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Understanding the Correlation between Induced Seismicity and Wastewater Injection in the Fort Worth Basin

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ABSTRACT: A basin-wide simulation of wastewater injection is performed for the Fort Worth Basin. Uncertainties in geology and limited availability of injection data were two of the main challenges that were encountered during the course of the research. Simulation results show some spatial and temporal correlation between the pore pressure change and earthquakes occurrence. There are also areas of substantial predicted pore pressure increase where no seismicity is detected. The results suggest that proper assessment of seismic risk requires good subsurface geology (flow characteristics and pre-existing fault geometry) as well as well injection rate and pressure data.

1. BACKGROUND AND MOTIVATION

One of the very first studies on induced seismicity due to fluid injection was performed on the Denver earthquakes which occurred in the 1960's due to injection into a disposal well at the Rocky Mountain Arsenal (RMA) [1]. Injection into the well at the RMA occurred between from 1962 to 1966 with a variable injection rate at different times during the injection periods [1, 2]. It was observed that seismic events continued to occur even after fluid injection was stopped [1, 2]. A few years following the event, an experiment conducted in Rangely, Colorado concluded that fluid injection can be used to control seismic events [3].

Since the 1960s, the link between earthquake clusters and disposal wells has been extensively examined [4]. Research has been done to correlate the various parameters, such as injection pressure and reservoir transmissivity, to the occurrence of induced earthquakes [1-4]. Yet, even though the mechanics behind induced earthquake is established, risk assessment and prediction is still difficult [1-4].

An increased number of earthquakes in the central and eastern United States within the last few years (mostly in the magnitude range of 2 to 3) has increased the visibility of induced seismic risk [5, 6]. Various articles in prominent newspapers and magazines speculated that the cause of the rise was due to increased oil and gas related activities [7, 8]. A leading theory is that the earthquakes are induced by the increasing amount of wastewater injection, a consequence of increased produced water from hydraulically fractured oil and gas wells [9]. Many studies correlating the location of earthquake activities and their proximity to injection wells have been done [5, 10-11]. Simulations correlating fluid injections and earthquakes have been performed on a local scale after the occurrences of uncharacteristically large magnitude earthquakes in various fields all over the world [12-14]. However, no basin-wide study correlating fluid injection and seismic activities have been performed. This could be attributed to the scarcity of accurately available public injection and geologic data related to the areas of interest.

The goal of modeling the whole basin instead of just focusing on injection wells in proximity to the earthquake locations is to assess negative correlations as well as positive ones (i.e., document areas of pressure change that are not associated with seismic activity). We also endeavor to estimate the areal extent of pressure change away from the immediate vicinity of individual injection wells or clusters of wells, as the pore pressure front may extend farther than anticipated, providing the possibility of activations of various faults and fractures located farther away from the point of injection [15]. An over-arching challenge in this work, however, is the difficulty in characterizing the geology at the basin scale with regard to flow properties and the presence of pre-existing faults that might be the locus of induced earthquakes.

2. MODELING EFFORTS

Using publicly available injection well data plus regional geology information, a flow simulation model was constructed of the Fort Worth Basin. The Implicit Explicit Black Oil (IMEX) finite difference simulator of the Computer Modeling Group (CMG) was used to model wastewater injection. The pore pressure increase at the end of the each injection period was observed and plotted. Then a spatial and temporal analysis between the increased pore pressure and seismic activities was performed.

Earthquake data were taken from the United States Geological Survey (USGS) National Earthquake Information Center (NEIC) database. The wastewater injection data were queried from the Railroad Commission of Texas (RRC). For all the injection wells located in the Fort Worth Basin within the focus area, the following information was obtained: well locations, injection volumes, injection pressures, and injection depths.

2.1. Simulation Domain

The simulated region includes Denton, Ellis, Erath, Hill, Hood, Jack, Johnson, Palo Pinto, Parker, Somervell, Tarrant, and Wise counties (Figure 1). The region is roughly bounded on the west by the Bend Arch, on the north by the Red River and Muenster Arches, and on the east by the Ouachita Thrust [16]. The total number of injection wells was 374. The simulation grid blocks were rectangular, with a 610 m x 610 m (2000 ft x 2000 ft) square top, and variable heights. The entire model included 342 by 330 by 9 grid cells in the x, y and z directions, respectively, for an areal extent of 210 km (130 miles) by 201 km (125 miles) and approximately 4.3 km (14,000 ft) thick. The injection duration was 199 months (start date: 1997-12-01).

2.2. Geologic Data

Geologic data plays a crucial role in the accuracy of the simulation results. However, it was quite difficult to obtain good data on the subsurface geology as detailed geologic information is often proprietary. Obtaining geologic data is one of the major challenges faced in this research.

