The 2016 $M_w$5.1 Fairview, Oklahoma earthquakes: Evidence for long-range poroelastic triggering at >40 km from fluid disposal wells (Supplementary material)

T. H. W. Goebel$^a$, M. Weingarten$^b$, X. Chen$^c$, J. Haffener$^c$, and E. E. Brodsky$^a$

$^a$University of California, Santa Cruz, California, USA.
$^b$Stanford University, Stanford, California, USA.
$^c$University of Oklahoma, Norman, Oklahoma, USA.

Contents

S1 Oilfield data and seismicity background rate variations S3

S2 Pressure step-response and pressure front migration S6

S3 Hydrological and geomechanical parameters S9

S4 Sensitivity analysis of pressure perturbations S11
  S4.1 Pressure change for injection in an infinite strip . . . . . . . . . . . . . . S16
  S4.2 Expected pressure changes within a 3D isotropic model . . . . . . . . . . S18
  S4.3 Numerical diffusion models and crustal heterogeneity . . . . . . . . . . . S21

S5 Sensitivity analysis of poroelastic stress perturbations S24

S6 Coulomb stress change, friction and principle stress orientation S29
Introduction

This supplementary file contains results from a detailed sensitivity analysis of pore-pressure changes and poroelastic effects associated with fluid injection activity. In addition, we provide more detailed information about utilized data, methods and modeling parameters which allow for easy reproduction of the results in the main manuscript.

This document is structured as follows: First, we briefly discuss the injection records obtained from the Oklahoma Cooperation Commission (OCC) and describe the different methods used for earthquake declustering and background seismicity rate determination (Section S1). We then show results of expected pressure front migration for different reservoir geometries and diffusivities (Section S2) and list the utilized hydrological and geomechanical parameters (Section S3). Section S4 focuses on the sensitivity of expected pore pressure changes to different diffusivity values and reservoir geometry. In Section S5, we perform a similar sensitivity analysis for poroelastic stress changes and compare the distance decay of pore pressure and poroelastic stress perturbations in 2D and 3D. Lastly, we consider the influence of different stress orientation and coefficient of friction on resolved Coulomb stress changes S6. The online supplement also contains an animation that shows seismicity migration patterns and temporal changes in injection activity within the study area (map_cross_sec_pref.avi).
S1 Oilfield data and seismicity background rate variations

The following analysis is based on public wastewater disposal and seismicity data sets obtained from the Oklahoma Cooperation Commission (OCC) and the Oklahoma Geological Survey (OGS). To obtain high-quality earthquake locations, we adopt a two-step approach using travel-time data archived by the OGS and a 3D velocity model [1]. We first relocate each earthquake individually using the SIMULPS algorithm [2]. For earthquakes that cannot be located with this algorithm, we use the original OGS 1D locations. We then employ the HypoDD-3D algorithm to improve relative location accuracy using relative travel time differences [3]. For earthquakes on the Fairview fault, we use waveform cross-correlation derived differential times to further improve the location accuracy, and to constrain the geometry of the fault.

In addition to the seismic data, we analyze wastewater disposal rates and well locations, which are recorded monthly by the OCC between 1995 until the end of 2014 [1]. After that, daily injection rates are also available for specific high rate injection rate, with the caveat that injection data are commonly published with several months delay. This study focuses on deep wastewater disposal wells that injected in the Arbuckle group which is thought to be in direct contact with the crystalline basement [4]. Our study region hosts 41 such wells of which 37 are active (see Fig. S4). The exact injection depth is not available from the OCC but can be inferred from packer depths or the average between the top and bottom of the targeted injection zone. This depth varies between ~2 to 2.5 km.

