event of 2011-07-26 17:44:22
- M 6.0 event of 2012-10-08 06:26:25
- M 6.6 event of 2013-10-19 17:55:03



IRIS DMS Combined Ground Motion Visualization

Gulf of California, 2007-2013

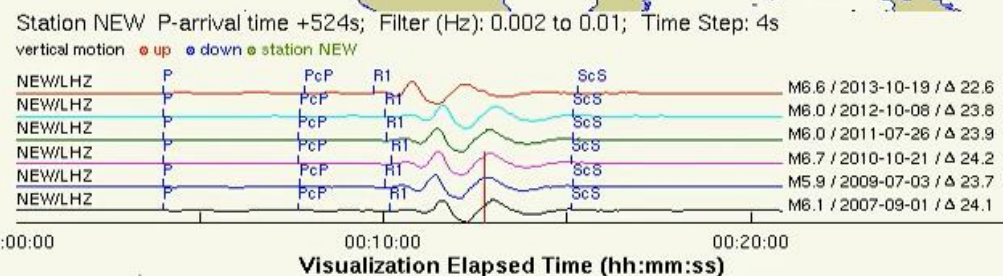
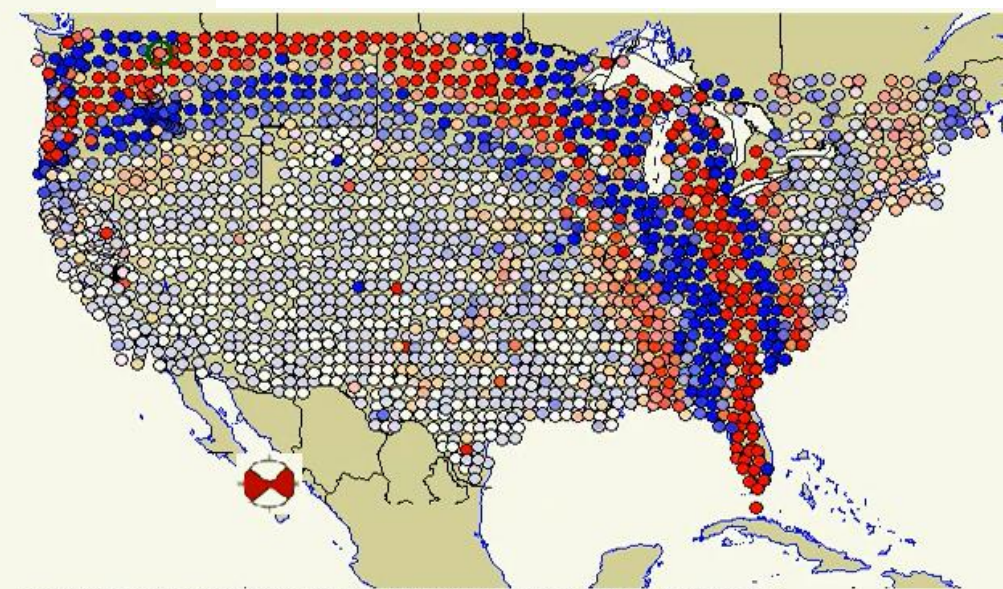
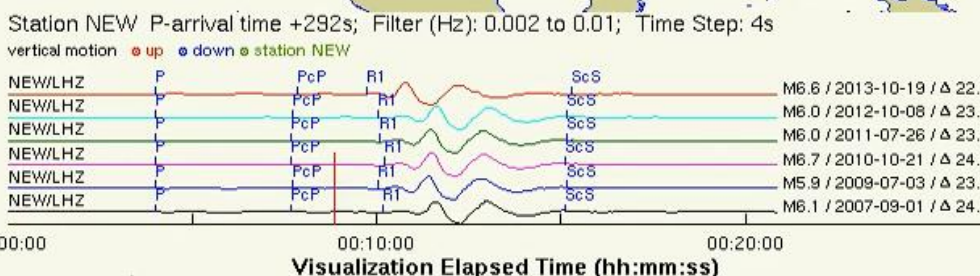
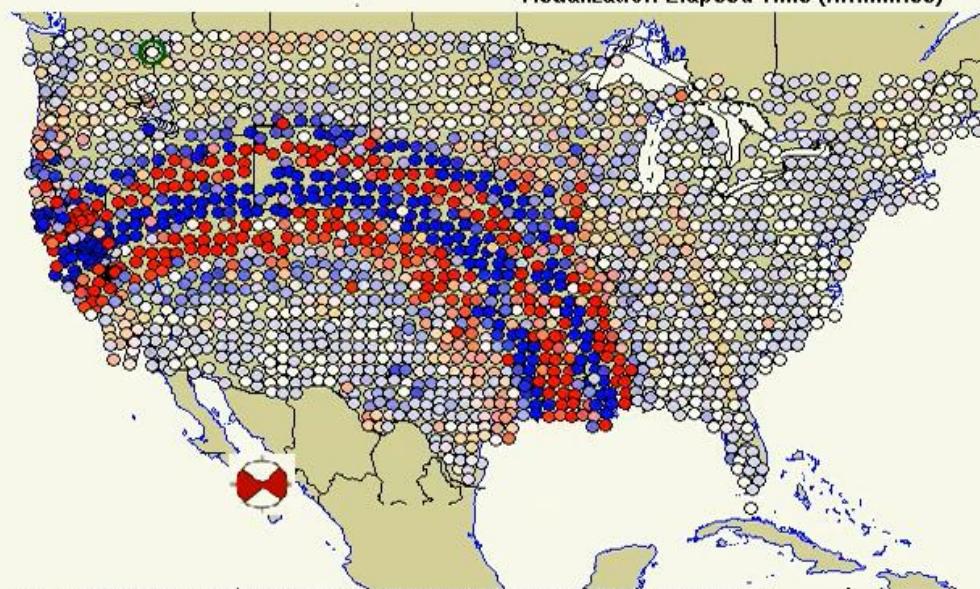
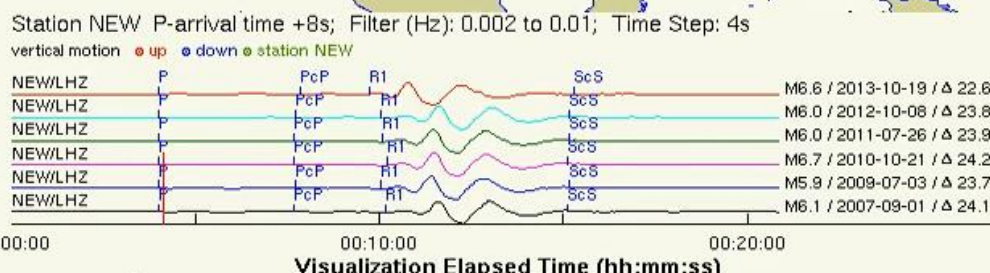
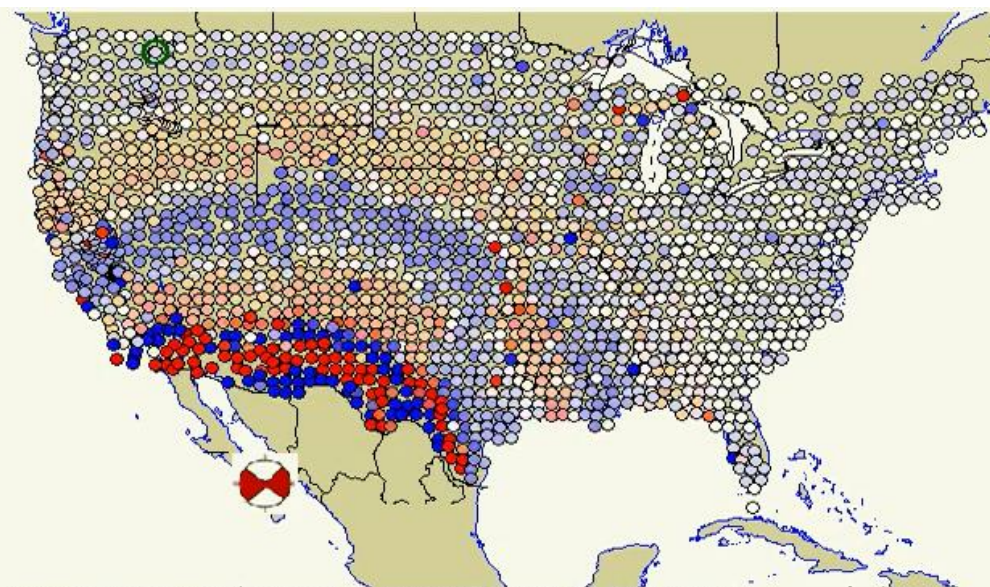


Max Lat: 26.20
 Min Lon: 110.00 Max Lon: 100.10
 Min Lat: 24.67

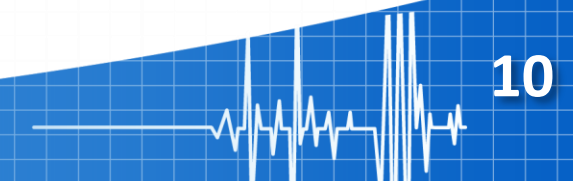
Start Date: 2007-09-01 00:00
 End Date:

Magnitude: 5.5 - 7.7
 Depth (km): 0 - 700
 Strike: 0 - 360
 Dip: 0 - 90
 Plane: -180 - 180

Event	Time (UTC)	Depth (km)	Mag	Latitude	Longitude	FM	Region
1	2013-10-19 17:55:03	15.1	6.6	26.17	-110.53	⊗	GULF OF CALIFORNIA
2	2012-10-08 06:26:25	19.7	6.0	25.17	-109.73	⊗	GULF OF CALIFORNIA
3	2011-07-26 17:44:22	17.5	6.0	25.06	-109.68	⊗	GULF OF CALIFORNIA
4	2010-10-21 17:53:19	14.2	6.7	24.83	-109.29	⊗	GULF OF CALIFORNIA
5	2009-07-03 11:00:17	14.4	5.9	25.20	-109.87	⊗	GULF OF CALIFORNIA
6	2007-09-01 19:14:26	14.9	6.1	24.78	-109.89	⊗	GULF OF CALIFORNIA

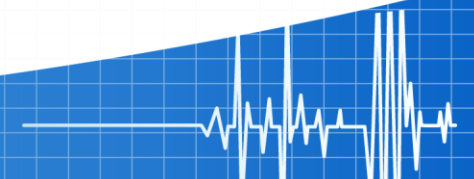
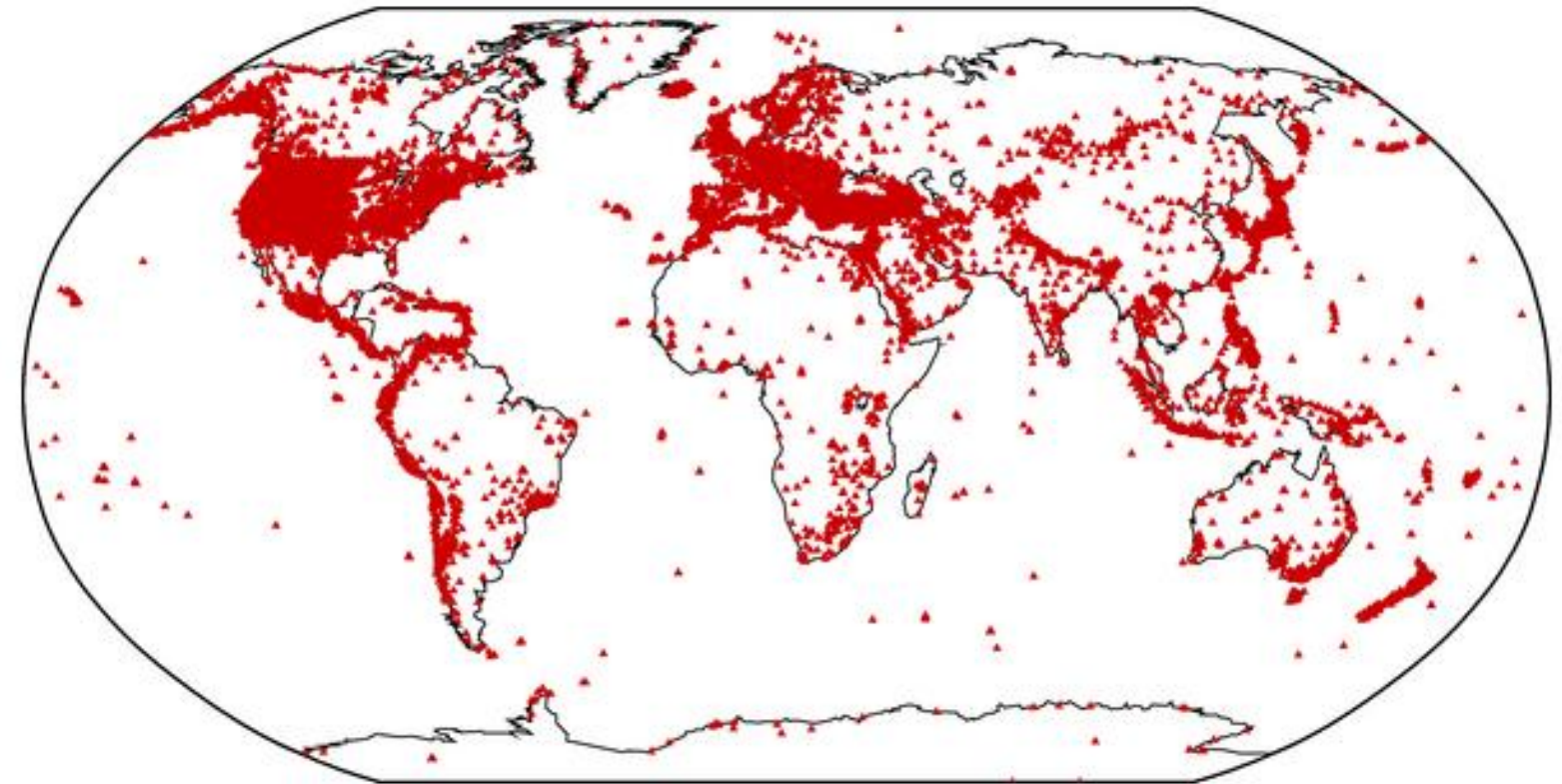


*Source: IRIS

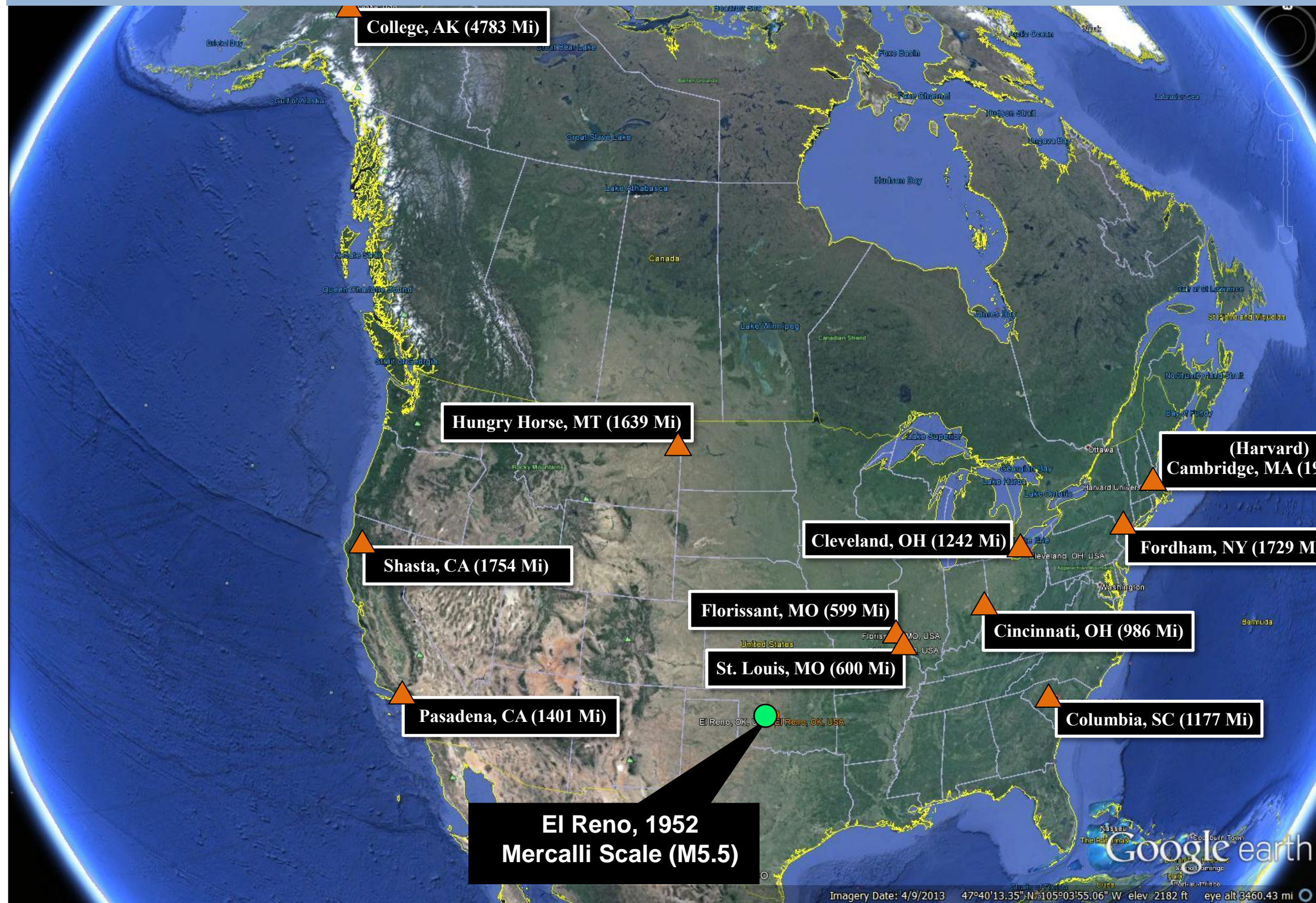


USGS: Are Earthquakes Really on the Increase?

- In 1931, there were about 350 stations operating in the world
- Today, more than 8,000 stations are in place and data now comes in rapidly via electronic mail, internet and satellite
- The NEIC(National Earthquake Information Center) now locates about 20,000 earthquakes each year (or 50 per day).
- According to long-term records (since about 1900), we expect about 17 major earthquakes (7.0 - 7.9) and one great earthquake (8.0 or above) in any given year.



Prior to 1961 there were no seismic stations in Oklahoma
The closest was in St Louis 600 Miles away



*Source: USGS, 2014; Google Earth

**** "Revised Instrumental Hypocenters and Correlation of Earthquake locations and tectonics in the central United States"
By David Gordon
US Geological Survey Professional Paper 1364 (1988)

“ Due to low station density and low instrument magnifications only a very few earthquakes were located instrumentally less than magnitude 4 until the 1960’s”

“The deployment of 10 stations starting in 1961 coincided with a dramatic increase in the number of instrumentally located earthquakes”

Modern day very different!

Seismometers in the permanent monitor grid in most of the central and eastern continental U.S. are spaced up to 200 miles apart.

With this spacing, the system is capable of measuring events down to approximately M3.0 or M3.5

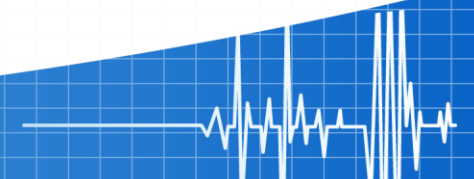
Some areas this may extend down to a M2.5.

