Final Report

Project title: Physics-based Induced Earthquake Forecasting: Process Understanding, and Hazards Mitigation

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1. Abstract

Disposal of saltwater co-produced with oil and gas is linked to elevated seismicity in the Central and Midwest US. There is a concern that these events may lead to widespread damage and an overall increase in seismicity. Thus an improved understanding of the spatially and temporally variable deformation and stress field associated with fluid injection operation is critically important for evaluating time-varying seismic hazards. Despite the improvements in seismic monitoring capacity and the resulting decrease in the magnitude detection threshold, estimates of induced earthquake probability remain elusive due to insufficient models incapable of accounting for the complex physics governing the process of induced seismicity.

The proposed research effort comprehensively analyzes, integrates, and interprets geodetic, injection and seismic data in the vicinity of the injection sites in Oklahoma to resolve the 4-dimensional distribution of pore pressure and stress in the shallow crust. This project, in particular, is focused on exploring the statistical relation between injection operation and increased earthquake hazard. The amplitude of and the extent to which pore pressure changes are determined by some factors, in particular, the hydrogeological properties of the rocks, such as diffusivity. Thus the available deformation data is used to constrain hydrogeological properties of the medium, to accurately resolve the evolution of crustal stresses due to fluid injection. Having the time-varying models of stress changes, a statistical framework is implemented to estimate the time-dependent probability of large earthquakes on the nearby fault systems. These data and models help to improve seismic hazard estimates and aid in constructing operational-induced earthquake forecast models. This information can also be integrated into the updated U.S. National Seismic Hazard Map, which local communities and authorities use in their earthquake risk estimates and mitigation efforts.

2. Highlights and Progress Report

Highlight 1. Shirzaei et al. (2019) EPSL. Fluid injection in some cases is accompanied by surface uplift detectable by using interferometric synthetic aperture radar (InSAR). To demonstrate that uplift can be measured and used to constrain subsurface mechanical properties and pore pressure evolution. We applied an advanced multitemporal interferometric algorithm to 35 synthetic aperture radar images acquired by ALOS L-Band satellite over a 4-year period before the 2012 Timpson earthquake sequence in east Texas, where large volumes of wastewater are

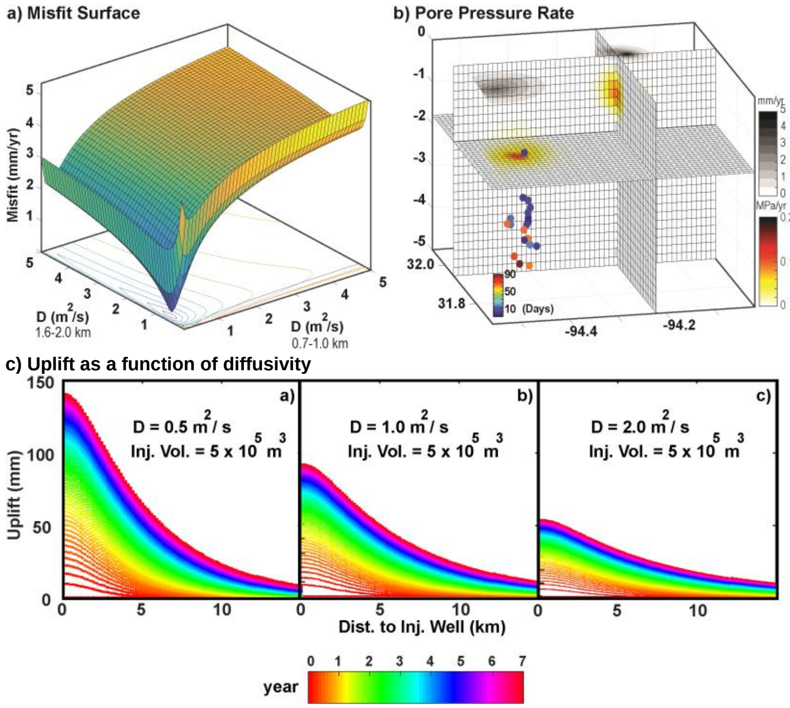


Fig 1. a) Misfit surface showing the difference between the observed and modeled uplift rates as a function of diffusivities (D). b) Pore pressure distribution for the model with optimum hydraulic diffusivities. The associated uplift rate is shown using the gray colorbar on top. Timpson earthquake sequence is color-coded with the occurrence date relative to the first event. c) The effect of hydraulic diffusivity in the measured uplift is investigated. After [24].