To correlate injection and seismic activity, we determine background seismicity

\[1\text{http://www.occeweb.com/og/ogdatafiles2.htm} \]
rate variations and isolate independent background events from aftershock clustering. This procedure results in declustered catalogs which are also used to determine seismicity migration patterns. We used three different methods for background rate computations and declustering:

First, we identify and remove aftershocks within a fixed space-time window from each main shock which is defined as the largest magnitude event of a cluster [5]. The space-time window is a function of main shock magnitude. Aftershock removal is done recursively starting with the most recent earthquake to account for secondary earthquake triggering.

Second, we resolve complete triggering chains of earthquake clusters based on interevent space-time-magnitude distances [6]. The distribution of these distances is bimodal with one mode connected to distant background activity and another mode to triggered events. Based on the proximity of event pairs in the space-time-magnitude domain, we separate independent background from clustered events (i.e. fore-, main- and aftershocks), removing all aftershocks to create a second declustered catalog. Both declustering methods yield similar results in terms of resolved migration patterns and pressure changes at the hypo centers.

Third, we use a non-parametric approach for computing background seismicity rate variations which does not require aftershock removal [7,8]. This method describes both short-period aftershock triggering and long-period background rates by fitting a gamma distribution to the observed interevent times. The Gamma-distribution parameters were estimated using a maximum likelihood fit of interevent time distributions within sliding time windows between 2010 and the end of the seismicity catalog in 2016. Both the original and background rate variations highlight that very few seismic events were recorded before the start of more extensive injection operations in 2012. Systematically increasing seismicity rates are
correlated with increasing injection rates but occur with a ∼2 year time lag.

In contrast to injection rates, both oil and gas production rates within the study area show no obvious temporal correlations with background seismicity. Both types of production have been recorded and archived by the OCC after 1970. Since then gas production rates within the study area varied between 1 to 1.8 million mcf per month with production rate maxima in 1974, 1989 and 2008. Oil production rates peaked in 1996 and showed a systematic increase between 2007 and 2014. Despite the longterm production activity only about 30 events between $M_L$1 and $M_L$3.1 were recorded before 2013, the largest event was a $M_L$3.1 earthquake in July 1989. The low seismicity rates during production activity indicate that the recent surge in earthquake activity was likely connected to a change in oilfield operations. A likely candidate for such a change is the disposal of large amounts of wastewater in wells that became active after 2010.

We also examined a possible role of hydraulic fracturing using data obtained from FracFocus. Large volume hydraulic fracturing jobs of several millions gallons were conducted within the study region; however frack-jobs occur generally dispersed throughout the region and are unlikely to systematically raise seismicity level as observed in the current case. According to FracFocus only 8 frack-jobs were conducted in 2014 in Woodward county and 4 frack-jobs in Woods county in 2016 which hosted much of the Woodward and Fairview earthquake sequences. There were no reported frack-jobs in close proximity (i.e. within ∼4 km of Fairview and ∼10 km of Woodward) to either earthquake sequence.

\(^2\text{https://fracfocus.org/}, \text{accessed 09/2016}\)
**S2 Pressure step-response and pressure front migration**

The extent and amplitude of induced pore pressure changes depend, in addition to hydraulic diffusivity, on crustal heterogeneity and permeability structure, i.e. if pressures are allowed to diffuse across the entire volume or if diffusive processes occur more localized. Here, we explore three end member diffusion models, i.e. 3D isotropic, 2D axisymmetric and diffusion in an infinite strip reservoir. In reality, pressure diffusion within the upper crust is expected to involve a combination of these three scenarios with different geometries capturing more of the underlying processes and permeability structure. For example, diffusion along a fault damage zone may be more accurately modeled by a strip reservoir [9, 10, 11], whereas diffusion within the Arbuckle formation may be more accurately represented by an axisymmetric model [12].

