

# Induced Earthquakes

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[Earthquake.colorado.edu](http://Earthquake.colorado.edu)



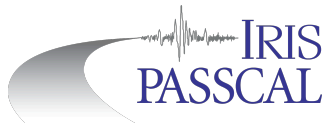
University of Colorado  
Boulder



Acknowledgements –

Jenny Nakai, Megan Brown, Shemin Ge – CU

Will Yeck, Harley Benz, Justin Rubinstein – USGS



*October 24, 2017 Morgan County Stakeholder Meeting*



# Outline

Induced Earthquakes definitions and causes

Historic Induced earthquakes

Recent Induced earthquakes

Weld County – Greeley earthquakes

Morgan County – current status

Lessons learned, recommendations



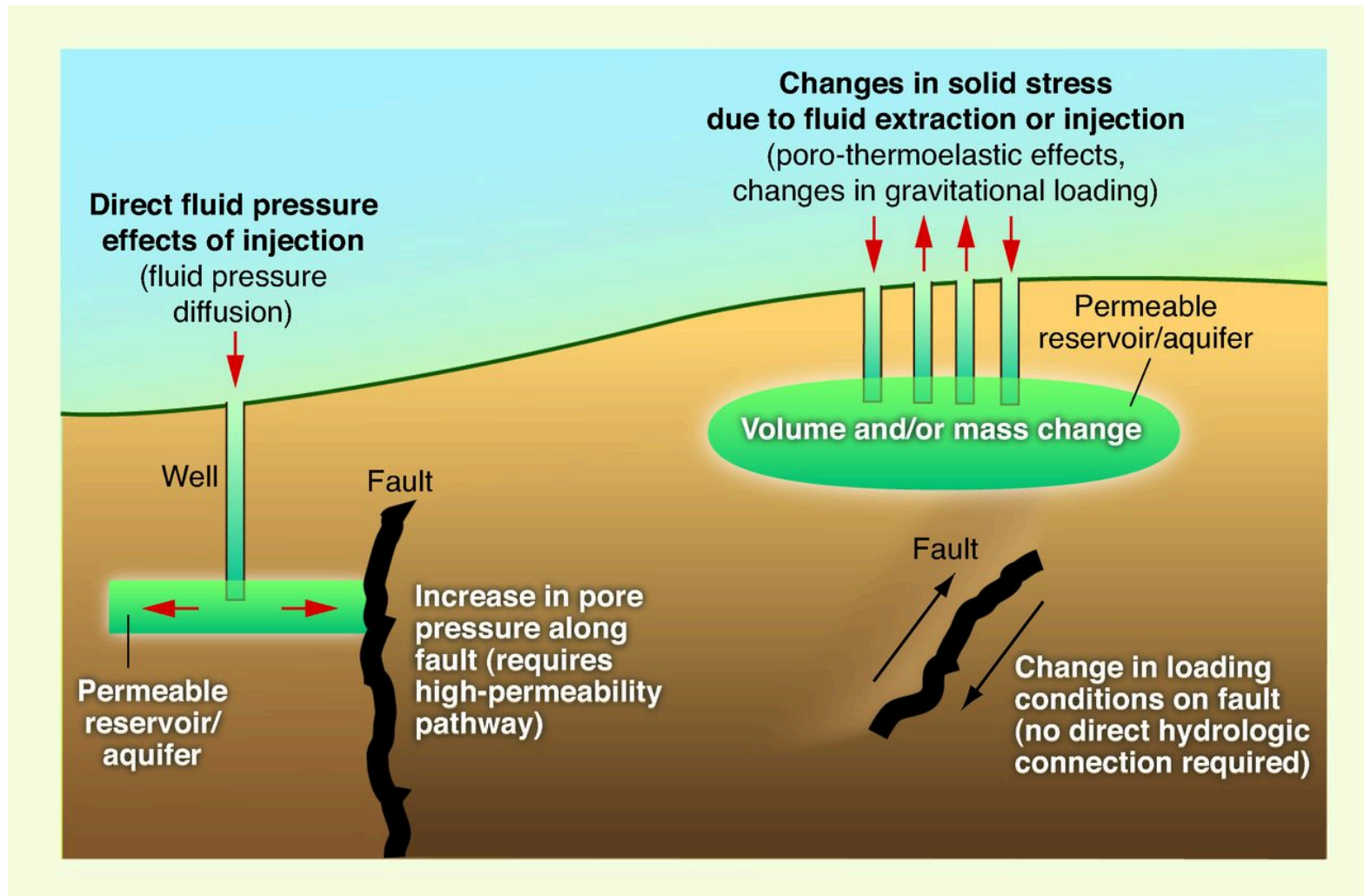
# What is an induced earthquake?

- An earthquake caused by human activities
- Examples –
  - Mining induced
  - Reservoir Impoundment
  - Fluid extraction
  - Enhanced Oil Recovery
  - **Fluid injection**
  - Hydraulic fracturing

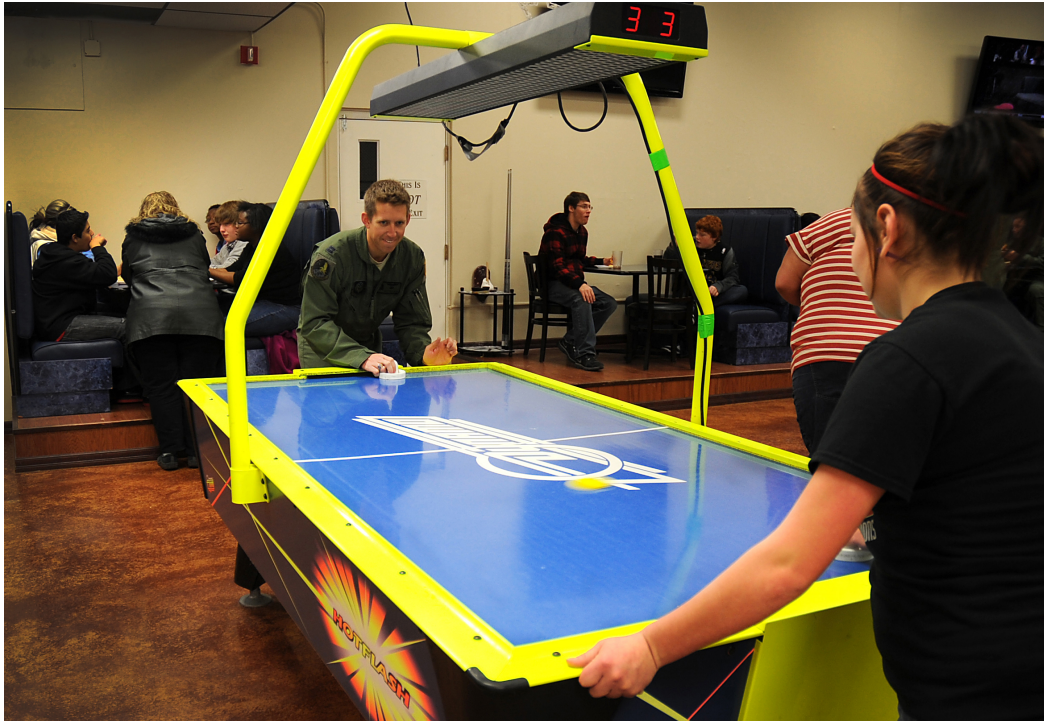


1967 Koyna India earthquake. 180 people killed. Reservoir induced. Magnitude 6.5.

**Schematic diagram of mechanisms for inducing earthquakes.** Earthquakes may be induced by increasing the pore pressure acting on a fault (left) or by changing the shear and normal stress acting on the fault (right).

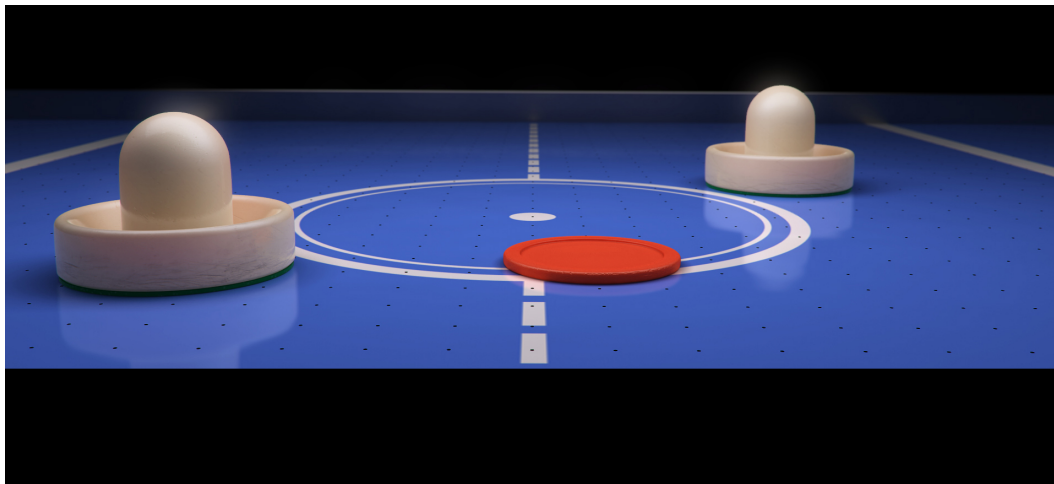


William L. Ellsworth Science 2013;341:1225942

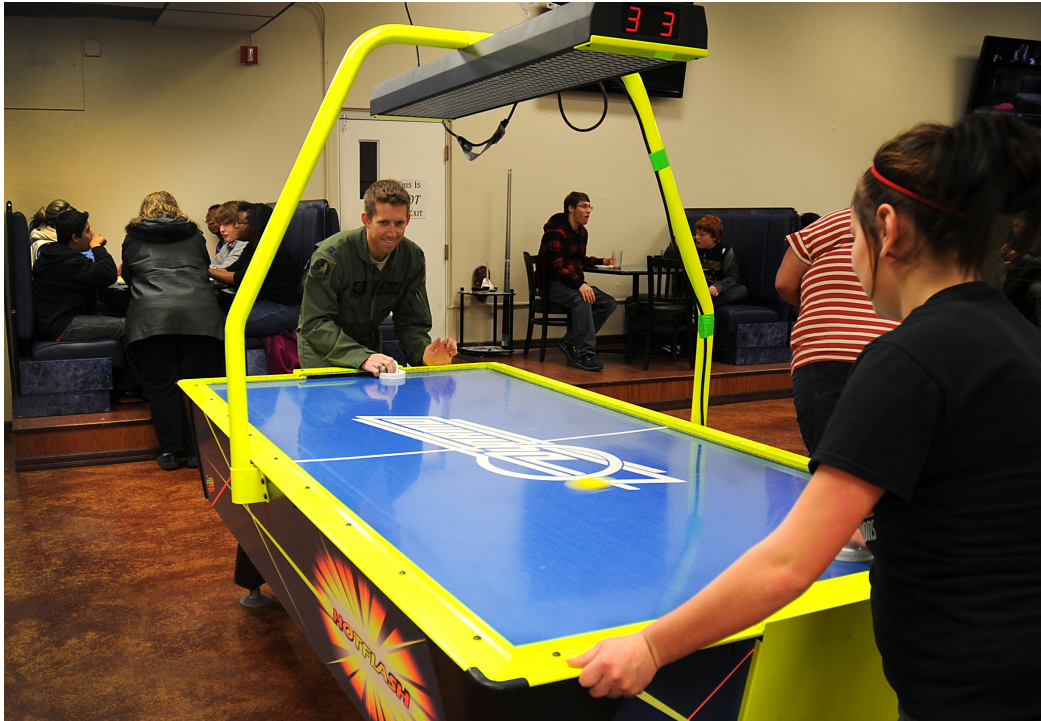


## Air hockey analogy to fluid injection-induced seismicity

When the air is off, the puck doesn't move, but turning the air on reduces the friction between puck and table and it slides easily.



