INDUCED SEISMICITY IN HYDROCARBON FIELDS

JENNY SUCKALE

ABSTRACT

Over the last few decades, it has become clear that various human activities have the potential to generate seismic activity. Examples include subsurface waste injection, reservoir impoundment in the vicinity of large dams, and development of mining, geothermal or hydrocarbon resources. Recently, induced seismicity has also become a concern in connection with geologic carbon sequestration projects. This study focuses on seismicity induced by hydrocarbon production by summarizing the published case studies and describing current theoretical approaches to model these. It is important to understand the conditions under which hydrocarbon production may lead to seismic activity in order to ensure that they are performed safely. Our knowledge of induced seismicity in hydrocarbon fields has progressed substantially over the last few years owing to more intensive high-quality instrumentation of oil fields and a continuous effort to understand the phenomenon theoretically. However, much of the available literature is dispersed over a variety of journals and specialized reports. This review aims at providing a first step toward making the current knowledge about induced seismicity in hydrocarbon fields more accessible to a broad audience of scientists.

KEY WORDS: Induced seismicity, hydrocarbon fields, poroelasticity, seismic hazard, monitoring, fluid extraction, fluid injection, midcrustal earthquakes, microseismicity.

1. INTRODUCTION

Numerous human activities are known to induce seismic activity of varying magnitudes. Patterns of induced seismicity vary from (1) continued microseismicity (e.g. mines as well as hydrocarbon and geothermal fields), (2) intense microseismicity for a short time after a certain event (e.g. hydraulic fracturing), (3) moderate seismic activity in the magnitude range between two and four (e.g. hydrocarbon fields and mines), to (4) catastrophic activity of magnitude 6 and above (e.g. reservoir induced seismicity). The largest induced earthquakes have been related to reservoir impoundments at Koyna Dam, India (Guha et al., 1971; Singh et al., 1975; Gupta and Rastogi, 1976), Hsingfengchian (also Xinfengjiang) Dam, China (Shen et al., 1974; Miaoyueh et al., 1976; Wang et al., 1976), Kariba Dam, Zambia/Zimbabwe (Gough and Gough, 1970), and Kremasta, Greece (Simpson, 1976; Stein et al., 1982). At least two of these, Kremasta and Koyna, caused deaths, injury and extensive property damage (Simpson, 1976; Guha, 2000).

Induced seismicity in hydrocarbon fields is typically small to moderate ($M_L \leq 4.5$). However, a connection to hydrocarbon production has also been suspected for two destructive earthquake sequences at Coalinga, USA, 1983-1987, and Gazli, Uzbekistan, 1976-1984 (see Section 6). While available observational evidence and theoretical
modeling indicate that the Coalinga sequence was probably not induced, the case of the earthquakes at Gazli field remains controversial. Should there be a connection between the Gazli earthquakes and hydrocarbon production, then these events would constitute the largest seismic events caused by human activity until today.

Before delving into a discussion of various cases for which a connection between hydrocarbon production and seismic activity might exist, it is worth noting that which events are considered to be “induced” is largely subjective. Quantitative models (Sections 4 and 5) focus on assessing changes in stress and/or pore pressure, but it is unlikely that any event is driven by these perturbing effects alone. The pre-existing stress field also plays an important role. Thus, a key challenge lies in deciding whether a given, production-related perturbation in stress or pore pressure is significant. This challenge is usually further exacerbated by lack of knowledge of the pre-existing stress field and exact production levels.

We have assembled 70 cases of hydrocarbon fields for which a connection between unusual seismicity patterns and hydrocarbon production has been suggested in the scientific literature (see Table 1). A striking feature is that occurrence of induced seismicity seems to have a distinctly regional character. It is most commonly observed only in two sedimentary basins, namely in the Permian basin, Texas, and in the Rotliegendes, Netherlands. In both regions, there were attempts to identify criteria why seismicity is induced only in certain fields and not in others, but with limited success (Doser et al., 1992; Van Eijs et al., 2006).

Not all induced seismicity in hydrocarbon fields is unwanted: hydraulic fracturing is commonly used to increase the permeability of a hydrocarbon reservoir through intentional creation of new fractures. Monitoring of the associated microseismicity can give important insight into the fracture pattern and fluid migration. Despite its importance for hydrocarbon development, we largely refrain from discussing hydraulic fracturing in this review. The reason is that during hydraulic fracturing seismicity is induced intentionally and thus constitutes a different phenomenon meriting separate treatment. That being said, it is inevitable to touch on hydraulic fracturing briefly in the context of seismic-monitoring techniques in hydrocarbon fields, since these draw heavily on advances made in the context of hydraulic fracturing.

The main focus of this review is a compilation of the observational evidence for induced seismicity in hydrocarbon fields and theoretical attempts to understand it (for a previous review see Grasso (1992b)). Induced seismicity in hydrocarbon fields can be broadly classified as being primarily related either to fluid injection or to fluid extraction. Needless to say, most cases cannot be easily grouped into one of these categories, because of concurrent fluid extraction (reservoir depletion) and injection (secondary recovery) and because fracturing of the involved geological units can lead to complex interconnected flow patterns throughout the field. Nevertheless, this categorization has proven useful in thinking about induced seismicity and it provides the starting point for most theoretical models.

This review is structured in the following way. In Section 2, we list all hydrocarbon fields for which a connection between seismicity and hydrocarbon production has been suggested in the scientific literature. We also summarize the most common observations regarding induced seismicity in hydrocarbon fields and briefly discuss the phenomenon that cases of induced seismicity are particularly common in certain regions.
Section 3 briefly discusses recent advances in seismic monitoring of hydrocarbon fields experiencing induced seismicity. Section 4 deals with injection induced seismicity and Section 5 with seismicity induced by the extraction of fluids. Section 6 reviews the controversy whether hydrocarbon production could induce major midcrustal earthquakes. Finally, Section 7 gives a brief summary and highlights important open questions.

2. Case Studies, Common Observations and Regional Occurrence

2.1. Documented Case Studies

The total number of hydrocarbon fields in which induced seismicity has been reported is difficult to pinpoint. An overview of all cases for which induced seismicity has been suspected in the scientific literature is given in Table 1. It is important to keep in mind that this list should not imply that all of these hydrocarbon fields truly exhibit induced seismicity. For some cases, a connection is generally agreed upon (e.g. Lacq, France), while for others (in particular: Coalinga, Kettleman, and Montebello fields, California) it is controversial or even unlikely. Contrary to a prior compilation (Grasso, 1992b), we list all cases discussed in the literature and not only those in which seismic activity exceeded a certain minimum magnitude. The reason is that information about magnitudes is not always available and, if it is, it might not be comparable for different fields due to the utilization of different magnitude scales. Finally, we stress that Table 1 does not contain hydrocarbon fields in which microseismicity was induced intentionally through hydraulic fracturing experiments.

The overview in Table 1 is inevitably incomplete for several reasons. (1) Induced seismicity in hydrocarbon fields typically falls into a small to moderate magnitude range. Thus, it might not be detected unless a local network is operated in its immediate vicinity. (2) The presence of natural seismicity can obscure the existence of induced events. (3) A lot of research regarding induced seismicity is done by the industry and not always publicly available.

2.2. Common Observations

Induced seismicity is related to stress changes in the reservoir and surrounding rocks that can be caused by various mechanisms ranging from pore pressure variations, to geochemical reactions, temperature effects, and either locking or reactivation of pre-existing faults. Accordingly, the patterns of induced seismicity vary a lot for different fields or events within the same field over space and time. For example, the substantial subsidence at Ekofisk field, North Sea, Norway, was considered as largely aseismic. Nonetheless, a sizeable event $M_w = 4.1 - 4.4$ occurred within the field in May 2002 (Ottemöller et al., 2005). A map of the regional seismicity around Ekofisk field is shown in Figs 1 and 2. Despite this variability in seismicity patterns, a few general observations can be made.

1. **Magnitude Range:** In most hydrocarbon fields, induced seismic activity has been limited to small and moderate magnitudes ($M_L \leq 4.5$).
2. **Correlation with production:** It is often challenging to determine the correlation between seismicity and hydrocarbon production exactly because of the lack of data detailing the production pattern at various wells. In cases where production data is
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available, an obvious correlation between production and seismic activity – in the sense of elevated seismicity levels immediately after increases in production rate – is rarely observed. An important exception is the controlled experiment at Rangely field (see Section 4.1). Furthermore, more complex correlations between temporal and spatial patterns of seismicity and production have been reported for various cases (see Sections 4 and 5).
3. **Location:** Induced seismicity often occurs either directly below or directly above the reservoir (e.g. Lacq (Grasso and Wittlinger, 1990) and War-Wink (Doser *et al.*, 1991)). This is illustrated for the Lacq field through the depth sections in Figs 3 and 4.