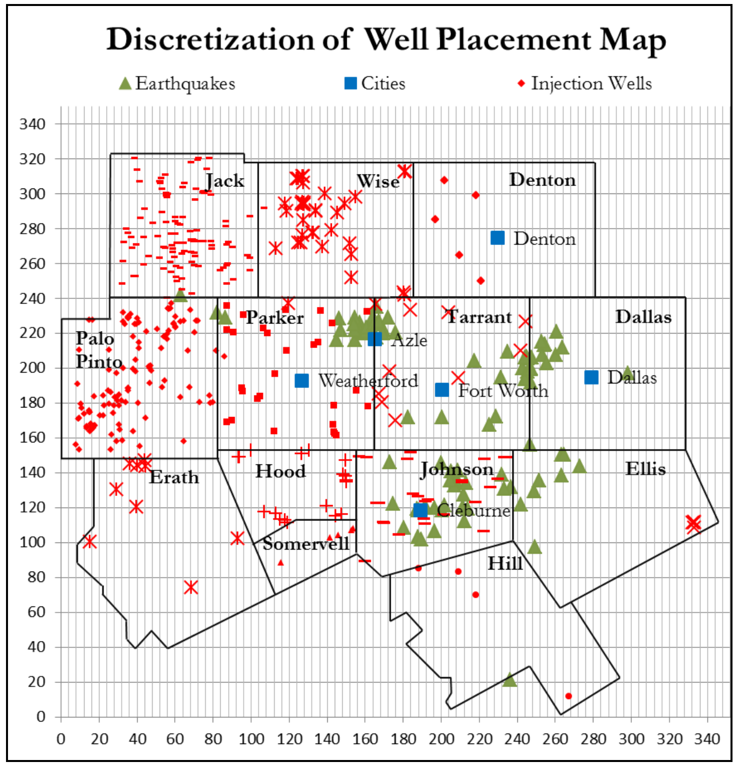


Fig. 1. Discretized well placement map.

2.2.1. Formation Top

Formation tops helped constrain the vertical height of the model based on data from IHS Petra. Tops for the Strawn, Marble Falls, Barnett, and Ellenburger formations were interpolated to fit the simulation domain. These formations correspond to the tops of layers 2, 4, 6, and 8 respectively. The top of layer 1 was taken as 0 ft, and the tops for layers 3, 5, and 7 were computed by taking an average between the top of the known layers where the unknown layer is sandwiched in between.

As can be seen in Figure 2, Petra has an extensive formation top data for a specific area. It covers the majority of the center of the simulation domain, but not the outer edge. To appropriately simulate the formation tops across the simulation domain, the area on the outer edge is populated with values between the maximum and minimum bounds of the edges at the center of the domain where real geologic data are available. The populated simulation domain can be seen in Figure 3. A built-in MATLAB interpolation scheme based on cubic spline interpolation method was then utilized to populate the whole region of interest with top data. The interpolated tops can be seen on Figure 4. From Figure 2 and Figure 4, it can also be observed that the top of the formations increases in depth as it moves to the East. This observation is especially prominent in the Barnett and the Ellenburger, which is consistent with the published structure contour map for the top of the Ellenburger and the top of the Barnett shale [17, 18].

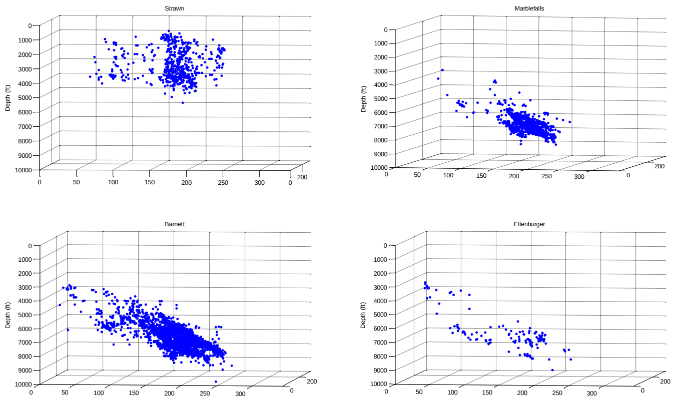


Fig. 2. Formation top data points from Petra.

