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Triggered Earthquakes and Deep Well Activities

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Abstract—Earthquakes can be triggered by any significant perturbation of the hydrologic regime. In areas where potentially active faults are already close to failure, the increased pore pressure resulting from fluid injection, or, alternatively, the massive extraction of fluid or gas, can induce sufficient stress and/or strain changes that, with time, can lead to sudden catastrophic failure in a major earthquake. Injection-induced earthquakes typically result from the reduction in frictional strength along preexisting, nearby faults caused by the increased formation fluid pressure. Earthquakes associated with production appear to respond to more complex mechanisms of subsidence, crustal unloading, and poroelastic changes in response to applied strains induced by the massive withdrawal of subsurface material. As each of these different types of triggered events can occur up to several years after well activities have begun (or even several years after all well activities have stopped), this suggests that the actual triggering process may be a very complex combination of effects, particularly if both fluid extraction and injection have taken place locally. To date, more than thirty cases of earthquakes triggered by well activities can be documented throughout the United States and Canada. Based on these case histories, it is evident that, owing to preexisting stress conditions in the upper crust, certain areas tend to have higher probabilities of exhibiting such induced seismicity.

Key words: Induced seismicity, triggered earthquakes, fluid injection, fluid extraction.

Introduction

The phenomena of earthquakes triggered by deep well activities are certainly not new or unusual. RICHTER (1958) discusses the effects of shallow "slump earthquakes" within the Wilmington oil field, California, near the Los Angeles harbor in the years 1947, 1949, 1951 and 1955. Although he did not specifically correlate the earthquakes to the extensive ground subsidence caused by the massive withdrawal of oil and gas from the field, he did note their spatial coincidence, and mentioned a series of similar triggered "slump earthquakes" in the Po Valley, Italy, attributed by CALOI *et al.* (1956) to the commercial extraction of methane gas. In the 1920s, a series of "slight earthquakes" was felt near the Goose Creek oil field in south Texas, where oil production there had caused the field to subside by as much as 1 m

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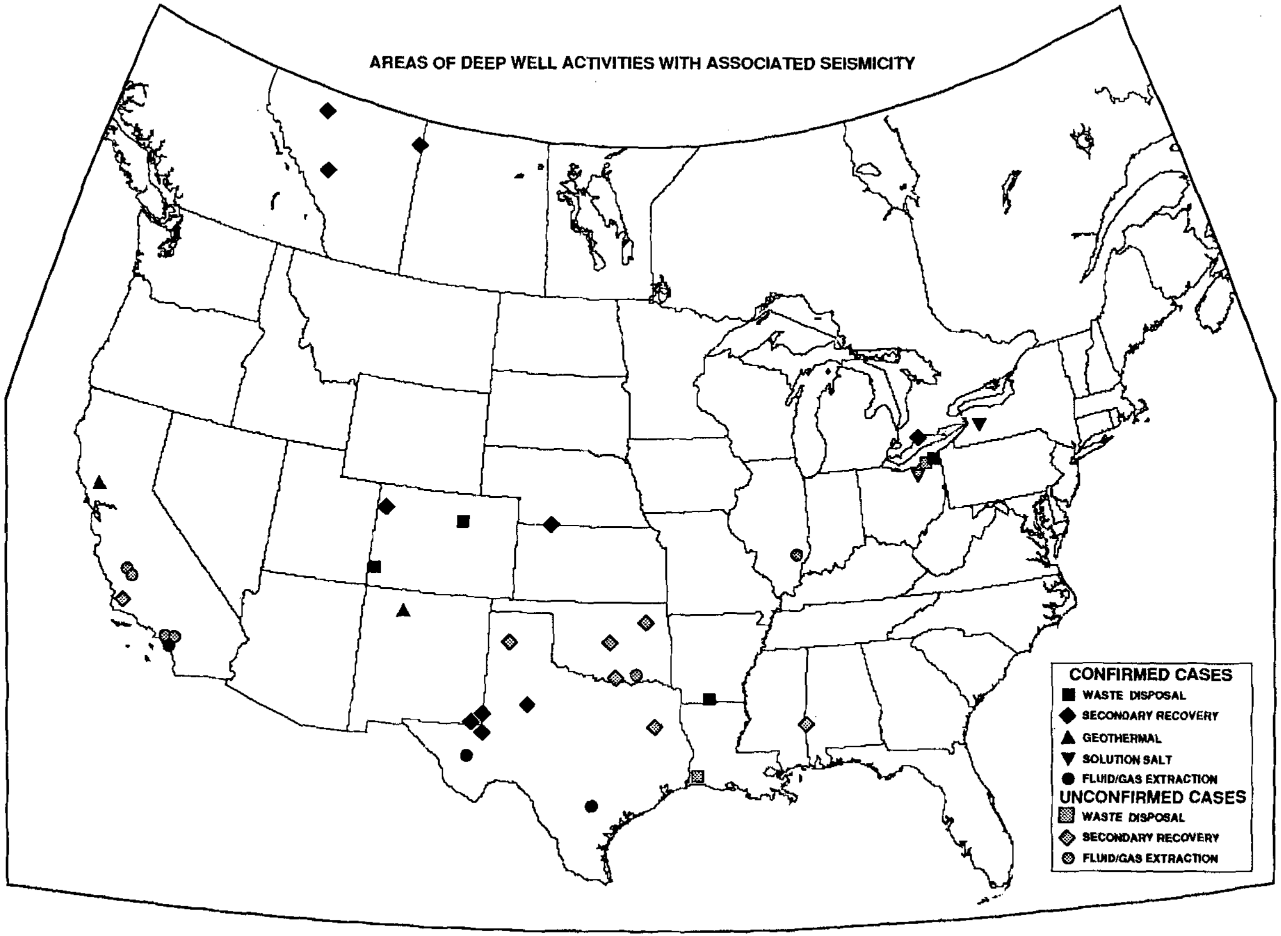

Figure 1

Sites of possible induced earthquakes that have occurred in close proximity to deep well activities. Symbol corresponds to predominant well operations at each site. Black symbols are sites that are either documented in the literature, or for which compelling evidence exists. Gray symbols are less well documented examples—for which, in many cases, only a simple spatial and temporal correlation exists.

between 1917 and 1925 (PRATT and JOHNSON, 1926; SEGALL, 1989). Similarly, the injection of fluid at relatively high pressures can also induce adjacent seismicity, if the area is already close to failure. Most of these cases of seismicity related to fluid injection are associated with either water-flood operations to enhance the secondary recovery of hydrocarbons, or with the commercial stimulation (i.e., hydraulic fracturing) of the well to increase fracture permeabilities (NICHOLSON and WESSON, 1990). There are, however, a few specific cases in which waste disposal by fluid injection has also induced adjacent seismicity, including the largest and probably the best known earthquake to have been triggered by fluid injection—a magnitude 5.5 earthquake near Denver, Colorado in 1967 (e.g., HEALY *et al.*, 1968).