We compare the expected pressure changes for the three different reservoir geometries as a function of distance and time after injection (Fig. S1). As expected, pressure decays more rapidly within a 3D volume than a 2D and a strip model. Similarly, pressures increase more rapidly within a strip than a 2D or 3D diffusion model and remain high over longer periods. Both effects are a result of pressure channeling within the strip and axisymmetric reservoir.
Figure S1: Pressure changes in response to a step increase in injection rates from \( Q=0 \) to \( Q=10,000 \) m\(^3\)/mo. Results are shown as a function of distance, five month after the injection step (left) and as a function of time at 1 km distance from the well (right). Pressure solutions are shown for three different diffusion models, i.e. a 3D isotropic, 2D axisymmetric and an infinite strip with width, \( w=300 \) m.

In addition to changes in pressure amplitudes, we determine migration characteristics of an initial pressure perturbation for the different diffusion models. The initial pressure front is determined by taking 0.5% of a reference pressure at 100 m distance and 1 month after the start of injection. The different reservoir geometries lead to a faster apparent pressure front migration and can lead to over- or under-estimation of hydraulic diffusivity if an incorrect geometry is assumed (Fig. S2).

As a consequence, the uncertainty in seismicity-inferred diffusivity can be a factor of two or more, which can be seen for example for seismicity along the Woodward fault. There, the inferred hydraulic diffusivity may vary between 0.1 and 0.2 m\(^2\)/s for strip or axisymmetric reservoirs (Fig. S3).
Figure S2: Pressure front migration in space and time for 3D isotropic, 2D axisymmetric and an infinite strip reservoir with \( w=100 \) m. The pressure front is defined as 0.5% of a reference pressure at 100 m distance and 1 month after the start of injection.
S3 Hydrological and geomechanical parameters

