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Potentially Induced Earthquakes during the Early Twentieth Century in the Los Angeles Basin

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Abstract Recent studies have presented evidence that early to mid-twentieth-century earthquakes in Oklahoma and Texas were likely induced by fossil fuel production and/or injection of wastewater (Hough and Page, 2015; Frohlich *et al.*, 2016). Considering seismicity from 1935 onward, Hauksson *et al.* (2015) concluded that there is no evidence for significant induced activity in the greater Los Angeles region between 1935 and the present. To explore a possible association between earthquakes prior to 1935 and oil and gas production, we first revisit the historical catalog and then review contemporary oil industry activities. Although early industry activities did not induce large numbers of earthquakes, we present evidence for an association between the initial oil boom in the greater Los Angeles area and earthquakes between 1915 and 1932, including the damaging 22 June 1920 Inglewood and 8 July 1929 Whittier earthquakes. We further consider whether the 1933 M_w 6.4 Long Beach earthquake might have been induced, and show some evidence that points to a causative relationship between the earthquake and activities in the Huntington Beach oil field. The hypothesis that the Long Beach earthquake was either induced or triggered by an foreshock cannot be ruled out. Our results suggest that significant earthquakes in southern California during the early twentieth century might have been associated with industry practices that are no longer employed (i.e., production without water reinjection), and do not necessarily imply a high likelihood of induced earthquakes at the present time.

Online Material: Summary of background information about the Wilmington oil field, information about revisited earthquakes between 1900 and 1935, tables of felt events, and accounts of three earthquakes.

Introduction

The greater Los Angeles area was one of the top oil-producing regions in the country during the early twentieth century (e.g., Case, 1923; Franks and Lambert, 1985). The emergence of Los Angeles as a population center was fueled (so to speak) in part by the discovery of oil. The initial oil boom in the greater Los Angeles area began when oil was struck on 20 April 1892 near the present-day location of Dodger Stadium, north of downtown Los Angeles (Fig. 1). Subsequent strikes were made over the next 20 years. Before 1920, production was concentrated in the Whittier area, where a number of separate fields were discovered starting in the late nineteenth century (Fig. 1). The Whittier field (proper) was first developed in 1897 (Norris, 1930); the adjacent Puente field, discovered in 1880, was one of the earliest fields of commercial importance in California (Norris, 1930). From 1900 onward, there was a general progression from shallow to deeper drilling. For example, through 1902, the greatest depth drilled in the Puente field was 1927 ft, with only modest production. (We preserve non-SI units for industry data because they are essentially part of the archival record, for industry data in particular, and provide an indication of the precision with which numbers were constrained.) In 1910, two wells were drilled to depths in excess of 2200 ft, still with only modest production. Another well was drilled to a depth of 4255 ft in 1910; although the well was abandoned due to the condition of the hole; considerable methane gas was encountered between 3300 and 3612 ft.

Most of the large oil fields in the Los Angeles area were discovered in the 1920s along the trend of the Newport–Inglewood (NI) fault (Fig. 1). Testa (2007) presents a historical retrospective of early oil exploration in the greater Los Angeles region, which we review briefly here (see also Wright, 1987). Testa (2007) focuses on the NI structural zone (NISZ), a series of active faults including the NI fault and

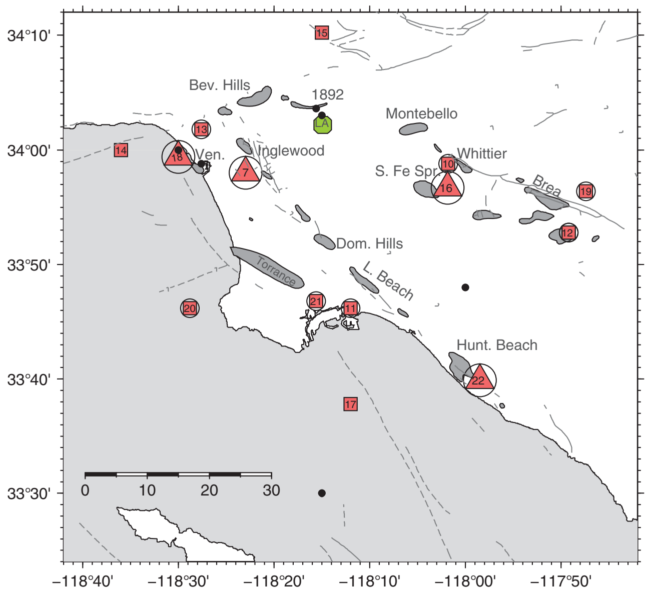

Figure 1. Locations of oil fields as of 1930 (gray regions; California Oil Fields: Summary of Operations [COF], 1930a) and the city of Los Angeles (green octagon). Location of earliest oil strike is indicated (1892). Earthquake locations including damaging events (red triangles); other notable events or sequences between 1911 and 1933 (red squares) are also shown, labeled by event numbers (Table 1). Black dots indicate locations of four early $M_w \geq 4.0$ events for which locations are especially uncertain. Circled symbols indicate events for which there is a spatial and temporal association with notable operations in adjacent oil fields, as discussed in this study. Fault traces are from Jennings (1994).

extensions thereof. Following the initial oil strike in 1892, the Beverly Hills oil field was discovered in July 1900, with a production zone between 2000 and 3000 ft deep (Testa, 2007). Later geologists concluded that this field is not part of the NI trend (Testa, 2007), and the field is not shown on some maps of oil fields along the NISZ (Wright, 1987; Testa 2007). The initial oil discovery along the NISZ was at Huntington Beach in 1920. Adjacent fields along the trend were discovered in the 1920s (Fig. 1).

Although Los Angeles basin fields accounted for roughly 20% of the world's total production of crude oil by 1923 (Franks and Lambert, 1985), Hauksson *et al.* (2015) recently concluded that, apart from the six small events in the Wilmington area identified previously by Kovach (1974), there is no evidence for significant induced earthquakes in the greater Los Angeles area between 1935 and the present. Nicholson and Wesson (1990) identified an M_w 3.7 event in 1962 that they suggested was induced by production in the Inglewood oil field. To our knowledge, no follow-up studies have been done to investigate this event. The only events in the region generally recognized to have been induced were associated with dramatic subsidence within the Wilmington oil field, which in 1932 was the last of the large fields in the area to be discovered (Wright, 1987). Within a year of its discovery, production in this field reached 100,000 barrels per day, making it the fourth largest oil field in North America and, as of 1970, believed to be the 48th largest in the world.

It is well established that the high rate of oil extraction in the Los Angeles region gave rise to dramatic surface subsidence in proximity to the active fields (Gilluly and U.S. Grant, 1949). Although by the direct account of Charles Richter and his colleagues (see Ⓔ the electronic supplement to this article), the association between small, shallow earthquakes and oil fields was recognized by local experts as early as 1932, to the authors' knowledge, a possible association between earthquakes in the Los Angeles region and oil extraction in the early twentieth century was not discussed in any published reports prior to Kovach (1974). McGarr (1991) suggested that several large, damaging earthquakes in California, including the 1987 Whittier Narrows earthquake, might have been induced by oil extraction. This conclusion was based on a correspondence between the size of the events and the mass removed by oil pumping, such that the earthquakes were proposed to be part of an isostatic adjustment process.

In light of recent studies that presented evidence that early oil and gas production and/or wastewater injection was associated with induced earthquakes as early as the early to mid-twentieth century (Hough and Page, 2015; Frohlich *et al.*, 2016), in this study we reconsider the question, "Is there any evidence that earthquakes were induced during the early oil boom in the Los Angeles area, which began in 1892?" To address this question, it is necessary to first consider carefully what is known about earthquakes during the historical and early instrumental eras. In the following sections, we review available sources of macroseismic and early instrumental data for events prior to the start of the instrumental catalog in January 1932, using demographic data to consider the completeness of the historical catalog. We compile a list of all felt events in the Los Angeles basin between 1900 and December 1931 (see the Ⓔ electronic supplement). Most of these caused light shaking reported by at most a few witnesses. We identify and focus on significant events, that is, events and/or sequences that were more widely felt, and review oil industry activities in proximity to these events using available industry records.

Historical and Early Instrumental Seismicity

Earthquakes in southern California prior to 1932 are generally known only from felt reports and, in some cases, limited early instrumental data. Available catalogs include information from a variety of sources. The present-day statewide catalog (Felzer, 2013) was compiled for the most recent Uniform California Earthquake Rupture Forecast v. 3 (UCERF3; Field *et al.*, 2013) project, and includes pre-1932 events with estimated magnitudes of M_w 4.0 and above; most magnitudes and locations are estimated from macroseismic observations (e.g., Toppozada *et al.*, 1978). For events before 1928, epicenters are generally given to the nearest 0.5° (sometimes 0.25°), in some cases even when macroseismic data clearly indicate a location is grossly in error (e.g., as discussed by Richter, 1970, for the 1920 Inglewood event). The historical catalog (Townley and Allen, 1939) for the period 1769 through the end of 1927 documents events that were weakly felt in the region, including over 300 that appear to have been centered in the Los Angeles area (see Ⓔ Table S1). Neither magnitude nor locations are available for these events, but some information can be gleaned from felt reports. Small felt earthquakes in the Los Angeles region are particularly poorly documented during the 4-year gap between the end of the Townley and Allen (1939) catalog in December 1927 and the start of the instrumental catalog in January 1932. Between January 1928 and December 1932, the UCERF3 catalog includes six events in the greater Los Angeles area with estimated $M_w > 4.0$ (see Ⓔ Table S1; Fig. 1). The best source of information about small events during these years are the United States Earthquake Reports that were published annually by the Coast and Geodetic Survey, drawing primarily from Weather Service reports of felt earthquakes (Heck and Bodle, 1930, 1931; Neumann, 1932, 1934; Neumann and Bodle, 1932; see Ⓔ Table S1). These reports include all reported felt events in the Los Angeles area. For 1928, 1929, 1930, 1931, and 1932, the reports list 6, 12, 2, 9, and 13 felt events, respectively. For 1930 and earlier years, intensities are noted for some accounts using the Rossi–Forel (RF) scale as described within the reports; from 1931, intensities are assigned using the modified Mercalli intensity (MMI) scale described by Neumann (1932). Intensities for many events can be downloaded from the National Oceanic and Atmospheric Administration (NOAA) Earthquake Intensity Database, which lists MMI values (see Data and Resources). It is important to revisit original accounts wherever possible: notably, it appears that when RF intensities were converted to MMI, values of 1 (definite not felt report) were converted to MMI II (very weakly felt).

