Physical and observational reasons for the lack of conspicuous induced seismicity in Central California

Report for SCEC Award #16170
Submitted October 14, 2015

Investigators: Emily E. Brodsky (UCSC), & Thomas H.W. Goebel (UCSC)

I. Project Overview

A. Abstract

In the box below, describe the project objectives, methodology, and results obtained and their significance. If this work is a continuation of a multi-year SCEC-funded project, please include major research findings for all previous years in the abstract. (Maximum 250 words.)

California is the third largest oil producing state in the United States with a history of oil extraction that dates back more than 100 years. Many hydrocarbon reservoirs in California require invasive injection methods to mobilize trapped oil and boost production. One of the unintended site effects of such injection activity are induced earthquakes triggered by waste fluid injection and hydraulic fracturing (e.g. Keranen et al. 2013; Holland 2013). Fluid injection is common practice throughout California oilfields yet no significant increase in seismicity rates has been detected much unlike the rapidly increasing induced earthquake rates in Colorado, Texas, Kansas and Oklahoma between 2001 and 2015 (Goebel 2015).

This project focuses on the apparent absence of large-scale induced seismicity in California oilfields. We investigate two primary contributors that may explain the lack of induced seismicity: 1) limitations within the seismic record due to instrumental constraints; 2) physical contributions related to reservoir characteristics, stress distributions and local geology.

Our results highlight that instrumental issues significant limit the ability to detect small earthquakes in California sedimentary basins. In addition, location uncertainties are high especially in regions between Northern and Southern California further complicating the statistical association of earthquake activity and injection wells.

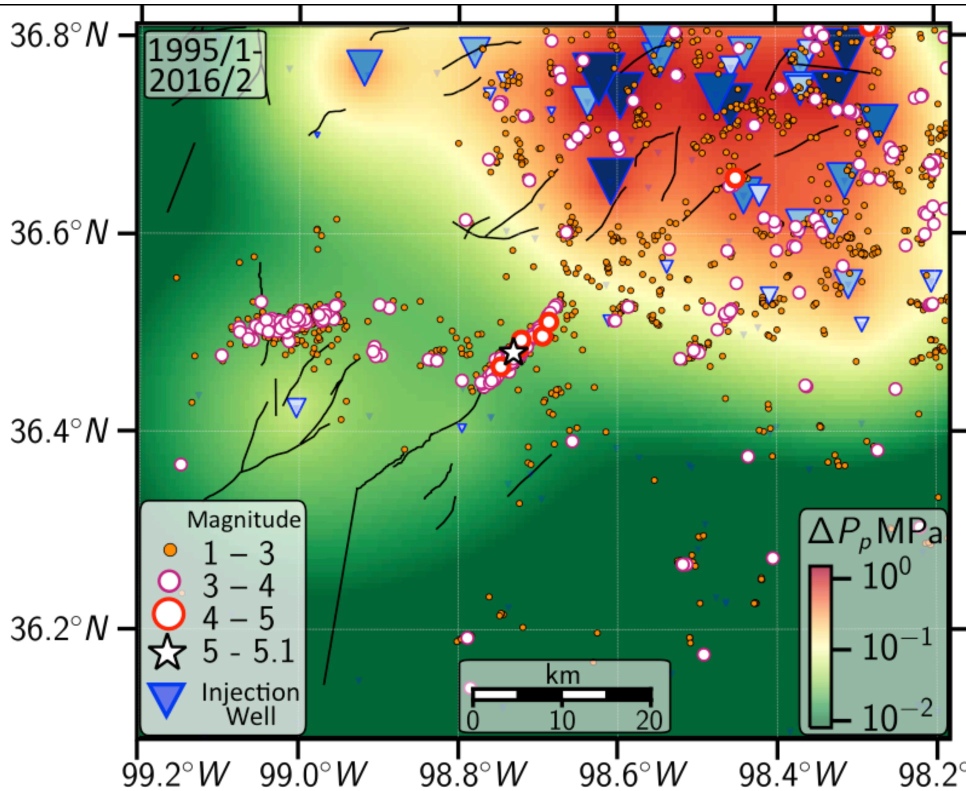
In addition, we find that reservoir characteristics significantly differ between Oklahoma, the state with the most severe increase in induced seismicity and California. The relatively homogeneous vertically stratified sedimentary basins in Oklahoma allow for efficient large-scale poroelastic stressing to distances of more than 40 km (Goebel et al, 2017). Such large-scale induced stress changes are likely absent in highly compartmentalized California oil fields.