The following table lists all utilized parameters with units, references and how they were estimated. One of the most important yet most difficult to measure parameter is formation permeability. The published values for Arbuckle permeability cover four order of magnitude between $10^{-16}$ and $10^{-12} \text{ m}^2$ [4, 13]. We expect that disposal sites were selected within the higher permeability range of the Arbuckle; however much seismicity occurs deeper within the crystalline basement, complicated the use of direct permeability measurements. Moreover, local measurements resolve only small-scale permeability, whereas average formation permeability may be influenced by large-scale heterogeneity. To avoid local measurement biases, we infer permeability based on seismicity-migration and storativity, resulting in a range of permeability values between $10^{-15}$ and $10^{-13} \text{ m}^2$. Our values should be understood as large scale, average permeability and are likely a combination of values for the Arbuckle formation and basement faults.
Table S1: List of hydrologic, elastic and geomechanic parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>variable</th>
<th>value or range</th>
<th>unit</th>
<th>notes / citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrologic</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>dynamic viscosity</td>
<td>( \eta )</td>
<td>( 0.28 \cdot 10^{-3} )</td>
<td>Pa ( s )</td>
<td>at 100°C, [14]</td>
</tr>
<tr>
<td>fluid compressibility</td>
<td>( \beta_{fl} ) (( \frac{1}{k_{fl}} ))</td>
<td>( 4.6 \cdot 10^{-10} )</td>
<td>Pa(^{-1} )</td>
<td>[14]</td>
</tr>
<tr>
<td>fluid density</td>
<td>( \rho_{fl} )</td>
<td>1000</td>
<td>kg/m(^3)</td>
<td>[14]</td>
</tr>
<tr>
<td>porosity</td>
<td>( \Phi )</td>
<td>0.2</td>
<td></td>
<td>[4]</td>
</tr>
<tr>
<td>reservoir thickness</td>
<td>( b )</td>
<td>500</td>
<td>m</td>
<td>[4]</td>
</tr>
<tr>
<td>specific storage</td>
<td>( S_s )</td>
<td>( 1.18 \cdot 10^{-6} )</td>
<td>m(^{-1} )</td>
<td>Eq. 7 main text</td>
</tr>
<tr>
<td>storativity</td>
<td>( S )</td>
<td>( 6 \cdot 10^{-4} )</td>
<td></td>
<td>from ( S_s ) and ( b )</td>
</tr>
<tr>
<td>diffusivity</td>
<td>( D )</td>
<td>( 0.1 - 2 )</td>
<td>m(^2/s)</td>
<td>max. values from seismicity migration</td>
</tr>
<tr>
<td>transmissivity</td>
<td>( T )</td>
<td>( 6 \cdot 10^{-5} - 10^{-3} )</td>
<td>m(^2/s)</td>
<td>from ( D ) and ( S )</td>
</tr>
<tr>
<td>permeability</td>
<td>( k )</td>
<td>( 10^{-15} - 10^{-13} )</td>
<td>m(^2)</td>
<td>Eq. 8 main text</td>
</tr>
<tr>
<td>Biot coefficient</td>
<td>( \alpha )</td>
<td>0.3</td>
<td></td>
<td>[15]</td>
</tr>
<tr>
<td>Skempton coefficient</td>
<td>( B )</td>
<td>0.74</td>
<td></td>
<td>Eq. 3.75 Wang (2000)[14]</td>
</tr>
<tr>
<td>fault zone width</td>
<td>( w )</td>
<td>&lt;300</td>
<td>m</td>
<td>[16, 17, 18]</td>
</tr>
<tr>
<td>Elastic</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shear modulus</td>
<td>( G )</td>
<td>16</td>
<td>GPa</td>
<td>[19]</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>( \nu )</td>
<td>0.25</td>
<td></td>
<td>[19]</td>
</tr>
<tr>
<td>undrained Poisson’s ratio</td>
<td>( \nu_u )</td>
<td>0.30</td>
<td></td>
<td>[19]</td>
</tr>
<tr>
<td>Geomechanic</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>coefficient of friction</td>
<td>( \mu )</td>
<td>0.75</td>
<td></td>
<td>see [20]</td>
</tr>
<tr>
<td>max. principle stress</td>
<td>( \sigma_1 )</td>
<td>61</td>
<td>MPa</td>
<td>general gradient [21]</td>
</tr>
<tr>
<td>min. principle stress</td>
<td>( \sigma_3 )</td>
<td>15</td>
<td>MPa</td>
<td>general gradient [21]</td>
</tr>
<tr>
<td>max. stress direction</td>
<td>( S_{H}^{max} )</td>
<td>90±15</td>
<td>°N</td>
<td>[22, 23]</td>
</tr>
</tbody>
</table>
Figure S4: Spatial variations in pressures in response to injection in a homogeneous reservoir using an axisymmetric diffusion model with $D = 0.1 \text{ m}^2/\text{s}$ between 01/1995 and 10/2014 (A) and 02/2016 (B). Injection wells and seismicity are shown by markers according to legend in B).

S4  Sensitivity analysis of pressure perturbations

In the following, we test the sensitivity of resolved pressure changes to different values of hydraulic diffusivity and reservoir structure using the injection data recorded by the OCC within the study region. Figures S4–S7 show injection-induced pressure changes in map-view for four different diffusivity values from 0.1 to 2 m$^2$/s and for two different injection periods between 1995 to October 2014 and 1995 to February 2016. At the lower end of these diffusivity values injection activity results in largely isolated zones of increased pressures whereas for higher diffusivity of 0.5 m$^2$/s and above the regions of high pressures start to coalesce forming a coherent region with pressures between 0.1 and 1 MPa and a radius of 10 to 15 km.
Figure S5: Same as Fig. S4 but with $D = 0.5 \text{ m}^2/\text{s}$.

Figure S6: Same as Fig. S4 but with $D = 1.0 \text{ m}^2/\text{s}$.
In addition to spatial differences in pressure perturbations, we also resolve expected pressure changes at each earthquake hypo center that occurred along the Fairview fault. While small diffusivity values are associated with uniformly small or even no pressure changes across the Fairview earthquake locations, large diffusivity values result in higher pressure perturbations up to 0.06 MPa (Fig S8).

