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Fracking in Tight Shales: What Is It, What Does It Accomplish, and What Are Its Consequences?

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Keywords

hydraulic fracturing, fracture permeability, shale oil, tight shales, slickwater

Abstract

Fracking is a popular term referring to hydraulic fracturing when it is used to extract hydrocarbons. We distinguish between low-volume traditional fracking and the high-volume modern fracking used to recover large volumes of hydrocarbons from shales. Shales are fine-grained rocks with low granular permeabilities. During the formation of oil and gas, large fluid pressures are generated. These pressures result in natural fracking, and the resulting fracture permeability allows oil and gas to escape, reducing the fluid pressures. These fractures may subsequently be sealed by mineral deposition, resulting in tight shale formations. The objective of modern fracking is to reopen these fractures and/or create new fractures on a wide range of scales. Modern fracking has had a major impact on the availability of oil and gas globally; however, there are serious environmental objections to modern fracking, which should be weighed carefully against its benefits.

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1. INTRODUCTION

Fracking is a popular term for hydraulic fracturing of oil and gas reservoirs to enhance production. A high-pressure fluid, typically water with additives, is injected from a well into the target formation, creating one or more open fractures. These fractures are held open by an injected proppant, typically sand. Oil and/or gas migrate through these fractures to a well for production.

Fracking is a particularly important technology that has enabled the extraction of oil and gas from shales. Silicic sedimentary rocks, including shales, are generated from the deposition and lithification of sand and mud. With burial, the coarse-grained sand can become sandstone and the fine-grained mud can become shale or mudstone. Under anoxic conditions, organic material in pore spaces is converted to oil and gas as the burial depth and temperature increase.

This conversion of organic material to oil and gas increases the pressure in the pore spaces. Coarse-grained sandstones have high granular permeability. As a result, the resistance to flow is low, and oil and gas can escape, reducing the excess pressure. In contrast, shales are very fine grained, and as a result, they have very low granular permeability. The increase in pressure of the oil and/or gas creates fractures on a wide range of scales. We refer to this process as natural fracking. Oil and gas can escape through these fractures, reducing the excess pressure, but a large fraction of the oil and/or gas remains trapped in the low-permeability source rock where it formed.

Traditional oil and gas production utilizes vertical wells into the producing formation. The pressure of the overlying rock drives some oil and gas to the producing well. This is primary production, and a large fraction of the oil and/or gas remains behind. Several techniques, notably low-volume traditional fracking, can enhance production. In traditional fracking, approximately one swimming pool volume of water ($\sim$200 m^3) is typically injected into the target formation. The injected water creates one (or a few) open fracture(s). A proppant, such as sand, is also injected to keep the fracture(s) open. Oil and gas migrate freely through the permeable rock to the fracture(s) and then through the fracture(s) to the producing well.

Traditional fracking is effective in enhancing production in sandstone reservoirs, but it is not effective in enhancing production from shale reservoirs. The granular permeability of shales is so low that gas and oil cannot migrate to the fractures produced by traditional fracking. In order to extract oil and gas from shale reservoirs, a new approach to fracking has been developed over the past 30 years. We refer to this approach as modern fracking to clearly distinguish it from traditional fracking. The objective of modern fracking is to reopen and/or create fractures over a wide range of scales so that oil and gas can migrate to a production well through the fractures. In a modern fracking treatment, approximately 100 swimming pools' worth of water ($\sim$20,000 m^3) is injected into the target formation. However, simply using large volumes of water in tight shale fracking is not successful. The major development leading to the success of modern fracking was the use of slickwater as the injection fluid. The main additive in slickwater is a low concentration of polyacrylamide, a high-molecular-weight chain polymer that suppresses fluid turbulence, thereby reducing the frictional resistance to fluid flow during injection. We discuss slickwater in some detail in Section 3.4.

The reason natural fracking, as discussed above, is so important is that the fractures naturally cover the required range of scales for the migration of oil and/or gas. It is generally accepted that the reactivation of natural fractures plays an important role in the success of modern fracking. It is also generally accepted that the natural fractures must be sealed by depositional processes in order for modern fracking to be successful (Gale et al. 2014). This sealing creates tight shales with very low fracture permeability. If the natural fractures are not sealed, the injected fluid leaks through the larger fractures without enhancing fracture permeability over a wide range of scales.

At this time, significant extraction of oil and gas from tight shales using modern fracking is limited to the continental United States. The distribution of shale formations in the United States

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Figure 1

Map of the major shale formations in the continental United States from which oil and/or gas are being extracted (current plays) and those with future potential (prospective plays). Also shown are the sedimentary basins in which the shale formations are found. From US EIA (2014).

is shown in **Figure 1**. The large quantities of gas and oil extracted from tight shales have had a major impact on prices. From the annual average US natural gas wellhead price for the period from 1970 to 2012 given in **Figure 2** it can be seen that the annual average US natural gas wellhead price dropped by about two-thirds between 2008 and 2012, from $7.97 per thousand cubic feet to $2.66 per thousand cubic feet. The production from the Marcellus Shale in Pennsylvania played a large role in this drop. This production was 168 billion cubic feet in 2005 and increased to 3,259 billion cubic feet in 2013, nearly 20 times as large. Today, Texas is the only state that produces more natural gas than Pennsylvania.

Unlike that of natural gas, the price of oil is quite uniform globally due to the ease of its transport. The large quantities of shale oil produced in the United States have had a major impact on global oil prices. In 2014, the price dropped from about $100 per barrel to about $50 per barrel during the year. The production of oil from the Bakken Shale in North Dakota played a large role in this drop. This production increased from 36 million barrels in 2005 to 397 million barrels in 2014. Today, Texas is the only state that produces more oil than North Dakota.

The use of modern fracking is also highly controversial. There are certainly valid environmental concerns about the risks associated with modern fracking techniques, including methane emissions, groundwater contamination, induced seismicity, and the explosive nature of the oil produced.

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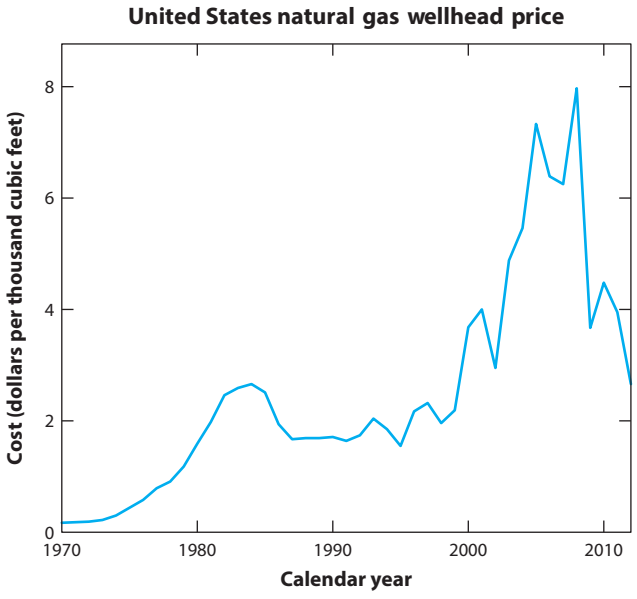

Figure 2

Annual average US natural gas wellhead price in dollars per thousand cubic feet for the period from 1970 to 2012 (US EIA 2015e).

There are also concerns that additional supplies and low prices of hydrocarbons that result from the widespread use of modern fracking in tight shales will slow the transition to renewable sources of energy. Oil and gas are finite nonrenewable resources, and their use emits greenhouse gases.

In order to provide the basis for understanding the challenges associated with the extraction of oil and gas from tight shales, we first give a brief explanation of how oil and gas are formed within shale reservoirs. Of particular importance is the role of natural fracturing during oil and gas formation. Natural fracking generates fractures in shales over a wide range of scales. In some shales, deposition of carbonate and silica seals these fractures. The reactivation and enhancement of this fracture permeability is the goal of modern fracking.

It is essential to understand the difference between low-volume traditional fracking and high-volume modern fracking. Traditional fracking typically uses low volumes of water and has been used on millions of wells for more than 50 years with few environmental concerns, but traditional fracking has not been effective in the extraction of oil and gas from tight shales. Modern fracking has been developed empirically. It uses large volumes of water and enables the extraction of large quantities of oil and gas from tight shale reservoirs at competitive prices. The physical and chemical processes associated with the success of modern fracking remain unclear.

We next consider in some detail the role of modern fracking in five black shales. We consider the successful extraction of large quantities of gas from the Barnett and Marcellus Shales and the successful extraction of large quantities of oil from the Bakken Shale. We also discuss the lack of success of modern fracking in the Antrim and Monterey Shales.

Many models of hydraulic fracturing have been published. Most of these models consider the growth of a single or a small number of discrete fractures. We review these and also consider continuum models, in which a damage variable quantifies fracture density, as well as percolation models. We also consider environmental problems in some detail.

Overviews of modern fracking from various points of view have been given by Curtis (2002), King (2012), Armor (2013), Wang et al. (2014), and Turcotte et al. (2014). An excellent overview of reservoir geomechanics has been given by Zoback (2010). The purpose of this article is to provide an overview of current practice and problems for academic geoscientists. As the development of modern fracking has been largely empirical, the scientific basis for understanding the success of modern fracking is limited. The proprietary nature of the studies of modern fracking and the dominant role played by small oil and gas companies have limited the development of an understanding of the relevant geophysical and geochemical processes.

2. ORIGIN OF TIGHT SHALE RESERVOIRS

Conventional production has historically focused on exploiting traps after gas and oil migrate out of the source. Utilizing the source reservoir directly has required both new technologies and new strategies. Of particular importance are the fractures generated during the thermal conversion of organic material to oil and gas and the sealing of these fractures by mineral deposition leading to low-permeability, tight shales.