B. SCEC Annual Science Highlights

Each year, the Science Planning Committee reviews and summarizes SCEC research accomplishments, and presents the results to the SCEC community and funding agencies. Rank (in order of preference) the sections in which you would like your project results to appear. Choose up to 3 working groups from below and re-order them according to your preference ranking.

Seismology
Stress and Deformation Through Time (SDOT)
Fault and Rupture Mechanics (FARM)

C. Exemplary Figure



The Fairview earthquake sequence which occurred in Northwestern Oklahoma between 2014 to 2016, provides evidence for long-range poroelastic stressing in Oklahoma. The figure shows the expected extent and amplitude of pore pressure perturbation (see color-bar) as a result of fluid injection into wastewater disposal wells (blue triangles) based on a semi-analytical model of radial flow in the Arbuckle formation (from Goebel et al. 2017). The significant difference in geological setting in California likely prevents such large-scale poroelastic stresses to unfold.

D. SCEC Science Priorities

In the box below, please list (in rank order) the SCEC priorities this project has achieved. See <u>https://www.scec.org/research/priorities</u> for list of SCEC research priorities. *For example: 6a, 6b, 6c*

B. Integration and Theory
Science objectives:
- 2f - Better understanding of induced seismicity
- 2a - Improvements of earthquake catalogs
- 2d - Community Stress Model development with constrains from induced seismicity
- 4a - Geologic, seismic, geodetic and hydrologic investigation of fault complexities

E. Intellectual Merit

How does the project contribute to the overall intellectual merit of SCEC? *For example: How does the research contribute to advancing knowledge and understanding in the field and, more specifically, SCEC research objectives? To what extent has the activity developed creative and original concepts?*

The study addresses four SCEC science objectives, i.e.,
2f: Improved understanding of induced seismicity and induced seismicity potential in different geologic and tectonic regions.
4a & 4b: by improving our understanding of crustal heterogeneity and the role of faults as fluid conduits or barriers;
2a: by assessing the quality of earthquake catalogs in small regions and by extending earthquake catalogs using template matching and joint-event-relocation methods.

In addition, induced seismicity sequences allow for the study of foreshocks and systematic event migration prior to the largest magnitude event of a sequence (EFP) which is rarely observed for tectonic earthquake sequences.

F. Broader Impacts

How does the project contribute to the broader impacts of SCEC as a whole? *For example: How well has the activity promoted or supported teaching, training, and learning at your institution or across SCEC? If your project included a SCEC intern, what was his/her contribution? How has your project broadened the participation of underrepresented groups? To what extent has the project enhanced the infrastructure for research and education (e.g., facilities, instrumentation, networks, and partnerships)? What are some possible benefits of the activity to society?*

Our study addressed some fundamental questions about fault zone hydrology and the connection between crustal heterogeneity and induced poroelastic stresses.
A more in-depth understanding of conditions that lead to more severe seismogenic consequences to fluid injection activity may also help guide future seismic hazard mitigation strategies.

G. Project Publications

All publications and presentations of the work funded must be entered in the SCEC Publications database. Log in at *http://www.scec.org/user/login* and select the Publications button to enter the SCEC Pubications System. Please either (a) update a publication record you previously submitted or (b) add new publication record(s) as needed. If you have any problems, please email *web@scec.org* for assistance.

T.H.W. Goebel, M. Weingarten, J. Haffener, X. Chen & E.E. Brodsky (2017). "The 2016 Mw5.1 Fairview, Oklahoma earthquakes: Evidence for long-range poroelastic triggering at >40 km from fluid disposal wells", *Earth Planetary Science Lett.*, 472, 50-61.

T.H.W. Goebel, J. Walter, K. Murray & E.E. Brodsky. "Comment on: How will induced seismicity in Oklahoma respond to decreased saltwater injection rates", *Science Advances* (in press).