In contrast, the expected pressure changes across the Woodward hypo centers is slightly higher for low diffusivity values. This is a result of injection into one well, Ww07 (see main manuscript), located within a distance of 8 km. Nevertheless, pressure changes are expected to be below 0.03 MPa for most earthquake locations and onset times (Fig S9).
Figure S8: Distributions of pore pressure change at the time and location of earthquakes along the Fairview fault for four different diffusivity values and 2D axisymmetric diffusion.
**Figure S9:** Distributions of pore pressure change at the time and location of earthquakes along the Woodward fault for four different diffusivity values and a 2D axisymmetric diffusion model. Pressures are generally expected to be smaller than in Fig. S8 because of the larger distance to high-rate injection wells.
S4.1 Pressure change for injection in an infinite strip

We further examine expected pore pressure changes due to injection into the closest Arbuckle well to the Woodward fault, i.e well Ww07. This well is located at \( \sim 9 \) km distance from where the seismic activity started on the Woodward fault (Fig S4). Injection started in 2007 at rates of \( \sim 35,000 \) m\(^3\)/mo and decreased systematically between 2008 and 2014, remaining at low levels of 4000 to 9000 m\(^3\)/mo until 2016. The long time delay between peak injection and the onset of seismicity of \( \sim 7 \) years requires small hydraulic diffusivity on the order of 0.1 m\(^2\)/s for pressures to still increase prior to the earthquakes (Fig S10). The resulting pressure perturbations are expected to be small for diffusion in an axisymmetric reservoir (see Fig. S9). We test an alternative reservoir geometry, i.e. a strip model which may approximate diffusion within a fracture or fault damage zone (Fig S10). The expected pressure change in a strip model increases by a factor of 3 to 10 compared to the axisymmetric solution for \( w=300 \) and 100 m. However, such strong pressure localization effects over a distance of \( \sim 9 \) km also require a high degree of crustal heterogeneity. Based on the present seismicity and geological data, no observational evidence for the existence of such heterogeneity could be identified.
Figure S10: Pore-pressure change at the Woodward fault as a function of time for a strip model with a width of 0.1 to 0.3 km. Blue curve shows injection rates for the nearest Arbuckle well located at ∼9 km distance.
S4.2 Expected pressure changes within a 3D isotropic model

In addition to the solutions for pressure changes within a 2D axisymmetric model shown in the main manuscript, we also explore solutions for 3D isotropic diffusion. Figures S11 and S12 show the expected distribution of induced pressure changes for earthquakes along the Fairview and Woodward faults assuming 3D isotropic diffusion and diffusivity values between 0.1 and 2 m$^2$/s. The determined pressures at each hypo center are based on the integration of pressure perturbations from individual wells. As expected, if pressures are allowed to diffuse throughout the volume and are not vertically confined, the resulting pressure changes at the distances and onsets of the Fairview and Woodward events are significantly smaller than in the 2D model, occupying values below 2 kPa for all diffusivity values.
Figure S11: Distribution of pore pressure changes across the Fairview hypo centers for four different diffusivity values assuming a 3D isotropic model. Note that pressures are significantly lower than for the 2D axisymmetric solution in Figure S8.
Figure S12: Distribution of pore pressure changes across the Woodward hypo centers for four different diffusivity values assuming a 3D isotropic model. Note that pressures are significantly lower than for the 2D axisymmetric solution in Figure S9.
S4.3 Numerical diffusion models and crustal heterogeneity

We develop a three-dimensional numerical model of fluid-pressure diffusion to assess the effect of crustal heterogeneity and anisotropy of fault-permeability extending from the Arbuckle formation to the underlying crystalline basement. Similar models have been employed to investigate the role of high-permeability faults during earthquake triggering in Texas, Arkansas and California [24, 25, 11]. In addition to model description and results, we present a sensitivity analysis of a realistic range of hydraulic parameters and idealized scenarios of fluid pressure diffusion along permeable fault damage zones.

