# Earthquakes, structural damage, and safety


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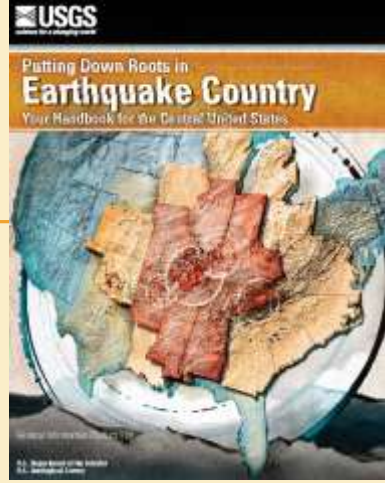
# Outline

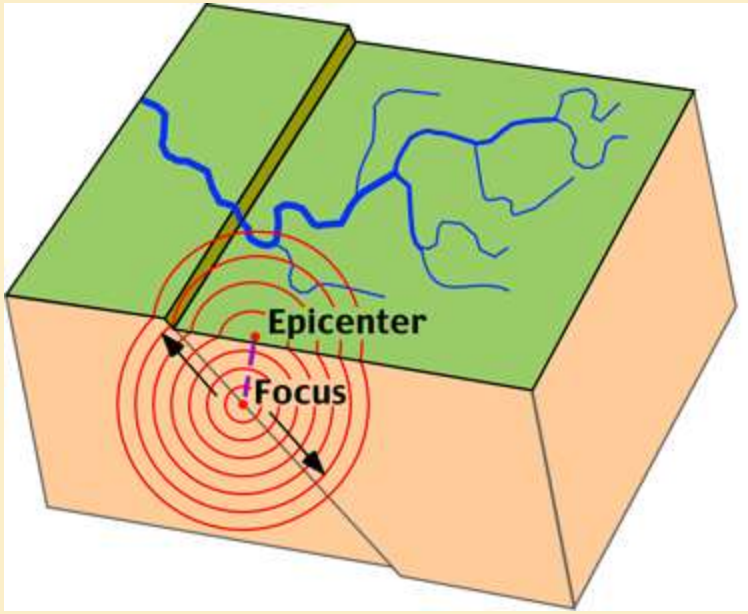



In this presentation, I will describe:

- Earthquake occurrence (seismic risk)
- How earthquakes damage buildings
- What types of buildings are most vulnerable to earthquake damage
- Case studies of earthquake damage to buildings
- How to be safe in an earthquake

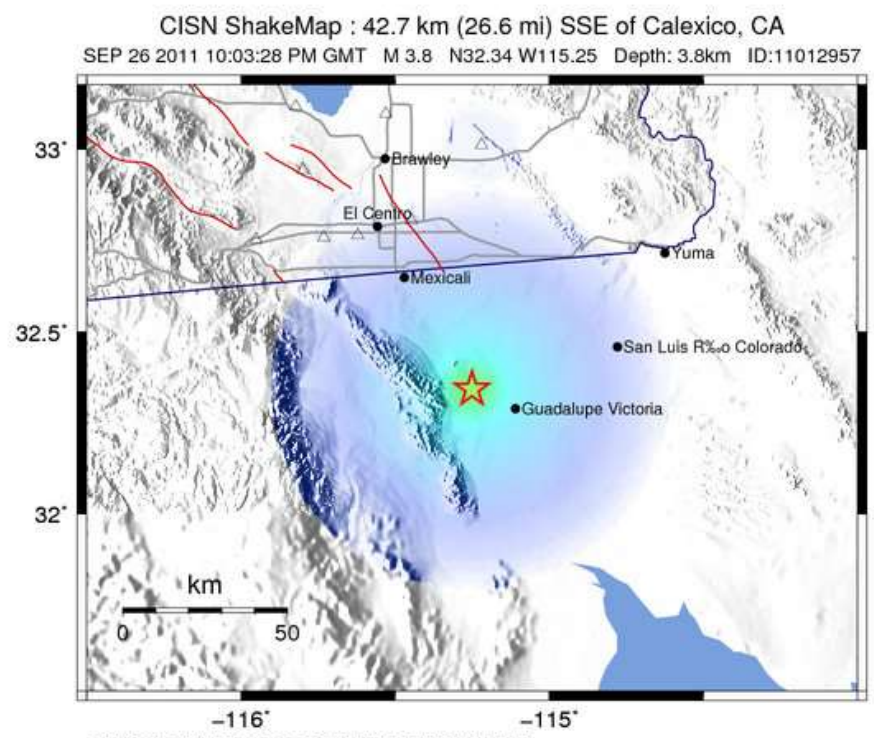
# Seismic risk

- Earthquakes occur when strain energy built up on fractures between rocks that move against each other is released.
- Earthquakes can happen nearly everywhere.
- Earthquake energy can be transmitted through the globe (M>8.0) or felt only on top of an epicenter (M~2).



# Siesmic risk

- Earthquake energy dissipates with distance from epicenters, but dissipation varies with geologic settings.
- Some areas have greater seismic risk than others.
- Most earthquakes release relatively little energy, causing little to no damage.