2.1. Black Shales

Oil and gas form from organic material included in sedimentary deposits. Sediments are primarily of two types: clastic, including silica-rich or carbonate-rich sand and mud, and chemical, which have high concentrations of calcium carbonate, halite, or gypsum. As sedimentation increases, the depth of burial and the associated pressure and temperature increase. Lithification converts the loose sediment to rock through compaction, cementation, and recrystallization. Sand becomes sandstone, mud becomes mudstone or shale, and calcium carbonate becomes limestone or dolostone. The increased temperatures due to burial lead to the thermal maturation of shales. This process has been reviewed by Bernard & Horsfield (2014). In this section, we concentrate on the mechanical aspects, particularly of natural fracking.

In order for the organic material in the sediments to form oil or gas, the deposition and burial must occur in an anoxic (reducing) environment. This environment requires restricted circulation of water that can oxidize the carbon in the sediment. Unlike in coarse sand, the flow of oxygenated water is strongly restricted in fine-grained mud, reducing the oxidation of the organic carbon. Thus, shales are a favored source rock for oil and gas.

A shale that contains significant quantities of organic carbon is known as a black shale due to its color. If enough organic deposition and burial of mud exhaust the oxygen supply in the environment, a black shale can form. Black shales generally contain 2–8% organic carbon by weight. Most black shales are marine in origin, and they can have horizontal extents of a thousand kilometers or more (Tourtelot 1979, Arthur & Sageman 1994).

As additional sedimentation occurs, the depth of burial increases, as do the pressure and temperature. A typical vertical thermal gradient during deposition is 30°C/km. Organic material is converted to kerogens at temperatures of about 50°C. Further heating breaks chemical bonds in the kerogens, generating oil. The pressure-temperature region in which this change occurs is the so-called oil window, with typical temperatures in the range 60–120°C and depths in the range 2–4 km. Further burial increases the temperature, and the oil is transformed to gas through a process often called cracking. The region where this transformation occurs is called the gas window and has typical temperatures in the range 90–180°C and depths in the range 3–6 km. These changes involve complex chemical phenomena, as summarized by Hunt (1996).

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The sediments that have produced most of the world's oil were deposited during a relatively small fraction of geological time. These periods were times when conditions enabled the generation of black shales. Detailed studies have shown that reservoirs that have produced some 90% of the world's oil were deposited in less than 40% of the Phanerozoic time (some 200 Ma out of the past 545 Ma) (Klemme & Ulmishek 1991, Trabucho-Alexandre et al. 2012).

2.2. Natural Fracking and Its Consequences

Whether or not the black shales ultimately keep the oil and gas in situ depends on the mechanisms available for fluid escape. The fine-grained nature of shales ensures low matrix permeability. However, the generation of oil and gas produces high fluid pressures, and the result is natural fracking with a network of fractures on a wide range of scales. This leads to the upward migration of some hydrocarbons into overlying formations. Once natural fracking occurs, consequences extend beyond simple hydrocarbon escape. Seeps, mud volcanoes, and sand dikes can all result. Understanding the consequences of natural fracking provides a template for predicting the consequences of high-volume modern fracking.

2.2.1. Natural fracking. Shale reservoirs contain extensive fractures on a wide range of scales. Some of these fractures have lateral offsets and are thus faults. The origins of faults can generally be attributed to stress differentials associated with tectonic processes; however, a large fraction of the fractures in shales have little or no lateral offsets and represent pure opening. These fractures are referred to as joint sets, and many are attributed to high fluid pressure. Secor (1965) described such fractures as extensional fractures perpendicular to the least principal compressive stress direction. These joint (fracture) sets are found in all black shales in which oil and gas have been generated (Olson et al. 2009) and are the result of natural fracking.

Books that consider fracture reservoirs in detail include those by Aguilera (1995) and Nelson (2001). A comprehensive review of natural fractures has been given by Gale et al. (2014). Walton & McLennan (2013) discussed in detail the role of natural fractures in producing oil and gas from tight shale formations. Gasparrini et al. (2014) have carried out a detailed study of the origins of natural fractures in the Barnett Shale, Texas. These authors recognized four distinct types of natural fractures with different origins: Type 1 fractures form at very shallow depths owing to initial compaction, Type 2 fractures form from compaction at greater depths owing to mechanisms such as pressure solutions of the shale, and Type 3 and 4 fractures result from the generation of oil and gas and the associated high fluid pressures. Lacazette & Engelder (1992) presented a detailed study of organic-rich black shales and concluded that the joint sets were generated synchronously with gas. Studies of natural hydraulic fractures by Engelder & Lacazette (1990) indicated that the generating pore pressure is about 85% of the pressure generated by the weight of the overlying rock (overburden).

Overpressure due to compaction has been considered in some detail by Swarbrick & Osborne (1998). Aydin (2014) discussed the role of overpressure in generating fractures, including the role of pressure solution during compaction. Our primary interest is in overpressures associated with oil and gas generation. Berg & Gangi (1999) and Swarbrick et al. (2004) quantified the generation of overpressured oil and gas in shales from volume changes associated with the transformations of kerogens to oil and gas. Barker (1990) determined the changes in volume and pressure during the thermal cracking of oil to gas in reservoirs and found that they are sufficient to cause fracturing if the permeability is low, as it is with shales.

Natural fracking produces fracture permeability in shales. Granular permeability, although very low, allows oil and gas to flow to the closely spaced joints. The joint sets provide pathways for

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the vertical migration of the oil and gas. This migration reduces the fluid overpressure and has two other consequences: (*a*) The oil flows upward from source rocks (in the oil window) into reservoirs of higher-permeability strata (often porous sandstones) overlain by very low-permeability strata that trap the oil and gas. Conventional oil and gas production has been primarily from these reservoirs, which are relatively easy to access through conventional production wells. (*b*) Extensive vertical migration without structural or stratigraphic traps leads to surface hydrocarbon seeps.

Because the objective of fracking is to produce fractures that allow oil and gas to flow to production wells, it is of considerable interest to understand how natural fracking enables the vertical migration of oil and gas. For example, over what scales do diffusion processes transport oil and gas in tight shales? Laubach (2003) presented a detailed study of the generation of natural fractures on a range of scales. Marquez & Mountjoy (1996) considered the creation of fractures by an increase in gas pressure associated with the thermal cracking of oil to gas. They argued that the initial phase creates microfractures (<1 mm in width). Engelder & Lacazette (1990) suggested that high-pressure joint initiation takes place on 10–30-mm-diameter flaws (i.e., fossils, concretions, flute casts). Lash et al. (2004) found typical joint spacings ranging from 0.1 to 6 m in Appalachian black shales. The overall conclusion is that the excess fluid pressure due to the generation of oil and gas initiates brittle fractures on zones of weakness in the shale.

Another very important aspect of natural fractures is that they are often sealed by mineral deposition, in many cases calcite. This deposition reduces the fracture permeability of black shales and creates low-permeability tight shales. Gale & Holder (2010) argued that many fractures produced by fracking are reactivated natural fractures. Their argument is based on the direction of propagation of the fractures and the role of weak calcite-filled natural fractures. They pointed out that these fractures are weak because there is no crystalline bond between the calcite and the shale.

2.2.2. Hydrocarbon seeps and mud volcanoes. In addition to the upward migration of hydrocarbons into sandstones and carbonate reservoirs, natural fracking leads to surface seeps of oil and the surface expulsion of gas. An excellent example of these processes is the upward migration of oil and gas from the Monterey Shale in California. The northern Santa Barbara Channel is one of the largest natural hydrocarbon seepage areas in the world (Hornafius et al. 1999). The most intense area of natural seepage is the Coal Oil Point seep field (about 15 km west of Santa Barbara, California). Resulting oil slicks have lengths of up to 10 km. Estimated leakage rates are $5.8 \pm 0.7 \times 10^3$ m^3/yr for oil and $6.2 \pm 1.1 \times 10^7$ m^3/yr ($4.1 \pm 0.7 \times 10^7$ kg/yr) for gas (Hornafius et al. 1999).

Another consequence of the upward migration of gas through natural fractures is the generation of mud volcanoes. Mud volcanoes are generated by the expulsion of fluidized sediment to Earth's surface. Sediment fluidization is typically due to the vertical migration of either water or gas. The extruded material forms a variety of morphological features, from domal forms to funnel-shaped depressions, over a wide range of sizes, from meters to kilometers. More than 1,800 mud volcanoes have been identified, and comprehensive reviews of the mud volcano literature have been given by Dimitrov (2002) and Etiope et al. (2009). Mud volcanoes can be damaging and prolonged, such as the LUSI eruption in East Java (Davies et al. 2008, Sawolo et al. 2009).

Mud volcanoes leave distinctive structures in the geological record that attest to their prevalence. Løseth et al. (2011) reported a detailed study of relic conduits associated with the vertical flows of hydrocarbons, gas, and oil from reservoirs. Over 100 seafloor craters have been observed in offshore Nigeria. They are 100 to 700 m in diameter and up to 30 m deep. Associated seismic anomalies can be traced to a source reservoir zone at depths of 1 to 1.3 km. Outcrop studies of similar structures in Rhodes, Greece, were used to provide further constraints on the blowout

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structures. The authors proposed that high fluid pressure in the reservoir generates hydrofractures through which gas and oil flow at high velocities for hours to weeks, generating pipe-like structures. Eventually, the reservoir pressure drops, and the natural blowout terminates.

It is recognized that mud volcanoes and natural blowout structures contribute significant quantities of methane to the global atmosphere. However, these quantities are difficult to determine. Dimitrov (2002) suggested that the methane flux from onshore and shallow-water mud volcanoes ranges from 10.3 to 12.6 teragrams (Tg) per year (15.6 to 19.2 $\times$ 10^9 m^3/yr). Milkov et al. (2003) suggested a flux of approximately 27 Tg/yr (4.1 $\times$ 10^{10} m^3/yr) from deep-water blowout structures and a total flux of approximately 33 Tg/yr (5.0 $\times$ 10^{10} m^3/yr). To put these values in perspective, the annual production of natural gas in the United States is approximately 25 Tg/yr.

