A comparison of seismicity rates and fluid-injection operations in Oklahoma and California: Implications for crustal stresses

Thomas Göbel[1]

Abstract

Fluid injection into deep wellbores can increase pore pressure, reduce effective stress, and trigger earthquakes. The extent of the seismogenic response to injection provides insight into how close faults are to failure in the injection-affected area. The seismogenic response to injection operations in hydrocarbon basins is examined in California and Oklahoma. Changes in spatial and temporal seismicity rates are tested for significant variations, and timing and location of such variations are determined based on nonparametric modeling of background seismicity rates. Oklahoma has experienced a recent surge of seismic events, which exceeded the 95% confidence limit of Poissonian background rates in c. 2010. Annual injection volumes in Oklahoma increased systematically between 1998 and 2013 and have been connected to several earthquake sequences. In California, injection volumes increased monotonically between 2001 and 2009; however, the seismogenic response was limited and was devoid of large-scale background rate increase. A detailed comparison of injection parameters in Oklahoma and California included well density, wellhead pressures, peak and cumulative rates, and injection depths. No detectable difference was found that could readily explain the observed changes in seismicity rate in Oklahoma and the lack thereof in California. A strongly different seismogenic response to similar pressure perturbations indicates that the injection parameters considered are only of secondary influence on the resulting earthquake activity. The primary controls on injection-induced earthquakes might be the specific geologic setting and the stress state on nearby faults.

Introduction — Injection-induced earthquakes in California and the central and eastern United States

The injection of waste fluids into deep disposal wells and its environmental consequences are a growing concern in the central and eastern United States. Such injection activities can increase pore pressures and poroelastic stresses, which might trigger earthquakes on faults close to failure (e.g., Ellsworth, 2013; Kim, 2013). Several regions in the central and eastern United States exhibited a pronounced increase in seismic activity coincident with injection operations in nearby wastewater-disposal wells.

The corresponding seismicity sequences include the 2011 M_W 4.7 sequence in Guy, Arkansas (Horton, 2012); the M_W 3.9 in Youngstown, Ohio (Kim, 2013); and the M_W 5.7 Prague, Oklahoma, earthquake sequence (Keranen et al., 2013). Many of those sequences were associated with nearby wastewater injection into high-permeability aquifers overlying igneous basement. The basement layers, which are connected hydraulically to the reservoirs above, host the majority of the induced earthquakes, including the largest-magnitude events.

Previous studies examined isolated cases of likely injection-induced seismicity. However, a synoptic identification of induced seismicity and its underlying causes is still missing in Oklahoma and the central United States. In central California, a comprehensive regional study revealed that induced seismicity is rare considering the extensive injection activity that has occurred in close proximity to active faults (Aminzadeh and Göbel, 2013). The authors identified three induced-seismicity sequences with magnitudes as high as M_W 4.7, based on a rigorous statistical assessment of correlations between injection and seismic activity.

This study focuses on a large-scale assessment of differences in injection operations and possibly induced seismicity in California and Oklahoma. Those two states exhibit strong differences in tectonic deformation and seismic activity. Although Oklahoma experienced generally low seismicity rates until 2009 (Ellsworth, 2013), seismicity rates in California are high as a result of pervasive tectonic deformation along many active faults. To isolate the possible influence of injection activity from tectonic earthquakes in California, I limit the analysis to seismicity that occurred in major hydrocarbon basins.

The article is structured as follows. First, I determine the cumulative distribution of earthquake rates and annual injection rates in California and Oklahoma between 1980 and 2014. I then test for statistically significant increases in background seismicity rates and determine when and where they occur. Finally, I examine whether differences in seismicity rate can be traced to differences in injection parameters between California and Oklahoma.

Seismicity and injection data in California and Oklahoma

This work concentrates on the most widely available and homogeneous seismicity and injection data sets, including earthquake catalogs, fluid-injection volumes, wellhead pressures, and injection depths. Injection data have been archived by the Oklahoma Corporation Commission (OCC) since c. 1975 and by the California Department of Conservation, Division of Oil, Gas and Geothermal Resources (DOGGR), since c. 1977. The seismicity record is archived by the U. S. Geological Survey Advanced National Seismic System in California and is available from Oklahoma Geological Survey.

Much of the seismicity in California is tectonically driven and localized along major fault traces. I exclude earthquakes along major faults and solely select seismicity within large hydrocarbon basins. For this purpose, I compute the largest convex hull of well-location vertices, using a Delaunay triangulation algorithm. The subset of seismicity within the hull corresponds to 12% of the total seismicity in California (Figure 1). For Oklahoma, essentially the entire earthquake record (99%) is used.

I evaluate changes in network recording quality as a function of time based on variations in the magnitude of completeness (M_C). The latter is computed by minimizing the misfit between the observed frequency-magnitude-distribution and the modeled

[1]California Institute of Technology.

DOI information...

fit assuming power-law-distributed data above M_C (Clauset et al., 2009). In California, M_C is generally close to 2 after 1995 but also shows short-period fluctuations, e.g., connected with the 1994 M_W 6.7 Northridge earthquake (Figure 1a). In Oklahoma, M_C varies between 1.5 and 2.5. Consequently, the seismicity record in both regions is cut below M_C = 2.5 to ensure catalog completeness. The following analyses are based on the cut catalogs within the convex hulls.