disposed at depths of ~800 m and ~1800 m. To solve for the hydraulic diffusivity of the injection layers, we jointly inverted the injected volume and uplift data, considering a poroelastic layered half-space. We found diffusivity values of 0.3 ± 0.1 m^2/s and 0.7 ± 1.5 m^2/s for shallow and deep injection layers, respectively. Combined with seismicity-derived bulk modulii, we constrained permeability values of 5.5×10^{-14} m^2 and 1.9×10^{-13} m^2 for these layers, consistent with the permeability range reported for Rodessa formation and well test values. Hydraulic conductivity determines the evolution of pore pressure and thus the origin and location of induced seismicity. This study

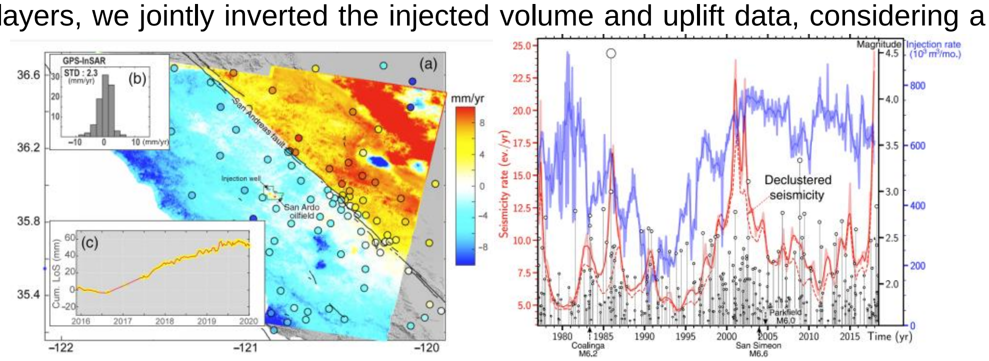


Fig 2. (a) Line-of-sight (LOS) velocities and displacements associated with injection activity in San Ardo. (b) comparison against GPS measurements, c) time series of LOS deformation at San Ardo, d) Seismicity (red curve) and fluid-injection (blue curve) rates within 20 km of the San Ardo oilfield between 1975 and 2019. After [25].

highlights the value of geodetic observations to constrain key hydrogeological properties of injection layers and to monitor the evolution of the subsurface pressure change. For more details, see fig.1 and [24].

Highlight 2. Goebel and Shirzaei (2021), SRL. We investigated California's induced seismicity, which is seldom observed, despite widespread injection close to seismically active faults. To this end, we chose the San Ardo oilfield, which began its operations in the early 1950s. The largest potentially induced events occurred in 1955 (ML 5.2) and 1985 (Mw 4.5) within ~6 km from the oilfield. We analyzed SAR images acquired by Sentinel-1A/B C-Band satellites between 2016 and 2020 and found surface deformation of up to 1.5 cm/yr, indicating pressure imbalance in parts of the oilfield. Fluid injection in San Ardo is concentrated within highly permeable rocks directly above the granitic basement at a depth of ~800 m. Seismicity predominantly occurs along basement faults at 6–13 km depths. Seismicity and wastewater disposal wells are spatially correlated to the north of the oilfield. Temporal correlations are observed over more than 40 yr with correlation coefficients of up to 0.71 for seismicity within a 24 km distance from the oilfield. Such large distances have not previously been observed in California but are similar to the large spatial footprint of injection in Oklahoma. For more details, see Fig. 2 and [25].