In this paper, we survey a number of possible induced earthquakes related to adjacent deep well operations. Figure 1 shows locations within the United States and southern Canada where significant earthquakes have been known to occur in close proximity to active well sites. In many cases, the only available evidence is simply a coincidence in space and time between specific earthquakes and known or inferred well activities. Few of these examples are well documented because of potential liability concerns of the respective well operators. We thus expect that many cases of possible induced deformation largely go unreported, either because the induced earthquakes are small (or the deformation is aseismic, DAVIS and PENNINGTON, 1989), or the well activities are not generally publicized.

Case Histories

Earthquakes related to well activities typically fall into two major classifications. Those that are largely related to fluid injection and the resulting increased pore fluid pressure this may cause (e.g., HEALY *et al.*, 1968; RALEIGH *et al.*, 1976), or those that appear to have occurred in areas that have experienced massive withdrawals of subsurface fluid or gas (e.g., KOVACH, 1974; YERKES and CASTLE, 1976; PENNINGTON *et al.*, 1986; WETMILLER, 1986; SEGALL, 1989; DOSER *et al.*, 1991; MCGARR, 1991). Table 1 lists a number of well sites that may have triggered adjacent seismicity. Detailed summaries of many of these case histories can be found in NICHOLSON and WESSON (1990).

Although we make a distinction between earthquakes associated with fluid injection versus earthquakes associated with fluid (or gas) withdrawal, in many cases where documentation exists, both deep well activities (extraction and injection) have taken place locally (Table 1). The exceptions tend to be either waste disposal, geothermal or stimulation operations (for fluid injection), or cases in which oil or gas production clearly predominate (for fluid extraction). Most other cases of earthquakes related to deep well activities seem to occur in areas where prior production decreased local formation pore pressure sufficiently to necessitate the initiation of secondary recovery operations. In such cases, the determination of

Table 1

Possible and probable induced earthquakes associated with well operations

Well site or field location	Type of well operation	BHP* (bar)	Year production began–ended‡	ΔBHP† (bar)	Year injection began–ended	Max M_L	Year of earthquakes
Apollo-Hendrick, TX	production/secondary recovery	?	1926–	?	1973–	2.0	1978–79
Ashtabula, OH	waste disposal	191	N/A	+100	1986–	3.6	1987
Attica, NY??	solution salt mining	40?	1880's–	+50?	1880's–	5.2	1929–67
Coalinga, CA??	oil production	230	1905–	−120	1952, 1961	6.5	1983–85
Catoosa, OK	gas withdrawal?	?	1941–	?	?	4.7	1956–60
Chaveroo field, NM	secondary recovery	?	1967?–	?	1992–	?	1992–
Cleveland, OH?	solution salt mining	?	1889–	?	1889–	3.0?	1898–07
Cogdell field, TX	secondary recovery	215	1949–	−136, +217	1953, 1956–	4.6	1974–79
Cold Lake, Alberta	secondary recovery/waste disposal	?	?	?	?	~2.0	1984–
Dale, NY	solution salt mining	43	?	+55	1971?–	1.0	1971
Denver (RMA), CO	waste disposal	269	N/A	+72	1962–1966	5.5	1962–67
Dollarhide, TX-NM	secondary recovery	228	1945–, 1949–	−165, +135	1959–	3.5	1979?–
Dora Roberts, TX	secondary recovery	324	1955–	−48, +431	1961–	3.0	1964–
East Durant, OK	gas withdrawal	?	1958–	?	?	3.5	1968
East Texas, TX	production/secondary recovery	70	1930–	−103, +83	1942–	4.3	1957
El Dorado, AR	waste disposal	230?	early-1920's–	+60	1970–, 1983–	3.0	1983–91
El Reno, OK??	oil/gas withdrawal?	?	1910's–	?	?	5.2	1918–79
Fenton Hill, NM	geothermal/stimulation	265	N/A	+200	1979	<1.0	1979
Fashing field, TX	gas withdrawal	352	1958–	−281	N/A	4.2	1973–93
The Geysers, CA	geothermal	35	1966–	−18	1966–	4.0	1975–
Gobles field, Ontario	secondary recovery	45	1960–	?	1969–	2.8	1979–84
Goose Creek, TX	oil production	?	1917–1925	?	?	?	1920's

Hunt field, MS?	secondary recovery?	?	?	?	?	3.6	1976–78
Imogene field, TX	oil production	246	1944–	−100	N/A	3.9	1973–83
Inglewood field, CA?	production/secondary recovery	48?	1924–	−39, > +100	1954, 1957–	3.7	1962?–
Kettleman Hills, CA?	oil production	325	1928–, 1930–	?	1967–	6.1	1985
Kermit field, TX	secondary recovery	198	1950–	−185, +221	1958–, 1964–	4.4	1964–
Keystone I&II, TX	secondary recovery	204	1930–, 1943–	−100, +176	1962–, 1964–	3.5	1964?–
Lake Charles, LA?	waste disposal?	?	?	+93	?	3.8	1983–
Lambert field, TX	secondary recovery	145	1979–	−15, +21	1979–	3.4	1983–84
Love Co., OK	secondary recovery/stimulation	?	1953–	−?, +277	1965–, 1978–	2.8?	1977–79
Monahans, TX	secondary recovery	131	1961–	−185, +207	1965–	3.0	1965–
Montebello, CA??	oil production	?	1917–, 1938–	?	1953–	5.9	1987
Orcutt field, CA	stimulation/oil production	?	1901–, 1905–	−?, +183	1951–, 1991	3.5	1991
Paradise Valley, CO	brine disposal	?	N/A	?	late-1991	0.8	late-1991
Perry, OH	waste disposal	200	N/A	+114	1975–	2.7	1983–87
Rangely, CO	secondary recovery/research	170	1945–	−?, +120	1957–	3.1	1962–75
Richland Co., IL??	oil production	?	?	?	1952?–	4.9	1987
Sleepy Hollow, NE	secondary recovery	115	?	−?, +56	1966–	2.9	1977–84
Snipe Lake, Alberta	secondary recovery	?	1954–	?	1963–	5.1	1970
Strachan, Alberta	gas withdrawal	500?	1973–	−250	N/A	4.0	1974–
Tomahawk field, NM	brine disposal	?	1972?	?	?	?	
Ward-Estes, TX	secondary recovery	103	?	−?, +117	1961–	3.5	1964?–
Ward-South, TX	secondary recovery	76	?	−?, +138	1960–	3.0	1964?–
War-Wink, TX	gas withdrawal	800+	1965–	?	1967–, 1969–	3.0	1975–79
Wilmington, CA	oil production	?	1932–, 1937–	?	1953–	5.1	1947–61

* BHP—Bottom Hole Pressure—initial formation fluid pressure (in bars) at time of production or injection.

