Earthquakes – Natural and Induced

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with thanks to Randi Jean Walters (Stanford) and Bob Kohler (Colorado Oil and Gas Conservation Commission

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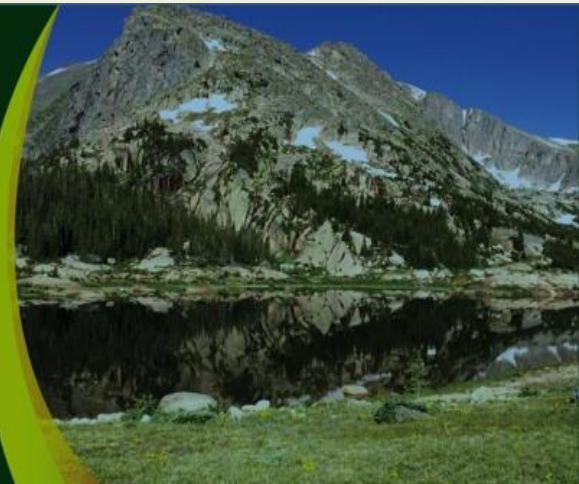


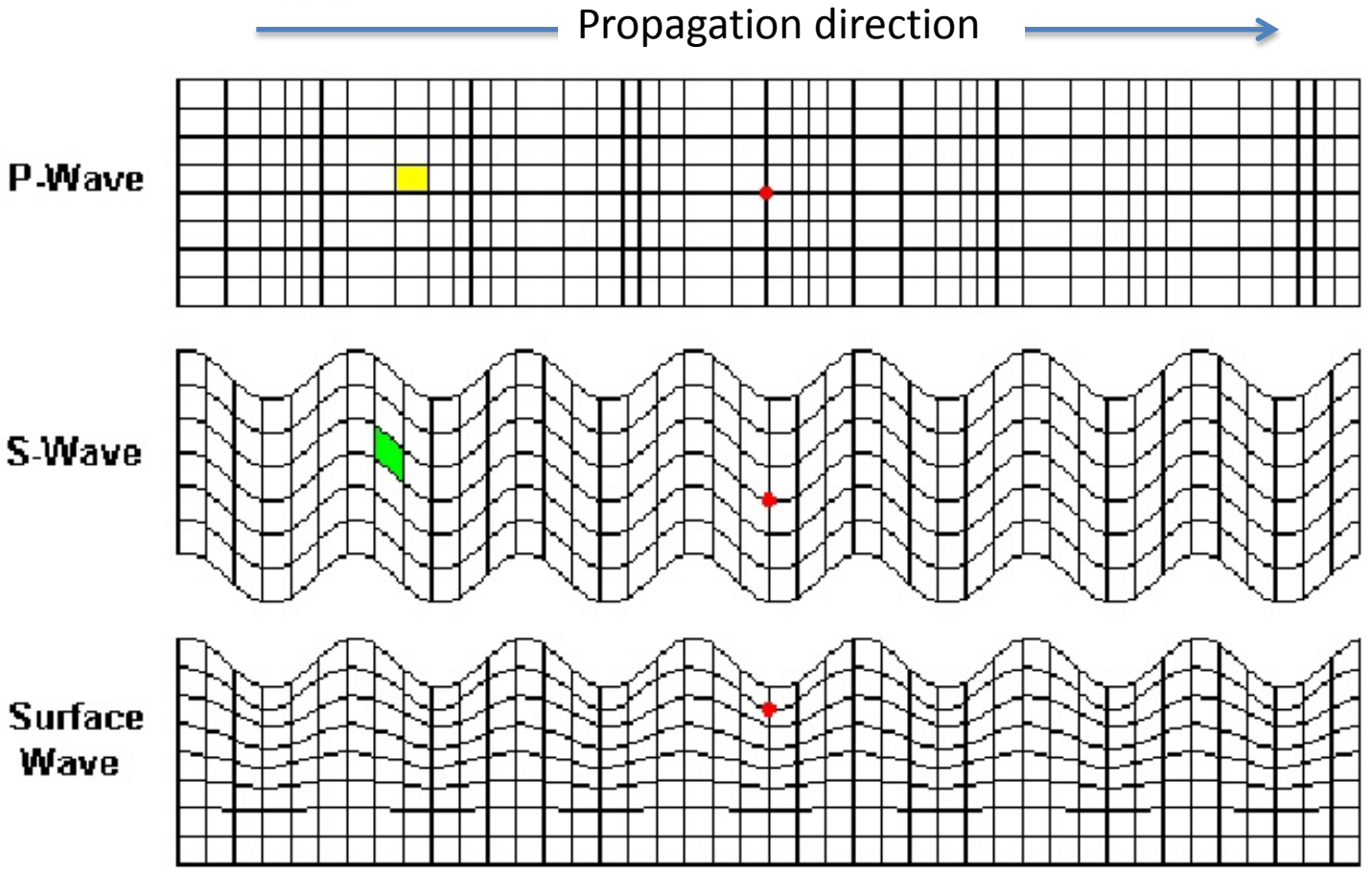
Overview

- What causes earthquakes?
- How do we detect, locate, and measure earthquakes?
- What is an *induced* earthquake?
- Where do earthquakes (historically and recently) occur in the U.S.?
- What have we learned about induced earthquakes in recent years?
- Is this a manageable problem (yes); how is it being managed in Colorado?

What Causes Earthquake?

- Earthquakes are sources of ***seismic*** *(elastic) waves* that propagate within the Earth.
- Most earthquakes arise from sudden slips on pre-existing (weak) faults within the Earth. Faulting can occur at depths that range from the surface to hundreds of miles deep.
- Seismic motion at the Earth's surface arises from seismic waves that radiate away from the ***earthquake hypocenter*** and that travel at typical speeds of several km/s.
- A ***felt earthquake*** occurs when ground motion becomes perceptible to human beings, which typically occurs when seismic accelerations become greater than a percent or so of the acceleration of gravity at the Earth's surface (9.8 m/s/s).

3 types of seismic waves



Surface and S waves from earthquakes usually have the largest amplitudes and cause the greatest damage. Shallower earthquakes generate a greater proportion of surface waves.

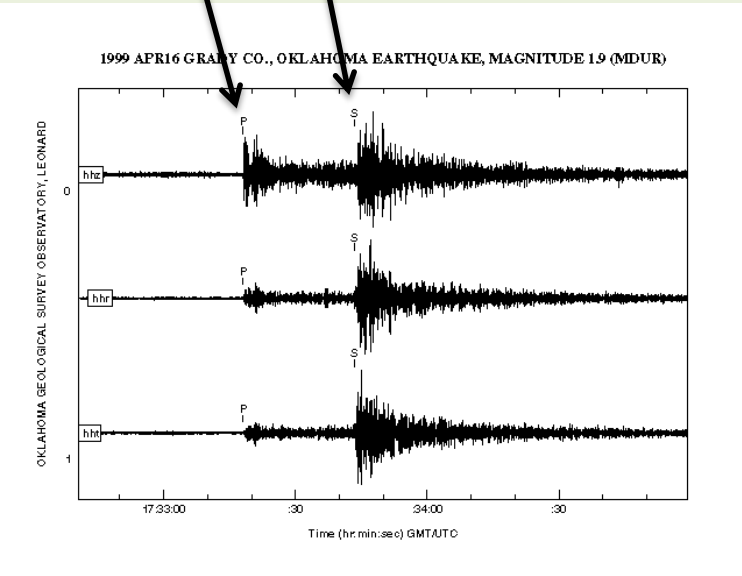
Seismic Waves Travel Efficiently Through the Earth

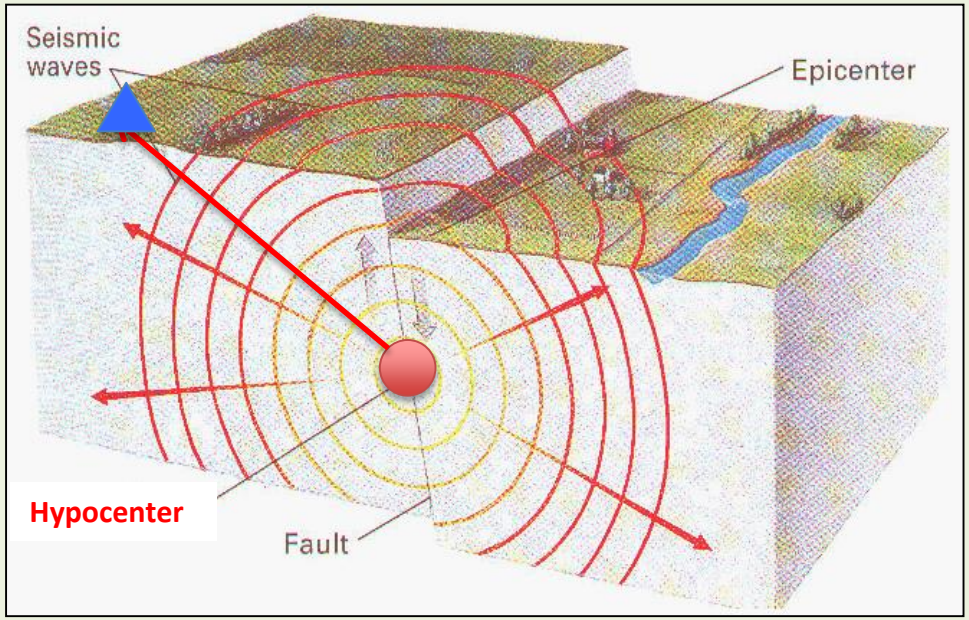
P and S waves

Hypocenter **(where slip begins; the projection of the hypocenter to the surface is the *epicenter*).**

2) Propagation of seismic waves

1) Seismic Source (an earthquake caused by slip on a fault)

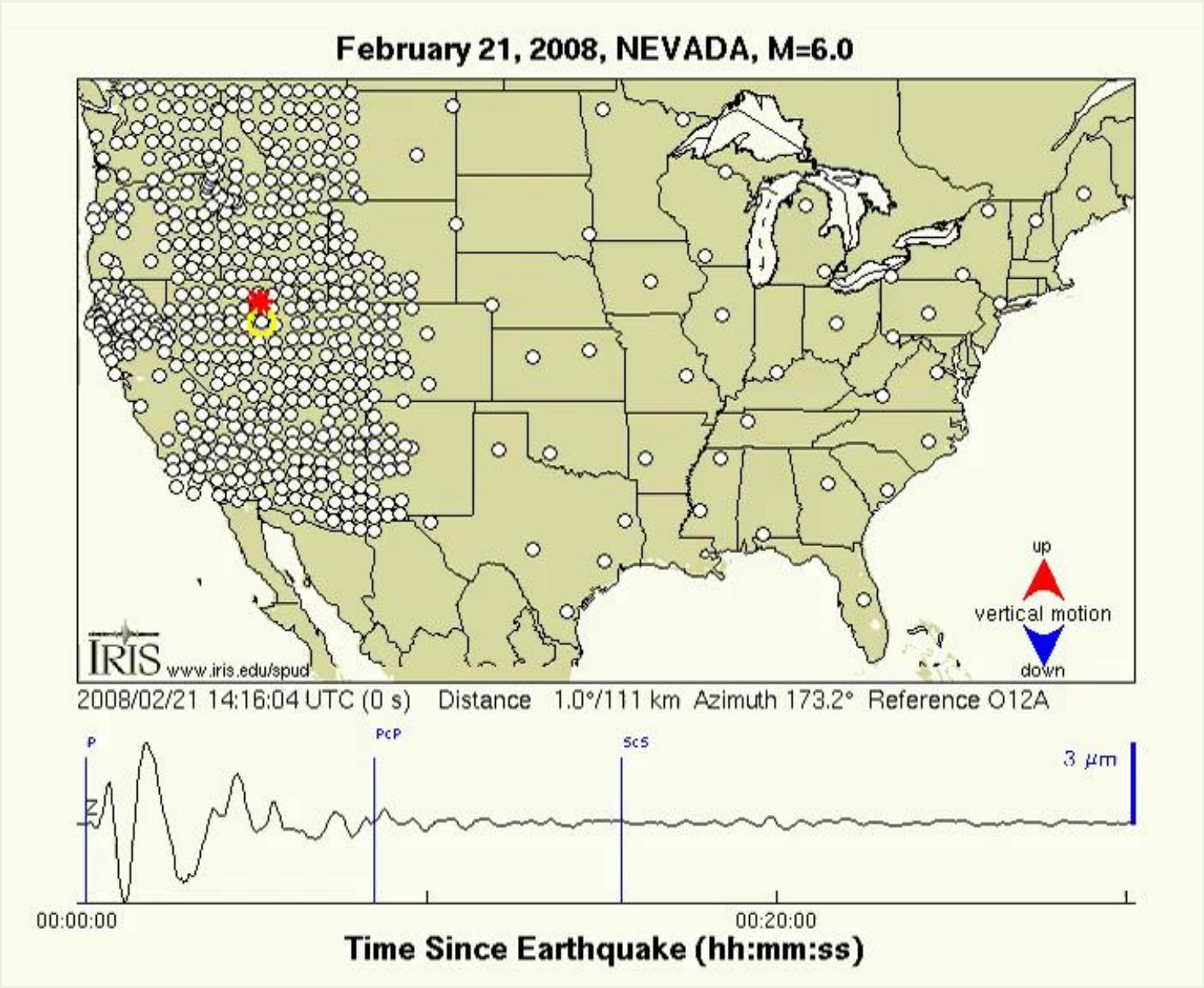




3) 3-dimensional record of ground motion at a seismograph ▲ installed near Earth's surface (a *seismogram*).

Fault offset greatly exaggerated!

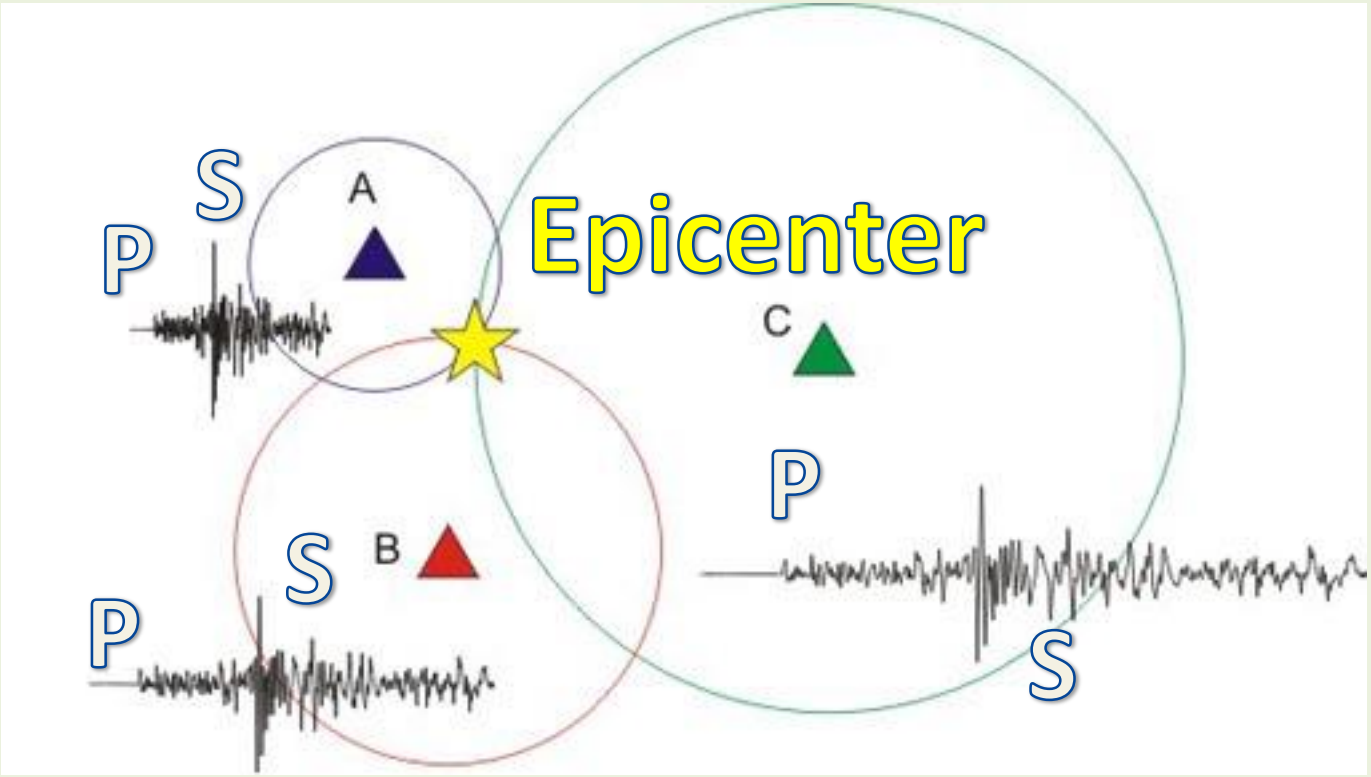
…and shaking can propagate to great distances (e.g., Mt. Everest is 200 km from the Nepal Earthquake fault zone)



Vertical ground motion for a magnitude 6.0 earthquake recorded across a large network of seismographs (c/o NSF; EarthScope Project). At the other side of the nation the amplitudes of these seismic waves are on the scale of microns (1/1,000,000 of a m or 0.00004 inches).

