Moderate-to-large seismicity induced by hydrocarbon production

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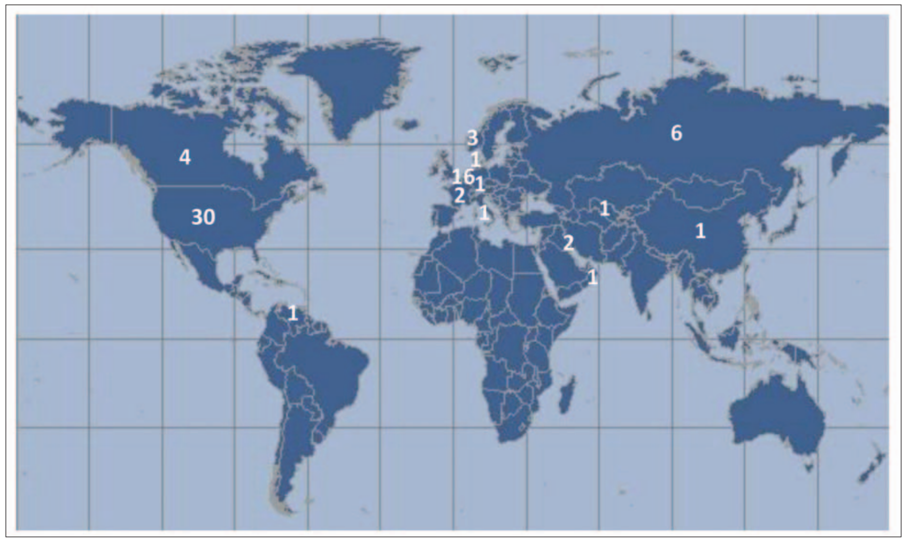

Figure 1. Overview of the worldwide distribution of the 70 reported cases of induced seismicity in hydrocarbon fields listed in Table 1.

It is well known that various human activities have the potential to generate seismic activity. Examples range from subsurface waste injection and reservoir impoundment in the vicinity of large dams to the development of mining, geothermal or hydrocarbon resources. Recently, induced seismicity in connection to geologic carbon sequestration projects has emerged as a new field of interest. This review discusses seismicity induced by hydrocarbon production. In particular, I focus on published cases for which earthquakes of moderate-to-large magnitudes—in other words earthquakes that can be felt on the surface—have been reported. I also discuss current theoretical approaches to model this phenomenon. The emphasis on moderate-to-large magnitudes is intended to complement the other contributions in this issue which focus primarily on microseismicity. Evidently, it is important to understand the conditions under which hydrocarbon production may induce seismic activity in order to ensure that field operations can be performed safely.

The last decades have seen substantial progress in our understanding of induced seismicity, which has been achieved through the availability of high-quality instrumentation of oil fields and continuous effort to understand the phenomenon theoretically. Unfortunately, many studies are dispersed over a variety of journals and specialized reports. The overview provided in this paper aims at improving the accessibility of our current knowledge about induced seismicity for a broad audience of scientists. The interested reader may also choose to refer to a more comprehensive version of this study for additional details and references (Suckale, 2009).

Before delving into the details of hydrocarbon fields for which a connection between production and seismic activity has been suggested, it is important to note that the characterization of a given event as "induced" is largely subjective. The reason is that it is unlikely that any moderate-to-large event would be caused by the perturbing effects of hydrocarbon production alone. The pre-existing, "natural" stress field plays an important role. Therefore, the main challenge in classifying a given event as natural or induced lies in deciding whether the production-related contribution to the pre-existing stress field is significant enough. This challenge is exacerbated by the fact that detailed information about the tectonic stress field and production levels over time is rarely available. For cases in which the man-made contribution to the stress field can be quantified, it is common to distinguish between "induced" seismicity (where the causative activity accounts for most of the stress change) and "triggered" seismicity (where the causative activity accounts for only a small fraction of the overall stress change). I will not follow this classification, because in the context of hydrocarbon field, it has so far rarely been possible to reliably quantify the production-related stress perturbations.

Compilation of case studies

I have assembled 70 cases of hydrocarbon fields in which hydrocarbon production has been related to unusually large seismic activity in the scientific literature (Table 1 and Figure 1). It is important to point out that not all of these hydrocarbon fields truly exhibit induced seismicity. While a connection between production and seismicity is thought to be well established for some cases (e.g., Lacq Field near Aquitaine, France), it is very controversial for others (e.g., Coalinga, Kettleman, and Montebello fields in California). I also note that Table 1 is inevitably incomplete for various reasons:

1) Induced seismicity in hydrocarbon fields typically generates small-to-moderate magnitudes that might not be detected unless a local network is operated in the immediate vicinity of the field.
2) Natural seismicity can obscure induced events.
3) The hydrocarbon industry may have reports of induced seismicity which are not publicly available.