Highlight 3. Zhai, Shirzaei and Manga (2021), PNAS. Although much of the induced seismicity is attributed to a direct pressure increase from deep wastewater disposal, this mechanism is not applicable where deep basement earthquakes are hydraulically isolated from shallow injection aquifers, leading to a debate about the mechanisms for induced seismicity. Thus, we compiled industrial, seismic, geodetic, and geological data within the Delaware Basin, western Texas, and calculated stress and pressure changes at seismogenic depth using a coupled poroelastic model. We showed that the widespread deep seismicity is driven by shallow wastewater injection through the transmission of poroelastic stresses (shallow seismicity may continue to arise from pore pressure increases). Comparing the poroelastic responses from injection and extraction operations, we find that the basement stress is most sensitive to shallow reservoir hydrogeological parameters, particularly hydraulic diffusivity. For more details, see Fig. 3 and [5].

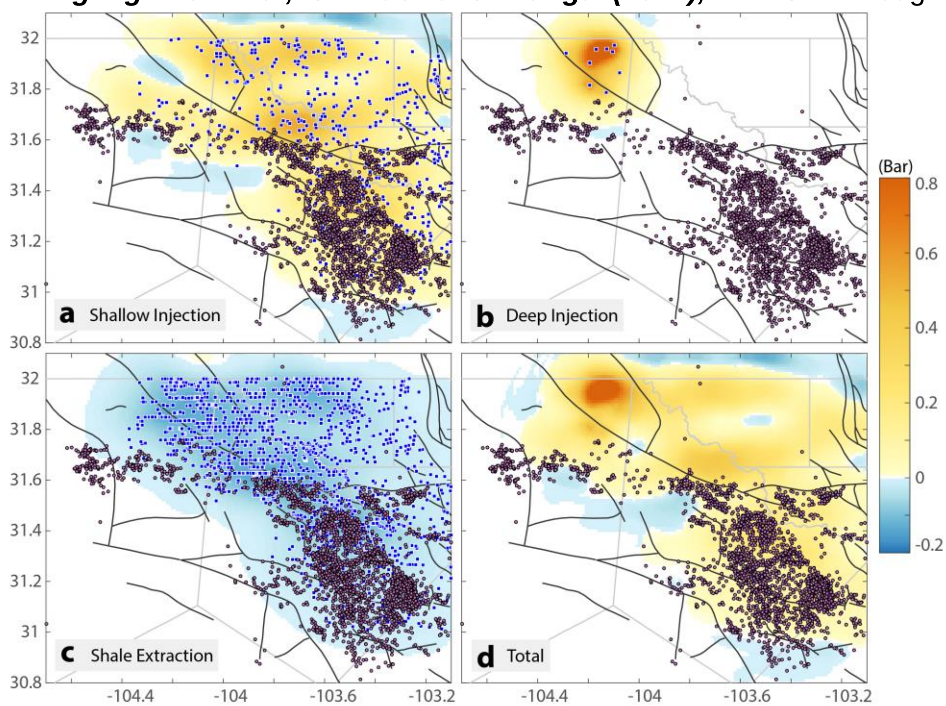


Fig 3. Cumulative Coulomb Failure Stress (CFS) from poroelastic stresses and pore pressure at seismogenic depth during 2014 – 2020. After [5].

Highlight 4. Zhai, Shirzaei et al. (2019), PNAS. We have developed the first physics-based induced earthquake forecasting framework for evaluating seismic hazard due to fluid injection, considering both pore pressure and poroelastic stresses. Applying this model to complex settings like Oklahoma, we showed that the regional induced earthquake timing and magnitude are controlled by the process of fluid diffusion in a poroelastic medium, and thus seismicity can be