† ΔBHP—change in Bottom Hole Pressure relative to initial formation fluid pressure—maximum increase (+) or decrease (−) (in bars) during either injection (+) or extraction (−) operations.

‡ Multiple start years indicate dates when significant new production (or injection) began.

the actual earthquake trigger process, or the mechanism of strain localization that led to failure, is a much more difficult procedure. The fact that injection operations have taken place locally may be only incidental to the crustal readjustments or poroelastic strain changes that were triggered in response to the massive withdrawal of subsurface material (e.g., SEGALL, 1989). Here we attempt to present case histories that are sufficiently distinct such that some understanding of the dominant physical mechanism of the earthquake trigger process can be recognized.

Overview of Earthquakes Induced by Deep Well Fluid Injection

Documented examples of seismic activity induced by fluid injection include earthquakes triggered by waste injection near Denver (HEALY *et al.*, 1968) and in south-central Arkansas (COX, 1991); by secondary recovery of oil in Colarado (RALEIGH *et al.*, 1972), southern Nebraska (ROTHE and LUI, 1983), West Texas (HARDING, 1981; DAVIS, 1985; DAVIS and PENNINGTON, 1989), western Alberta (MILNE and BERRY, 1976), and southwestern Ontario (MEREU *et al.*, 1986); by solution mining for salt in western New York (FLETCHER and SYKES, 1977); and by fluid stimulation to enhance geothermal energy extraction in New Mexico (PEARSON, 1981). In one specific case near Rangely, Colorado (RALEIGH *et al.*, 1976), an experiment to control directly the behavior of large numbers of small earthquakes by manipulation of the fluid injection pressure was conducted successfully. Other cases of triggered seismicity, which were the result of either fluid injection or reservoir impoundment, were reviewed and discussed by SIMPSON (1986).

Of the well-documented cases of earthquakes related to fluid injection, most are associated with water-flood operations for the purpose of secondary recovery of hydrocarbons. This is because secondary recovery operations often entail large arrays of wells injecting fluids at high pressures into small confined reservoirs that have low permeabilities. Often, the producing field is a structural trap that may be defined by fault-controlled boundaries. In contrast, waste-disposal wells typically inject at lower pressures into large porous aquifers with high permeabilities that are away from known fault structures. This explains, in large part, why, of the many hazardous and nonhazardous waste-disposal wells in the United States, only three have ever been conclusively shown to be associated with triggering significant adjacent seismicity. These are wells located near Ashtabula, Ohio, El Dorado, Arkansas, and Denver, Colorado.

In the case near Ashtabula, a series of small shallow earthquakes was triggered close to the bottom of a 1.8-km deep well (RS#1, Figure 2); the largest of these was a magnitude 3.6 earthquake that occurred in 1987 (ARMBRUSTER *et al.*, 1987). The injection well had been in operation only since 1986, and typically operated at injection pressures of about 100 bars. Investigations of earlier earthquake activity in adjacent Lake County (Figure 2, top), indicated that injection pressures of 100 bars

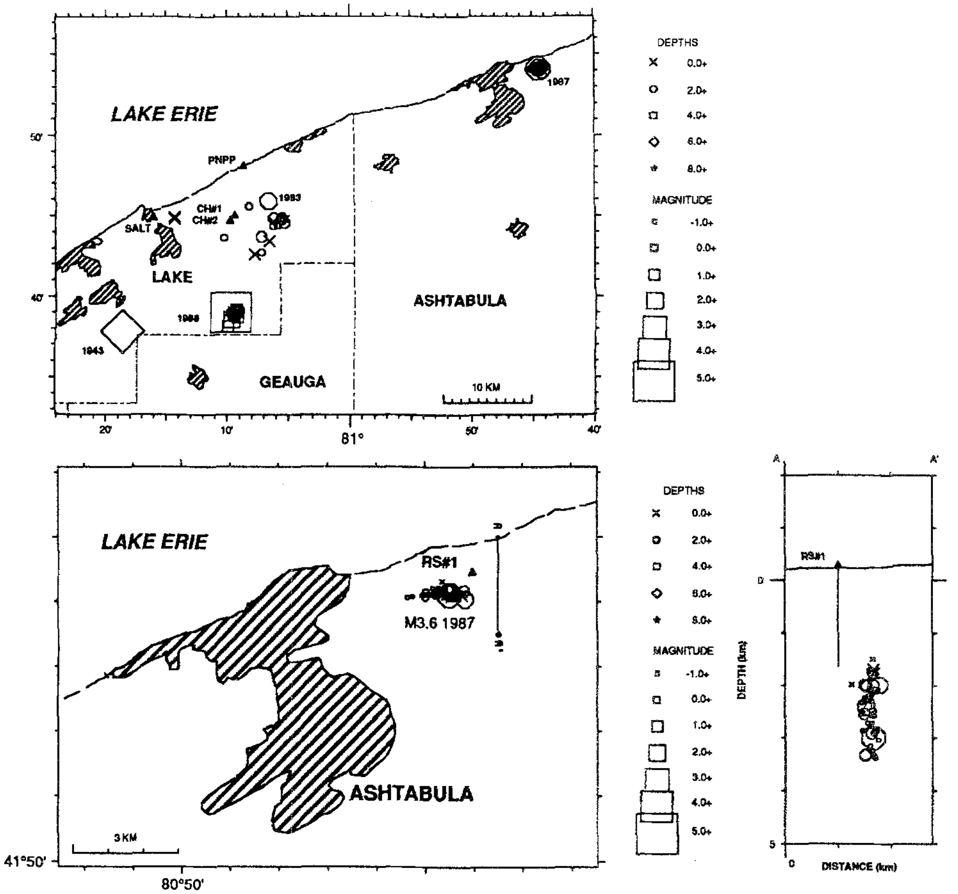

Figure 2

(top) Location of the 1987 induced earthquake sequence in northeastern Ohio near Ashtabula relative to earlier earthquakes (1943–1986) in Lake County. Striped areas are regions of dense population. Triangles are waste disposal wells; PNPP is the Perry Nuclear Power Plant (see NICHOLSON *et al.*, 1988, for more details). (bottom) Map and cross section of the 1987 Ashtabula earthquake hypocenters relative to the location of a nearby active, high-pressure, waste-disposal injection well (Triangle, RS#1). Ashtabula earthquake data provided courtesy of John Armbruster.

