A century of oil-field operations and earthquakes in the greater Los Angeles Basin, southern California

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Abstract

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 oil fields that have been in production for almost a century and cover ~ 17% of the basin. In a recent study, first the influence of industry operations was evaluated by analyzing seismicity characteristics, including normalized seismicity rates, focal depths, and *b*-values, but no significant difference was found in seismicity characteristics inside and outside the oil fields. In addition, to identify possible temporal correlations, the seismicity and available monthly fluid extraction and injection volumes since 1977 were analyzed. Second, the production and deformation history of the Wilmington oil field were used to evaluate whether other oil fields are likely to experience similar surface deformation in the future. Third, the maximum earthquake magnitudes of events within the perimeters of the oil fields were analyzed to see whether they correlate with total net injected volumes, as suggested by previous studies. Similarly, maximum magnitudes were examined to see whether they exhibit an increase with net extraction volume. Overall, no obvious previously unidentified induced earthquakes were found, and the management of balanced production and injection of fluids appears to reduce the risk of induced-earthquake activity in the oil fields.

Introduction

We searched for evidence of induced earthquakes associated with oil-field operations in the seismically active Los Angeles Basin (LA Basin). Such anthropogenic earthquakes can be caused by changes in loading on the adjacent crust as well as inflation or collapse of an oil-field reservoir when large volumes of fluids are injected or extracted (Segall, 1989). In addition, triggered earthquakes located away from the reservoir might be caused by diffusion of fluids from the oil-field reservoir into a nearby fault zone.

Numerous large oil fields in the basin have been in production for almost a century (Wright, 1987). The geographic locations of the oil fields follow major tectonic trends such as the Newport-Inglewood fault, the Whittier fault, and the thrust belt at the north edge of the LA Basin (Figure 1). More than 71 oil fields have wells that serve as extraction, disposal and, in a few cases, hydraulic-fracturing wells. At the beginning of the 20th century, fluid extraction in some cases caused ground subsidence, likely because there was almost no injection of fluids (Wright, 1987).

The last century of seismicity in the Los Angeles area includes numerous small earthquakes and a few $M_W > 5$ earthquakes. Most of these earthquakes occur beneath the sediments and are associated with transpressional tectonics related to the big bend in the San Andreas fault (Wright, 1987), but some could be associated with activities in large oil fields. Distinguishing induced earthquakes from tectonic events is difficult because the oil fields are aligned preferentially with the major faults (Wright, 1987). Kovach (1974) documents six damaging events of as much as M_L 3.3 induced by fluid extraction from 1947 to 1961 in the Wilmington oil field, before fluid injection became common. These M_L3 events caused damage by shearing off numerous oil wells at depths of ~ 500 m.

In 2014, a flurry of moderate earthquakes in the Los Angeles region raised concern as to whether some of the seismicity was of anthropogenic rather than tectonic origin. The 2014 M_W 5.1 La Habra sequence was located near several major oil fields, but the 2014 M_W 4.4 Encino sequence was away from oil fields, in the Santa Monica Mountains. Previously, both the 1933 M_W 6.4 Long Beach and the 1987 M_W 5.9 Whittier Narrows earthquakes occurred close to major oil fields, the Huntington Beach and Montebello fields. However, none of these earthquakes was