4. **Spatial clustering:** Nearly all studies of induced seismicity in hydrocarbon fields (e.g. Rangely (Raleigh *et al.*, 1976), Gobles (Mereu *et al.*, 1986), Sleepy Hollow (Evans and Steeples, 1987), Romashkino (Turuntaev and Razumnaya, 2002), and Lacq (Bardainne *et al.*, 2006)) have confirmed that earthquakes have a pronounced tendency to form clusters or swarms. Often it is possible to associate a substantial part of the observed seismicity with a pre-existing fault or heterogeneity (e.g. Valhall (Arrowsmith and Eisner, 2006), Fashing, Imogene (Pennington *et al.*, 1986), Lacq (Grasso, 1992b), and Shuaiba (Sze, 2005)). Figure 5 shows the
Fig. 3. Schematic representation of Lacq field (contour lines mark the depth to the top of the gas reservoir) and the induced seismicity associated with it. In accordance with Fig. 4, triangles represent events that occurred between 1976 and 1979 and circles those that occurred between 1982 and 1992. The location of epicenters was computed based on the velocity model by Guyoton et al. (1992). The boxes correspond to the location and width of the two cross sections shown in Fig. 4. 

Source: Figure reproduced from Segall et al. (1994, Fig. 3, p. 15426).

correlation between microseismicity recorded at Shuaiba field and the fault lines cutting through it.

5. Temporal patterns: A characteristic time lapse of several years between the beginning of production and notable increases in the seismicity level has been observed in numerous fields (e.g. Sleepy Hollow (Rothe and Lui, 1983), Cogdell Canyon Reef (Davis and Pennington, 1989), Strachan (Baranova et al., 1999), Lacq (Grasso and Wittlinger, 1990), and Wilmington (Kovach, 1974)). It should be noted, however, that quality of recording contributes to the perceived time lapse: Instrumentation is typically increased as a response to seismicity being felt by the population or observed by other networks. Thus, a potential buildup of seismicity might occur but go by unnoticed. On the other hand, in the case of extraction induced seismicity, a time-lapse between production and seismicity is in accordance with theoretical expectations from poroelastic modeling (Segall, 1985).

6. Faulting: The faulting in hydrocarbon fields which exhibit induced seismicity is dominated by the pre-existing stress field, since production-related stress pertubations are small in comparison. Nonetheless, production can lead both to the activation of pre-existing faults (e.g. Valhall (Zoback and Zinke, 2002), Fashing, Imogene (Pennington et al., 1986), and Rotliegendes (Van Eijs et al., 2006)) or
Fig. 4. Vertical cross sections through the reservoir at Lacq field. Location of the width of the cross sections is shown in Fig. 3. The gas reservoir is indicated by the regions shaded in gray. In accordance with Fig. 3, seismic activity between 1976 and 1979 is marked by triangles and that between 1982 and 1992 by circles.

Source: Figure reproduced from Segall et al. (1994, Fig. 4, p. 15426).

to the formation of new faults as has been documented amongst others for Goose Creek (Yerkes and Castle, 1976) and Wilmington (Kovach, 1974). In the latter two cases, the formation of new faults is correlated with substantial subsidence due to extensive fluid extraction.

7. Source Mechanisms: The source mechanism of induced seismicity remains a topic of active research. Although many events tend to be well described by a double-couple mechanism, notable exceptions exist (e.g. Console and Rosini (1998); Talebi and Boone (1998); Foulger et al. (2004); Vavrycuk et al. (2008)). In fact, a special session of the 2008 meeting of the European Seismological Commission was devoted to non-double-couple cases.

Finally, we note that anisotropy studies have recently become a common tool in the industry to characterize dynamic changes in hydrocarbon reservoirs as reviewed by Helbig and Thomsen (2005); Crampin and Peacock (2005). In the context of fields with induced seismicity, a striking correlation between shear-wave anisotropy and subsidence
FIG. 5. Illustration of the collapsing technique for improving the localization of induced microseismicity. Shown are the locations of epicenters recorded at Shuaiba field prior to (top) and after collapsing (bottom), as well as the relevant tectonic features. Collapsing clearly reduces the scatter in localizations.

Source: Figure reproduced from Sze (2005, Fig. 2.21, p. 65).)

has been observed, in particular for Ekofisk (Van Dok et al., 2003) and Valhall (Olofsson et al., 2003). A plot of the azimuthal anisotropy and the measured seabed subsidence for Valhall is reproduced in Fig. 6. As pointed out by Olofsson et al. (2003), the azimuthal anisotropy is largest where the strain associated with subsidence is largest.
This correlation could be caused by small cracks formed during reservoir subsidence which lead to a directionally dependent shear-wave speed. We note that not only shear waves but also compressional waves have been used successfully to characterize spatial variations in hydrocarbon fields (e.g. at Valhall (Hall and Kendall, 2003)).

2.3. Regional Occurrence

According to Perrodon (1983) there are about 600 sedimentary basins worldwide out of which 400 have been drilled and 160 are (or were) used for commercial hydrocarbon production. Only 25 of these represent cumulative discoveries of substantial size (more than 1.4 billion tons) and thus concentrate about 85% of the total worldwide discoveries to date. Out of these 25, frequent incidents of induced seismicity have been clearly established only for two, namely the Permian basin, Texas, and Rotliegendes, Netherlands. However, even in these two regions not all hydrocarbon fields are similarly affected (Doser et al., 1992; Van Eijs et al., 2006). This observation raises the question why seismic activity is induced in certain regions and within these regions why only in certain fields and not in others.
Although numerous oil and gas fields are located in the Permian Basin, only a limited number of these fields exhibit induced seismicity in a magnitude range that is sufficient for surface recording. Clearly, this does not imply that microseismicity might not exist at depth. The relationship between induced seismicity and oil production in the Permian Basin was investigated by Doser et al. (1992). Based on a careful relocation of the seismic events recorded between 1975 and 1979, the authors found that seismicity appears to be correlated to a variety of effects including fluid migration, natural occurrence of overpressured fluids, tectonic activity, reservoir production, and enhanced recovery operations. For example, Doser et al. (1992) observed that seismicity in both the War-Wink and the Apollo-Hendrick fields tends to cluster in regions where the horizontal pressure gradient exceeds 15 MPa/km. Interestingly, seismic activity is not confined to the extent of the hydrocarbon fields: more than half the events occurring outside the Permian Basin network (or after it had ceased operation) were located between fields, which could indicate the importance of fluid movement or pressure gradients between fields (Doser et al., 1992). We note that an event with magnitude $m_b = 4.7$ to $m_{blg} = 5.0$ occurred in the region on January 2, 1992 highlighting the importance of assessing the possibility that moderate to large events could be induced by hydrocarbon production.

In the large on-land gas reservoirs in the Netherlands induced seismicity is such a commonly observed phenomenon that Dutch law requires a seismic hazard and risk estimate study for each concession since 2003 (Van Eck et al., 2006). Out of the 124 producing fields, 16 have shown induced seismicity (Van Eijs et al., 2006). For an overview of the hydrocarbon fields exhibiting induced seismicity in the Netherlands see Fig. 7. While natural tectonic activity occurs in the southern part of the Netherlands, induced seismicity is mostly confined to the north. An overview map of natural and induced seismicity in the Netherlands is reproduced from Van Eck et al. (2006) in Fig. 8. Though most of this activity is small in magnitude ($M_L \leq 3.5$), it is shallow in depth and thus occasionally causes non-structural damage (Van Eck et al., 2006).

The three most active fields in terms of induced seismicity in the Netherlands are Groningen, Roswinkel, and Bergermeer fields. Groningen is the largest gas field in the Netherlands. Out of the roughly 340 induced events recorded until 2006, about 180 epicenters occurred in Groningen Field alone (Van Eck et al., 2006). Most of these earthquakes seemed to occur along NW-SE trending faults at reservoir level in the northwestern part of the field. Compared to Groningen, Roswinkel, and Bergermeer are both relatively small gas fields. Interestingly, the observed seismicity patterns in these two fields are quite different from each other: while the Bergermeer field has so far only generated 4 moderately sized events ($3.0 \leq M_L \leq 3.5$), more than 36 events ranging from small ($M_L \geq 1.0$) to moderate size ($M_L \leq 3.4$) have been recorded at Roswinkel (Van Eck et al., 2006).

This observation has been interpreted as evidence for the hypothesis that induced seismicity is a chaotic phenomenon (Van Eck et al., 2006). A similar hypothesis was also investigated by Grasso and Sornette (1998) and led the authors to conclude that the potential seismic hazard associated with areas of large pre-existing stresses might extend well beyond the zone where natural activity is common. Van Eijs et al. (2006) tested the correlation between reservoir parameters, production characteristics, and the occurrence of induced seismicity in the northern part of the Netherlands in an attempt to identify which hydrocarbon field might be prone to induced seismicity before production
begins. They concluded that three key parameters (pressure drop, fault density in the reservoir, and stiffness ratio between the seal and the reservoir rock) showed a correlation with seismicity and identified critical values that each of these parameters has to exceed in order for induced seismicity to occur. Their analysis is supported by numerical models (Mulders, 2003) and based on the observation that induced seismicity in the Netherlands is probably primarily the result of reactivation of normal faults in the reservoir. Future investigations will show whether these findings can be successfully applied to anticipating seismic hazard.

