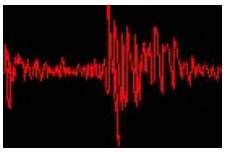

Earthquakes Triggered by Humans in Colorado — a background paper by the Colorado Geological Survey

TABLE OF CONTENTS

Natural Earthquakes and Earthquakes Triggered by Humans in Colorado

Colorado has experienced numerous natural earthquakes, including a magnitude 6.6 earthquake in 1882. However, the state is world famous for its triggered (induced) earthquakes. A variety of human activities in Colorado have triggered earthquakes during the past half century:

- During the 1960s, the triggering of earthquakes from injection of waste fluids at the Rocky Mountain Arsenal near Denver made news around the world.
- In the 1970s, an experiment involving a waterflood at the Rangely oil field in northwest Colorado was the first time in human history that earthquakes were intentionally turned off and on, by varying the injection pressures of water underground.
- Two earthquakes greater than magnitude 5.0 were created in 1969 and 1973 by underground nuclear explosions that were part of an experiment to increase extraction of natural gas.
- A seven-fold increase in earthquakes was recorded during filling of the Ridgeway reservoir in 1986.
- Beginning in the 1990s, injection of brine water beneath the Paradox Valley of western Colorado triggered thousands of earthquakes that increased in magnitude up to 4.2, but decreased in magnitude after the injection protocol was modified.
- Nearly 200 earthquakes with magnitude 2.8 to 3.4 were recorded in a two-year period (2007-2009) in the Paonia area, and are attributed to underground coal mining activity.

With this background in human-caused seismicity in Colorado, it is normal to ask whether any new earthquake activity occurring in the state is triggered by some human activity. It is important in this discussion to remember that Colorado is an active tectonic province that is essentially being pulled apart where the Rio Grande Rift cuts north/south across the mountainous, central part of the state. The high

mountains in the state are a result of uplift on faults (with associated earthquakes) that are part of the rift system.

Three faults in the state have received sufficient study to be included in the USGS National Seismic (Earthquake) Hazard Map, and are listed as being capable of generating earthquakes of 7.0 magnitude, or greater. There are many more faults in the state that could probably generate significant earthquakes, but have not received sufficient study, or documentation, to be included in the hazard map. With our current state of knowledge, it is not possible to predict when or where, the next large earthquake might occur in Colorado.

Hydraulic Fracturing (Hydro-fracs) and Earthquakes

Using water to artificially fracture rock layers below ground in order to increase oil and gas production has been conducted in the United States since 1947. Before that, nitro glycerin was used to artificially fracture the rock. Nearly all of the oil and gas wells drilled in Colorado today require hydro-fracing in order to produce economic quantities of oil and gas.

There are only two instances in the world where hydro-fracing near faults has been interpreted to cause earthquakes, one in Oklahoma and one in Great Britain. Both of these were less than magnitude 3.0, which causes a shaking intensity that most people would not notice. The USGS states, "Fracking causes small earthquakes, but they are almost always too small to be a safety concern." Scientists at both the state and federal level have been frustrated by the widespread misrepresentation in the media that "fracking causes earthquakes".

Waste Fluid Disposal from Oil & Gas Operations and Earthquakes

Oil and natural gas operations commonly produce water that must be handled within strict state and federal regulations.

- Small amounts of water are produced with normal, natural-gas wells and oil wells.
- Larger amounts of water can be produced from coalbed methane wells, from water-flooding of an oil field, and from very old oil wells.
- After a well is hydro-frac'ced, not all of the water stays in the formation, but some of the water is recovered and flows back to the surface (~ 9% of all oil & gas waste fluids in Colorado).

Any water brought to the surface during oil and gas operations, must be disposed of properly. There are several common ways to deal with the water depending on its chemical properties.

- Putting it into lined ponds and evaporating the water,
- Disposing of it directly into streams or applying it to the surface (must meet water-quality standards),
- Treating it to water-quality standards before putting into streams or rivers,

- Re-injecting it into the ground in a Class II UIC well under guidelines promulgated by the US EPA and administered by the Colorado Oil and Gas Conservation Commission (COGCC). There are approximately 145,000 of these wells in the U.S., and 309 in Colorado.

Several recent earthquake swarms across the U.S. have generated questions as to whether they were triggered by oil and gas operations. Indeed, the USGS created a recent flurry of publicity and controversy by claiming that an increase in earthquake activity throughout the midcontinent (including Colorado), is "almost certainly manmade". The directors of the Oklahoma and Colorado Geological Surveys independently characterized these conclusions for their states as premature.

A number of earthquakes in several states are currently being investigated in order to determine whether it is plausible that water injection may have triggered them.

- The Center for Earthquake Research at the University of Memphis and the Arkansas Geological Survey jointly concluded that water disposal from oil and gas operations was the most probable cause of more than 1200 micro-earthquakes on a fault near Guy, Arkansas.
- The Youngstown, Ohio area experienced several small earthquakes, culminating in a 4.0 magnitude event on January 1st, 2012. Current evidence suggests these events were triggered by a nearby brine injection well. Scientists continue to gather data and investigate the connection between the quakes and well.
- Oklahoma experienced a 5.6 magnitude earthquake near some injection wells. Scientists are investigating whether there is a causal link between the two.
- Earthquakes in the Raton Basin of Colorado and New Mexico are currently being re-studied to evaluate whether there is a link between injection of water from coalbed methane production and earthquakes in that area.