II. Technical Report

A. Introduction

The burst of seismicity in Oklahoma in recent years has catapulted induced seismicity into the national agenda (*Holland*, 2013; *Keranen et al.*, 2013; *Sumy et al.*, 2014; *McGarr et al.*, 2015). Although the detailed mechanisms of this sudden increase in seismicity in Oklahoma and the central U.S. are far from clear, the general correlation between increased wastewater injection and seismicity makes the anthropogenic nature of the earthquakes incontrovertible (*Ellsworth*, 2013). A less-discussed, but equally important issue is the lack of conspicuous oilfield seismicity in California (*Goebel*, 2015; *Hauksson et al.*, 2015). The economic factors that drove the increase in waste-water injection in Oklahoma since 2000 also encouraged a significant increase in production and injection activity in Central California.

In Oklahoma, much seismicity has been attributed to a few wells with anomalously large injection rates. In California, wells with similarly-high average injection rates have been active from the mid 60's until present day. Although a few cases of apparently induced earthquake sequences have been documented in the region, no seismicity acceleration comparable to Oklahoma is observed (*Goebel et al.*, 2015; *Kanamori and Hauksson*, 1992).

This work aims to unravel two major contributors to the absence of observed induced seismicity acceleration in California's sedimentary basins: 1) observational limitations in seismic recording and 2) physical contributors to earthquake generation connected to crustal conditions and well operational practices.

This project leveraged a collaboration with Lawrence Berkeley Laboratory and the California Division of Oil and Gas Resources into a process-oriented study. The LBL project was focussed on data quality evaluation strictly in California and short-term recommendations to the state. That work provided a launching point for comparing the controls on induced earthquakes in California and Oklahoma.

B. Results

1 Instrumental limitations and quality of the seismicity record

The detection of potentially induced seismicity is strongly effects by the magnitude of completeness which is significantly higher within California sedimentary basins than along active faults due to the sparse station coverage. The magnitude of completeness is especially high within the Central Valley. Based on estimates using a goodness-of-fit criterion between observed and modeled Gutenberg-Richter relations for magnitude distributions, we determine a magnitude of completeness of M2.1 or higher (Figure 1).

These high values are especially problematic for a robust statistical assessment of potential induced seismicity which requires a large number of earthquakes per space-time bin compared to the rate of background seismicity (Goebel et al, 2015).

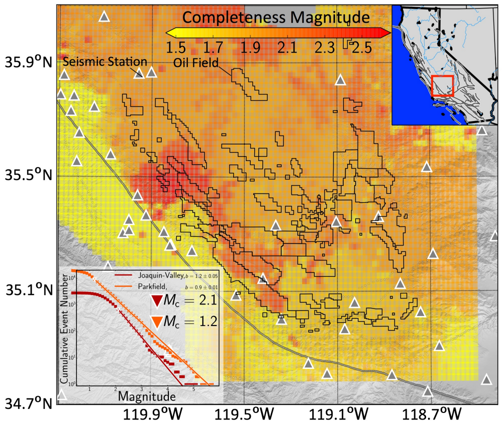


Figure 1: Estimates of spatial variations of the magnitude of completeness within the southern part of the Central Valley with values up to *M*c=2.5. The magnitude of completeness is estimated based on a deviation form power law behavior at lower magnitudes using a goodness-of-fit criterion (Clauset et al., 2009)

The relatively high magnitude of completeness is a result of the sparse station coverage within sedimentary basins. Another result of sparse station coverage are relatively high location uncertainties and large trade-offs between lateral and depth uncertainty of earthquake hypocenters. In most places within the Central Valley substantial event-station distances prevent high-accuracy depth estimates which are important in assessing potentially induced earthquake sequences. This issue can only partially be resolved through relocating events with more detailed velocity models and relative relocation methods. The latter does not improve absolute locations and may rather results in significant lateral shifts of earthquake clusters in areas where focal depths cannot be resolved. Location uncertainties are especially high within the San Joaquin valley where most of the oil production and fluid injection activity occurs. The azimuthal gaps in this area can be 180 degrees or higher since many seismic events are located using SCSN or NCSN stations only. Future work should include a refined earthquake catalog using picks from both networks, if available.