* “Revised Instrumental Hypocenters and Correlation of Earthquake locations and tectonics in the central United States”

By David Gordon

US Geological Survey Professional Paper 1364 (1988)

**Quote from USGS website 2014



Magnitude	Description	Mercalli intensity	Average earthquake effects	Average frequency of occurrence (estimated)
Less than 2.0	Micro	I	<u>Microearthquakes, not felt, or felt rarely by sensitive people. Recorded by seismographs.[15]</u>	Continual/several million per year
2.0–2.9	Minor	I to II	Felt slightly by some people. No damage to buildings.	Over one million per year
3.0–3.9		II to IV	Often felt by people, but very rarely causes damage. Shaking of indoor objects can be noticeable.	Over 100,000 per year
4.0–4.9	Light	IV to VI	Noticeable shaking of indoor objects and rattling noises. Felt by most people in the affected area. Slightly felt outside. Generally causes none to minimal damage. Moderate to significant damage very unlikely. Some objects may fall off shelves or be knocked over.	10,000 to 15,000 per year
5.0–5.9	Moderate	VI to VIII	Can cause damage of varying severity to poorly constructed buildings. At most, none to slight damage to all other buildings. Felt by everyone. Casualties range from none to a few.	1,000 to 1,500 per year
6.0–6.9	Strong	VII to X	Damage to a moderate number of well-built structures in populated areas. Earthquake-resistant structures survive with slight to moderate damage. Poorly designed structures receive moderate to severe damage. Felt in wider areas:	100 to 150 per year
7.0–7.9	Major	<u>VIII or greater[16]</u>	Causes damage to most buildings, some to partially or completely collapse or receive severe damage. Well-designed structures are likely to receive damage. Felt across great distances with major damage mostly limited to 250 km from epicenter. Death toll ranges from none to 250,000.	10 to 20 per year
8.0–8.9	Great		Major damage to buildings, structures likely to be destroyed. Will cause moderate to heavy damage to sturdy or earthquake-resistant buildings. Damaging in large areas. Felt in extremely large regions. Death toll ranges from 1,000 to 1 million.	One per year

magnitude 4 is light

slight felt outside

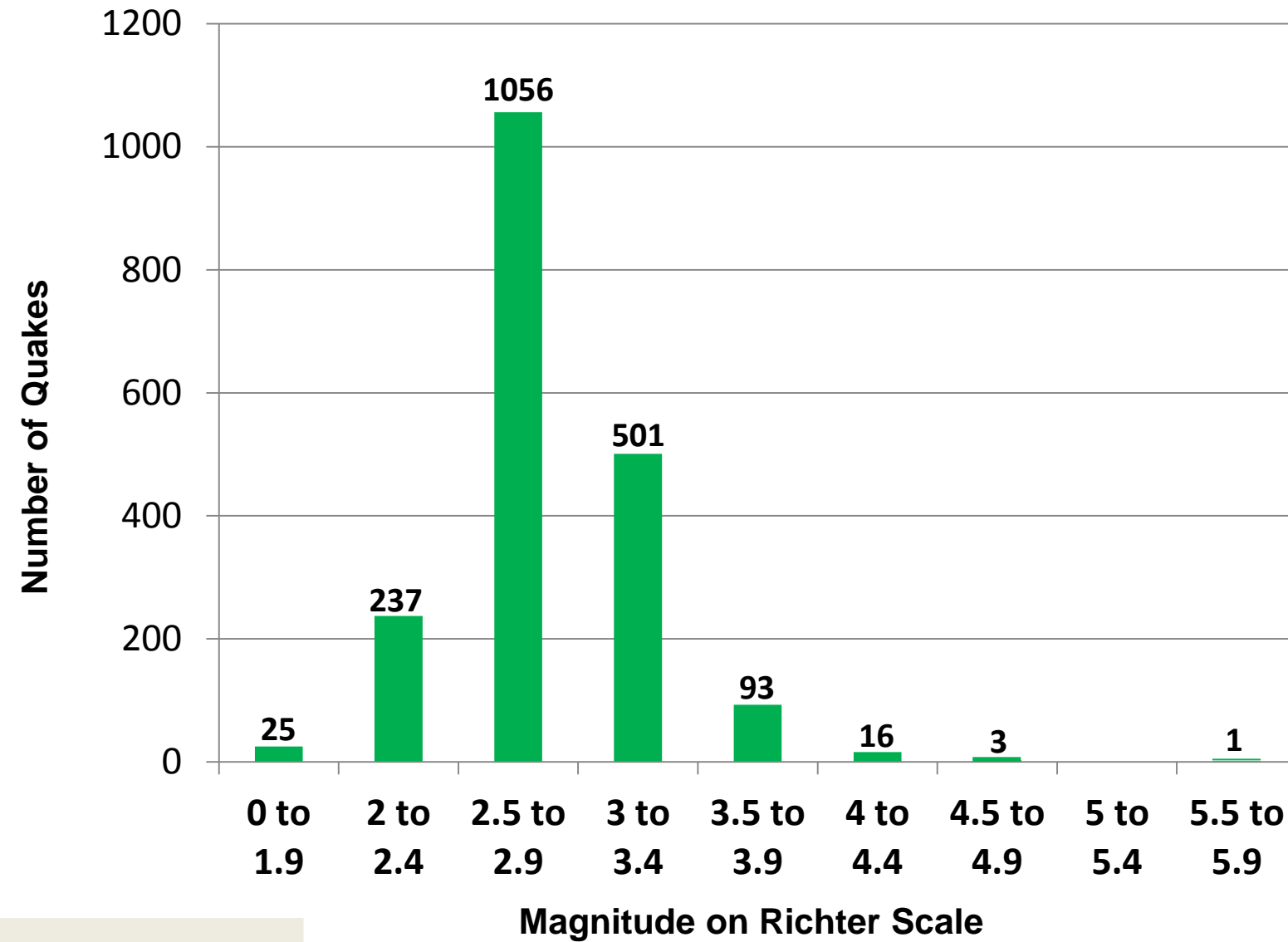
no to minimal damage

some objects may fall off shelves

World Earthquakes

Magnitude	Average Annually
8 and higher	1
7 - 7.9	15
6 - 6.9	134
5 - 5.9	1319
4 - 4.9	13,000
3 - 3.9	130,000
2 - 2.9	1,300,000

Oklahoma Earthquakes from 1/1/2009 to 9/9/14



Source USGS Earthquake database June 25th 2014

How Much Bigger ... Calculator

Input Magnitude 1:

[Range is -3. to 10.]

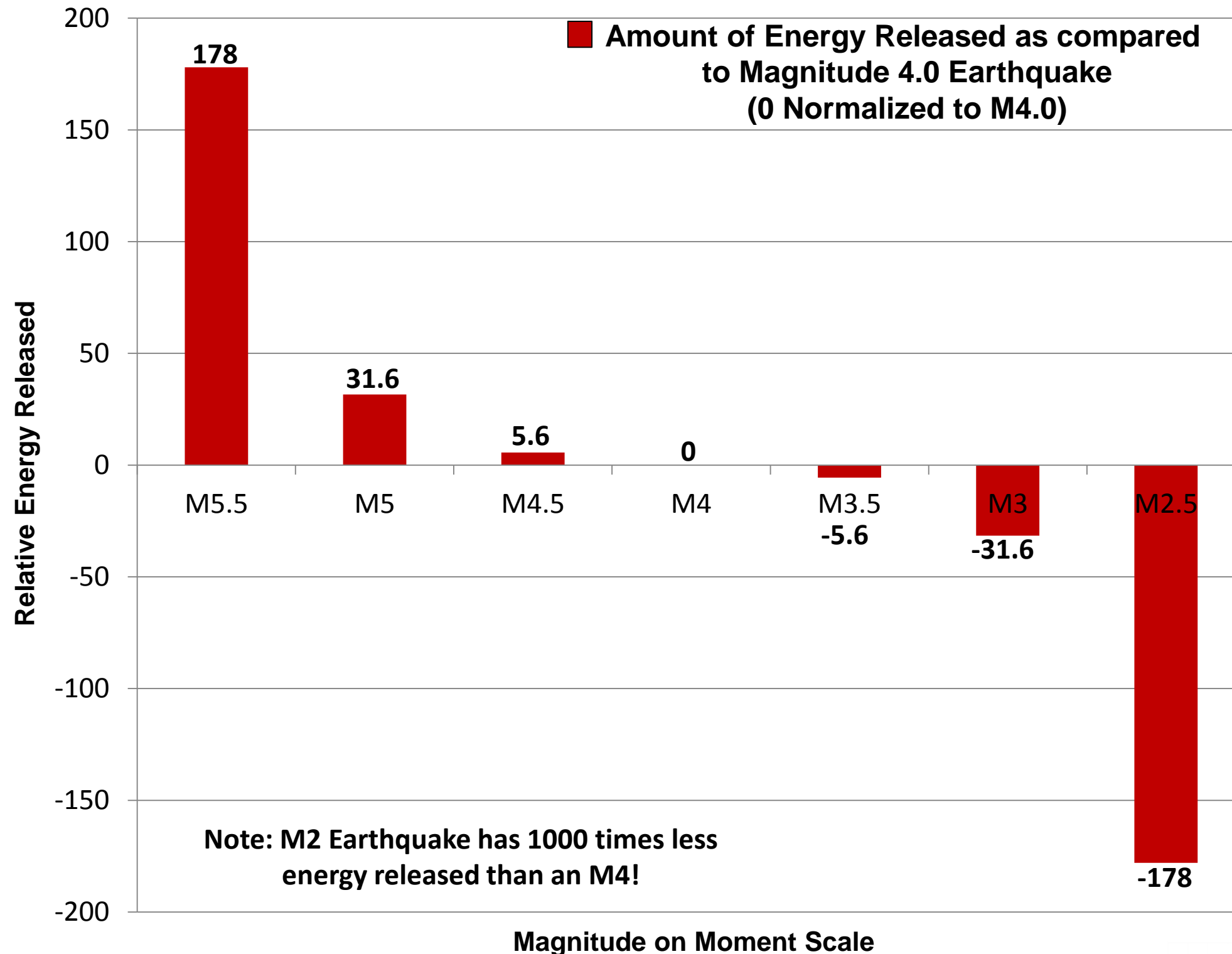
Input Magnitude 2:

[Range is -3. to 10.]

Magnitude Difference:

A magnitude earthquake is times **bigger** than a magnitude earthquake on a seismogram, but is times **stronger** (energy release).

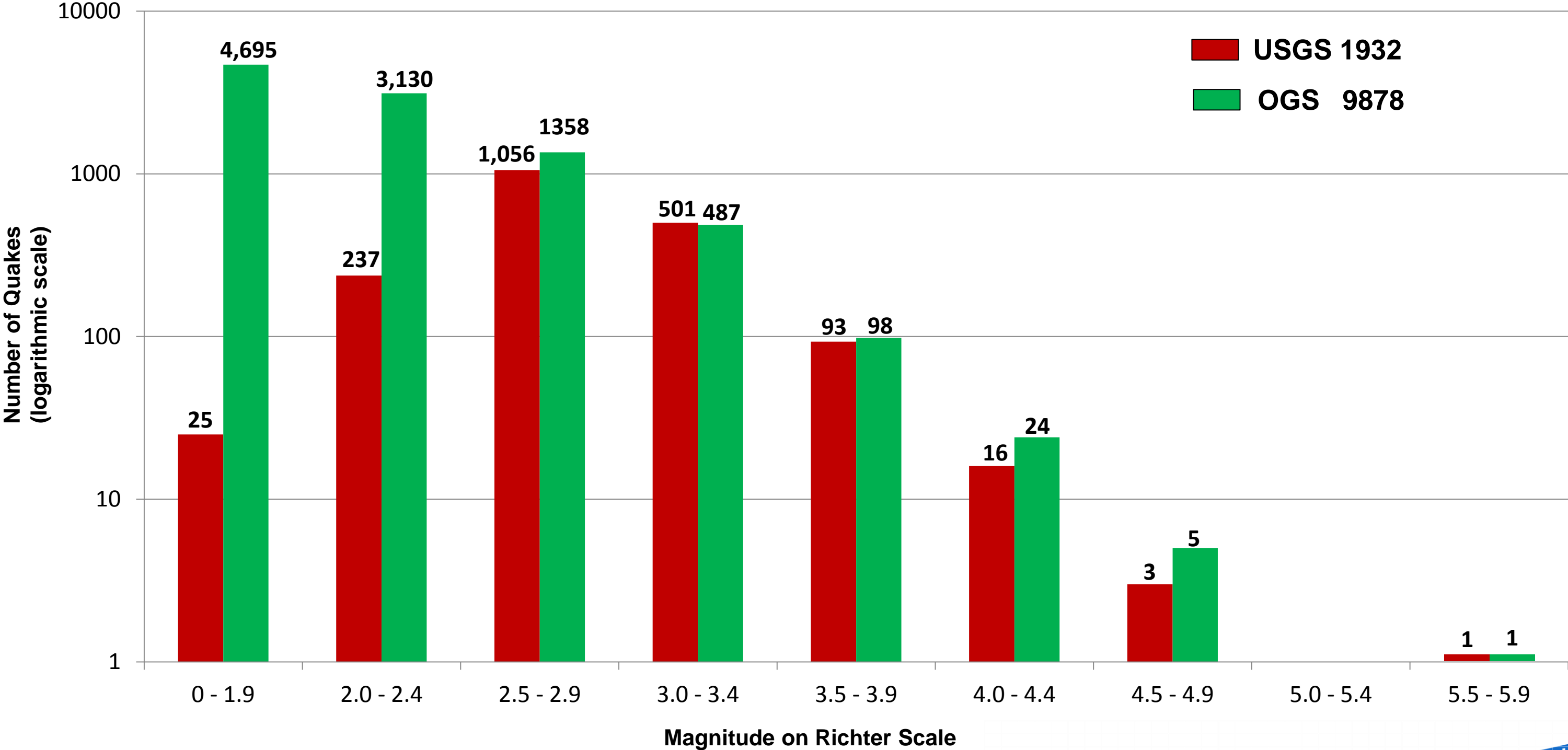
Earthquake Energy



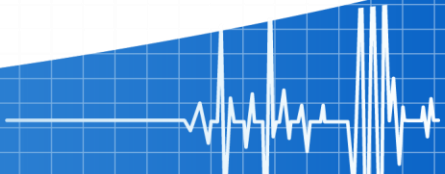
Magnitude 4 to 4.9 is still considered “light” and “slight felt outside” Generally causes none to minimal damage with “some objects may fall off shelves”

1, 2 and 3 magnitudes are obviously less significant

Oklahoma Earthquakes from 1/1/2009 to 6/25/2014



*Sources: USGS & OGS, 2014



year	0-1.9	2.0 -2.4	2.5-2.9	3.0 -3.4	3.5- 3.9	4.0-4.4	4.5-4.9	5.0-5.4	5.5-5.9
2009	1	15	12	15	4	0	0	0	0
2010	611	320	91	28	10	3	0	0	0
2011	742	488	168	49	12	1	2	0	1
2012	575	278	84	34	4	1	0	0	0
2013	1764	718	252	88	16	3	1	0	0
2014	1002	1311	751	273	52	16	2	0	0
	4695	3130	1358	487	98	24	5	0	1

Oklahoma Geologic survey		OGS database by year		Source OGS database by year							
9878	OGS	Total	quakes								

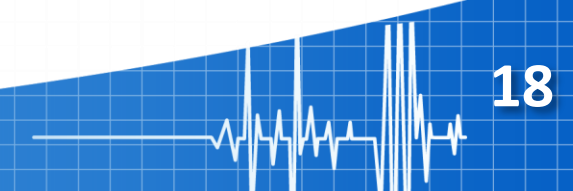
Quakes by year

Oklahoma & South Kansas

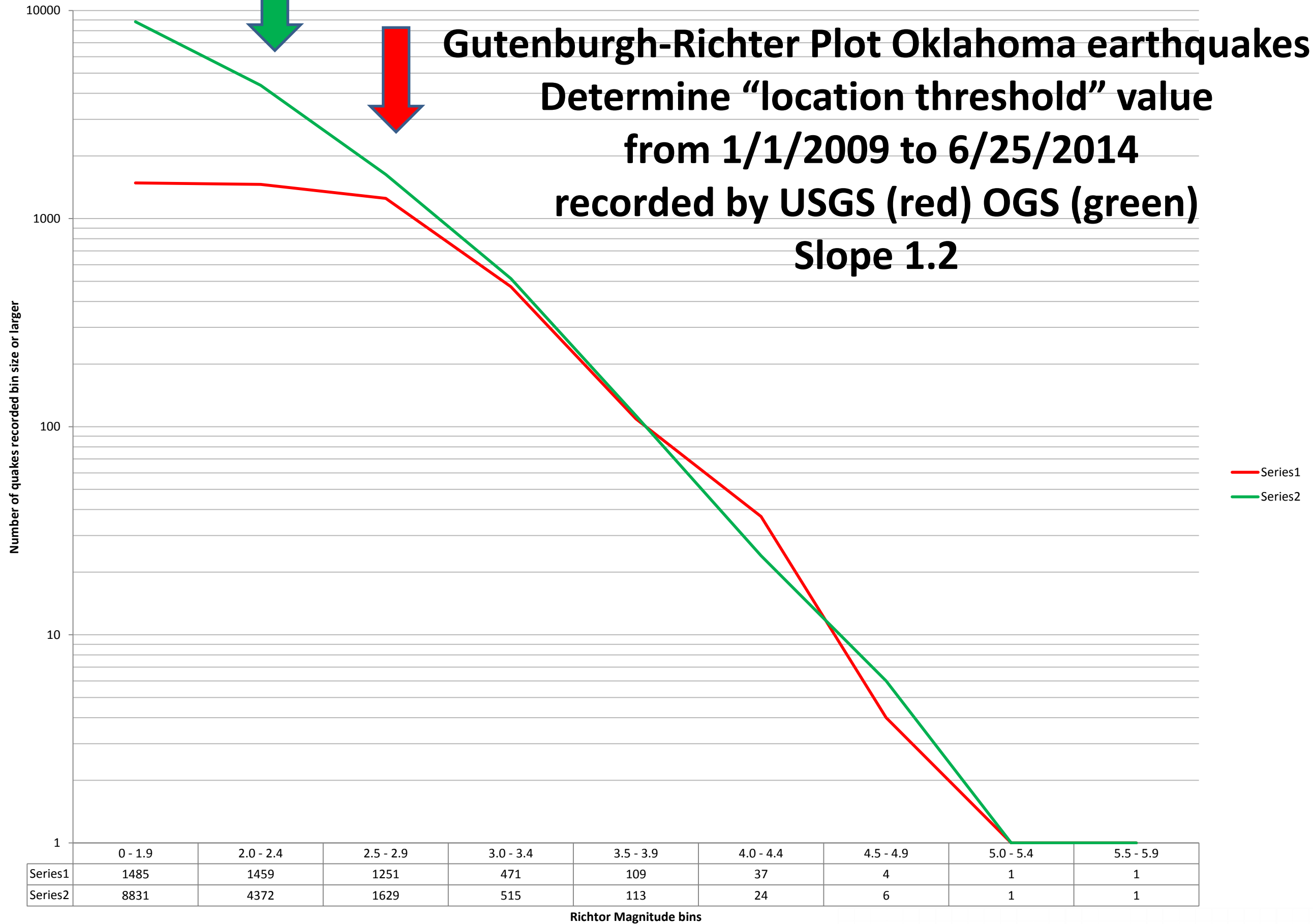
year	0-1.9	2.0 -2.4	2.5-2.9	3.0 -3.4	3.5- 3.9	4.0-4.4	4.5-4.9	5.0-5.4	5.5-5.9
2009	1	16	13	16	5	0	0	0	0
	6	37	101	35	7	2	0	0	0
2011	3	13	87	48	11	1	2	0	1
2012	1	12	49	32	2	1	0	0	0
2013	11	59	145	82	16	2	1	0	0
2014	3	100	661	288	52	10	0	0	0
	25	237	1056	501	93	16	3	0	1

January 1st 2009 to September 9th 2014

USGS		USGS		ANSS							
1932	USGS	Total	quakes	Source	ANSS						

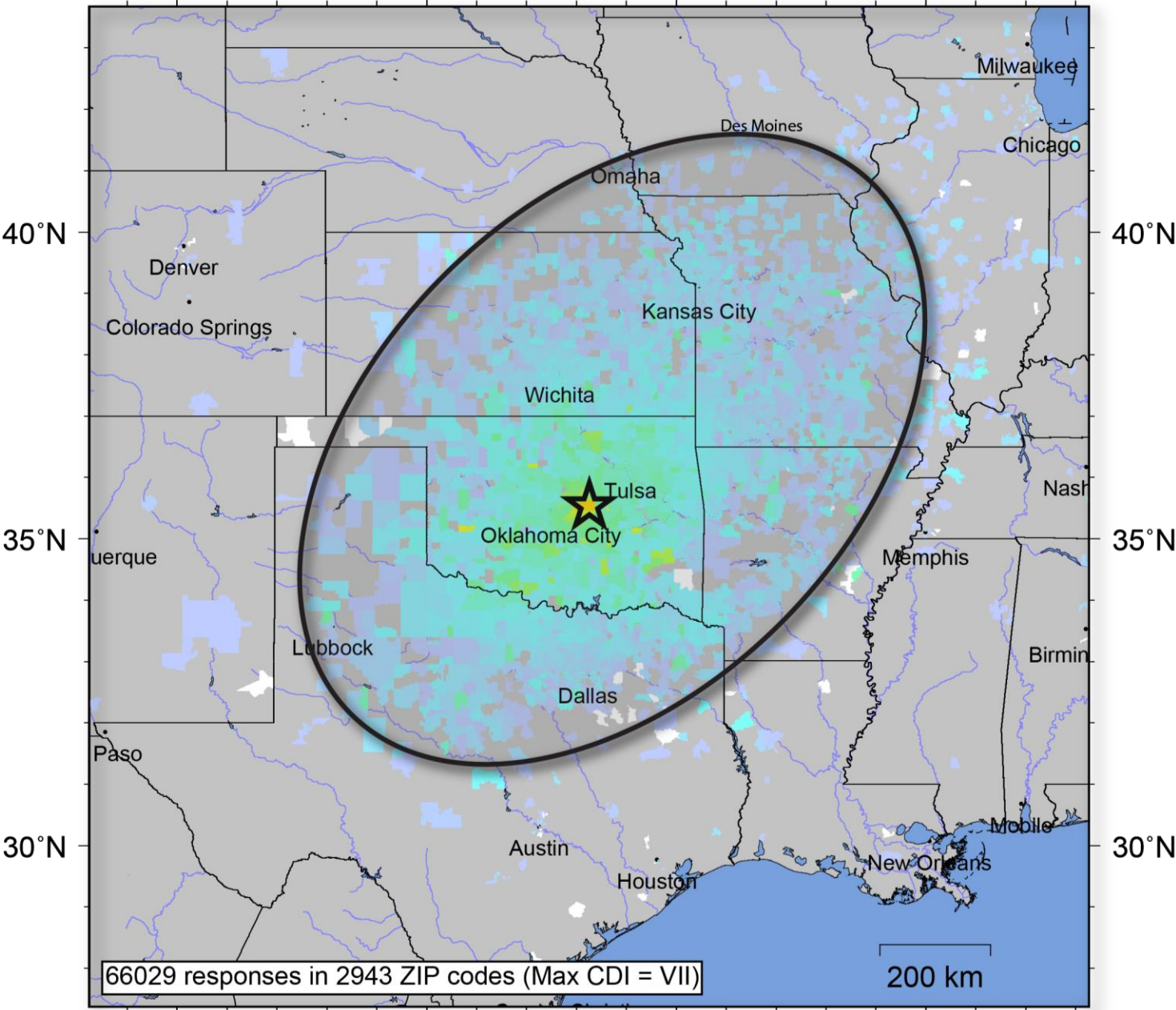


Gutenberg-Richter Plot Oklahoma earthquakes
Determine “location threshold” value
from 1/1/2009 to 6/25/2014
recorded by USGS (red) OGS (green)
Slope 1.2