We utilize the groundwater modeling code, MODFLOW, which is based on a modular finite-difference approach to calculate the three-dimensional pore pressure change associated with fluid injection in the Fairview region [26, 27]. MODFLOW solves the groundwater flow equation for a fluid of constant density, dynamic viscosity under isothermal conditions (see Equ. 1 in the main manuscript). Heterogeneity and anisotropy can be directly specified for each nodal point in the three-dimensional finite difference grid.

The model domain simulates pore pressure change in a 109 km (north-south) by 128 km (east-west) rectangular grid with variable finite difference discretization. The rectangular grid encompasses the entire region shown in Figure S13 from -99.2 to -98.2 degrees west and from 36.1 to 36.8 degrees north. All model boundaries are sufficiently far from the injection region to have no interaction with the study region pressure build-up. Arbuckle group injection in the region is comprised of 37 injection wells operating at depths between 2.4 and 2.9 km. The finite-difference grid discretization varies from 75 m^2 to 100 m^2 in the faulted regions and up to 200 m^2 in the injection well region (Figure S13). The model calculates fluid pressure
Figure S13: Plan view of numerical model domain showing grid discretization (A) and locations of the Woodward and Fairview faults (red) as well as injection wells as black squares (B). The blue highlighted regions in (A) and (B) delineate the region of 200 m$^2$ grid spacing while the yellow highlighted region in (A) and (B) delineate 75 to 100 m$^2$ grid spacing. The black lines show the extended representations of the Woodward and Fairview faults to explore the consequences for expected pressure change.

change at more than 3.2 million cells with 712 columns, 419 rows and 11 layers.

The primary interior boundary conditions of the model are the injection wells, represented as source terms of the groundwater flow equation. Source term data on well location and reported monthly injection rates are available from the Oklahoma Corporation Commission (OCC) database. Monthly injection data from January 2005 through February 2016 is simulated using 135 pumping periods and more than 1100 time steps.

One of the main features of our numerical model is the specification of anisotropic, high-permeability damage zones along the Woodward and Fairview faults (Figure S14). Both faults are parameterized to preferentially channel flow along and down a 300 m wide damage zone. Based on linear regions with much seismicity, we can determine the Woodward and Fairview fault length between $\sim$13–14 km, high-
Figure S14: Cross-section of one model scenario of spatial heterogeneity and anisotropy of hydraulic parameters. Hydraulic diffusivity is related to conductivity as $D = K/S_s$.

A cross-section of one heterogeneous, anisotropic model parameterization shows how isotropic crystalline basement diffusivity contrasts with Arbuckle group and faulted crystalline basement diffusivity (Figure S14).

The Woodward and Fairview damage zones are approximated by vertical conduits of increased diffusivity. Discretization in the vertical direction throughout the model domain is comprised of 4 uniformly spaced layers in the Arbuckle Group and 7 layers in the crystalline basement increasing in thickness to a total depth of 12 kilometers. The simulated model represents an end member case in that the isotropic basement allows no fluid pressure transmission while all fluid pressure change occurs in the Arbuckle Group or fault damage zones. Table S2 summarizes the expected range of pore pressure changes for the tested model scenarios.
Table S2: Expected pore pressure changes from numerical finite difference modeling