In addition to the seismicity records, I examine large-scale injection data to identify possible temporal and regional variations. The overall well density in Oklahoma is ~ 0.05 km^2 (i.e., about one well every 20 km^2), which is significantly lower than in California basins, with a density of 0.7 km^2 (i.e., one well every 1.4 km^2). In California, injection data are recorded monthly for each well and categorized according to the type of injection activity, i.e., wastewater-disposal (WD) and enhanced oil-recovery (EOR) wells. The latter are classified further into waterflooding (WF), steam flooding, cyclic steam injection, and pressure maintenance. Injection into WD and WF wells represents the largest contribution to the total injected volumes.

In Oklahoma, insufficient information about wastewater disposal versus enhanced oil recovery is available so that both well types are treated jointly. The overall contribution of WD wells to annual injection volumes is ~ 50% in Oklahoma (Murray, 2014), and it is only ~ 20% to 30% in California.

In California, the DOGGR publishes cumulative injection rates for each year, but with a significant time lag, so that 2009 is the most recent year with a complete record. Injection rates peaked in the mid-1980s and in 2000 and have increased continuously since 2001 (Figure 2a). Moreover, some regions in California, such as the major oil fields in Kern County, experienced a continuous increase in injection rates over even longer periods, e.g., since c. 1995, highlighting that injection-rate variations are not homogeneous in space (California Department of Conservation, Division of Oil, Gas and Geothermal Resources, 2014). This is explored in more detail below through a spatial correlation of large-volume injection wells and variations in seismicity rate.

In Oklahoma, cumulative annual injection volumes were determined by summing over all individual well records from the OCC database and comparing them with published values between 2009 and 2013 (Murray, 2014). Murray (2014) performs a detailed data-quality assessment and removes obvious outliers. Consequently, annual injection rates are lower compared with the OCC database, especially after 2010. Nevertheless,

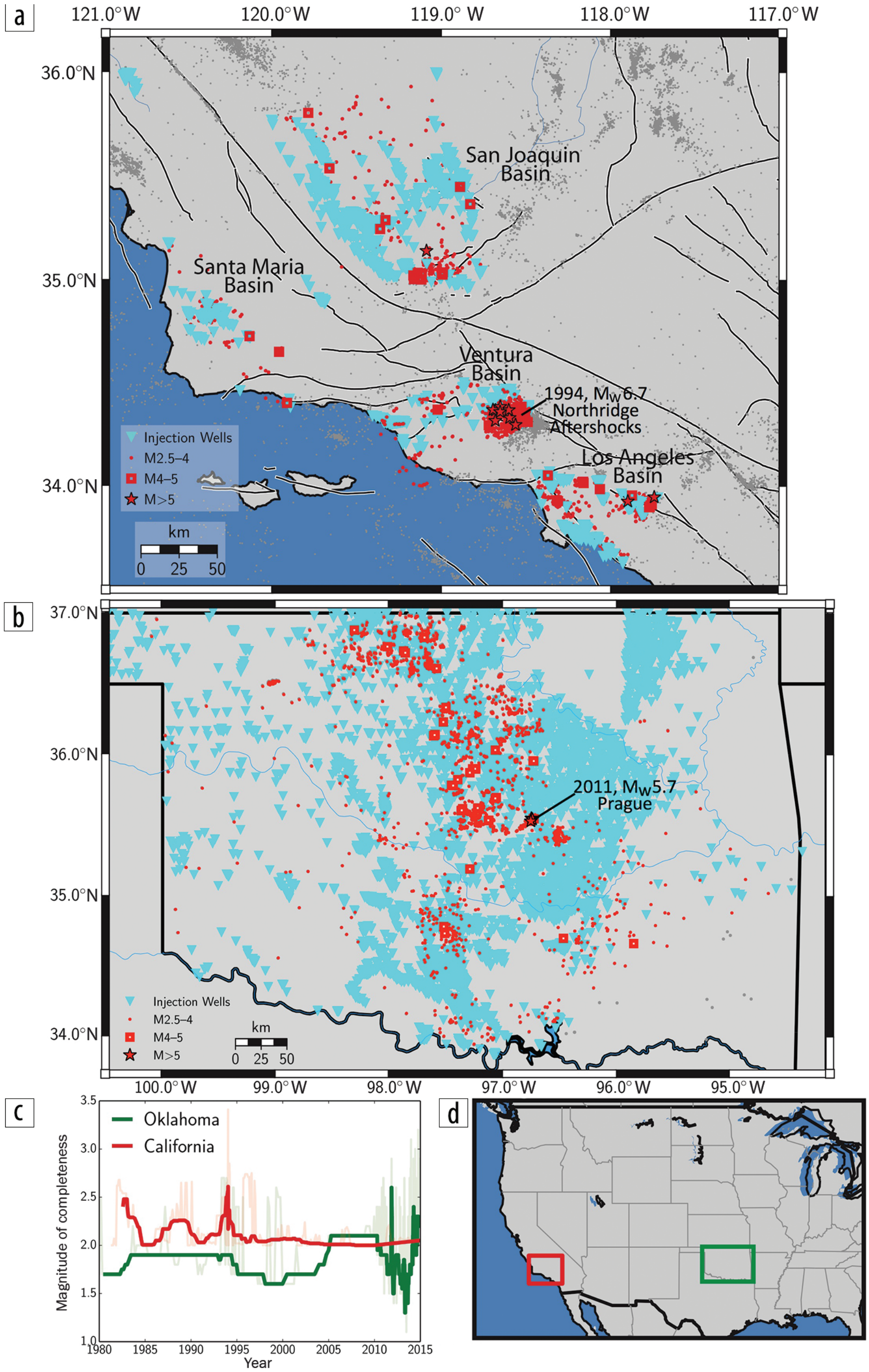

Figure 1. Seismicity (red dots, squares, stars; see legend for magnitudes) and injection-well locations (blue triangles) in (a) California and (b) Oklahoma. Major active faults in California are highlighted by black lines in part (a). Gray dots represent earthquakes that were not used in the following analysis. (c) M_c variations for moving windows of 200 events (thin lines) and after applying a 25-point median filter to remove high-frequency variations (thick lines). (d) Locations of study regions in California (red rectangle) and Oklahoma (green rectangle).

both data sets indicate a systematic increase in annual injection rates between 2008 and 2013 (Figure 2b). OCC injection data prior to 2006 are incomplete but suggest a largely monotonic increase between 1998 and 2013, assuming that relative injection variations are depicted reliably even in the incomplete data set.