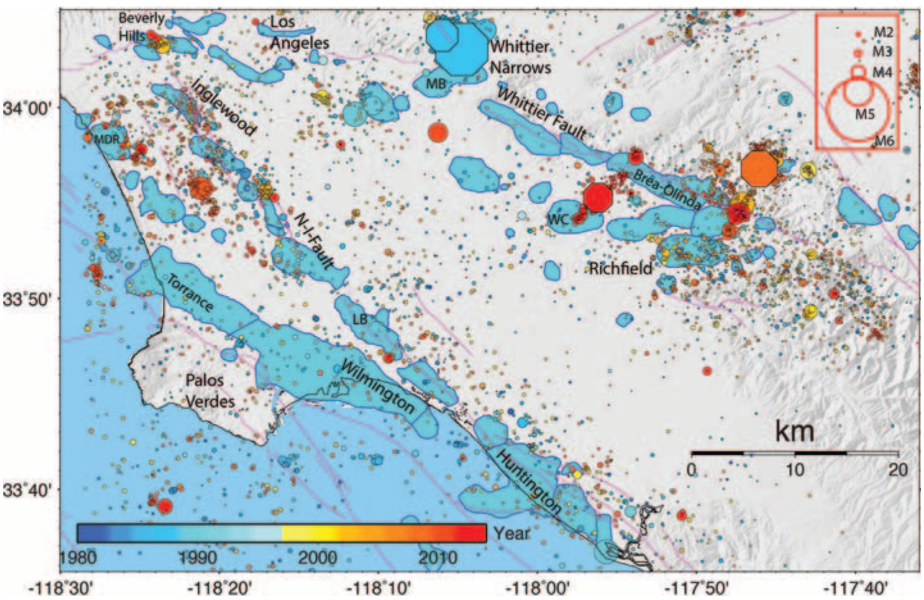

Figure 1. Relocated seismicity 1981–2014/06 recorded by the Southern California Seismic Network (SCSN) and oil fields shown as irregular light blue areas (from the California Department of Conservation, Division of Oil, Gas, and Geothermal Resources [DOGGR] Web site). Symbol sizes are scaled to earthquake magnitude, with $M_W \geq 5$ shown as octagons (see scale in upper right corner), and are color-coded by date. LB — Long Beach oil field; MB — Montebello oil field; MDR — Marina del Rey; N-I-Fault: Newport-Inglewood fault; WC — West-Coyote.

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attributed to oil-field activity because they occurred at depths more than 5 km below the bottom of the oil-field reservoirs.

Data sources and analysis

We analyzed the relocated Caltech/USGS Southern California Seismic Network (SCSN) earthquake catalog for two separate time periods, 1935 through 2014 for above M_L 2.5 and 1981 through 2014 for $M_L \geq 1.5$, which are the average levels of magnitude of completeness before and after 1980. We chose the start year of 1935 to avoid complications caused by abundant aftershocks from the 1933 M_W 6.4 Long Beach earthquake (Hauksson and Gross, 1991).