During the early decades of the twentieth century, instrumental recordings of earthquakes were available from the Berkeley Seismological Laboratory (dating back to 1887) and other early instruments at regional distances, which could detect only moderate to large events in southern California. Regional earthquake monitoring in southern California began in the early 1920s with the development and deployment of Wood–Anderson seismometers (Anderson and Wood, 1925; Goodstein, 1982); the earliest strong-motion accelerographs were installed in the state in the early 1930s (Ulrich, 1935). Following the development of the magnitude scale (Richter, 1935), earthquakes in southern California began to be routinely cataloged, including recorded events back to January 1932 (see Hutton *et al.*, 2010). The recent study by Hauksson *et al.* (2015) considers the catalog from 1935 onward to avoid complications caused by aftershocks of the Long Beach earthquake. Some earthquakes in the greater Los Angeles area prior to the start of the instrumental catalog can be investigated using limited early instrumental data. By spring of 1924, an experimental Wood–Anderson instrument was operating in Pasadena; the first true network station was installed in Riverside in October 1926, and by 1929 a total of six more stations had been installed in southern California (Goodstein, 1982; Hutton *et al.*, 2010). Although events prior to January 1932 were never cataloged, some of the early instrumental data were used to analyze notable events (e.g., Wood and Richter, 1931; Gutenberg *et al.*, 1932).

The quality and density of felt reports also grew from 1890 onward as the local population grew. The quality of information from felt reports, and thus the reliability of earthquake information extracted from them, always depends critically on settlement patterns, which we review briefly here and show in Figure 2. Following the incorporation of the city of Los Angeles in 1850, the population of Los Angeles County grew slowly through most of the nineteenth century. The population grew threefold between 1880 and 1890; by 1890 a number of adjacent cities had been incorporated. By 1900, fueled largely by the initial discovery of oil in 1892, the population of Los Angeles County had grown to over 170,000, with over 2000 and 3000 people in Long Beach and Santa Monica, respectively (Fig. 2). By 1900, a number of other towns had also sprung up but not yet been incorporated as cities. From 1900 onward, the augmented Townley and Allen (1939) compilation of events is therefore generally able to pinpoint where local shocks were most strongly felt within Los Angeles County (see Ⓔ Table S1). For events that are not large enough to have well-characterized intensity distributions, we assign event epicenters to the location of the city where the strongest effects were reported, assuming that small shocks would only have been felt in proximity to the epicenter. Given the distribution of cities, epicenters are likely to be accurate to ~5–8 km, with events clustered at about 20 locations (see Ⓔ Table S1). Although we do not attempt to estimate magnitudes for most of these events, we will draw on data from the modern "Did You Feel It?" (DYFI) system (Wald *et al.*, 1999) to estimate magnitudes for key events using their reported felt extents if intensity data are insufficient for more detailed analysis. Notable felt events or sequences between 1913 and 1933 are also listed in Table 1 and shown in Figure 1. We note that the Townley and Allen (1939) catalog includes no reported felt events within the Los Angeles basin between 1900 and fall 1913.

Locations and in some cases times of most pre-1932 are imprecise, with some reported earthquakes possibly being booms associated with offshore battleship exercises (Townley and Allen, 1939) and many events reported were felt by a few or even one person. Seven of the smaller events and sequences included in Table 1 (3, 4, 8, 9, 11, 12, and 13), although more notable than most events, cannot be investigated in detail due to limited information. A rigorous consideration of spatiotemporal correlation with oil production is therefore not warranted. Instead of considering every felt event, we consider in detail the 14 events between 1900 and 1935 that reportedly caused damage and/or have estimated $M_w \geq 4.0$ as reported by the UCERF catalog (indicated event numbers correspond to numbers in Table 1). Results for smaller events are presented in see Ⓔ the electronic supplement; in the following sections, we summarize results for key events.

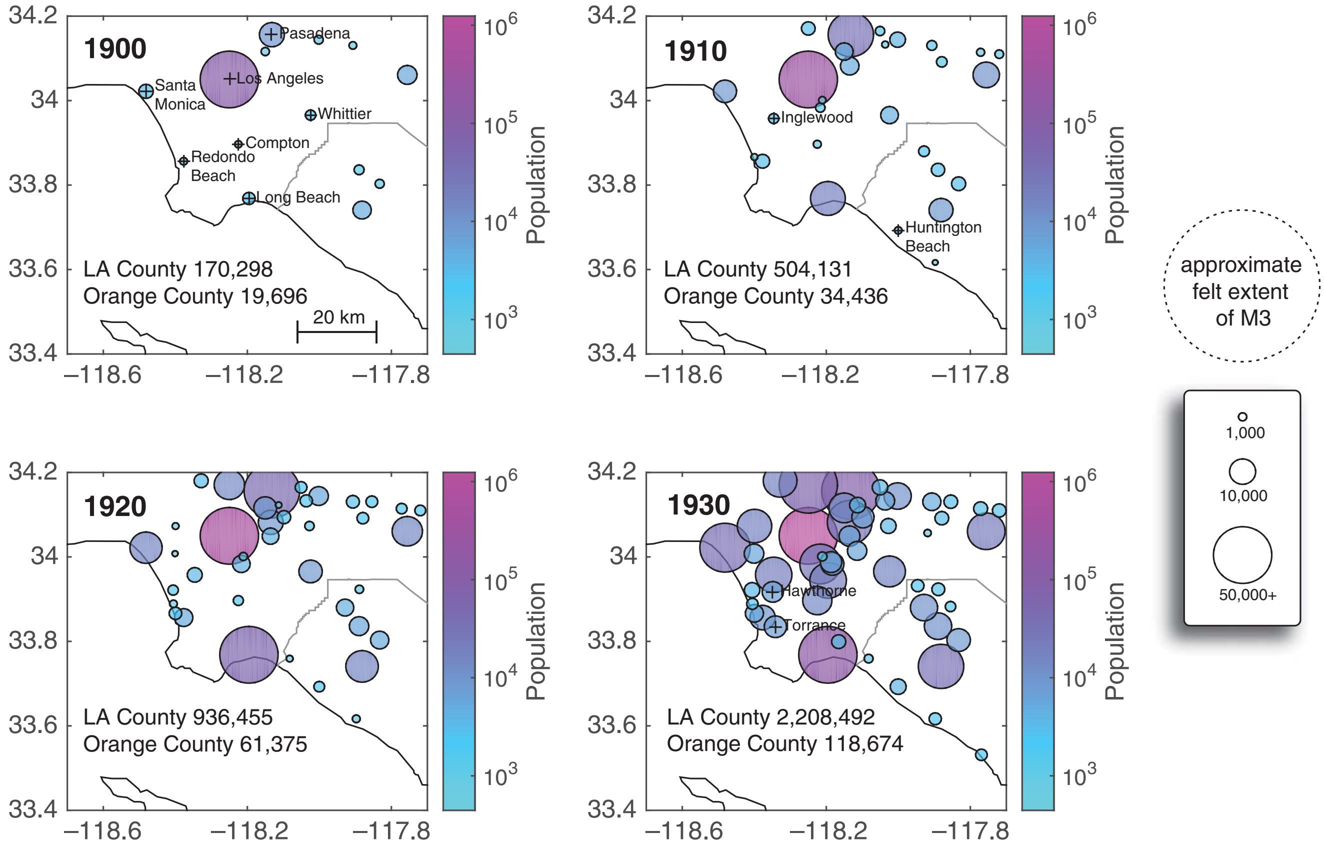

Figure 2. Population growth of incorporated cities in Los Angeles (LA) County as of 1900 (upper left), 1910 (upper right), 1920 (lower left), and 1930 (lower right), not including towns that had not yet incorporated at the time. Size and hue of circles scaled by population as indicated. The dashed circle indicates approximate felt extent of M_w 3 earthquake as estimated from "Did You Feel It?" data (Wald *et al.*, 1999) for recent earthquakes, assuming that shaking will be felt at decimal intensity 2.5.

22 June 1920 M_w 4.9 Inglewood (7) and the Inglewood/Hawthorne Oil Fields

The modern catalog location for the earthquake that occurred in the evening (local time [LT]) of 21 June 1920 is given as 34.0° N, 118.5° W (Felzer, 2013; Fig. 3a). This location is from the International Seismological Summary (Turner, 1925) based on instrumental recordings from Berkeley and a total of eight other instruments throughout North America. As noted by Richter (1970), the location, which persists in the UCERF catalog, is grossly in error; a mapped epicenter based on macroseismic effects places the event near 33.967° N, 118.383° W, near or immediately west of the then-center of Inglewood (Taber, 1920). Comparing the macroseismic effects of this event with those of later earthquakes recorded by local network stations, Richter (1970) estimated M_L 4.9 for the event. As discussed by Taber (1920), who undertook a field survey of effects in the days following the earthquake, the event caused severe damage (estimated intensity 8.5 on the RF scale) tightly concentrated less than a mile west of central Inglewood. Taber (1920) further commented on the surprisingly small overall felt effects of the event, given the severity of near-field effects, with the felt event extent reaching only 56 miles east and 57 miles to the northwest. The event predates the 1927 establishment of the Seismological Laboratory in Pasadena; it is likely that the especially severe damage motivated the detailed field study undertaken by Taber. This event is the first damaging earthquake in the Los Angeles region during the twentieth century. We review and reconsider in detail the available macroseismic data.