3. Seismic Monitoring

The monitoring of induced seismic activity is pivotal for improving our understanding of the phenomenon. Many of the advances in the continuous monitoring of microseismic...
Fig. 8. Overview of the seismicity in the Netherlands and surroundings since 1900, reproduced from Van Eck et al. (2006). The radius of the circles is a measure of the magnitude of the event. The shading of the circles indicates the nature of the event: dark gray for natural tectonic events and light gray for earthquakes that were induced by human activity. Note that this map includes induced seismicity from both mining and hydrocarbon production. Gas fields are highlighted in gray. Mapped fault lines are plotted in gray.

Source: Figure as given by Van Eck et al. (2006, Fig. 1, p. 106).

and acoustic activity (Albright et al., 1994) were pioneered in the geothermal (the earliest studies include Pearson (1981) and Albright and Pearson (1982), and many followed thereafter), and mining industry (see Gibowicz and Lasocki (2001) for a recent review of mining induced seismicity). Amongst others, it was demonstrated that the quality of the collected data was sufficient to allow tomographic imaging of the fractured
volume (Block et al., 1994). However, the majority of geothermal experiments have taken place in hard-rock environments, which are characterized by an efficient propagation of elastic waves. Contrary to this, most hydrocarbon reservoirs are located in sedimentary environments with less favorable properties. This led to the notion that microseismic monitoring is only applicable to reservoirs with high rock velocities (Jupe et al., 1998). Nonetheless, recent studies (Jupe et al., 1998; Phillips et al., 1998) in environments ranging from shallow unconsolidated sands to chalks showed that this concern is not necessarily justified. Thus, interest in using induced seismicity to monitor reservoir dynamics in hydrocarbon fields has grown considerably during recent years (Jupe et al., 1998; Fehler et al., 2001; Maxwell and Urbancic, 2005).

Apart from hydraulic fracturing not discussed in this review, the most relevant applications of passive monitoring in hydrocarbon fields are as follows.

1. Improving well and casing design: Hydrocarbon production from the soft chalk formation at Valhall field led to compaction, which resulted in casing deformations in the overburden. Since production began in 1982, 28 out of 102 production wells have suffered severe tubular deformations (Kristiansen et al., 2000). The observation that the locations of microseismic events correlated well with the distribution of casing deformations demonstrated the potential of continuous microseismic monitoring for improving well constructions and led to the installation of a permanent array on the seafloor with 120 km of ocean-bottom-seismometer cable and more than 10,000 geophones and hydrophones covering the field. The main purpose of the array is 4D monitoring (see Section 7), but its potential for passive monitoring is being actively investigated as well. This innovation was honored with the 12th Offshore Northern Seas Innovation Award that was awarded to BP Norway.

2. Fault mapping: During a temporary microseismic monitoring project of 18 days at Ekofisk field, it was possible to identify the fault pattern under the gas cloud on top of the reservoir, which obscures the structure in classical active source studies (Maxwell and Urbancic, 2005), see Fig. 9.

3. Mapping fluid movements: Based on a comparison of the location of the seismically active faults at Seventy-six oil field, Kentucky, in combination with additional data regarding the production history, well logs and drill tests, Rutledge et al. (1998) concluded that the seismically active fractures in the field had been partially drained by previous production and subsequently re-saturated with brine (water).

Two key issues in monitoring microseismicity successfully are (1) accuracy of event location and (2) reduction of ambient noise. While the latter is mostly dependent on a careful installation and sensitive, low-noise instrumentation (Maxwell and Urbancic, 2005; Kristiansen et al., 2000), event localization remains challenging. Conventional earthquake location techniques are usually insufficient to get detailed information about reservoir structure, fracture orientation, and hydraulic behavior (Fehler et al., 2001). Apart from the generally low magnitude of events, the limited availability of wells or boreholes requires severe compromises regarding the ideal spatial distribution of sensors.

Adequate localization of events is particularly critical to the study of induced seismicity, because the spatial correlation between earthquake occurrence and
hydrocarbon production wells is usually the main indication for a possible connection between the two phenomena. There were a number of cases in which the possibility that the earthquake might have been induced was only realized after a more precise relocalization of the event. One example is the event on 20 October 2004, ($M_L = 4.5$) at Rotenburg/Soltau, Germany (Dahm et al., 2007).

Since there typically is limited flexibility regarding the network geometry, recent research efforts concentrated mostly on the development of sophisticated processing techniques. Important progress in this context was made through the international research collaboration project named “More Than Cloud (MTC)” initiated in 1992 by Professor Hiroaki Niitsuma, Tohoku University. The goal of the MTC project was to develop new technology that would allow resolving more details in a “cloud” of microseismicity (Fehler et al., 2001). One of the main accomplishments of the MTC project was the development of a new location technique called “collapsing” (Jones and Stewart, 1997). The key idea behind collapsing is to use the location uncertainties as a guide in processing the data.

An example of how collapsing can improve the localization of induced seismicity is the Shuaiba oil reservoir. Sze (2005) compared the results of different location algorithms to assess the stability of the epicentral relocations and to estimate reasonable bounds on the relocation errors. The microseismic data utilized by Sze (2005) in his study were collected by the Petroleum Development Oman (PDO) using a downhole geophone array between October 1999 and June 2001. The network recorded 802 events during this period. The effect of collapsing on the observed seismicity pattern as previously determined by the nonlinear grid-search technique is illustrated in Fig. 5. The top figure shows the epicenters of microseismicity before collapsing, and the bottom figure, after. The scattering of events is notably reduced. The relocated seismicity now delineates the complex zone of faults of Shuaiba field more clearly.
4. SEISMICITY INDUCED BY FLUID INJECTION

It is well known and not unexpected that fluid injection can induce seismic activity, because it decreases the effective stress: the injected fluid enters a pre-existing fracture and supports a part of the normal stress equivalent to the pressure of the fluid. As the fluid has no shear strength, the effective normal stress and the frictional resistance to sliding are lowered. If the fracture is subject to shear stress greater than the product of this effective normal stress and the coefficient of friction, the rock will slip and generate an earthquake. The argument is visualized in Fig. 10 through a Mohr circle with a Coulomb type failure criterion. In the earlier literature, the same argument is also referred to as the Hubbert-Rubey principle of effective stress.

Nicholson and Wesson (1992) listed more than 30 documented cases of potential injection induced seismicity in the USA and Canada alone, most of which are not related to hydrocarbon production but to fluid injection in different contexts. In hydrocarbon fields, massive injection of fluids is used for a variety of purposes including: (1) to replace extracted fluids in a field that has been under production for a while (secondary recovery), (2) to stimulate production by creating fractures and thereby producing new flow conduits (hydraulic fracturing), (3) to sweep fluids to producing wells, and (4) for pressure maintenance. Often the transition between these strategies is gradual.

4.1. Controlled Experiments of Fluid Injection in Hydrocarbon Fields

The Mohr-Coulomb argument of reduction of effective stress invites the conjecture that it might be possible to control earthquakes through variation of fluid injection rates. This hypothesis was tested in an experiment at Rangely oil field (Raleigh et al., 1976). At Rangely field, secondary recovery of oil through injection of water at high pressures had started in 1957. The exact date of onset of seismicity is not known. Between November

Fig. 10. Mohr diagram illustrating the effect of how injection of fluids brings a rock closer to failure.
Source: Figure as given by Sminchak and Gupta (2003, Fig. 2, p. 83).
1962 and January 1970 the Uinta Basin Observatory recorded 976 earthquakes in its immediate vicinity (Gibbs et al., 1973). In fact, Gibbs et al. (1973) had already suggested a connection between the fluid injections and the recorded seismicity, but did not observe a correlation between pressure and seismic activity similar to that later found by Raleigh et al. (1976).

The experiment at Rangely oil field began in 1969, when a seismic network of 14 short-period, vertical seismometers was installed. For one year, the network recorded the seismic activity under unaltered fluid pressure conditions. During that time, Raleigh et al. (1972) used hydraulic fracturing of rock in boreholes to quantify the in-situ state of stress. Given these results and their analysis of the orientation of the fault and slip direction determined from focal plane solutions of nearby earthquakes, the authors published a prediction about the critical pressure (Raleigh et al., 1972). Between October 1969 and May 1973, two full cycles of increased fluid injection and backflowing were performed at Rangely. Raleigh et al. (1976) found that seismic activity responded promptly to changes in fluid pressure. They concluded that the experiment at Rangely had both confirmed the hypothesis that (1) earthquakes could be induced by increases in pore pressure and (2) that a simple Mohr-Coulomb argument based on the reduction of effective stress accounts for this phenomenon not only qualitatively, but also quantitatively. Figure 11 shows the fault plane solutions of the seismic activity recorded during the experiment.