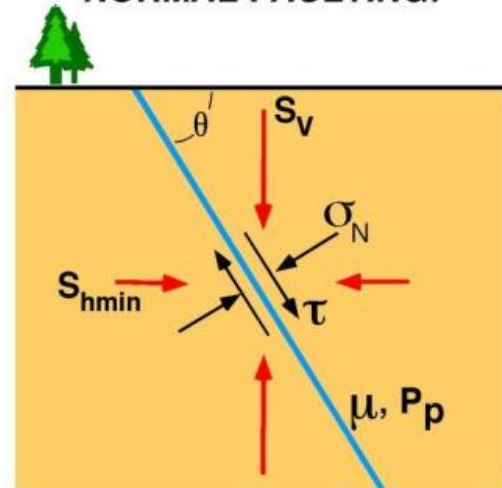




# Air hockey analogy to fluid injection-induced seismicity

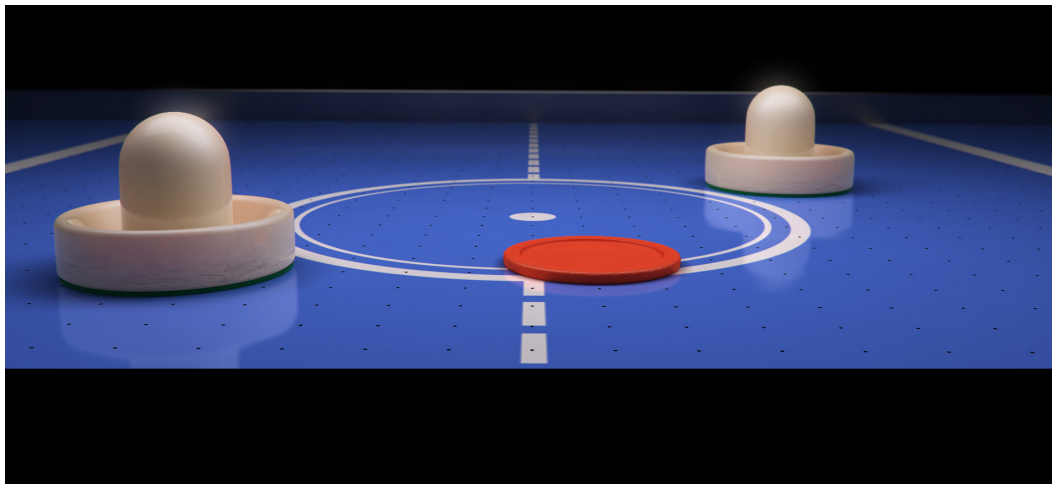
When the air is off, the puck doesn't move, but turning the air on reduces the friction between puck and table and it slides easily.

**COULOMB FAILURE LAW,  
NORMAL FAULTING:**



$$\tau_{\text{critical}} = \mu (\sigma_N - P_p) + S$$

$$\mu = 0.6 - 1.0 \text{ (Byerlee's Law)}$$

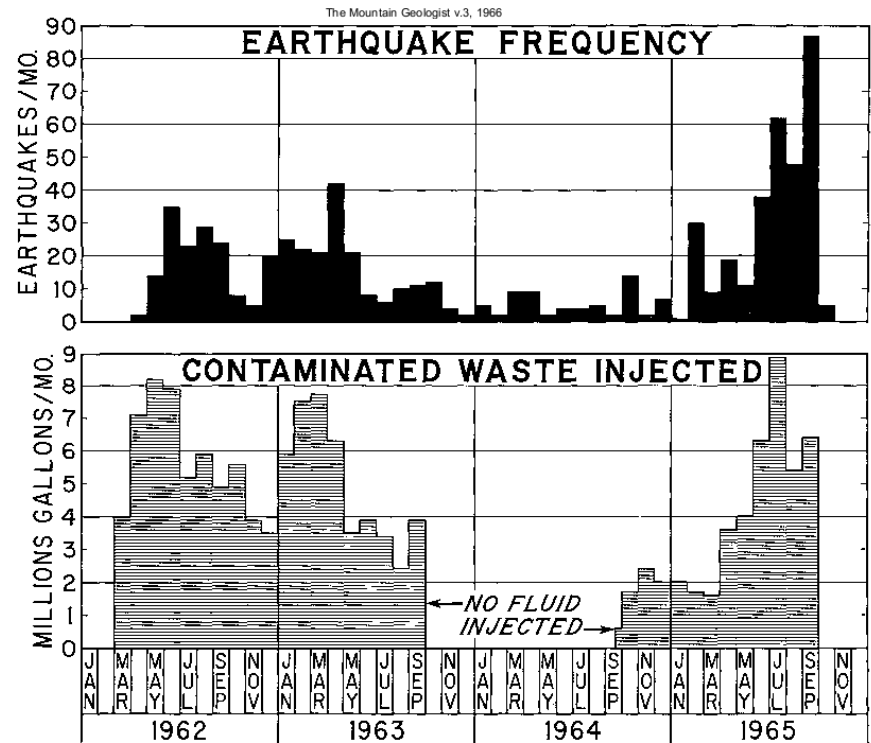




# The discovery of injection-induced earthquakes: **Rocky Mountain Arsenal**



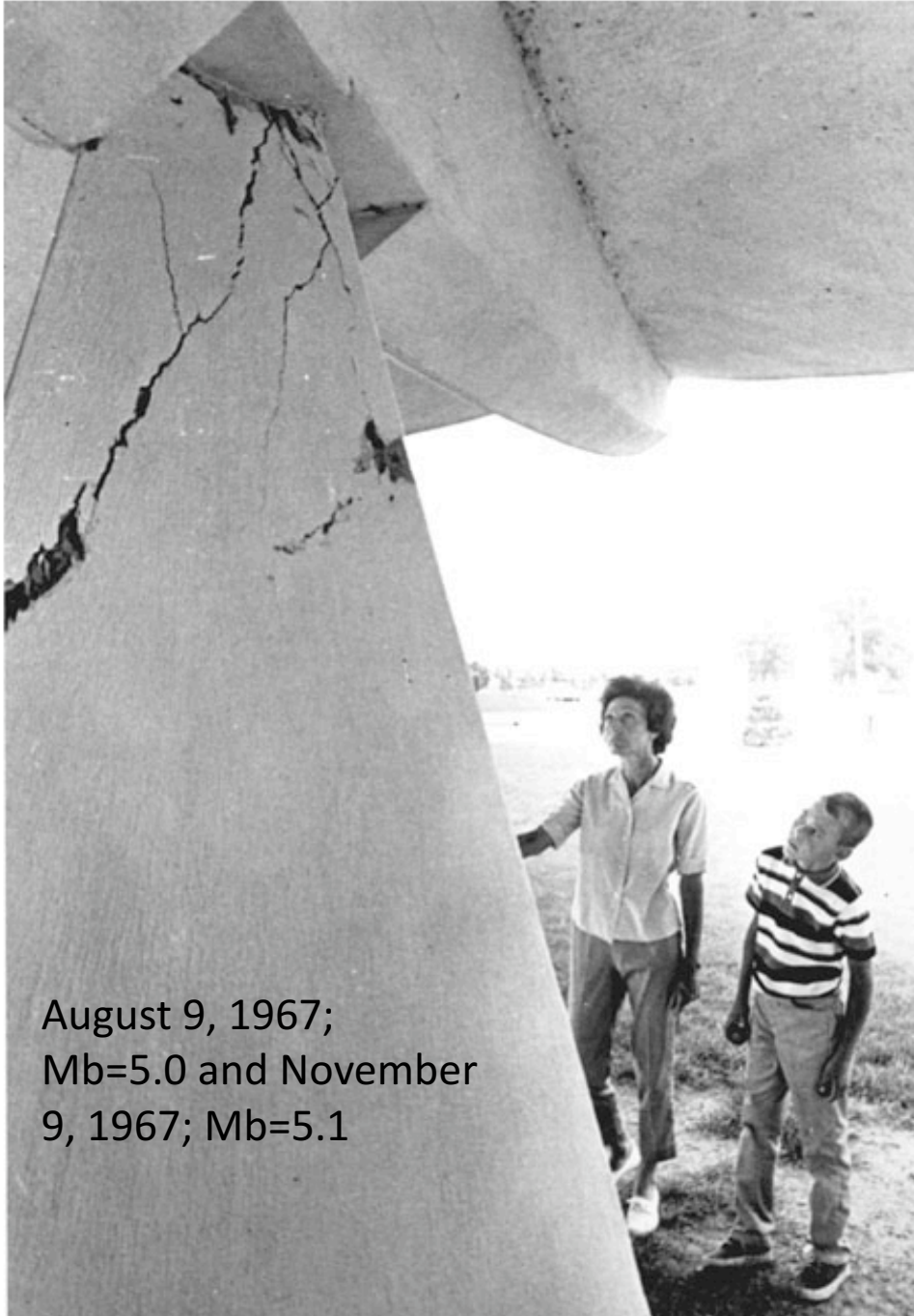
- Fluid injection begins 1962
  - 130,000 barrels/month
- Earthquakes began shortly after injection



Evans, D.M. (1966), The Denver Area Earthquakes and the Rocky Mountain Arsenal Well, *The Mountain Geologist*.

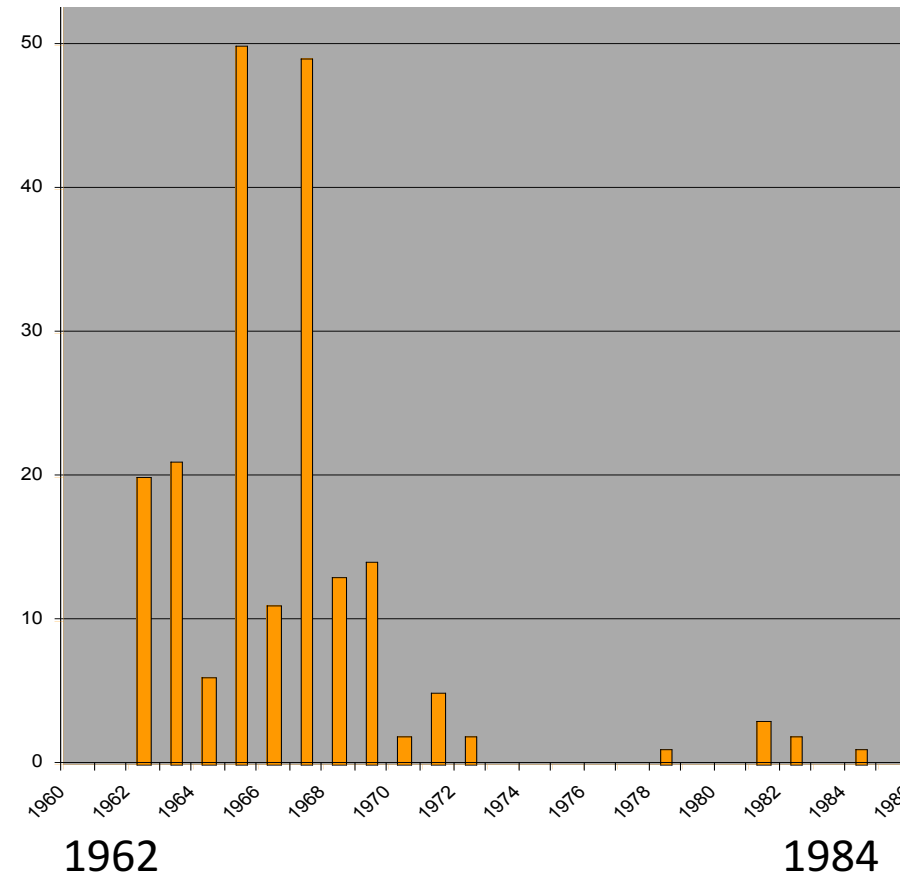
# Denver Earthquakes Rocky Mountain Arsenal 1962-1984

Cracks in highway overpass; concrete pillars damaged at a church; foundations, concrete floors, and walls cracked; windows broken.