<u>The Trinidad Earthquakes</u>

The Raton Basin of Colorado and New Mexico has more than 3,000 wells producing natural gas from coal beds (coalbed methane or CBM). Trinidad, Colorado is located near the eastern apex of the basin. The earthquakes occurring in the basin are commonly referred to as the "Trinidad earthquakes"; although the earthquakes extend out more than 30 miles to the southwest, west, northeast, and northwest from Trinidad. The Colorado portion of the Raton Basin has 22 Class II UIC wells disposing of produced water. Most of these wells are not using pressure to inject the water, but are simply flowing into the underground layers 4,000 to 5,000 feet deep under gravity. Other produced water in the basin is disposed of on the surface.

The Trinidad area has a history of natural earthquakes:

- In 1966, a 4.5 magnitude earthquake was reported northeast of Trinidad.
- In 1973, a swarm of four earthquakes ≤4.2 magnitude was reported west of Trinidad, decades before water injection began.
- In 1983, a magnitude 3.2 earthquake was reported northeast of Trinidad.
- In 1996, a series of three earthquakes ≥3.2 magnitude hit northeast of Trinidad.

- During this era, detection and location of earthquakes in Colorado was significantly inadequate.

In 2001, a swarm of earthquakes culminating in a magnitude 4.6 occurred west of Trinidad.

- Initial location of the earthquakes showed the epicenters scattered over 75 square miles with a random pattern.
- USGS deployed 12 portable seismometers.
- Several lines of data and studies demonstrated that the earthquakes were actually occurring along a previously unrecognized, normal fault that trends northeast-southwest, and is inclined ~75 degrees toward the southeast.
- Two water-disposal wells are located within 7,400 feet of the fault.
- Separate, and different, analyses conducted by CGS and USGS both concluded the data was equivocal as to whether the earthquakes were triggered by fluid injection.
- The earthquakes on the fault mapped in 2001 stopped, even though injection in the wells continued at the same rate.

For the next decade, no earthquakes were reported on the fault by the National Earthquake Information Center (NEIC). However, small earthquakes (most too small to feel) occurred fairly regularly throughout the rest of the Raton Basin. These earthquakes appeared to follow no pattern, but seemed fairly random. It should be remembered that seismograph coverage in Colorado was inadequate to pinpoint the epicenters of earthquakes. Errors of plus or minus ten miles, or more, could be experienced.

During this decade, the Earthscope Transportable Array moved across Colorado providing better data for locating earthquakes during the two years that those seismographs were in place. The Earthscope data showed several clusters of earthquakes (rather than the random patterns seen before), with the largest cluster in the New Mexico portion of the basin. CGS purchased one of those stations east of Trinidad in an effort to improve the accuracy of locating earthquakes. Researchers have recently studied the Earthscope data and attempted to retroactively improve the NEIC locations.

A damaging, magnitude 5.3 earthquake struck the Trinidad area in August 2011. This event renewed interest in whether the earthquakes were triggered by underground disposal of produced water. Several seismographs were deployed by the USGS in the area immediately after the 5.3 M earthquake. In December, the oil and gas industry deployed additional seismographs deep underground to complement the USGS instruments. Excellent data is now being obtained on the location, number, and size of the earthquakes; most of which are too small to feel. This new data will provide researchers with information to perhaps finally understand the cause(s) of the earthquakes in the Raton Basin.

<u>The Colorado Oil and Gas Conservation Commission (COGCC) and the Potential for Triggering Earthquakes</u>

In 2011, the COGCC took a proactive stance toward the possibility of injection wells causing earthquakes and asked the Colorado Geological Survey (CGS) to review all new permit applications for water disposal wells. CGS has been reviewing those applications since October 2011 and is making recommendations to COGCC. CGS is also working with COGCC to understand the origin of the Trinidad earthquakes.

Resources on Colorado Earthquakes

Earthquake Reference Collection

This CGS collection consists of more than 500 publications relevant to Colorado earthquakes, including many that are hard to find. A large number of these are available online as PDFs.

Earthquake and Fault Map Server

This CGS online resource shows earthquakes and young faults in Colorado. Mousing over an earthquake will show the date and magnitude/intensity. Double-clicking on an earthquake will bring up an information sheet on the event.

Mousing over a fault will show the name of the fault. Double-clicking on a fault will bring up an information sheet on the event. The sheet will include a variety of information including applicable literature references.

Induced Earthquake Bibliography

This is an excellent online resource for publications relevant to the triggering of earthquakes by a variety of means.

We Don't Have Earthquakes in Colorado, Do We?

This 2002 RockTalk publication by CGS is a primer on earthquakes in Colorado. It also has a summary of the USGS and CGS investigations of the 2001 Trinidad earthquake swarm.

Earthquake Hazards Brochure

This map and information brochure contains locations of earthquakes and Quaternary faults in Colorado. It was produced by the Colorado Earthquake Hazard Mitigation Council in 2008. You can obtain free hard copies from the Colorado Geological Survey, or view it online.