Oklahoma Large Earthquakes: Past and Present

Prague, Oklahoma
5.6 event on November 7th 2011



INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+
SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy

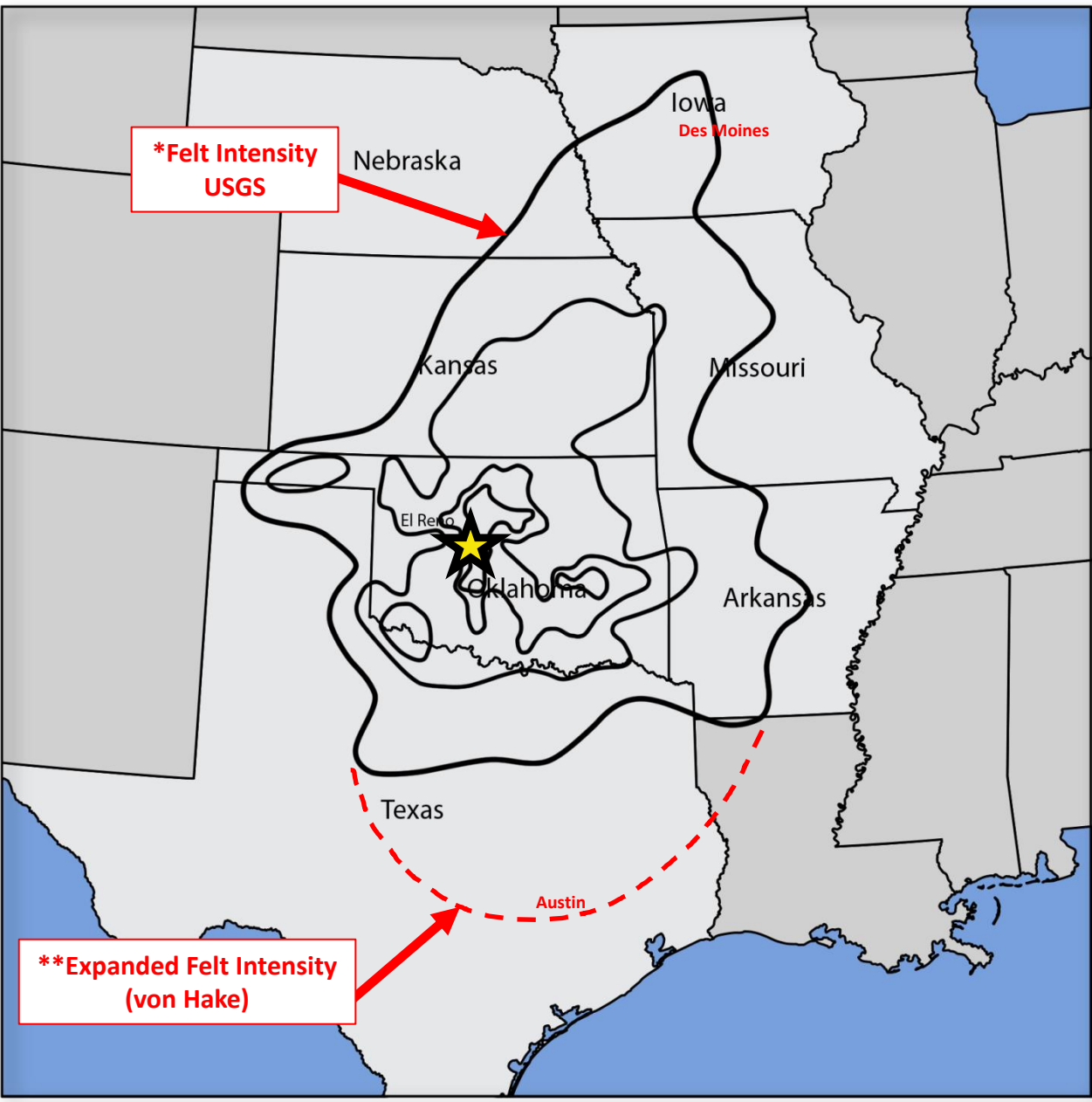
Processed: Mon Aug 12 18:22:02 2013

USGS Community Internet Intensity Map

OKLAHOMA

Nov 5 2011 10:53:10 PM local 35.5373N 96.7466W M5.6 Depth: 5 km ID:usb0006klz

El Reno, Oklahoma
5.5 event on April 9th 1952

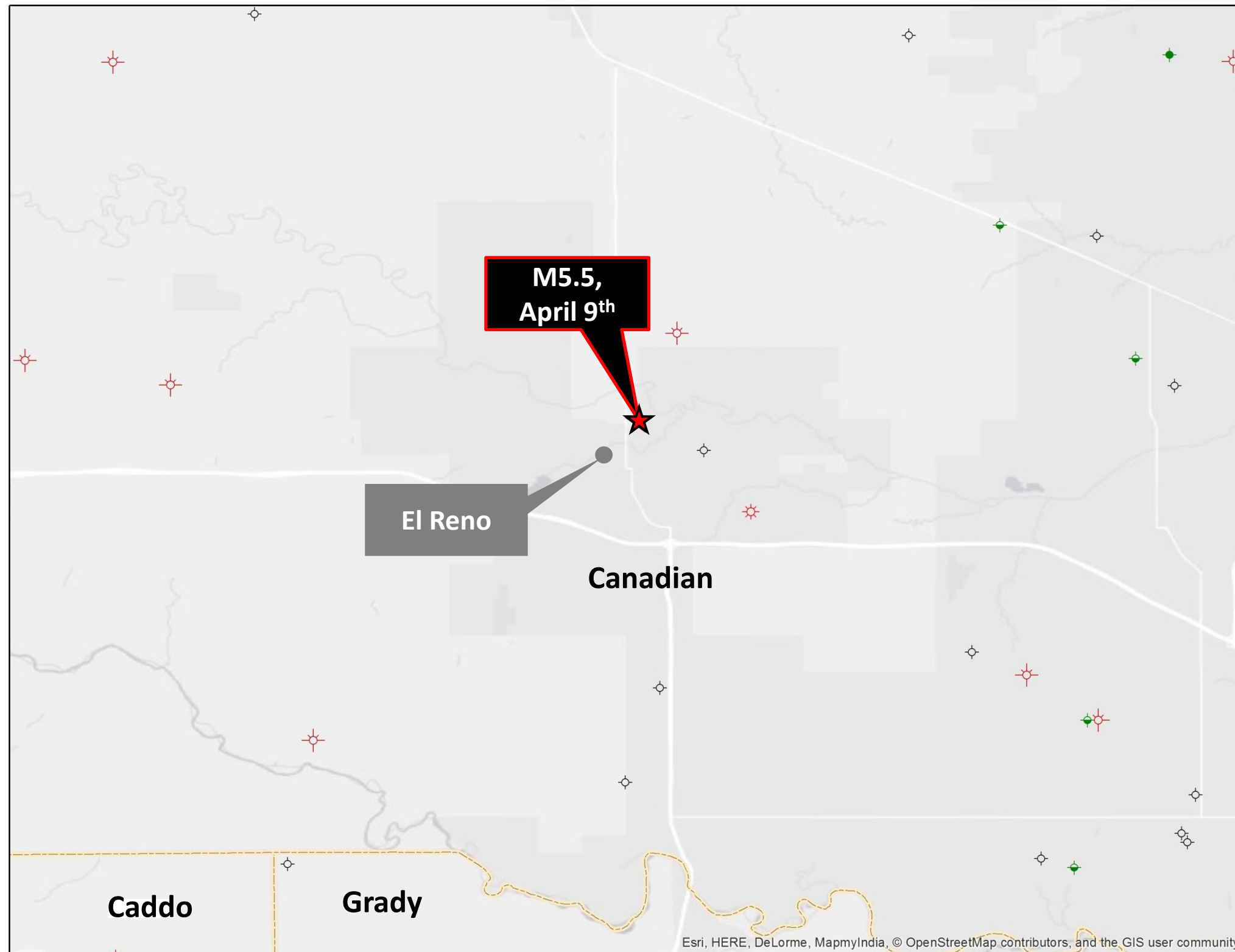


Limited detection by people and damage only and no internet to collect data

*Abridged from Seismicity of the United States, 1568-1989 (Revised), by Carl W. Stover and Jerry L. Coffman, U.S. Geological Survey Professional Paper 1527, United States Government Printing Office, Washington: 1993.

**Graphic representation as per textual information contained in the Earthquake Information Bulletin, Volume 8, Number 2, March - April 1976, by Carl A. von Hake

El Reno Quake – Wells Prior to April 1952



*Sources: USGS, 2014

EL Reno Ok has long history of quakes

- 27 reported “felt” quakes in 1908, 1910, 1918(4),
1929, 1933, 1952 (16),1953(3)

September 1918

“Objects were thrown from shelves”

”It cracked the bank building in Union City”

December 27, 1929

“at least one chimney fell “

“clocks stopped, objects moved, and some reports indicated
the walls and floors seemed to sway.”

“ In several cities, people rushed from their homes in alarm. “

“It sounded as though an automobile had crashed into our house””

“ I thought my furnace has exploded”!

Newspaper reports from El Reno 1952

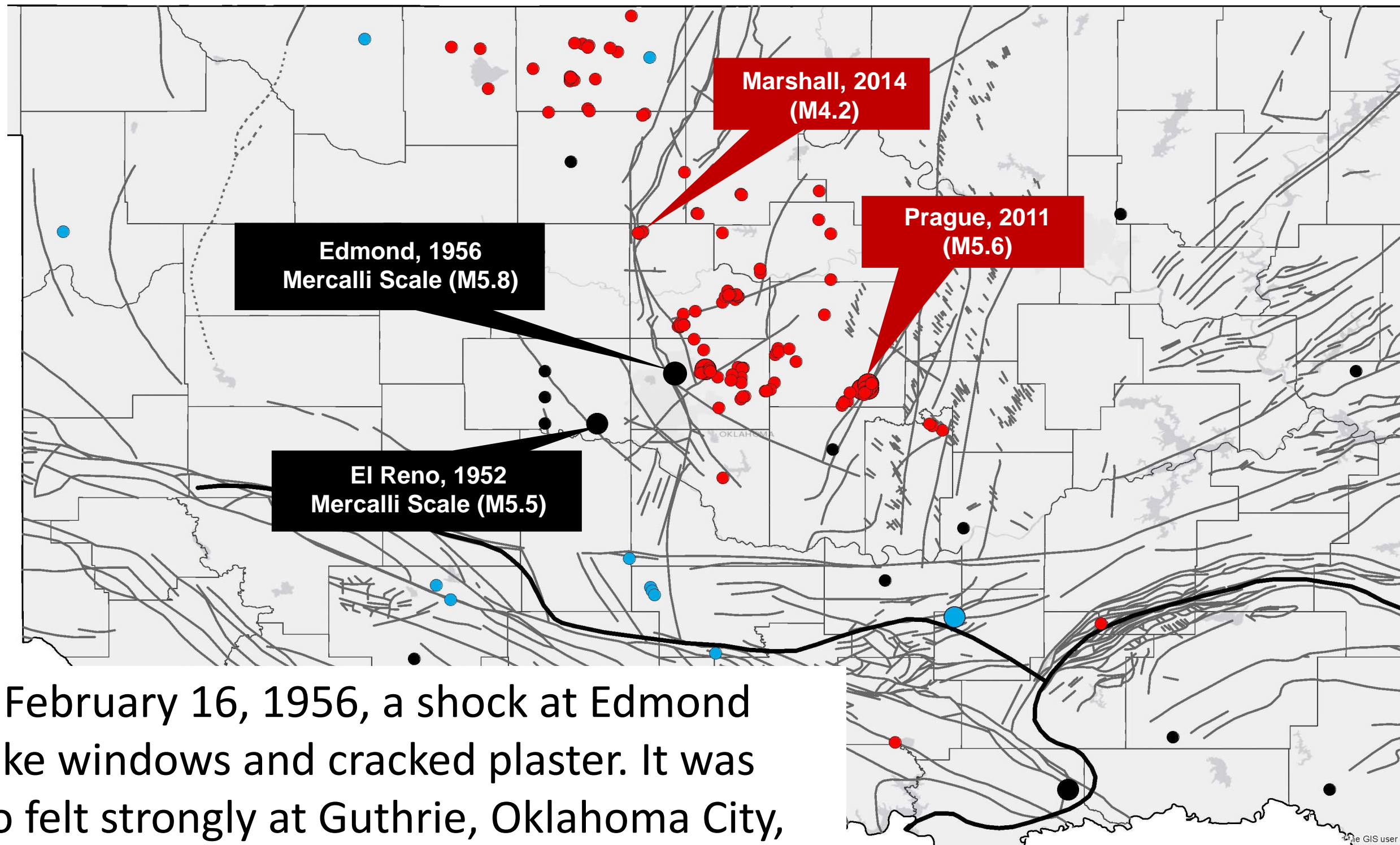
- “Windows and water pipes were broken in many areas”
- “Bomb burst feared”
- “An El Reno infant narrowly escaped death when a brick chimney crashed into the room where he slept”
- “It almost shook me out of bed, it sounded like something blew up in the basement”
- One women reported “a man is under my bed” she said she “awoke and saw the bed move and wanted police to investigate!”

El Reno 1952/1953 continued

- “buildings swayed for 23 minutes ”
- “ Oklahoma City’s Lynn Groom was knocked down while trying to get out of bathtub and required stitches”
- “Mrs Deshaw was cut and bruised by falling plaster in her home ”
- “ Dr. Hamm was dumped out of his chair in Norman by the shocks”
- “Oklahoma City Policeman said the quake nearly shook the phone right out of his hand”
- “A two foot neon sign was jarred loose and fell to the pavement “

Oklahoma Fault Map

First recorded quake in the state was in Dec 2nd 1897 in Grant County

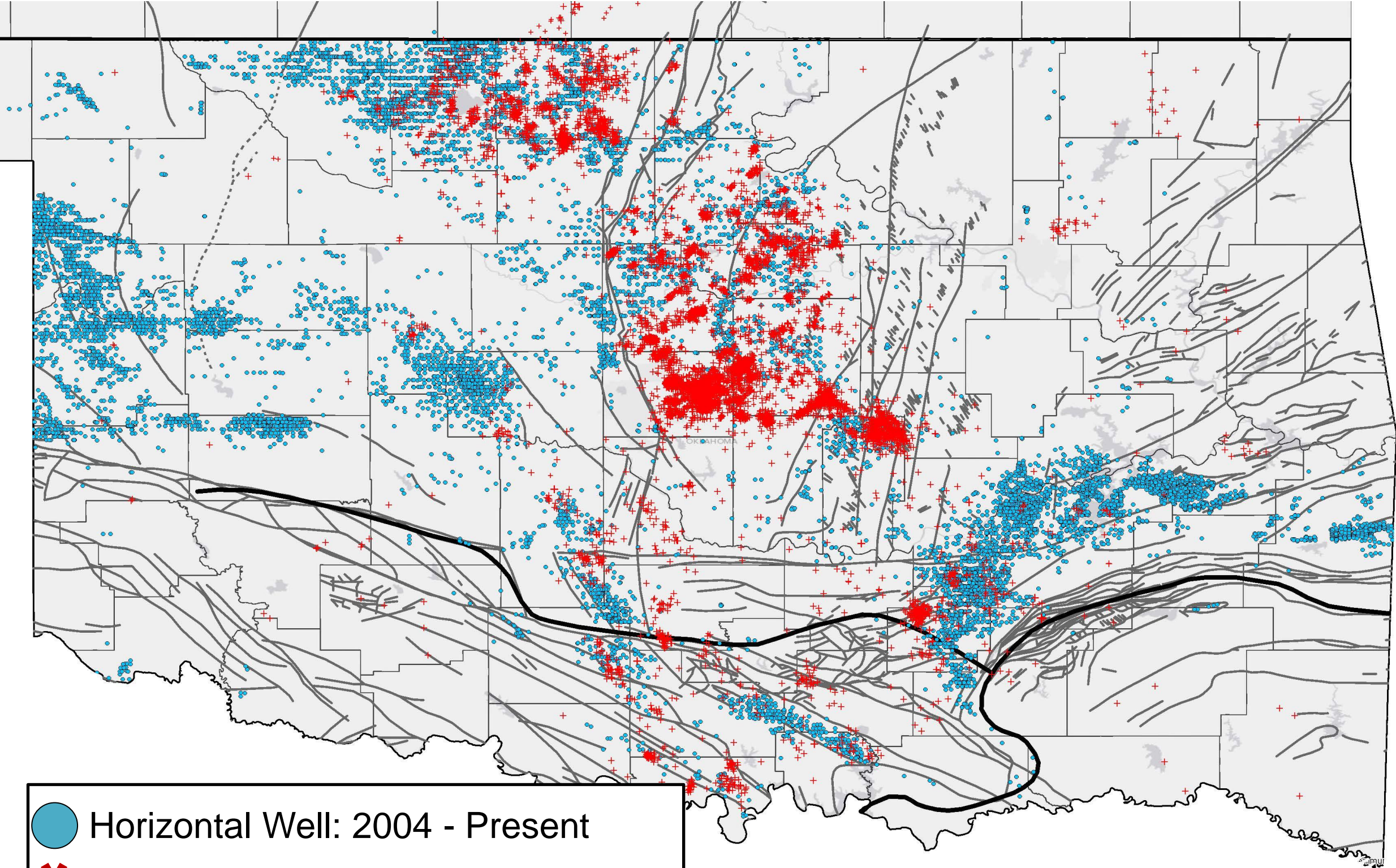


Edmond
population
1960 = 8,577
2012 = 85,885

On February 16, 1956, a shock at Edmond broke windows and cracked plaster. It was also felt strongly at Guthrie, Oklahoma City, and Pawnee

*Source: OGS, USGS September 2014; Abridged from *Earthquake Information Bulletin*, Volume 8, Number 2, March - April 1976, by Carl A. von Hake

Earthquakes not in same areas as Horizontal Oil and Gas activity!



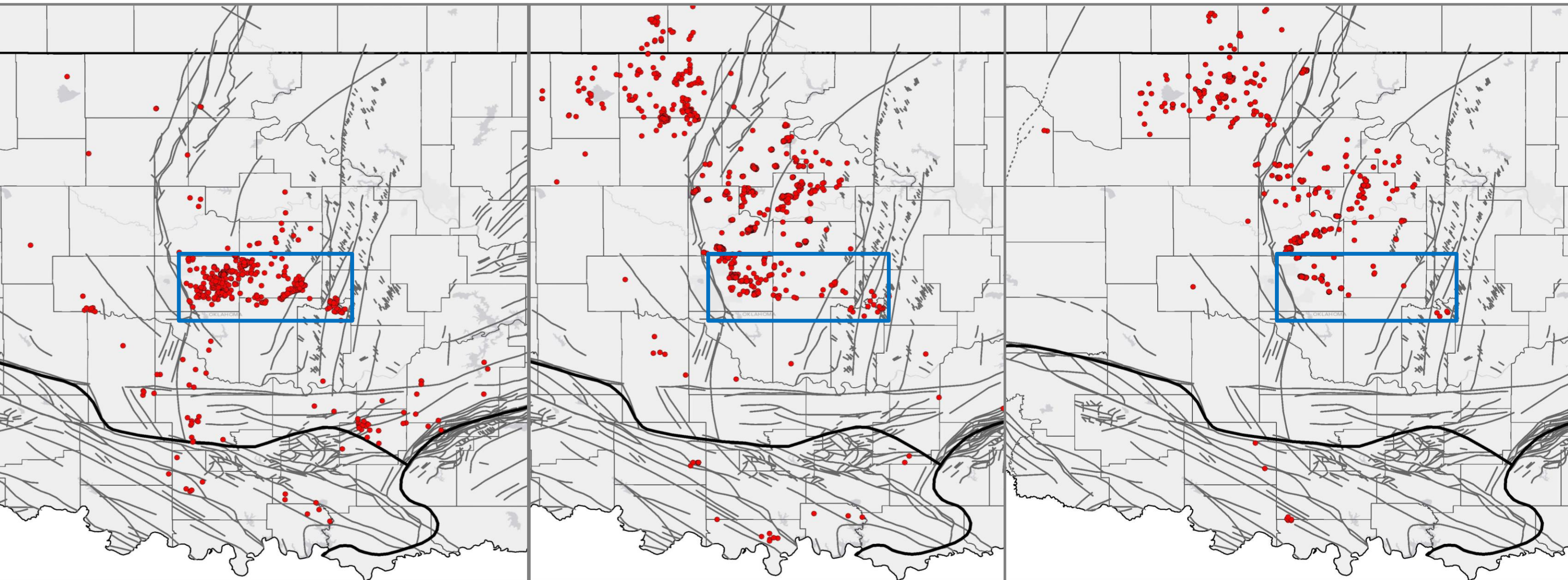
- Horizontal Well: 2004 - Present
- ✕ Earthquake Activity: 2004 - Present

“These earthquakes had absolutely nothing to do with hydraulic fracturing, we can say that with confidence.”