Annual injection volumes in Oklahoma are comparable to those in California only in 2006, with 2.0 Gbbl/yr and 2.3 Gbbl/yr, respectively, and are generally lower than in California during all other periods. Moreover, injection in Oklahoma occurs over a wider area so that the difference in injection volume per area is even higher in California compared with that in Oklahoma.

In addition to differences in fluid injection, net-fluid production rates and volumes can influence the seismogenic response in a region. However, the assessment of net-fluid production is complicated by geologic and reservoir complexity as well as fluid-density variations and thus is not considered here.

Spatial and temporal changes in background seismicity rates

Changes in seismicity rates commonly are dominated by aftershock clustering (Figure 2) and thus provide only limited insight into changes in external driving forces such as pressure increases. Such additional forces are assessed more readily by using the rate of independent main shocks, i.e., the background seismicity rate (λ_0) (Hainzl et al., 2006). To determine λ_0, I employ two methods:

1) I remove all events within a specific space/time window after a main shock, here the largest-magnitude event within a sequence. This method takes advantage of the strongly localized occurrence of aftershocks in space and time. The size of this window is a function of main-shock magnitude (Gardner and Knopoff, 1974). As expected, aftershock removal demotes abrupt seismicity-rate changes, and large rate increases, for example, connected with the Northridge earthquake sequence, disappear.
2) To avoid inherent biases of the aftershock window selection, I also use a nonparametric method to determine main-shock fractions and rates (Hainzl et al., 2006). The method uses a gamma distribution to fit the observed interevent time distributions (ITD), i.e., the distribution of time intervals between consecutive earthquakes (e.g., Hainzl et al., 2006):

$$p(\tau)=C\cdot\tau^{\gamma-1}e^{-\frac{\tau}{\beta}}, \quad (1)$$

where C is a scaling constant, τ is the interevent time normalized by earthquake rate, and γ and β are parameters describing the shape and scale of the underlying distribution. The background seismicity rate can be computed from the parameter β and the observed rate, λ, of the clustered catalog:

$$\lambda_0=\frac{1}{\beta}\cdot\lambda\,. \quad (2)$$

The gamma-distribution parameters were estimated using a maximum likelihood fit of ITDs within sliding time windows between 1980 and 2014.

Applying the nonparametric method to the California seismicity data set, I find that λ_0 decreased systematically from 12 to six events per year between 1983 and 2011. However, this variation falls well within the 95% confidence interval of Poissonian distributed data with a mean of nine events per year (Figure 3a). In Oklahoma, λ_0 showed little variation between 1983 and 2009 but increased rapidly thereafter to 23 events in 2011 and 58 in 2013. Those values exceed the 95% confidence interval of Poissonian distributed data with a mean of 4 in c. 2010. I tested the sensitivity of these results to the selected time window by varying its length from four to 15 years. The results are independent of particular time-window selections such that the systematic increase in λ_0 is observed consistently for all time windows as well as for the declustered catalog by using Method 1, described above.

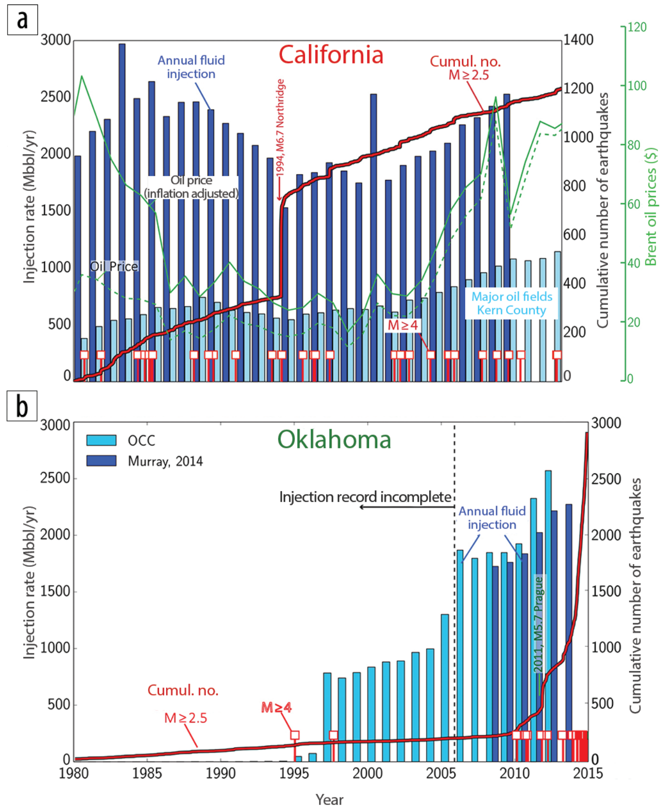

Figure 2. Annual fluid injection (vertical bars) and number of earthquakes (thick curves) in (a) California and (b) Oklahoma from 1980 through 2014. Earthquakes above M4 are shown by red squares. Actual and inflation-adjusted oil prices are highlighted by dashed and solid green lines, respectively, in part (a). The light blue bars in (a) show annual injection rates for the largest oil fields in Kern County, California. The dark and light blue bars in part (b) are injection volumes from Murray (2014) and from the OCC database. Mbbl/yr refers to million barrels per year.