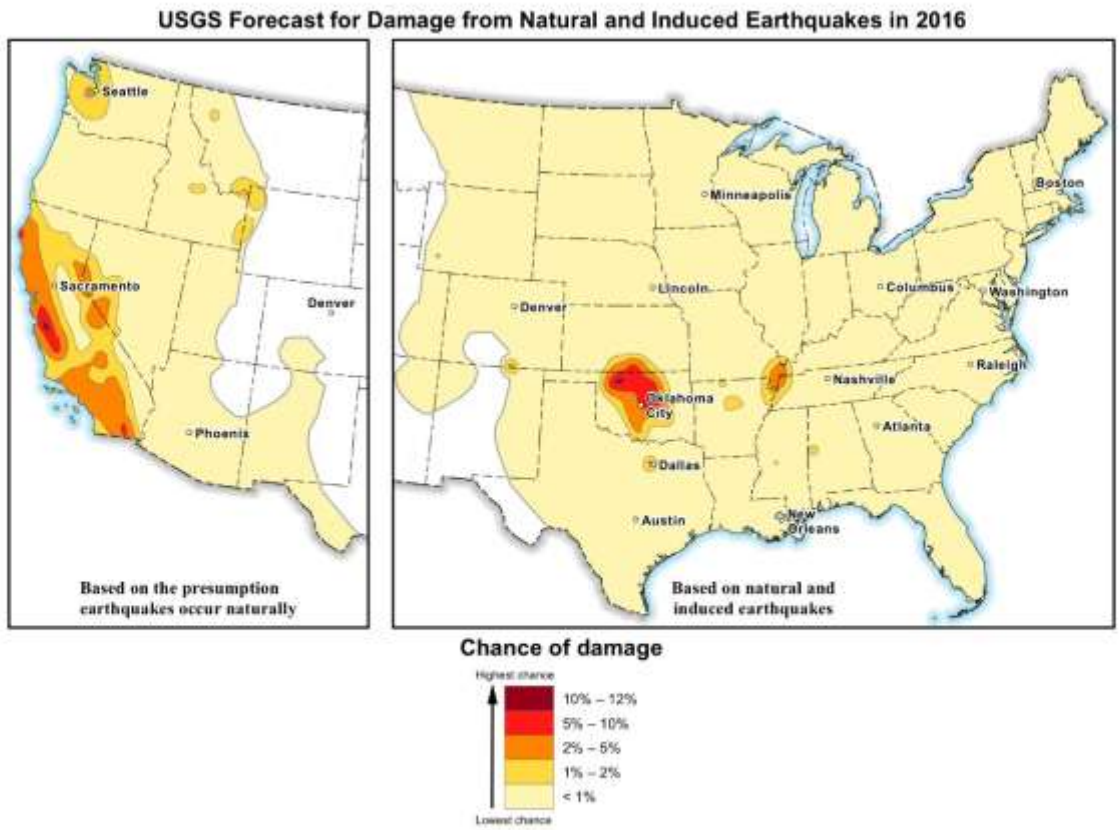



Map Version 2 Processed Mon Sep 26, 2011 11:22:18 PM GMT

| PERCEIVED SHAKING | Not felt | Weak | Light | Moderate | Strong | Very strong | Severe | Violent | Extreme |
|---|---|---|---|---|---|---|---|---|---|
| POTENTIAL DAMAGE | none | none | none | Very light | Light | Moderate | Moderate/Heavy | Heavy | Very Heavy |
| PEAK ACC.(%g) | <0.17 | 0.17–1.4 | 1.4–4.0 | 4.0–9 | 9–17 | 17–32 | 32–61 | 61–114 | >114 |
| PEAK VEL.(cm/s) | <0.12 | 0.12–1.1 | 1.1–3.4 | 3.4–8 | 8–16 | 16–31 | 31–59 | 59–115 | >115 |
| INSTRUMENTAL INTENSITY | I | II–III | IV | V | VI | VII | VIII | IX | X+ |

Scale based upon Wald, et al.; 1999

# Current Earthquake Risk

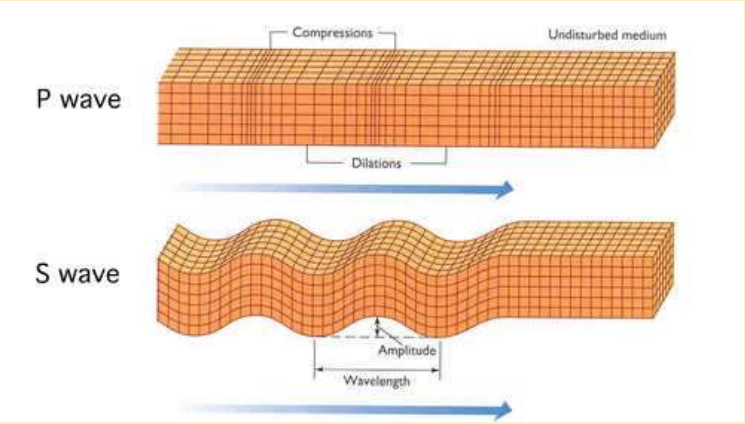


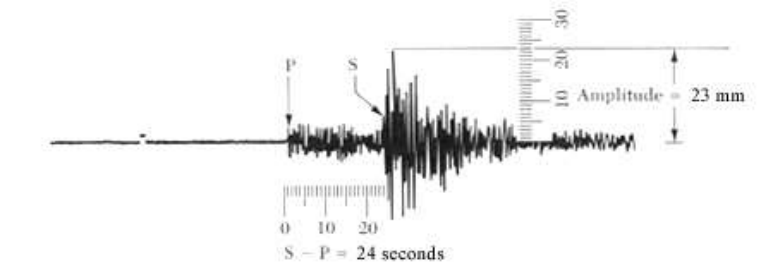

USGS map displaying potential to experience damage from natural or human-induced earthquakes in 2016. Chances range from less than 1 percent to 12 percent.

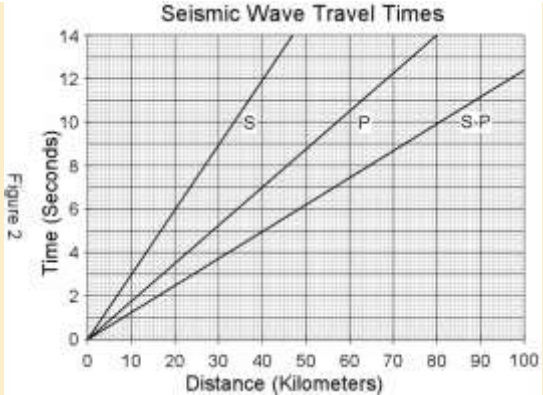
- Based on 2015 earthquakes, the USGS has estimated that there is similar risk of damage from earthquakes in some parts of Oklahoma as there is in better-known earthquake-risk areas of California.
- These risk estimates will be updated annually and hopefully will decline with recent decreases in earthquakes.
- However, the number of 4.0 M or greater earthquakes in 2016 has been on par with 2015.

# Measuring earthquakes

- Earthquake locations and strengths are measured with seismographs.
- Compressional waves (P-waves) and shear waves (S-waves) travel at different speeds.
- The time between the arrival of P-waves and S-waves at a seismograph enables calculation of distance from the epicenter to the seismograph.
- Greater amplitudes on seismographs are proportional to greater shaking (note greater amplitudes of S-waves) .



