A Possible Causative Mechanism of Raton Basin, New Mexico and Colorado Earthquakes using recent seismicity patterns and pore pressure modeling

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Introduction and Motivation

The Raton Basin hosts coal-bed methane deposits, mined in the 1800s and now extracted by hydraulic fracturing. Wastewater is produced as a byproduct. Wastewater disposal began continuously in 1999 and the rate of earthquakes rapidly increased in 2001. The Basin is split between Colorado and New Mexico.

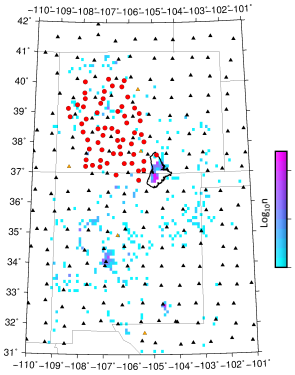

Figure 1. Log_{10} of the number of earthquakes (n), 2008-2010, from earthquake catalog of Nakai et al. [2017]. The Raton basin had the highest concentration of seismicity in Colorado and New Mexico during 2008-2010. EarthScope Transportable Array seismometer stations are black triangles, CREST stations are red circles, and ANSS stations are orange triangles.

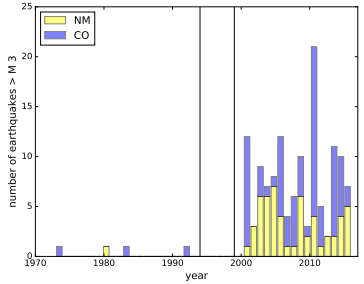

Figure 2. Earthquakes greater than M_W 3 from 1973-2016 in the Raton Basin from the USGS ComCat [USGS, 2017] in a stacked bar plot. Earthquakes in New Mexico are shown in yellow, earthquakes in Colorado are purple.

Black lines denote beginning of wastewater disposal in the Raton Basin in 1994 and beginning of injection of well 22 in 1999.

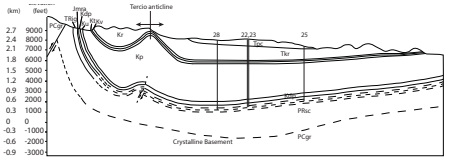

Figure 3. Cross-section of the Raton Basin (A-A' in Figure 1). Data is constrained by drillholes for formations above the Dakota and by a basement map of New Mexico (Suleiman and Keller, 1985). Vertical exaggeration is 10.4:1.

Results

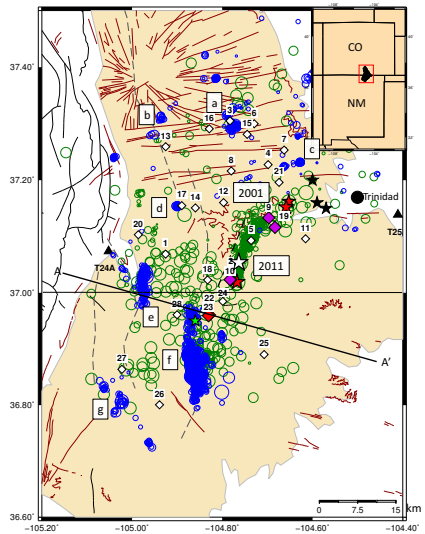

Figure 4. Study area and seismicity of the Raton Basin. Seismicity from Rubinstein et al. (2014) relocated catalog (1973-2016, green) and our catalog from 2008-2010 (blue). Dikes and sills (dark red), and faults (black lines) are shown. Axes of anticlines and synclines are dashed grey lines. Black dashed line is the modeled fault from Barnhart *et al.* [2014]. White diamonds are saltwater disposal injection wells and are numbered.

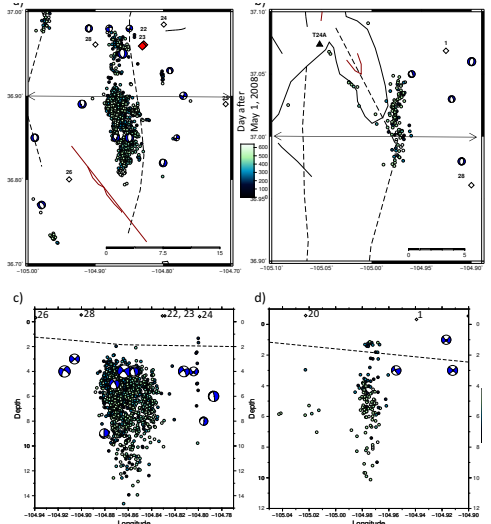

Figure 5. Seismicity at Vermejo Park and Tercio (groups e and f in Figure 1). a) Vermejo Park fault. The lineament contains Injection wells shown with unfilled diamonds. b) Tercio Lineament. The grey lines are mapped surface faults, the dashed black lines are the Cuatro syncline (left) and the Tercio anticline (right). Dark red lines are mapped dikes/sills.

Results and Conclusions

Pore pressure modeling

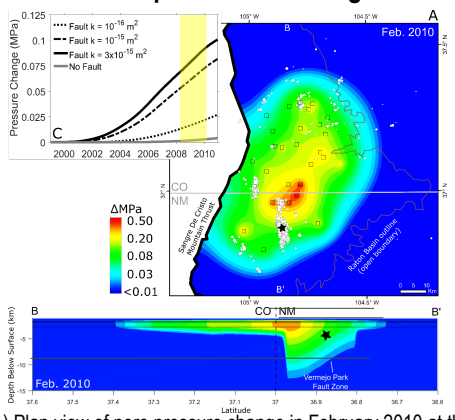

Figure 6. A) Plan view of pore pressure change in February 2010 at the depth of Dakota Formation in the Raton Basin. Earthquake epicenters from February 2008 to February 2010 are plotted as white circles. B) Cross section B-B'of pore pressure change running north-south through the Raton Basin along strike of the Vermejo Park fault zone. The black star denotes the 4.5 km depth of calculated pressure histories shown in 7C. C) Pressure versus time for four modeled Vermejo Park fault zone permeabilities.

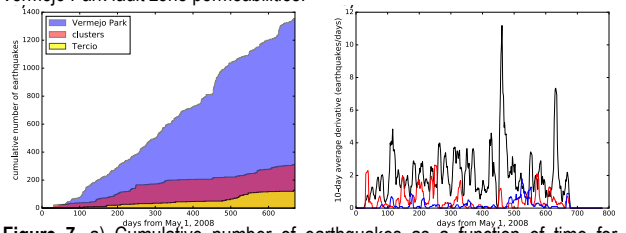

Figure 7. a) Cumulative number of earthquakes as a function of time for Vermejo Park, Tercio, and other clusters. Vermejo Park (blue) is continuously active throughout 2008-2010 and the remainder of the earthquake clusters and Tercio are more episodic. b) 10-day moving average of derivative of cumulative number of earthquakes per day in Vermejo Park (black), Tercio (blue), and the remaining clusters (red).

Conclusions

1) The spatial patterns of seismicity we observe are reflected in distribution of wastewater injection and modeled pore pressure change.

2) Modeled pore pressures at seismogenic depths are well above the earthquake triggering threshold under a variety of possible fault permeability scenarios.

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