In addition to changes in λ_0 over time, I examine spatial variations in numbers of main shocks and correlate them with locations of large-volume injection wells in Oklahoma and California. Spatial variations are computed within a grid of 0.1° spacing in California and 0.4° spacing in Oklahoma. The rates at each node are then smoothed using an isotropic, Gaussian kernel preserving the initial rates and normalized by the corresponding time interval and grid spacing.

I compare the smoothed rates in California before and after the most recent pronounced increase in fluid-injection rates in 2001 (Figure 2a) and highlight regions that experienced an increase in λ_0 above the 95% confidence limit of a Poissonian

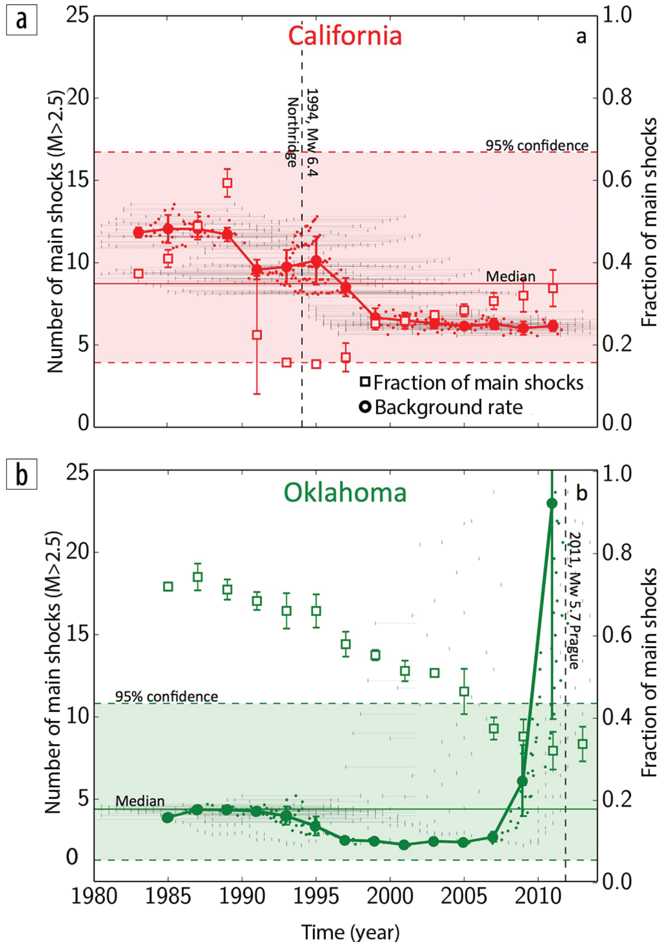

Figure 3. Background seismicity rates (large dots) and fraction of main shocks (squares) for (a) California and (b) Oklahoma. Solid and dashed lines show median values and 95% confidence interval assuming a stationary Poisson process, respectively. I explored the influence of time bins by varying the bin size from four to 15 years (small dots and gray error) and averaged over these different intervals using a two-year time step (large dots). Vertical error bars show the corresponding standard deviations from bootstrap resampling.

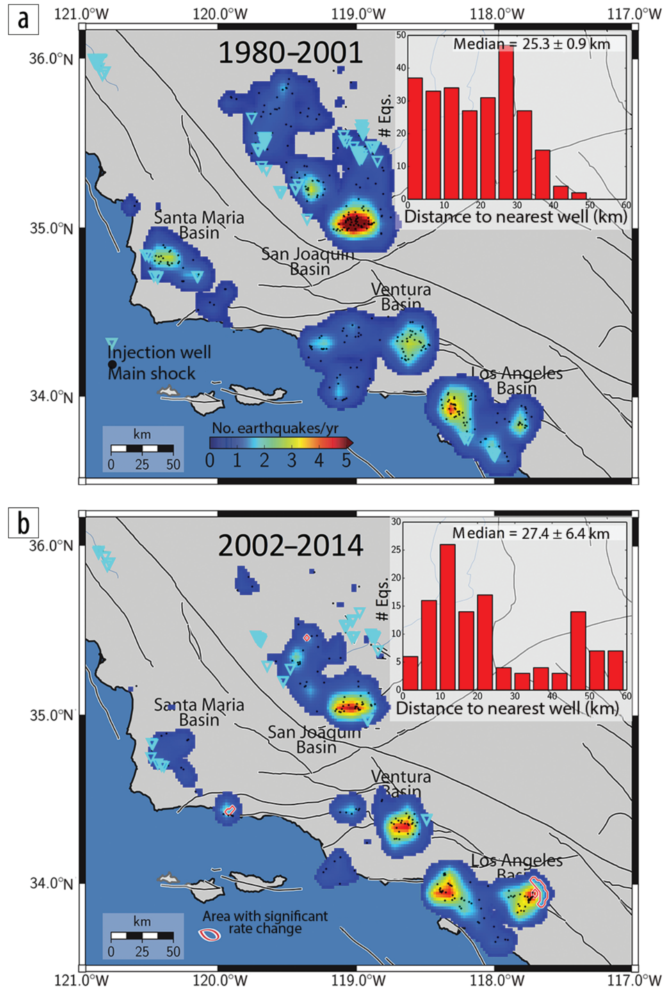

Figure 4. Smoothed, spatial variation in background seismicity rates in California basins in (a) 1980 through 2001 and in (b) 2002 through 2014. Earthquake locations are shown by black dots, location of high-volume injection wells (> 40,000 m^3/mo) by blue triangles, and areas of significant rate increase by red contours. Insets show the distance between earthquake and closest high-volume injection well.

process (Figure 4). California exhibits only localized areas with significant rate increase, connected with the 2013 M_W 4.8 Isla Vista event [–119.9°N, 34.4°W] and the 2008 M_W 5.4 Chino Hills earthquakes [–117.8°N, 34.0°W].