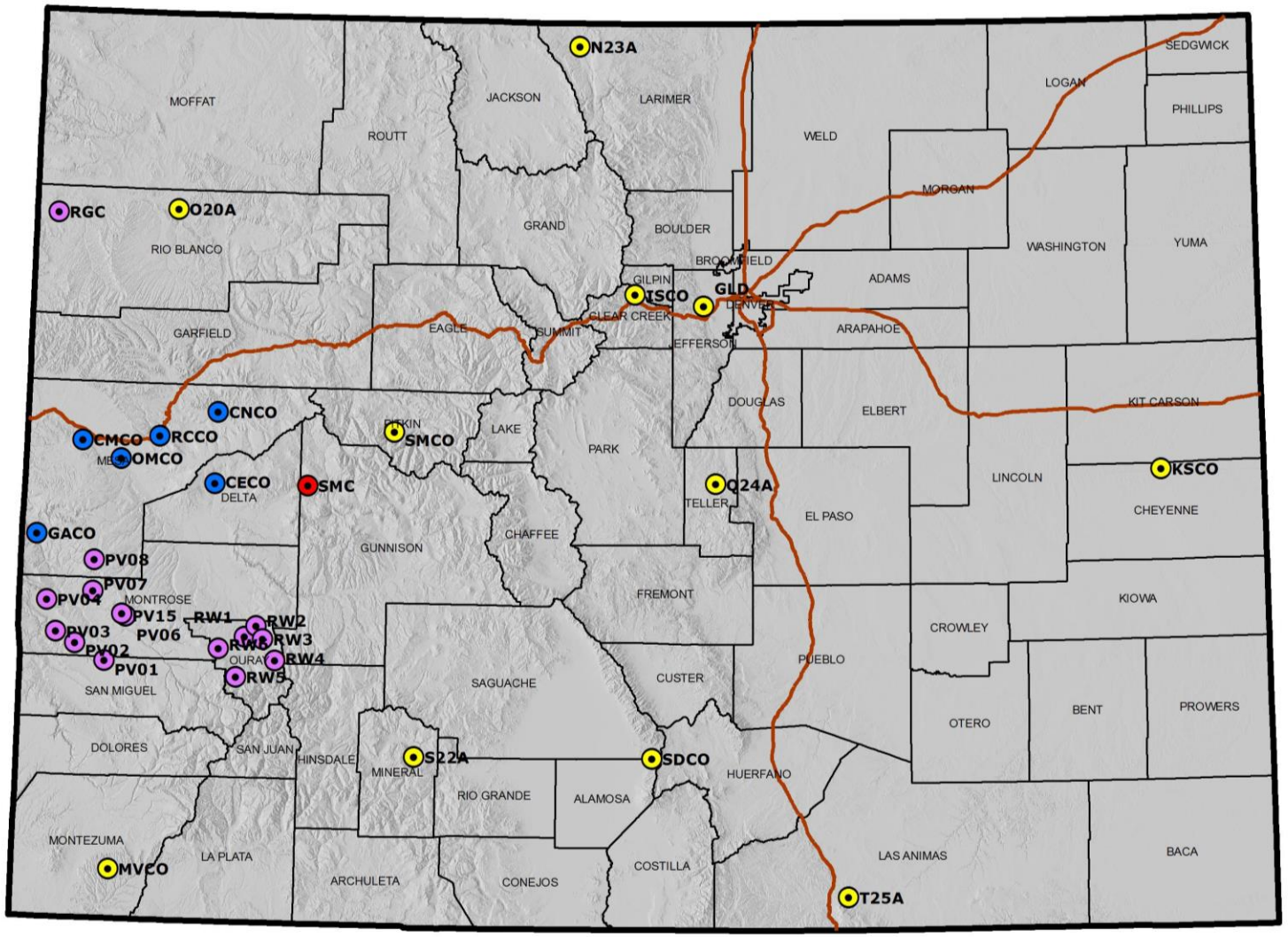
How are Earthquakes Recorded and Located?

- Seismic motions are detected and timed by accurately timed and highly sensitive ***seismographs*** (that can measure that is much to small to be felt ground motion from very tiny or distant events). A record of ground motion is a ***seismogram***.
- Using models of how fast seismic waves travel within the Earth, the source ***hypocenter*** and ***epicenter*** can be estimated from the arrival times of seismic phases (e.g., P and S).
- With a network of 8 or more nearby (e.g., km to 10s of km) accurate locations, sizes, and mechanisms of faulting can commonly be estimated. Reliable depth estimation commonly requires at least one very close station. **However, large areas of Colorado are very sparsely instrumented at present, although efforts are underway to improve this situation.**



A portable seismograph

Seismic network coverage in Colorado is currently sparse, however…



Seismometer Networks

- National Earthquake Information Center (NEIC)
- US Bureau of Reclamation (USBUR)
- Colorado Mesa University (CMU)
- National Institute for Occupational Safety and Health (NIOSH)

100 km

2015 publically accessible seismographs
c/o Colorado Geological Survey

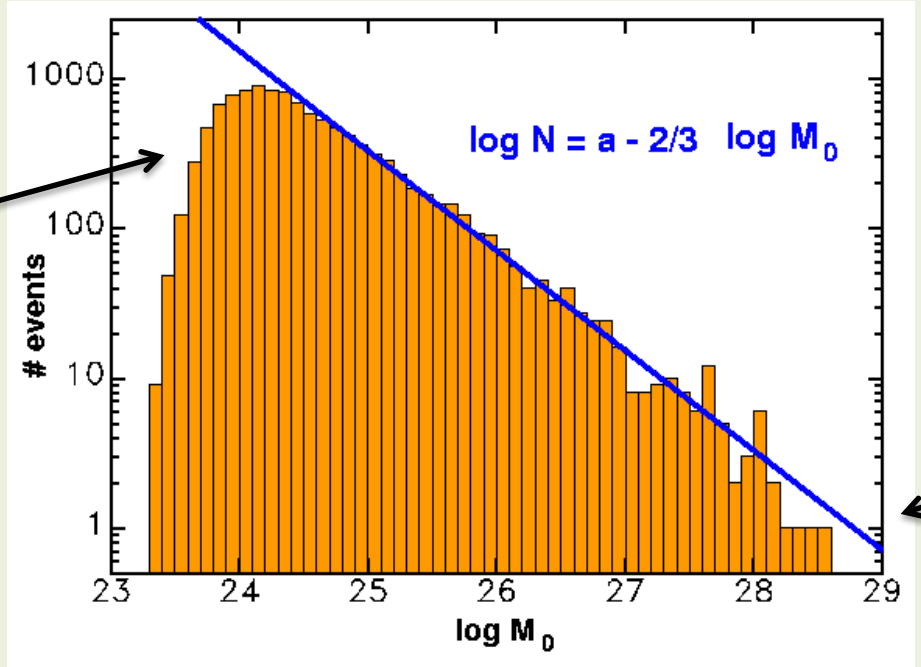
How are Earthquakes Detected and Measured?

- The ***magnitude, m,*** of an earthquake is an intrinsic measure of its size that requires calibrated measurements and a solid hypocenter determination.
  - **The magnitude scale is logarithmic**; an increment of 2 magnitude units (e.g., *m*=4 to *m*=6 corresponds to roughly a 1000-fold increase in seismic energy.
  - It would thus take 1000 magnitude 4's to equal the energy released in a magnitude 6 (!).

How are Earthquakes Detected and Measured?

- In most earthquake regions globally, there are about 10 times as many earthquakes of magnitude *m*-1 as magnitude *m*; i.e., 10 times as many 2's as 3's, and thus 1000 times as many 2's as 5's, etc.
- ***In theory, this allows for event forecasting and seismicity management if the background rate of small earthquakes can be measured.***

Incomplete at the smallest magnitudes

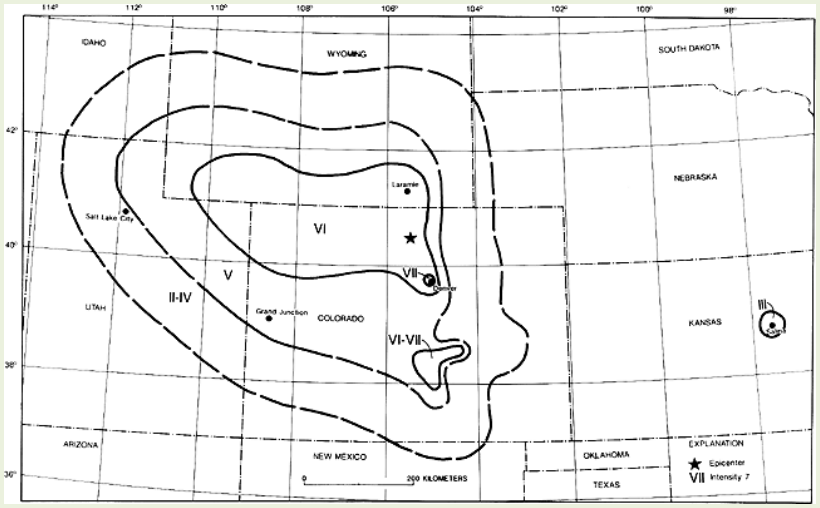


The *Gutenberg-Richter relationship* (the number of events in some time period versus magnitude on a log-log scale produces a linear relationship).

Truncates at some maximum magnitude

How are Earthquakes Detected and Measured?

- ***Intensity*** is a measure of how hard the surface shakes (and how much damage may occur) at a particular location.
- Intensities range from I (not felt) to, rarely, XII (extreme; objects thrown upwards in the air).
- Intensity depends on the size and depth of an earthquake, but is also sensitive to regional and local geology.



1882 "Denver Earthquake" intensity contours m 6.6 (?); USGS.

Mercalli Intensity Scale:

I. Not felt Not felt except by a very few under especially favorable conditions.
II. Weak Felt only by a few persons at rest, especially on upper floors of buildings.
III. Weak Felt quite noticeably by persons indoors, especially on upper floors of buildings..
IV. Light Felt indoors by many, outdoors by few during the day. At night, some awakened.
V. Moderate Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned.
VI. Strong Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
VII. Very Strong Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.
VIII. Severe Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse
IX. Violent Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb.
X. Extreme Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations.
XI. Extreme Few, if any (masonry), structures remain standing. Bridges destroyed. Broad fissures in ground
XII. Extreme Damage total.

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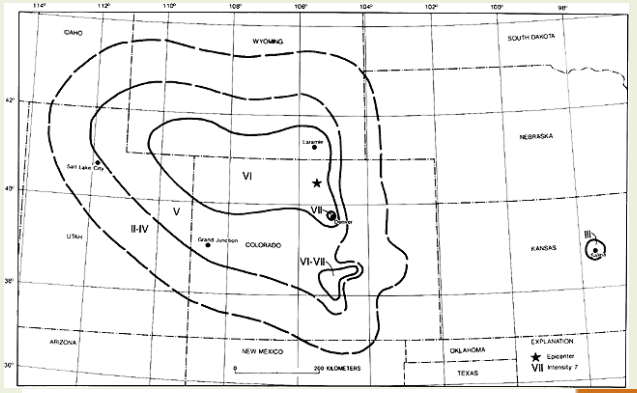
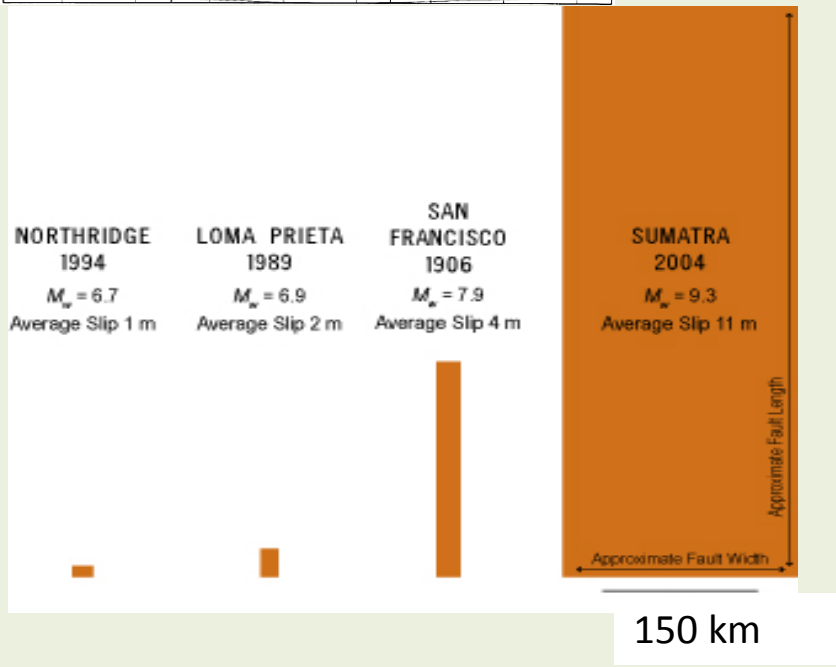
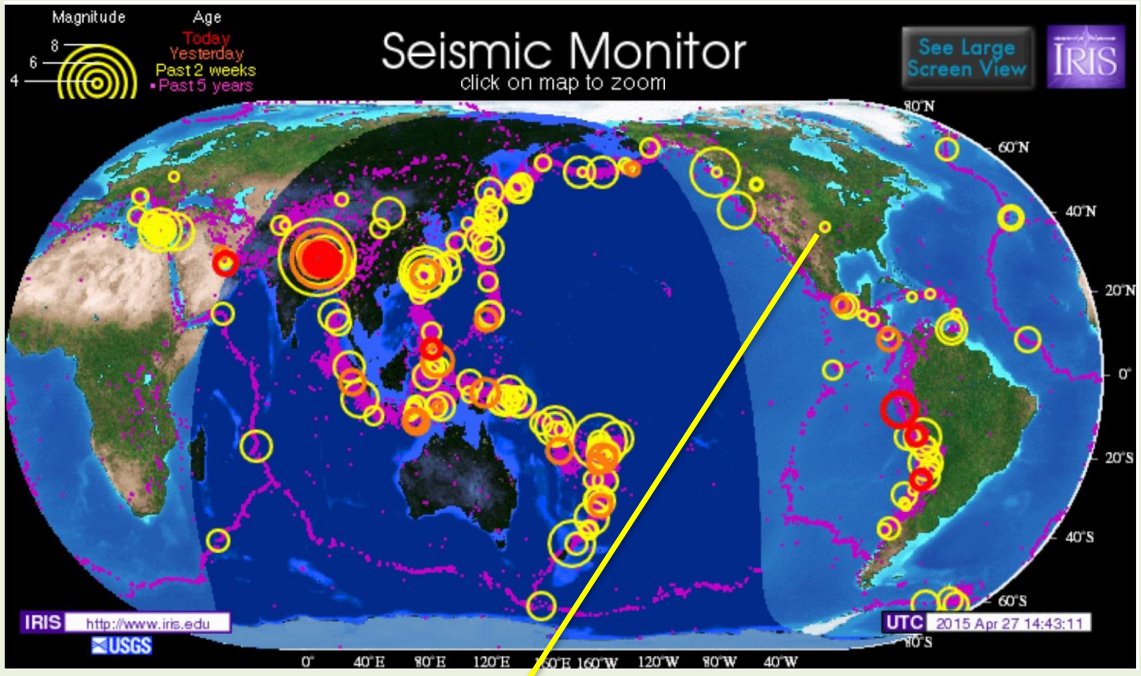
- The ***moment*** of an earthquake is a size measure that is particularly useful for characterizing and studying earthquakes :
  - *Moment* M_0 = ***Fault Area*** times ***fault slip*** times the ***rigidity*** (elastic stiffness;, μ) of the fault zone rocks (M_0=*A x d x* μ)
  - M_0 can be estimated from seismograms and converted to a ***moment magnitude*** (M_w), which scales as 2/3 x $\log_{10}(M_0)$, is the universally used modern measurement of earthquake size.



