Enter Your Project Title

Report for SCEC Award #12345
Submitted October 14, 2015

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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.)

Within the scope of the SCEC-funded project, we investigated a potential case of injection-induced earthquakes associated with San Ardo oilfield operations which began in the early 50's. The largest potentially induced events occurred in 1955 (M_L5.2) and 1985 (M_w4.5) within 6 km from the oilfield. We analyzed InSAR interferometric 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. Fluid-injection in San Ardo is concentrated within highly-permeable rocks directly above the granitic basement at depth of 800 m. Seismicity predominantly occurs along basement-faults at 6 to 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 years with correlation coefficients up to 0.71 for seismicity within 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. The San Ardo seismicity shows anomalous clustering with earthquakes consistently occurring at close spatial-proximity but long inter-event times. Similar clustering has previously been reported in California geothermal fields and may be indicative of seismicity due to long-term, spatially-persistent external forcing. The complexity of seismic behavior at San Ardo suggests that multiple processes, such as elastic stress transfer and aseismic slip transients, contribute to the potentially induced earthquakes.

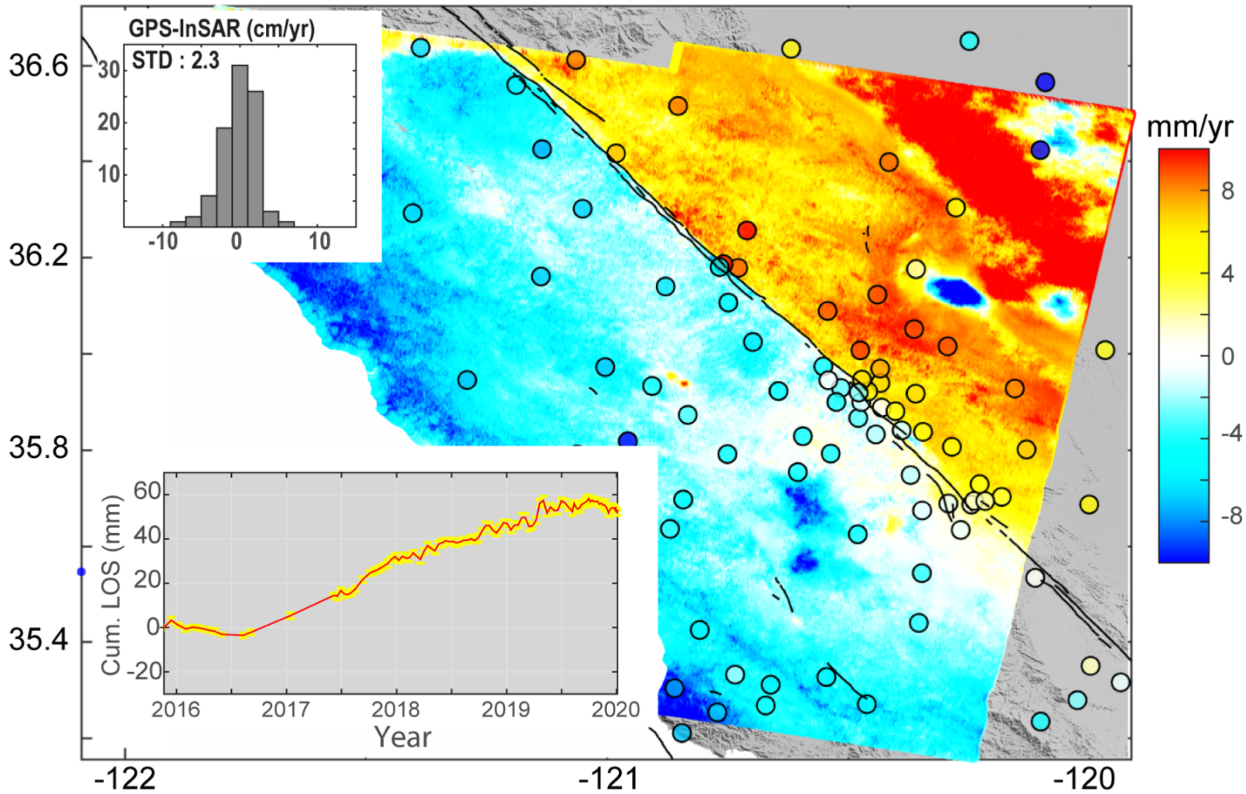
B. SCEC Annual Science Highlights

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.

Fault and Rupture Mechanics (FARM)
Stress and Deformation Through Time (SDOT)
Community Modeling Environment (CME)

C. Exemplary Figure

Select one figure from your project report that best exemplifies the significance of the results. The figure may be used in the SCEC Annual Science Highlights and chosen for the cover of the Annual Meeting Proceedings Volume. In the box below, enter the figure number from the project report, figure caption and figure credits.