An interesting aspect of the cases of induced seismicity listed in Table 1 and shown in Figure 1 is their tendency to cluster regionally: Out of the approximately 600 sedimentary basins worldwide, 400 have been drilled and 160 are (or were) used for commercial hydrocarbon production. Only 25

Hydrocarbon field	Country	Potential cause
Snipe Lake	Alberta, Canada	
Strachan	Alberta, Canada	extraction
Gobles	Appalachian, Canada	injection
Eagle&Eagle West	British Columbia, Canada	extraction
Shengli	Shandong Province, China	injection
Dan	North Sea, Denmark	extraction
Lacq	Aquitaine, France	extraction
Meillon	Aquitaine, France	extraction ?
Söhlingen / Rotenburg	Rotliegendes, Germany	
Caviaga	Po Valley, Italy	
Umm Gudair	Kuwait	burning
Burgan	Kuwait	burning
Groningen	Rotliegendes, Netherlands	extraction/fault reactivation
Roswinkel	Rotliegendes, Netherlands	extraction/fault reactivation
Bergermeer	Rotliegendes, Netherlands	extraction/fault reactivation
Eleveld	Rotliegendes, Netherlands	extraction/fault reactivation
Bergen	Rotliegendes, Netherlands	extraction/fault reactivation
Annerveen	Rotliegendes, Netherlands	extraction/fault reactivation
Appelscha	Rotliegendes, Netherlands	extraction/fault reactivation
Emmen	Rotliegendes, Netherlands	extraction/fault reactivation
Dalen	Rotliegendes, Netherlands	extraction/fault reactivation
Roden	Rotliegendes, Netherlands	extraction/fault reactivation
VriesNoord	Rotliegendes, Netherlands	extraction/fault reactivation
Ureterp	Rotliegendes, Netherlands	extraction/fault reactivation
Emmen-Nw. A'Dam	Rotliegendes, Netherlands	extraction/fault reactivation
Schoonebeek	Rotliegendes, Netherlands	extraction/fault reactivation
VriesCentraal	Rotliegendes, Netherlands	extraction/fault reactivation
Coevorden	Rotliegendes, Netherlands	extraction/fault reactivation
Ekofisk	North Sea, Norway	extraction
Valhall	North Sea, Norway	extraction
Visund	North Sea, Norway	various
Shuaiba	Oman	
Romashkino	Volga-Ural, Russia	injection
Novo-Elkhovskoye	Volga-Ural, Russia	
Starogroznenskoye	Russia	
Barsa-Gelmes-Vishka	Russia	
Gudermes	North Caucasus, Russia	
Grozny	Tchetchny	
Big Escambia Creek	Alabama, USA	extraction ?
Little Rock	Alabama, USA	extraction ?
Sizemore Creek	Alabama, USA	extraction ?
Coalinga	California, USA	extraction/fault reactivation/isostasy
Kettleman	California, USA	extraction/fault reactivation/isostasy
Montebello	California, USA	extraction/fault reactivation/isostasy
Orcutt	California, USA	injection
Wilmington	California, USA	extraction
Rangely	Colorado, USA	injection
South Eugene Island	Louisiana, USA	injection
Hunt	Mississippi, USA	injection ?
Sleepy Hollow	Nebraska, USA	injection ?
Catoosa District	Oklahoma, USA	injection ?
Love County	Oklahoma, USA	injection ?
East Durant	Oklahoma, USA	injection ?
Gobles	Ontario, USA	injection
Apollo-Hendrick	Texas, USA	injection ?
Blue Ridge	Texas, USA	extraction/subsidence
Clinton	Texas, USA	extraction/subsidence
Cogdell Canyon Reef	Texas, USA	injection ?
Fashing	Texas, USA	extraction/fault reactivation
Goose Creek	Texas, USA	extraction/subsidence
Imogene	Texas, USA	extraction/fault reactivation
Kermit	Texas, USA	injection
Keystone	Texas, USA	
Mykawa	Texas, USA	extraction/subsidence
South-Houston	Texas, USA	extraction/subsidence
War-Wink	Texas, USA	extraction ?
Webster	Texas, USA	extraction/subsidence
Dollarhide	Texas/New Mexico, USA	injection ?
Gazli	Uzbekistan	erratic production/fault reactivation ?
Costa Oriental	Lake Maracaibo, Venezuela	extraction/subsidence

***Table 1.** Compilation of 70 reported cases of induced seismicity in hydrocarbon fields. Please refer to Suckale, 2009, for details and additional references.*

of these represent cumulative discoveries of substantial volume (more than 10 billion BOE) and thus concentrate about 85% of the total worldwide reserves to date. Common incidents of induced seismicity have been reported only for two of these 25, the Permian Basin in Texas and Rotliegendes in the Netherlands.