2 Physical reasons for the apparent lack of induced seismicity in California

One significant difference between sedimentary basins in Oklahoma (the state with the most severe increase in induced seismicity) and California are reservoir characteristics and specifically the permeability structure of targeted injection zones. In Oklahoma most of the injection activity is concentrated within the laterally extensive Arbuckle formation, overlying the crystalline basement. This formation allows for large-scale pressure diffusion and poro-elastic stressing so that earthquakes can be induced at more than 40 km distance from injection wells (Keranen et al, 2013; Goebel et al, 2017). Such large-scale effects can be observed during the 2016 M5.1 Fairview earthquake sequence, which occurred at more than 15 km from the closest high-rate injection well (Figure 2). The Arbuckle formation which hosts much of the disposal wells in the area is vertically stratified but laterally largely homogeneous allowing for far reaching pressure effects. Moreover a comparison between the amplitude of direct pore-pressure effects and poro-elastic stress changes showed that elastic stresses clearly dominate the far-field response and are likely responsible for the distant Woodward as well as the Fairview earthquake sequences (Figure 3). The high density of injection wells northeast of the Fairview fault (see Figure 2) result in a large pressurized region with expected pore pressure changes beyond 1 MPa. This pressurized region acts as a finite source in the far-field thereby significantly extending the seismogenic reach of waste water disposal wells. Poro-elastic stress changes within the Arbuckle formation are more readily transmitted into the underlying crystalline basement leading to moderate earthquakes on tectonically stressed faults (Goebel et al. 2017; Barbour et al.; 2017).

In California on the other hand the crystalline basement is significantly deeper in many areas and there is a significant vertically separation between injection zone and tectonically stressed faults within the basement. Moreover reservoirs are highly compartmentalized preventing large-scale diffusive processes to be active. This compartmentalization is evident in reservoir maps and extensive gradients in initial reservoir pressures during the discovery of the fields (Doggr Tech. Report, 2009).

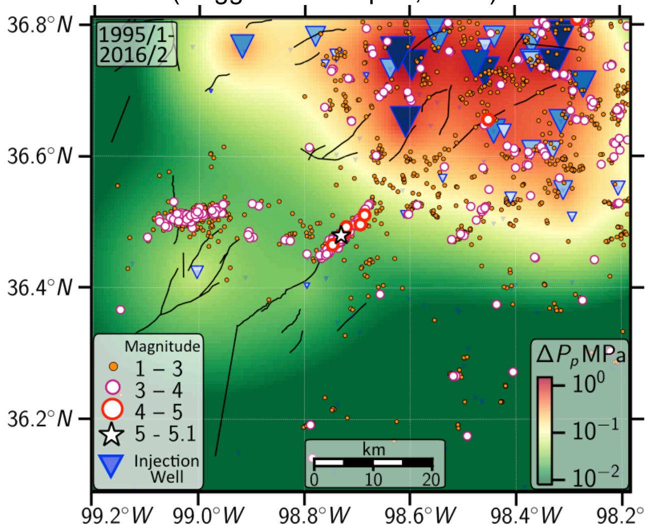


Figure 2: Expected extent and amplitude of pore pressure perturbations (see color-bar) as a result of fluid injection into Arbuckle wells (blue triangles). Pressure changes are computed based on a semi-analytical diffusion model and complete injection history of the wells for a diffusivity of *D*=0.5 m^2/s. Pressure changes and seismicity are shown at the time of the Mw5.1 Fairview earthquake (white star) in February 2016 (from Goebel et al. 2017).