<table>
<thead>
<tr>
<th>Model scenario</th>
<th>Arbuckle diffusivity [m$^2$/s]</th>
<th>Fault diffusivity [m$^2$/s]</th>
<th>Basement diffusivity [m$^2$/s]</th>
<th>Faults extend to high-rate injectors</th>
<th>$\delta P_P$ Woodward [kPa]</th>
<th>$\delta P_P$ Fairview [kPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1</td>
<td>0.1</td>
<td>$10^{-10}$</td>
<td>No</td>
<td>11–14</td>
<td>13–25</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>0.1</td>
<td>$10^{-10}$</td>
<td>No</td>
<td>16–21</td>
<td>22–49</td>
</tr>
<tr>
<td>3</td>
<td>1.0</td>
<td>0.1</td>
<td>$10^{-10}$</td>
<td>No</td>
<td>16–23</td>
<td>36–78</td>
</tr>
<tr>
<td>4</td>
<td>2.0</td>
<td>0.1</td>
<td>$10^{-10}$</td>
<td>No</td>
<td>17–29</td>
<td>48–101</td>
</tr>
<tr>
<td>5</td>
<td>0.5</td>
<td>0.1</td>
<td>$5 \cdot 10^{-2}$</td>
<td>No</td>
<td>4–17</td>
<td>3–29</td>
</tr>
<tr>
<td>6</td>
<td>0.5</td>
<td>1.0</td>
<td>$10^{-10}$</td>
<td>No</td>
<td>22–23</td>
<td>37–52</td>
</tr>
<tr>
<td>7</td>
<td>0.5</td>
<td>0.1</td>
<td>$10^{-10}$</td>
<td>Yes</td>
<td>17–23</td>
<td>11–22</td>
</tr>
</tbody>
</table>

The tested model scenarios are listed from 1–7 and corresponding diffusivity values are presented for the Arbuckle and basement formation as well as for the Woodward and Fairview faults. Pore pressure changes are reported in the last two columns as the highest pressure recorded at $\sim$5 and $\sim$3 km depth.

### S5 Sensitivity analysis of poroelastic stress perturbations

Poroelastic stresses are expected to exceed direct pressure effects at large distances for injection in a vertically confined reservoir. For the current case, this cross-over distance beyond which poroelastic effects become dominant is $\sim$15 km for a diffusivity of 0.5 m$^2$/s (see main manuscript).

Here, we test the sensitivity of expected poroelastic stress changes to injection in a 2D compared to a 3D reservoir model with diffusivity values between 0.1 to 2.0 m$^2$/s. Injection in a 3D model results in significantly lower poroelastic stresses which also decay more rapidly as a function of distance ($\sim 1/r^3$ vs. $\sim 1/r^2$ in 2D). Figure S15 exemplifies poroelastic stress changes as a result of injection in the largest well in the study area. While pressure and stress changes are small in the 3D...
Figure S15: Decrease in pore-pressure (blue curve) and poroelastic stresses (red curve) as a function of distance from the largest injection well within the study region, assuming a 3D isotropic reservoir with $D=0.5 \text{ m}^2/\text{s}$. Note that poroelastic effects become dominant for distances beyond $\sim 16 \text{ km}$.

model, we observe a similar trend of pressure effects exceeding poroelastic stresses within the near field of injection activity. Poroelastic effects are more dominant beyond distance of $\sim 16 \text{ km}$. Thus, both the 3D and 2D solutions suggest a crossover distance beyond which poroelastic effects are expected to be more dominant than direct pressure effects.

The expected pressure and poroelastic stress decay in 2D reveal an interesting correlation with seismicity density decay as a function of distance. Both the seismicity density and pore pressure changes show an extended plateau with a radius
of 10 to 15 km for diffusivity values above 0.1 m$^2$/s (Fig. S16). At larger distances, pressures decrease significantly faster than seismicity density. At these distances poroelastic effects are dominant and may explain the local increase in seismicity density associated with the Fairview and Woodward clusters.

In addition to the role of diffusivity, we also explore the extent to which the crossover distance between pore pressure and poroelastic stress dominance is dependent on poroelastic parameters, namely Biot coefficient, $\alpha$. Biot-$\alpha$ is defined as the ratio of fluid volume added to storage over change in bulk volume under constant pressure. It can be determined using the following relationship [28][14]:

$$\alpha = 1 - \frac{K}{K_s'},$$

where $K$ is the bulk modulus and $K_s'$ is the unjacketed bulk modulus. The latter can be understood as grain or mineral bulk modulus for homogeneous, single phase rocks. For soft rocks, $K_s'$ is commonly significantly larger than $K$ resulting is higher $\alpha$ values whereas crystalline rocks exhibit lower values for $\alpha$ and consequently poroelastic effects are expected to be small. The latter is characteristic for example for deep injection in geothermal reservoirs.