August 9, 1967;  
Mb=5.0 and November  
9, 1967; Mb=5.1

Cracks in highway overpass pillar in the Denver, Colorado, area caused by the August 9, 1967, earthquake. (Photograph by the Denver Post.)



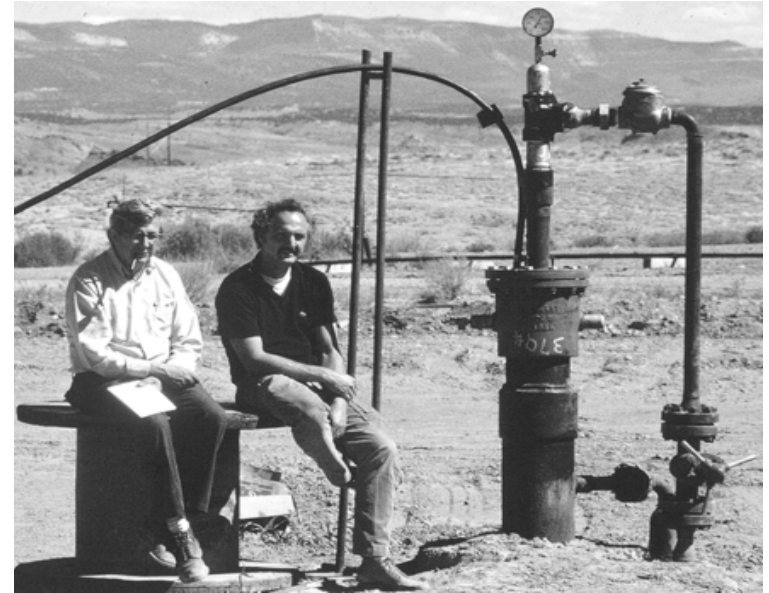
# Rangely, Colorado

USGS researchers carried out a controlled induced seismicity experiment from 1970 - 1974 (Raleigh et al., 1976) in cooperation with Chevron Oil Company in the Rangely oil field.

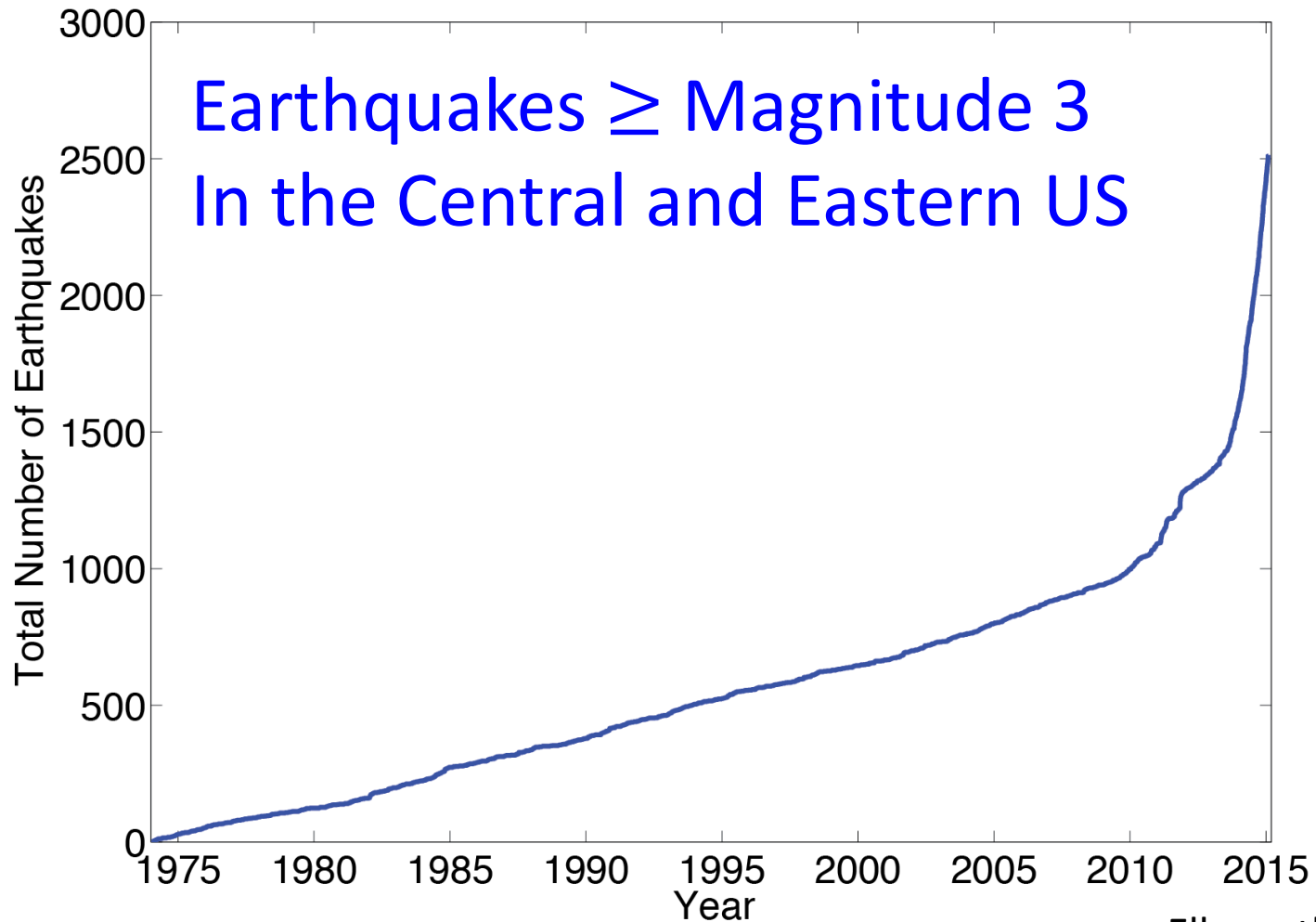
Tested whether pore pressure increases would cause earthquakes.

Turned seismic events “on” and “off” by cycling the pore pressures above and below the critical reservoir pore pressure.

Raleigh, C.B., Healy, J.H. and Bredehoeft, J.T, 1976, *An Experiment in Earthquake Control at Rangely, Colorado*; *Science*, v. 191, p. 1230-1237.