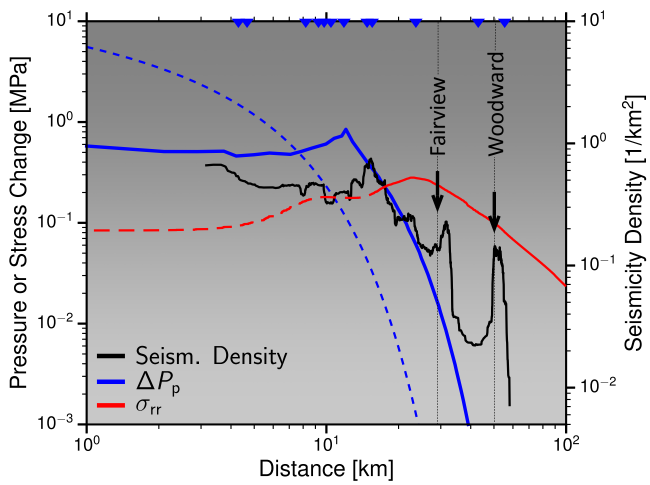


Figure 3: Decrease in pore-pressure (blue curves), seismicity density (black line) and poroelastic stresses (red curve, dashed portion highlights near-field) as a function of distance for a diffusivity, *D*=0.5 m^2/s. Location of injection wells are highlighted by blue triangles at the top of the figure. The dashed blue curve shows theoretical pore-pressure response to injection of the cumulative volume from all wells into one central well (from Goebel et al. 2017). Note the dominance of the far-reaching elastic stresses at distances beyond 15 km.

Much of the induced seismic activity in Oklahoma is associated with high-volume injection wells that may inject at rates above 100,000 m^3/mo (Keranen et al., 2014; Weingarten et al., 2015). Densely space high-rate injection can result in especially far-reaching poro-elastic stress perturbations with significant seismogenic consequences (Goebel et al., 2017). Wells with similarly high injection rates operate in California mainly in the Central Valley but also in the Los Angeles, Santa Maria and Salinas Basins. For the present analysis, we focused on high-rate injection in the Salinas Basin due to its high-quality seismic monitoring network. Much of the high-rate injection activity in the Salinas Basin is focused just north and east of the San Ardo oil field which is located between the seismically active Parkfield segment of the San Andreas fault and the 2003, M6.5 San Simeon earthquake sequence. Oil production in the San Ardo field began in 1952 with peak production and injection activity as a result of enhanced recovery methods in the 1960's.

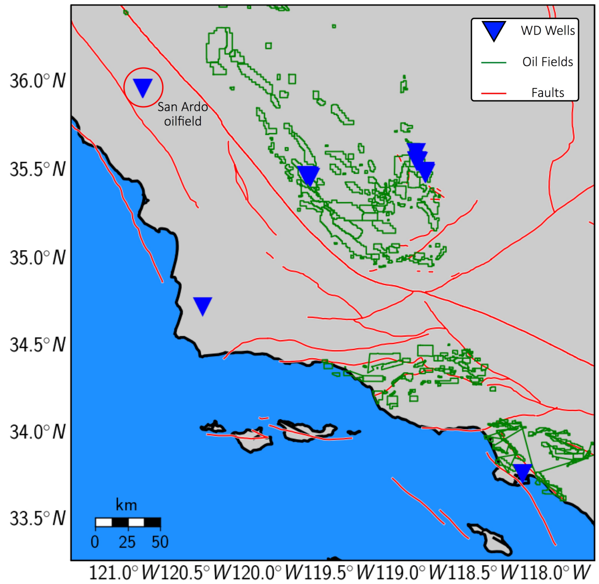


Figure 4: Locations of high-rate waste water disposal wells with average injection rates of more than 100,000 m³/mo. Based on observations in Oklahoma, these high-rate injectors maybe especially problematic resulting in far reaching pressure and elastic stress changes and potentially in induced seismicity (Weingarten et al., 2015; Goebel et al., 2017).

We analyzed the available seismicity record from 1964 to 2017 and well injection data available from the California Division of Oil Gas and Geothermal Resources after 1977. We identified a seismicity cluster directly north of the high-rate injection wells with four events above M4 (Figure 5). We compare the observed spatial clustering with randomized locations based on Monte Carlo-type simulations of random uniform earthquake catalogs and find that spatial clustering is significant at the 99% level. While the locations of earthquakes and wells are significantly correlated, temporal correlations are more difficult to assess because no instrumental seismicity record exists before the early 60's which is when wide-spread injection activity started. Temporal rate changes within the existing seismicity record and injection rates (i.e. records between 1977 - 2016) show no obvious correlations.