2.2.3. Sand dikes. The upward migration of gas and oil due to natural fracking has also been associated with the formation of sand dikes and sills. These are often referred to as sand intrusions because their emplacement strongly resembles the emplacement of basaltic magma intrusions. They are referred to as sand injectites because the sand has clearly been entrained in either water or hydrocarbon fluids. Sand injectites are widely present in petroleum reservoirs and play an important role in hydrocarbon extraction owing to their high permeabilities. Jolly & Linergan (2002) have given an extensive discussion concerning all aspects of sand intrusions. Jenkins (1930) pointed out that sand dikes are common in the shales of the San Joaquin Valley, California, and range in thickness from about 0.1 to 20 m. Jonk (2010) suggested that sand dikes can act as conduits for upward petroleum migration from oil shales. Thompson et al. (2007) have studied extensive Miocene age sand dikes and sills associated with the Santa Cruz mudstones and suggested that the fluidization associated with their emplacement resulted from the upward migration of gas. The relationship between sand injectites (including sand dikes and sills) and fracking has been discussed in detail by Braccini et al. (2008). These authors suggested that injectites can be a natural analog to fracking performed to stimulate reservoirs, with the entrained sand analogous to the proppant sand used in fracking.

3. HYDRAULIC FRACTURING (FRACKING)

The production of oil and gas requires a pressure differential between the target strata and the well to drive the fluid to the well. The lithostatic pressure generated by the weight of the overlying rock increases with depth. The well pressure is the weight of the liquid in the well reduced by pumping at the well head. The well pressure during production is typically one-half to one-third the formation pressure. The ability to extract oil and gas is primarily determined by the resistance to flow/permeability of the formation. In sandstones, the dominant permeability is granular; in shales, the dominant permeability results from natural fractures.

The purpose of hydraulic fracturing (fracking) is to enhance the formation permeability by using the injection of water to open existing fractures and create new fractures. Treatments are designed to maximize the permeability increase, the volume of the affected area, and the duration of the permeability increase.

3.1. Traditional Fracking

Traditional fracking has been used in a large fraction of the wells drilled into sandstone reservoirs. A perforation is made in the casing of the vertical well, and high-pressure water with additives is injected. The objective is to create a single or, at most, a few hydraulic fractures through

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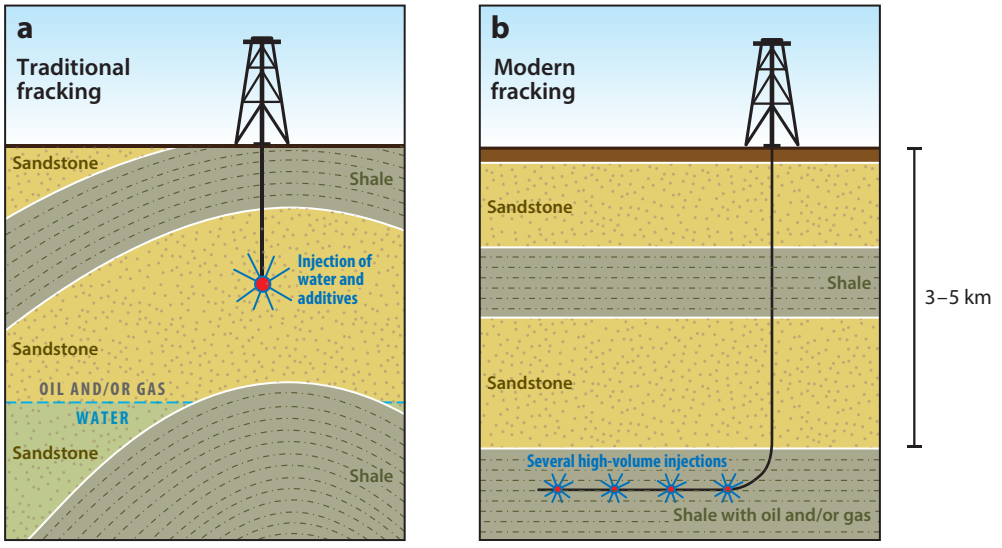

Figure 3

Schematic diagrams of traditional and modern fracking. (*a*) Traditional fracking. A sandstone reservoir lies below a low-permeability shale sedimentary trap in an anticlinal fold. A vertical well is drilled into the formation, and a fracking injection of water with additives (including sand as a proppant) from a vertical production well creates a single hydraulic fracture through which oil and/or gas flow to the production well. (*b*) Modern (high-volume) fracking. Directional drilling produces a horizontal production well in the horizontal target stratum, allowing several high-volume fracking injections of large volumes of a fluid with low frictional resistance to create a wide distribution of hydraulic fractures. Oil and gas migrate through this network of fractures to the production well.

which the oil and/or gas can flow to the production well (Yew 1997, Fjaer et al. 2008). Small volumes of water are usually used and are injected at low flow rates. Traditional fracking typically uses 75 to 300 m^3 of water per injection event. Large volumes of a proppant (generally sand) are also injected in order to keep the fractures open. In order to help in the transport of the proppant, guar gum or hydroxyethyl cellulose is added to increase the viscosity of the water. The propagation of fractures away from the well is relatively slow, and the velocity is determined by the viscous resistance to flow (Spence 1989). Traditional fracking can increase the yield of oil and gas by approximately a factor of two. The fracture or fractures reach a larger volume of reservoir than that accessed by granular flow to the well alone. It is estimated that production from 80% of producing wells in the United States has involved traditional fracking (Montgomery & Smith 2010). **Figure 3*a*** schematically illustrates traditional fracking. A sandstone reservoir containing oil and/or gas lies beneath an impermeable trapping structure, which prevents the upward migration of the hydrocarbon. A vertical well is drilled into the reservoir, and a traditional fracking injection creates a single horizontal propagating fracture.

Sandstone and shale reservoirs contain much of Earth's oil and gas. The high permeability of sandstone reservoirs allows efficient extraction of oil and gas from traditional wells. Typical permeabilities range from 0.01 to 1 darcy (10^{-14} to 10^{-12} m^2). In shales, however, the small pores combined with surface tension and electrostatic forces between very small clay mineral grains strongly impede granular flow. Typical permeabilities range from 10^{-7} to 10^{-9} darcy (10^{-19} to 10^{-21} m^2). These values are 6 to 8 orders of magnitude lower than typical sandstone reservoir permeabilities.

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3.2. Modern Fracking

Natural fracking allows oil and gas to flow upward out of the shale, reducing the excess fluid pressure. Although some of the oil and gas from shales flows naturally upward into more permeable sandstones and in some cases to the surface, a large fraction of the oil and gas remains trapped in the reservoir. With time, the natural fractures in the shales may be sealed by the deposition of silica or carbonates (primarily calcite).

Traditional fracking injections in shale reservoirs do not allow economical oil and/or gas recovery. Supported by the US Department of Energy, Mitchell Energy carried out sequences of empirical studies of high-volume injections into the Barnett Shale, Texas, during the 1980s and 1990s. The breakthrough that led to success was the use of slickwater as a fracking fluid. A detailed discussion of slickwater is given in Section 3.4.

The frictional resistance of slickwater is approximately an order of magnitude less than the frictional resistance of water under the same conditions, and approximately two orders of magnitude less than the frictional resistance of traditional fracking fluids. This reduction in frictional resistance allows the injection of much larger volumes of fluid at the same driving pressure. A typical modern fracking injection stage uses 7.5×10^3 to 11.0×10^3 m^3 of water, approximately 100 times as much water as in a typical traditional fracking injection (Montgomery 2013b). The typical rate of injection for a single modern fracking event is 0.4 m^3/s, and the injection time is approximately 6 h. High-pressure injection of slickwater typically reopens sealed natural fractures and generates new fractures.

Another important aspect of modern fracking is the use of horizontal drilling. This technique allows the driller to turn the well from a vertical to a horizontal direction and allows the well to produce over a much greater volume. This advantage stems from the fact that the potential production reservoir is generally in a nearly horizontal sedimentary stratum with a typical thickness of 100 m. The production well is drilled vertically until it reaches the target stratum. The horizontal extension is typically several kilometers in length. It is desirable to target relatively deep reservoirs, 3 to 5 km below the surface, so that there is high overburden pressure (and maximum principal stress) to drive the hydrocarbons out. Plugs or packers are used to block off a section of the well, and explosives are used to perforate the well casing. High-volume injections of slickwater through the blocked-off perforations create distributed hydrofractures, as illustrated in **Figure 3*b***. A sequence of high-volume fracking injections called stages are carried out as shown. Proppants are added just like in traditional fracking. Modern practice has expanded the range of proppants available, and current industry efforts are focused on strategies for proppant emplacement to maximize structural support for the fracture without clogging the fracture. A fraction of the injected fluid then flows back out of the well, and recovery of oil and/or gas begins.

3.3. Seismic Monitoring of Fracking

Sudden breaking of rocks releases seismic waves, generating a distribution of microseismic events that document the complex fracture growth that results from the high velocities and fluid pressures during injection. In order to determine fracture extent and accessed reservoir volume, it is standard practice to drill one or more monitoring wells, with seismometers distributed along their lengths. These seismometers help to locate the accompanying microseismicity in real time, and this information is used to control the rates of injection. **Figure 4** shows a typical distribution of seismic events from the Barnett Shale in Texas (Maxwell 2011). Similar data sets are documented by Busetti et al. (2014), Busetti & Reches (2014), and Warpinski (2013, 2014).

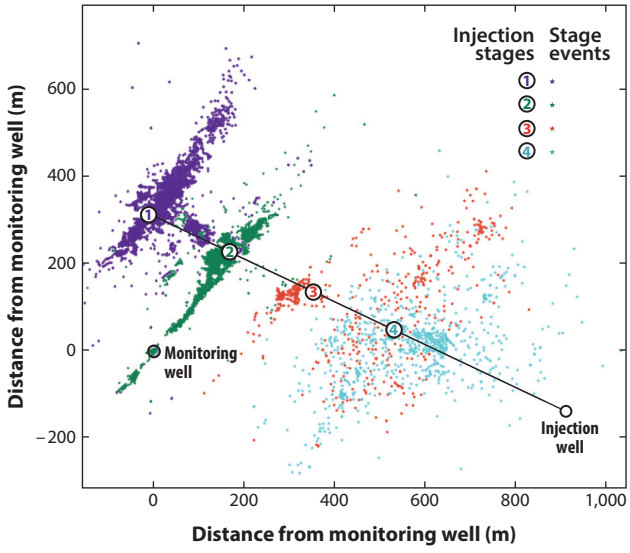

Figure 4

Map of the epicenters of microseismic events from a four-stage modern fracking treatment of the Barnett Shale, Texas. Figure adapted with permission from Maxwell (2011).