In Oklahoma, on the other hand, the number of main shocks increased significantly after 2009. This increase was concentrated in central and northern Oklahoma (Figure 5). Moreover, the newly emerging main-shock activity exceeds the 95% confidence limit of Poissonian distributed data in a large region (red contours in Figure 5b), which is in agreement with Llenos et al. (2014). The significant increase in λ_0 occurred in the neighborhood of some large-volume injectors with maximum monthly rates of more than 1 Mbbl/mo (i.e., million barrels per month). The median distance between individual earthquakes and the closest high-volume injection wells decreased significantly from 39 to 20 km after 2009 (Figure 5b). This decrease in distance is observed for wells with both intermediate and high peak injection rates and is primarily a result of a northward seismicity migration.

The extensive, newly appearing main-shock activity in Oklahoma after 2009 represents a strong contrast to the lack of observable changes in seismic activity in California. If much of this activity is induced, it also might indicate a substantial difference in injection parameters between the two states. In the following, I perform a detailed comparison of injection operations between California and Oklahoma to identify possible systematic differences.

Comparison between injection operations and focal depths in California and Oklahoma

Injection rates and pressures might significantly influence the seismogenic potential of fluid injection. I determine the maximum wellhead pressures and injection rates from the DOGGR and OCC databases for individual active wells to determine whether statistically significant differences in injection parameters can be identified. In California, I examine wastewater-disposal and waterflood wells, the latter as a proxy for typical EOR wells. In Oklahoma, both well types are treated jointly.

As expected, much of the injection activity is conducted at comparably low pressures and rates. The two study regions show strong similarities in median peak pressures, i.e., 4.3 ± 0.2 MPa in Oklahoma and 5.5 ± 0.2 MPa in California, and peak injection rates, i.e., 2900 ± 200 m^3/mo in Oklahoma and 4700 ± 200 m^3/mo in California (Figure 6). Both peak rates and pressures are higher for WD compared with WF wells in California, but no systematic differences between California and Oklahoma could be identified that could be responsible for the observed difference in seismic activity.

Besides rates and pressures, injection depth can control induced-seismicity potentials. In Oklahoma, the packer depth of injection wells, which is a minimum value for injection depth, is readily available from the OCC Web site. In California, on the other hand, detailed depth information is available only in the form of nonsearchable pdf files. I used those files to extract the effective depth, which provides a rough estimate of injection depth, using open-source optical-character-recognition software. The quality of the pdf files requires visible inspection of each value so that I limited the analysis to 300 randomly sampled WD and 300 randomly sampled WF wells.

In agreement with Jordan and Gillespie (2013), I find that WD injection occurs on average at shallower depth than WF injection in California (Figure 7). The mean depth of the former is ~ 0.9 km, which is comparable with the mean depth of 1 km of injection activity in Oklahoma. The mean depth of joint WD and WF depths in California increases to ~ 1.5 km, in agreement with values reported by the DOGGR. This depth is substantially deeper than the value reported for Oklahoma. In summary, I find no evidence that injection activity is deeper in Oklahoma; on the contrary, fluid injection in California occurs on average ~ 0.5 km deeper than in Oklahoma.

Although injection depths in California and Oklahoma generally were limited to the upper 4 km, the focal depths of seismic events in both states are significantly deeper. To compare focal depths in the two states, I use a waveform-relocated catalog (Hauksson et al., 2012) and the single event depth in the OGS catalog.

In California, much of the seismic activity is distributed within the upper 15 km, with a mean of 10 km (Figure 8). Events between M4 and M5 and above M5 show a wide depth range, from ~ 1 to 27 km in 1980 through 2001. Many of the shallow earthquakes are aftershocks of the 1994 Northridge earthquake, whereas deep events occur close to Ventura Basin. The focal depths in Oklahoma did not change significantly between 1980–2001 and 2002–2014, exhibiting the same mean depth of 5 km. The more abundant earthquakes above M4 in Oklahoma from 2002 to 2014 (Figure 8) occurred within a relatively localized depth layer extending from ~ 2 to 7 km.

Although substantial uncertainties in focal depth are expected, especially in regions with limited station coverage and poorly constrained velocity models such as Oklahoma, the observed systematic differences between California and Oklahoma seem to be a robust feature within the data. Focal depths are significantly deeper in California than in Oklahoma.