Within each of these basins, only a limited number of fields exhibit seismicity in a magnitude range that is sufficient for surface recording. For example, 16 out of 124 producing fields in the Netherlands are seismically active (Van Eijs et al., 2006). Figure 2 gives an overview of seismicity in connection to hydrocarbon production in the Netherlands.

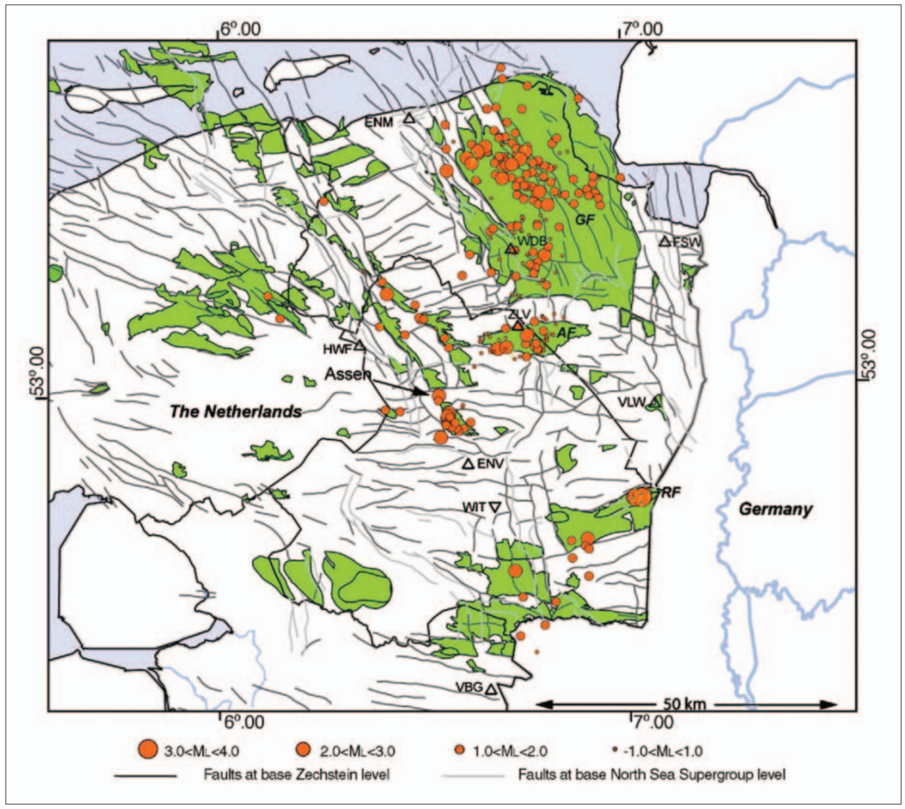

Figure 2. *Illustration of the spatial correlation between hydrocarbon fields (green), major fault structures, and seismicity (solid orange circles) in the northeastern part of The Netherlands. The major gas fields are indicated: Roswinkel Field (RF); Groningen Field (GF), Eleveld Field (EF), Annerveen Field (AF). Seismic stations are shown as triangles. (Figure reproduced from Van Eck et al., 2006).*