We test the influence of $\alpha$ on the resolved difference in pore pressure vs. poroelastic stress dominance as a function of distance by varying $\alpha$ between 0.15 to 0.45. Our results show that within a reasonable range of $\alpha$, poroelastic stresses remain dominant at distances beyond 15 to 20 km. In focusing on the influence of $\alpha$, we did not consider the connection between Biot $\alpha$ and specific storage coefficient, $S_s$. Coupling these two parameters would further reduce the pressure response due to an increase in $S_s$ with larger Biot-$\alpha$ so that poroelastic stresses are expected to be dominant over even more extensive regions.
Figure S16: Decrease in pore-pressure (blue curves), seismicity density (black line) and poroelastic stress perturbations (red curve) as a function of distance for four different diffusivity values between $D=0.1$ to 2 m$^2$/s. The dashed blue curve shows theoretical pore-pressure perturbation for the hypothetical scenario of the entire injection activity being concentrated in only one well.
Figure S17: Decrease in pore-pressure (blue curve), seismicity density (black line) and poroelastic stress perturbations (red curves) as a function of distance. Poroelastic stress changes are shown for three different values of Biot’s coefficient.
S6  Coulomb stress change, friction and principle stress orientation

Resolving the expected Coulomb stress changes for different poroelastic stress perturbations depends strongly on principle stress orientations and coefficient of friction. We test the sensitivity of poroelastically-induced fault-stress-changes by varying the coefficient of friction between 0.2 and 1. Our sensitivity analysis suggests that poroelastic effects are expected to exceed pressure induced Coulomb stress changes along for Fairview fault if the coefficient of friction is above 0.3 (Figure S18). For lower coefficients of friction or different fault strike angle pore-pressure effects will be more dominant and control the expected seismogenic response.

The sensitivity analysis for the Woodward fault suggests that at these distances and fault orientations poro-elastic stresses are always dominant because of the combined effects of the azimuth between injection wells and faults relative to $\sigma_1$ and the more slip-favorable fault strike. The relatively smaller angle between fault strike and $\sigma_1$ may indicate a higher coefficient of friction along the Woodward fault.

Lastly, we test the influence of varying principle stress orientations on resolved fault stress changes due to poroelastic effects. For this purpose, we rotate the principle stress axes by 5°N resulting in a stress orientation similar to Alt & Zoback (2014)[29]. This rotation has a stronger effect on stress changes along the Fairview fault because of a more favorable alignment between the fault and well azimuth within the new stress field (Fig. S19 & S20). Both faults would experience larger Coulomb stress changes in the rotated stress field but stress changes along the Fairview fault now exceed those along the Woodward fault.
Figure S18: Change in Coulomb stresses for injection-induced pressure and poroelastic stress perturbations at the Fairview (left) and Woodward (right) fault. Different colors correspond to friction values between 0.2 to 1.0 (see legend) used to determine reference stress states and resolved Coulomb stress changes.

Figure S19: Same as Figure S18 but with stress field rotated by 5°N. Note that y-axis limits are different from Figure S18.
Figure S20: Left: For easier comparison, we plotted the original stress field shown in Figure 8 in the main manuscript. Right, Inset: Change in differential stress due to poroelastic stresses as a function of azimuth from the pressurized area. The principle stresses are rotated by 5°N relative to the stress field in the main manuscript in agreement with stress inversions by Alt & Zoback, (2014) [29]. Right, Main Axis: Change in Coulomb stress for Woodward (green) and Fairview (red) as a function of fault strike, with Woodward and Fairview fault strikes highlighted again by green and red arrows. Solid curves show the coupled poroelastic stress contributions whereas dashed lines show the pressure contribution.
References