Only six intensity values for the 22 June 1920 event are included in the NOAA intensity database. These can be reviewed and augmented using original accounts, including details provided by Taber (1920), as well as newspaper accounts, and reconsidered to infer MMI values (see Ⓔ Table S2). The results can be compared with the intensity distribution of the 18 May 2009 M_w 4.7 Inglewood earthquake, for which over 40,000 DYFI responses were received. This event was relatively deep, with an estimated depth of 15.1 km. Since its introduction in 1999, the DYFI system has generated unprecedented volumes of consistently determined intensity data for recent earthquakes from online questionnaires filled out by users (Wald *et al.*, 1999). The form of the questionnaire and the algorithm used to calculate intensities are based on the work of Dengler and Dewey (1998), who determined community decimal intensity (CDI) values from telephone surveys using a weighted average of responses

Table 1
Notable Events in Los Angeles Area between 1900 and 1933

Event Number	Date (yyyy/mm)	Location	Description	Comments	
1	1913/10	Orange County (33.8° N, 118.0° W)	Location extremely uncertain; M_w 4.0	Brea-Olinda field in operation since 1884	U
2	1914/11	Offshore Santa Monica (34° N, 118.6° W)	Location extremely uncertain; M_w 4.5	Predates discovery of Venice field	N
3	1916/11	Yorba Linda (33.88° N, 117.82° W)	Sequence of felt small events	Coyote East field discovered 1911	P
4	Mid-1917	South Los Angeles (34.05° N, 118.25° W)	Series of small felt events	Location of events not clear; possibly close to Los Angeles oil field	U
5	1918/03	Santa Monica (34° N, 118.5° W)	Location uncertain; M_w 4.0	Beverly Hills oil field discovered 1900	P
6	1920/06	Offshore (33.5° N, 118.25° W)	Location highly uncertain; M_w 4.5		N
7	1920/06	Inglewood (33.967° N, 118.383° W)	Sequence of small events including damaging event on 22 June; M_w 5.0	Shortly after discovery of natural gas (see the 22 June 1920 M_w 4.9 Inglewood (7) and the Inglewood/Hawthorne Oil Fields section)	L
8	Summer 1920	Northwest Los Angeles (34.06° N, 118.26° W)	Sequence of small felt events; locations uncertain	Locations not clear; possibly close to Los Angeles oil field	U
9	1921/11	Venice (33.98° N, 118.46° W)	Several shocks felt; locations uncertain		U
10	1923/12	Santa Fe Springs (33.98° N, 118.03° W)	Event felt throughout basin, damaged oil derrick	Period of high production in Santa Fe Springs oil field	L
11	Spring 1925	Long Beach (33.77° N, 118.20° W)	Several shocks felt	Long Beach field discovered 1921	L
12	1926/11	Yorba Linda (33.88° N, 117.82° W)	Several shocks felt	Richfield oil field discovered 1923	L
13	Early 1927	Sawtelle (34.03° N, 118.46° W)	Two strongly felt shocks; locations uncertain	Near Inglewood oil field	P
14	1927/08	Offshore Santa Monica (34.0° N, 118.6° W)	Estimated M_w 5.0 event offshore	Offshore location supported by macroseismic observations	N
15	1927/10	Glendale (34.17° N, 118.25° W)	Estimated M_w 3.7. (mislocated in catalog)		N
16	1929/07	Whittier (33.945° N, 118.031° W)	Damaging event, estimated M_w 5.0	Resurgence of production in Santa Fe Springs field (see the The 8 July 1929 Whittier Earthquake (16) and the Santa Fe Springs Oil Field section)	L
17	1929/09	Catalina (33.63° N, 118.20° W)	Offshore, estimated M_w 4.0		N
18	1930/08	Santa Monica (33.99° N, 118.5° W)	Damaging event, estimated M_w 5.1; location uncertain	Period of high production in Playa Del Rey field	P
19	1931/03	Yorba Linda (33.94° N, 117.79° W)	Small event, estimated M_w 3.5		P
20	1931/04	Redondo Beach (33.77° N, 118.48° W)	Offshore, estimated M_w 4.4	Torrance field discovered 1922	P
21	1931/11	Wilmington (33.78° N, 118.26° W)	Near Wilmington, estimated M_w 3.2	Magnitude likely overestimated; within 5 km of Torrance field	P
22	1933/03	Long Beach (33.665° N, 117.975° W)	M_w 6.4 Long Beach earthquake	Followed initiation of directional drilling methods (see the The 11 March 1933 M_w 6.4 Long Beach Earthquake (22) and the Huntington Beach Oil Field section)	P

Last column indicates evidence for association with oil production activities: N, none; P, possible; L, likely; and U, uncertain.

to different questions. Dengler and Dewey (1998) showed that CDI values for modern earthquakes are consistent with traditionally assigned MMI values but are characterized by lower scatter. To estimate CDI, the DYFI system calculates a value from each questionnaire and then calculates an average of all values within a given ZIP code. DYFI intensities are therefore representative estimates within a given spatial footprint.

Although CDI values reflect representative shaking levels, traditionally determined MMI values assessed from archival accounts tend to track the most dramatic effects (Hough, 2013, 2014a). For the 1920 event, intensities are primarily determined from the detailed, scientific survey of Taber (1920), which does provide documentation of representative effects and allows the assessment of MMI values that can be compared directly with DYFI data. Notably, although high (MMI VII+) intensities for historical events are sometimes assigned based on fragmentary reports of nonrepresentative damage (Hough, 2013), Taber (1920) documents extensive damage to masonry

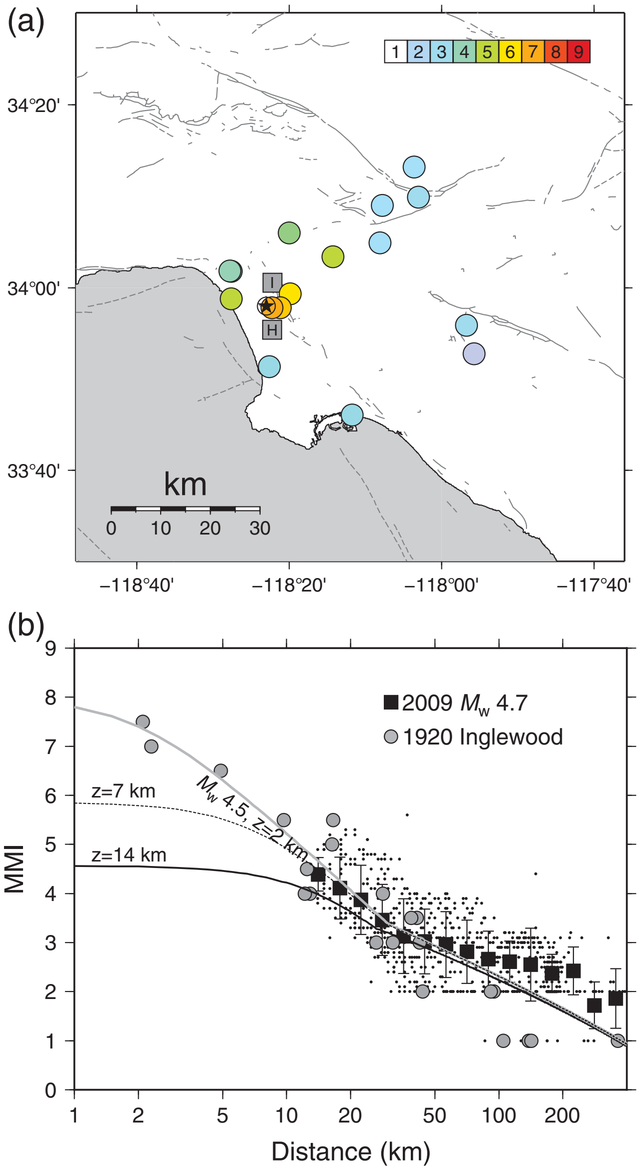

Figure 3. (a) Intensities from the 22 June the 1920 Inglewood earthquake, constrained at 22 separate locations (color scale indicated). Inferred epicenter (circled black star), and locations of early wells (gray squares) in Hawthorne (H) and Inglewood field (I). Faults are from Jennings (1994). (b) Intensities as a function of hypocentral distance for the 2009 M_w 4.7 Inglewood earthquake including average values within ZIP codes (small dots) and bin-averaged (±1 standard deviation) values (black squares). Intensities for the 1920 Inglewood earthquake (this study) are also shown (gray circles). The black line indicates predicted intensities using the intensity-prediction equation of Atkinson and Wald (2007) for M_w 4.7; thick gray and dashed gray lines indicate predicted intensities using the same equation assuming M_w 4.5 and depths of 2 and 7 km. MMI, modified Mercalli intensity.

buildings and chimneys in the presumed epicentral area near central Inglewood. To compare with DYFI data, it is necessary to estimate depth so that hypocentral distance can be calculated. We assume a very shallow depth (2 km), noting that a deeper assumed depth would serve to make the near-field intensities even more anomalous. The comparison of intensities from the two events (Fig. 3b) reveals that the intensity distribution for the 1920 event includes significantly higher near-field intensities and a smaller overall felt extent. The overall felt extent, which might be difficult to establish for most historical earthquakes, is also reliable in light of the focused field investigation by Taber (1920), which documents explicitly the extent of the felt area.

CDI values from the DYFI system are fit by intensity prediction relationships that include a nonlinear magnitude term as well as a piecewise distance decay

$$\mathrm{CDI}(M,R) = d_1 + d_2(M-6) + d_3(M-6)^2 + d_4\log(R) + d_5R + d_6B + d_7M\log(R),$$

in which $R = \mathrm{sqrt}(D^2 + h^2)$, and

$$B = 0 \quad \text{for } D \le D_t;$$
$$B = \log(D/D_t), \qquad D > D_t, \tag{1}$$

(Gasperini, 2001; Atkinson and Wald, 2007, hereafter, AW07), in which d_1–d_7 are constants (12.27, 2.27, 0.1304, −1.30, −0.0007070, 1.95, and −0.577, respectively), M is the magnitude, R is the hypocentral distance, and D_t is a transition distance that AW07 estimates to be 30 km for California earthquakes. The parameter D is defined to be the nearest distance to the fault, which in theory is equivalent to hypocentral distance for small to moderate events. The parameter h is introduced to stabilize the inversion and can be regarded as an effective depth.