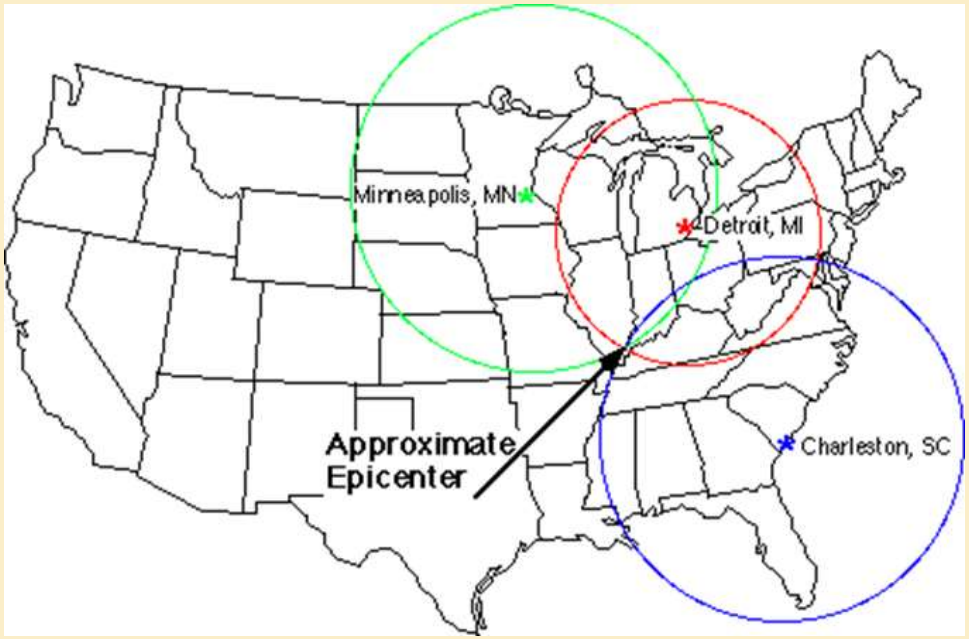




Images from Northwestern University, Tulane University, and Michigan Tech

# Determining epicenters

- P-wave versus S-wave arrival times at a seismograph only provide an estimate of earthquake location at a fixed distance surrounding the seismograph.
- With two seismographs, there are two intersections of those distance circles or two possible epicenter locations.
- With three seismographs, the intersection of the three distance circles coincide at one point, the epicenter of the earthquake.




Michigan Tech image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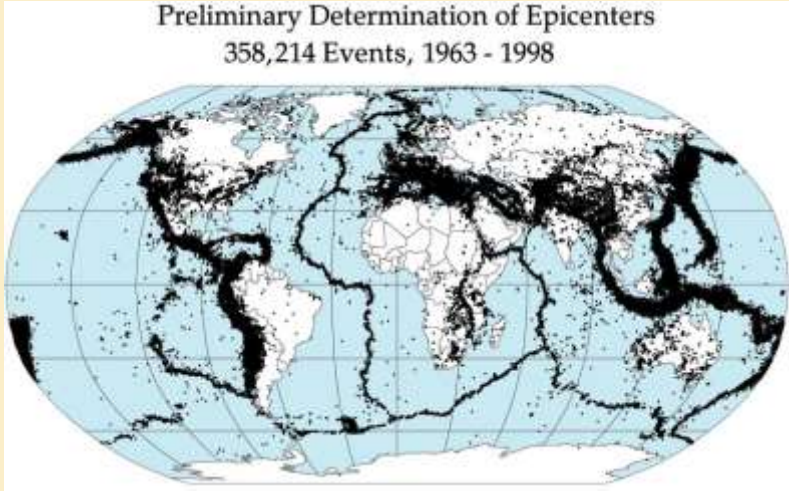
# Earthquake depths and locations

- Earthquakes can occur near the Earth's surface or at depths up to 300 miles.
- Patterns of compressive p-waves and shearing s-waves are used to determine depths of earthquake foci below the land surface.
- For about the past 100 years, earthquake epicenter locations have been recorded by networks of seismographs.
- Older earthquakes can be determined by age dating of chemical isotopes in sediments moved during earthquakes.

# Where earthquakes occur

- Rocky plates of the lithosphere comprise the surface of the earth slide over molten rocks of the asthenosphere, which lie about 120 miles below the earth's surface.
- Where lithosphere plates separate or collide, earthquakes occur frequently.
- Less frequently, earthquakes occur because of movement along boundaries of smaller rock units in the middle of the plates, such as those that occur in the central or eastern U.S.
- Epicenter locations and strengths of historical earthquakes have been mapped around the world, enabling development of maps of relative seismic risk.