was more than sufficient to cause failure along favorably-oriented faults with frictional coefficients of 0.6 and cohesive strengths of 40 bars (NICHOLSON *et al.*, 1988). As a result, waste disposal wells located near Perry, Ohio (CH#1 and CH#2, Figure 2, top), apparently triggered several small earthquakes at distances less than 5 km. These wells operated at injection pressures of 100 bars or more. Other earthquakes located at greater distances (that included a magnitude 5.0 event in 1986) could not be sufficiently distinguished from natural background seismicity (such as the 1943 event) that their occurrence could be considered induced (Figure 2, top) (NICHOLSON *et al.*, 1988); although earthquakes in southwestern Ontario

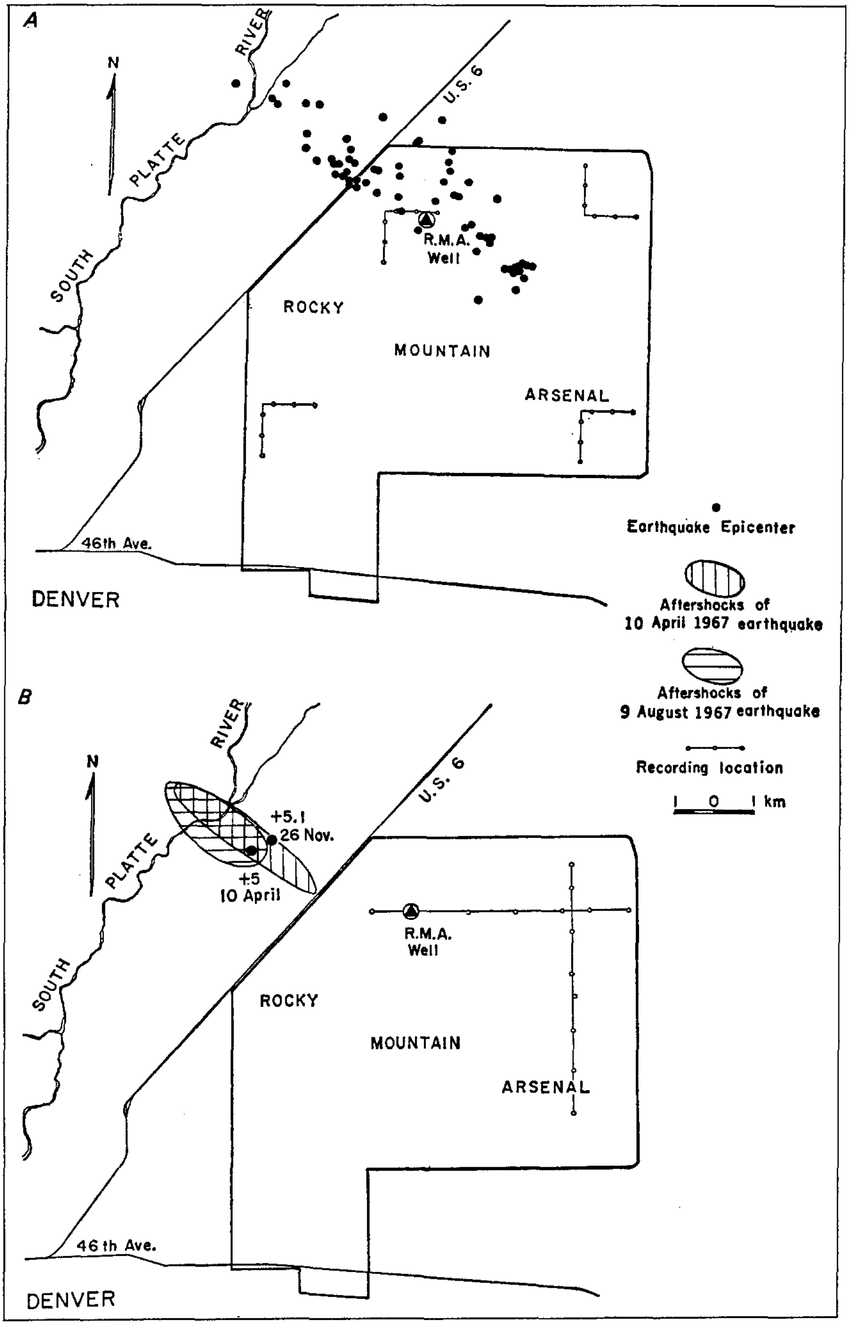

Figure 3
Earthquake activity near the Rocky Mountain Arsenal waste-disposal well, Colorado. (A) Epicentral distribution of earthquakes during January and February 1966. (B) Aftershock distributions of the large 1967 earthquakes. Reprinted with permission from HEALY *et al.* (1968).

(MEREU *et al.*, 1986) and western New York (FLETCHER and SYKES, 1977) have been associated with similar adjacent deep well activities (Figure 1).

Near El Dorado, the disposal of waste brine under pressure, triggered a series of small earthquakes that have continued to the present; the largest of which was a magnitude 3.0 event in 1983. Although oil production had occurred in the area since the early 1920s and disposal of waste brine had begun in the 1970s, no earthquake activity was reported until 1983, shortly after large-volume injection activities began at relatively high pressures (COX, 1991). Since 1983, a strong correlation between rates of seismicity and sudden increases in injection volumes was also observed.

In the most prominent case of induced seismicity by fluid injection, the injection well responsible was located at the Rocky Mountain Arsenal near Denver, where fluid was being injected into relatively impermeable crystalline basement rock. This caused the largest known injection-induced earthquakes to date (three earthquakes between magnitude 5 and 5.5), the largest of which caused an estimated $0.5 million in damages in 1967. Although these induced earthquakes were by no means devastating, they did occasion extensive attention and concern and led, at least in the Denver case, to the cessation of all related injection well operations.

The Rocky Mountain Arsenal case is thus considered to be the classic example of earthquakes induced by deep well injection. Before this episode, the seismic hazard associated with deep well injection had not been fully appreciated. At the Rocky Mountain Arsenal, injection into the 3,700-m deep disposal well began in 1962 and was quickly followed by a series of small earthquakes, many of which were felt in the greater Denver area (Figure 3). It was not until 1966, however, that a correlation was noticed between the frequency of earthquakes and the volume of fluid injected (Figure 4) (EVANS, 1966). Pumping ceased in late 1966 specifically because of the possible hazard associated with the induced earthquakes; after which, earthquakes near the bottom of the well stopped. Over the next 2 years, however, earthquakes continued to occur up to 6 km from the well as the anomalous pressure front, which had been established around the well during injection, continued to migrate outward from the injection point (Figure 3). The largest earthquakes in the sequence (with magnitudes between 5.0 and 5.5) occurred in 1967, long after injection had stopped and well away from the point of fluid injection itself.