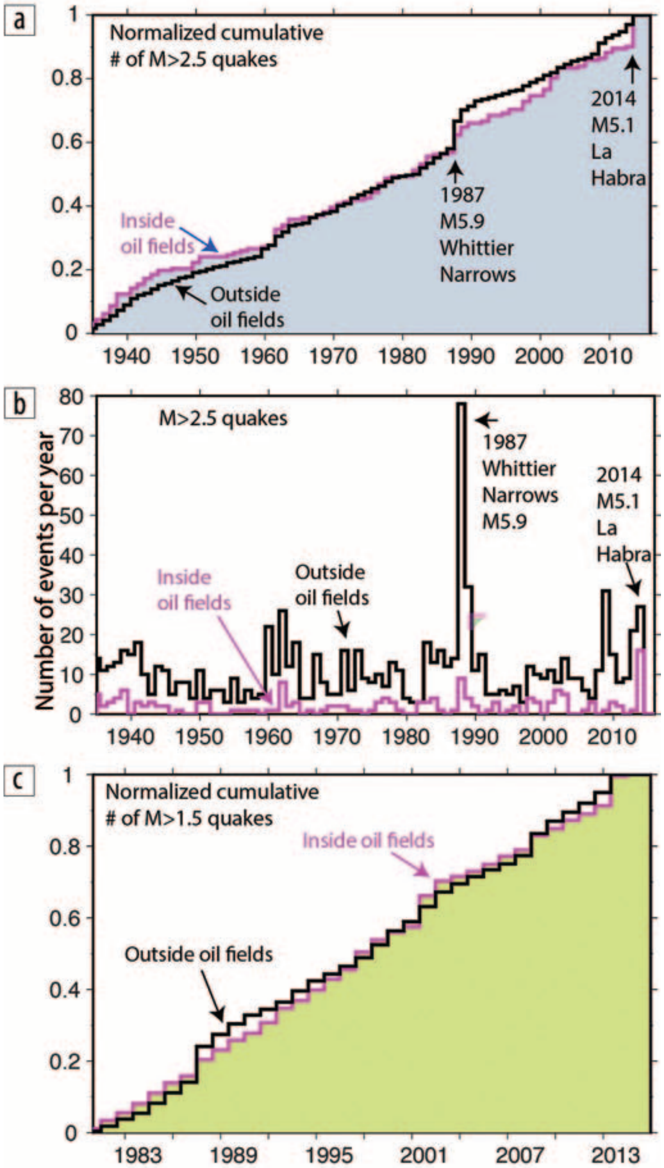

Figure 2. (a) Normalized cumulative histogram of 1935–2014 (M_L > 2.5) seismicity inside (magenta) and outside (black) oil fields shows no preference for earthquakes occurring within oil fields. (b) Histogram of the number of earthquakes per year in 1935–2014 shown for seismicity inside (magenta) and outside (black) oil fields. Two large sequences, 1987 M_W 5.9 Whittier Narrows and 2014 M_W 5.1 La Habra, also are labeled. (c) Normalized cumulative histogram of 1981–2014 seismicity inside (magenta) and outside (black) Los Angeles Basin oil fields.

In the more recent waveform-relocated 1981–2014 catalog, horizontal absolute error is ~ ± 1 km, and depth error is typically on the order of ~ ± 2 km (Hauksson et al., 2012). In contrast, the older catalog (1935–1980) has horizontal and vertical errors at least twice as large, and therefore, some events near the reservoir perimeter could be mislocated inside or outside the field.

We assumed in this study that only earthquake epicenters within the surface boundaries of the oil fields are potentially associated with changes in loading within that oil field (Segall, 1989). We also assumed that any earthquakes outside the perimeters are of tectonic origin because there is no apparent clustering of seismicity adjacent to the perimeters of the oil fields. Within the fields, most of the events had focal depths (> 5 km) well below the depth of the oil-field production zones.

We analyzed the SCSN seismicity catalog and the oil-field production data sets (since 1977) of the California Department of Conservation, Division of Oil, Gas, and Geothermal Resources (DOGGR) (California Department of Conservation, Division of Oil, Gas, and Geothermal Resources, 2015). Oil-field production data from 1935 through 1977 are rarely publicly available. However, various Internet sources such as Wikipedia have some historical information about most LA Basin oil fields.

Industry operations and seismicity

Oil fields 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 earthquakes that occurred within and outside the perimeters of the oil fields. No M_W > 5 main shocks but numerous small earthquakes had occurred in the oil fields. The absolute seismicity rate within the perimeters of the oil fields is ~ 17% of the rate outside the fields (Figure 2a). Thus, the area-normalized rates of seismicity within and outside the oil fields are almost identical. However, the lower absolute seismicity rate in the oil fields 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 in the oil fields and 0.955 ± 0.02 outside the fields. The annual rate of earthquakes exhibits a greater variability of event frequency and a lower mean rate of events within the oil fields (Figure 2b).

Although the normalized rate of seismicity inside and outside the oil fields over the examined ~ 80-year time period is similar and independent of oil-field operations, spatial and temporal patterns do exist, such as in the 1950s and 1960s when 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 regions.

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 oil fields (Figure 1). The normalized cumulative rates of seismicity inside and outside the fields are also similar (Figure 2c). As mentioned above, seismicity within the oil fields exhibited apparent rate increases related to the 1987 M_W 5.9 Whittier Narrows sequence near Montebello, the 2001 sequence beneath the Beverly Hills oil field, and the 2014 M_W 5.1 La Habra sequence near the abandoned West-Coyote field.

Those increases are most likely not associated with oil-field activities because they occurred at depth (> 5 km), mostly outside the boundaries of the associated reservoirs, and are not correlated with significant changes in oil-field fluid injection or extraction.

More than 98% of the earthquakes in the greater LA Basin are below depths of 5 km (Figure 3). There is no significant difference in depth distribution between earthquakes outside or inside the oil fields, which suggests that the events are of tectonic origin. However, Segall (1989) shows that crustal-deformation models predicted the occurrence of earthquakes above and below the production zone. Hence, poroelastic stress changes resulting from injection or extraction of fluids might 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 significant changes in seismicity rate associated with temporal changes in fluid extraction or injection. Figure 4 shows two examples of monthly injection and production data from the Wilmington and Long Beach oil fields. There is no obvious correlation between seismicity rates or magnitudes with total net cumulative injection volumes in the two fields.

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.