Austin Holland,
Oklahoma Geological
Survey research seismologist

Source:
Shaking up state
By Bailey Elise McBride
Associated Press, May 2014

**Source: September 2014 OGS, DI Desktop, & GDS



Jan 1st 2009 to June 9th 2013 quakes in OK

June 9th 2013 to June 9th 2014 quakes in OK

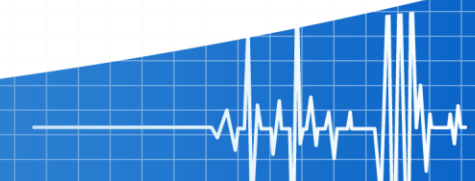
June 9th 2014 to September 9th 2014 quakes in OK

initial 3 ½ years

15 to 3 months ago

Last three months

Quakes in Oklahoma are moving north!



Velocity Model

An initial 1D velocity model (figure 2) was developed by digitizing and averaging compressional sonic logs for the 22 closest wells to the Wilzetta Fault to constrain the shallowest ~2km of the crust (figure). Deeper velocities were constrained by analyzing surface wave dispersion curves (Robert Herman, personal communication, 2012).

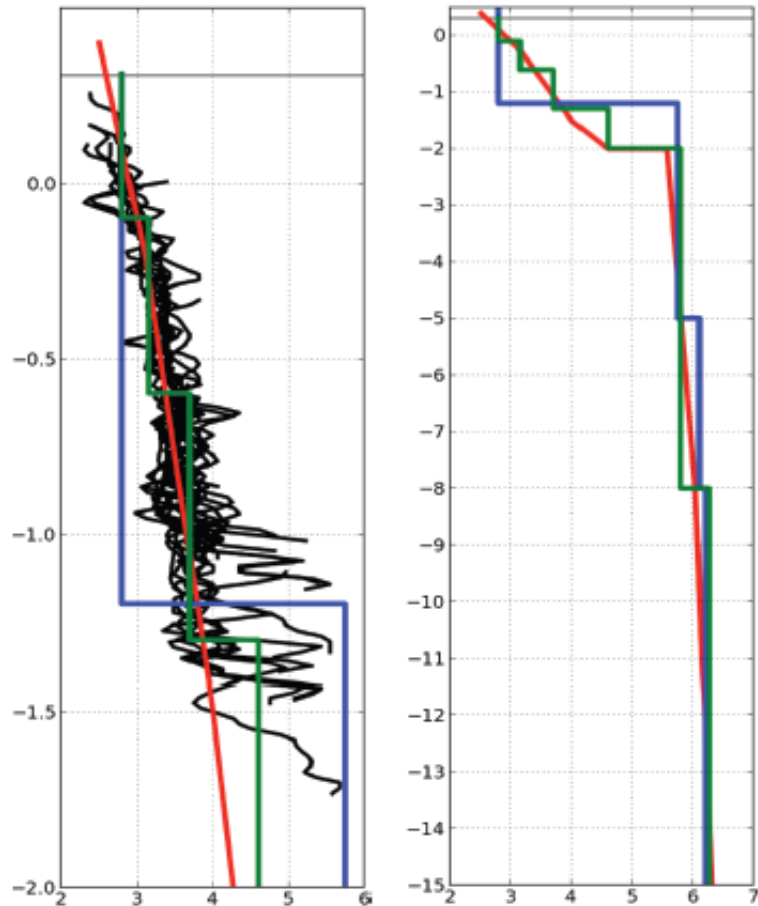
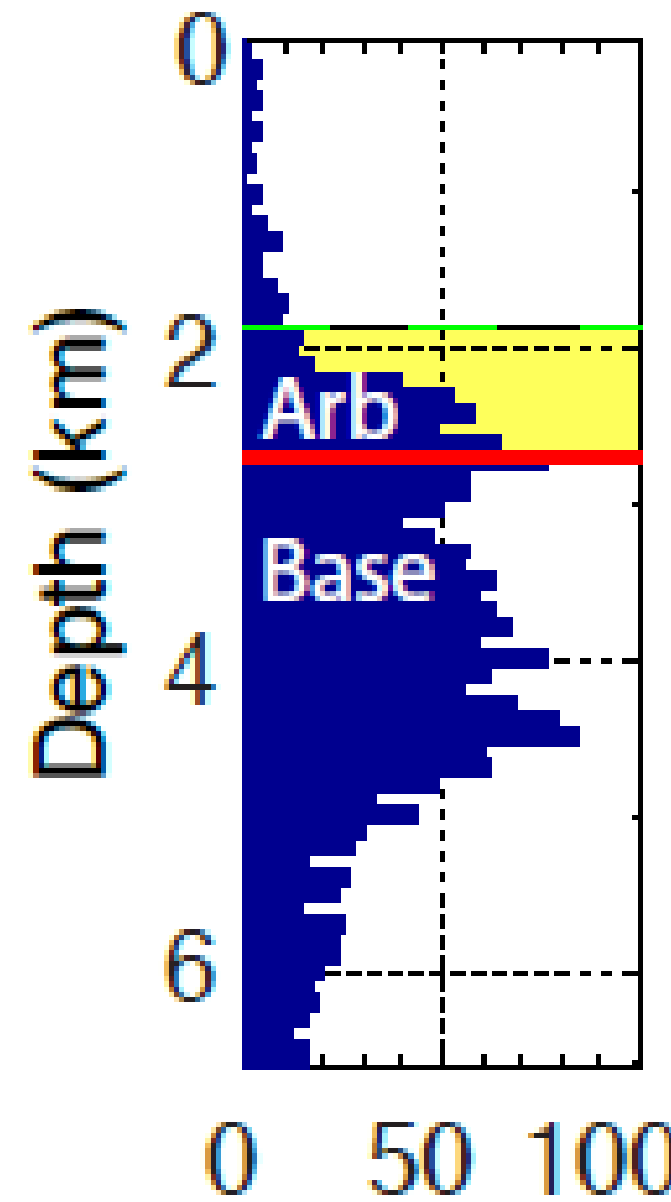


Figure 2: Left: Velocity models and sonic logs from the Wilzetta Fault area down to 2km deep, the top of crystalline basement (Luza and Lawson, 1981).

Right: Velocity models down to 15 km.

Blue: final 1D model used in Keranen et al (2013).
Red: gradient-based starting model used in this study (input for NonLinLoc).
Green: discrete-layer starting model used in this study (input for HypoDD2.1b and FMTomo).
Black: Smoothed sonic logs.
Grey: Average station elevation.



From Keranen et al 2014
 Claims that
 “over 20% of the quakes are in the sedimentary column”

From Toth, Chen Holland 2014
 “in the 100 quakes near the Prague event only approximately 7.5% were in the sedimentary column less than 2 KM”

The locations here are significantly deeper than those reported in Keranen (2013).



Separation of the Earthquake Tomography Inverse Problem to Refine Hypocenter Locations and Tomographic Models A Case Study from Central Oklahoma

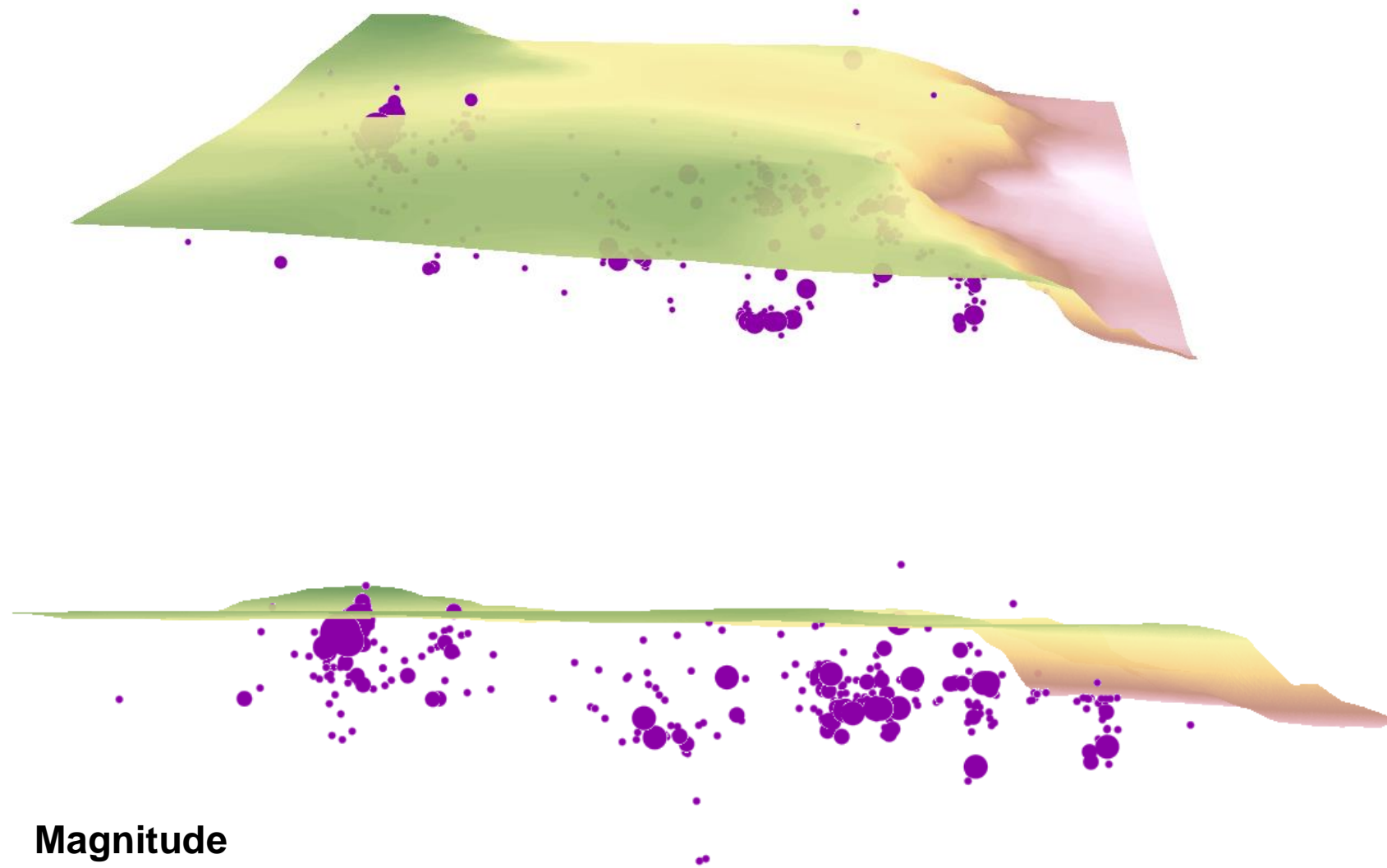
2014

Toth, C.R.¹, Chen, C.¹, Holland, A.A.²

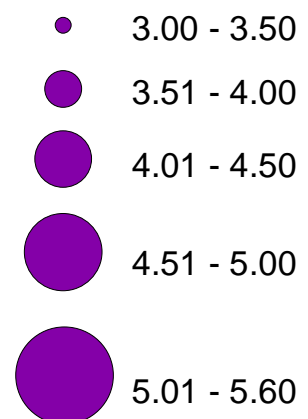
¹ University of Oklahoma, Norman; ² Oklahoma Geological Survey



Central Oklahoma Quake events 3 or greater from OGS database 2009 to July 2014

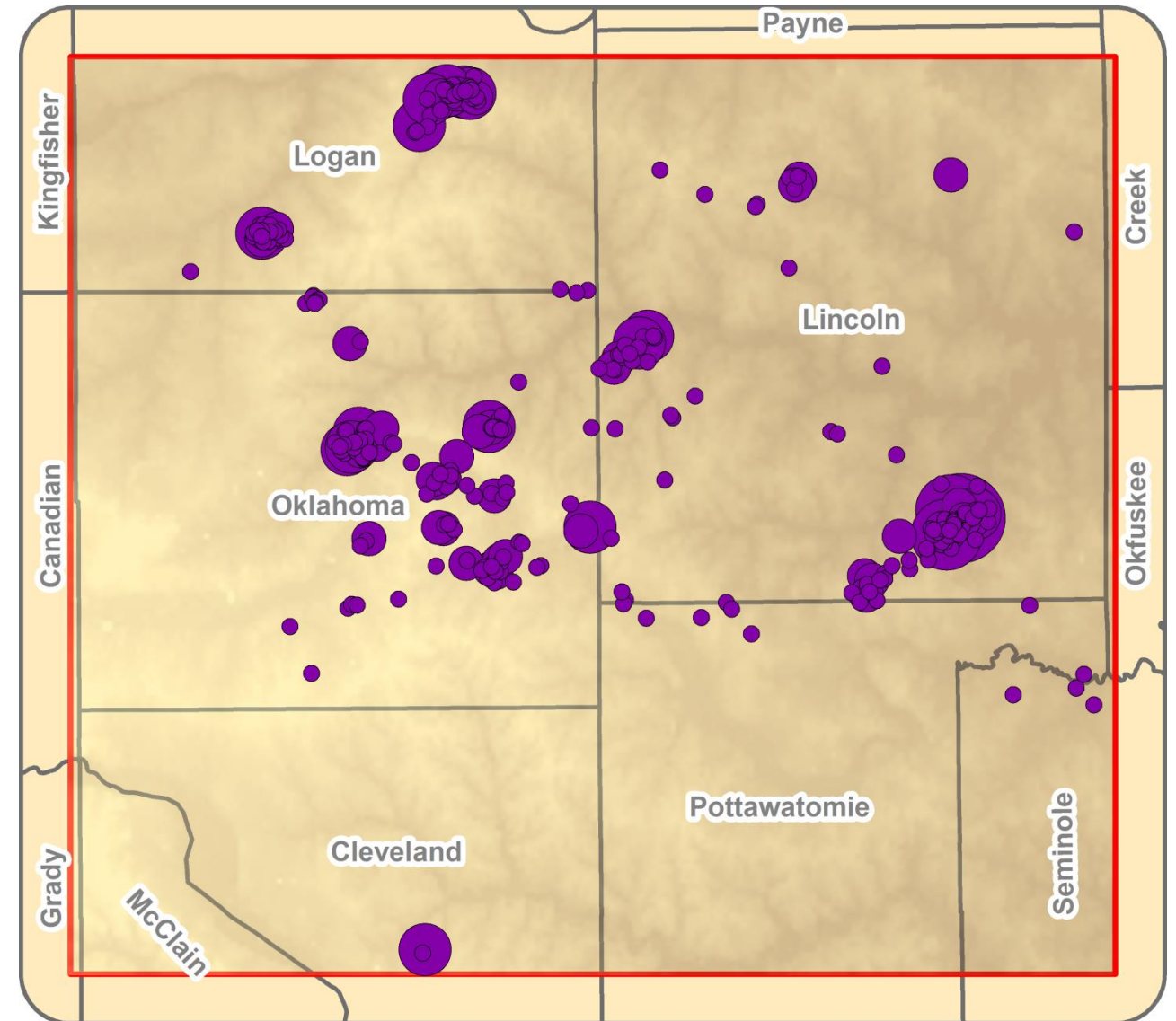


Magnitude



View looking southeast
Datum = ground level

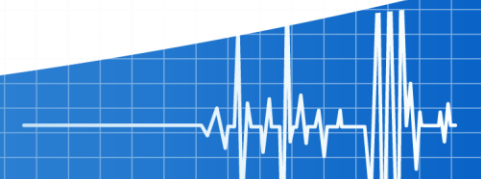
Quakes 3D plotted as compared to
depth to magnetic basement
by Earthfield Technology Project Elephant Merge
**data accuracy +/-10% of total depth
2x vertical exaggeration



Median depth of quakes in Northern Oklahoma and Logan County

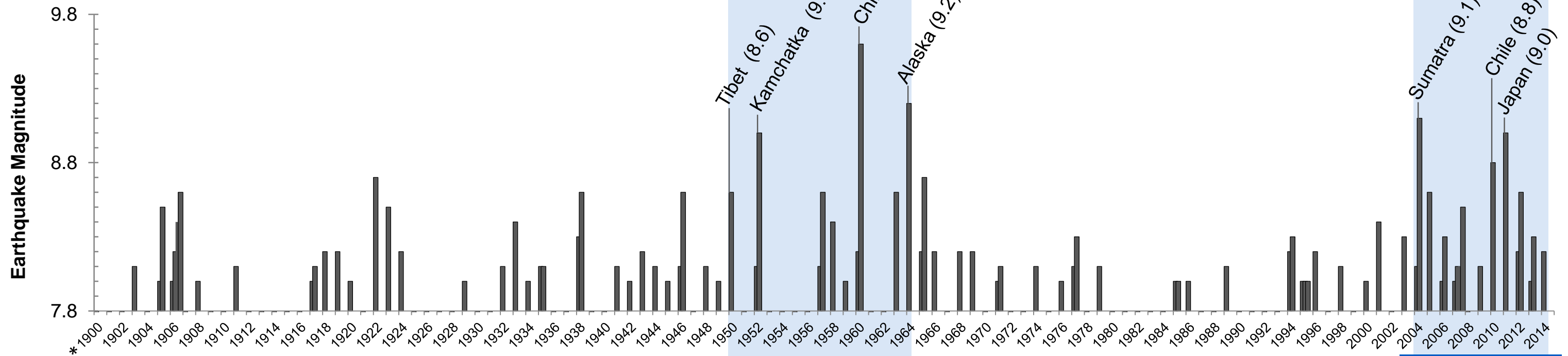
- Choctaw 6.8 KM 4.2 Miles 22,176 feet
- Arcadia 5.6 KM 3.5 Miles 18,480 feet
- Waterloo 5.0 KM 3.1 Miles 16,380 feet
- Liberty 5.0 KM 3.1 Miles 16,380 feet
- Langston 5.0 Km 3.1 Miles 16,380 feet
- Marshall 4.6 KM 2.85 Miles 15,048 feet
- **Average 17,477feet**