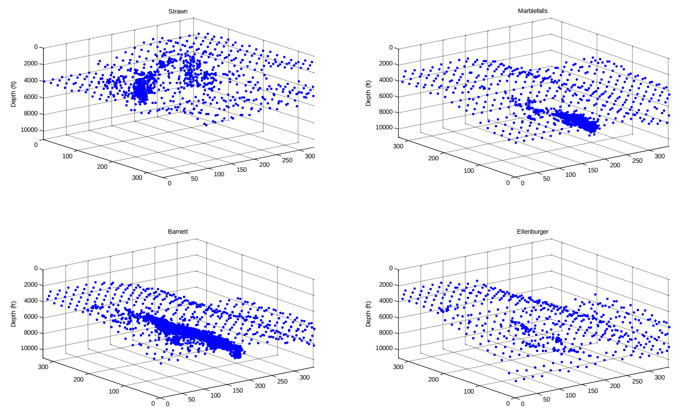


Fig. 3. Populated formation top data to cover the simulation domain**.**

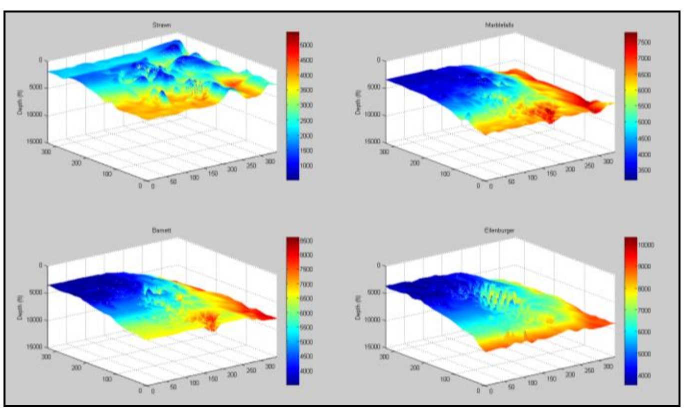


Fig. 4. Interpolated top surfaces based on cubic spline interpolation approach.

The formation cross-sections in the simulator can be seen in Figure 5. In general, there is a thickening of sedimentation from West to East and from South to North.

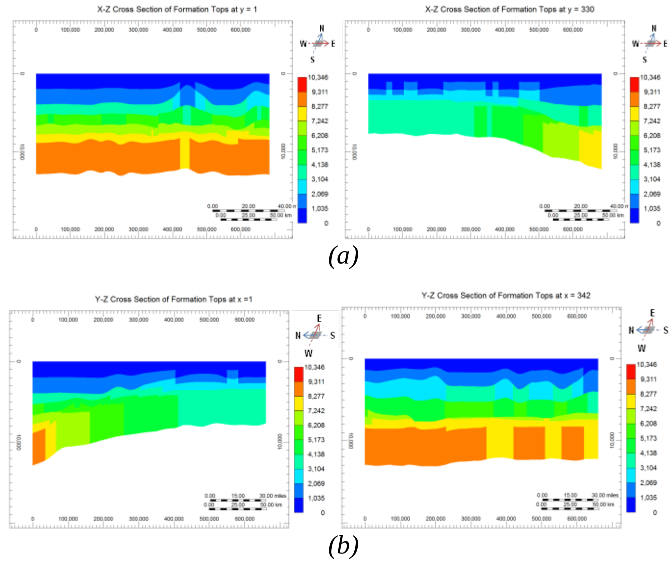


Fig. 5. a) Formation cross-section in the x-z direction. b) Formations cross-section in the y-z direction.

2.2.2. Layer Permeability and Porosity

Based on published data available, the following porosity and permeability values were used in the first pass of the simulation. When no data was available, an average between the known values was taken to represent the unknown porosity and permeability values. It was assumed that the porosity and permeability were constant in each layer in order to simplify the simulation.

Table 1. Permeability and porosity of each layer used in the initial simulation

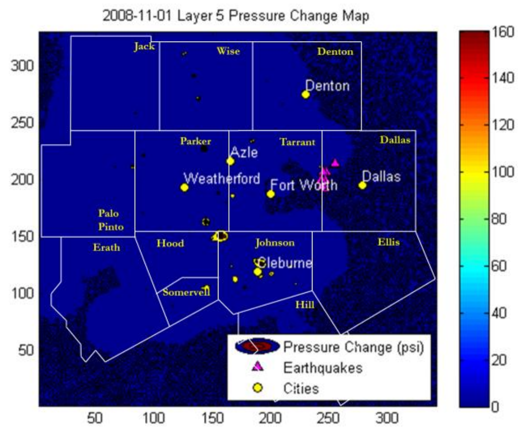
Layer	k_{horiz} **(md)**	k_{vert} **(md)**	**Porosity**
1	75 [19]	7.5	0.20 [19]
2	40	4.0	0.13
3	1 [20]	0.1	0.05 [21]
4	5	0.5	0.07
5	9 [16]	0.9	0.06 [22]
6	13	1.3	0.11
7	16 [23]	1.6	0.09 [23]
8	9	0.9	0.07
9	16	1.6	0.09

3. RESULTS AND DISCUSSION

Based on Figure 1, it can be seen that there are roughly three areas within the Fort Worth Basin where earthquake clusters have been recorded recently. These areas are the Dallas - Fort Worth Airport (DFW), and the cities of Cleburne and Azle. The goal of the research is to see if there are any pore pressure changes that occurred throughout the injection period which coincides with the location of the seismic activities. The discussion of the result is divided into three sections based on the identified earthquake cluster locations.

3.1. Dallas – Fort Worth Airport (DFW) Earthquakes

Figure 6 shows the overall pore pressure changes across layers 5, 6, 7, 8, and 9 on November 1st, 2008. It can be seen that on Figures 6a, b, c and d that there are some localized pressure increases in the various layers in the basin, but particularly in layer 9 (Fig. 6e). However, there is no evidence of pore pressure increase in the vicinity of where the earthquakes occurred. Upon closer examination of each layer, there are two wells injecting into layer 8 close to where the earthquakes occurred (Figure 7).