Shown are the microseismic epicenters from a four-stage modern fracking treatment as well as the locations of the horizontal injection/production well and the vertical monitoring well. The first and second stages produced relatively narrow clusters of seismicity, whereas the third and fourth stages produced much broader clusters indicating less localized fractures. The narrow clusters probably resulted from the orientation of the least principal compressional stresses being parallel to the horizontal injection well. It is important to note that the volume activated by the fracking treatment is more extensive than can easily be explained by a single fracture.

The seismic events are indicative of failure in the rock and are therefore useful to assess the affected volume. However, the details of the failure process are less clear. Rocks can fail either in tension, resulting in open fractures, or in shear, resulting in an offset on the fracture. Tensional failure occurs when the effective confining stress is low relative to the fluid pressure. At depth, the confining stress is usually large, and therefore shear failure is the more common result of deviatoric stresses. Opening of a dike or vein is tensional; earthquakes are generally shear failures. Both opening and shear failure can be produced by an increase in fluid pressure and therefore can be indicative of fluid migration. For tensile failure, the fluid pressure directly pushes open the crack. For shear failure, the fluid pressure reduces the normal effective stress on the fault and therefore reduces the effective friction locking the fault. Only opening cracks can directly increase permeability. Shear cracks can indirectly generate permeability through dilation of the surrounding rock and dynamic coupling with the porous media.

Interpreting the role of seismic events in the fracking process requires determining the sense of motion for individual events. Detailed studies with fully released data have suggested that failures are dominantly shear (Rutledge & Phillips 2003). Therefore, the seismic cloud is not directly an indicator of the opening of fluid channels. Using the earthquakes simply as an indicator of high fluid pressure is more robust, but also is not an absolute conclusion (Shapiro 2015). The elastic stresses transmitted around the fracture can produce shear failure even in the absence of pore pressure increase at the site of the seismic events. Such a propagating fracture is observed around diking (Rubin et al. 1998).

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The shear failure recorded seismically may or may not contribute to the permeability enhancement. The permeability could be increased through processes that do not generate seismic waves such as slow-opening fractures. Evidence for a slow failure process is provided by tiltmeter data, observations of tremor accompanying fracking, and a lack of correlation between seismicity and productivity (Warpinski 2014, Das & Zoback 2013, Zoback et al. 2012). The low values of the total radiated seismic energy are sometimes used to infer aseismic processes during fracking (Goodfellow et al. 2015), but such arguments must be used with care, as it is known that the seismic radiated energy can be a low percentage of the elastic energy release during ordinary earthquakes due in part to dissipative processes on the shearing fault plane (Kanamori et al. 1998, Kanamori & Brodsky 2004). Alternatively, the seismic events affect the permeability through either shear dilation (Zoback et al. 2012) or a more complex process such as feedback from the seismic waves to unclog existing fractures (Elkhoury et al. 2006, Candela et al. 2014). Determining the mechanism of permeability enhancement in the volume is the crux of understanding the effectiveness of current fracking treatments.

Another important implication of shear failure as the seismic source is that the recorded events are not observationally different from ordinary earthquakes. The events are therefore sometimes called microseismic events, with the implication that they are distinctly different in size from ordinary earthquakes. This is not a physically founded distinction, as all observable earthquakes have a distribution of sizes, with most earthquakes in any earthquake population being small.

3.4. Slickwater

The major discovery leading to the success of modern fracking was the use of slickwater as the injection fluid. The important additive in slickwater is polyacrylamide, a long-chain polymer with a molecular weight greater than 10^7. Required concentrations range from 0.15 to 2 parts per thousand by volume. The role of polyacrylamide is to inhibit the transition from laminar flow to turbulent flow as the Reynolds number (velocity) of the flow rate increases. The frictional resistance of laminar flow is 2–10 times less than the frictional resistance of turbulent flow at the same flow rate.

The ability of polymers to reduce frictional resistance was discovered by Toms (1948). Because polyacrylamide is inexpensive and nontoxic and only low concentrations are required, its use as a friction reducer has found a wide range of applications, as summarized by Gyr & Bewersdorff (1995). One application is in oil pipelines, where its use substantially reduces the pumping pressures required to drive flow at a specified rate. It should be noted that the actual mechanism by which the polymers suppress turbulence is poorly understood, which is not surprising given that turbulent flows are not well understood.

When slickwater containing polyacrylamide is used in modern fracking, one result is clear: The frictional resistance of the slickwater flowing down the well is substantially reduced. This allows substantially greater flow rates for the same pressure at the well head. One important question is what role the polymers play after being injected into the formation. The answer to this question is not known. A detailed discussion of additives used to generate slickwater has been given by Montgomery (2013a).

4. EXAMPLES OF US TIGHT SHALES

We now consider the production of oil and gas from five shales in the United States. Our purpose is to illustrate both successful and unsuccessful examples of the application of modern fracking. We begin with two examples of successful extraction of gas. The first is the Barnett Shale, in

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Texas, where modern fracking was developed with great success. The second is the Marcellus Shale, in Pennsylvania. Pennsylvania has become the state with the second-largest production of natural gas.

We then consider the Bakken Shale, in North Dakota, where modern fracking was developed for the extraction of oil. North Dakota is now the state with the second-largest production of oil. Finally, we consider two examples where modern fracking has not been successful in the extraction of oil and/or gas from tight shales. The first is the Antrim Shale, in Michigan, and the second is the Monterey Shale, in California. In both cases we associate the lack of success with the open natural fractures generated during the maturation of the organic material to form oil and gas.

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4.1. Barnett Shale

The Barnett Shale, in Texas, was the site of the original development of modern fracking. The Barnett Shale is a black shale of Lower Carboniferous age (340–323 Ma) located in the Fort Worth Basin (see **Figure 1**). Comprehensive summaries of the geology of the Barnett Shale have been given by Montgomery et al. (2005) and by Jarvie et al. (2007).

Successful high-volume injections of slickwater were developed by Mitchell Energy in the late 1980s to mid-1990s, supported by the Department of Energy (Curtis 2002). Combined with horizontal drilling, this technique has allowed for large quantities of gas to be produced from the tight Barnett Shale. Production rapidly accelerated in the early 2000s with the refinement of modern fracking technology. So far some 8,000 wells have been drilled in the Barnett Shale, about 90% of them since the year 2000. Most of these wells are horizontal and have involved modern fracking treatments.

The Barnett Shale is the second-largest producer of tight shale gas in the United States, with an annual production of some 0.5 Tcf (Tcf stands for trillion cubic feet; 1 Tcf $= 2.8 \times 10^{10}$ m^3) of gas. This figure compares with a total US annual production of some 25 Tcf. Accessible gas reserves in the Barnett Shale are estimated to be 43 Tcf (US EIA 2014). Gale et al. (2007) conducted detailed studies of natural fractures in cores from the Barnett Shale. They argued that calcite-filled fractures act as planes of weakness that are reactivated during fracking injections. Reactivation occurs because the bonding between the calcite and shale is weak, and it is relatively easy for the high-volume fracking injection to open the sealed fractures. Bowker (2007, p. 525) stated that the "Barnett is not a fractured shale play; it is a shale-that-can-be-fractured play." It should be emphasized that modern fracking is mostly successful if the tight shale is brittle, i.e., has low ductility. The Barnett Shale satisfies this condition.

4.2. Marcellus Shale

The Marcellus Shale is of Middle Devonian age (394–380 Ma) and is located in the Appalachian Basin (see **Figure 1**) (Lash & Engelder 2011, Lash & Blood 2014). Although most gas production has occurred in Pennsylvania, the Marcellus Shale extends into New York, West Virginia, and Ohio, with a total area of approximately 250,000 km^2. The average thickness is in the range of 15 to 60 m, and production is generally from depths of 1.2 to 2.5 km. The Marcellus Shale is relatively little deformed, mostly horizontal, and slightly older than the Bakken Shale. **Figure 5*a*** shows the annual production of gas for the period 2000 to 2013. Production increased rapidly from 0.20 Tcf in 2008 to 3.25 Tcf in 2013. Pennsylvania now produces more gas than any state except Texas, with estimated reserves of 1,500 Tcf.

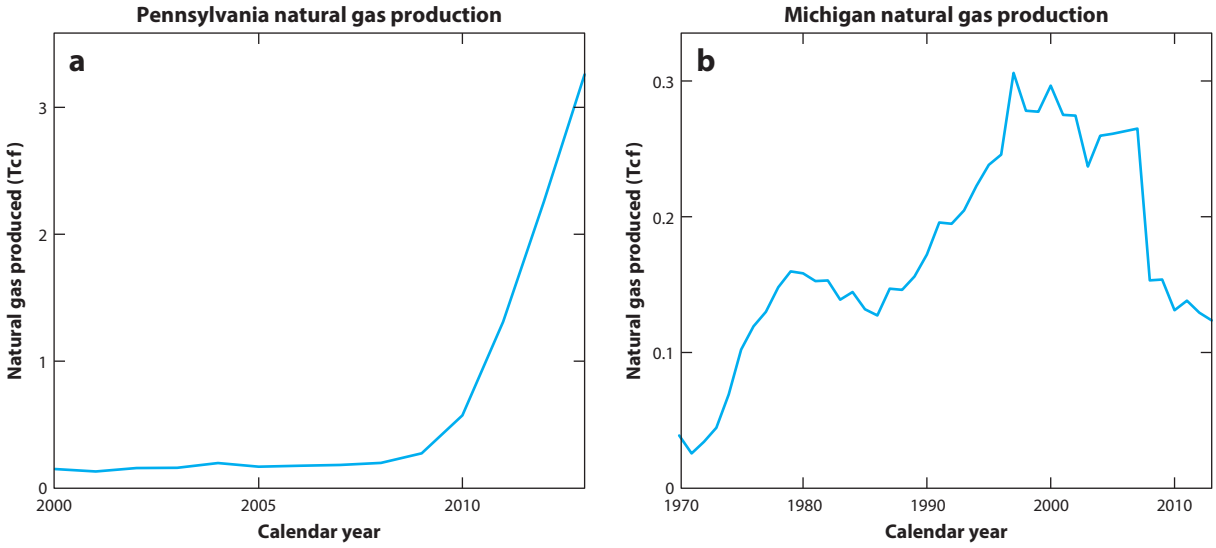

Figure 5

(*a*) Annual production of natural gas in Pennsylvania for the period 2000 to 2013 (US EIA 2015d). (*b*) Annual production of natural gas in Michigan for the period 1970 to 2013 (US EIA 2015b). Abbreviation: Tcf, trillion cubic feet.