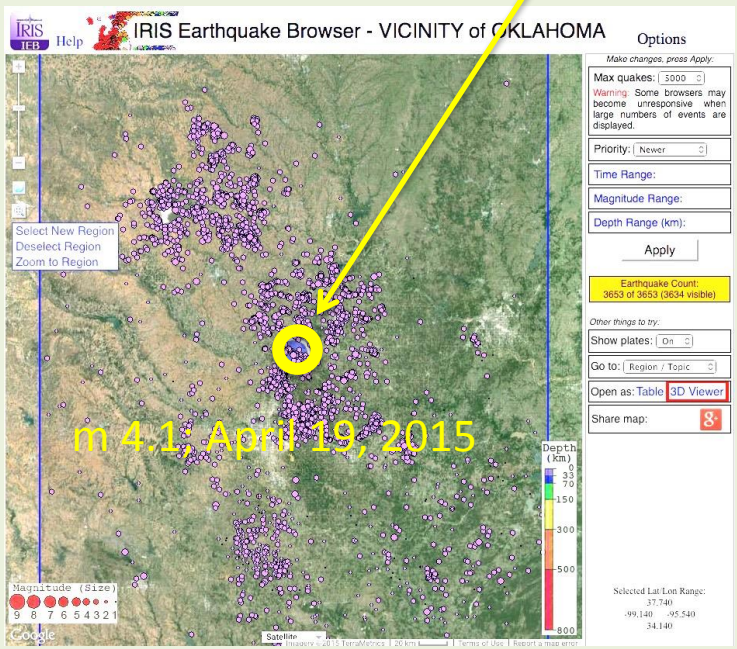
1882 "Denver Earthquake" intensity contours m 6.6 (?); USGS.



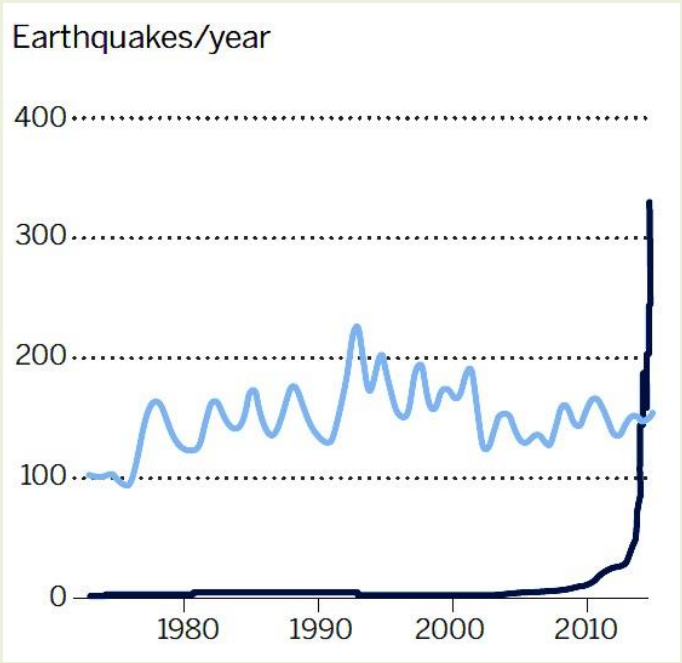
- ***M_w*=2 earthquake: ~ a 45 m x 45 m x fault slipping by 2 cm (e.g., ~150 ft x 150 ft fault slipping by 1 inch).**
- ***M_w*=0 earthquake: ~ a 6 m x 6 m fault slipping by 1 mm.**



Earth is a very seismically active planet (e.g., 15+ magnitude 7+ earthquakes a year and 14,000+ magnitude 4+ earthquake a year). *Find the induced earthquake on this map.*

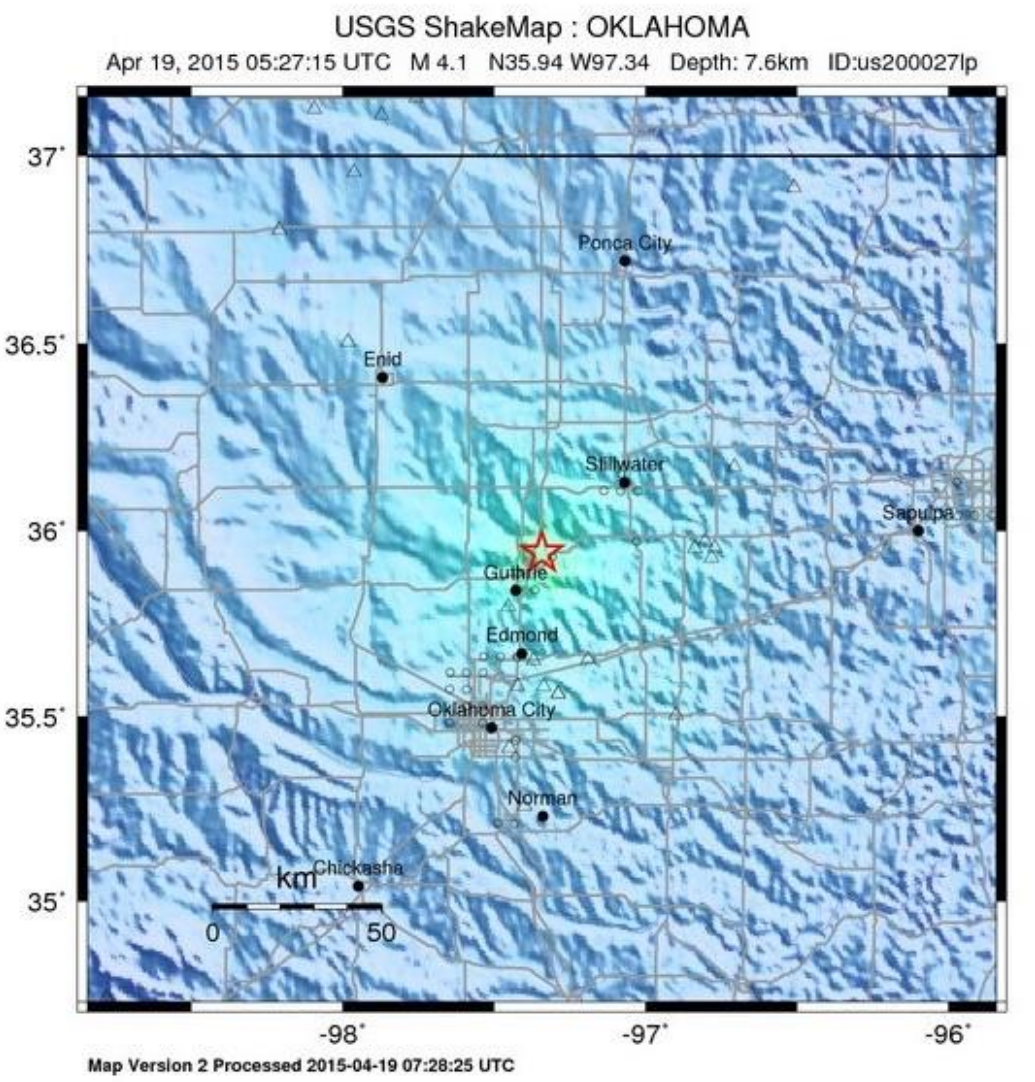


3563 other earthquakes on this map



M 3 and above earthquakes in California (blue) and Oklahoma (black) since 1973 (USGS).

McGarr et al. (2015).



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.(%g)	<0.007	0.08	1.0	5.0	8.8	15	27	47	>83
PEAK VEL.(cm/s)	*<0.003*	*0.04*	*0.5*	*3.0*	*6.5*	*14*	*30*	*63*	*>136*
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Atkinson & Kaka, 2007

USGS “Did you Feel It”http://earthquake.usgs.gov/earthquakes/dyfi reports of ground shaking (370 responses in 123 zip codes).

http://earthquake.usgs.gov/earthquakes/shakemap/global/shake uses all available data to create an ***isoseismal map*** of shaking.

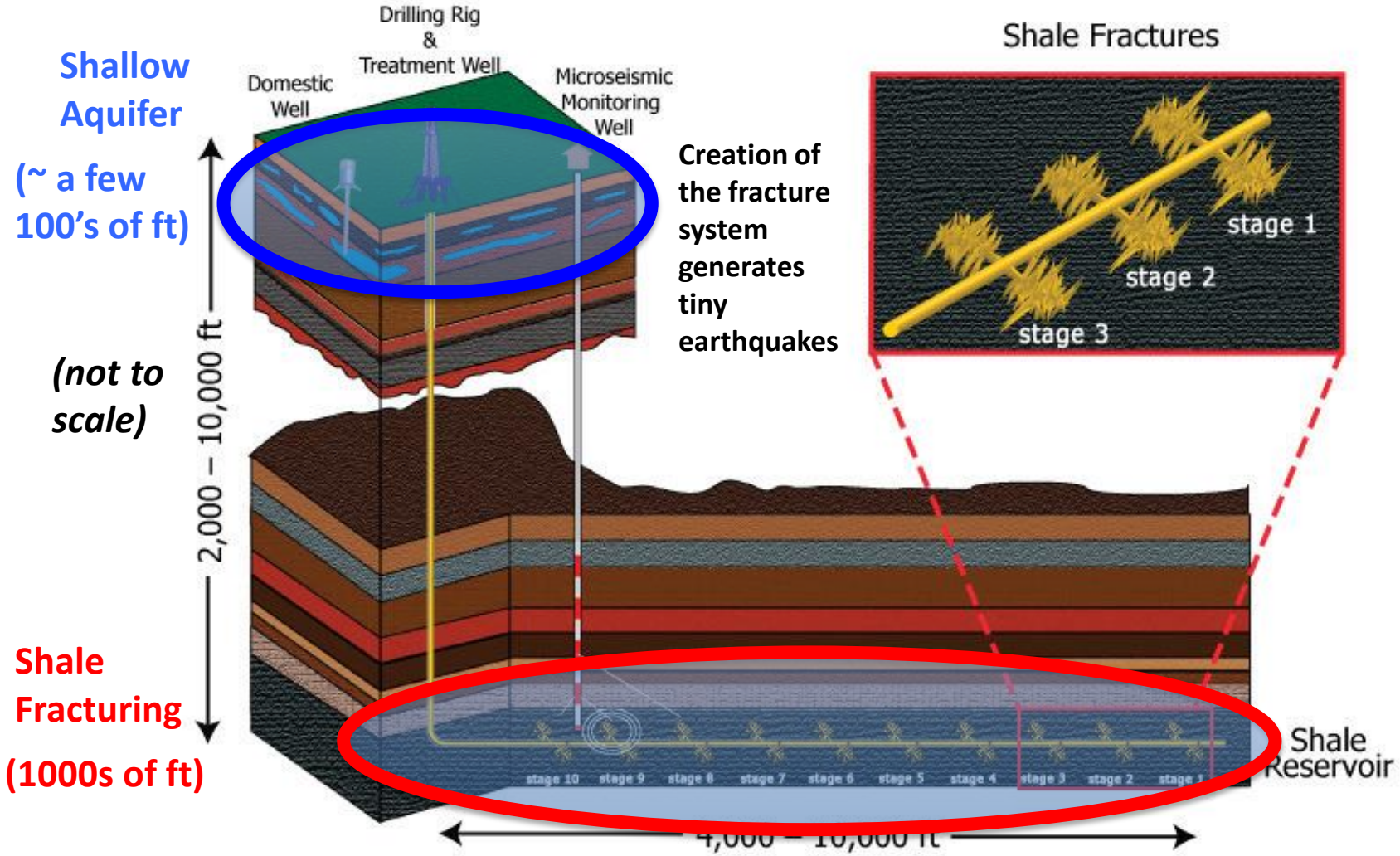
These maps are produced very rapidly by the USGS National Earthquake Information Center (NEIC) in Golden

What is an *Induced* Earthquake?

- An induced earthquake is a seismic events that (to a high degree of certainty) would not have occurred without human influences applied to the surface or subsurface. Known ways to induce earthquakes include:
  - Filling of reservoirs, which creates new gravitational loads and/or hydrological conditions.
  - Direct fracturing (fracking) of subsurface rocks with overpressure also produces (small) earthquakes, ***but this process by itself is not a significant seismic hazard issue.***
  - **Injection and/or withdrawal of fluids (water, CO_2, hydrocarbons, brine) into/from the Earth.**

Ways to induce earthquakes…

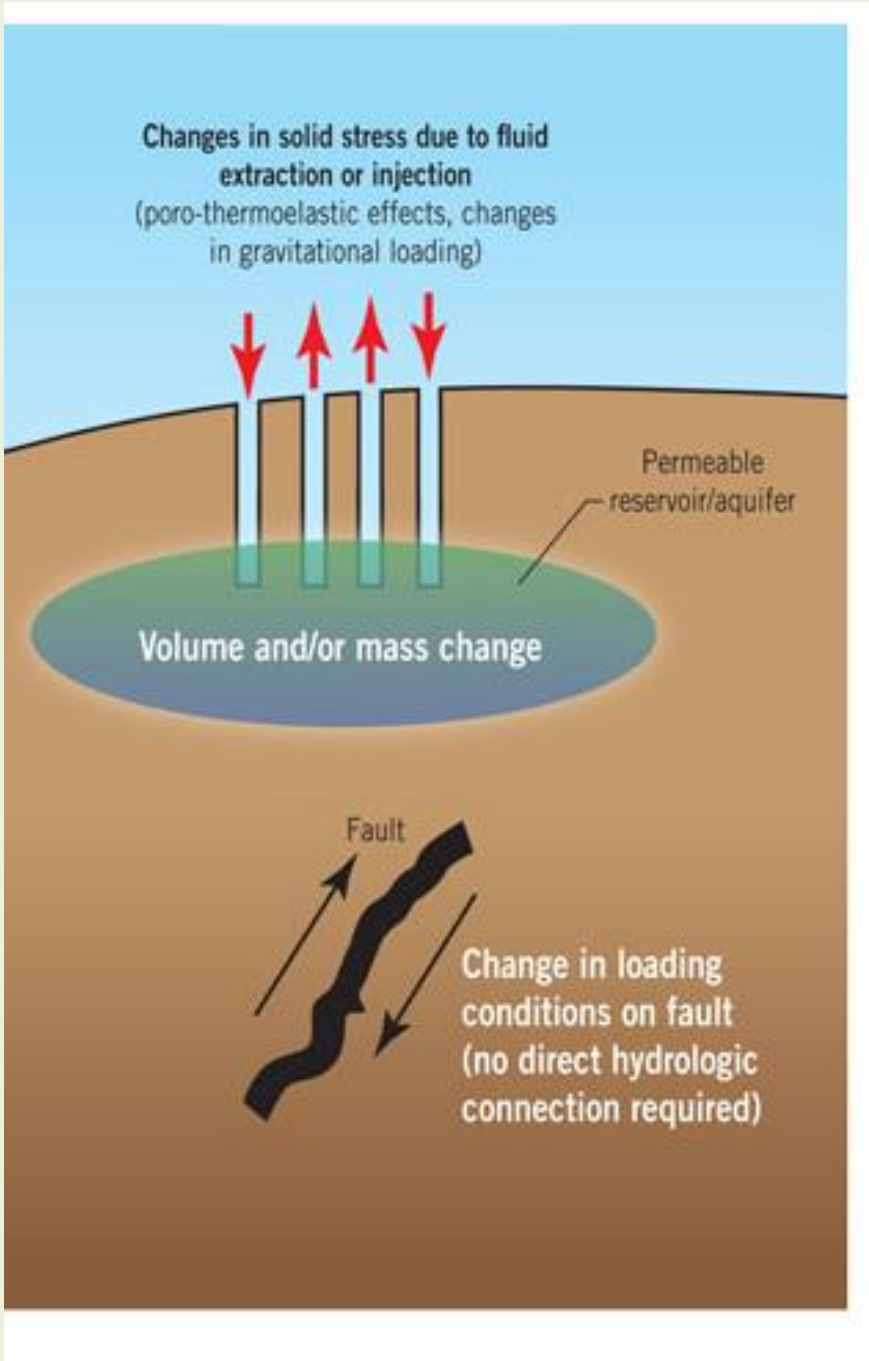
I. Direct fracturing of rock by fluid injection (fracking)



Fracking only very rarely results in felt earthquakes (e.g., events with m > 2) and most events are extremely small (m < 0).