These results imply that the fluid pressure effects from injection operations can extend well beyond the expected range of actual fluid migration. Indications have shown, however, that the risk posed by such triggered earthquakes can be mitigated by careful control of the activity responsible for the induced seismicity. As shown by a number of cases (NICHOLSON and WESSON, 1990), seismicity eventually can be stopped either by ceasing the injection or by lowering pumping pressures. The occurrence of the largest earthquakes involved in the Rocky Mountain Arsenal case

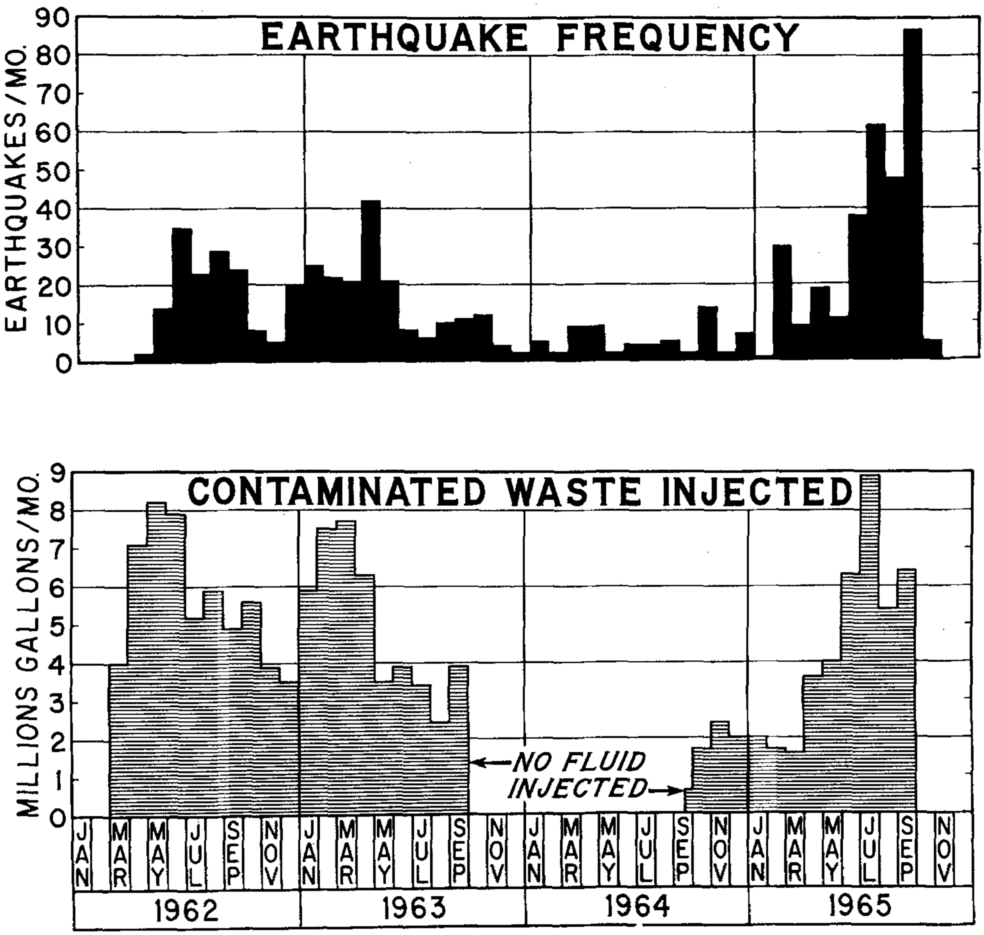

Figure 4
Correlation between earthquake frequency (top) and volume of contaminated waste injected (bottom) at the Rocky Mountain Arsenal well, Colorado. Reprinted with permission from HEALY *et al.* (1968).

a year after all pumping had ceased, however, indicates that the process, once started, may not be controlled completely or easily.

In each of the well-documented examples of earthquakes associated with deep injection wells, convincing arguments that the earthquakes were induced relied upon three principal characteristics of the earthquake activity. First, there was a very close geographic association between the zone of fluid injection and the locations of the earthquakes in the resulting sequence. Second, calculations based on the measured or the inferred state of stress in the earth's crust and the measured injection pressure indicated that the theoretical threshold for frictional sliding along favorably oriented preexisting fractures likely was exceeded. And, third, a clear disparity was established between any previous natural seismicity and the subsequent earthquakes, with the induced seismicity often characterized by large numbers of small earthquakes at relatively shallow depths that persisted for as long as elevated pore pressures in the hypocentral region continued to exist.

Many of the sites where injection-induced earthquakes have occurred operate at injection pressures above 100 bars ambient (Table 1). The exceptions tend to be sites characterized by a close proximity to recognized surface or subsurface faults. In the Rangely and the Sleepy Hollow Oil Field cases, faults are located within the pressurized reservoir and were identified on the basis of subsurface structure contours. At Attica and Dale, New York, the earthquakes occurred close to a prominent fault zone exposed at the surface (the Clarendon–Linden fault system). At the Rocky Mountain Arsenal well, fluid was inadvertently injected directly into a major subsurface fault structure, which was identified later only on the basis of the subsequent induced seismicity (HEALY *et al.*, 1968) and the properties of the reservoir into which fluid was being injected, as reflected in the pressure-time record (HSIEH and BREDEHOEFT, 1981).

Overview of Earthquakes Related to Massive Fluid or Gas Extraction

Triggered earthquakes that spatially correlate with areas of massive fluid (or gas) withdrawal often fall into two distinct categories: (1) shallow induced earthquakes—within or near the producing formation—that typically exhibit normal or reverse faulting focal mechanisms and may be associated with the rapid subsidence and poroelastic strain changes resulting from the large volumes of material extracted (KOVACH, 1974; YERKES and CASTLE, 1976; WETMILLER, 1986; SEGALL, 1989; DOSER *et al.*, 1991); or (2) deep induced earthquakes—which may occur near the base of the seismogenic zone—that often exhibit thrust mechanisms and may be related to stress and/or strain changes associated with unloading effects caused by the large amounts of material locally removed from an area experiencing crustal convergence (e.g., SIMPSON and LEITH, 1985; MCGARR, 1991). These latter induced events can be much larger in magnitude and can be much more difficult to distinguish than the shallow induced earthquakes, as the shallow seismicity is much more likely to exhibit temporal variations that correlate with specific activities at the adjacent producing wells.