D. SCEC Science Priorities

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

P3.f., P3.a., P1.e.

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 complexity of seismic behavior at San Ardo suggests that multiple processes, such as elastic stress transfer and aseismic slip transients, contribute to the potentially induced earthquakes.

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?*

The present observations show that fluid-injection operations occur close to seismically-active faults in California. Yet, seismicity is predominantly observed on smaller unmapped faults with little observational evidence that large faults are sensitive to induced stress changes.

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.

Goebel, T. H. W., & Shirzaei, M. (2021). More Than 40 yr of Potentially Induced Seismicity Close to the San Andreas Fault in San Ardo, Central California. *Seismological Research Letters*, *92*(1), 187–198. https://doi.org/10.1785/0220200276

II. Technical Report

Project Overview

Induced earthquakes frequently occur at large distances and depths from injection wells, for instance in Canada, Oklahoma, Kansas, Texas, Colorado and Ohio. However, there is an even greater number of injection wells with limited or no seismic activity. We proposed to investigate the conditions that promote or inhibit induced earthquakes in southern California hydrocarbon basins. We built on recent results from the Salinas basin (*Goebel and Shirzaei*, 2020) that provided a robust framework for the detection of induced events in the presence of much natural earthquake activity and induced events at distances of 20 km or more. Using a combination of seismicity clustering characteristics, spatial-temporal correlations and surface deformation above oilfields from GPS and InSAR analysis , we identified seismogenic oilfield operations. Southern California provides the opportunity to probe the necessary conditions for induced seismicity because, unlike in Oklahoma and Kansas, geologic settings vary widely between different oilfields and high-resolution seismic and geodetic records have been available for many decades. Ultimately, this research is expected to result in the creation of a detailed database of oilfields with and without induced earthquakes, as well as underlying geologic and operational parameters. This database may provide key contributions to fundamental questions such as: What conditions promote induced seismicity? How sensitive are large tectonic faults in southern California to induced stress perturbations and what mechanisms promote induced stress transfer to large distances and depths?

Introduction

Fluid injection induced earthquakes continue to be a large concern close to hydrocarbon and geothermal reservoirs in North America and Europe (e.g. *Atkinson et al.*, 2016; *Bao and Eaton*, 2016; *Ellsworth*, 2013; *Evans et al.*, 2012; *Keranen et al.*, 2014). Two recent notable induced events include a M_w5.3 induced earthquake in South Korea and a M_w5.0 induced earthquake in west Texas in 2020 (*Kim et al.*, 2018; *Skoumal et al.*, 2020). Many previous studies focused on direct fluid pressure effects as primary mechanism for induced earthquakes. However, more recent observations highlight the importance of additional processes such as (poro)elastic stress changes which may be most pro- nounced at sedimentary injection sites above the crystalline basement (e.g. *Barbour et al.*, 2017; *Chang and Segall*, 2016; *Goebel and Brodsky*, 2018; *Segall and Lu*, 2015). Additional sources of elastic stress include stress transfer between successive seismic events or aseismic transients, which significantly extend induced earthquake sequences (*Bourouis and Bernard*, 2007; *Cochran et al.*, 2018; *Cornet et al.*, 1997; *Duboeuf et al.*, 2017; *Guglielmi et al.*, 2015; *Sumy et al.*, 2014). Such stress transfer and triggering processes can make the identification of causative wells especially challenging. To account for these complexities, we will build on our recent results from the Salinas basin (*Goebel and Shirzaei*, 2020), and perform an integrated analysis of seismicity, surface deformation, geological setting and operational parameters associated with oilfield operations in southern California (SC).

Several studies suggest that oilfield operations in SC may have impacted seismic activity over many decades (*Goebel and Shirzaei*, 2020; *Goebel et al.*, 2016; *Hough and Bilham*, 2018; *Hough et al.*, 2017). We recently completed a detailed analysis of seismicity and wastewater disposal in San Ardo, finding a significant spatial and temporal correlation over more than 40 years with correlation coefficients up to 0.71 for earthquakes within 24 km distance from the oilfield. Such large distances were not considered in earlier studies in California but agree with the large spatial foot- print of injection e.g. in Oklahoma. Injection activity in San Ardo includes some of the largest injectors in California with rates and volumes within the 99th percentile of all disposal wells (*Göbel*, 2015). High-volume and high-rate injectors are expected to increase the probability of measur- able seismogenic effects (*McGarr*, 2014; *Weingarten et al.*, 2015). The San Ardo seismicity showed anomalous clustering with earthquakes consistently occurring at close spatial-proximity but long inter-event times. Similar clustering has previously been reported in California geothermal fields and may be indicative of seismicity due to long-term, spatially-persistent external forcing (*Schoenball et al.*, 2015; *Zaliapin and Ben-Zion*, 2016).