Unfortunately, this type of clear correlation between induced seismicity and injection patterns is only found in the context of hydraulic fracturing experiments. The described experiment at Rangely field falls into this category (despite evidence for previous activity) as well as 76 field, Kentucky and Carthage Cotton Valley gas field, Texas, for which similar correlations have been reported (Rutledge et al., 1998; Rutledge and Phillips, 2003).
4.2. Moderate Seismicity Related to Fluid Injection

Although fluid injection is typically associated with microseismicity, several events with moderate to large magnitudes have also been related to fluid injections and it is important to understand better the conditions under which moderate to large events might occur. No obvious correlation between seismicity and injection rate could be established for any of the cases exhibiting moderate seismicity. Partly, this might be due to inaccuracies in the location of hypocenters (e.g. Sleepy Hollow field (Evans and Steeples, 1987)) and missing data regarding the precise injection pattern (e.g. Gobles field (Mereu et al., 1986)). Also, it is important to note that injection and depletion generally happen at different wells, which leads to a complex underground flow pattern. Thus, it is not always clear as to how the volume of fluid injected is related to the spatial variations in net pore pressure.

An additional complexity arises from the commonly observed time lapse between the beginning of fluid injections as a means of secondary recovery and the onset of seismic activity. For example, at Sleepy Hollow field, Nebraska, fluid injection for the purpose of enhancing oil production was initiated in 1966, six years after the discovery of the field (Rothe and Lui, 1983). The first indication of augmented seismic activity in the immediate vicinity of the oil field dates back to 1977. During 1979-1980, a first array of four portable seismographs was operated and in 1982 the U.S. Geological Survey installed an eight-station telemetered analog network. Rothe and Lui (1983) suggested that there probably was a connection between the earthquakes and hydrocarbon production, but were unable to rule out a tectonic cause. Evans and Steeples (1987) reassessed their results a few years later. They noted no significant correlation between average injection pressure and earthquake occurrence, but did not consider this finding 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.

One of the largest events in likely association with an injection operation had magnitude 4.6-4.7 and occurred at Cogdell Canyon Reef field in June 1978 (Harding, 1981; Nicholson and Wesson, 1990). Water injection as a means of secondary recovery was used at Cogdell Canyon Reef since April 1956 (Davis and Pennington, 1989). Following this event, the U.S. Geological Survey operated a local network from February 1979 to August 1981, which located a total of 20 epicenters in the Cogdell oil field. Additionally, the University of Texas/NASA seismic array recorded seismic activity in the Snyder area from April 1977 to February 1979 (Dumas, 1979). Based on this data, Davis and Pennington (1989) tested both the classic Mohr-Coulomb failure model and whether stress loading might have resulted from the weight of injected fluids. They concluded that both mechanisms are relevant, since if fluid pressures alone controlled the seismicity, it would be expected that seismic activity is concentrated in areas of high fluid pressure, which was not observed. We note that it is contentious whether the weight of fluid plays an important role in induced seismicity, because dimensional analysis suggests that this effect is comparatively small (Segall, 1985).

Another interesting case regarding the correlation between production rates and induced seismicity is that of the Romashkino oil field, Russia. From 1986 to 1992 a local seismic network operated by the Tatnaftegeophysica seismic service recorded 391 local events with magnitudes up to 4.0 (Adushkin et al., 2000). An epicenter map of the
Seismic activity at Romashkino field is shown in Fig. 12. Although a connection between production and seismic activity is not immediately obvious, Turuntaev and Razumnaya (2002) found quasi-harmonious oscillations of seismic activity, which are synchronized in time with changes of injection effectiveness. Taken over the entire observation period, seismic activity in Romashkino oil field occurred in two cycles, each lasting for about five years. Figure 13 shows a smoothed plot of the normalized seismic activity during these two cycles superimposed. Certain aspects of the two curves coincide. Most of the literature on Romashkino is in Russian; additional references can be found in Adushkin et al. (2000) and Turuntaev and Razumnaya (2002).

Despite these examples of injection induced seismicity, it is important to note that most hydrocarbon fields subject to similar secondary-recovery measures do not respond with increased seismic activity. Very little is known about why moderate seismic events are induced in some cases and not in others. Several attempts have been made to
generalize known case studies (e.g. Kisslinger (1976) and Davis and Frohlich (1993)), but with moderate success.

4.3. Stress Corrosion and Geochemical Processes

There is little doubt that material properties of reservoir rocks and geochemical processes play a role in understanding induced seismicity. The potential importance of stress corrosion as a mechanism relevant to induced seismicity in fluid injection environments was first pointed out by Kisslinger (1976). Laboratory experiments have proven that the time to failure is shortened substantially by increasing the water content in quartz. Similarly, the rate of crack growth under a constant load is accelerated in quartz with higher water content (Martin, 1972; Scholz, 1972). The presumed cause for this weakening or static fatigue, is the hydration of silicon-oxygen molecules, indicating that the effect might occur generally in silicate rocks and thus be relevant in the context of induced seismicity. A connection between stress corrosion and seismicity has also been hypothesized for Fashing gas field, Texas (Davis et al., 1995).

Possibly the best known case for the importance of geochemical processes for reservoir management is Ekofisk field, North Sea, Norway. Although Wilmington field, located about 30 km south of Los Angeles, is infamous for being the hydrocarbon field with the largest degree of surface subsidence reported worldwide so far (9 m in 27 years), Ekofisk field has caught up over the last few years, reaching a vertical subsidence of 8.26 m in August 2002 (Ottemöller et al., 2005). Discovered in 1969, Ekofisk is one of the most important oil fields in the Central graben area. The reservoir is trapped in an elongated anticline and consists of three naturally fractured, partly vertically separated chalk reservoirs at an average depth of 3000 m subsea (Key et al., 1998). Although moderate events have occurred at Ekofisk (Ottemöller et al., 2005), most of the deformation at Ekofisk is considered to be aseismic.
Seabed subsidence was first noted in 1984. In an attempt to reverse the impact of subsidence, full-field water flooding operations were initiated in 1987. Nonetheless, subsidence continued at a stable rate of approximately 38 cm/yr (Zoback and Zinke, 2002). At the same time, reservoir pressure began to increase (Guilbot and Smith, 2002). Detailed laboratory studies on chalk yielded the result that as hydrocarbons were produced and replaced with water, the pressured chalk began to redissolve at microscopic inter-grain contacts and redeposit in a more compact, lower porosity configuration (Torsaeter, 1984; Hermansen et al., 2000; Cook et al., 2001; Nagel, 2001; Heggheim et al., 2005). We stress that these studies primarily demonstrate the importance of geochemical effects for subsidence, not necessarily for seismicity.

5. SEISMICITY INDUCED BY FLUID EXTRACTION

Based on the argument that injection of fluid increases effective stress, it might seem counter-intuitive that seismicity could also result from the extraction of fluids. The decrease of pore pressure should decrease effective stress and thus inhibit failure. This effect plays an important role in the vicinity of pre-existing faults which are subject to a spatially heterogeneous decrease in pore pressure (Pennington et al., 1986; Nagelhout and Roest, 1997; Mulders, 2003) or if the pore pressure decrease causes a previously aseismically slipping fault to lock up and eventually release accumulated energy in a seismic event. A similar mechanism might also account for the seismicity at Grozny field, Tchetchenya (see Grasso (1992b) and references in Russian therein).

But the effect of fluid extraction is more complex than can be captured by a Mohr-circle-type argument, because poroelastic stresses have to be taken into account. Evidently, reservoir rocks are composite materials incorporating a pore volume which influences their elastic response and yield stresses. The theory of poroelasticity was pioneered by Biot (1941) and a recent overview with numerous applications is given in Wang (2000). In the context of hydrocarbon reservoirs, declining pore pressures cause the reservoir rocks to contract. Because the reservoir is elastically coupled to the surrounding rocks, this contraction stresses the neighboring crust.

The substantial vertical subsidence of Goose Creek Oil field led to the first realization of the coupling between large volumes of fluid extraction and large-scale mechanical deformation (Pratt and Johnson, 1926). This case aroused the interest of Geertsma, who developed a lot of the early analytical techniques to model the effect of large groundwater withdrawals (e.g. Geertsma (1966)). However, his studies were targeted at subsidence and did not explicitly address the question of seismicity. The first to make that connection was Segall (1985). Segall derived analytic solutions for two specific symmetries: an infinitely extended horizontal reservoir (Segall, 1985, 1989) and an axisymmetric reservoir (Segall, 1992). Both models are summarized briefly below, each followed by one successful application.

5.1. Fluid Extraction from an Infinitely Extended Horizontal Reservoir

Segall (1985) modeled the oil field as a line of oil wells extracting fluid from a permeable reservoir layer embedded in an impermeable, infinite half-space. Additionally, he assumed that the depth of the permeable layer is much larger than its thickness. This setup is summarized in Fig. 14.
FIG. 14. Poroelastic model for fluid extraction from a horizontal layer by Segall (1985). The producing horizon of thickness $T$ is characterized by permeability $k$; the half-space is impermeable ($k = 0$). Furthermore, fluid extraction is assumed to occur homogeneously along the line of wells on the surface. The lines of oil wells on the surface, the producing horizon at depth $D$, and the half-space are assumed to extend to infinity.

Source: Figure reproduced from Baranova et al. (1999, Fig. 8, p. 55).