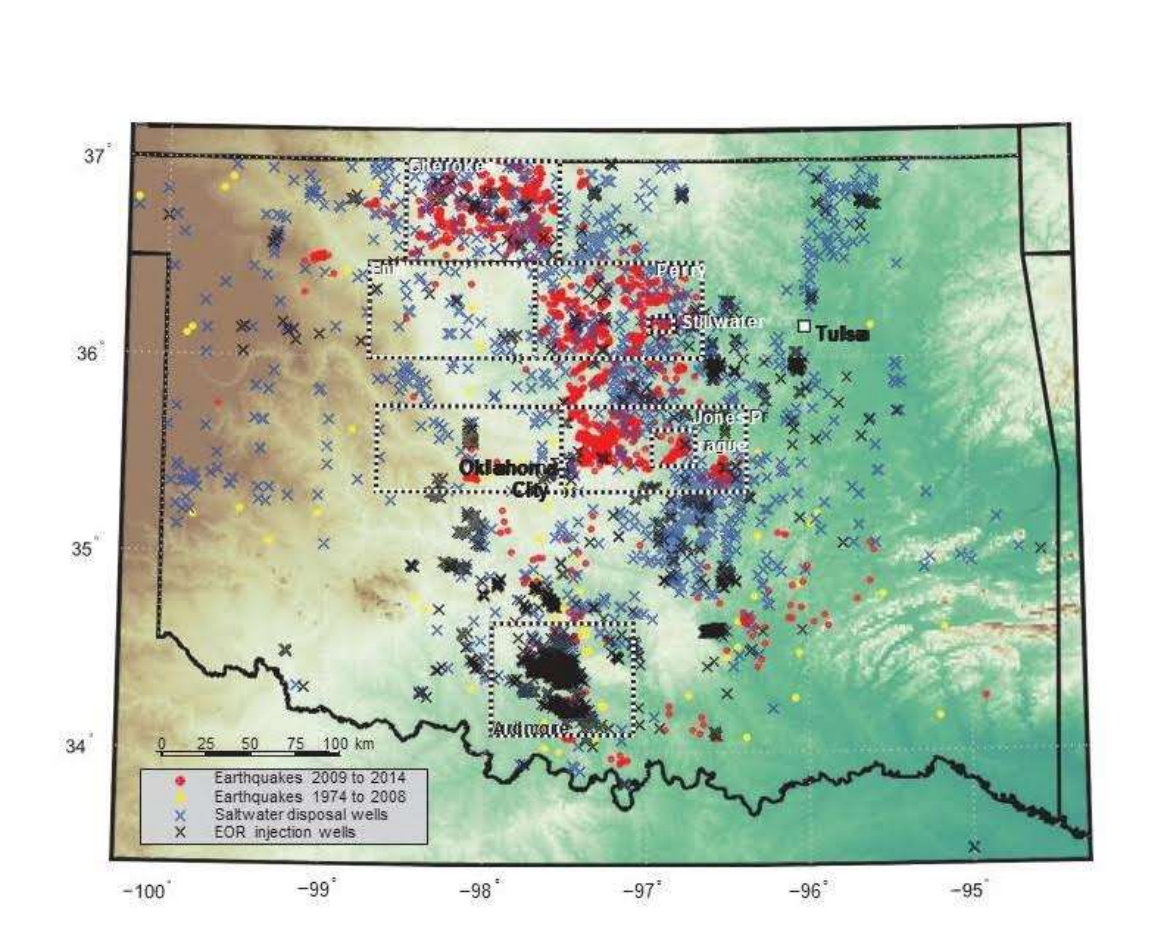



NASA image

# Oklahoma earthquakes

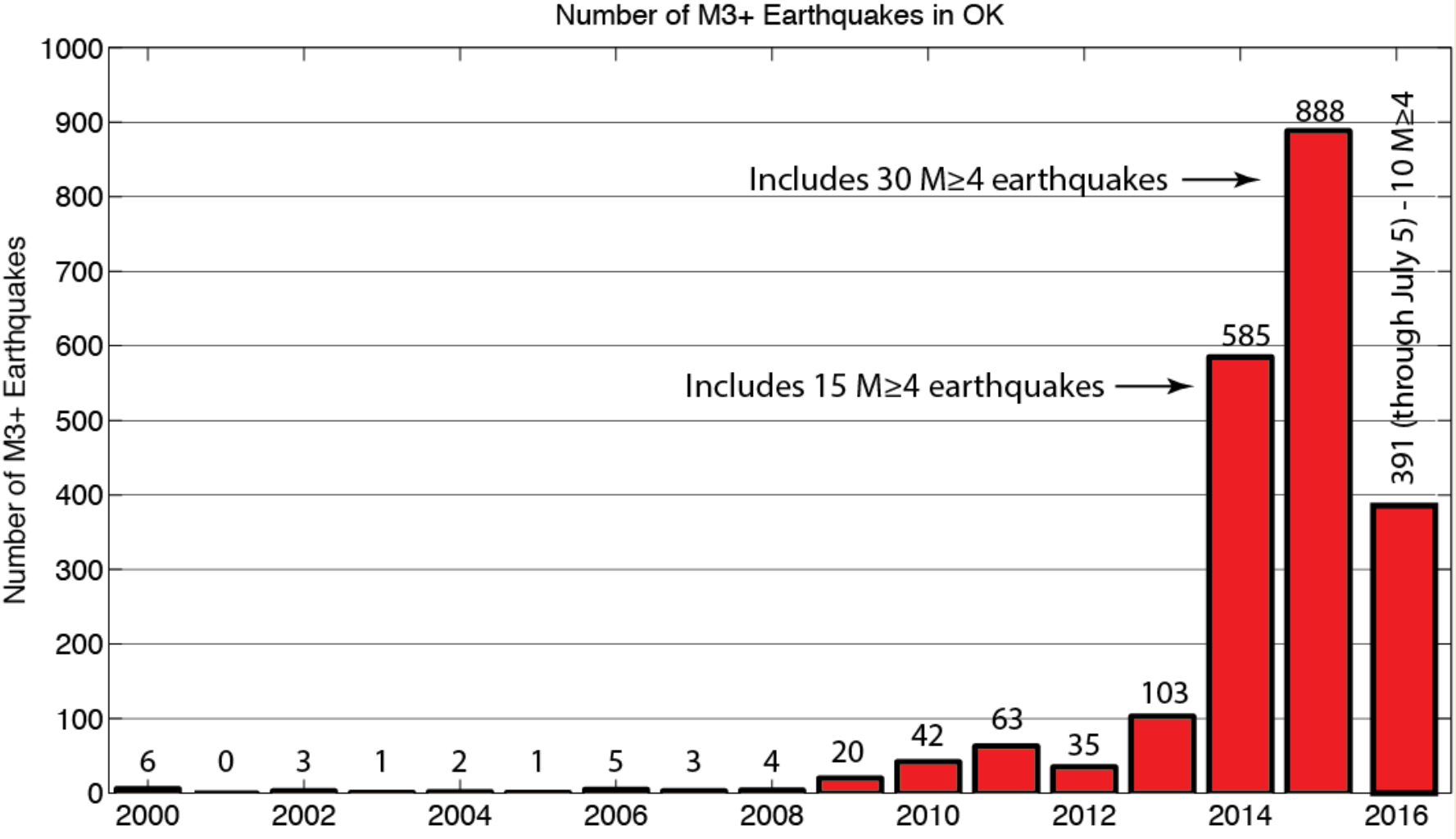
The number of earthquakes in Oklahoma with magnitude greater than 3 increased from about 2 per year prior to 2010 to more than 500 in the past couple of years.

Several studies have indicated likely connections between volumes of injected wastewater with earthquake stimulation.




(Walsh and Zoback, 2015)

# Oklahoma earthquake numbers

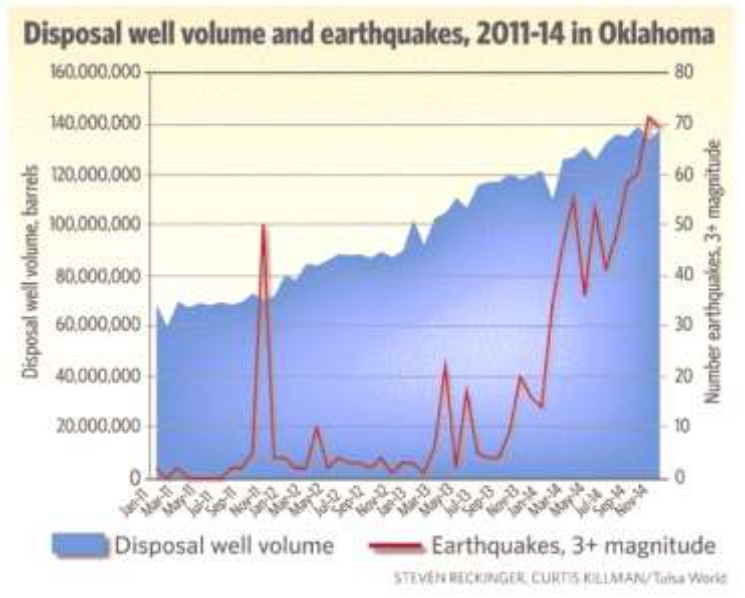



The number of >3 M quakes is about 19% less than last year, the number of >4 M quakes is about the same.