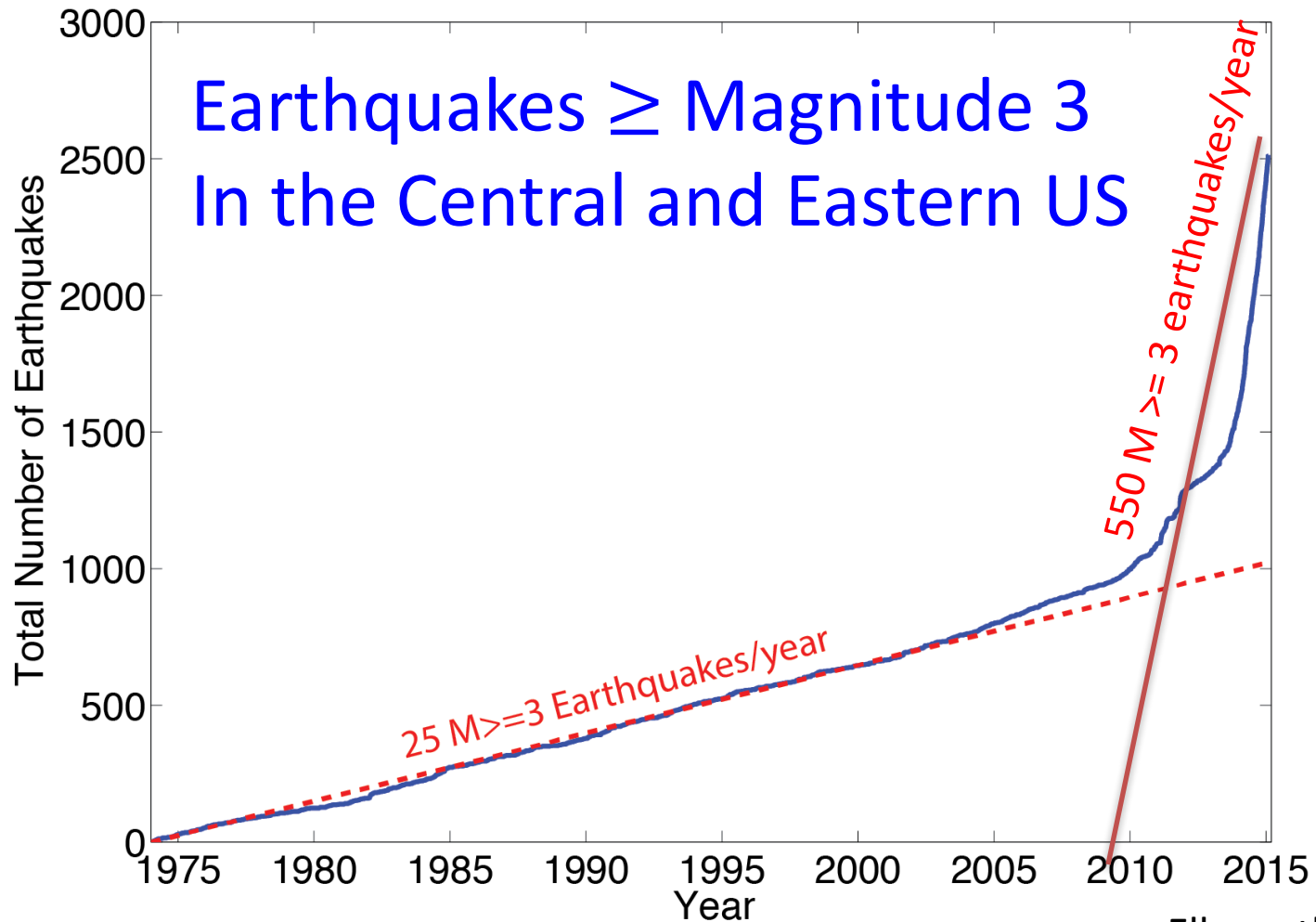


# Why are Induced Earthquakes Suddenly an Issue?





# Why are Induced Earthquakes Suddenly an Issue?



# Why are Induced EQs Suddenly an Issue?

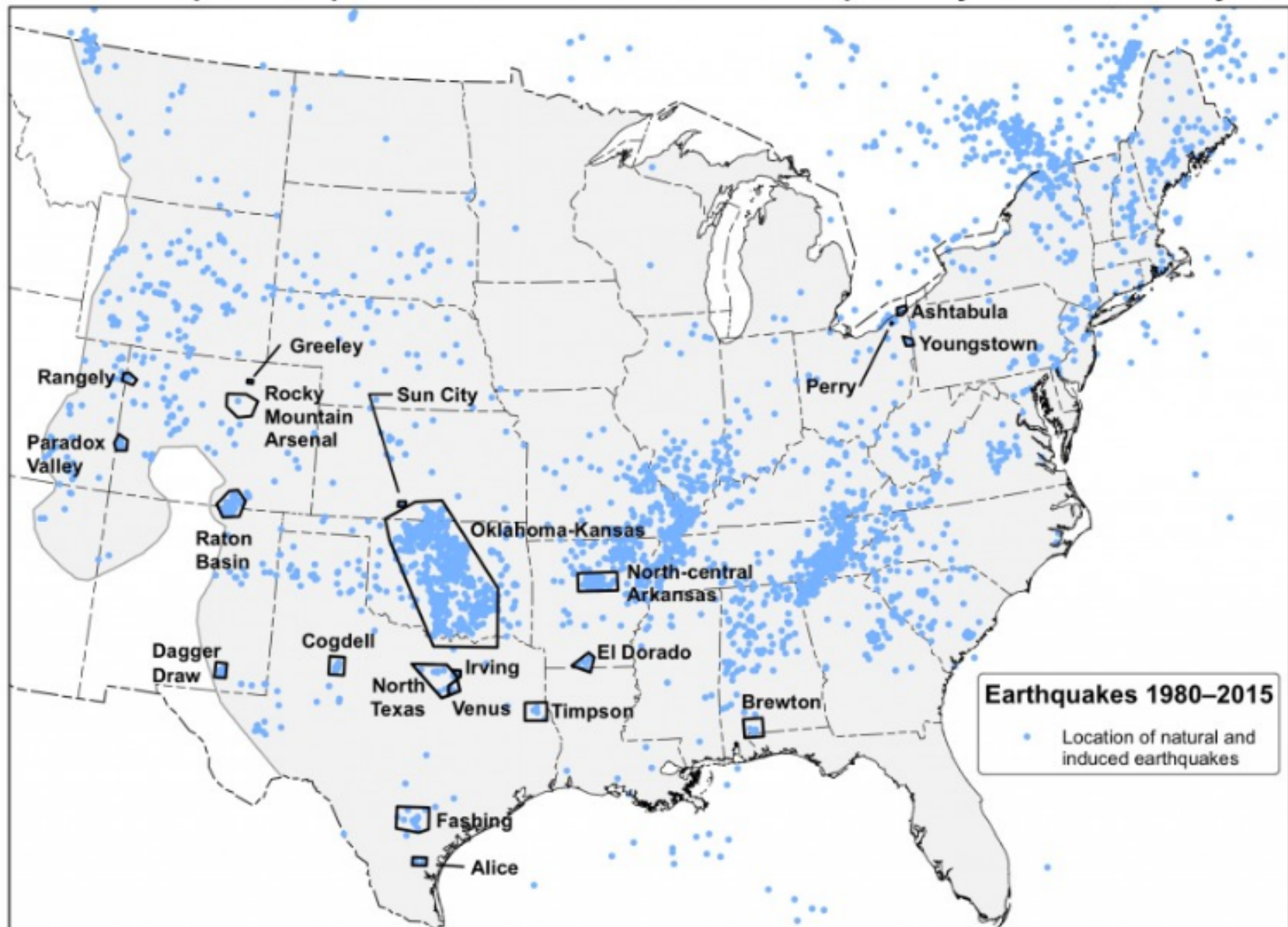


Damage from M5.3 Trinidad, CO Earthquake

Damage from M5.6 Prague, OK Earthquake



## USGS Map of Earthquakes since 1980 and Recent Areas Impacted by Induced Seismicity

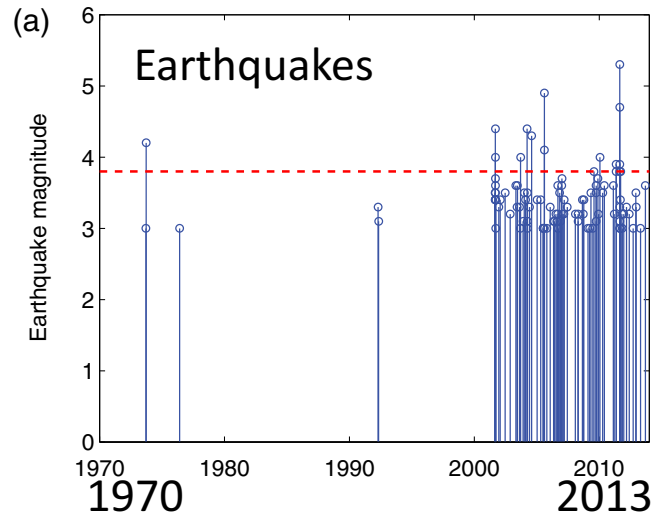


USGS map displaying 21 areas where scientists have observed rapid changes in seismicity that have been associated with wastewater injection. The map also shows earthquakes—both natural and induced—recorded from 1980 to 2015 in the central and eastern U.S. with a magnitude greater than or equal to 2.5.

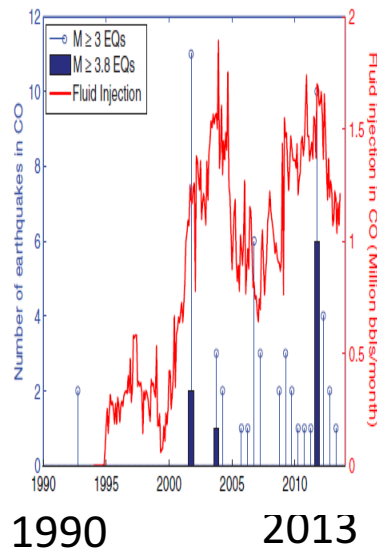
<https://pubs.er.usgs.gov/publication/ofr20161035>



# Raton Basin, Colorado



Fluid  
Injection



*Rubinstein et al., 2014*



AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Solid Earth

## RESEARCH ARTICLE

10.1002/2017JB014415

### Key Points:

- We infer a 20 km long Vermejo Park fault from seismicity that shows pore pressure changes of 0.08 MPa by 2008
- Pore pressure modeling shows changes up to 0.50 MPa, despite an underpressured disposal interval not in direct contact with the basement
- The number of earthquakes and

## A Possible Causative Mechanism of Raton Basin, New Mexico and Colorado Earthquakes Using Recent Seismicity Patterns and Pore Pressure Modeling

J. S. Nakai<sup>1,2</sup>, M. Weingarten<sup>3</sup>, A. F. Sheehan<sup>1,2</sup>, S. L. Bilek<sup>4</sup>, and S. Ge<sup>1</sup>

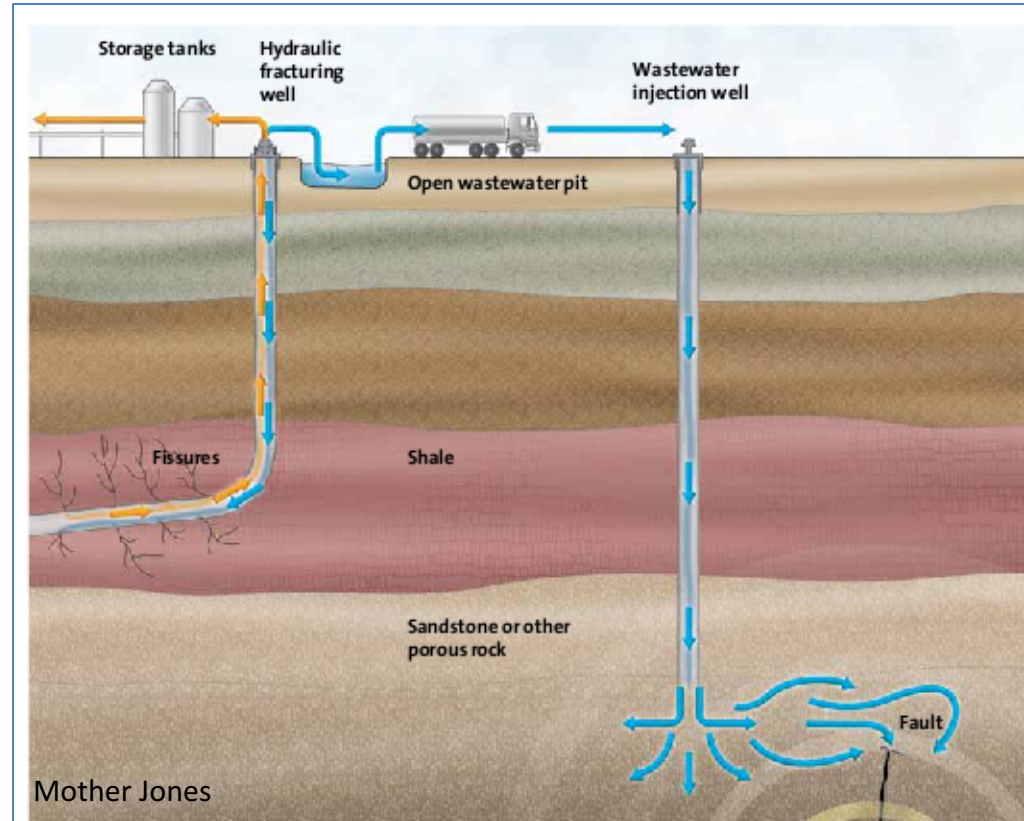
<sup>1</sup>Department of Geological Sciences, University of Colorado Boulder, Boulder, CO, USA, <sup>2</sup>Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, Boulder, CO, USA, <sup>3</sup>Department of Geophysics, Stanford University, Stanford, CA, USA, <sup>4</sup>Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM, USA

*Nakai et al., 2017*



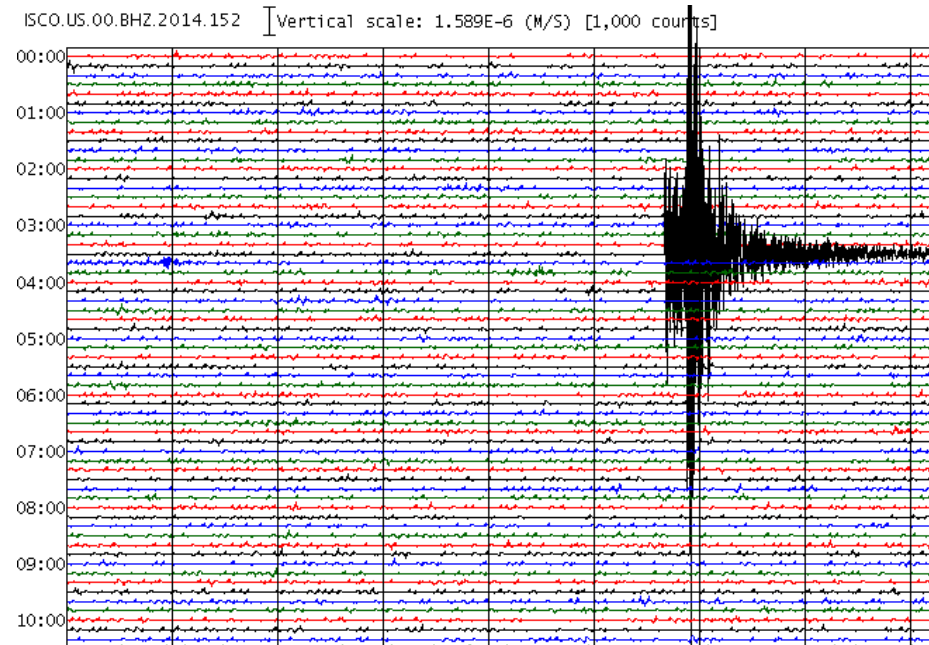
# Wastewater Disposal

- Wastewater is produced at nearly every oil and gas well, not just hydraulic fracturing sites
- Wastewater is disposed of in deep wells by injecting into porous formations
- Inject for years or more
- Up to 1 million barrels/month
- ~180,000 Class II disposal wells in the US