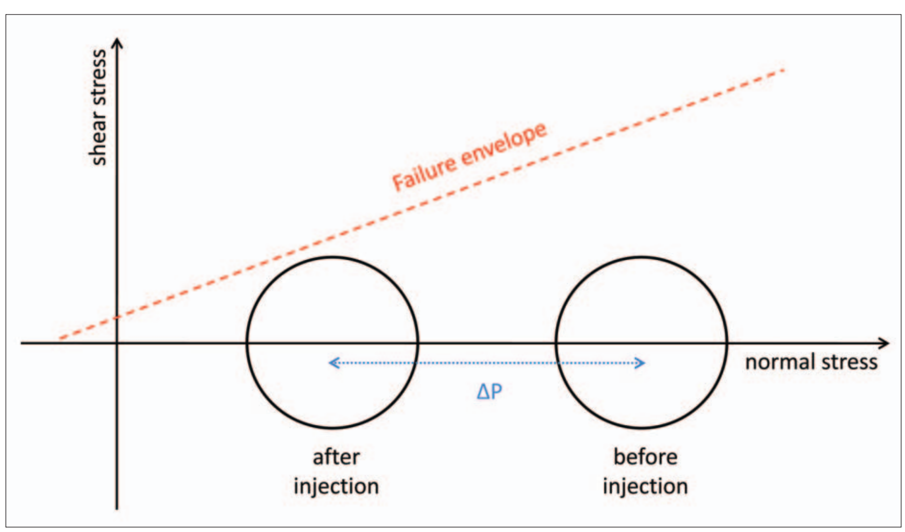

Figure 3. *Mohr-Coulomb diagram illustrating how fluid injection lowers the normal stress and thereby brings rock closer to failure.*

Seismicity induced by fluid injection

It is not unexpected that fluid injection has the potential of inducing seismic activity. Before injection, the state of stress is determined by the local tectonic stresses which can be visualized through a Mohr circle, where the intersection of the Mohr circle with the abscissa represents the two principal stresses (Figure 3). As the injected fluid enters pre-existing microfractures in the rock, it supports part of the normal stress. Since fluids have no shear strength, the effective normal stress and the frictional resistance to sliding are lowered by an amount equivalent to the pressure of the fluid. The new state of stress after injection is thus closer to failure than before (Figure 3).

The Mohr-Coulomb argument invites the conjecture that earthquakes could be controlled solely through variation of fluid-injection rates. This hypothesis was tested through a series of injection experiments at the Rangely oil field (Raleigh et al., 1976). The experiments began in 1969 with the installation of a seismic network of 14 short-period, vertical seismometers. Between October 1969 and May 1973, two full cycles of increased fluid injection and back-flowing were performed. The result was a prompt response of seismic activity to changes in fluid pressure.

Unfortunately, Rangely Field is the exception. No obvious correlation between seismicity and injection rate has since been established for any of the other hydrocarbon fields with moderate-to-large seismicity. There are two possible explanations for the absence of a clear connection between injection rates and seismicity with moderate or large magnitude; either there is a direct relationship that cannot be detected or there is not a simple relationship between production and seismicity

Some reasons to explain our inability to detect the relationship are:

1) Inaccuracies in the location of hypocenters. Example: Only a more precise relocalization of the event on 20 October 2004 (ML = 4.5) at Rotenburg/Soltau led to the realization that it might have been induced (Dahm et al., 2007).
2) Lack of data regarding the precise injection pattern over time. Example: At Gobles Field, Mereu et al. (1986) had to rely on oral records regarding the production patterns which jeopardized a detailed quantitative comparison of injection rates and seismic activity.
3) Lack of high-quality instrumentation during the onset of seismic activity. Example: At Sleepy Hollow, no significant correlation between average injection pressure and earthquake occurrence could be established (e.g., Evans et al., 1987). The authors did not find this result surprising. They argued that after almost 19 years of continuous injection, it would be unlikely that changes in the injection pattern—without a substantial increase in overall pressure—would change the seismicity pattern.
4) Clustering of seismicity might obscure the fact that selected events are closely related to injection patterns. Example: Doser et al. (1991) investigated seismicity at War-Wink and identified three clusters out of which they believe only two to be related to field operations.

Reasons for the absence of a simple relationship between production and seismicity include:

1) The usage of different wells for injection and extraction in combination with pre-existing discontinuities in the ground could lead to complex underground flow patterns. Lumley, 2001, observed a convoluted flow path of gas injected at Gullfaks Field, Norway.
2) The interaction of fluid flow with pre-existing faults or compositional discontinuities. Example: Doser et al., 1992, analyzed induced seismicity in the Permian Basin and found that events tend to cluster in overpressured areas indicating a close connection to fluid injection. On the other hand, they also observed that a substantial number of events were located between fields, which they interpreted as an indication for the importance of fluid movement and pressure gradients.
3) Complexities of either a geochemical or mechanical nature not captured in the simple Mohr-Coulomb-type arguments. Example: Despite substantial subsidence, Ekofisk was considered as largely aseismic prior to May 2002, when a sizeable event of Mw of 4.1–4.4 in likely connection to fluid injection (Ottemöller et al., 2005) occurred within the field.

Another piece of evidence indicating that Mohr-Coulomb-type arguments might be oversimplified is the commonly observed time lapse between the beginning of fluid injections and the onset of seismic activity. Cogdell Canyon Reef Field is a typical example: In June 1978, an event with Mw = 4.6–4.7 occurred in the field—one of the largest events in likely association with an injection operation. At that point, water injection as a means of secondary recovery had been used for approximately 18 years.