Previous ground subsidence and seismicity

Although overall fluid injection and extraction show no correlation to seismicity, historical production at the Wilmington oil field was linked to significant surface subsidence as well as some induced seismicity. The subsidence in the Wilmington field reached more than 9 m in 1926–1968 and affected the Los Angeles harbor and adjacent regions (Mayuga and Allen, 1969). A repressurization effort was started in 1958, and it halted the subsidence by 1968.

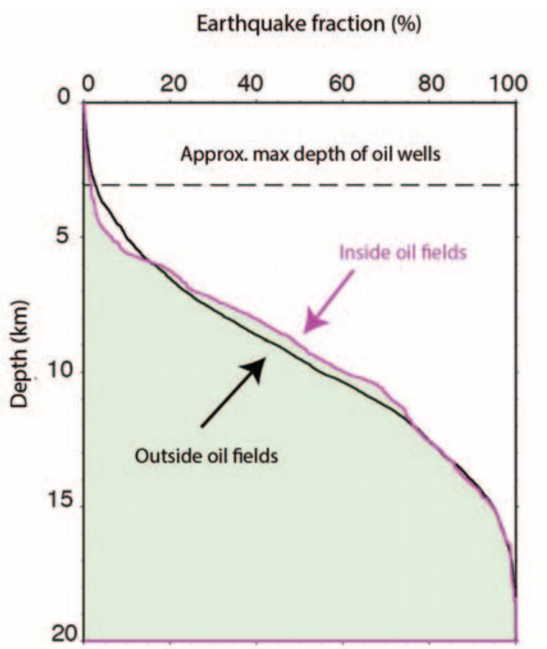

Figure 3. Distribution of focal depths for seismicity (1981–2014) inside (magenta) and outside (black) oil fields. Nearly all the seismicity is at depth below the reservoirs or deeper than ~ 3 km.

Land subsidence caused by fluid extraction exerted large horizontal stresses, resulting in shortening of near-surface sediments in the center of the subsidence bowl (Segall, 1989). Stresses from decreases in pore pressure and loading were released through continuous creep and numerous induced (M_L 2 to M_L 3.3) earthquakes (Kovach, 1974). Sudden release of shear forces at depths of 450 and 600 m below the surface caused casing damage. After one of the earthquakes, an offset of 0.23 m along slippage planes in cores at ~ 500-m depth was reported (Kovach, 1974).

To understand whether other oil fields are likely to experience similar subsidence in the future, we used the normalized fluid-extraction numbers for the Wilmington oil field as a benchmark to evaluate currently active fields.