- Source OGS OF1 2014 Town hall Meeting Edmond

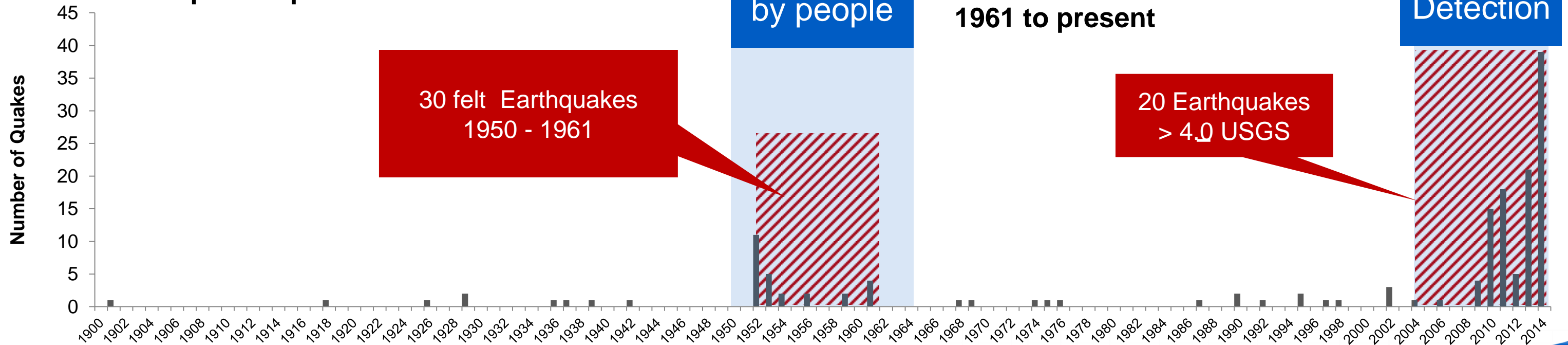


Worldwide Quakes

Worldwide $\geq 8^*$



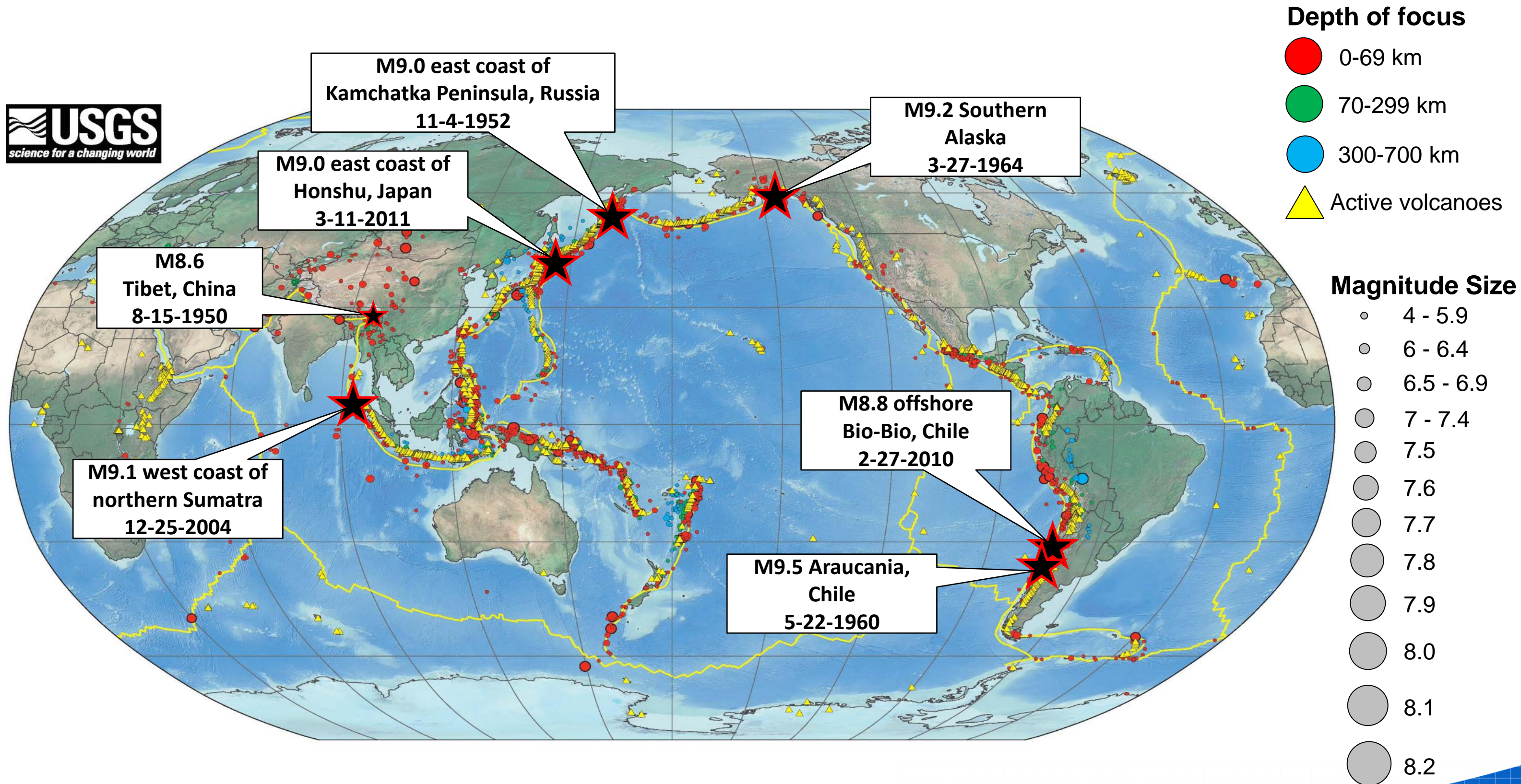
Felt quakes prior to 1961



*Sources: USGS, 2014

**Source: OGS, 2014

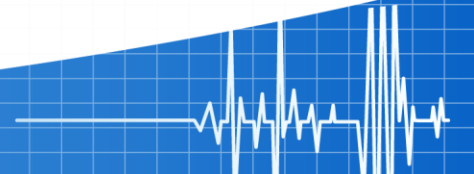
Worldwide Earthquakes Larger than M8.8



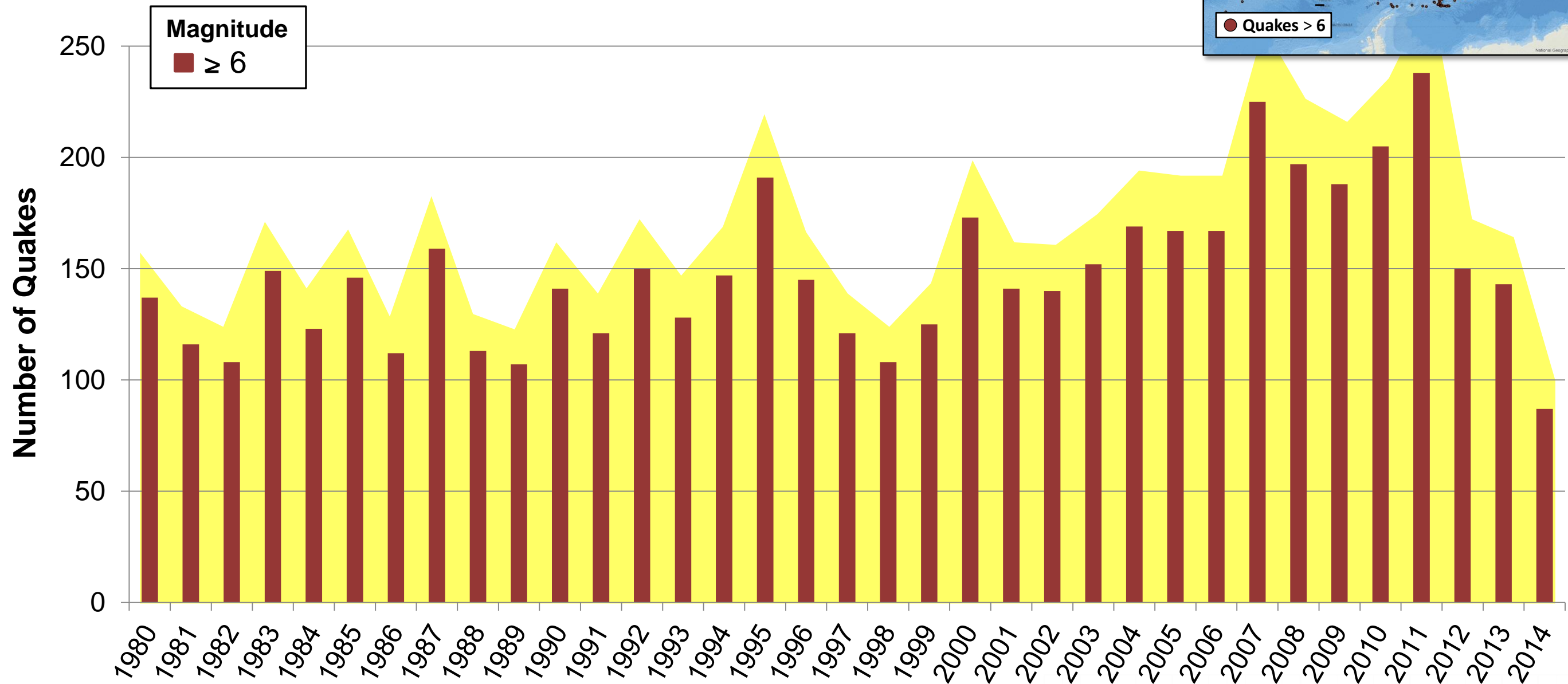
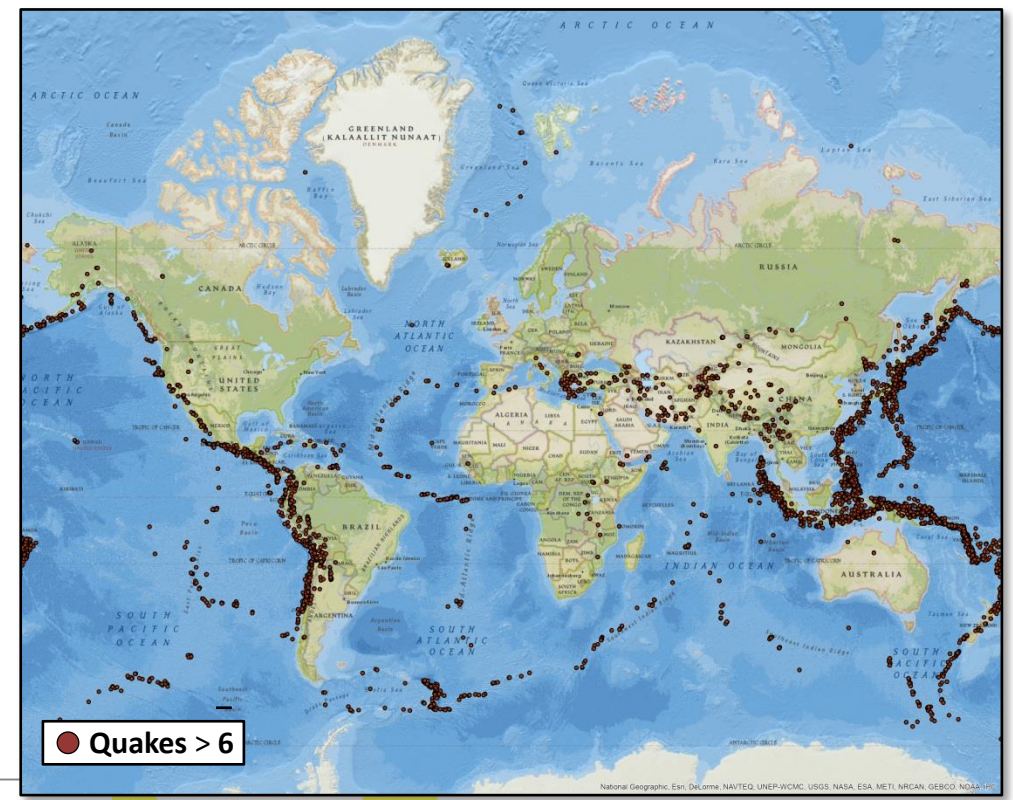
*Sources: USGS, 2014

Summary of Large World Quakes

- Since 1900 there have been 6 Earthquakes magnitude 8.8 or greater.
- 3 happened after 2004
- 3 happened between 1952 and 1964
- The 9.1 Indonesian event in 2004 sped up the rotation of the earth by 3 microseconds (Nature, Dec 30 2004).
- The 2011 magnitude 9 event offshore Japan shifted the planet on its axis by nearly 4 inches and shortened the day by 1.8 milliseconds (Nasa Earth 3/14/2011)
- Both Earthquakes resulted in widespread Tsunami damage.

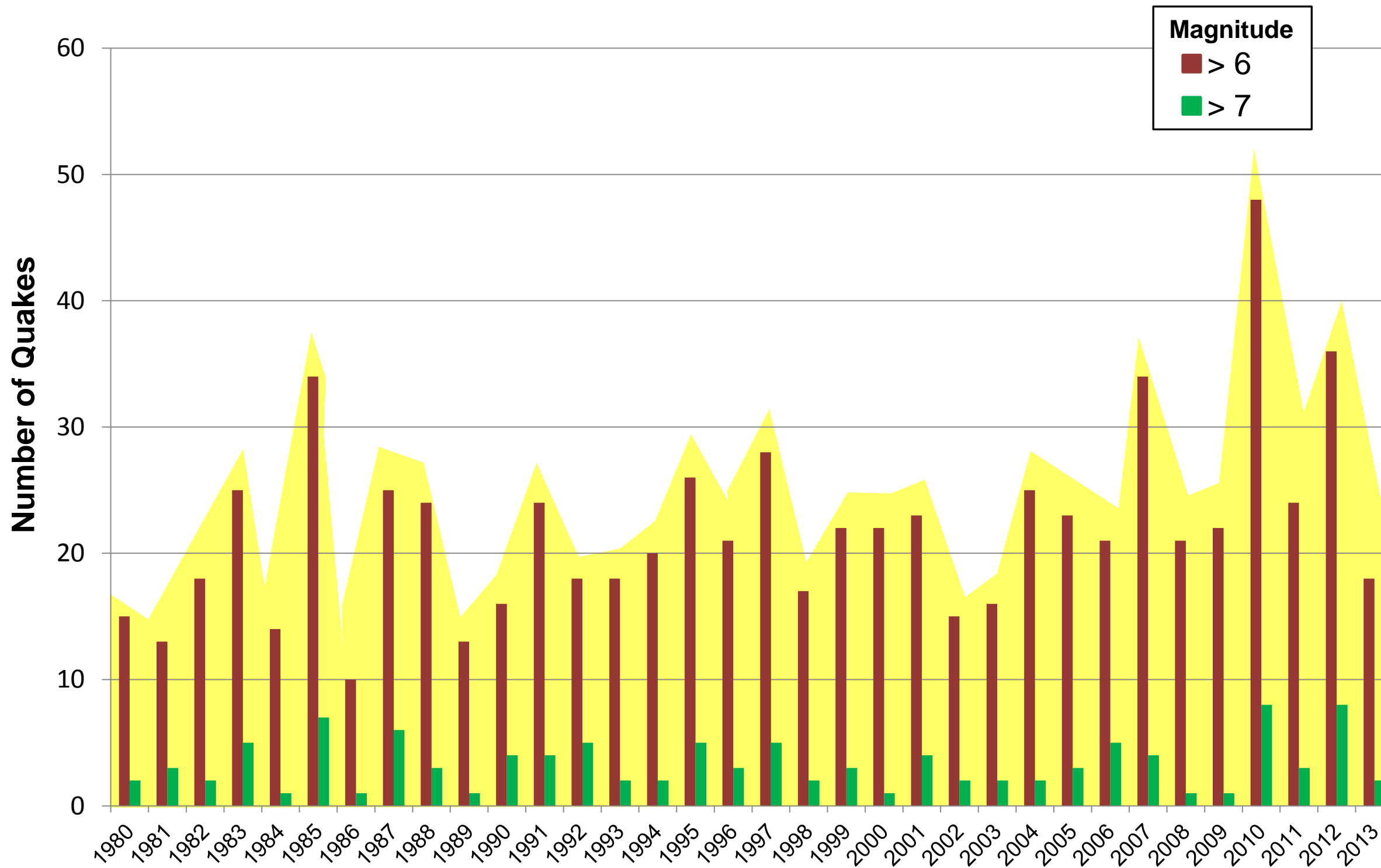


World Earthquakes 1980 – June 2014



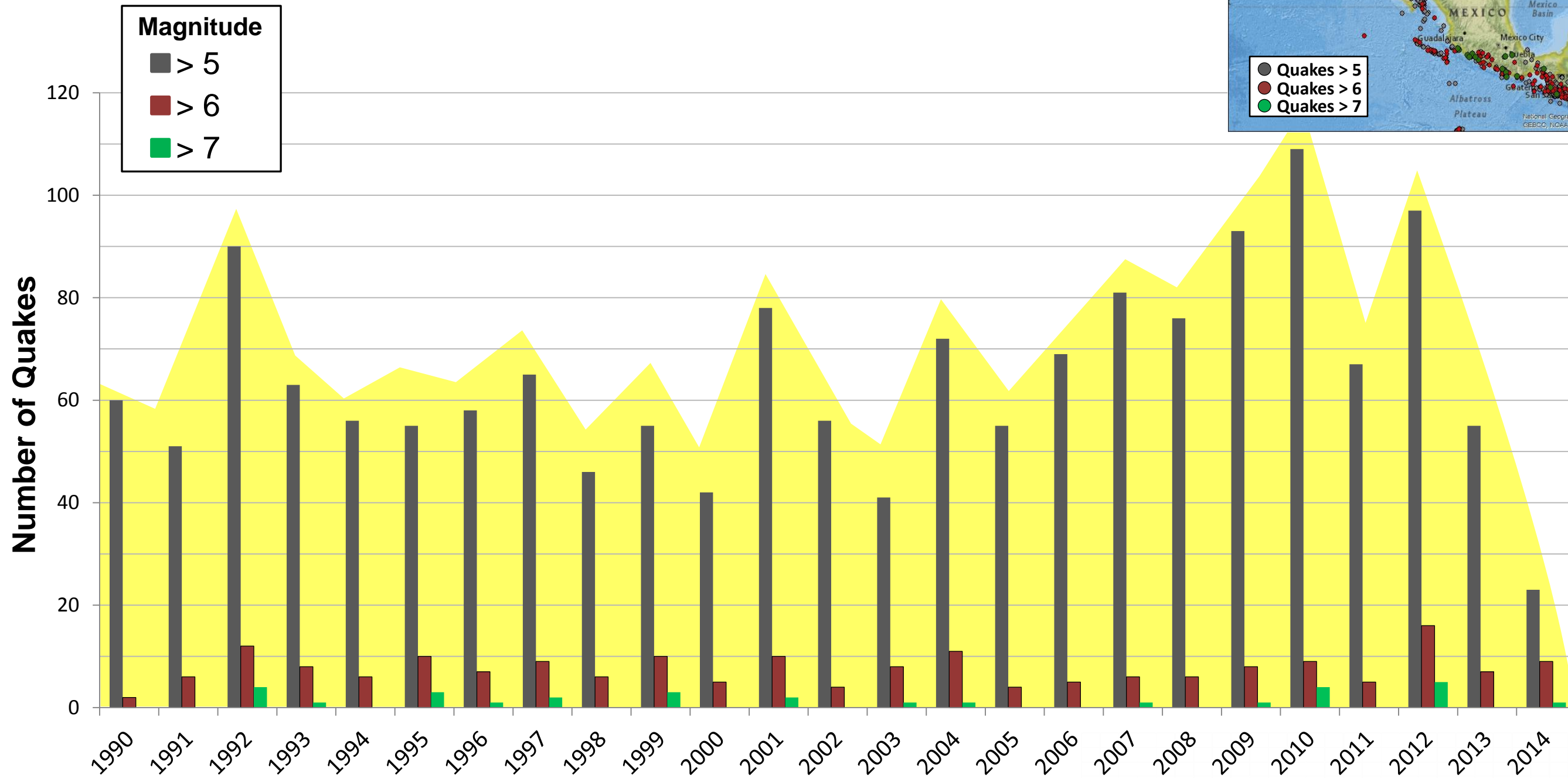
*Source: USGS, June 2014

North, South, & Central America's Earthquakes 1980 to 2013



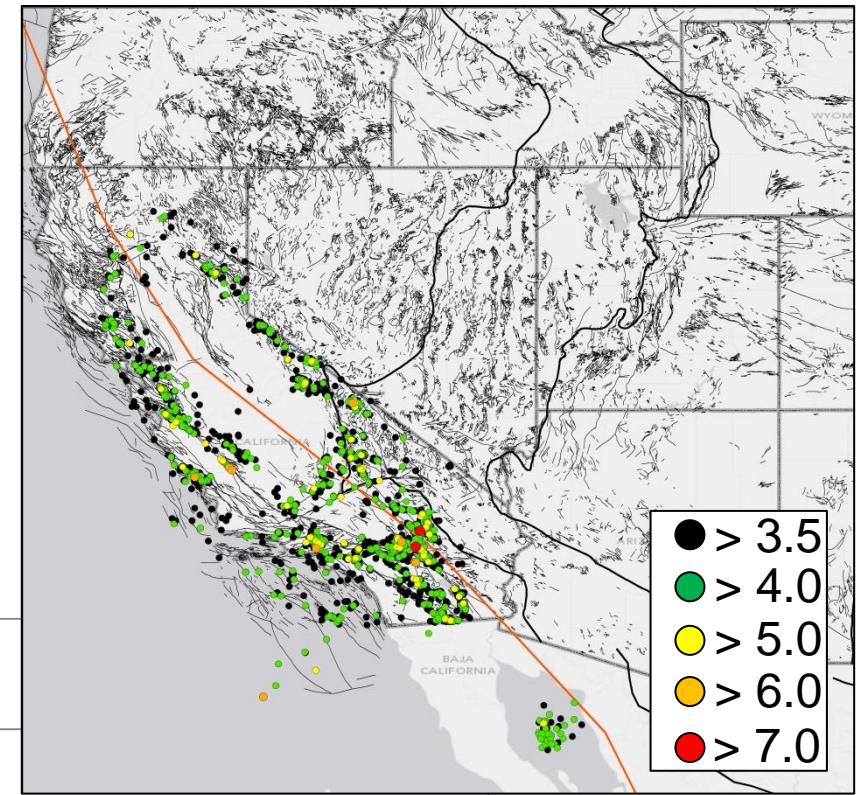
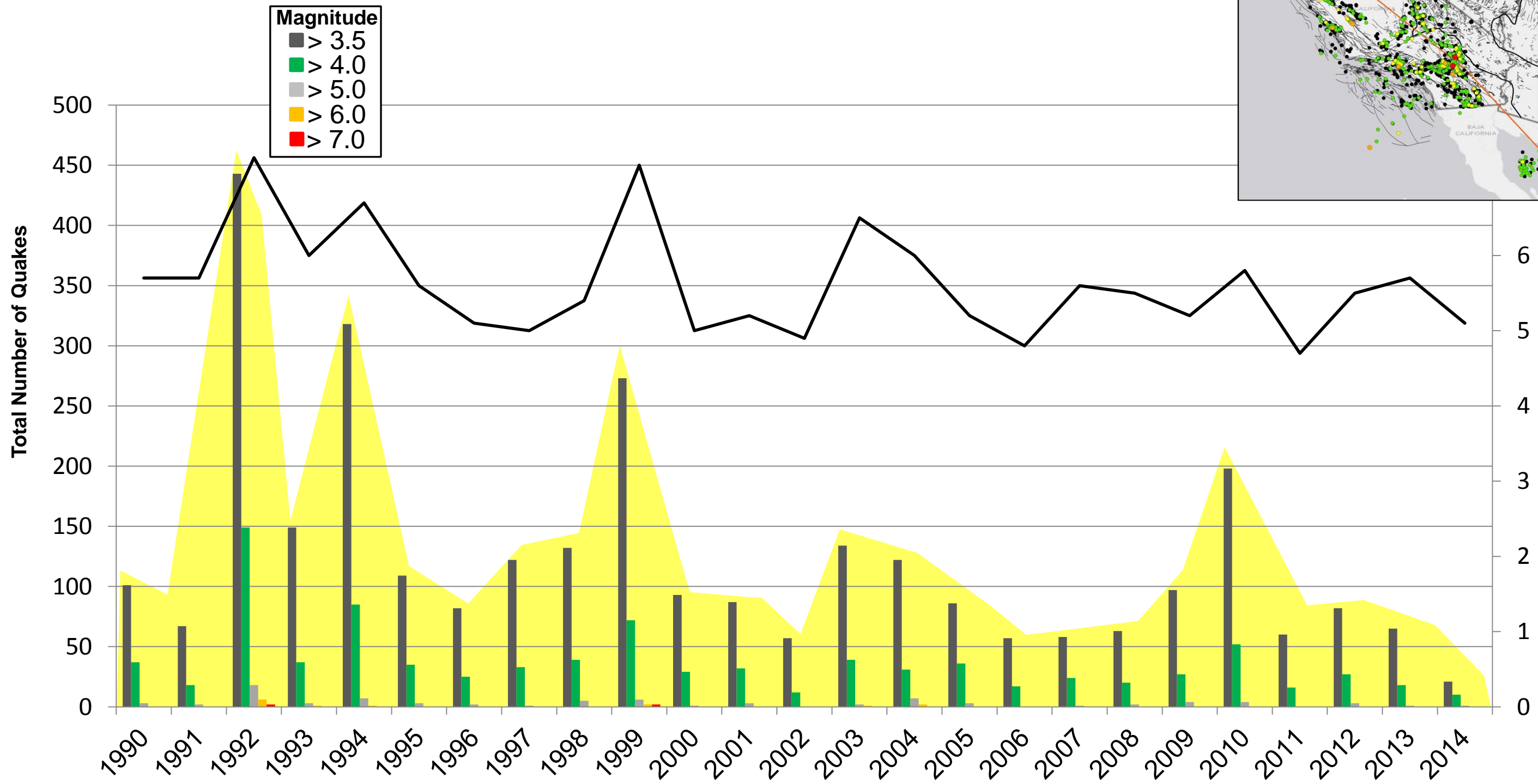
*Source: USGS, 2014