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4.3. Bakken Shale

The Bakken Shale is a black shale of Late Devonian age (385–340 Ma) located in the Williston or Western Canada Basin (Kuhn et al. 2012). Most production has been in North Dakota, but the shale extends into Montana and Canada. The Bakken Shale is a little-deformed, mostly horizontal shale in which modern fracking was first shown to be effective in extracting oil from a tight shale. There are more than 6,000 producing wells in the Bakken Shale, primarily horizontal. **Figure 6*a*** shows the annual production of oil in North Dakota for the period 2000 to 2014. Production increased rapidly from 0.03 billion barrels (Bbbl) in 2004 to 0.40 Bbbl in 2014. This compares with a total US annual production of 3.16 Bbbl in 2013. North Dakota now produces more oil than any state but Texas.

The Bakken Shale is peculiar in producing oil rather than gas. Even with the increased permeability produced by fracking, the physical process of extracting viscous oil is perplexing. It is possible either that the oil resides in high-permeability sandstone pockets that merely need to be accessed by the frack or, alternatively, that the fracking permeability-enhancement mechanism is much more effective than a naive assessment of fracture widths would suggest.

4.4. Antrim Shale

The Antrim Shale is a black shale of Late Devonian age (370–354 Ma) in the horizontally stratified Michigan Basin. The Antrim and Bakken Shales are similar in age, depositional environment, and tectonic setting. They differ in hydrocarbon content—the Antrim Shale contains abundant gas with little oil, whereas the Bakken Shale has large quantities of oil.

Some 9,000 wells produce gas in the Antrim Shale, almost entirely traditional wells using traditional production techniques. **Figure 5*b*** shows the annual production of gas in Michigan for the period 1970 to 2013. Production peaked in 1997 and has subsequently declined. This production exploits open natural fractures that have remained largely unsealed (Curtis 2002). As

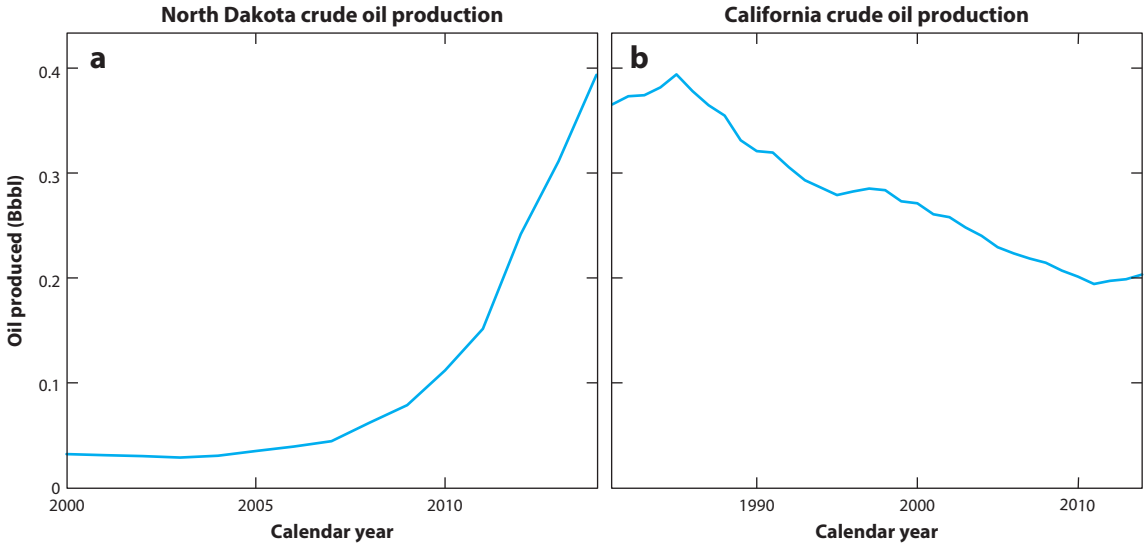

Figure 6

(*a*) Annual production of oil in North Dakota for the period 2000 to 2014 (US EIA 2015c). (*b*) Annual production of oil in California for the period 1981 to 2014 (US EIA 2015a). Abbreviation: Bbbl, billion barrels.

a result of the permeability of existing fractures, modern fracking has proven ineffective. The slickwater used in a modern fracking injection apparently migrates through the open preexisting natural fractures without effectively increasing the reservoir permeability. The inability of modern fracking to increase production can explain the decline in production of gas from the Antrim Shale at the same time that gas production from the Marcellus Shale was rapidly increasing (compare **Figure 5*a*** with **Figure 5*b***).

4.5. Monterey Shale

The Monterey Shale, in California, is quite different from the previous four shales we have considered. The Monterey Shale is much younger in age (17–8 Ma). In addition, it has evolved in a very active tectonic environment with significant fault displacements (Finkbeiner et al. 1997). The deposition of the Monterey Shale occurred in several sedimentary basins. On the east side of the San Andreas fault, the primary site of deposition is the San Joaquin Basin on the Sierra Nevada microplate. On the west side of the San Andreas fault, deposition occurred in several pull-apart basins associated with displacements between the Sierra Nevada microplate and the Pacific plate.

The Monterey Shale is a diverse, rhythmically bedded unit of organic-rich layers (black shale) alternating with silica-rich beds derived principally from the shells of diatoms, and minor sandstones and limestones. The shale can be 300–500 m thick (Behl 1999). A photograph of a surface exposure of a Monterey Shale equivalent near the Hayward fault in Berkeley, California, is given in **Figure 7**. The Monterey Shale has extensive fracture permeability from both natural fracking and tectonic deformation. This fracture permeability has allowed a large volume of oil to migrate from the shale to sandstones reservoirs, but the low matrix permeability of the black shale layers prevents a large fraction of the oil from escaping.

The sedimentary basins containing the Monterey Shale have yielded large quantities of oil for more than 100 years. The Monterey Shale is the accepted source rock for this oil, although a large

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Figure 7

Photograph of the highly fractured Monterey-equivalent (Claremont Formation) black shale exposed near the Hayward fault in Berkeley, California. Tectonic movements have brought this sedimentary rock from depth to the surface and rotated the beds from horizontal to vertical.

fraction of the production has been from younger sandstone strata into which the oil migrated. The total oil production from California basins has been some 29 Bbbl. The Los Angeles Basin, including the Long Beach, Huntington Beach, and Wilmington fields, has been one of the world's most productive oil regions per unit area (Norris & Webb 1990). **Figure 6*b*** shows the annual production of oil in California from the period 1981 to 2014. The production reached a maximum of 0.39 Bbbl in 1985 and has decreased steadily since.

The Department of Energy estimated that the total recoverable oil in the 48 contiguous states is 24 Bbbl (US EIA 2014). The report attributed 15 Bbbl of this figure to the Monterey Shale and 3.6 Bbbl to the Bakken Shale. Clearly the Monterey Shale has great potential for future petroleum production; however, there are obstacles to the recovery of this oil. Attempts to use modern fracking to extract oil have so far not been successful. This failure of modern fracking led the Department of Energy to reduce the estimated recoverable oil in the Monterey Shale from 15.4 to 0.6 Bbbl (US EIA 2014). Our hypothesis, as stated above, is that modern fracking requires a tight shale reservoir with sealed fractures to be successful. Large quantities of oil certainly remain trapped in the Monterey Shale, but significant extraction will require major technological advances. Norris et al. (2016) have provided an in-depth summary of the possible use of modern fracking in the Monterey Shale.

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5. FRACKING MODELS

A successful model for modern fracking should predict both the permeability enhancement and the affected volume produced by a given injection pressure and flow rate. A fully accurate predictive model of this type is not currently available, in part because some of the fundamental processes controlling the permeability enhancement and seismically imaged activation volume are not well documented.

The starting point for modeling fracking is a single planar hydraulic fracture. Such models have been extensively published primarily for application to traditional fracking as summarized by Valko & Economides (1995) and by Mack & Warpinski (2000). It should be pointed out that fluid injections can trigger tectonic earthquakes: High-pressure fluid can reduce the frictional resistance on a fault, resulting in the initiation of a rupture. Once initiated, this rupture can propagate like any other tectonic earthquake.

In this section, we emphasize models that have been developed for modern fracking. These include models for multiple fractures and models for the interaction between a propagating fracture and a preexisting natural fracture. Additional models for modern fracking include continuum damage models and invasion percolation models for the reactivation of natural fractures.

5.1. Fracture Models

The basic theory for the one-dimensional propagation of a planar hydraulic fracture has been given by Spence & Turcotte (1985, 1990). We consider an approximate estimate for the velocity of propagation of such a fracture. Fluid with a viscosity μ is injected at one end with an excess pressure Δp. The medium is elastic, with a Young's modulus E. The excess fluid pressure holds the fracture open and drives the fluid into the fracture, extending its length. Assuming laminar channel flow, the mean velocity of the injected fluid and associated fracture growth is approximately given by Rubin (1995):

$$v = \frac{L(\Delta p)^3}{\mu E^2}. \tag{1}$$

Taking $L = 10$ m, $\Delta p = 1$ MPa, $\mu = 10^{-3}$ Pa·s (for water), and $E = 100$ GPa (for shale), we obtain $v = 1$ m/s. The viscous resistance to flow gives relatively low velocities. Rates of fracture propagation are determined by the viscous pressure drop due to the flow of the fluid in the fracture. Adachi et al. (2007) provided an overview of numerical models used to simulate single planar hydraulic fractures under various constraints. Gupta & Duarte (2014) carried out finite element studies of the stability and propagation of a single hydraulic fracture with complex geometry.

