# Observations and mechanisms of distant and deep injection induced earthquakes in California and Oklahoma hydrocarbon basins

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**Abstract**

The complexity of induced seismicity mechanisms significantly hampers seismic hazard assessment around injection wells. The largest magnitude events are commonly thought to be controlled by the size of the injection-affected area, but what controls the size of this area and what is the role of the regional geologic setting? Here we explore observations of deep and distant induced earthquakes in Oklahoma and California. Despite wide-spread injection close to seismically active faults, fluid injection-induced seismicity is comparably rare in California hydrocarbon basins. We identified a potential case of injection-induced earthquakes associated with San Ardo oilfield operations, with the largest events occurring in 1955 (ML5.2) and 1985 (Mw4.5) within 6 km from the oilfield. We performed an interferometric analysis of SAR images acquired by Sentinel-1A/B satellites between 2016 and 2020, and find surface deformation of up to 1.5 cm/yr, indicating pressure-imbalance in parts of the oilfield. Temporal correlations are observed over more than 40 years, with correlation coefficients of up to 0.71 for seismicity within 24 km of the oilfield. Such large distances have not previously been observed in California but are similar to the large spatial footprint of injection in Oklahoma. The San Ardo seismicity shows anomalous clustering with earthquakes consistently occurring at close spatial proximity but long inter-event times, analogous to induced earthquakes in geothermal reservoirs. The complexity of seismic behavior at San Ardo indicates that multiple processes, such as elastic stress transfer and aseismic slip transients, contribute to the potentially induced earthquakes. The observed power-law distance decay of induced events from the reservoir is in line with observations of stress decay from poroelastic models in which basement faults may be hydraulically isolated from the injection zone. Our model's resolved fluid/solid stress interactions suggest that shallow injection can 1) activate deep basement faults and 2) lead to spatially extensive induced earthquake sequences. Both of these observations may significantly elevate the seismic hazard associated with fluid injection operations.

# More than 40 years of potentially induced seismicity close to the San Andreas fault in San Ardo, central California

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## 1. Research Objectives

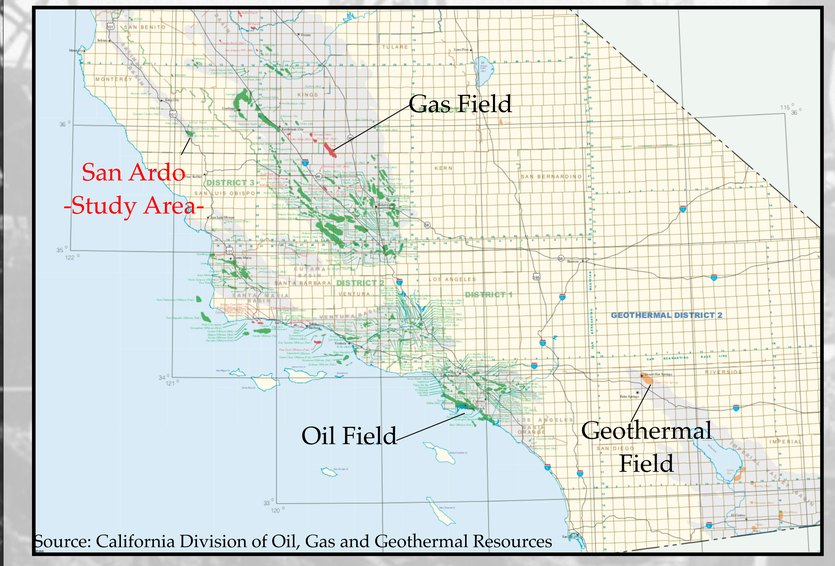
Evidence for fluid injection-induced seismicity is rare in California hydrocarbon basins, despite wide-spread injection close to seismically active faults. We investigate a potential case of injection-induced earthquakes associated with San Ardo oilfield operations which began in the early 50's.

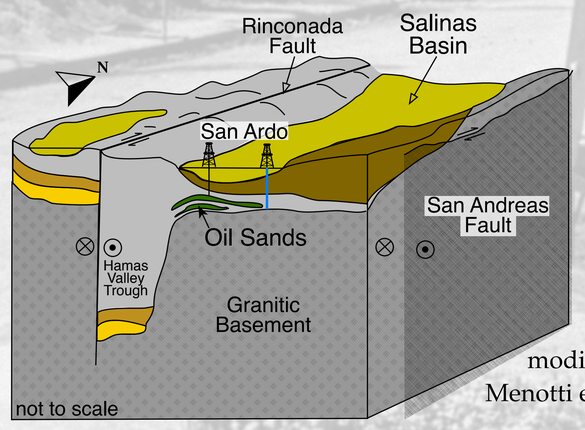
## 2. Key findings

1) San Ardo seismicity shows anomalous space-time clustering consistent with induced seismicity in geothermal fields.
2) Surface deformation of up to 1.5 cm/yr indicate pressure-imbalance in parts of the oilfield.
3) Temporal correlations are observed over more than 40 years with correlation coefficients up to 0.71 for seismicity within 24 km distance.
4) Elastic stress transfer and aseismic slip transients may contribute to the potentially induced earthquakes.