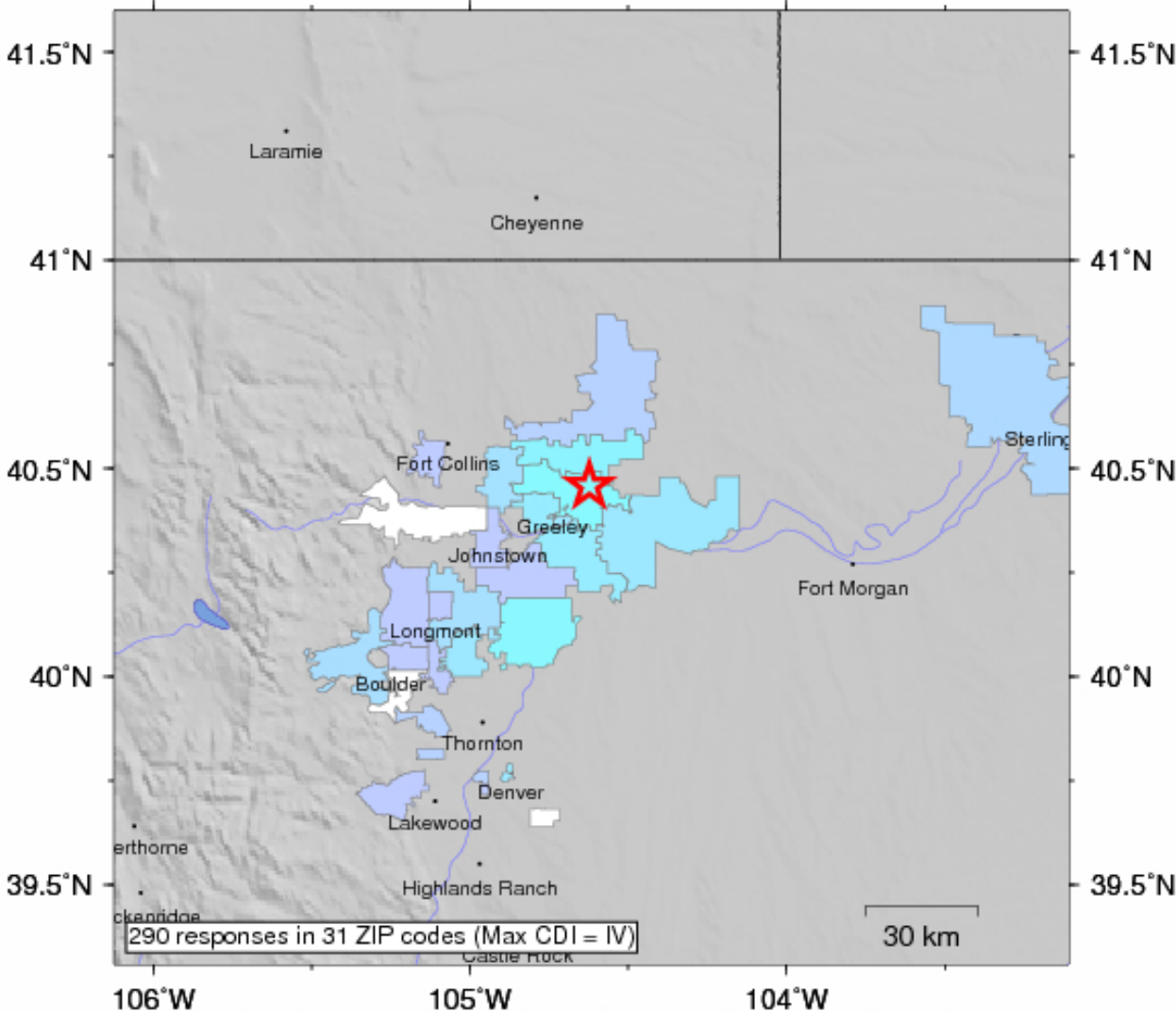
# Earthquakes in Weld County

- Widely felt earthquake near Greeley on June 1, 2014
- No prior seismicity nearby
- Closest prior earthquakes were the Rocky Mountain Arsenal earthquakes



USGS Community Internet Intensity Map  
COLORADO

May 31 2014 09:35:21 PM local 40.4582N 104.623W M3.2 Depth: 1 km ID:usc000r9pp



Greeley earthquake,  
May 31, 2014  
Magnitude 3.2

USGS DYFI (Did you  
feel it) report

290 responses

Felt over 60 miles  
away from the  
epicenter

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

| 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: Sat Jun 14 01:35:17 2014



# Geophysicists collecting data from farm near epicenter of Greeley earthquake

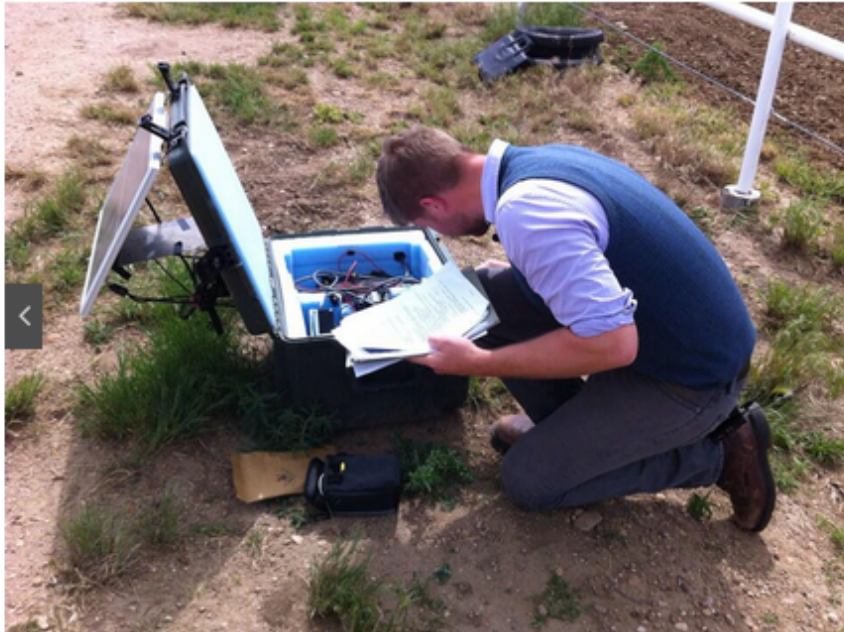


BY: Lance Hernandez

POSTED: 12:06 PM, Jun 11, 2014

UPDATED: 7:03 PM, Jun 11, 2014

TAG: weld county | greeley | earthquake | wastewater injection wells | seismographs



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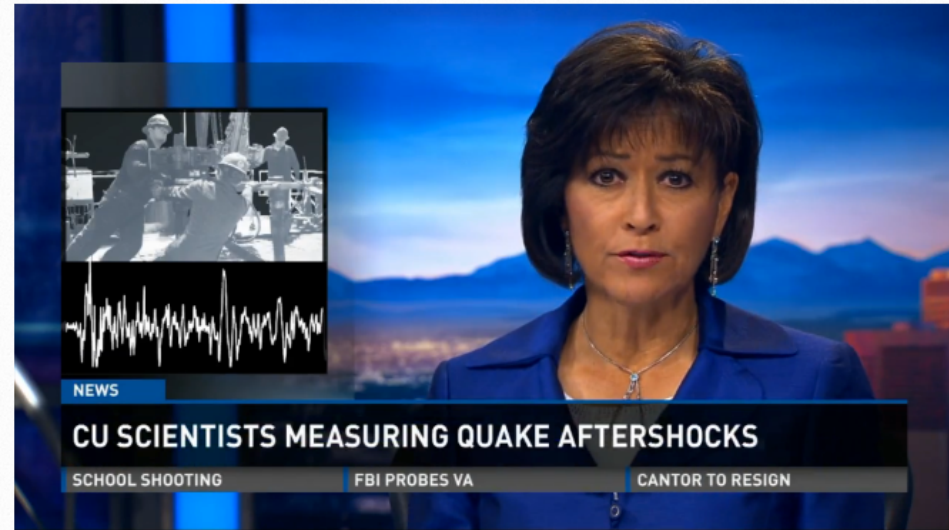


RELATED

GREELEY, Colo. - The 3.4 magnitude earthquake that struck Weld County on May 31 caused very little damage, but it did raise concerns about fracking and wastewater injection.

CU researchers say it's way too early to know whether the tremor was induced or occurred naturally, but they're trying to find out.

## What caused Greeley earthquake?



What caused Greeley earthquake? 9NEWS at 4 p.m. 06/11/14.

KUSA 6:44 p.m. MDT June 11, 2014



(Photo: KUSA)

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GREELEY - Researchers from the University of Colorado-Boulder have put seismic monitors around Weld County to measure aftershocks in the hopes of discovering just what caused the May 31 earthquake.

It was the first quake there in decades and the first that most people can remember. The goal is to pinpoint the exact epicenter of the quake, both in terms of depth and location on a map.

MORE STORIES



Turning 15 on 12/13/14  
Dec. 13, 2014, 8:53 p.m.