While temporal correlations provide no further evidence for a potentially induced origin of the earthquakes, the geologic setting in the greater San Ardo area shows many similarities to areas with induced seismicity in Oklahoma.

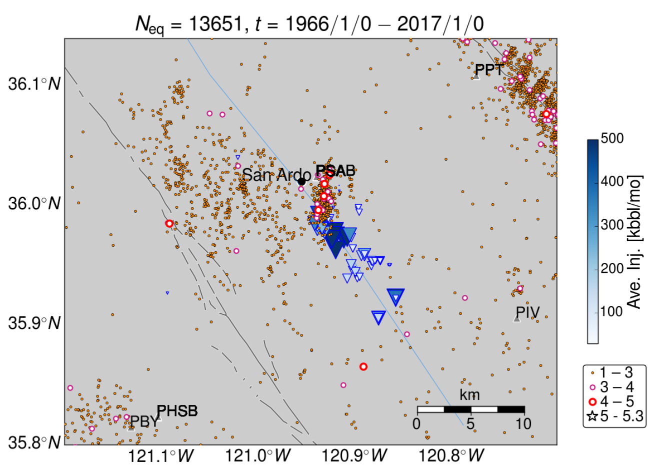


Figure 5: Waste water disposal wells and seismic activity associated with the San Ardo oil field in central California. Injection and seismic activity show significant spatial correlation. Since the beginning of extensive fluid injection operations in the San Ardo field in the 1960's there were four events above M4, however, the seismic record does not extent far enough into the past to examine seismic activity before operations started.

In San Ardo most of the produced waste-water from oilfield operations is re-injected into the Aurignac formation which overlies the crystalline basement. Injection activity at depth close to the basement is especially problematic and can lead to productive induced earthquake sequences (e.g. Kim 2013; Keranen et al. 2013). Seismic reflection images highlight that the granitic basement beneath the San Ardo oilfield is highly faulted and these faults may be activated by poro-elastic stress changes due to injection and production activity. Nevertheless, most of the seismic activity in the San Ardo sequence occurs at depths significantly below the injection zone, which may indicate primary tectonic causes of the earthquakes or far-reaching induced stress changes that can activate faults are larger distances and depths.