Many papers have been published involving multifracture models. For example, Chuprakov et al. (2014) presented an analytic solution for the interaction of a propagating hydraulic fracture that intersects a natural fracture. Kresse & Weng (2013) have modeled interactions between a single propagating hydrofracture and a natural fracture. Kresse et al. (2013) extended this model to multiple interacting hydraulic and natural fractures. Zhang & Jeffrey (2012) modeled the complex interactions between a set of induced fractures and natural fractures.

We also cite a couple of representative models that have considered particular aspects of hydraulic fracture applications. Rutqvist et al. (2013) carried out numerical simulations of fluid injection into an existing fracture, including the generation of seismic activity. McClure & Horne (2011) coupled fluid injection with rate-and-state frictional failure on an existing fracture. Patzek et al. (2014) presented a very simple one-dimensional diffusion model for the drawdown of oil and gas after fracking from a horizontal well. These authors assumed that planar fractures extend

infinitely from the producing well and that oil and gas flow under pressure to the fractures, and they obtained good agreement with data. Flewelling et al. (2013) modeled the height of hydraulic fractures using a simple energy balance.

Fracture models are certainly applicable to traditional fracking involving only one or a few fractures, but their applicability to modern fracking is questionable. Modern fracking must create or reactivate fractures on a wide range of scales to be effective. We now discuss two alternative approaches to the modeling of modern fracking.

5.2. Damage Models

The objective of modern fracking is to produce open fractures on a wide range of scales in order to allow oil and/or gas to migrate to the production well. A uniform distribution of micro- and macrofractures can be quantified using damage mechanics (Shcherbakov & Turcotte 2003). In order to quantify the deviation from linear elasticity, the damage variable α is introduced in the stress-strain relation

$$\sigma = E_0(1 - \alpha)\epsilon, \tag{2}$$

where σ is the stress, ϵ is the strain, and E_0 is the Young's modulus of the undamaged rock. The damage variable α is a direct measure of the rock strain that can be attributed to slip and opening on micro- and macrocracks.

Norris et al. (2015a) obtained a spherically symmetric solution for the damage generated by the injection of a high-pressure fluid. It was assumed that water is injected from a small spherical cavity into a homogeneous elastic medium. The high pressure of the injected water generates circumferential stresses that reactivate natural fractures in tight shales. These fractures migrate outward as water is added, creating a spherical volume of damaged rock. The additional porosity volume associated with damage is assumed to be equal to the water volume injected. Applications of this model to a typical tight shale reservoir lead to predicted water volumes that are in good agreement with those used in modern fracking.

Smart et al. (2014) carried out a sequence of two-dimensional finite element numerical simulations. The matrix was modeled as a material subjected to continuum damage and plastic yielding. Deformation tended to concentrate in fault-like regions. The influence of preexisting faults, tectonic stresses, and structural variability was considered.

5.3. Invasion Percolation Models

The migration of fluid during natural fracking bears a strong resemblance to the flow of water through drainage networks. Stark (1991) successfully modeled the structure of drainage networks using an invasion percolation model. Rainwater drains into the smallest streams, which merge to form larger and larger streams with a fractal structure. This physical process strongly resembles the upward flow of oil and gas during natural fracking.

Invasion percolation models were developed to simulate the flow of a fluid into a complex medium. Many variations of this model have been considered and have been summarized by Ebrahimi (2010). To illustrate the use of an invasion percolation model to simulate modern fracking, we consider a two-dimensional square lattice. The sites are connected by bonds. A square array of sites are considered to be pore spaces on sealed natural fractures that the injected fluid will fill. The bonds are given random strengths. Fluid is introduced at a central site and migrates through the weakest bonds in the square lattice. Wilkinson & Barsony (1984) introduced the invasion percolation model, and Norris et al. (2014, 2015b) applied the model to modern fracking.

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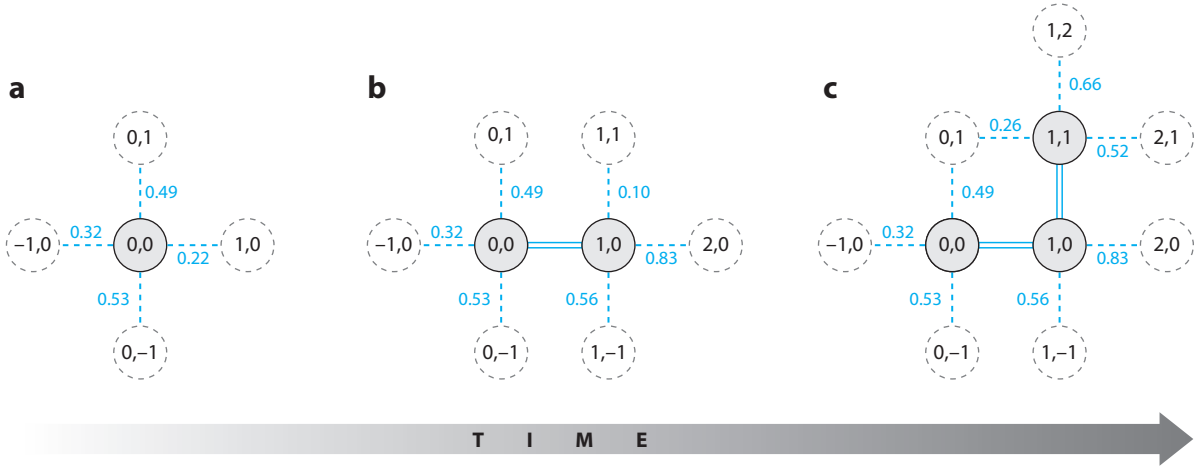

Figure 8

Illustration of an invasion percolation model. Fluid-filled sites are shown as solid circles and adjacent accessible sites as dashed circles. The numbers in the circles identify the sites. Open bonds between fluid-filled and adjacent accessible empty sites are shown as dashed lines. The numbers next to the unbroken bonds are the random assigned strengths s. At each time step, the weakest (smallest s) unbroken bond breaks, and fluid flows to the adjacent accessible site. A sequence of time steps is shown.

The initial evolution of an invasion percolation model is illustrated in **Figure 8**. Occupied sites are shown as solid circles, and adjacent accessible sites are shown as dashed circles. The numbers in the circles identify the sites. Opened bonds (open fractures) between sites are shown as double solid lines, and unopened bonds (sealed pathways) are shown as dashed lines.

High-pressure fluid is introduced at the central site. Closed bonds connecting the central site to four neighboring sites are given random strengths s in the range [0, 1). The weakest bond (smallest s) opens, and the high-pressure fluid flows into the adjacent site. Three new closed bonds connecting the newly invaded site to three new neighboring sites are given random strengths. At the next time step, fluid flows through the weakest of the six available bonds, and new closed bonds are added to the growing perimeter. This process continues, and at each time step, the weakest bond to an adjacent empty site breaks, the adjacent site fills with fluid, and closed bonds are added. The invading cluster grows outward as illustrated in **Figure 9**. It is clear from this figure that the boundary of the growing cluster is complex, with fingers of occupied sites extending in all directions.

A number of authors have recognized that cluster growth in invasion percolation occurs in bursts (Roux & Wilkinson 1988, Roux & Guyon 1989, Paczuski et al. 1996). When a growing cluster enters a region with low bond strengths, a subcluster forms. A burst is defined as a sequence of bond ruptures in which the s values are less than a specified threshold. Three examples of burst structures are illustrated in **Figure 10**. The four largest bursts are shown in color. The burst structures tend to resemble the microseismicity in a modern frack as illustrated in **Figure 4**. The frequency-size statistics of the invasion percolation bursts are Gutenberg-Richter, just like the frequency-size statistics of the microseismicity in modern fracks (Norris et al. 2014).

6. ENVIRONMENTAL PROBLEMS

Some environmental problems are inherent in the fracking process, such as the requirement for large volumes of water. Others can possibly be reduced or mitigated, such as atmospheric and

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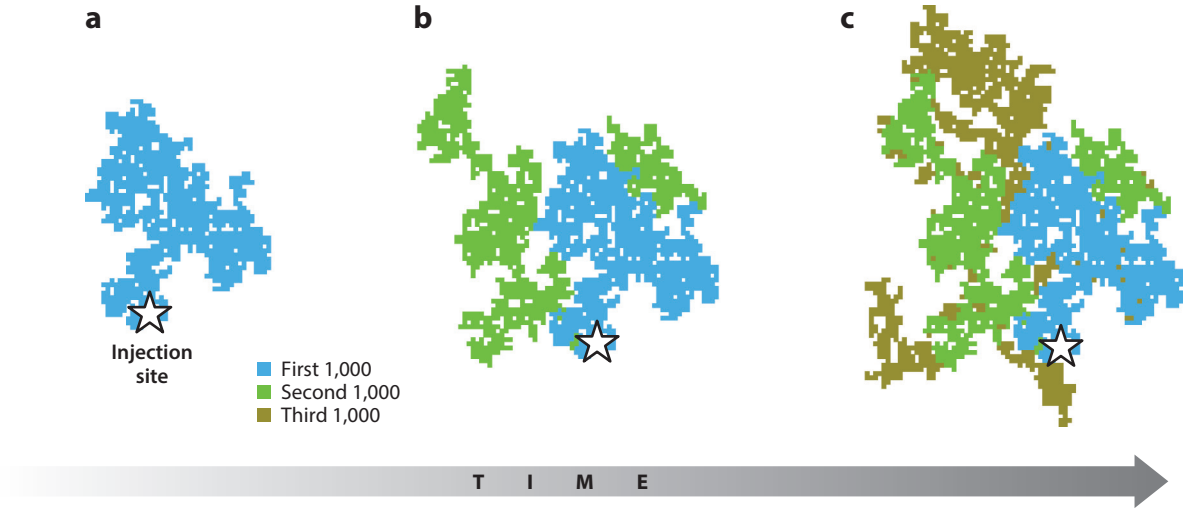

Figure 9

Growth of a typical invasion percolation cluster. Three steps in the growth are shown.

groundwater contamination. Some modern fracking treatments were carried out by relatively small companies, which in some cases did not apply proper safety precautions. In other cases, states with little prior oil and/or gas production had no regulatory framework in place.

