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Analysis of Earthquake Data from the Greater Los Angeles Basin and Adjacent Offshore Area, Southern California

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ABSTRACT

We synthesize and interpret local earthquake data recorded by the Caltech/USGS Southern California Seismographic Network (SCSN/CISN) in southern California. The goal is to use the existing regional seismic network data to: (1) refine the regional tectonic framework; (2) investigate the nature and configuration of active surficial and concealed faults; (3) determine spatial and temporal characteristics of regional seismicity; (4) determine the 3D seismic properties of the crust; and (5) delineate potential seismic source zones. Because of the large volume of data and tectonic and geologic complexity of the area, this project is a multi-year effort and has been divided into several tasks.

RESULTS

A hundred years of oilfield operations and earthquakes in the greater Los Angeles basin, southern California

Most of the seismicity in the Los Angeles basin (LA basin) occurs at depth below the sediments and is caused by transpressional tectonics related to the big bend in the San Andreas Fault. However, some of the seismicity could be associated with fluid extraction or injection in oilfields that have been in production for almost a century and cover ~17% of the area of the LA basin. First, we evaluated the influence of industry operations by analyzing seismicity characteristics, including normalized seismicity rates, focal depths, and b-values, but found no significant difference in seismicity characteristics inside when compared to the outside of the oilfields. Also to identify possible temporal correlations, we analyzed the seismicity and available monthly fluid extraction and injection volumes since 1977. Second, we used the production and deformation history of the Wilmington oilfield to evaluate if other oilfields are likely to experience similar surface deformation in the future. Third, we analyzed whether the maximum earthquake magnitudes of events located within the perimeters of the oilfields correlate with total net injected volumes, as suggested by previous studies, and similarly we examined if maximum magnitudes exhibit an increase with net extraction volume. Overall, we found no obvious previously

unidentified induced earthquakes, and that the management of balanced production and injection of fluids appears to reduce the risk of induced earthquake activity in the oilfields.

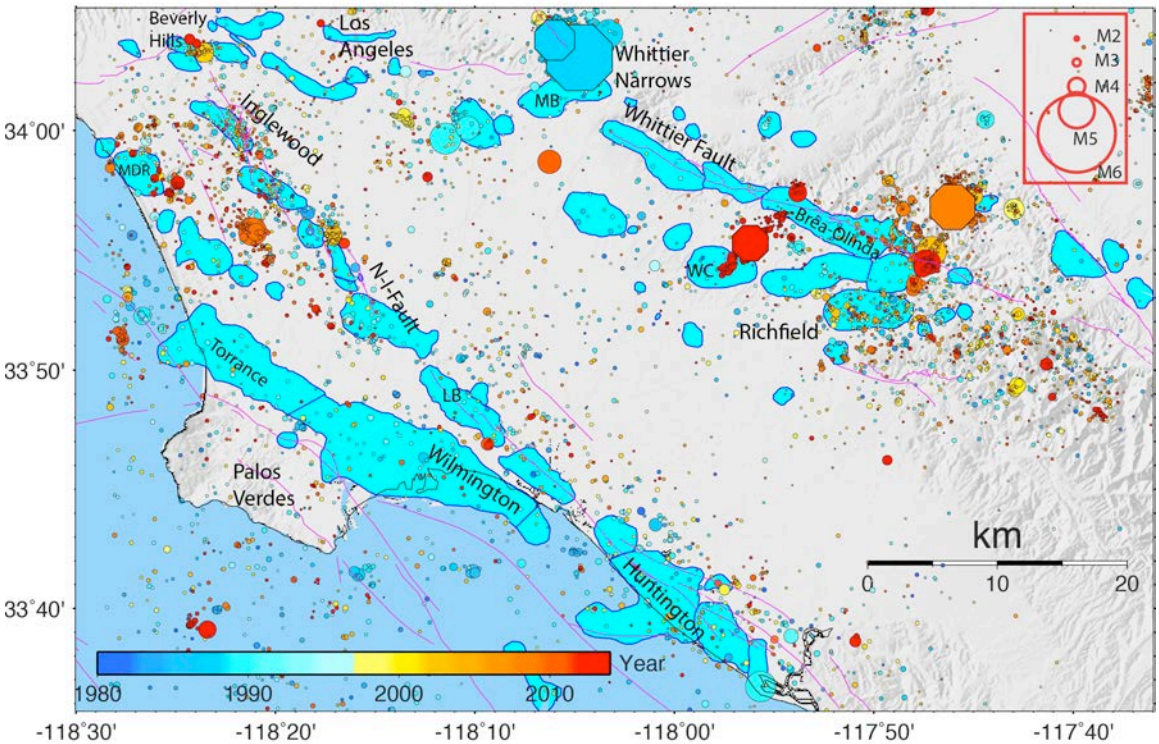

Figure 1. *Relocated seismicity 1981-2014/06 recorded by SCSN and oilfields shown as irregular light blue areas (DOGGR web site). Symbol sizes are scaled with the earthquake magnitude with $M_w \geq 5$ shown as octagons (see scale in upper right corner), and color-coded by date. LB – Long Beach oilfield; MB – Montebello oilfield; MDR – Marina Del Rey; N-I-Fault: Newport-Inglewood Fault; WC – West-Coyote.*