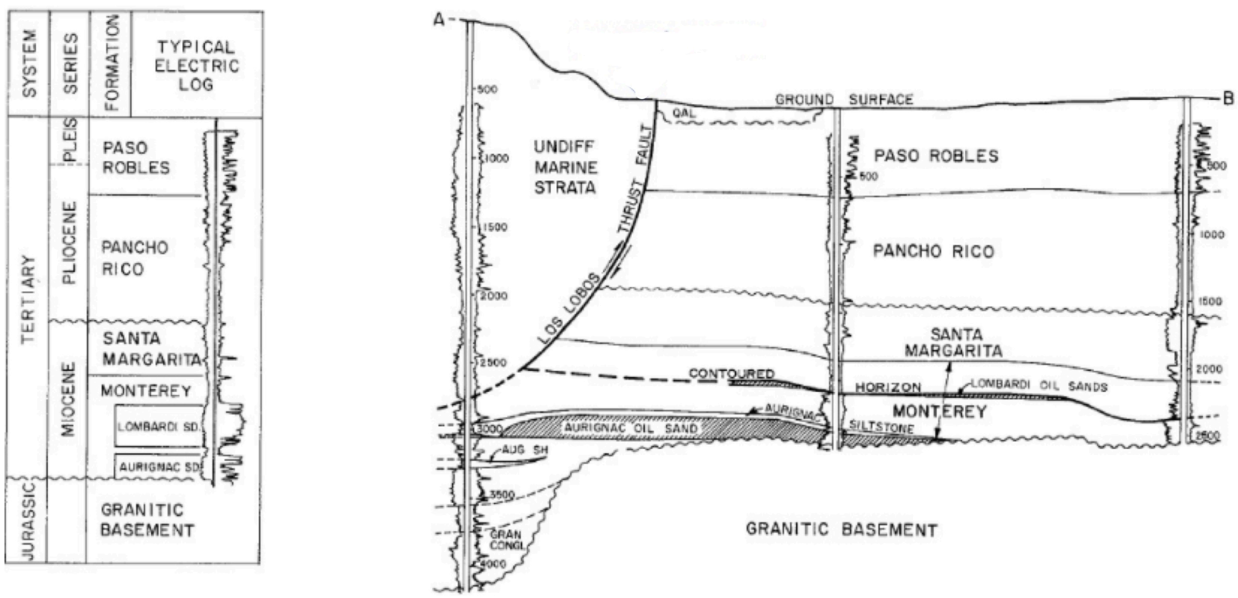


Figure 6: Stratigraphy in the Salinas basin and greater San Ardo area (from DOGGR Technical Reports, 1992). The targeted injection zones are the Lombardi oil sands and the relatively extensive Aurignac sandstone formation. The latter directly overlies the granitic basement similarly to the geological setting in Oklahoma.

III. Conclusion

Our preliminary results indicate that instrumental limitations significantly contribute to the difficulties in identifying potentially induced earthquakes in California. Instrumental limitations are especially apparent in areas where the magnitude of completeness and azimuthal gaps are high for example in the San Joaquin Valley. We found that several factors, such as dense well spacing, high injection rates, lateral extensive reservoirs and close proximity to faults within the crystalline basement, may increase the potential for inducing earthquakes in California oil fields. However, most injection activity occurs at shallower depth and highly compartmentalized reservoirs, which may limit the spatial extent of diffusive processes within the injection zone. Thus in addition to the instrumental factors, depth to basement and reservoir compartmentalization may explain the lack of conspicuous earthquake activity associated with fluid injection in California oil fields.

A. References

Barbour, A. J., Norbeck, J. H., & Rubinstein, J. L. (2017). The Effects of Varying Injection Rates in Osage County, Oklahoma, on the 2016 M w 5.8 Pawnee Earthquake. *Seismological Research Letters*.

Brodsky, E. E., and L. J. Lajoie (2013), Anthropogenic seismicity rates and operational parameters at the Salton Sea Geothermal Field, *Science.*, *341*(6145), 543–546.

CA Department of Conservation (2012), Division of Oil, Gas and Geothermal Resources: Production History in California, *DOGGR Annu. reports*.

Clauset, A., Shalizi, C. R., & Newman, M. E. (2009). Power-law distributions in empirical data. *SIAM review*, *51*(4), 661-703.

DOGGR Technical Report (1992), CA Department of Conservation, Division of Oil, Gas and Geothermal Resources: California Oil & Gas Fields, *DOGGR Techn. reports*. Vol. II, 645 pages

Das, I., and M. D. Zoback (2011), Long-period, long-duration seismic events during hydraulic fracture stimulation of a shale gas reservoir, *Lead. Edge*, *30*(7), 778, doi:10.1190/1.3609093.

Ellsworth, W. L. (2013), Injection-induced earthquakes, *Science.*, *341*(6142).

Goebel, T. H. W. (2015), A comparison of seismicity rates and fluid injection operations in Oklahoma and California: Implications for crustal stresses, *Lead. Edge*, *34*(6), 640–648, doi:10.1190/tle34060640.1.

Goebel, T. H. W., E. Hauksson, F. Aminzadeh, and J.-P. Ampuero (2015), An objective method for the assessment of possibly fluid-injection induced seismicity in tectonically active regions in central California, *J. Geophys. Res.*, doi:10.1029/2015JB.

Goebel, T.H.W., M. Weingarten, J. Haffener, X. Chen & E.E. Brodsky (2017). "The 2016 Mw5.1 Fairview, Oklahoma earthquakes: Evidence for long-range poroelastic triggering at >40 km from fluid disposal wells", *Earth Planetary Science Lett.,* 472, 50-61.

Goebel, T.H.W., J. Walter, K. Murray & E.E. Brodsky. "Comment on: How will induced seismicity in Oklahoma respond to decreased saltwater injection rates", *Science Advances* (in press).

Hainzl, S. (2004), Seismicity patterns of earthquake swarms due to fluid intrusion and stress triggering, *Geophys. J. Int.*, *159*(3), 1090–1096, doi:10.1111/j.1365-246X.2004.02463.x.