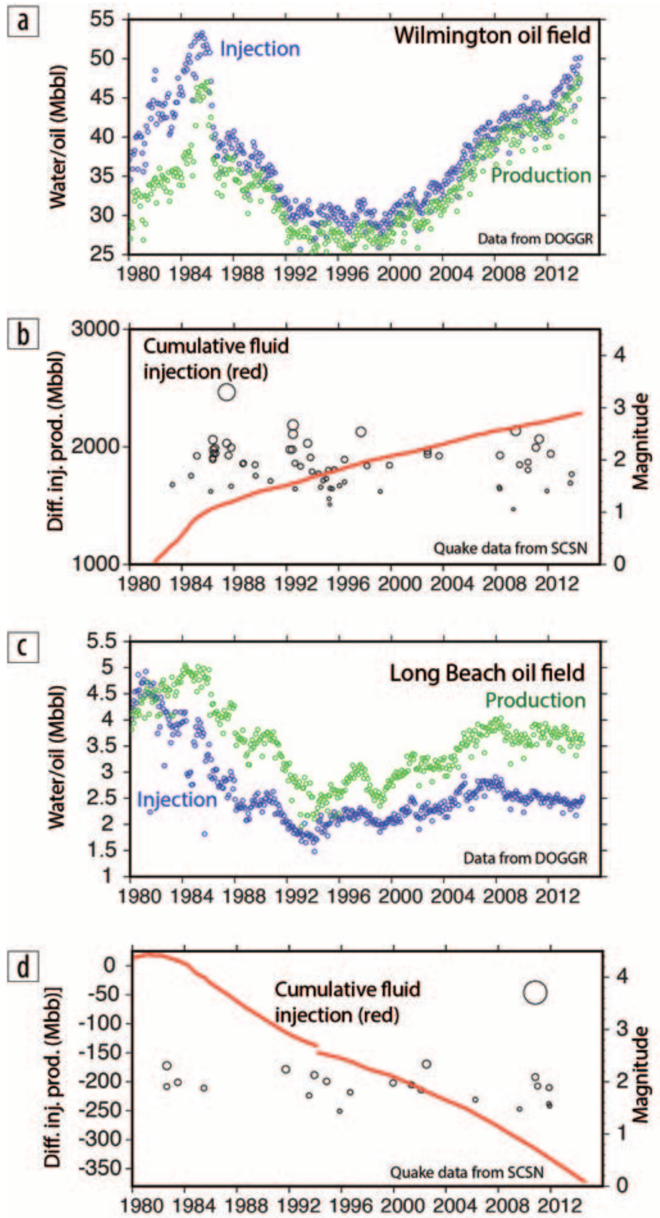

Figure 4. (a) Monthly extraction/production (green) and injection (blue) data in the Wilmington oil field. (b) Net cumulative fluid injection and earthquake magnitudes versus time for earthquakes within the perimeter of the Wilmington field. Symbol size is scaled to magnitude. (c) Same as part (a) for the Long Beach oil field. Negative injection means net fluid extraction. (d) Same as part (b) for the Long Beach field.

To investigate how fluid injections or extractions since 1977 from the 18 largest active oil fields compare in size with the extreme fluid extraction in the Wilmington oil field in 1926–1958, we normalized the cumulative production data and seismicity by the volume of each oil field. We determined the approximate volume of the oil fields from their measured surface area and by assuming an average production-zone thickness of 2 km (Wright, 1987). This volume calculation is approximate because each field might consist of several separated oil-production zones. Each volume could be overestimated by possibly as much as half, but we expect all the volumes to be overestimated by a similar fraction and the relative volumes to be comparable.

Since 1977, the net extraction and injection volumes have been similar at most oil fields, and the corresponding normalized cumulative changes in fluid volume are small (Figure 5). In contrast, wells in the Richfield and Wilmington oil fields have been injecting at high normalized rates, leading to a net increase in fluid volume in the reservoirs. The Richfield oil field is the only one associated with both high rates of injection and seismicity. However, the high seismicity rate in the field is similar to the seismicity rate in the adjacent region outside the field.

Overall, we found no obvious correlation between normalized net-production volumes and seismicity. For most of the oil fields, the volume of extracted fluid is more than a factor of three smaller than the normalized Wilmington extraction volume from 1926 through 1958 (Figure 5). The extraction volume for the Long Beach oil field since 1977 is high, but it is still a factor of two (in terms of normalized withdrawn volume) smaller than the extraction volume that caused the Wilmington collapse (Figure 4). Consequently, this analysis suggests that none of the oil fields is close to experiencing surface collapse and associated seismicity.

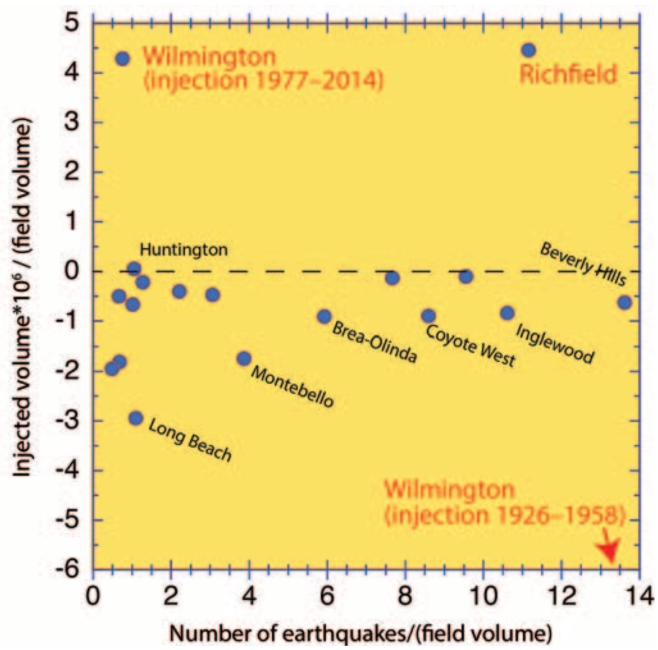

Figure 5. Cumulative fluid-injection volumes and seismicity in 1977–2014, normalized by each field volume. For most fields, the normalized cumulative changes in fluid volume are small and show slow, steady withdrawal of fluids. The Richfield, Wilmington, and Huntington Beach oil fields have been injected at high, normalized rates, leading to a net increase in fluid volume in the reservoirs. The red arrow indicates the approximate value of the estimated fluid withdrawal from the Wilmington oil field from 1926 through 1958 and inferred seismicity of $M_L \geq 1.5$ based on the Kovach (1974) catalog and a *b*-value of 1.0.