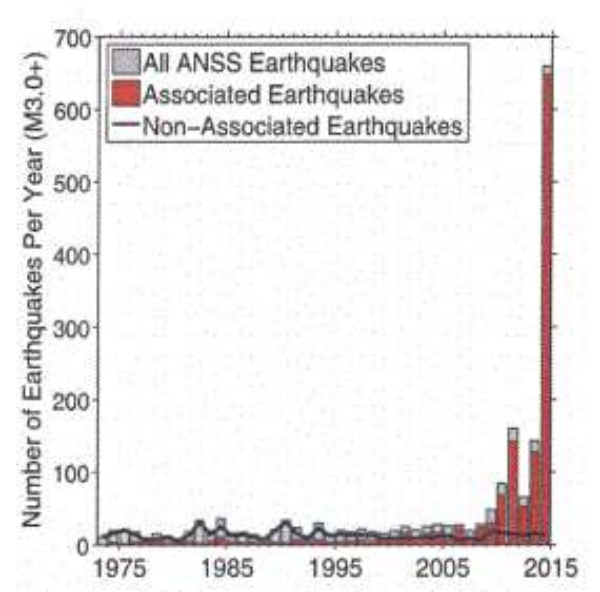
(Justin Rubinstein, 2016)

# Wastewater injection

- Injected wastewater volumes have had greater association with earthquake incidence rather than injection pressures.
- The largest recent Oklahoma earthquakes, in 2011 and 2016 occurred along or near to the Wilzetta Fault.



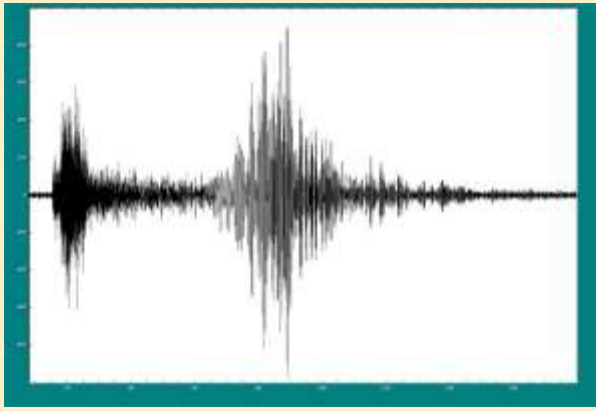

Tulsa World, 2016)




Weingarten and others, 2015

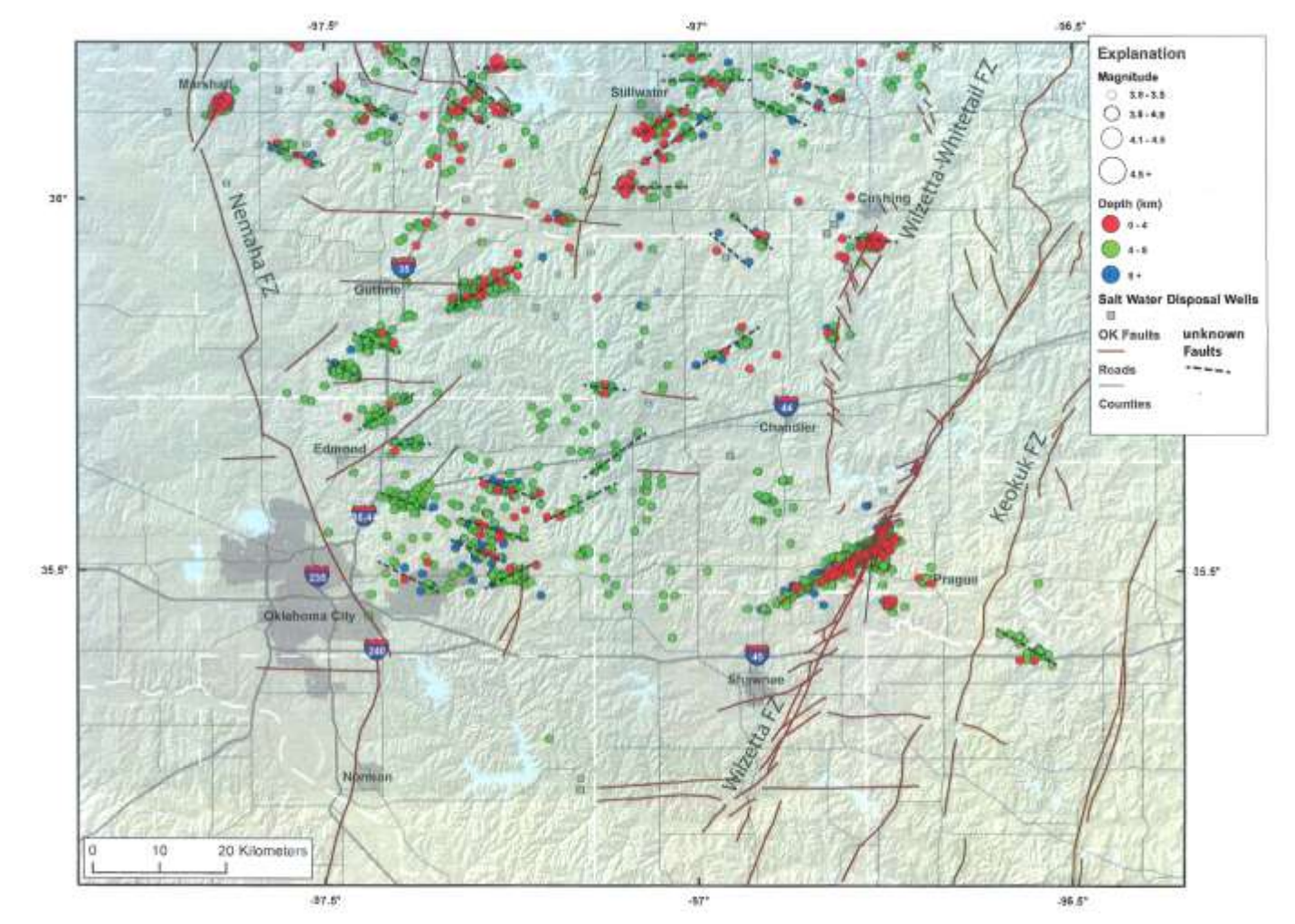
# Earthquake strengths

- Earthquake strengths are measured on a number of scales that are related to the amount of energy released by an earthquake at an epicenter.
- Earthquake magnitude (measured by the moment magnitude scale) is calculated from the amplitude (vertical motion) of the largest/strongest seismic wave recorded for an earthquake.
- The moment magnitude scale is logarithmic, meaning that an earthquake of magnitude 2 on the scale has 10 times the amplitude and 32 times the energy of an earthquake of magnitude 1.