Saint Joseph moves to new location



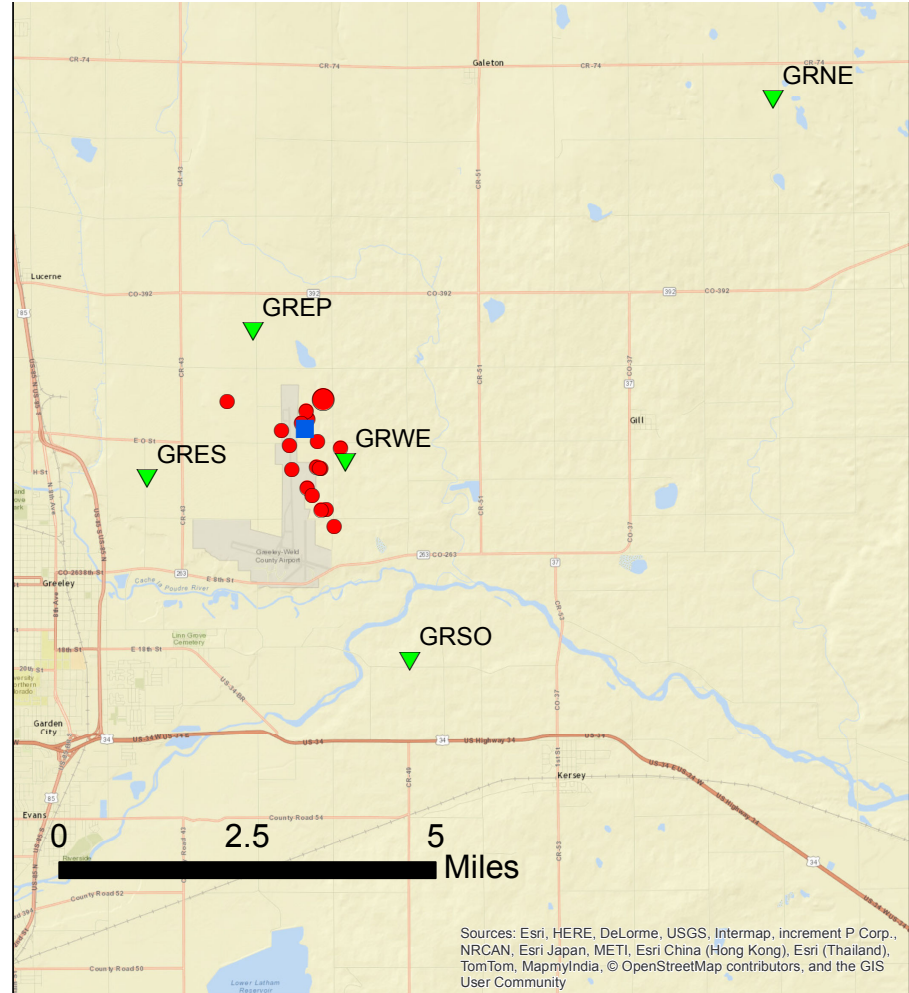
## June 8-20, 2014 earthquakes

## First aftershock locations from CU study.

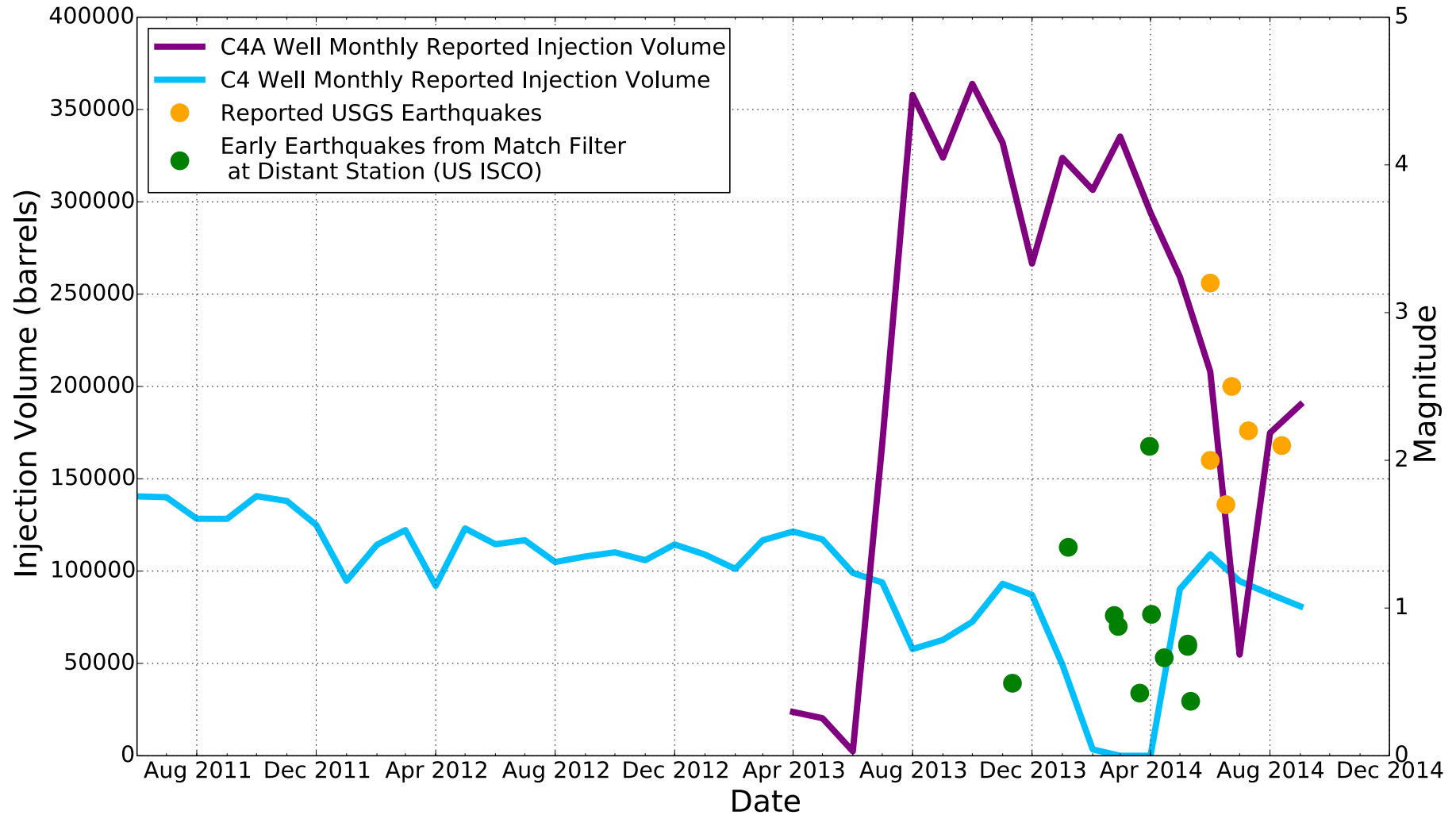
Large red circle is USGS epicenter.

Blue square is C4a well.

Green inverted triangles are CU temporary seismic stations. Station GRES was telemetered to USGS.



# Injection History and Earthquakes, Greeley



Used matched filter to search for earthquakes prior to May 31, 2014 felt earthquake.  
No earthquakes found from 8/11-10/13, first earthquake match November 2013.  
C4A high volume injection started July 2013.

# Colorado officials shut down drilling waste well in Greeley after 2nd earthquake in less than month



BY: [Jaclyn Allen \(mailto:jaclyn@thedenverchannel.com\)](mailto:jaclyn@thedenverchannel.com)

POSTED: 5:11 PM, Jun 24, 2014

UPDATED: 11:02 PM, Jun 24, 2014



Colorado officials ordered the shutdown of an oil and gas wastewater well near Greeley after two earthquakes rattled the area.

VIDEO BY KMGH



Trenton Sperry  
[tsperry@greeleytribune.com](mailto:tsperry@greeleytribune.com)

Back to:  
June 24, 2014

## After second Greeley earthquake, COGCC orders halt of nearby wastewater injection well

After a second earthquake northeast of Greeley, the Colorado Oil and Gas Conservation Commission has asked High Sierra Water Services to stop disposing wastewater into one of its injection wells.

The request came after a team of University of Colorado seismologists tracked a 2.6-magnitude earthquake Monday afternoon in the area. The team began monitoring the region after a 3.4-magnitude earthquake May 31.

High Sierra agreed Monday to a 20-day halt to wastewater injection as a precaution.

"High Sierra has been entirely cooperative," said COGCC Director Matt Lepore. "Their big point has I think been the same as ours, which is let's get the best available scientific data and act accordingly."



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### ENVIRONMENT

2:49 PM  
Tue June 24, 2014

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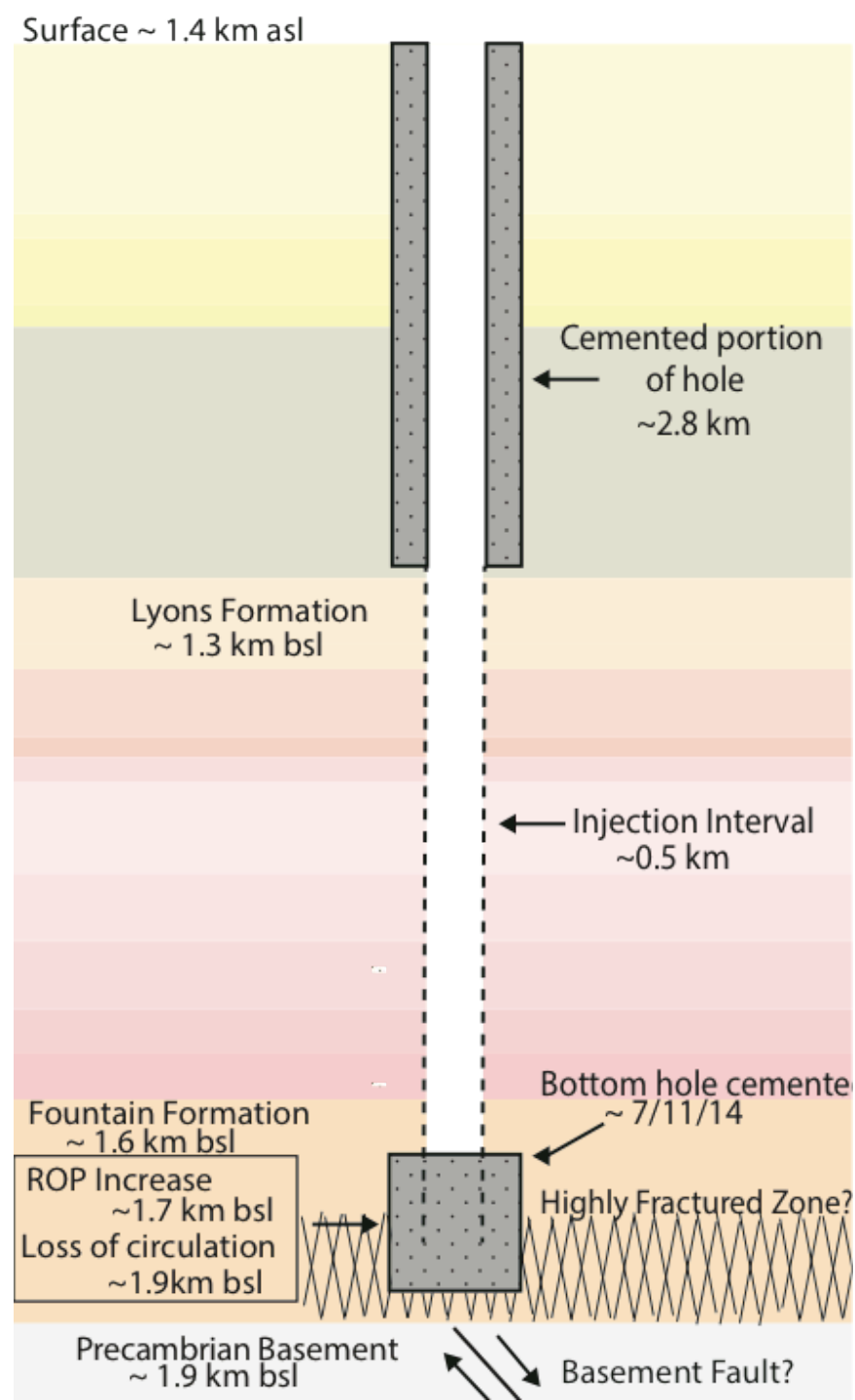
## Injection Well Halted By COGCC As Greeley Quakes Again

By [Stephanie Paige Ogburn](#)