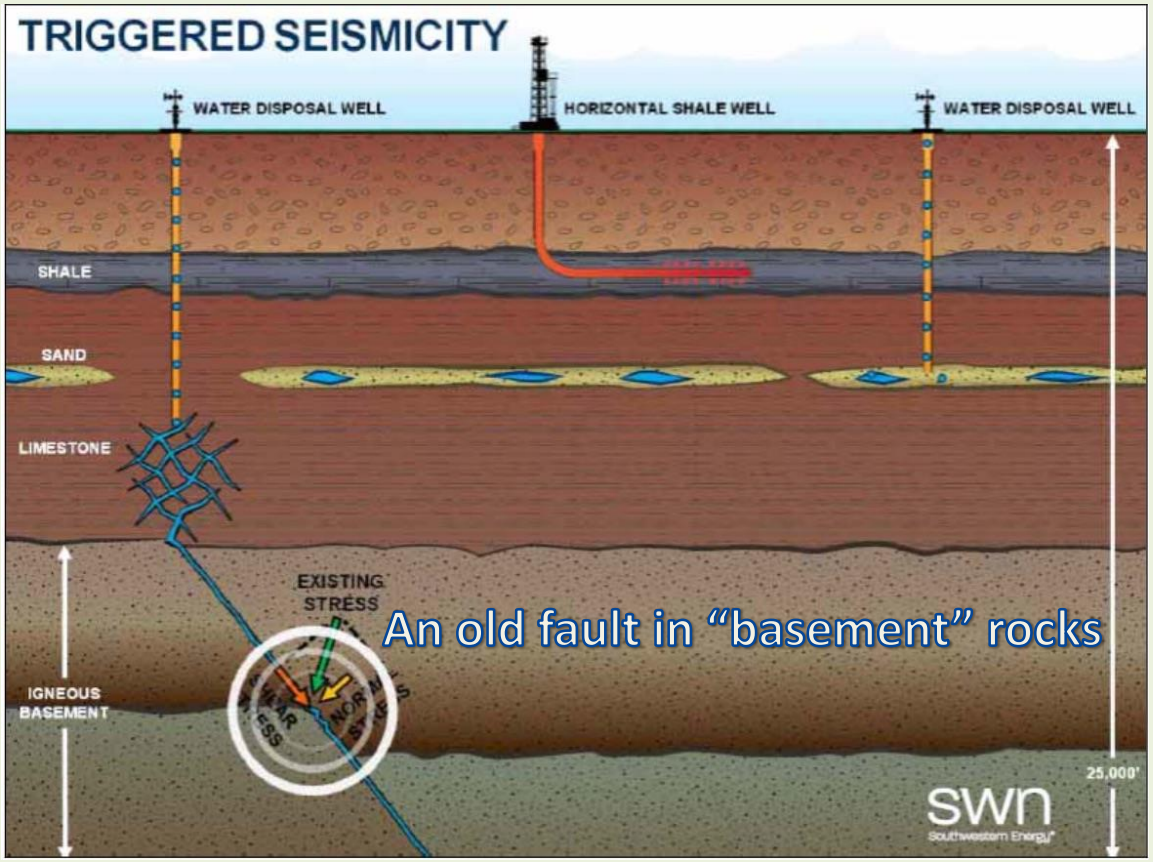
Ways to induce earthquakes (cont'd)…

II. Changes in stress from mass injection or withdrawal without a direct fluid connection



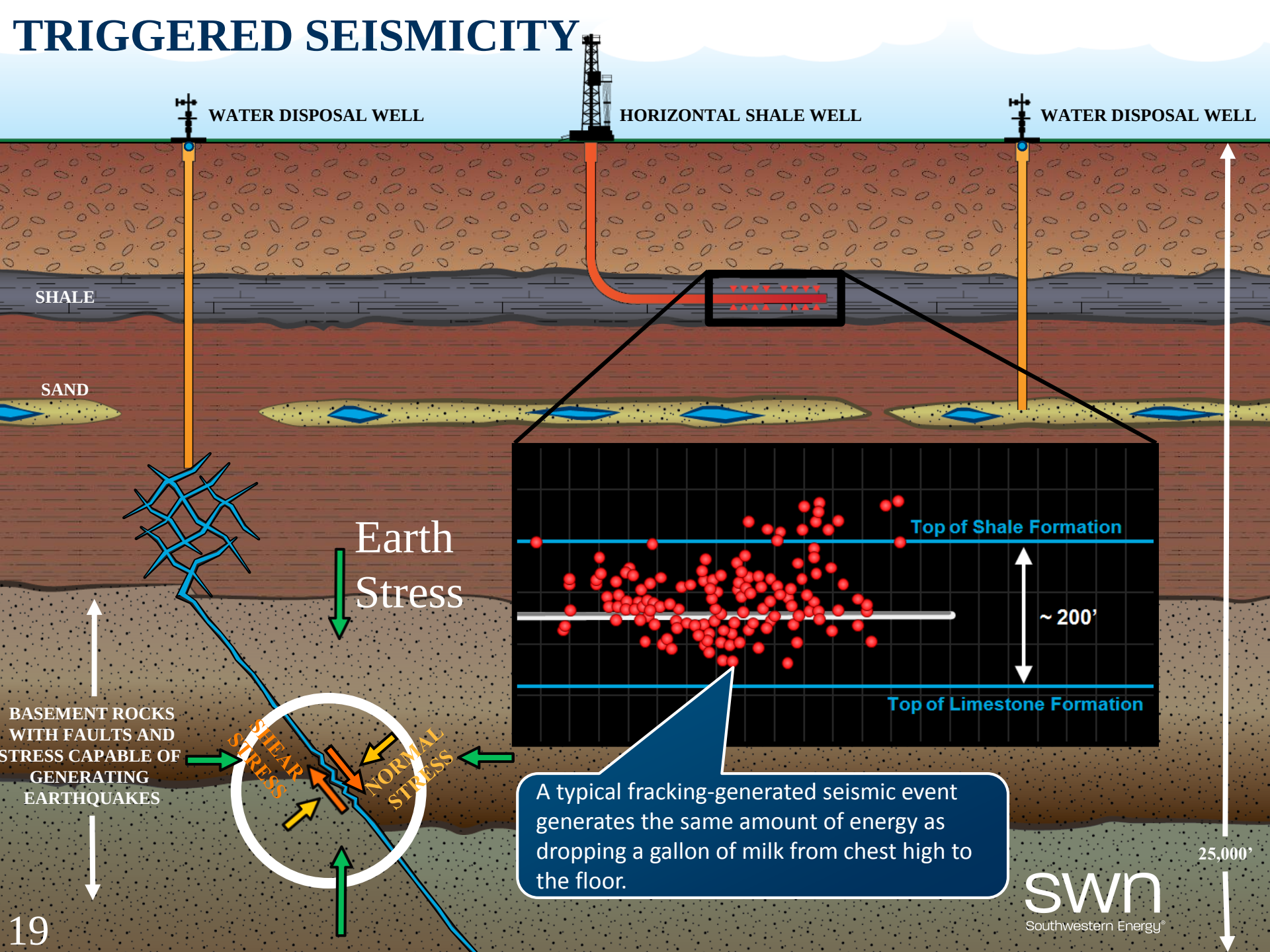
Ways to induce earthquakes (cont'd)…

III. Changes in fluid pore pressure with a direct fluid connection



Southwestern Energy

TRIGGERED SEISMICITY



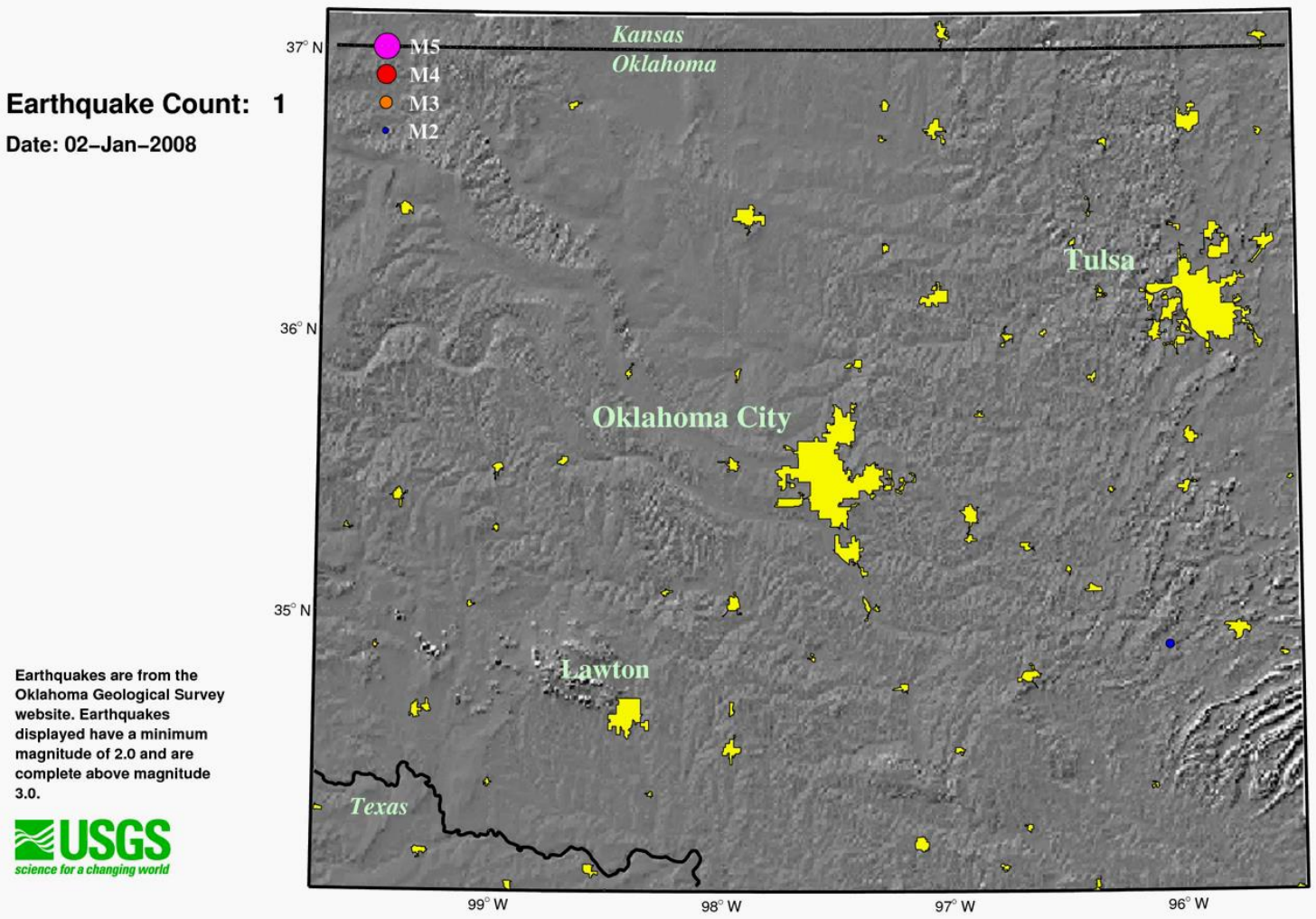
A typical fracking-generated seismic event generates the same amount of energy as dropping a gallon of milk from chest high to the floor.

swn Southwestern Energy®

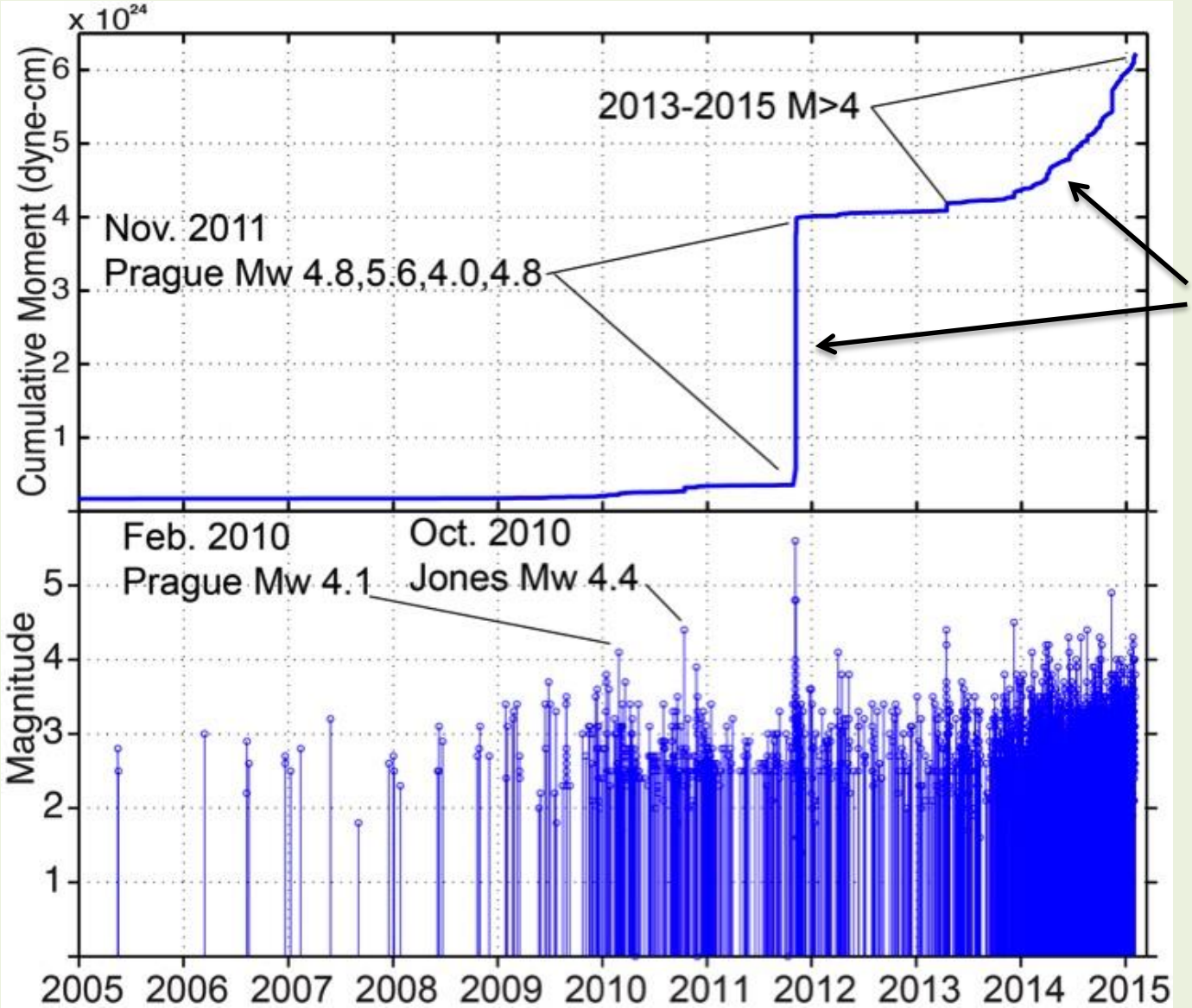
How Does Fluid Injection Create Earthquakes?