Fluid extraction from this idealized geometry can only occur in the $y$-direction and is thus one-dimensional. As fluid is withdrawn from the reservoir, flow toward the $y = 0$ plane is induced in the producing layer. Therefore, the diffusion equation describing alterations in pore fluid mass (Rice and Cleary, 1976) reduces to

$$c \frac{\partial^2 \Delta m}{\partial y^2} = \frac{\partial \Delta m}{\partial t},$$

where $c$ is the mass diffusivity, $\Delta m$ the alteration in pore fluid mass, $t$ the time, and $y$ the spatial coordinate. The solution to this equation subject to constant mass flux at $y = 0$ is known (Carslaw and Jaeger, 1959). From this model, three predictions follow:

1. The temporal change in pore fluid mass content $\Delta m$ depends most importantly on the diffusivity within the reservoir.
2. The mean stress is compressive below the point of extraction ($y = 0$) and slightly extensional along the flanks. With increasing time since the onset of extraction the extensional zones migrate further outward and the compressive zone further down.
3. The rates of fluid extraction and surface subsidence are related linearly.
Baranova et al. (1999) applied the model by Segall (1985) to investigate whether the October 1996 event ($M = 3.9$) at Strachan gas field, Alberta, was induced by hydrocarbon production. The first indication of unusual seismic activity in north central Alberta was an earthquake of magnitude $m_b = 5.1$ which occurred on 8 March 1970. Since there are no active tectonic features in the vicinity of the epicentral area, Milne (1970) speculated about a possible connection between the earthquake and local hydrocarbon production which started in 1954. In 1980, Wetmiller (1986) deployed a seismic network consisting of one digital and six conventional seismographs and confirmed that the seismicity was induced by fluid extraction, but did not attempt to quantify the exact mechanism.

Baranova et al. (1999) investigated the event at Strachan gas field on 19 October 1996 in more detail. The authors concluded that the model is well suited to describing the phenomenon, because:

1. The measured and theoretically expected focal mechanisms of the October 1996 event corresponded well.
2. There was the expected characteristic time lag between the beginning of production in 1970 and the onset of seismicity in 1975/1976 during which enough stress perturbations built up to induce seismic events.
3. There was a correlation between the occurrence of seismic events and the production rate at the Strachan D3-A pool.

5.2. Fluid Extraction from Axisymmetric Reservoirs

Segall (1992) presented an analytic solution for the stresses and surface deformation induced by fluid extraction from disk-shaped, axisymmetric reservoirs. His study builds on previous work by Geertsma (1973). Segall et al. (1994) demonstrated that the original model can easily be extended to axisymmetric dome-shaped reservoirs.

The starting point is the four governing poroelastic equations in the pure compliance formulation. In terms of displacements $u_i$ and pore fluid mass $\Delta m$, they take the form

$$\mu \nabla^2 u_i + \frac{\mu}{1-2\nu_u} \frac{\partial^2 u_j}{\partial x_i \partial x_j} - \frac{B K_u}{\rho_0} \frac{\partial \Delta m}{\partial x_i} = 0 \quad \text{for } i = 1, 2, 3. \quad (2)$$

$$c \nabla^2 (\Delta m) = \frac{\partial \Delta m}{\partial t}, \quad (3)$$

where $\mu$ denotes the shear modulus, $\nu_u$ the Poisson ratio, $B$ Skempton’s pore-pressure coefficient, $K_u$ the bulk modulus, and $\rho_0$ the fluid density in the reference state. In Eq. (2) and the following expressions, the subscript $u$ refers to the undrained state.

It is important to note that the change in fluid mass content and thus also the pore pressure $p$ enters the equations equivalent to a body force $f_i$.

$$\mu \nabla^2 u_i + \frac{\mu}{1-2\nu} \frac{\partial^2 u_j}{\partial x_i \partial x_j} - \alpha \frac{\partial p}{\partial x_i} + f_i = 0, \quad (4)$$

where $\alpha$ is the Biot pore pressure coefficient. Due to this correspondence it is possible to use the elastostatic Green’s function $g^f_\ell(x, \zeta)$, which is the displacement in the
\(i\)-direction at \(\vec{x}\) due to a body force in the \(k\)-direction at \(\zeta\), to calculate the displacements induced by gradients in pore pressure. Assuming a localized pore pressure disturbance, Segall (1992) obtained

\[
\mu u_i(\vec{x}) = \alpha \int_V p(\zeta) \frac{\partial g_i^k(\vec{x}, \zeta)}{\partial \zeta_k} \, dV_\zeta. \tag{5}
\]

Note that the expression \(\frac{\partial g_i^k(\vec{x}, \zeta)}{\partial \zeta_k}\) describes a sum of force couples acting along three orthogonal axes; in other words, a center of dilatation. The problem is thus reduced to finding the displacement Green’s function for a center of dilatation defined as

\[
g_i(\vec{x}, \zeta) \equiv \frac{\partial g_i^k(\vec{x}, \zeta)}{\partial \zeta_k} \tag{6}
\]

(Love, 1944). The calculation of the appropriate Green’s function is facilitated by the prior work of Goodier (1937), who showed that the thermoelastic equations could be reduced to the Poisson equation by introducing a displacement potential \(\Phi\) such that

\[
\frac{\partial \Phi}{\partial x_i} = u_i. \tag{7}
\]

Mindlin and Cheng (1950) showed that Goodier’s method can be extended to a homogeneous half-space. Thus, the problem is reduced to finding the solution to the Poisson equation for radial symmetries (Segall, 1992).

The resulting vertical Green’s function for a ring of dilatation at radius \(\rho\) and various depths \(d\) is shown in Fig. 15. For a shallow source, a radially symmetric increase in pore pressure leads to a ring of vertical uplift at the source radius. With increasing depth of the pore-pressure source, the ring of uplift broadens and decreases in amplitude until it eventually transforms into a central bulge (Fig. 15). Beyond that depth, the deformation at the free surface caused by a toroidal source becomes indistinguishable from that of a point source (Segall, 1992). The vertical displacement shown in Fig. 16 is the convolution of the vertical Green’s function with the pressure distribution.

From Green’s functions, Segall (1992) calculated the perturbations of radial, vertical, hoop, and shear stresses. Knowledge of these perturbing stresses allows determining whether hydrocarbon production brings a fault of a given orientation closer to failure. However, knowledge of the tectonic background stresses is required to ultimately determine whether a given perturbation is significant enough to cause earthquakes. Thus, an identification of areas of increased seismic risk due to hydrocarbon production is strictly only possible if the natural stress field can be constrained (Segall, 1992).

Summarizing, the prediction of the effects of fluid extraction for axisymmetric reservoirs is as follows.

1. A linear relationship between decrease in pore pressure and surface subsidence.
2. The amount of subsidence depends on the elastic and poroelastic properties of the reservoir. For stiff reservoirs (e.g. Lacq), only a few centimeters of surface
3. For a shallow reservoir, a radially symmetric decrease in pore pressure leads to a ring of vertical depression. For a reservoir of intermediate depth, the depression

Subsidence are expected. In weaker reservoirs where subsidence is large (e.g. Wilmington (Kosloff et al., 1980a,b), Ekofisk (Teufel et al., 1991), Costa Oriental near Lake Maracaibo, and Venezuela (Xu, 2002)), nonlinear effects become important (Kosloff et al., 1980b).

Source: Figures reproduced from Segall (1992, Fig. 2, p. 544).
is broader and decreases in amplitude toward the center of the reservoir. Finally, a deep reservoir is characterized by a central bulge of deformation. Beyond a certain depth, the deformation at the free surface caused by a toroidal source becomes indistinguishable from that of a point source. In that case, the radial displacements are oriented inward.

Segall et al. (1994) applied this model to the Lacq gas field, Aquitaine, France. The Lacq gas field in southwestern France is one of the best documented cases of seismicity induced by the extraction of fluids (Feignier and Grasso, 1990; Grasso and Feignier, 1990; Grasso and Wittlinger, 1990; Maury et al., 1992; Guyoton et al., 1992; Grasso et al., 1992; Herquel and Wittlinger, 1994; Lahaie and Grasso, 1999). Since 1969, hundreds of shallow earthquakes with small to moderate magnitudes have been recorded by the French National network in its vicinity. Additionally, a local seismic network was operated and confirmed that the epicenters of the events coincided well with the extent of the gas field (Grasso and Wittlinger, 1990). Information about surface subsidence at Lacq has been obtained through repeated leveling. The first leveling was done well before the beginning of production in 1887, and then again in 1967, 1979, 1989, and 1990 (Segall et al., 1994).

Despite the low permeabilities of the rocks in the producing horizon, the pore-pressure distribution within the central reservoir has been largely uniform, which Segall et al. (1994) interpreted as an attestation of the high fracture permeability in the reservoir. This recognition also led to the concentration of production wells at the center of the reservoir, which yields an approximately axisymmetric symmetry in agreement with the model assumptions. This makes Lacq an ideal test for the poroelastic model and a successful one: it could both explain the observed linear relationship between pore pressure in the gas reservoir and maximum subsidence (Fig. 17) and reproduce the measured surface subsidence satisfactorily (Fig. 18). Evidently, the fit of theoretical and experimental subsidence is more accurate if the domal structure of the reservoir is accounted for. The tendency of the observed subsidence to be concentrated more at the center of the field might be an indication for the presence of inelastic effects (Segall et al., 1994).