Davis and Pennington (1989) tested both the classic Mohr-Coulomb failure model and the hypothesis that stress loading might have resulted from the weight of injected fluids. They observed that seismic activity was not concentrated in areas of high fluid pressure, which raised doubts about the exact role of the fluid injections in causing the seismicity. In this context, it should be noted that the observed time lapse between injection and seismicity might be at least partly related to the lack of high-quality instrumentation. The U.S. Geological Survey operated a local network at Cogdell Canyon Reef from February 1979 to August 1981. A potential buildup of seismicity before that time may have occurred but gone by unnoticed because of the lack of local instrumentation.

Seismicity induced by fluid extraction

Based on the Mohr-Coulomb argument that injection of fluid brings rocks closer to failure, it may seem counter-intuitive that seismicity could also result from fluid extraction. Instead, one might expect that the decrease of pore pressure should inhibit failure. This effect does indeed exist. It is particularly important if pre-existing faults are in immediate contact with the reservoir and subject to a spatially heterogeneous decrease in pore pressure (Pennington et al., 1986). As a consequence of fluid extraction, strain accumulates either due to differential compaction or continued aseismic slip of nearby portions of the fault which builds up stress along the locked portions of the fault. Eventually, the accumulated stress will exceed the strength of these asperities and be released in the form of an earthquake. The process is expected to repeat itself as long as the pore pressure continues to decrease along the active fault. An important prediction of this model is that the magnitude of earthquakes should increase over time (Pennington et al.,1986). The asperity model might account for the seismicity observed at the Imogene and Fashing fields. The largest events in seismically quiescent South Texas occurred at Fashing in July 1983 (mbLg = 3.4 and at Pleasanton in March 1984 (mbLg = 3.9). On 9 April 1993, another large earthquake (mbLg = 4.3) was recorded. The ideas proposed by Pennington et al. (1986) have been applied and expanded to include geometrical effects and to model induced seismicity in the Netherlands.

A different approach to understanding seismicity related to fluid extraction is based on the analysis of poroelastic stresses. As fluid is extracted, declining pore pressures cause the permeable reservoir rocks to contract, which stresses the neighboring crust. The poroelastic equations governing this behavior can be solved analytically only for specific geometries and modeling assumptions. Two special cases of particular interest for modeling fluid extraction from hydrocarbon reservoirs are infinitely extended, horizontal reservoirs (Segall, 1985) and axisymmetric reservoirs (Segall, 1992).

Fluid extraction from an infinitely extended, horizontal reservoir can only occur vertically and is thus a 1D process.

Figure 4 shows the model setup assumed by Segall (1985) and applied to Strachan by Baranova et al. (1999). As fluid is withdrawn from the reservoir, flow toward the line of extraction is induced in the producing layer. In this idealized geometry, the poroelastic equations can be solved analytically yielding the following three predictions:

1) The changes in pore fluid mass content over time depend heavily on the diffusivity within the reservoir.
2) The induced mean stress is compressive below the point of extraction and slightly extensional along the flanks. Over time, the extensional zones migrate further outward and compressive zones further down.
3) The rate of fluid extraction is related linearly to the surface subsidence.

Segall's model has been applied successfully to demonstrate that the October 1996 event at Strachan Field in Alberta, Canada, (M = 3.9) was likely induced by hydrocarbon production (Baranova et al., 1999).

The model has also been tested through analog modeling by Odonne et al., (1999) who confirmed the general validity of the model albeit suggesting some minor deviations. See Figure 5 for a comparison of the model initially suggested by Segall (1985) and the modifications added by Odonne et al. (1999).

In 1992, Segall derived a second analytical solution to the poroelastic equations in which the permeable reservoir is assumed to be axisymmetric and disk- or dome-shaped. It is embedded in an impermeable half-space and fluids are extracted through a well located at its center. In this setup, fluid extraction is expected to have the following characteristics:

1) The decrease in pore pressure is related linearly to the surface subsidence.
2) The expected subsidence depends sensitively on the elastic and poroelastic properties of the reservoir. In the case of a stiff reservoir (e.g., Lacq gas field in France), only a few centimeters of surface subsidence are expected. In weaker reservoirs, however, subsidence might be substantial (e.g., Wilmington, Ekofisk, or Costa Oriental) requiring that nonlinear effects be taken into account.
3) The expected deformation depends on the depth of the reservoir. For a shallow reservoir, a radially symmetric decrease in pore pressure is expected to generate a ring of vertical depression. For a reservoir of intermediate depth, the depression is expected to be broader and decreases in amplitude towards the center. A sufficiently deep reservoir is expected to exhibit a central bulge of deformation.