The oilfields are dispersed across the major tectonic trends and cover ~17% of the LA Basin area. To compare seismicity rates since 1935 inside and outside the fields, we separated out earthquakes that occurred within and outside of the perimeters of the oilfields. No M_w>5 mainshocks but numerous small earthquakes occurred within the oilfields. The absolute seismicity rate within the perimeters of the oilfields is ~17% of the rate outside the fields (Figure 2A). Thus the area-normalized rates of seismicity within and outside the oilfields are almost identical. However, the lower absolute seismicity rate within the oilfields leads to a somewhat larger scatter in the normalized cumulative rate. Similarly the *b*-values are the same within errors, with *b*-values of 1 +/- 0.04 within the oilfields, and 0.955 +/- 0.02 outside the oilfields. The annual rate of earthquakes exhibits a greater variability of event frequency and a lower mean rate of events within the oilfields (Figure 2B).

Although over the examined ~80 year time period, the normalized rate of seismicity inside and outside the oilfields is very similar and independent of oil field operations, spatial and temporal patterns do exist such as in the 1950s and 1960s where the South

Bay area was the most seismically active. In the last decade this changed and the Whittier-La Habra area to the east, and Hawthorn to Playa-del-Rey area to the west, became the most seismically active region.

The spatial distribution of the waveform relocated ($M_L \geq 1.5$) seismicity since 1981 also shows earthquakes fairly evenly dispersed outside and inside the oilfields (Figure 1). The normalized cumulative rates of seismicity both inside and outside of the fields are also very similar (Figure 2C). As mentioned above, seismicity within the oilfields exhibited apparent rate increases related to the 1987 M_w5.9 Whittier Narrows near Montebello, the 2001 sequence beneath the Beverly Hills oilfield, and the 2014 M_w5.1 La Habra sequence near the abandoned West-Coyote field. These increases are most likely not associated with oilfield activities because they occurred at depth (>3.0 km) mostly outside the boundary of the associated reservoir and are not correlated with significant changes in the oilfield fluid injection or extraction.

More than 98% of the earthquakes in the greater LA basin are located below depths of 3 km. There is no significant difference in the depth distribution between earthquakes located outside or inside the oilfields, which suggests that the events are of tectonic origin. However, Segall (1989) showed that crustal deformation models predicted the occurrence of earthquakes both above and below the production zone. Hence, poro-elastic stress changes resulting from either injection or extraction of fluids may trigger events at depths below active reservoir production.

A joint analysis of the SCSN catalog and the DOGGR records of fluid production and injection did not reveal