North & Central America Earthquakes 1980 – June 2014



*Source: USGS, June 2014

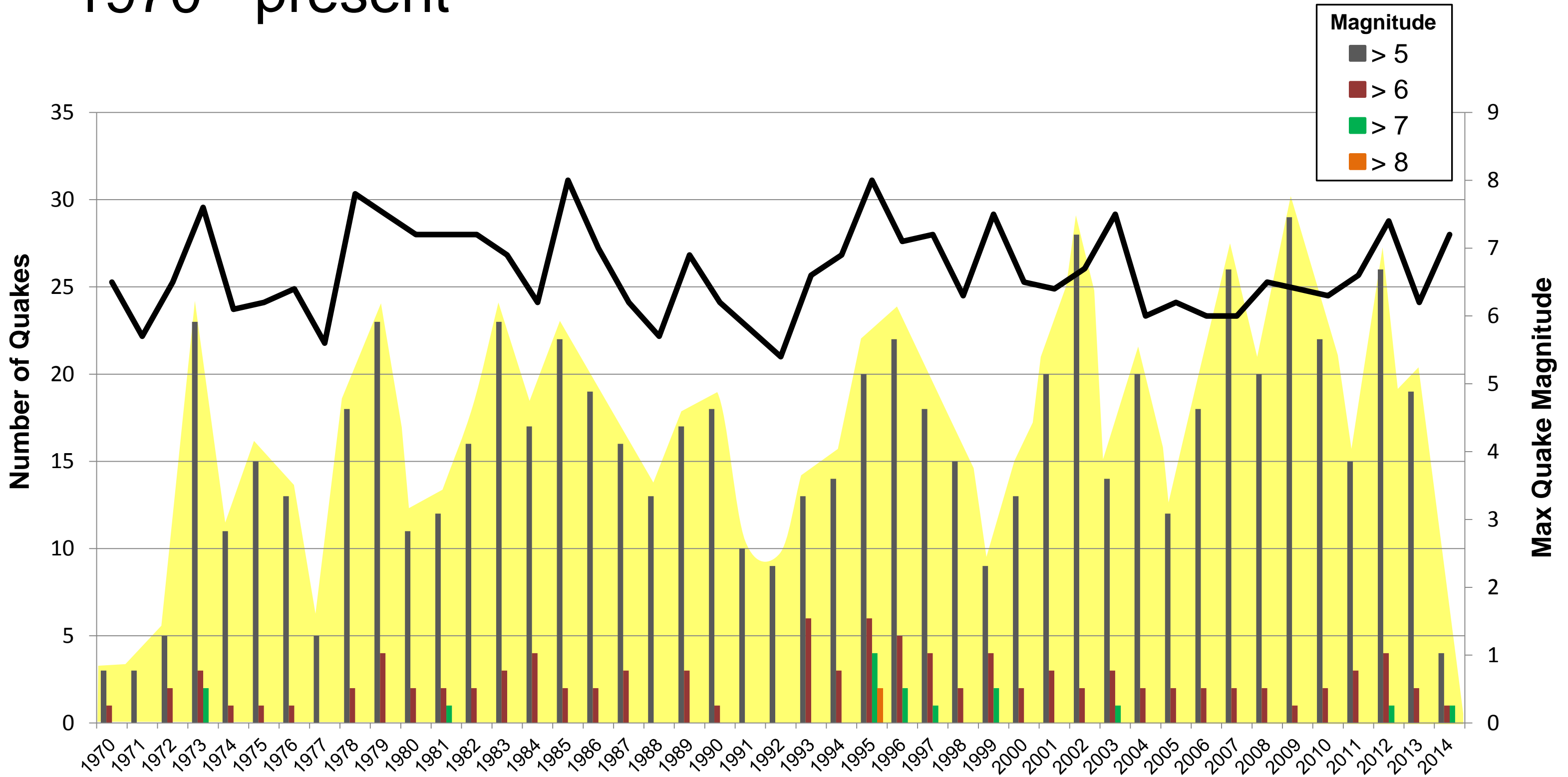
California 1990 - Present



*Sources: USGS, June 2014

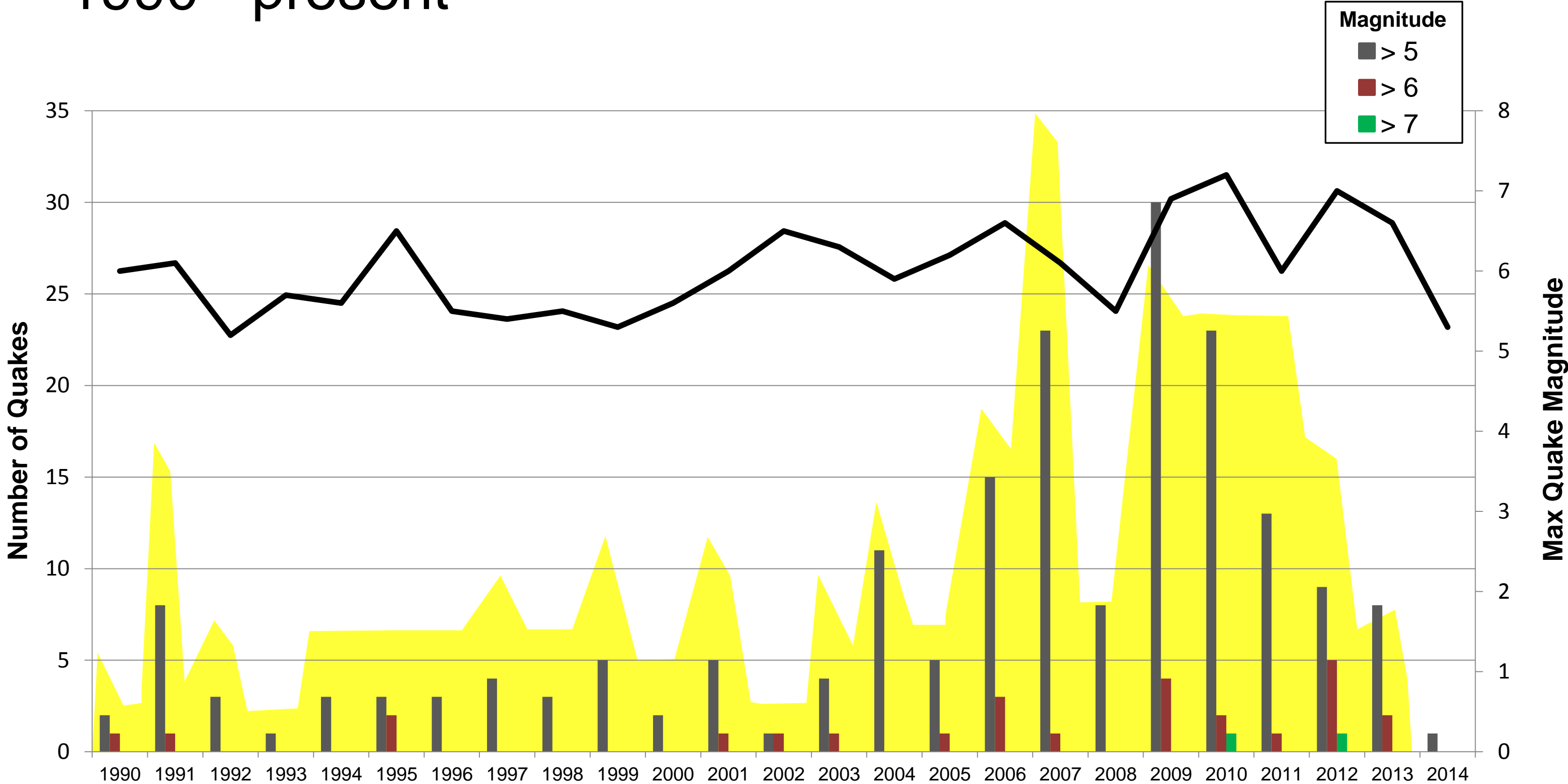
Subduction Area of Southern Mexico

1970 - present



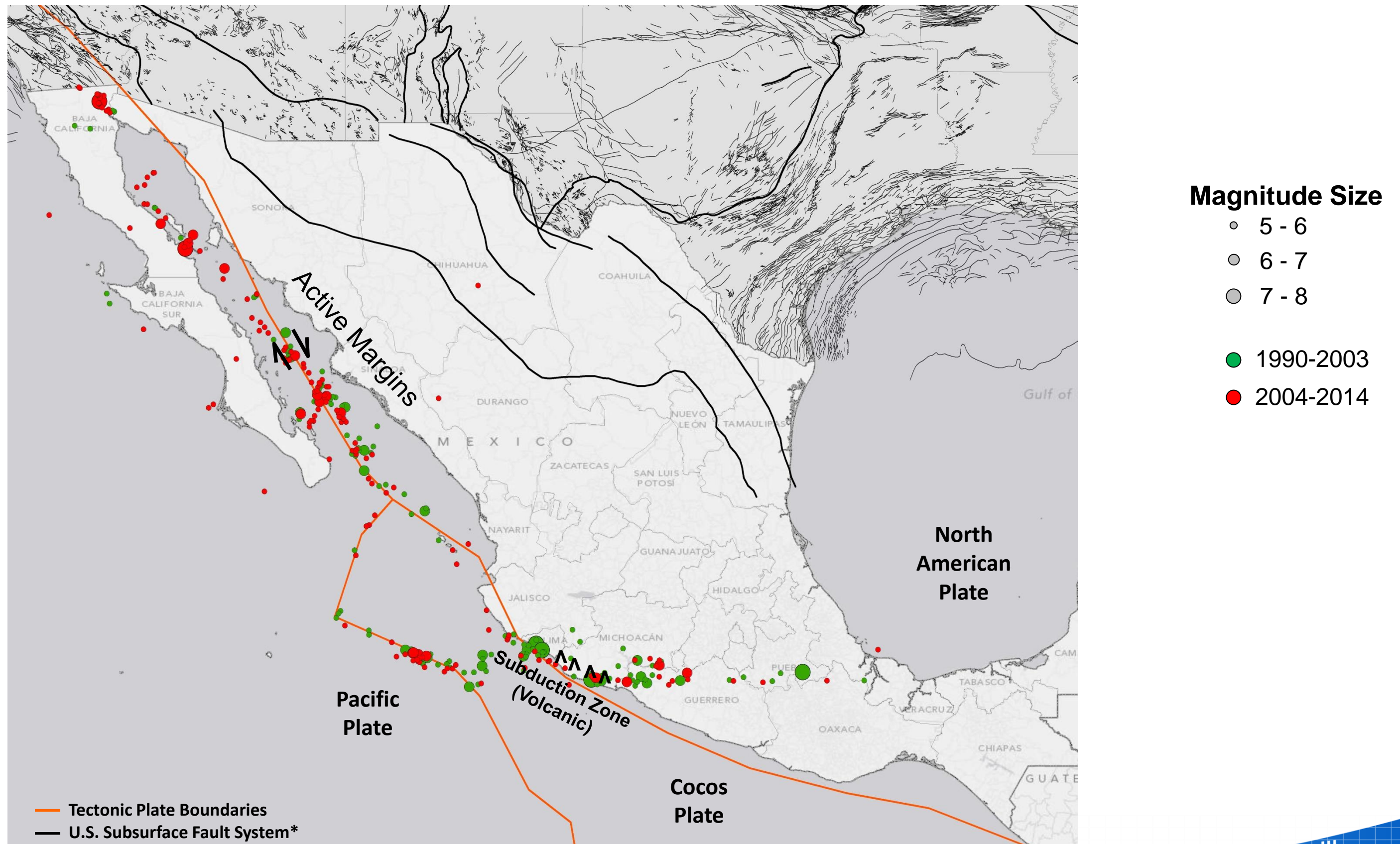
*Source: USGS, June 2014

Gulf of California 1990 - present



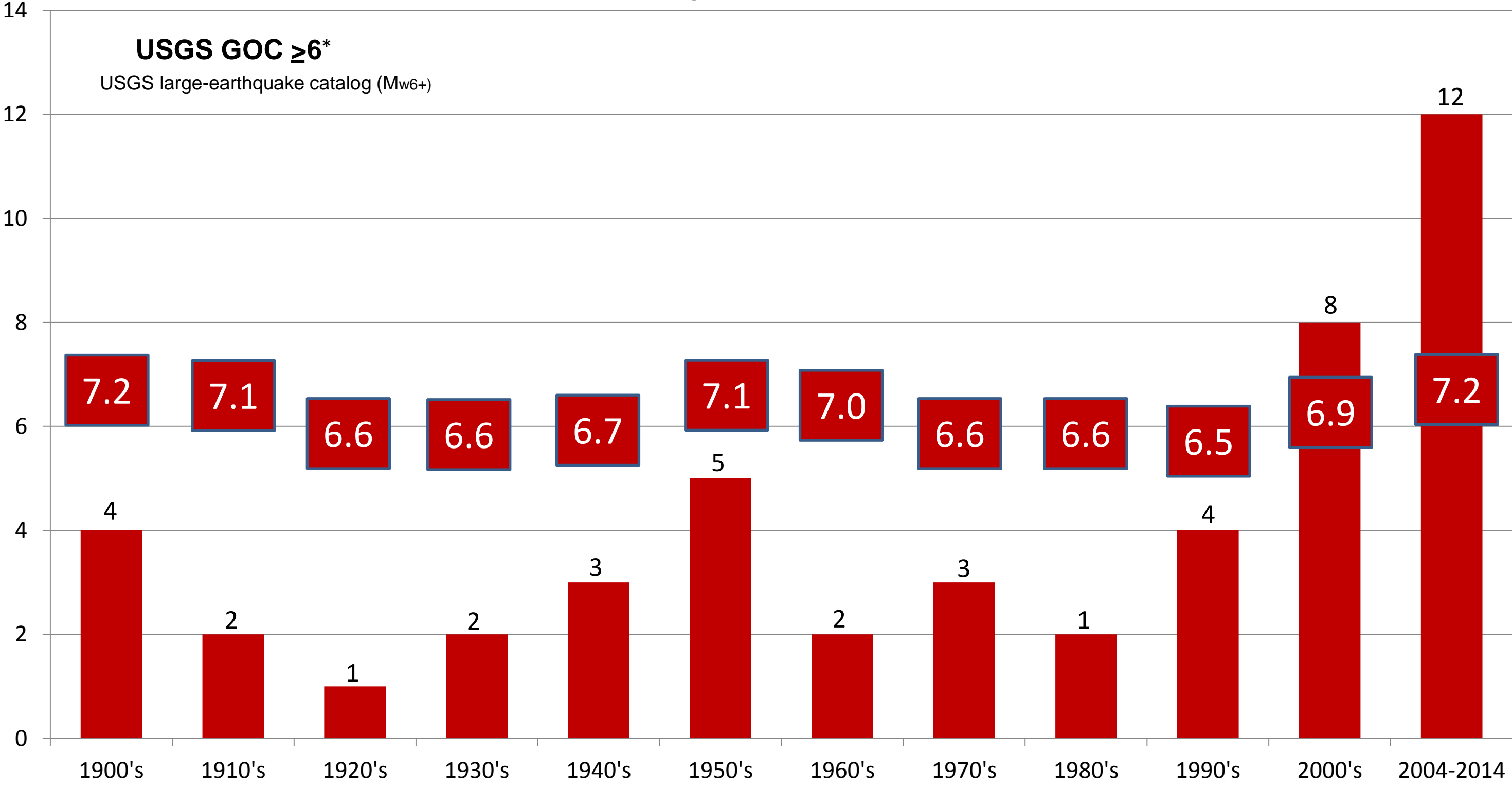
*Source: USGS, June 2014

Gulf of California (GOC) & South Mexico Subduction Area

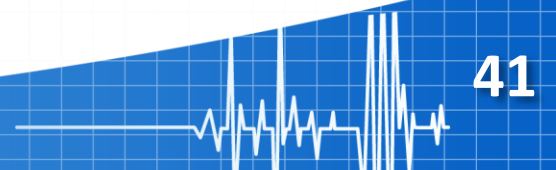


*Source: USGS, June 2014

Gulf of California: Quake History count and Maximum Magnitude by decade



*Sources: USGS, 2014; Latitude 22.0° to 32.6°N, Longitude -105.2° to -117.3°W



More evidence of seismicity in
the 50's!