One of the best examples of shallow induced earthquakes related to fluid withdrawal occurred near Los Angeles, California. The massive withdrawal of oil from one of the largest fields in the basin, the Wilmington oil field, resulted in significant subsidence within the city limits of Long Beach. Up to 8.8 m of surface subsidence was observed over an elliptically-shaped area between 1928 and 1970. This rapid subsidence, which reached a maximum rate of 71 cm/yr in 1951, 9 months after peak oil production, resulted in several damaging earthquakes, specifically in the years 1947, 1949, 1951, 1954, 1955, and 1961 (Figure 5) (KOVACH, 1974). In most cases, the earthquakes were unusually shallow and generated

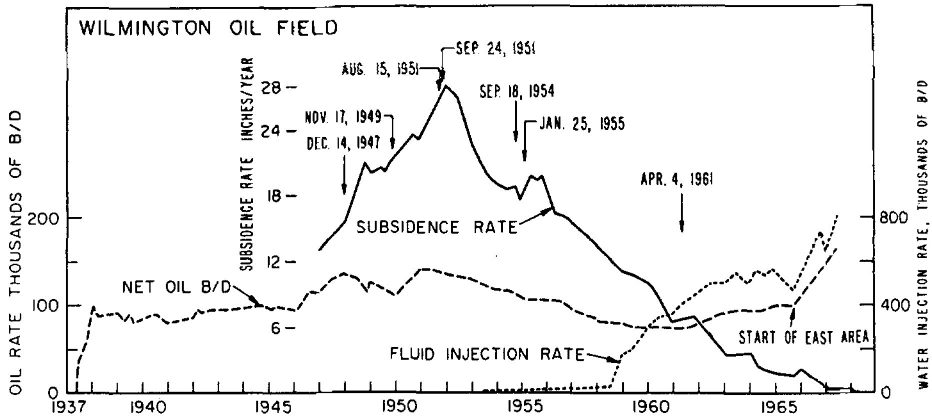

Figure 5
Subsidence rate in the center of the Wilmington oil field, California, compared with oil production and water injection rates. Arrows are dates of major damaging earthquakes. Reprinted with permission from KOVACH (1974).

high intensities for their size. The largest earthquake occurred in 1949, and caused nearly 200 wells to go off production, many of them permanently (RICHTER, 1958). Damage was estimated to be in excess of $9 million. The area affected equaled over 5.7 km^2 and involved measured displacements of 20 cm. This would correspond to an earthquake of moment magnitude 4.7, and is consistent with a magnitude of 5.1 estimated from the unusually well developed surface waves generated by the event (KOVACH, 1974).

SEGALL (1989) presents a model that explains the local subsidence and the occurrence of shallow thrust faulting above and below the producing horizon as a result of poroelastic effects in response to reservoir compaction. The massive fluid extraction causes the reservoir rock to contract. This in turn induces the strata above and below the reservoir to be driven into local compression. Areas farther away from the reservoir are displaced less than the rock immediately above and below the reservoir—which causes flanking regions to extend and may result in normal faulting near the edges of the producing area (SEGALL, 1989). Oil production from the Inglewood field within the Los Angeles basin produced near-surface extensional creep events near the edge of the field, starting in 1952 (HAMILTON and MEEHAN, 1971). Water-flood operations that began in 1954 apparently accelerated this normal faulting, produced increased shallow seismicity starting in 1962, and eventually led to the failure of the Baldwin Hills water storage facility in 1963 that killed 5 people and caused $12 million damage.

In contrast, the earthquakes in the Wilmington oil field were apparently generated by low-angle reverse slip on bedding planes at depths of 470 to 520 m, while virtually all the compaction that caused the surface subsidence was localized in the producing beds at depths of 650 to 1050 m (KOVACH, 1974; ALLEN and MAYUGA, 1970; SEGALL, 1989). Water flooding of the Wilmington field and adjacent areas was initiated in 1954 in an attempt to halt subsidence and to enhance the secondary recovery of oil. TENG *et al.* (1973) reported on the seismic activity associated with fourteen oil fields operating within the Los Angeles Basin where water-flood operations were taking place. Although much of the seismicity in the area is natural and occurs predominantly at depths as deep as 16 km along the Newport–Inglewood fault, seismic activity during 1971 appeared to correlate, at least in part, with injection volumes from nearby wells (TENG *et al.*, 1973). However, many of the earthquakes detected were small (less than magnitude 3.0) and occurred at depths of 5 km or more, which made it difficult to distinguish them from the natural background seismicity. Subsequent injection operations have since stabilized to the point where fluid injection nearly equals fluid withdrawal and little, if any, seismic activity can be directly attributable to injection well operations.

Similar shallow induced earthquake activity has been associated with the withdrawal of natural oil and gas from several fields in Texas, including the Goose Creek, Fashing, Imogene and War-Wink fields (e.g., PRATT and JOHNSON, 1926; PENNINGTON *et al.*, 1986; DOSER *et al.*, 1991). No significant injection operations had taken place in these areas, so much of the induced earthquake activity was inferred to be related to local subsidence and compaction caused by production (SEGALL, 1989). The earthquakes associated with the Goose Creek field in south Texas occurred on normal faults that broke the surface along the northern and southern margins of the subsiding region (PRATT and JOHNSON, 1926). Detailed analysis of the seismicity near the War-Wink field (DOSER *et al.*, 1991) confirmed that many of the earthquakes were localized above and below producing horizons, and that many events exhibited normal and reverse focal mechanisms. However, not all the earthquake activity could be explained so easily or simply. Some of the earthquakes occurred at depths greater than 4 km. Poroelastic effects associated with reservoir compaction are limited to the shallow crust near the producing horizon (SEGALL, 1989). The deep crustal earthquakes associated with areas of massive fluid extraction thus require further explanation. Possible mechanisms proposed to account for various aspects of the observed seismicity near the War-Wink field include: (1) the natural occurrence of deep (>4 km) crustal earthquakes along preexisting faults in response to the existing regional stress field, (2) strain localization in naturally overpressured zones resulting from production, or (3) shallow earthquakes resulting from compaction or the upward migration of high fluid pressures (DOSER *et al.*, 1991).

The possible correlation between very deep (>10 km) earthquake activity and the massive extraction of fluid or gas from the shallow crust is much more ambiguous (MCGARR, 1991). In such cases, the triggering mechanism is thought to be related to the isostatic imbalance caused by the net extraction of fluid or gas from the upper crust. As the ductile lower crust will deform in response to this imbalance, this readjustment will increase the applied load in the upper seismogenic layer, which may then fail seismically so as to restore local static equilibrium. If the upper crust already has been folded and faulted in response to applied horizontal tectonic compression, the stress and strain readjustments associated with restoring the isostatic imbalance will be concentrated on these preexisting structures. Thus, earthquakes near the base of the upper crust may be an expected outcome of major oil or gas production from growing anticlines—irrespective of the depths of the producing formation (McGarr, 1991).