Assuming the intensity-prediction equation from AW07, estimated intensities for the 1920 event are consistent with a magnitude of 4.5 and an extremely shallow depth (2 km, Fig. 3b). The intensity pattern for this event is clearly different from that of the deeper 2009 Inglewood earthquake, which had a roughly comparable magnitude. Although few earthquakes are observed at such shallow depths, a photograph included in Taber (1920) shows a "small ridge made by the fault," running through what appears to be a flat floodplain, suggesting that the modest event might have generated minor surface rupture, or at a minimum been especially shallow. It is moreover possible that the moment magnitude of the earthquake was larger than an estimate based on intensities, which reflect high-frequency ground motions. Hough (2014b) shows that induced earthquakes in Oklahoma give rise to intensity distributions commensurate with magnitudes on average 0.8 units lower than instrumentally determined moment magnitude estimates, which suggests that the stress drops of induced earthquakes are on average a factor of 3 lower than stress drops of tectonic earthquakes (Hanks and Johnston, 1992; Hough, 2014b). This result has subsequently been supported by analysis of instrumental data (e.g., Boyd *et al.*, 2015). As noted by Richter (1970), the degree to which the event was recorded at distant stations, including Berkeley, is consistent with a magnitude near 5. The M_w 4.9 UCERF catalog estimate, presumably taken from the M_L 4.9 estimate of Richter (1970) is thus not unreasonable. We suggest that, in light of the uncertainties, M_w 5 is a reasonable estimate for this event. There is compelling evidence for an especially shallow source depth, and perhaps some evidence (i.e., low effective intensity magnitude relative to M_w; Hanks and Johnston, 1992; Hough, 2014b) suggesting a low stress drop.

Oil was first discovered in the Inglewood oil field in 1924, but some drilling activity was reported before 1920 (Testa, 2007). In the Inglewood field, a total of six test wells were drilled starting in August 1916. The initial well was drilled to a depth of 4500 ft; a second well, drilled in 1919 to a depth of 5010 ft, found only a small amount of heavy oil and was abandoned (Testa, 2007). At the time, these wells were unusually deep: as of 1919, the average depth of U.S. oil wells was 2000–2500 ft (Williamson *et al.*, 1963); by 1930 it was slightly above 3000 ft. Testa (2007) states without attribution that two wells drilled near the extreme northwest edge of the field, near the town of Culver City, hit methane gas in 1920. The first successful oil discovery came 4 years later, in late September 1924. Testa (2007) cites Huguenin (1926) as a reference for the early unsuccessful wells as well as the history after 1924, but provides no citation for the discovery of gas in 1920 or development of the field between 1920 and 1924, which Huguenin (1926) does not mention. The dates of oil strikes are generally well known because they were, as a rule, conspicuous events. The timing of gas strikes was not generally as well documented.

Industry activities were documented in the monthly "California Oil Fields: Summary of Operations" (COF) reports that were published starting in 1919 by the State. These reports documented drilling permit approvals in addition to reported well abandonments, as well as other data. Well locations are identified using the Public Land Survey System, in which locations are specified by township, range, and section. Each township and range corresponds to a 6 by 6 mile square which is divided into 36 sections, each 1 mile (1.6 km) square. Well locations can thus be located to within ~1 km. In January 1920 (COF, 1920a), Standard Oil abandoned well number "Cienega" 1 within T2S, R14W, S9, and received approval for a new well, "Cienega" 2, within T2S, R14W, S8 (34.0096° N, 118.3701° W; Fig. 3a). In May 1920 (COF, 1920b), Duplex Oil received approval to drill within T2S, R14W, S18 (33.9961° N, 118.3875° W); records indicate an expected oil or gas–sand layer at about 2000 ft. These well locations correspond to the locations mentioned by Testa (2007), providing corroboration for the statement that natural gas was struck in Inglewood in 1920, likely by May of that year.

South of the city of Inglewood, the Milwaukee Foundation Trust Corporation struck oil near the city of Hawthorne in mid-August 1920; according to an article in the Los Angeles Herald, natural gas had been encountered at the same well "several weeks" earlier (*Los Angeles Herald*, 13 August 1920). In August 1920, the Milwaukee Foundation Trust Corporation had received approval to re-drill a well at T3S, R14W, S8 (33.9236° N, 118.3706° W; Fig. 3a) after earlier encountering gas in the same well (COF, 1920d). The precise date of the initial strike was not reported; the well had been permitted in October 1919 (COF, 1919).

Archival records are thus inconclusive, but suggest that early wells first struck methane gas reserves by May 1920 in the Inglewood field, that is, about a month before the 22 June 1920 Inglewood earthquake. It is further possible that methane gas was struck in the Hawthorne area by this time as well. At a minimum, drilling to depths of 4500–5000 at both wells predated the earthquake. The Hawthorne and Inglewood wells were both within about 5 km of the inferred epicenter of the 1920 event (Fig. 3a).

The 6 December 1923 Santa Fe Springs Event (10)

Limited information is available for this event, which occurred at ~12:57 p.m. (LT). Mild shaking was reported over a wide area, "from the ocean inland to Whittier and beyond" (*Riverside Daily Press*, 7 December 1923). Reported damage was limited to oil field reports indicating that an oil derrick had been wrecked by the tremor. Although it is not possible to map the intensity distribution in detail, available reports, including the overall distribution of accounts as well as the account of the wrecked derrick, suggest that the earthquake was quite shallow and centered near Santa Fe Springs. It is not possible to estimate a magnitude from available intensity data for this event and other small events considered below, but one can estimate an approximate magnitude by comparing the documented overall felt extent with data from the DYFI system. These data provide an indication of the distance to which small earthquakes are generally felt (see Fig. 2), discounting probably spurious reports from large distances (Boatwright and Phillips, 2013). In general, DYFI data reveal that earthquakes are generally felt at CDI 2.5 and above. For the 1923 Santa Fe Springs earthquake, a reported felt radius of at least 30 km suggests a magnitude of ~3.5. Though we cannot know the extent of the damage, the fact that such a modest event "wrecked" an oil derrick suggests that it was shallow and located very close to the Santa Fe Springs oil field, discussed in the following section.

The 8 July 1929 Whittier Earthquake (16) and the Santa Fe Springs Oil Field

A series of earthquakes near and to the south of Whittier began in late October 1927, with subsequent events in December 1928 and May 1929, and a damaging earthquake at 8:46 a.m. on 8 July 1929. The 8 July earthquake was investigated by Wood and Richter (1931), who considered both macroseismic effects and early instrumental data from Wood–Anderson instruments in operation at Pasadena, Mount Wilson, Riverside, and La Jolla, as well as three recordings from regional distances (Berkeley, Stanford, and Tucson). Macroseismic effects were mapped in detail via direct field surveys undertaken by Charles Richter and his colleagues, including Perry Byerly, on 8 and 9 July, who assigned RF intensities at 95 specific locations (Richter, 1929; see Data and Resources). Following Richter's unpublished notes, we retrace his route and assign 71 MMI values for locations that can be determined from the descriptions provided (see Ⓔ Table S3). The most severe effects, estimated to be commensurate with RF VIII, included substantial damage to brick buildings, damage to single-family homes, broken chimneys, disarranged furniture, broken small objects, broken flanges on oil towers, and broken plaster (Wood and Richter, 1931). A state hospital in a then-remote part of Norwalk, described as being of "substantial construction" sustained significant damage, with several chimneys dislodged and four concrete arches cracked (Richter, 1929; see Data and Resources). The most severe documented effects, including two houses shifted on their foundations and severed water and gas mains, are consistent with MMI VIII. We also revisit Weather Service accounts summarized in the United States Earthquakes report for 1929 (Heck and Bodle, 1931) as well as other summary accounts and assign intensities for an additional 56 locations (see Ⓔ Table S4). The resulting intensity distribution is shown in Figure 4.

For this event, macroseismic effects do not point unambiguously to a precise epicentral location or depth. Considering both macroseismic and early instrumental data, Wood and Richter (1931) infer an epicentral location of 33.913° N, 118.04° W (Fig. 4a), with an estimated, presumably poorly resolved depth of 13 km. Wood and Richter (1931) note that the field data indicate a "shallow origin." As illustrated in Figure 4a, detailed macroseismic observations suggest a location several kilometers to the north-northeast: 33.945° N, 118.031° W. Using the Bakun and Wentworth (1997) method with the intensity-prediction equation developed by Bakun (2006) yields an optimal location of 33.927° N, 118.043° W, with an estimated effective intensity magnitude of 4.3, lower than the UCERF catalog magnitude of M_w 4.7. This location is very close to the one inferred from our subjective consideration of the intensity distribution. The inferred effective intensity magnitude does not change significantly if the location is fixed to either the epicenter estimated by Wood and Richter (1931) or that suggested by macroseismic observations.

A comparison of the intensity distribution with that from the 1920 Inglewood event suggests that the Whittier event was somewhat larger and shallower but perhaps not as shallow as the Inglewood event. The intensity distribution for the 1929 event can also be compared with DYFI data from the M_w 5.1 La Habra earthquake on 29 March 2014, which occurred at a relatively shallow reported depth of 5.1 km (Fig. 4b). The latter event was much more widely felt but caused less severe effects in the immediate epicentral region, suggesting that the 1929 earthquake was shallower than the La Habra earthquake. (The extent of the felt area for the 1929 event is well constrained by not-felt reports documented by Heck and Bodle, 1931.)

The 1929 event was within a few kilometers of the Santa Fe Springs oil field (Fig. 4a). The Santa Fe Springs oil field was one of the top oil-producing fields in the region during the 1920s (Case, 1923; Yerkes *et al.*, 1965). As summarized by Yerkes *et al.* (1965), the first oil-producing well was completed in early 1917, producing about 3000 barrels per day from about 4568 ft. Oil production at Santa Fe Springs peaked at 332,000 barrels per day in July 1923, at the time fully one-sixth of the total U.S. oil production and equal to nearly one-half of the entire production from Oklahoma (Case, 1923; Wright, 1987). Over 49 million barrels were pumped during the second half of 1923, with a peak production rate of 356,000 barrels per day in July 1923 (COF, 1920c, 1924). In January and February 1923, several wells in the field experienced blowouts when they encountered pressurized gas reserves; water-bearing layers were encountered by some of these wells as well (COF, 1923). The 6 December 1923 event was thus another likely shallow event that occurred in spatial and temporal proximity to notable industry activities.