- Must occur in a region where there are:
  - Faults (weak quasi-planar zones that might host sudden slip)
  - Oriented ***deviatoric*** (not pressure alone) stresses (forces within the Earth that might push faults to slip)
- Even if there is deviatoric stress in a region, earthquakes will not occur unless the corresponding fault-oriented forces (tractions) exceed the frictional strength of the fault.
- Injection of fluids can drive a fault to failure ***either*** by increasing the stress levels on the fault (e.g., by adding mass) ***and/or*** by lowering the frictional strength of the fault by increasing the static hydrological pressure (in essence pushing towards opening the fault and thus reducing its frictional strength; consider an air hockey puck…).
- There are roughly 50,000 Class II wells across the United States used to dispose of brines and other fluids for disposal, enhancement of hydrocarbon recovery, or hydrocarbon storage. A very small number of these (i.e., ~a few percent at most) are near to or clearly associated with some level of induced seismicity.

Oklahoma (2008 – late 2014)

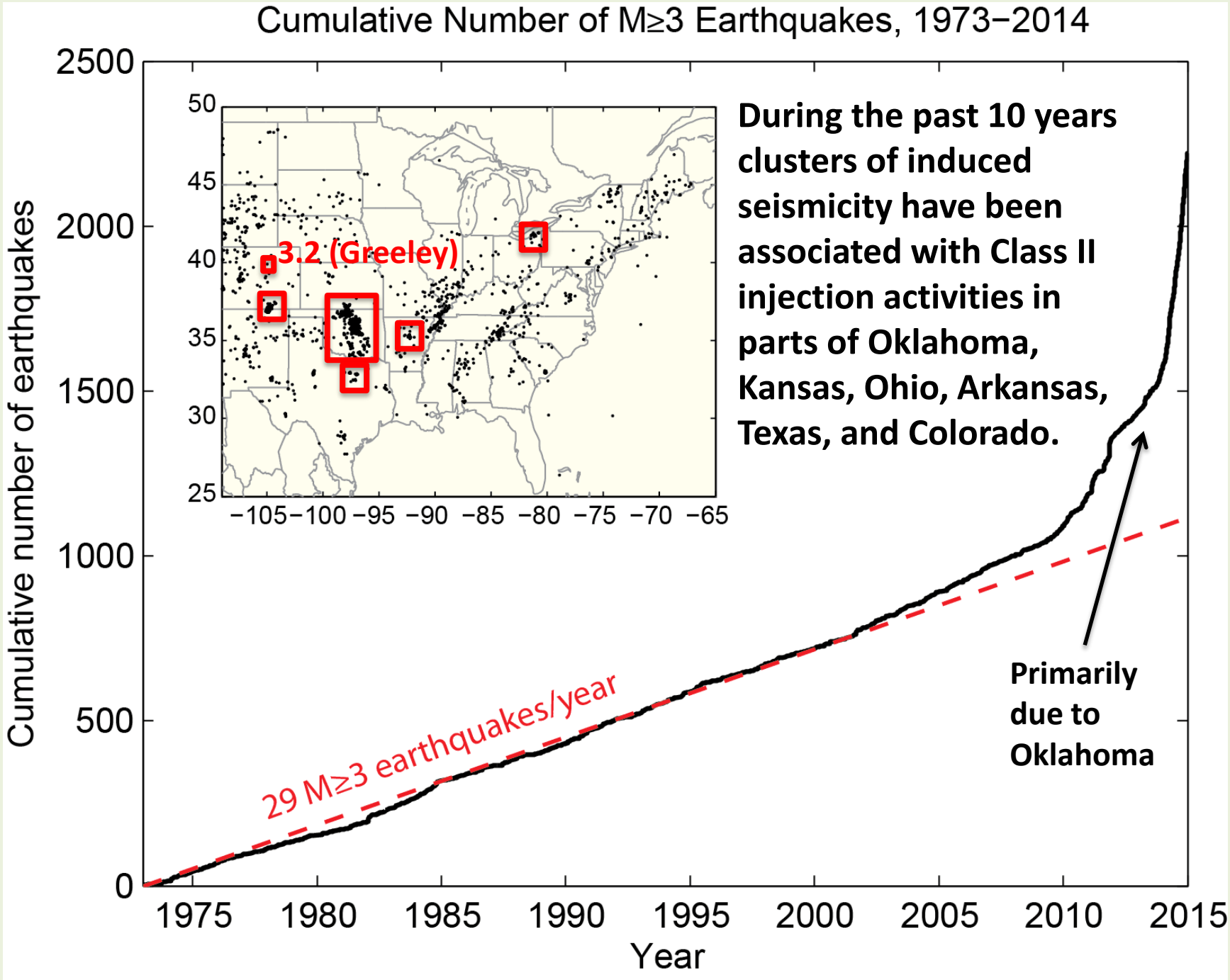


Earthquake activity in central Oklahoma between 1/2005 and 3/2015

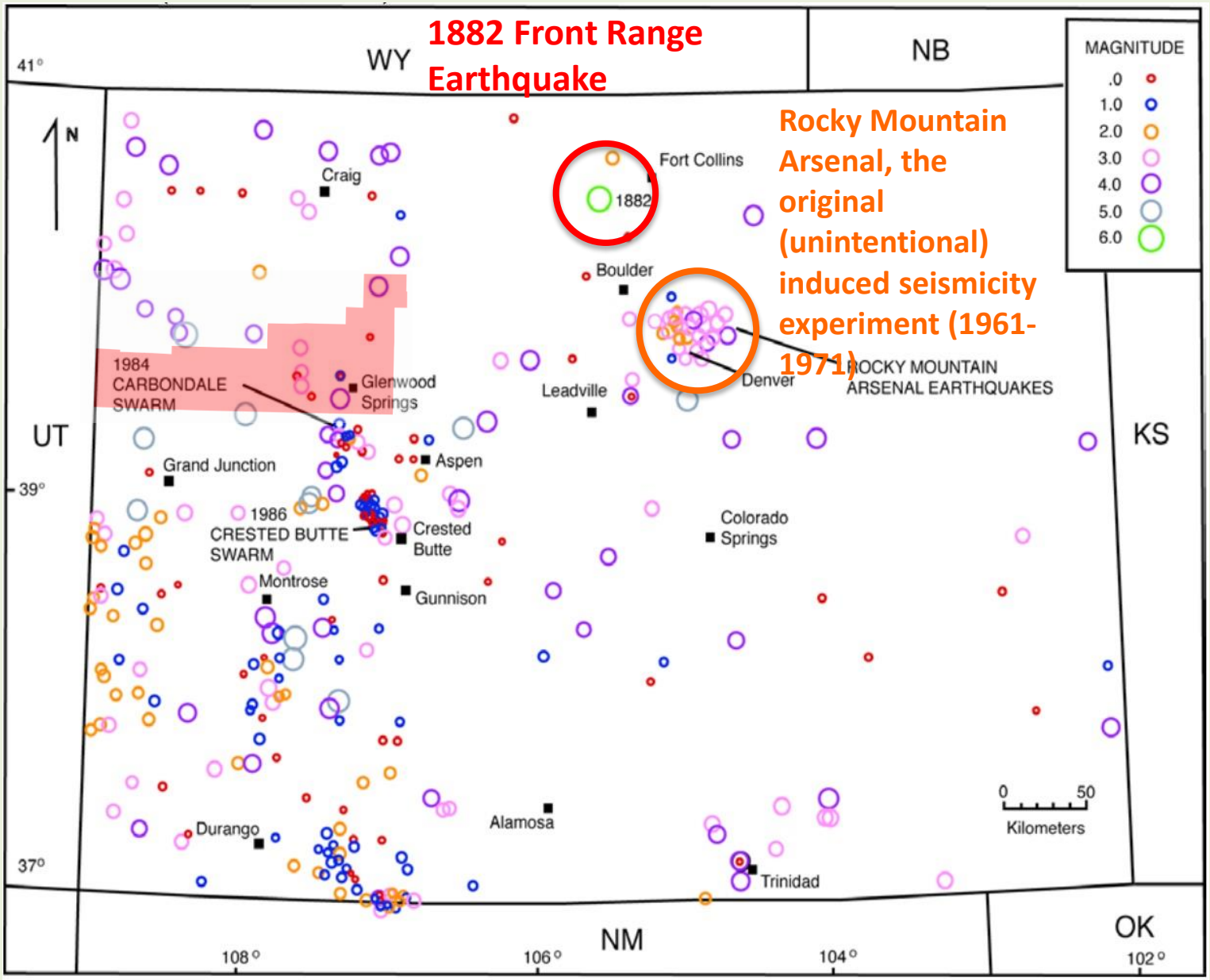


More than half **of the earthquake moment/energy release in the past 10 years occurred in just these four earthquakes, but the background earthquake event level continues to increase.**

McNamara et al. (2015)


Cumulative Number of M≥3 Earthquakes, 1973−2014
Cumulative number of earthquakes
Year
2500
2000
1500
1000
500
0
1975
1980
1985
1990
1995
2000
2005
2010
2015
50
45
40
35
30
25
−105 −100 −95 −90 −85 −80 −75 −70 −65
3.2 (Greeley)
During the past 10 years clusters of induced seismicity have been associated with Class II injection activities in parts of Oklahoma, Kansas, Ohio, Arkansas, Texas, and Colorado.
29 M≥3 earthquakes/year
Primarily due to Oklahoma

Historical Seismicity of Colorado (After Sheehan et al., 2003)



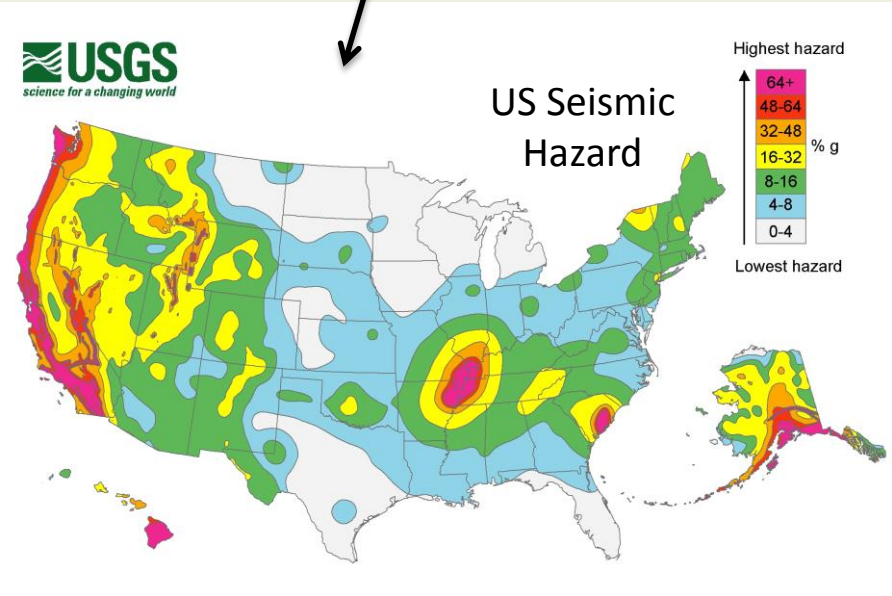
Take-Home: Induced seismicity is a geological interaction between pre-existing earthquake potential and perturbation of Earth's stress state by human activities.

Parts of Oklahoma, and a few other areas in the conterminous U.S., are highly susceptible to injection-induced earthquakes

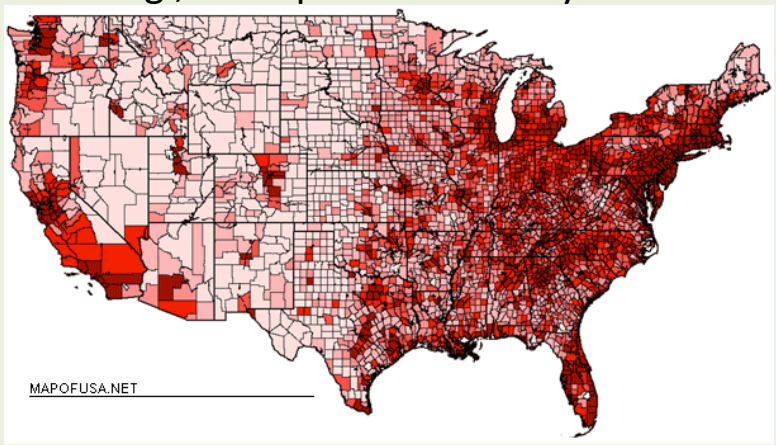
- Susceptibility is the exception, however*; the vast majority of class II injection wells in the U.S. are not associated with significant earthquakes, (even in Oklahoma). Induced seismicity has been successfully mitigated in Arkansas, Ohio, and Colorado (Oklahoma and Texas are catching up).*
- *Through seismic and injection monitoring, scientifically and technically well-informed regulation, and the (infrequent) alteration of injection well operations to avoid perturbing the stress state of active basement faults, induced seismicity can be effectively mitigated.*
- *Induced seismicity is a manageable issue, however, effective management requires seismic monitoring, scientifically informed policies and procedures, and followup from regulatory agencies (Colorado Oil and Gas Conservation Commission has regulartory primacy in CO).*

Defining earthquake hazard and earthquake risk

earthquake hazard * vulnerability = earthquake risk



e.g., US Population Density

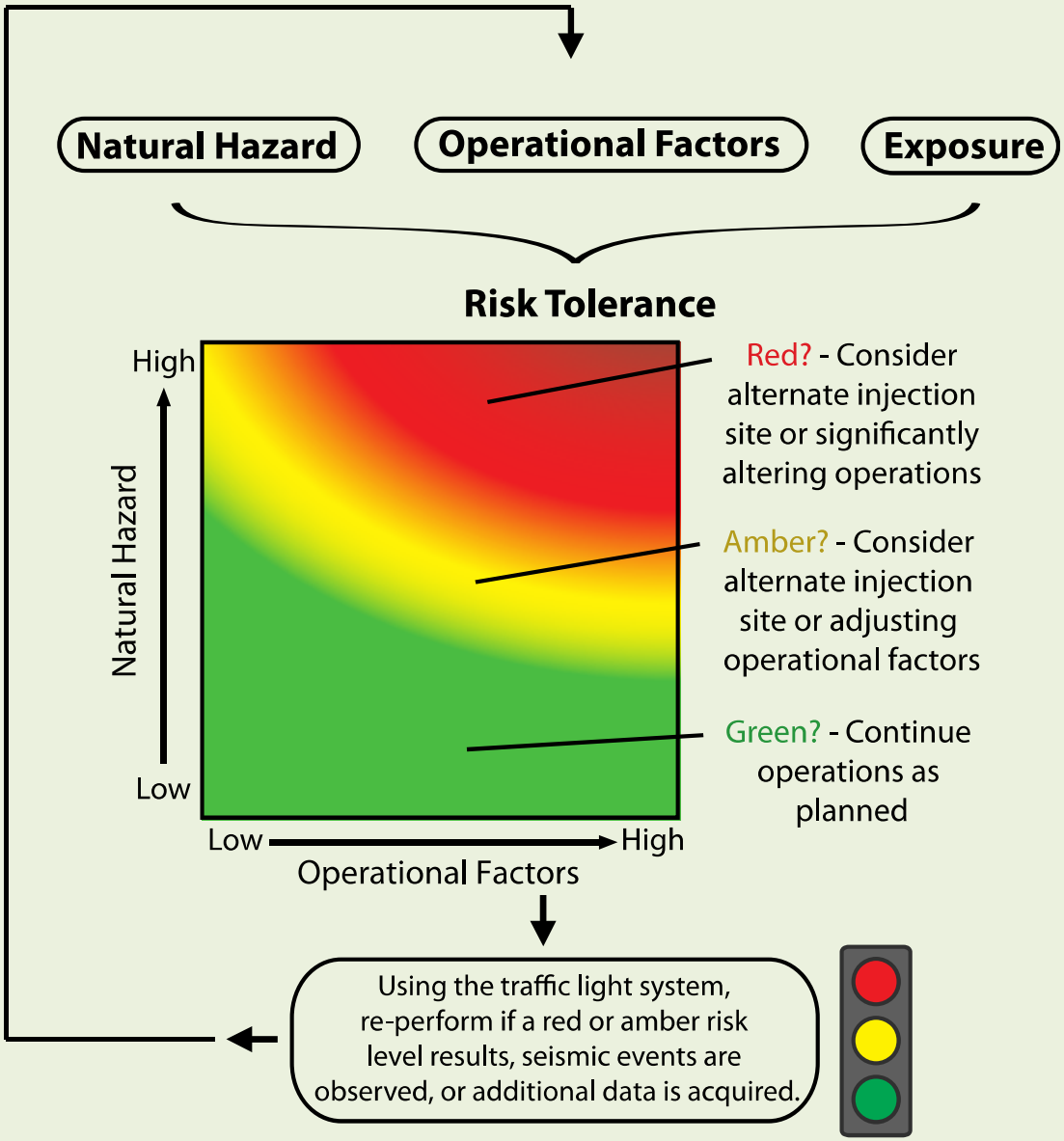


See the guide: "Scientific Principles Affecting Protocols for Site-characterization and Risk Assessment Related to the Potential for Seismicity Triggered by Saltwater Disposal and Hydraulic Fracturing"

By R. J. Walters, M. D. Zoback, J. W. Baker, and G. C. Beroza

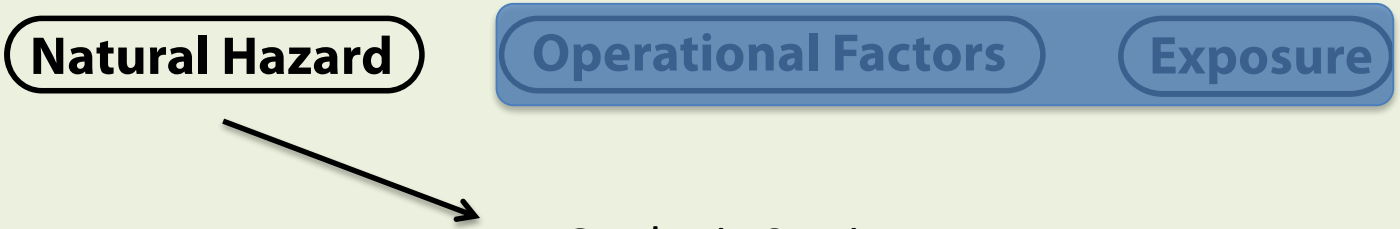
https://scits.stanford.edu/scientific-principles-affecting-protocols-site-characterization-and-risk-assessment-related

Hazard and risk assessment workflow



Considering the necessary factors

Considering the necessary factors



Geologic Setting

What do we know about the geology in the area (formations, faults)?