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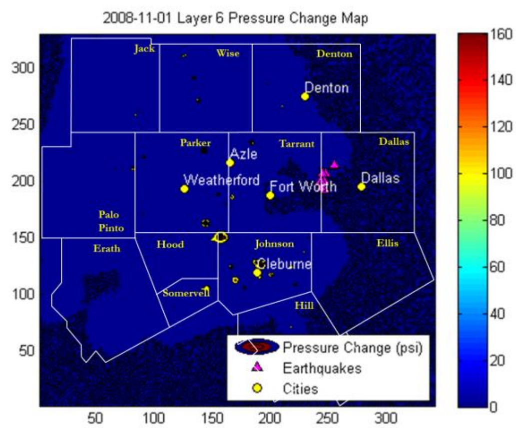

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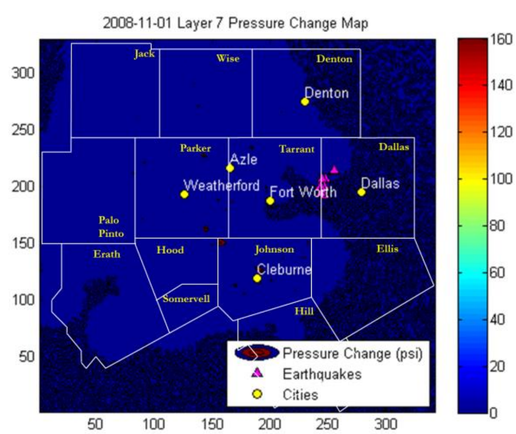

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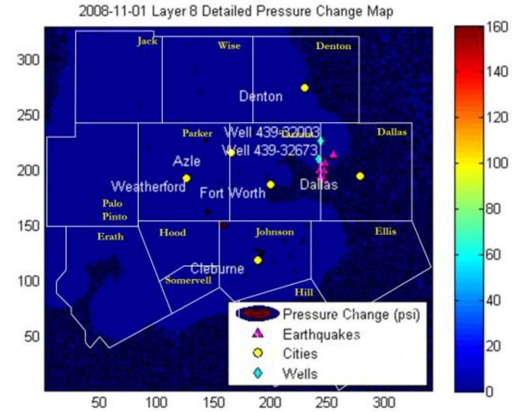

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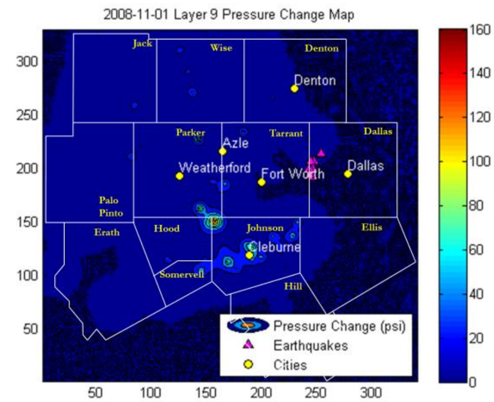

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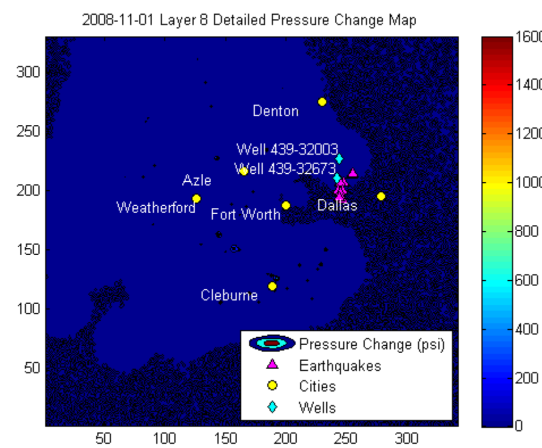
Fig. 6. a-e) Pore pressure change map for layer 5 to layer 9 respectively.



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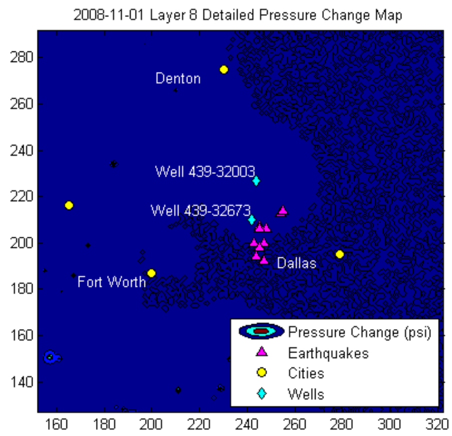

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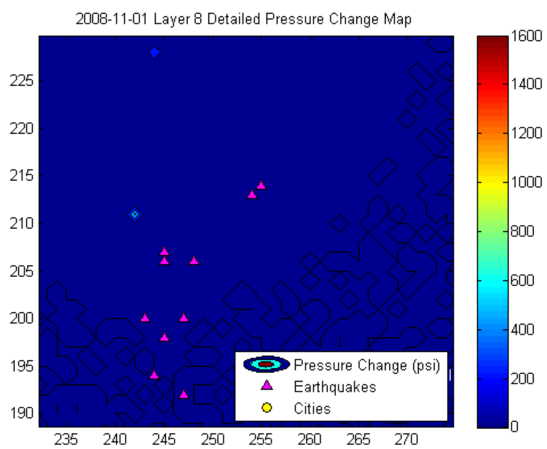
Fig. 7. a-b) Well location maps.