Although the successes of modern fracking in terms of larger production rates and lower prices for oil and gas are well known, there is a widespread concern that these will reduce motivation for the short-term replacement of hydrocarbons with renewable energy sources such as hydro, wind, solar, and biomass. Oil and gas are nonrenewable resources, so that their replacement remains a high priority. Natural gas is replacing power generation using coal and thus reducing CO_2 emissions by a significant amount; however, these emissions contribute to climate change.

We share these global concerns, but choose to focus here on the environmental problems specifically associated with modern fracking in order to highlight relevant technical needs and

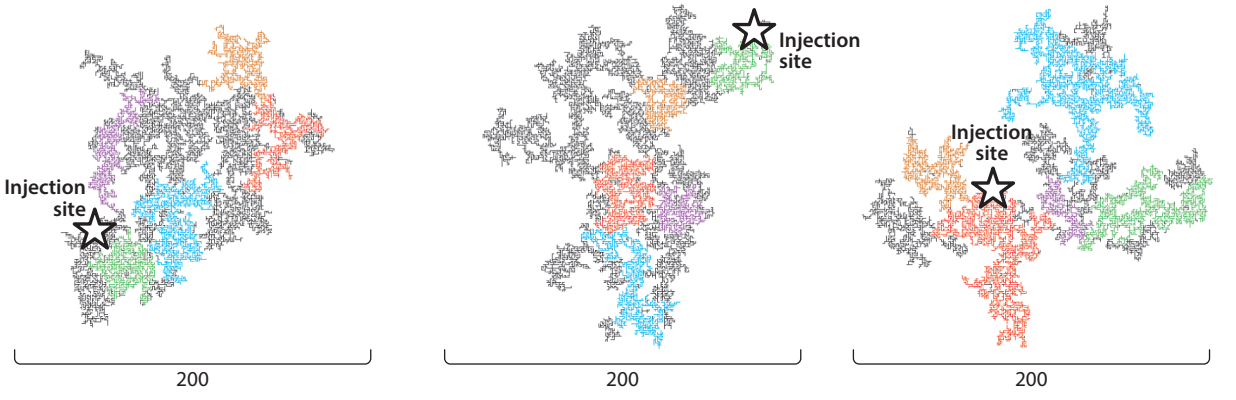

Figure 10

Three examples of clusters with burst structures. In each realization $M = 10{,}000$. The four largest bursts are shown in color. Smaller bursts and nonburst bonds are shown in black.

knowledge gaps. In places, we are guided by the understanding built from the consequences of natural fracking discussed above. Comprehensive reviews of the environmental problems associated with modern fracking have recently been given by King (2012), the California Council on Science and Technology (Calif. Counc. Sci. Technol. 2014), Jackson et al. (2014), and Sovacool (2014).

6.1. Water Use and Toxicity

Large quantities of water are required for modern fracking, which is of serious concern in arid areas, such as North Dakota and California. Additionally, concerns have been expressed about the toxicity of the injection fluids. These problems have been discussed in detail by Montgomery (2013b) and by the California Council on Science and Technology (Calif. Counc. Sci. Technol. 2014). It was concluded that only a few of the injected chemicals are toxic and that most are of equivalent toxicity to many commonly used industrial and household chemicals.

Also of concern is the fate of the injected water and chemicals. Only 20% to 40% of the injected water returns to the well head after an injection has ceased. This water is further contaminated by naturally occurring radiogenic isotopes and other contaminants from the reservoir rock. Because of the large volume of water used in modern fracking, surface storage and disposal of this contaminated water present serious problems. There have been documented cases of leakage from on-site storage ponds and spills during wastewater transportation. Large volumes of wastewater are reinjected, with several environmental problems, including contamination of shallow aquifers and induced seismicity.

There is also concern about the fate of the fraction of the injected water that is not returned to the well head. One particular question is whether some of this water can migrate upwards and contaminate shallow aquifers. The US Environmental Protection Agency concluded that the question of migration of modern fracking fluids to the water table has not been resolved so far (US EPA 2012).

6.2. Atmospheric Emissions

Methane is a greenhouse gas, and its emission into the atmosphere during modern fracking is of serious concern. As noted above, natural fracking leads to large emissions of methane from associated mud volcanoes. There are also documented examples of injected fluids generating mud volcanoes with methane emissions (Løseth et al. 2011). It is clearly desirable to minimize any methane emission into the atmosphere during oil and/or gas extraction. After a modern fracking injection, the flowback fluid can contain substantial concentrations of methane that can escape to the atmosphere. It is technologically feasible to prevent the escape of some 99% of this methane. Allen (2014) has given a comprehensive overview of atmospheric emissions associated with modern fracking.

Oil production in North Dakota's Bakken Shale has produced large quantities of methane in addition to oil. Pipelines are not available to transport all of this gas to market, and most is currently flared (burned). This practice is clearly undesirable in terms of air pollution and greenhouse gas production and as a waste of a natural resource. Alaska requires oil producers on the North Slope to reinject gas that cannot be utilized. Efforts to require similar practices in North Dakota and other localities are ongoing.

The total volume of flared and vented natural gas in the United States in 2013 was 7.37×10^9 m^3; for North Dakota in 2013, the total volume was 2.91×10^9 m^3 (US EIA 2014). To put these numbers in perspective, the total production of natural gas from the Barnett Shale during 2013 was 14×10^9 m^3.

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6.3. Groundwater Contamination

A major environmental problem of serious concern is whether modern fracking injections can transport gases (methane) and other contaminants upward to the water table. It has been demonstrated that methane has contaminated groundwater near modern fracking injections in some cases (Osborn et al. 2011). Studies of documented cases of groundwater contamination conclude that the leakage is associated with shallow leakage through the well casing or failures of the cementation of the well casing to the rock. Observationally, Davies et al. (2012) have reviewed the vertical extent of hydraulic fractures and estimated that the longest induced hydraulic fracture measured so far is 558 m and the longest natural hydraulic fracture is 1,106 m, significantly smaller than the typical depths of shale reservoirs. Vengosh et al. (2014) have presented a comprehensive review of groundwater contamination associated with modern fracking.

6.4. Induced Earthquakes

Human-induced earthquakes have been documented for 100 years. The definitive experiment demonstrating induced earthquakes involved injecting pressurized water into wells in a sandstone configuration similar to traditional fracking wells (Rayleigh et al. 1976). The seismic monitoring data discussed above show that earthquake generation is an intrinsic part of the modern fracking process. The key hazard question is whether the resultant earthquakes are physically required to be small and close to the well.

Most of the observed seismicity during a modern frack consists of earthquakes with magnitudes between $M = -4$ and $M = -1$ (Warpinski 2013). This is consistent with the behavior of earthquakes in general, where most of the seismicity in any region is small. The Gutenberg-Richter law is an empirical relationship that finds that the number of earthquakes of magnitude $\geq M$ is proportional to 10^{-bm}, where b is typically around 1. Therefore, if for a typical well there are $\sim 10^3$ events of magnitude -2 or greater, $b = 1$, and because there have been at least 10^5 fracking wells operating in North America over the past decade, we expect to have seen an earthquake $M \approx 6$ or greater near a fracking well during that period. This has not been observed. The largest earthquakes attributed directly to fracking occurred in the Horn River Basin, British Columbia, in 2014 and near Fox Creek, Alberta, in 2015, both with magnitudes $M = 4.4$ (Rubinstein & Mahani 2015).

The discrepancy between prediction and observation can be reconciled in at least two ways: (*a*) increasing the b value or (*b*) reducing the average number of magnitude -2 or greater events per well to 50. A b value of 1.2 is within the range of b values commonly seen for seismicity. Some suggest b values as high as 2.5 are appropriate for fracking-induced earthquakes, in which case the observed number of moderate earthquakes actually exceeds the statistical prediction (Eaton et al. 2014). Assessing the average number of $M > -2$ events per well is difficult because of the lack of publicly released data sets. In the handful of published data sets, significant variability in seismic productivity is observed even between stages of a single well (Warpinski 2013). We conclude based on a strictly statistical approach that the chance of triggering a moderate earthquake on a given well is small, but in aggregate, the large number of wells in the United States allows rare events to be realized.

Atkinson et al. (2015) pointed out that the shallow depths of induced seismicity combined with the low attenuation in the mid-continent can make even moderate earthquakes potentially damaging. The lack of earthquake-specific engineering in areas with low natural seismicity also contributes to a disproportionate hazard from even magnitude $M = 4$ events.

The statistical approach avoids the question of the physical mechanism for generating earthquakes and therefore runs the danger of extrapolating into an unphysical regime. As discussed

in Section 3.3, the connection between hydraulic fracturing and the associated cloud of seismic events is unresolved. One aspect that is unclear is the relative contributions of the loading from the fracking process to the preexisting stresses on nearby faults. McGarr (2014) argued that, if the earthquakes are entirely attributable to the stress from injection and confined to the weakened volume, the maximum magnitude is limited by the volume of fluid injected. On the other hand, if the fracking merely loads faults with extensive regions already near failure, then the limit on maximum magnitude is the size and connectivity of faults influenced by the coupled elastic and fluid fields. Borehole breakout studies have generally suggested that active faults are critically loaded and therefore triggering is a likely scenario (Zoback & Harjes 1997). The rate of naturally triggered earthquakes by seismic waves suggests that, over a sufficiently large region, the stresses required for fault failure are uniformly distributed over the fault's loading cycles, and therefore the distinction between induced and new earthquakes is a continuum (Brodsky & van der Elst 2014).