Fluid injection or extraction and M_{max}

Although we did not identify any obvious induced events, we have analyzed the oil-field production data and the SCSN catalog to assess how the maximum magnitude (M_{max}) of the seismicity in the perimeters of the oil fields compares with the M_{max} of induced seismicity recorded in other parts of the United States. McGarr (2014) suggests that the expected M_{max} of earthquakes induced by fluid injection is proportional to the total injected volume, using a data set that included many induced earthquakes such as the 2011 M_W 5.6 earthquake in Oklahoma. Although this relationship does not account for local conditions such as geology, permeability, past fluid injection, extraction history of the field, or uncertainties in other parameters, it provides a consistent upper limit for M_{max}.

Only three oil fields — Huntington Beach, Richfield, and Wilmington — have experienced net injection since 1977 and can be compared directly to the McGarr (2014) study. The injected volumes for Richfield and Wilmington exceed the volume related to the 2011 Oklahoma sequence, but the maximum magnitude in these fields has reached only M_L 3.1 and M_L 3.2 (Figure 6). Because of fluid withdrawal during the preceding decades, the net injected volume is low, suggesting that the probability of large-magnitude induced earthquakes is small, assuming a direct connection between expected earthquake size and net injection volumes.

Earthquakes induced by extraction might be less likely to occur than events caused by injection because crustal stress changes resulting from fluid extraction are approximately an order of magnitude lower than for fluid injection (Troiano et al., 2013). Thus, the M_{max} for extraction-induced earthquakes might be expected to be lower than for injection-induced events for similar volumes.

To analyze the effects of fluid extraction on M_{max}, we determined the net extracted volume for the 16 largest oil fields that

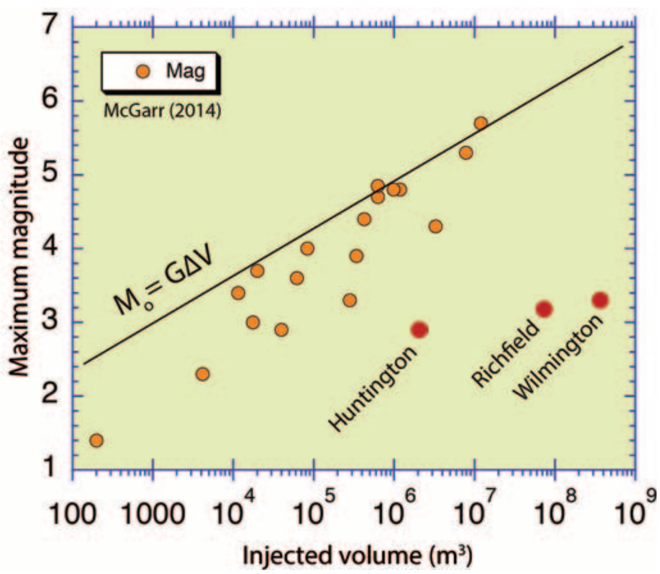

Figure 6. Maximum earthquake magnitude versus injected volume for data published by McGarr (2014) (orange solid circles) and from the three Los Angeles Basin oil fields that have net injection (red solid circles, this study). The black line from McGarr (2014) shows how the upper bound in seismic moment (M_0) is related to the product of the modulus of rigidity (G) and the total volume of injected fluid (ΔV).

have experienced net fluid withdrawal since 1977. The sizes of extraction volumes are similar to the injection volumes in the McGarr (2014) study. The largest event is an M_L 4.2 earthquake below the Beverly Hills oil field. The maximum magnitudes of earthquakes within perimeters of the oil fields suggest a slight positive correlation with withdrawn volume, similar to injection but with significant scatter (Figure 7).