Seismograph from 9.0 scale Sumatra earthquake of 12/26/2004 (PA Geological Survey image)

# “New” Faults in Oklahoma




- Earthquakes have enabled us to detect the locations of previously unknown faults in granitic Precambrian-age basement rocks.
- Larger earthquakes are more likely to occur along longer faults.

# Earthquake magnitude versus damage

| Moment Magnitude | Earthquake effects | Estimated annual number |
|---|---|---|
| 2.0 to 2.9 | Usually not felt | 1,300,000 |
| 3.0 to 3.9 | Often felt | 130,000 |
| 4.0 to 4.9 | Cause minor damage | 13,000 |
| 5.0 to 5.9 | Cause moderate damage | 1,319 |
| 6.0 to 6.9 | Cause substantial damage | 134 |
| 7.0 to 7.9 | Cause substantial widespread damage | 15 |
| 8 and higher | Can cause total destruction near epicenter | 1 |

USGS data

# Earthquake damage

- In addition to earthquake magnitude, a number of other factors affect damages caused by an earthquake.
- The energy released in earthquakes decreases with distance from an epicenter, so areas further from epicenters have less damage.
- Unconsolidated soils and geological units tend to amplify ground motions by 2-6 times compared to bedrock, causing greater damage (common in California). Unconsolidated soils also can slump/fail.
- Hard consolidated rocks typical of the eastern U.S. are better able to transmit earthquake energy over longer distances, but usually with less damage. (Think of the force transmitted by hitting a block of stone compared to hitting a block of jello and imagine the greater shaking of the bowl of jello).

DIY network and Jell-o images

# Structural damage from earthquakes

- Damage to buildings and other man-made structures is caused by ground shaking.
- The (1) magnitude of an earthquake, (2) distance from an epicenter, (3) depth of a focus (shallow is worse), (4) type of material underlying a building, and (5) the type of construction and materials in a building control the amount of damage caused by an earthquake.
- The horizontal shaking that we feel is caused by shear or S-waves.
- Side-to-side motions cause the shaking that tends to shear and fracture masonry walls and building support beams.

Damage from 5.8 magnitude earthquake in Pawnee, OK, Sept 3, 2016 (UPI image).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# Central Italy Earthquakes, 8/24/16

- At 3:30 in the morning on Aug. 24, a 6.2 M earthquake with a focus <u>10 km deep</u> destroyed substantial parts of the villages of Amatrice, Pescara del Tronto, Arquata del Tronto, and Accumoli, Italy. Hundreds of aftershocks followed.
- Most people were sleeping. During summer, the population in this area increases 10-fold from vacationers.
- At least 267 people were killed and many more were injured as dozens of ancient masonry homes collapsed.
- The focus was shallower than most quakes in Oklahoma and the buildings were more susceptible to damage than most buildings in Oklahoma.
- This type of event is what causes seismologists, geologists, and emergency responders to worry.

# Reducing damage to buildings

- Buildings are damaged by the force, frequency, direction, and duration of ground shaking.
- Buildings can better withstand vertical motions of earthquakes if they are designed to support large dynamic loads generated by vertical shaking.
- Resistance to horizontal motions can be improved by lateral bracing to hold structural elements together.
- Continuous structural paths from the roof to foundation are more resistant to shaking than discontinuous structures.
- Masonry buildings are far less flexible than buildings with wood or steel frames.

Concentric braced steel frame designed to transfer lateral loads from floors and roofs to foundation (Gabor and Lorant Architects, Inc. image)

# Reducing damage to buildings

- Construction materials of lighter mass have less inertia and are better able to sway.
- Non-structural elements such as chimneys, parapets, ceiling tiles, and building contents that are poorly attached to a building are more likely to be dislodged than the body of a building.
- Taller buildings are subject to greater shear or swinging motions from ground movement and wind than shorter buildings (see Euler-Bernoulli bending theory for more information).
- Base-isolation bearings can absorb forces transmitted from the ground to a building.

Base-isolation bearing (Gabor Lorant Architects, Inc. image)

# Reducing damage to belongings

- Fasten fragile objects to walls or fixed furnishings.
- Anchor heavy and tall furniture to walls or floors.
- Put latches on cabinet doors.
- Secure water heater to wall studs and other major appliances to a wall or floor.
- Have pliable gas-line tubing.
- Store hazardous chemicals in a sturdy cabinet.
- Maintain fire extinguishers.

Earthquake Country Alliance Image

# Case studies

- The 5.8-magnitude earthquake in Virginia on August 23, 2011 is a useful example of the vulnerabilities of some types of buildings to earthquake damage.
- Let's look at a couple of damaged buildings:

  A) The Washington Monument

  B) The National Cathedral

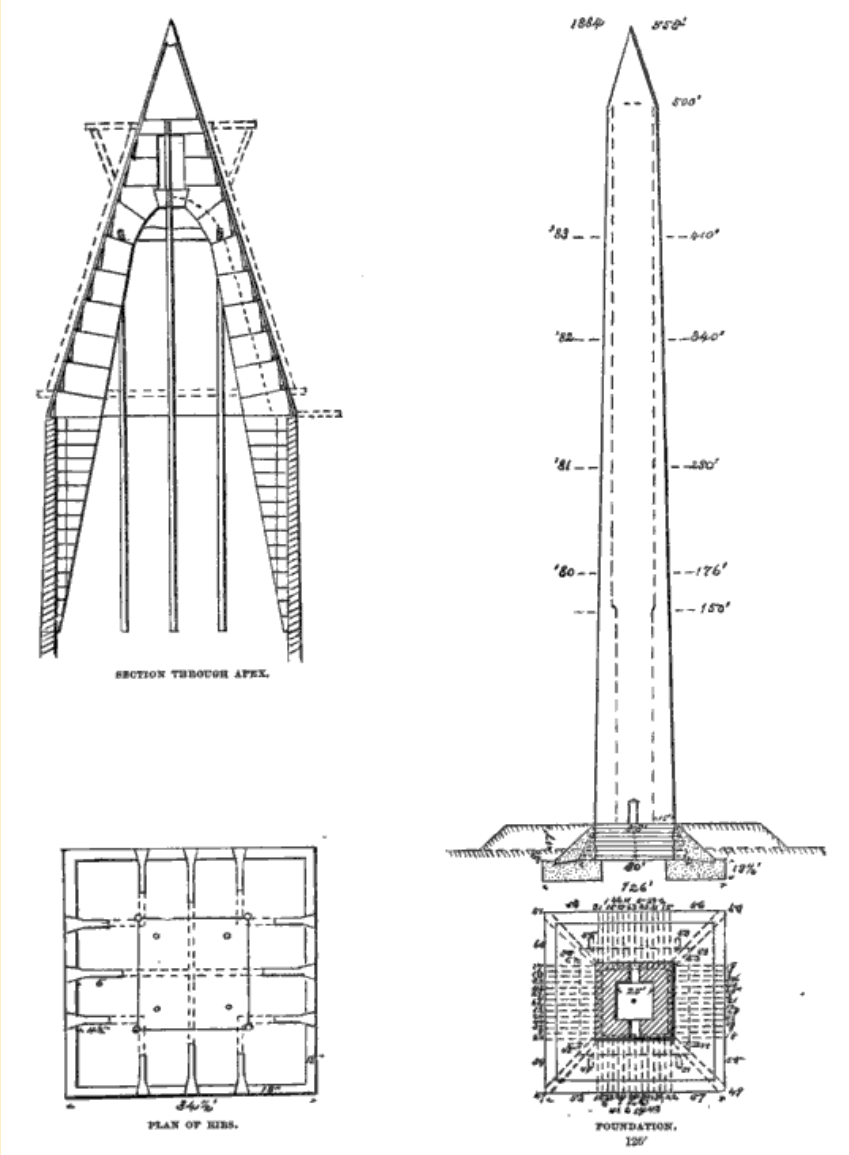
# The Washington Monument

- The Washington Monument is an all-masonry shell obelisk standing 555 ft 5 1/8 inches tall in Washington--the world's tallest masonry structure.
- The Monument, constructed between 1848 and 1884, rests on piers set through unconsolidated fill to local bedrock.
- The monument weighs more than 40,000 tons.
- There is an internal steel structure of a stairway and an elevator shaft.

National Park Service image

# The Washington Monument

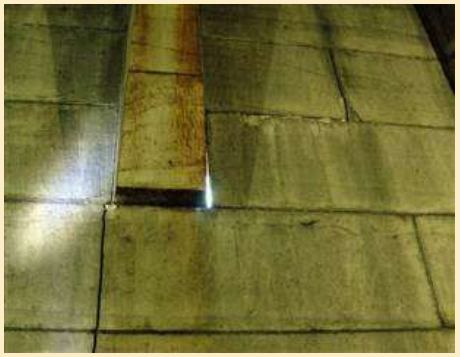
- The bottom part of the structure consists of mortared blocks of bluestone (meta basalt) about 15 feet thick near the base, tapering down to 18 inches thick below the top observation deck.
- The upper pyrimidion consists of mortared white marble blocks ranging from 18-12 inches thick.
- **Q:** Is this type of structure likely to be damaged in an earthquake. If so, why?



# Video from top of the Washington Monument

# The Washington Monument

- Repairs to the monument took almost 3 years, with tours being allowed starting on May 12, 2014.
- Multiple cracks were found in the blocks and supporting marble joists near the top.
- A large amount of water leaked into the structure during Hurricane Irene, which passed through several days after the earthquake.
- Earthquakes are unexpected in the Washington D.C. Area. Methods to minimize earthquake damage to buildings were unknown in the 1800s. The rigid, tall, unreinforced, all-masonry structure of this building makes it likely to sustain damage from relatively small earthquakes.



Cracks in marble blocks on the upper outside, inside next to a marble-block joist, and further down the shaft (U.S. National Park Service images)

# The National Cathedral

- The National Cathedral is the 6th largest cathedral in the world.
- The cathedral is built with blocks of Indiana limestone and mortar over a masonry core with load-bearing steel trusses in the roof.
- Lateral supports of the building consist of stone flying buttresses, with much of the surface area of the sidewalls consisting of stained-glass windows.
- There is substantial ornamentation on the interior and exterior, consisting of carved decorations, gargoyles, and numerous pinnacles.
- **Q:** What construction details are similar between the National Cathedral and the Washington Monument?

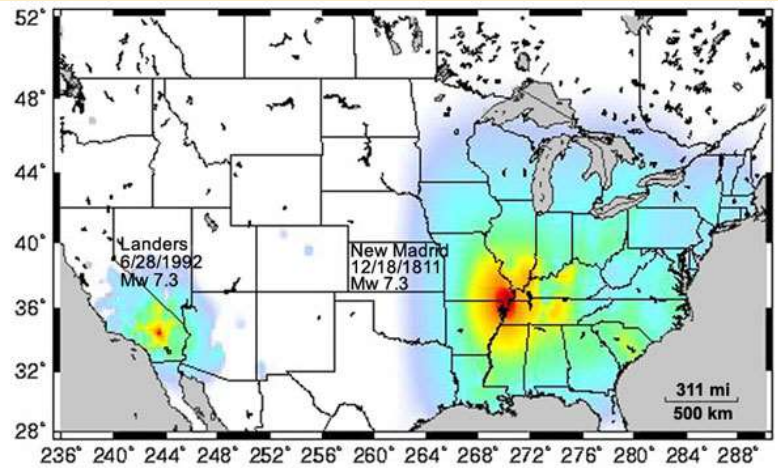
# The National Cathedral

- **A:** Similar to the Washington Monument, the National Cathedral is a tall, solid masonry structure with little flexibility or steel reinforcement.
- Similar to the Washington Monument, damage occurred at the highest part of the cathedral, where 4 major pinnacles tilted or fell.
- Those and other structural damages will require more than $25 million to repair, with the cathedral being closed until Nov. 2011. Repairs were ongoing through 2015.
- Due in part to wet ground from Hurricane Irene, a crane used to repair the tower collapsed, causing additional damage.