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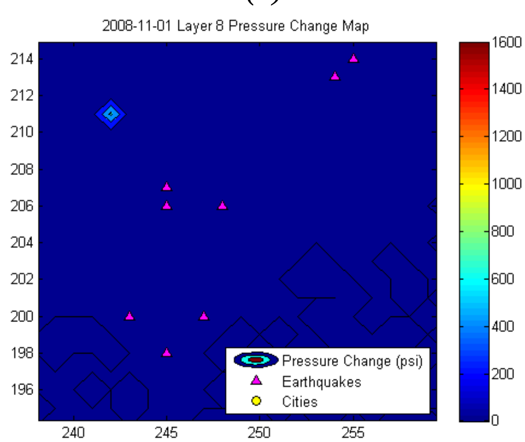


(b)

Fig. 8. a-b) Detailed view of layer 8 in the vicinity of earthquake cluster**.**

From Figure 8, it is evident that there is a pore pressure increase in the vicinity of the earthquake cluster. The pressure change located closer to the swarm of earthquake cluster has a maximum pressure change of approximately 4.14 MPa (600 psi). This change in pore pressure coincides with the location of Well 439-32673 located in the Northeastern part of Tarrant County. The well has a total injection of 165,224 BPM in the month of September 2008, and the wellbore pressure at the time of interest is 7.48 MPa (1085 psi). The injection history of the well shows that there was no injection prior to September of 2008, and injection stopped after August of 2009.

The location of the earthquake swarm is roughly 1 mile away from the well location (Figure 8), which is not a close spatial correlation between the earthquake locations and the injection well. However, a more detailed study utilizing better instrumentation to record the seismic activity surrounding the DFW area [24] produced more accurate earthquake locations (Figure 9) such that coincide exactly with an injection well (the injection well corresponds to Well 439-32673 in the simulation model).

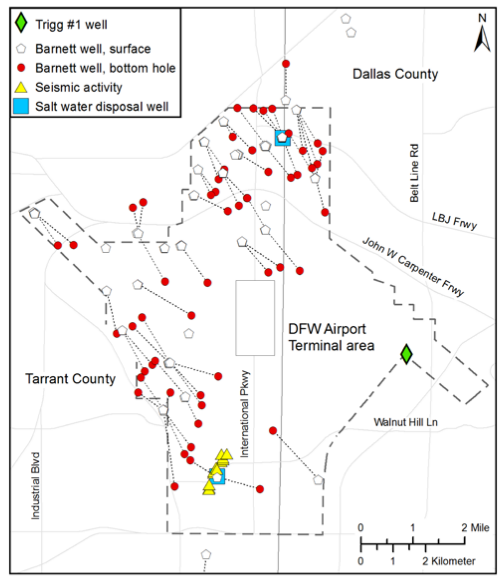


Fig. 9. Map of the DFW airport with location of injections wells and earthquake activities mapped, from Frohlich et al. [19]

Taking the earthquakes location from the Frohlich et al. paper, and based on the location of the injection well, it can be concluded that there is a spatial and temporal correlation between the DFW earthquakes and the increased of pore pressure. The pore pressure change is confined to an area of roughly 1 km (3,500 ft) x 1.3 km (4,000 ft), with a pore pressure increase in the range of approximately 2.07 – 4.14 MPa (300 – 600 psi).

3.2. Cleburne Earthquakes

Most of the injection that occurred in the Cleburne area around August 2012 occurred in layer 8. The locations of all the injection wells that injecting into layer 8 can be seen in Figure 10. The black circle with an arrow going across it represents a well that was injecting into the layer; while the empty circle represent a well that is not injecting into the layer at the time of analysis.