Possible candidates for this particular type of triggered deep seismicity include the 1983 M_L 6.5 Coalinga earthquake beneath the Coalinga oil field, the 1985 M_L 6.1 Kettleman Hills earthquake beneath the Kettleman North Dome oil field, and the 1987 M_L 5.9 Whittier Narrows earthquake beneath the Montebello oil field (Table 1). In each case, a mechanical connection is suggested between oil production and the earthquakes because—in each case—the total seismic deformation (moment) released during these earthquake sequences is nearly equal to that required to offset the force imbalance caused by the oil production (McGarr, 1991). In addition, all three events exhibited nearly pure reverse motion on low-angle faults that core active folds responsible for originally trapping the oil.

An alternative explanation for this deep seismicity may be related to possible naturally occurring fluids in the deep crust. If, for example, preexisting high fluid pressures (approaching lithostatic) exist in the mid-to-lower crust, then the massive withdrawal of near-surface material may induce sufficient changes in the local hydrogeologic regime such that significant migration of fluids at depth is initiated. Thus, crustal unloading as a result of production may create pressure differentials that cause a preferential migration of deep fluids towards the producing area. The enhanced saturated condition beneath the producing area may then lend itself to increased strain localization, and to cyclic pressure variations, hydrothermal sealing, permeability reduction, and fault-valve behavior proposed by Sibson (1992) for earthquake rupture nucleation and recurrence, particularly in compressional tectonic regimes on faults that are otherwise unfavorably oriented for reactivation in the prevailing stress field. In either case, the crustal response to existing stress and/or strain regimes is therefore affected by production, and earthquakes may be preferentially localized beneath the producing region.

Previously, the major difficulty in recognizing the possible correlation between these events and oil production is that, in each case, the earthquakes occur at depths greater than 10 km, and considerable delays are observed between peak production and the earthquake occurrence. Peak production at Coalinga occurred in 1912; at Kettleman Hills, peak production occurred in the years 1936, 1941, 1948, 1957 and 1964 for separate subfields; and at Montebello, peak production occurred in 1939. It is thus hard to imagine how changes in stress related to production could have significant effects at such large distances and long time intervals. However, the apparent triggering of earthquakes at depths greater than

15 km beneath Lake Nasser 19 years after impoundment began behind the Aswan High Dam, Egypt (SIMPSON *et al.*, 1982), strongly suggests that such long-range interactions between the upper and lower crust do occur.

If such earthquakes are indeed considered to be triggered events, then several other earthquakes within the conterminous United States may also represent potentially induced sequences. These include: historical earthquakes near Attica, New York, in 1929, 1966 and 1967, that may be related to local solution salt mining; the extensive earthquake activity near El Reno, Oklahoma (including the 1952 M_L 5.5 event), that may be related to local oil and gas production; and the 1987 M_L 4.9 earthquake in southeastern Illinois that occurred adjacent to Lawrence County, one of the most productive oil regions of the state. Even the occurrence of the major damaging 1933 M_L 6.3 Long Beach, California, earthquake may have been related to production in the adjacent Wilmington and Huntington Beach oil fields. The important point is that, in each of these cases, the earthquakes represent some of the largest events ever to have occurred in any of these given areas, and so represent a significant local seismic hazard. However, unlike many of the proposed, deep potentially-induced earthquakes in California (MCGARR, 1991), these earthquakes typically exhibit focal mechanisms with a larger component of strike-slip motion, suggesting that faulting in these areas tends to occur as oblique-slip on faults at depth with steeper dips and so the spatial correlation with the specific active folds may not be apparent.

Discussion and Conclusions

Based on the case histories examined so far, it is evident that, owing to existing stress conditions in the upper crust, certain areas tend to have a relatively high probability of exhibiting seismicity related to fluid injection. In these areas, it appears that elevating formation fluid pressures by only a few megapascals (tens of bars) can trigger increased shallow seismicity. One such area prone to injection-induced seismicity is the Great Lakes region of the Appalachian Plateau, where fluid injection operations (at pressures ranging from 60 to 100 bars) have already triggered earthquakes in northeastern Ohio, western New York and southwestern Ontario (Figures 1 and 2). In most cases, the fluid injection and the triggered earthquakes are below a regional salt layer (the Silurian Salina Formation) that acts to mechanically decouple the shallow crust (where earthquake triggering is apparently less likely) from a more critical stress state at depth (EVANS, 1988). Other cases of injection-induced seismicity that have occurred in Colorado (Rangely), Texas, Nebraska, Oklahoma, Arkansas, and possibly Mississippi, Louisiana and Alberta, typically involve higher injection pressures, larger volumes of injected fluid, or multiple injection wells.

The recognition that both fluid injection and the massive extraction of oil and gas may potentially trigger adjacent large earthquakes makes evaluating the seismic hazard from deep well operations considerably more complicated. As each of these different types of triggered events can occur up to several years after well activities have begun (or even several years after all well activities have stopped), this suggests that the actual triggering process may be a very complex combination of effects, particularly if both fluid extraction and injection have taken place locally. In particular, it may be that, in such cases, it is the fact that *both* extraction and injection have taken place that is the major critical observation: extraction to localize strain, and injection to enhance inhomogeneities in pore fluid pressure and reduce the effective friction strength of preexisting faults (DAVIS and PENNINGTON, 1989). However, the important point is that models for triggered seismicity which involve local perturbations of the fluid pressure regime, or stress and strain localization resulting from massive fluid or gas withdrawal, may thus help to explain what is otherwise a rather perplexing and unusual inhomogeneous distribution of earthquakes in the central and eastern United States—an intraplate region that exhibits all the properties of a fairly homogeneous tectonic environment.

Because many events induced by fluid injection are relatively shallow and may occur in close proximity to the wellbore, they pose an additional risk to both the well site and the local surrounding community. In the case of hazardous-waste disposal, there is also the potential seismic risk to the integrity of the confining layer, which if ruptured may permit the upward migration of hazardous fluid and the local contamination of potable water supplies. Because of this added risk, criteria have been established to assist in regulating well operations so as to minimize the potential for earthquake triggering by deep-well fluid injection (NICHOLSON and WESSON, 1990). Important considerations include analyses of the hydrologic properties of the reservoir, the existing state of stress, and proximity to known or inferred fault structures. This information can then be used to help set guidelines for estimating maximum allowable injection pressures for waste disposal.

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REFERENCES

ALLEN, D. R., and MAYUGA, M. N. (1970), *The mechanics of compaction and rebound, Wilmington oil field, Long Beach, California, U.S.A.* In *Land Subsidence* (International Association of the Science of Hydrology, UNESCO Publ. *89*, 2) pp. 410–423.

ARMBRUSTER, J. G., SEEBER, L., and EVANS, K. (1987), *The July 1987 Ashtabula Earthquake (m_b 3.6) Sequence in Northeastern Ohio and a Deep Fluid Injection Well* (abstract), Seismol. Res. Lett. *58*, 91.