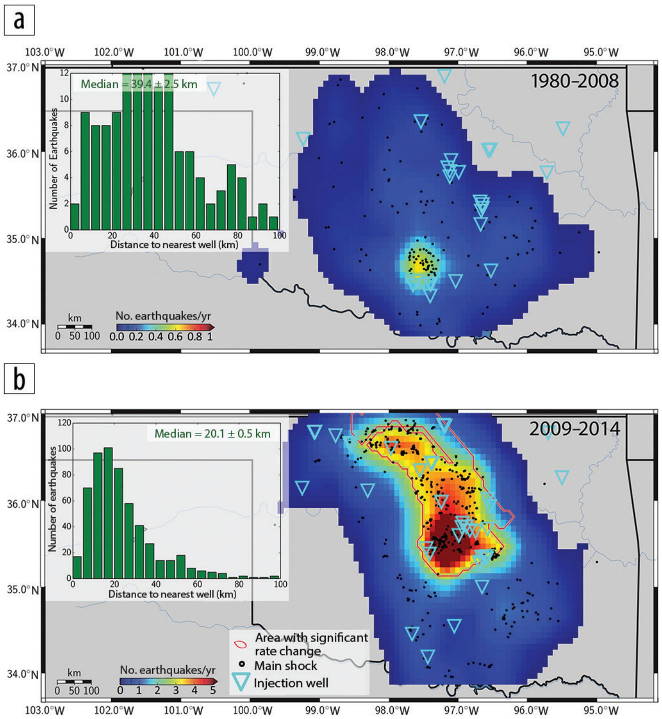

Figure 5. Smoothed, spatial variation in background seismicity rates in Oklahoma in (a) 1980 through 2008 and in (b) 2009 through 2014. Earthquake locations are shown by black dots, location of high-volume injection wells (> 50,000 m^3/mo) by blue triangles, and areas of significant rate increase by red contours. Histograms show changes in distance between earthquake and closest high-volume injection well between the two time periods.

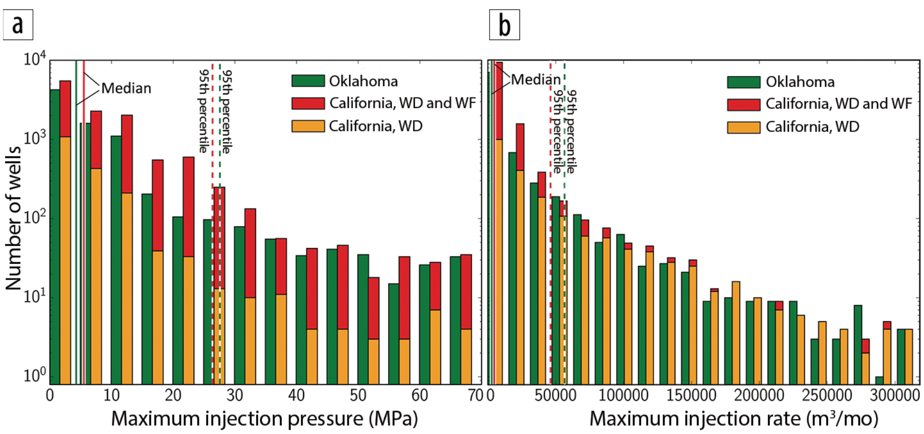

Figure 6. (a) Maximum injection pressure and (b) injection rate for all wells in Oklahoma (green) and for WD (orange) and WD + WF wells (red) in California. Solid and dashed lines show median values and 95th percentiles, respectively.

Discussion

In this study, I compared fluid-injection operations and examined temporal and spatial seismicity variations in California and Oklahoma. California showed no large-scale correlation between a recent increase in injection volumes and seismic activity. Seismicity is generally deeper in California than in Oklahoma, and surficial injection operations likely have only limited influence on earthquake activity. This is expected, considering the low upper-crustal stresses and frictional properties of shallow basin faults, which inhibit seismic activity and large earthquake ruptures.

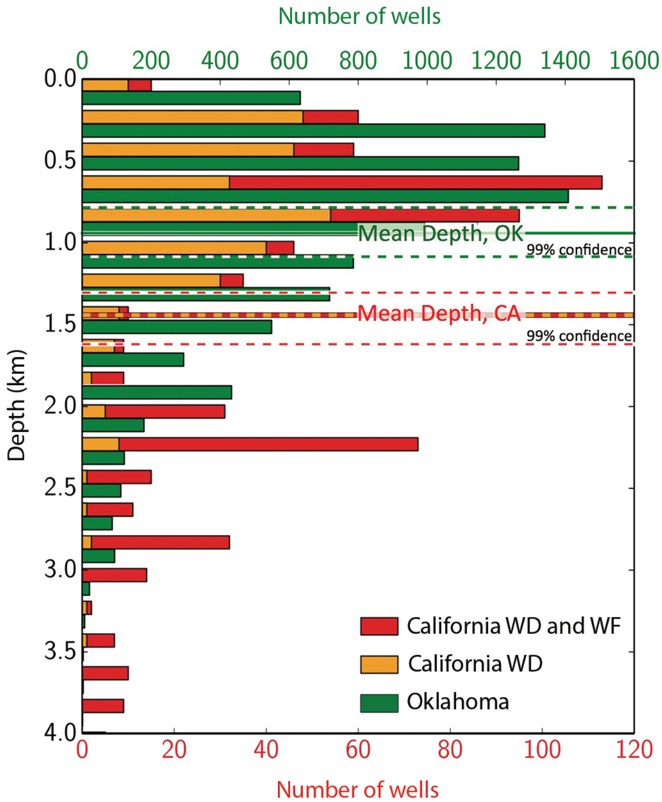

Figure 7. Injection depth in Oklahoma (green) and California (orange for WD, red for WD + WF wells). Solid and dashed lines show mean depths and 99% confidence intervals, respectively. Note that waterflooding occurs on average deeper than wastewater disposal in California. Depth in Oklahoma is reported as packer depth, whereas depth in California is reported as effective surface depth.