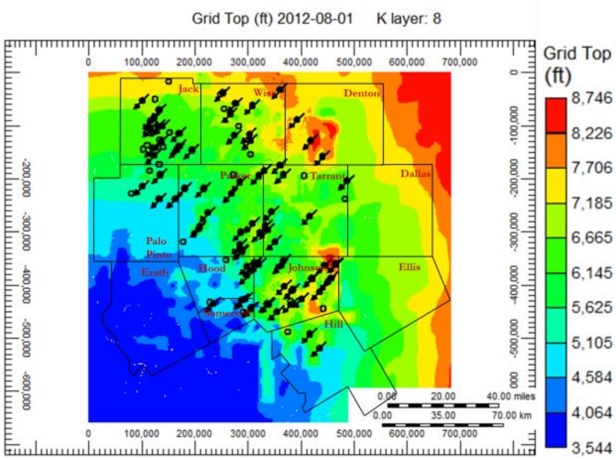
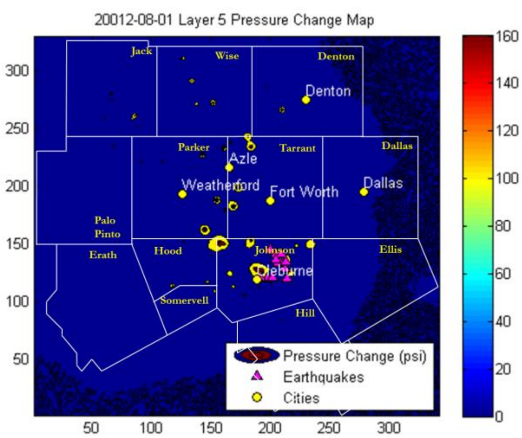


Fig. 10. Map of wells injecting into layer 8 on August 1st, 2012.

From Figure 10, it can be seen that there were many wells injecting into layer 8 at the same time. In Johnson County itself, during the time period of interest, there were also wells injecting into layers 7 and 5. Figure 11 shows the pore pressure change map for layers 5 through 9 for the area of interest on August 2012.



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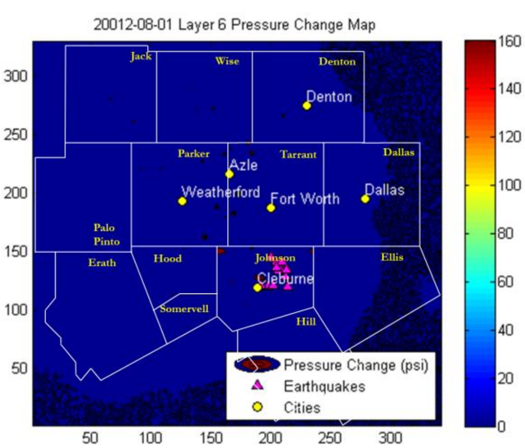

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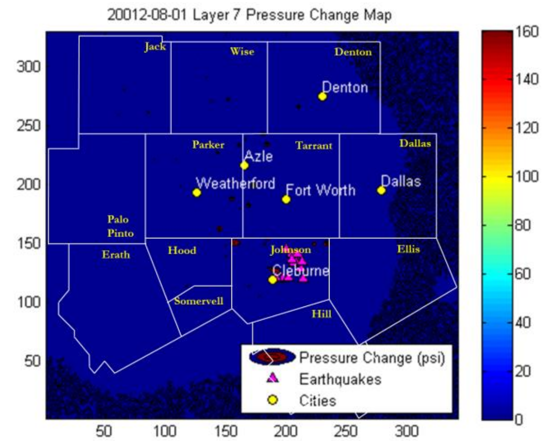

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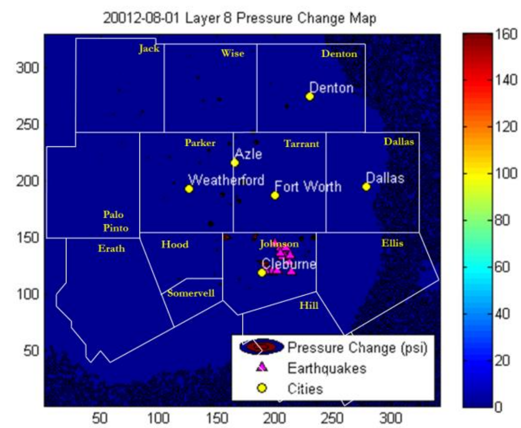

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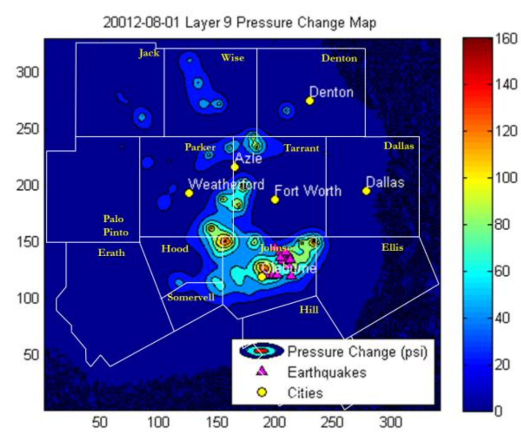
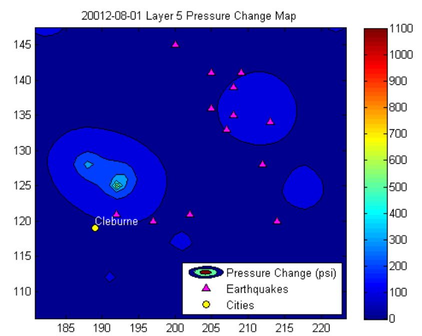


(e)

Fig. 11. a-e) Pore pressure change map for layer 5 to layer 9 respectively.