CALOI, P., DEPANFILIS, M., DEFILIPPO, D., MARCELLI, L., and SPADEA, M. C. (1956), *Terrimoti della Val Padana del 15–16 Maggio 1951*, Ann Geophys. *9*, 63–105.

COX, R. T. (1991), *Possible Triggering of Earthquakes by Underground Waste Disposal in the El Dorado, Arkansas Area*, Seismol. Res. Lett. *62*, 113–122.

DAVIS, S. D. (1985), *Investigations of Natural and Induced Seismicity in the Texas Panhandle*, M.S. Thesis, University of Texas, Austin, Texas, 230 pp.

DAVIS, S. D., and PENNINGTON, W. D. (1989), *Induced Seismic Deformation in the Cogdell Oil Field of West Texas*, Bull. Seismol. Soc. Am. *79*, 1477–1495.

DOSER, D. I., BAKER, M. R., and MASON, D. B. (1991), *Seismicity in the War-Wink Gas Field, Delaware Basin, West Texas, and its Relationship to Petroleum*, Bull. Seismol. Soc. Am. *81*, 971–986.

EVANS, D. M. (1966), *The Denver Area Earthquakes and the Rocky Mountain Arsenal Disposal Well*, Mountain Geologist *3*, 23–36.

EVANS, K. F. (1988), *Assessing Regional Potential for Induced Seismicity from Crustal Stress Measurements: An Example from Northern Ohio*, NCEER Technical Rep., 30 pp.

FLETCHER, J. B., and SYKES, L. R. (1977), *Earthquakes Related to Hydraulic Mining and Natural Seismic Activity in Western New York State*, J. Geophys. Res. *82*, 3767–3780.

HAMILTON, D. H., and MEEHAN, R. L. (1971), *Ground Rupture in the Baldwin Hills*, Science *172*, 333–344.

HARDING, S. T. (1981), *Induced Seismicity in the Cogdell Canyon Reef Oil Field*, U.S. Geol. Surv. Open-file Report *81-167*, 452–455.

HEALY, J. H., RUBEY, W. W., GRIGGS, D. T., and RALEIGH, C. B. (1968), *The Denver Earthquakes*, Science *161*, 1301–1310.

HSIEH, P. A., and BREDEHOEFT, J. D. (1981), *A Reservoir Analysis of the Denver Earthquakes: A Case of Induced Seismicity*, J. Geophys. Res. *86*, 903–920.

KOVACH, R. L. (1974), *Source Mechanisms for Wilmington Oil Field, California, Subsidence Earthquakes*, Bull. Seismol. Soc. Am. *64*, 699–711.

MCGARR, A. (1991), *On a Possible Connection between three Major Earthquakes in California and Oil Production*, Bull Seismol. Soc. Am. *81*, 948–970.

MEREU, R. F., BRUNET, J., MORRISSEY, K., PRICE, B., and YAPP, A. (1986), *A Study of the Microearthquakes of the Gobles Oilfield Area of Southwestern Ontario*, Bull. Seismol. Soc. Am. *76*, 1215–1223.

MILNE, W. G., and BERRY, M. J. (1976), *Induced Seismicity in Canada*, Eng. Geol. *10*, 219–226.

NICHOLSON, C., ROELOFFS, E., and WESSON, R. L. (1988), *The Northeastern Ohio Earthquake of January 31, 1986—Was it Induced?*, Bull Seismol. Soc. Am. *78*, 188–217.

NICHOLSON, C., and WESSON, R. L. (1990), *Earthquake Hazard Associated with Deep Well Injection*, U.S. Geol. Surv. Bull. 1951, 74 pp.

PEARSON, C. (1981), *The Relationship between Microseismicity and High Pore Pressures during Hydraulic Stimulation Experiments in Low Permeability Granitic Rocks*, J. Geophys. Res. *86*, 7855–7864.

PENNINGTON, W. D., DAVIS, S. D., CARLSON, S. M., DUPREE, J., and EWING, T. E. (1986), *The Evolution of Seismic Barriers and Asperities Caused by the Depressuring of Fault Planes in Oil and Gas Fields of South Texas*, Bull. Seismol. Soc. Am. *76*, 939–948.

PRATT, W. E., and JOHNSON, D. W. (1926), *Local Subsidence of the Goose Creek Oil Field*, J. Geol. *34*, 577–590.

RALEIGH, C. B., HEALY, J. H., and BREDEHOEFT, J. D. (1972), *Faulting and crustal stress at Rangely, Colorado.* In *Flow and Fracture of Rocks* (AGU Geophys. Monogr. Series *16*) pp. 275–284.

RALEIGH, C. B., HEALY, J. H., and BREDEHOEFT, J. D. (1976), *An Experiment in Earthquake Control at Rangely, Colorado*, Science *191*, 1230–1237.

RICHTER, C. F., *Elementary Seismology* (W. H. Freeman and Co., San Francisco and London 1958) 768 pp.

ROTHE, G. H., and LUI, C.-Y. (1983), *Possibility of Induced Seismicity in the Vicinity of the Sleepy Hollow Oil Field, Southwestern Nebraska*, Bull. Seismol. Soc. Am. *73*, 1357–1367.

SEGALL, P. (1989), *Earthquakes Triggered by Fluid Extraction*, Geology *17*, 942–946.

SIBSON, R. H. (1992), *Implications of Fault-valve Behavior for Rupture Nucleation and Recurrence*, Tectonophysics *211*, 283–293.

SIMPSON, D. W. (1986), *Triggered Earthquakes*, Ann. Rev. Earth Planet Sci. *14*, 21–42.

SIMPSON, D. W., KEBEASY, R. M., MAAMOUN, M., ALBERT, R., and BOULOIS, F. K. (1982), *Induced Seismicity at Aswan Lake, Egypt* (abstract), EOS, Trans. Am. Geophys. Union *63*, 371.

SIMPSON, D. W., and LEITH, W. (1985), *The 1976 and 1984 Gazli, U.S.S.R. Earthquakes—Were they Induced?* Bull. Seismol. Soc. Am. *75*, 1465–1468.

TENG, T. L., REAL, C. R., and HENYEY, T. L. (1973), *Microearthquakes and Water Flooding in Los Angeles*, Bull. Seismol. Soc. Am. *63*, 859–875.

WETMILLER, R. J. (1986), *Earthquakes near Rocky Mountain House, Alberta, and their Relationship to Gas Production Facilities*, Canadian J. Earth Science *23*, 172–181.

YERKES, R. F., and CASTLE, R. D. (1976), *Seismicity and Faulting Attributed to Fluid Extraction*, Eng. Geol. *10*, 151–167.

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