Earthquake History

What are the frequency of occurrence, sizes, and locations of past earthquakes?

Hydrologic Properties

How do we expect pore pressure changes to migrate?

Is there a sealing formation between the injection horizon and the crystalline basement rock?

Geomechanical State

What is the state of stress?

What faults orientations would be active?

Considering the necessary factors

Natural Hazard | **Operational Factors** | Exposure

Formation Characteristics

Where is the injection horizon with respect to the basement?
Is the injection horizon in hydrologic communication with the basement?

Injection Operations

What are the plans for injection rates, volumes, and pressures?

Operating Experience

Has there been injection in the area before?
Are the affects of cumulative injection a concern?
Have earthquakes been triggered before?

Considering the necessary factors

Natural Hazard | Operational Factors

Exposure

low

medium

high

Populations

What is the total population and population density in the area?

Critical Facilities

Are there hospitals, schools, airports or power plants nearby?

Structures and Infrastructure

What are the sizes and density of buildings, roads, bridges, or reservoirs?

What engineering standards do the structures and infrastructure follow?

Environment

Are there historical sites or other sensitive factors that should be considered nearby?

Considering the necessary factors

What does risk tolerance mean?

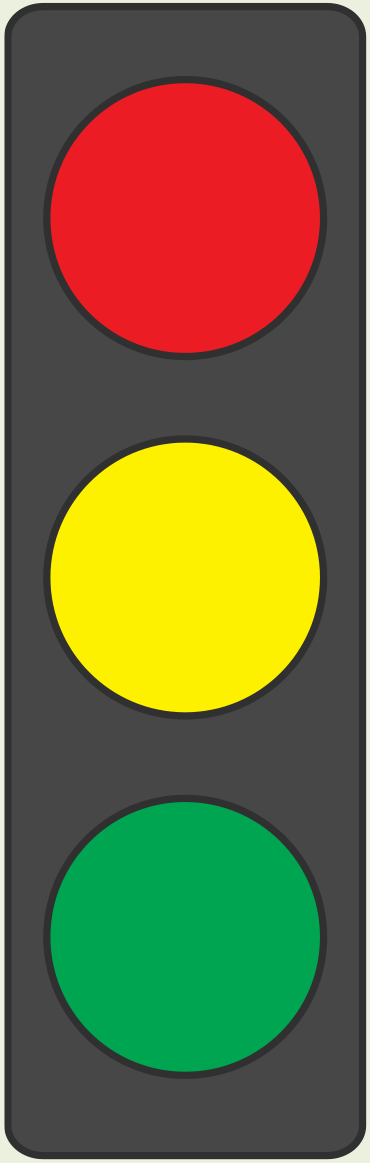
Considering the necessary factors

Every individual, community, regulating body, and oil and gas company likely has a different tolerance for risk.

It is important to identify the tolerance for risk at a particular site before determining a mitigation strategy.

What is *your* tolerance for risk?

Example of a pro-active traffic light system



Observations:
- Unacceptable ground motions and/or magnitudes
- Events define a fault capable of producing a potentially damaging earthquake, especially when located in the basement rock

Actions:
- Limit injection and consider well abandonment
- Continue earthquake monitoring and analysis
- Report observations and actions to area regulators and neighboring operators

Observations:
- Events have larger magnitudes than expected
- Events occur further from injection location and migrate more quickly than expected
- Events migrate into the basement rock

Possible Actions:
- Avoid pre-existing faults during fracture stages
- Reduce injection volumes and rates
- Increase real-time earthquake monitoring and analysis
- Utilize 3D seismic data

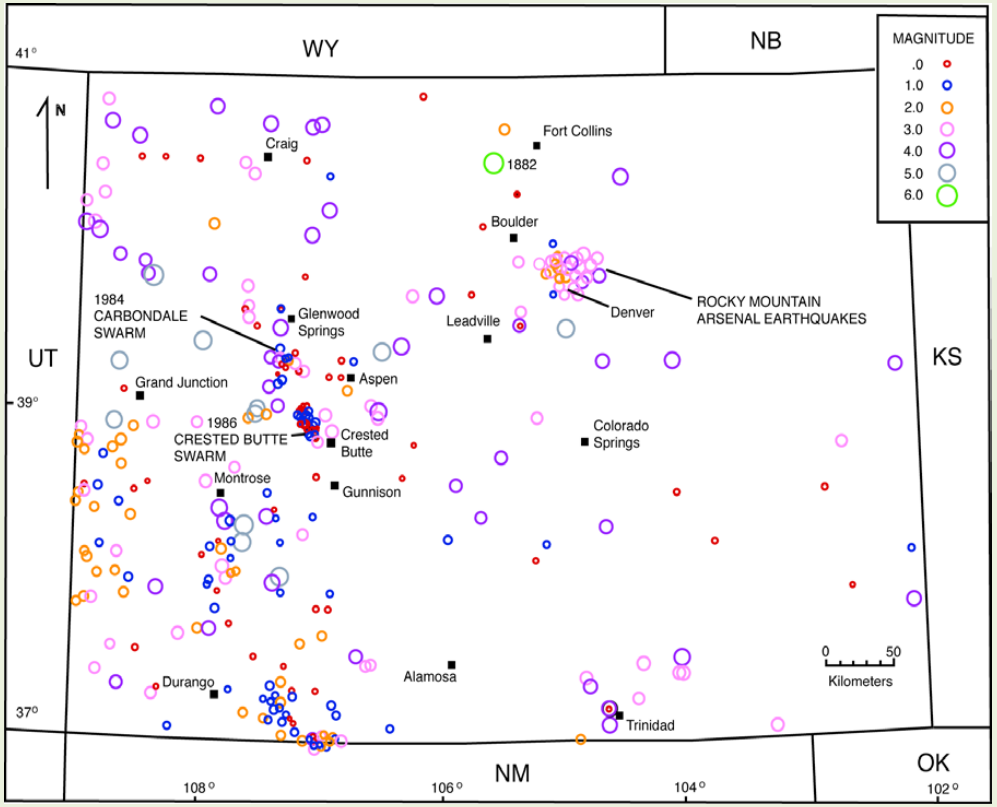
Observations:
- No anomolous seismic events detected

Actions:
- Operations and monitoring continue as planned

Management Priorities

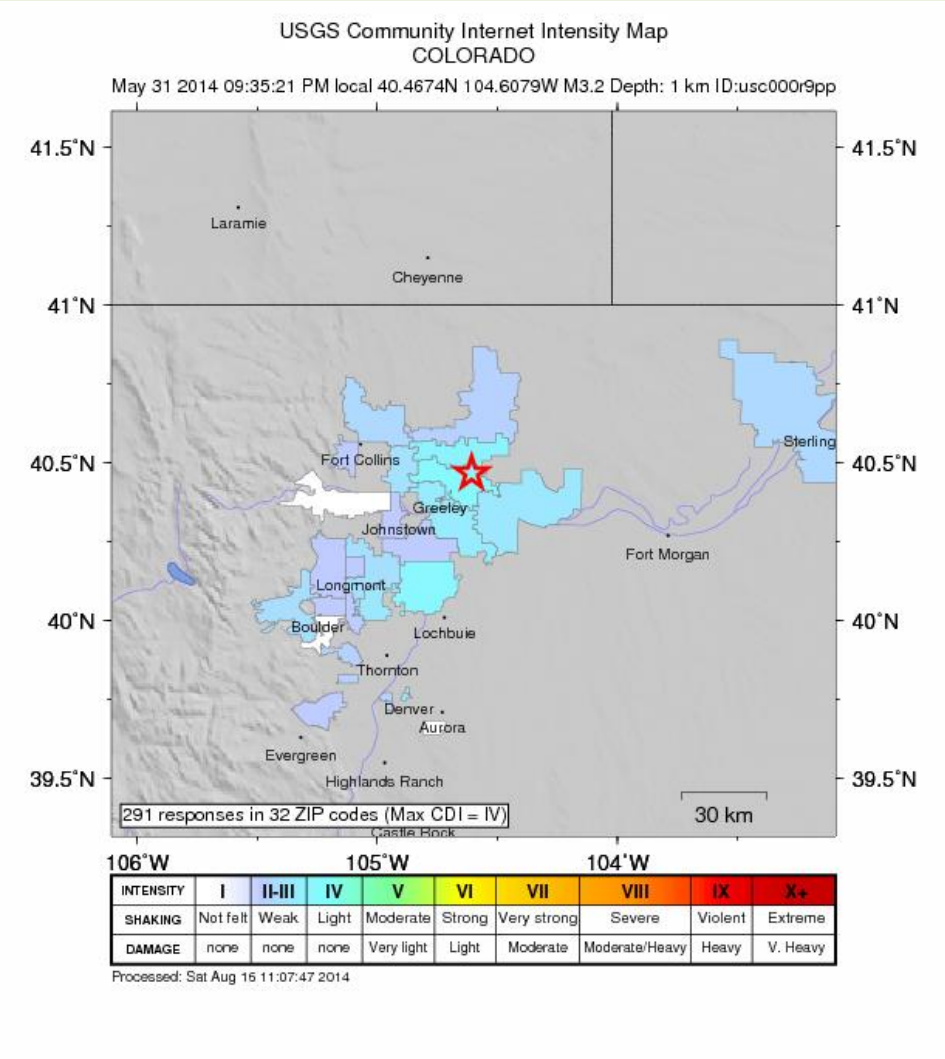
- ***Avoid*** injecting into formations that are in communication with the crystalline basement rock.
- ***Perform*** a site-specific risk assessment, i.e.,
  - Earthquake history
  - Geology, including locations of potentially active faults (don't inject near there!)
  - Assess any neighboring injection wells
- ***Implement and utilize*** a risk management system (i.e. sufficient monitoring and a pro-active traffic light system).

Colorado Seismicity



Sheehan et al., 2003;
Bolt and Wong, 1995

May 31, 2014 Greely CO Induced (M 3.2) Event



Felt from Greeley to Fort Collins; no damage though.

Rapid monitoring follow-up (COGCC/CU/CSU/USGS)

Subsequent 2.6 on June 23; injection halted.

Well problem mitigated (bottom 410 feet plugged under COGCC oversight) to remove interactions with high permeability zone at bottom of well.

Injection resumed in mid-July.

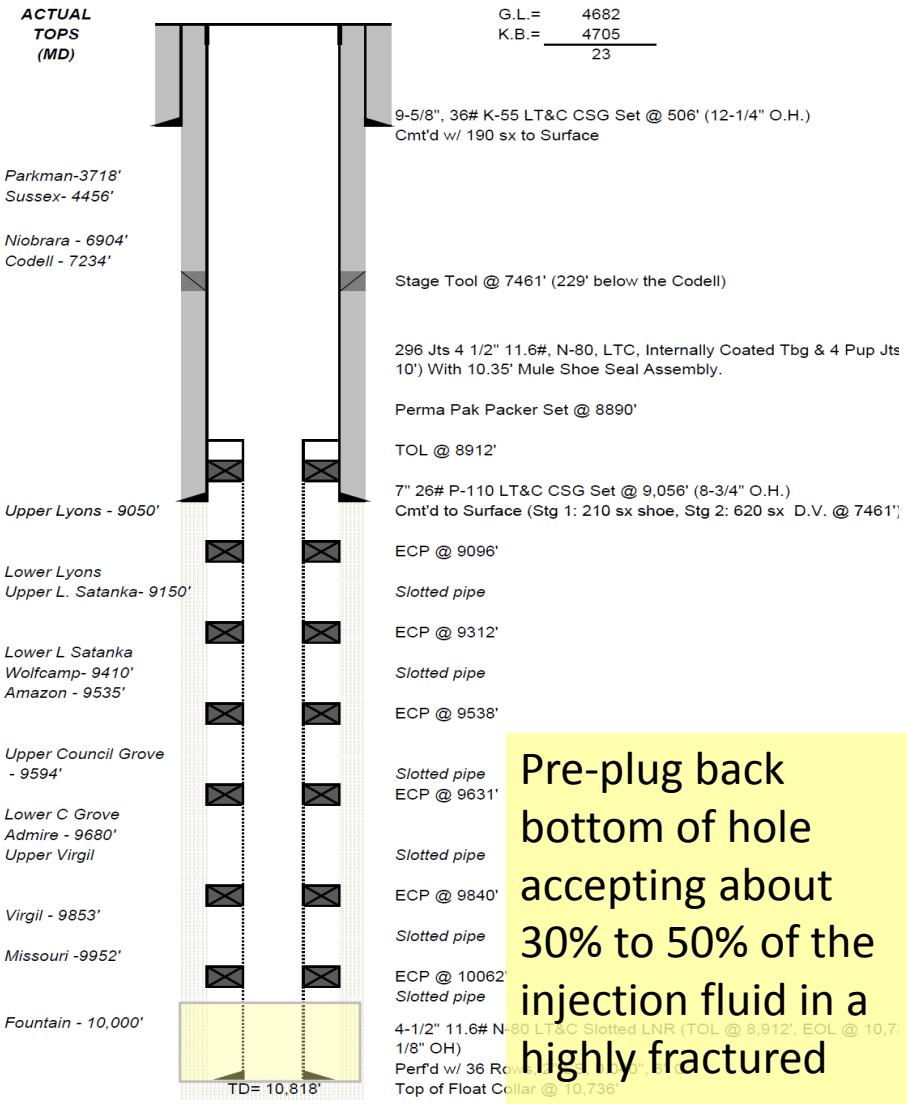
Now injecting at <15,000 barrels/day without concerning seismicity.

Establishment of a COGCC/University/USGS Induced Seismicity Partnership to improve monitoring and regulation in Colorado.