As can be seen from Figure 11a, b, c, and d, there are many locations with a high pressure change response in the various layers during the time line of interest. From figure 11e, there is a clearer pore pressure change gradient that does show that the earthquakes are correlated to the increased pore pressure in layer 9. The maximum pore pressure increase in layer 9 that corresponds to the location of seismic event is roughly 2.07 MPa (140 psi).

A detailed view of the pore pressure in the area surrounding the earthquake locations for layers 5 through 8 can be seen in Figure 12. It can be observed that several seismic events fall within areas of pore pressure change in some layers, for example as can be seen in Figure 12a. However, most of the time, the seismic events occurred very close to the area of high pore pressure change, as can be seen in Figure 12b, c, and d. The earthquake locations in this example are also from the NEIC database, and the locations are only accurate within a few miles (100 m (0.06 miles) to 10 km (6 miles) depending on spacing of seismograph network) because of the small number of permanent stations available to the USGS.



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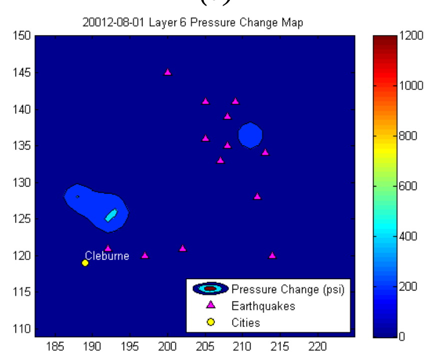

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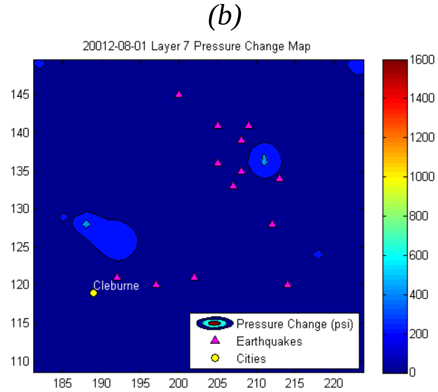

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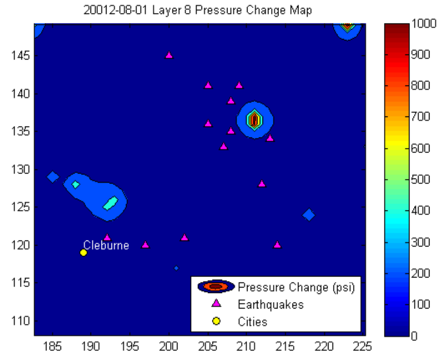

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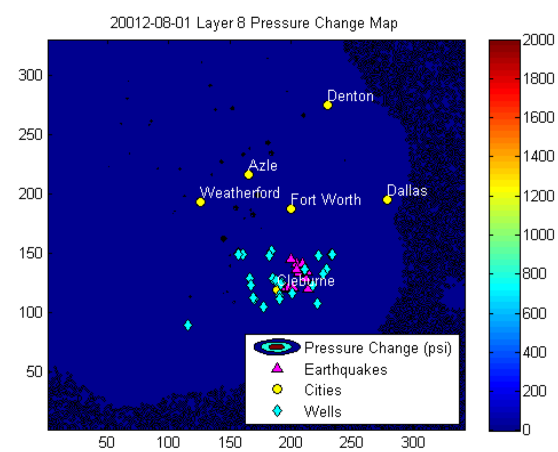
Fig. 12. a-d) Detailed view of pore pressure change in layers 5 to 8 respectively.

For a basin-wide modeling, where the resolution is low, the above can be said to have shown a correlation between pore pressure change and the occurrence of earthquakes. As in the case of the DFW earthquakes, there is a more detailed study associated with an earlier cluster of earthquakes in the Cleburne area that occurred from June 2009 to June 2010 [25]. In the study conducted by Justinic et al., where more instrumentation were utilized in the analysis, it was concluded that the earthquake sequence that occurred from June 2009 to June 2010 may possibly be induced by the injection activities that occurred in the area due to the proximity of the events to injection activities, and because there was no historical earthquakes recorded in the area [26].

The well location surrounding the Cleburne area is presented in Figure 13. It can be seen that based on the current simulation model, that the injection wells are correlated to the location of pore pressure change, which is correlated to the seismic activities.