Although there is a weak correlation between extracted volumes and magnitude, these earthquakes are most likely tectonic in origin because the normalized rate in the oil fields is similar to the background rate outside the basins. Further, these events all occurred below reservoir depths and are not directly induced within the reservoir. However, we could not fully rule out the possibility that the earthquakes might have been triggered by loading effects or, less likely, by pore-fluid diffusion (Segall, 1989). Overall, it appears that fluid injection or extraction in the Los Angeles Basin has not significantly altered seismicity and the corresponding hazard.

Discussion

There is a high rate of seismicity in the greater LA Basin region caused by strain loading along regional tectonic structures (Hauksson et al., 2012). The oil fields are collocated with these tectonic structures of strike-slip faulting straddling the Newport-Inglewood and Whittier faults, along the west and east sides of the basin, and the thrust belt at the north edge of the basin (Wright, 1987). Therefore, separating tectonic and possible induced earthquakes is difficult at best.

Through this investigation, we found that fluid production and injection rates are fairly steady over months to years, and sudden injection or extraction events are extremely rare. Consequently, sudden stress changes that could trigger earthquakes do not occur. In addition, net fluid extraction or injection volumes at most oil fields in the area since 1977 have been relatively small. Temporal delays of hours to decades between injection and the occurrence of induced seismicity are to be expected and make it difficult to correlate seismicity with changes in pumping rates. For instance, the Wilmington earthquakes began about two decades after the initiation of extraction (Kovach, 1974).

The lack of apparent induced seismicity also could be attributed to oil and gas reservoirs being traps that are well sealed (Wright, 1987). Both impermeable sedimentary layers and fault zones enclose the reservoirs. When too much fluid is pumped out, the reservoir surface subsides, but negligible groundwater appears to flow into the reservoir (Wright, 1987). Similarly, when fluid is pumped in, the ground surface reaches equilibrium or rises (Bawden et al., 2001). Hence, substantial fluid movements in and out of the reservoirs are unlikely to affect the adjacent, mostly impermeable faults.

It is difficult to address the question of whether induced seismicity occurs just outside the perimeter of an oil field. Such earthquakes would imply that fluids leaked out of the reservoir or loading conditions within the reservoir changed enough to also change stresses on nearby faults. At first glance, there are no obvious clusters of earthquakes adjacent to the fields that might suggest that an adjacent oil field is affecting seismicity (Figures 1 and 2). It also has been shown that groundwater does not migrate easily into the fields when they are depleted. Therefore, these barriers likely prevent fluid flow out of the oil fields.

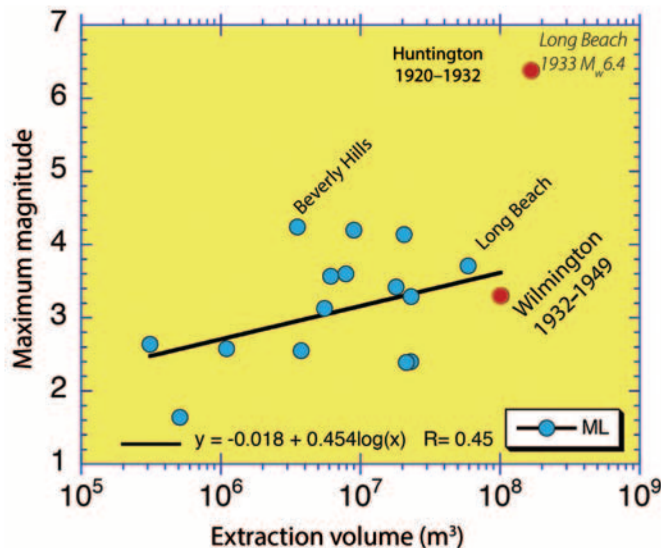

Figure 7. Maximum magnitude of earthquakes that occurred in 1977–2014 versus the corresponding net extraction volume for selected Los Angeles Basin oil fields. The largest event (M_L 4.2) occurred beneath the Beverly Hills oil field. The largest induced Wilmington earthquake (M_L 3.2) also is plotted (red solid dot), with estimated extraction volume (Kovach, 1974). The estimated withdrawal from the Huntington oil field prior to the 1933 M_W 6.4 Long Beach earthquake also is shown, as a red dot in the upper right corner. The fit equation and R-value describing the solid black logarithm fit line also are shown.