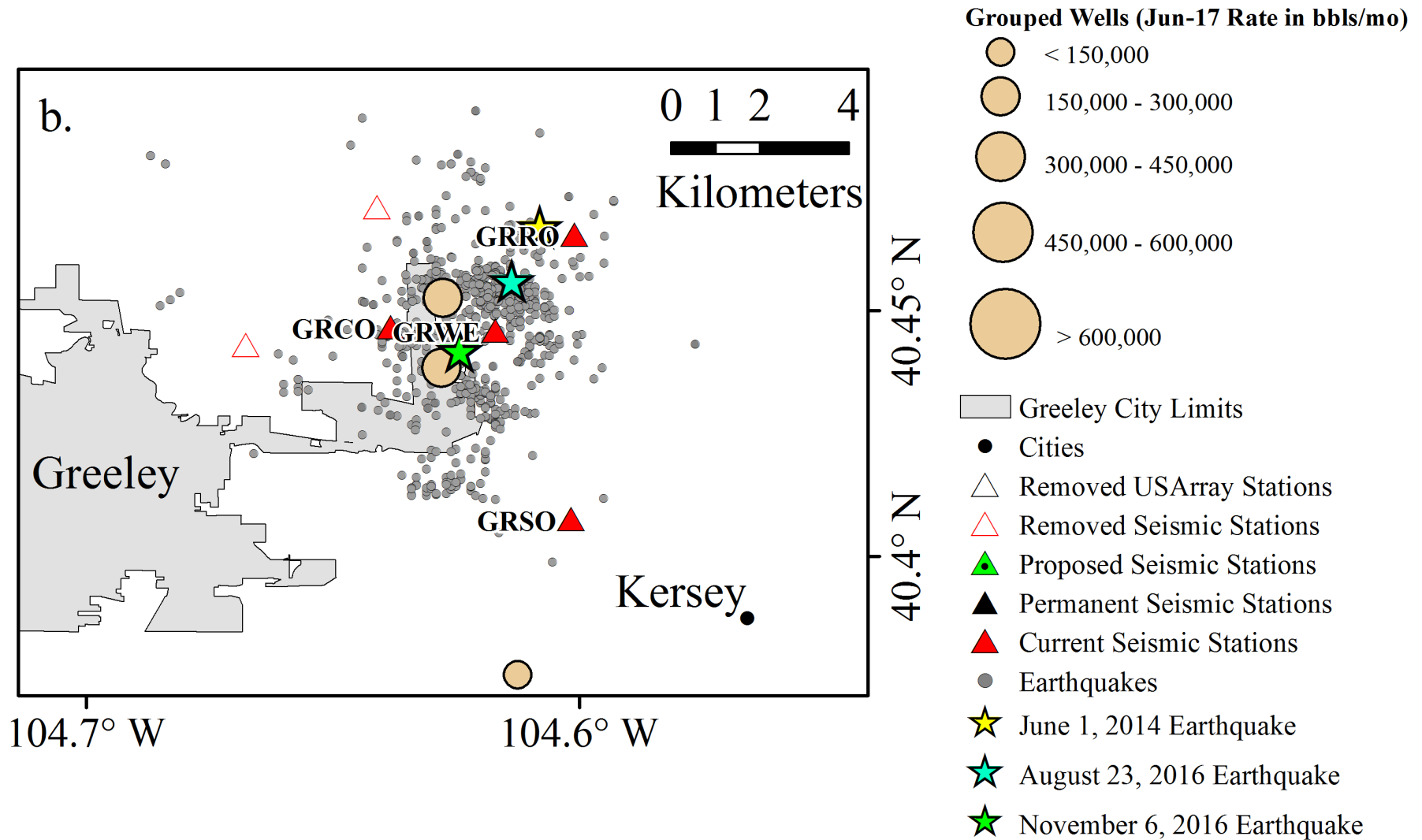


Jenny Nakai, a seismologist and doctoral student and Matthew Weingarten, a hydrogeologist and doctoral candidate from the University of Colorado align, level and bury a seismometer outside of Gill, Colo., June 4, 2014.

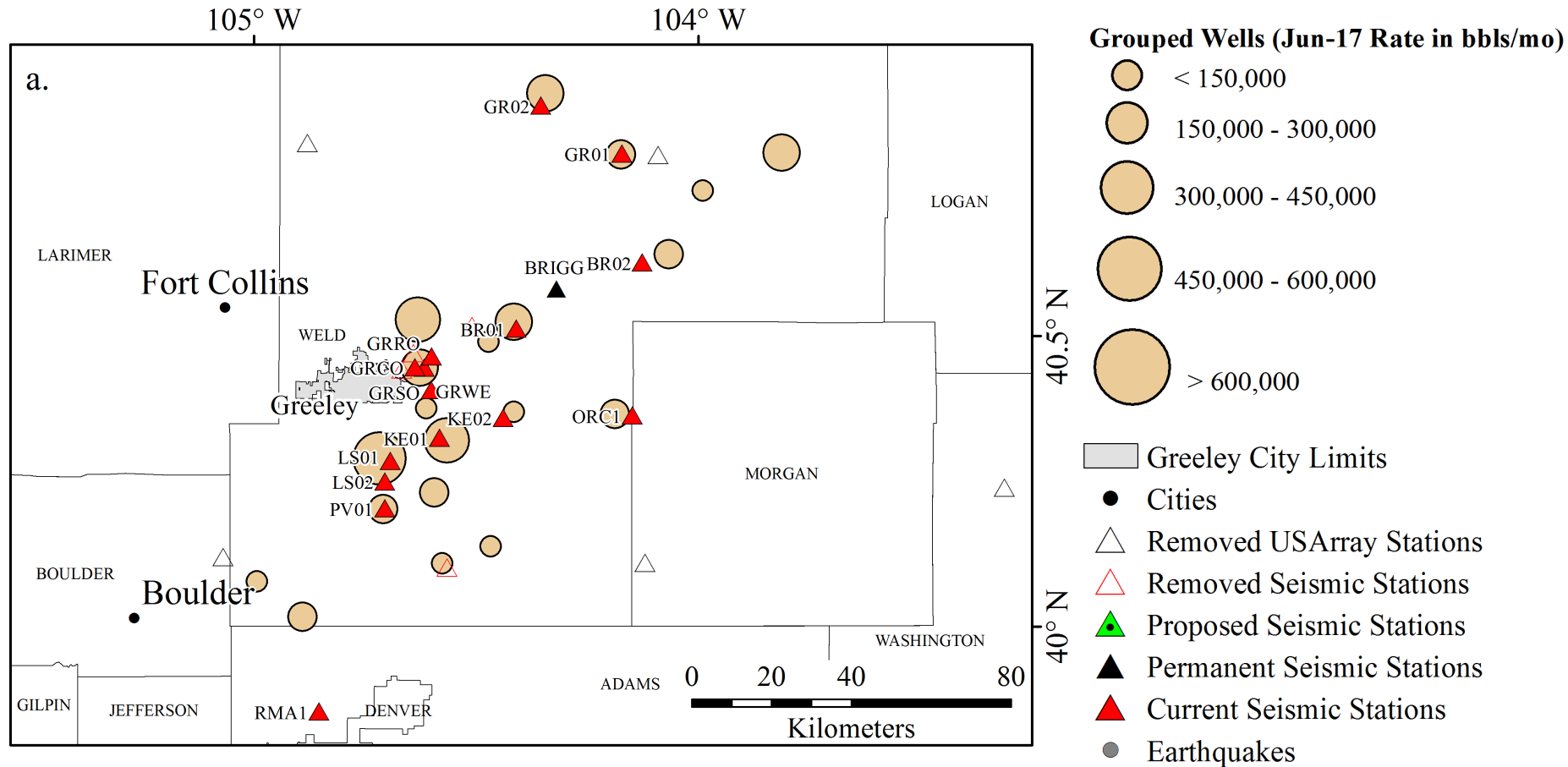
Greeley C4A well  
modifications



## Continued seismic monitoring in Greeley area



# Ongoing research: Seismometers and Injection Wells in Weld County



Morgan County: No 'deep' wells, injection rates are low, no earthquakes



# Denver Basin Stratigraphic Column

**Figure 2.** Stratigraphic section of rock units in outcrop and the adjacent Denver Basin. Light blue zones are periods of erosion or nondeposition. Green text marks formations that produce oil and (or) gas. Red text marks formations that have the potential to produce coal-bed methane. Hydrocarbon source rocks are marked with purple text. Sources of information include Hoyt (1963), Momper (1963), Irwin (1976), Sonnenberg and Weimer (1981), Higley and Schmoker (1989), Hjellming (1993), and MacLachlan and others (1996).

| NORTHERN FRONT RANGE, OUTCROP |                                            |                                        |                                       |                        | ADJACENT DENVER BASIN                                |                              |                         |  |  |
|-------------------------------|--------------------------------------------|----------------------------------------|---------------------------------------|------------------------|------------------------------------------------------|------------------------------|-------------------------|--|--|
| QUAT.                         | Undifferentiated alluvial deposits         |                                        |                                       |                        | Undifferentiated alluvial deposits                   |                              |                         |  |  |
| TERTIARY                      |                                            |                                        |                                       |                        |                                                      |                              |                         |  |  |
|                               | Undifferentiated boulder & gravel deposits |                                        |                                       |                        |                                                      |                              |                         |  |  |
|                               |                                            |                                        |                                       |                        |                                                      |                              |                         |  |  |
| UPPER CRETACEOUS              | Denver Formation                           |                                        |                                       |                        | Castle Rock Conglomerate<br>Dawson-Denver Formations |                              |                         |  |  |
|                               | Arapahoe Formation                         |                                        |                                       |                        | Arapahoe Formation                                   |                              |                         |  |  |
|                               | Laramie Formation                          |                                        |                                       |                        | Laramie Formation                                    |                              |                         |  |  |
|                               | Fox Hills Sandstone                        |                                        |                                       |                        | Fox Hills Sandstone                                  |                              |                         |  |  |
|                               | Pierre Shale                               | Richard Sandstone Mbr.                 |                                       |                        | Pierre Shale                                         | Terry "Sussex" Ss. Member    |                         |  |  |
|                               |                                            | Terry Sandstone Mbr.                   |                                       |                        |                                                      | Hygiene "Shannon" Ss. Member |                         |  |  |
|                               |                                            | Hygiene Sandstone Mbr.                 |                                       |                        |                                                      | Sharon Springs Member        |                         |  |  |
|                               | Niobrara Formation                         | Smoky Hill Shale Mbr.                  |                                       |                        |                                                      | Niobrara Formation           | Smoky Hill Shale Member |  |  |
|                               |                                            | Fort Hays Limestone Mbr.               |                                       |                        | Fort Hays Limestone Member                           |                              |                         |  |  |
|                               |                                            | Codell Sandstone Mbr.<br>Carlile Shale |                                       |                        | Codell Sandstone Member<br>Carlile Shale             |                              |                         |  |  |
|                               | Greenhorn Limestone                        |                                        |                                       |                        | Greenhorn Limestone                                  |                              |                         |  |  |
|                               | Graneros Shale                             |                                        |                                       |                        | Graneros Shale "D" sandstone                         |                              |                         |  |  |
| Mowry Shale                   |                                            |                                        |                                       | Mowry Shale equivalent |                                                      |                              |                         |  |  |
| LOWER CRETACEOUS              | Dakota Group                               | South Platte Fm.                       | South                                 |                        | North                                                |                              | Muddy ("J") Sandstone   |  |  |
|                               |                                            |                                        | Upper members, South Platte Formation |                        | Muddy ("J") Sandstone                                |                              |                         |  |  |
|                               |                                            |                                        | Skull Creek Shale                     |                        | Skull Creek Shale                                    |                              |                         |  |  |
|                               |                                            |                                        | Plainview Ss. Member                  |                        | "Dakota" of drillers                                 |                              |                         |  |  |
|                               |                                            | Lytle Formation                        |                                       |                        |                                                      | "Lakota" of drillers         |                         |  |  |
| JURASSIC                      | Morrison Formation                         |                                        |                                       |                        | Morrison Formation                                   |                              |                         |  |  |
|                               | Ralston Creek Formation                    |                                        |                                       |                        | Older Jurassic rocks may be present                  |                              |                         |  |  |
|                               | Sundance Formation                         |                                        |                                       |                        |                                                      |                              |                         |  |  |
| TRI.                          | Jelm Formation                             |                                        |                                       |                        | Jelm Formation                                       |                              |                         |  |  |
| PERMIAN                       | Lykins Formation                           |                                        |                                       |                        | Lykins Formation                                     |                              |                         |  |  |
|                               | Lyons Sandstone                            |                                        |                                       |                        | Lyons Sandstone                                      |                              |                         |  |  |
|                               | Owl Canyon Formation                       |                                        |                                       |                        | Owl Canyon Formation                                 |                              |                         |  |  |
|                               | Ingleside Formation                        |                                        |                                       |                        | Ingleside Formation                                  |                              |                         |  |  |
| PENNSYLVANIAN                 | Fountain Formation                         |                                        |                                       |                        | Fountain Formation                                   |                              |                         |  |  |
| MISS.                         |                                            |                                        |                                       |                        | Mississippian rocks                                  |                              |                         |  |  |
| DEV.                          |                                            |                                        |                                       |                        | Devonian rocks                                       |                              |                         |  |  |
| SIL.                          |                                            |                                        |                                       |                        | Ordovician rocks                                     |                              |                         |  |  |
| ORD.                          |                                            |                                        |                                       |                        | Cambrian rocks                                       |                              |                         |  |  |
| CAM.                          |                                            |                                        |                                       |                        |                                                      |                              |                         |  |  |
| PRE-CAM.                      | Metamorphic and intrusive rocks            |                                        |                                       |                        |                                                      |                              |                         |  |  |