## 3. Introduction

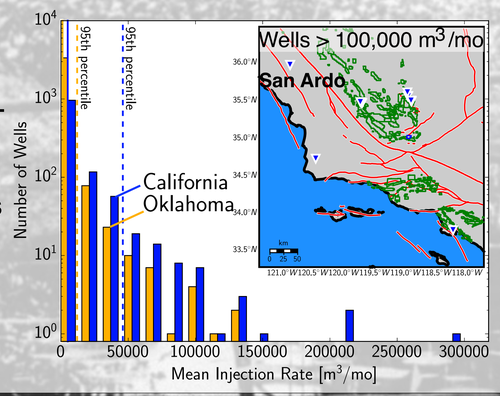
Oil and gas fields are ubiquetous in California, however documented induced seismicity gases have been rare, compared to the overall spatial extent and duration of operational activities.



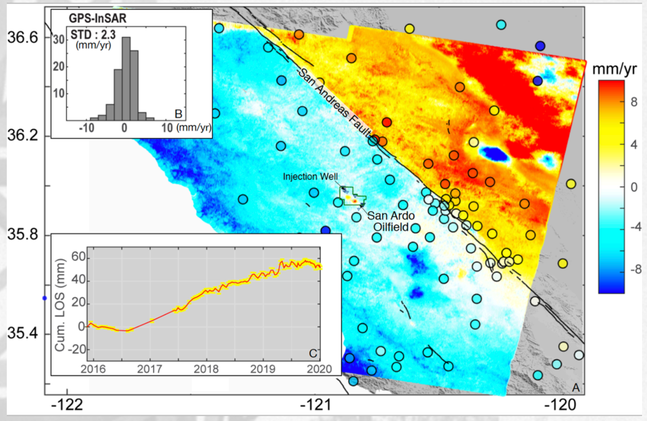




modified from Menotti et al. 2014

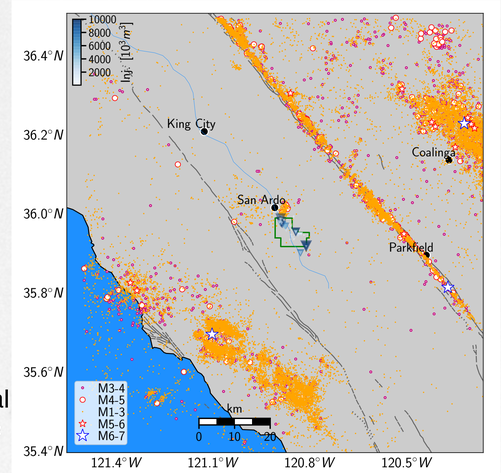
San Ardo stands out amongst oilfields in California because of high-rate injection operations which are comparable to Oklahoma. Injection occurs at depth right above the granitic basement.




## 4. Surface deformation and seismicity



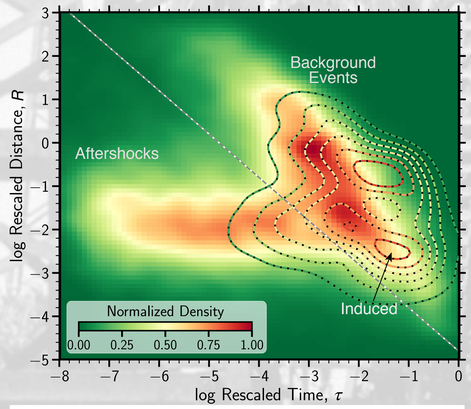

We analyzed SAR interferometric images acquired by Sentinel-1A/B satellites between 2016 and 2020, and resolved surface deformation of up to 1.5 cm/yr, indicating pressure-imbalance in parts of the oilfield.

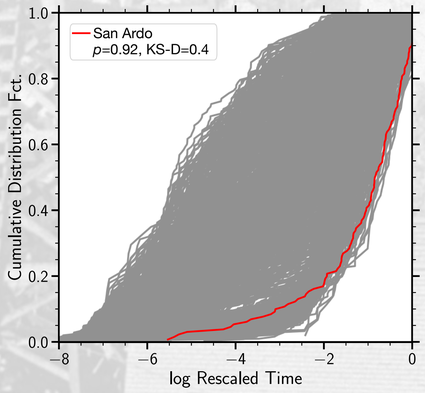


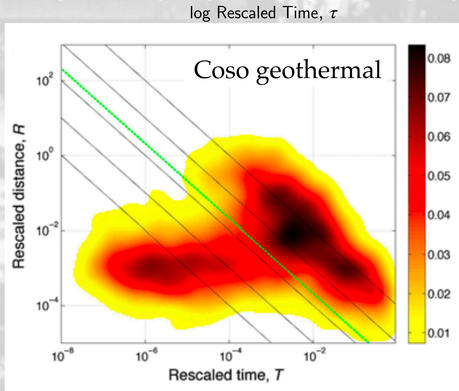

Seismicity and wastewater disposal wells are spatially-correlated to the north of the oilfield.