Segall et al. (1994) calculated the perturbation in the pre-existing tectonic stress field, which results from fluid extraction from the gas reservoir and concluded that changes in Coulomb stress as small as 0.1 MPa were sufficient to induce earthquakes. Thus, the state of stress is clearly still determined by tectonic stresses and detailed knowledge of the natural stress state is essential for anticipating which parts of a hydrocarbon field might be most prone to induced seismic activity. Adopting a simple Coulomb failure criterion and assuming a thrust faulting environment with the largest stress component oriented parallel to the Pyrenees, Segall et al. (1994) attempted a prediction where induced seismicity should be observed predominantly. Figure 19 shows the resulting Coulomb failure stress and observed earthquakes. Theoretically, all earthquakes should cluster in the center of the dark shaded area.

Despite the progress made by Segall et al. (1994), the details of the spatial and temporal distribution of seismicity at Lacq remain puzzling. As pointed out by Grasso (1992b), it failed to offer an explanation for the decrease of seismic activity since 1980 or for spatial clustering (Grasso and Wittlinger, 1990). Feignier and Grasso (1990) and Grasso and Feignier (1990) looked at the role of pre-existing discontinuities of either
Fig. 17. Plot of the gas pressure decline in MPa over the maximum observed surface subsidence in mm at Lacq gas reservoir, Aquitaine, France. This observation confirms the model prediction of a linear relationship between subsidence and pore pressure.  
Source: Figure after Segall et al. (1994, Fig. 7, p. 15429).

Fig. 18. Comparison of measured vertical displacement and model predictions for both a flat axisymmetric reservoir and an anticlinal dome structure at Lacq gas reservoir, Aquitaine, France for the period 1887-1989.  
Source: Figure after Segall et al. (1994, Fig. 9, p. 15432).

tectonic or lithological nature. Furthermore, a recent study by Bardainne et al. (2006) showed that at least part of the seismic activity at Lacq is likely due to fluid injection.
Fig. 19. Superposition of the induced and the assumed pre-existing tectonic Coulomb stress state in a horizontal section at a depth of 4.5 km. The pre-existing stress field is constructed with respect to the Pyrenees: the largest principal stress component was chosen to be perpendicular to the Pyrenees (N45°E) and the smallest is vertical. Dark shading indicates regions where reverse slip is promoted; light shading indicates areas where reverse slip is inhibited as a consequence of fluid extraction. Theoretically, earthquakes are expected to cluster in the center of the dark shaded area.

Source: Figure after Segall et al. (1994, Fig. 13, p. 15,435).

5.3. Fluid Extraction in the Vicinity of Pre-existing Faults

Poroelastic modeling usually assumes that the reservoir is embedded in a homogeneous medium. This is clearly rarely a realistic assumption. Pennington et al. (1986) suggested a different mechanism through which fluid extraction could lead to earthquakes on pre-existing faults in immediate contact with the reservoir. The key idea of their model is that a decrease in pore pressure strengthens a fault by increasing the effective normal stress acting on it and thus increases its strength. As a consequence, a barrier to slip develops in the immediate vicinity where the fluid is being extracted. Stress builds up along these locked portions of the fault, because strain accumulates either due to differential compaction or continued aseismic slip of nearby portions of the fault. Eventually, the accumulated stress will exceed the strength of these asperities and result in an earthquake. This process repeats itself as long as the fault is active and the pore pressure continues to decrease. An important prediction of this model is that as fluid withdrawal continues, the magnitude of future earthquakes is expected to increase (Pennington et al., 1986).
Small relative shear displacements may occur along a vertical boundary fault.

(a) Small relative shear displacements may occur along a vertical boundary fault. (b) Downward displacement on an oblique fault with a dip toward the reservoir. (c) Displacement, directed upward, at the bottom of the reservoir.

(d) Concentration of displacements on two different levels. Boundary effects do not reinforce each other.

(e) Displacements occur in opposite directions at the same level. They reinforce each other.

Reverse fault

Normal fault

Fig. 20. Impact of geometrical effects on a fault as suggested by Roest and Mulders (2000)

Source: Figure reproduced from Roest and Mulders (2000, Fig. 2, p. 334).

Pennington et al. (1986) argued that their model might account for the seismicity observed at Imogene oil field near Pleasanton, Texas, and Fashing gas field near Fashing, Texas. Both fields are seismically active without showing massive subsidence, are characterized by structural traps formed by the offset of porous limestone along normal faults, and have experienced substantial pressure drops since the beginning of production. At the initiation of production at the Imogene oil field in 1944, fluid pressure within the field was at 24.6 MPa. By 1973 it had dropped to 14.6 MPa. At the Fashing gas field, production began in 1958 and at that time, the fluid pressure within the reservoir was approximately 35.2 MPa. In 1983, it had decreased to about 7.1 MPa near the fault (Pennington et al., 1986).

The largest events in the prior seismically quiescent area of South Texas occurred at Fashing in July 1983 (\(m_{bLg} = 3.4\)) and at Pleasanton in March 1984 (\(m_{bLg} = 3.9\)). On April 9th, 1993, another large earthquake (\(m_{bLg} = 4.3\)) shook south-central Texas. Its vicinity to the Fashing gas field generated new interest in the question of induced seismicity in the field. A study by Davis et al. (1995) confirmed the conclusion by Pennington et al. (1986) that seismicity in both the Fashing and the Imogene field is induced by fluid extraction. Additionally, Davis et al. (1995) pointed out that production at Fashing and Imogene might be affected by the geochemistry in the fields. In fact, at Fashing, water has been reported to leak through the trapping fault and encroach into the gas field.

The ideas by Pennington et al. (1986) have been applied and carried further, both generally to include geometrical effects (Nagelhout and Roest, 1997; Roest and Kuilman, 1994) and specifically to model induced seismicity in the Netherlands (Mulders, 2003). Figure 20 gives an overview of the geometrical effects in the vicinity of a pre-existing fault (Roest and Mulders, 2000). In order to study the influence of various parameters on stress development and fault slip, Mulders (2003) computed 2D and 3D geomechanical models of gas reservoirs based on the finite element software package DIANA. The
5.4. Analog Models of Faulting Induced by Fluid Extraction

_Odonne et al._ (1999) designed an analog model to get experimental insights into the geometry and location of brittle deformation associated with depleting hydrocarbon reservoirs. The authors represented the depleted reservoir either by a latex balloon or by undercompacted ground sand, which is embedded in a sand-silicone box. Vertical sections cut into the model after the cessation of subsidence revealed three distinct areas: a contracted center, an extended ring, and a fixed periphery. Furthermore, _Odonne et al._ (1999) observed reverse faults with high dips, which is in accordance with the observations at Strachan (Wetmiller, 1986) and Lacq field (Feignier and Grasso, 1990). In the analog model, these steep reverse faults were located at the boundary of the reservoir and delimited a cone-shaped volume with an upward-directed apex as shown in Fig. 21. The curved profile of the fault seemed to depend on the ability of the fault to cut the surface of the model; in other words, in the case of the analog model on the thickness of the sand cover (_Odonne et al., 1999_).

Based on their results, _Odonne et al._ (1999) offered a new interpretation of the analytic model by _Segall_ (1989). The main change from Segall’s model is that _Odonne et al._ (1999) suggested choosing the steep nodal plane at depth instead of the gentle one. Furthermore, they continued this steep plane upward toward the surface, resulting in a cone-shaped fault. Both the original cross section by _Segall_ (1989) and the suggested modified cross section by _Odonne et al._ (1999) are shown in Fig. 22.

6. THE CONTROVERSY SURROUNDING MAJOR MIDCRUSTAL EARTHQUAKES

All cases of induced seismicity in hydrocarbon fields presented so far have exhibited small or moderate seismicity. A similar range of magnitude has been observed for
FIG. 22. Comparison of the schematic cross section summarizing surface deformation, faulting, and fault mechanisms associated with fluid extraction after Odonne et al. (1999). The top cross section (a) is reproduced from Segall (1989) and the bottom cross section (b) is the modification suggested by Odonne et al. (1999) based on their analog models. White arrows indicate horizontal displacement and black errors the sense of faulting. The focal mechanism associated with the faults are shown as beach balls. 
Source: Figure as given by Odonne et al. (1999, Fig. 4, p. 113).

Seismicity caused by other human activities such as mining. However, there are two examples of destructive earthquake sequences which occurred in the immediate vicinity of oil fields and which were not related to a previously known fault. These have given rise to speculations about the possibility that hydrocarbon production might cause destructive earthquakes. Apart from their size, a common feature of these earthquake sequences is that they occurred at midcrustal depths (around 10 km). Thus, the question about a possible connection to hydrocarbon production is closely related to the question of how induced stress perturbations could propagate to these depths.
Fig. 23. Deviatoric (a) and mean (b) stress resulting from fluid extraction from a single horizontal layer of infinite extent. The contours are lines of constant stress change after 10 years (dashed) and 100 years (solid), respectively. Compressive stresses are labeled negative and extensional stresses positive.

Source: Figure reproduced from Segall (1985, Fig. 9).