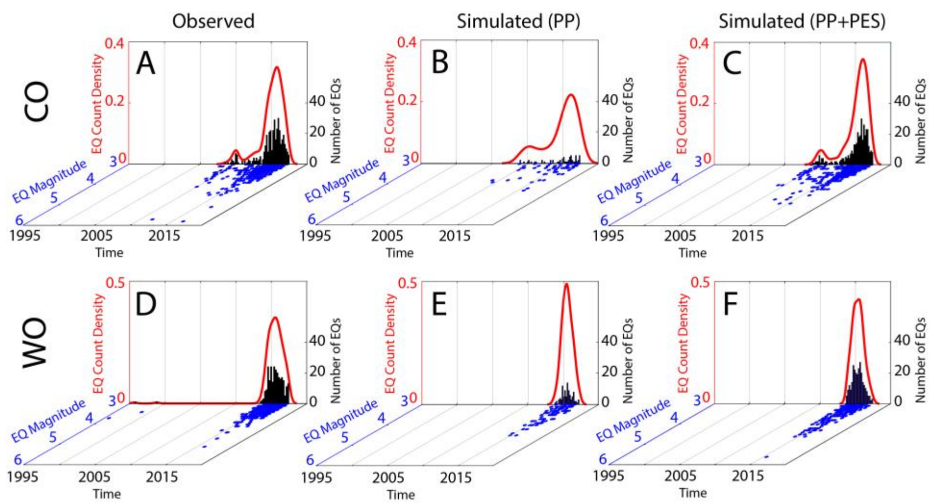
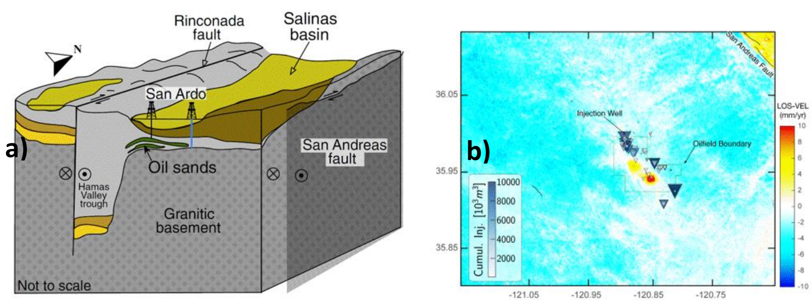


Fig 4. Observed and predicted M3+ earthquakes in central (C.O.) and western (W.O.) Oklahoma through the physics-based approach. Left. Annual earthquake magnitude exceedance probabilities. After [7]

successfully forecasted using a rate-and-state earthquake nucleation model. We found that pore pressure diffusion controls the induced earthquakes in Oklahoma. However, its impact is enhanced by poroelastic effects. This finding has significant implications for induced earthquake-forecasting efforts by integrating the physics of fluid diffusion and earthquake nucleation. For more details, see Fig. 4 and [7].

***Highlight* 5. Shirzaei et al. (2022) in prep.** The fluid injection can not only induce earthquakes but also suppress large earthquakes or at least delay their occurrence, thereby mitigating seismic hazards. The Parkfield segment of the San Andreas fault has produced fairly regular earthquakes with similar magnitudes (m_b > 5.5) and near-identical waveforms between 1857 and 1966. This observation has led scientists to predict that no later than 1993, a similar event would likely strike the area. However, the next event of comparable size did not occur until September 28, 2004, with a delay of ~11 years. Several mechanisms have been



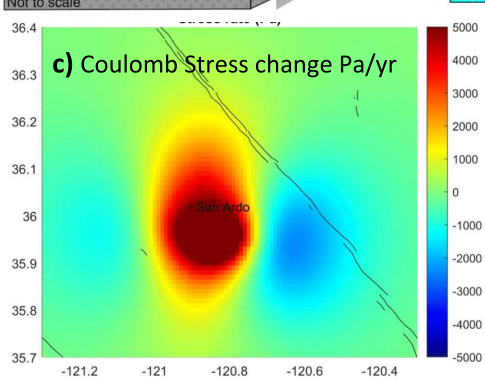


Fig 5. a) Schematic showing San Ardo injection site and major fault segments. b) location of injection wells colorcoded to injected volume. After [25]. c) Coulomb Failure stress change at the focal depth of Parkfield Eq 2004.

suggested to explain this delay, including viscoelastic relaxation of the crust following the 1857 Fort Tejon earthquake, stress shadowing due to the 1983 Coalinga-Nuñez earthquakes, and stress release through slow slip events [26]. None of these mechanisms can explain the entire delay. In our ongoing research, we created models that suggest a link between the delayed occurrence of the 2004 Parkfield event and wastewater injection at the San Ardo oilfield, 22 km west of the San Andreas Fault. Our coupled poroelastic model indicated that San Ardo wastewater injection had imparted a Coulomb stress change of -1.5 KPa/yr on the Parkfield segment of the San Andreas Fault, causing an 8-13 year clock delay.