By the end of 1923, daily production from 500 wells had declined to about 125,000 barrels per day, and by the end of 1926 production declined further (Fig. 5). The discovery of oil in deeper strata, 5856 ft in July 1928, sparked a second drilling boom. The Nordstrom zone was discovered by accident in September 1928 in a well that produced 5500 barrels per day plus 9 million cubic feet of natural gas. By December 1928, a total of 222 new wells were being drilled into this zone, and some older wells were deepened. In February 1929, the O'Connell zone was discovered at a depth of 6360 ft and, when completed, produced 1300 barrels of oil and 2000 barrels of water per day. Older wells were subsequently deepened into this zone and into the Clark zone, about 1000 ft below the O'Connell zone. During this subsequent boom, the daily production rate increased from about 58,000 barrels per day at the end of 1927 to about 212,000 barrels per day by the end of 1929. During the first half of 1929, production within the field totaled 33,048,873 barrels (COF, 1929; Fig. 5). Most of the production during 1929 was within two sections (5 and 6) of Township 3S, Range 11W (COF, 1929; Fig. 4a). The July 1929 Whittier earthquake thus occurred less than 5 months after the discovery of oil at depths exceeding 6000 ft, during a period when numerous wells were drilled or re-drilled to reach deeper production horizons than had previously been exploited. The earthquake also occurred shortly after production volume increased to a level comparable with that during the initial boom in 1923. Although the precise location of the 1929 event remains uncertain to several kilometers, inferred epicentral locations based on both early instrumental data (Wood and Richter, 1931) and macroseismic observations (this study) are within 3 km of the two sections where high-volume production wells were tightly concentrated (Fig. 4a). We further note that, as discussed by Wood and Richter (1931), other notable activity occurred in the same area prior to the 8 July 1929 event. Although we conclude that some of these events, including an earthquake on 8 October 1927, were not in the immediate Whittier area (see Ⓔ the electronic supplement), a series of events in early May 1929 was likely close to the epicenter of the July event. This earlier activity follows even more closely to the deepening of wells in the Santa Fe Springs.

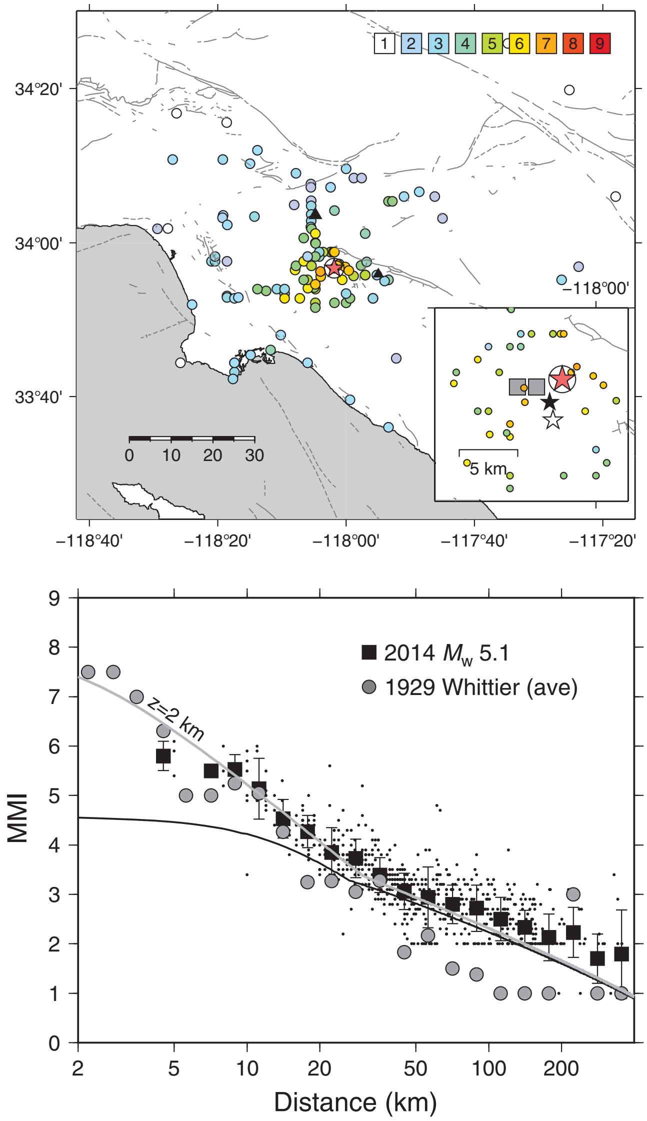

Figure 4. (a) Intensity distribution for the 8 July the 1929 Whittier earthquake constrained at 127 locations (color scale indicated). Open circles indicate locations where intensities are estimated; circled red star indicates preferred epicenter. Locations of the 1987 Whittier earthquake and the 2014 La Habra earthquake are also shown (large and small black triangles, respectively). Inset shows close-up view of intensities in the Whittier area (filled circles). Open star indicates location inferred by Wood and Richter (1931); circled red star and black star indicate locations suggested by macroseismic observations, respectively, and estimated from the method of Bakun and Wentworth (1997). Gray squares indicate location of sections within Township 3S, Range 11W. Faults are from Jennings (1994). (b) Intensities as functions of hypocentral distance for the 2014 M_w 5.1 La Habra earthquake including average values within ZIP codes (small dots) and bin-averaged (±1 standard deviation) values (black squares). Bin-averaged intensities for the 1929 Whittier earthquake (this study) are also shown (gray circles). The black line indicates predicted intensities using the intensity-prediction equation of Atkinson and Wald (2007) for M_w 4.7; the gray line indicates predicted intensities using the same equation assuming M_w 4.5 and a depth of 2 km.

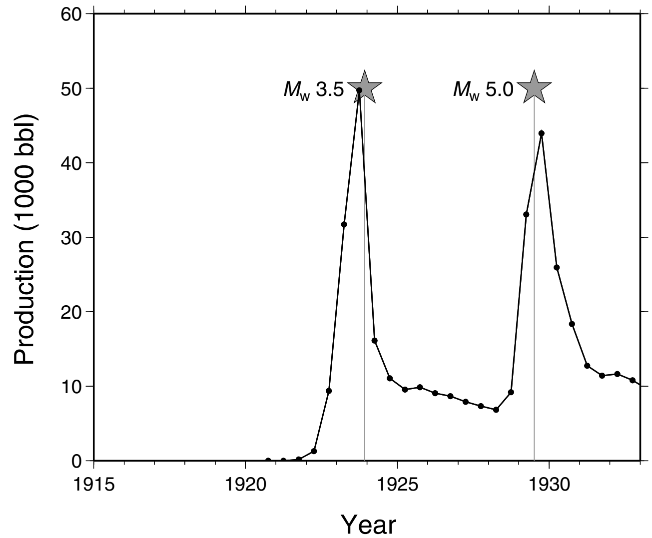

Figure 5. Production, as reported biannually, in 1000s of barrels (42 U.S. gallons, ~6.7 m^3) in Santa Fe Springs oil field between the discovery of the field and 1933 (black line and black dots), with times of December 1923 and July 1929 earthquakes indicated (gray stars).

The 30 August 1930 Earthquake near Santa Monica (14, 18) and the Playa Del Rey Field

The most notable earthquake in the greater Los Angeles region in 1930 occurred on the afternoon (LT) of 30 August 1930 (00:40 31 August [UTC]). The effects of this event are summarized by Neumann and Bodle (1932), with detailed analysis presented by Gutenberg *et al.* (1932); Hauksson and Saldivar (1986) later reconsidered the event. The *Los Angeles Times* (31 August 1930) reported that it was felt over a 75 mile (120 km) radius, with damage to chimneys and brick cornices in various parts of Los Angeles and coastal towns. The earthquake caused damage estimated at RF VIII in Venice and Santa Monica, as well as minor damage (cracks in buildings, damage to plaster) in downtown Los Angeles (Fig. 6; Neumann and Bodle, 1932). The earthquake was reportedly not felt in San Diego and was barely felt in San Bernardino and San Juan Capistrano (*Los Angeles Times*, 31 August 1930). Gutenberg *et al.* (1932) considered limited early instrumental data and estimated an epicenter at 33.95° N, 118.63° W. This location is ~10 km offshore of Santa Monica (Fig. 6). Reconsidering the instrumental data, Hauksson and Saldivar (1986) place the epicenter at 34.02° N, 118.63° W, ~10 km north of the location estimated by Gutenberg *et al.* (1932; Fig. 6). As discussed by Hauksson and Saldivar (1986), the phase picks for the event are inconsistently reported by extant records including original phase cards. The 10 km separation between the two instrumentally constrained locations provides an indication of uncertainty of the results.

In light of the ambiguity of the instrumental results, one can reconsider the intensity distribution, which can be characterized in some detail from the accounts in Neumann and Bodle (1932). A felt radius of ≈400 km implies a magnitude of $M_w \sim 5.4$. Relatively severe effects were documented in Los Angeles, including fallen plaster, minor cracks in buildings, and broken dishes; given the presence of relatively tall buildings, these effects are possibly attributed to relatively long-period ground motions. Along the coast, the strongest intensities were tightly concentrated (Fig. 6). Using the Bakun and Wentworth (1997) method, the optimal location is implausibly far north due to relatively high intensity values well inland to the north (34.1° N, 118.5° W). We instead fix the epicenter at 33.99° N, 118.5° W based on a visual assessment of the intensity distribution; for this assumed location, the magnitude estimate is 5.1 (Fig. 6). This location results in overall misfit to the intensity data that is over a factor of 2 lower than the misfit assuming either of the instrumental locations. We note that, although the epicenter clearly remains uncertain, there is evidence that the epicenter was closer to the coast than inferred by analysis of early instrumental data. Our preferred location is slightly offshore, with a high east–west uncertainty.

We note that, although the intensity distribution for the 31 August 1930 Santa Monica event suggests a location close to the coast, more limited macroseismic data support the inferred offshore location for the earlier 4 August 1927 earthquake (Townley and Allen, 1939). This event was felt quite noticeably ~80 km to the west in Ventura despite its early morning (04:24 a.m.) origin time. It was also recorded instrumentally as far away as Toronto and Ottawa, Canada. The absence of reported damage in Los Angeles area beach towns or elsewhere suggests that the location was indeed offshore. The catalog magnitude estimate M_w 5.0, although highly uncertain, is reasonable in light of the fact that the event was recorded at regional distances. Given the felt radius on the order of 400 km, it is possible that the event was larger and somewhat farther offshore.