Oklahoma, on the other hand, showed a significant increase in background seismicity rates starting in 2009. This newly appearing seismic activity encompasses a region that also hosts large-volume injection wells in central and northern Oklahoma. The spatial-temporal correlation between injection and seismicity indicates that fluid injection might contribute to seismic activity at a large scale, as pointed out by several previous studies (Ellsworth, 2013; Keranen et al., 2013; Llenos and Michael, 2013; Keranen et al., 2014).

The injection operations in Oklahoma and California show many remarkable similarities. These include overall well count, injection depths, wellhead pressures, and peak injection rates. Some of the differences in injection operations include (1) overall density of injection wells and (2) generally larger annual injection volumes in California. However, none of those differences is likely to cause the significantly stronger seismogenic response to fluid injection in Oklahoma.

Several mechanisms might explain the strong seismogenic response in Oklahoma. First, the observed changes in seismicity rate might be part of natural rate variations that occur over long timescales. The large recurrence times of intraplate earthquakes and the limited temporal extent of the corresponding seismicity record support this possibility. However, the strong correlation between injection and seismic activity in several areas in Oklahoma make this scenario less likely.

Second, large-scale average injection parameters might not be representative of the seismogenic potential of fluid injection in an entire region. The seismogenic potential might be controlled by individual wells that strongly deviate from average operational parameters. Nonetheless, the reported cases of likely induced seismicity in Oklahoma and California were associated with wells of average injection activity and do not seem to support this hypothesis (Keranen et al., 2013; Aminzadeh and Göbel, 2013).

Third, perhaps the considered set of operational parameters is not complete, and additional factors such as net production rate, reservoir pressure, or rate of change of injection rate might affect poroelastic stresses, resulting in seismic activity within a region.

Finally, the difference in seismogenic response to fluid injection in California and Oklahoma might be driven by an overall difference in geologic setting and crustal stresses between plate boundary and intraplate regions. The existence of higher crustal stresses at shallower depth in Oklahoma is supported by shallower focal depths, which are consistent over time. Moreover, several studies suggest that the upper crust in Oklahoma is close to failure. For instance, the passage of seismic waves from large teleseismic earthquakes and connected small dynamic

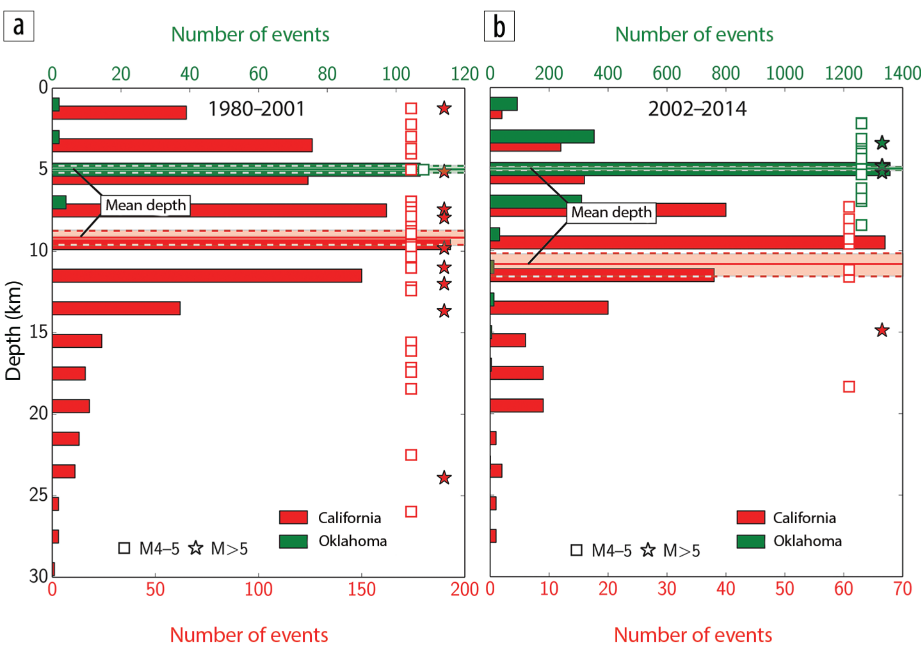

Figure 8. Comparison of focal depth in (a) 1980 through 2001 and (b) 2002 through 2014 in California (red) and Oklahoma (green). Solid and dashed lines show mean values and 95% confidence intervals, respectively. Depth of M4–M5 events is shown by colored squares and M > 5 events by colored stars. Seismicity rates in Oklahoma did not increase significantly until c. 2009, but the focal depth in part (b) still is dominated by the more abundant events after 2009.

strains are observed to result in an uncharacteristically strong seismogenic response in the form of triggered earthquakes (van der Elst et al., 2013). Furthermore, some areas in Oklahoma might produce induced-earthquake sequences as a result of pressure perturbations as small as 0.07 MPa (Keranen et al., 2014).

Besides the difference in crustal stresses, the larger-scale geologic homogeneity in Oklahoma likely results in extensive hydraulic connectivity of the upper crust. Keranen et al. (2014) suggest that this hydraulic connectivity might result in lateral diffusion of pressure perturbations as high as 20 to 35 km. In California, the upper crust is subject to constant tectonic deformation so that crustal heterogeneity and especially mature fault zones might limit lateral migration of pressure perturbations.