Hainzl, S., and Y. Ogata (2005), Detecting fluid signals in seismicity data through statistical earthquake modeling, *J. Geophys. Res.*, *110*(B5), doi:10.1029/2004JB003247.

Hainzl, S., F. Scherbaum, and C. Beauval (2006), Estimating background activity based on interevent-time distribution, *Bull. Seism. Soc. Am.*, *96*(1), 313–320.

Hauksson, E., T. Göbel, J. Ampuero, and E. Cochran (2015), A century of oil-field operations and earthquakes in the greater Los Angeles Basin , southern California, *Lead. Edge*, *34*(6), (June).

Holland, A. (2013), Earthquakes triggered by hydraulic fracturing in south-central Oklahoma, *Bull. Seism. Soc. Am.*, *103*, 1784–1792.

Horton, S. (2012), Disposal of Hydrofracking Waste Fluid by Injection into Subsurface Aquifers Triggers Earthquake Swarm in Central Arkansas with Potential for Damaging Earthquake, *Seismol. Res. Lett.*, *83*(2), 250–260, doi:10.1785/gssrl.83.2.250.

Kanamori, H., and E. Hauksson (1992), A slow earthquake in the Santa Maria Basin, California, *Bull. Seism. Soc. Am.*, *82*(5), 2087–2096.

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 Mw 5.7 earthquake sequence, *Geology*, *41*(6), 699–702, doi:10.1130/G34045.1.

Keranen, K.M., Weingarten, M., Abers, G. (2014), Sharp increase in central Oklahoma seismicity since 2008 induced by massive wastewater injection, *Science*, 345, 448-451

Kim, W. Y. (2013), Induced seismicity associated with fluid injection into a deep well in Youngstown, Ohio, *J. Geophys. Res. Solid Earth*, *118*(7), 3506–3518, doi: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, *Bull. Seismol. Soc. Am.*, *103*(5), 2850–2861, doi:10.1785/0120130017.

Main, I. G., L. Li, K. J. Heffer, O. Papasouliotis, and T. Leonard (2006), Long-range, critical-point dynamics in oil field flow rate data, *Geophys. Res. Lett.*, *33*(18), 1–5, doi:10.1029/2006GL027357.

McGarr, A. et al. (2015), Coping with earthquakes induced by fluid injection, *Science.*, *347*(6224), 830–831.

Meng, X., X. Yu, Z. Peng, and B. Hong (2012), Detecting earthquakes around Salton Sea following the 2010 Mw7. 2 El Mayor-Cucapah earthquake using {GPU} parallel computing, *Procedia Comput. Sci.*, *9*, 937–946.

Murray, K. E., and E. B. Street (2014), Class II Underground Injection Control Well Data for 2010 – 2013 by Geologic Zones of Completion , Oklahoma Open-File Report (OF1-2014) University of Oklahoma,

Ogata, Y. (1999), Seismicity analysis through point-process modeling:a review, *Pure Appl. Geophys.*, *155*, 471–507.

Shelly, D. R., D. P. Hill, F. Massin, J. Farrell, R. B. Smith, and T. Taira (2013), A fluid-driven earthquake swarm on the margin of the Yellowstone caldera, *J. Geophys. Res. E Planets*, *118*(9), 4872–4886, doi:10.1002/jgrb.50362.

Skoumal, R. J., M. R. Brudzinski, B. S. Currie, and J. Levy (2014), Optimizing multi-station earthquake template matching through re-examination of the Youngstown, Ohio, sequence, *Earth Planet. Sci. Lett.*, *405*, 274–280, doi:10.1016/j.epsl.2014.08.033.

Sumy, D. F., E. S. Cochran, K. M. Keranen, M. Wei, and G. a. Abers (2014), Observations of static Coulomb stress triggering of the November 2011 M 5.7 Oklahoma earthquake sequence, *J. Geophys. Res. Solid Earth*, *119*(3), 1904–1923, doi:10.1002/2013JB010612.Received.

Utsu, T. (1999), Representation and Analysis of the Earthquake Size Distribution: A Historical Review and Some Approaches, *Pure Appl. Geophys.*, *155*, 509–535.