Historically, the largest earthquake to rupture across an LA Basin oil field was the 1933 M_W 6.4 Long Beach earthquake. It initiated near or within the Huntington Beach oil field and extended toward the city of Long Beach along the Newport-Inglewood fault (Hauksson and Gross, 1991). When we compared the extracted volume from 1920 to 1932 from the Huntington oil field to volumes and maximum earthquake magnitude in other oil fields since 1977, the magnitude of the Long Beach earthquake exceeds the expected magnitude by ~ 3 units (Figure 7). This suggests a tectonic cause, although possible foreshock or main-shock triggering effects cannot be ruled out completely, and the cause might never be resolved.

Conclusions

The normalized rates of earthquakes since 1935 and focal depths and *b*-values within and outside oil fields in the Los Angeles Basin show no significant differences. The early practice of rapid oil extraction that caused compaction of the oil-producing strata and led to 9 m of subsidence and damaging $M_L \leq$ 3.2 induced earthquakes in the Wilmington oil field from 1949 to 1961 has been abandoned. Since then, no clear instances of induced earthquakes ($M_L > 1.5$) related to production and injection of fluids in LA Basin oil fields have occurred, presumably because the fields are maintained mostly in volumetric balance. The balanced exchange of fluid volumes likely minimizes variations in reservoir pressures and poroelastic stresses.

Based on our results, we do not expect significant anomalous induced seismicity associated with oil-field activities in the LA Basin in the long term, barring significant changes in production practices. In most cases, more than 90% of the presently recoverable oil has been removed, and secondary or tertiary recovery is proceeding at a slow but steady pace. However, if drastically different recovery techniques were applied, such as extensive horizontal drilling and associated hydraulic fracturing (fracking) and/or deep fluid injection, the potential for induced seismicity would need to be reassessed. TLE

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References

Bawden, G., W. Thatcher, R. S. Stein, K. W. Hudnut, and G. Peltzer, 2001, Tectonic contraction across Los Angeles after removal of groundwater pumping effects: Nature, **412**, no. 6849, 812–815, http://dx.doi.org/10.1038/35090558.

California Department of Conservation, Division of Oil, Gas and Geothermal Resources (DOGGR), 2015, http://www.conservation.ca.gov/dog/Pages/Index.aspx, accessed 1 February 2015.

Hauksson, E., and S. Gross, 1991, Source parameters of the 1933 Long Beach earthquake: Bulletin of the Seismological Society of America, **81**, no. 1, 81–98.

Hauksson, E., W. Yang, and P. M. Shearer, 2012, Waveform relocated earthquake catalog for southern California (1981 to June 2011): Bulletin of the Seismological Society of America, **102**, no. 5, 2239–2244, http://dx.doi.org/10.1785/0120120010.

Kovach, R. L., 1974, Source mechanisms for Wilmington oil field, California, subsidence earthquakes: Bulletin of the Seismological Society of America, **64**, no. 3, part 1, 699–711.

Mayuga, M. N., and D. R. Allen, 1969, Subsidence in the Wilmington oil field, Long Beach, California, U.S.A.: Proceedings of the Tokyo Symposium on Land Subsidence, International Association of Scientific Hydrology, Studies and reports in hydrology, IASH-UNESCO, **1**, no. 88, 66–79.

McGarr, A., 2014, Maximum magnitude earthquakes induced by fluid injection: Journal of Geophysical Research: Solid Earth, **119**, no. 2, 1008–1019, http://dx.doi.org/10.1002/2013JB010597.

Segall, P., 1989, Earthquakes triggered by fluid extraction: Geology, **17**, no. 10, 942–946, http://dx.doi.org/10.1130/0091-7613(1989)017<0942:ETBFE>2.3.CO;2.

Troiano, A., M. G. Di Giuseppe, C. Troise, A. Tramelli, and G. De Natale, 2013, A Coulomb stress model for induced seismicity distribution due to fluid injection and withdrawal in deep boreholes: Geophysical Journal International, **195**, no. 1, 504–512, http://dx.doi.org/10.1093/gji/ggt229.

Wright, T., 1987, Geologic summary of the Los Angeles Basin, *in* T. Wright and R. Heck, eds., Guidebook: Petroleum geology of coastal southern California: Pacific Section, AAPG, 21–30.