The Lacq geometry makes it an ideal test-case for Segall's model and a successful one. The poroelastic model could both explain the observed linear relationship between pore pressure and maximum subsidence and reproduce the measured surface subsidence satisfactorily (Segall et al., 2004). Nonetheless, the details of the spatial and temporal distribution of seismicity at Lacq remain puzzling. For example, poroelastic modeling failed to offer an explanation for the decrease of seismic activity since 1980 or for spatial clustering (Grasso and Wittlinger, 1990).

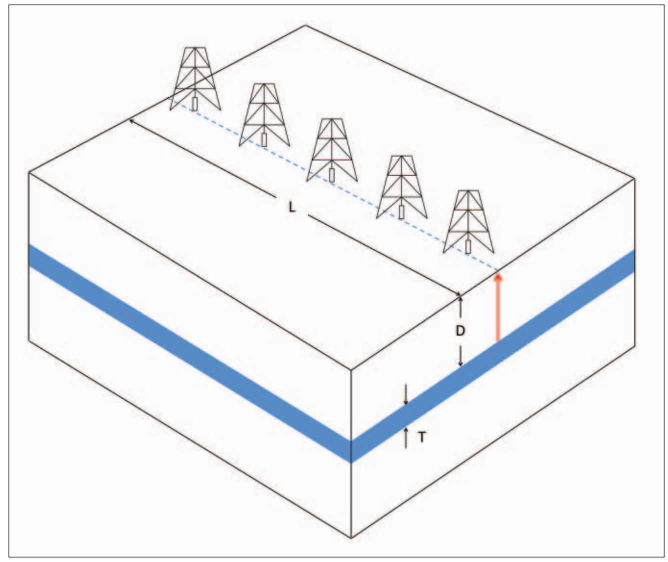

Figure 4. *Schematic geometry of the hydrocarbon field in the poroelastic model for fluid extraction from a horizontal layer by Segall (1985). The producing horizon of thickness T is located at depth D and is assumed to be embedded in an impermeable half-space. Fluid is extracted homogenously along the line of wells on the surface.*

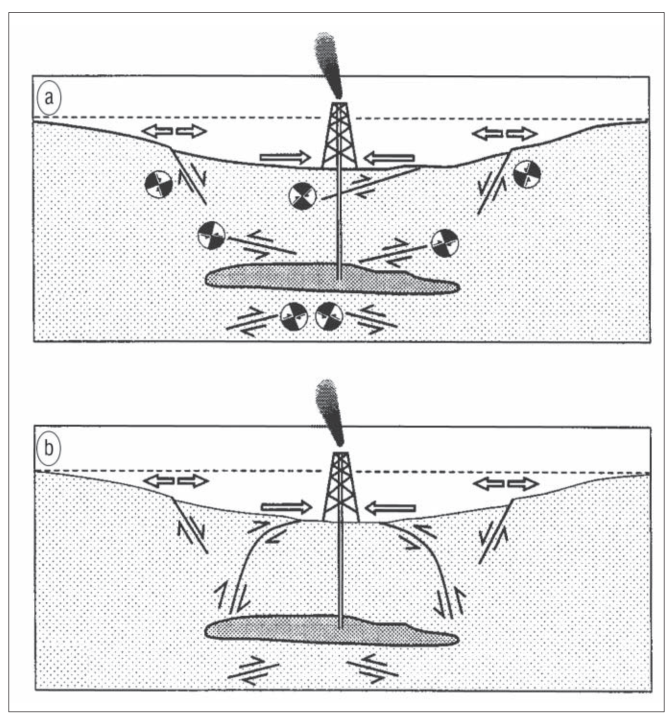

Figure 5. *Comparative cross sections summarizing surface deformation, faulting, and fault mechanisms around a hydrocarbon reservoir from which fluids are extracted. The top cross section (a) is based on Segall's poroelastic model and the bottom cross section (b) contains modifications suggested by Odonne et al. (1999), based on their analog experiments. White arrows indicate horizontal displacement and black errors the sense of faulting. The expected focal mechanisms are shown as beach balls. (Figure reproduced from Odonne et al., 1999).*

The controversy surrounding major midcrustal earthquakes

The cases of induced seismicity in hydrocarbon fields presented so far were characterized by small or moderate seismicity. Nonetheless, there are two examples of destructive earthquake sequences which occurred in the immediate vicinity of oil fields and were not clearly associated with a previously known fault. These incidents have given rise to speculation that hydrocarbon production might have the potential to cause destructive earthquakes. Apart from their size, a common feature of the two earthquake sequences in question is that they occurred at midcrustal depths. Therefore, the question about a possible connection to hydrocarbon production is closely related to the question of whether production-related stress perturbations could propagate to such large depths.