“Shake Rattle and Roll “
Bill Haley and the Comets 1954

“Whole Lotta’ Shakin’ Going On”
Jerry Lee Lewis 1957

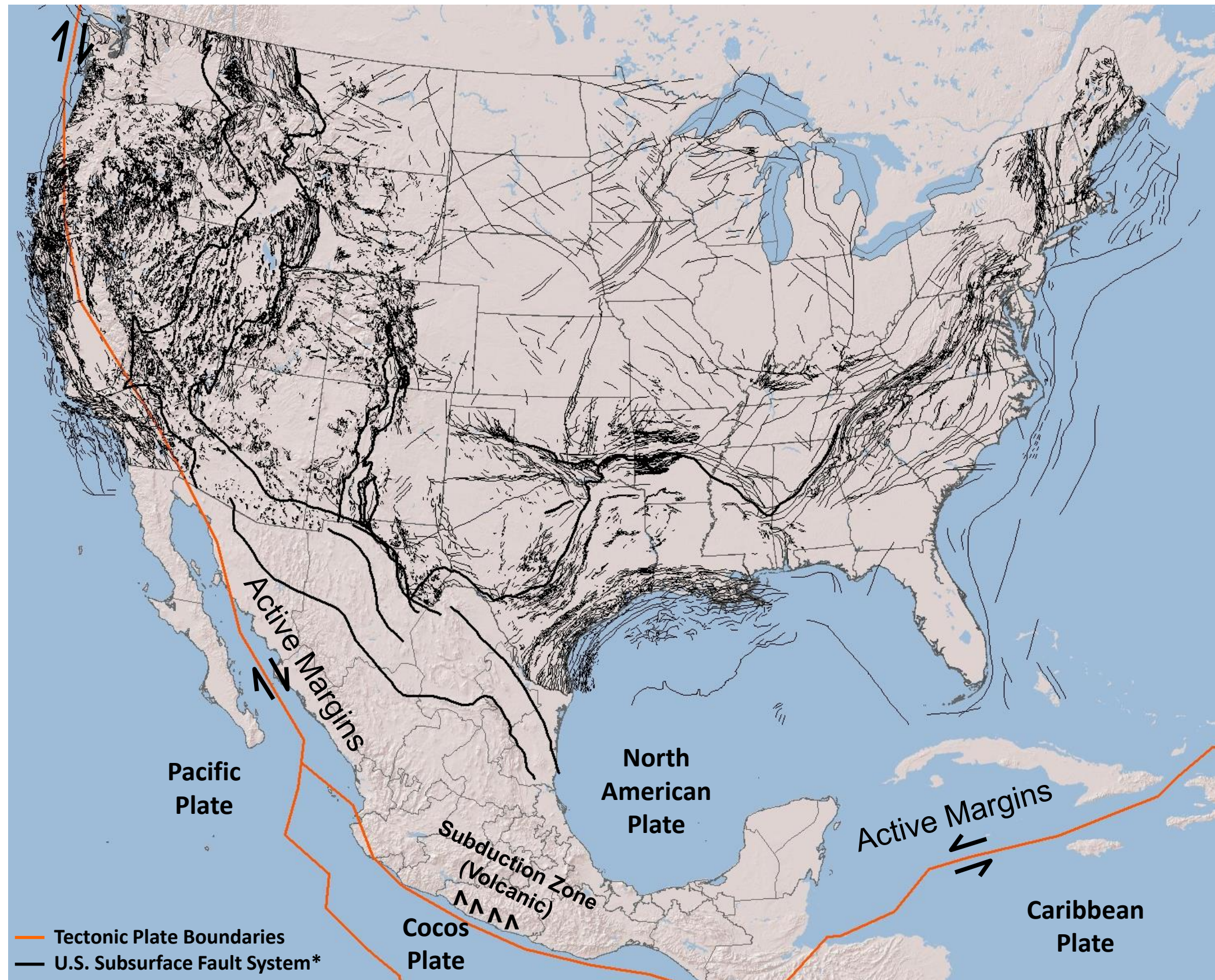


“All Shook Up”

Elvis Presley 1957



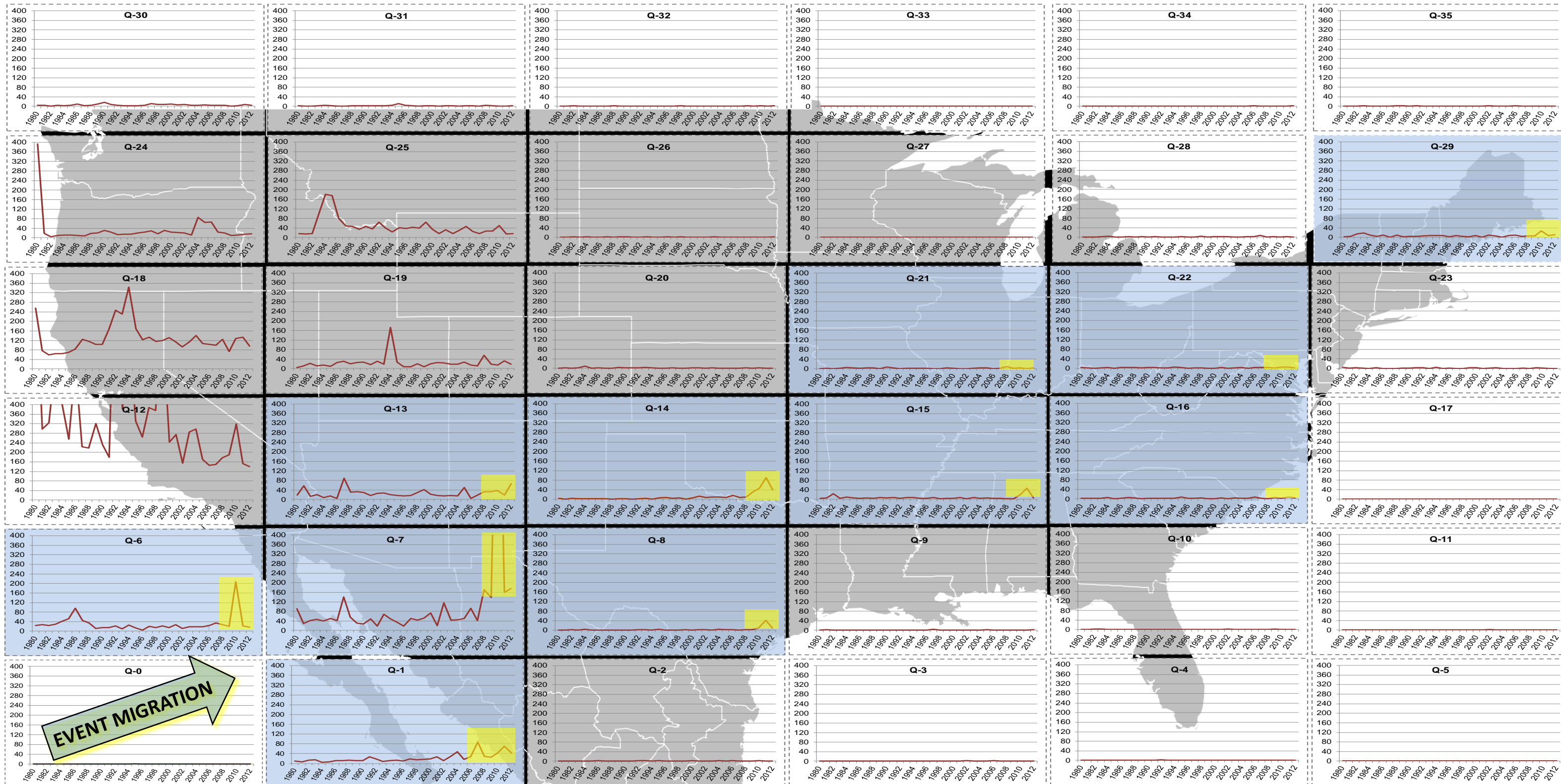
The Rest of the Story!



*Source: Geologic Data Systems

North America Map by Lat/Long Quadrant

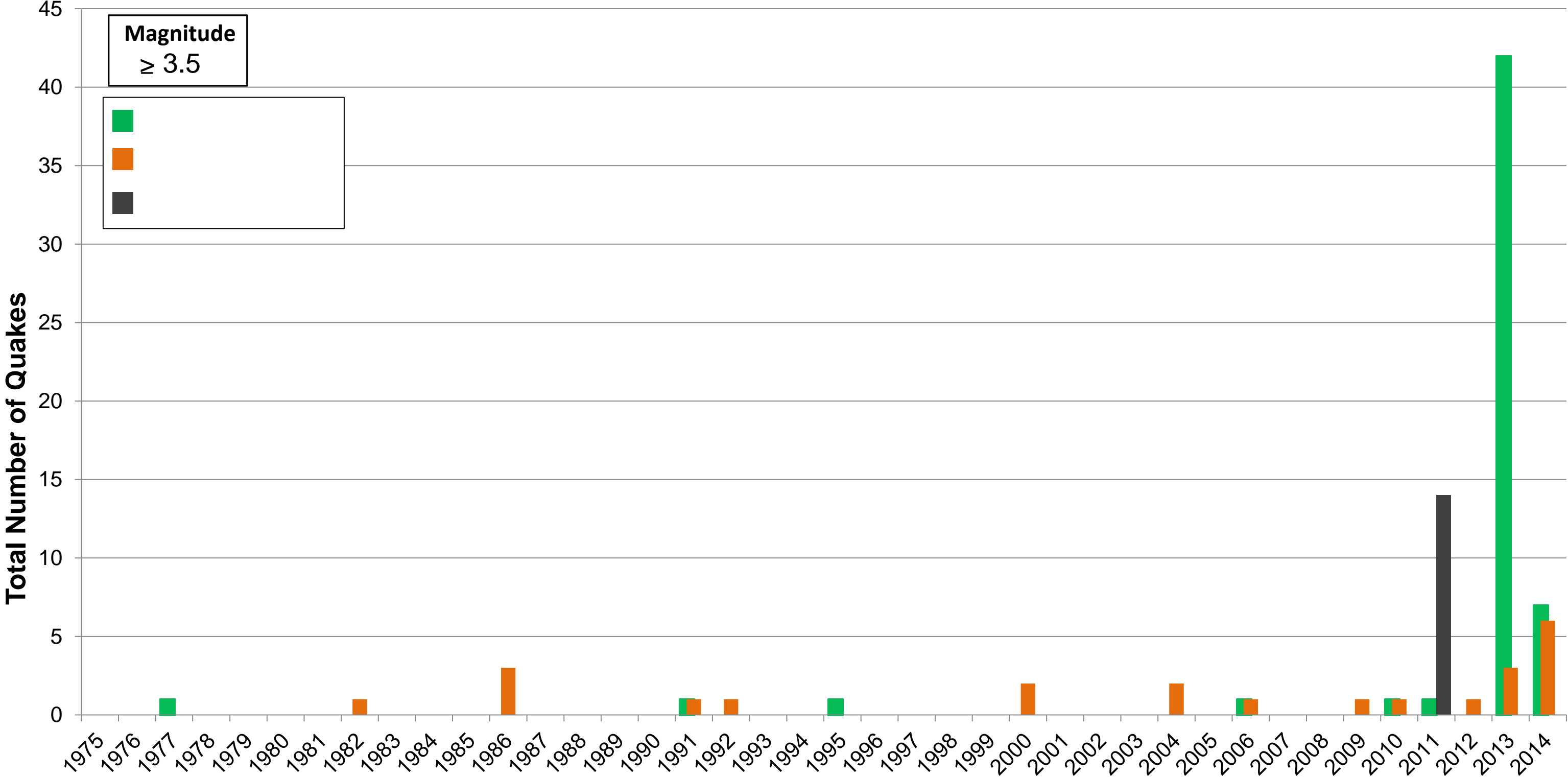
Magnitude ≥ 3
(Scale 400 on Y axis)



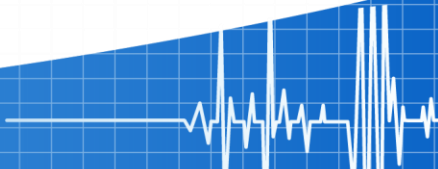
*Source: USGS, 2014

Data trend from 1980 - 2013

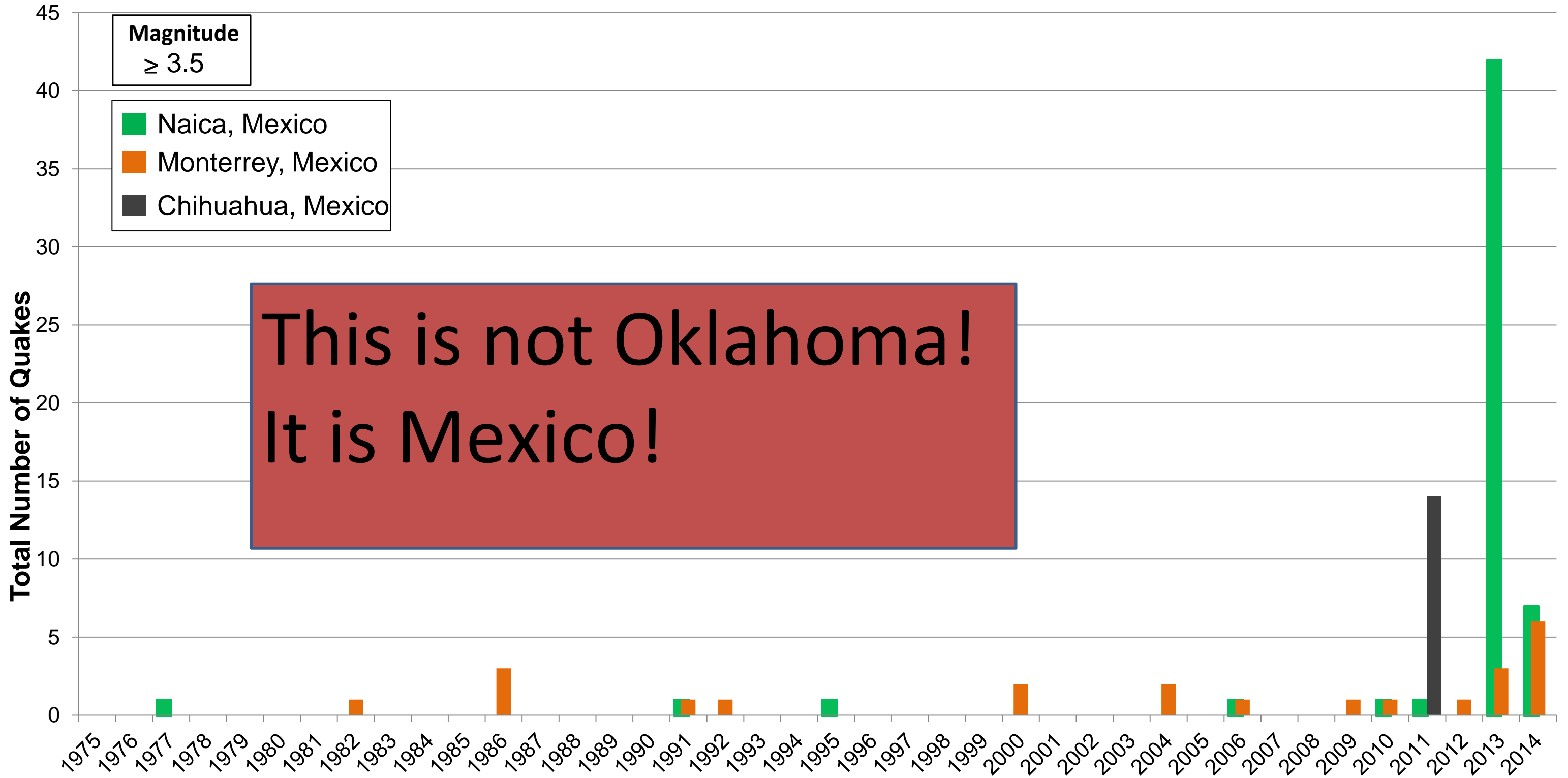
Historical Earthquake Count



*Source: USGS, 2014

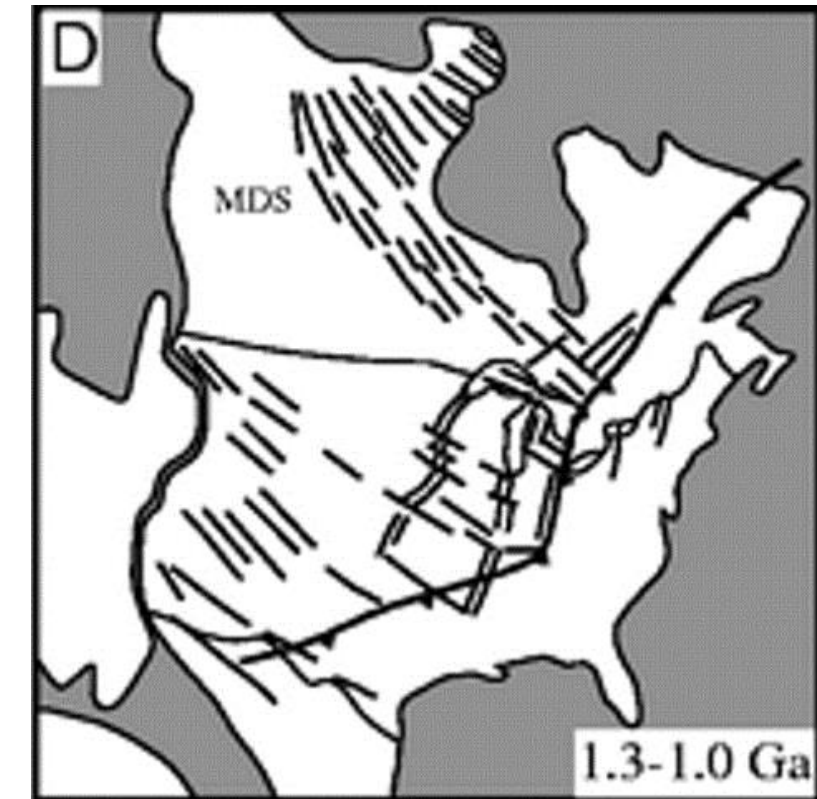
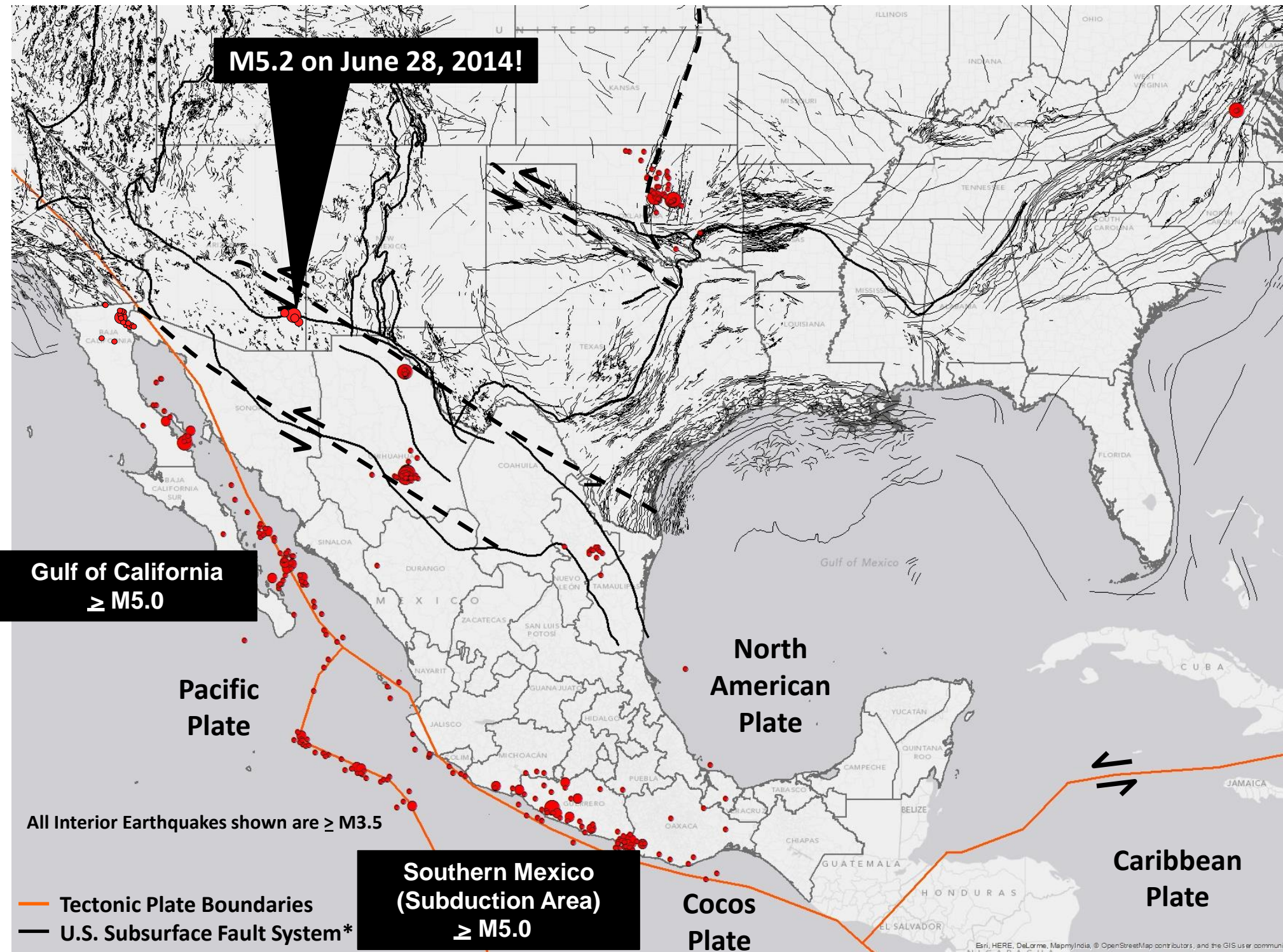