Conclusion

My results suggest that operational parameters of surficial fluid injection are likely of secondary importance for the resulting seismogenic response. The primary controls on injection-induced seismicity are the specific geologic setting, e.g., hydraulic connectivity, and the stress state on nearby faults. The view that injection-induced earthquakes have been avoided successfully in California in the past because of less invasive injection operations is likely erroneous. The scarcity of induced seismicity in California might simply be an expression of lower stresses at injection depth and lack of large-scale hydraulic connectivity within hydrocarbon basins. Although less probable, earthquakes might be induced in California through injection in areas of active faulting, as shown by a recent study. The largely similar injection operations in California and Oklahoma and the absence of noticeable seismogenic response in California indicate a fundamental difference in the state of stress between the two study areas. The specific geologic conditions responsible for individual induced-earthquake sequences remain to be understood. TLE

Acknowledgments

I would like to thank Andrea Llenos, Sebastian Hainzl, Robert Habiger, and Gregory Beroza for their detailed reviews of the initial manuscript. The present work benefited from discussions with Preston Jordan and Kyle Murray. I thank the Oklahoma Corporation Commission and the California Division of Oil, Gas and Geothermal Resources for making the injection databases publicly available. The earthquake data sets were provided through the U. S. Geological Survey Advanced National Seismic System and Oklahoma Geological Survey. I am grateful to Whenzeng Yang, Egill Hauksson, and Peter Shearer for creating high-quality earthquake catalogs and to Jeremy Zechar, who made his declustering algorithm available online. Finally, I would like to thank the Statistical Seismology Community for the many useful online resources on corssa.org.

Corresponding author: tgoebel@gps.caltech.edu

References

Aminzadeh, F., and T. Göbel, 2013, Identifying induced seismicity in active tectonic regions: A case study of the San Joaquin Basin, California: AGU Fall Meeting Abstracts, **1,** 6, abstract no. S31F-06.

California Department of Conservation, Division of Oil, Gas and Geothermal Resources (DOGGR), 2014, www.conservation.ca.gov/dog/, accessed 31 December 2014.

Clauset, A., C. R. Shalizi, and M. E. J. Newmann, 2009, Power-law distributions in empirical data: SIAM Review, **51**, no. 4, 661–703, http://dx.doi.org/10.1137/070710111.

Ellsworth, W. L., 2013, Injection-induced earthquakes: Science, **341**, no. 6142, http://dx.doi.org/10.1126/science.1225942.

Gardner, J. K., and L. Knopoff, 1974, Is the sequence of earthquakes in southern California, with aftershocks removed, Poissonian?: Bulletin of the Seismological Society of America, **64**, no. 5, 1363–1367.

Hainzl, S., F. Scherbaum, and C. Beauval, 2006, Estimating background activity based on interevent-time distribution: Bulletin of the Seismological Society of America, **96**, no. 1, 313–320, http://dx.doi.org/10.1785/0120050053.

Hauksson, E., W. Yang, and P. M. Shearer, 2012, Waveform relocated earthquake catalog for southern California (1981 to June 2011): Bulletin of the Seismological Society of America, **102**, no. 5, 2239–2244, http://dx.doi.org/10.1785/0120120010.

Horton, S., 2012, Disposal of hydrofracking waste fluid by injection into subsurface aquifers triggers earthquake swarm in central Arkansas with potential for damaging earthquake: Seismological Research Letters, **83**, no. 2, 250–260, http://dx.doi.org/10.1785/gssrl.83.2.250.

Jordan, P., and J. Gillespie, 2013, Potential impacts of future geological storage of CO_2 on the groundwater resources in California's Central Valley: Southern San Joaquin Basin oil and gas production analog for geologic carbon storage: California Energy Commission, Division Research and Development Division, publication no. CEC-500-2014-029.

Keranen, K. M., H. M. Savage, G. A. Abers, and E. S. Cochran, 2013, Potentially induced earthquakes in Oklahoma, USA: Links between wastewater injection and the 2011 M_W 5.7 earthquake sequence: Geology, **41**, no. 6, 699–702, http://dx.doi.org/10.1130/G34045.1.

Keranen, K. M., M. Weingarten, G. A. Abers, B. A. Bekins, and S. Ge, 2014, Sharp increase in central Oklahoma seismicity since 2008 induced by massive wastewater injection: Science, **345**, no. 6195, 448–451, http://dx.doi.org/10.1126/science.1255802.

Kim, W.-Y., 2013, Induced seismicity associated with fluid injection into a deep well in Youngstown, Ohio: Journal of Geophysical Research: Solid Earth, **118**, no. 7, 3506–3518, http://dx.doi.org/10.1002/jgrb.50247.

Llenos, A. L., and A. J. Michael, 2013, Modeling earthquake rate changes in Oklahoma and Arkansas: Possible signatures of induced seismicity: Bulletin of the Seismological Society of America, **103**, no. 5, 2850–2861, http://dx.doi.org/10.1785/0120130017.

Llenos, A. L., J. L. Rubinstein, W. L. Ellsworth, C. S. Mueller, A. J. Michael, A. McGarr, M. D. Petersen, M. Weingarten, and A. A. Holland, 2014, Increased earthquake rates in the central and eastern US portend higher earthquake hazards: AGU Fall Meeting, Abstract U34A-02.

Murray, K. E., 2014, Class II underground injection control well data for 2010–2013 by geologic zones of completion, Oklahoma: Oklahoma Geological Survey Open-File Report OF1-2014.

van der Elst, N. J., H. M. Savage, K. M. Keranen, and G. A. Abers, 2013, Enhanced remote earthquake triggering at fluid-injection sites in the midwestern United States: Science, **341**, no. 6142, 164–167, http:dx.doi.org/10.1126/science.1238948.