6.1. Earthquakes in the Vicinity of Coalinga

On 2 May 1983, an earthquake of magnitude $M_L = 6.7$ occurred about 12 km northeast of the town of Coalinga, California. It was located 35 km northeast of the San Andreas fault, in a region that had previously been known only for scattered seismicity. The event was not associated with any known or suspected active fault. Its proximity to two major producing oil fields, Coalinga Eastside and the Nose area of the Coalinga East Extension, led to speculation of a possible connection between the event and oil field operations (Bennett and Sherburne, 1983).

Segall (1985) and Segall and Yerkes (1990) analyzed how production-related decreases in pore pressure alter the state of stress at various depths. Based on his previously developed poroelastic model for the plane strain case (Segall, 1985), he calculated that in the case of Coalinga the stress induced by fluid extraction is only 0.02 MPa at hypocentral depth. Figure 23 shows the mean and deviatoric stress due to fluid extraction from a single horizontal layer based on poroelastic modeling. As an independent validation for the model, Segall (1985) used it to model the surface subsidence at Coalinga oil field and found a very good fit of theory and observations. The theoretically predicted surface subsidence for various time intervals after onset of production is reproduced in Fig. 24. Pore pressure changes calculated on the basis of this
Fig. 24. Expected surface subsidence (mm) in time increments of 20 years starting 20 years after onset of production and ending 100 years later, as computed from the poroelastic model by Segall (1985). The left figure (a) is computed based on a diffusivity $c$, which is a tenth of the diffusivity used in the right figure (b), highlighting the great importance of that parameter. The other quantities are specified in Segall (1985).

Source: Figure reproduced from Segall (1985 Fig. 8).

model, also agreed well with observed changes (Segall and Yerkes, 1990), thus lending credibility to the poroelastic approach.

The U.S. Geological Survey initiated a detailed study of the event (Rymer and Ellsworth, 1990). This report came to the 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. A mechanism related to hydrocarbon production was ruled out for the following three reasons.

1. The shale units which underlie the oil-producing horizon have extremely low permeability and act as a hydraulic isolation between the oil field and the earthquake’s focal region.
2. Despite the usage of fluid injection in the course of secondary recovery projects, the net effect of oil production was a 50-percent decline in reservoir fluid pressure between 1938 and 1983 (Segall and Yerkes, 1990).
3. Except for one aftershock on June 11, all other aftershocks and the main shocks had focal depths of 9 to 12 km. Any pore pressure disturbance resulting from oil field operations would have had to penetrate at least 8 km during the 45 years since operation of the field started in 1938. However, Segall and Yerkes (1990) estimated that the pressure disturbance will only be able to penetrate 100 m in 45 years. There remained, of course, the possibility of a highly fractured zone linking the oil field and the focal region. However, as argued by Yerkes et al. (1990), considerable evidence supports the conclusion that the rocks below the oil-bearing strata hydraulically isolate the oil field.

After the question of a possible connection between oil field operations and midcrustal earthquakes had seemingly been answered for the 1983 Coalinga earthquake, new interest
arose after the occurrence of two other major events in the vicinity of Coalinga, the 1985 Kettleman North Dome and the 1987 Whittier Narrows event, that were also located directly beneath important oil fields (McGarr and Simpson, 1997).

McGarr (1991) highlighted the similarity between the three events and suggested a new mechanism that might account for a possible connection between their occurrence and oil field production. He argued that net extraction of oil and water reduces the average density of the upper crust, thus causing an isostatic imbalance. The deformation induced by this imbalance results in an increasing load on the seismogenic layer. As pointed out by McGarr himself, it is not so much a question whether the removal of mass from the crust creates an isostatic imbalance, but whether the resulting deformation would occur on a time scale corresponding to oil field operations.

The following similarities between the three events led him to believe that isostasy might account for the connection between their occurrence and oil production: (1) All three events occurred beneath major oil fields and the aftershocks also clustered in the general area of the fields (Segall, 1985; Ekström et al., 1992; Davis et al., 1989), (2) the focal mechanisms of all three events are predominantly of thrust type (Eaton, 1990; Ekström et al., 1992; Hauksson et al., 1988), (3) the hypocenters were located at midcrustal depths and separated from the producing formation, (4) they all have comparable magnitudes, (5) the ratio of net fluid production to total seismic moment is similar, and (6) the three oil fields in question, Coalinga, Kettleman, North Dome, and Montebello, are situated on anticlines that have undergone recent uplift as a consequence of horizontal tectonic compression of the crust.

Based on his mechanism, McGarr (1991) expected that other Californian oil fields might be candidates for induced midcrustal seismicity. These are oil fields that are both located along the Coast Range-Sierran Block boundary zone and characterized by high net liquid extraction. In particular, he named Midway-Sunset, Belridge South, Elk Hills, Cymric, and McKittrick oil fields (McGarr, 1991). Apart from microseismicity related to hydraulic fracturing, no large or unexpected earthquakes have been associated with these oil fields until today. Finally, we note that Segall (1985) argued that the stress change due to mass redistribution is small in comparison to poroelastic effects based on dimensional analysis.

6.2. The Gazli Earthquake Sequence

From 1976 to 1994 an unusual earthquake sequence was recorded in the Gazli gas field located in Central Asia about 100 km northwest of Bukhara, Uzbekistan. The first destructive event occurred on 8 April 1976 with magnitude $M_S = 7.0$. It was followed shortly afterward, on 17 May 1976, by a second similarly sized event ($M_S = 7.0$) approximately 20 km west of the first event. A medium sized event ($M_S = 5.7$) followed on 4 June 1978. A few years later, on 19 March 1984, a fourth major event with $M_S = 7.0$ was located 15 km southwest of the second event in 1976 (Eyidoğan et al., 1985). All three earthquakes, including some of their aftershocks, were widely felt and caused major damage in the town Gazli. Their exact locations, rupture kinematics and focal mechanisms remain a subject of debate (Eyidoğan et al., 1985; Amorèse et al., 1995; Amorèse and Grasso, 1996; Bossu et al., 1996; Bossu and Grasso, 1996). The main events of this sequence and the available focal mechanisms are shown in Fig. 25. For details on the displayed events see Table 2.
The giant Gazli gas field with an estimated size of 456 billion m$^3$ was discovered in 1956. Gas is pumped from a shallow reservoir at 2 km depth, although the gas must originate considerably deeper. The field is characterized by several fold and fault structures, which are part of the Bukhara-Gissar system continuing further east into a seismically more active region (Bossu, 1996). Simpson and Leith (1985) were the first to suggest a connection between the earthquake and hydrocarbon production, based on the following rationale.
1. Previously to this earthquake sequence, the region had been seismically inactive since medieval ages (Bossu, 1996).
2. The occurrence of two magnitude 7 events, followed by a third event 8 years later does not follow a typical aftershock pattern.
3. Hydrocarbon production had led to a huge decrease in pressures in the Gazli field since the beginning of its operation.

On the other hand, Eyidoğan et al. (1985) interpreted the Gazli earthquake sequence as an indication for the presence of a major fault zone to the north of Gazli. The authors argued that the observed continuous uplift of the region since the Quaternary is evidence of a long-term process with a distinctly episodic character. This might explain the absence of historic seismic activity in the area (Eyidoğan et al., 1985).

Plotnikova et al. (1990) and Plotnikova et al. (1996) presented details regarding the production patterns and the gas pressure in the field, which indicate large temporal and spatial variations in pressure. Generally, injection patterns at Gazli were selective and erratic and resulted in drastic surface level changes of the gas-water contact, which rose by over 40 m in the northern and eastern parts of the field. Plotnikova et al. (1990) also reported subsidence of 16 mm in that area over the same time period 1972-1974. From these observations, Plotnikova et al. (1990) concluded that gas field operations impacted the seismic activity at Gazli. More precisely, the authors claimed that the events in 1976 were induced, while the second in 1984 was not. They based this distinction primarily on a statistical analysis of moderately sized seismicity prior to the two events.

In order to investigate seismic activity at Gazli in greater detail, a collaborative field survey was initiated in 1991 between the University of Grenoble and the Academy of Sciences of the Uzbek Republic (Bossu and Grasso, 1996; Bossu et al., 1996). Bossu et al. (1996) found that the seismicity had migrated about 90 km unilaterally in the N240°E direction since the onset of the sequence in 1976. They interpreted this finding to indicate that an immature fault zone was present in the study area. This fault zone could explain both the major earthquakes and the variety of fault plane solutions computed through the field survey. See Figs 26 and 27 for details on the seismicity recorded during the field survey in 1991.

Bossu (1996) also came to the conclusion that the events at Gazli are most likely of tectonic origin. Bossu (1996) tested the possibility that crustal unloading might impact the occurrence of seismic activity at Gazli, as suggested by McGarr (1991) in the context of the California events. However, since water injection and gas extraction counteract, the stress disturbance created through that effect would only lie in the range of 0.06 bars and thus be comparable to tidal stresses.