In addition, we observed significant surface uplift centered at the San Ardo oilfield (Fig. 1). We analyzed SAR interferometric images acquired by Sentinel-1A/B satellites between 2016 and 2020, and found surface deformation of up to 1.5 cm/yr, indicating pressure-imbalance in parts of the oilfield. The complexity of seismic behavior suggests that multiple processes, such as elastic stress transfer and aseismic slip transients, contribute to the potentially induced earthquakes.

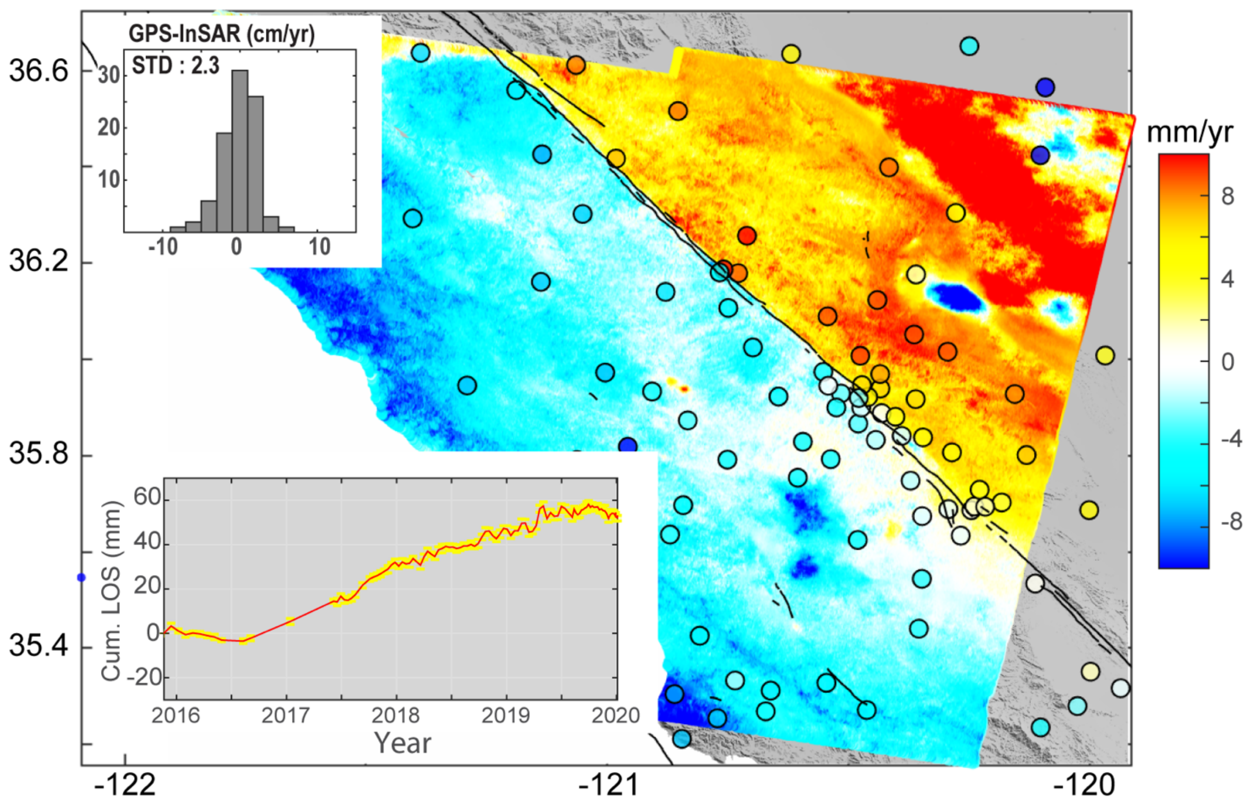


Figure 1: The San Ardo oilfield (green polygon) shows the most significant, relative surface uplift west of the San Andreas fault. A: InSAR line-of-sight velocity and local GPS measurements (black circles) with 3D displacement projected onto the line-of-site direction of the imaging satellite. The velocity map is dominated by the right-lateral shearing along the San Andreas Fault. Blue triangles show injection wells. B: The histogram shows the differences between InSAR and GPS with a standard deviation of 2 mm/yr. C: InSAR displacement time series at the center of the oilfield between 2016 and 2020. The yellow envelope indicates the 1-sigma error range.