Current Morgan County Injection Interval

Confining Layer

Main Weld County Injection Interval

'Basement'

Higley and Cox, 2007

# What have we learned about the link between wastewater disposal and induced earthquakes?

Earthquakes happen near some wells and not others. We are still trying to learn why. Some things we do know:

Don't inject into a fault (but we don't know where all of the faults are)

Don't inject into basement (the deep crystalline rocks below the sedimentary layers)

High injection rates can be a problem – (COGCC recommends seismic monitoring)

High cumulative volume can be a problem – wells close together all contribute to increased pore pressure

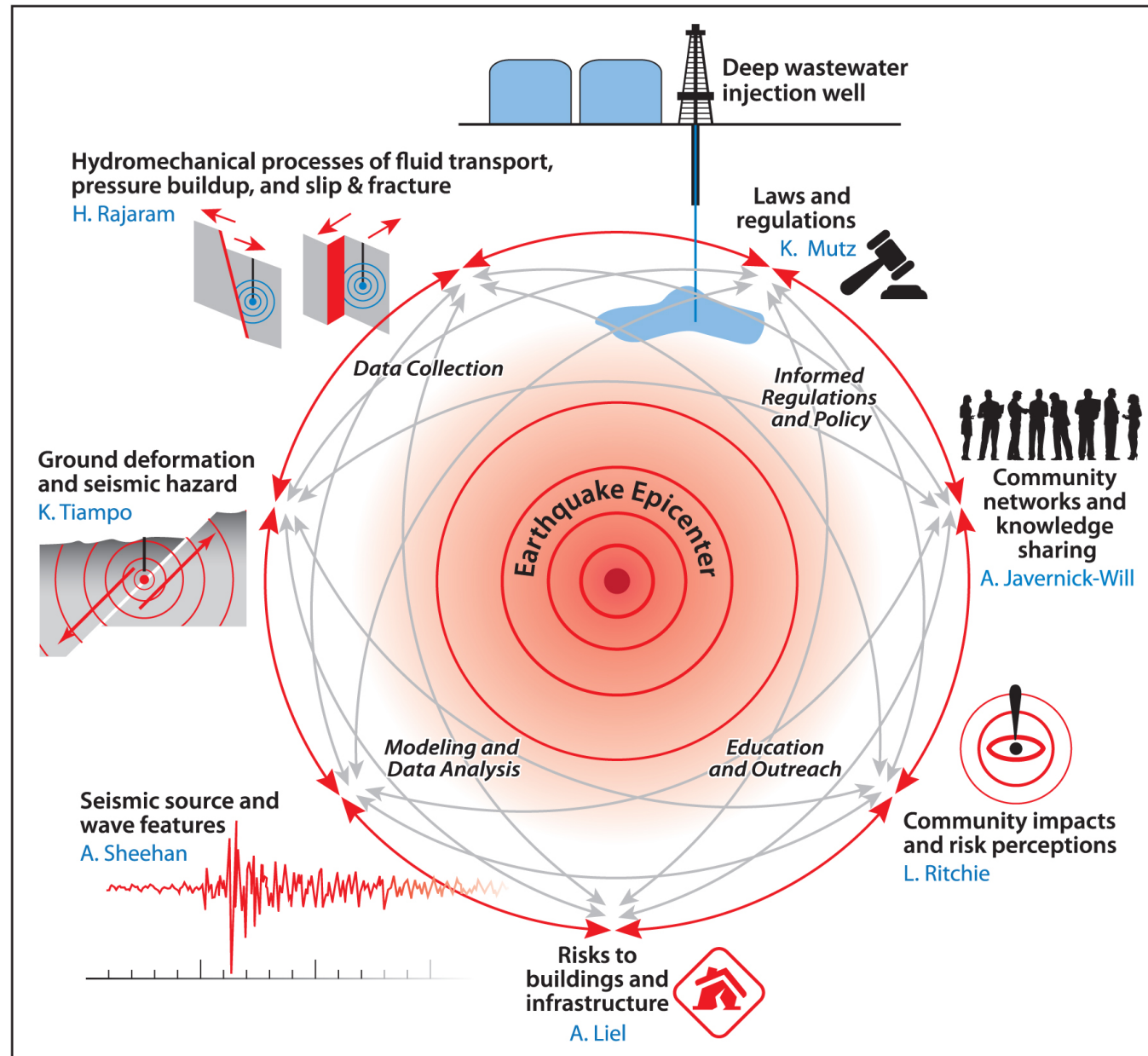
Injecting at high pressure can be a problem, but induced earthquakes can also occur in cases where injection is by gravity feed

Seismic monitoring is needed, but seismic network coverage in Colorado is sparse

Induced seismicity is a manageable issue, however, effective management requires seismic monitoring, injection monitoring, scientifically informed policies and procedures, and follow up from regulatory agencies (Colorado Oil and Gas Conservation Commission has regulatory primacy in CO)

# NSF Hazards SEES project on Induced Seismicity at CU

Integrate geoscience,  
social science and  
engineering in study of  
science and impact of  
induced earthquakes



\* SEES = Science, Engineering, and Education for Sustainability



# Thank You

[Anne.Sheehan@colorado.edu](mailto:Anne.Sheehan@colorado.edu)

[Earthquake.colorado.edu](http://Earthquake.colorado.edu)

[www.iris.edu](http://www.iris.edu)



06.04.2014





## RESEARCH ARTICLE

10.1002/2017JB014456

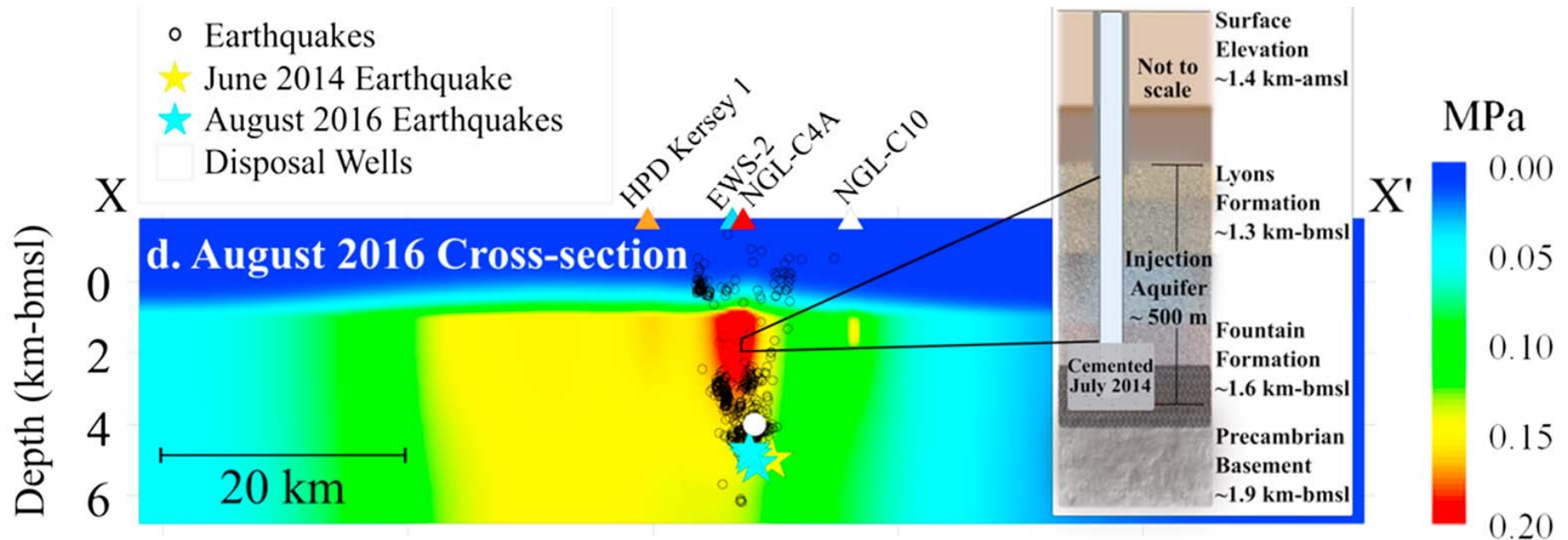
## Key Points:

- Pore pressure modeling of injection from 22 wastewater disposal wells within 30 km of seismicity
- Injection from Far-field Wells between 15 and 30 km contributes a significant portion of pore pressure increase near the induced seismicity
- Reduction of spatially aggregated injection rate by decrease of individual rates or farther well spacing may be more effective mitigation

# Evaluating the effectiveness of induced seismicity mitigation: Numerical modeling of wastewater injection near Greeley, Colorado

Megan R. M. Brown<sup>1</sup>, Shemin Ge<sup>1</sup>, Anne F. Sheehan<sup>1,2</sup>, and Jenny S. Nakai<sup>1,2</sup>
<sup>1</sup>Department of Geological Sciences, University of Colorado Boulder, Boulder, Colorado, USA, <sup>2</sup>Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, Boulder, Colorado, USA

**Abstract** Mitigation of injection-induced seismicity in Greeley, Colorado, is based largely on proximity of wastewater disposal wells to seismicity and consists of cementation of the bottom of wells to eliminate connection between the disposal interval and crystalline basement. Brief injection rate reductions followed



# Next steps :

## **CU – continue monitoring**

- seismology
- pore pressure modeling
- InSAR

## **COGCC - traffic light system being considered**

- earthquake monitoring requirement for high rate wells
- staged injection requirement for high rate wells
- inspect drilling reports for lost circulation zones



## **Colorado Geological Survey –**

- 2 new seismic stations in Colorado
- Induced seismicity working group