On 2 May 1983, an earthquake (magnitude ML = 6.7) occurred about 12 km northeast of the town of Coalinga, California. It was located approximately 35 km northeast of the San Andreas Fault, in a region that used to be characterized only by scattered seismicity. The proximity of the epicenter to two major oil fields, Coalinga Eastside and the Nose area of the Coalinga East Extension, raised the question about a potential connection to oil-field operations. Segall (1985) estimated that the poroelastic stress change as a consequence of fluid extraction was only approximately 0.01–0.03 MPa at hypocentral depth—a relatively small contribution given the overall stress drop associated with the earthquake. A detailed study initiated by the U.S. Geological Survey came to the similar conclusion that the earthquake was closely associated with a fault zone concealed beneath folds developed along the structural boundary between the Coast (Diablo) Ranges and the San Joaquin Valley. After the question of a production-related cause of the 1983 Coalinga earthquake had seemingly been answered, new interest arose after two other major events occurred in the vicinity of Coalinga: the 1985 Kettleman North Dome and the 1987 Whittier Narrows events. Both earthquakes happened to be located directly beneath important oil fields. McGarr (1991) fueled new debate on the topic by pointing to the similarity between the three events. He suggested that net extraction of oil and water might have reduced the average density of the upper crust, thus causing an isostatic imbalance. He further hypothesized that the deformation induced by this imbalance resulted in an increased load on the seismogenic layer. Based on this mechanism, McGarr expected that other California oil fields might be candidates for induced midcrustal seismicity, namely the oil fields that are both located along the Coast Range-Sierran Block boundary zone and characterized by high net liquid extraction such as Midway-Sunset, Belridge South, Elk Hills, Cymric, and McKittrick. However, apart from microseismicity related to hydraulic fracturing, no large or unexpected earthquakes have been associated with these oil fields.

Regarding the isostasy model, it is worth noting that dimensional analysis indicates that stress changes resulting from mass redistribution are small in comparison to poroelastic effects, shedding some doubt on their relevance for inducing large midcrustal earthquakes.

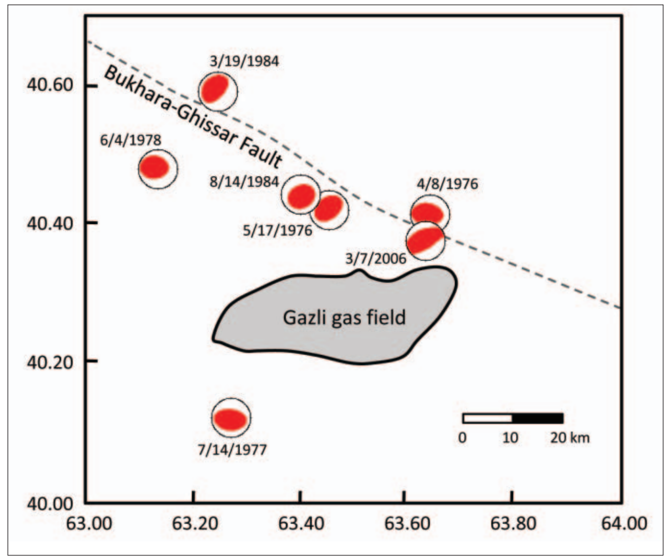

Figure 6. *Focal mechanisms of the major events in the immediate vicinity of Gazli Field (indicated in gray) as listed in the Harvard CMT catalog. Numerous more events (> 7000) were located by the Uzbek network (e.g., Bossu et al., 1996).*

The second sequence of major earthquakes that might be production-related occurred in the immediate vicinity of Gazli gas field about 100 km northwest of Bukhara, Uzbekistan. The first major event occurred on 8 April 1976 (magnitude MS = 7.0). A few weeks later, 17 May 1976, it was followed by a second, similarly sized event (MS = 7.0) approximately 20 km west of the first event. A medium-sized event (MS = 5.7) occurred on 4 June 1978. A few years later, on 19 March 1984, a fourth major event (MS = 7.0) was recorded 15 km southwest of the second event in 1976. The earthquake sequence caused severe damage in the city of Gazli. Numerous papers have argued for and against the possibility that one or several of the Gazli events were related to field operations. The most comprehensive study was a collaborative field survey initiated in 1991 by the University of Grenoble and the Academy of Sciences of the Uzbek Republic. Based on this data, Bossu et al. (1996) came to the conclusion that the events at Gazli are most likely of tectonic origin, because the stress disturbance created by field operations at hypocentral depth were insufficient to cause a major earthquake. The two main arguments invoked in favor of a connection between seismicity and hydrocarbon production are:

1) The absence of any major events (M > 6.5) in the area since 1208 in combination with a notable clustering of activity since 1976 (Figure 6).
2) The selective and erratic production patterns at Gazli which resulted in drastic surface-level changes of the gas-water contact by over 40 m in the northern and eastern part of the field.