Mexico Interior Historical Earthquake Count



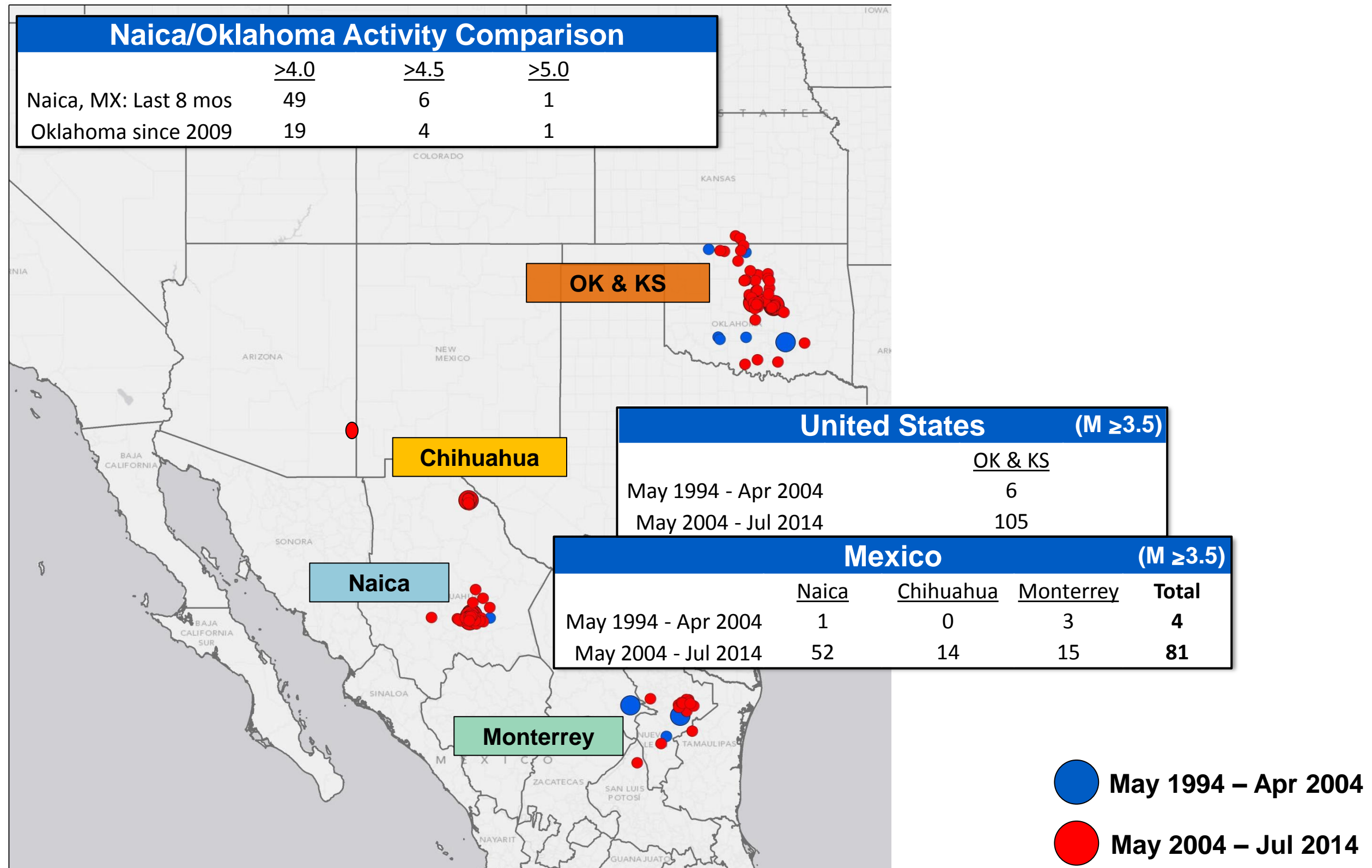
*Source: USGS, 2014

North America Key Earthquake Activity



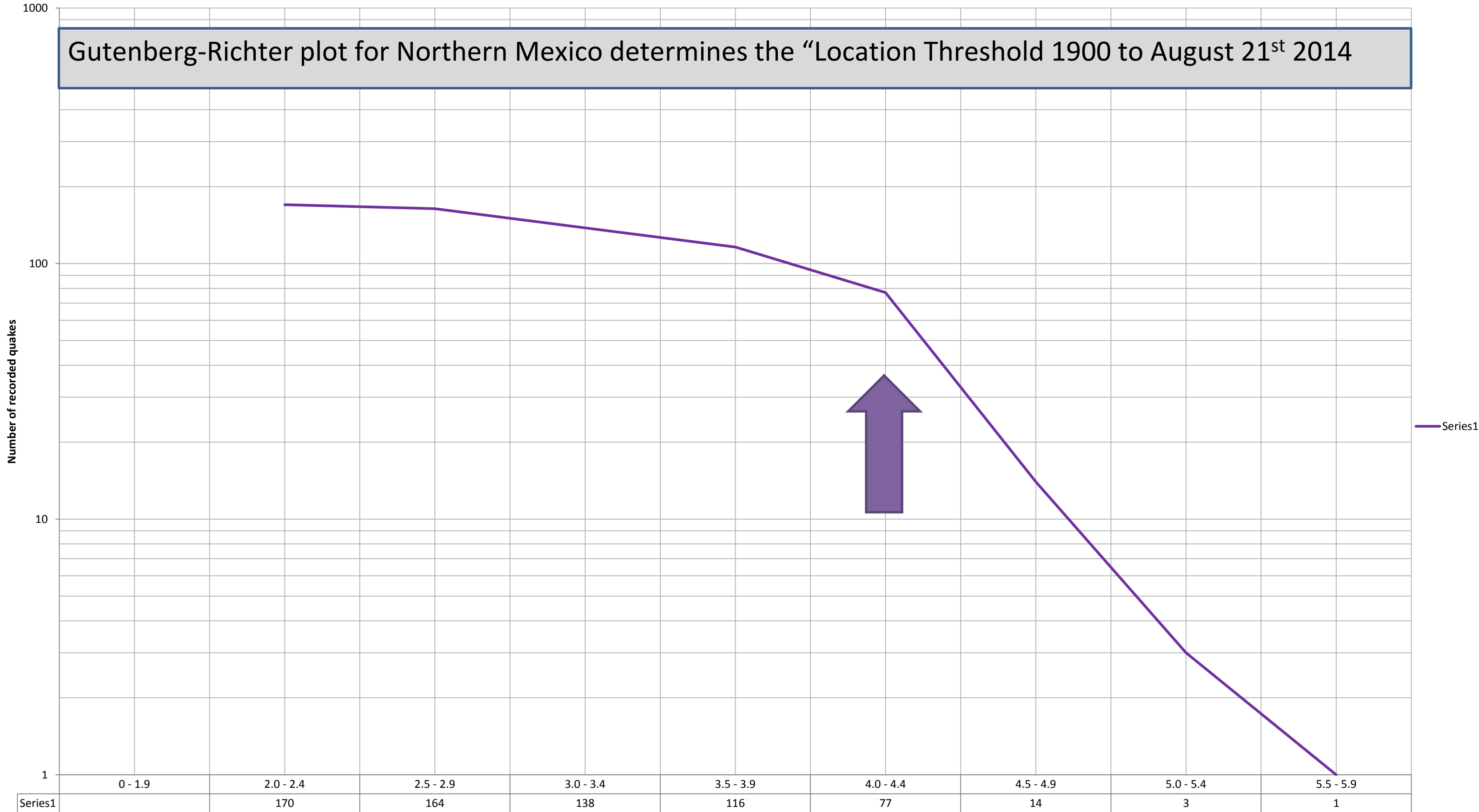
*Source: Geologic Data Systems, USGS July 2014

Intra-plate Earthquake Activity on the Rise



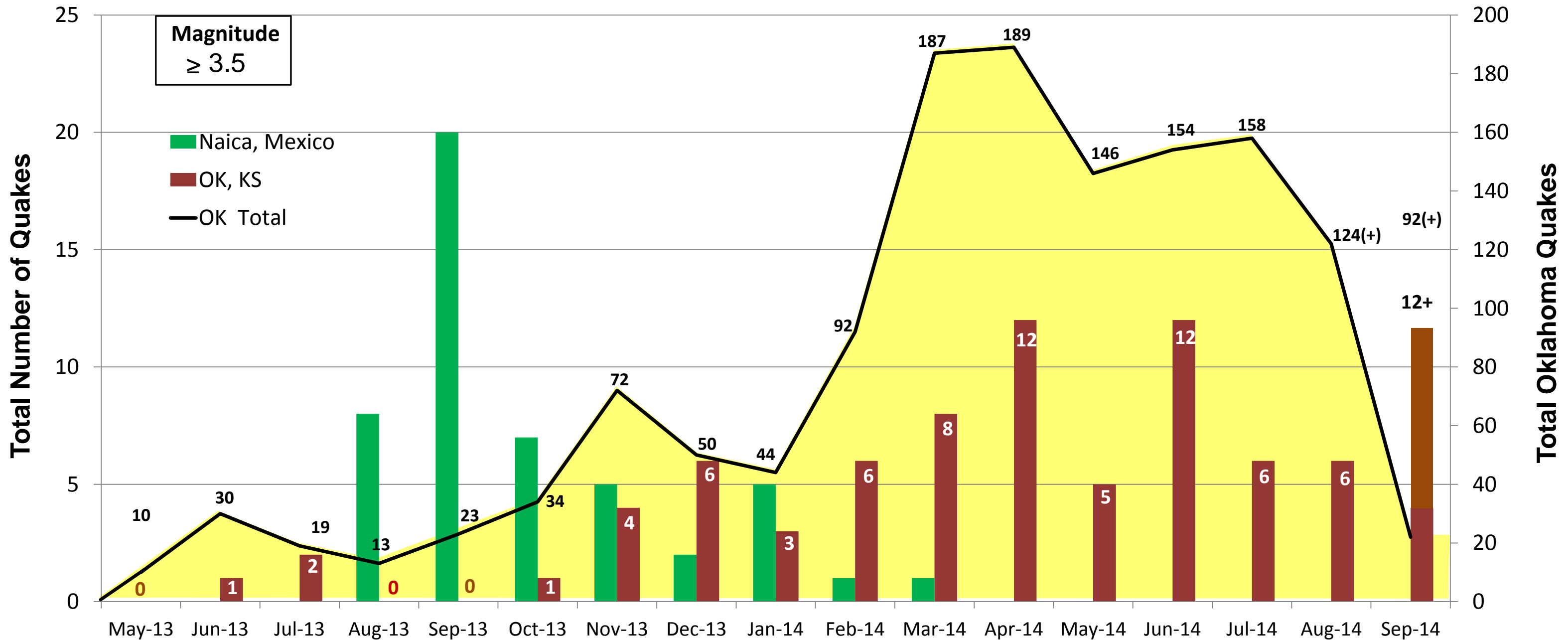
*Source: USGS, 2014

Gutenberg-Richter plot for Northern Mexico determines the "Location Threshold 1900 to August 21st 2014



Gutenberg-Richter plot for Northern Mexico slope -1.25 1900 to Aug 21,2014

Oklahoma vs Naica, Mexico Since May 2013

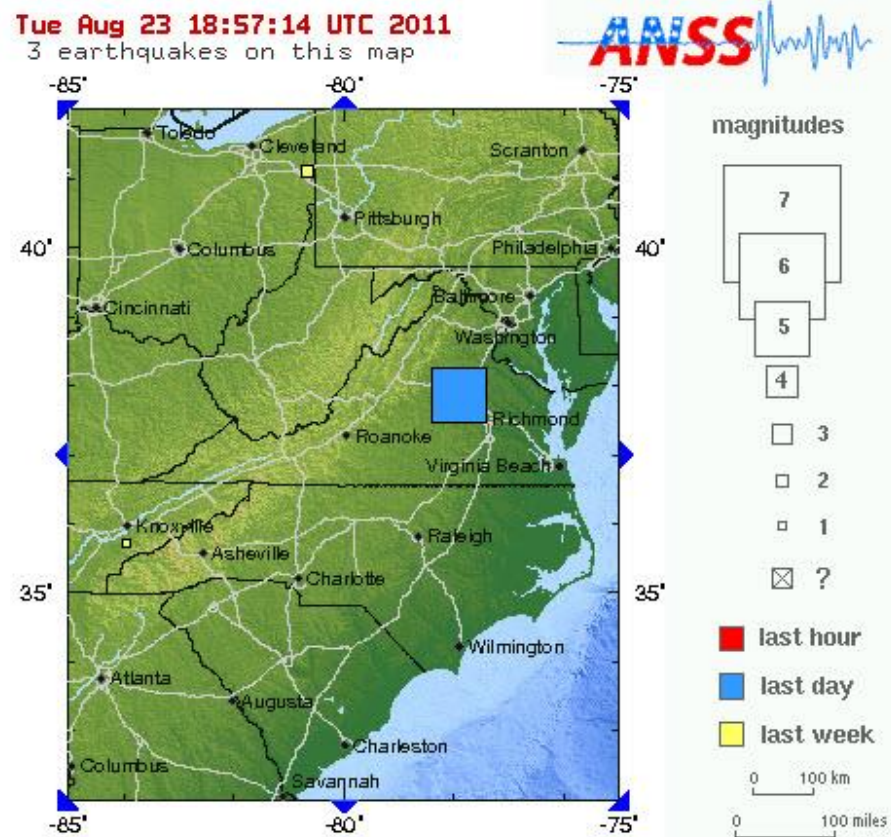


*Source: USGS updated
September 9th 2014

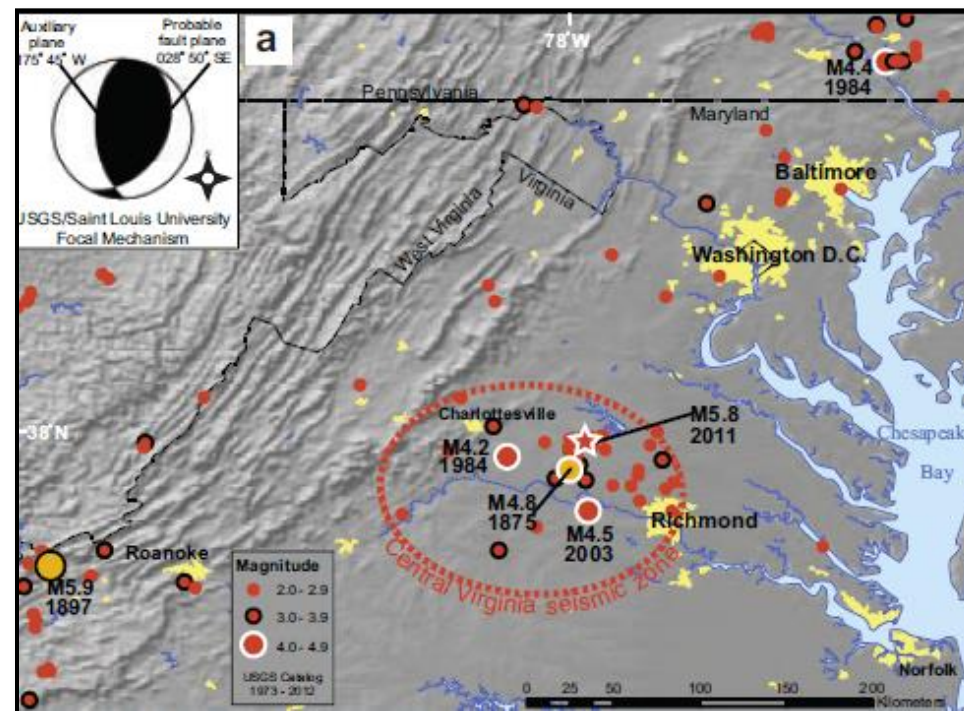
Virginia Quake August 23rd, 2011

5.8 Richter

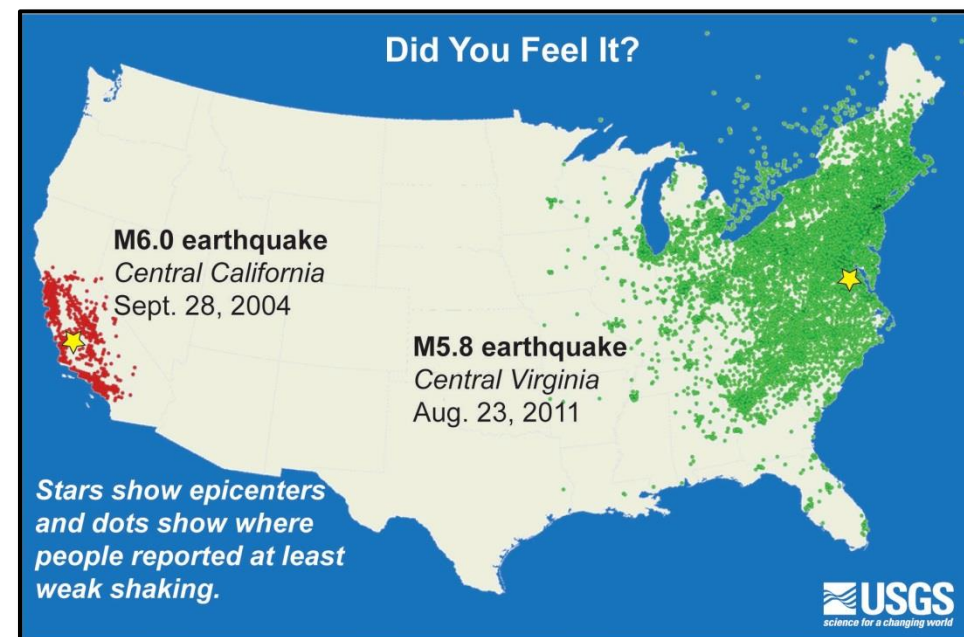
“This may be the largest earthquake to strike the central and eastern United States since the M=5.8 earthquake near Cornwall and Massena, N.Y., in 1944”



Source: VOLUME 93 NUMBER 33, 14 AUGUST 2012, PAGES 317–324, EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION



The M = 5.8 earthquake in Central Virginia seismic zone has a moment tensor solution <http://earthquake.usgs.gov> indicating reverse motion on an east-southeast-dipping plane consistent with aftershocks.

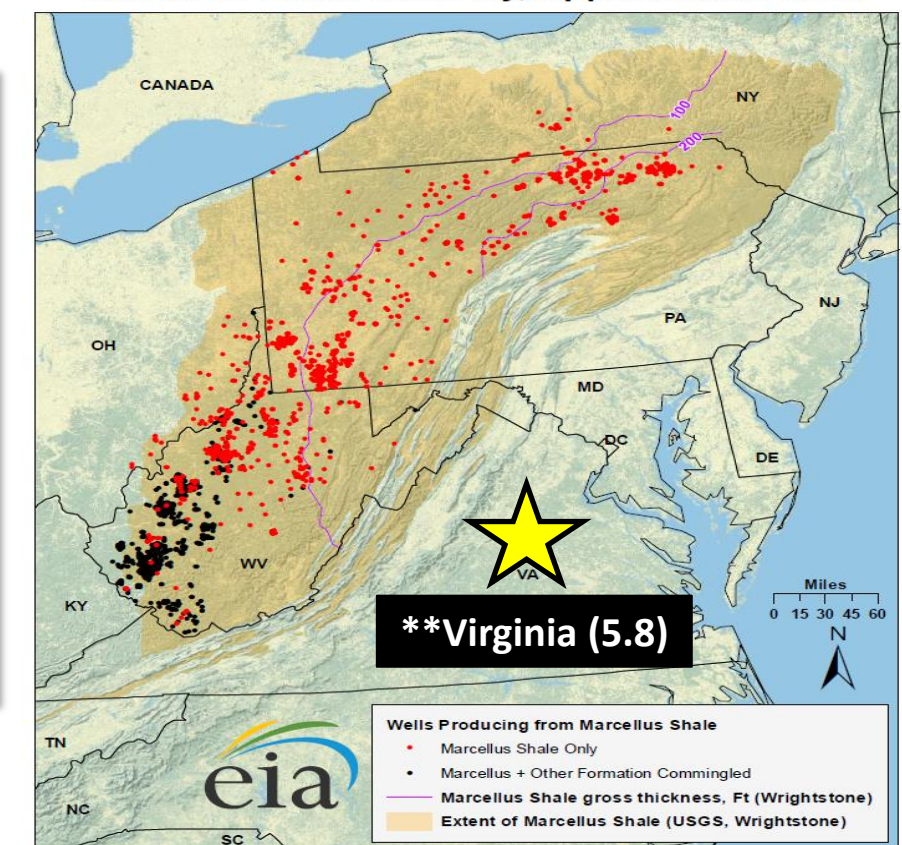


U.S. Geological Survey “Did You Feel It?” data from the M = 5.8 Virginia earthquake (green) and from one of similar magnitude and depth in California (red) illustrate how earthquakes are felt over much larger areas in the eastern United States than those west of the Rocky Mountains.



Photo by J. Scott Applewhite, Associated Press
Damage to buildings such as the Washington National Cathedral in Washington, D.C., 135 kilometers northeast of the central Virginia epicenter,

Marcellus Shale Gas Play, Appalachian Basin



Source: US Energy Information Administration based on data from WV GCS, PA DCMR, OH DGS, NY DEC, VA DMME, USGS, Wrightstone (2009). Only wells completed after 1-1-2003 are shown. Updated June 1, 2011

Be careful of false information on the Internet



Don't Get "Buffaloed!"*

**As per Urban dictionary definition*

The animals are supposedly evacuating themselves in anticipation of an eruption at the Yellowstone National Park, which sits on a huge volcanic system.

Curiosity was further fueled by the recent magnitude 4.8 earthquake last month, the largest at the park in 30 years.

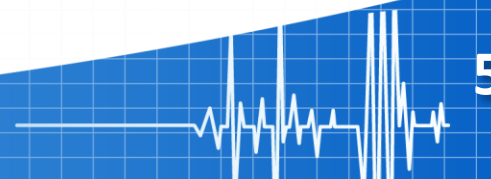
But the warning turned out to be a hoax!

Yellowstone released the explanation that it's not unusual for wildlife to leave the park during the winter to seek food.

The Bison featured in the video are actually running into the park—that is, "towards" the volcano.

Summary

- Oklahoma seismic activity uptick in last 5 years is not unprecedented, what is unprecedented is our ability to measure them
- During the 50's and early 60's a similar active earthquake period occurred in Oklahoma but "under-reported" as compared to today
- Both earthquake prone periods in Oklahoma history were each coincident with 50% of the largest Worldwide quakes over 8.8 Richter Scale during 1900-2014
- Oklahoma activity is likely related to these large quakes despite being away from actual plate boundaries (normally "protected areas")
- Earthquake locations in Oklahoma are inversely related (statistically) to horizontal drilling, fracking and/or salt water disposal
- Synchronous earthquake activity /swarms have occurred in Virginia, South Carolina, Arizona, NW Alaska and neighboring Mexico where no oil and gas activity is present





QUESTIONS
or
COMMENTS
(Misc Slides)