Overall, despite the striking correlation between seismic activity and hydrocarbon production, the causal relation between the Gazli earthquake sequence and hydrocarbon production remains contentious. We stress that a substantial body of literature (see references in Adushkin et al. (2000)) on Gazli field was published in Russian and was not included in this review. In this context, it is interesting to note that Adushkin et al. (2000) presented Gazli as a case study for how an erratic production pattern might induce seismicity in hydrocarbon fields. In fact, they argued that the earthquake sequence might have been prevented through a more careful depletion strategy.
Over the last few decades, the possibility that hydrocarbon production may induce earthquakes has become a dynamic field of research. The interest in this phenomenon was initially provoked by several prominent cases (e.g. Wilmington oil field or the earthquake series in the vicinity of Coalinga; see Section 6), in which a connection between seismicity and hydrocarbon production was suspected. Since then, a causal relationship between seismicity and hydrocarbon production has been suggested for 70 cases (see Table 1) based on spatial and temporal association of seismicity and field operation. Quantitative models (Sections 4 and 5) assess the change in stress or pore pressure as a consequence of production. However, these models are often hindered by a lack of detailed information about production patterns and by the inherent difficulty of judging whether a perturbation of a certain size is significant in comparison to the pre-existing tectonic stress field or not. This difficulty highlights the challenge of drawing the line between natural and induced events.

Over the following years, induced seismicity is likely to remain an important research question, not only in the context of hydrocarbon production. Evaluating the possibility of inducing an event of moderate to large magnitude is not only relevant in the context of oil and gas reservoirs, but also for geothermal fields (Majer and Peterson, 2007), waste disposal wells (Nicholson et al., 1988; Seeber et al., 2004), and alternative usage of old reservoirs such as carbon sequestration. Continuing research targeted at assessing the seismic hazard associated with these operations is essential in order to perform them safely. In regions where induced seismicity is common, it has
already become a social concern, particularly in the northern part of the Netherlands (Gussinklo et al., 2001). As a reflection of that, 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 model hazard from induced seismicity in actively
producing fields (Van Eck et al., 2006). Deriving an estimate for expected future hazard prior to production, however, requires knowledge of the factors that control induced seismicity, which are little understood. Van Eijis et al. (2006) investigated the correlation between reservoir properties and induced seismicity in the Netherlands (see Section 2.3). Adushkin et al. (2000) attempted a similar comparison on a global scale. Unfortunately, their results were based on reservoir characteristics different from those of Van Eijis et al. (2006), but also tend to indicate that hydrocarbon fields with induced seismicity deviate from a random sample of 200 hydrocarbon fields worldwide (see Fig. 28). Continued monitoring of induced seismicity over the following decades will allow determining whether these differences are statistically significant.

Arguably, the availability of high-quality data is the single most important requirement for evaluating the correlation between hydrocarbon production and seismicity. As a reflection of this necessity, the industry increasingly devotes resources to improving the instrumentation of oil fields and the data analysis. One prominent example is Valhall field which is equipped with a dense onshore and offshore seismic array (see Section 3). Another area of active research is the acquisition of time-dependent data (commonly referred to as time-lapse or 4D data). Since their introduction in the 1980s (Greaves and Fulp, 1987; Britton et al., 1983), 4D techniques have advanced rapidly over the last few years. In 2001, Lumley (2001a) estimated that at that time there were about 75 active 4D seismic projects worldwide and the total annual expenditure on these projects ranged in the order of US $ 50-100 million. Most 4D monitoring projects are located in the North Sea. Of the total cumulative expenditure of US $ 500 million on 4D services, about $ 400 million (80%) has been spent in the North Sea (Lumley, 2004). Apart from mapping fluid flows, 4D images can potentially provide a better image of reservoir compartmentalization and fault properties, which could be useful for the optimal design of production facilities in complex reservoirs (Lumley, 2001a; Albright et al., 1994). An example of a successful application of 4D seismic imaging for identifying the flow patterns at Gullfaks reservoir, North Sea, is shown in Fig. 29. The negative side of 4D monitoring is, apart from the costs involved, the fact that not all reservoirs are ideal candidates, because a sufficient signal-to-noise ratio is required to resolve subtle changes in the seismic image. Although 4D techniques are mostly used on similar data sets, it is also possible to cross match different data sets (Hall et al., 2005). It will be interesting to see to which degree different data sets can be integrated in order to constrain changes in reservoir properties over time.

The acquisition of more and better data opens up new possibilities for geomechanical modeling of production-related changes in the reservoir over time. One concern often related to that of induced seismicity in hydrocarbon fields is surface subsidence (e.g. Goose Creek, Texas, USA (Pratt and Johnson, 1926), Wilmington, California, USA (Kosloff et al., 1980a,b), Groningen, Rotliegendes, Netherlands (Barends et al., 1995), Po Valley, Italy (Cassiani and Zoccatelli, 2000), and Costa Oriental, Lake Maracaibo, Venezuela (Xu, 2002)). The conditions under which subsidence is related to seismicity, however, are not trivial and little understood. In some hydrocarbon fields, subsidence is considered to be largely aseismic (e.g. Belridge, California, USA), but the moderate event at Ekofisk, North Sea, Norway (Ottemöller et al., 2005) – for which this was long thought to be the case – highlighted the uncertainty associated with such judgments. In yet another case, at Wilmington oil field, California, substantial subsidence was associated
with moderate seismic activity and the combination of both effects caused considerable damage in the port of Long Beach, California (Kosloff et al., 1980a). The costs of the largest earthquake in the field on 17 November 1949 exceeded $9 million at that time (Nicholson and Wesson, 1990). These cases show that the correlation between the magnitude of subsidence and seismicity is complex. In fact, it is possible that potentially large stresses build up in a comparatively stiff rock, which due its stiffness will only yield modest subsidence. Finally, we note that in the case of Goose Creek Oil field, surface subsidence also had legal consequences. A brief description of the case can be found in Wang (2000). A more extensive description of the potential legal implications of induced seismicity in the USA was provided by Cypser and Davis (1998).

Recent efforts in geomechanical modeling have focused and will hopefully continue to focus on: (1) Capturing the changes in reservoir properties over time and verifying

FIG. 28. Comparison of the properties of 40 hydrocarbon reservoirs exhibiting induced seismicity (black line) with a worldwide random sample of 200 reservoirs that do not (gray line). Shown are the probability distributions for the parameters, reservoir depth (km), initial pressure (atm), permeability (mD), porosity (%), and thickness (m).

Source: Figure reproduced from Adushkin et al. (2000, Fig. 7, p. 114).
Fig. 29. Map of seismic amplitudes at Gullfaks reservoir in the North Sea, operated by Statoil. Two wells are indicated: WellA-9H is a production well and A-42 an injection well. The seismic amplitudes indicate that instead of flowing through the shortest possible path between the two wells, the injected gas takes a more convoluted route through the reservoir crossing a major fault boundary. This example demonstrates how time-lapse seismic imaging was successfully applied to identify fluid flow patterns.

Source: Figure reproduced from Lumley (2001b, Fig. 2, p. 1)

the modeling results with available data. An example highlighting the mutual benefits of high-quality data and sophisticated modeling is Ekofisk (Guilbot and Smith, 2002). Fig. 30 shows the map of the compaction distribution derived from seismic data (left) and the corresponding compaction map resulting from geomechanical modeling of the reservoir (right). (2) Analyzing the interaction of production, changes in reservoir properties, and pre-existing faults. This question has received particular attention in the Netherlands, because induced seismicity in hydrocarbon fields is thought to be predominantly related to the reactivation of pre-existing discontinuities (e.g. Mulders (2003)). (3) Making the connection between mechanical properties (e.g. reservoir compaction or surface subsidence), seismicity and stress corrosion or geochemical effects. At this point, the potential importance of these processes for subsidence has been recognized (e.g. at Ekofisk; see Section 4.3). It will be interesting to see whether they are relevant to earthquake generation as well. (4) The problem of nonlinear deformation and the connection to seismic activity. Although linear poroelastic models have been
FIG. 30. Left: Compaction map of the reservoir at Ekofisk field derived from 4D seismic data. Right: Compaction map computed from geomechanical modeling. Water injection wells are displayed as black dots in both cases. Source: Figure as given by Guilbot and Smith (2002, Fig. 8, p. 306 and Fig. 10, p. 307).

Successfully applied to understanding induced seismicity (e.g. Segall et al. (1994)), the importance of nonlinear effects is evident from the mere magnitude of subsidence in hydrocarbon fields (Kosloff et al., 1980b). One possible way forward is to differentiate between seismic events occurring within the reservoir materials as opposed to those occurring above and below. Assuming that anelastic effects are limited to the reservoir materials, one can couple a nonlinear model of the reservoir with an elastic model of the surrounding rock using Eshelby inclusion arguments (Segall and Fitzgerald, 1998).

Concluding, we argue that three of the main challenges in improving our understanding of induced seismicity in hydrocarbon fields will be (1) the development of tools for probabilistic seismic hazard assessments both prior to 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, and (3) the development of more sophisticated geomechanical models. Finally, we believe that an important opportunity in the field is to develop a fruitful and active dialogue among industry, academia, and the public. The compilation of observational evidence and modeling advances presented in this study is intended to add to this dialogue. Hopefully, it will be complemented by and expanded upon by future reviews.
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