Plotnikova et al. (1996) investigated the large temporal and spatial variations in pressure and concluded that these were sufficient to impact seismicity. Thus, the question of whether or not the Gazli sequence was induced ultimately hinges on evaluating which stress disturbance and which rate of stress change is significant. It might never be possible to conclusively answer that question, but the case of Gazli highlights the possibility of inducing earthquakes through erratic production rates. Continuing that line of thought, it is worth wondering whether the earthquakes and the damage they caused could have been prevented through a more careful extraction strategy?

Conclusions and outlook

The interest in induced seismicity in hydrocarbon fields was initially provoked by several prominent cases of hydrocarbon fields (e.g., Wilmington, California) for which a connection between seismicity and hydrocarbon production was suspected. Over the last few decades, this question has been investigated in at least 70 cases (see Table 1 and Figure 1) based on spatial and temporal associations of seismicity and field operations.

While quantitative models exist on which the production-related stress perturbation can be estimated, two main challenges in applying these remain: the lack of detailed information about production rates and patterns and the inherent difficulty of judging whether a certain perturbation is significant in comparison to the preexisting tectonic stress field or not. These difficulties highlight the ambiguity of drawing a strict line between natural and induced events.

In regions where induced seismicity is common, such as in the northern part of the Netherlands, it has become a social concern. Since 2003, Dutch mining laws require quantitative estimates of the likelihood of future seismic activity and the associated damage for every onshore field. Already, the traditional tools of probabilistic seismic hazard analysis have been extended to assess the hazard posed by induced seismicity in actively producing fields (Van Eck et al., 2006). Deriving an estimate for expected future hazard prior to production, however, is even more demanding and requires knowledge of the factors that control induced seismicity, which remain little understood. Based on the correlation between hydrocarbon production and seismicity in the Netherlands, Van Eijs et al. (2006) investigated whether certain reservoir properties make hydrocarbon fields more prone to induced seismicity. Adushkin et al. (2000) attempted a similar compilation on a global scale. Continued data acquisition, monitoring, and modeling of induced seismicity over the next decades will hopefully allow us to determine whether the patterns observed in these two studies are statistically significant.

Another concern which is often closely related to that of induced seismicity in hydrocarbon fields is surface subsidence (e.g., at Goose Creek, Wilmington, Groningen, Caviaga, and Costa Oriental). The relationship between subsidence and seismicity is more complex than one might think: for some hydrocarbon fields, such as Ekofisk, subsidence was long thought to occur aseismically, but the moderate event that occurred at Ekofisk in 2001 demonstrated the uncertainty associated with such judgments. In other cases, such as Wilmington, California, substantial subsidence had been associated with a continued sequence of seismic events of moderate-to-large size. The combination of subsidence and seismicity caused considerable damage in the port of Long Beach, California. The costs of the largest earthquake at Wilmington Field, which occurred on 17 November 1949, exceeded US$9 million at that time.

From a theoretical point of view, it is not surprising that the connection between subsidence and seismicity is highly variable and complex; large stresses are more likely to build up in stiff rock, which because of its stiffness, will only yield modest subsidence. It should also be noted that, in the case of Goose Creek oil field, surface subsidence also had legal consequences. The question of potential legal implications of induced seismicity in the USA is discussed in detail by Cypser and Davis (1998).

Concluding, I hypothesize that the following three research areas will have particular potential for advancing our understanding of induced seismicity in hydrocarbon fields, namely:

1) The development and testing of tools for probabilistically assessing the hazard associated with induced seismicity both prior and during production.
2) The acquisition of high-quality data sets and the integration of different data-sets to form a more complete picture of how the reservoir properties change over time.
3) The development of more sophisticated geomechanical and geochemical models for understanding production-related changes in hydrocarbon reservoirs.

Finally, I believe that the field would benefit from a more intense dialogue between industry, academia, and the public. This brief overview of observational evidence and modeling approaches is intended to add to this exchange. Hopefully, it will be complemented by and expanded upon by future studies. TLE

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