The 1930 earthquake occurred close to the Playa del Rey oil field. The Playa del Rey (Venice) oil field (Fig. 1) was discovered in December 1929 when the Ohio Oil company struck oil near the town of Venice at a depth of 6199 ft (COF, 1930a). Oil exploration activities throughout the Los Angeles basin waned with the start of the Great Depression in the fall of 1929. According to Huguenin (1932) and COF (1930c), one of a few outstanding activities of 1930 within the Los Angeles District was the development of the Playa del Rey field (Barnds, 1968). The annual California Oil Field report for 1929 (COF, 1930a) lists low production (25,121 barrels) from this field for the latter 6 months of 1929 but shows approval to drill 20 new wells within T2S, R15W, S21 (33.97° N, 118.46° W; Fig. 6). Within a year, there were 50 oil-producing wells in the field (COF, 1930b). Production totaled 264,832 and 4,201,871 barrels during the first and second halves of 1930 (COF, 1930b), respectively. The location of this field is shown in Figure 6. The 31 August 1930 Santa Monica earthquake thus occurred just as production rates increased sharply, with exploitation of deeper than average production horizons (Williamson *et al.*, 1963). The location of this event is not well constrained, with limited early instrumental data suggesting a location farther offshore (Gutenberg *et al.*, 1932; Hauksson and Saldivar, 1986) than suggested by macroseismic data. In any case, the event was no farther than 15 km from the concentration of new production wells in the Playa del Rey oil field; there is some evidence that the event was closer to the field.

The 11 March 1933 M_w 6.4 Long Beach Earthquake (22) and the Huntington Beach Oil Field

The moderately strong earthquake that struck the Long Beach area on 11 March 1933 caused substantial damage to masonry structures and has been investigated by many subsequent studies. Analyzing regional and teleseismic data, Hauksson and Gross (1991) estimate M_w 6.4 and a hypocentral depth of 13 km for the mainshock, which they note is relatively deep for events in the region. Aftershock locations, though generally not well constrained, are scattered over a depth range of 0–20 km. The relocated epicenter is toward the southern end of the inferred mainshock rupture (33.665° N, 117.975° W), near the town of Huntington Beach (Fig. 7). Earlier studies (Hileman *et al.*, 1973; Hutton *et al.*, 2010) located the epicenter at essentially the same latitude, but just offshore. Hauksson and Gross (1991) suggest that location uncertainties are likely on the order of 2–4 km and larger in an east–west direction than north–south. The rupture is inferred to have propagated 13–16 km unilaterally to the northwest along the NI fault.

The intensity distribution of the M_w 6.4 Long Beach earthquake was documented in considerable detail; intensities for 234 locations are available in the NOAA database. Although a reconsideration of original archival sources should ideally be taken for analysis of any historical earthquake, in this case the original intensity data reveal more spatial detail than would be possible to image from traditional archival sources such as newspaper accounts (Fig. 7).

Unlike the 1920 Inglewood and 1929 Whittier earthquakes, intensities for the 1933 Long Beach earthquake are not estimated by the authors based on detailed field surveys and are not expected to be comparable with DYFI intensities (Hough, 2013). To analyze further the intensity distribution for the 1933 earthquake, we therefore use the correction curve approach introduced by Hough (2014a) to allow direct comparison of traditional MMI and CDI values. This approach exploits the separately developed intensity-prediction equations for CDI (discussed above) and for traditional MMI (e.g., Bakun and Wentworth, 1997), typically of the form

$$\mathrm{MMI_T}(M_\mathrm{I}, D) = C_0 + C_1 M_\mathrm{I} + C_2 D + C_3 \log(D), \quad (2)$$

in which M_I is the intensity magnitude, $\mathrm{MMI_T}$ denotes intensities assigned using traditional practice from written (media)

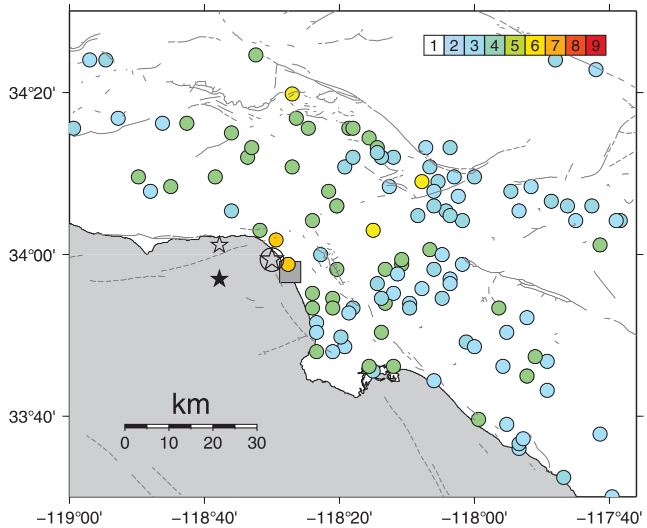

Figure 6. Intensities within the Los Angeles basin of the 31 August 1930 Santa Monica earthquake (color scale indicated). Proposed epicentral locations from Gutenberg *et al.* (1932) (black star), Hauksson and Saldivar (1986) (small open star), and this study (circled black star). Gray square indicates location where initial production was concentrated in the Playa Del Rey (Venice) oil field. Faults are from Jennings (1994).

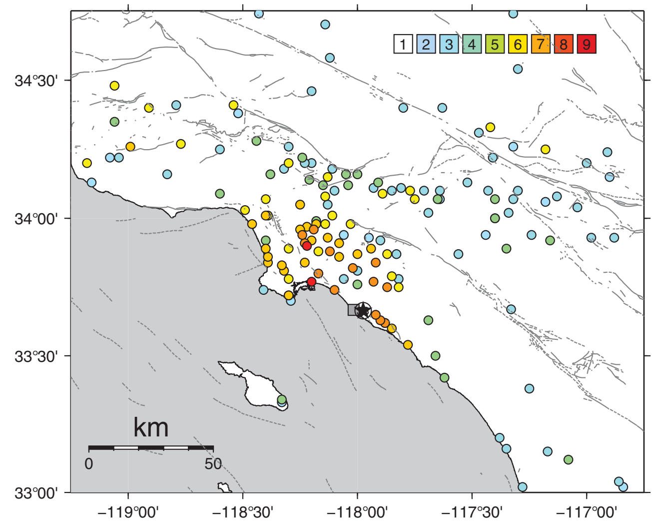

Figure 7. Intensity distribution for the 1933 Long Beach earthquake (intensity color scale indicated). Circled black star indicates location inferred by Hauksson and Gross (1991). Gray square indicates location of Number "Jones" 1 well. Faults are from Jennings (1994).

accounts, D is the hypocentral epicentral distance, C_0 and C_1 are constants related to the scaling of $\mathrm{MMI_T}$ with magnitude, and C_2 and C_3 are constants that can be associated with attenuation and geometric spreading, respectively. In this study, we use the constants determined by Bakun (2006) for southern California, which uses calibration events in northern as well as southern California: $C_0 = 1.64$, $C_1 = 1.41$, $C_2 = -0.00526$, and $C_3 = -2.63$.

As discussed by Hough (2014a), the functional forms of equations (1) and (2) differ, giving rise to systematic differences in predicted intensity values at different distances. Using the constants determined by Bakun (2006) and AW07 for California earthquakes (assuming an average depth of 14 km for the AW07 relation), relative to equation (1), equation (2) predicts higher intensities at close distances and lower intensities at distances greater than ≈300 km. The different functional forms of equations (1) and (2) suggest a simple empirical approach: the development of correction curves from the relationships that fit $\mathrm{MMI_T}$ distributions for historical earthquakes in a region and relationships that fit CDI distributions for modern earthquakes in the same region (Hough, 2014a). Correction curves for a given region are derived from the predicted difference in intensity values between equations (2) and (1), that is, $\mathrm{CDI}(M,R) - \mathrm{MMI_T}(M,R)$. Because equation (1) includes nonlinear magnitude dependence, these correction curves will be dependent on magnitude as well as distance. However, Hough (2014a) concluded that the magnitude dependence is weak. These curves can then be used to estimate equivalent CDI values for a given $\mathrm{MMI_T}$ data set (denoted by $\mathrm{MMI_{cC}}$). For predicted intensity values below 1.0, $\mathrm{MMI_{cC}}$ is set to 1 identically, mimicking the (DYFI) practice of assigning MMI = 1 for a "not felt" account.

Applying the correction curve approach to intensities for the Long Beach earthquake yields the results shown in Figure 8b. Estimated $\mathrm{MMI_T}$ values are consistent with predictions from the AW07 relationship given an instrumentally determined magnitude of 6.4, suggesting an average stress drop (Hough, 2014b). A typical stress drop estimate of 44–76 bars was also inferred from available instrumental data (Hauksson and Gross, 1991). Both available macroseismic and instrumental data are thus generally consistent with expectations for a tectonic M_w 6.4 earthquake.

Events preceding the 1933 mainshock also bear mentioning. The catalog includes only a single recorded foreshock on 9 March 1933. Richter (1958), however, noted that there was a slight general increase in the number of felt events in the Los Angeles region during 1932. He further noted that so many small shocks were felt at Huntington Beach that local resident Martin Murray set up a homemade seismograph to record them. Murray, an amateur scientist and instrumentalist of some renown (Gleason, 1936), corresponded with Harry Wood and Charles Richter from April 1932 through January 1935, exchanging information and sometimes recordings and making an appointment to meet in person in May 1932 (Wood, 1932). Correspondence between May 1932 and April 1933 is missing from what appears to be an otherwise complete file of mail correspondence following an initial letter in April 1932. Attempts to locate this correspondence have not been successful. However, a 1933 Popular Science article "Observatory Built of Junk" notes that Murray had noticed an increase in the number of tremors in December 1932 and that his instrument recorded 14 shocks between 16 and 26 December 1932. The