WELLBORE DIAGRAM
High Sierra Water Services
SWD #C4A
SWSE, Sec. 26, T6N, R65W
Weld County , CO
SHL: 1040' FSL, 1924' FEL
BHL: 1089' FNL, 1471' FEL
API #: 05-123-35841

ACTUAL W/ ECP SETTING DEPTH

Directions: WCR 47 at WCR 64, 0.4 mi West, N into



Pre-plug back bottom of hole accepting about 30% to 50% of the injection fluid in a highly fractured zone

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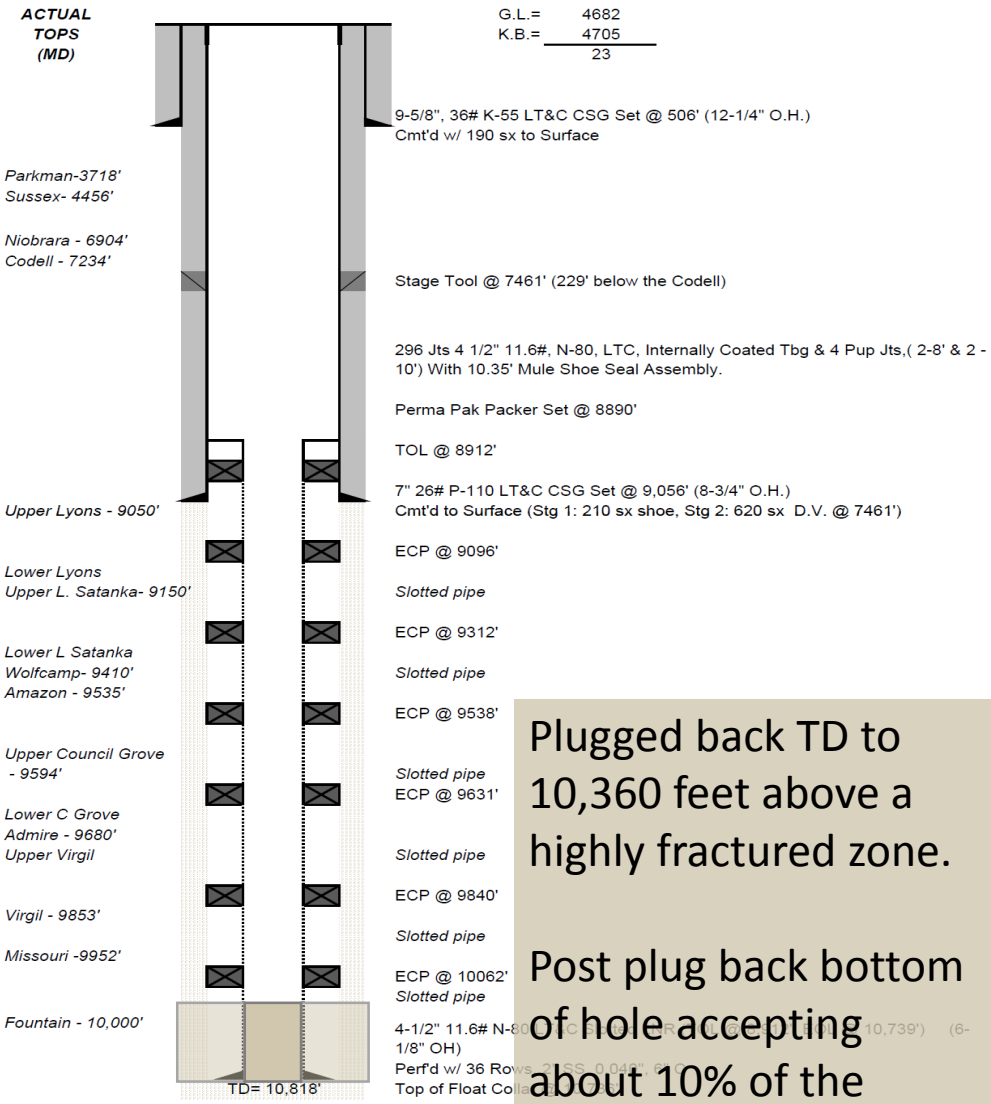


Plugged back TD to 10,360 feet above a highly fractured zone.

Post plug back bottom of hole accepting about 10% of the injection fluid.

Take-home points (cont'd)

- Human activities can and do induce earthquakes in regions with seismogenic geological conditions. Where faults are sufficiently large and sufficient internal stress exists, these earthquakes can be disruptive and/or damaging.
- Injection of waste fluids into deep formations that subsequently influence faults in deeper, stiffer ("basement") rock formations, is the principal way that this occurs, and the fault physics is reasonably well understood.
- A small (~<1%) number of U.S. injection wells are associated with induced seismicity; many wells do not induce earthquakes (even in Oklahoma!).
- With geophysical monitoring and regulatory oversight, this is a manageable problem.
- Colorado has established an effective partnership between COGCC, Universities, the Colorado Geological Survey, and the USGS that has good a knowledge base (and one example of practical success in the Greeley case) in addressing induced seismicity.

Take-home points

- Colorado has established an induced seismicity advisory group between COGCC, Universities, the Colorado Geological Survey, and the USGS that has good a knowledge base (and one example of practical success in the Greeley case) in addressing induced seismicity.
- The COGCC currently has a policy that injection well operators will be engaged in the event of a 2.5 (typically the threshold for being felt) or larger magnitude earthquake within 2.5 miles of an injection well.
- The COGCC and partners are augmenting the current state network, and the USGS will incorporate these data sources to ensure that relevant events (magnitude 2.5 or above, and in some cases smaller) are detected, located, reported and communicated to COGCC, its partners, and to the public in near-real-time.

Thank You

http://www.columbiaenvironmentallaw.org/articles/finding-fault-induced-earthquake-liability-and-regulation

https://scits.stanford.edu/scientific-principles-affecting-protocols-site-characterization-and-risk-assessment-related

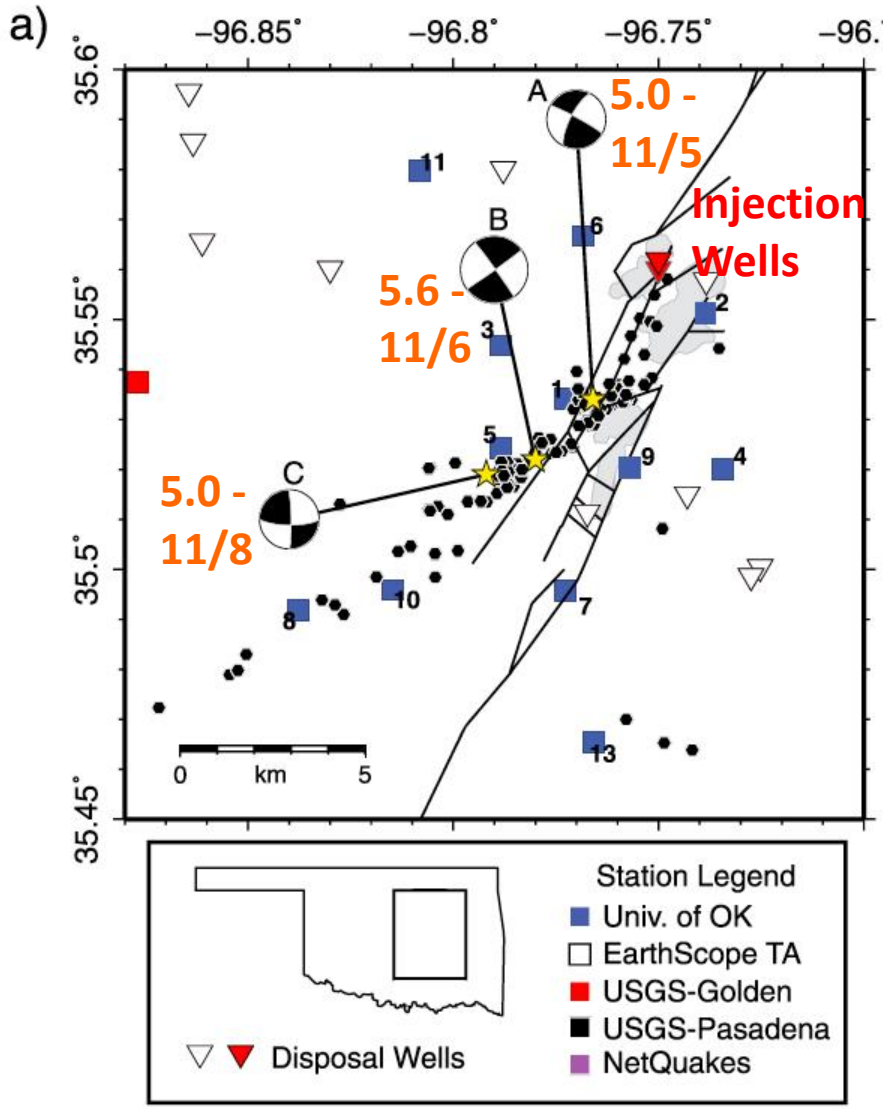
Relevant Colorado Regulations (e.g., see www.garfield-county.com Energy Advisory Board online PPTs)

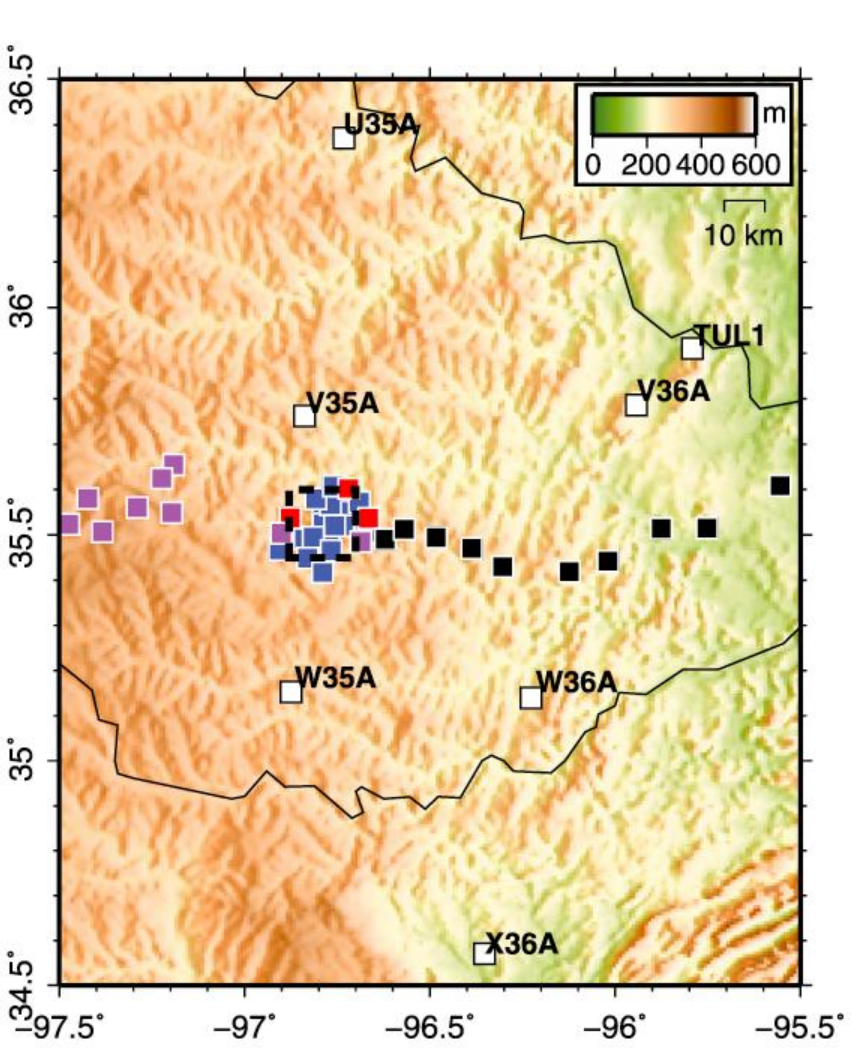
- CO Rule 325 defines the management of Class II injection wells with fundamental objectives of
  - Protecting aquifers
  - Isolating activities from other wells
  - Respecting mineral and surface owner rights
  - The mechanical integrity of wells and their formations.

Relevant Colorado Regulations

- CO Rule 324b defines aquifer requirements for Class II injection suitability
  - Water quality test data is required from the disposal formation.
  - If total dissolved solids (TDS) is greater than 3,000 milligrams per liter (mg/l) and less than 10,000 mg/l, then an aquifer exemption is required in addition to a UIC permit application.
  - COGCC publishes notices of aquifer exemption requests in a local newspaper for a 30-day public comment period.
  - The notice is also forwarded to U.S. EPA for their review.
  - COGCC sets maximum injection pressures uniquely defined for each injection well; this minimizes the potential for injection-induced seismicity.