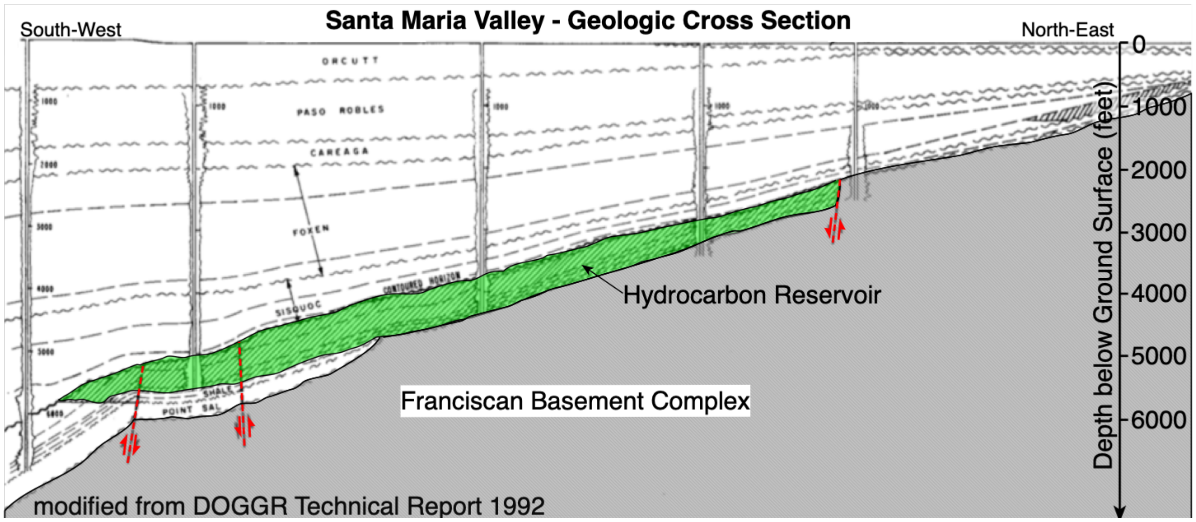


Figure 2: Example of well locations either directly above or within the basement below the Santa Maria Val- ley oil-field. Oil-bearing formations are highlighted in green, basement in gray and faults, extending from the basement into the reservoir, in red (modified from *CA Department of Conservation*, 1998).

We extended the temporal correlation analysis developed for the San Ardo oilfield for other areas west of the San Andreas, focusing on the Arroyo Grande, Santa Maria, Lompoc, Orcutt, Guadalupe and Zaca oilfields in the greater Santa Maria Basin. Arroyo Grande stood out in our analysis due to the high correlation between injection/production and seismicity rates. In addition, earthquake depth are much shallower than is other regions and oilfield operations occur directly above the crystalline basin.