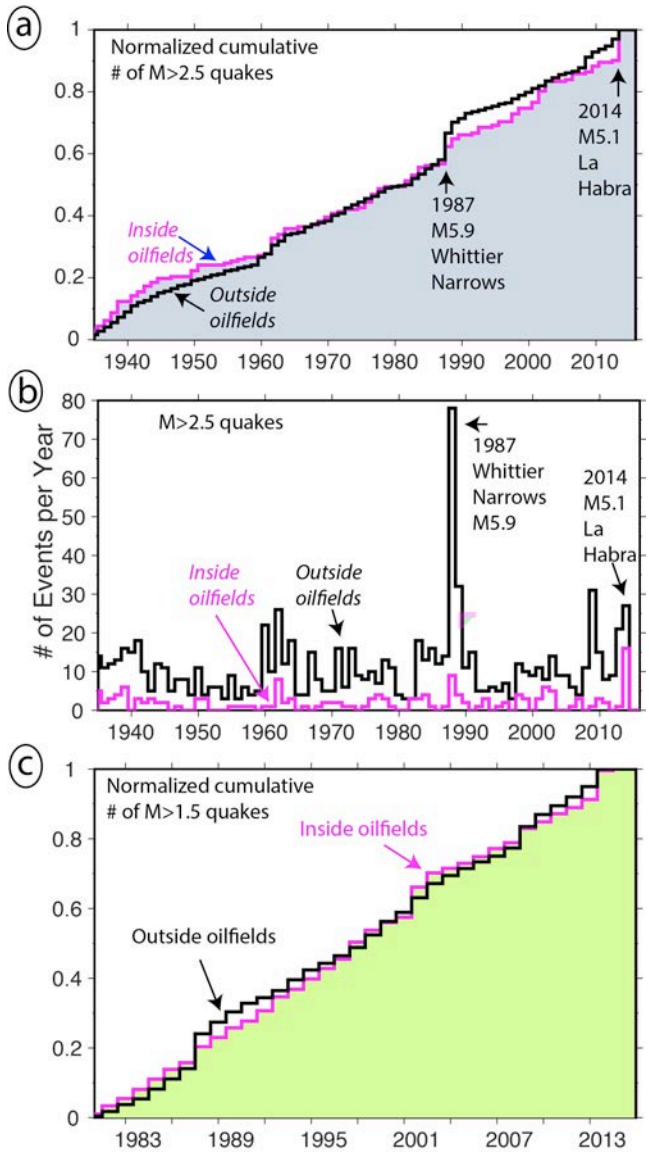

Figure 2. *(a) Normalized cumulative histogram of 1935-2014 (M_L>2.5) seismicity inside (magenta) and outside (black) oilfields shows no preference for earthquakes occurring within oilfields. (b) Histogram of number of earthquakes per year 1935-2014 shown for seismicity inside (magenta) and outside oilfields (black). Two large sequences, 1987 M_w5.9 Whittier Narrows, and 2014 M_w5.1 La Habra are also labeled. (c) Normalized cumulative histogram of 1981-2014 seismicity inside (magenta) and outside (black) the Los Angeles basin oilfields.*

significant seismicity rate changes associated with temporal changes in fluid extraction or injection. Two examples of both monthly injection and production data from the Wilmington and Long Beach oilfields are shown in Figure 4. There is no obvious correlation between the seismicity rates or magnitudes with total net cumulative injection volumes in these two oilfields. We also applied an objective statistical test to the time series data from 184 Class II wells and the seismicity catalog but found no significant correlation with seismicity. (*For more details, see Hauksson et al., 2015*).

An objective method for the assessment of waste-water injection induced seismicity and application to tectonically active regions in central California

Changes in seismicity rates, whether of tectonic or induced origin, can readily be identified in regions where background rates are low, but are difficult to detect in seismically active regions. We present a novel method to identify likely induced seismicity in tectonically active regions based on short-range spatio-temporal correlations between changes in fluid injection and seismicity rates. The method searches through the entire parameter space of injection rate thresholds and determines the statistical significance of correlated changes in injection and seismicity rates. Applying our method to Kern County, central California, we find that most earthquakes within the region are tectonic in origin. However, fluid injection contributes to seismicity in four different cases. Three of these are connected to earthquake sequences with events above M4. Each of these sequences followed an abrupt increase in monthly injection rates of at least 15,000 m^3. The probability that the seismicity sequences and the abrupt changes in injection rates in Kern County coincide by chance is only 4%. The identified earthquake sequences display low Gutenberg-Richter b-values of ~0.6-0.7 and at times systematic migration patterns characteristic for a diffusive process.

Our results show that injection-induced pressure perturbations can influence seismic activity at distances of 10 km or more. These large distances may be facilitated by complex local geology and faults in tectonically active regions. Our study provides the first comprehensive, statistically robust assessment of likely injection induced seismicity within a large, tectonically active region.

Our study is focused on central California, including the Southern San Joaquin basin and seismically active faults to the west, east, and south of the basin. The tectonic deformation west of the basin is dominated by strike-slip faulting along the San Andreas fault, while the east shows mainly normal faulting associated with the Breckenridge fault (Figure 3).

The tectonics south of the basin are characterized by a series of strike-slip and thrust faults, including the Wheeler Ridge, Pleito and White Wolf faults (Yang and Hauksson, 2013; Unruh et al., 2014). The latter have produced the largest magnitude earthquake within the study area, the 1952 M_w7.5 Kern County event (Figure 3). The more recent, moderate magnitude earthquakes to the north and south of the basin have not substantially changed the long-term background seismicity rates within the basin.

We analyzed the Advanced National Seismic System earthquake (ANSS) catalog between 1975 and 2014 which includes ~17,000 events from both the Southern and

Northern California Seismic Networks. The completeness magnitude, M_c, of the ANSS catalog is 2.0 within the region, determined by inverting for the lower magnitude cutoff that minimizes the misfit between observed and modeled power-law distributions (Goebel et al., 2014). M_c varies in space and time, likely reaching higher values to the north and within the central-part of the basin where the station density is low. In addition to the ANSS catalog, we also use the waveform relocated catalog by Hauksson et al. (2012) to obtain more accurate relative location-uncertainties and focal depth-estimates in areas of denser station density south of the San Joaquin basin. (*More details are provided in Goebel et al. (2015); in review at GJR*).