National Cathedral images

# Central U.S.–the New Madrid earthquake

- The largest known earthquake to affect the central U.S. was of 7.7 magnitude near New Madrid, Missouri in 1811.
- Although settlement was sparse, substantial damage occurred for several hundred miles around the epicenter, with a shift occurring in the course of the Mississippi River.
- A similar earthquake would cause substantial damage in an area now populated by 44 million people and might cause light damage into eastern Oklahoma.
- There are differing opinions about whether this seismic activity occurs at any given time frequency.




| PERCEIVED SHAKING | Not felt | Weak | Light | Moderate | Strong | Very strong | Severe | Violent | Extreme |
|---|---|---|---|---|---|---|---|---|---|
| POTENTIAL DAMAGE | None | None | None | Very light | Light | Moderate | Mod./Heavy | Heavy | Very Heavy |
| PEAK ACC. | <.17 | .17-1.4 | 1.4-3.9 | 3.9-9.2 | 9.2-18 | 18-34 | 34-65 | 65-124 | >124 |
| PEAK VELOCITY | <0.1 | 0.1-1.1 | 1.1-3.4 | 3.4-8.1 | 8.1-16 | 16-31 | 31-60 | 60-116 | >116 |
| INSTRUMENTAL INTENSITY | I | II-III | IV | V | VI | VII | VIII | IX | X+ |

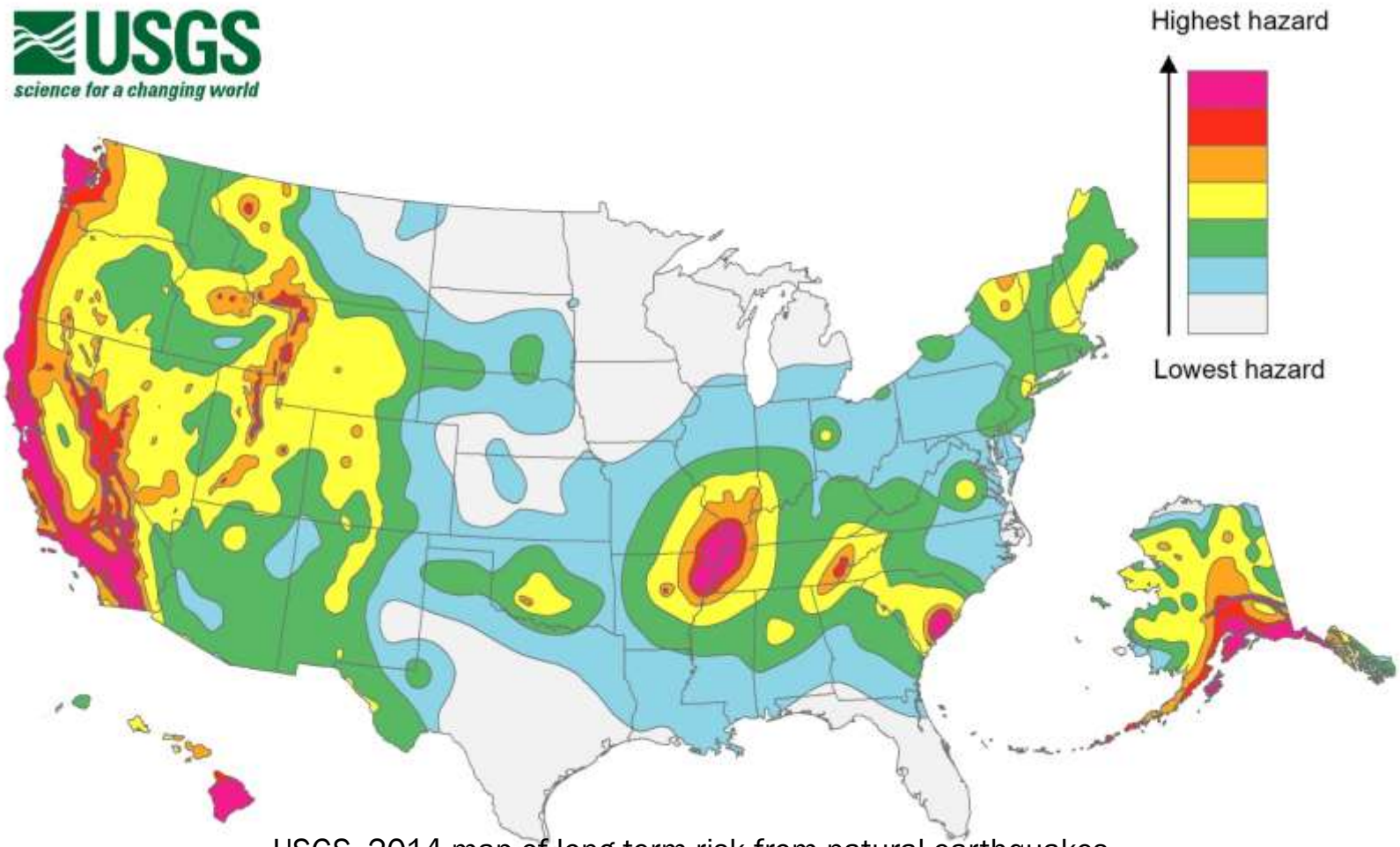
# How to be safe in an earthquake

- From the New Madrid earthquake of 1811 through 2003, about 4,000 Americans had been killed in earthquakes, with many thousands more injured and displaced from their homes.
- Since 1990, about 1 million people have lost their lives around the world from direct effects of earthquakes, many from collapse of poorly-constructed buildings, landslides, and tsunamis.
- During an earthquake, if indoors, take cover under a table away from windows until the shaking stops. If outdoors, stay outdoors away from buildings and utilities.
- Do not try to leave a building during an earthquake, as falling glass and masonry can be dangerous near the outside of buildings.

# Closing thoughts

- Although relatively frequent, earthquakes with epicenters in Oklahoma typically are of such small magnitudes that they rarely cause substantial structural damage.
- Substantial structural damage might occur from a large earthquake (magnitude 6 or greater) happening locally or a very large earthquake with an epicenter several hundred miles away in the New Madrid fault zone near Memphis, which is estimated to have a 7-10% chance of occurring in the next 50 years.
- Simple design strategies, common to many modern buildings, can be used to minimize earthquake damage and resultant injuries.

# Questions?




USGS, 2014 map of long-term risk from natural earthquakes