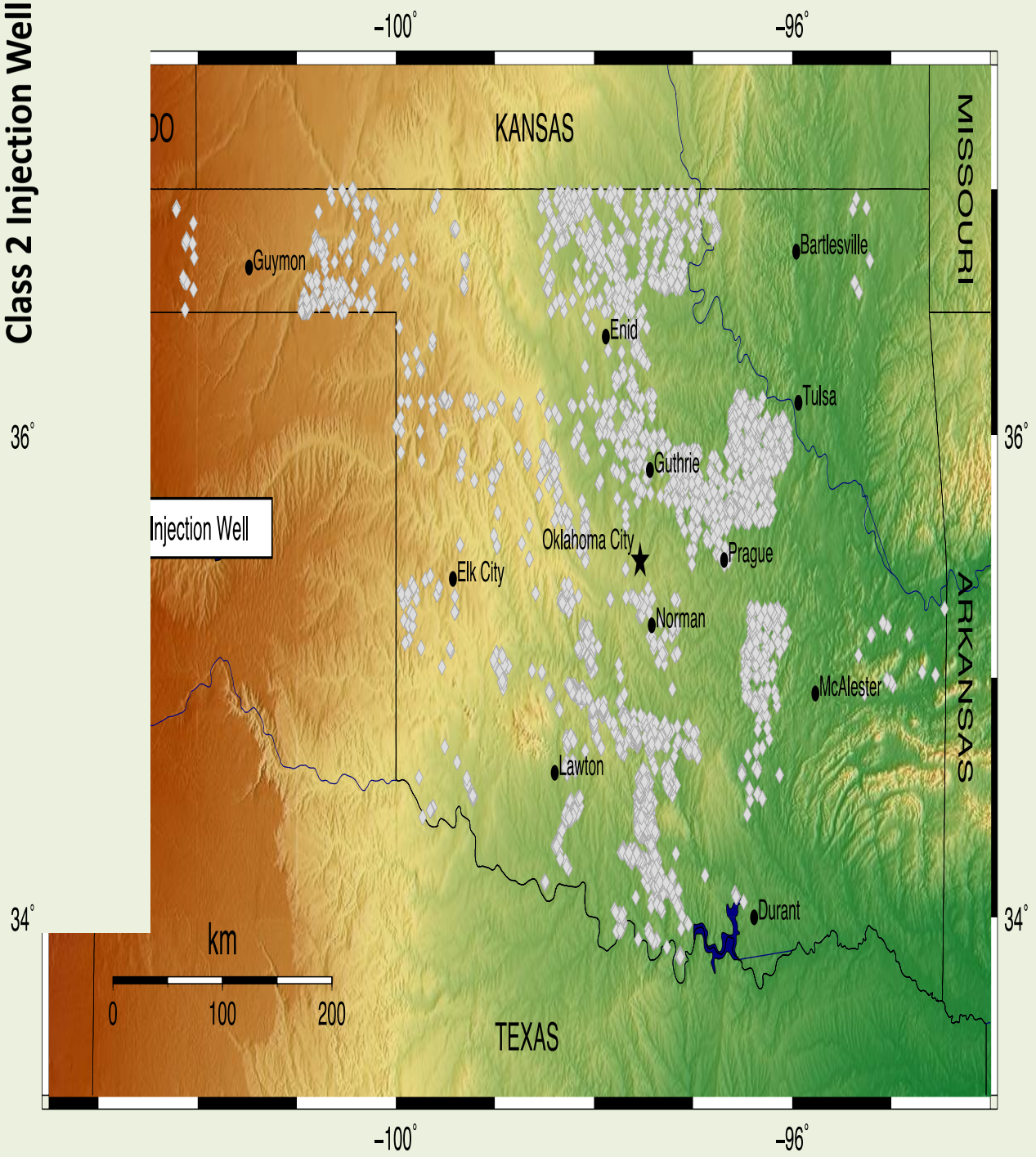
2011 Prague, OK Sequence



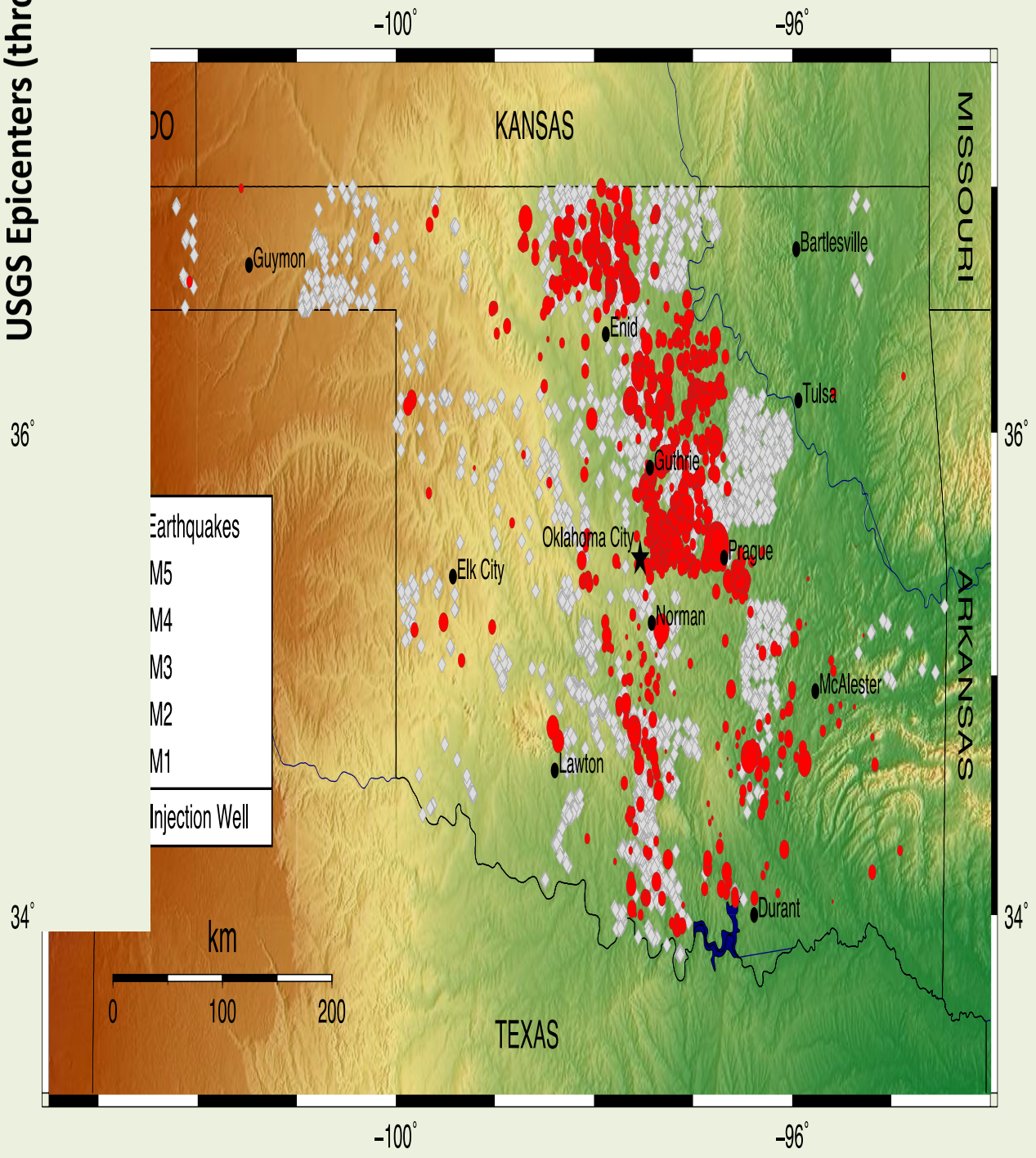


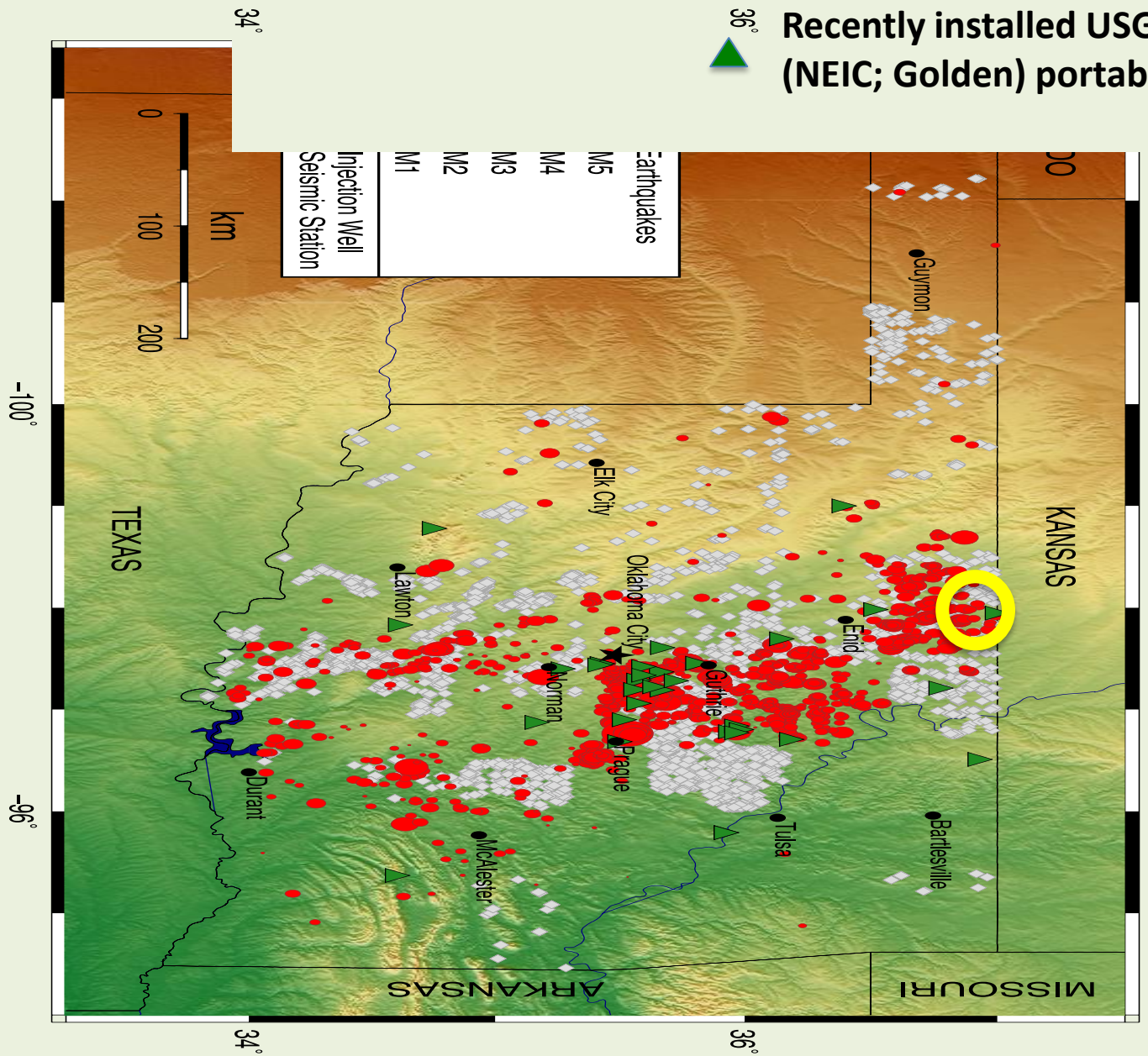
Sumy et al. (2014)

Class 2 Injection Wells (subset)



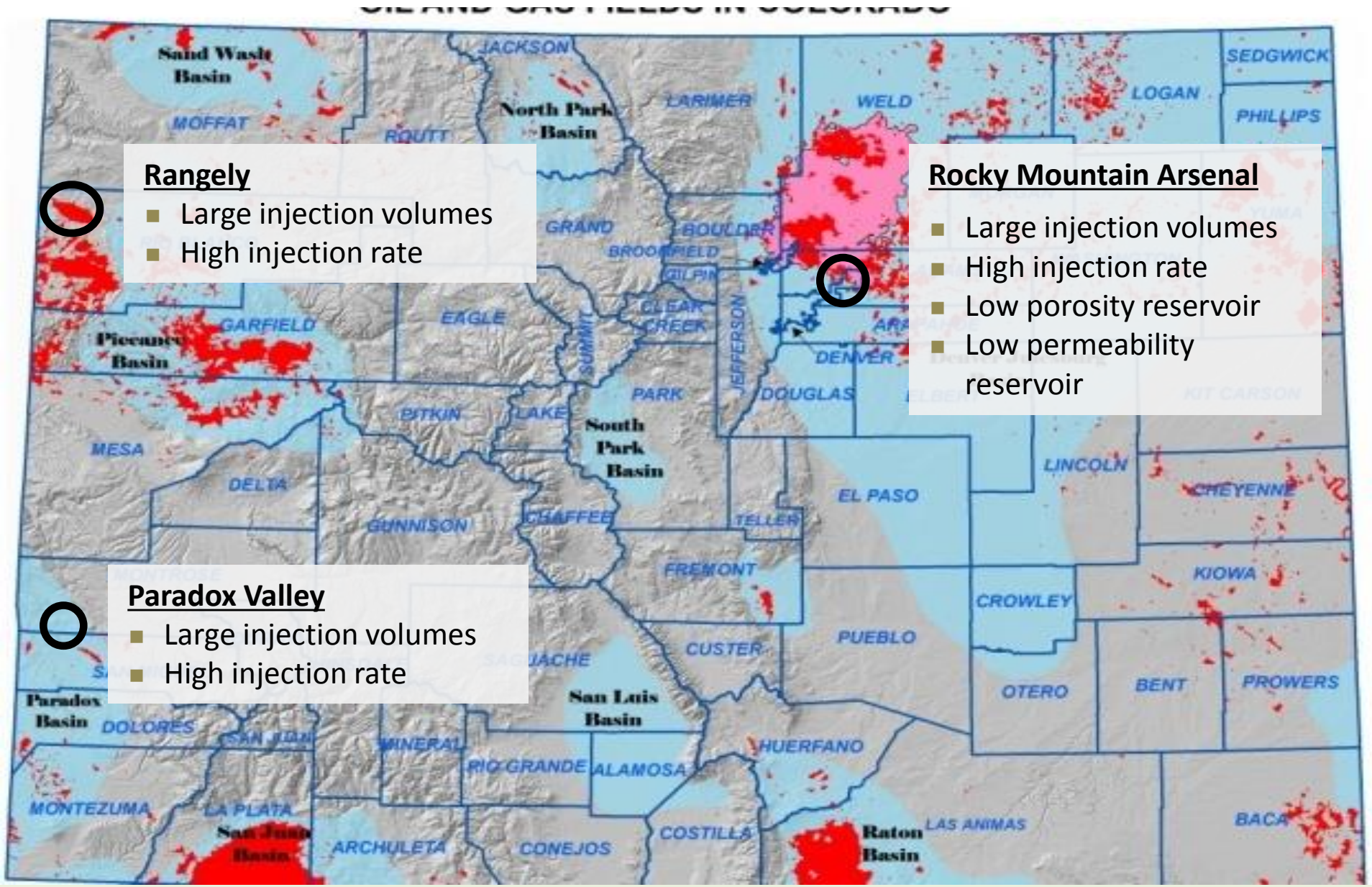
USGS Epicenters (through 9/30/14)





Prague, OK sequence (11/5/11; M 4.8 - 5.6 – 4.8 – 4.8); Reactivation of the Pennsylvanian (~310 My old) Wilzetta Fault system; See: Keranen et al. (2013); Sumy et al. (2014)

Historical Examples of Induced Seismicity in Colorado



Rangely

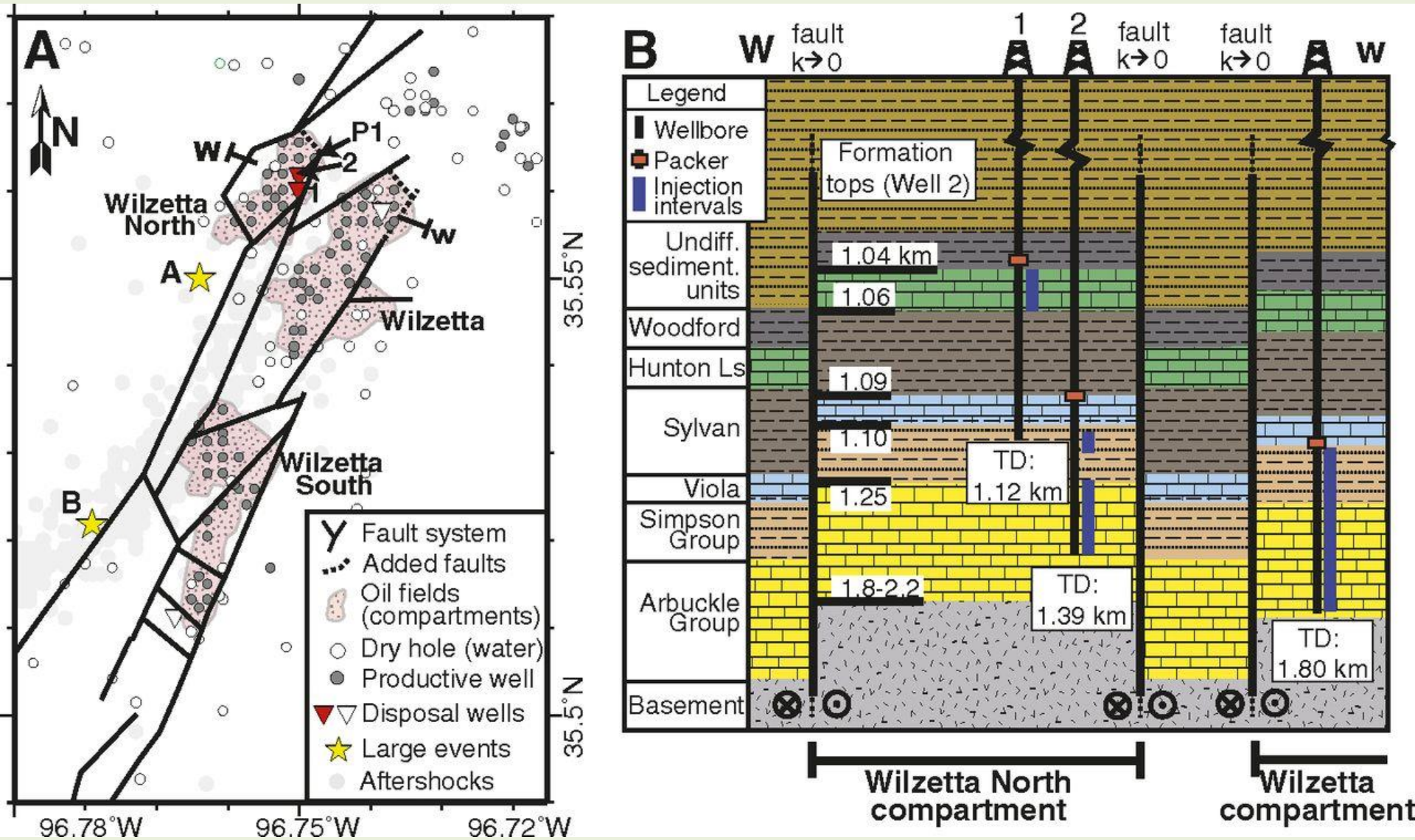
- Large injection volumes
- High injection rate

Rocky Mountain Arsenal

- Large injection volumes
- High injection rate
- Low porosity reservoir
- Low permeability reservoir

Paradox Valley

- Large injection volumes
- High injection rate


A
N
W
P1
2
1
w
Wilzetta North
A
Wilzetta
Wilzetta South
B
Fault system
Added faults
Oil fields (compartments)
Dry hole (water)
Productive well
Disposal wells
Large events
Aftershocks
35.55°N
35.5°N
96.78°W
96.75°W
96.72°W
B
W
fault k→0
1
2
fault k→0
fault k→0
W
Legend
Wellbore
Packer
Injection intervals
Formation tops (Well 2)
Undiff. sediment. units
Woodford
Hunton Ls
Sylvan
Viola
Simpson Group
Arbuckle Group
Basement
1.04 km
1.06
1.09
1.10
1.25
1.8-2.2
TD: 1.12 km
TD: 1.39 km
TD: 1.80 km
Wilzetta North compartment
Wilzetta compartment