All natural earthquakes have aftershocks. Human-induced earthquakes appear to follow this pattern as well. Accounting for the aftershocks allows the Salton Sea geothermal field seismicity to be well correlated to the fluid extraction in the field (Brodsky & Lajoie 2013). The aftershocks potentially extend the reach of the induced earthquake sequence in both space and time. Ascertaining the relative contribution of aftershocks to the cloud of seismicity around a frack is an important remaining challenge.

Wastewater disposal from fracking produces another, and usually larger, source of earthquakes. Fracking wastewater has been associated with $M \geq 4$ earthquakes in Ohio, Arkansas, and Oklahoma, with the seismicity extending tens of kilometers from the causative wells (Ellsworth 2013). Disposal wells currently pose the largest seismic risk associated with fracking (Weingarten et al. 2015). Alternative wastewater disposal means would reduce the seismic problem but may not be practical because of groundwater contamination concerns. Current research is focused on determining why certain disposal wells produce abundant seismicity while others do not. As fracking commonly occurs in areas without high natural seismicity, the local seismic networks are generally sparse, resulting in poor knowledge of the historic seismicity. This problem is particularly acute when assessing the relative propensity of some areas to become activated, and knowledge of the local seismicity seems to be a factor. Densification of long-term regional networks is a key requirement for attribution studies.

The challenges in disaggregating effects on a regional basis are illustrated by the case of Oklahoma. Oklahoma is currently the location of the most vigorous earthquake sequences in the continental United States. The largest sequences have been associated with disposal of wastewater, primarily from sources other than fracking (Keranen et al. 2014). Most of the wastewater is a byproduct of submersible pumps used to dewater a high-permeability, water-rich formation and extract the accompanying oil and gas. Pinpointing the cause of the seismicity relied heavily on publicly released pressure, injection, and extraction data as well as the sparse regional seismic network. Key breakthroughs have been made by utilizing a temporary, academic seismic network (Keranen et al. 2013). Release of routinely collected seismic monitoring data on fracks and high-temporal-resolution injection data would greatly improve our ability to properly analyze, and ultimately avoid, unwanted seismicity.

6.5. Blowouts and Mud Volcanoes

Drilling and fracking rock require control of the wellhead pressure while puncturing overpressured units. As pressures and flows fluctuate, unstable eruptions of mud, fluid, and gas can occur. If the eruption is channeled within the borehole, the result is a well blowout. If the eruption forms a

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new conduit outside the borehole, a mud volcano or natural blowout results. In either case, the breaching and uncontrolled depressurization can pose a significant hazard.

Blowouts are a well-recognized drilling hazard. Blowout protectors are a standard safety feature when drilling; nonetheless, accidents do occasionally happen, as illustrated by the Deepwater Horizon failure. Løseth et al. (2011) also discussed a 40-m-diameter 7-m blowout crater close to the Tordis field in the Norwegian North Sea. This blowout was triggered by the injection of wastewater at a depth of 900 m below the seafloor. The injection lasted 5.5 months at an average rate of approximately 7,000 m^3 per day, and the blowout lasted at least 16 days and possibly as long as 77 days. Fracking well blowouts in recent years have occurred in Colorado, Pennsylvania, and Ohio.

Mud volcanoes are not a well-studied potential hazard. As the geological record of natural fracking illustrates, depressurization can produce violent events. The largest recent mud eruption formed the LUSI mud volcano in East Java. The eruption of this hybrid hydrocarbon/hydrothermal mud volcano began on May 29, 2006, and is still ongoing. The erupted mud has covered more than 7 km^2 and displaced more than 25,000 people; the maximum flow rate was greater than 10^5 m^3/day (Davies et al. 2008). Although some blame the eruption on a $M = 6.3$ earthquake that occurred 250 km away on May 27, 2006, the active gas exploration well 150 m from the initial eruption site makes drilling the more likely immediate cause (Davies et al. 2008, Sawolo et al. 2009).

6.6. Explosive Nature of Bakken Shale Oil

Oil produced from tight shale reservoirs, such as the Bakken Shale, tends to be volatile and explosive. This volatility arises from dissolved light hydrocarbons, such as methane, butane, and propane, with volume concentrations in the range 2% to 12%. Due to the large volumes of oil extracted from the Bakken Shale in North Dakota over a short period of time, pipelines for transport of the oil are not available. A large fraction of this oil travels by rail in tank cars, typically 600,000 barrels per day. Primary destinations are refineries in the northwest that previously used Alaskan crude and refineries in the northeast that previously used Middle Eastern crude. There have been several tank car explosions involving Bakken Shale oil, including one in Quebec that killed 47 people.

Oil from the Eagle Ford Shale, in South Texas, has similar volatility to Bakken Shale crude, but almost all of this oil has been treated using stabilizers. Stabilizers use heat and pressure to force light hydrocarbons out of solution. Pipeline companies generally require stabilization, and as a large fraction of the Eagle Ford Shale oil is transported by pipeline, stabilization has become routine. The companies responsible for oil production from the Bakken Shale in North Dakota made the decision not to stabilize the oil and to ship it by rail tank cars. Stabilization of the Bakken crude is clearly very desirable but will require considerable investment. An alternative under consideration is a federal requirement to use specially designed tank cars that can safely confine volatile crude, but the conversion from older tank cars will also take time and money.

7. CONCLUSIONS

Modern fracking has had a major impact on global economics and political balances. Fracking has also generated large-scale public opposition. The purpose of this review has been to summarize our current understanding of fracking and how it may evolve in the future. In so doing, we have been guided repeatedly by the observations of analogous, natural processes.

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The origin of tight black shales provides important insights into their potential for future oil and gas extraction. The very low granular permeability, owing to the fine-grained structures of shales, has both positive and negative implications for hydrocarbon production. This low permeability restricts water circulation, reducing the oxidation of the organic carbon. The result is that some shales—black shales—contain large quantities of oil and/or gas.

The conversion of the organic carbon to oil and, especially, to gas generates high fluid pressures. In the absence of fluid migration by granular flow, these high pressures generate hydrofractures on a wide range of scales. We refer to this process as natural fracking. The resulting fracture permeability allows oil and gas to migrate upward to the surface and into other sedimentary formations, particularly sandstones. This migration relieves the excess fluid pressure, but much of the oil and gas remains trapped in the black shales.

In some cases, the fracture permeability allows the extraction of oil and gas from black shales using traditional extraction methods. However, over geological times, the natural fractures are often sealed by the deposition of minerals, particular calcite. The Monterey Shale, in California, is an example of a relatively young, approximately 10 Ma, formation from which oil has been extracted using vertical wells. Another example is the Antrim Shale, in the Michigan Basin, from which relatively large quantities of gas have been extracted using vertical wells. Other older shales, such as the Barnett, Bakken, and Marcellus Shales, yielded very small quantities of oil and gas when traditional extraction techniques were applied. The natural fractures in these black shales have been largely sealed by the deposition of carbonates and silicates. For this reason they are referred to as tight shales.

Many attempts have been made to extract oil and gas from black shales using traditional hydraulic fracturing, but these attempts were essentially unsuccessful even with very large volumes of water. With the support of the Department of Energy, Mitchell Energy carried out extensive empirical studies of high-volume fracking in the Barnett Shale in the 1980s and 1990s. These were finally successful in the early 2000s. It is quite clear that the success was due to the use of slickwater, specifically the addition of polyacrylamide. The ability of slickwater to inhibit the transition from laminar flow to turbulent flow had long been recognized. This allows larger quantities of water to be injected at the same wellhead pressure. We speculate that the polymer additive also diverts the flow in the formation through both small and large fractures; however, this speculation has not been confirmed.

It is important to note that the current status of modern fracking is rather primitive in the sense that the fraction of oil extracted is in the 10–20% range (King 2012). This value is similar to that of traditional oil production before secondary recovery techniques such as water flooding were developed. It should be possible to increase the fraction of oil and gas extracted in both existing and new tight shale reservoirs. In addition, new developments in modern fracking techniques may enable the extraction of oil and gas from shales with open fractures such as the Monterey Shale.

It is clearly desirable to obtain a better understanding of how modern fracking works. One approach is to develop applicable models; however, modern fracking is clearly a complex phenomenon. Fractures must be reactivated or created on a wide range of scales to access trapped gas and/or oil in the tight shale. Three model classes are (*a*) models that prescribe a deterministic set of fractures, (*b*) damage models that hypothesize a homogeneous distribution of microcracks, and (*c*) percolation models based on models of drainage networks. Norris et al. (2014) used an invasion percolation model to explain modern fracking. A hierarchy of fracture sizes is a natural consequence of this type of model.

After natural fractures form during oil and gas generation, depositional processes tend to seal the smaller fractures first, leaving the larger fractures open. Modern fracking at this point is not successful because the injected fluid flows through the large open fractures. For modern fracking

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to be successful, the depositional processes must seal essentially all fractures, creating a tight black shale.

The rapid development of modern fracking has also contributed to some serious environmental incidents. There are certainly a range of environmental concerns associated with modern fracking. Many, but not all, can be addressed by enforced regulatory requirements. At the conclusion of a fracking injection, large quantities of contaminated slickwater are returned to the well head. The storage, transportation, and disposal of this water need to be regulated. To reduce environmental contamination and waste, gas produced during oil extraction should be recaptured with little or no atmospheric release, along with a prohibition on flaring. For safety during transportation, oil with explosive potential should be processed to remove volatiles.

Contamination of groundwater and the atmosphere by the upward migration of oil, gas, and slickwater can be greatly reduced by proper drilling practices. However, it is impossible to completely eliminate the risk of triggering upward fluid flows such as those associated with mud volcanoes. The risk of a directly triggered earthquake at any given frack is small, but the large number of fracks makes the aggregated risk higher. Wastewater disposal from fracks produces a larger but potentially more easily addressed risk. Developing safe, effective fracking and determining the appropriate limits of its use are daunting challenges that will require transdisciplinary expertise and access to the wealth of industrial observational data.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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