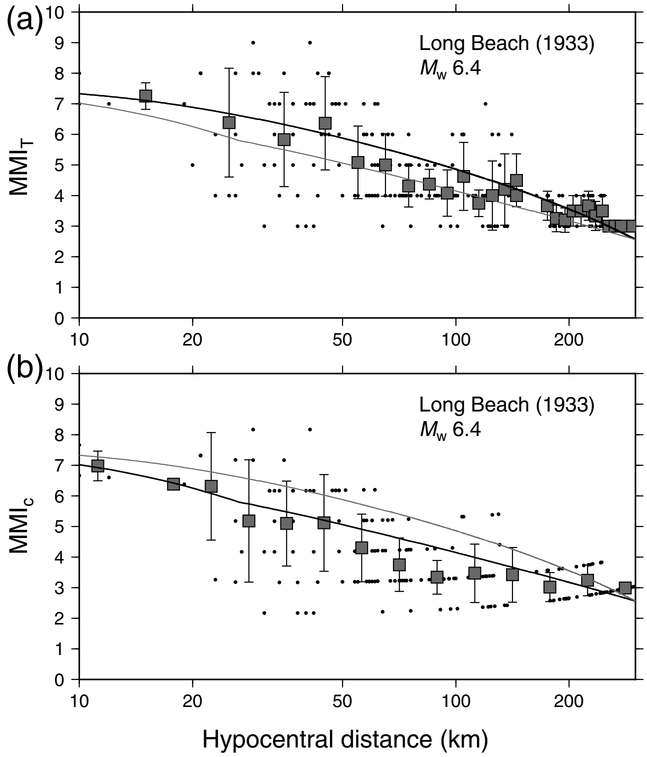

Figure 8. (a) Traditional intensities (MMI_T) for the 1933 Long Beach earthquake (black dots), bin-averaged values (gray squares), and predicted MMI using the intensity-prediction equations of Bakun (2006) (black line) and Atkinson and Wald (2007) (gray line) for M_w 6.4. (b) Estimated MMI_c values using correction-curve approach (black dots and gray squares), predicted intensities using Atkinson and Wald, (2007, referred to as AW07) relationship for M_w 6.4 assuming a depth of 14 km (black line) and Bakun (2006) relation (gray line).

southern California catalog includes no earthquakes during this period, indicating that the events recorded by Murray's instrument must have been small, local events. The account of Richter (1958) suggests that the upswing in earthquakes that were felt during 1932 at Huntington Beach was notable; catalog locations reveal event locations that were distributed around the Los Angeles region. It is not clear whether there was also an increase in the rate of small events near Huntington Beach earlier than December. The United States Earthquakes Report does list three small shocks felt at Huntington Beach during July–August 1931 (Neumann, 1932; see Ⓔ Table S1).

The preferred epicenter of the 1933 earthquake is within the Huntington Beach oil field (Fig. 1). The earliest oil discovery along the NISZ, as now recognized, was at Huntington Beach, where the Huntington A number 1 well produced 70 barrels per day in June 1920. By the end of 1920, a second nearby well came in at 2000 barrels per day (Wright, 1987). The epicenter of the 1933 Long Beach earthquake lies within the Huntington Beach oil field. By 1930 the initial boom along the NISZ had subsided, with a good well producing several hundred barrels per day (Wright, 1987). The one notable operation in Huntington Beach during 1932 was the Superior Oil Company Number "Jones" 1 well (COF, 1933). The Number "Jones" 1 well, north of Ocean Avenue and 22nd Street (33.6672° N, 118.0159° W; Fig. 7), had been originally completed on 30 July 1926 (COF, 1942). Redrilling began in September 1930; drilling was suspended for 21 months after cementing a so-called water string (a length of casing cemented into a well to shut off water when a water-bearing layer is encountered) at 3395 ft. Operations resumed in June 1932, and the well was completed on 29 June, producing at a rate of 329 barrels per day from an interval between 3695 and 4185 ft (COF, 1942). This production rate greatly exceeded production in neighboring wells, creating what is described (COF, 1942) as a then "general belief" that the wells had tapped into an offshore reserve. This well effectively marked the start of the so-called directional drilling; other directional wells soon followed, with the greatest horizontal drift in excess of 1400 ft (COF, 1942). After it became clear that wells had indeed trespassed laterally into State-owned tidelands, the State obtained an injunction in September 1933 to halt further operations (COF, 1942). The State Lands Act, approved on 24 March 1938, set the stage for further orderly development of offshore reserves.

In addition to the initiation of directional drilling, there was a notable deepening of wells in the Huntington Beach oil field starting in 1931. According to the State reports (COF, 1932a, pp. 18), "The only operation of major interest in 1931 was the search for deeper production horizons" in the Huntington Beach oil field. By 1932, wells were deepened in the Long Beach field as well; at one point, the deepest well in the world, reaching a depth of over 8000 ft, was within this field (COF, 1932b).

Thus, although oil drilling in the Huntington Beach oil field had been underway for over a decade by the time the 1933 Long Beach earthquake occurred, the event occurred less than 9 months after directional drilling first extended into offshore tideland reserves, reaching depths of over 4000 ft. The substantial water-bearing layer encountered by the "Jones" 1 well in September 1930 could have been an active fault strand. The epicenter estimated by Hauksson and Gross (1991) is within about 4 km of the well in question (with a ±4 km east–west uncertainty in epicenter; Fig. 7). There is, moreover, evidence that a dramatic increase in the rate of small locally felt events began in proximity to the eventual epicenter in the months prior to the mainshock, notably in December 1932, and possibly earlier that year (Richter, 1958). This increase in small local events thus began less than 6 months following the first exploitation of offshore reserves. The Long Beach earthquake also occurred following the exploitation of notably deep production horizons.

Correspondence between Earthquake Rates and Industry Activities

Returning to the list of 22 events in Table 1, and discounting four small events for which locations are especially uncertain (events 1, 4, 8, and 9), there is possible or likely association between 13 of the remaining 18 events and industry activities. Although some of the associations are more tentative than others, and the assessment of likely versus possible is subjective, we presented evidence that there is a possible or likely association between the four damaging events (7, 16, 18, and 22) and industry activities.

It is difficult to test the statistical significance of the correspondence between earthquakes and oil fields because of the close correspondence between oil fields and faults (Hauksson *et al.*, 2015). In addition to the investigation of individual events, we can also consider available industry data to explore whether there is evidence for a general correspondence between industry activity and earthquakes. For this analysis, we consider the total oil production for Los Angeles fields as reported by California Oil Field Reports between 1919 and 1933. The comparison of (cumulative) oil production and earthquake rates is shown in Figure 9.

As an initial observation, we note that few felt events were documented in the Los Angeles basin before 1915, whereas over 300 felt events were reported between 1915 and the end of 1932 (see Ⓔ Table S1). Given that the *Los Angeles Herald* and *Los Angeles Times* began daily publication before 1900, with the population of the county reaching 150,000 by 1915, it is unlikely that significant events were missed before 1915. Considering the expected felt extent of small events (Fig. 2), we conclude that events as small as M_w 2.5 could have been felt by 1900, and events as small as M_w 3.0 would have probably been felt. Considering recent DYFI data, it is highly unlikely that an event of M_w 4 or larger within the Los Angeles basin would have been missed after 1900. We consider cumulative moment release rather than the rate of felt events because the latter is more influenced by catalog incompleteness.

Figure 9 reveals that, fundamentally, both oil production and moment release increased between 1900 and 1932 (Fig. 9a). There is some further suggestion that notable increases in cumulative moment release coincided with increases in total production, with a tendency for larger earthquakes to occur shortly after periods of rapid increases in production volume (Fig. 9b). Although we cannot estimate cumulative moment release prior to 1900, we can compare activity between 1900 and 1932 with the rate of activity since 1933. The total cumulative moment release prior to 1933 is much lower than the total release from the start of 1933 through the present, a period that included the 1933 Long Beach, 1987 Whittier, and 2008 Chino Hills events. Within the study area, however, discounting immediate Long Beach aftershocks, only seven $M_w \geq 5$ events occurred between late 1933 and 2016, compared to four events with estimated M_w close to five between 1915 and December 1932. Our conclusion that the 1920 Inglewood, 1929 Whittier, 1930 Santa Monica, and 1933 Long Beach earthquakes were likely induced is based primarily on the spatial and temporal association with notable industry activities. The relatively high rate of moderate ($M_w \geq 5$) events during the initial oil boom between 1915 and 1932 provides an additional measure of evidence for our conclusion. We note that, though it is generally assumed that the Los Angeles basin has a high rate of natural tectonic earthquakes, if the damaging earthquakes analyzed in this study were in fact induced, our estimate of the rate of tectonic seismicity in this region might be inflated.

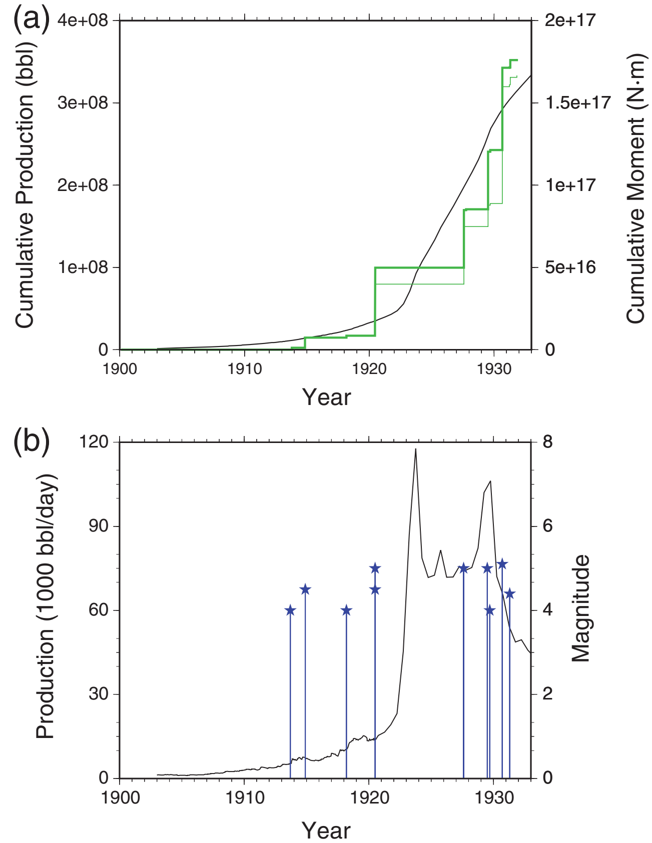

Figure 9. (a) Cumulative oil production (1000s of barrels) from Los Angeles area fields (black line; COF reports) and cumulative moment release (N·m) assuming magnitudes indicated in Table 1 (heavy green line) and from the Uniform California Earthquake Rupture Forecast v. 3 (UCERF3) catalog (light green line). (b) Incremental oil production from Los Angeles area fields (black line) versus earthquake activity (blue lines and stars).

In addition to the spatial and temporal association between events analyzed in this study and notable industry activities, we presented evidence from macroseismic observations suggesting that both the 1920 Inglewood and 1929 Whittier earthquakes were unusually shallow and probably low-stress-drop events. Both events thus seem to show characteristics similar to those proposed by Hough (2014b) for fluid-injection-induced earthquakes in the central United States.