Below is the complete list of journal articles (published/in prep) resulting from the current support. This list does not include the nearly dozen conference presentations supported by the current funding. Students and postdoc authors are highlighted in bold.

- G. **Zhai**, M. Shirzaei, and M. Manga, "Widespread deep seismicity in the Delaware Basin, Texas, is mainly driven by shallow wastewater injection," Proceedings of the National Academy of Sciences, vol. 118, no. 20, 2021.
- T. H. Goebel and M. Shirzaei, "More Than 40 yr of Potentially Induced Seismicity Close to the San Andreas Fault in San Ardo, Central California," Seismological Society of America, vol. 92, no. 1, pp. 187-198, 2021.
- G. **Carlson**, M. Shirzaei, S. Werth, G. **Zhai**, and C. **Ojha**, "Seasonal and Long-Term Groundwater Unloading in the Central Valley Modifies Crustal Stress," *Journal of Geophysical Research: Solid Earth,* vol. 125, no. 1, p. e2019JB018490, 2020.
- G. **Zhai**, M. Shirzaei, and M. Manga, "Elevated Seismic Hazard in Kansas Due to High-Volume Injections in Oklahoma," Geophysical Research Letters, vol. 47, no. 5, p. e2019GL085705, 2020.
- S. **Tung**, G. **Zhai**, and M. Shirzaei, "Potential link between 2020 Mentone, West Texas M5 earthquake and nearby wastewater injection: implications for aquifer mechanical properties," Geophysical Research Letters, p. 2020GL090551, 2020.
- G. **Carlson**, M. Shirzaei, C. **Ojha**, and S. Werth, "Subsidence-Derived Volumetric Strain Models for Mapping Extensional Fissures and Constraining Rock Mechanical Properties in the San Joaquin Valley, California," Journal of Geophysical Research: Solid Earth, vol. 125, no. 9, p. e2020JB019980, 2020.
- M. Manga, G. **Zhai**, and C. Y. Wang, "Squeezing marsquakes out of groundwater," Geophysical Research Letters, vol. 46, no. 12, pp. 6333-6340, 2019.
- G. **Zhai**, M. Shirzaei, M. Manga, and X. Chen, "Pore-pressure diffusion, enhanced by poroelastic stresses, controls induced seismicity in Oklahoma," Proceedings of the National Academy of Sciences, p. 201819225, 2019, doi: 10.1073/pnas.1819225116.
- G. **Zhai** and M. Shirzaei, "Fluid injection and time-dependent seismic hazard in the Barnett Shale, Texas," Geophysical Research Letters, vol. 45, no. 10, pp. 4743-4753, 2018, doi: 10.1029/2018GL077696.
- G. **Zhai**, M. Shirzaei, and M. Manga, " Mapping distribution of hydraulic diffusivity using surface deformation, applications to fluid injection reservoirs,"2022, in prep.
- M. Shirzaei, G. **Zhai**, T. Goebel, T. Taira, M. Khoshmanesh, "Parkfield earthquake delay caused by wastewater injection at the San Ardo oilfield," 2022, in prep.
- S. **Tung**, K. R. Blake, M. Shirzaei, M. A. Cardiff, T. Masterlark, H. F. Wang, K. L Feigl, "Temporal Evolution and Spatial Distribution of stress and strain at Coso Geothermal Field: January 2005 through June 2019," 2022, in prep.
- R. **Koirala**, T. Goebel, G. Kwiatek M. Shirzaei and E. Brodsky, "Seismic and deformation response of geothermal power operation', 2022, in prep.

- G. **Zhai**, M. Shirzaei, **"**Characterizing Tropospheric Turbulence Phase Delay in SAR Interferometry Using Spectral Analysis", 2022, GRL, in review. **2.1. Manoochehr**

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