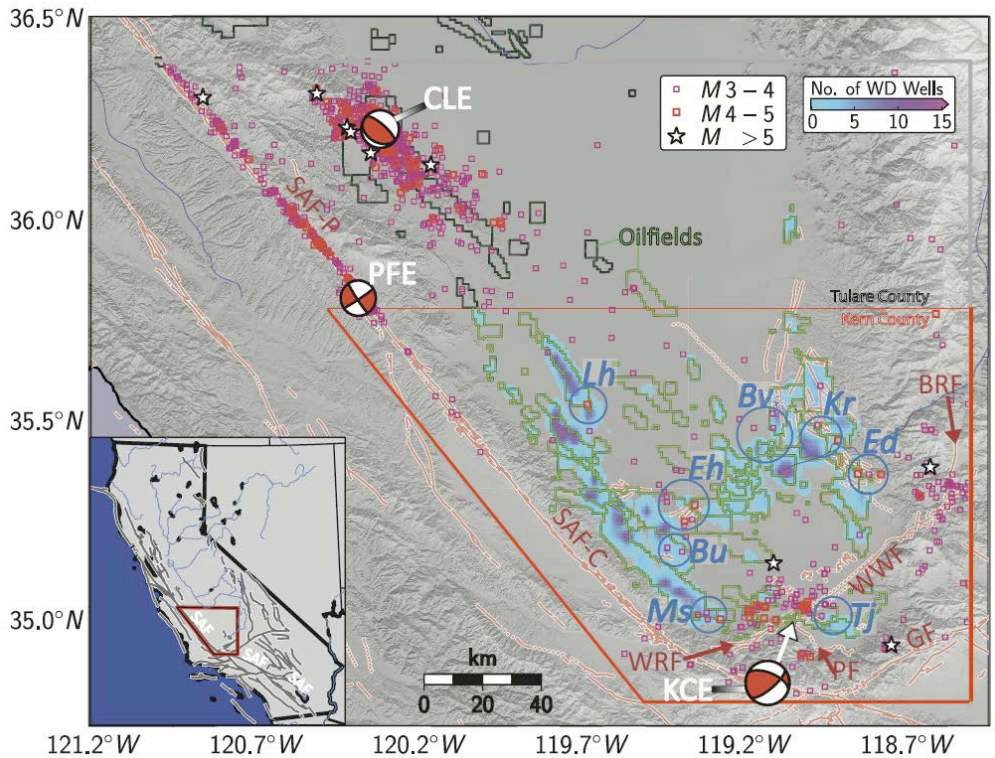

Figure 3. *Seismicity above M3 (squares and stars), faults (red lines) and oilfields (green polygons) within San Joaquin Basin. Major faults include the Wheeler Ridge (WRF), Pleito (PF), Garlock (GF), White Wolf (WWF), and Brecken Ridge faults (BRF) as well as the Parkfield (SAF-P) and Carrizo (SAF-C) segment of the San Andreas fault. The three largest earthquakes (red beach-balls) are the 1952 Mw7.5 Kern County (KCE), the 2004 Mw6.0 Parkfield (PFE), and the 1983 Mw6.4 Coalinga event (CLE). The 8 regions with M > 3 earthquakes close to active oilfields are highlighted by blue circles (Ed: Edison, Kr: Kern-River, Bv: Bellevue, Lh: Lost-Hills, Eh: Elk-Hills, Bu: Buena-Vista, Ms: Midway-Sunset, Tj: Tejon). Magnitudes here are local magnitudes.*

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T. H. Goebel, E. Hauksson, J.-P. Ampuero, F. Aminzadeh, F. Cappa, and J. B. Saleeby Waste water injection induced seismicity in naturally-active, seismogenic regions in central California, (2014 SCEC Annual Meeting Invited Talk)

A. Plesch, C. Nicholson, C. Sorlien, J. H. Shaw, and E. Hauksson, SCEC Community Fault Model Version 5.0, (2014 SCEC Annual Meeting Poster 096)

J. M. Fletcher, M. E. Oskin, O. J.Teran, and E. Hauksson, Large Earthquakes and Three Dimensional Strain on Interlocking Networks of Small Faults, (2014 SCEC Annual Meeting Poster 130)

Goebel, T. H., E. Hauksson, A. Plesch, and J. H. Shaw, A comparative study of the seismo-tectonics in the San Gorgonio and Ventura Special Fault Study Areas, (2014 SCEC Annual Meeting Poster 196)

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