## 5. Spatial and temporal seismicity statistics

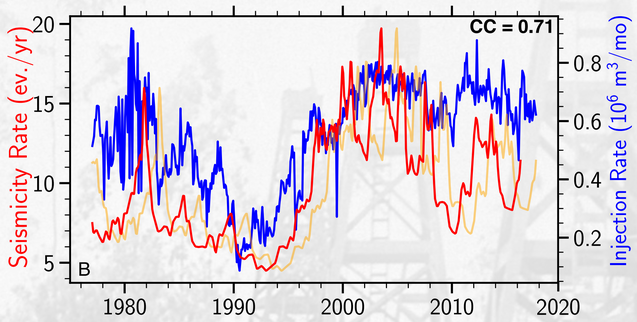
Space-time clustering of seismicity in San Ardo (contour lines) is notably different from tectonic seismicity in Northern California but comparable to observations in the Geysers and in Coso. The observed clustering at short distances and long inter-event times is charactertistic for induced seismicity in California.



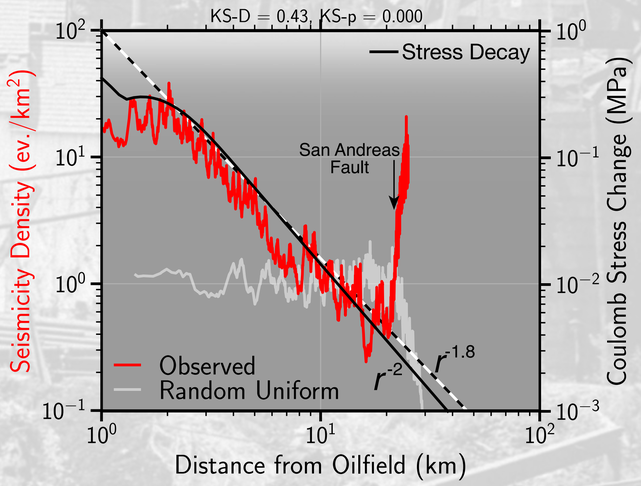




Zaliapin & Ben-Zion, 2016




Seismicity and injection rates are highly correlated with CC up to 0.71 between 1977 and 2018. The average time-lag is about 13 months but may vary between different time periods.

The spatial decay of seismic events from waste water disposal wells is similar to isolated induced cases (see Goebel & Brodsky, 2018) and in line with expectations for poroelastic stress decay.

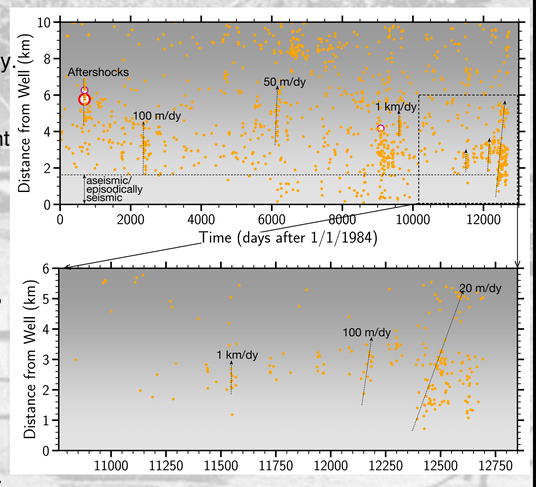



## 6. Discussion

Detailed analysis of more than 40 years of seismic data indicates a potential connection between wastewater disposal and seismic activity. Temporal correlations are strongest for events within 24 km from the disposal wells which is also the distance to the near-by San Andreas fault. We find that seismicity clustering, specifically at small inter-event distances but long inter-event times, is anomalous compared to average behavior in Northern California. Similar clustering characteristics have been observed for induced events in geothermal reservoirs.

Criteria that elevate injection-induced seismic hazard in California and elsewhere are: 1) Injection directly above basement, 2) high-rate, broad-scale injection into permeable zones, and 3) the presence of tectonically-stressed faults.

Several factors may have contributed to the earthquakes near San Ardo. The observed spatial seismicity decay approximately matches power-law elastic stress decay outside of a pressurized reservoir. In addition, linear seismicity migration may indicate aseismic slip transients associated with episodic earthquakes at seismic asperities.

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