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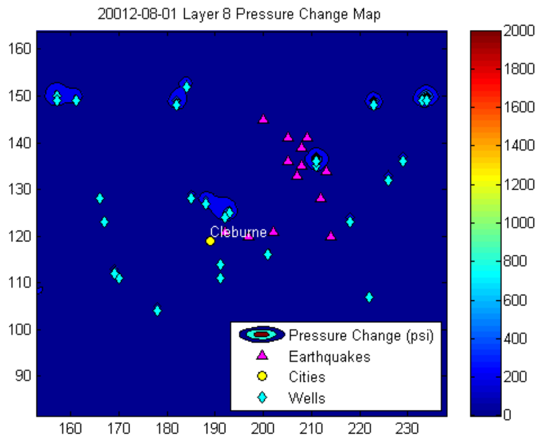

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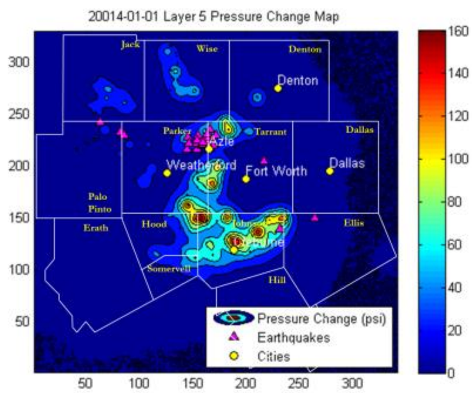
Fig. 12. a-b) Well location map.

3.3. *Azle Earthquakes*



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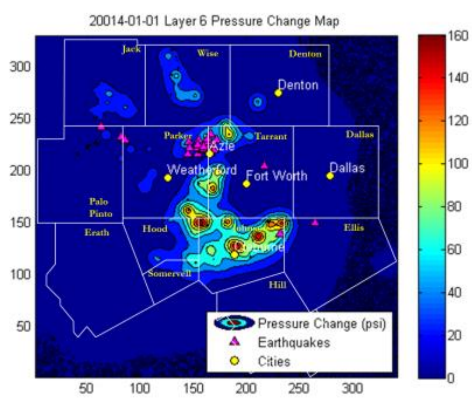

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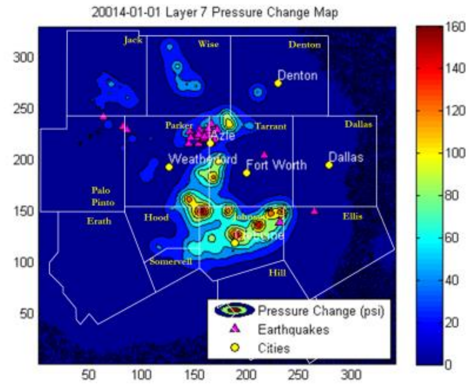

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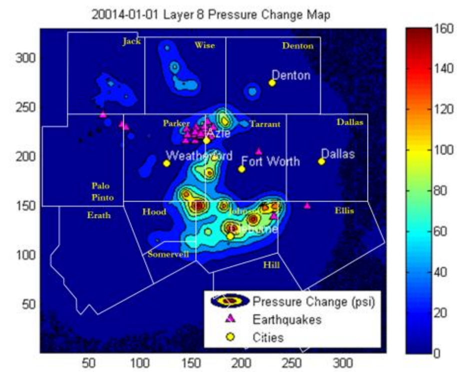

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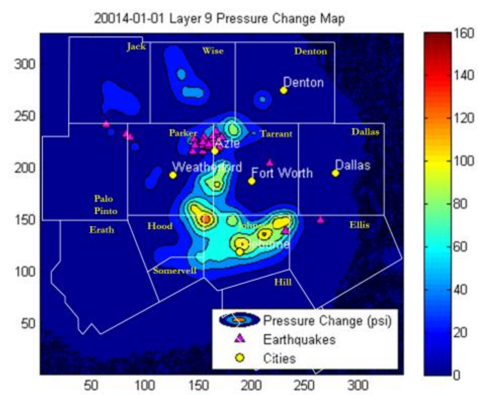

(e)

Fig. 13. a-e) Pore pressure change map for layer 5 to layer 9 respectively.

The Azle earthquake cluster occurred between November 2013 and January of 2014. Our simulation results show an increase in pore pressure in the area that experienced earthquakes. Perhaps a more interesting result, however, is that no earthquakes appear to occur where the predicted pressure change was greatest (Figure 14). Due to the coarseness of our simulations, it is certainly possible that the pressure distributions could be inaccurate, but another interpretation is that the geology in Hood and Johnson Counties, where the highest pressures are predicted, is not conducive to earthquakes, possibly due to a lack of favorably oriented pre-existing faults.

4. CONCLUSIONS

The overall simulation result shows that throughout the simulation period, for the areas of interest, DFW, Cleburne and Azle, there is a spatial and temporal correlation between seismic activity and pore pressure change. However there is also a lack of seismicity in areas of predicted increase in pressure. This implies, as others have suggested, that favorably oriented and sized pre-existing faults are required in addition to the change in pore pressure in order to induce seismicity. Further conclusions are difficult to draw without more detailed geology and refined locations for all the earthquakes examined. In addition to better subsurface geology information (layering, faulting and permeability), mechanical prediction of failure would require a much more comprehensive in situ stress characterization than is currently available.

5. ACKNOWLEDGEMENTS

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