In contrast to the observations from the 1920 and 1929 events, instrumental and macroseismic data suggest that source properties of the 1933 Long Beach earthquake, including depth and stress drop, were consistent with expectations for a typical tectonic event. The event nucleated within the Huntington Beach oil field, which had a total oil production of nearly 4 million barrels in 1932 (Bush, 1933). As discussed here, the epicenter is moreover within about 4 km of the first directional well drilled in the field, which struck oil at a depth of ~4000 ft in late June 1932, having 21 months earlier encountered a water-bearing layer at 3395 ft. Grant *et al.* (1997) conclude that the active strand of the NI fault is onshore. The fault zone is clearly complicated, however, with offshore branches suggested to extend south of Huntington Beach (Grant *et al.*, 1997). In any case, given the spatiotemporal correspondence between the epicenter and both the initiation of directional drilling and the initial exploitation of deeper production horizons, one cannot rule out the possibility of a connection between the Long Beach earthquake and industry activities.

Physical Mechanisms

One can further consider physical mechanisms that might plausibly account for induced earthquakes associated with production in the early twentieth century. We note that even with modern seismic and industry data, it remains unclear exactly what controls the rate of induced earthquakes, many of which are thought to be associated with wastewater injection, not production (e.g., Healy *et al.*, 1968). Different studies of injection-induced earthquakes have pointed to overall volume and rates of fluid withdrawal or injection (McGarr, 1991; Walsh and Zoback, 2015), proximity to high-rate injection wells (Weingarten *et al.*, 2015), and proximity of deep wells to fault zones (Zhang *et al.*, 2013; McNamara *et al.*, 2015; Walters *et al.*, 2015). Both injection-induced and hydraulic-fracturing-induced earthquakes have been plausibly attributed to poroelastic perturbations in proximity to pre-existing faults (e.g., Raleigh *et al.*, 1976; Baranova *et al.*, 1999; Segall and Lu, 2015), including elevation of fluid pressure leading to reduced effective normal stress (e.g., Raleigh *et al.*, 1976; Nicholson and Wesson, 1990; Zoback and Harjes, 1997; Skoumal *et al.*, 2015). It is therefore not surprising that there may be no single factor, such as production volume, that tracks earthquake activity induced by production.

In general, oil production is expected to reduce pore pressure on nearby faults; this will tend to inhibit failure assuming a standard Coulomb failure criteria. An observational association between induced earthquakes and production is, however, well established (Segall, 1989). In theory, production can potentially promote failure on nearby faults if the pore-pressure effect is blocked by an impermeable barrier, allowing the normal stress change (the undrained response) to dominate. Alternatively, McGarr (1991) proposed that several moderate events in California, including the 1987 M_w 5.9 Whittier earthquake, were induced by oil extraction, effectively as part of an isostatic adjustment process. The correspondence illustrated in Figure 5 for the Santa Fe Springs field suggests that total volume was an important factor for the 1923 Santa Fe Springs and 1929 Whittier earthquakes. To further explore the mechanism proposed by McGarr (1991), one can consider the total mass of fluid (including coproduced water) extraction during both 1923 and the first half of 1929. A standard U.S. barrel of oil contains 42 U.S. gallons; assuming that crude oil has a density of 790 kg/m^3, we estimate a total mass extraction of $\sim 10^{10}$ kg during 1923 and 0.5×10^{10} kg during the first 6 months of 1929. These totals are ~10% of the total mass extraction (1.35×10^{11} kg) that McGarr (1991) estimated in the Montebello field for the years 1924–1987. Following the calculation presented by McGarr (1991)—that is, assuming that the 1929 Whittier earthquake was induced by the same mechanism that he proposed, associated with production in the Santa Fe Springs field—a total seismic moment on the order of 10% of that of the 1987 Whittier earthquake would result from mass extraction prior to 1929. Given M_w 5.9 for the 1987 event, one estimates $M_w \approx 5.1$ for an event induced by mass extraction before July 1929. Although there is clearly not a one-to-one relationship between mass removal and earthquake magnitude, we conclude that the mechanism proposed by McGarr (1991) can plausibly account for the size and timing of the 1929 Whittier earthquake.

The mechanism proposed by McGarr (1991) is not, however, plausible for the 1920 Inglewood earthquake, given the low prior total production, or the Long Beach earthquake, given its strike-slip mechanism. We suggest that the 1920 earthquake was a moderate event that was induced by poroelastic perturbations close to an active fault and was locally damaging by virtue of an especially shallow source depth.

The fact that the source properties and ground motions for the 1933 Long Beach earthquake are consistent with expectations for a tectonic event, and the fact that the rupture extended beyond the confines of the Huntington Beach oil field, suggests that, if accepted as an induced event, it serves as an example of an earthquake that either nucleated because of human activities but grew into an event that released significant tectonic stress (e.g., Sumy *et al.*, 2014), or as an example of a tectonic earthquake triggered by an earlier induced event. In support of this triggering hypothesis, Richter (1958) stated that a foreshock of magnitude 4 was sharply felt at Huntington Beach at 01:13 a.m. LT on 9 March 1933. Hauksson and Gross (1991) estimate M_w 2.9 for this event, with a location within a few kilometers of the mainshock hypocenter. The fact that Richter (1958) estimated a significantly larger magnitude suggests that it was either bigger than 2.9 or especially shallow. Either way, a simple calculation supports Richter's designation of the 9 March event as a foreshock: the instantaneous rate of $M_w \geq 6.4$ aftershocks within 10 km of the 9 March event at the time of the Long Beach earthquake was 4.7×10^{-6}/day to 4.7×10^{-5}/day, if we assume that the 9 March event had a magnitude between 2.9 and 4.0 (Reasenberg and Jones, 1989). This is 80–800 times the background rate of $M_w \geq 6.4$ earthquakes in this area (5.7×10^{-8}/day, as given by UCERF3; Field *et al.*, 2013). Therefore, the 1933 Long Beach earthquake was perhaps triggered by a foreshock. Although there is insufficient information to investigate the foreshock event crudely, evidence presented in this study suggests that it may have been an induced event. Further investigation of the detailed structure of the NI fault in proximity to the epicenter of the 1933 earthquake might reveal whether or not there is an active fault strand just offshore the location, in a location that would have been disturbed by early directional drilling.

Although it is possible that the (inferred) induced earthquakes identified in this study were induced by different physical mechanisms, in most if not all cases the precise location of production wells appears to have been important, as evidenced by the spatial association between notable activity and the precise location of industry activity over the 6–12 preceding months. The depth of wells also emerges as a key factor. The timing of many if not most of the significant inferred induced earthquakes corresponds to times when wells were being significantly deepened. For example, the 1929 Whittier earthquake occurred about 5 months following the initial exploitation of production horizons at depths below 6000 ft, and the 1933 Long Beach earthquake occurred shortly after wells in the Huntington Beach oil field reached depths in excess of 8000 ft. Prior to 1920, production was almost entirely concentrated in the greater Whittier area, in the northeast quadrant of Figure 1. A progressive deepening of wells tapped into progressively deeper reserves, in this case resulting in increased production in both 1923 and 1929 (Fig. 5). Throughout the late 1920s and early 1930s, wells along the NISZ were progressively deepened as shallow reserves were progressively depleted; although the overall production did not necessarily increase as a result, the wells remained economically viable as deeper production horizons were tapped.

Conclusions

The results presented in this study suggest that several of the damaging early twentieth-century earthquakes in the Los Angeles basin may have been induced by oil and/or gas production. If so, then our results suggest that the total volume of fluid (oil and water) withdrawal may have been a factor in the occurrence of several of the earthquakes reviewed in this study, notably the 1923 and 1929 earthquakes near Whittier. Other factors may also have played roles, including proximity of wells to active faults and well depth. Although it is beyond the scope of this study, we note that several other damaging earthquakes, including the 1925 Santa Barbara, 1927 Ventura, and 1952 Kern County earthquakes also struck in regions where there was substantial oil production. A reconsideration of what caused these events might be worthwhile.

Our results contrast with the results of Hauksson *et al.* (2015), who found no evidence for an overall correlation between earthquake activity and injection or production in oil fields in the Los Angeles basin from 1935 to the present. The results of the present study suggest that, although overall production might contribute in some cases to the occurrence of induced earthquakes, the precise location and depth of wells is of paramount importance. Induced earthquakes did not occur commonly in the Los Angeles basin during the early twentieth century despite the enormous volume of oil production, and many large fields, including the Wilmington field, were associated with at most minor seismic activity. Our results thus suggest that detailed consideration of industry activities, including production volume and well locations, is critical for exploring a possible link between industry activities and earthquakes. It is further possible that significant induced earthquakes in the early twentieth century might have been associated with industry practices that are no longer employed, that is, production without water reinjection to balance pressure. (The so-called water-flooding recovery methods were first used in different fields at different times, beginning around the mid-twentieth century.) A better identification of induced and tectonic events would improve our characterization of background (tectonic) earthquake rates in the region. For example, within the study area shown in Figure 1, the 1933 Long Beach earthquake is the only $M_w > 6$ event since the start of the historical record, and, apart from the 1933 mainshock and large aftershocks, only seven $M_w > 5.0$ events have occurred in this area since 1900. It is thus possible that the estimated background rates of earthquakes within the Los Angeles basin has been influenced perceptibly by induced events. A detailed reconsideration of events after 1933 together with available industry data, that is, with consideration of specific industry activities in proximity to notable events, would be useful to explore the extent to which induced earthquakes contribute to the catalog.

Data and Resources

All "Did You Feel It?" data were downloaded from the U.S. Geological Survey website http://earthquake.usgs.gov/data/dyfi/ (last accessed October 2016). Monthly "California Oil Fields: Summary of Operations" published by the State Oil and Gas Supervisor are available from ftp://ftp.consrv.ca.gov/pub/oil/Summary_of_Operations (last accessed October 2016). C. F. Richter's unpublished field notes on the 1929 earthquake and private correspondence are available from the Caltech Archives (papers of C. F. Richter), Pasadena, California. The private correspondence of J. P. Buwalda is also available from the Caltech Archives (papers of J. P. Buwalda), Pasadena, California.

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