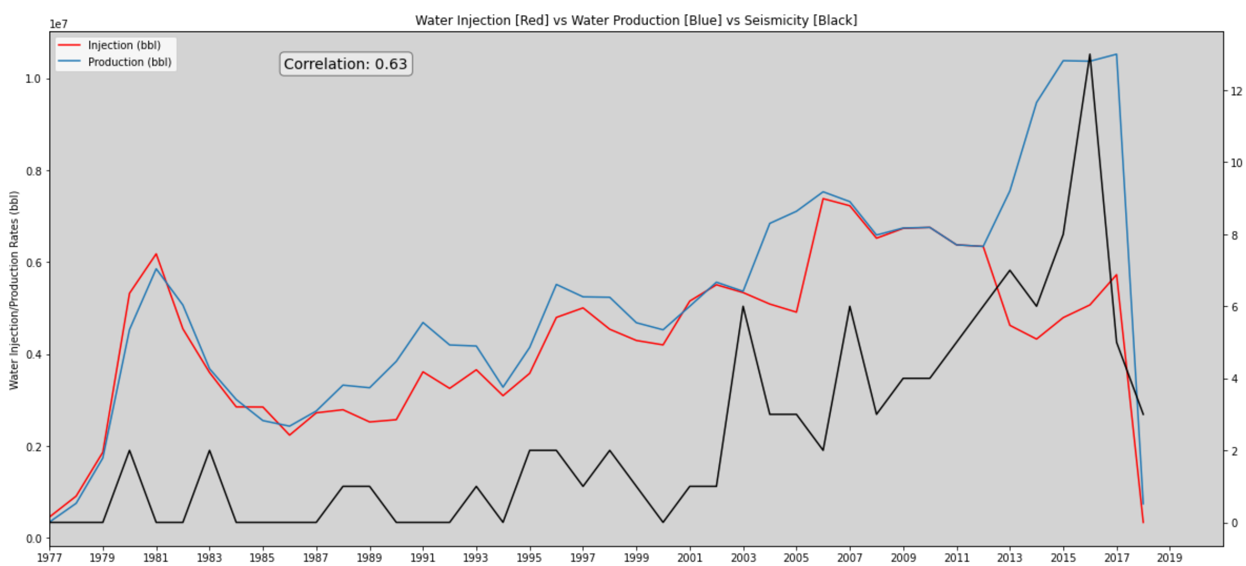


Figure 3: Exemplary time series plot of injection (red), production (blue) and seismicity (black) rates within 20 km of the arroyo seco oilfield. Arroyo seco is notably different to other oilfields within the greater Santa Maria area due to the relatively shallow nature of seismicity and oilfield operations that concentrate directly above the crystalline basement.

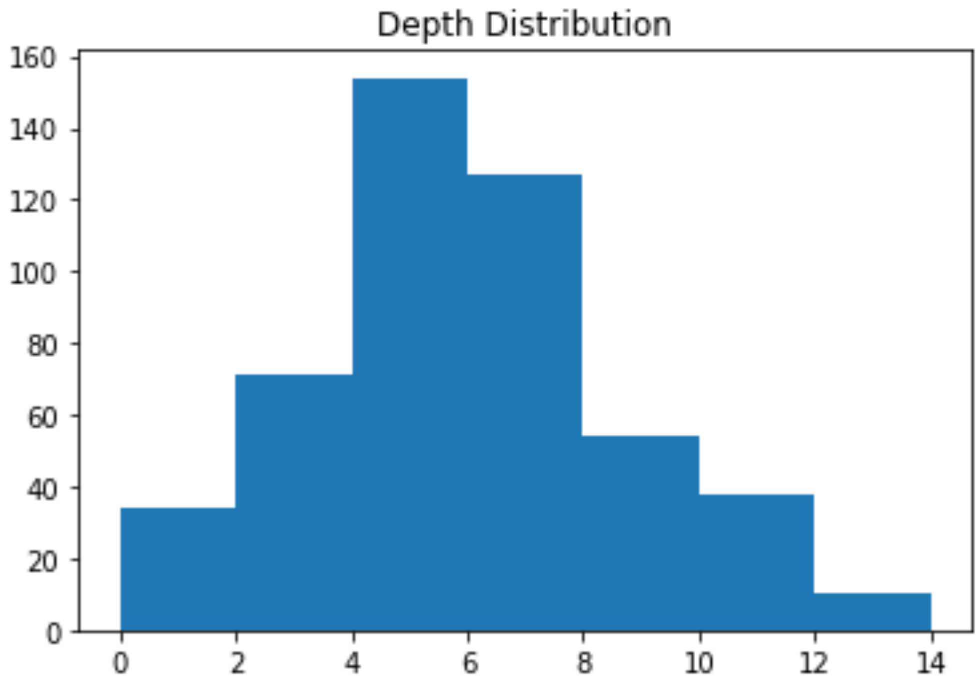


Figure 4: Depth distribution of earthquakes within 20 km from Arroyo Grande oilfield.

Discussion

Several observations indicate that the San Ardo earthquakes are may not be the only induced events in California hydrocarbon basins

We observed both temporal and spatial correlation between seismicity and wastewater disposal in San Ardo and Arroyo Grande. Injection in both cases occurs in close proximity to the granitic basement which has been identified as a particularly problematic depth for injection operations (*Goebel and Brodsky*, 2018; *Hincks et al.*, 2018; *Horton*, 2012; *Skoumal et al.*, 2018). The injection rates in San Ardo are high, comparable to seismogenic injection in the central U.S.. High-volume and high-rate injectors are expected to increase the probability of measurable seismogenic effects (*McGarr*, 2014; *Weingarten et al.*, 2015). Seismicity clustering in space and time is comparable to observations of induced events in geothermal fields (*Schoenball et al.*, 2015; *Zaliapin and Ben-Zion*, 2016). Such clustering is particularly interesting because it may provide a way to detect induced sequences without any knowledge of oilfield operations.

Induced seismicity in California remains difficult to detect outside of geothermal reservoirs. We showed that the combination of long-term seismic, hydrological and geodetic records can be useful in evaluating potentially induced events. Previous studies in California hydrocarbon basins mainly reported subsidence due to production (e.g. *Jolivet et al.*, 2015; *Kovach*, 1974), whereas we presented novel observations of significant surface uplift. This highlights that fluid volumes are not always balanced, leading to increasing reservoir pressure and poroelastic expansion.

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